UNIVERSITY OF NAIROBI

School of Engineering

MSc. ELECTRICAL AND ELECTRONIC ENGINEERING

MULTI-OBJECTIVE AND MULTI-AREA OPTIMIZATION OF HYDROTHERMAL DYNAMIC ENVIRONMENTAL ECONOMIC DISPATCH USING HYBRIDIZED BAT ALGORITHM

BY

Name: **Seline Akinyi Olang'o (F56/88848/2016)**

Previous Degree: **Bsc. Electrical and Electronic Engineering (Hons)**

Institution: **Jomo Kenyatta University of Agriculture and Technology (JKUAT), 2009**

A research thesis submitted in partial fulfillment of the degree of Master of Science in Electrical and Electronic Engineering in the Department of Electrical and Information Engineering in the University of Nairobi.

Date of Submission: **11 October 2019**

DECLARATION

This MSc. research thesis is my original work and has not been presented for a degree award in this or any other university

SIGNATURE……………………………DATE…………………………………

Seline Akinyi Olang'o

Reg. No.: F56/88848/2016

APPROVAL

This MSc. research thesis has been submitted for examination to the School of Engineering, Department of Electrical and Information Engineering, of The University of Nairobi with our approval as University supervisors

1. Dr. Peter Moses Musau: SIGNATURE… ……………….DATE………………..

2. Prof. Nicodemus Abungu Odero: SIGNATURE………………….DATE……………….

DECLARATION OF ORIGINALITY

NAME OF STUDENT: Seline Akinyi Olang'o

REGISTRATION NUMBER: F56/88848/2016

COLLEGE: Architecture and Engineering

FACULTY/ SCHOOL/ INSTITUTE: Engineering

DEPARTMENT: Electrical & Information Engineering

COURSE NAME: Master of Science in Electrical & Electronic Engineering

TITLE OF WORK: **Multi-Objective and Multi-Area Optimization of Hydrothermal Dynamic Environmental Economic Dispatch using Hybridized Bat Algorithm**

1) I understand what plagiarism is and I am aware of the university policy in this regard.
2) I declare that this research thesis is my original work and has not been submitted elsewhere for examination, award of a degree or publication. Where other people's work, or my own work has been used, this has properly been acknowledged and referenced in accordance with the University of Nairobi's requirements.
3) I have not sought or used the services of any professional agencies to produce this work
4) I have not allowed, and shall not allow anyone to copy my work with the intention of passing it off as his/her own work
5) I understand that any false claim in respect of this work shall result in disciplinary action, in accordance with University anti- plagiarism policy

Signature: ....

Date: ....

DEDICATION

To my children, Cyril, Abigail and Bridget,

You inspire me to always bring out my best.

May you never cease to be all you dream and desire to be!!!

ACKNOWLEDGEMENT

I would like to take this opportunity to first and foremost thank God who said to me every day during this research, and even today still says to me in Isaiah 41:10 "*Don't be afraid, for I am with you. Don't be discouraged, for I am your God. I will strengthen you and help you. I will hold you up with my victorious right hand*" Truly without Him, I would not have had the wisdom or the strength or the physical ability finish this work.

My sincere gratitude goes to my supervisors, Dr. Peter Moses Musau and Prof. Nicodemus Abungu Odero, for their invaluable input, commitment and guidance throughout all the phases of this research work. They devoted so much time in patiently reading and reviewing this work over and over again. I'm also grateful to them for setting very high standards and ensuring that I achieved them.

My deepest gratitude also goes to my Husband, Peter Rimba, for all his support, encouragement and patience during the period of this work. He diligently tracked my progress, reviewed my reports and created a conducive environment that made all this possible.

I am thankful also to my family; Mum, Dad, Sister Ann and Friends Caro & Janet for their encouragement and for being part of my cheering squad.

Finally my appreciation goes to all the staff of the Electrical and Information Engineering Department of the University of Nairobi, for their tireless effort in ensuring we delivered our best and achieved our goals.

ABSTRACT

Multi-Objective and Multi-Area Optimization of Hydrothermal Dynamic Environmental Economic Dispatch using Hybridized Bat Algorithm

Economic Dispatch (ED) is one of the most important aspects of power systems planning and operation which must be considered in a Multi Area Power System for utilities in electricity exchange agreements to reap the benefits of system interconnections. This thesis presents a new formulation for ED problem called Multi Objective, Multi Area Hydrothermal Dynamic Environmental Economic Dispatch (MOMAHDEED) problem which determines the hourly optimal generating levels of all the hydro and thermal generating units in a multi area system to adequately supply the varying area load demands, such that the total fuel cost of thermal plants in all areas and emissions are simultaneously curtailed while satisfying physical and operational constraints.

The multi objective functions in MOMAHDEED problem are combined using weighted sum method and optimal solutions are selected using cardinal priority ranking. MOMAHDEED is then solved using Hybridized Modified Bat Algorithm (HMBA) which is a new algorithm developed by modifying Bat Algorithm (BA) and hybridizing it with Differential Evolution (DE). The Bat Algorithm is a metaheuristic algorithm which is inspired by echolocation behavior of micro bats. HMBA is developed by modifying the velocity and frequency equations of BA to improve its exploitation and exploration capability and further hybridizing it using the Differential Evolution (DE) to increase its accuracy.

The effectiveness and capability of the HMBA is tested by solving the Multi Area Environmental Economic Dispatch (MAEED) problem for four - area multi - area systems consisting of twelve and sixteen generating units. The scalability of HMBA is tested by solving the dynamic MOMAHDEED problem for a larger multi area system consisting of four areas, each with six generating units of larger capacities considering the effects of valve point loading, varying nature of demand and stochastic nature of water availability. HMBA realizes lower fuel costs and lower emissions compared to traditional BA and Particle Swarm Optimization (PSO) and its variants, Teaching – Learning Based Optimization (TLBO) and Pareto – Based Chemical- Reaction Optimization (PCRO) Algorithm for the same systems.

Keywords: *Bat Algorithm (BA), Differential Evolution (DE), Economic Dispatch (ED), Hybridized Modified Bat Algorithm (HMBA), Multi Objective, Multi Area Hydrothermal Dynamic Environmental Economic Dispatch (MOMAHDEED).*

Name: **Seline Akinyi Olang'o** Reg. No**: F56/88848/2016**

TABLE OF CONTENTS

List of Figures

List of Tables

Nomenclature

ABC – PSO	Artificial Bee Colony – Particle Swarm Optimization hybrid algorithm
BA	Bat Algorithm
BSA	Backtracking Search Algorithm
CGA	Controlled Genetic Algorithm
CSA	Cockoo Search Algorithm
DE	Differential Evolution
DED	Dynamic Economic Dispatch
EAPP	East African Power Pool
ED	Economic Dispatch
EED	Environmental, Economic Dispatch
EP	Evolutionary Programming
FCGA	Fuzzy Controlled Genetic Algorithm
FGALO	Fuzzy Guided Ant Lion Optimization
GA	Genetic Algorithm
HMBA	Hybridized Modified Bat Algorithm
INFP	Incremental Network Flow Programming
IWD	Intelligent Water Drop Algorithm
MA-DED	Multi-Area Dynamic Economic Dispatch
MAED	Multi-Area Economic Dispatch
MAHEED	Multi-Area Hydrothermal Environmental Economic Dispatch
MBA	Mutated Bat Algorithm
MFA-LF-DM	Modified Firefly Algorithm with Levy Flight and Derived Mutation
MFO	Moth Flame Optimization
MODE	Multi – Objective Differential Evolution
MOMAHDEED	Multi-Objective, Multi-Area, Hydrothermal Dynamic Environmental Economic Dispatch
MOMAHEED	Multi – Objective Multi-Area Hydrothermal Environmental Economic Dispatch
NBA	Novel Bat Algorithm
NEPOOL	New England Power Pool
NSGA-II	Non- Sorting Genetic Algorithm II
NYPP	New York Power Pool
PDF	Probability Distribution Function
PSO	Particle Swarm Optimization Algorithm
PSO_TVAC	Particle Swarm Optimization with Tine Varying Acceleration Coefficients
RCGA	Real – Coded Genetic Algorithm
RE	Renewable Energy
RECs	Regional Economic Communities
SAPP	Southern African Power Pool
SFLA	Shuffled Frog Leaping Algorithm
TLBO	Teaching Learning Based Optimization
WAPP	West African Power Pool
εv-MOGA	ε-Multi- Objective Genetic algorithm

CHAPTER ONE

1. INTRODUCTION

1.1. Background

1.1.1. Multi-Area Systems

A Multi-Area system is formed when multiple power system utilities in a state or in countries in distinct geographical locations are interconnected to form one big system via tie-lines.
In a Multi-Area system every country/power system utility consists of its own generation, loads and a control area. Coordination of loads and generation among the areas is done via the tie-lines[1].

Around the world many neighbouring countries are entering into inter-utility electricity exchange agreements (power pool) in order to lower electricity production costs, improve energy security including support during emergencies, make their networks more reliable and share their reserves. These interconnected utilities, by sharing their generation capacities and operational reserves are able to avoid incurring additional generation infrastructure investment costs and ensure a secure and an economically efficient operation of each utility and the interconnected system as a whole.

For nearly half a century now, interconnections and cross-border electricity exchanges have been in existence in Africa, and the development of these multi-area systems as a means of power pooling and electricity integration within Regional Economic Communities (RECs) has been encouraged in the recent years. [2]
Examples of electricity power pools around the world are; Nord Pool, New England Power Pool (NEPOOL), Greater Mekong Sub-region, South Asia Region, Southern African Power Pool (SAPP), West African Power Pool (WAPP), East African Power Pool (EAPP) among others.[2].

1.1.2. Economic Dispatch Problem

In order to recover the cost of project investment and make profit, economic operation of a power system is very important. Operational economics in power generation and delivery can be divided into two parts

i) Economic Dispatch (ED) which deals with minimizing cost of power production while satisfying the load.
ii) Delivery of the generated power to the loads at a minimum loss

The main aim of Economic Dispatch is to satisfy the load demand by scheduling the power output for each committed generator unit among the generating plants in such a way that they incur the least possible operating cost while satisfying all operational and physical constraints of the power systems[3].

In addition to the fuel consumption cost, the operating cost of a thermal unit includes fuel transportation cost, labour cost and maintenance cost. However for simplicity we only consider the fuel cost as the only variable cost since all the other costs are included as a fixed percentage of the fuel cost.

In hydro power stations, the energy cost is apparently free making the fuel cost not that meaningful hence the operational cost is negligible. Fuel cost is however very significant in the case of thermal and nuclear plants, but nuclear plants are operated at constant output levels and therefore this research only considers the fuel costs of thermal plants. Hydro plants have to be utilized fully to minimize overall cost in a hydrothermal system.

The relationship of the input (fuel) and output (electrical power) of a thermal power plant can be expressed as a convex curve shown in Figure 1.1 [4] and the fuel cost expressed as a smooth quadratic function .

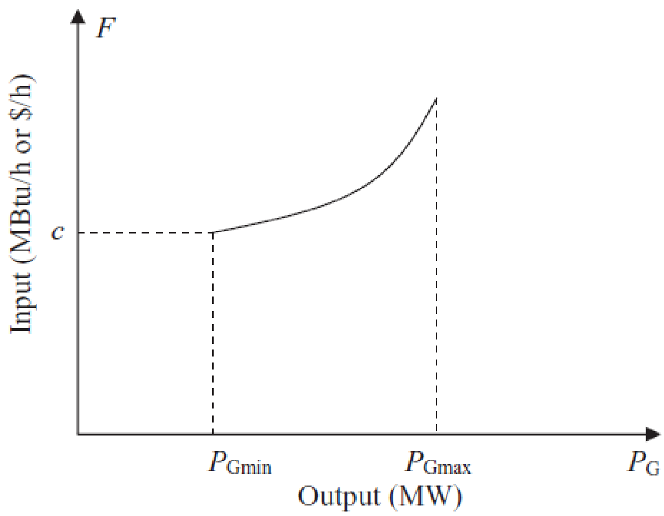


Figure 1:1 Input - output characteristic (Fuel cost curve) of a thermal generating unit [4]

The sole objective of classical ED is to minimize the total fuel cost based on the following assumptions:

i) The cost function is smooth

ii) Economic Dispatch is a static problem
iii) Environmental pollutant emissions of thermal power plants are not considered
iv) The startup and shut down costs are also neglected.

With these assumptions ED problem can be solved by using the traditional methods such as gradient search method, lambda iteration, Lagrange multiplier method, dynamic programming, linear programming etc. [4] However, these assumptions are impractical in the real world and do not give accurate results.

The concept of single area classical ED is also suited for the interconnected multi-area system since the generator cost functions are different for different areas.

1.1.3. Multi-Area Hydrothermal Economic Dispatch Problem

The main aim of Economic Dispatch in Hydrothermal Multi-Area systems is to satisfy the load demands of all areas by scheduling the power output for each committed generator unit among the hydroelectric and thermal plants in such a way that the thermal plants incur the least possible operating cost while satisfying all operational and physical constraints of the hydrothermal plants and the power systems.

Multi-Area Hydrothermal Economic Dispatch (MAHED) problem which aims to minimize the operating cost of a hydrothermal system can be viewed as one of minimizing the fuel cost of thermal plants under the constraint of water availability (storage and inflow) for hydro generation[5].

In a practical hydrothermal power system the following realities exist and must be incorporated in the Multi-Area Hydrothermal Economic Dispatch (MAHED) problem to achieve reasonable results;

i) Non smooth cost functions due to the effects of valve – point loading.
ii) Due to enforcement of environmental regulations, emission control to minimize environmental pollution caused by fossil-fueled generating units has to be considered.
iii) MAHED is dynamic when the varying nature of demand is considered.
iv) The limited capacity of water reservoirs and the fact that the availability of water is stochastic in nature makes the problem more complex for hydrothermal systems as compared to pure thermal systems [6].

i) Non-smooth Cost Functions With Valve-Point Loading Effects

Large turbine generators have a number of fuel admission valves and if increase in generation is needed, these valves are opened in sequence. This opening of a valve rapidly increases the throttling losses leading to a sudden rise in the incremental heat rate. This valve-point loading effect introduces ripples (Figure 1.2, [7]) in the heat-rate curves and is modelled mathematically as the superposition of sinusoidal functions and quadratic functions. This therefore make the objective function discontinuous, non-convex and with multiple minima.

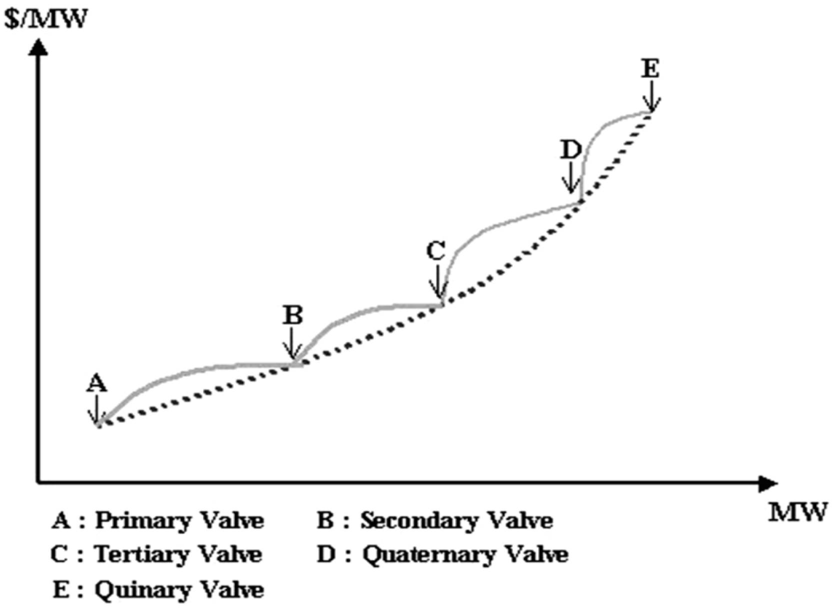


Figure 1:2: Non- Linearity in practical cost functions [7]

ii) Generator Emissions Function

With the rising environmental concerns, and the increasing public awareness of the environmental effects of power generation, utilities are forced to modify their operational strategies to reduce pollution and atmospheric emissions like Nitrogen Oxides (NO_x), Carbon Dioxide (CO_2) and Sulphur Dioxide (SO_2) generated by the fossil fuelled generating power plants. Emissions from power generation reached about 13 Gt, or 38% of total energy-related CO2 emissions in 2018 [8].

The single objective MAHED problem is no longer sufficient, hence the need to include environmental aspects in the MAHED problem resulting in Multi-Area Hydrothermal Environmental Economic Dispatch (MAHEED) [9].

By considering the fact that demand varies with time, MAHEED problem evolves to Multi Objective, Multi-Area Hydrothermal Dynamic Environmental Economic Dispatch (MOMAHDEED), which determines the optimal generating level of all the hydro and thermal generating units and inter-area power transactions to adequately supply the demand over a given time horizon, such that the total fuel cost of thermal plants in all areas and emissions are simultaneously curtailed while satisfying all physical and operational constraints.

In MOMAHDEED problem, which is the subject of this study, the two conflicting objective functions of minimizing cost and minimizing emissions are solved subject to the following constraints:

i) Thermal and Hydro units Generation Capacity Constraint
ii) Area power balance constraint considering transmission loss
iii) Area spinning reserve constraint
iv) Tie – line Capacity constraint
v) Dynamic water balance constraint
vi) Reservoir Capacity Constraints
vii) The Water Discharge Constraints

With the inclusion of all these constraints , the MOMAHDEED problem becomes a combination of nonlinear and non-convex multi objective problem which can no longer efficiently and accurately be solved by the traditional methods[9] due to the following shortcomings:

i) They are incapable of handling inequality constraints
ii) Linearization leads to loss of accuracy
iii) They employ derivative operations
iv) They have high execution time
v) They can only handle single objective functions
vi) Getting trapped in local optimal positions

To handle the above shortcomings, Meta-heuristic methods such as: Simulated annealing, Tabu search, Evolutionary computation, Ant colony algorithm, Differential evolution, Harmony search techniques, Artificial immune systems, Bat algorithm, Particle swarm optimization etc [10]. are being used to solve the complex MAHEED problem.

1.2. Problem Statement

For the power system utilities in a multi area system to reap the benefits of system interconnection, economic operation of the power system is critical especially with the challenges of growing demand and the escalating fuel prices. Economic Dispatch which deals with minimizing cost of power production while satisfying the demand and constraints is one of the most important optimization problems in power system planning and operation. However, the increasing public awareness on the effects of environmental pollution caused by power generation using fossil fuels has resulted in increased pressure on utilities to minimize emissions that is currently at 13Gt/yr, and hence utilities are faced with the challenge of simultaneously minimizing power generation costs and emissions.

To accurately represent a modern multi area system, it must be considered that most multi area systems are hydrothermal. Emissions, the varying nature of demand over time, reserve constraints as well as the stochastic nature of water availability need also to be considered when formulating MAED problem. This makes MAHEED problem dynamic and very complex.

Meta-heuristic methods have been used previously to solve nonlinear and non-convex MAED problem, but they suffer from challenges of premature and slow convergence, getting trapped in the local optima, high sensitivity to the parameters and settings and malfunctioning of algorithm for large systems. Hybridizing these algorithms has been proved to be an efficient way to overcome these challenges.

This research seeks to formulate and solve for the very first time a Multi-Objective, Multi-Area Hydrothermal, Dynamic Environmental Economic Dispatch (MOMAHDEED) problem using a Hybridized Modified Bat Algorithm (HMBA), as there is no evidence that exists in open literature of an approach similar to this.

1.3. Objectives

1.3.1. Main Objective

To formulate and solve a Multi-Objective, Multi-Area, Hydrothermal, Dynamic Environmental Economic Dispatch (MOMAHDEED) problem, using a Hybridized Modified Bat Algorithm (HMBA).

1.3.2. Specific Objectives

S1) To formulate the MOMAHDEED problem considering the major pollutant emissions and the physical and operational constraints of a modern hydrothermal multi-area system.

S2) To develop a Hybridized Modified Bat Algorithm (HMBA) and apply it in solving MOMAHDEED problem.

S3) To evaluate the performance of the algorithm in (S2) above by comparing and validating the HMBA results with those obtained by the traditional Bat Algorithm (BA) as well as the results obtained by other researchers.

1.4. Justification of the study

The number of multi-area systems is rapidly increasing as a result of increase in power pooling arrangements among neighboring utilities. Considering that most of these power pools are hydrothermal systems, there is need to solve MAHED problem that is formulated to closely resemble a modern multi area system to make it easy to adapt in real power pools.

Moreover due to the rising pressure to minimize environmental effects of power generation using fossil fuels, solving a single objective MAHED problem is no longer sufficient in determining the economic operation of a multi area power system. This therefore calls for a lot of research to find the most efficient and accurate solutions for the MAHEED problem that will enable utilities to reap the benefits of system interconnection while at the same time conserving the environment.

This research therefore seeks to formulate and solve for the first time a Multi Objective MAHED problem that represents a modern multi area system while considering emissions, contingency requirements and the dynamic nature of demand. This is a more robust formulation for modern interconnected power systems and makes the solutions more accurate and realistic.

1.5. Scope of Work

i) Formulation of MOMAHDEED problem considering the physical and operational constrains for a modern inter-connected hydrothermal power system.

ii) Developing Bat Algorithm (BA), Modified Bat Algorithm (MBA) and Hybridized Modified Bat Algorithm (HMBA) models in MATLAB

iii) Testing the algorithm on a:

  a) Four area test system with a total of twelve generating units;

  b) Four area test system with a total of sixteen generating units

  c) Four- area test system with a total of twenty four generating units

iv) Results analysis, validation via comparison with other methods and publishing of research work.

1.6. Contribution

In this research, a dynamic MAED problem which considers hydrothermal systems, emissions, varying nature of demand, effects of valve point loading, reserve constraint and the stochastic nature of water availability has been formulated and solved.

A more robust algorithm has also been developed by modifying the Bat Algorithm and hybridizing it using the Differential Evolution method. Weighted sum method has been used to convert the multi-objective problem into a single objective one and Cardinal Priority ranking used to select optimal solutions. The Hybridized Modified Bat Algorithm (HMBA) with Cardinal Priority ranking presented in this research has resulted in better results in terms of lower fuel costs, reduced emissions as well as lower transmission losses. HMBA is therefore proven to be superior in accuracy, robustness and convergence compared to other algorithms.

The developed MAED problem formulation represents a modern power pool more accurately, and the hybrid algorithm leads to more accurate and realistic results. The output of this research leads to better optimization of the multi-area power system operation in general and eases applicability to modern power pools.

1.7. Thesis Organization

This thesis has six chapters as follows:

Chapter One presents an introduction to the Multi Area Economic Dispatch problem, thesis problem statement, research objectives and scope of work.

Detailed review of previous works of other researchers in MAED, MAEED and MAHED is given in Chapter Two, culminating in a research gap.

Problem Formulation is given in Chapter Three which gives a detailed theoretical framework of formulation of MOMAHDEED problem.

Chapter Four presents an introduction to Bat Algorithm, modifications implemented in BA and describes how MBA is hybridized using Differential Evolution (DE). The pseudocode, flowchart and implementation procedure of the HMBA are also presented here.

Chapter Five shows the results obtained by BA, MBA and HMBA when applied to the formulated MAED, MAEED, MAHEED and MOMAHDEED problems and tested on a four-area and a five-area test systems.

In Chapter Six analysis and discussions of the results are presented and the results compared with those obtained by other researchers using other methods. Areas of further research are also identified for future work.

Chapter Seven concludes the thesis.

1.8. Chapter Conclusion

In this chapter a literature introduction to various aspects of Multi Area Economic Dispatch and the problem statement are presented. Justification of this study and Objectives are also discussed in this chapter as well as the scope of the study and the research contribution.

CHAPTER TWO

2. LITERATURE REVIEW

2.1. Review of Previous works

This section extensively reviews the works that have been done by various researchers in solving various aspects of MAED problem using different methods. The hybrid methods that have been used in solving MED are also discussed. The areas that are not addressed by these researchers are identified and summarized as a research gap.

2.1.1. Multi-Area Economic Dispatch (MAED)

Multi-Area Economic Dispatch (MAED), determines the optimal generating level of the generating units and inter-area power transactions such that total fuel cost in all areas are curtailed while satisfying generation capacity constraints, area power balance constraint, tie-line and other operational constraints. MAED problem was solved for the first time in 1981 using Dantzig-Wolfe decomposition principle[12] and then in 1995 using Network Flow Programming (NFP) [13]. MAED has been receiving a lot of attention in research since 2009 with over 100 publications to date as a result of the increasing number of power pools in the world. Various algorithms have since been proposed which include among others; Moth-Flame Optimization (MFO) [14], Electro Search Optimization [15], Backtracking Search Algorithm (BSA)[16], Flower Pollination Algorithm[17], λ-Concept and Tie line matrix [18], Self - Learning Cuckoo Search Algorithm [19]**,** Hybrid of Cuckoo Search and Teaching-Learning Based Algorithm (TLBO)[20], Real–Coded Genetic Algorithm (RCGA)[21] Differential Evolution[9], [22], PSO and its variants [1], [9], [23], Fuzzy Logic [24] and Direct (non-iterative) method [25]

MAED is however a single objective problem which is no longer sufficient especially with the rising awareness of the effects of environmental pollution resulting from emissions of fossil fueled power plants, and the ever increasing pressure to minimize them.

2.1.2. Multi- Area Environmental Economic Dispatch (MAEED)

A. Jinbei Li, 2018 [26] solved MAEED problem using Multi Objective Crisscross Optimization Algorithm (MOCSO), a combination of Pareto Multi-Objective Processing Strategy and Crisscross Optimization Algorithm (CSO). In MOCSO two interactive search operators were applied which characterized the crossover operation (Vertical crossover and horizontal crossover). By adopting a mechanism for cross-border search, horizontal crossover ensured global search ability, while vertical crossover applied dimensional crossover approach which prevented the algorithm from getting trapped in convergence stagnancy. A population of offspring called moderation solutions was alternatively reproduced by the two search operators which represented the solutions of MAEED problem. A greedy selection mechanism in MOCSO, where only the offspring with better fitness than the parent was maintained ensured speedy convergence. The objective functions were modelled as quadratic cost functions considering the effects of valve point loading which was solved subject to Generator capacity constraint, Generation power balance constraint considering transmission loss and Tie-line capacity constraint. The best compromise solution for the two conflicting objectives was selected using fuzzy set theory. The algorithm was tested on a four area test system with sixteen generating units and a four area test system with forty generating units. MOCSO realized a fuel cost of 7,709.265$/hr and emissions of 8965.2157ton/hr for the sixteen generator system and fuel cost of 124,460.7540$/hr and emissions of 234,003.702ton/hr for the forty generator system. In both cases the results were lower than those obtained by Chaotic Global Best Artificial Bee Colony Algorithm (GB-ABC) and Non- Sorting Genetic Algorithm II (NSGA II)

Balachandar et al, 2017 [27] proposed a Fuzzy Guided Ant Lion Optimizer (FGALO) to solve MAEED problem for an interconnected power system considering multiple fuel sources. The main Algorithm utilized was the Ant Lion Optimizer, developed form the hunting mechanism of Ant Lions. MAEED solutions were represented by the positions of Ant Lions and fitness of solutions represented by ants. For each ant, an ant lion was selected using Roulette Wheel selection. The fuel cost objective function was modelled as quadratic cost function considering the effects of valve point loading for Multiple Fuel sources and the emissions expressed as a piecewise segment function. This was solved subject to Generator capacity constraint, Generation power balance constraint without considering transmission loss and Tie-line capacity constraint. The best compromise solution for the two conflicting objectives was selected using Fuzzy decision making mechanism. The algorithm was tested on a 10 – generator test system modelled as a three area system and resulted in fuel costs of 657.684$/hr and emissions of 6399.9813ton/hr which were lower than those obtained by TLBO, DE, and RCGA with a far less execution time.

Azizivahed et al, 2017 [28] presented a hybrid of Shuffled Frog Leaping Algorithm (SFLA) and PSO to solve MAEED problem considering load uncertainty. Movement of frogs in SFLA was done by updating the Velocity implemented in PSO and included in each memeplexes of the SFLA. The positions of frogs in SFLA represented MAEED solutions. The objective functions were modelled as quadratic cost functions considering the effects of valve point loading which was solved subject to Generator capacity constraint, Generation power balance constraint considering transmission loss and Tie-line capacity constraint. Pareto – front strategy was applied to optimize both objectives. The uncertainty of stochastic nature of consumption of electrical energy was modelled by scenario reduction where roulette-wheel was used to generate a set scenarios sampled from discrete normal Probability Distribution Function (PDF). These were then sorted based on their probability and the scenario with highest probability was selected. The algorithm was tested on a 10 – generator test system divided in three areas and a 40 – generator test system divided into four areas. The algorithm resulted in fuel cost of $121,619.8 and emissions of 9,385,714.94ton for a 10 – generator test system which were lower fuel costs and emissions compared to TLBO, DE and Evolutionary Programming (EP). By considering 60 scenarios to simulate the uncertainty of load, the algorithm also realized a fuel cost of $136,258.54 and emissions of 10,002,160.3ton for the 40 – generator test system which was the best compromising solution for the two conflicting objectives.

Junqing et al, 2017 [10] proposed a Pareto-based Chemical Reaction Optimization Algorithm(PCRO) to solve the MAEED problem where a chemical molecule was used to represent each solution. PCRO is an improvement of Chemical Reaction Optimization Algorithm (CRO) developed by simulating the behaviour of molecules in a chemical reaction. In PCRO, the four elementary reactions of CRO which are; on-wall ineffective collision, inter-molecular ineffective collision, decomposition and synthesis were improved to enhance the local and global search abilities. Global search ability was enhanced by a kinetic-energy based search procedure together with an ensemble of effective neighbourhood approaches consisting of five neighbourhood structures and an encoding mechanism developed to further enhance the performance of the algorithm. In order to increase the search ability while still maintaining the population diversity, a mechanism for self-adaptive neighbourhood structure selection was embedded in the PCRO. To enable the algorithm converge near a Pareto front, a grid based crowding distance strategy was introduced. The minimization objectives were modelled as a quadratic cost function considering valve point loading, SO_X and NO_X emissions also computed as approximations of quadratic generator cost function considering valve point loading. These were solved subject to Generator capacity constraint, Generation power balance constraint considering transmission loss and Tie-line capacity constraint. The problem formulation however did not include reserve constraints and prohibited operating zone constraints. The proposed algorithm was tested for three different cases.

In the first case, the proposed algorithm was tested on IEEE 30-bus system with six generators achieving the best fuel cost solution of 600.123$/hr and the best emission solution of 0.22114ton/hr. These solutions were found to be superior to those obtained by BB-MOPSO, LP, NSGA, NPGA, SPEA, NSGA-II and FCPSO.

In the second case, the PCRO algorithm was tested on IEEE 30-bus system with six generators while considering transmission losses in order to validate the constraint handling ability of the algorithm. The best generated solutions were; fuel cost solution of 603.108$/hr, emission solution of 0.217835ton/hr and loss solution of 0.0115006pu. These results were compared to those obtained using SMOPSO, CMOPSO, TV-MOPSO and BB-MOPSO algorithms where it was seen to be superior to the four algorithms.

Finally in the third case to further validate performance, PCRO was tested on a four area test system with each area having four generators, and the results compared to those obtained using MOPSO, TLBO, TV-MOPSO and BB-MOPSO, where it resulted in better solutions with minimum fuel cost of 1984.3$/hr and minimum emissions of 0.023902ton/hr. It was therefore concluded that PCRO was a superior algorithm resulting in better quality of results and faster convergence.

Rasoul et al, 2016 [29] solved a Dynamic MOMAEED problem using a hybrid of gradient search method and improved Jaya algorithm (IGJA). The improved gradient-based Jaya algorithm was used to generate a feasible set of Pareto-optimal solutions that corresponded to the operation cost and emission calculated through bi-objective gradient-based method. A new mutation strategy consisting of mutation and crossover operators was embedded in the Jaya Algorithm to prevent the algorithm from converging prematurely and also to make the Pareto-optimal solutions more accurate. The strong exploitation capability and fast convergence features of Gradient-based method were employed to ensure that the solution obtained was a near-global Pareto optima. The problem was formulated as a Bi-Objective minimization problem with the fuel cost function expressed as a quadratic function considering valve point loading and multiple fuel options, while the emissions objective modelled as a respective approximation of the generator output. These were solved subject to Generator capacity constraint, area power balance restriction considering transmission loss, up and down ramp constraints, Prohibited operating zone constraints, up and down spinning reserve constraint and

Tie-line capacity constraint. The most preferable solution among the different Pareto-optimal solutions was obtained using fuzzy decision making procedure.
In solving the Bi-objective problem, the proposed algorithm was tested on a four-area system with each area having four generators. When the effects of valve point loading were considered, the algorithm yielded a solution of minimum fuel cost $ 2151.6960 and emission values of 3.02967 tons, in 0.0307 seconds of CPU computation time. IGJA algorithm resulted in lower operation cost and lower emissions, and faster computation times compared to DE with fuzzy selection algorithm.

Musau et al, 2016 [30] solved Multi Area, Multi Objective Dynamic Economic Dispatch (MAMODED) problem considering Renewable Energy (RE) sources (Solar and Wind) using a three method hybrid of Modified Firefly Algorithm with Levy Flights and Derived Mutation (MFA-LF-DM). Thermal and emission functions were modelled using cubic functions with consideration of valve point effects for more realistic results. MAMODED was defined as a five objective problem considering the objectives of thermal, emissions, solar, wind and tie line losses. A weighting factor was used to convert the multi-objective problem to a single objective. Scenario Based Method (SBM) was used to model the uncertainty and variability of RE sources. RE constraints with stochastic variables were also considered together with the static constraints. The problem was then solved subject to, Import/Export Area Power Balance Constraint considering Tie line losses, Area Spinning Reserve Constraint, Transmission Capacity Limits, Tie line Flow constraint, Thermal unit generation limits, Ramp up and ramp down constraint, Net actual demand constraint, Dispatched RE constraints and Reserved Power Constraint. The algorithm was tested on a five-area test case with six thermal sources in each area considering all the three emissions (SO_2, NO_2 and CO_2). The algorithm resulted in optimal benefits of $2128.99 and emissions of 990.09ton/MWh at the 11th iteration which were superior to optimal benefits of $2108.23 and emissions of 985.87ton/MWh obtained using OCD [31] for the same number of iterations.

Musau et al, 2016 [32] solved for the first time, MAMODED problem considering Renewable Energy (RE) sources (Solar and Wind) and Multi Terminal DC Tie lines using a three method hybrid of Modified Firefly Algorithm with Levy Flights and Derived Mutation (MFA-LF-DM). Scenario Based Method (SBM) was used to model the variability and uncertainties of RE sources. The Thermal Cost Function and the Emissions Cost Functions were modelled as cubic functions. MAMODED was defined as a five objective problem considering the objectives of thermal, emissions, solar, wind and MTDC tie line. A weighting factor was used to convert the multi-objective problem to a single objective, the random movement of the objective function was then reduced using Levy Flights and exploration of the candidate solution improved by derived mutations. The problem was then solved subject to, Import/Export Area Power Balance Constraint, Area Spinning Reserve Constraint, Thermal unit generation limits, Ramp up and ramp down constraint, Net actual demand constraint, Dispatched RE constraints, Reserved Power Constraint and MTDC constraints of transmission capacity, Tie line Flow, Converter Tap Ratio, Converter Ignition and extinction angles, and HVDC Current and Voltage Constrains. The algorithm was tested on a five-area test case with six thermal sources in each area considering all the three emissions (SO_2, NO_2 and CO2).The emissions and tie-line losses were considered after accounting for the RE sources. The algorithm resulted in lower emissions of 980.87ton/MWh and higher optimal benefit of $2133.99 for MAMODED with MTDC compared to MOMADED with HVAC which resulted in emission values of 990.09ton/MWh and optimal benefit of $2108.23 for the same number of iterations (11th iteration). The reduced operation cost was attributed to the fact that MTDC interconnections have fewer and smaller conductors which have less corona losses, are highly efficient and reliable, and use lighter and cheaper towers. This also leads to reduced wayleave requirement thus reducing the environmental impacts on the land. The lower emissions were attributed to the fact that the flexible RE sources forced offline and subsequently replaced the most polluting and inflexible thermal power plants resulting in an overall reduction of emission values.

Jadoun et al, 2015 [1] proposed an Enhanced particle Swarm Optimization to solve MAEED problem with Reserve Constraints. The cost and emissions objective functions were modelled as quadratic functions considering valve point loading. Fuzzy membership functions were used to convert the multi objective problem to a single objective which was then solved subject to Power balance constraint, Generator output limits, Tie line capacity constraints and Area spinning reserve constraint where a contingency requirements of every area was met by a fixed reserve kept in the respective area while the pool reserve was shared. The initial population was randomly created with each particle satisfying the constraints. Infeasible solutions created by the update of velocity and position were corrected by constraint handling algorithm which resulted in better results. To regulate particle’s velocity dynamically, the control equation was modified by incorporating suitable exponential constriction functions while preceding experiences used to modify the cognitive and social behaviors of the swarm guiding them towards the global optima. For validation purposes, the algorithm was tested on a four-area test system each with four thermal generating units while neglecting transmission losses. Three cases were considered where in case 1, area interconnection was assumed not to exist and so every area had to satisfy their own reserve requirement which was specified as 30% of area power demand. The proposed EPSO resulted in lower fuel cost and emissions of 2172.522$/hr and 2.997 ton/hr respectively compared to Pareto solutions obtained by [33]for the same system which had fuel costs varying from 2191.140$/hr to 2191.270$/hr and corresponding emissions varying from 3.749 ton/hr to 3.692 ton/hr.

In the second case, the areas were interconnected and the 30% individual area reserve requirements shared. The proposed EPSO resulted in lower fuel cost and emissions of 2165.7987$/hr and 2.8929ton/hr respectively compared to Pareto solutions obtained by [33] for the same system which had fuel costs varying from 2178.2000$/hr to 2166.8200$/hr and corresponding emissions varying from 3.2301ton/hr to 3.3152 ton/hr. This reserve sharing scheme and inter-area power flow also resulted in a reduction of fuel costs from 2172.522 $/hr to 2165.7987 $/hr and emissions from 2.997 ton/hr to 2.8329 ton/hr.

In case 3, the areas were interconnected, each area was required to meet their contingency reserve specified as 7% of the area's power demand, while the pooling reserve specified as 30% of the power demand of the area with the highest loading, was shared and contributed by all areas. The proposed EPSO resulted in lower fuel cost and emissions of 2164.8558$/hr and 2.4304ton/hr respectively. This proposed reserve sharing scheme resulted in a reduction of fuel costs from 2165.7987 $/hr to 2164.8558$/hr and emissions from 2.8329 ton/hr to 2.4304ton/hr when compared to reserve sharing method in case 2.

To test the algorithm for large and complex system a four-area system with each area having 10 generating units was considered. The Fuel costs and emission values were obtained as 129324.92$/hr and 106.5239ton/hr respectively for case 1 and 128519.35$/hr and 87.6159ton/hr respectively for case 2 with the spinning reserve specified as 20% of power demand for each individual area. In case 3, the contingency reserve was specified as 7% and pooling spinning reserve specified as 25% of the power demand of area 2. This resulted in lower fuel cost of 127036.79$/hr and lower emission values of 83.1192ton/hr. The reserve sharing scheme proposed further resulted in reduced total reserve requirement of the multi area system.

Lingfeng Wang & Chanan Singh, 2009 [33] solved RCMAEED problem using Multi-Objective Particle Swarm Optimization (MOPSO). The cost and emission objectives were both modelled as quadratic functions without consideration of the effects of valve point loading. This was solved subject to Generation capacity constraints, Area power balance constrains considering Tie-line losses, Tie-line constraints and Area spinning reserve constraints, where reserve sharing was only applied where there was an area with insufficient generation capacity to fulfil its reserve requirements. Only two types of emissions (SO_2 and NO_X) were considered and transmission losses were not considered. A set of Pareto-optimal solutions are obtained using MOPSO, and the best solution arrived at by employing fuzzification mechanism. The algorithm was tested on a four-area test system with four generating units in each area and resulted in Pareto solutions where fuel costs varied between 2178.2000$/hr and 2166.8200$/hr and corresponding emissions varied from 3.2301ton/hr and 3.3152 ton/hr . These results were lower than those obtained on the same system using the same algorithm without reserve sharing or inter-area power transfer where fuel costs varied from 2191.27$/hr to 2191.14$/hr and corresponding emissions varied from 3.6923ton/hr to 3.7493ton/hr.

Whereas MAEED problem considers both fuel cost and emission reduction, these researchers did not consider hydroelectric systems yet most multi area systems are hydrothermal in nature, hence they do not accurately represent modern power pools. With the continued research into metaheuristic algorithms there is also a lot of room to apply the newly developed algorithms into solving more complex versions of ED problem.

2.1.3. Multi- Area Hydrothermal Economic Dispatch

Alireza Soroudi & Abbas Rabiee, 2013 [31] proposed an Optimality Condition Decomposition (OCD) technique along with parallel computation ability to solve Multi-Area Dynamic Economic Dispatch (MA-DED) model for a retailer while taking into consideration hydro plants, wind plants and power pool market. Uncertainties of wind generation, electricity demand and electricity prices were modelled using SBM and OCD technique used to decompose MA-DED problem into several independent area-based Dynamic Economic Dispatch (DED) problems which were then solved simultaneously using parallel computation ability thus reducing the execution time and so making the proposed approach applicable in real-time for practical power pools. The objective function was modelled as a quadratic function and solved subject to Generator output limits, Hydro unit constraints (Water balance and Water-to- Power conversion), and Power balance in each area. The approach was then tested on two separate systems i.e. three-area and five-area test systems. The three-area system consisted of area A1 with 10 thermal units and 250 MW of wind generation, area A2 with 13 thermal units and 150 MW of wind generation and area A3 with 10 thermal units same as those in A1, hydro power generating units and power pool. The OCD technique generated a total benefit of $1,886,324.22 which was 9.13% lower than the corresponding benefit of the purely deterministic approach. To test the capability of the algorithm in large systems, a five-area test system was used resulting in a total benefit of $2,127,629.34 and converged in 13 iterations.

C. Wang & S.M. Shahidehpour, 1993 [34] solved MA-DED problem by decomposing the hydrothermal system into respective thermal and hydro sub problems which were then coordinated using Lagrange multipliers. To ensure system reliability, load forecasting errors and generator forced outages were taken into account using a probabilistic method. The hydro units were modelled as a set of cascaded hydro stations. Water usage was coordinated over the entire study time using network flow concept and reduced gradient method used to obtain an optimal solution by overcoming the linear characteristic of the network flow method. This approach was tested on a four-area system where each area has 20 thermal units and 4 cascaded hydro stations in a branched river. The operation cost increased considerably during peak load periods as some expensive thermal plants were brought online. However, increasing the generation capacity of hydro stations during peak load periods increased the efficiency of the natural water resource and reduced the overall operation cost as hydro generating stations were used to replace the thermal stations during peak load periods.

Only these two researchers have considered hydroelectric plants when solving MAED problem, however without considering emissions reduction in their research their work fall short in addressing the current challenges associated with the environmental effects of power generation and rising pressures to minimize them.

2.1.4. Review of Algorithms used in solving MAED

From a review of publications in IEEE xplore digital library[35], researchers have used deterministic and heuristic methods to solve MAED problem as summarized in Figure 2.1. It is evident that there has been an increase in the use of heuristic/metaheuristic methods in the recent past, and this can be attributed to increased development of new metaheuristic algorithms, the ability of metaheuristic algorithms to handle large and complex optimization problems efficiently as well as their flexibility to hybridize with other algorithms.

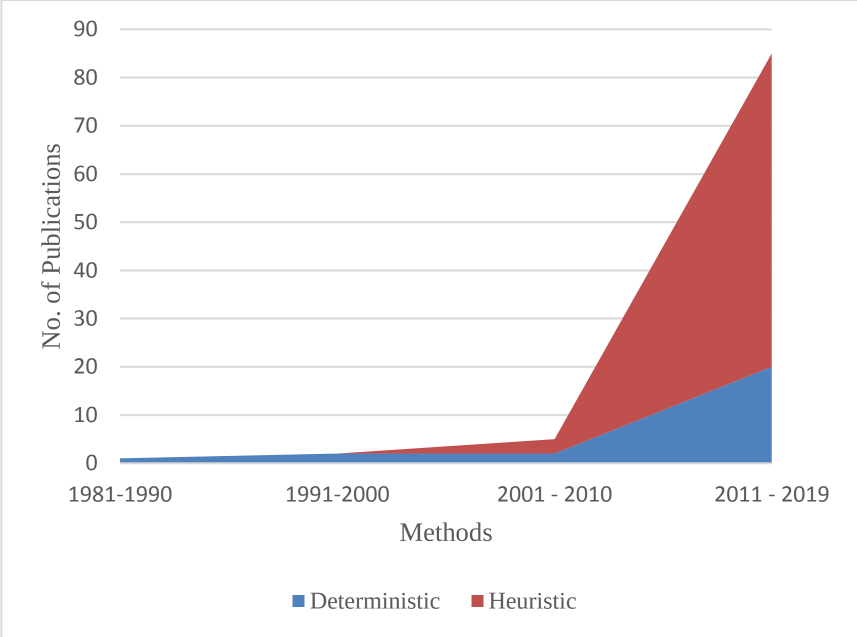


Figure 2:1: Methods used in solving MAED

Hybrid Algorithms for MAED

Various hybrids have been used to solve MAED problem which are briefly stated as follows: *Azizivahed et al,* [28] presented a hybrid of Shuffled Frog Leaping Algorithm (SFLA) and PSO to solve MAEED problem considering load uncertainty where movement of frogs in SFLA was done by updating the Velocity implemented in PSO and included in each memeplexes of the SFLA; *Musau et al* [30] introduced a hybrid of three-methods consisting of Modified Firefly Algorithm with Levy Flights and Derived Mutation to solve MOMAEED considering RE sources. Scenario Based Method (SBM) was used to model the variability and uncertainties of RE sources. *Nguyen et al* [36] proposed a hybrid of Cuckoo Search Algorithm with Teaching-Learning Based Optimization (TLBO) to solve MAED problem where the Cuckoo eggs were led to follow better current solutions by using the learner stage of TLBO. *Rasoul et al* [29] presented a hybrid of gradient search method and improved Jaya algorithm to solve a practical MOMAEED where the fast convergence and strong exploitation capability features of GM were employed to find the best solution and a mutation strategy added to Jaya Algorithm to enhance the accuracy of the Pareto-optimal solutions and prevent the Jaya Algorithm from premature convergence. *Prasanna et al* [24] presented two sets of Hybrids consisting of Fuzzy logic strategy incorporated in Evolutionary Programming called Fuzzy Mutated Evolutionary Programming (FMEP) and another one incorporating Fuzzy logic strategy and Tabu-search Algorithm termed Fuzzy Guided Tabu-Search (FGTS) to solve

Security Constrained MAED. PSO and its variants have also been used in [1], [23], [33], [37].to solve MAED problems considering various constraints

Generally these hybrids have shown great improvement in addressing the MAED problem by improving the quality of solutions, in terms of reduced fuel costs, reduced emissions, better convergence and faster computation times. However, with the continuous development of new superior Meta-heuristic Algorithms, there is a necessity to continuously solve MAED problem using the new algorithms for more superior solutions.

2.2. Summary of Literature review

Research in MAED has been going on since early 1980's and has been receiving a lot of attention since 2009 with over 100 publications as a result of increasing development of power pools in the world. MAEED problem on the other hand has received very little attention even with the increasing public awareness of environmental effects of power generation using fossil fuels forcing utilities to change their operation strategies to minimize emissions.

With the continuous development of Heuristic and Meta-heuristic algorithms, methods like Genetic algorithm, Differential Evolution, Chemical Reaction, Jaya, Frog – Leaping Algorithm, Flower pollination, Cuckoo search, Particle Swarm Optimization, Bat and their variants have been successfully used to solve the multi-objective MAEED problem faster producing better results each time.

However only two researchers have considered hydro plants while solving MAED problem even though most power pools are hydrothermal systems, and these researchers did not include emissions reduction concept in their studies.

In order to accurately represent a modern power pool, there is a great need to formulate and solve MAED problem for hydrothermal system considering emission reductions, the stochastic nature of water availability, the varying nature of demand and the modern power system constraints.

Hybridizing of Algorithms has also been proven to result in lower fuel costs, lower emissions and faster convergence when used to solve MAEED problem, an aspect which should also be greatly considered.

2.3. Research Gap

With the rising number of multi-area systems as a result of increasing power pooling arrangements, a lot of research is being done in solving MAED problem. However, very little effort has been put towards solving MAED problem while considering emissions even with the ratification of The Kyoto Protocol & Paris Agreements and the rising pressure on utilities to reduce environmental effects of power generation using fossil fuels.

Moreover, since most power pools are hydrothermal systems, the constraints and representations of a modern multi-area system need to be considered to enable easy customization of the algorithm to a real power pool and this involves formulating a dynamic MAED problem for hydrothermal systems considering emission reduction, the stochastic nature of water availability, the varying nature of demand and the constraints of a modern power system.

From the available literature this kind of formulation has not been attempted, and therefore this research seeks to formulate and solve for the very first time a Multi-Objective and Multi-Area Optimization of Hydrothermal Dynamic Environmental Economic Dispatch using Hybridized Bat Algorithm.

2.4. Theoretical Framework

MOMAHDEED aims to dispatch the generators of a power pool for the forecasted load over a given time horizon in a way that minimizes the fuel cost and pollutant emissions from thermal units while satisfying generation capacity constraints, area power balance constraint, tie-line constraints, reservoir capacity constraints, water discharge and other operational constraints. The mathematical formulation of MOMAHDEED is described:

2.4.1. Objective Functions

MOMAHDEED is a multi-objective minimization optimization problem with the following objective functions:

i) Minimizing Generator Fuel Cost

The fuel cost includes the cost of generation of power in an area plus exports or imports.

Thermal Generator Fuel Cost Function with Valve Point Loading

The rapid opening or closing of steam valves introduce ripples in the heat-rate curves which is modelled as a superposition of sinusoidal and quadratic functions in the generator cost function as shown in equation (2.1)[1]

$$F_{c,t}(P_{GTkj,t}) = \sum_{k=1}^{N}\sum_{j=1}^{N_{GTk}} \left(a_{kj} + b_{kj}P_{GTkj,t} + c_{kj}P^{2}{}_{GTkj,t}\right) + |\, d_{kj}\sin\left(e_{kj}\left(P_{GTkj}^{min} - P_{GTkj,t}\right)\right)| \qquad (2.1)$$

Where: a_{kj}, b_{kj} and c_{kj} are the cost coefficients

d_{kj} and e_{kj} are the valve point effect coefficients of the j^{th} generator in area k

P_{GTkj} is the real power output of the j^{th} generator in area k at time t.

P_{GTkj}^{min} is the minimum generation limit of the j^{th} generator in area k

N is the number of areas

N_{GTk} is the number of committed thermal generating units in the system in area k.

ii) Tie Line Transmission Cost Function

The cost of transmitting power from one area to another and the tie line losses are lumped together and expressed as [33]

$$F_{T,t}(P_T) = \sum_{k=1}^{N-1}\sum_{l=k+1}^{N} f_{kl}P_{Tkl,t} \qquad (2.2)$$

Where: P_{Tkl} is the active power transferred from area k to area l at time t

f_{kl} is the transmission cost coefficient relevant to P_{Tkl}

P_T is the vector of real power transmission given by

$P_T = [P_{T1,2}, \dots, P_{T1,k}, P_{T2,3}, \dots, P_{T2,k}, P_{Tk-1,k}]$

The power exchange between any two interconnected areas k and l are equal but opposite and is expressed as[30]

$$P_{Tkl} = -P_{Tlk} \qquad (2.3)$$

The Total Generator Cost function is calculated as[33]

$$F_{FC,t}(P_{GTkj,t}) = F_{c,t}(P_{GTkj,t}) + F_{T,t}(P_T) \tag{2.4}$$

Where: $F_{FC,t}(P_{GTkj,t})$ is the total generation fuel cost function considering exports and imports at time t

$F_{c,t}(P_{GTkj,t})$ is the fuel cost function of thermal generators at time t

$F_t(P_T)$ is the transmission cost function of imports/exports at time t

iii) Minimizing Emissions Cost Function

The major gaseous pollutant emissions of fossil fuelled thermal plants which is NO_X, is modelled as a sum of quadratic and exponential functions given by[38]:

$$F_{E,t}(P_{GTkj,t}) = \sum_{k=1}^{N}\sum_{j=1}^{N_{GTk}}[\alpha_{kj} + \beta_{kj}P_{GTkj,t} + \gamma_{kj}P_{GTkj,t}^2 + \zeta_{kj}exp(\delta_{kj}P_{GTkj,t})] \tag{2.5}$$

for r = 1,2,3

Where: α_{kj}, β_{kj}, γ_{kj}, ζ_{kj} and δ_{kj} are the emission coefficients of the j^{th} thermal generator in area k

The complex multi-objective problem is formulated as[39]:

$$Min\ F = [F_{FC,t}(P_{GTkj,t})\ , F_{E,t}(P_{GTkj,t})\ ] \tag{2.6}$$

Where: $F_{FC,t}(P_{GTkj,t})$ is the total generation fuel cost function of thermal generators

$F_{E,t}(P_{GTkj,t})$ is the Nitrogen Oxide emission function

The multi-objective function is combined into a single objective function using a weighted sum method expressed as:

$$Min\ F = \left[\mu F_{FC,t}(P_{GTkj,t}\right) + (1-\mu)F_{E,t}(P_{GTkj,t})] \tag{2.7}$$

Where: μ is the weighting factor which represent the trade-off or the relative importance between the fuel cost and emissions.

2.4.2. Constraints

The objective function (Equation 2.7) is solved subject to the following constraints.

i) Generator Capacity Constraint

The power output of each generator is restricted within its minimum and maximum limits for stable operation of the generator. These limits are expressed as [1]:

$$P_{GTkj}^{min} \leq P_{GTkj} \leq P_{GTkj}^{max}$$
$$P_{GHkr}^{min} \leq P_{GHkr} \leq P_{GHkr}^{max} \tag{2.8}$$

Where: P_{GTkj}^{min} and P_{GTkj}^{max} are the minimum and maximum power produced by the j^{th} thermal generator in area k

P_{GHkr}^{min} and P_{GHkr}^{max} are the minimum and maximum power produced by the r^{th} hydro generator in area k

ii) Area power balance Constraint

The total power generation in area k at a given time interval must satisfy the total demand in area k (P_{Dk}) while considering exports and imports and transmission losses in area k at that particular time. This is expressed as[40]:

$$\sum_{j=1}^{N_{GTk}} P_{GTkj}(t) + \sum_{r=1}^{N_{GHk}} P_{GHkr}(t) = P_{Dk}(t) + P_{Lk}(t) + \sum_{l,l\neq k}^{k} P_{Tkl}\,(t) \tag{2.9}$$

Where: $P_{GTkj}(t)$ is the power generated by j^{th} thermal plant in area k at a given time t.

$P_{GHkr}(t)$ is the power generated by r^{th} hydro plant in area k at time t given by equation 2.13 below.

$P_{Dk}(t)$ is the total demand in area k at a given time t.

$P_{Tkl}(t)$ is the power transferred from area k to area l at time t.

P_{Lk}(t) is the total transmission loss in area k at time t defined by Kron's Formula [41] given in equation 2.10 below.

$$\sum_{k}^{N} P_{Lk} = \sum_{k}^{N} (\sum_{i=1}^{N_{Gk}} \sum_{j=1}^{N_{Gk}} P_{Gkj} B_{kij} P_{Gki} + \sum_{j=1}^{N_{Gk}} B_{0kj} P_{Gkj} + B_{00k} \tag{2.10}$$

Where: i and j are generators in area k

B_{kij}, B_{0kj} and $B_{00k}$are the line loss coefficients

iii) Area Spinning Reserve Constraint

Each area keeps a fixed reserve to meet the individual contingency requirements which is called Contingency Spinning Reserve. A pooling spinning reserve which is shared is also kept to meet emergency requirements of the pool. The total available spinning reserve per area is given by:

$$\sum_{j=1}^{N_{GTk}} S_{Tkj} + \sum_{j=1}^{N_{GHk}} S_{Hkr} \geq S_{Ck} + S_{Pk} + \sum_{l,l\neq k}^{k} S_{RCkl} \tag{2.11}$$

And,

$$S_{Tkj} = P_{GTkj}^{max} - P_{GTkj} \tag{2.12}$$

$$S_{Hkj} = P_{GHkr}^{max} - P_{GHkr}$$

Where: S_{Tkj} is the available spinning reserve on the j^{th} thermal generator in area *k*

S_{Hkr} is the available spinning reserve on the r^{th} hydro generator in area *k*

S_{Ck} is the contingency spinning reserve of area *k*

S_{Pk} is the pooling spinning reserve in area *k*

S_{RCkl} is the pooling reserve contributed from area *k* to area *l*

The *Power output of Hydro generation Plant* is given by:

$$\begin{aligned} P_{GHkr}(t) = {} & C_{1kr}V_{Hkr}^2(t) + C_{2kr}Q_{Hkr}^2(t) + C_{3kr}V_{Hkr}Q_{Hkr}(t) + C_{4kr}V_{Hkr}(t) \\ & + C_{5kr}Q_{Hkr}(t) + C_{6kr}(t) \end{aligned} \tag{2.13}$$

Where: $C_{1kr}, C_{2kr}, C_{3kr}, C_{4kr}, C_{5kr}$ and C_{6kr} are the coefficients of r^{th} hydro turbine in area *K*

V_{Hkr} is the storage volume of the r^{th} reservoir at time t.

Q_{Hkr} is the water flow rate of the r^{th} reservoir at time t.

iv) Tie-Line Capacity Limits

For security considerations, the transfer of real power (Generation and Reserve) from one area to another e.g. area k to l, should not exceed the tie line transfer capabilities. This is expressed as:

$$-P_{Tkl}^{max} \leq P_{Tkl} + S_{RCkl} \leq P_{Tkl}^{max} \tag{2.14}$$

Where: P_{Tkl}^{max} is the maximum power transfer capacity limit of the tie line connecting areas k and l

v) Hydro Generation Constrains

The Constraints of a Hydro Generating units are given by the equations below:

a) Dynamic Water Balance Equation

This is formulated for every reservoir assuming no time delays as:

$$V_{Hkr}(t) = V_{Hkr}(t-1) + [(I_{Hkr}(t) - Q_{Hkr}(t) - S_{Hkr}(t)) \times \tau] \tag{2.15}$$

Where: $V_{Hkr}(t)$ is the storage volume of r*th* reservoir in area k at the end of time interval t
$I_{Hkr}(t)$ is the inflow rate into r*th* reservoir in area k during time interval t
$Q_{Hkr}(t)$ is the outflow rate from the r*th* reservoir in area k during time interval t
$S_{Hkr}(t)$ is the spillage rate of the r*th* reservoir in area k during time interval t
τ is the length of time interval t

b) Discharge rates limits

$$Q_{Hkr}^{min} \leq Q_{Hkr}(t) \leq Q_{Hkr}^{max} \tag{2.16}$$

Where: Q_{Hkr}^{min} and Q_{Hkr}^{max} are the minimum and maximum outflow rates of r*th* reservoir in area *k.*

c) Reservoir Storage limits

The amount of water in the reservoir at any given time interval should be between the minimum and maximum capacities of the reservoir. At the beginning of a given time horizon the initial volume of water in the reservoir should equal the specified initial volume and similarly at the end of the time horizon the final volume should equal the specified final volume. This is expressed as in Eq.2.17 and Eq. 2.18

$$V_{Hkr}^{min} \leq V_{Hkr}(t) \leq V_{Hkr}^{max} \tag{2.17}$$

$$V_{Hkr}(t_0) = V_{Hkr,initial} , V_{Hkr}(t_\tau) = V_{Hkr,final} \quad t = 1, 2, \dots, \tau \tag{2.18}$$

Where: V_{Hkr}^{min} and V_{Hkr}^{max} are the minimum and maximum volume of water of r^{th} reservoir in area *k*.

$V_{Hkr}(t)$ is the actual volume of water of r^{th} reservoir in area *k* at time t.

$V_{Hkr,initial}$ and $V_{Hkr,final}$ are the specified initial and final volume of water of r^{th} reservoir in area *k*.

2.5. Chapter Conclusion

This chapter has reviewed the existing methods and algorithms for solving MAED problems. It is evident that a lot of research has been done in solving single objective MAED problem that minimizes fuel costs only and research on multi objective MAEED problem that simultaneously minimize fuel costs and emissions is on the rise.

However very little research has been done for single objective MAED problem while considering hydrothermal system and no research in open literature has solved a multi objective MAEED problem for a hydrothermal system. This is a research gap identified in this chapter which this study seeks to address.

The theoretical framework considers hydrothermal systems, emissions, varying nature of demand, effects of valve point loading, reserve constraint and the stochastic nature of water availability which leads to a problem formulation that accurately represents a modern power pool leading to a better optimization of the multi-area power system operation in general.

CHAPTER THREE

3. METHODOLOGY

This thesis presents the use of a new Meta-heuristic algorithm known as Bat Algorithm (BA) which is inspired by the echolocation behaviour of micro-bats. Since MOMAHDEED is a multi-objective optimization problem, a weighted sum method is used to convert the multi objective function into a single objective one and optimal solutions are selected using cardinal priority ranking. Modifications to the velocity and frequency equations of BA are implemented to improve its exploitation and exploration capability. The Modified Bat Algorithm (MBA) is further hybridized using the Differential Evolution (DE) to increase its accuracy.

3.1. Bat Algorithm

Bats are flying mammals that have advanced echolocation capability. Micro-bats use echolocation to detect prey, locate their roosting crevices and avoid obstacles in the dark.
Bat algorithm is a meta-heuristic algorithm developed by Xin-She Yang in 2010 [42] which is inspired by the echolocation behaviour of micro-bats.
Bat Algorithm can be formulated when some echolocation characteristics are idealized.
For simplicity, the following rules are considered:

1) All bats have a way to differentiate food, prey and other background barriers when they sense the distance to these objects by using echolocation.
2) To search for food, Bats fly randomly with velocity V_i at position x_i with a fixed frequency f_{min} , varying wavelength λ and loudness A_o. Depending on how close their targets are, Bats either increase or decrease the wavelength (or frequency) of their emitted pulses and the rate of pulse emission *r* automatically.
3) The loudness is assumed to vary from a large value A_o to a minimum constant value A_{min}.

In BA, the frequency $\boldsymbol{f_i}$ and velocities $\boldsymbol{v_i}$ are updated using equations 3.1 and 3.2 below and thereafter positions $\boldsymbol{x_i}$ updated using equation 3.3 to obtain new solutions at time step *t* in the search space.

$$f_i = f_{min} + (f_{max} - f_{min})\beta \tag{3.1}$$

$$v_i^t = v_i^{t-1} + (x_i^t - x_{best})f_i \tag{3.2}$$

$$x_i^t = x_i^{t-1} + v_i^t \tag{3.3}$$

Where: β is a random number between [0, 1] and

x_{best} is the current global best location (or solution).

Local search is done by random walk where upon selection of the current best solutions, new solutions are generated locally using equation 3.4:

$$x_{new} = x_{old} + \varepsilon A^t \quad (3.4)$$

Where: ε is a random number between [0, 1]

A^t is the average loudness of all the Bats in this time step.

Bats increase pulse emission rates while decreasing the loudness as they approach the target. This is implemented using the equations below respectively

$$A_i^{t+1} = \alpha A_i^t \quad (3.5)$$

$$r_i^{t+1} = r_i^0[1 - exp(-\gamma t) \quad (3.6)$$

Bat Algorithm (BA) can be summarized in the pseudo code below:

Bat Algorithm pseudo code

Objective function f(x), $x = (x_1, ..., a_d)^T$
Initialize the bat population i.e Position x_i *and velocities* V_i for i = 1, 2, ..., n
Define pulse frequency f_i *at* x_i
Initialize pulse rates r_i *and the loudness* A_i
while *(*t *<Max number of iterations)*
Generate new solutions by adjusting frequency,
and updating velocities and locations/solutions [equations (3.1) to (3.3)]
if *(rand* > r_i*)*
Select a solution among the best solutions
Generate a local solution around the selected best solution
end if
Generate new solutions by flying randomly (equation 3.4)
if *(rand* < A_i & $f(x_i) < f(x_{best})$*)*
Accept the new solutions
Increase r_i *and reduce* A_i (3.5 & 3.6)
end if
Rank the bats and find the current best x_{best}
end while
Post-process results and visualization

Figure 3:1: Bat Algorithm Pseudo Code [35]

BA combines all the major advantages of PSO, GA and Harmony Search and has parameters which can be finely tuned for even faster convergence. The efficiency and accuracy of BA has been proven to be superior to other algorithms [42]

3.2. Applications of Bat Algorithm

Bat Algorithm has been applied in various fields which include among others; mathematical problems e.g. numerical problems with variables of continuous nature [43], data mining applications [44], Biomedical Systems like in [45] where it was used for diagnosis of Diabetes Mellitus, Network and Routing Problems [46] where Bat Algorithm was used for wireless sensor networks localization, Image processing[47], Scheduling [48] and power systems where it has been used in Optimal Capacitor placement [49] and extensively in economic dispatch as discussed below.

3.3. ED using Bat Algorithm

Various researchers have used Bat Algorithm to solve ED, EED and MAED problems and has been proven to provide superior results compared to other algorithms. These works include: Economic Load dispatch solved using Novel Bat Algorithm with quantum and mechanical behavior by *Hafiz et al* [50] in 2017; Multi-objective optimal economic emission power dispatch solved using Bat algorithm by *Kumar et al* [51] in 2017; Economic and Emission dispatch solved using multi-objective chaotic bat algorithm by *Liang et al* [52] in 2017**;** Dynamic economic dispatch on 150kV Mahakam power system solved by *Yun et al* [53] in 2017 using chaotic bat algorithm; Optimal load dispatch problem solved using enhanced BAT optimization algorithm by *Gunanidhi et al* [54] in 2017; MAED problem considering Multi – Fuel Options, valve point loading, prohibited zones solved using an Improved Bat Algorithm by *Vijayaraj et al* [40]and [55] in 2016, where Bat algorithm was improved by using dynamic frequency varying concept; *Gautham et al* [56] in 2016 used Novel Bat Algorithm which incorporated the Doppler Effect and movement of bats between different habitats, to solve ED Problem considering the effects of valve point loading; EED problem was solved by *Nguyen and Sang*, [57] in 2016 using Bat Algorithm and in 2015 by *Dimitrios and Aristdis* [38] using Bat Algorithm variants (HBA and MBA); *Latif and Palensky*, [58] in 2014 presented a Modified Bat Algorithm for solving classic ED problem where the Bat algorithm was modified by adding Bad experience component to steer the solution away from bad positions and Non-linear Inertia weight component to provide balance between local and global exploitation for better convergence; Economic load dispatch including wind power was solved in [59] using

Bat Algorithm by *Julia .T. Jose* in 2014; In 2013 *Biswal et al* [60] used Bat Algorithm to solve ED problem considering Valve point loading and prohibited operating zones.

Hybrids of Bat Algorithm have been implemented two researchers and have proven to provide even better results compared to traditional BA and hybrids of other algorithms. *Dimitrios and Vlachos* [38] in 2015 implemented a hybridized Bat Algorithm where Bat Algorithm was hybridized with Differential Evolution, in which DE was used for the local search instead of a random walk; Liang et al [61] in 2018 presented a hybrid of Bat Algorithm with chaotic map and random black hole model. Chaotic map was used to prevent premature convergence, and the random black hole model was used to increase the global search ability by enlarging exploitation area and accelerating convergence speed. The results of both hybrids were proven to be superior to those of traditional BA and other algorithms.

Bat Algorithm has excellent intensification capability and weak diversification capability and therefore converges very fast when used in lower-dimensional optimization problem. These characteristics however lead to premature convergence to local optimum when BA is used in higher-dimensional optimization problems. This research therefore proposes hybridization and modifications to address these shortcomings.

3.4. Modifications of BA

To overcome the challenges of premature convergence and getting stuck in local minima, two modifications are proposed in this research:

3.4.1. Incorporation of Bad experience component

In order to enhance the exploration capability of BA, the velocity update equation (3.2) is modified as:

$$v_i^{(t)} = v_i^{(t-1)} + \{ f_i^{(t)} [C_1 \left(x_i^{(t)} - x_{best} \right) + C_2 \left(x_{worst} - x_i^{(t)} \right)] \} \tag{3.7}$$

Where : x_{best} and x_{worst} are the global best and worst positions respectively.

C_1 is a random number between [0,2] that accelerates the bat towards global best position

C_2 is a random number between [0,1] that steers the bat away from the global worst position [58].

This modification steers bats away from bad positions thereby allowing them to accelerate towards better positions

3.4.2. Dynamic Frequency Varying Concept

To enhance the exploitation capability of BA, dynamic frequency varying concept is used instead of random generation of frequency. This ensures that bats near the global best position do not steer further to irrelevant positions. This is implemented as:

$$D_i = \sqrt{(x_i - x_{best})^2} \tag{3.8}$$

$$d = \max(D_i) - \min(D_i) \tag{3.9}$$

$$f_i = f_{\min} + \{(\frac{\sqrt{(\min(D_i) - D_i)^2}}{d}) * (f_{\max} - f_{\min})\} \tag{3.10}$$

The pseudocode for the Modified Bat Algorithm is as shown below.

Modified Bat Algorithm pseudo code

Objective function f(x), $x = (x_1, ..., x_d)^T$
Randomly initialize the bat population i.e Position x_i *and velocities* V_i for $i = 1, 2, ..., n$
Define pulse frequency f_i *at* x_i
Initialize pulse rates r_i *and the loudness* A_i
while *(*t *<Max number of iterations)*
Generate new solutions by adjusting frequency using equations (3.8) to (3.10),
and updating velocities using equation (3.7) and locations/solutions using (3.3)
if *(rand* $> r_i$*)*
Select a solution among the best solutions
Generate a local solution around the selected best solution
end if
Generate new solutions by flying randomly (equation 3.4)
if *(rand* $< A_i$ & $f(x_i) < f(x_{best})$*)*
Accept the new solutions
Increase r_i *and reduce* A_i (3.5 & 3.6)
end if
Rank the bats and find the current best x_{best}
end while
Post-process results and visualization

Figure 3:2: Modified Bat Algorithm Pseudocode

The Modified Bat Algorithm (MBA) is then hybridized using DE where DE is used in local search rather than random walk to increase the accuracy of the results.

3.5. Differential Evolution

Differential Evolution (DE) [62] was introduced by Price and Storn in 1996. DE is implemented by combining the existing candidate vectors (solutions) to obtain new solutions and a vector with the best fitness/score depending on the objective function value is maintained. The steps involved in DE algorithm are mutation, crossover and selection.

Mutation

Two solutions are randomly selected, and a weighted difference between them added to a third solution. This process is called mutation and expressed as:

$$u_i^t = x_{r1}^t + MF(x_{r2}^t - x_{r3}^t) \tag{3.11}$$

Where: i = 1,2, . . .,.*NP* and *NP* is the population size.

$MF \in [0,1]$ is a scaling factor that controls the rate of amplification

$x_{r1}^t, x_{r2}^t, x_{r3}^t$, are randomly selected with $r_1,\ r_2,\ r_3 \in \{1,2,\dots,NP\}$ and

$r_1 \neq r_2 \neq r_3 \neq i$

Crossover

To make the population more diverse, a differential crossover operation is applied where parameters of the target vector are mixed with the parameters of the mutated vector and a trial vector q_i is created as follows:

$$q_{ij}^t = \begin{cases} v_{ij}^t, & rand(j) \leq CR \vee j = j_{rand} \\ x_{ij}^t, & rand(j) > CR \wedge j \neq j_{rand} \end{cases} \tag{3.12}$$

Where: $rand(j) \in [0,1]$is a uniformly distributed random number newly generated for the j^{th} parameter of the i^{th} vector,

CR is the crossover constant within [0,1],

j_{rand} is a random integer from [1,2,…,D]

D is the number of real parameters in the objective function. This ensures that at least one parameter from the mutated vector is selected for the trial vector.

Selection

Differential selection is then carried out using equation 3.13:

$$x_i^{t+1} = \begin{cases} q_i^t, & f(q_i^t) > f(x_i^t) \\ x_i^t, & f(q_i^t) \leq f(x_i^t) \end{cases} \tag{3.13}$$

The DE scheme described is denoted as "***DE/rand/1/bin***" where the base vector is randomly selected, 1 vector difference added to it, and the number of modified parameters in mutation vector follows binomial distribution.

3.6. Cardinal Priority Ranking

Equation 2.7 generates non inferior solutions with explicit trade-offs between the conflicting objectives. By exploiting the Fuzzy decision making theory, membership functions are defined which relate to the objectives and are used to find the optimal trade-off level among the non – inferior solutions.

The membership function represents the degree of accomplishment of each original objective function as a value between 0 and 1. By taking account of the minimum and maximum values of each objective function together with the rate of increase of membership satisfaction, the decision maker must in a subjective manner, determine the membership function $\mu(F_i)$ given by:

$$\mu(F_i) = \begin{cases} 1 & ; F_i \le F_{imin} \\ \dfrac{F_{imax} - F_i}{F_{imax} - F_{imin}} & ; F_{imin} \le F_i \le F_{imax} \\ 0 & ; F_{imax} \le F_i \end{cases} \tag{3.14}$$

Where: F_{imax} and F_{imin} are the minimum and maximum values of i^{th} objective function where the solution is expected.

The value of the membership function indicate how much a non-dominated solution has satisfied the i^{th} objective.

The 'accomplishment' of each solution in satisfying the objectives can be rated with respect to all the N non-dominated solutions by normalizing its 'accomplishment' over the sum of the 'accomplishment' of the N non-dominated solutions as follows:

$$\mu_D^k = \frac{\sum_{i=1}^{L} \mu_k(F_i)}{\sum_{k=1}^{N} \sum_{i=1}^{L} \mu_k(F_i)} \tag{3.15}$$

The accomplishments μ_D^k result in a set of non dominated solutions, from which the maximum value is selected as the optimal result.

3.7. HMBA Implementation Procedure

In the Hybridized Modified Bat Algorithm (HMBA), each Bat is a potential solution for the MOMAHDEED problem. The Bats are generated for each generating unit in each area considering all the constraints.

Steps

1. Representation of the Bat Population

The Bat population is formed by the water discharge rates of hydro plants and real powers of thermal units. For a multi-area system with **k** number of areas each with **j** thermal units and **r** hydro units, the position of the Bats is represented by a vector of length ((k*(j+r)) + tie lines) and for $\boldsymbol{N_b}$ Bats, the complete population is represented as:

$$X_i = \begin{bmatrix} P_{GT111} \cdots & P_{GT1kj} & Q_{H111} & \cdots & Q_{H1kr} & P_{T111} & \cdots P_{T1lk} \\ \vdots & \ddots & & & \vdots & & \\ P_{GTi11} & P_{GTikj} & Q_{Hi11} & \cdots & Q_{Hikr} & P_{Ti11} & \cdots P_{Tilk} \end{bmatrix} \quad (3.16)$$

for i=1,2,. . . N_b

2. Initialization

Each Bat position is randomly initialized within the acceptable ranges according to the constraints in Equations 2.8 and 2.16 such that $X_{imin} = P_{GTkj}^{min}$ and $X_{imax} = P_{GTkj}^{max}$ for thermal units while $X_{imin} = Q_{Hkr}^{min}$ and $X_{imax} = Q_{Hkr}^{max}$ for hydro plants.

Initialization is done using equation 3.17 below

$$X_i = X_{imin} + rand * (X_{imax} - X_{imin}) \quad (3.17)$$

3. Calculation of Fitness

The objective function is calculated for each position of a Bat. For every Bat, the weights for the Cost function is increased while simultaneously decreasing the weights for emissions in steps of 0.1. Cardinal Priority ranking (Equations 3.14 and 3.15) is then used to determine the optimal weighted position for every Bat which are taken as the local best solutions for each Bat. The Bat with the lowest weighted function chosen as the Global best solution x_{best}

Initial Loudness A_i and Pulse rates r_i are also randomly generated for each Bat typically between [1, 2] and [0, 1] respectively.

4. Generating new solutions

For each Bat, the frequency is calculated using equations 3.8 to 3.10. The velocity is then updated using equation 3.7 while taking the initial value as 0.

The new solutions/positions (x_f) are then obtained using equation 3.3 for each Bat.

5. Local search using DE

A random number is generated and compared with the pulse rate r_i.. If this generated random number is greater than r_i, local solutions are generated by DE as illustrated below:

i) Mutation

The objective function is calculated for the new population (x_f) and a new Global best solution identified which is then selected as a target vector x_{r1}^t. Two other solutions x_{r2}^t and x_{r3}^t are then randomly selected from the population of Bats and a trial vector u_i^t calculated using equation 3.11.

ii) Crossover

The trial vector u_i^t is recombined with the parent vector x_f and an offspring q_{ij}^t is produced as per equation 3.12.

iii) Selection

The fitness of the parent vector x_f and that of the offspring q_{ij}^t is calculated and compared. Deterministic selection is then carried out using equation 3.13. The best local solution x_l is then determined.

6. Evaluation of Solutions

The fitness of solutions x_f, and x_l are compared and the best solution x_{best} selected among them.

7. Termination Criterion

The random number generated in step 4 is compared to the Loudness A_i and the fitness of the current solution compared with that of the previous global best solution.

If *rand* < A_i and $f(x_i) < f(x_{best})$, the current solution is accepted as the new Global best solution. Pulse rate is increased, Loudness reduced and iteration done from step 3 by updating frequency and velocity. When this termination criterion is met or maximum number of iterations is achieved, the resultant current solution is taken as the optimal solution.

3.8. HMBA Mapping

The table below shows the various parameter values of BA and DE as implemented in HMBA and also gives the meaning of these parameters as mapped to the MOMAHDEED optimization problem.

Table 3.1: HMBA Parameter Mapping

Parameter	**Meaning**	**Value**
Bat Algorithm Parameters		
Bats	Vector of Potential Solution	$[P_{GHkj}, Q_{Hkr}, P_{Tlk}]$
Population	Set of Potential Solutions	30
Fitness	Objective function	Weighted Fuel cost at maximum cardinal priority ranking accomplishment
Position X_i	Generation level for thermal plants	$P_{GHkj}^{min} \leq P_{GHkj}(t) \leq P_{GHkj}^{max}$
	Discharge rates for Hydro plants	$Q_{Hkr}^{min} \leq Q_{Hkr}(t) \leq Q_{Hkr}^{max}$
Velocity v_i	Exploration of search space (Distance and Direction of movement of Bats	From 0
Frequency f_i	Rate of Movement of bats in the search space	Random number [0, 1.5]
Pulse rate A_i	Distance to Global Optima	Random number [1, 2]
Loudness r_i	Location of Global Optima	Random number [0, 1]
Alpha (α)	Tolerance	0.99
DE Parameters		
Population	Positions of Bats (X_i) as in BA	$P_{GHkj}^{min} \leq P_{GHkj}(t) \leq P_{GHkj}^{max}$
		$Q_{Hkr}^{min} \leq Q_{Hkr}(t) \leq Q_{Hkr}^{max}$
CR	Crossover constant	0.5
MF	Scaling Factor	0.8
Maximum Number of iterations	Termination criterion	20

3.9. HMBA Pseudocode

The HMBA Pseudocode is as described in Figure 3.3

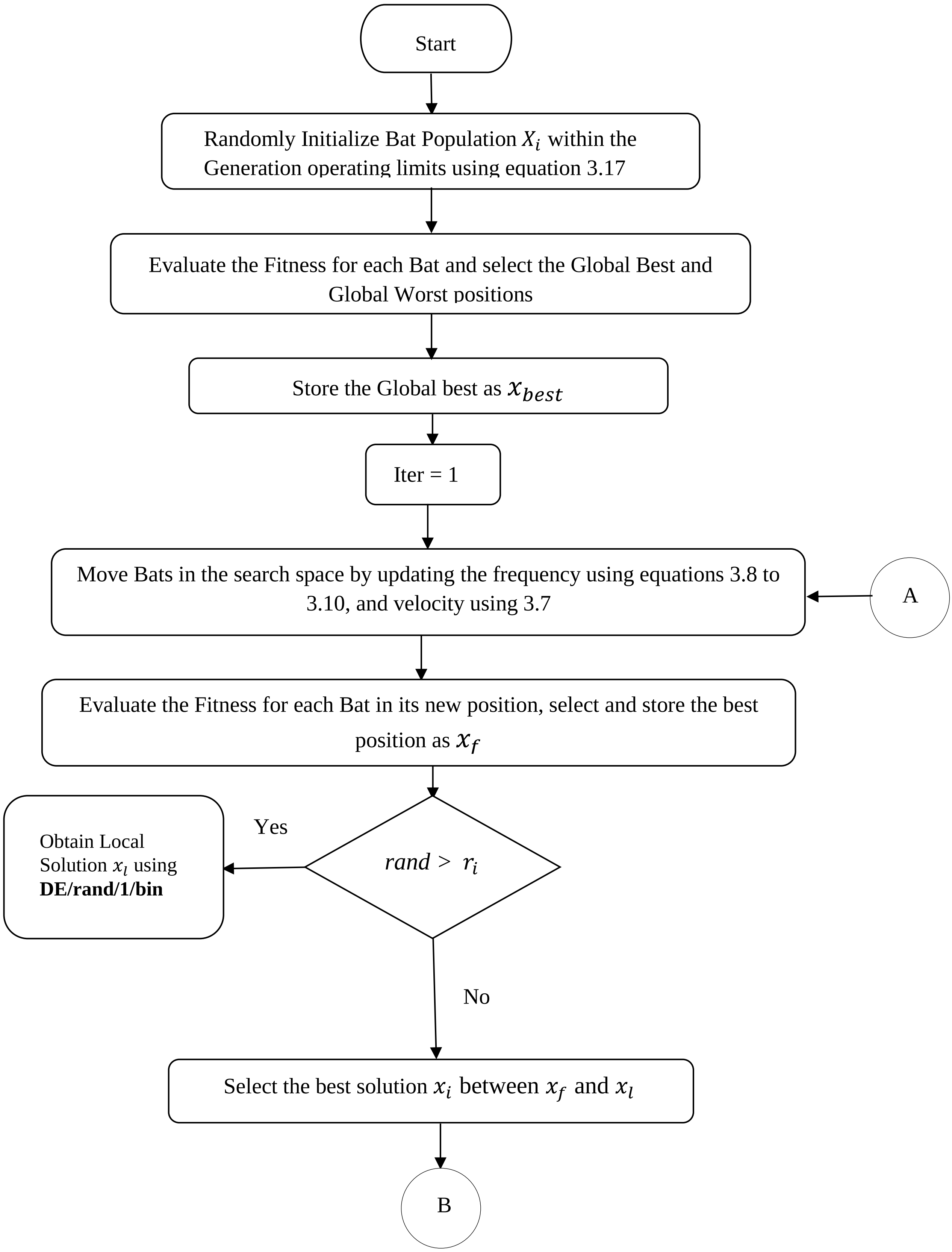
Hybridized Modified Bat Algorithm pseudo code

Objective function f(x), $x = (x_1, ..., x_d)^T$
Randomly initialize the bat population i.e Position x_i *and velocities* V_i for $i = 1, 2, ..., n$
Define pulse frequency f_i *at* x_i
Initialize pulse rates r_i *and the loudness* A_i
while *(*t <*Max number of iterations)*
Generate new solutions $\boldsymbol{X_f}$ *by adjusting frequency using equations (3.8) to (3.10),*
and updating velocities using equation (3.7) and locations/solutions using (3.3)
if *(rand* > r_i*)*
Modify the solution using ***DE/rand/1/bin*** to get a local solution $\boldsymbol{X_l}$
end if
Select the best solution $\boldsymbol{X_{best}}$ *among* $\boldsymbol{X_l}$ *and* $\boldsymbol{X_f}$
if *(rand* < A_i & $f(x_i) < f(x_{best})$*)*
Accept the new solutions
Increase r_i *and reduce* A_i (3.5 & 3.6)
end if
Rank the bats and find the current best x_{best}
end while
Post-process results and visualization

Figure 3:3: Hybridized, Modified Bat Algorithm Pseudocode

3.10. Flow Chart for the Proposed Algorithm

The proposed Hybridized Modified Bat Algorithm can be summarized in the flow chart shown in Figure 3.4.


Start
Randomly Initialize Bat Population X_i within the Generation operating limits using equation 3.17
Evaluate the Fitness for each Bat and select the Global Best and Global Worst positions
Store the Global best as x_{best}
Iter = 1
Move Bats in the search space by updating the frequency using equations 3.8 to 3.10, and velocity using 3.7
A
Evaluate the Fitness for each Bat in its new position, select and store the best position as x_f
$rand > r_i$
Yes
Obtain Local Solution x_l using **DE/rand/1/bin**
No
Select the best solution x_i between x_f and x_l
B

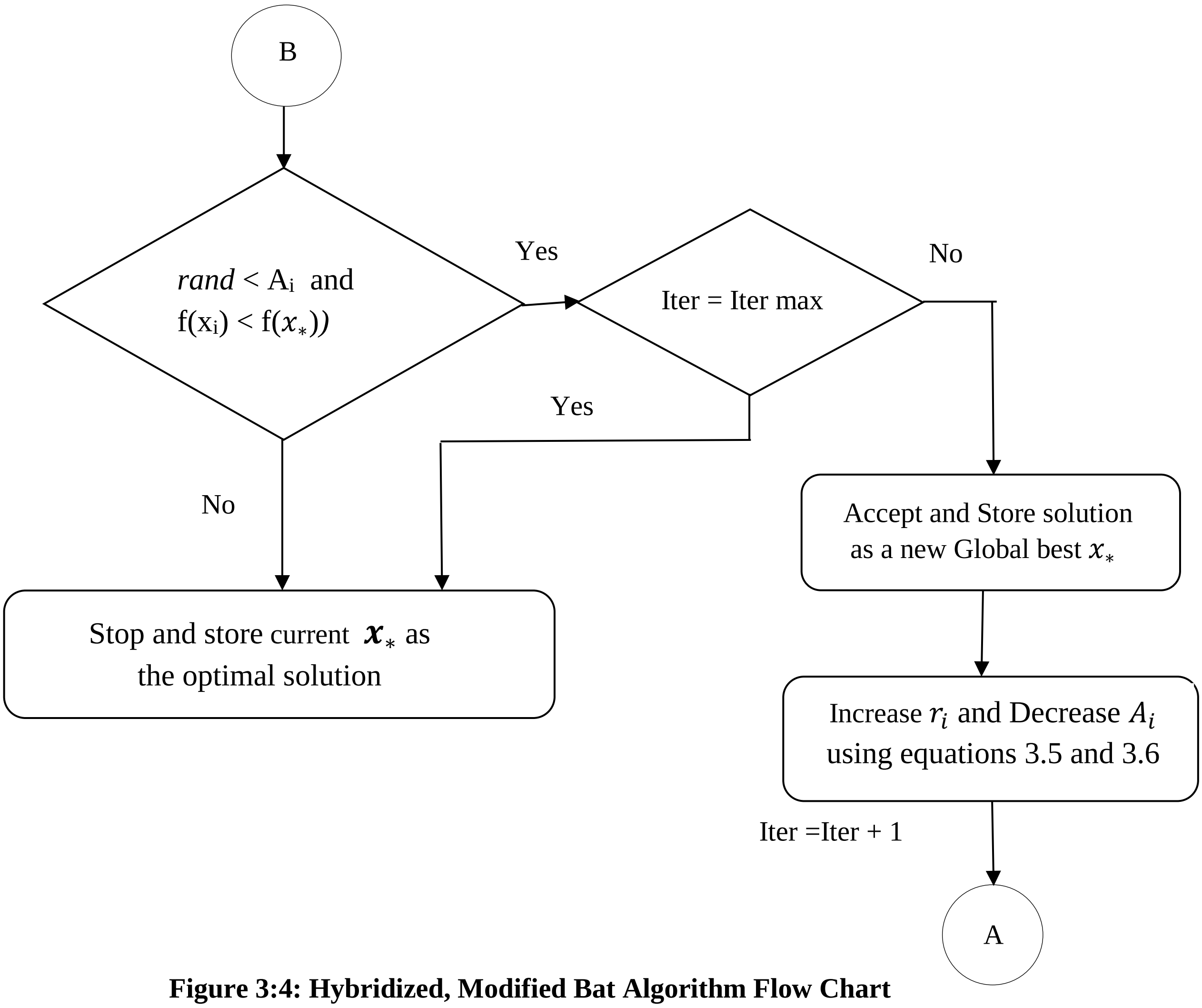


Figure 3:4: Hybridized, Modified Bat Algorithm Flow Chart

3.11. Chapter Conclusion

A new algorithm has also been developed by modifying the Bat Algorithm and hybridizing it using the Differential Evolution method. The Bat Algorithm has an excellent intensification capability and a weak diversification capability which leads to premature convergence and getting stuck in local optima when used in higher-dimensional optimization problems.

Modifications to the velocity and frequency equations of BA are implemented to improve its exploitation and exploration capability. The Modified Bat Algorithm (MBA) is further hybridized using the Differential Evolution (DE) to increase its accuracy. The Hybridized Modified Bat Algorithm (HMBA) is superior in accuracy, robustness and convergence compared to other algorithms by yielding better quality results in terms of lower fuel costs, reduced emissions as well as lower transmission losses.

CHAPTER FOUR

4. RESULTS WITH LIMITED INTERPRETATION

The Bat Algorithm (BA), Modified Bat Algorithm (MBA) and the Hybridized Modified Bat Algorithm (HMBA) are executed in Matlab R2015a on an Intel Core i7, 2.5GHz PC with 8GB memory. Various cases are considered for a four area test system with a total of twelve generating units whose data, taken from [11] is shown in Table 4.1, Table 4.2 and Table 4.3.

MAEED problem is also solved for a four area test system with a total of sixteen generating units whose data shown in Table 4.4 and Table 4.5 is taken from [10] .

MOMAHDEED is tested in a four area test system with a total of twenty four generating units. The test system is described in detail in section 4.1.3.

4.1. Test System Data

4.1.1. Four Area, 12 Generating units test system

The Coefficients for Fuel cost and emissions as well as the generators maximum and minimum capacities for this system are given in Table 4.1.

Table 4.1: Generator Fuel and Emissions data for a Four Area 12 Generating units Test System

Area	Unit	P^{min}	P^{max}	Fuel Coefficients			Emission Coefficients		
	i	*MW*	*MW*	*a* ($/MW²h)	*b* ($/MWh)	*c* ($/h)	*α* (kg/MW²h)	*β* (kg/MWh)	*γ* (kg/h)
1	1	35	210	0.000532	0.574583	18.65297	0.00683	-0.54551	40.2669
	2	130	325	0.000317	0.544917	24.87854	0.00461	-0.5116	42.89553
	3	125	315	0.00027	0.574056	20.34989	0.00461	-0.5116	42.89553
2	1	10	150	0.002287	0.572396	11.35198	0.00484	-0.32767	33.85932
	2	35	110	0.00042	0.605948	6.749966	0.00754	-0.54551	50.63931
	3	125	215	0.002225	0.5751	8.378544	0.00661	-0.63262	45.83267
3	1	15	175	0.001588	0.692387	6.769877	0.00914	-0.43211	48.2156
	2	30	215	0.001126	0.657534	10.0954	0.00533	-0.61173	52.4521
	3	50	335	0.00179	0.759482	7.960799	0.00674	-0.49731	41.1042
4	1	15	175	0.001588	0.692387	12.76988	0.00728	-0.6821	30.3632
	2	30	215	0.002033	0.615567	15.578	0.00479	-0.5066	25.1765
	3	50	335	0.001344	0.503432	19.28861	0.00387	-0.4934	27.7549

The power demand for every area is given in Table 4.2.

Table 4.2: Area Power Demand

Area	Power Demand (MW)
1	500
2	410
3	580
4	600

The B_{mm} matrix for the loss coefficients in all the four areas is given in Table 4.3.

Table 4.3: Loss Coefficient Matrix

Area	B_{mm} matrix		
1	0.000071	0.00003	0.000025
	0.00003	0.000069	0.000032
	0.000025	0.000032	0.00008
2	0.000056	0.000045	0.000015
	0.000023	0.000042	0.000047
	0.000032	0.000023	0.000027
3	0.00002	0.000028	0.000053
	0.000086	0.000034	0.000016
	0.000053	0.000016	0.000028
4	0.000074	0.00003	0.000025
	0.000049	0.000069	0.000037
	0.000022	0.000032	0.000083

4.1.2. Four Area, 16 Generating units test system

The Coefficients for Fuel cost and emissions as well as the generators maximum and minimum capacities for this system are given in P.U in Table 4.4 and 4.5.

Table 4.4: Generator Fuel data for a Four Area 16 Generating units Test System

Area	Unit	P^{min}	P^{max}	Fuel Coefficients (P.U)			
	i	*MW*	*MW*	*a* *($/MW²h)*	*b* *($/MWh)*	*c* *($/h)*	*Demand* *(P.U)*
1	1	0.0005	0.14	150	189	0.50	0.23
	2	0.0005	0.10	115	200	0.55	
	3	0.0005	0.13	40	350	0.60	
	4	0.0005	0.12	122	315	0.50	
2	1	0.0005	0.25	125	305	0.50	0.43
	2	0.0005	0.12	70	275	0.70	
	3	0.0005	0.20	70	345	0.70	
	4	0.0005	0.18	70	345	0.70	
3	1	0.0005	0.30	130	245	0.50	0.38
	2	0.0005	0.30	130	245	0.50	
	3	0.0005	0.30	135	235	0.55	
	4	0.0005	0.30	200	130	0.45	
4	1	0.0005	0.11	70	345	0.70	0.52
	2	0.0005	0.20	45	389	0.60	

	3	0.0005	0.30	75	355	0.60	
	4	0.0005	0.30	100	370	0.80	

The Emissions coefficients are given in Table 4.5

Table 4.5: Emission coefficients for a Four Area 16 Generating units Test System

Area	**Unit**	**Emissions Coefficients (P.U)**				
	i	***α* *(t/MW²h)***	***β* *(t/MWh)***	***γ* *(t/h)***	**ζ (t/hr)**	**δ (1/MW)**
1	1	0.016	-1.500	23.333	2.0 X 10^{-4}	2.122
	2	0.031	-1.820	21.022	5.0 X 10^{-4}	1.233
	3	0.013	-1.249	22.050	1.0 X 10^{-6}	6.000
	4	0.012	-1.355	22.983	1.0 X 10^{-3}	1.523
2	1	0.020	-1.900	21.313	1.0 X 10^{-6}	8.000
	2	0.007	0.805	21.900	3.0 X 10^{-5}	5.167
	3	0.015	-1.401	23.001	2.0 X 10^{-4}	3.857
	4	0.018	-1.800	24.003	1.0 X 10^{-6}	3.333
3	1	0.019	-2.000	25.121	2.0 X 10^{-3}	7.000
	2	0.012	-1.360	22.990	1.0 X 10^{-6}	3.000
	3	0.033	-2.100	27.010	2.0 X 10^{-4}	6.000
	4	0.018	-1.800	25.101	1.0 X 10^{-5}	1.667
4	1	0.018	-1.810	24.313	2.0 X 10^{-4}	3.857
	2	0.030	-1.921	27.119	5.0 X 10^{-4}	5.233
	3	0.020	-1.200	30.110	1.0 X 10^{-6}	4.000
	4	0.040	-1.400	22.500	2.0 X 10^{-3}	3.000

4.1.3. Four area, 24 Generating units test system

The system consists of four areas, area 1 and 2 being IEEE 30 bus system with 6 thermal generating units whose data is taken from [63] and shown in Tables 4.8 and 4.9. Areas 3 and 4 are constituted by 5 thermal generating units whose system data is taken from [64] and shown in Tables 4.6 and 4.7, there is also an additional hydro generation of 250MW and 350MW respectively whose data is taken from [31] as shown in Tables 4.10 – 4.12. Transmission losses and the effects of valve point loading are also considered. All the four areas are interconnected using six tie lines as shown in Figure 4:1 and the tie line limits are as given in Table 4.13. Each area is mandated to keep its own contingency reserve of 7% and the pool reserve which is set at 25% of the peak power demand of area 4 is shared by each area as shown in Table 4.14.

Table 4.6: Generator Fuel and Emissions data for a 5 Generating units Test System

Generator Numbers	**1**	**2**	**3**	**4**	**5**

Generator limits[MW]	*Pmin*	10	20	30	40	50
	Pmax	75	125	175	250	300
Fuel cost coefficients with valve point	a ($/hr)	25	60	100	120	40
	b ($/MWh)	2.0	1.8	2.1	2.0	1.8
	c ($/MW^{2}h)	0.0080	0.0030	0.0012	0.0010	0.0015
	d ($/hr)	100	140	160	180	200
	e (rad/MW)	0.042	0.040	0.038	0.037	0.035
effect Emission coefficients with valve point effect	α (t/hr)	80	50	60	45	30
	β (t/MWh)	-0.805	-0.555	-1.355	-0.600	-0.555
	γ (t/MW^{2}h)	0.0180	0.0150	0.0105	0.0080	0.0120
	ζ (t/hr)	0.6550	0.5773	0.4968	0.4860	0.5035
	δ (1/MW)	0.02846	0.02446	0.02270	0.01948	0.02075

Table 4.7: Loss Coefficient Matrix for a 5 Generating units Test System

Matrices	Matrix Elements				
	0.000049	0.000014	0.000015	0.000015	0.000020
	0.000014	0.000045	0.000016	0.000020	0.000018
B	0.000015	0.000016	0.000039	0.000010	0.000012
	0.000015	0.000020	0.000010	0.000040	0.000014
	0.000020	0.000018	0.000012	0.000014	0.000035

Table 4.8: Generator Fuel and Emissions data for IEEE 30 bus Test System

Generator Numbers		**1**	**2**	**3**	**4**	**5**	**6**
Generator limits[MW]	*Pmin*	5	5	5	5	5	5
	Pmax	150	150	150	150	150	150
Fuel cost coefficients with valve point	a ($/hr)	10	10	20	10	20	10
	b ($/MWh)	2.00	1.50	1.80	1.00	1.80	1.50
	c ($/MW^{2}h)	0.01	0.012	0.004	0.006	0.0040	0.01
	d ($/hr)	15	10	10	5	5	5
	e (rad/MW)	6.283	8.976	14.784	20.944	25.133	18.48
effect Emission coefficients with valve point effect	α (t/hr)	4.091	2.543	4.258	5.426	4.258	6.131
	β (t/MWh)	-0.5554	-0.6047	-0.5094	-0.355	-0.5094	-0.5555
	γ (t/MW^{2}h)	0.06490	0.05638	0.04586	0.03380	0.04586	0.05151
	ζ (t/hr)	0.0002	0.0005	0.000001	0.002	0.000001	0.00001
	δ (1/MW)	0.02857	0.03333	0.0800	0.020	0.0800	0.06667

Table 4.9: Loss Coefficient Matrix for IEEE 30bus system

Matrices	Matrix Elements

B	0.0000218	0.0000107	-0.00004	-0.000011	0.000055	0.000033
	0.0000107	0.000017	-0.00002	-0.000018	0.000026	0.000028
	-0.00004	-0.00002	0.00002459	-0.000013	-0.000012	-0.000079
	-0.000011	-0.0000179	-0.00001328	0.0000265	0.000098	0.000045
	0.000055	0.000026	-0.0000118	0.000098	0.0000262	-0.00001
	0.000033	0.000028	-0.000079	0.000045	-0.00001	0.0000297
B0	[0.000011 0.000018 -0.000041 0.0000385 0.0000138 0.0000555]					
B00	[0.000014]					

The characteristics of Hydro generating stations are as shown in Tables 4.10 - 4.12.

Table 4.10: Coefficients of Hydro turbines

Hydro unit	C1	C2	C3	C4	C5	C6
1	−0.0042	−0.42	0.03	0.9	10	−50
2	−0.004	−0.3	0.015	1.14	9.5	−70
3	−0.0016	−0.3	0.014	0.55	5.5	−40
4	−0.003	−0.31	0.027	1.44	14	−90

Table 4.11: Natural inflows of each hydro station (*10^4 m^3)

Period (Hr)	Reservoir 1	Reservoir 2	Reservoir 3	Reservoir 4
1	10	8	8.10	2.80
2	9	8	8.20	2.40
3	8	9	4	1.60
4	7	9	2	0
5	6	8	3	0
6	7	7	4	0
7	8	6	3	0
8	9	7	2	0
9	10	8	1	0
10	11	9	1	0
11	12	9	1	0
13	10	8	2	0
13	11	8	4	0
14	12	9	3	0
15	11	9	3	0
16	10	8	2	0
17	9	7	2	0
18	8	6	2	0
19	7	7	1	0
20	6	8	1	0
21	7	9	2	0
22	8	9	2	0
23	9	8	1	0
24	10	8	0	0

Table 4.12: Hydro system parameter limits (*10^4 m^3)

Hydro Unit	Reservoir Storage Volumes				Discharge Rates	
	V^{min}	V^{max}	$V_{initial}$	V_{final}	Q^{min}	Q^{max}

1	80	150	100	120	5	15
2	60	120	80	70	6	15
3	100	240	170	170	10	30
4	70	160	120	140	6	20

The maximum transfer capabilities of the tie lines is as given in Table 4.13

Table 4.13: Tie line flow limits

Tie Lines	Min. Power (MW)	Max. Power (MW)
T_{1-2}	5	100
T_{1-3}	5	100
T_{2-4}	5	100
T_{3-4}	5	100
T_{1-4}	5	100
T_{2-3}	5	100

Pool Reserve which is 25% of the peak power demand of Area 4 (highest of all areas) is contributed by all areas as shown in Table 4.14.

Table 4.14: Pool Reserve sharing scheme

Area	% Pool reserve contribution
Area 1	20%
Area 2	20%
Area 3	30%
Area 4	30%

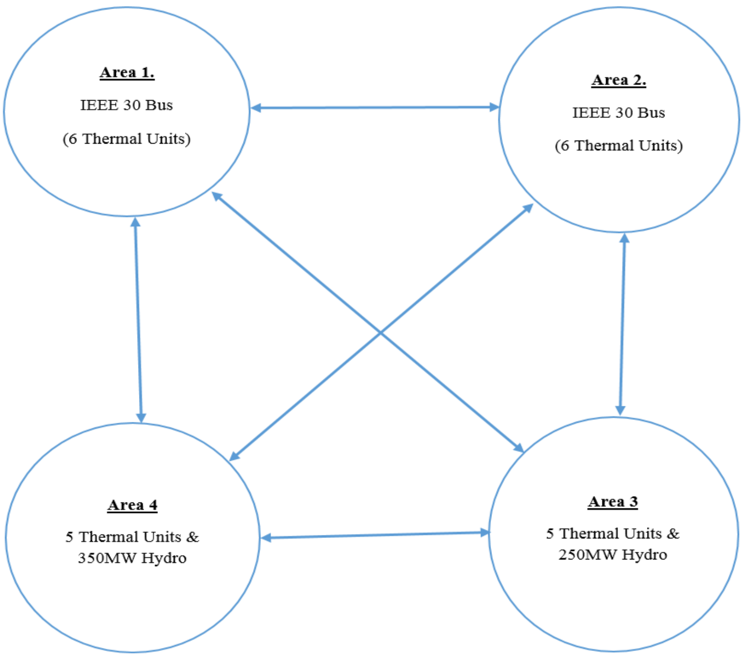


Figure 4:1: Multi Area System Interconnection

The hourly demand for each area is as shown in Table 4.15.

Table 4.15: Hourly Expected Demand (MW)

Time (Hr)	Power Demand (MW)				
	Area 1	Area 2	Area 3	Area 4	Total Pool Demand
1	478	410	478	755	2121
2	465	435	537	742	2179
3	476	475	563	753	2267
4	453	530	615	730	2328
5	458	558	687	735	2438
6	486	608	820	763	2677
7	512	626	928	789	2855
8	546	654	906	823	2929
9	649	690	813	926	3078
10	673	714	751	950	3088
11	724	743	726	1001	3194
12	758	760	588	1035	3141
13	713	732	691	990	3126
14	774	704	678	1051	3207
15	786	690	683	1063	3222
16	773	654	639	1050	3116
17	744	608	631	1021	3004
18	725	685	733	1002	3145
19	682	763	998	959	3402
20	615	784	733	892	3024
21	546	728	695	823	2792
22	507	670	590	784	2551
23	498	508	559	775	2340
24	483	437	528	760	2208

The graphical representation of the load profiles for each area and the Multi Area system is shown in Figures 4:2 and 4:3.

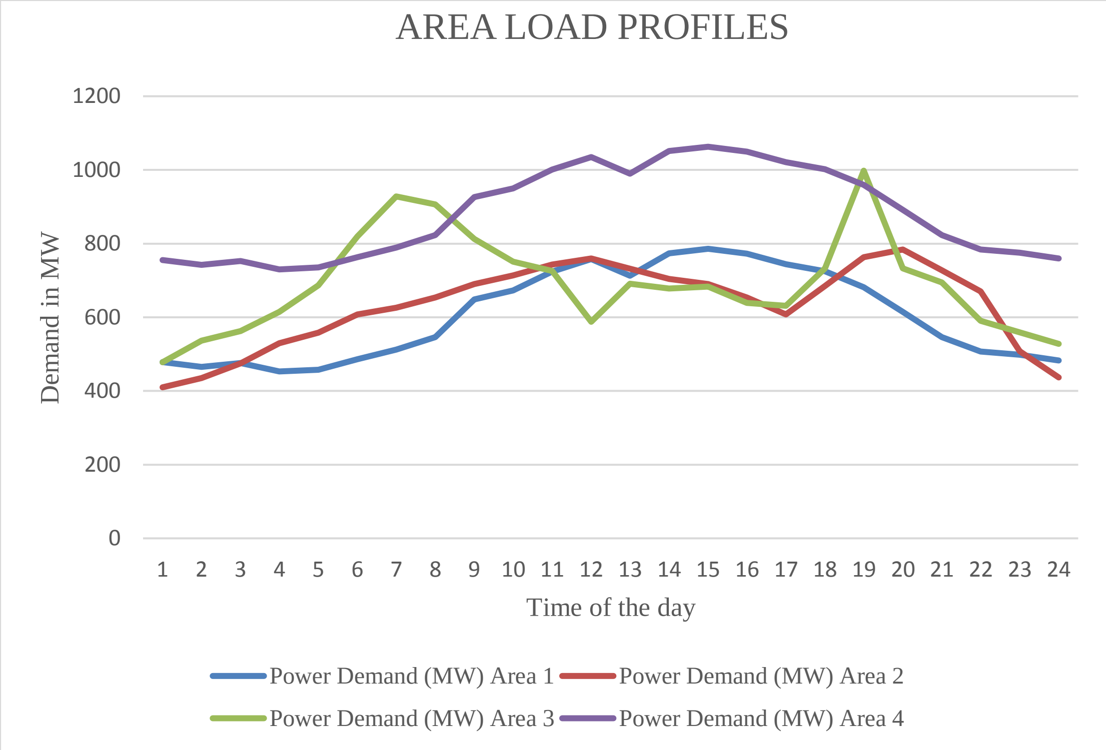


Figure 4:2: Load Profile for each Area

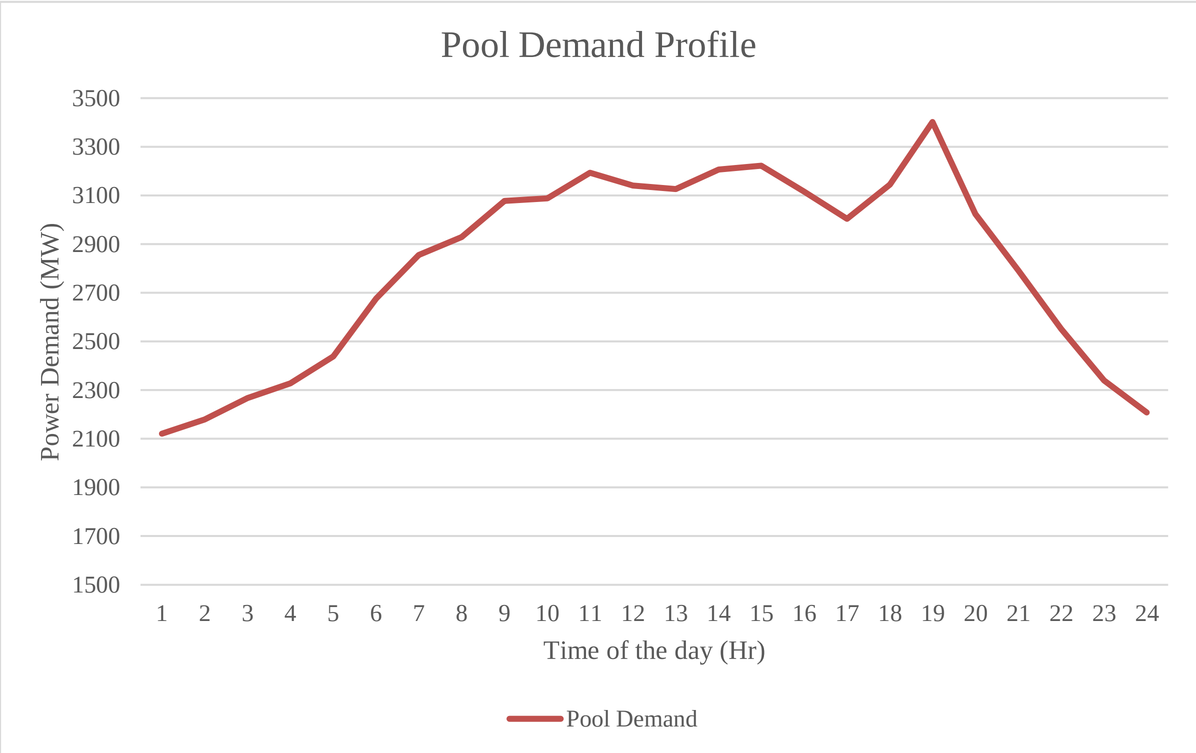


Figure 4:3: Load Profile for the Multi Area system

Using the test data, the following results are obtained for the different test cases.

4.2. Bat Algorithm Results

Four test cases are considered as follows.

i. Test Case 1: Mono objective MAED problem (Minimizing fuel costs only)
ii. Test Case 2: Multi objective MAEED problem (Minimizing both fuel costs and emissions)
iii. Test Case 3: Multi-Objective MAHEED problem (Minimizing both fuel costs and emissions while considering hydro generation)
iv. Test Case 4: Dynamic Multi-Objective MAHEED problem

4.2.1. Test Case 1: MAED using BA

In this case, BA is tested for MAED Problem (Minimizing Fuel cost only) and results in total fuel cost of 2049.49$/hr with total emissions of 2168.77Kg/hr. The total transmission network power loss in all the areas is 49.93MW. These results are as shown in Table 4.16.

Table 4.16: MAED - BA Results

	Area 1	**Area 2**	**Area 3**	**Area 4**
P1(MW)	35.00	150.00	175.00	175.00
P2(MW)	153.39	110.00	200.54	215.00
P3(MW)	325.00	155.29	215.00	228.00
P_{loss} (MW)	13.40	5.83	12.70	18.00
Total P_{loss} (MW)	**49.93**			
P_{total} (MW)	513.39	415.29	590.54	618.00
Emissions (Kg/hr)	465.99	282.47	932.25	488.06
Total Emissions (Kg/hr)	**2168.77**			
Fuel Cost($/hr)	389.66	386.67	644.73	628.43
Total Fuel Cost ($/hr)	**2049.49**			

4.2.2. Test Case 2: MAEED using BA

In this case, BA is tested for MAEED problem which simultaneously curtails fuel cost and emissions. This results in total fuel cost of 2226.17$/hr with total emissions of 2034.74Kg/hr and total transmission network power loss of 49.96MW as shown in Table 4.17.

Table 4.17: MAEED - BA Results

	Area 1	**Area 2**	**Area 3**	**Area 4**
P1(MW)	38.44	141.51	162.38	174.28
P2(MW)	275.59	96.17	91.94	113.45
P3(MW)	199.73	177.51	335.00	327.70
P_{loss} (MW)	13.08	5.66	12.36	18.86
Total P_{loss} (MW)	**49.96**			
P_{total} (MW)	513.77	415.20	588.53	615.44
Emissions (Kg/hr)	406.04	294.15	890.93	443.62
Total Emissions (Kg/hr)	**2034.74**			
Fuel Cost($/hr)	396.71	394.61	761.59	673.28
Total Fuel Cost ($/hr)	**2226.19**			

4.2.3. Test Case 3: MOMAHEED using BA

In this case, hydroelectric units of 100MW are each included in areas 3 and 4. MOMAHEED problem is then solved using BA and results in total fuel cost of 1937.88$/hr with total emissions of 1488.65Kg/hr. The total transmission network power loss in all the areas is 39.69MW. These results are as shown in Table 4.18.

Table 4.18: MOMAHEED - BA Results

	Area 1	**Area 2**	**Area 3**	**Area 4**
P1(MW)	96.95	130.93	151.81	168.09
P2(MW)	181.42	100.16	110.89	52.97
P3(MW)	227.97	184.09	228.98	291.77
P_{Hydro}(MW)	0	0	100.00	100.00
P_{loss} (MW)	11.90	5.61	8.76	13.42
Total P_{loss} (MW)	**39.69**			
P_{total} (MW)	506.34	415.18	591.68	612.82
Emissions (Kg/hr)	319.24	298.95	524.04	346.42
Total Emissions (Kg/hr)	**1488.65**			
Fuel Cost($/hr)	461.17	393.30	564.87	517.54
Total Fuel Cost ($/hr)	**1937.88**			

4.2.4. Test Case 4: MOMAHDEED using BA

BA is tested for a more complex Multi-Objective, Multi – Area Hydrothermal Dynamic Environmental Economic Dispatch problem considering the varying nature of load (power demand), the limited capacity of water reservoirs and the stochastic nature of water availability in hydro generating systems. A summary of the results are as shown in Table 4.19 while a more detailed set of results showing generation levels for every generator to meet their respective hourly area demands are as shown in Appendix A.

Table 4.19: MOMAHDEED - BA Results

Time (Hour)	Pool Demand (MW)	Total Power Gen. (MW)	Power loss (MW)	Total Emissions (t/hr)	Total Fuel Cost($/hr)
1	2121	2595.4230	20.3361	6009.5370	491,629.3132
2	2179	2466.0767	13.8824	5609.5123	368,161.9908
3	2267	2663.8038	23.2864	6642.5238	588,063.3843
4	2328	2457.6343	17.9618	6025.6172	609,412.8844
5	2438	2652.3568	25.7145	6135.8232	612,486.9067
6	2677	3070.3241	25.9130	8339.0926	961,997.9024
7	2855	2844.5048	21.9507	6593.0621	739,542.4694
8	2929	2929.2909	23.7743	7194.6638	820,811.8686
9	3078	3211.4592	27.6586	9122.7094	1,101,762.287
10	3088	3240.9815	28.5987	9506.8267	1,130,657.3014
11	3194	3088.4655	25.7313	9978.8681	980,395.9161
12	3141	3210.2309	25.915	9953.5085	1,102,504.5300
13	3126	3013.8764	21.5678	9663.0843	910,147.0206
14	3207	3214.5823	27.9361	9655.2414	1,104,962.8344
15	3222	3191.4390	29.1884	9921.8348	1,080,366.3623
16	3116	3057.2692	23.3159	8837.6810	952,063.8219
17	3004	3251.0337	29.1629	10432.5883	1,140,408.6237
18	3145	3232.8879	29.5769	9574.6299	1,120,810.2249
19	3402	3445.253	30.9596	10099.0018	1,313,077.3680
20	3024	3051.7676	23.6179	9189.8902	946,015.4275
21	2792	3137.3669	28.6128	9701.9410	1,027,111.5130
22	2551	2830.4951	24.6655	7329.3465	722,948.7116
23	2340	2819.9934	19.0944	7435.8498	718,146.3028
24	2208	2646.8182	23.7587	6528.7829	539,677.7679

4.2.5. Hydro Hourly Generation using BA

The hourly Hydro generation in areas 3 and 4 is as given in Table 4.20.

Table 4.20: BA Hourly Hydro Scheduling in Areas 3 and 4

Hydro Generation Scheduling using BA			
Hour	**Area 3**	**Area 4**	**Total Hydro Gen**
1	115.1754	201.3489	316.52
2	161.1132	237.1092	398.22
3	104.1332	181.9407	286.07
4	100.0000	170.9337	270.93
5	55.7954	210.3489	266.14
6	161.1132	237.1092	398.22
7	161.0357	236.9330	397.97
8	159.6022	233.8614	393.46
9	158.5497	231.7740	390.32
10	140.8244	203.6182	344.44
11	100.0000	238.0743	338.07
12	159.4071	233.4657	392.87
13	145.1189	209.8192	354.94
14	144.2902	214.9165	359.21
15	149.5916	236.9330	386.52
16	154.5490	224.5792	379.13
17	160.2422	235.1937	395.44
18	160.0027	221.1412	381.14
19	233.4657	205.8454	439.31
20	145.1189	208.6042	353.72
21	100.0000	170.5755	270.58
22	161.5275	177.3989	338.93
23	144.1872	208.4540	352.64
24	100.0000	160.9833	260.98

4.3. Modified Bat Algorithm Results

Two test cases are considered as follows:

i. Test Case 5: Multi objective MAEED problem.

ii. Test Case 6: Multi objective MAHEED problem.

4.3.1. Test Case 5: MAEED using MBA

In this case, MBA is used to solve MAEED problem and results in total fuel cost of 2120.87$/hr with total emissions of 1890.22Kg/hr. The total transmission network power loss in all the areas is 50.10MW. These results are as shown in Table 4.21.

Table 4.21: MAEED MBA Results

	Area 1	**Area 2**	**Area 3**	**Area 4**
P1(MW)	49.02	115.20	174.17	174.95
P2(MW)	170.49	108.89	132.81	138.07
P3(MW)	293.36	191.08	284.14	303.22
P_{loss} (MW)	13.48	5.57	12.55	18.5
Total P_{loss} (MW)	**50.10**			
P_{total}	512.86	415.17	519.12	616.26
Emissions (Kg/hr)	409.14	307.29	759.39	414.40
Total Emissions (Kg/hr)	**1890.22**			
Fuel Cost($/hr)	396.36	290.83	682.66	651.01
Total Fuel Cost ($/hr)	**2120.87**			

4.3.2. Test Case 6: MOMAHEED using MBA

MOMAHEED problem is solved using MBA and results in total fuel cost of 1905.63$/hr with a total emissions of 1477.43Kg/hr. The total transmission network power loss in all the areas is 41.75MW. These results are as shown in Table 4.22

Table 4.22: MOMAHEED MBA Results

	Area 1	**Area 2**	**Area 3**	**Area 4**
P1(MW)	36.49	130.37	128.88	77.26
P2(MW)	204.2	106.49	170.26	119.68
P3(MW)	268.43	178.35	192.22	318.89
P_{Hydro}(MW)	0.00	0.00	100.00	100.00
P_{loss} (MW)	13.18	5.65	8.53	14.39
Total Ploss (MW)	**41.75**			
P_{total}	509.12	415.20	591.35	615.83
Emissions (Kg/hr)	382.32	318.63	469.15	307.33
Total Emissions (Kg/hr)	**1477.43**			
Fuel Cost($/hr)	444.43185	389.375	539.56755	532.254
Total Fuel Cost ($/hr)	**1905.63**			

4.4. Hybridized Modified Bat Algorithm Results

Four test cases are considered as follows:

i. Test Case 7: Multi objective MAEED problem for a 4 area, 12 generating units system.
ii. Test Case 8: Multi objective MAEED problem for a 4 area, 16 generating units system.
iii. Test Case 9: Multi objective MAHEED problem.
iv. Test Case 10: Multi objective Dynamic MAHEED Problem

4.4.1. Test Case 7: MAEED using HMBA for 12 Generator system

MOMAEED problem is solved using HMBA and results in total fuel cost of 2079.67$/hr with total emissions of 1765.21Kg/hr. The total transmission network power loss in all the areas is 49.07MW. These results are as shown in Table 4.23

Table 4.23: MAEED HMBA Results for 12 Generating unit system

	Area 1	**Area 2**	**Area 3**	**Area 4**
P1(MW)	67.33	137.16	123.23	144.27
P2(MW)	169.79	106.35	179.92	171.65
P3(MW)	275.59	171.71	288.16	301.5
P_{loss} (MW)	13	5.70	11.68	18.69
Total P_{loss} (MW)	**49.07**			
P_{total} (MW)	512.71	415.22	591.31	617.42
Emissions (Kg/hr)	375.47	289.97	706.17	393.61
Total Emissions (Kg/hr)	**1765.21**			
Fuel Cost($/hr)	389.6661	388.7598	662.02125	639.2211
Total Fuel Cost ($/hr)	**2079.67**			

4.4.2. Test Case 8: MAEED using HMBA for 16 Generator system

MOMAEED problem is solved using HMBA for a sixteen generator unit multi area system and results in total fuel cost of 1,013.23$/hr with total emissions of 379.65Kg/hr. These results are as shown in Table 4.24

Table 4.24: MAEED HMBA Results for 16 Generating unit system

	Area 1	Area 2	Area 3	Area 4
P1(MW) p.u	0.1236	0.2317	0.1602	0.0281
P2(MW) p.u	0.035	0.02	0.082	0.1588
P3(MW) p.u	0.0494	0.0866	0.1072	0.2408
P4(MW) p.u	0.0241	0.0919	0.0307	0.0923
P_{total}	0.2321	0.43	0.3801	0.52
Emissions(Kg/hr)	87.8097	89.508	99.062	103.274
Total Emissions (kg/hr)	**379.6537**			
Fuel Cost($/hr)	143.3253	283.471	208.6301	377.8034
Total Fuel Cost ($/hr)	**1013.2298**			

4.4.3. Test Case 9: MOMAHEED using HMBA

MOMAHEED problem is solved using HMBA and results in total fuel cost of 1879.96 $/hr with total emissions of 1452.48Kg/hr. The total transmission network power loss in all the areas is 40.43MW. These results are as shown in Table 4.25

Table 4.25: MOMAHEED HMBA Results

	Area 1	Area 2	Area 3	Area 4
P1(MW)	43.7	109.4	172.81	172.97
P2(MW)	205.75	104.00	158.84	80.81
P3(MW)	259.23	201.74	159.28	260.36
P_{Hydro}(MW)	0	0	100	100
P_{loss} (MW)	12.95	5.5	9.02	12.96
Total Ploss	**40.43**			
P_{total} (MW)	508.68	415.15	590.93	614.13
Emissions (Kg/hr)	397.85	294.71	441.69	318.23
Total Emissions (Kg/hr)	**1452.48**			
Fuel Cost($/hr)	446.5308	395.9786	519.77055	517.6769
Total Fuel Cost ($/hr)	**1879.96**			

4.4.4. Test Case 9: MOMAHDEED using HMBA

HMBA is further tested for a more complex Multi-Objective, Multi – Area Hydrothermal Dynamic Environmental Economic Dispatch problem considering the varying nature of load (power demand), the limited capacity of water reservoirs and the stochastic nature of water availability in hydro generating systems. A summary of the results are as shown in Table 4.26 while a more detailed set of results showing generation levels for every generator to meet their respective hourly area demands is shown in Appendix B.

Table 4.26: MOMAHDEED - HMBA Results

Time (Hour)	Pool Demand (MW)	Total Power Gen. (MW)	Power loss (MW)	Total Emissions (t/hr)	Total Fuel Cost($/hr)
1	2121	2146.9315	13.1131	4451.0810	396,840.3741
2	2179	2197.9049	13.6139	4973.8629	421,404.6413
3	2267	2287.6909	12.9511	4380.6899	497,747.2324
4	2328	2372.1610	16.9320	4991.4530	612,790.1634
5	2438	2453.4655	6.6441	4021.3269	640,776.0913
6	2677	2699.8116	14.9473	4909.4471	697,417.1426
7	2855	2889.7168	22.6172	5916.4950	714,820.9835
8	2929	2960.9416	23.5384	6764.1154	810,157.6622
9	3078	3104.5305	23.0617	8154.8436	830,159.2607
10	3088	3127.8957	27.6253	8236.4929	852,093.1488
11	3194	3227.2909	26.3012	9392.7650	928,879.6605
12	3141	3175.3807	25.7561	9176.8339	891,291.9012
13	3126	3156.5314	20.0489	9229.3503	881,507.8046
14	3207	3235.2259	23.1930	9249.2726	938,040.9370
15	3222	3253.6409	26.9889	9517.6871	968,908.6820
16	3116	3143.7479	23.1081	8621.6442	865,287.1349
17	3004	3028.4925	20.4334	8864.7312	827,438.9979
18	3145	3177.2804	28.8942	8922.5580	909,800.9569
19	3402	3445.4491	30.8338	9763.8140	1,041,121.0498
20	3024	3059.6105	21.1323	8023.8757	845,680.1106
21	2792	2819.5163	22.4499	7879.0569	685,189.8102
22	2551	2572.7572	17.5728	7417.4126	660,114.9573
23	2340	2362.6378	18.8514	5542.1849	618,809.9415
24	2208	2231.0914	14.4376	3504.6532	445,415.2868

4.4.5. Hydro Hourly Generation using HMBA

The hourly Hydro generation in areas 3 and 4 is as given in Table 4.27.

Table 4.27: HMBA Hourly Hydro Scheduling in Areas 3 and 4

Hydro Generation Scheduling using HMBA			
Hour	**Area 3**	**Area 4**	**Total Hydro Gen**
1	170.0795	208.3724	378.4519
2	139.5318	181.5063	321.0381
3	144.1469	168.4627	312.6096
4	187.0053	194.4190	381.4243
5	251.3347	211.3347	462.6694
6	234.8904	182.0189	416.9093
7	198.1981	251.3347	449.5328
8	119.2407	293.4629	412.7036
9	214.2309	256.7482	470.9791
10	188.6049	243.4563	432.0612
11	187.7814	293.4629	481.2443
12	242.1571	285.0191	527.1762
13	262.1571	268.0815	530.2386
14	251.3555	297.4830	548.8385
15	255.2762	351.6131	606.8893
16	211.3555	297.4830	508.8385
17	202.1571	285.0191	487.1762
18	248.4439	268.0815	516.5254
19	318.0815	351.7630	669.8445
20	238.4439	219.2407	457.6846
21	167.7630	267.5006	435.2636
22	162.1571	218.0815	380.2386
23	163.4267	218.0815	381.5082
24	131.3921	162.1571	293.5492

4.5. Chapter Conclusion

This chapter describes the test systems used for testing Bat Algorithm, Modified Bat Algorithm and Hybridized Modified Bat Algorithm. The results obtained using these algorithms are also presented in this chapter. HMBA realizes lower fuel costs and lower emissions for all the test systems as compared to MBA and BA.

CHAPTER FIVE

5. ANALYSIS AND DISCUSSIONS

5.1. DISCUSSIONS ON PROBLEM FORMULATION

This problem formulation is based on existing equations whereby, the fuel cost and the emission functions were modelled as quadratic equations, the effects of valve point loading are superimposed on these quadratic equations making the fuel cost and emission functions discontinuous and non-convex in nature.

Weighting function is used to convert the multi-objective function into a single objective one, where the weights are varied from 1 to 0, contradictorily for both objectives, resulting in 11 sets of results. The decision making tool employed to determine the optimal compromise solution among these is Cardinal priority ranking, where accomplishment functions are arrived at using membership functions, and the solution with the highest accomplishment selected as the optimal one.

5.2. STATIC MOMAHEED RESULTS COMPARISON AND ANALYSIS

5.2.1. MAED, MAEED and MOMAHEED using BA comparison

The results of MAED, MAEED and MOMAHEED optimization problems solved using BA are compared in Table 5.1.

The single objective MAED problem results in total fuel cost of 2049.49$/hr , with emissions of 2168.77 kg/hr and total transmission loss of 49.93MW. When both fuel costs and emissions were curtailed in MAEED, the total fuel costs increase by 8.62% to 2226.19 $/hr and emissions reduce by 6.18% to 2034.74kg/hr. This is because generation from the low cost, high polluting fossil fuels is reduced, while increasing generation from the high cost, less polluting fossil fuels.

By introducing hydroelectric generating units into MAEED problem, the total fuel cost is reduced by 12.95% and total emissions reduced by 26.84%, since some of the electricity generated by thermal plants is displaced by the hydroelectric generation which has zero fuel cost and zero emissions. This scheduling also leads to a reduction in transmission losses by 20.56%.

Table 5.1: MAED, MAEED and MOMAHEED using BA results comparison

	MAED	MAEED	MOMAHEED
Total Fuel Cost ($/hr)	2049.49	2226.19	1937.88
Total Emissions (Kg/hr)	2168.77	2034.74	1488.65
Transmission Loss (MW)	49.93	49.96	39.69

5.2.2. MAEED and MOMAHEED using MBA comparison

In Table 5.2, results of MAEED problem solved using MBA are compared to those of MOMAHEED solved using MBA. MAEED results in total fuel cost of 2120.87$/hr, with emissions of 1890.22kg/hr and total network transmission loss of 50.1MW. Solving MOMAHEED problem using MBA results in total fuel cost of 1905.63$/hr which is a reduction of 10.15% and similarly emissions are reduced by 21.84% to 1477.43kg/hr. Transmission losses are also reduced by 16.67%. This is attributed to reduced thermal generation, as hydro generation which has zero fuel cost and zero emissions displaces some power that was being generated by thermal plants.

Table 5.2: Comparison of MAEED and MOMAEED using MBA

	MAEED	MOMAHEED	% Reduction
Total Fuel Cost ($/hr)	2120.87	1905.63	10.15%
Total Emissions (Kg/hr)	1890.22	1477.43	21.84%
Transmission Loss (MW)	50.1	41.75	16.67%

5.2.3. MAEED and MOMAHEED using HMBA comparison

HMBA is used to solve MAEED and MOMAHEED problems and the results compared in Table 5.3. A 9.60% reduction in fuel cost and a 17.72% reduction in emissions is realized when hydroelectric component is incorporated in MAEED problem. Transmission losses are also reduced by 17.61%.

Table 5.3: MAEED and MOMAHEED using HMBA results comparison

	MAEED	MOMAHEED	% Reduction
Total Fuel Cost ($/hr)	2079.67	1879.96	9.60%
Total Emissions (Kg/hr)	1765.21	1452.48	17.72%
Transmission Loss (MW)	49.07	40.43	17.61%

5.2.4. MAEED using BA, MBA and HMBA comparison

The results of MAEED problem solved using BA, MBA and HMBA are as compared in Table 5.4. MBA results in a total fuel cost of 2120.87$/hr which is a reduction of 4.73% when compared to BA and a total emissions of 1890.22kg/hr, which is an emission reduction of 7.10% when compared to BA.

HMBA results in total fuel cost of 2079.67$/hr which is a reduction of 1.94% and 6.58% when compared to MBA and BA respectively; and emissions of 1765.21kg/hr, which is an emission reduction of 6.61% and 13.25% when compared to MBA and BA respectively. Network transmission losses are comparative in all cases.

Table 5.4: MAEED using BA, MBA and HMBA results comparison

	BA	**MBA**	**HMBA**
Total Fuel Cost ($/hr)	2226.19	2120.87	2079.67
Total Emissions (Kg/hr)	2034.74	1890.22	1765.21
Transmission Loss (MW)	49.96	50.10	49.07

5.2.5. MOMAHEED using BA, MBA and HMBA comparison

The results of MOMAHEED problem solved using BA, MBA and HMBA are compared in Table 5.5. MBA resultes in a total fuel cost of 1905.63$/hr which is a reduction of 1.66% when compared to BA and total emissions of 1477.43kg/hr, which is an emission reduction of 0.75% when compared to BA.

HMBA results in total fuel cost of 1879.96$/hr which is a reduction of 1.35% and 2.99% when compared to MBA and BA respectively; and emissions of 1452.48kg/hr, which is an emission reduction of 1.69% and 2.43% when compared to MBA and BA respectively. Network transmission losses are however increased by 5.19% and 1.86% for MBA and HMBA respectively as compared to BA results.

Table 5.5: MOMAHEED using BA, MBA and HMBA results comparison

	BA	**MBA**	**HMBA**
Total Fuel Cost ($/hr)	1937.88	1905.63	1879.96
Total Emissions (Kg/hr)	1488.65	1477.43	1452.48
Transmission Loss (MW)	39.69	41.75	40.43

Figure 5.1 represents the results obtained using BA, MBA and HMBA for MAED, MAEED and MOMAHEED optimization problems for a four area, twelve generating unit system.

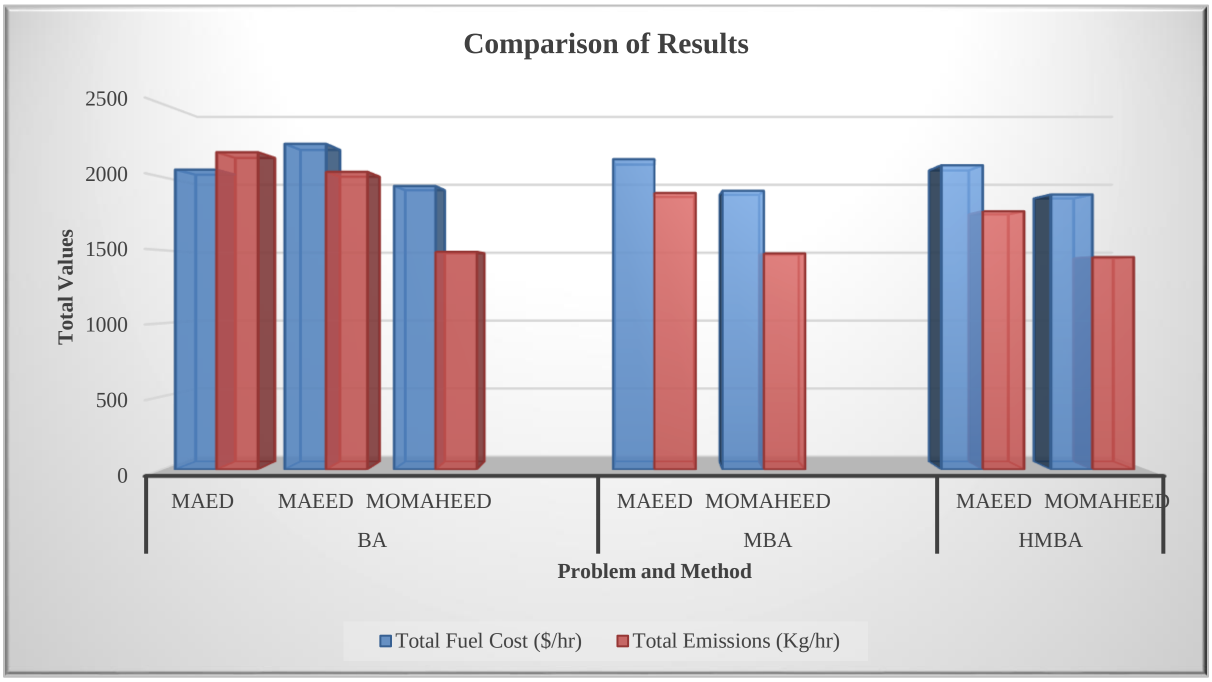


Figure 5:1: Comparison of BA, MBA & HMBA Results

5.2.6. HMBA comparison with other algorithms

To validate the algorithm the results of HMBA are compared to those of PSO taken from [11] for the same MAEED problem for a four area, twelve generating units system and tabulated in Table 5.6. HMBA resulted in a reduction of total fuel cost of 48.60% and a slight increase in emissions of 7.29% when compared to PSO. The increase in emissions is attributed to the use of Cardinal Priority ranking in selecting the optimal trade-off level of the two conflicting objectives which selected a weight of 0.6 for fuel cost function and a weight of 0.4 for emissions, whereas in PSO the weights were fixed at 0.8 and 0.2 for fuel cost objective and emission objective respectively. Total network transmission losses obtained using HMBA was comparable to that obtained using PSO.

Table 5.6: Comparison of HMBA and PSO

	PSO [11]	**HMBA**	**% Reduction**
Fuel Cost($/hr)	4046.21	2079.67	48.60%
Emissions Kg/hr)	1645.20	1765.21	-7.29%
Transmission Loss (MW)	48.59	49.07	-0.99%

HMBA was further validated by comparing its results to those of MOPSO, TLBO, TV-MPSO, BB-MOPSO and PCRO taken from [10] for various aspects of MAEED problem for a four area, sixteen generating units system as tabulated in Table 5.7. For all the algorithms fuel costs and emission values obtained while considering only the objective of minimizing fuel costs where HMBA resulted in lower fuel costs and lower emissions compared to all the algorithms. Similarly fuel costs and emission values were obtained while considering only the objective of minimizing emissions. HMBA resulted in lower fuel costs than all the other algorithms while emission values were higher than those obtained by PCRO and comparable to the other algorithms.

HMBA was also implemented for MAEED problem where the objectives were simultaneously curtailed leading to lower fuel costs and comparable emissions when compared than those obtained by the other algorithms for the respective single objective optimization problems. It is therefore evident that HMBO is a superior algorithm than MOPSO, TLBO, TV-MPSO, BB-MOPSO and PCRO.

Table 5.7: Comparison of HMBA and other algorithms

Algorithm	Minimizing Fuel Objective		Minimizing Emissions Objective		Combined Fuel & Emissions Objectives	
	Fuel Cost ($/hr)	Emissions (Kg/hr)	Fuel Cost ($/hr)	Emissions (Kg/hr)	Fuel Cost ($/hr)	Emissions (Kg/hr)
MOPSO	2005.21	635.20	2107.55	344.81	-	-
TLBO	2002.35	663.51	2105.25	347.96	-	-
TV-MPSO	1998.64	698.58	2084.00	364.98	-	-
BB-PSO	1995.80	716.42	2071.47	382.89	-	-
PCRO [10]	1984.30	872.63	2098.88	239.02	-	-
HMBA	522.94	381.71	1792.25	339.78	1013.23	380.65

The fuel costs and emissions comparison was as represented in Figures 5:2 and 5:3.

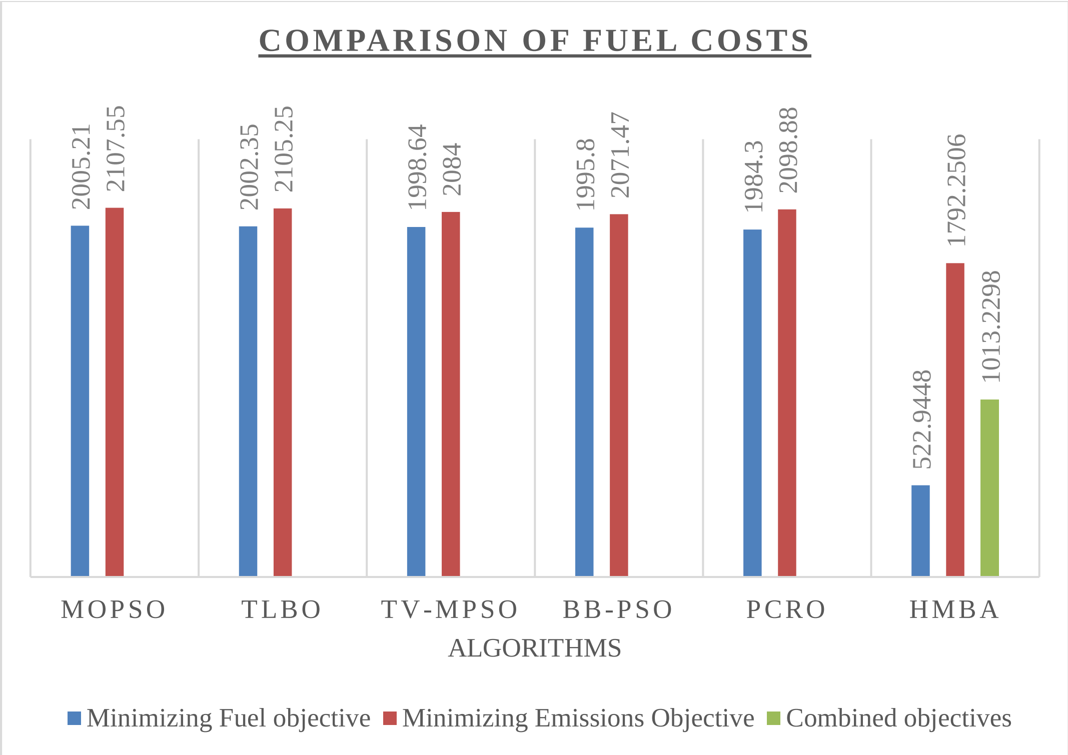


Figure 5:2: Comparison of HMBA Fuel Costs with those of other Algorithms

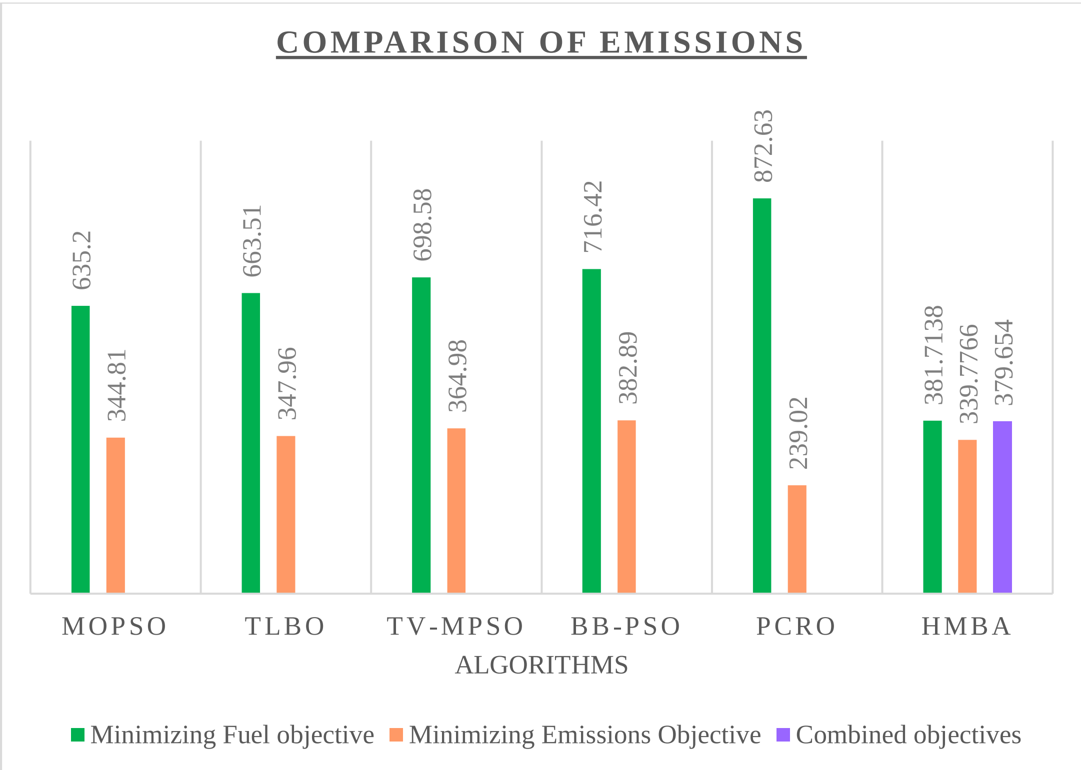


Figure 5:3: Comparison of HMBA Emissions with those of other Algorithms

5.3. DYNAMIC MOMAHEED RESULTS COMPARISON AND ANALYSIS

5.3.1. Spinning Reserve analysis

The pool reserve sharing scheme led to a significant reduction in spinning reserve per area as shown in Table 5.8.

Table 5.8: Spinning Reserve Analysis

Area	Peak Hour	Peak Load (MW)	Area Reserve without Reserve Sharing (MW)	Area Reserve with Reserve sharing (MW)	Reduction in Reserve
1	15	786	235.8	108.1700	46%
2	20	784	235.2	108.0300	46%
3	19	998	299.4	149.5850	50%
4	15	1063	318.9	154.1350	48%
Pool	19	3402	1020.6	503.8900	49%

5.3.2. Algorithm Accuracy

i) Bat Algorithm Accuracy

The Accuracy of BA in solving dynamic MOMAHEED problem is shown graphically below where BA optimal total power generated per hour was compared with the respective demand in that hour. The Standard Deviation (SD) of BA was found to be 184.56. The minimum error value of BA obtained was 0.14% and the maximum error value obtained was 21.41%. From the trend, lower accuracy was realized for lower demand values.

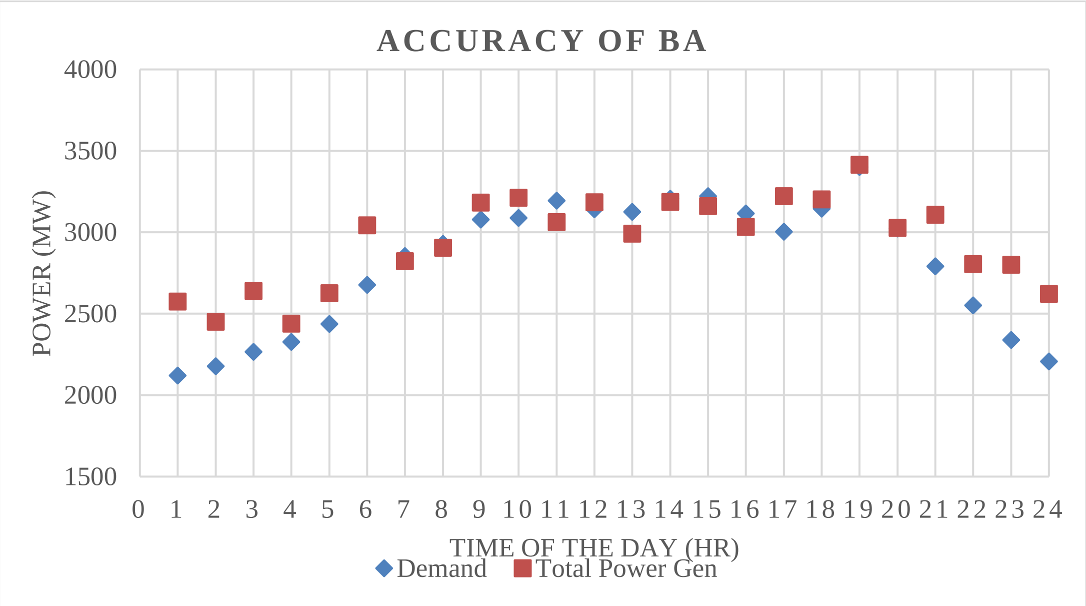


Figure 5:4: Accuracy of Bat Algorithm

5.3.3. Hybridized Modified Bat Algorithm Accuracy

Similarly the accuracy of HMBA in solving dynamic MOMAHEED problem is shown graphically in Figure 5:5 where the minimum error value of HMBA obtained was 0.11% and the maximum error value obtained was 1.17%. The Standard Deviation (SD) of HMBA was found to be 7.27.

HMBA results in more accurate solutions compared to BA

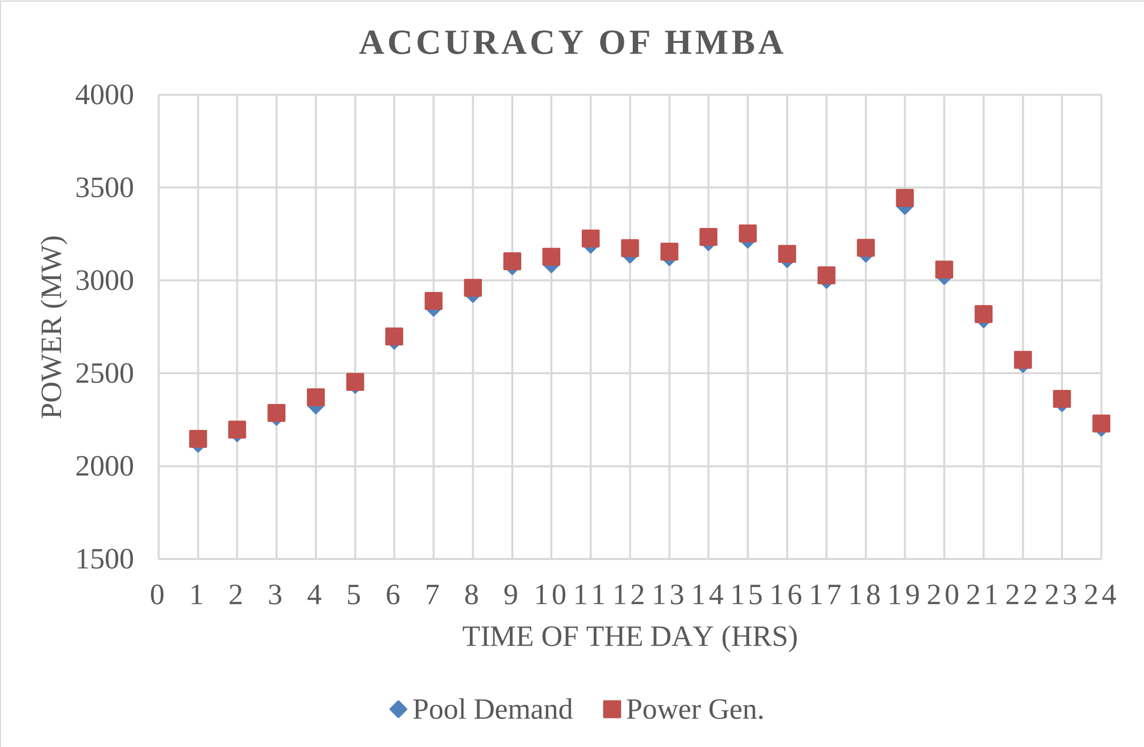


Figure 5:5: Accuracy of Hybridized Modified Bat Algorithm

5.3.4. Comparison of Bat Algorithm and Hybridized Modified Bat Algorithm Results

The following aspects of the results obtained using BA and HMBA are compared in this section:

i. Hourly total power schedule against hourly demand
ii. Hourly Power Loss
iii. Total Hourly Emissions
iv. Total Hourly Fuel costs
v. Hourly Hydro generation schedule

Table 5.9: Comparison of BA and HMBA in solving dynamic MOMAHEED

Hour	Demand (MW)	BAT ALGORITHM				HYBRIDIZED MODIFIED BAT ALGORITHM			
		Power Generated (MW)	Power loss (MW)	Total Emissions (ton/hr)	Total Fuel cost ($/hr)	Power Generated (MW)	Power loss (MW)	Total Emissions (ton/hr)	Total Fuel cost ($/hr)
1	2121	2595.423	20.3361	6309.5370	491,629.3132	2146.9315	13.1131	4451.0810	396,840.3741
2	2179	2466.0767	13.8824	5609.5123	368,161.9908	2197.9049	13.6139	4973.8629	421,404.6413
3	2267	2663.8038	23.2864	6642.5238	588,063.3843	2287.6909	12.9511	4380.6899	497,747.2324
4	2328	2457.6343	17.9618	6025.6172	609,412.8844	2372.161	16.932	4991.4530	612,790.1634
5	2438	2652.3568	25.7145	6135.8232	612,486.9067	2453.4655	6.6441	4021.3269	640,776.0913
6	2677	3070.3241	25.9130	8339.0926	961,997.9024	2699.8116	14.9473	4909.4471	697,417.1426
7	2855	2844.5048	21.9507	6593.0621	739,542.4694	2889.7168	22.6172	5916.4950	714,820.9835
8	2929	2929.2909	23.7743	7194.6638	820,811.8686	2960.9416	23.5384	6764.1154	810,157.6622
9	3078	3211.4592	27.6586	9122.7094	1,101,762.287	3104.5305	23.0617	8154.8436	830,159.2607
10	3088	3240.9815	28.5987	9506.8267	1,130,657.3014	3127.8957	27.6253	8236.4929	852,093.1488
11	3194	3088.4655	25.7313	7978.8681	980,395.9161	3227.2909	26.3012	9392.7650	928,879.6605
12	3141	3210.2309	25.9150	9953.5085	1,102,504.5300	3175.3807	25.7561	9176.8339	891,291.9012
13	3126	3013.8764	21.5678	8663.0843	910,147.0206	3156.5314	20.0489	9229.3503	881,507.8046
14	3207	3214.5823	27.9361	9655.2414	1,104,962.8344	3235.2259	23.1930	9249.2726	938,040.9370
15	3222	3191.439	29.1884	8921.8348	1,080,366.3623	3253.6409	26.9889	9517.6871	968,908.6820
16	3116	3057.2692	23.3159	8837.6810	952,063.8219	3143.7479	23.1081	8621.6442	865,287.1349
17	3004	3251.0337	29.1629	10432.5883	1,140,408.6237	3028.4925	20.4334	8864.7312	827,438.9979
18	3145	3232.8879	29.5769	9574.6299	1,120,810.2249	3177.2804	28.8942	8922.5580	909,800.9569
19	3402	3445.253	30.9596	10099.0018	1,313,077.3680	3445.4491	30.8338	9763.8140	1,041,121.0498
20	3024	3051.7676	23.6179	9189.8902	946,015.4275	3059.6105	21.1323	8023.8757	845,680.1106
21	2792	3137.3669	28.6128	9701.9410	1,027,111.5130	2819.5163	22.4499	7879.0569	685,189.8102
22	2551	2830.4951	24.6655	7329.3465	722,948.7116	2572.7572	17.5728	7417.4126	660,114.9573
23	2340	2819.9934	19.0944	7435.8498	718,146.3028	2362.6378	18.8514	5542.1849	618,809.9415
24	2208	2646.8182	23.7587	6528.7829	539,677.7679	2231.0914	14.4376	3504.6532	445,415.2868

i) *Hourly total power schedule against hourly demand*

In Figure 5:6, total hourly power scheduling using BA and HMBA was compared against hourly demand for the Multi area system. HMBA achieved an optimal schedule of power output of generators that closely matched the demand trends as compared to BA whose scheduling was greatly haphazard. The Standard Deviation (SD) of BA was found to be 184.56 while that of HMBA was 7.27, confirming the high accuracy level of HMBA.

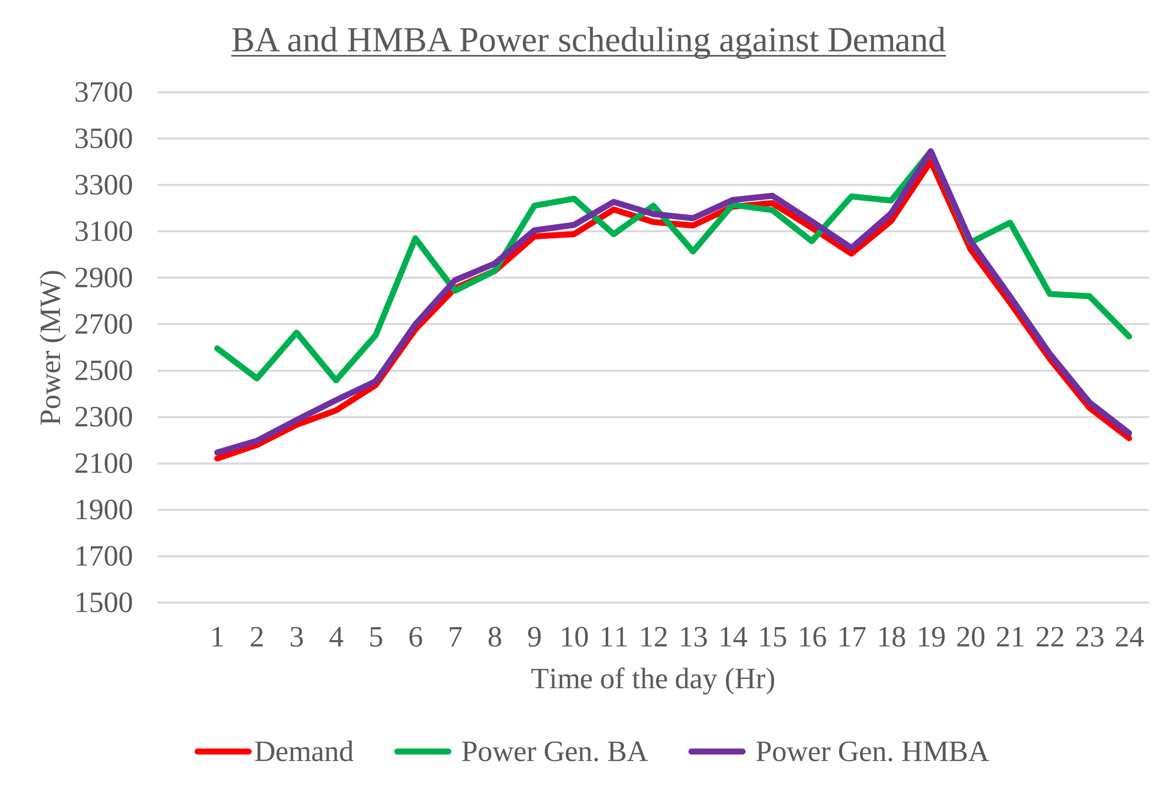


Figure 5:6: BA and HMBA Hourly Power Scheduling against Demand

ii) *Hourly Power Loss*

HMBA resulted in comparatively lower power loss values over 24hr period as shown in Figure 5:7. HMBA realized a minimum power loss value of 6.6441MW against demand of 2438MW at 0500hrs compared to a minimum power loss of 13.8824MW realized by BA at 0200hrs against a demand of 2179MW. Both algorithms realized maximum power loss values at the pool peak demand of 3402MW at 1900hrs, where BA power loss value was 30.9596MW and HMBA power loss value was 30.8338MW.

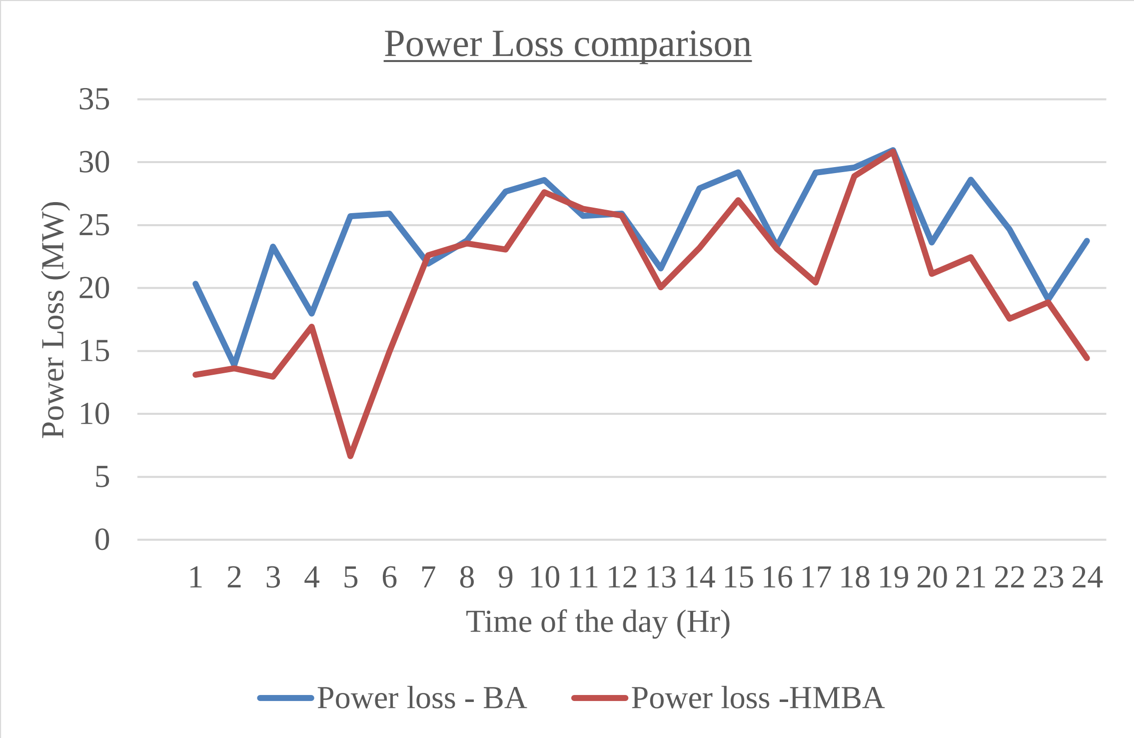


Figure 5:7: Comparison of BA and HMBA Power Loss Values

iii) Total Hourly Emissions against Demand

Figure 5:8 compared emission values attained using BA and HMBA over a period of 24hrs against the respective Power demand values. Emission trends for both algorithms matched the demand trends with lower emission values being attained at lower demand values and higher emission values being attained at higher demand values. Emission values increased with increasing demand due to increased generation from thermal plants.

HMBA realized lower emission values compared to BA due to its higher accuracy level in optimally scheduling generation to match demand as well as its higher dispatch of Hydro generators which displace some generation from thermal plants.

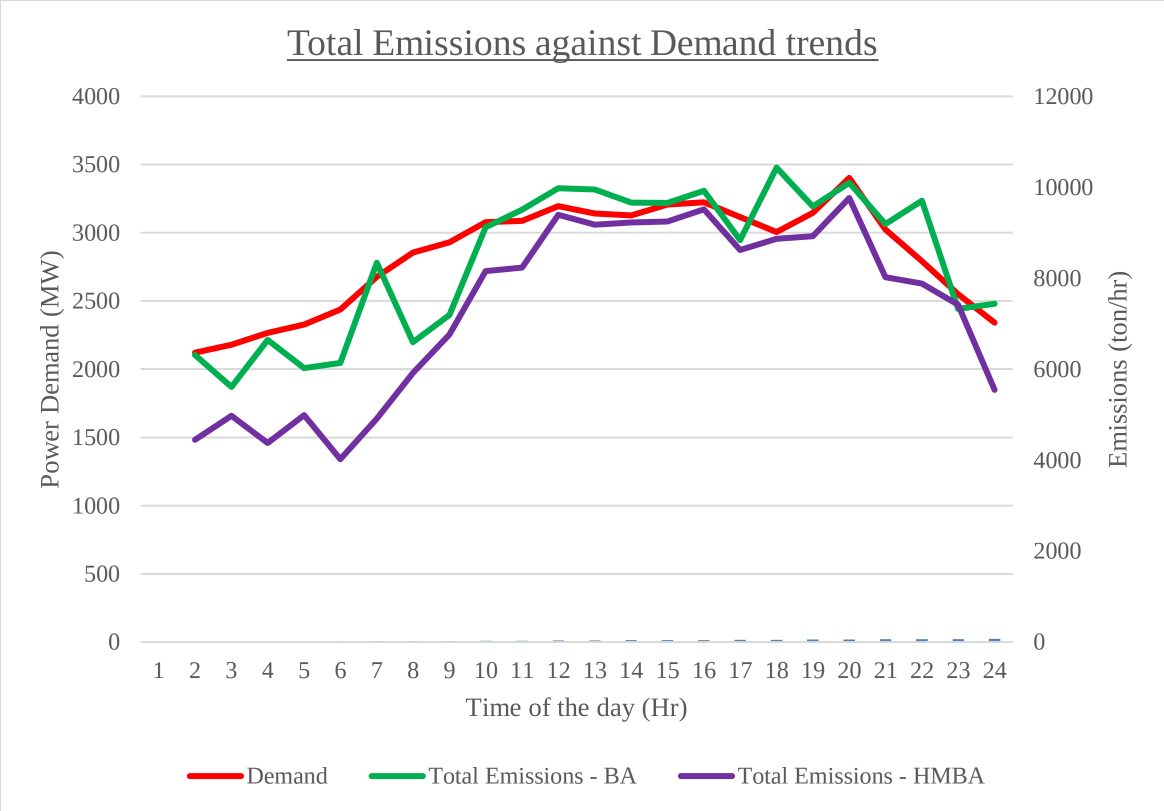


Figure 5:8: Comparison of Total Emissions and Demand trends

iv) Total Hourly Fuel Costs against Demand

HMBA resulted in lower Fuel Cost values over 24hr period as shown in Figure 5:9. HMBA realized a minimum fuel cost value of 396,840.374$/hr compared to 491,629.3132$/hr realized by BA at a minimum load demand of 2121MW at 0100hrs. Thus resulting in a fuel cost reduction of 19.28%.

Consequently, HMBA realized a maximum fuel cost value of 1,041,121.05$/hr compared to 1,313,077.368$/hr realized by BA at a maximum load demand of 3402MW at 1900hrs. Thus resulting in a fuel cost reduction of 20.71%.

The reduction in Fuel costs realized by HMBA was attributed to its higher accuracy level in optimally scheduling generation to match demand as well as its higher dispatch of Hydro generators which have zero fuel costs which displace some generation from thermal plants.

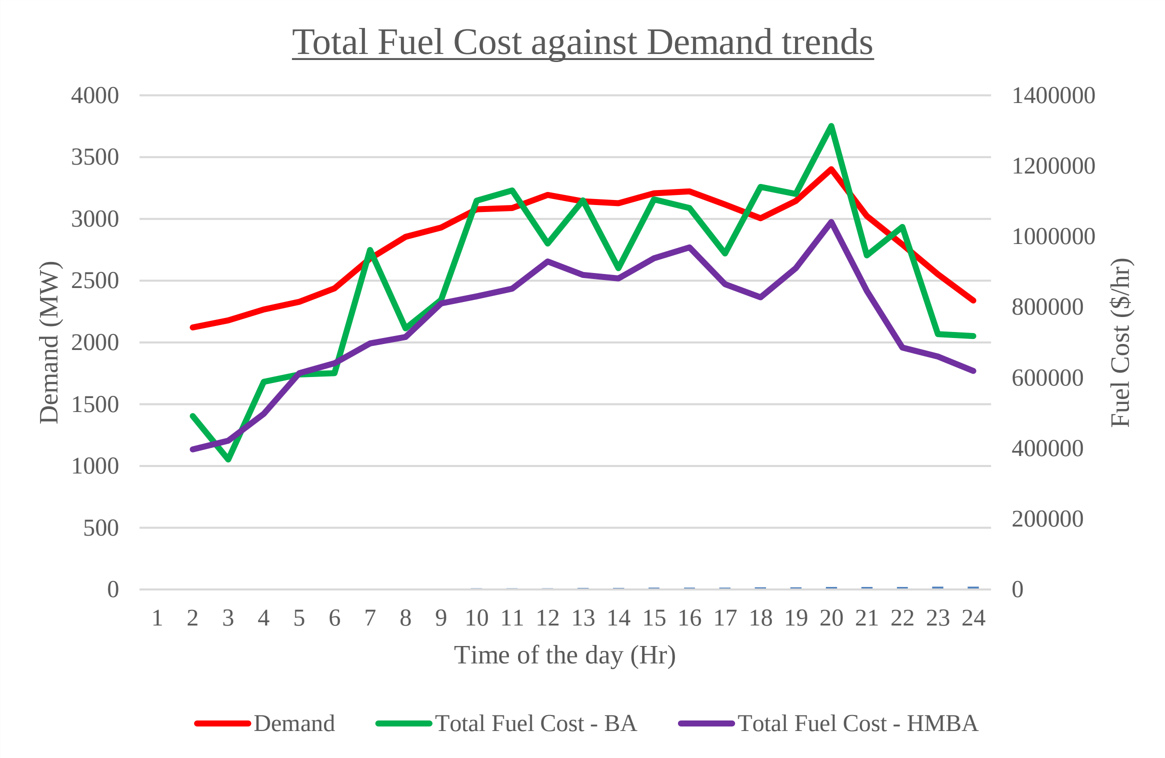


Figure 5:9: Comparison of Fuel costs against Demand trends

v) Hourly Hydro generation schedule

Both HMBA and BA resulted in Hydro scheduling trends that closely match the demand trends i.e. Hydro scheduling increased with increasing demand with lower hydro dispatch at lower demands and higher hydro dispatch at higher demands.

Both algorithms realized maximum hydro generation values at the pool peak demand of 3402MW at 1900hrs, where BA hydro generation was 439.31MW and HMBA hydro generation was 669.84MW.

HMBA resulted in higher hydro dispatch scheduling than BA over the whole period of time as shown in Figure 5:10.

The scheduling was done while considering the limited capacity of water reservoirs and the stochastic nature of water availability.

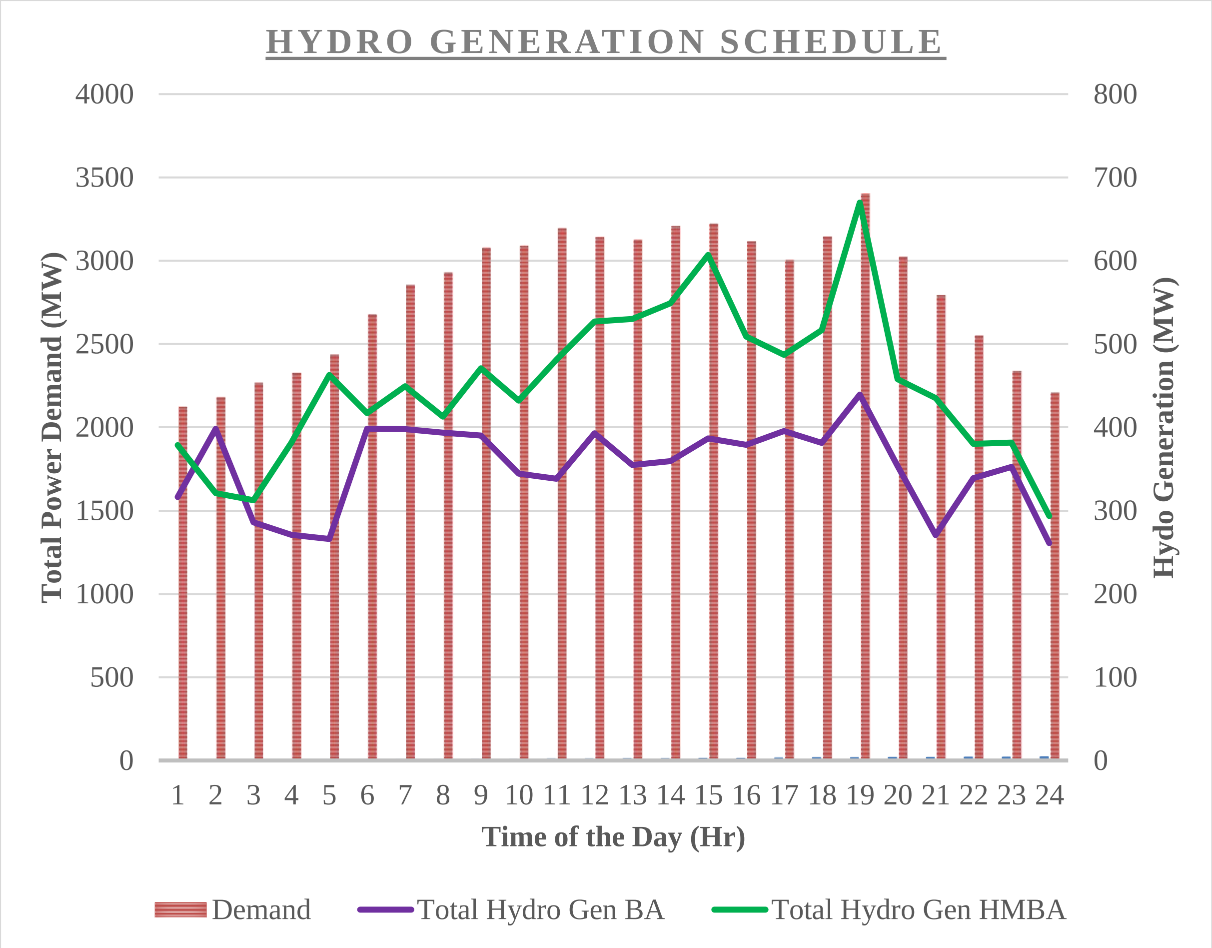


Figure 5:10: Hydro Generation scheduling against demand

5.4. Chapter Conclusion

Generally HMBA has better performance when handling both static and dynamic multi area multi objective economic dispatch problems than BA and other optimization algorithms.

It is evident that the proposed hybrid of Modified Bat Algorithm and Differential Evolution yield better results for multi-objective and multi-area optimization of hydrothermal combined environmental and economic dispatch in all the cases tested.

The method was tested in solving Multi-objective MAEED and MAHEED problems on a four area system each with three generating units and also in solving Dynamic Multi-objective MAHEED problem on a four area system each with six generating units. In all cases the method realized better results in terms of accuracy of scheduling and lower operation cost and lower emissions compared to the traditional BA, PSO, MOPSO, TLBO, TV-MPSO, BB-MOPSO and PCRO.

The better results obtained using the hybrid method can be attributed to the individual strengths of the algorithms which constitute the hybrid. Bat Algorithm has the following strengths:

- High Accuracy due to the increase in the number of probable solutions in the library, thus a wide range of options available.
- High efficiency in handling highly non-linear problems
- Ability to auto-zoom into regions where optimal solutions can be found
- Faster and stable convergence
- Simplicity of the algorithm hence easy to implement
- Flexibility which allows it to easily hybridize.

BA however has the following weaknesses:

- Rate of convergence is very fast at early stages and then slows down, this can lead to premature convergence, getting stuck in local minima, or non-convergence.
- The link between the rate of convergence and the parameters has not been mathematically analyzed and moreover the best values for parameters have not been established for most applications, hence a lot of trials are needed to tune the algorithm.

Differential Evolution has the following strengths:

- Enhanced capacity for local search
- Few control variables hence easy implementation
- Ability to handle computation intensive functions due to its parallelizability and high performance

The shortcoming of DE is its unstable convergence and ease of getting stuck in local optima.

The hybrid takes advantage of enhanced capacity for local search possessed by DE, and the high accuracy and efficiency of BA. Furthermore modifications are implemented in the Bat Algorithm to enhance its exploitation and exploration ability thus preventing premature convergence and getting stuck in local minima.

Hence the resultant hybrid of Modified Bat Algorithm and Differential Evolution (HMBA) possesses the following strengths which account for the better results it achieves:

- High Accuracy
- High efficiency
- Good and stable convergence properties
- High quality of results due to its better ability to reach global optimal solutions
- Robustness
- Ease of implementation

HMBA however, has the following weaknesses

- High computation times
- Slower convergence compared to BA, DE and PSO.

CHAPTER SIX

6. CONCLUSIONS AND RECOMMENDATIONS

6.1. CONCLUSIONS

This chapter concludes the findings of this research. Conclusions are drawn on the proposed problem formulation and algorithm, their strengths and shortcomings. The effects of hydroelectric generation and the proposed reserve sharing scheme are also highlighted as well as proposed areas of future work.

6.1.1. Problem Formulation

In this research a new formulation has been developed for a Multi Area Economic Dispatch (MAED) problem which takes into account the following aspects of modern power pools:

i) The hydrothermal nature of the power pools which is addressed in the formulation by introducing hydro component into the formulation while also considering the constraint of limited capacity of water reservoirs and the stochastic nature of water availability.

ii) The rising pressure to minimize environmental effects of power generation using fossil fuels handled by simultaneously minimizing operation cost and emissions thus formulating the optimization problem as a multi objective minimization problem.

iii) The dynamic nature of demand which is addressed by formulating the problem as a Multi Area Dynamic Economic Dispatch (MADED) problem and not a static MAED problem.

iv) The fact that utilities in a power pool are mandated to meet their own contingencies by keeping a definite contingency reserve even when in a reserve sharing scheme, which is considered in the reserve sharing scheme utilized.

In considering the above aspects a Multi-Objective, Multi-Area Hydrothermal, Dynamic Environmental Economic Dispatch (MOMAHDEED) problem has been successfully formulated and solved for the very first time as there is no evidence that exists in open literature of an approach similar to this.

This formulation represents a modern power pool more accurately which then leads to more realistic results and better optimization of the multi-area power system operation in general.

6.1.2. Algorithm

In this research also a new algorithm has been developed for solving the formulated multi-objective problem which constitutes a hybrid of Modified Bat Algorithm and Differential Evolution. The Bat Algorithm (BA) is a metaheuristic algorithm which is inspired by echolocation behavior of micro bats. It has successfully been used in solving many tough optimization problems in various fields. BA however has a weak diversification capability which leads to premature convergence and getting stuck in local optima when used in higher-dimensional optimization problems. Modifications have been done to the velocity and frequency equations of BA to improve its exploitation and exploration capability. The Modified Bat Algorithm (MBA) has been further hybridized using the Differential Evolution (DE) to increase its accuracy. A weighted sum method has been used to convert the multi objective function into a single objective one and optimal solutions are selected using cardinal priority ranking.

The effectiveness and capability of the new algorithm has been tested by solving the Multi Area Environmental Economic Dispatch (MAEED) problem for a multi area system consisting of four areas each with three generating units. The results of HMBA have been validated by comparing them to those obtained by the traditional BA and PSO for the same system. HMBA resulted in a reduction of total fuel cost of 48.60% with comparable emissions and power losses when compared to PSO and a reduction of 6.58% of fuel costs and 13.25% reduction on emissions when compared to BA. Hence it is evident from the results that HMBA is superior and robust in solving complex multi-objective optimization problems.

To further confirm the algorithms' applicability and scalability, HMBA was used in solving MOMAHDEED problem for a larger multi area system consisting of four areas each with six generating units of larger capacities. Hourly load demand and hourly hydro scheduling were considered as well as the effects of valve point loading. The results were validated by comparing them to those obtained by the traditional BA for the same systems.

The following observations were made which further confirm the above strengths of the algorithm:

i) HMBA achieved an optimal hourly schedule of power output of generators that closely matched the hourly demand trends as compared to BA whose scheduling is greatly haphazard, thereby confirming the good and stable convergence properties of the algorithm near global optimal solutions as well as its high level of accuracy.

ii) HMBA resulted in a fuel cost reduction of up to 20% and emissions reduction of up to 40% which is attributed to its higher accuracy level in optimally scheduling generation to match demand as well as its higher dispatch of Hydro generators. This shows the robustness of the algorithm and its ability to achieve high quality results.

It is evident that HMBA produced better results in terms of lower fuel costs, lower emissions and lower power losses when compared to the traditional BA when tested in solving the more complex and dynamic MOMAHDEED problem.

Therefore, it can be concluded that HMBA can efficiently handle larger complex optimization problems with better results.

6.1.3. Effect of Hydroelectric generation

The introduction of hydroelectric generating units into the MAEED problem led to a reduction of total fuel cost by 13% and total emissions reduced by 26.8%, since some of the electricity generated by thermal plants is displaced by the hydroelectric generation which has zero fuel cost and zero emissions.

6.1.4. Reserve sharing scheme

In this research also a new reserve sharing scheme is investigated where each area is mandated to keep its own contingency reserve of 7% and a pool reserve which is 25% of the peak power demand of area 4 (being the area with the highest peak demand) is shared. This reserve sharing scheme leads to a significant reduction in spinning reserve per area of 46% to 50% when compared to a case where each area keeps its own spinning reserve of 30% without sharing. Therefore utilities in a power pooling arrangement are able to avoid incurring additional generation infrastructure investment costs and make their networks more secure when spinning reserve is shared in this manner.

With the main aim of this research being to formulate and solve a Multi-Objective, Multi-Area, Hydrothermal, Dynamic Environmental Economic Dispatch (MOMAHDEED) problem, using a Hybridized Modified Bat Algorithm (HMBA), the problem formulated, the hybrid algorithm developed and the results obtained satisfy the intended objective.

These research findings will lead to better optimization of the multi-area power system operation in general.

6.2. RECOMMENDATIONS

1. This work is recommended for adoption and use by utilities and ISO in power pools for optimal scheduling of their generators
2. In order to address the shortcomings of this algorithm and further extend this work, the following areas are proposed for further research
   - Fine tuning of HMBA parameters to improve execution speed and increase its rate of convergence
   - Application of HMBA to larger systems with 60 – 100 generators to further assess its applicability and scalability
   - Application of HMBA to a real practical power pool to assess its suitability in real-time applications.
   - Case study application
   - Use of cubic cost functions to further enhance the accuracy

6.3. LIST OF PUBLICATIONS

1. Seline .A. Olang'o; Peter .M. Musau; Nicodemus .A. Odero, "Multi Objective Multi Area Hydrothermal Environmental Economic Dispatch using Bat Algorithm" in 2018 International Conference on Power System Technology (POWERCON2018). Year: 2018, Pages 198 – 203. Published in IEEE Xplore on 7TH January 2019

   Abstract

   This paper presents a Multi Objective, Multi Area Hydrothermal Environmental Economic Dispatch (MOMAHEED) problem which determines the optimal generating level of all the hydro and thermal generating units to adequately supply the demand, such that the total fuel cost of thermal plants in all areas and emissions are simultaneously curtailed while satisfying all physical and operational constraints. MOMAHEED is solved using Bat Algorithm (BA) which is inspired by echolocation behavior of micro bats. The multi objective function is converted to a single objective one using weighted sum method. The algorithm is tested on a four-area system considering three test cases and results in lower fuel costs as compared to Particle Swarm Optimization (PSO) Algorithm.

Index Terms— Bat Algorithm (BA), Multi Objective Multi Area Hydrothermal Environmental Economic Dispatch (MOMAHEED), Particle Swarm Optimization Algorithm (PSO).

DOI: 10.1109/POWERCON.2018.8601543

[*https:*//ieeexplore.ieee.org/document/8601543](https://ieeexplore.ieee.org/document/8601543)

2. Seline .A. Olang'o; Peter .M. Musau; Nicodemus .A. Odero, " Hybridized Modified Bat Algorithm with Cardinal Priority Ranking for solving Multi Area Environmental Economic Dispatch Problem" in 2019 5th International Conference on Soft Computing and Machine Intelligence (ISCMI2018). Year: 2018, Pages 198 – 203. Published in IEEE Xplore on 2ND May 2019

Abstract

The Bat Algorithm (BA) is a metaheuristic algorithm which is inspired by echolocation behavior of micro bats. It has successfully been used in solving many tough optimization problems in various fields. BA however has a weak diversification capability which leads to premature convergence and getting stuck in local optima when used in higher-dimensional optimization problems. This paper presents modifications to the velocity and frequency equations of BA to improve its exploitation and exploration capability. The Modified Bat Algorithm (MBA) is further hybridized using the Differential Evolution (DE) to increase its accuracy. The Hybridized Modified Bat Algorithm (HMBA) is then used to solve the Multi Area Environmental Economic Dispatch (MAEED) problem which is a multi-objective, nonlinear power system optimization problem. A weighted sum method is used to convert the multi objective function into a single objective one and optimal solutions are selected using cardinal priority ranking. HMBA is tested on a four-area system and results in lower fuel costs and lower emissions as compared to BA, MBA and Particle Swarm Optimization.

Keywords-Bat Algorithm (BA); Differential Evolution (DE); Hybridized Modified Bat Algorithm (HMBA); Modified Bat Algorithm (MBA); Multi Area Environmental Economic Dispatch (MAEED)

DOI: 10.1109/ISCMI.2018.8703217

[*https:*//ieeexplore.ieee.org/document/8703217](https://ieeexplore.ieee.org/document/8703217)

REFERENCES

[1] V. K. Jadoun, N. Gupta, K. R. Niazi, A. Swarnkar, and R. C. Bansal, “Multi-Area Environmental Economic Dispatch with Reserve Constraints using Enhanced Particle Swarm Optimization,” *Electr. Power Components Syst.*, 2015.

[2] Economic Commission for Africa, “Assessment of power poolong arrangement in Africa,” 2004.

[3] J. J. Grainger and W. D. J. Stevenson, *Power system analysis*. McGraw Hill, 2003.

[4] J. Zhu, *Optimization of Power System Operation,* John Wiley & Sons inc. 2009.

[5] D. P. Kothari and I. J. Nagrath, *Modern Power System Analysis*. 2003.

[6] M. O. Hassan, E. Z. Yahia, and G. A. Mohammed, “Short Term Hydrothermal Scheduling using Particle Swarm Optimization,” *Int. J. Adv. Eng. Res.*, vol. 3, no. 11, 2016.

[7] T. Niknam, H. D. Mojarrad, and H. Z. Meymand, “Non-smooth Economic Dispatch computation by Fuzzy and Self Adaptive Particle Swarm Optimization,” *Appl. Soft Comput. J.*, vol. 11, no. 2, pp. 2805–2817, 2011.

[8] “iea” [Online]. Available: https://www.iea.org/geco/electricity/

[9] M. A. Abido, “Environmental/Economic Power Dispatch using Multiobjective Evolutionary Algorithms,” *IEEE Trans. Power Syst.*, vol. 18, no. 4, 2003.

[10] M. Sharma, M. Pandit, and L. Srivastava, “Multi-Area Economic Dispatch with Tie-Line Constraints employing Evolutionary Approach,” *Int. J. Eng. Sci. Technol.*, 2010.

[11] J. Li, Q. Pan, P. Duan, H. Sang, and K. Gao, “Solving Multi-Area Environmental/Economic Dispatch by Pareto-Based Chemical-Reaction Optimization Algorithm" *IEEE/CAA Journal of Automatica Sinica.* 2017

[12] R. Romano, V. H. Quintana, R. López, and V. Valadez, “Constrained Economic Dispatch of Multi-Area Systems using the Dantzig-Wolfe Decomposition Principle,” *IEEE Trans. Power Appar. Syst.*, 1981.

[13] D. Streiffert, “Multi-Area Economic Dispatch with Tie Line Constraints,” *IEEE Trans. Power Syst.*, 1995.

[14] A. Ali, H. M. Dubey, and M. Pandit, “Dispatch : A Novel Heuristic Paradigm,” *2017 Int. Conf. Energy, Commun. Data Anal. Soft Comput.*, no. 4, pp. 1068–1073, 2017.

[15] M. Yazdandoost, P. Khazaei, S. Member, and S. Saadatian, “Distributed Optimization Strategy for Multi Area Economic Dispatch Based on Electro Search Optimization Algorithm,” *2018 World Autom. Congr.*, pp. 1–6, 2018.

[16] H. M. Dubey, M. Pandit, N. Tyagi, and B. K. Panigrahi, “Wind Integrated Multi Area Economic Dispatch using Backtracking Search Algorithm,” *IEEE Trans. Power Syst.*, 2016.

[17] S. Vijayaraj and R. K. Santhi, “Multi-Area Economic Dispatch using Flower Pollination Algorithm,,” in *International Conference on Electrical, Electronics, and Optimization Techniques, ICEEOT 2016*, 2016.

[18] A. V. V Sudhakar, K. Chandram, and A. J. Laxmi, “Multi Area Economic Dispatch with Tie Line Loss using Lambda-Concept and Tie line matrix,” in *IEEE Recent Advances in Intelligent Computational Systems, (RAICS 2015),* 2016.

[19] K. P. Nguyen and G. Fujita, “Multi-Area Economic Dispatch in bulk system using Self-Learning Cuckoo Search Algorithm,” *Int. Univ. Power Eng. Conf.*, vol. 2, no. 2, pp. 1–6, 2017.

[20] K. P. Nguyen, N. D. Dinh, and G. Fujita, “Multi-area Economic Dispatch Using Hybrid Cuckoo Search Algorithm” *International Universities Power Engineering Conference, (UPEC 2015),* 2015

[21] H. Thi, T. Binh, and T. K. Toan, “Real-Coded Genetic Algorithm for Solving Multi-Area Economic Dispatch Problem,” *IEEE Symp. Comput. Intell. Eng. Slns.*, 2013.

[22] M. Sharma, M. Pandit, and L. Srivastava, “Reserve Constrained Multi-Area Economic Dispatch employing Differential Evolution with Time-Varying Mutation,” *Int. J. Electr. Power Energy Syst.*, 2011.

[23] C. Rani, E. Petkov, K. Busawon, and M. Farrag, “Particle Swarm Optimization with Exponentially Varying Inertia Weight Factor for solving Multi-Area Economic Dispatch problem” in *3rd International Symposium on Environment Friendly Energies and Applications, (EFEA 2014)*, 2014.

[24] Prasanna T. S and Somasundaram P, “Multi-Area Security Constrained Economic Dispatch by Fuzzy-Stochastic Algorithms,” *J. Theor. Appl. Inf. Technol. 2009*..

[25] U. Fragomeni, “Direct method to Multi-Area Economic Dispatch,” *International Conference on Advances in Power Conversion and Energy Technologies, (APCET 2012)*, 2012.

[26] Jinbei .A. Li, “Improve Crisscross Optimization Algorithm for Solving the Multi-Area Economic/Emission Dispatch,” *China Int. Conf. Electr. Distrib.*, no. 201802260000013, pp. 453–461, 2018.

[27] P. Balachandar, S. Ganesan, N. Jayakumar, S. Subramanian, “Economic / Environmental Dispatch of an Interconnected Power System considering Multiple Fuel Sources,” *Int. Conf. Circuit, Power Comput. Technol.*, no. 2017, pp. 1–7, 2017.

[28] A. Azizivahed, S. Ghavidel, M. J. Ghadi, L. Li, and J. Zhang, “Multi - Area Economic Emission Dispatch Considering Load Uncertainty,” *Int. Conf. Electr. Mach. Syatems*, no. 2017, pp. 1–6, 2017.

[29] R. Azizipanah-Abarghooee, P. Dehghanian, and V. Terzija, “Practical Multi-Area Bi-Objective Environmental Economic Dispatch equipped with a Hybrid Gradient Search Method and Improved Jaya Algorithm,” *IET Gener. Transm. Distrib.*, 2016.

[30] M. Peter Musau, N. A. Odero, and C. W. Wekesa,, “Multi Area Multi Objective Dynamic Economic Dispatch with Renewable Energy and Emissions,” *IEEE Trans. Power Syst.*, pp. 112–117, 2016.

[31] A. Soroudi and A. Rabiee, “Optimal multi-area generation schedule considering renewable resources mix: a real-time approach,” *IET Gener. Transm. Distrib.*, vol. 7, no. 9, pp. 1011–1026, 2013.

[32] M. Peter Musau, N. A. Odero, and C. W. Wekesa, “Multi Area Multi Objective Dynamic Economic Dispatch with Renewable Energy and Multi Terminal DC Tie Lines,” *IEEE Trans. Power Syst.*, 2016.

[33] L. Wang and C. Singh, “Reserve-Constrained Multiarea Environmental/Economic Dispatch based on Particle Swarm Optimization with Local search,” *Eng. Appl. Artif. Intell.*, vol. 22, pp. 298–307, 2009.

[34] C. Wang and S. M. Shahidehpour, “Power generation scheduling for Multi-Area Hydro-Thermal systems with Tie Line constraints, cascaded reservoirs and uncertain data,” *IEEE Trans. Power Syst.*, vol. 8, no. 3, pp. 1333–1340, 1993.

[35] “IEEE Xplore.” [Online]. Available: www.ieeexplore.ieee.org.

[36] K. P. Nguyen, N. D. Dinh, and G. Fujita, “Multi-area Economic Dispatch using Hybrid Cuckoo Search Algorithm,” *IEEE Trans. Power Syst.*, 2015.

[37] V. K. Jadoun, N. Gupta, K. R. Niazi, A. Swarnkar, and R. C. Bansal, “Multi-area Economic Dispatch using Improved Particle Swarm Optimization,” *Energy Procedia*, vol. 75, no. September, pp. 1087–1092, 2015.

[38] D. Gonidakis and A. Vlachos, “Bat Algorithm Approaches for solving the Combined Economic and Emission Dispatch Problem,” *International Journal for Computer Applications*,vol. 124, no. 1, pp. 1–7, 2015.

[39] N. Mishra and M. Pandit, “Economic Emission Dispatch using Weighted Sum Based PSO with Fuzzy Decesion Making: Application of Artificial Intelligence,” *Annu. Int. Conf. Emerg. Res. Areas, AICERA and Int. Conf. Microelectron. Commun. Renew. Energy, ICMiCR - Proc.*, 2013

[40] S. Vijayaraj and R. K. Santhi, “Economic Dispatch with Multi-Fuel option using Improved Bat Algorithm,” *Int. J. Multidiscip. Res. Mod. Educ. ISSN Vol. II, Issue II*, pp. 2454–6119, 2016.

[41] G. Kron, “Tensorial Analysis of Integrated Transmission Systems; Part II. Off-Nominal Turn Ratios,” *Trans. Am. Inst. Electr. Eng. Part III Power Appar. Syst.*, vol. 71, no. 1, pp. 505–512, 1952.

[42] X. Yang, “A new Metaheuristic Bat- Inspired Algorithm" *Nature Inspired Cooperative Strategies for Optimization (NICSO)*, vol. 284, no. May, 2010.

[43] W. U. Kabir, N. Sakib, S. M. Rahman Chowdhury, and M. S. Alam, “A Novel Adaptive Bat Algorithm to Control Explorations and Exploitations for Continuous Optimization Problems,” *Int. J. Comput. Appl.*, vol. 94, no. 13, pp. 15–20, 2014.

[44] A. M. Taha and A. Y. C. Tang, “Bat Algorithm for Rough Set Attribute,” *J. Theor. Appl. Inf. Technol.*, vol. 51, no. 1, pp. 1–8, 2013.

[45] O. S. Soliman, “A Chaotic Levy Flights Bat Algorithm for Diagnosing Diabetes Mellitus,” *Int. J. Comput. Appl.*, vol. 111, no. 1, pp. 36–42, 2015.
[46] S. Goyal and M. S. Patterh, “Wireless Sensor Network Localization Based on BAT Algorithm” *International Association of Scientific Innovation and Research (IASIR) & International Journal of Emerging Technologies in Computational and Applied Sciences (IJETCAS)*, pp. 13–192, 2013.
[47] J. W. Zhang and G. G. Wang, “Image Matching using a Bat Algorithm with Mutation,” *Appl. Mech. Mater.*, vol. 203, no. February, pp. 88–93, 2012.
[48] M. K. Marichelvam and T. Prabaharan, “A Bat Algorithm for realistic Hybrid Flowshop Scheduling Problems to minimize Makespan and Mean Flow Time,” *ICTACT J. Soft Comput.*, vol. 03, no. 01, pp. 428–433, 2012.
[49] V. U. Reddy and A. Manoj, “Optimal Capacitor Placement for Loss Reduction in Distribution Systems using Bat Algorithm,” *IOSR J. Eng.*, vol. 2, no. 10, pp. 23–27, 2012.
[50] F. Hafiz Tehzeeb ul Hassan; Muhammad Usman Asghar; Muhammad Zunair Zamir; Hafiz .M. Aamir, “Economic Load Dispatch using Novel Bat Algorithm with Quantum and Mechanical Behaviour,” *Int. Symp. Wirel. Systems Networks*, no. November 2017, 2017.
[51] V. G Ravi Kumar; Allaparthi Rohith; G, Priyanka; G, “Multi-objective Optimal Economic Emission Power Dispatch using Bat algorithm,” *Innov. Power Adv. Comput. Technol.*, no. April 2017, 2017.
[52] Huijun Liang; Yungang Liu; Yanjun Shen; Fengzhong L, “A Multiobjective Chaotic Bat Algorithm for Economic and Emission Dispatch,” *Chinese Autom. Congr.*, 2017.
[53] Yun Tonce Kusuma Priyanto; Muhammad Febrin Maulana; Andhika Giyantara, “Dynamic Economic Dispatch using Chaotic Bat Algorithm on 150kV Mahakam power system,” *Int. Semin. Intell. Technol. its Appl.*, vol. August 201, p. 150, 2017.
[54] D. Pradhan, Gunanidhi; P, D, “Solving optimal load dispatch problem using Enhanced Bat Optimization Algorithm,” *Innov. Power Adv. Comput. Technol.*, no. April 2017, 2017.
[55] S. Vijayaraj and R. K. Santhi, “Multi-Area Economic Dispatch with Prohibited Operating Zones using Improved Bat Algorithm,” *Int. J. Multidiscip. Res. Mod. Educ. ISSN Vol. II, Issue II*, pp. 2454–6119, 2016.
[56] S. Gautham and J. Rajamohan, “Economic Load Dispatch using Novel Bat Algorithm,” *IEEE 1st Int. Conf. Power Electron. Intell. Control Energy Syst.*, no. July 2016, pp. 1–4, 2016.
[57] T. T. Nguyen and S. D. Ho, “Bat Algorithm for Economic Emission Load Dispatch Problem,” *Int. J. Adv. Sci. Technol.*, vol. 86, pp. 51–60, 2016.
[58] A. Latif and P. Palensky, “Economic dispatch using Modified Bat Algorithm,” *Algorithms*, vol. 7, no. 3, pp. 328–338, 2014.
[59] Julia. T. Jose, “Economic Load Dispatch including wind power using Bat Algorithm,” *Int. Conf. Adv. Electr. Eng.*, vol. Jan 2014, 2014.
[60] S. Biswal, A. K. Barisal, A. Behera, and T. Prakash, “Optimal Power Dispatch using Bat Algorithm,” *Int. Conf. Energy Effic. Technol. Sustain.*, pp. 1018–1023, 2013.
[61] Huijun Liang; Yungany Liu; Yanjun Shen; Fengzhong Li; Yongchao M, “A Hybrid Bat Algorithm for Economic Dispatch with Random Wind Power,” *IEEE Trans. Power Syst.*, vol. 33, no. 5, pp. 5052–5061, 2018.
[62] R. Storn and K. Price, “Differential Evolution – A Simple and Efficient Heuristic for global Optimization over Continuous Spaces,” *J. Glob. Optim.*, vol. 11, no. 4, pp. 341–359, 1997.
[63] K. Balamurugan, R. Muralisachithnndam, and S. R. Krishnan, “Differential Evolution based solution for Combined Economic and Emission Power Dispatch with Valve Loading Effect,” *Int. J. Electr. Eng. Informatics*, vol. 6, no. 1, pp. 74–92, 2014.
[64] S. Krishnamurthy and R. Tzoneva, “Comparative analyses of Min-Max and Max-Max price penalty factor approaches for multi criteria power system dispatch problem using Lagrange’s method,” *Int. Conf. Recent Adv. Electr. Electron. Control Eng. IConRAEeCE’11 - Proc.*, pp. 36–43, 2011.

APPENDICES

APPENDIX A: MOMAHDEED - BA Detailed Results

This shows a detailed set of results of Dynamic MOMAHEED using Bat Algorithm showing generation levels for every generator to meet their respective hourly area power demands, cost of generation, power losses and emissions for every area in every hour of the day.

Appendix A: MOMAHDEED - BA Detailed Results

Time/ Hour	Area	Demand (MW)	P1 (MW)	P2 (MW)	P3 (MW)	P4 (MW)	P5 (MW)	P6/PH (MW)	Ploss (MW)	Total Power Gen (MW)	Total Emissions (t/hr)	Total Fuel Cost ($/HR)
1	1	478	111.7053	147.4645	122.3283	68.0298	41.5405	25.7987	0.2956	516.8672	2721.3650	18214.4991
	2	410	88.2529	91.5005	66.8975	88.3356	129.1107	79.4703	4.4556	543.5674	2053.3923	130647.971
	3	478	74.0115	108.6618	125.6748	246.4567	82.2271	115.18	8.6416	752.2074	874.0416	165314.8551
	4	755	61.7245	85.5202	152.7556	193.9407	87.491	201.35	6.9433	782.781	660.7381	177451.988
	Pool Totals	**2121**							**20.3361**	**2595.423**	**6009.5370**	**491629.3132**
2	1	465	109.4523	107.65	135.137	102.7908	40.4474	30.3521	0.1470	525.8296	2472.5275	27270.1007
	2	435	115.0735	97.5143	93.5668	53.6174	53.8655	31.5714	0.8746	445.2090	1834.4759	35630.1327
	3	537	70.8941	114.496	105.0972	219.226	83.1996	161.1132	7.4780	754.0261	752.3287	168179.6938
	4	742	54.9206	69.6382	109.9977	202.736	66.6103	237.1092	5.3828	741.0120	550.1802	137082.0636
	Pool Totals	**2179**							**13.8824**	**2466.0767**	**5609.5123**	**368161.9908**
3	1	476	53.5286	137.3222	105.0174	83.1823	97.9938	9.7573	2.1200	486.8017	2206.2484	16862.3068
	2	475	131.4714	71.9352	90.7712	128.5580	108.2463	146.9209	5.6485	677.9031	2895.0866	264254.3889
	3	563	51.0812	124.8287	141.3249	190.2337	50.00000	104.1332	6.6445	661.6017	679.6505	76543.4448
	4	753	51.8082	111.8812	158.4759	218.6303	114.761	181.9407	8.8734	837.4973	861.5383	230403.2438
	Pool Totals	**2267**							**23.2864**	**2663.8038**	**6642.5238**	**588063.3843**

4	1	453	55.6959	137.2187	71.2607	123.2314	92.328	11.5359	3.0209	491.2706	2181.3917	33111.9759
	2	530	81.5976	105.0092	129.0749	28.0605	128.5295	89.0518	1.3347	561.3234	2449.1361	251668.7446
	3	615	63.6594	107.7843	167.5216	163.6095	50.00	100.00	6.3813	652.5748	634.5744	107772.178
	4	730	20.9151	117.6187	163.63	207.0299	72.3382	170.9337	7.2249	752.4655	760.515	216859.9859
	Pool Totals	**2328**							**17.9618**	**2457.6343**	**6025.6172**	**609412.8844**
5	1	458	102.8146	53.4167	35.6496	116.4333	129.6346	32.9873	5.3746	470.936	1944.041	35985.7985
	2	558	122.0715	85.2682	77.7438	122.973	111.7117	135.5309	5.8770	655.2992	2707.0454	241561.3619
	3	687	68.2224	44.8139	146.9519	146.9519	237.871	55.7954	6.5530	699.1326	714.9303	114161.3443
	4	735	52.3869	124.8004	133.1859	196.7149	109.552	210.3489	7.9099	826.989	769.8065	220778.402
	Pool Totals	**2438**							**25.7145**	**2652.3568**	**6135.8232**	**612486.9067**
6	1	486	109.4523	107.4523	135.137	102.7908	40.4474	30.3521	0.1470	525.8296	2472.5275	27270.1007
	2	608	109.1624	137.0519	117.5422	140.2913	140.8415	150.0000	6.9227	794.8792	3999.3806	380288.8359
	3	820	38.2175	113.9564	159.8456	246.2805	131.6741	161.1132	9.9204	851.0874	1012.8754	263039.1998
	4	763	74.593	102.2869	136.9065	202.3446	145.2877	237.1092	8.9229	898.5279	854.3091	291399.7660
	Pool Totals	**2677**							**25.9130**	**3070.3241**	**8339.0926**	**961997.9024**
7	1	512	122.9618	73.2878	89.4315	135.2396	86.5797	39.6284	3.314	547.1289	2391.0079	45391.1889
	2	626	99.4914	104.991	115.8336	136.578	48.3505	123.7784	1.9715	629.0229	2555.4512	218966.5215
	3	928	73.3921	68.9639	174.0166	248.5915	138.3571	161.0357	10.0986	864.357	1020.9812	276167.2944
	4	789	58.3978	76.7017	145.5685	188.2656	98.1294	236.933	6.5666	803.996	625.6218	199017.4646
	Pool Totals	**2855**							**21.9507**	**2844.5048**	**6593.0621**	**739542.4694**
8	1	546	89.9562	86.7291	116.6843	71.204	145.7135	41.9221	3.2823	552.2091	2487.4984	50447.8832
	2	654	110.783	28.7586	128.3032	136.3658	123.4912	142.9635	4.4397	670.6653	2926.5165	258402.237
	3	906	74.745	105.8196	160.6218	231.5176	144.6762	159.6022	10.5081	876.9823	1015.1914	288417.1097
	4	823	69.4455	102.3465	90.6314	222.4938	110.6556	233.8614	5.5442	829.4342	765.4575	223544.6387

	Pool Totals	**2929**							**23.7743**	**2929.2909**	**7194.6638**	**820811.8686**
9	1	649	128.7942	79.5167	119.2483	124.9510	148.4259	131.4845	6.0886	732.4205	3537.8504	228257.5648
	2	690	130.1859	141.0184	140.3809	65.3075	98.4105	150.0000	2.4125	725.3032	3694.2799	315207.6517
	3	813	43.9430	124.5731	171.8188	206.3433	117.6912	158.5497	9.1061	822.9191	894.7359	235626.6557
	4	926	57.9965	124.4911	140.4262	214.7312	161.3973	231.7740	10.0514	930.8164	995.8432	322670.4149
	Pool Totals	**3078**							**27.6586**	**3211.4592**	**9122.7094**	**1101762.287**
10	1	673	119.4323	141.3367	128.7896	149.5851	65.7832	139.2798	3.2308	744.2067	3705.8948	243181.5903
	2	714	141.5563	114.3124	122.2921	77.1680	123.3865	150.0000	4.1572	728.7151	3605.6679	316796.7842
	3	751	35.6832	111.9887	149.7280	248.2768	98.7881	140.8244	8.8195	785.2891	941.8879	198229.0703
	4	950	67.5911	117.1496	163.7580	243.3795	187.2742	203.6182	12.3912	982.7706	1253.3761	372449.8566
	Pool Totals	**3088**							**28.5987**	**3240.9815**	**9506.8267**	**1130657.3014**
11	1	724	109.1392	126.0639	149.6194	84.4623	116.1267	118.0741	2.5424	703.4856	3924.9064	202944.9825
	2	743	78.5580	100.1862	122.1260	137.6923	72.1008	128.2297	2.5954	638.8929	3481.4824	228140.8973
	3	726	67.4442	98.7743	165.6695	230.7712	75.0652	100.0000	8.5014	737.7245	1039.5738	150982.4046
	4	1001	67.1286	123.8443	157.3899	221.7958	200.1295	238.0743	12.0921	1008.3625	1532.9055	398327.6317
	Pool Totals	**3194**							**25.7313**	**3088.4655**	**9978.8681**	**980395.9161**
12	1	758	110.0227	143.0685	124.1603	136.9168	135.0967	150.0000	6.3581	799.2651	4072.4463	295308.4245
	2	760	149.8370	134.2564	142.8981	116.6352	73.5410	150.0000	2.7818	767.2244	4086.1324	356787.3628
	3	588	70.9120	20.5571	169.7134	186.5476	50.0000	159.4071	5.2088	657.1371	583.6555	73375.1914
	4	1035	44.5596	103.7047	174.7829	240.8446	189.2467	233.4657	11.5663	986.6043	1211.2743	377033.5513
	Pool Totals	**3141**							**25.915**	**3210.2309**	**9953.5085**	**1102504.5300**
13	1	713	146.0283	140.6693	128.5206	103.7172	54.3787	107.9743	1.7330	681.2884	4103.0249	181724.5040
	2	732	123.0190	138.5443	123.2515	96.3908	60.3802	150.0000	2.2640	691.5859	3745.8364	281483.3565
	3	691	58.1621	52.3757	161.5441	227.7179	57.4844	145.1189	6.5764	702.4031	699.8773	117403.3931

	4	990	54.3400	122.8180	143.6664	242.7586	165.1967	209.8192	10.9944	938.5990	1114.3457	329535.7670
	Pool Totals	**3126**							**21.5678**	**3013.8764**	**9663.0843**	**910147.0206**
14	1	774	124.3296	136.0403	134.6225	141.8341	127.4676	150.0000	5.9416	814.2969	4251.2311	310822.5732
	2	704	140.9369	57.1751	141.5266	147.9751	97.7217	150.0000	3.9686	735.3354	3566.2777	323650.1596
	3	678	61.6056	119.3513	165.0632	149.2445	52.2513	144.2902	6.2771	691.8061	631.9058	107074.5150
	4	1051	45.9771	122.6811	174.6352	232.4438	182.4902	214.9165	11.7488	973.1439	1205.8268	363415.5866
	Pool Totals	**3207**							**27.9361**	**3214.5823**	**9655.2414**	**1104962.8344**
15	1	786	126.9661	135.9834	110.2772	110.8657	109.8045	126.2148	4.7786	720.1118	4007.9062	217561.7608
	2	690	131.2030	91.6718	121.9599	98.7412	128.3605	150.0000	4.5603	721.9363	3850.8501	309548.7393
	3	683	38.4319	96.6178	159.7338	204.2240	61.2927	149.5916	6.6393	709.8919	675.2178	124822.2522
	4	1063	74.9871	119.7069	146.4583	245.7908	215.6230	236.9330	13.2102	1039.4990	1387.8607	428433.6100
	Pool Totals	**3222**							**29.1884**	**3191.4390**	**9921.8348**	**1080366.3623**
16	1	773	136.9680	142.1976	123.4188	80.2976	105.4304	121.0577	3.5200	709.3701	3657.5347	208014.8532
	2	654	122.1067	147.4520	128.7430	64.6740	67.0434	147.9996	1.7514	678.0186	3296.9788	268659.6959
	3	639	57.1178	122.3272	157.9858	107.5347	50.0000	154.5490	5.1663	649.5146	550.6908	65777.5701
	4	1050	64.9082	115.4674	170.0905	239.2323	206.0882	224.5792	12.8782	1020.3659	1332.4767	409611.7027
	Pool Totals								**23.3159**	**3057.2692**	**8837.6810**	**952063.8219**
17	1	744	148.8354	146.0230	134.0231	135.3548	141.4166	150.0000	7.0525	855.6530	4924.2364	351261.3401
	2	608	149.6746	116.8671	121.0842	15.5738	109.3793	129.2344	2.1300	641.8133	3383.6879	231840.4117
	3	631	57.0151	56.1126	164.5930	187.5917	50.0000	160.2422	5.5539	675.5546	572.9857	91480.3261
	4	1021	72.5555	115.7265	174.2099	245.4439	234.8834	235.1937	14.4265	1078.0128	1551.6783	465826.5458
	Pool Totals	**3004**							**29.1629**	**3251.0337**	**10432.5883**	**1140408.6237**
18	1	725	136.2462	140.8768	132.2741	140.1121	116.7582	150.0000	5.7224	816.2673	4360.8301	312871.3731
	2	685	59.3080	149.9618	101.4035	107.2783	144.9479	150.0000	5.5775	712.8994	3316.6136	298886.4765

	3	733	65.9928	36.0099	174.0095	228.0538	76.5816	160.0027	7.0337	740.6504	754.2415	155256.4330
	4	1002	46.8569	121.5604	170.7871	225.2349	177.4903	221.1412	11.2433	963.0708	1142.9447	353795.9423
	Pool Totals	**3145**							**29.5769**	**3232.8879**	**9574.6299**	**1120810.2249**
19	1	682	97.6838	149.6310	122.1274	72.1489	142.2233	115.5748	4.0210	699.3892	3528.5899	197713.7337
	2	763	149.8937	134.2564	142.8981	116.6352	73.5410	150.0000	2.7818	767.2244	4086.1324	356787.3628
	3	998	44.5596	103.7047	174.7829	240.8446	189.2467	233.4657	11.5663	986.6043	1211.2743	377033.5513
	4	959	68.3707	121.0589	167.2240	237.6219	191.9142	205.8454	12.5905	992.0351	1273.0052	381542.7200
	Pool Totals	**3402**							**30.9596**	**3445.253**	**10099.0018**	**1313077.368**
20	1	615	148.9297	120.4395	133.9962	110.5015	26.8779	76.4303	0.0804	617.1751	3322.4223	118804.9412
	2	784	129.6971	147.2768	116.3507	102.9422	129.9273	150.0000	5.7103	776.1941	4028.1886	363043.9649
	3	733	71.3523	40.6869	166.5690	240.3769	76.5364	145.1189	7.4352	740.6404	796.2332	154882.1921
	4	892	72.4934	97.4006	135.6718	248.8025	154.7853	208.6042	10.3920	917.7580	1043.0461	309284.3293
	Pool Totals	**3024**							**23.6179**	**3051.7676**	**9189.8902**	**946015.4275**
21	1	546	89.7848	141.0000	142.0363	123.5644	138.8406	150.0000	4.9603	785.2266	3930.8774	282503.8361
	2	728	140.8262	148.5702	108.8371	97.8487	103.7548	150.0000	4.9843	749.9371	3865.4361	337436.9189
	3	695	40.2922	111.2270	154.7941	244.7791	63.3945	100.0000	8.1404	714.4869	859.5828	128053.3807
	4	823	65.9966	92.2215	171.3783	247.7619	139.7826	170.5755	10.5278	887.7163	1046.0447	279117.3773
	Pool Totals	**2792**							**28.6128**	**3137.3669**	**9701.9410**	**1027111.5130**
22	1	507	111.6344	134.1395	91.2948	82.4642	91.4644	43.6300	2.7676	554.6272	2584.7909	53460.7093
	2	670	53.7124	114.0747	110.0561	136.3273	135.5809	150.0000	5.4685	699.7515	2958.6978	286399.3556
	3	590	68.2493	30.1105	151.0335	235.6072	58.9868	161.5275	6.3190	705.5149	708.0481	120739.7411
	4	784	19.1090	122.3502	170.8667	249.6989	131.1779	177.3989	10.1104	870.6015	1077.8097	262348.9056
	Pool Totals	**2551**							**24.6655**	**2830.4951**	**7329.3465**	**722948.7116**
23	1	498	42.0749	146.0560	141.3969	135.5608	59.6245	58.7891	1.1620	583.5021	2802.8650	84246.9427

	2	508	97.6280	102.5024	134.0871	58.6636	142.5998	150.0000	2.6891	685.4809	3089.8859	274825.5683
	3	559	24.1929	120.5713	160.0304	189.6843	51.3913	144.1872	6.4313	690.0574	688.6004	105163.8599
	4	775	66.4147	105.3883	130.9455	223.2890	126.4616	208.4540	8.8120	860.9530	854.4985	253909.9319
	Pool Totals	**2340**							**19.0944**	**2819.9934**	**7435.8498**	**718146.3028**
24	1	483	97.2632	105.8304	117.6820	117.9071	45.6236	18.6269	0.6463	502.9332	2224.4815	3571.1229
	2	437	103.9435	143.3932	46.5920	86.7369	91.3483	88.2752	4.5821	560.2891	2446.8972	147405.2274
	3	528	52.1798	100.2388	158.0594	228.0601	51.0008	100.0000	7.4343	689.5388	767.7179	103754.4310
	4	760	73.5688	119.3759	150.4837	24.7449	142.9005	160.9833	11.0960	894.0571	1089.6863	284946.9866
	Pool Totals	**2208**							**23.7587**	**2646.8182**	**6528.7829**	**539677.7679**

APPENDIX B: MOMAHDEED - BA Detailed Results

This shows a detailed set of results of Dynamic MOMAHEED using Hybridized Modified Bat Algorithm showing generation levels for every generator to meet their respective hourly area power demands, cost of generation, power losses and emissions for every area in every hour of the day.

Appendix B: MOMAHDEED - HMBA Detailed Results

Time/ Hour	Area	Demand (MW)	P1 (MW)	P2 (MW)	P3 (MW)	P4 (MW)	P5 (MW)	P6/PH (MW)	Ploss (MW)	Total Power Gen (MW)	Total Emissions (t/hr)	Total Fuel Cost ($/HR)
1	1	478	89.9298	138.3243	40.5181	86.6822	111.2797	20.0693	4.0840	486.8034	2280.7935	81075.6284
	2	410	22.3980	23.3687	35.6658	39.4098	144.6425	150.0000	2.3421	415.4848	1284.6907	152603.9930
	3	478	30.6385	114.0003	57.9388	59.1294	50.0000	170.0795	2.1628	481.7866	356.1472	62553.8225
	4	755	72.5130	209.1204	91.1892	131.6618	50.0000	208.3724	4.5242	762.8567	529.4496	100606.9302
	Pool Totals	**2121**							**13.1131**	**2146.9315**	**4451.0810**	**396840.3741**
2	1	465	129.6691	104.7128	42.3844	123.6685	36.6022	31.1697	1.9294	468.2068	2174.8209	53701.2099
	2	435	98.7195	21.8396	23.2837	44.8553	144.9481	103.6675	1.3202	437.3137	1677.6325	118913.6558
	3	537	38.9883	85.9687	168.2993	58.7422	50.0000	139.5318	3.4763	541.5303	420.4222	117478.2124
	4	742	70.9286	82.7305	143.7026	221.9862	50.0000	181.5063	6.8880	750.8541	700.9873	131311.5632
	Pool Totals	**2179**							**13.6139**	**2197.9049**	**4973.8629**	**421404.6413**
3	1	476	37.1731	94.2812	52.1726	55.6636	89.1665	150.0000	1.7026	478.4569	1298.9699	175388.3643
	2	475	123.2349	71.9111	97.5094	110.1790	15.0086	58.6365	0.0936	476.4795	1971.5872	126297.9022
	3	563	38.9768	117.5124	83.9428	133.5372	50.0000	144.1469	3.8987	568.1160	415.4418	119180.0305
	4	753	52.3341	89.8323	144.4928	192.3051	117.2116	168.4627	7.2562	764.6385	694.6910	76880.9354
	Pool Totals	**2267**							**12.9511**	**2287.6909**	**4380.6899**	**497747.2324**
4	1	453	69.3279	18.1524	96.4128	9.5342	113.1423	150.0000	1.0057	456.5695	1470.6873	164737.2052
	2	530	27.8384	88.3102	89.0099	139.8354	142.6061	61.8577	5.0515	549.4577	2260.6475	177260.5151

	3	615	59.7663	92.7209	38.2432	197.3142	50.0000	187.0053	4.4460	625.0498	552.0082	118463.6981
	4	730	51.9119	52.7956	154.9446	237.0128	50.0000	194.4190	6.4288	741.0840	708.1100	152328.7450
	Pool Totals	**2328**							**16.9320**	**2372.1610**	**4991.4530**	**612790.1634**
	1	458	47.0733	72.4722	97.4339	25.1024	66.3210	150.0000	0.1187	458.4028	1219.3783	163427.8237
	2	558	87.2327	62.9549	17.6347	137.4531	103.9038	150.0000	0.6322	559.1792	1951.4417	172743.0622
5	3	687	76.8284	69.5886	81.2784	68.4574	147.3926	251.3347	2.5702	694.8802	445.8930	174922.3708
	4	735	62.8614	116.5509	121.2535	179.0027	50.0000	211.3347	3.3230	741.0033	404.6139	129682.8346
	Pool Totals	**2438**							**6.6441**	**2453.4655**	**4021.3269**	**640776.0913**
	1	486	94.1031	41.6093	97.8328	135.6136	103.1644	16.8175	3.4375	489.1406	1314.6858	189016.1931
	2	608	124.9691	62.5625	120.4831	129.2838	96.0469	78.8375	3.2302	612.1830	1701.3376	137262.2340
6	3	820	68.1148	118.1532	90.4649	225.4004	94.3999	234.8904	5.8562	831.4236	739.2069	172013.5363
	4	763	44.1000	27.0110	133.6142	80.3204	300.0000	182.0189	2.4234	767.0644	1154.2168	199125.1792
	Pool Totals	**2677**							**14.9473**	**2699.8116**	**4909.4471**	**697417.1426**
	1	512	90.4068	148.7915	10.4359	72.1960	45.8123	150.0000	4.2164	517.6425	1645.0297	162542.7852
	2	626	45.3750	138.7764	47.7961	114.6107	140.4966	150.0000	6.1635	637.0549	2211.2098	163971.8662
7	3	928	137.1349	84.9554	133.7203	84.8793	300.0000	198.1981	7.7776	938.8880	1521.5627	166194.7066
	4	789	110.2691	70.9713	102.3242	211.1350	50.0971	251.3347	4.4597	796.1314	538.6928	222111.6255
	Pool Totals	**2855**							**22.6172**	**2889.7168**	**5916.4950**	**714820.9835**
	1	546	62.8423	12.5194	136.4327	49.3182	138.1354	150.0000	1.4588	549.2480	2159.6848	212312.5881
	2	654	82.2773	133.6436	124.3896	31.8991	134.3984	150.0000	2.0556	656.6080	2032.4730	163238.9127
8	3	906	72.3757	74.2863	125.8516	230.3619	300.0000	119.2407	13.6163	922.1161	1871.7788	258817.0530
	4	823	26.5126	124.9364	129.1226	208.9350	50.0000	293.4629	6.4077	832.9695	700.1788	175789.1084
	Pool Totals	**2929**							**23.5384**	**2960.9416**	**6764.1154**	**810157.6622**
9	1	649	139.1121	133.2155	105.1652	77.8596	46.9425	150.0000	2.2902	652.2949	2590.1296	179733.9856

	2	690	125.0608	74.4424	94.2073	148.4419	101.8747	150.0000	3.8558	694.0270	2471.5895	177622.8372
	3	813	22.5258	53.2343	126.5875	103.7830	300.0000	214.2309	6.8753	820.3614	1473.3000	259727.4500
	4	926	50.8452	116.6380	81.4970	132.1187	300.0000	256.7482	10.0404	937.8472	1619.8245	213074.9879
	Pool Totals	**3078**							**23.0617**	**3104.5305**	**8154.8436**	**830159.2607**
10	1	673	120.4641	96.8916	141.7180	116.9254	128.7823	73.4531	3.9112	678.2344	2377.5605	172545.1345
	2	714	146.9566	135.5176	83.1223	114.0194	91.7348	150.0000	5.9119	721.3506	2569.5323	237436.9189
	3	751	49.9409	123.5343	99.3509	54.0445	250.0000	188.6049	8.7332	765.4754	1578.5744	129181.5672
	4	950	43.8593	74.4845	88.3245	212.7107	300.0000	243.4563	9.0690	962.8353	1710.8257	312929.5282
	Pool Totals	**3088**							**27.6253**	**3127.8957**	**8236.4929**	**852093.1488**
11	1	724	148.7664	130.8252	111.1898	82.1662	105.1917	150.0000	3.4262	728.1393	3686.2096	180168.5123
	2	743	140.8262	148.5702	108.8371	97.8487	103.7548	150.0000	4.9843	749.9371	3365.4361	241291.3476
	3	726	68.2985	80.5718	167.0427	182.6461	50.0000	187.7814	7.3177	736.3404	747.8582	217486.1371
	4	1001	30.1226	25.3352	141.1747	247.7567	257.0221	293.4629	10.5730	1012.8741	1593.2611	289933.6635
	Pool Totals	**3194**							**26.3012**	**3227.2909**	**9392.7650**	**928879.6605**
12	1	758	143.0679	130.8811	128.3734	144.0103	140.2261	79.3856	5.0294	765.9443	3554.7822	192354.8380
	2	760	98.9170	125.8367	118.8983	132.4052	140.0794	150.0000	5.6908	766.1365	3102.6779	265643.4354
	3	588	10.2628	78.4681	60.5445	55.8940	145.5213	242.1571	4.2296	592.8478	804.4826	115539.4335
	4	1035	56.3828	108.3396	165.1524	201.5903	233.9679	285.0191	10.8063	1050.4521	1914.8912	317754.1943
	Pool Totals	**3141**							**25.7561**	**3175.3807**	**9176.8339**	**891291.9012**
13	1	713	140.3733	139.7428	136.8922	110.5563	74.6544	117.9258	3.4491	720.1447	3499.6381	185645.4829
	2	732	120.4641	96.8916	141.7180	116.9254	128.7823	131.8292	4.2080	736.6106	3126.1490	190834.7098
	3	691	68.8015	25.7810	140.0106	149.2676	50.4466	262.1571	5.2318	696.4643	738.1774	217677.0179
	4	990	73.7023	60.2238	110.7991	190.5051	300.0000	268.0815	7.1600	1003.3118	1865.3858	287350.5940
	Pool Totals	**3126**							**20.0489**	**3156.5314**	**9229.3503**	**881507.8046**

14	1	774	147.3733	139.7428	137.8922	110.5563	124.6544	117.9258	2.4491	778.1447	3799.6381	292542.7852
	2	704	121.5255	114.9566	134.1761	146.8663	92.2725	99.7658	4.5594	709.5628	3465.8844	187638.7407
	3	678	52.3395	110.8602	141.9380	79.4485	50.0000	251.3555	6.0501	685.9418	607.9048	138160.6237
	4	1051	63.0913	83.9597	156.4933	195.9086	264.6408	297.4830	10.1344	1061.5766	1375.8453	319698.7874
	Pool Totals	**3207**							**23.1930**	**3235.2259**	**9249.2726**	**938040.9370**
15	1	786	120.4641	126.8916	147.7180	126.9254	138.7823	129.5798	4.1289	790.3612	3686.4149	302175.8970
	2	690	102.1231	127.5143	149.3849	106.8839	57.6844	150.0000	3.1139	693.5905	3262.0346	176333.8655
	3	683	53.9251	26.1175	156.9962	149.1092	50.0000	255.2762	6.2662	691.4242	750.3050	149824.1859
	4	1063	88.0639	111.7808	161.8489	135.0041	229.9542	351.6131	13.4799	1078.2650	1818.9326	340574.7336
	Pool Totals	**3222**							**26.9889**	**3253.6409**	**9517.6871**	**968908.6820**
16	1	773	140.0506	144.2692	126.2686	95.3857	121.5152	150.0000	3.5829	777.4894	3616.2211	297070.8235
	2	654	138.5357	28.6631	116.2944	110.2409	115.6007	150.0000	4.1898	659.3348	2990.6652	142734.2360
	3	639	55.5076	104.8899	67.2230	85.6594	120.1219	211.3555	5.1718	644.7574	672.3124	102349.1716
	4	1050	52.0196	66.6292	170.5213	233.0842	242.4290	297.4830	10.1636	1062.1663	1342.4455	323132.9038
	Pool Totals	**3116**							**23.1081**	**3143.7479**	**8621.6442**	**865287.1349**
17	1	744	115.1586	144.4503	135.2024	119.6363	81.0620	150.0000	1.4597	745.5096	3407.8924	280111.2052
	2	608	142.5540	37.7999	142.7774	11.4435	124.0997	150.0000	0.4012	608.6745	3086.4494	136394.9656
	3	631	33.9750	78.1085	116.5218	157.5208	50.0000	202.1571	4.8967	638.2831	523.9469	102879.8625
	4	1021	80.9626	105.1087	153.9588	211.6272	199.3489	285.0191	13.6758	1036.0253	1846.4425	308052.9646
	Pool Totals	**3004**							**20.4334**	**3028.4925**	**8864.7312**	**827438.9979**
18	1	725	138.0422	116.3833	143.9585	139.6252	69.4304	124.2822	5.9966	731.7217	3662.5931	272455.4196
	2	685	78.5511	134.4130	69.2421	143.3851	115.0120	150.0000	3.9878	690.6033	2919.5692	186333.8886
	3	733	22.8935	96.3669	123.7932	197.6464	50.0000	248.4439	6.0045	739.1440	713.2752	162670.5808

	4	1002	55.7181	85.5465	164.1016	214.7771	227.5866	268.0815	12.9053	1015.8114	1627.1205	288341.0679
	Pool Totals	**3145**							**28.8942**	**3177.2804**	**8922.5580**	**909800.9569**
19	1	682	103.8561	30.6504	119.1467	138.5703	147.5820	148.5976	5.7107	688.4031	3019.4479	275049.2736
	2	763	115.7963	144.8450	94.6931	126.6188	148.2655	141.4576	6.6578	771.6764	3621.7293	202378.9887
	3	998	30.0997	106.2121	154.2707	221.9462	182.2592	318.0815	9.0672	1012.8694	1707.3388	288457.4514
	4	959	52.4969	124.8085	146.9915	145.5291	150.9111	351.7630	9.3981	972.5002	1415.2980	275235.3361
	Pool Totals	**3402**							**30.8338**	**3445.4491**	**9763.8140**	**1041121.0498**
20	1	615	80.9135	109.4621	130.0000	105.6570	145.0344	49.1121	3.1850	620.1792	2818.0596	247573.0406
	2	784	131.6212	143.5871	128.0515	125.5811	138.8401	126.0799	5.8732	793.7608	2748.8851	212245.1998
	3	733	35.8432	100.8094	164.6025	157.6411	50.0000	238.4439	4.0872	739.3400	631.9061	168290.0948
	4	892	40.9813	104.5214	128.6024	112.9848	300.0000	219.2407	7.9869	906.3305	1825.0249	217571.7754
	Pool Totals	**3024**							**21.1323**	**3059.6105**	**8023.8757**	**845680.1106**
21	1	546	117.0675	53.2853	21.4238	103.1105	109.0104	150.0000	7.0182	553.8976	2057.9871	274144.6123
	2	728	140.3733	139.7428	137.8922	110.5563	74.6544	130.1784	3.5869	733.3973	3838.7676	164414.0650
	3	695	65.3385	67.6722	164.9714	162.1929	71.9730	167.7630	4.7820	699.9109	559.8965	118412.4415
	4	823	44.9547	48.9462	105.9269	64.9820	300.0000	267.5006	7.0628	832.3105	1422.4057	128218.6914
	Pool Totals	**2792**							**22.4499**	**2819.5163**	**7879.0569**	**685189.8102**
22	1	507	12.8745	104.9280	106.4143	60.2451	77.2222	150.0000	2.7749	511.6842	1644.8142	259545.3097
	2	670	120.4641	95.8916	140.7180	115.9254	128.7823	73.3937	3.9143	675.1751	3379.1381	158698.5805
	3	590	10.1619	90.3408	35.3462	62.5010	234.4423	162.1571	4.3957	594.9493	893.5330	115600.3923
	4	784	30.5665	76.4366	38.4850	127.3791	300.0000	218.0815	6.4879	790.9486	1499.9273	126270.6748
	Pool Totals	**2551**							**17.5728**	**2572.7572**	**7417.4126**	**660114.9573**
23	1	498	129.1065	46.3777	79.4191	30.4453	65.8364	150.0000	2.6918	501.1853	1821.2342	235648.6795

	2	508	7.2126	20.2884	69.0955	117.3724	149.0085	150.0000	4.5432	512.9773	1843.9013	146390.6714
	3	559	63.1467	112.7400	65.1274	110.2317	50.0000	163.4267	4.4954	564.6724	427.5132	113721.9518
	4	775	20.4596	49.9025	71.7731	123.5861	300.0000	218.0815	7.1210	783.8028	1449.5362	123048.6388
	Pool Totals	**2340**							**18.8514**	**2362.6378**	**5542.1849**	**618809.9415**
24	1	483	15.6215	35.1843	96.2785	129.3512	59.4239	150.0000	2.0006	485.8594	1364.9966	120074.6906
	2	437	53.0220	57.2134	89.1721	52.0792	37.5685	150.0000	1.4084	439.0552	1024.3401	106384.3305
	3	528	50.2890	78.1214	118.6900	103.7095	50.0000	131.3921	3.2416	532.2020	345.8823	105985.6827
	4	760	40.5273	110.5773	168.4535	202.8665	89.3931	162.1571	7.7870	773.9748	769.4342	112970.5830
	Pool Totals	**2208**							**14.4376**	**2231.0914**	**3504.6532**	**445415.2868**

APPENDIX C: PUBLISHED PAPERS