Multi-Area Economic Dispatch using Bio-inspired Optimization

Submitted by

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CERTIFICATE

This is to certify that the project titled **MULTI-AREA ECONOMIC DISPATCH USING BIO-INSPIRED OPTIMIZATION** is a record of the bonafide work done by **SHIVANK S MISRA** (*170906134*) submitted in partial fulfilment of the requirements for the award of the Degree of Bachelor of Technology (B.Tech.) in **ELECTRICAL AND ELECTRONICS ENGINEERING** of Manipal Institute of Technology, Manipal, Karnataka, (A Constituent Institute of Manipal Academy of Higher Education), during the academic year 2020-2021.

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ABSTRACT

Economic dispatch (ED) is the process of determining the power output from a system of power generators while satisfying system and operational constraints. The main aim of Multi Area Economic Dispatch (MAED) is to determine the optimal amount of power to be generated from power generators dispersed in various areas with the motive of satisfying system and operational constraints. MAED is used to solve the critical problem of reducing the cost of the fuel used in electricity generation while meeting its demand and has a socio-economic impact. Using MAED efficiently to solve the problems can result in a much lower environmental pollution and reduced electricity cost to the end customer along with ensuring safety at power generation plants. MAED can be modelled as an optimization problem and solved by a heuristic method. There is a need to develop heuristics that arrive at more accurate solutions, as there is no assurance that they will provide a globally optimal solution. The search space of the optimization problem is multi-dimensional, leading to a need for computationally efficient solutions.

Researchers have used various artificial intelligence heuristics to solve MAED and have yielded optimal solutions. Swarm intelligence (which has been proved to yield more effective solutions) models candidate solutions as a set of decentralized agents that collectively converge towards more accurate solutions. SI algorithms are often inspired by biological systems occurring in nature. For example, researchers have developed solutions to MAED based on Artificial Bee Colony Optimization (ABCO), Particle Swarm Optimization (PSO) and Improved Particle Swarm Optimization (IPSO). IPSO is a highly effective technique both in terms of computational efficiency and in terms of computing the best fuel cost as compared to previous approaches

Inspired by biological systems, Genetic algorithms (GA) are another class of optimization algorithms. Even in situations with incomplete information, GA is a metaheuristic that operates well and also capable of searching in high dimensional spaces. In this project, how problem of MAED is solved using Genetic Algorithm will be explored and compared to results from existing SI techniques.

Hardware and Software Requirements:

1. Hardware:

- A computer system based on i5 or higher processor.

2. Software:

- Python Interpreter and IDE
- Windows 10 operating system
- MS Office and MS Excel

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CHAPTER 1
INTRODUCTION

This chapter introduces the concept of Economic dispatch (ED) as well as Multi-Area Economic Dispatch (MAED) and discusses the bio-inspired optimization method, which will be used to solve the MAED problem.

1.1 ***Introduction***

Economic dispatch (ED) is a complex constrained optimization problem of integrated power systems [1]. Assigning Power Demand to the units of generator in an inexpensive/low-cost fashion is the main aim of ED in such way that necessary limitations are satisfied.

An extension of ED, Multi-area economic dispatch (MAED) has the goal of calculating how much power is generated as well as the exchanging electrical power keeping the cost as least as possible along with task/objective to satisfy additional power transmission capacity constraints(which makes MAED problem even more difficult and complicated to be solved). Hence, to obtain the solution for optimizing such a complicated problem with constraints, a latest as well as efficient bio-inspired optimization approach is the need of the hour.

1.1.1 **Bio-inspired optimization**

Bio inspired optimization approaches have gained relevance due to increasing size and complexity of actual-world problems. Bio inspired techniques use randomness for searching a solution. These optimization techniques have been adapted from natural processes and employ aspects of evolution (mutation, selection, survival of fittest etc), collective behavior (swarm based) and ecological phenomenon etc. [2].

Some of the well-known similar methods are Differential Evolution (DE)[3], Backtracking Search Algorithm(BSA)[4] and Genetic Algorithm[5].

Genetic Algorithms

Genetic algorithms [6] are a bio-inspired search heuristic that are based on Darwinian evolution and survival of the fittest theory. Genetic algorithms are a good fit for problems with a search space containing multiple local maxima/minima. Genetic algorithms have the following advantages:

1. Capable of dealing with high dimensional spaces
2. Efficient in comparison to machine learning approaches such as neural networks
3. Can combine candidate solutions independently in all dimensions resulting in convergence in the search space.

A genetic algorithm performs the following tasks:

● **Initialization:** Encode the first set of candidate solutions as chromosomes. Each solution is a chromosome in the population. A standard method is to represent chromosomes as an array of bits.

● **Fitness Calculation:** Compute the fitness of each chromosome by populating the objective function with parameters from the chromosome.

● **Parent Selection:** A variable number of **parent** pairs are be chosen based on fitness values or by random selection. These parent pairs breed the next generation

●**Mutation:**Creates genetic diversity in solutions by altering bits randomly in the chromosome encoding

● **Crossover:** Two parent solutions are combined to obtain new solutions

● **Termination:** The algorithm can terminate based on multiple criteria. Some standard criteria are:
a. The solution is stuck in a local maxima or minima and is not improving in successive generations
b. The solution satisfies the required threshold

The typical Genetic Algorithm flowchart is shown in Fig 1.1

*1.2 **Motivation***

Consider a system of power generators evenly dispersed in a certain number of areas. Each area certain demand and load constraints depending on the area, type of energy, cost, etc. The objective is to find and meet the power demand in each area while minimizing economic costs. This optimization problem has the following major constraints:
1. Maintaining security at power generation plants by making sure that the load does not exceed capacity.
2. Minimizing emissions of harmful byproducts of fuel combustion. This may be gases such as carbon dioxide or nuclear waste depending on the type of fuel used.
3. Maximizing profit by minimizing the bottom line – fuel transmission costs.
4. Matching power generation areas to end customers.

*1.3 **Relevance of Work***

The parameters in the MAED optimization function can be modelled as variables in a high dimensional search space. Each candidate solution will then be a point in this high dimensional space. An ideal approach would be to use Genetic Algorithms (GA) to achieve

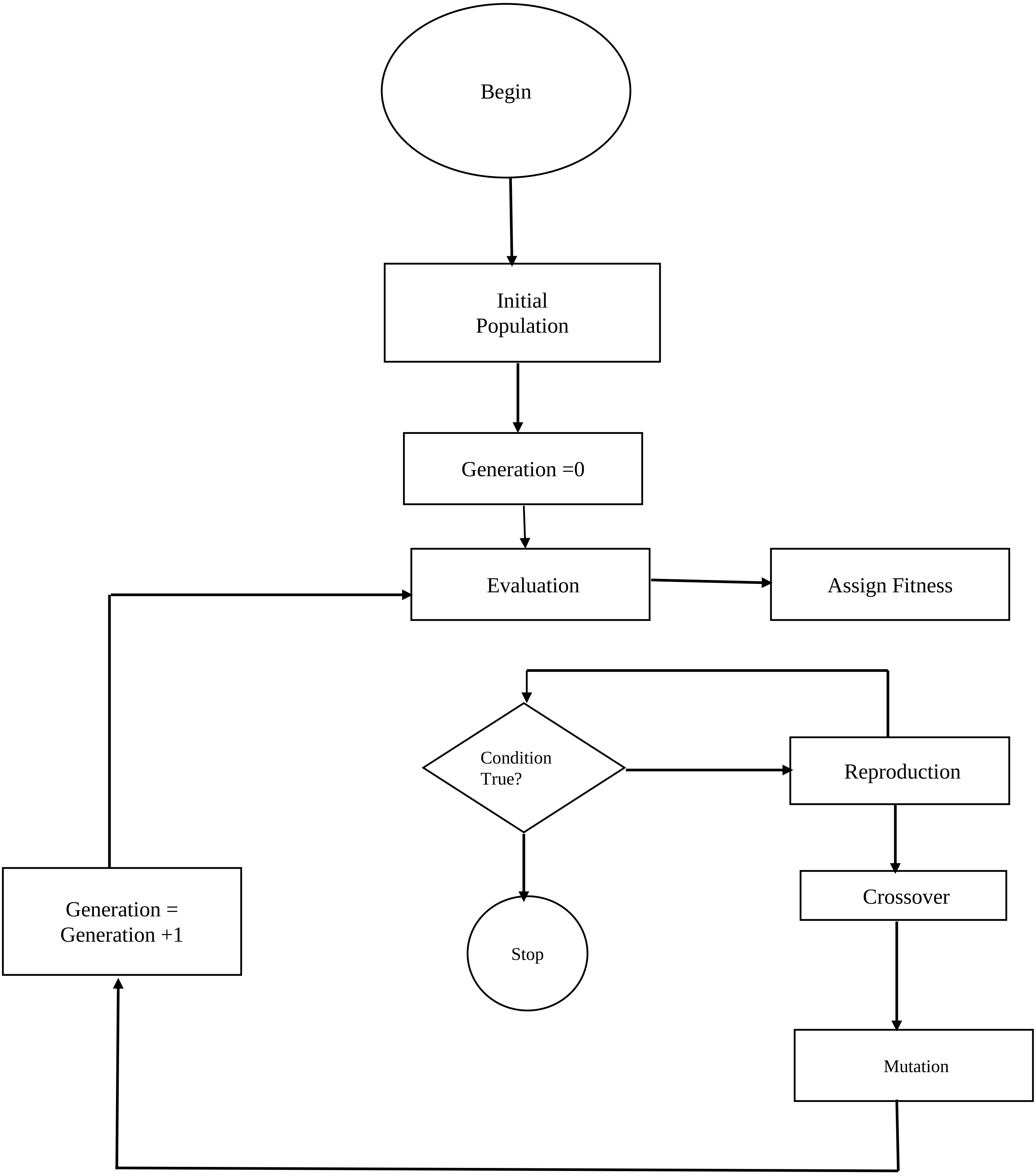

Fig.1.1 Typical Genetic Algorithm Flow Chart [7]

optimization in such a scenario. GA attempts to capture individual dimensions within each of these points that minimize the objective function and incorporate them in a final solution by an iterative process that attempts to improve the solutions probabilistically over each iteration.

1.4 ***Significance of the project***

Economic dispatch (ED) has the objective of allocation of the power generators in such a manner that the total fuel cost is minimized while all operating constraints are satisfied. Since the power generation is very expensive, ED can reduce and hence save a considerable amount of revenue.

To produce cheap electricity, power utilities can be used which can provide high efficiency of operation. There is intense competition in the electricity supply industry for economical operation in its generation that is the operating cost of a power pool can be cut and subsided if the areas having more economic units generate larger power than their load, and export the surplus power to other areas with more expensive units.

Multi Area Economic Dispatch tries to minimize the overall cost of power generation thus making it more efficient and competitive.

CHAPTER 2
LITERATURE REVIEW AND OBJECTIVES

2.1 Literature Review

This chapter discusses about resources that were used to accomplish the work and has the overview of the work done previously regarding MAED and Bio-inspired Optimization techniques and the objectives that has to be completed.

Wood AJ, Wollenberg BF [1] is a definitive work on power systems. It gives an insight to the methods used in modern power system for its Control, Operation and Generation of power. The book is considered as the standard reference in the field. Vishal Chaudhary, Hari Mohan Dubey, Manjaree Pandit, Jagdish Chand Bansal, [2] deals with “Multi-area economic dispatch with stochastic wind power using Salp Swarm Algorithm.”. It applies swarm algorithm to solve MAED problem for wind power. Storn R, Price K. [3] talks about evolutionary aspects and deals with DE methods for optimization. Civicioglu P [4], deals with the mathematical aspects of Backtracking search algorithms with their application to numerical optimization problems. The video “Real Coded Genetic Algorithm”[5] explains the concept of Real Coded Genetic Algorithm and discusses the benefits of Real Coded Genetic Algorithm over Binary Coded Genetic Algorithm and demonstrates how Real Coded GA is applied by giving the example of minimizing the sphere function and gives out a pseudo code of the algorithm.Goldberg DE, Holland JH [6] deals with Genetic Algorithm basics and machine learning aspects. ScienceDirect [7] deals with the applications of Genetic Algorithms to a broad spectrum of fields i.e. Modelling the structure of woven fabrics, Optimal design of heat exchanger networks, Natural Gas Liquefaction Cycle Enhancements and Optimization, Computational modelling of atherosclerosis etc. The video “Genetic Algorithms Explained by example”[8] gives an overview of genetic algorithms using an example of the Knapsack Problem and lists out different applications of this evolutionary algorithm such as solving Hard Combinational Problems, and its limitations like high Runtime of fitness functions causing long time to generate solutions. The video “Binary Coded Genetic Algorithm”[9] explains the basic flow chart of Genetic Algorithm and elaborates about its each step. It also explains the concept of Binary Coded Genetic Algorithm and demonstrates how the algorithm is applied by giving the example of minimizing the sphere function and gives out a pseudo code of the algorithm. Genetic Algorithms Tutorial [10] introduces genetic algorithm and explains its applications, strengths and limitations. Vinay K. Jadoun, Nikhil Gupta, K. R. Niazi, Anil Swarnkar, R.C. Bansal [11] applies an Improved version of Particle Swarm Optimization method to solve MAED problem. The study compares its results with other methods’ results available in literature and shows that IPSO method give better results in less number of iterations.

Vishal Chaudhary, Hari Mohan Dubey, Manjaree Pandit, Jagdish Chand Bansal, [12] gives the Power balance equation, which is to be applied in each Area of the system to balance the values of the sum of Power values of generators present in the area and Power Demand and Tie-line values. M. Fesanghary, M.M. Ardehali [13] provides information on distribution of total power demand of a sixteen unit thermal generator system and illustrates how the power demands are distributed in each area of the system and also provides the cost function equation of the 16 unit system. The video “Real Coded Genetic Algorithm”[14] introduces the SBX crossover and provides the formula of the crossover and illustrates the use of Polynomial Mutation in the case of Real Coded Genetic Algorithm.Vishal Chaudhary, Hari Mohan Dubey, ManjareePandit, Jagdish Chand Bansal,[15] provide the network topology of 16 unit thermal power system and 40 unit thermal power system and also have given the Optimized values of other optimization techniques for comparison.

2.1 ***OBJECTIVES***

The objectives of this study are the following:

1. Develop a technical understanding of MAED and its socio-economic significance
2. Formulate MAED as an optimization problem in a high dimensional search space
3. Theoretically understand GA and learn how to use it to solve real world problems
4. Develop a software framework in python that uses GA to solve the problem formulated in objective 2.
5. Thorough testing of code in objective 3.
6. Analyze results from GA framework for MAED
7. Compare results from GA with other results from Swarm Intelligence based approaches in the literature.

CHAPTER 3
METHODOLOGY

The project was divided into the following phases to make the process efficient and conscious of requirements:

1. Review previous work done in the area by reviewing relevant literature that solves MAED as an optimization problem utilizing heuristics.

2. The programming language used in the work is Python and the necessary Python modules that were imported and used are :

    i. NumPy – To perform fast operations and necessary tasks on multi-dimensional arrays and also provides information on the shape of the array in the form of tuple of rows and columns.

    ii. Pandas – This module was used to enable Python to access the necessary data required for the work. The module is used to access and read the data from the device by Python and Manipulate it using the programming language.

    iii. Random – It enables the programming language rand(lower_limit,upper_limit) which assigns a random value between lower_limit and upper_limit values that are given as arguments to the function.

    iv. Math – The module enables Python to compute sine values and absolute values that are used to evaluate fitness of the individual using cost function.

3. Obtain a dataset and organize it to obtain a form that can be accessed as well as readby the Python program.
   An excel (XLSX) file was prepared in which the Minimum and Maximum values were arranged according to the generator unit which were used to check, assign as well as maintain the generator power values within the constraints. The XLSX file also included cost coefficients of each generator which are essential to compute the cost value of each generator unit.

4. Create a function that reads in the dataset and parses it to a form understandable by the Python program.
   The function calls the library function read_excel( ) which can be used after importing pandas module and the read_excel function takes the path of the excel data file in the system andname of the sheet in which relevant data is given.

The read_excel( ) is used by the function to extract and return the excel data column-wise by taking index as its argument.

5. The Initial population number is assigned as 20 for 16 unit system where each population memberis an array matrix having the shape as [1,22] (1 row x 22 columns) where,
   22 columns consist of 16 units of thermal power generators along with the six tie-lines connecting the four areas, each of them having 4 thermal power generators.
   Using random function, a random floating point value is assigned to:
   i. 2^{nd},3^{rd} and 4^{th} thermal power units of 16 unit Power system which are present in the 1^{st} Area.
   ii. 6^{th}, 7^{th} and 8^{th} thermal power units of 16 unit Power system present in 2^{nd} Area.
   iii. 10^{th},11^{th} and 12^{th} thermal power units of 16 unit Power system which are present in 3^{rd} Area.
   iv. 14^{th},15^{th} and 16^{th} thermal power units of 16 unit Power system which are present in 4^{th} Area.

As per the Power balance equation[12]:

$$\sum_{j=1}^{M} \mathrm{Pij} = \mathrm{PDi} + \mathrm{PLi} \qquad (1)$$

Where,

"i" is the Area number.

"j" is the Generator unit number.

Pij is Power value of j^{th} Generator in i^{th} Area.

PDi is total power demand in the i^{th} Area.

PL is the Tie-line power connected in Area i.

i) For Area 1 :

$i = 1$

$PDi = PD_1 = 400$ MW [13]

$P_{1,1} + P_{1,2} + P_{1,3} + P_{1,4} = 400 + PL_1$

The First Unit (1^{st} Unit of 16 unit system) of Generator in the First Area is assigned the value,

$P_{1,1} = (400 + PL_1) – (P_{1,2} + P_{1,3} + P_{1,4})$

ii) For Area 2 :

$i = 2$

$PDi = PD_2 = 200$ MW [13]

$P_{2,1} + P_{2,2} + P_{2,3} + P_{2,4} = 200 + PL_2$

The First Unit (5th Unit of 16 unit system) of Generator in the Second Area is assigned the value,

$P_{2,1} = (400 + PL_2) – (P_{2,2} + P_{2,3} + P_{2,4})$

iii) For Area 3 :

i = 3

PDi = PD_3= 350 MW [13]

$P_{3,1} + P_{3,2} + P_{3,3} + P_{3,4} = 200 + PL_3$

The First Unit (9th Unit of 16 unit system) of Generator in the Third Area is assigned the value,

$P_{3,1} = (400 + PL_3) – (P_{3,2} + P_{3,3} + P_{3,4})$

iv) For Area 4 :

i = 4

PDi = PD_4= 300 MW [13]

$P_{4,1} + P_{4,2} + P_{4,3} + P_{4,4} = 300 + PL_4$

The First Unit(13th Unit of 16 unit system) of Generator in the Fourth Area is assigned the value,

$P_{4,1} = (400 + PL_4) – (P_{4,2} + P_{4,3} + P_{4,4})$

On Assigning 20 as number iterations as number of initial population,

The resulting initial Array, thus created has the shape (20,22) having 20 rows and 22 columns.

6. A program unit is created which checks if all the assigned values are within the range of Minimum and Maximum limits which are stored as data in the excel file, which is read by the Python program.

If all the four assigned values of an Initial Population member are within the range of Minimum limits and Maximum limits, that Initial Population member is appended to the final array which is created, on which all the operations of GA are performed.

If length of the final array is less than 20, more number of Initial Population members are created and the Population whose assigned values are in the range of Minimum and Maximum limits is appended to the final array and the process is repeated using “while” loop until the length of the final array is equal to 20 or more than 20.

The corresponding cost values of the final array elements is calculated.

7. The Initial population number is assigned as 50 for 40 unit system where each population member is an array matrix having the shape as (1,40) (1 row x 40 columns) where, 40 columns consist of 20 units of thermal power generators in Area 1, and the other 20 units in Area 2 , both Areas are connected by a tie-lie.

   Using random function, a random floating point value is assigned to:

   i) 2^{nd},3^{rd},4^{th},5^{th},6^{th},7^{th},8^{th},9^{th} and 15^{th} to 20^{th} thermal power units of 40 unit Power system which are present in the 1^{st} Area.
   ii) 21^{st} to 40^{th} thermal power units of 40 unit Power system present in 2^{nd} Area.
   iii) A user-defined function is created which assigns a random value between Minimum and Maximum values in the excel data as well as are not in the range of Prohibited Operating Zones (POZ) as operation in the POZ power ranges is restricted.

- For Area 1 :

  $i = 1$

  $PDi = PD_1 = 7500$ MW [13]

  $(P_{1,1} + P_{1,2} + P_{1,3} + P_{1,4} + P_{1,5} + P_{1,6} + P_{1,7} + P_{1,8} + P_{1,9} + P_{1,10} + P_{1,11} + P_{1,12} + P_{1,13} + P_{1,14} + P_{1,15} + P_{1,16} + P_{1,17} + P_{1,18} + P_{1,19} + P_{1,20}) = 7500 + PL_1$

  The First Unit (1^{st} Unit of 40 unit system) of Generator in the First Area is assigned the value,

  $P_{1,1} = (7500 + PL_1) – (P_{1,2} + P_{1,3} + P_{1,4} + P_{1,5} + P_{1,6} + P_{1,7} + P_{1,8} + P_{1,9} + P_{1,10} + P_{1,11} + P_{1,12} + P_{1,13} + P_{1,14} + P_{1,15} + P_{1,16} + P_{1,17} + P_{1,18} + P_{1,19} + P_{1,20})$

- For Area 2 :

  $i = 2$

  $PDi = PD_2 = 3000$ MW [13]

  $P_{2,1} + P_{2,2} + P_{2,3} + P_{2,4} + P_{2,5} + P_{2,6} + P_{2,7} + P_{2,8} + P_{2,9} + P_{2,10} + P_{2,11} + P_{2,12} + P_{2,13} + P_{2,14} + P_{2,15} + P_{2,16} + P_{2,17} + P_{2,18} + P_{2,19} + P_{2,20} = 3000 + PL_2$

  The First Unit(21^{st} Unit of 40 unit system) of Generator in the Second Area is assigned the value,

  $P_{2,1} = (3000 + PL_2) – (P_{2,2} + P_{2,3} + P_{2,4} + P_{2,5} + P_{2,6} + P_{2,7} + P_{2,8} + P_{2,9} + P_{2,10} + P_{2,11} + P_{2,12} + P_{2,13} + P_{2,14} + P_{2,15} + P_{2,16} + P_{2,17} + P_{2,18} + P_{2,19} + P_{2,20})$

8. A program unit is created which checks if all the assigned values are within the range of Minimum and Maximum limits which are stored as data in the excel file, which is read by the Python program.

If all the four assigned values of an Initial Population member are within the range of Minimum limits and Maximum limits, that Initial Population member is appended to the final array which is created, on which all the operations of GA are performed.

If length of the final array is less than 50, more number of Initial Population members are created and the Population whose assigned values are in the range of Minimum and Maximum limits is appended to the final array and the process is repeated using “while” loop until the length of the final array is equal to 50 or more than 50.

The corresponding cost values of the final array elements is calculated.

9.A program unit was created which incorporates Genetic Algorithm in the program and performs its operations on the final array that was created for 16 and 40 unit Generator system. The program unit has the sub-units that perform :

i) **Parent Selection Operation**: In this operation, any 5 random population members are chosen out of the final array.Out of 5 random members, the member whose cost value is minimum is appended into the array Mating Pool and the member is termed as a Parent.

The process of Parent Selection Operation is repeated for 20 times by looping the sub-unit into a “for” loop that runs from 0^{th} to 19^{th} iteration and hence the Mating Pool has the length of 20 elements of 1-D array of Power values.

ii) **Cross-over Operation**: In this operation, a crossover probability is assigned to a variable ‘pc’ which can be taken as input from the user.

Any two random Parents are selected from the Mating Pool and random probability is assigned to a variable ‘r’.

If ‘r’ value is more than or equal to ‘pc’, then the crossover operation on the Parents is omitted and they are copied as Offsprings into the 2-D Offspring arrays.

Else , the cross-over of the parents take place and the type of crossover used is the Simulated Binary Crossover[13] (SBX crossover) which gives two Offsprings as outputs after operation.

In SBX cross-over :

- An empty array ‘u’ is created.
- If the operation is on 16 unit system, 22 random floating point values of range 0 to 1 are appended in ‘u’ array.
- If the operation is on 40 unit system, 40 random floating point values of range 0 to 1 are appended in ‘u’ array.

- An empty array ‘β’ is created and the value of probability distribution η_c is assigned to particular value. Depending on the value of an element of ‘u’ array and η_c , the value of the array element that has to be appended to the ‘β’ array is determined.

For example :

If $u[i] <= 0.5$, then $\beta[i] = (2*u[i])^{(1/(\eta c+1))}$
Else,
$\beta[i] = (1/(2*(1-u[i])))^{(1/(\eta c+1))}$

where,

$u[i]$ is the value of i^{th} element of ‘u’ array.
$\beta[i]$ is the value of i^{th} element of ‘β’ array.

1^{st} Offspring = $([(1+\beta[i])*(Parent\_1) + (1-\beta[i])*(Parent\_2)]/2)$
2^{nd} Offspring = $([(1-\beta[i])*(Parent\_1) + (1+\beta[i])*(Parent\_2)]/2)$

The Crossover operation repeats 10 times as the sub-unit is looped in a “for” loop having 0^{th} to 9^{th} iterations and each iteration produces two outputs that is 1^{st} Offspring and 2^{nd} Offspring. Hence the Offspring array formed by Crossover has the length 2*10 = 20 elements.

iii) **Mutation Operation :** In this operation, a mutation probability is assigned to a variable ‘pm’ which can be taken as input from the user.
Each Offspring is selected one by one from the array of Offsprings formed by Crossover and random probability is assigned to a variable ‘r’ every time an offspring is selected.
If ‘r’ value is more than or equal to ‘pm’, then the mutation operation on the Parents is omitted and they are copied as Offsprings into the new 2-D Offspring arrays.
Else , the mutation of the offsprings take place and the type of mutation used is the Polynomial Mutation[13] which gives the mutated Offspring as an outputs after operation.

In Polynomial Mutation :

- An empty array ‘u’ is created.

- If the operation is on 16 unit system, 22 random floating point values of range 0 to 1 are appended in ‘u’ array.

- If the operation is on 40 unit system, 40 random floating point values of range 0 to 1 are appended in ‘u’ array.

- An empty array ‘δ’ is created and the value of probability distribution η_m is assigned to particular value. Depending on the value of an element of ‘u’ array and η_m, the value of the array element that has to be appended to the ‘δ’ array is determined.

For example :

If u[i] <= 0.5, then $\delta[i] = ((2*u[i])^{(1/(\eta m+1))} -1)$
Else,
$\delta[i] = (1-(2*(1-u[i])^{(1/(\eta c+1))}))$

where,

u[i] is the value of i^{th} element of ‘u’ array.
β[i] is the value of i^{th} element of ‘β’ array.

Modified Offspring of i^{th} element of Offspring array after mutation,
Offspring’= Offspring[i] +(Pmax[i] - Pmin[i])*δ[i]

Where,
Pmax[i]= Maximum limit of Generator i
Pmax[i]= Minimum limit of Generator i

Each array element of the Modified Offspring Array is checked to be within constraints by a user defined function which takes the 1-D Array as an argument and verifies if each element of the Array is in its Maximum and Minimum Power range and obeys POZ constraints. This function is used to filter out values that are not obeying the constraints. If the length of resulting Offspring Array formed after filtering out unwanted values is less than 20, the process of Cross-over and Mutation is repeated until the length of the Final Offspring Array is equal to or more than 20.
An array is created to store the cost values of the Offsprings that are created from Crossover and Mutation and follow the constraints.

iv) **<u>Generation of New Population</u>** :In this operation, the final Offspring Array created after Crossover and Mutation process is concatenated with the array containing the Initial population. The initial population members as well as new offsprings are arranged together in the ascending order of their cost values.

The first 10 elements of the resulting concatenated and sorted array are considered to be the best elements that can form a New Population with size=10.

The initial population array is declared as an empty array and the 10 best elements of the merged and sorted array are appended to the initial population array.

Using the new initial population array, the process of Crossover, Mutation and the Generation of New Population is repeated until the Offspring values created by the operations stop changing in the further iterations and remain stagnantthereby reaching a point of ‘Convergence’ of Optimized Values.

10. The results obtained from applying GA on Initial Population generated are compared with the results obtained by solving the MAED probem by other techniques.

CHAPTER 4
RESULTS AND ANALYSIS

This chapter elaborates about the results and graphs obtained by applying GA to solve the MAED problem and comparison of results by other techniques that were used in the past to solve the MAED problem.

The practical fuel cost function (that is including Valve Point Loading effects)of thermal power generating unit j of the i^{th} area can be expressed as :

$$f_{ij}(P_{ij}) = a_{ij}P_{ij}^2 + b_{ij}P_{ij} + c_{ij} + |e_{ij} * \sin (f_{ij} * (P_{ij}^{min} - P_{ij})| \quad (2)$$

where:

a_{ij}, b_{ij}, c_{ij},e_{ij},$f_{ij}$are Fuel Cost Coefficients

P_{ij} is Power of j^{th} Thermal Generator at i^{th} area

P_{ij}^{min} is minimum Power limit of thermal Generator

Due to the term $\boldsymbol{a_{ij}P_{ij}^2}$ **,**unit of a_{ij} is $/MW^2

Due to the term $\boldsymbol{b_{ij}P_{ij}}$, unit of b_{ij} is $/MW

Due to the term $\boldsymbol{c_{ij}}$,unit of c_{ij} is $

Generation Limit

The Minimum and the Maximum value of Power that can be allocated to a Generator Unit is given as :

$$\boldsymbol{P_{ij}^{min} \leq P_{ij} \leq P_{ij}^{max}} \quad (3)$$

where:

$\boldsymbol{P_{ij}^{min}}$are minimum limit of Power that has to be assigned to the j^{th} Generator of i^{th} Area

$\boldsymbol{P_{ij}^{max}}$ is the maximum limit of Power that can be assigned to the j^{th} Thermal Generator at i^{th} Area

Test case 1 has the data for four different areas. Every single area comprises of 4 units of power generating systems linked by the means of six tie lines.

The minimum and maximum power generation limits of each generator unit of 16 unit system, the cost coefficients, as well as the area each generator belongs to, is given in Table 4.1.

Table 4.1-Relevant data of system for 16 unit Generators (Case 1) [15]

Unit	P_{min}	P_{max}	a_i	b_i	c_i	Area
1	50	150	0	4	0.01	1
2	25	100	0	2	0.03	1
3	25	100	0	3	0.05	1
4	25	100	0	1	0.04	1
5	50	150	0	4	0.05	2
6	25	100	0	2	0.04	2
7	25	100	0	3	0.08	2
8	25	100	0	1	0.06	2
9	50	150	0	4	0.1	3
10	25	100	0	2	0.12	3
11	25	100	0	3	0.1	3
12	25	100	0	1	0.13	3
13	50	150	0	4	0.01	4
14	25	100	0	2	0.03	4
15	25	100	0	3	0.05	4
16	25	100	0	1	0.04	4
T12	-100	100	0	1	0	N/A
T13	-100	100	0	1	0	N/A
T14	-100	100	0	1	0	N/A
T23	-100	100	0	1	0	N/A
T24	-100	100	0	1	0	N/A
T34	-100	100	0	1	0	N/A

The network topology of the 16 unit system, depicting the interconnection between each area and the flow of power between the areas is given in Fig 4.1.

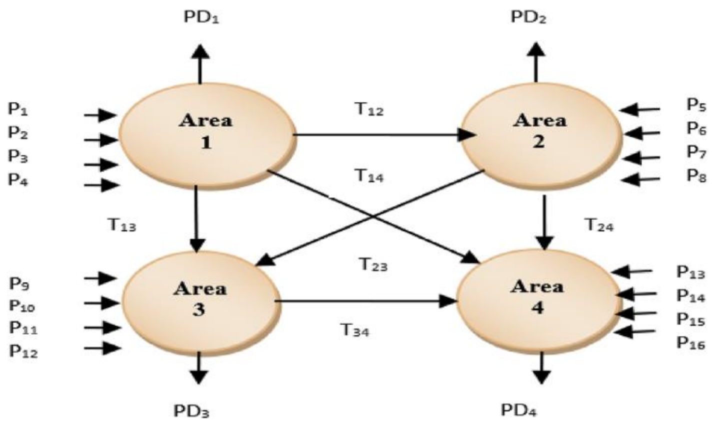

Fig. 4.1 Network Topology of the Sixteen Unit system[15]

Ramp Rate Limits

Ramp Rate Limit (RRL): It is the minute-to-minute change in Power of the GeneratorUnit of RRL is MW/minute. It is one of the measures of flexibility of power system.It can be defined as the rate at which the power is increased or decreased.

$$\text{Max}(P_{ij}^{min} , P^{o}_{ij}- DR_{ij})\leq P_{ij} \leq \text{Min}(P_{ij}^{max} , P^{o}_{ij} + UR_{ij}) \qquad (3)$$

$$-T_{il}^{max} \leq T_{ij} \leq T_{ij}^{max} \qquad (4)$$

Where,
$P^{o}$is the previous hour output.
$DR_{ij,}UR_{ij,}$are down and up ramping rate limits.
T_{il} is power flow over transmission line.

The minimum and maximum power generation limits of each generator unit of 40 unit system, the cost coefficients, as well as the area each generator belongs to, is given in Table 4.2

Table 4.2: Relevant data of system for Forty units of Generators (Case 2 Test Data)[15]

Unit	P_{min}	P_{max}	a_i	b_i	c_i	d_i	e_i	P_o	UR	DR	Area
1	36	114	0.0069	6.73	94.705	100	0.084	100	114	114	1
2	36	114	0.0069	6.73	94.705	100	0.084	100	114	114	1
3	60	120	0.02028	7.07	309.54	100	0.084	90	120	120	1
4	80	190	0.00942	8.18	369.03	150	0.063	150	100	150	1
5	47	97	0.0114	5.35	148.89	120	0.077	80	97	97	1
6	68	140	0.01142	8.05	220.33	100	0.084	120	80	125	1
7	110	300	0.00357	8.03	287.71	200	0.042	280	165	200	1
8	135	300	0.00492	6.99	391.98	200	0.042	200	165	200	1
9	135	300	0.00573	6.6	455.76	200	0.042	230	165	200	1
10	130	300	0.00605	12.9	722.82	200	0.042	240	155	190	1
11	94	375	0.00515	12.9	635.2	200	0.042	210	150	185	1
12	94	375	0.00569	12.8	654.69	200	0.042	210	150	185	1
13	125	500	0.00421	12.5	913.4	300	0.035	230	206	235	1
14	125	500	0.00752	8.84	1760.4	300	0.035	355	260	290	1
15	125	500	0.00708	9.15	1728.3	300	0.035	350	186	215	1
16	125	500	0.00708	9.15	1728.3	300	0.035	350	186	215	1
17	220	500	0.00313	7.97	647.85	300	0.035	460	240	270	1
18	220	500	0.00313	7.95	649.69	300	0.035	470	240	268	1
19	242	550	0.00313	7.97	647.83	300	0.035	500	290	315	1
20	242	550	0.00313	7.97	647.81	300	0.035	500	290	315	1
21	254	550	0.00298	6.63	785.96	300	0.035	510	335	360	2

22	254	550	0.00298	6.63	785.96	300	0.035	520	335	360	2
23	254	550	0.00284	6.66	794.53	300	0.035	520	335	362	2
24	254	550	0.00284	6.66	794.53	300	0.035	450	350	378	2
25	254	550	0.00277	7.1	801.32	300	0.035	400	350	380	2
26	254	550	0.00277	7.1	801.32	300	0.035	520	350	380	2
27	10	150	0.52124	3.33	1055.1	120	0.077	20	95	145	2
28	10	150	0.52124	3.33	1055.1	120	0.077	20	95	145	2
29	10	150	0.52124	3.33	1055.1	120	0.077	25	98	145	2
30	47	97	0.0114	5.35	148.89	120	0.077	90	97	97	2
31	60	190	0.0016	6.43	222.92	150	0.063	170	90	145	2
32	60	190	0.0016	6.43	222.92	150	0.063	150	90	145	2
33	60	190	0.0016	6.43	222.92	150	0.063	190	90	145	2
34	90	200	0.0001	8.95	107.87	200	0.042	190	105	150	2
35	90	200	0.0001	8.62	116.58	200	0.042	150	105	150	2
36	90	200	0.0001	8.62	116.58	200	0.042	180	105	150	2
37	25	110	0.0161	5.88	307.45	80	0.098	60	110	110	2
38	25	110	0.0161	5.88	307.45	80	0.098	40	110	110	2
39	25	110	0.0161	5.88	307.45	80	0.098	50	110	110	2
40	242	550	0.00313	7.97	647.83	300	0.035	512	290	315	2

Test Case 2 deals with system of two areas where each area comprises of 20 generating units, linked by the means of a tie-line having 1500 MW capacity. Hence the second test case has the data of the total forty generating units (Thermal Power). Itconsiders VPL effects, RRL, and POZ. As per the area, Power demands are 7500 MW and 3000 MW respectively, therefore the total power demand is 10500 MW.

The network topology of the 40 unit system, depicting the interconnection between each area and the flow of power between the areas is given in Figure 4.2

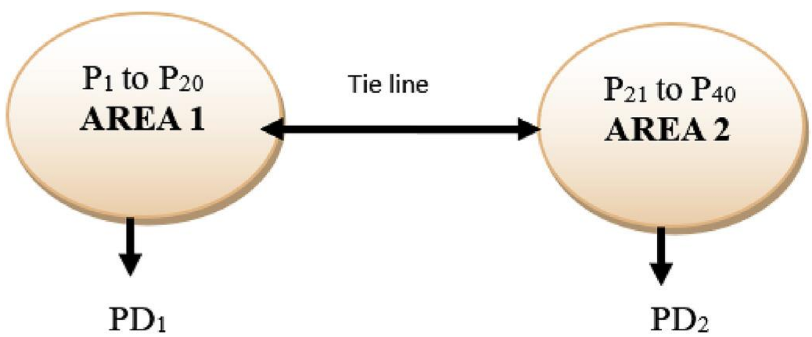

Fig. 4.2 Network Topology of 40 unit system [15]

<u>Prohibited Operating Zones(POZ)</u>: Physical limitations restrict the operations of generating units in concerned zones of operations.

$$P_{ij}^{min} \leq P_{ij} \leq P_{ij,1}^{l\_lim} \quad (5)$$

$$P^{u\_lim}_{ij,m-1} \leq Pij \leq P^{l\_lim}_{ij,m} \quad (6)$$

$$P^{u\_lim}_{ij,nij} \leq Pij \leq P^{max}_{ij} \quad (7)$$

Where: $P^{l\_lim}_{ij,m}$ and $P^{u_lim}_{ij,m-1}$are lower and upper limits of m^{th} and (m-1)th POZ and n_{ij} is jth POZ of generating unit for i^{th} area.

The POZs or the Power generation range limits in which the operation of Power generators of a particular unit are strictly prohibited, given in Table 4.3

Table 4.3: Prohibited Operating Zones of Forty unit system(Case 2 Test Data)[15]

Unit	Prohibited Operating Zones (MW)
10	[130 150] [200 230] [270 299]
11	[100 140] [230 280] [300 350]
12	[100 140] [230 280] [300 350]
13	[150 200] [250 300] [400 450]
14	[200 250] [300 350] [450 490]

4.1 ***Results Observed after applying GA on 16 unit Data***

Number of Initial Population generated = 20

The constraints of each of the initial population arrays are verified using the user defined function created with the same purpose.

The function checks if the given Array in its argument satisfies two conditions:

- All the array elements are within the limts of their corresponding Minimum and Maximum values.
- Satisfies the area-wise Power balance equation.

The population Arrays satisfying the constraints are appended into the 2D array which is considered as the Population Array on which GA operations are to be performed. The process of Population Generation, Constraint verification and appending the correct population arrays into the final 2D arrays is looped in a 'while' loop with the condition that length of the 2D array is greater than 20. The length of the resulting 2D array so formed after the loop execution was 23.

The sum of cost values of each of the 23 elements of these final array elements are evaluated. The maximum value of the sum of costs was as high as 9500 \$/hr and minimum value is around 8000 \$/hr.

The array elements, considered as new initial population are subjected to GA operations that are Cross-over, Mutation and Generation of New Population and the operations keep performing in iterations till the optimized values stop getting decremented over further iterations.

The Cross-over probability is fixed at 0.8 and the Mutation probability is fixed at 0.3.

The trajectory of the optimized cost values over each iteration is given in Fig 4.3.

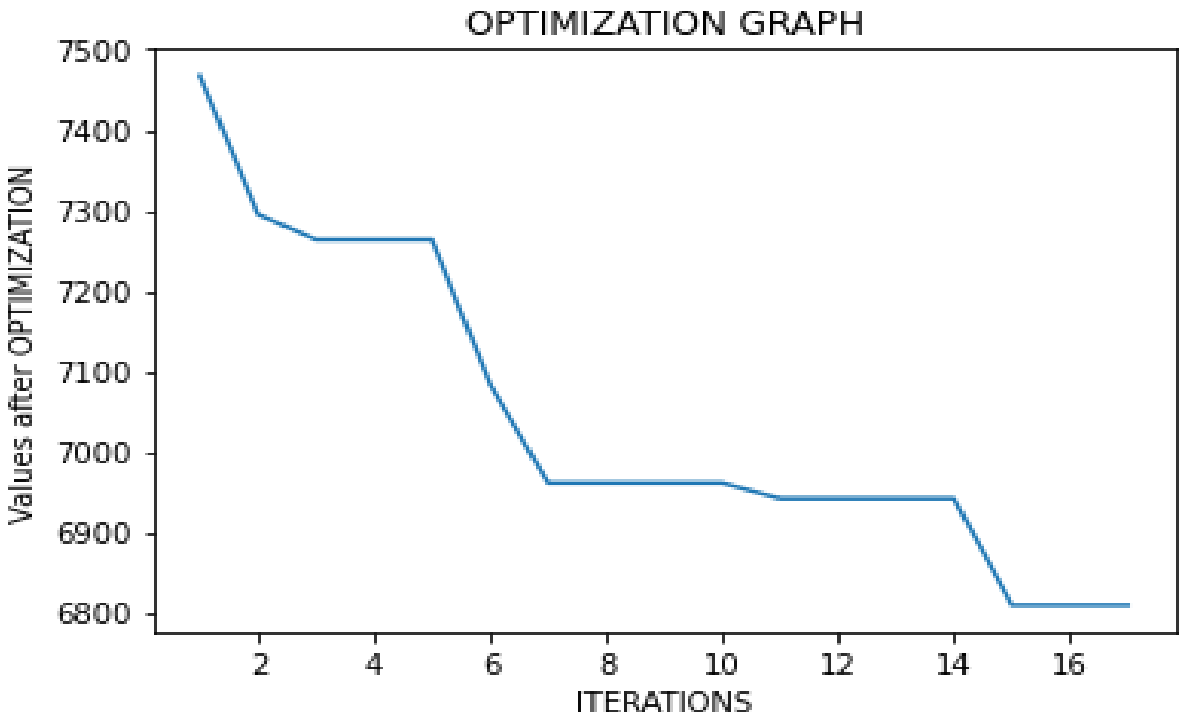

Fig 4.3 Optimization Graph (Optimized Values V/s Iterations)

As per graph in Figure 4.3, the optimized sum of cost values of the 16 unit generators keeps decreasing from 1st to 15th round of iteration.

After 15th iteration the optimized cost value does not decrease further and remains stagnant at $6809.0335/hr, thereby attaining the Point Of Convergence.

Area-wise Power values thus obtained in each area after optimization through GA on 16 unit system are given in Table 4.4

Table 4.4 : Power Values obtained in each Area after applying GA on 16 unit system

AREA	Generator Unit	Power Value (MW)
1	1	80.495
1	2	74.07
1	3	57.739

1	4	74.115
2	1	57.77
2	2	27.70
2	3	73.45
2	4	73.38
3	1	70.147
3	2	38.935
3	3	39.846
3	4	51.873
4	1	117.4156
4	2	81.724
4	3	78.384
4	4	86.696

Tie-line values obtained after optimization through GA on 16 unit between the two areas are given in Table 4.5

Table 4.5: Tie-line Values obtained in each Area after applying GA on 16 unit system

AREAS connected through tie-line and the power flow	Values (MW)
Area 1 to Area 2	83.121
Area 3 to Area 1	31.711
Area 1 to Area 4	1.252
Area 2 to Area 3	82.693
Area 2 to Area 4	32.743
Area 3 to Area 4	98.216

The best cost obtained after optimization through is compared with the best values of other optimized techniques used before. The comparison of best cost and the statistical values obtained are shown in Table 4.6

Table 4.6 : Comparison of Results of optimization (16 unit system)

Technique Applied	**Best Cost ($/hr)**	**Mean Cost ($/hr)**	**STD**
IMPROVED HARMONY SEARCH[15]	7337.275	-	-

HYBRIDIZING SUM LOCAL SEARCH OPTIMIZER[15]	7337.0299	-	-
MOTH-FLAME OPTIMIZATION[15]	7337.0139	-	-
GENETIC ALGORITHM	6809.0335	7105.636	237.86

*4.2*Results observed after applying GA on 40 unit Generator system

Number of Initial Population generated = 50
The constraints of each of the initial population arrays are verified using the user defined function created with the same purpose.
The function checks if the given Array in its argument satisfies two conditions:

- All the array elements are within the limts of their corresponding Minimum and Maximum values.
- Satisfies the area-wise Power balance equation.
- Value of each element is not lying in the range of POZ values.

The population Arrays satisfying the constraints are appended into the 2D array which is considered as the Population Array on which GA operations are to be performed. The process of Population Generation, Constraint verification and appending the correct population arrays into the final 2D arrays is looped in a ‘while’ loop with the condition that length of the 2D array is greater than 50. The length of the resulting 2D array so formed after the loop execution was 89.
The sum of cost values of each of the 89 elements of these final array elements are evaluated. The maximum value of the sum of costs was as high as 149000 \$/hr and minimum value is around 135000 \$/hr.
The array elements, considered as new initial population are subjected to GA operations that are Cross-over, Mutation and Generation of New Population and the operations keep performing in iterations till the optimized values stop getting decremented over further iterations.
The Cross-over probability is fixed at 0.8 and the Mutation probability is fixed at 0.3.

The trajectory of the optimized cost values over each iteration is given in Fig 4.4.

As per graph in Figure 4.4, the optimized sum of cost values of the 40 unit generators keeps decreasing from 0th to 25th round of iteration.
After 25th iteration the optimized cost value does not decrease further and remains stagnant at \$126115.5/hr, thereby attaining the Point of Convergence.
The value of Tie line connecting Area 1 to Area 2 is 1500 MW.

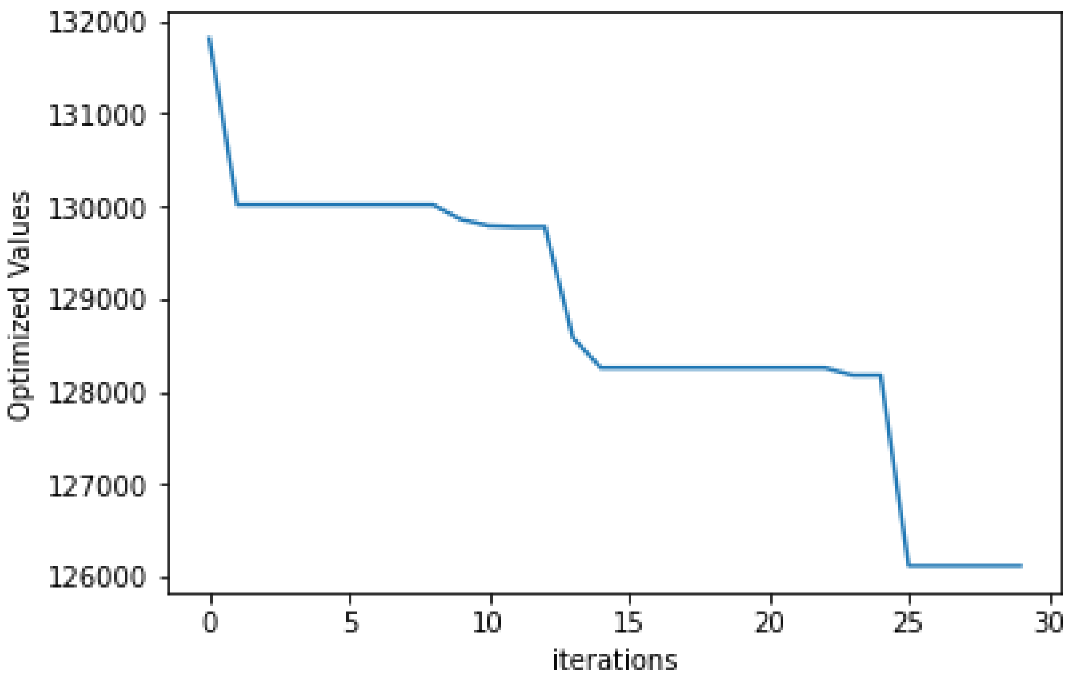

Fig 4.4 Optimization Graph (Optimized Values V/s Iterations)

The best cost obtained after optimization through is compared with the best values of other optimized techniques used before. The comparison of best cost and the statistical values obtained are shown in Table 4.7

Table 4.7: Comparison of Results of optimization (40 unit system)

Technique Applied	**Best Cost ($/hr)**	**Mean Cost ($/hr)**	**STD**
DIFFERENTIAL EVOLUTION[15]	131549.6	-	-
DIFFERENTIAL EVOLUTION PARTICLE SWARM OPTIMIZER-3[15]	127386.3364	-	-
DIFFERENTIAL EVOLUTION PARTICLE SWARM OPTIMIZER-4[15]	128641.7046	-	-
GENETIC ALGORITHM	126115.5	128697.5	1486.7

CHAPTER 5
CONCLUSION AND FUTURE SCOPE

5.1 ***Summary*** :

Multi Area Economic Dispatch (MAED) aims to determine the optimal power generation and transportation from geographically dispersed power generators organized into areas while satisfying system and operational constraints.The parameters in the MAED optimization function can modelled as variables in a high dimensional search space. Each candidate solution will then be a point in this high dimensional space.

Genetic Algorithm attempts to solve the MAED problem in such a way that in every iteration, after performing operations on its population, only (offsprings) those optimized results are considered as the new initial population for successive iterations of GA which are not violating Power limit constraints as well as satisfying Area-wise Power balance equation.

The GA operations repeat in multiple iterations until and unless there are no offsprings left that are satisfying the constraints and the optimized cost values stop getting decremented (improved) and repeats itself in the next successful iterations and this 'converged' value is considered to be the best value.

5.2 ***Conclusion*** :

In the present study, the MAED problem was studied and formulated as an optimization problem in a high dimensional search space. Various optimization techniques were studied and Genetic Algorithms (GA) was selected for MAED optimization whichhas been quite effective in achieving optimization in a high dimensional search space. GA attempts to capture individual dimensions within each of these points that minimize the objective function and incorporate them in a final solution by an iterative process that attempts to improve the solutions probabilistically over each iteration.Two cases were considered, a 16 unit generator system and a 40 units generator system.The results found using GA, in each of these two cases, were compared with results available in literature for other optimization techniques and were found to be significantly better.

5.3 ***Future Scope*** :

Efficiently solving MAED can result in lower environmental pollution and reduced cost of electricity to the end customer while ensuring safety at power generation plants.MAED can not only be effective in reducing the cost of fuel consumption and generation of Power but can also prove to be beneficial in lowering the cost of transportation of electrical Power as it considers costs due to tie-lines into consideration for minimization of overall costs.For establishing the suitability or otherwise of GA to solve MAED problems, the GA algorithm could be further improved and fine-tuned by applying it to a larger number of cases with different data sets. This will establish the strengths and limitations of GA as a technique to solve MAED problems.

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PROJECT DETAILS

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