

ECONOMIC DISPATCH AND UNIT COMMITMENT
BY BIOGEOGRAPHY BASED OPTIMIZATION
METHOD

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR
THE DEGREE OF
Master of Science
In

Electrical and Electronics Engineering

By

Zakaryia Mohamad Jaffar Ahmad Hasani



Department of Electrical and Electronics Engineering (EE)

University of Bahrain

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2012

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Under the Guidance of

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Department of Electrical and Electronics Engineering

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2012

DECLARATION

I declare that this work is the result of my own investigation and that it has not already been accepted in the substance for any degree, nor it is being currently submitted for any degree.

Signed: _____



Date: _____

16/9/2012

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UNIVERSITY OF BAHRAIN

College of Engineering

Thesis

Submitted in partial fulfillment of the requirements for the degree of
Master of Science In Electrical Engineering

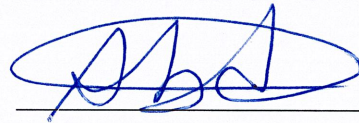
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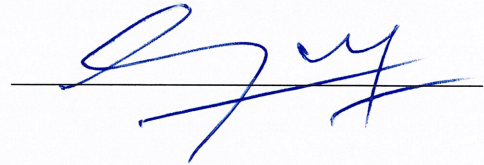
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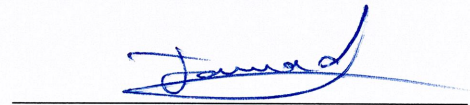
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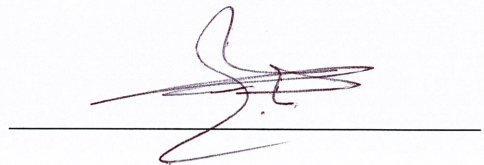
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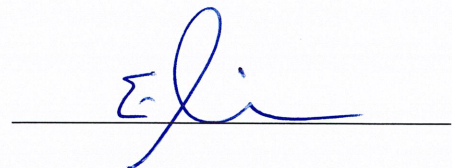
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June 7th, 2012

ACKNOWLEDGMENT

It is a pleasure to thank those who made this thesis possible. To a few of them I offer my word of gratitude.

I would like to express my gratitude and sincere thanks and appreciation to my thesis supervisor Dr.Jawad Talaq for his great assistance and guidance throughout the thesis work.

Special acknowledgement for my family for their support, motivations and providing me all the time required to reach this point.

ABSTRACT

This thesis proposes the application of biogeography-based optimization (BBO) to solve both economic dispatch (ED) and unit commitment (UC) problems of power systems operation. Biogeography is the study of the geographical distribution of biological organisms. Mathematical models of biogeography describe how species migrate from one habitat to another, how species arise, and how species become extinct. BBO has features in common with other biology-based optimization methods, such as genetic algorithms (GAs) and particle swarm optimization (PSO). Hence BBO is applicable to many of the same types of problems that GAs and PSO are used for. The proposed method has a simple procedure to find a near optimal solution for the non-smooth and non-convex problems mainly through two steps: migration and mutation. Economic dispatch (ED) main objective is to minimize the generation cost while satisfying the load demand and the system constraints. There are many constraints in the economic dispatch problem such as generators capacity, ramp rate limit, and prohibited operation zones. Unit commitment (UC) problem is mainly finding the minimum cost schedule to a set of generators by turning each one either on or off over a given time horizon to meet the demand load and satisfy different operational constraints. The cost function consists of the operation cost, startup, and shut down cost. There are many constraints in unit commitment problem such as spinning reserve, minimum up/down, crew, must run and fuel constraints. Economic dispatch is used in Unit commitment to find the minimum cost of generated power from the committed units for a certain load demand at a certain period in the schedule. UC problem is a nonlinear, large scale, mixed integer combinatorial optimization method with constraints. In the study, BBO will be applied to solve the economic dispatch and unit commitment problems of non-smooth and non-convex objectives. Results will be compared with other heuristic methods presented in literature.

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NOMENCLATURE

Symbol	Meaning
μ	emigration rate
a_i, b_i, c_i	fuel cost coefficients of generator i
B_{ij}, B_{oi}, B_{oo}	power losses coefficients
C	total unit commitment cost for N unit for T periods
E	maximum emigration rate
e_i, f_i	valve point coefficients of cost function for generator i
F_i	fuel cost function for generator i
F_t	total Fuel cost
HSI	habitat suitability index
I	maximum immigration rate
i	generation unit number
k	island number
L_l	start up cost coefficient
L_o	cold start up cost
m	mutation rate
$m_{\max}$	maximum mutation rate
n	total number of islands
P_D	total demand power
P_i	the output power from generator i
P_i down ramp limit	ramp-down rate limit of generation unit i
$P_i^{\max}, P_i^{\max}$	maximum power generation limit of generator i
$P_i^{\min}$	minimum power generation limit of generator i
P_i up ramp limit	ramp-up rate limit of generation unit i
P_i^m	output power of unit i at iteration m
P_L	transmission power losses
P_{mod}	modification probability
P_R	required spinning reserve
P_{rs}	probability that a habitat contains exactly S species
$P_{rs \max}$	maximum probability that a habitat contains exactly S species
SC	start up cost
SIV	suitability index variable

$S_{\max}$	maximum number of species
$t_{i \text{ cold}}$	cold start hours of unit i
T_{down}	minimum down time
$T_{i \text{ OFF}}$	continuous off time duration of generating unit i
$T_{i \text{ ON}}$	continuous on time duration of generating unit i
T_{up}	minimum up time
λ	immigration rate
λ_c	Incremental cost rate (Lagrange multiplier)

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CHAPTER 1

1 INTRODUCTION

1.1 INTRODUCTION

Economic dispatch and unit commitment are very essential problems in power system operation and planning. The main objective of both problems is reducing the cost while satisfying the load demands and not violating constraints. A new optimization method is examined in this thesis to solve both problems. This Introduction is organized as follows: the research objectives are defined in section 1.2. A literature review for economic dispatch is provided in section 1.3. A literature review for unit commitments problem is provided in section 1.4. Major contributions in this thesis are provided in section 1.5. Finally organization of the thesis is provided in section 1.6.

1.2 RESEARCH OBJECTIVES

The objective of this master thesis is:

1. Study and analyze the Biogeography based optimization (BBO) method.
2. Design a Matlab program using (BBO) to solve the Economic dispatch problem with different constraints such as generators capacity, ramp rate limit, valve point loading effects, and prohibited operation zone constraints.
3. Test the Economic dispatch program using the following systems:
 - a. Three units system.
 - b. Six units system.
 - c. Thirteen units system.
 - d. Fifteen units system.
 - e. Forty units system.

4. Compare the result with other methods presented in literature.
5. Design a Matlab program using BBO to solve the Unit commitment problem with spinning reserve, minimum up and minimum down constraints.
6. Test the Unit commitment program using the following test systems:
 - a. Three units system.
 - b. Four units system.
 - c. Ten units system.
 - d. Twenty units systems by duplicating the ten units system.
 - e. Forty units systems by duplicating the twenty units system.
7. Compare the result with other methods presented in literature.

1.3 ECONOMIC DISPATCH LITERATURE REVIEW

Economic dispatch(ED) main objective is to minimize the generation cost while satisfying the load demand and the system constraints as pointed by Wang et al. [1]. There are many constraints in the economic dispatch problem such as generators capacity, ramp rate limit, and prohibited operation zones. Several methods were proposed to solve the economic dispatch problem such as lambda iteration method, gradient method, base point and participation factor method as mentioned in Wood and Wollenberg [2]. All these methods assume that the cost curve is continuous and monotonically increasing (convex and smooth objective). But the modern generation unit has input-output characteristics which are highly nonlinear because of the valve point effect and ramp rate limits and discontinuous due to prohibited operation zones. Using the classical methods with the new units may lead to infeasible solutions or may lead to suboptimal solution. Hence the classical methods fail in solving such problems with non-smooth / non-convex objectives. Dynamic programming proposed by Wood and Wollenberg [2] to solve the economic dispatch imposes no restriction on the nature of the input/output characteristic; hence dynamic programming (DP) succeeds in solving ED problem with non-smooth / non-convex objectives but it suffers from the curse of dimensionality. Heuristic methods were used to solve the economic dispatch problem. Hopfield network is used to solve the ED problem with prohibited operating zones and without considering the power losses. Yalcinoz and Short [3] proposed an improved hopfield network for solving the economic dispatch considering the transmission capacity constraints. Hopfield network method requires two phase computations and suffers from very slow convergence due to sigmoid function used in hopfield model. Genetic algorithms (GAs) was presented to solve the economic dispatch problem by Chang and Chen [4] including transmission loss, ramp rate limit and valve point zone. GA use parallel search technique so it is faster than other algorithms such as simulated annealing algorithm. Gaing [5] addressed a solution to the economic dispatch using Particle swarm optimization (PSO). PSO is a modern heuristic optimization algorithm which has a simple concept, easy in implementation, robust in solving continuous non linear optimization problem and can generate high quality solutions within

shorter time. Differential evolution (DE) algorithm is a simple population based, stochastic parallel search evolutionary algorithm. Three operations to improve the population of candidate solution over several generations: mutation, crossover and selection operator. . After satisfying all constraints DE provide better results in a faster way. The advantageous of DE are its simple structure, easy use, convergence property, quality of solution, and robustness as mention in Coelho, and Mariani [6]. Evolutionary strategies (ES) and evolutionary programming (EP) provide an efficient solution to the nonlinear economic dispatch problem with non-smooth / non-convex objectives. Jayabarathi et al. [7] presented the evolutionary programming for solving the economic dispatch (ED) problem considering the prohibited operating zones. Recently New algorithm proposed in the applications of engineering optimization field by Simon [8] known as biogeography based optimization (BBO). This algorithm will be tested in this thesis in solving the economic dispatch with different constraints and the results will be compared with other results presented in literature to experience the efficiency of this algorithm.

1.4 UNIT COMMITMENT LITERATURE REVIEW

Unit commitment (UC) problem is mainly finding the minimum cost schedule to a set of generators by turning each one either on or off over a given time horizon to meet the demand load and satisfy different operational constraints as mentioned in Sheblea and Fahd [9]. The cost function consists of the operation cost, startup, and shut down cost. There are many constraints in unit commitment problem such as spinning reserve, minimum up/down ,crew , must run and fuel constraints as mentioned in Wood and Wollenberg [2]. Economic dispatch is used in unit commitment to find the minimum cost of generated power from the committed units for a certain load demand at a certain period in the schedule. UC problem is a nonlinear, large scale, mixed integer combinatorial optimization method with constrains. Several methods were proposed to solve the unit commitment problem. Classical methods such as exhaustive enumeration, priority list, mixed integer programming, dynamic programming, branch-bound, interior point optimization

decomposition technique and Lagrangian relaxation were used to solve the UC problem. Wood and Wollenberg [2] demonstrated the exhaustive enumeration, priority list, dynamic programming and lagrangian relaxation as solution methods for the unit commitment problem. Exhaustive enumeration has a major problem in practice and not suitable for large scale utilities as pointed by Wood and Wollenberg [2]. Priority list is fast and simple in concept but it is highly heuristic and usually achieves schedules with relatively high operating cost as mentioned in Wood and Wollenberg [2]. Dynamic programming method is limited to very small sized systems because of the curse of dimensionality problem as pointed by Wood and Wollenberg [2] and Zhu [10]. Cohen et al. [11] proposed branch and bound method for solving the unit commitment problem. Branch and bound method suffers from the curse of dimensionality hence the application is limited to small scale systems. This method has the problem of a deficiency of storage capacity and the calculation time increases enormously for large scale systems. Interior Point optimization method has good convergence characteristics and the parameter tuning is not a critical issue as mentioned in Madrigal and Quintana [12]. In the decomposition technique a large scale problem is divided into a set of smaller sub problems and finding the solution of these sub problems is the main challenge. Mixed Integer programming guarantees convergence to the optimal solution in a finite number of steps while providing a feasible and accurate modeling framework. Carrion and Arroyo [13] presented a new mixed-integer linear formulation for the unit commitment problem. According to Zhu [10] lagrange relaxation is the most realistic and efficient method for large scale systems. The main problem with LR method is the difficulty encountered in obtaining a feasible solution, because of the convergence to feasible solution after a limited number of iterations is not guaranteed and its inherent sub optimality. Meta Heuristic techniques were proposed as solution methods to the unit commitment problem to cover the shortages and shortcomings of the classical methods and search for the optimal solution. Meta heuristic methods include: Expert Systems, Simulating Annealing, Artificial Neural Networks, Genetic Algorithm, Ant Colony Search Algorithm, and Tabu Search methods. In Mokhtari et al. [14] unit commitment solved using the expert system. Expert system method is mainly used for search and optimization because it reduces the complexity in

calculation and reduces the computation time. The main problem of this method arises if new schedule is different from schedule in the database. Simulated annealing is a general powerful method that converges asymptotically to global optimum solution as pointed by Zhuang and Galiana [15]. Artificial Neural Network methods can accommodate more complicated constraints and the solution convergence is rapid and has a good quality. Sendaula et al. [16] proposed a combination of hopfield artificial neural networks to solve the unit commitment and the associated economic unit dispatch problems. Genetic Algorithm is a general purpose stochastic and parallel search method based on the mechanics of natural selection and natural genetics. Genetic Algorithm is mainly used for search and optimization. In 1996 Kazarlis et al. [17] addressed a solution to the unit commitment problem using genetic algorithm. This method has a potential of obtaining near optimal global solution, obtain accurate result within short time and the constraints are included easily. Ant colony search algorithms are considered as powerful tools to solve optimization problems in power systems such as economic dispatch problem and unit commitment problem. Tabu search (TS) Algorithm is iterative improvement procedure that uses a short term memory of recent solutions to escape from local optima to a better near global or global solution. In Mantawy et al. [18] TS proposed as a solution to the unit commitment problem. A New method recently was proposed to solve the engineering optimization problems known as biogeography based optimization (BBO). In this thesis this method will be tested in solving the unit commitment with different constraints for several test systems and the results will be compared with those of different methods presented in literature to test the efficiency of this method.

1.5 MAJOR CONTRIBUTION OF THE THESIS

Here in this work it is shown that the BBO algorithm is capable of:

1. Solving the economic dispatch problem with different constraints such as generators capacity, ramp rate limit, and prohibited operation zone constraints using BBO optimization method.
2. Solving the unit commitment problem with spinning reserve, minimum up and minimum down constraints using the BBO optimization method.

1.6 ORGANIZATION OF THE THESIS

The thesis includes five chapters altogether. The chapters are organized as follows:

Chapter 1

This chapter introduces a brief outline of the thesis problems, literature review of the related topics of the problems. This chapter also includes the objective of the thesis and the major contribution in this thesis.

Chapter 2

This chapter briefly covers the economic dispatch problem and its various constraints. Also the mathematical formulations of economic dispatch problem with and without considering the transmission line losses and valve point effect. This chapter also introduces the main classical solution methods for this problem.

Chapter 3

Chapter 3 introduces the unit commitment problem, its main constraints, mathematical formulation of unit commitment and the main used classical solution methods.

Chapter 4

This chapter introduces briefly the Biogeography based optimization algorithm which is proposed to solve the economic dispatch and the unit commitment problems. Also this chapter includes the procedure of the algorithm used to solve each problem separately.

Chapter 5

This chapter includes the simulation results for five systems in the economic dispatch problem and five systems in the unit commitment.

Chapter 6

This chapter includes the conclusion and the suggestion for future work.

CHAPTER 2

2 ECONOMIC DISPATCH

2.1 INTRODUCTION

The main aim of economic dispatch is to reduce the operation cost while satisfying the different constraints which will provide a competitive price for the consumers, reduce the fuel consumption and satisfy the load demands. This chapter will introduce the concept of economic dispatch, formulation of economic dispatch, constraints of economic dispatch and the classical methods for solving the economic dispatch problem.

2.2 ECONOMIC DISPATCH

Economic dispatch (ED) is finding the minimum cost of generating electrical energy while satisfying the load demand and the system constraints. The importance of this optimization problem is that of saving a lot of money. There are many constraints in economic dispatch problem such as generators capacity, ramp rate limit, prohibited operation zone constraints as mentioned in Bhattacharya and Chattopadhyay [19].

2.3 GENERATOR INPUT- OUTPUT MODEL OF THERMAL GENERATION UNITS

Each thermal generation unit has a cost function which maps the thermal generation unit output active power with the input fuel cost. The total cost includes the fuel cost, labor cost and maintenance cost. The labor and maintenance are assumed to be a fixed percentage of the incoming fuel cost as pointed by El-Hawary and Christensen [20]. This model is approximated to be a quadratic function and derived from the Input - output characteristic of the generation unit shown in Figure 1. The cost function for the i^{th} generation unit is modeled as follows:

$$F_i(P_i) = a_i P_i^2 + b_i P_i + c_i \quad (2.1)$$

a_i, b_i, c_i : fuel cost coefficients of generator i .

P_i : the output power from generator i .

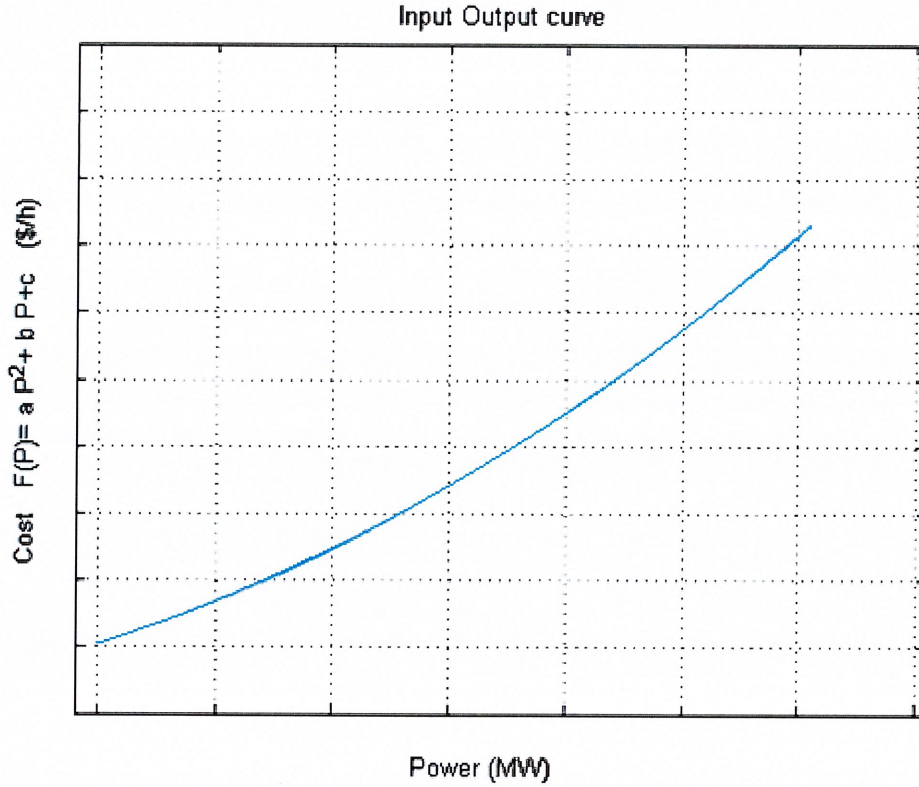


Figure 1 Input-output characteristic of a thermal unit

Due to the valve point effect the Input - output characteristic of the generating unit becomes a non convex curve as shown in Figure 2. The generation cost function F_i considering the valve point effect as given in Bhattacharya and Chattopadhyay [19] can be represented as follows:

$$F_i(P_i) = a_i P_i^2 + b_i P_i + c_i + |e_i \sin(f_i (P_{i \min} - P_i))| \quad (2.2)$$

e_i, f_i : valve point coefficients of cost function for generator i .

$P_{i \min}$: minimum power generation limit of generator i .

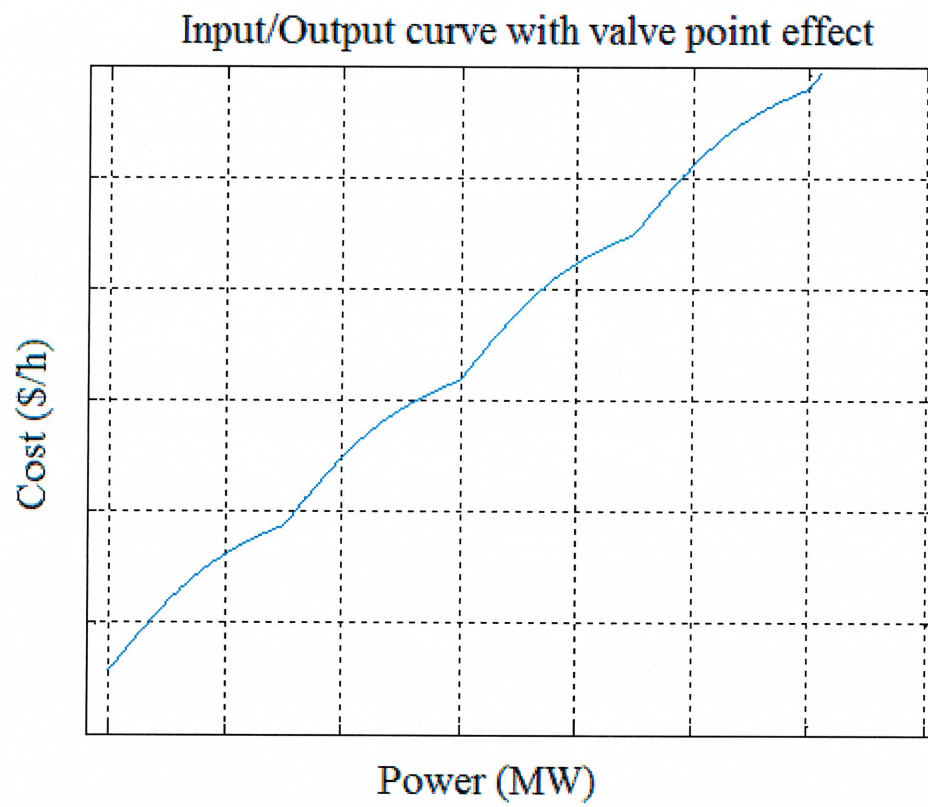


Figure 2 Input output characteristic curve with valve point effect

2.4 CLASSICAL ECONOMIC DISPATCH PROBLEM

The main objective of economic dispatch problem is to find the power distribution that minimizes the total fuel cost and satisfy the load demand and the different economic dispatch constraints. The simplest case for economic dispatch problem is the lossless case when multiple generators are connected to a bus and the bus feed the required load as shown in Figure 3. Assuming that the cost curve is continuous and monotonically increasing. Since the input output curves of the generators are not necessarily identical. The problem can be described as shifting the loads among the generators until minimum total fuel input cost is obtained. Economic dispatch is a constrained optimization problem which has the following objective function:

Minimize

$$F_t = \sum_{i=1}^N F_i(P_i) \quad (2.3)$$

Subjected to

$$\sum_{i=1}^N P_i = P_D \quad (2.4)$$

$$P_{i \min} \leq P_i \leq P_{i \max} \quad (2.5)$$

$P_{i \max}$: Maximum power generation limit of generator i.

$P_{i \min}$: Minimum power generation limit of generator i.

P_D : Total demand power.

Lagrangian multiplier method is used for solving this problem and finding the economic distribution of load between generators. The method arrives to a very important conclusion that for N generators to find the optimum solution the equal incremental cost of the units shown in Figure 4 should satisfy the following Equation as given in Zhu [10]:

$$\frac{dF_1}{dP_{G1}} = \frac{dF_2}{dP_{G2}} = \frac{dF_3}{dP_{G3}} = \dots \dots \dots = \frac{dF_N}{dP_{GN}} = \lambda_c \quad (2.6)$$

λ_c : Incremental cost rate (Lagrange multiplier).

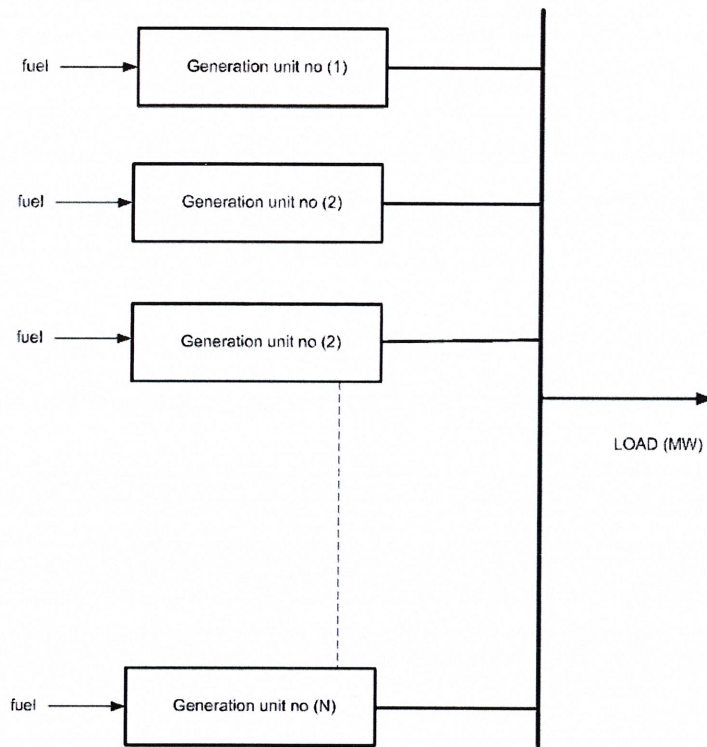


Figure 3 N thermal units connected to the demand load

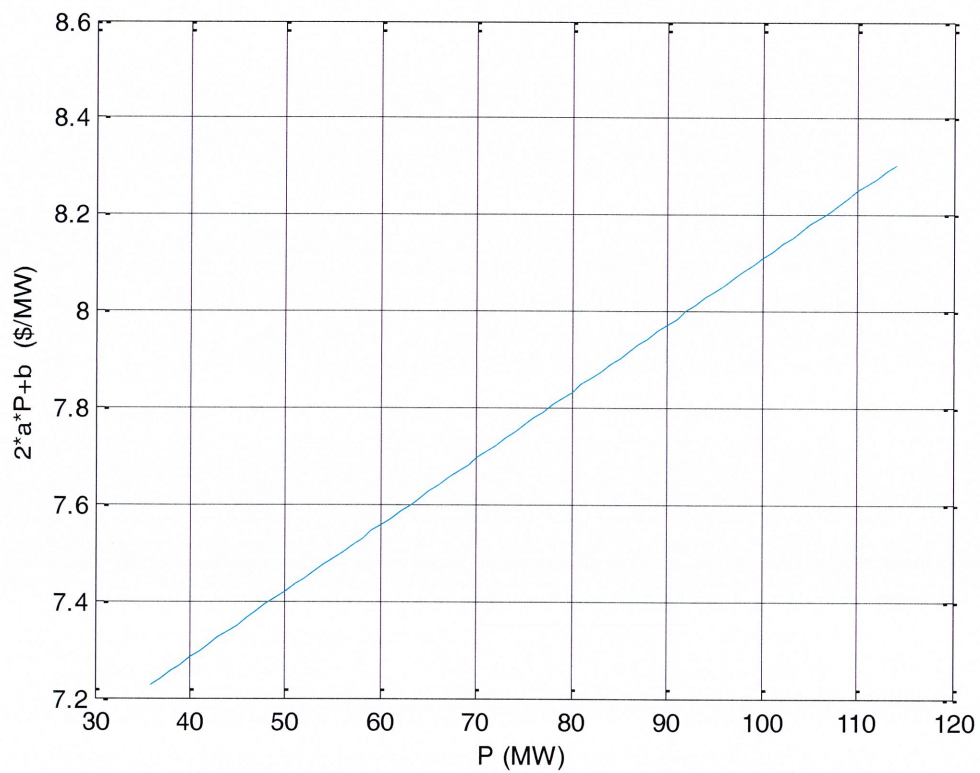


Figure 4 Fossil fuelled generator unit incremental cost curve

2.5 ECONOMIC DISPATCH WITH LOSSES

The transmission losses can be included in the economic dispatch problem in Equation 2.4 as shown in Equation 2.7 and calculated from Equation 2.8 using B-coefficients as given in Wood and Wollenberg [2].

$$\sum_{i=1}^N P_i = P_D + P_L \quad (2.7)$$

$$P_L = \sum_{i=1}^N \sum_{j=1}^N P_i B_{ij} P_j + \sum_{i=1}^N B_{oi} P_i + B_{oo} \quad (2.8)$$

P_L : Transmission power losses.

B_{ij}, B_{oi}, B_{oo} : Power losses coefficients.

2.6 ECONOMIC DISPATCH CONSTRAINTS

2.6.1 REAL POWER BALANCE CONSTRAINT

The generated power should satisfy the Demand and the losses as given in Wood and Wollenberg [2].

$$\sum_{i=1}^N P_i - P_D - P_L = 0 \quad (2.9)$$

2.6.2 REAL POWER GENERATION LIMITS

Each generator in the network has real power limits as pointed by Wood and Wollenberg [2].

$$P_{i \min} \leq P_i \leq P_{i \max} \quad (2.10)$$

$P_{i \min}$: Minimum output power of generation unit i.

$P_{i \max}$: Maximum output power of generation unit i.

2.6.3 RAMP RATE LIMIT CONSTRAINT

According to Bhattacharya and Chattopadhyay [19] generators have an up ramp limit and down ramp limit in power change from one value to a new value.

$$P_{i\ old} - P_{i\ new} \leq P_{i\ down\ ramp\ limit} \quad (2.11)$$

$$P_{i\ new} - P_{i\ old} \leq P_{i\ up\ ramp\ limit} \quad (2.12)$$

$P_{i\ up\ ramp\ limit}$: Ramp-up rate limit of generation unit i .

$P_{i\ down\ ramp\ limit}$: Ramp-down rate limit of generation unit i .

2.6.4 PROHIBITED OPERATING ZONES

Due to steam valve operation or shaft bearing vibration there are prohibited zones in the input-output characteristics of the generator as pointed by Bhattacharya and Chattopadhyay [19]. Figure 5 shows the discontinuity resulted from these zones.

$$\begin{aligned} P_{i\ min} &\leq P_i \leq P_{i,1} \\ P_{i,1} &\leq P_i \leq P_{i,2} \\ P_{i,2} &\leq P_i \leq P_{i,j} \\ P_{i,j} &\leq P_i \leq P_{i\ max} \end{aligned} \quad (2.13)$$

$$i = 1, 2, \dots, n$$

$$j = 1, 2, \dots, m_i$$

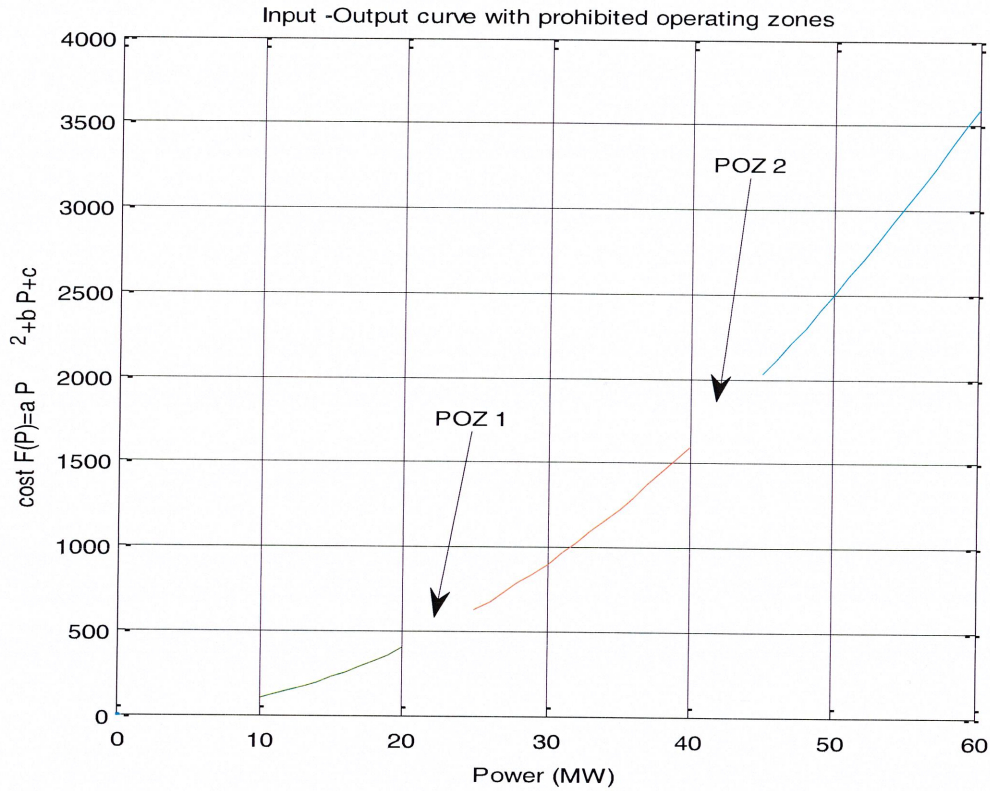


Figure 5 Input-Output characteristics curve with prohibited operating zones

2.7 ECONOMIC DISPATCH CLASSICAL SOLUTION METHODS

2.7.1 LAMBDA ITERATION METHOD

The simplest approach to solve the economic dispatch problem neglecting the losses is λ - iteration method. According to Wood and Wollenberg [2] the following procedure is used:

1. Set λ^0 to value greater than the largest intercept of the incremental cost of the various generators.
2. Compute $P_i^m = \frac{\lambda_c - b_i}{2 c_i}$.
3. Check if the relation $\sum_{i=1}^N P_i^m - P_D \leq \varepsilon$ is satisfied.

4. If the generation is less than the demand, then assign new value for $\lambda^{m+1} = \lambda^m + \Delta\lambda$ and repeat step (2) and (3).
5. If the generation is greater than the demand, then assign new value for $\lambda^{m+1} = \lambda^m - \Delta\lambda$ and repeat step (2) and (3).
6. If step (3) satisfies stop the iteration process.

Lambda iteration is sensitive in choosing the value of lambda because sometimes it may have an oscillatory behavior which results in that the solution is not converging.

2.7.2 GRADIENT SEARCH METHOD

Lambda iteration method is useful when the cost function is quadratic and equal incremental cost is applied but when the function becomes non quadratic and complex, lambda iteration becomes difficult in solving such problem. Basic methods can be used such as Newton method and Gradient search method. The general idea of gradient search method is that the minimum is found by taking the steps in the direction of the downward. For function $f(x)$

$$x^m = x^{m-1} + \alpha \nabla f(x^{m-1}) \quad (2.14)$$

Where

$$\nabla f = \begin{bmatrix} \frac{\delta f}{\delta x1} \\ \frac{\delta f}{\delta x2} \\ \frac{\delta f}{\delta x3} \\ \vdots \\ \frac{\delta f}{\delta xn} \end{bmatrix} \quad (2.15)$$

$$L = F_t - \lambda(\sum_{i=1}^N P_i - P_D) = \sum_{i=1}^N F_i(P_i) - \lambda(\sum_{i=1}^N P_i - P_D) \quad (2.16)$$

$$\nabla L = \begin{bmatrix} \frac{\delta L}{\delta P_{G1}} \\ \frac{\delta L}{\delta P_{G2}} \\ \vdots \\ \frac{\delta L}{\delta P_{GN}} \\ \frac{\delta L}{\delta \lambda} \end{bmatrix} = \begin{bmatrix} \frac{dF_1}{\delta P_{G1}} - \lambda \\ \frac{dF_2}{\delta P_{G2}} - \lambda \\ \vdots \\ \frac{dF_N}{\delta P_{GN}} - \lambda \\ \sum_{i=1}^N P_i - P_D \end{bmatrix} \quad (2.17)$$

$$x^m = \begin{bmatrix} P_{G1}^m \\ P_{G2}^m \\ \vdots \\ P_{GN}^m \\ \lambda^m \end{bmatrix} \quad (2.18)$$

To solve this optimization problem Lagrange function should be constructed using Equation 2.3 and 2.4 as given in Zhu [10], the augmented Lagrangian function shown in Equation 2.16. Initially x^0 should be given to solve the problem and stop until we reach $\nabla L = 0$. Sometimes using this method will not lead to a convergence to the solution. According to Zhu [10] three gradient methods can be used to solve such problem:

1. Gradient method 1:

In calculation of the gradient lambda will be subtracted from the gradient as shown in Equation 2.17 and the value of lambda will always set equal to the average of the incremental cost of the generators at the iterated generation values .

2. Gradient method 2:

This method is a modified version from method 1 but in each iteration we should check the power balance equation.

3. Gradient method 3:

This method is a modified version from method 1 and simplified one from method 2. In this method we set a unit as slack machine as mentioned in Zhu [10].

2.7.3 NEWTON'S METHOD

In the gradient search method the solution converges if $\nabla L = 0$ but the problem was that the gradient search method was slow. According to Wood and Wollenberg [2] if Newton raphson method applied to the gradient the speed of finding $\nabla L = 0$ will increase. Newton method for function $f(x)$ can be written as

$$f(x + \Delta x) = f(x) + [f'(x)]\Delta x = 0 \quad (2.19)$$

The objective function is $f(x) =$
$$\begin{bmatrix} f_1(x_1, x_2, \dots, x_n) \\ f_2(x_1, x_2, \dots, x_n) \\ \vdots \\ f_n(x_1, x_2, \dots, x_n) \end{bmatrix} \quad (2.20)$$

The jacobian $f' =$
$$\begin{bmatrix} \frac{\delta f_1}{\delta x_1} & \dots & \frac{\delta f_1}{\delta x_n} \\ \vdots & \ddots & \vdots \\ \frac{\delta f_n}{\delta x_1} & \dots & \frac{\delta f_n}{\delta x_n} \end{bmatrix} \quad (2.21)$$

Solving for Δx and substituting $f(x) = \nabla L$ the jacobian becomes

$$\frac{\delta \nabla L}{\delta P_{Gi}} = \begin{bmatrix} \frac{d^2 L}{dP_{G1}^2} & \frac{d^2 L}{dP_{G1}^1 dP_{G2}^1} & \frac{d^2 L}{dP_{G1}^1 dP_{Gn}^1} \\ \frac{d^2 L}{dP_{G1}^1 dP_{Gn}^1} & & \frac{d^2 L}{dP_{GN}^2} \end{bmatrix} \quad (2.22)$$

This matrix which consists of second order derivative is called Hessian matrix. This method required that the objective function have continuous first and second order derivative inside the feasible region.

CHAPTER 3

3 UNIT COMMITMENT

3.1 INTRODUCTION

The load demand of the power system is not constant but always varying from hour to hour during the whole day. Hence finding a permanent solution to the system is not possible and it is not economical to run all the available units all the time. The demand load in a power system experiences a cycle; it is higher during the day time and lower during the late evening and early morning, depending on the season and the place. Due to the cyclical load demand it is advisable to plan for generation of electrical power in hourly bases and it is necessary to decide in that plan which unit should be ON (start up) , which unit should be OFF (shut down) , when to connect them to the network , the sequence for units shut down and for how long. Finding the answer of all these questions is known as unit commitment (UC). This chapter covers the unit commitment problem definition, formulation, constraints and introduces the most important techniques for the solutions of a UC problem.

3.2 UNIT COMMITMENT

According to Sheblea and Fahd [9] unit commitment (UC) problem is mainly finding the minimum cost schedule to a set of generators by turning each one either on or off over a given time horizon to meet the demand load and satisfy different operational constraints. The cost function consists of the operation cost, startup, and shut down cost. There are many constraints in the unit commitment problem such as spinning reserve, minimum up/down ,crew , must run and fuel constraints as mentioned in Wood and Wollenberg [2]. Economic dispatch is used in Unit commitment to find the minimum cost of generated power from the committed units for a certain load demand at a certain period in the schedule.

3.3 UNIT COMMITMENT PROBLEM FORMULATION

3.3.1 UNIT COMMITMENT COST FUNCTION

Suppose that there are N generation units that will feed the demand load over a time horizon consisting of T periods (usually hours). According to Wood and Wollenberg [2] unit commitment cost function can be written as:

$$C = \sum_{i=1}^T \sum_{j=1}^N [F(P_j(i)) + SC_j(i)] \quad (3.1)$$

C : Total unit commitment cost for N unit for T periods (hours).

$SC_j(i)$: Start up cost for unit j at period i .

$F(P_j(i))$: Fuel cost function for unit j at period i .

3.3.2 START UP COST

Start up cost is a function of the time that unit has been OFF where the start up cost price will be decided based on the time. Cold start up cost is considered if the unit is off for a long time, otherwise a hot start up cost is considered. There are mainly two functions that are commonly used to calculate the start up cost of the generation units: two step function as given in Kazarlis et al. [17] and exponential function as given in Bard [21].

Two step function:

$$SC(t) = \begin{cases} C_{hot} & , T_{i OFF} \leq t_{i down} + t_{i cold} \\ C_{cold} & , T_{i OFF} > t_{i down} + t_{i cold} \end{cases} \quad (3.2)$$

$T_{i OFF}$: Continuous off time duration of generating unit 'i'.

$t_{i down}$: Minimum down time of unit 'i'.

$t_{i cold}$: Cold start hours of unit 'i'.

Exponential function:

$$SC(t) = l_0 \left(1 - e^{\frac{-\max(0, -T_{iOFF})}{k}} \right) + l_1 \quad (3.3)$$

T_{iOFF} : Continuous off time duration of generating unit.

l_0 : Cold start up cost.

l_1, k : Start up cost coefficients.

3.3.3 UNIT COMMITMENT CONSTRAINTS

There are many constraints in unit commitment problem such as spinning reserve, minimum up/down ,crew , must run and fuel constraints.

3.3.3.1 SPINNING RESERVE

Spinning reserve can be defined as the total amount of generation available from all synchronized units minus the demand power and the losses of the system. The importance of the spinning reserve is that when a unit or more is lost the system frequency will not drop. Spinning reserve is specified as percentage of peak load or making up the largest unit on the system. Spinning reserve should be distributed around the system to avoid transmission limitation as pointed by Wood and Wollenberg [2].

$$\sum_{i=1}^N P_i^{max} \geq P_D + P_R \quad (3.4)$$

P_R : Required spinning reserve.

P_D : Total demand power.

3.3.3.2 MINIMUM UP TIME

If the unit is turned on it should not be turned off before a minimum up time as mentioned in Wood and Wollenberg [2].

$$T_{i\text{ ON}} \geq T_{up} \quad (3.5)$$

$T_{i\text{ ON}}$: Continuous on time duration.

T_{up} : Minimum up time.

3.3.3.3 MINIMUM DOWN TIME

If the unit is turned off it should not be turned on before a minimum down time as mentioned in Wood and Wollenberg [2].

$$T_{i\text{ OFF}} \geq T_{down} \quad (3.6)$$

$T_{i\text{ OFF}}$: Continuous off time duration.

T_{down} : Minimum down time.

3.3.3.4 CREW CONSTRAINT

If a plant consists of more than one unit, these units cannot be started at the same time because of that there are not enough crew to start all these units as mentioned in Wood and Wollenberg [2].

3.3.3.5 MUST RUN UNITS

There are some units in the network that must be run at certain time in the schedule due to needs in the network such as the security issues to increase the network stability by supplying for example the reactive power needs to avoid the voltage instability. Sometimes the needs are different such as the steam requirement of the cogeneration plants as pointed by Wood and Wollenberg [2].

3.3.3.6 FUEL CONSTRAINT

Fuel constraint is considered in the unit commitment problem if some units in the system which is under study have a limited fuel or else have constraints that required them to burn specified amount of fuel in a given time. This present the most challenging problem in unit commitment problem as mentioned in Wood and Wollenberg [2].

3.4 UNIT COMMITMENT SOLUTION METHODS

Finding the optimum solution of the unit commitment is important because there will be a lot of saving in the resources. The most famous methods used to solve the unit commitment are three methods:

1. Priority list method.
2. Dynamic Programming.
3. Lagrange relaxation.

3.4.1.1 PRIORITY LIST METHOD

Priority list is the simplest and fastest method for solving unit commitment problem but its solution is sub optimal. In this method the generation units are ordered in a way that the most efficient unit is used first to supply the load and if the demand load is greater than the capacity of that unit the balanced is satisfied using the second most efficient unit and followed by the less efficient unit in order as the demand load increases. The factor used to decide the efficiency of the unit is the full load average production cost and then the unit costs are arranged of ascending order to commit the demand load based on this arrangement. The general procedure for this method is as follows as mentioned in Momoh [22]:

1. Check at the end of each hour whether the load is decreasing. If the load is decreasing determine whether shutting down the next unit in priority list will satisfy the load demand and the spinning reserve. If not no change in unit commitment at that hour.

2. If the unit can be dropped. Determine the number of hours the unit will be shut down, then if the number of hours is less than the minimum shut down for the unit; keep the unit commitment without any change.
3. Calculate the cost of operation for the required load for the unit commitment without dropping that unit and with dropping that unit and compare the two costs. The case which has the minimum cost should be chosen.
4. Repeat the process for the next hour.

3.4.1.2 DYNAMIC PROGRAMMING

Dynamic programming is used for medium and small power network because it has the advantages of reducing the dimensionality of the problem compared with enumeration scheme. There are two types of dynamic programming:

1. Forward dynamic programming.
2. Backward dynamic programming.

Forward dynamic programming is always used in unit commitment because it has many advantages over the backward dynamic programming such as:

1. The initial conditions are known.
2. Since the start up cost is a function of time then the forward dynamic programming is better because the history of the unit will be known.

According to Wood and Wollenberg [2] in dynamic programming method we assume that:

1. The startup cost is fixed.
2. The cost of shutting down a unit equal zero.
3. There is a strict priority order, and in each interval a specified minimum amount of capacity must be operating.
4. A state consists of an array of units with specified units operating and the remaining units are off line.

If the committed units can supply the required load and can meet the minimum amount of capacity each period. Then a feasible state is founded.

In enumeration scheme, there are 2^n-1 states for n units. The computation amount is large. Assumption no (3) discards some infeasible states as well as high – cost states. Considering the unit minimum uptime and minimum downtime constraints, also can reduce the states. In this way, the computation amount of dynamic programming will be reduced as pointed by Wood and Wollenberg [2].

3.4.1.3 LAGRANGE RELAXATION

Lagrange relaxation is a technique which is suitable for problems where the constraints can be divided into two categories, easy constraints and hard constraints. Easy constraints are defined as constraints when presented in the problem the problem is solved easily. The hard constraints when involved, the problem becomes hard to solve. The main idea is to relax the problem by adding the hard constraints to the objective function scaled by a constant called Lagrange multiplier. Each multiplier is a penalty factor added to the solution that does not satisfy the particular constraints. This method is used for large network and can overcome the dimensionality problem in dynamic programming when used for large network and discarding the optimum scheme in priority list. As mentioned in Wood and Wollenberg [2] this method has many advantages such as:

1. No priority list is imposed which mean more flexibility compared with dynamic programming.
2. Can be modified easily to model specific utilities.
3. Adding constraints is easy and dealing with different constraints is done with high flexibility even the coupling constraints which were relaxed.
4. Efficient in solving large system compared with other methods.

This method also has disadvantages:

1. The obtained optimal solution rarely satisfies the coupling constraints.
2. The sensitivity problem may lead to committing unnecessary units and lead to near optimal solution.

CHAPTER 4

4 BIOGEOGRAPHY BASED OPTIMIZATION

4.1 INTRODUCTION

Several Meta heuristic algorithms were proposed to solve optimization problems in engineering field because those problems were either difficult to solve or impossible using classical methods. These algorithms include genetic algorithm, simulated annealing, tabu search, particle swarm optimization, and so forth. Advantages of the meta heuristic methods compared with classical methods is mainly the development time for new methods is very shorter for the heuristic method , the solution algorithms are very robust to dynamic changes , conceptually simple compared with classical methods and have many applications in many fields. Recently a new optimization method called Biogeography Based Optimization was proposed by Simon [8]. This chapter will briefly introduce the biogeography and BBO. This chapter also will include the BBO general algorithm, BBO algorithm for Economic dispatch problem and BBO algorithm for Unit Commitment problem.

4.2 OVERVIEW OF BIOGEOGRAPHY

Biogeography is the study of distribution of species in Habitats (Islands). Until 1960s biogeography does not have a mathematical model. In the early 1960 Robert MacArthur and Edward Wilson start together the work to develop a mathematical model to biogeography and they succeeded in 1967 as pointed by Simon [8]. Biogeography mathematical model is the bases for developing other new optimization algorithm: Biogeography Based Optimization (BBO). Natural distribution of species in Biogeography is similar to general problem solutions. Suppose that there is a problem with candidate solutions with a quantifiable measure of suitability to each solution. A good solution is considered as Island well suited for species to live in because it has many features. A bad solution is also island but they have limited

features. A well suited island resists the change while limited feature island doesn't. Well suited islands tend to share their features through migration process with limited feature islands without losing their features. The new features which added to the poor solution may raise the quality of those solutions. BBO has feature in common with GA and PSO such as all these algorithm are biologically motivated, population based algorithm, and sharing information between solutions. Hence the application of BBO in engineering is similar to the application of GA and PSO as mentioned by Simon [8].

4.3 BIOGEOGRAPHY BASED OPTIMIZATION

Mathematical models of BBO describe the migration of species from one island to another, how species arise and become extinct. Island in BBO is defined as any habitat that is isolated geographically from other habitats. Well suited habitat for species are said to have high habitat suitability index (HSI) while the habitat that is not well suited is said to have low HSI. Each habitat consists of features (such as rain fall, diversity of vegetation, and land area) that decide the HSI for the habitat. These features are considered as independent variables and called suitability index variables (SIV) which map the value of the HSI of the habitat. High HSI habitat has a large number of species while low HSI habitat has small number of species. High HSI habitat has a high emigration (from the island to the neighboring islands) rate μ and low immigration (from the neighboring islands to the island) rate λ as shown in Figure 6 which represents the model of species abundance in a single habitat. Low HSI habitat has a low emigration rate μ and high immigration rate λ as shown in Figure 6. Emigration of species from one habitat to other habitat does not mean that all the species will disappear from its home, only a few prehensile species emigrate [8].

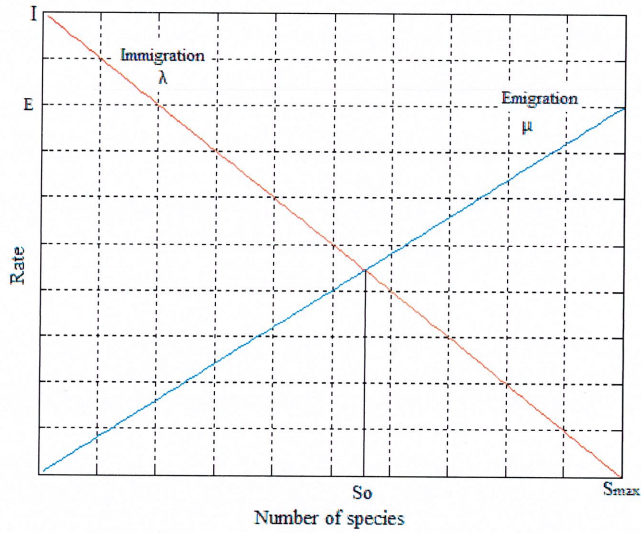


Figure 6 Species model for a single habitat

μ : Emigration rate.

λ : Immigration rate.

E: Maximum emigration rate.

I: Maximum immigration rate.

S_{max} : Maximum number of species.

S_0 : Equilibrium number of species.

In BBO there are two main operations, namely migration and mutation. Migration process may raise the HSI of the habitat. However if the HSI does not rise, the species in that habitat will tend to go extinct due to mutation process and replaced by new species. P_{rs} is the Probability that a habitat contains exactly S species as given in Simon [8].

$$P_{rs}(t + \Delta t) = P_{rs}(t)(1 - \lambda_s \Delta t - \mu_s \Delta t) + P_{rs-1} \lambda_{s-1} \Delta t + P_{rs+1} \mu_{s+1} \Delta t \quad (4.1)$$

In order to have S species at time $(t + \Delta t)$ we should have one of the following:

1. S species at time t and no immigration or emigration occurred between t and $t + \Delta t$.
2. $S-1$ species at time t and one species immigrated.
3. $S+1$ species at time t and one species emigrated.

A useful way to calculate Ps in programs is using the differentiation of Ps as shown in the

$$\frac{dP_{rs}(t)}{dt} \cong \frac{P_{rs}(t + \Delta t) - P_{rs}(t)}{\Delta t}$$

$$= \begin{cases} -(\lambda_s + \mu_s)P_{rs} + P_{rs+1}\mu_{s+1} & S = 0 \\ -(\lambda_s + \mu_s)P_{rs} + P_{rs-1}\lambda_{s-1} + P_{rs+1}\mu_{s+1} & 1 \leq S \leq S_{max} - 1 \\ -(\lambda_s + \mu_s)P_{rs} + P_{rs-1}\lambda_{s-1} & S = S_{max} \end{cases} \quad (4.2)$$

$$P_{rs}(t + \Delta t) = P_{rs}(t) + \frac{dP_{rs}(t)}{dt} \Delta t \quad (4.3)$$

Where $P_{rs}(t + \Delta t)$ is the new probability value that S species is available in the island, $P_{rs}(t)$ is the old value and Δt always set equal to one. From Figure 6 μ and λ can be calculated which are important for BBO algorithm in migration process, mutation process and for HSI calculation.

$$\mu_k = \frac{E k}{n} \quad (4.4)$$

$$\lambda_k = I \left(1 - \frac{k}{n} \right) \quad n = S_{max} \quad (4.5)$$

μ_k : Emigration probability for habitat k.

λ_k : Immigration probability for habitat k.

E: Maximum emigration probability. E=1 in all programs used in this work.

I: Maximum immigration probability. I=1 in all programs used in this work.

k: Island number.

n: Number of islands.

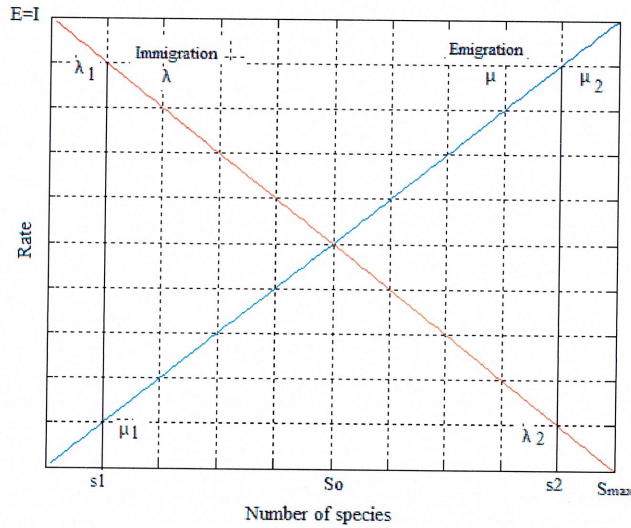


Figure 7 Two candidate solutions S1 and S2 to some problem

BBO concept is mainly based on migration and mutation operations. The basic principle of choosing λ and μ to utilize the selection job is based on Figure 7 (where $E=I$) and we can conclude the following:

1. S_1 is poor solution because the number of species is small which has λ_1 and μ_1 as shown in Figure 7.
2. S_2 is good solution because the number of species is large which has λ_2 and μ_2 as shown in Figure 7.
3. $\lambda_1 > \lambda_2$ which means that as λ increases the solution will be poor and hence we use λ as indication of poor solution.
4. $\mu_2 > \mu_1$ which means that as μ increases the solution will be good and hence we use μ as indication of good solution.

4.3.1 MIGRATION

A process of probabilistically sharing information between habitat using the immigration and emigration rates is known as migration. We modify each solution based on other solutions. In Figure 7, solution S1 represents a low HSI solution since the number of species is small and considered as bad solution while S2 represents a high HSI solution since the number of species is large and considered as good solution. S1 has high immigration rate λ and low emigration rate μ . S2 has low immigration rate λ and high emigration rate μ . Hence high HSI habitat can be selected based on probability which is proportional to the emigration rate μ (high value) and low HSI habitat can be selected based on probability which is proportional to the immigration rate λ (high value). Consider H_i as habitat with low HSI and need to be modified using the migration process and has λ_i and H_x as habitat with high HSI as source of modification with μ_x . In migration operation first H_i (poor habitat) with low HSI is selected to be modified. The selection should be with probability proportional to λ_i . After that H_x with high HSI is selected to be the source of modification. The selection should be with probability proportional to μ_x . Then randomly SIV_m (good feature) is selected from H_x . Finally randomly replace SIV in H_i with SIV_m . The migration algorithm can be described as follows.

Let P_{mod}=constant value such that $0 \leq P_{mod} \leq 1$ where P_{mod} is the probability of modification which decides the process of modification of islands which include the migration and mutation to be implemented or not.
Let h=random number such that $0 \leq h \leq 1$
If $h > P_{mod}$ Go to the next generation without executing the below instructions end usually $P_{mod}=1$ and in all the programs in this work it is either selected to be 1 or not included in the program.
For $i=1$:total number of islands
For $j=1$:number of species (number of variables)
Let x=random number such that $0 \leq x \leq 1$
If $x < \lambda(i)$ where $\lambda(i)$ is immigration probability for habitat i used here to select H_i the habitat required to be modified. Another form can be used such as $x > \lambda(i)$, $x < \lambda$ (constant number) and $x > \lambda$ (constant number). This step will modify almost all the islands but the

best islands (2 or 3) are saved in order to inject them after finishing the migration and mutation process in the islands by replacing the worst islands. i: is the selected island number which will be modified.
Let $y = \text{random number}$ such that $0 \leq y \leq 1$
Select Island=1 initial value for the variable that will determine the number of the island in which it is the source of modification usually it is from the best islands as it is applied here in this work. $1 \leq \text{Select Island} \leq \text{total number of islands}$
$z = y \times \text{total number of island} / k$ where z will decide the number of islands considered as modification source by changing the value of k (k :user define constant).
let $M = \mu(1)$ Initial value for variable used for selecting processes of source of modification island.
While ($z > M$) and ($\text{Select Island} \leq \text{total number of islands}$)
$M = M + \mu(\text{Select Island})$ increase the value of M until the condition in the while loop becomes false.
Select Island = Select Island + 1
end
Let $n = \text{random number}$ such that $0 \leq n \leq 1$ $\text{Species number} = \text{integer}(1 + n \times (\text{number of species} - 1))$ this equation will generate random variable such that $1 \leq \text{Species number} \leq \text{number of species}$.
$H(i, \text{Species number}) = H(\text{Select Island}, \text{Species number})$ this equation will migrate the SIV in source of modification island to the selected island to be modified.
end
end
end

4.3.2 MUTATION

Severely destructive events can extremely change the HSI of a habitat and can cause the species count to deviate from its equilibrium point. In BBO the mutation is modeled as SIV mutation using species count probabilities to determine mutation rate. Very high HSI and very low HSI solutions are likely to be mutated to a different solution using the mutation rate m that is calculated using

$$m(s) = m_{max} \left(1 - \frac{P_{rs}}{P_{rs max}}\right) \quad (4.6)$$

where $m(s)$ is the mutation rate, m_{max} is the maximum mutation rate, P_{rs} is the probability that S species are in a habitat, and $P_{rs max}$ is the maximum probability that S species are in a habitat. This mutation approach which applied to low HSI solutions may improve them to better solutions and applied to high HSI solutions which may improve them to better solutions. The average HSI solutions have a better chance to improve during migration so we avoid mutating them. We use an elitism approach to save the features the best habitat in order not to lose them after the mutation process. Mutation process is a problem dependent and in this thesis two mutation approaches were tested. The first one is simply when a solution is selected for mutation then we replace a randomly chosen SIV in the habitat with a new randomly generated SIV. The second one is replacing randomly the whole habitat as pointed by Simon [8]. The procedure of mutation process is described as follows:

For $i=1$: number of island
Calculate $P_{rs}(t + \Delta t)$ using λ and μ as shown in Equations (4.3). P_{rs} is used to calculate mutation rate $m(s)$.
Calculate $P_{rs max} = \max (P_{rs}(t + \Delta t))$ which is used to calculate mutation rate $m(s)$
Calculate $m(s)$ using Equation (4.6)
end
For $j=\text{total number of island}/2$: total number of island
Let $y=\text{random number}$ such that $0 \leq y \leq 1$
If $y > m(j)$
Replace H_j with randomly generated H_{new} this will replace the bad habitat with new one
end ; end

4.4 GENERAL BBO ALGORITHM

The overall algorithm of BBO can be described as follows.

1. Initialize the BBO parameters such as maximum emigration rate E , maximum immigration rate I , maximum mutation rate, maximum species count $S_{\max}$, modification probability P_{mod} , numerical integration step size Δt , elitism parameter (number of best solutions saved), maximum generation, etc. Find a method of mapping a problem solutions to SIVs and habitats.
2. Generate a random set of habitats that consists of SIVs which represent a candidate feasible solution to the required problem.
3. For each habitat find a function for HSI as function of number of species S , the immigration rate λ , and the emigration rate μ .
4. Probabilistically use immigration rate λ and emigration rate μ to modify each non-elite habitat by using migration process. After that recalculate the HSI for all habitats.
5. For each habitat update the probability of its species count using Equation (4.3). Then mutate each non elite habitat based on its probability using mutation process.
6. Go to step (3) for the next iteration. This loop can be terminated after a predefined number of generations or after an acceptable problem solution has been found.

After the modification of each habitat (steps 2, 4, 5) the feasibility of the habitat as candidate solution should be tested and if it is not feasible then some method needs to be applied to convert it to a feasible solution as mentioned in Simon [8]. Figure 8 present the general (BBO) algorithm.

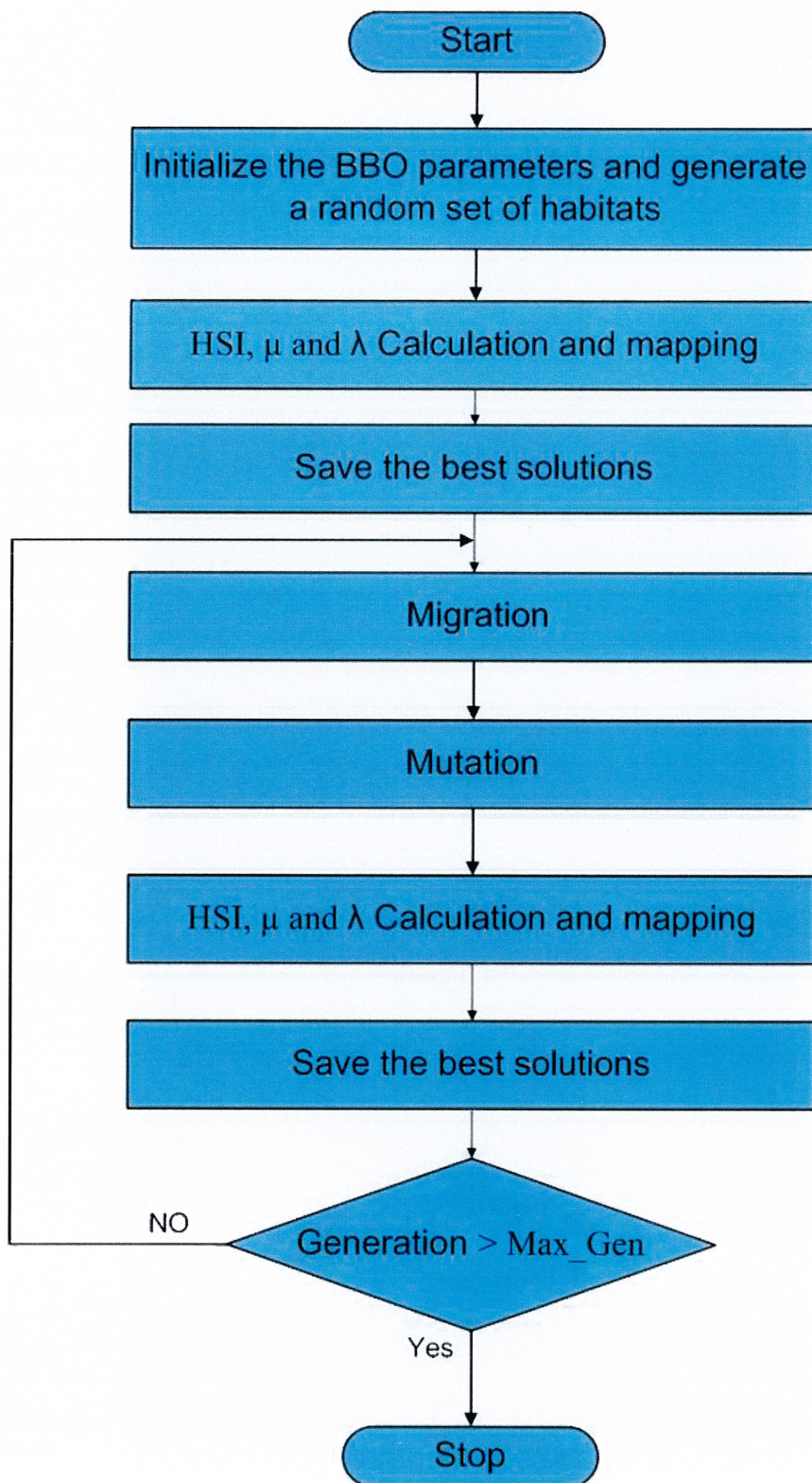


Figure 8 General BBO algorithm

4.5 BBO ALGORITHM FOR ECONOMIC DISPATCH PROBLEM

In the economic dispatch problem each habitat represents a candidate solution consist of SIVs. Each SIV represents the output power generated by a specific generation unit and satisfying its different constrains such as real power generation limit, ramp rate limit, and prohibited operation zones.

The algorithm:

1. Initialize the BBO parameters such as maximum emigration rate E , maximum immigration rate I , maximum mutation rate, maximum species count S_{max} , modification probability P_{mod} , numerical integration step size Δt , elitism parameter, maximum generation ,etc. Find a method of mapping a problem solutions to SIVs and habitats.
2. Generate a random set of habitats that consists of SIVs which represent a candidate output power generation for each unit and satisfy the different economic dispatch constraints required in the problem.
3. Calculate the HSI which is chosen to be the cost of each habitat and calculate μ and λ and map them to the HSI.
4. Save the best solutions based on the HSI value.
5. Probabilistically use λ and μ to modify the non elite habitat using the migration process.
6. Based on species count probability of each habitat mutate the non-elite habitat then go to step (3).
7. After specified number of generations this loop is terminated.

After the modification of each habitat (steps 2, 5, 6) the feasibility of the habitat as candidate solution should be tested and if it is not feasible then some method needs to be applied to convert it to a feasible solution. This is achieved in this work by developing a function in the programs to check the problem constraints such as power generation limits, ramp rate limit and prohibited operation zones. If one of the constraints is violated, this function will adjust the values and convert it to a feasible solution. If one unit violate any constraints new value will be generated to the unit and the difference between the demand load and the generated power will be distributed in iterative way and in each iteration all the

constraints will be checked. Any unit reach any limit will be excluded from this operation. The main objective function used here is shown below and depend upon the test case system other constraints are added such as ramp rate limit and prohibited operating zones.

4.5.1 OBJECTIVE FUNCTION

The objective function for economic dispatch problem can be written as follows:

Minimize $F_t = \sum_{i=1}^N F_i(P_i)$

Where $F_i(P_i) = a_i P_i^2 + b_i P_i + c_i$

Subjected to $\sum_{i=1}^N P_i = P_D + P_L$

$$P_{i \min} \leq P_i \leq P_{i \max}$$

Where $P_L = \sum_{i=1}^N \sum_{j=1}^N P_i B_{ij} P_j + \sum_{i=1}^N B_{oi} P_i + B_{oo}$

This function and the constraints were modified depend upon the test system used. In the case of valve point effect, the cost function is modified by adding valve point effect cost coefficients. Whereas in the case of ramp rate limits and prohibited operation zones the constraints were modified. In the last case the program has a function which ensures that the power value generated satisfies all the constraints in the initialization state and through the execution of the program.

4.5.2 HABITAT SUITABILITY INDEX (HSI) FUNCTION

The HSI function used in the economic dispatch problem is the total fuel cost F_t .

$$HSI = F_t = \sum_{i=1}^N F_i(P_i)$$

Where $F_i(P_i) = a_i P_i^2 + b_i P_i + c_i$

4.6 BBO ALGORITHM FOR UNIT COMMITMENT PROBLEM

In the UC problem of 24 hours horizon, each habitat presents a candidate solution is $(24 \times N)$ matrix of zeros and ones where N represents the generation unit, zeros represent the off Unit and ones represent the committed units. The SIVs are the zeros and ones, based on the load and other UC constraints such as the minimum up time, minimum down time, capacity limits, power reserve and other constraints the SIV are decided. For each hour the economic dispatch is applied and the optimum solution is selected.

The algorithm:

1. Initialize the BBO parameters such as maximum emigration rate E , maximum immigration rate I , maximum mutation rate, maximum species count $S_{\max}$, modification probability P_{mod} , numerical integration step size Δt , elitism parameter, maximum generation ,etc. Find a method of mapping a problem solutions to SIVs and habitats.
2. Generate a random set of habitats that satisfy the demand load constraints required in the problem for the 24 hours.
3. Calculate the HSI for each habitat then calculate μ and λ and map them to the HSI. The fuel cost is calculated using lambda iteration method.
4. Save the best solutions based on the HSI value.
5. Probabilistically use λ and μ to modify the non elite habitat using the migration process.
6. Based on species count probability of each habitat mutate the non-elite habitat then go to step (3).
7. After specified number of generations this loop is terminated.

After the modification of each habitat (steps 2,5,6) the feasibility of the habitat as a candidate solution should be tested and if it is not feasible then some method needs to be applied to convert it to a feasible solution. This method simply search the source of infeasibility in the ON/OFF schedule (Island) and change the state value in order to convert the solution to feasible solution. In order to reduce the unfeasible solutions, it is insured that SIV_x at time t migrate to SIV_y at the same time in the other island in the migration process from one island to another. Also at generation process the method used is that the same state of unit operation at time t will add or remove unit if needed due to demand load and spinning reserve requirement which will contribute in reducing the violations in the minimum up or down of generation units. The economic dispatch constraints checked and adjusted in the function which calculates the fuel cost using lambda iteration method.

4.6.1 OBJECTIVE FUNCTION

The objective function for N generation units that will feed the demand load over a time horizon consisting of T periods (usually hours) can be written as follows:

Minimize
$$C = \sum_{i=1}^T \sum_{j=1}^N [F(P_j(i)) + SC_j(i)]$$

where $F(P_j(i))$ is the fuel cost of generator j at time i .

$$F(P_j(i)) = a_j P_j^2(i) + b_j P_j(i) + c_j$$

and $SC_j(i)$ is the start up cost for generator j at time i .

$$SC_j(i) = \begin{cases} C_{hot} & , Toff_j \leq t_{j_down} + t_{j_cold} \\ C_{cold} & , Toff_i > t_{j_down} + t_{j_cold} \end{cases}$$

Subjected to constraints:

a) Total demand

$$\sum_{i=1}^N P_i = P_D$$

b) Power generation limits

$$P_{i_min} \leq P_i \leq P_{i_max}$$

c) Spinning reserve

$$\sum_{i=1}^N P_i^{max} \geq P_D + P_R$$

d) Minimum up/down limits

$$T_{i\ ON} \geq T_{up}$$

$$T_{i\ OFF} \geq T_{down}$$

4.6.2 HABITAT SUITABILITY INDEX (HSI) FUNCTION

Minimum up and down time violation are penalized through a penalty factor and added to the objective function to form the HSI function (fitness function). Other constraints such as spinning reserve, total load demand and power generation limits constraints are adjusted in the program at the initialization state and throughout the execution of the algorithm. HSI function of a solution I (an island) can be written as follows:

$$HSI(I) = Total\ fuel\ cost(I) + start\ up\ cost\ (I) + \\ Penalty\ (I)$$

$$HSI(I) = C(I) + Penalty\ (I)$$

Where

$$C = \sum_{i=1}^T \sum_{j=1}^N [F(P_j(i)) + SC_j(i)]$$

$$Penalty\ (I) = k \times MUD(I)$$

Penalty(I): Penalty function for island I.

k : Penalty factor (the value of k depend on the test system).

MUD: Total number minimum up/down violations.

CHAPTER 5

5 RESULTS AND DISCUSSION

5.1 INTRODUCTION

In this chapter, the results of Economic dispatch and unit commitment after the implementation of the proposed BBO method are discussed. This chapter is divided into two sections; the first section discusses the results generated from economic dispatch of five different cases. These are a three generators system with quadratic cost function and with valve-point loading effects, a six generators system with prohibited operating zones and ramp rate limits and transmission loss, a thirteen generators system with valve-point loading effects without transmission loss, a fifteen generators system with prohibited operating zones and ramp rate limits and transmission loss, and a forty generators system with valve-point loading effects without transmission loss. While the next section discusses the results generated from unit commitment of five different cases. These are a three generators system, four generators system, ten generators system, twenty generators system and forty generators system with quadratic cost function with specified power demand plus spinning reserve.

5.2 ECONOMIC DISPATCH RESULTS

For all the economic dispatch test cases the software was written in MATLAB-7.5 and executed on a 3.06 GHz Intel® Core™ i3 CPU 540 personal computer with 4GB RAM.

5.2.1 TEST CASE 1

Test case 1 consists of three generating units with quadratic cost functions and the effects of valve-point loadings as given in Table 20 in appendix A. Table 20 contains the unit characteristics of cost coefficients, and generators operating limits which are taken from Sinha et al. [23]. BBO parameters: generation=150, island = 300, integration probability step size $\Delta t = 1$, and maximum mutation probability = 0.007. The result obtained using the proposed algorithm are shown in Table 1, and compared with GA and PSO given in Simon et al. [24]. It is mentioned in Simon et al. [24] that the optimal solution for this system is 8234.07 \$/h. Hence the proposed algorithm succeeds in finding the optimum value. Figure 9 shows the cost vs. generation curve which clearly shows the convergence behavior of the algorithm. Table 2 shows the minimum, maximum and average cost obtained out of 50 runs for the proposed algorithm.

Table 1 Comparison results for test case1 with Load=850MW

Unit	BBO	GA [24]	PSO [24]
	Power	Power	Power
1	300.2829	299.100	300.268
2	149.7377	150.800	149.732
3	399.9794	399.00	400.00
Total Power(MW)	850	850	850
Total Cost(\$/hr)	8234.0777	8239.20	8234.72
Time(sec)	26.239785	-	-

Table 2 minimum, maximum and average cost for 50 trials

TRIALS	Minimum Cost	Average cost	Maximum cost
50	8234.073	8234.1215	8235.0669

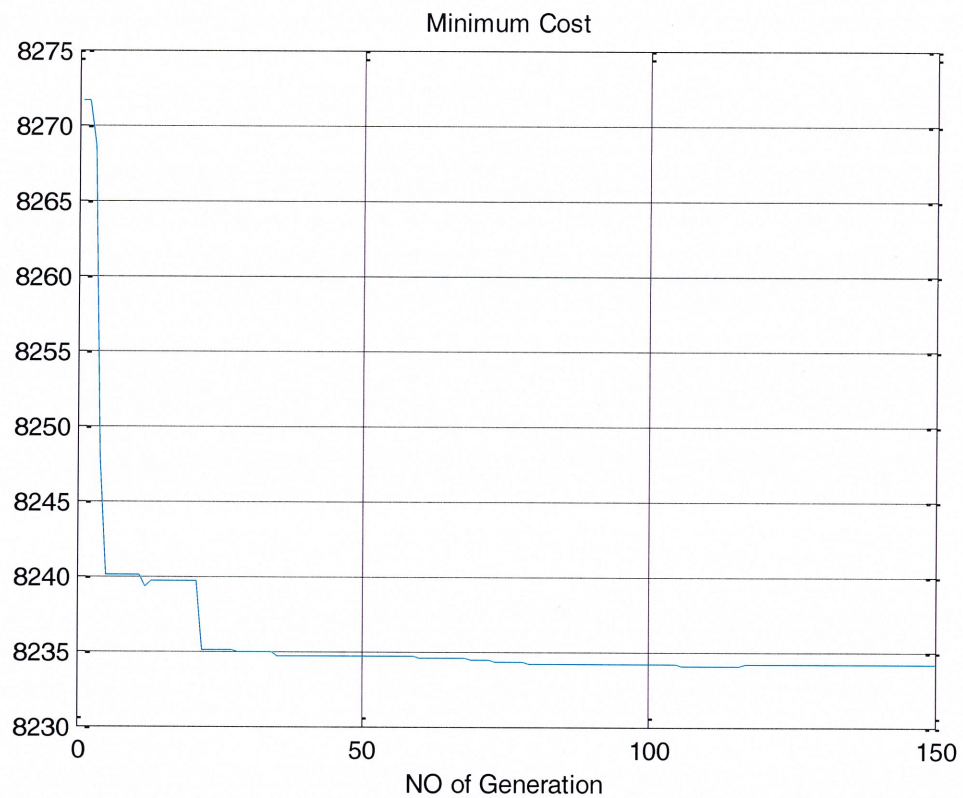


Figure 9 Cost vs. number of generations curve for test system 1

5.2.2 TEST CASE 2

This test system consists of 6 generation units with quadratic cost functions, transmission losses, ramp rates limits and prohibited operating zones of these thermal units. Table 21 in appendix A contains the unit characteristics of cost coefficients, and generators operating limits which are taken from Gaing [5]. BBO parameters: generation=100, island = 60, integration probability step size $\Delta t = 1$, and mutation probability = 0.005. Table 3 lists the optimum result obtained using the proposed algorithm and also shows the results obtained using GA and PSO as given in Gaing [5]. Table 3 also lists the results obtained using SOH_PSO and New MPSO as given in Bhattacharya and Chattopadhyay [19]. Obviously, the minimum total cost generated by the proposed algorithm is lower than that obtained using GA, PSO, SOH_PSO and New MPSO [19]. Table 4 shows the minimum, mean and the maximum cost acquired by the proposed algorithm obtained out of 50 runs of the program. Figure 10 shows the convergence characteristics of the 6-generator system using the BBO algorithm.

Table 3 Comparison results for test case 2 with Load=1263MW

Unit	BBO	GA [5]	PSO [5]	SOH_PSO [19]	New MPSO [19]
	Power	Power	Power	Power	Power
1	447.8362	474.8066	447.497	438.21	446.71
2	172.6412	178.6363	173.3221	172.58	173.01
3	263.8161	262.2089	263.4745	257.42	265
4	139.0640	134.2826	139.0594	141.09	139
5	165.0392	151.9039	165.4761	179.37	165.23
6	87.0456	74.1812	87.1280	86.88	86.78
Total Power(MW)	1275.4423	1276.03	1276.01	1275.55	1275.73
P_{loss} (MW)	12.4423	13.0217	12.9584	12.55	12.733
Total Cost(\$/hr)	15443.083	15459	15450	15446.02	15,447
Time(sec)	22.837647	-	-	-	-

Table 4 minimum, maximum and average cost for 50 trials

TRIALS	Minimum Cost	Average cost	Maximum cost
50	15443.083	15443.2813	15443.8918

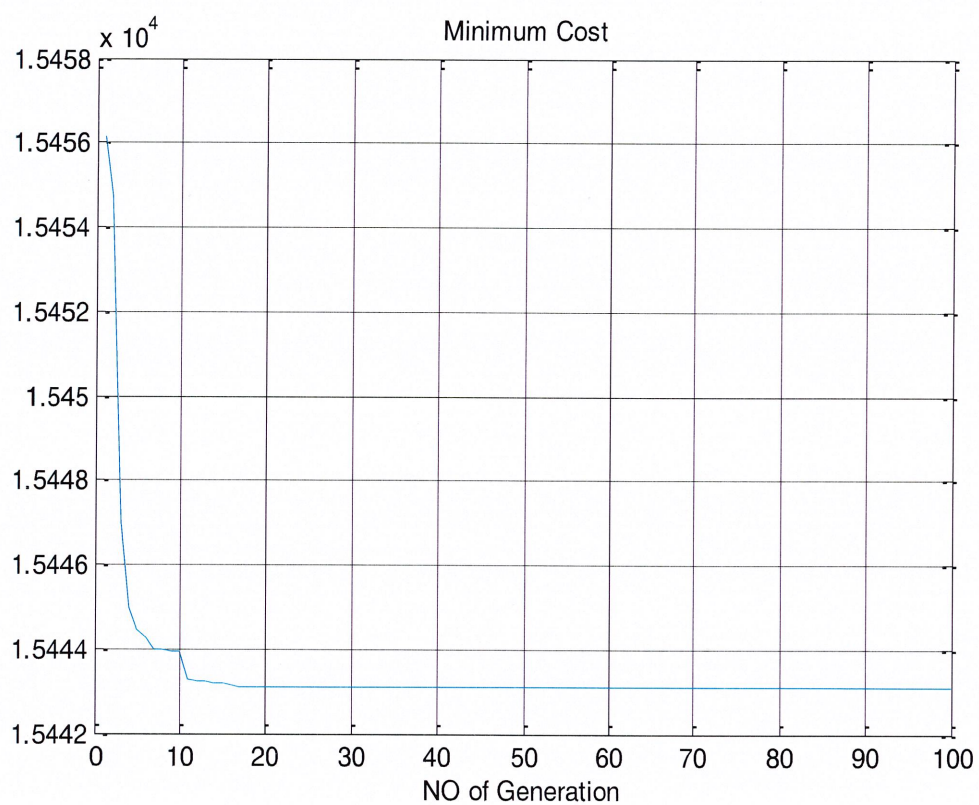


Figure 10 Cost vs. number of generations curve for six units system

5.2.3 TEST CASE 3

Test case 3 consists of thirteen generating units with quadratic cost function and the effects of valve-point loadings as given in Table 22. This Table contains the unit characteristics like cost coefficients, and generators operating limits which are taken from Sinha et al. [23]. BBO parameters: generation=100, island = 50, integration probability step size $\Delta t = 1$, and mutation probability = 0.009. Table 5 shows the results of the applied algorithm and the results using FAPSO-NM given in Akhtar et al. [25], FAPSO-VDE given in Niknam et al. [26], and PSO given in Chen and Yeh [27]. It is obvious that the cost generated by the proposed algorithm is better than the PSO and almost equal to the results in the other two techniques. The convergence characteristics of the 13-generation unit system using BBO is shown in Figure 11. Table 6 shows the minimum, mean and maximum cost for the proposed algorithm obtained out of 50 runs of the program.

Table 5 Comparison results for test case 2 with Load=1800MW

Unit	BBO	FAPSO-NM [25]	FAPSO-VDE [26]	PSO [27]
	Power	Power	Power	Power
1	627.4094	628.32	628.3185	538.561
2	223.9911	222.75	227.749	299.355
3	149.4163	149.6	149.599	75.037
4	60.0000	109.87	60	159.734
5	109.7842	109.87	109.8665	60.078
6	109.8296	109.87	109.8665	109.864
7	109.8499	109.87	109.8665	109.913
8	109.8591	60	109.8665	159.753
9	109.8632	109.87	109.8665	60.069
10	40.0000	40	40	40.035
11	40.0000	40	40	77.561
12	55.0000	55	55	55.042
13	55.0000	55	55	55.00
Total Power(MW)	1800.0027	1800	1800	1800
Total Cost(\$/hr)	17965.8098	17963.84	17963.82	18014.16
Time(sec)	6.63	~6.8	~4.1	-

Table 6 minimum, maximum and average cost for 50 trials

TRIALS	Minimum Cost	Average cost	Maximum cost
50	17965.8098	17969.9618	17979.2198

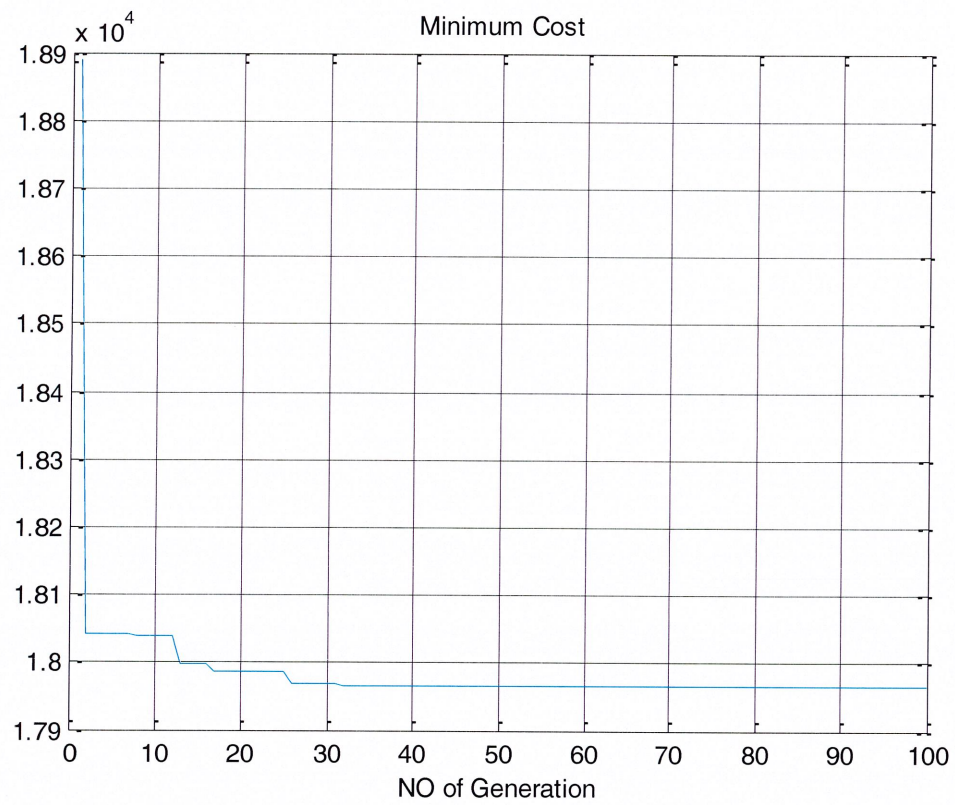


Figure 11 Cost vs. number of generations curve for thirteen units system

5.2.4 TEST CASE 4

This test system consists of fifteen generating units with quadratic cost function, transmission losses, ramp rate limits and prohibited operating zones of these thermal units. Table 23 contains the unit characteristics like cost coefficients, and generators operating limits which are taken from Gaing [5]. BBO parameters: generation=100, island = 90, integration probability step size $\Delta t = 1$, and mutation probability = 0.007. Table 7 lists the optimum results obtained using the proposed algorithm and also shows the results obtained using GA and PSO given in Gaing [5]. It is obvious that, the minimum total cost generated by the proposed algorithm is lower than that obtained using GA and PSO. Table 8 shows the minimum, average and the maximum cost generated by the proposed algorithm result from 50 runs of the program. Figure 12 shows the convergence characteristics of the 15-generator system using the BBO algorithm.

Table 7 Comparison results for test case 2 with Load=2630MW

Unit	BBO	GA [5]	PSO [5]
	Power	Power	Power
1	455.0000	415.3108	439.1162
2	380.0000	359.7206	407.9727
3	130.0000	104.4250	119.6324
4	130.0000	74.9853	129.9925
5	170.0000	380.2844	151.0681
6	460.0000	426.7902	459.9978
7	430.0000	341.3164	425.5601
8	132.9000	124.7867	98.5699
9	80.2745	133.1445	113.4936
10	79.9471	89.2567	101.1142
11	77.7728	60.0572	33.9116
12	78.5762	49.9998	79.9583
13	25.3010	38.7713	25.0042
14	16.0175	41.9425	41.4140
15	15.0343	22.6445	35.6140
Total Power(MW)	2660.8234	2668.4	2662.4
P_{loss} (MW)	30.8234	38.2782	32.4306
Total Cost(\$/hr)	32715.2037	33113	32858
Time(sec)	84.201066	-	-

Table 8 minimum, maximum and average cost for 50 trials

TRIALS	Minimum Cost	Average cost	Maximum cost
50	32715.2037	32727.5982	32744.2581

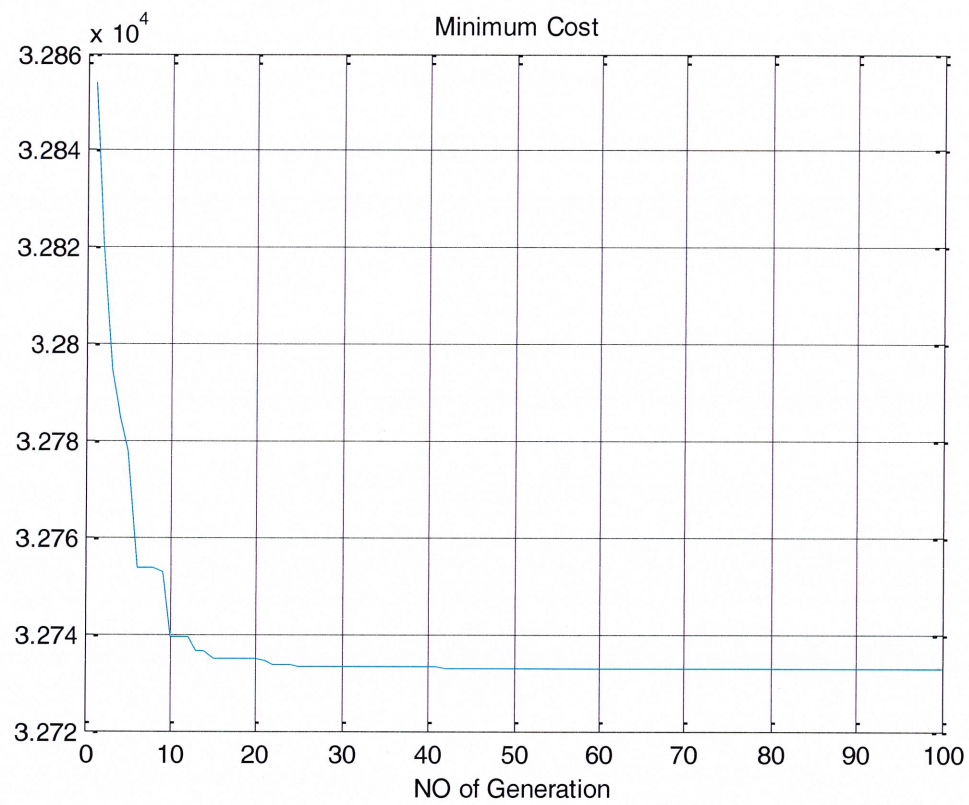


Figure 12 Cost vs. number of generations curve for test fifteen units system

There are forty generating units with quadratic cost function, cost function and the effects of valve-point loadings as given in Table 24 of these thermal units without transmission losses. Table 24 contains the unit characteristics like cost coefficients, and generators operating limits which are taken from Sinha et al. [23]. BBO parameters: generation=100, island = 500, integration probability step size $\Delta t = 1$, and mutation probability = 0.007. Table 9 shows the results of the applied algorithm, the results using PSO algorithm given in Chen and Yeh [27] and the results using FAPSO-NM given in Akhtar et al. [25]. It is obvious that the generated cost by the proposed algorithm is better than the PSO and close to the results of FAPSO-NM. The convergence characteristics of the 40-generation unit system using BBO is shown in Figure 13. Table 10 shows the minimum, mean and maximum cost for the proposed algorithm obtained out of 50 runs of the program.

Unit	BBO	PSO [27]	FAPSO-NM [25]
1	110.7998	113.116	111.38
2	110.7998	113.01	110.93
3	97.3999	119.702	97.41
4	179.7331	81.647	179.33
5	87.7999	95.062	89.22
6	140	139.209	140
7	259.5997	299.127	259.62
8	284.5997	287.491	284.66
9	284.5997	292.316	284.66
10	204.7998	279.273	130
11	170.699	169.766	168.82
12	95.1717	94.344	168.82
13	125.7229	214.871	214.75
14	394.7254	304.79	394.28
15	394.5545	304.563	304.54
16	394.4491	304.302	394.3
17	489.2794	489.173	489.29
18	489.2794	491.336	489.29
19	511.3841	510.88	511.28
20	511.344	511.474	511.29

Unit	BBO	PSO [27]	FAPSO-NM [25]
20	511.344	511.474	511.29
21	523.3192	524.814	523.33
22	523.304	524.775	523.48
23	523.2945	525.563	523.33
24	523.2887	522.712	523.33
25	523.2851	503.211	523.33
26	523.2829	524.199	523.33
27	10	10.082	10
28	10	10.663	10
29	10.0035	10.418	10
30	87.7999	94.244	88.7
31	190	189.377	190
32	190	189.796	190
33	190	189.813	190
4	164.7998	199.797	165
35	164.7998	199.284	166
36	164.7998	198.165	165
37	110	109.291	110
38	110	109.087	110
39	110	109.909	110
40	511.2816	512.348	511.3
Total Power(MW)	10500	10500	10500
Total Cost(\$/hr)	121510.849	122323.97	121418.3

Table 9 Comparison results for test case 2 with Load=10500MW

Table 10 minimum, maximum and average cost for 50 trials

TRIALS	Minimum Cost	Average cost	Maximum cost
50	121510.7684	121749.179	121899.6994

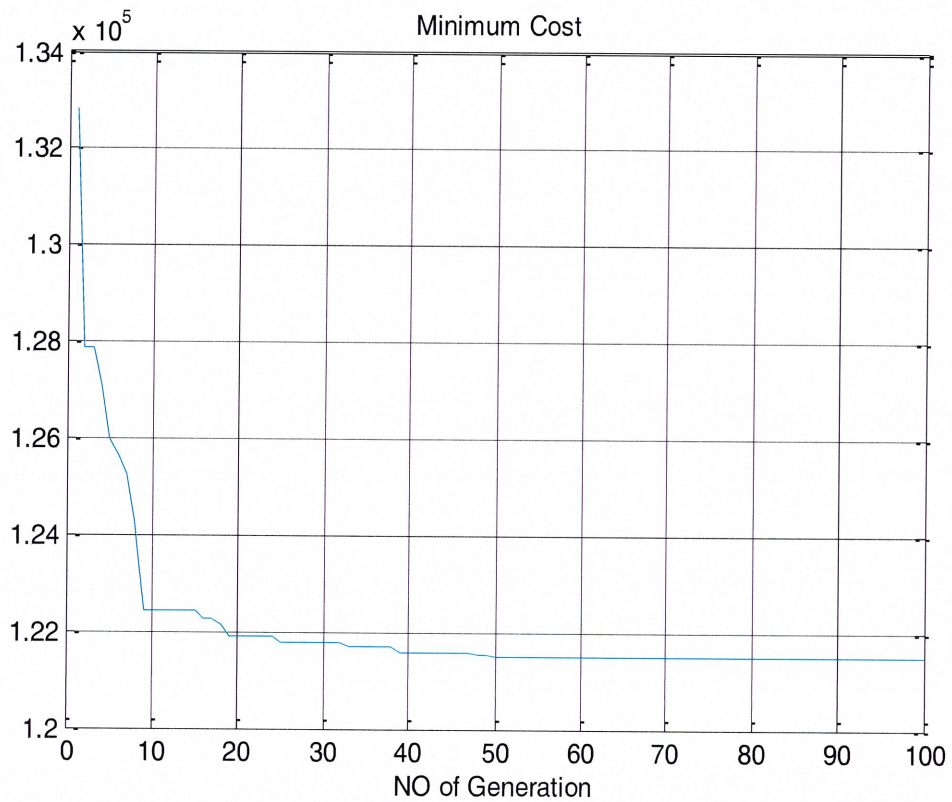


Figure 13 Cost vs. number of generations curve for test system 5

5.3 UNIT COMMITMENT RESULTS

For all the unit commitment test cases the software was written in MATLAB-7.5 language and executed on a 3.06 GHz Intel® Core™ i3 CPU 540 personal computer with 4GB RAM.

5.3.1 TEST CASE 1

A 3_unit system is selected as a test system. System data and load demand are given in Tables 25 and 26 taken from Puri [28]. The spinning reserve is not considered in this case. The proposed BBO method parameters: generation=200, island =50, integration probability step size $\Delta t = 1$, and mutation probability = 0.005. The results obtained using the proposed algorithm are shown in Table 11. Table 12 shows the minimum costs obtained by the proposed algorithm, dynamic programming (DP) and PSO algorithm given in Puri [28]. Obviously the proposed algorithm generates the minimum cost among the three costs. Figure 14 shows the convergence of the HSI function while Figure 15 shows the cost vs. no of generations curve for the three units system.

Table 11 Result of 3-units system using BBO

Hours	Unit commitment	Unit		
		1	2	3
1	1 1 1	600	400	200
2	1 1 1	600	400	150
3	1 1 1	600	400	100
4	1 1 1	600	400	50
5	1 1 1	550	400	50
6	1 1 1	500	400	50
7	1 1 1	460.8795	389.1205	50
8	1 1 1	433.181	366.819	50
9	1 1 1	405.4826	344.5174	50
10	1 1 0	405.4826	344.5174	0
11	1 1 0	377.7841	322.2159	0
12	1 1 0	350.0857	299.9143	0
13	1 0 0	600	0	0
14	1 0 1	500	0	50
15	1 0 1	450	0	50
Fuel cost	124367.0862\$			
Startup cost	650\$			
Total cost	125017.0862\$			
Time(sec)	34.976224			

Table 12 Minimum cost for BBO, DP and PSO.

Method	Minimum Cost
BBO	125017.0862
DP [28]	128832.41
PSO [28]	126027.6111

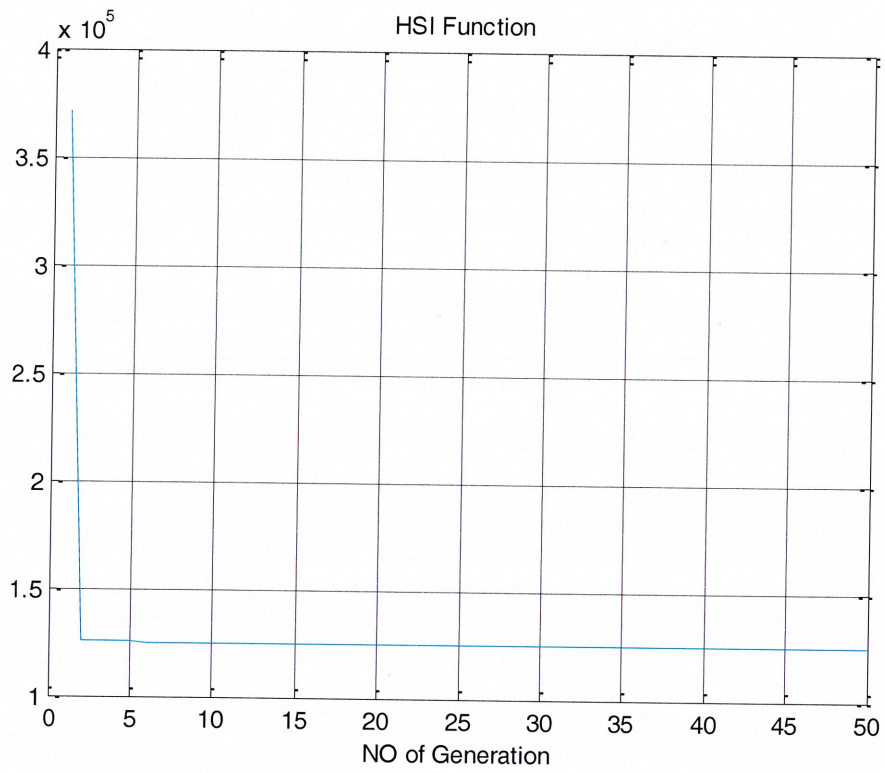


Figure 14 HSI Function vs. No of Generations for three units system

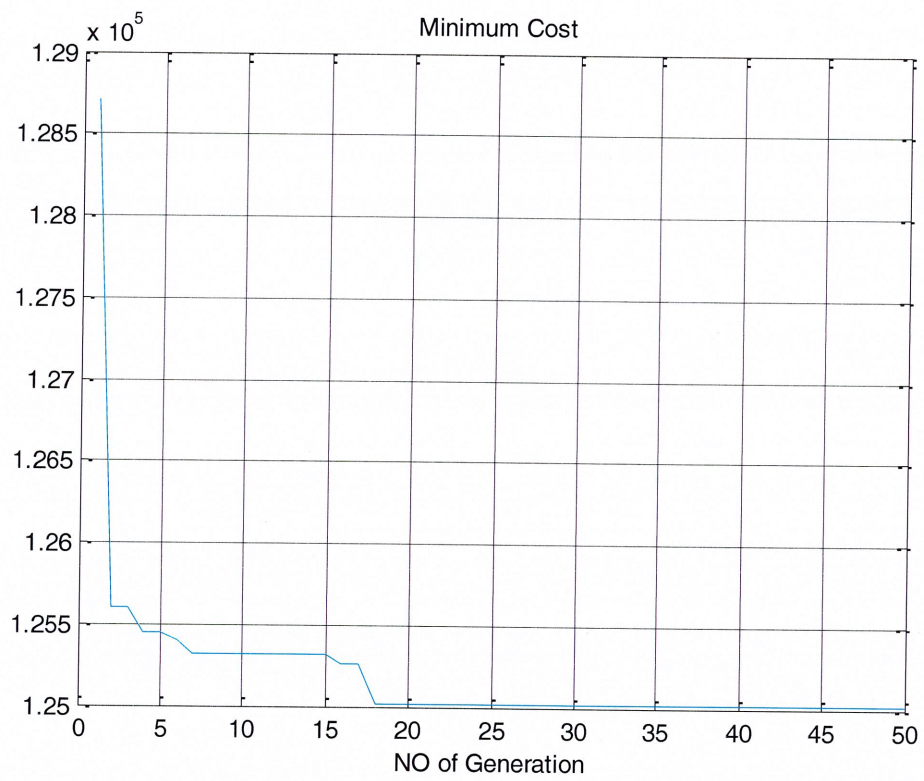


Figure 15 Cost vs. No of Generations curve for Test case 1

5.3.2 TEST CASE 2

A 4-unit system is selected as a test system. System data and load demand are given in Tables 27 and 28 taken from Khanmohammadi et al. [29]. The spinning reserve is assumed to be 10% of the demand. The proposed BBO method parameters: generation=200, island = 50, integration probability step size $\Delta t = 1$, and mutation probability = 0.005. Table 13 lists the optimum results obtained using the proposed algorithm. Table 14 shows the optimal costs for the proposed algorithm, LR algorithm, PSO-LR algorithm, B.SMP algorithm, and A.SMP algorithm as given in Khanmohammadi et al. [29]. It is obvious that, the minimum total cost generated by the proposed algorithm is lower than that obtained using other algorithms. Figure 16 shows the convergence of the HSI function while Figure 17 shows the cost vs. number of generations for the four generator system using the BBO algorithm.

Table 13 Result of 4-units system using BBO

Hours	Unit commitment	Unit			
		1	2	3	4
1	1 1 0 0	300	150	0	0
2	1 1 1 0	300	205	25	0
3	1 1 1 1	300	250	30	20
4	1 1 1 0	300	215	25	0
5	1 1 0 0	276.1905	123.8095	0	0
6	1 1 0 0	196.1905	83.80952	0	0
7	1 1 0 0	202.8571	87.14286	0	0
8	1 1 0 0	300	200	0	0
Fuel cost	73866.02357\$				
Startup cost	150.0200\$				
Total cost	74016.04357\$				
Time(sec)	84.669692				

Table 14 Minimum cost for BBO, LR, PSO-LR, B.SMP, and A.SMP.

Method	Minimum Cost
BBO	74016.04357
LR [29]	75232
PSO-LR [29]	74808
B.SMP [29]	74812
A.SMP [29]	74812

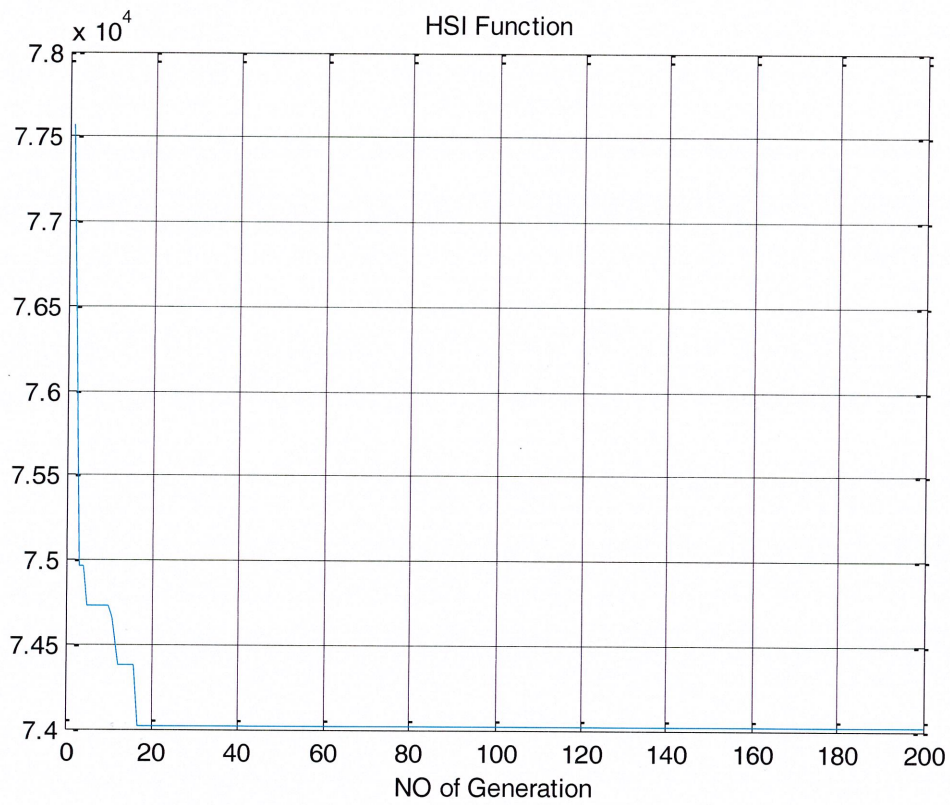


Figure 16 HSI Function vs. No of Generations for Test case 2

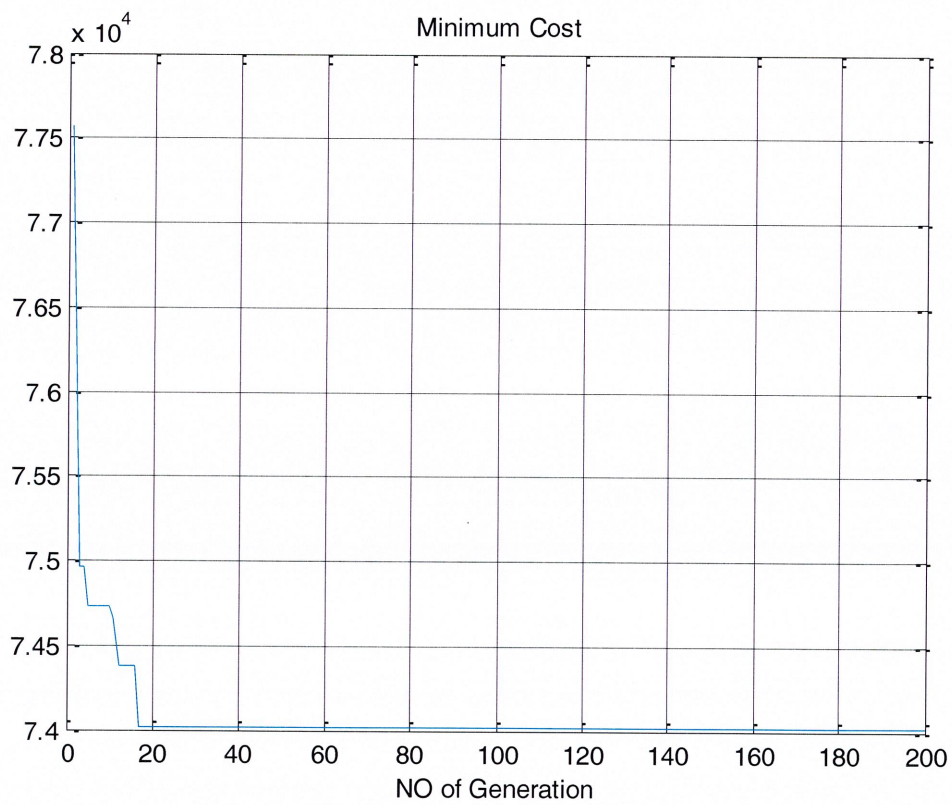


Figure 17 Cost vs. No of Generations curve for Test case 2

5.3.3 TEST CASE 3

A 10-unit system given in Khanmohammadi et al. [29] is selected as a test system. System data and load demand are given in Tables 29 and 30. The spinning reserve is assumed to be 10% of the demand. The proposed BBO method parameters: generation=100, island = 150, integration probability step size $\Delta t = 1$, and mutation probability = 0.009. Table 16 and Table17 list the optimum results obtained using the proposed algorithm.

Table 15 shows the minimum costs obtained by the proposed algorithm, LR algorithm, DP algorithm, and GA algorithm given in Khanmohammadi et al. [29]. Obviously the proposed algorithm generates the minimum cost among the six costs. Figure 18 shows the convergence characteristics of the HSI function while Figure 19 shows the cost vs. no of generations curve for the ten units system.

Table 15 Minimum cost for BBO, LR, DP and GA.

Method	Minimum Cost
BBO	563150.4125
LR [29]	565,825
DP [29]	565,825
GA [29]	565,852
B.SMP [29]	564,017.73
A.SMP [29]	563,937.26

Table 16 Result of 10-units system using BBO

Hours	Unit commitment										Fuel cost (\$)	Start up cost(\$)
1	1	1	0	0	0	0	0	0	0	0	13683.13	0
2	1	1	0	0	0	0	0	0	0	0	14554.5	0
3	1	1	0	1	0	0	0	0	0	0	16892.15	560
4	1	1	1	1	0	0	0	0	0	0	19261.5	550
5	1	1	1	1	0	0	0	0	0	0	20132.56	0
6	1	1	1	1	0	0	0	1	0	0	22623.99	30
7	1	1	1	1	1	0	0	0	0	0	23261.98	900
8	1	1	1	1	1	0	0	0	0	0	24150.34	0
9	1	1	1	1	1	0	1	0	1	0	27575.09	290
10	1	1	1	1	1	1	1	0	1	0	30075.86	170
11	1	1	1	1	1	1	1	1	1	0	31219.63	30
12	1	1	1	1	1	1	1	1	1	1	33890.16	30
13	1	1	1	1	1	1	0	1	1	1	30057.55	0
14	1	1	1	1	1	1	0	1	0	0	27251.06	0
15	1	1	1	1	1	0	0	0	0	0	25079.33	0
16	1	1	1	1	1	0	0	0	0	0	20895.88	0
17	1	1	1	1	1	0	0	0	0	0	20020.02	0
18	1	1	1	1	1	0	0	0	0	0	22606.98	0
19	1	1	1	1	1	0	0	0	0	0	24150.34	0
20	1	1	1	1	1	1	0	1	1	1	30057.55	260
21	1	1	1	1	1	1	0	0	1	0	27251.06	0
22	1	1	1	0	0	1	0	1	1	0	22387.04	30
23	1	1	0	0	0	1	0	1	0	0	17795.28	0
24	1	1	0	0	0	0	0	0	0	0	15427.42	0
Total cost=563150.4125\$											560300.4125\$	2850\$

Table 17 Result of 10-units system using BBO

Hours	Units									
	1	2	3	4	5	6	7	8	9	10
1	455	245	0	0	0	0	0	0	0	0
2	455	295	0	0	0	0	0	0	0	0
3	455	265	0	130	0	0	0	0	0	0
4	455	235	130	130	0	0	0	0	0	0
5	455	285	130	130	0	0	0	0	0	0
6	455	375	130	130	0	0	0	10	0	0
7	455	410	130	130	25	0	0	0	0	0
8	455	455	130	130	30	0	0	0	0	0
9	455	455	130	130	95	0	25	0	10	0
10	455	455	130	130	162	33	25	0	10	0
11	455	455	130	130	162	80	25	13	0	0
12	455	455	130	130	162	80	25	43	10	10
13	455	455	130	130	162	38	0	10	10	10
14	455	455	130	130	100	20	0	10	0	0
15	455	455	130	130	30	0	0	0	0	0
16	455	310	130	130	25	0	0	0	0	0
17	455	260	130	130	25	0	0	0	0	0
18	455	360	130	130	25	0	0	0	0	0
19	455	455	130	130	30	0	0	0	0	0
20	455	455	130	130	162	38	0	10	10	10
21	455	455	130	130	100	20	0	0	10	0
22	455	455	130	0	0	40	0	10	10	0
23	455	415	0	0	0	20	0	10	0	0
24	455	345	0	0	0	0	0	0	0	0
Fuel cost	560300.4125\$									
Startup cost	2850\$									
Total cost (\$)	563150.4125\$									
Time (sec)	91.872417									

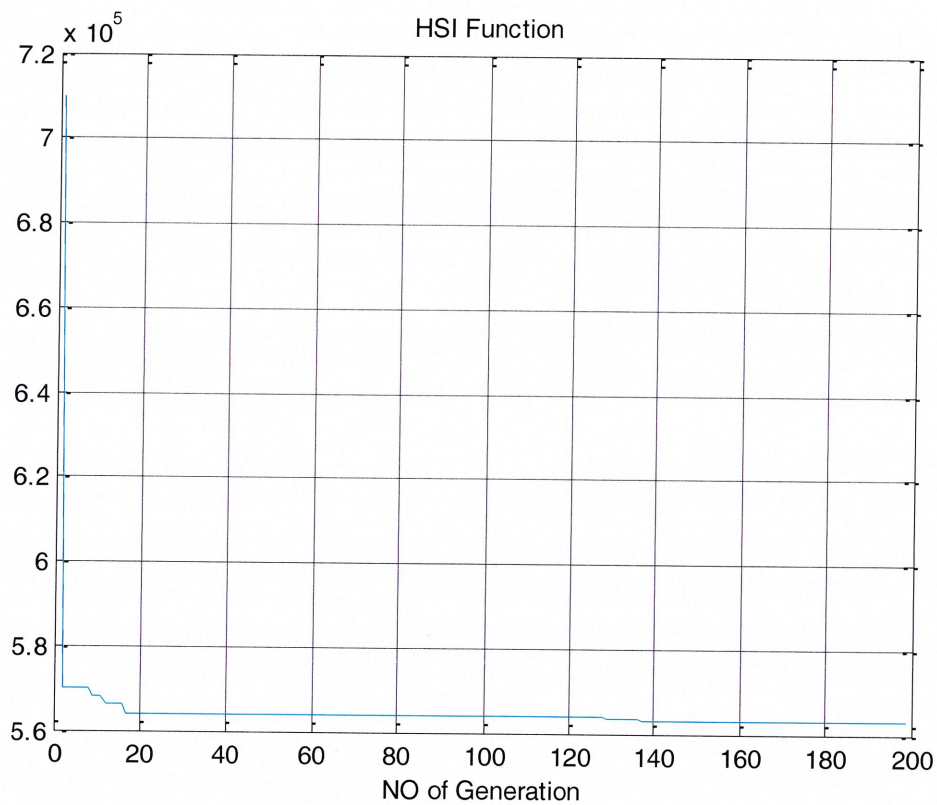


Figure 18 HSI Function vs. No of Generations for Ten units system

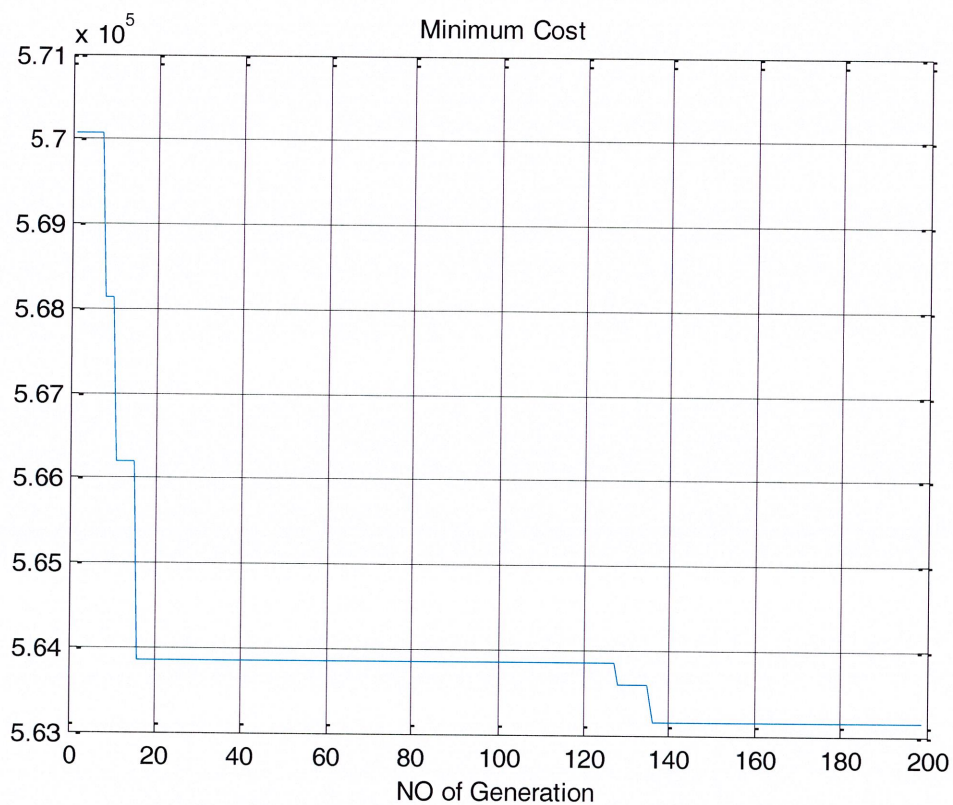


Figure 19 Cost vs. No of Generations for Ten units system

5.3.4 TEST CASE 4

A twenty unit system is selected as a test system. System data was repeated for the test case 3 and the load demands are doubled. The spinning reserve is assumed to be 10% of the demand. The proposed BBO method parameters: generation=100, island = 200, integration probability step size $\Delta t = 1$, and mutation probability = 0.009. Table 18 presents the results obtained by applying the BBO algorithm on the twenty units system. Figure 20 shows the convergence characteristics of the BBO on the HSI function. Figure 21 shows the cost vs. no of generations curve for the twenty units system. It is clear that the total cost in this case is approximately the double of the ten units' system case.

Table 18 Result of 20-units system using BBO

Hours	Unit commitment	Fuel cost (\$)	Start up cost(\$)
1	1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	27366.2595	0
2	1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	29108.9995	0
3	1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0	33348.359	30
4	1 1 1 1 0 0 0 0 0 0 0 0 0 0 1 1 0 1 1 1	40161.83	120
5	1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0	39673.853	1660
6	1 1 1 1 1 1 1 1 0 0 0 0 0 0 1 1 0 0 0 0	45247.9755	620
7	1 1 1 1 1 1 1 1 1 0 0 0 0 0 0 1 0 0 0 0	46761.33237	900
8	1 1 1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0	48300.6815	900
9	1 1 1 1 1 1 1 1 1 1 1 1 0 0 0 1 0 0 0 0	53891.9855	370
10	1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 1 1 0 0 0	60133.4096	550
11	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0	62407.21271	60
12	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	67345.60913	60
13	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0 0 0	60115.1006	0
14	1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0 0 0 0 0	54502.112	0
15	1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0 0 0 0 0	50683.2	0
16	1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0 0 0 0 0	45441.96	0
17	1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0 0 0 0 0	43701.08	0
18	1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0 0 0 0 0	47185.94	0
19	1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0 0 0 0 0	50683.2	0
20	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0 0 0 0	60115.1006	60
21	1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0 0 0 0 0	54502.112	0
22	1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0	44266.27838	0
23	1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0	35590.5635	0
24	1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	30854.8395	0
Total cost= 1136718.9939\$		1131388.994\$	5330\$

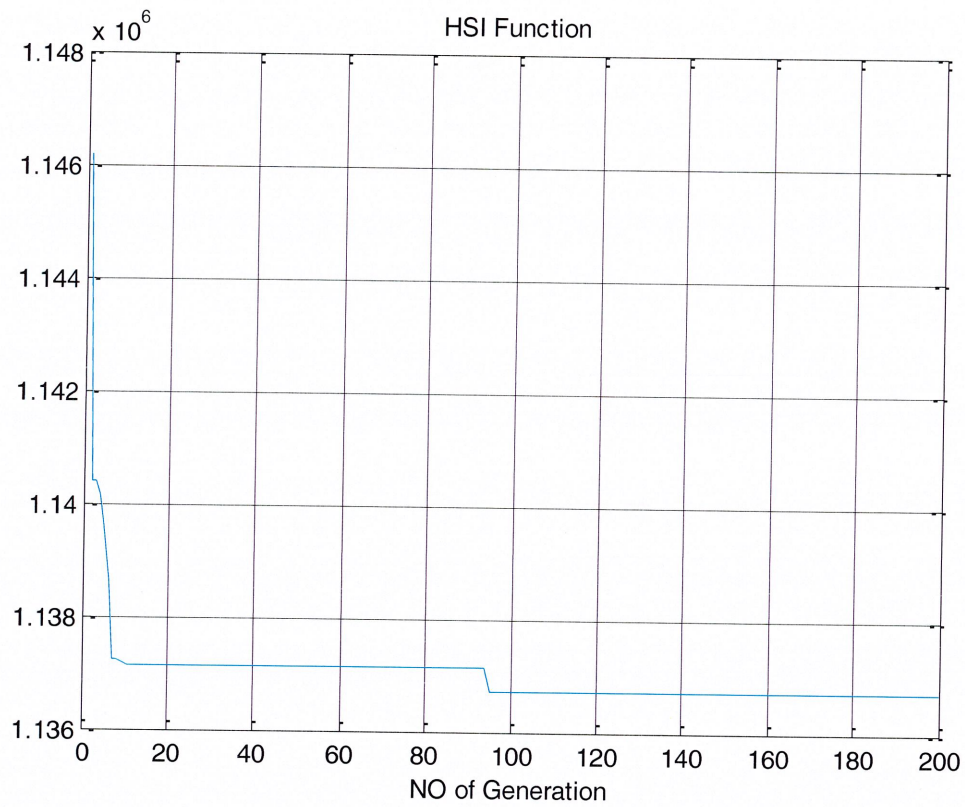


Figure 20 HSI Function vs. No of Generations for twenty units system

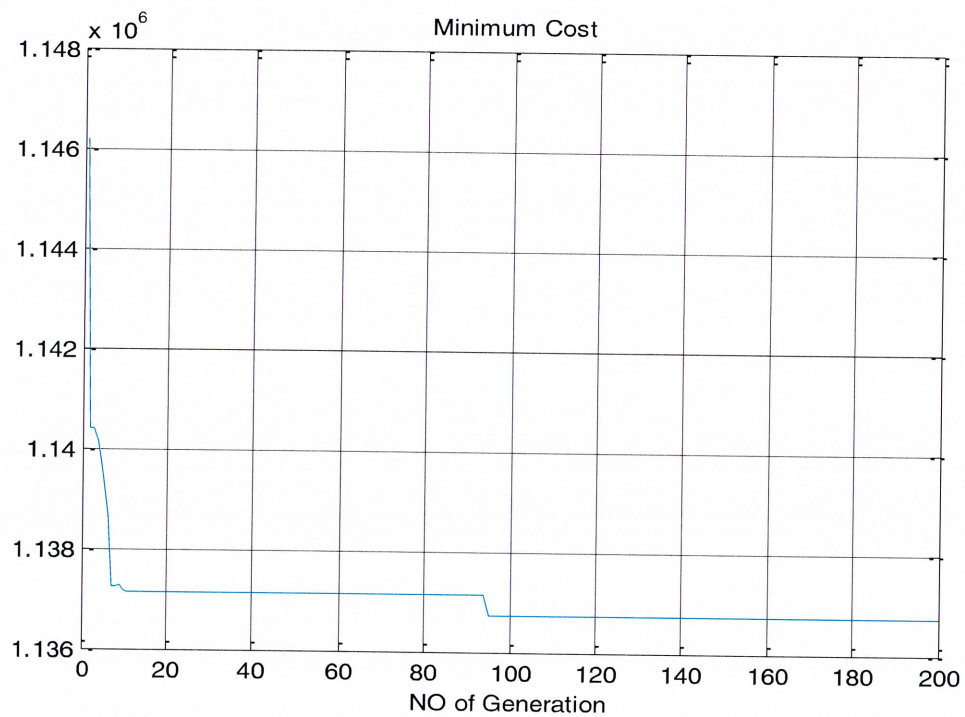


Figure 21 Cost vs. No of Generations for twenty units system

5.3.5 TEST CASE 5

A 40-unit system is selected as a test system. System data was repeated two times for the test case 3 and the load demands multiplied by four. The spinning reserve is assumed to be 10% of the demand. The proposed BBO method parameters: generation=100, island = 200, integration probability step size $\Delta t = 1$, and mutation probability = 0.007. Figure 23 shows the cost vs. no of generations curve for the forty units system. Figure 22 shows the convergence characteristics of the proposed algorithm on the HSI function. It is obvious that the total cost in this case is approximately four times the cost of the ten units system case.

Table 19 Result of 40-units system using BBO

[illegible]

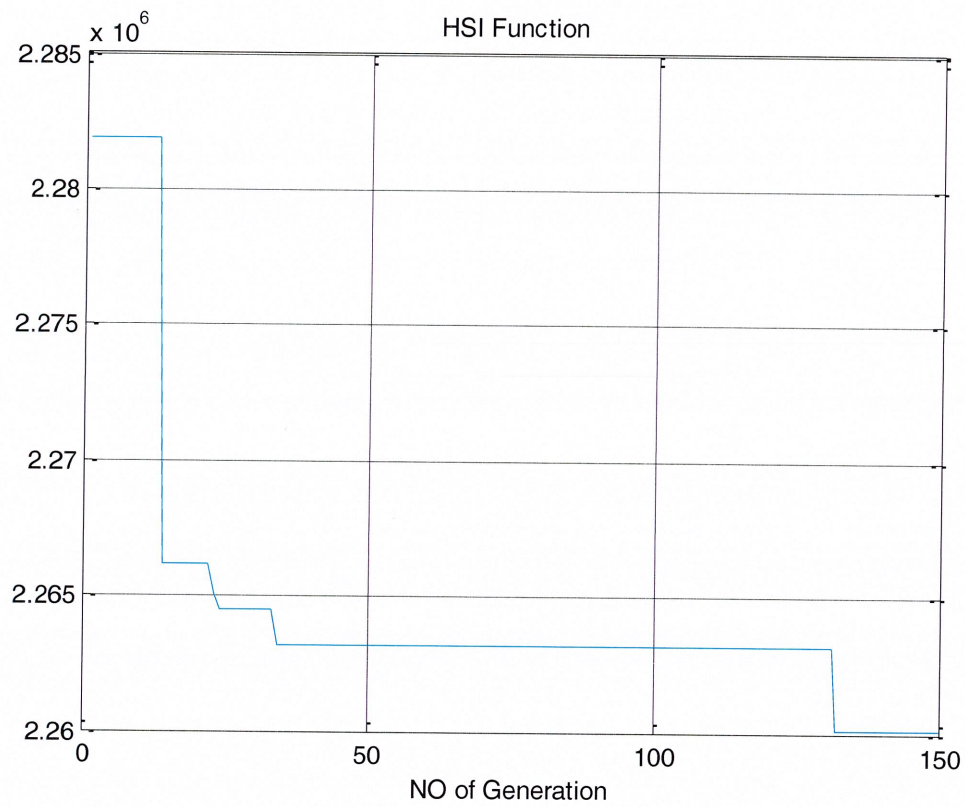


Figure 22 HSI Function vs. No of Generation for forty units system

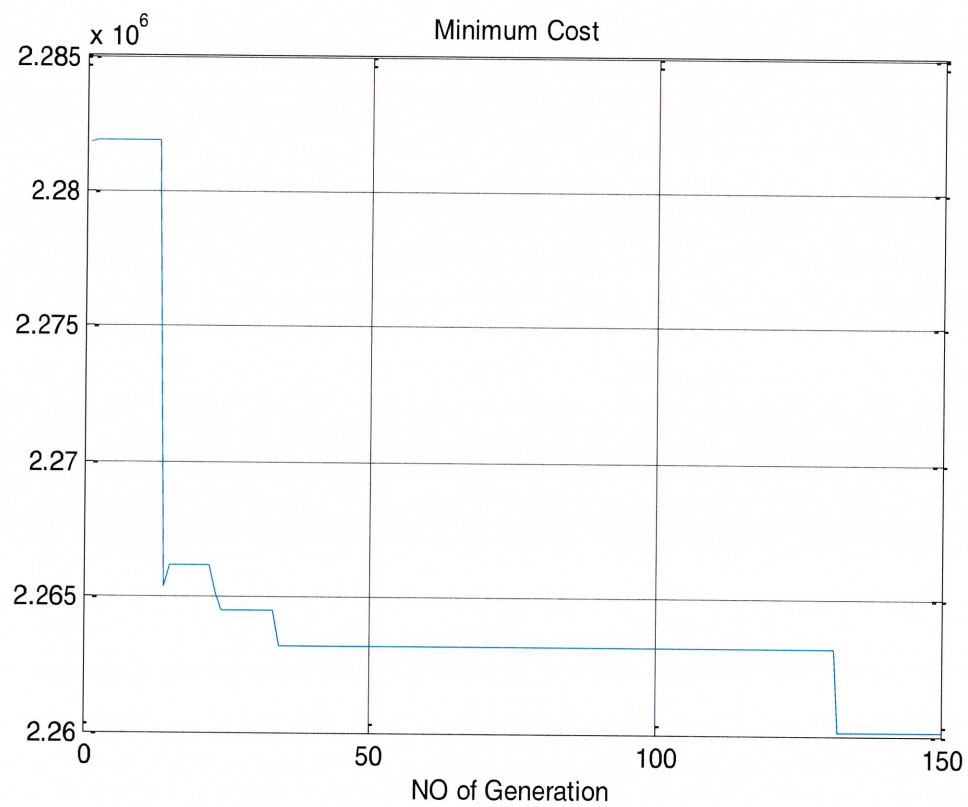


Figure 23 Cost vs. No of Generation for forty units system

CHAPTER 6

6 CONCLUSION AND SCOPE OF FUTURE WORK

6.1 CONCLUSION

Economic dispatch and unit commitment are fundamental optimization problems in power system operation. In this thesis, biogeography based optimization (BBO) algorithm was employed to solve both problems and algorithms were proposed to solve each problem in chapter four with different constraints.

The proposed algorithm for economic dispatch problem is capable of solving the economic dispatch problem with different constraints such as real power balance, generators power limits, ramp rate limits and prohibited operating zones. Also including the valve point effect and transmission losses. Five test cases with three, six, thirteen, fifteen, and forty generators are tested. The results obtained by the algorithm was compared with other techniques presented in literature. It is obvious that the proposed algorithm have the capability to obtain better solutions than other techniques in terms of minimal fuel cost.

For the unit commitment problem, the developed algorithm solves the problem with its minimum up/down constraint and spinning reserve constraint. Effectiveness of this algorithm has been tested on five systems comprising three units, four units, ten units, twenty units and forty units. The results were compared for total operating cost with other techniques for the first three systems. It is found that the results obtained for the unit commitment using biogeography based optimization (BBO) algorithm are better than the results obtained from others techniques presented in literature. The twenty units system cost is approximately double the cost in the ten unit system case and in forty units system the cost is approximately four times the cost of ten unit system.

6.2 SCOPE OF FUTURE WORK

6.2.1 SCOPE OF FUTURE WORK IN ECONOMIC DISPATCH

6.2.1.1 ECONOMIC DISPATCH WITH MULTIPLE FUEL

Practically the power generation units are supplied with different fuel sources. The main objective of economic dispatch with multiple fuels is to determine which fuel if used will result in minimum cost for each unit. Piecewise quadratic function is used to model the cost function using multiple fuel options. For example if we have a unit with three fuels option the costs function will be written as shown below:

$$F_i(P_i) = \begin{cases} a_{i1} P_{i1}^2 + b_{i1} P_{i1} + c_{i1} & P_{i \min} \leq P_i \leq P_{i,1} \\ a_{i2} P_{i2}^2 + b_{i2} P_{i2} + c_{i2} & P_{i,1} \leq P_i \leq P_{i,2} \\ a_{i3} P_{i3}^2 + b_{i3} P_{i3} + c_{i3} & P_{i,2} \leq P_i \leq P_{i \max} \end{cases}$$

6.2.1.2 ENVIRONMENTAL \ ECONOMIC DISPATCH USING BBO AS MULTIOBJECTIVE OPTIMIZATION METHOD

Thermal power plants generate electricity but also pollution to the environments. The combustion of fossil fuel produces particular materials and gaseous pollutants. The particular materials do not cause a serious problem in air contamination but the gaseous does. The main gaseous generated are COx, SOx and NOx. The main aim of economic dispatch with environmental constraints is to satisfy the required demand with minimum cost under environmental constraints. The emission of each gas is modeled as quadratic function with power as independent variable. Hence for each generation power for a given type of fuel the amount of NOx, Cox, and Sox can be determined. In this type of problems we will have four objective functions to be minimized and subjected to the same constraints of the normal economic dispatch.

6.2.2 SCOPE OF FUTURE WORK IN UNIT COMMITMENT

Unit commitment can be solved by adding more constraints such as crew constraint, must run units constraints and fuel constraint. More units can be added to increase the problem complexity. Economic dispatch constraints can also be added such as fuel constraints, ramp rate limit, prohibited zones and also adding the valve point effect and transmission losses. Security conditions for power system can also be included to make the problem of unit commitment more realistic.

APPENDIX A: AC DISPATCH DATA

This appendix contains the data of the test systems used in this thesis. The appendix is divided into two sections: economic dispatch test systems and unit commitment test systems.

A.1 ECONOMIC DISPATCH DATA:

A.1.1 THREE UNITS SYSTEM:

This system consists of three generation units and it is taken from Sinha et al. [23]. The cost coefficients with valve point loading effect are shown in Table 20 and the required demand load is 850 MW.

Table 20 Units data for three units system with valve point effect

Generator	$P_{\min}$ (MW)	$P_{\max}$ (MW)	a	b	c	e	f
Unit 1	100	600	0.001562	7.92	561	300	0.0315
Unit 2	50	200	0.00482	7.97	78	150	0.063
Unit 3	100	400	0.00194	7.85	310	200	0.042

A.1.2 SIX UNITS SYSTEM

This system consists of six generation units taken from Gaing [5]. The cost coefficients are shown in Table 21 with ramp rate limits, prohibited zones, and the transmission loss B-coefficients with 100 MVA base. The required demand load is 1263 MW.

Table 21 Units data for six units system include ramp rate limits, prohibited zones and transmission loss B-coefficients.

Generator	$P_{\min}$	$P_{\max}$	a	b	c	P^0	UR	DR	Prohibited zones
1	100	500	0.007	7	240	440	80	120	[210 240] [350 380]
2	50	200	0.0095	10	200	170	50	90	[90 110] [140 160]
3	80	300	0.009	8.5	220	200	65	100	[150 170] [210 240]
4	50	150	0.009	11	200	150	50	90	[80 90] [110 120]
5	50	200	0.008	10.5	220	190	50	90	[90 110] [140 150]
6	50	120	0.0075	12	190	110	50	90	[75 85] [100 105]

B_{ij}	[0.0017 0.0012 0.0007 -0.0001 -0.0005 -0.0002 0.0012 0.0014 0.0009 0.0001 -0.0006 -0.0001 0.0007 0.0009 0.0031 0 -0.0010 -0.0006 -0.0001 0.0001 0 0.0024 -0.0006 -0.0008 -0.0005 -0.0006 -0.0010 -0.0006 0.0129 -0.0002 -0.0002 -0.0001 -0.0006 -0.0008 -0.0002 0.0150]
B_{oi}	[-0.3908 -0.1297 0.7047 0.0591 0.2161 -0.6635] $\times 10^{-3}$
B_{oo}	0.056

A.1.3 THIRTEEN UNITS SYSTEM

This system consists of thirteen generation units taken from Sinha et al. [23]. The cost coefficients with valve point effect are shown in Table 22 and the required demand load is 1800 MW.

Table 22 Units data for thirteen units system with valve point effect

Generator	$P_{\min}$	$P_{\max}$	a	b	c	e	f
1	0	680	0.00028	8.1	550	300	0.035
2	0	360	0.00056	8.1	309	200	0.042
3	0	360	0.00056	8.1	307	200	0.042
4	60	180	0.00324	7.74	240	150	0.063
5	60	180	0.00324	7.74	240	150	0.063
6	60	180	0.00324	7.74	240	150	0.063
7	60	180	0.00324	7.74	240	150	0.063
8	60	180	0.00324	7.74	240	150	0.063
9	60	180	0.00324	7.74	240	150	0.063
10	40	120	0.00284	8.6	126	100	0.084
11	40	120	0.00284	8.6	126	100	0.084
12	55	120	0.00284	8.6	126	100	0.084
13	55	120	0.00284	8.6	126	100	0.084

A.1.4 FIFTEEN UNITS SYSTEM

This system consists of fifteen generation units taken from Gaing [5]. The cost coefficients are shown in Table 23 with ramp rate limits, prohibited zones, and the transmission loss B- coefficients. The required demand load is 2630 MW.

Table 23 Units data for fifteen units system include ramp rate limits, prohibited zones and transmission loss coefficients B.

Generator	$P_{\min}$	$P_{\max}$	a	b	c	P^0	UR	DR	Prohibited operation zones
1	150	455	0.000299	10.1	671	400	80	120	[0 0] [0 0] [0 0]
2	150	455	0.000183	10.2	574	300	80	120	[185 225] [305 335] [420 450]
3	20	130	0.001126	8.8	374	105	130	130	[0 0] [0 0] [0 0]
4	20	130	0.001126	8.8	374	100	130	130	[0 0] [0 0] [0 0]
5	150	470	0.000205	10.4	461	90	80	120	[180 200] [305 335] [390 420]
6	135	460	0.000301	10.1	630	400	80	120	[230 255] [365 395] [430 455]
7	135	465	0.000364	9.8	548	350	80	120	[0 0] [0 0] [0 0]
8	60	300	0.000338	11.2	227	95	65	100	[0 0] [0 0] [0 0]
9	25	162	0.000807	11.2	173	105	60	100	[0 0] [0 0] [0 0]
10	25	160	0.001203	10.7	175	110	60	100	[0 0] [0 0] [0 0]
11	20	80	0.003586	10.2	186	60	80	80	[0 0] [0 0] [0 0]
12	20	80	0.005513	9.9	230	40	80	80	[30 40] [55 65] [0 0]
13	25	85	0.000371	13.1	225	30	80	80	[0 0] [0 0] [0 0]
14	15	55	0.001929	12.1	309	20	55	55	[0 0] [0 0] [0 0]
15	15	55	0.004447	12.4	323	20	55	55	[0 0] [0 0] [0 0]

$B_{ij} \times 10^4$	14	12	7	-1	-3	-1	-1	-1	-3	5	-3	-2	4	3	-1
	12	15	13	0	-5	-2	0	1	-2	-4	-4	0	4	10	-2
	7	13	76	-1	-13	-9	-1	0	-8	-12	-17	0	-26	111	-28
	-1	0	-1	34	-7	-4	11	50	29	32	-11	0	1	1	-26
	-3	-5	-13	-7	90	14	-3	-12	-10	-13	7	-2	-2	-24	-3
	-1	-2	-9	-4	14	16	0	-6	-5	-8	11	-1	-2	-17	-3
	-1	0	-1	11	-3	0	15	17	15	9	-5	7	0	-2	-8
	-1	1	0	50	-12	-6	17	168	82	79	-23	-36	1	5	-78
	-3	-2	-8	29	-10	-5	15	82	129	116	-21	-25	7	-12	-72
	-5	-4	-12	32	-13	-8	9	79	116	200	-27	-34	9	-11	-88
	-3	-4	-17	-11	7	11	-5	-23	-21	-27	140	1	4	-38	168
	-2	0	0	0	-2	-1	7	-36	-25	-34	1	54	-1	-4	28
	4	4	-26	1	-2	-2	0	1	7	9	4	-1	103	-101	28
	3	10	111	1	-24	-17	-2	5	-12	-11	-38	-4	-101	578	-94
	-1	-2	-28	-26	-3	3	-8	-78	-72	-88	168	28	28	-94	1283
$B_{oi} \times 10^4$	-1	-2	28	-1	1	-3	-2	-2	6	39	-17	0	-32	67	-64
B_{oo}	0.0056														

A.1.5 FOURTY UNITS SYSTEM

This system consists of forty generation units taken from Sinha et al. [23]. The cost coefficients with valve point effect are shown in Table 24 and the required demand load is 10500 MW.

Table 24 Units data for forty units system with valve point effect

Generator	P _{min}	P _{max}	a	b	c	e	f
1	36	114	0.0069	6.73	94.705	100	0.084
2	36	114	0.0069	6.73	94.705	100	0.084
3	60	120	0.0203	7.07	309.54	100	0.084
4	80	190	0.0094	8.18	369.03	150	0.063
5	47	97	0.0114	5.35	148.89	120	0.077
6	68	140	0.0114	8.05	222.33	100	0.084
7	110	300	0.0036	8.03	287.71	200	0.042
8	135	300	0.0049	6.99	391.98	200	0.042
9	135	300	0.0057	6.6	455.76	200	0.042
10	130	300	0.0060	12.9	722.82	200	0.042
11	94	375	0.0052	12.9	635.2	200	0.042
12	94	375	0.0057	12.8	654.69	200	0.042
13	125	500	0.0042	12.5	913.4	300	0.035
14	125	500	0.0075	8.84	1760.4	300	0.035
15	125	500	0.0071	9.15	1728.3	300	0.035
16	125	500	0.0071	9.15	1728.3	300	0.035
17	220	500	0.0031	7.97	647.85	300	0.035
18	220	500	0.0031	7.95	649.69	300	0.035
19	242	550	0.0031	7.97	647.83	300	0.035
20	242	550	0.0031	7.97	647.81	300	0.035
21	254	550	0.0030	6.63	785.96	300	0.035
22	254	550	0.0030	6.63	785.96	300	0.035
23	254	550	0.0028	6.66	794.53	300	0.035
24	254	550	0.0028	6.66	794.53	300	0.035
25	254	550	0.0028	7.1	801.32	300	0.035
26	254	550	0.0028	7.1	801.32	300	0.035
27	10	150	0.5212	3.33	1055.1	120	0.077
28	10	150	0.5212	3.33	1055.1	120	0.077
29	10	150	0.5212	3.33	1055.1	120	0.077
30	47	97	0.0114	5.35	148.89	120	0.077
31	60	190	0.0016	6.43	222.92	150	0.063
32	60	190	0.0016	6.43	222.92	150	0.063
33	60	190	0.0016	6.43	222.92	150	0.063
34	90	200	0.0001	8.95	107.87	200	0.042
35	90	200	0.0001	8.62	116.58	200	0.042
36	90	200	0.0001	8.62	116.58	200	0.042
37	25	110	0.0161	5.88	307.45	80	0.098
38	25	110	0.0161	5.88	307.45	80	0.098
39	25	110	0.0161	5.88	307.45	80	0.098
40	242	550	0.0031	7.97	647.83	300	0.035

A.2 UNIT COMMITMENT DATA:

A.2.1 THREE UNITS SYSTEM

Table 25 Units characteristics for three units system as given in Puri [28]

	Unit 1	Unit 2	Unit 3
$P_{\max}$	600	400	200
$P_{\min}$	150	100	50
a	0.001562	0.00194	0.005784
b	7.92	7.85	9.564
c	561	310	93.6
Minimum up time (h)	4	5	5
Minimum down time (h)	2	3	1
Hot start up cost (\$)	150	170	500
Cold start up cost (\$)	350	400	1100
Cold start time(h)	4	5	5
Initial state	-5	8	8

Table 26 Load demands for three units system for 15 hours as given in [28].

Hour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Load	1200	1150	1100	1050	1000	950	900	850	800	750	700	650	600	550	500

A.2.2 FOUR UNITS SYSTEM

Table 27 characteristics for four units system as given in Khanmohammadi et al. [29]

	Unit 1	Unit 2	Unit 3	Unit 4
$P_{\max}$	300	250	80	60
$P_{\min}$	75	60	25	20
a	0.0021	0.0042	0.0018	0.0034
b	16.83	16.95	20.74	23.6
c	684.74	585.62	213	252
Minimum up time (h)	4	3	2	1
Minimum down time (h)	5	5	4	1
Hot start up cost (\$)	500	170	150	0
Cold start up cost (\$)	1100	400	350	0.02
Cold start time(h)	5	5	4	0
Initial state	8	8	-5	-6

Table 28 Load demands for four units system for 8 hours as given in Khanmohammadi et al. [29]

Hour	1	2	3	4	5	6	7	8
Load	450	530	600	540	400	280	290	500
Reserve	45	53	60	54	40	28	29	50

A.2.3 TEN UNITS SYSTEM

Table 29 characteristics for ten units system as given in Khanmohammadi et al. [29]

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6	Unit 7	Unit 8	Unit 9	Unit 10
$P_{\max}$	455	455	130	130	162	80	85	55	55	55
$P_{\min}$	150	150	20	20	25	20	25	10	10	10
a	0.00048	0.00031	0.002	0.00211	0.00398	0.00712	0.00079	0.00413	0.00222	0.00173
b	16.19	17.26	16.6	16.5	19.7	22.26	27.74	25.92	27.27	27.79
c	1000	970	700	680	450	370	480	660	665	670
Minimum up time (h)	8	8	5	5	6	3	3	1	1	1
Minimum down time (h)	8	8	5	5	6	3	3	1	1	1
Hot start up cost (\$)	4500	5000	550	560	900	170	260	30	30	30
Cold start up cost (\$)	9000	10000	1100	1120	1800	340	520	60	60	60
Cold start time(h)	5	5	4	4	4	2	2	0	0	0
Initial state	8	8	-5	-5	-6	-3	-3	-1	-1	-1

Table 30 Load demands for ten units system for 24 hours as given in Khanmohammadi et al. [29]

Hour	1	2	3	4	5	6	7	8	9	10	11	12
Load	700	750	850	950	1000	1100	1150	1200	1300	1400	1450	1500
Reserve	70	75	85	95	100	110	115	120	130	140	145	150
Hour	13	14	15	16	17	18	19	20	21	22	23	24
Load	1400	1300	1200	1050	1000	1100	1200	1400	1300	1100	900	800
Reserve	140	130	120	105	100	110	120	140	130	110	90	80

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