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Using Stochastic Fractal Search Algorithm to Solve Environmental-Economic Dispatch Including Wind Power

A Thesis Submitted to
The Department of Electrical Power Engineering

In partial fulfillment of the requirements for the degree of
Master of Science

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Dedication

Dedicated to Prof. Muwaffaq Alomoush

For the valuable guidance and advice

Dedicated to my family

For their endless love, support and encouragement.

Dedicated to all faculty members and staff, friends and colleagues

Dedicated to my country

Zaid Basel Oweis

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Declaration

I, Zaid Oweis, recognize what plagiarism is and I hereby declare that this thesis, which is submitted to the department of Electrical Power Engineering at Hijjawi Faculty for Engineering Technology, for the partial fulfillment of the requirements of Master in Engineering, is my own work. I have not plagiarized from any sources. All references and acknowledgments of sources are given and cited in my thesis. I have used the conventional citation and referencing. Each significant contribution to and quotation in this report from work of other people has been attributed and referenced.

Zaid Basel Sulieman Oweis

December, 2016

List of Symbols and Abbreviations

C_i	The operating cost of thermal unit $i,\ \$/hour$.
IC_i	Incremental cost of thermal unit $i, \$/MWh$.
E_i	The emission of thermal unit $i,\ kg/hour$.
C_T	The total operating cost, $\$/hour$.
C_g	The total operating cost of thermal generating units, $\$/hour$.
E_T	The total emission, $kg/hour$.
f_T	Sum of the total operating cost and the total emission.
r_i	Weight factor between cost and emission of thermal unit i.
C_{w}	The total cost of wind generation $\$/hour$.
$C_{\mathrm{w}.f}$	Direct electrical energy cost coefficient of unit w in wind farm f, $\$/MWh$.
$C_{\mathrm{us,w}.f}$	Underestimation electrical energy cost coefficient of unit w in wind farm f,$\$/MWh$.
$C_{\mathrm{os,w}.f}$	Overestimation electrical energy cost coefficient of unit w in wind farm f, $\$/MWh$.
P_{GT}	Total real power generated of all units, MW.
P_D	Total real power demand of the load, MW.
P_l	Total real power system losses, MW.
P_{Gi}	The real power output of thermal unit i, MW.
$P_{w.f}$	The real power output of unit w in wind farm f, MW.
$\hat{P}_{w.f}$	Expected real power output of unit w in wind farm$f$, MW.
P_{Gi}^{min}	Minimum real power output limit of thermal unit i, MW.
P_{Gi}^{max}	Maximum real power output limit of thermal unit i, MW.
P_{Gi}^{l}	Lower limit of the j^{th} prohibited zone Zi, MW.
$P_{Gi,Zi}^{U}$	Upper limit of the j^{th} prohibited zone Zi, MW.
P_{Gi}^{0}	Real power output of generator before dispatch hour, MW.
P_{air}	Airflow power, MW.
P_w	Wind turbine extracted power, MW.

P_r	Wind turbine rated power, MW.
C_p	Wind turbine power coefficient.
V_i, V_r, V_o	Wind turbine cut-in, rated and cut-out speed, respectively, m/s.
DC_w	Direct cost of the wind power $\$/hour$.
OS_w	Overestimation cost of the wind power $\$/hour$.
US_w	Underestimation cost of the wind power $\$/hour$.
DR_i	Down ramp limit of thermal unit $i, MW/hour$.
UR_i	Upper ramp limit of thermal unit $i, MW/hour$.
$\mathcal{T}$	Number of dispatch hours $, hour$.
B_{ij}, B_{oj}, B_{oo}	Quadratic, linear and constant loss coefficients, respectively.
α_i	Constant cost coefficient of thermal unit $i, \$/hour$.
β_i	Linear cost coefficient of thermal unit $i, \$/MWh$.
γ_i	Quadratic cost coefficient of thermal unit $i, \$/MW^2h$.
η_i, χ_i	Valve-point effect coefficients of thermal unit i $\$/hour,\ rad/MW$.
a_i	Constant emission coefficient of thermal unit $i, kg/hour$.
b_i	Linear emission coefficient of thermal unit $i, kg/MWh$.
c_i	Quadratic emission coefficient of thermal unit $i, kg/MW^2h$.
d_i, δ_i	Valve-point effect coefficients of thermal unit$i$, $kg/hour,\ 1/MW$.
E, W	Kinetic energy and work, $Joule$.
F	Force, $Newton$.
a, V, d	Acceleration, velocity and distance, respectively, $m/s^2, m/s, m$.
m, v, ξ	Mass, volume and density, $kg, m^3, kg/m^3$.
$\mathrm{GW}_1, \mathrm{GW}_2$	Gaussian walks.
$\mu_{\mathrm{BP}}, \mu_{\mathrm{P}}, \sigma$	Gaussian means and standard deviation.
g	Generation number.
UB, LB	Upper and lower bounds.
NG	Number of generating units.
NF	Number of wind farms.
NW	Number of wind power units.

SFS	Stochastic Fractal Search.
GA	Genetic Algorithm.
PSO	Particle Swarm Optimization.
GSA	Gravitational Search Algorithm.
DE	Differential Evolution.
MODE	Multi-Objectives Differential Evolution.
PDE	Pareto Differential Evolution.
NSGA	Non-dominating Sorting Genetic Algorithm.
SPEA	Strength Pareto Evolutionary Algorithm.
TLBO	Teaching Learning Based Optimization.
SQP	Sequential Quadratic Programming.
SOA	Seeker Optimization Algorithm.

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Abstract

Economic dispatch is one of the major problems in electrical power systems. It is a nonlinear optimization problem with a number of constrains, that has to be solved to obtain the minimum operating costs while respecting all physical limits of generating units and considering transmission losses and environmental concerns.

The economic dispatch is the operation of generation facilities to produce energy at the lowest cost to reliably serve consumers, taking in a count any operational limits of generation and transmission facilities. Many considerations must be considered while solving economic dispatch problem, like generators physical limits, load demand, transmission lines limits and losses and gas emissions.

Historically, a large number of optimization methods have been used to solve the economic dispatch problem. These methods can be classified as classical optimization methods and heuristic optimization algorithms.

The classical methods include gradient method, lambda iteration method, Lagrange relaxation method and linear programming methods. Because of the nonlinearity of the economic dispatch problem as well as the large number of constraints and physical limits, the classical methods usually give local optimum solutions and did not guarantee a global solution.

Stochastic Fractal search (SFS) is one of the recent metaheuristic optimization algorithms which have been introduced in 2015. It can be used effectively in solving economic dispatch problems. Solving economic dispatch problem includes nonlinear characteristics of generators such as cost functions, power limits, prohibited zones and ramp rate limits. Another important factor which should be considered when solving the economic dispatch problem is gas emission rates of the generating units that can be reduced to get less environmental impacts when using fossil fuel.

The results of SFS algorithm have shown a better performance in finding global solution, with less number of iterations and less time compared with other existing algorithm solutions. Comparing the results of SFS algorithm with other algorithms such as genetic algorithm (GA) and particle swarm optimization (PSO) have shown the effectiveness of the method. The results obtained in this thesis have shown that the proposed algorithm solution outperforms other older algorithms solutions. In the first system that has been studied, the power loss in the system has been reduced by 24.6 KW/h compared. In the second system, which consists of 13 thermal generating units, the total cost obtained using SFS was lower than other solution methods by $5.5/h. By obtaining a better optimal solution, and production and operating costs can be reduced significantly.

Keywords: Economic Dispatch, Emission Dispatch, Combined Economic and Emission Dispatch, Evolutionary Algorithm, Global Optimization, Metaheuristic Algorithms, Wind Power, Stochastic Fractal Search, Transmission Losses, Valve-Point Effects.

1

INTRODUCTION

1.1. INTRODUCTION

Economic dispatch (ED) is one of the most important concerns in electric power systems generation and operation. Solving economic dispatch problem is very important in order to achieve the minimum operating cost and lowest emission rates, while satisfying a number of constrains. The considered constrains are the load demand, transmission losses, physical limits of the generating units and environmental impact by lowering gaseous pollution levels.

Because of the importance of environmental effect on using fossil fuel, emission rates are considered in solving economic dispatch problem to lower pollution levels as much as possible to reflect the environmental concerns. Using fossil fuel produces a number of polluting gaseous emission such as Carbon monoxide (CO), Carbon Oxide (CO_2), Nitrogen Oxides (NO_X), and Sulfur Oxides (SO_X) [1]. Therefore, finding the optimum solution for economic dispatch problem, both cost and emission rates are considered and the problem becomes combined economic-emission dispatch.

Wind power is gradually growing around the globe. Including wind power is an important factor in economic dispatch problem.

Many techniques have been used to solve the economic dispatch problem. Conventional methods include lambda iteration method, gradient method, Lagrange method, base point participation factor method and linear programming method [1]. These methods usually obtain local solutions rather than global solution due to the complexity, non-linearity and multiple constrains of economic dispatch problem and therefore, the solution obtained cannot be guaranteed to global solution or near global solution.

Since 1990s many methods have been introduced to solve nonlinear optimization problems that provide better global solutions and have enhanced capabilities compared to conventional methods. Metaheuristic algorithms are natural inspired algorithms, which simulate natural phenomena or behavior and aims to find global optimum solution rather than local optimum solutions.

Many evolutionary algorithms have been proposed in previous years to solve economic dispatch problems, that use different approaches to find global optimum solution. In the last few years, many evolutionary algorithms are introduced to get better and faster solutions. Each method has its points of strength and weaknesses. Stochastic Fractal Search is one of the latest evolutionary algorithms that has been proposed by Salimi, Hamid in 2015 [2]. The name of the algorithm comes from the natural behavior that it imitates.

1.2. LITERATURE REVIEW

To solve economic dispatch problem, many algorithms have been used to obtain the optimal solution. Genetic Algorithm [3] and Particle Swarm Optimization [4, 5] are the most well-known algorithms.

Another evolutionary algorithms have been used such as Gravitational Search Algorithm (GSA) [6], Artificial Bee Colony (ABC) [7], Simulated Annealing (SA) [8], Firefly Algorithm (FA) [9], Ant Colony Optimization (ACO) [10], Cuckoo Search (CS) [11], Evolutionary Programming (EP) [12], Harmony Search Algorithm (HSA) [13], Teaching Learning Based Optimization (TLBO) [14], Cultural Algorithm (CA) [15], Biogeography-Based Optimization (BBO) [16], Artificial Immune System (AIS) [17], Neural Network (NN) [18], Bacterial Foraging (BF) [19], Differential Evolution (DE) [20], Honey Bee Mating Optimization (HBMO) [21], Evolutionary Strategy Optimization (ESO) [22], Tabu Search (TS) [23] and Real-Coded Chemical Reaction Optimization (RCCRO) [24].

The work presented in [4] solves economic dispatch problem using particle swarm optimization considering generator limits: ramp rate limit and prohibited zones. Solutions for 6, 15 and 40-unit systems are compared with genetic algorithm solution. A comparison between the two methods solutions in terms of generating cost and time to obtain solution (iteration time) has shown that particle swarm optimization outperform genetic algorithm solution.

Author in [5] solves economic dispatch problem using modified particle swarm optimization (MPSO) including valve-point effect and generator limits, and then shows that the results obtained by his method outperform genetic algorithm solution and other classical methods solutions.

Combined economic and emission dispatch using gravitational search algorithm for 6, 11, 15 and 40 generating units has been presented in [6]. Both emission and cost are considered in the solution. In addition, generator limits, valve-point effect and transmission losses are taken in count. The results obtained by gravitational search algorithm were compared with other solution obtained by other techniques such as lambda iteration, particle swarm optimization, differential evolution and genetic algorithm.

Solution of economic dispatch problem using quantum genetic algorithm (QGA) including wind power system and considering generator limits, spinning reserve and valve-point effect has been presented in [25]. The author studied the effect of wind power on solving economic dispatch problem.

The work in [26] presents a comparison between differential evolution algorithm and a combination of differential evolution, with chaos sequence and sequential quadratic programming (DEQ-SQP), in solving economic dispatch problem for 13 and 40 thermal generation units including valve-point affect. Losses are not considered in this study.

In [27], the authors solve economic dispatch problem for 3, 6, 15 and 40 generating units, which are combination of oil, gas, diesel, coal and combined cycle units. Transmission losses and generators maximum and minimum power limits are considered using modified particle swarm optimization.

Author in [28] solves multi objective environmental economic dispatch including wind power for 6, 14 and 40 thermal and wind generating units. Generator power limits, transmission losses and emission rates are considered. The impact of wind power is also included.

In [29], bacterial foraging algorithm has been presented in solving economic dispatch problem considering valve-point effects, power losses. Wind power is also included. Different test systems have been studied using this algorithm and the results obtained was compared with the corresponding results of other algorithm solutions previously used.

The works presented in [30] and [31] study the impact of wind power on thermal generation unit commitment and dispatch. The authors studied the benefits of using wind power regarding both cost and emission levels.

Artificial bee colony algorithm to solve environmental-economic dispatch considering wind power has been proposed in [32]. Solutions for 6, 15 and 40 unit system obtained using this algorithm include transmission losses, generators physical limits (minimum, maximum, ramp rate and prohibited zones) and valve loading effect. The author studies the IEEE 30-bus system consisting of 6 thermal units with and without wind power. In case of including wind power, two wind farms have been included in the system.

Dynamic economic-emission dispatch considering load and wind power uncertainties has been presented in [33]. The author has applied particle swarm optimization technique for four test systems; 5, 10, 30 and 100 unit systems including system losses, ramp rate limits and valve-point effect for 24 hours period

In [34], a hybrid technique combining seeker optimization algorithm and sequential quadratic programming (SOA-SQP) has been presented to solve dynamic economic dispatch problem including valve-point effect for 24 hours period was used. The author has studied two systems, 5 and 10 generating units. Losses is considered in the 5 unit system and neglected in the 10 unit system.

1.3. MOTIVATION

In the last decade, demand on electric power has been increased significantly. Lowering the operating cost can affect all aspects in production of energy. Emission rates are considered in solving economic dispatch problem due to the importance of lowering pollution levels and reflecting the environmental concerns.

These days, renewable energy including wind power is merging with conventional power systems, which are mostly thermal generating units. Therefore the importance of studying economic dispatch problem including wind power has increased significantly in the last few years.

Using new techniques to solve economic dispatch problem can reduce the operating costs and emission rates.

1.4. THESIS OBJECTIVES AND CONTRIBUTION

The main objective is the introduction of a new technique or algorithm to solve economic dispatch problem to obtain a better, near global solution, so that obtaining lower generating cost and emission rates. This new technique has to handle the complexity and non-linearity of economic dispatch problem.

One of the main contributions of this thesis is to apply the very recent algorithm, stochastic fractal search, in solving economic dispatch problem. This will include:

1. Mathematical model of environmental economic dispatch problem including wind power is presented
2. All constrains are included in the model, which include:
    a. Total real power transmission losses

   b. Real power balance equation

   c. Emission rates

   d. Generator upper, lower and ramp rate limits

   e. Prohibited zones

   f. Valve-point effects

3. The impact of wind power on economic dispatch solution is discussed

Different scenarios including emission and wind power are discussed. The results obtained by stochastic fractal search are compared with the results of other techniques used to solve economic dispatch. By getting a lower operating cost and lower emission rates the effectiveness of using this method will be proved.

1.5. THESIS LAYOUT

Solving methods are introduced in chapter 2, which are divided into two parts. First part discusses some classical methods and the second part discusses some heuristic methods and evolutionary algorithms.

Chapter 3 presents a description and mathematical representation of environmental economic dispatch problem including wind power. All aspects of the problem such as generators limits and constrains are included. Chapter 4 presents stochastic fractal search algorithm.

In chapter 5 all studied scenarios, systems and a comparison between other techniques solutions and stochastic fractal search solutions are discussed. Last chapter, chapter 6, presents conclusions and recommendations for future work.

2

OPTIMIZATION PROBLEM AND SOLVING METHODS

2.1. OPTIMIZATION PROBLEM FORMULATION

2.1.1. Objective Function

The objective function expresses one or more quantities which are to be minimized or maximized. The optimization problems may have only one objective function or more than one objective functions. The problem with multi-objectives can be rewritten as single objective problems either by forming a weighted combination of the different objectives or by treating some of the objectives as constraints.

2.1.2. Variables

Variables are set of unknowns, which have to be determined. The variables are used to characterize the objective function and constrains. The design of the variables is chosen to satisfy certain specified function and other needs. The design variables can be continuous or discrete.

2.1.3. Constrains

A set of constraints allow the unknowns to take on certain values and eliminate other values. They are conditions that must be satisfied to make the design workable.

Once the design variables, constraints, objectives and the relationship between them have been selected, the optimization problem can be defined.

The general form for a single objective optimization problem with equality and inequality constrains can be written in the following form [35]:

Minimize

$$f(x) \tag{1}$$

Subject to:

$$g_j(x) \leq 0 \qquad \mathrm{j} = 1,2 \ldots m_{ineq} \tag{2}$$

$$\mathrm{h}_k\,(x) = 0 \qquad k = 1,2 \ldots m_{eq} \tag{3}$$

$$x_i^l \leq x_i \leq x_i^U \qquad \mathrm{i} = 1,2 \ldots n \tag{4}$$

$f(x)$ is the objective function to be optimized, $g_j(x)$ and $\mathrm{h}_k\,(x)$ represent the inequality constrains and equality constrains functions, respectively. The x vector form the n design variables that will be obtained to achieve the optimum solution of the objective function. x_i^l and x_i^U are the lower and upper limits of the objective function, respectively. The objective function and constrains functions can be linear or nonlinear functions.

Optimization methods are designed to provide the best values of system design and operating strategy, values that lead to the highest levels of system performance. These methods can be divided in to classical methods and heuristic methods [36].

2.2. CLASSICAL OPTIMIZATION METHODS

The classical methods for optimization are suitable in finding the optimal solution of continuous and differentiable functions. These methods are analytical and make use of the methods of differential calculus in locating the optimum points [35]. Since some of the practical problems involve objective functions that are not continuous and/or differentiable, the classical optimization techniques have limited scope in practical applications [36].

The classical or conventional methods include lambda iteration method, gradient projection methods, interior point method, linear programming, Lagrange relaxation and dynamic programming. These methods usually find relative (local) minimum or maximum solution rather than finding the global solution. Figure 2-1 shows local and global solution.

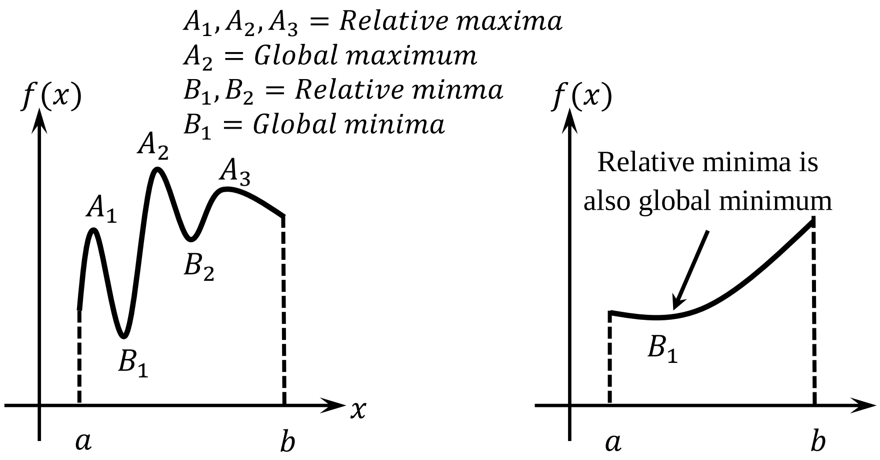

Figure 2-1: Local and global solution

2.3. METAHEURISTIC METHODS AND EVOLUTIONARY ALGORITHMS

Evolutionary algorithms are techniques inspired by natural or biological evolution and imitation processes of life such as reproduction, mutation, recombination, natural selection and survival of fittest. They are associated with artificial intelligent.

Finding the solution involves evolving a population of solutions to an optimization problem through iterative application of randomized processes of recombination and selection, until a termination criterion is met. Evaluating the population using different selection, recombination, and mutation to generate new population. Each member of the population represents a candidate solution.

In computer science and mathematical optimization, a metaheuristic is a higher level technique or heuristic designed to find, generate, or select a heuristic (partial search algorithm) that may provide an adequately decent solution to an optimization problem.

Two major components are involved in any metaheuristic algorithms. These are intensification and diversification, or exploitation and exploration. Diversification means to generate diverse solutions so as to explore the search space on a global scale, while intensification means to focus the search in a local region knowing that a current solution is found in this region. A balance between intensification and diversification should be found during the selection of the best solutions to improve the rate of algorithm convergence.

Some well-known metaheuristic optimization methods which are used to solve nonlinear optimization problems are given in the following paragraphs.

Simulated annealing is a global optimization technique based on the metal annealing processing. It involves in controlling heating and cooling of metal with minimum energy in order to obtain larger crystal size which results in reducing the metal defects [37].

Genetic algorithm is based on Darwin's theory of survival of the fittest and principles of natural genetics and natural selection, GA relays on three basic elements; reproduction, crossover and mutation [37].

Ant colony optimization is based on the foraging behavior of social ants. Ants initially search randomly for the food, after finding it, they return to their colony depending on pheromone trails. Other ants will keep searching randomly, but when they find pheromone trail made by former ants, which will use it to find the food source [37].

Particle swarm optimization is based on swarm behavior observed in nature such as fish and bird schooling [38]. Bee algorithm is class of metaheuristic algorithms, inspired by the foraging behavior of bees [39].

Firefly algorithm is based on the flashing patterns and behavior of fireflies [40]. Differential evolution is a vector-based evolutionary algorithm, and can be considered as a development of genetic algorithms [41]. Tabu search algorithm uses memory and the search history is a major component of the method [42]. Harmony search is heuristic optimization algorithm related to the improvisation process of a musician [43].

Cuckoo search is a nature-inspired metaheuristic algorithm which is based on the brood parasitism of some cuckoo species [44]. Bat algorithm is a metaheuristic algorithm inspired by the echolocation behavior of bats, with varying pulse rates of emission and loudness [45]. Gravitational search algorithm is a nature inspired algorithm based on the Newton’s law of gravity and the law of motion [46].

The grey wolf optimizer algorithm mimics the leadership hierarchy and hunting mechanism of grey wolves in nature [47]. Multi-verse optimizer inspired by three concepts in cosmology: white hole, black hole, and wormhole [48]. Teaching learning based optimization algorithm based on the effect of influence of a teacher on learners [49].

In summary, to form an optimization problem, objective function, variables and constrains must be determined. Solving methods can be divided to classical optimization methods and heuristic optimization methods. Next chapter presents a mathematical representation of environmental economic dispatch problem in power systems including wind power.

3

ECONOMIC DISPATCH IN POWER SYSTEMS

3.1. INTRODUCTION

Solving an economic dispatch problem involves obtaining the minimum value of an objective function while meeting physical constrains and limits. The objective function is usually the operating cost function, which can be expressed by approximated quadratic function or by more precise function including valve-point effects. An emission function can be added to the cost function to form the objective function. The emission function can also be expressed in the same way as the cost function. Since the total generation capacity is larger than the total demand and the power system spreads out on a large geographical area, the division of a load among all generators is most important to be determined to obtain the lowest cost, emission and total transmission power loss.

An economic dispatch problem is considered as a part of the unit commitment problem that can be defined as the planning for which of the generators will be turned on and which will be turned off for specific period of time in a power system, so that deciding the generators that will be connected to the network and the generators that will be shut down for that specified period.

3.2. COST, EMISSION AND VALVE-POINT EFFECT

Cost and emission functions are needed to be optimized. Therefore it is needed to develop a relationship between the output power, and the operating cost and emission. In order to do that, a thermal generating unit consisting of a boiler (steam supply), a turbine and a generator is considered as shown in Figure 3-1.

The output generated power supplying not only the load demand but also 2% to 5% of the output power feeds the station auxiliaries such as boiler feed pumps, fans and condenser circulating pumps [50].

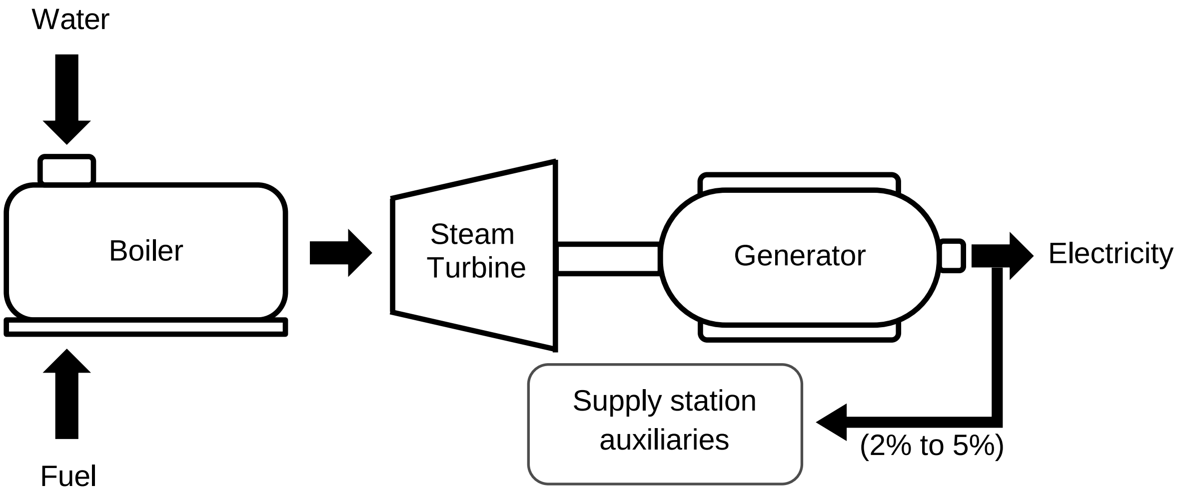

Figure 3-1: Thermal generation system

Generation cost can be represented in four different curves; input/output curve, fuel cost curve, heat rate curve and incremental cost curve.

The input power to the thermal unit can be measured either in British thermal unit per hour (Btu/h) or cal/hour. The total output power of a thermal unit is measured in MW. Figure 3-2 shows the input/output curve of a thermal unit, power input in Btu/h versus power output in MW. Btu is defined as the amount of heat needed to raise 1 pound of water at maximum density through one degree Fahrenheit that is equivalent to 1055 joules.

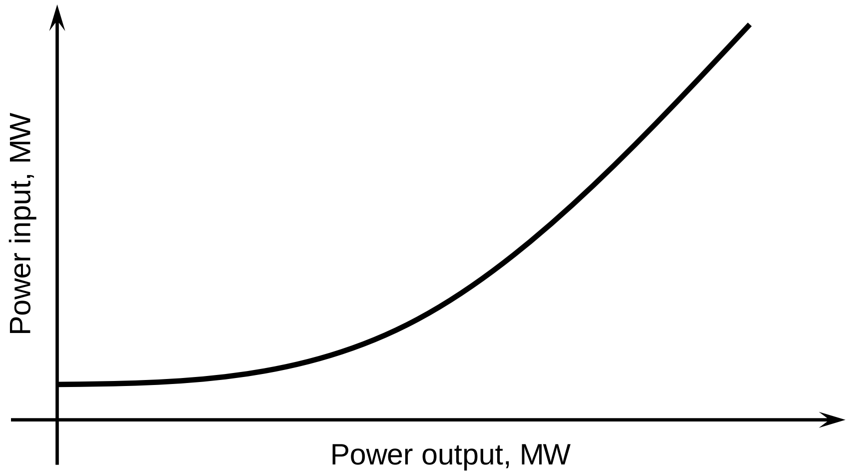

Figure 3-2: Input/Output curve of a thermal generation unit

Operating cost curve is the same as input/output curve but scaled to fuel cost; multiplying the fuel input by the cost of fuel in $/Btu. It is resulted in the curve that is shown in Figure 3-3. The operating cost function is usually given in quadratic equation.

The quadratic operating cost function of generator i without valve-point effect can be expressed as [51]:

$$C_i(P_{Gi}) = \alpha_i + \beta_i P_{Gi} + \gamma_i {P_{Gi}}^2 \quad \$/h \tag{5}$$

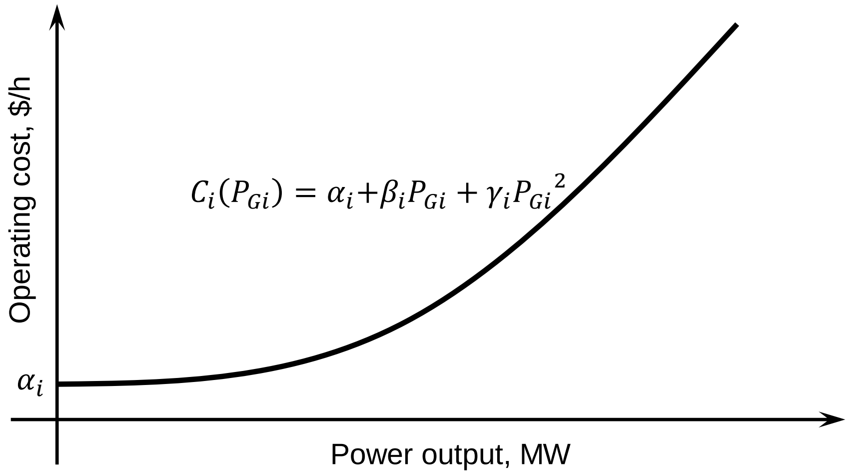

Figure 3-3: Operating cost curve of a thermal generation unit

The derivative of the operating cost function is the incremental cost function curve, which shows how the cost will increase to generate the next increment of power, as shown in Figure 3-4 [51].

The incremental cost is defined as [51]:

$$IC_i = \frac{dC_i}{dP_{Gi}} = \beta_i + 2\gamma_i P_{Gi} \quad \$/MWh \tag{6}$$

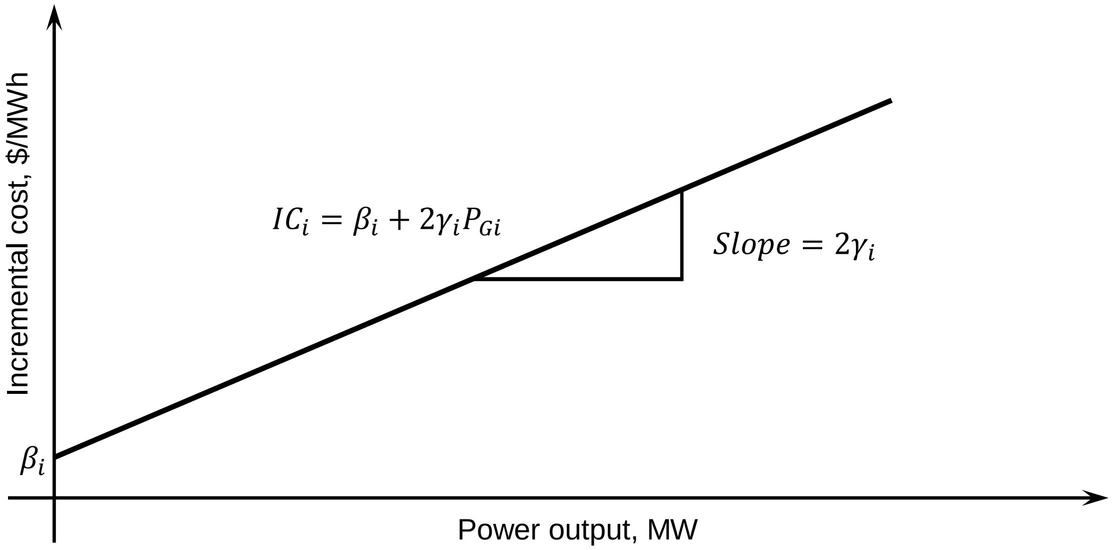

Figure 3-4: Incremental cost curve of a thermal generation unit

Heat rate curve or incremental fuel rate curve is the same as input/output curve, but scaled to MW. It represents the ratio of fuel input in Btu to energy output in MWh, it indicates the fuel efficiency. Therefore, lower heat rates imply higher fuel efficiency [51].

Thermal efficiency of a generating unit can be affected by several factors such as condenser pressure, re-heat stages, condition of steam and steam cycle used [50]. Figure 3-5 shows heat rate curve of a thermal generation unit [52].

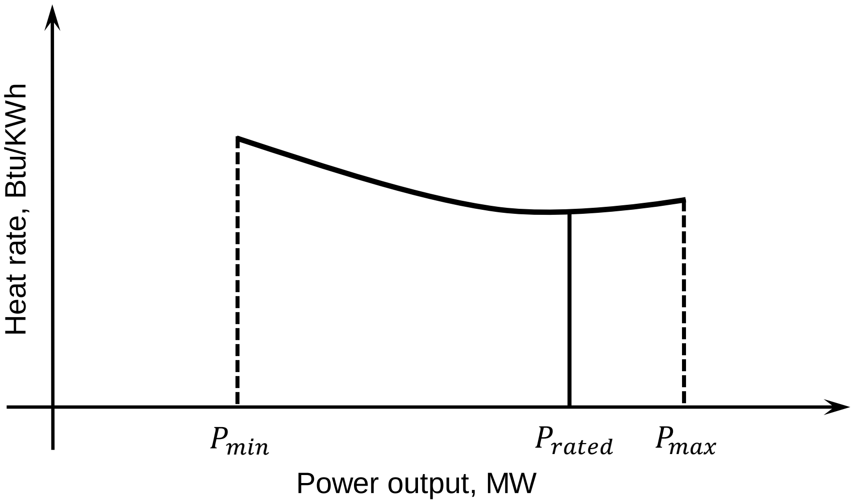

Figure 3-5: Heat rate curve of a thermal generation unit

In large steam turbine generators, a number of steam controlling valves are used to control the steam amount fed to the turbine. These valves open in sequence to increase the output power of the generation unit. Therefore, the earlier quadratic cost function becomes non-smooth cost function. Figure 3-6 and Figure 3-7 show the input/output characteristics of a four-valve thermal unit and the incremental heat rate, respectively.

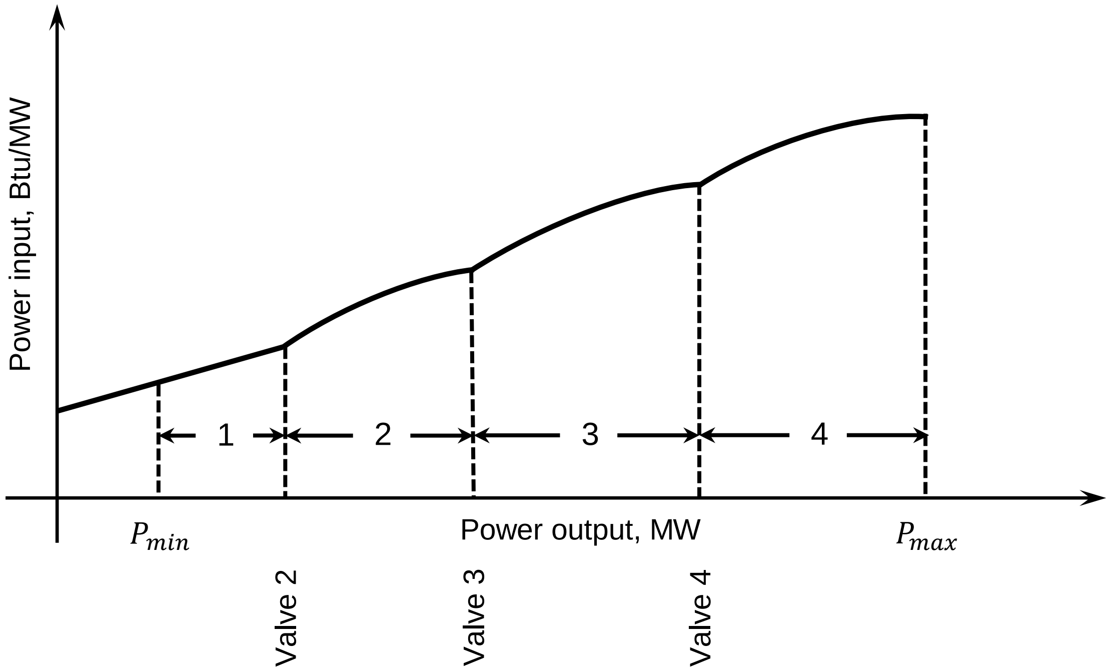

Figure 3-6: Input/Output curve of a thermal generation unit with multi valve effect

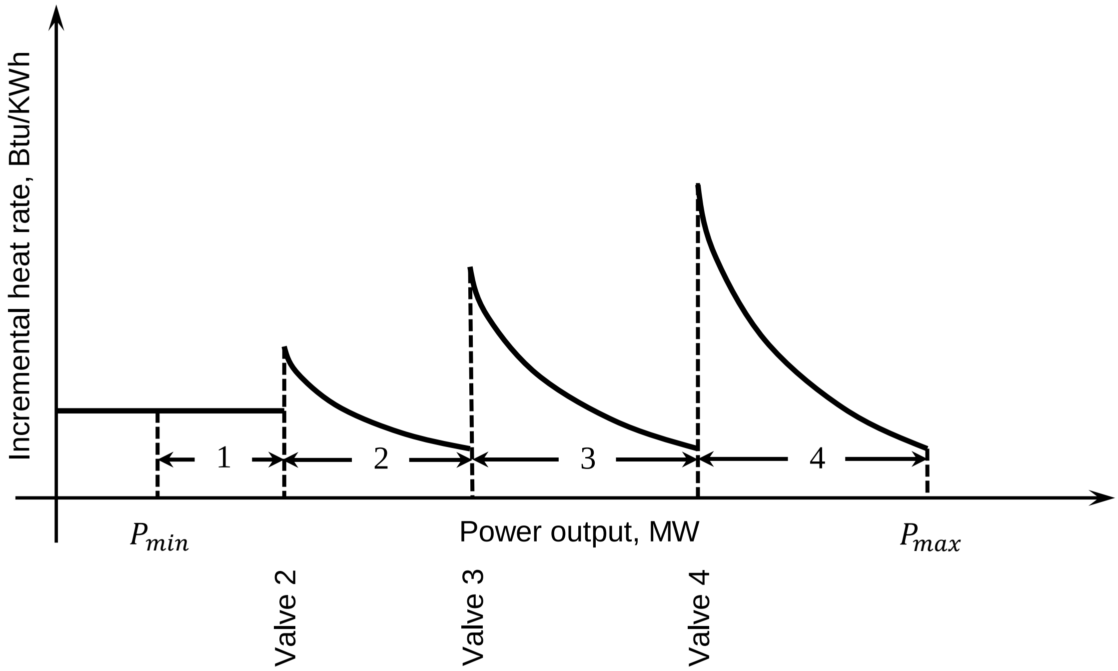

Figure 3-7: Incremental heat rate including multi valve effect

To model the valve-point effect, the additional sinusoidal term is added to the quadratic cost function. Figure 3-8 shows the electric energy operating cost function without valve-point effect and the non-smooth electrical energy cost function with multiple valve-points effects. The term $\left|\eta_i \sin(\chi_i(P_{Gi}^{min} - P_{Gi})\right|$ is added to include the effect of valve-point to cost function [28].

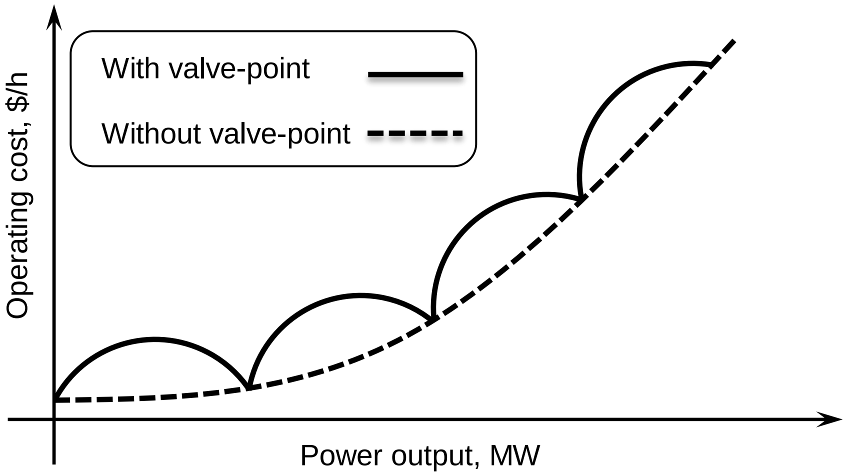

Figure 3-8: Operating cost function with and without valve-points of a thermal generation unit

The cost function of generator i including valve-point effect can be expressed by [28]:

$$C_i(P_{Gi}) = \alpha_i + \beta_i P_{Gi} + \gamma_i {P_{Gi}}^2 + \left|\eta_i \sin(\chi_i(P_{Gi}^{min} - P_{Gi})\right| \quad \$/h \tag{7}$$

The first three terms represent the quadratic operating cost function of power generation of generator i and the fourth term represent the effect of valve-point to the cost function.

The total amount of emissions, such as Carbon Oxide (CO_2), Nitrogen Oxides (NO_X), and Sulfur Oxides (SO_X), released by using fossil fuels in thermal power plants, can be defined as the sum of a quadratic function and an exponential function. The quadratic emission function of generator i without valve-point effect can be expressed by [6]:

$$E_i(P_{Gi}) = a_i + b_i P_{Gi} + c_i {P_{Gi}}^2 \quad Ton/h \tag{8}$$

The exponential term $d_i \exp(\delta_i P_{Gi}^{max})$ is added to (8) to include valve-point effect to the emission function. Therefore, the emission function of generator i including valve-point effect can be expressed by [6]:

$$E_i(P_{Gi}) = a_i + b_i P_{Gi} + c_i {P_{Gi}}^2 + d_i \exp(\delta_i P_{Gi}^{max}) \quad Ton/h \tag{9}$$

3.3. WIND POWER

A wind turbine converts the kinetic energy of a moving air to the form of mechanical energy and electrical energy.

The kinetic energy of an object having mass m and velocity V is equal to the work done W in displacing that object from rest to a distance d under a force F [53].

$$E = W = F \times d \tag{10}$$

According to Newton's Second law, force is given by:

$$F = m \times a \tag{11}$$

Relating initial velocity, final velocity and acceleration of the air flow by the third equation of motion gives:

$$V^2{}_{final} = V^2{}_{initial} + 2a \times d \tag{12}$$

Assuming that the initial velocity of airflow is zero, the acceleration of air flow becomes:

$$a = \frac{V^2{}_{final}}{2d} \tag{13}$$

The kinetic energy in the airflow can now be given by:

$$E = \frac{1}{2} m \times V^2 \tag{14}$$

The mass of the air can be obtained by multiplying the volume v of the air by its density ξ:

$$m = v \times \xi \tag{15}$$

Hence the kinetic energy in the wind becomes:

$$E = \frac{1}{2} v \times \xi \times V^2 \tag{16}$$

Considering a wind rotor of cross area A exposed to airflow with density ξ and speed V, the power in the airflow can be written in the form [53]:

$$P_{air} = \frac{1}{2} \xi \times A \times V^3 \tag{17}$$

where $\xi \times A \times V$ is the mass flow rate of air.

Not all the power of the airflow can be extracted by the wind turbine rotor. The power coefficient is defined as the ratio between the extracted power by the turbine rotor and the airflow power available [53].

$$C_p = \frac{P_w}{P_{air}} \tag{18}$$

The power extracted by the wind turbine is given by:

$$P_w = C_p \times P_{air} = \frac{1}{2} C_p \times \xi \times A \times V^3 \tag{19}$$

The maximum value of power that can be extracted from the fluid flow is known by Betz limit, which says that a turbine cannot extract more than 59 % of the power from the air stream [53].

$$C_{p,max} = \frac{16}{27} = 0.59 \tag{20}$$

A variable rotation speed wind turbine can operate at maximum C_p over a range of wind speed as shown in Figure 3-9 [53].

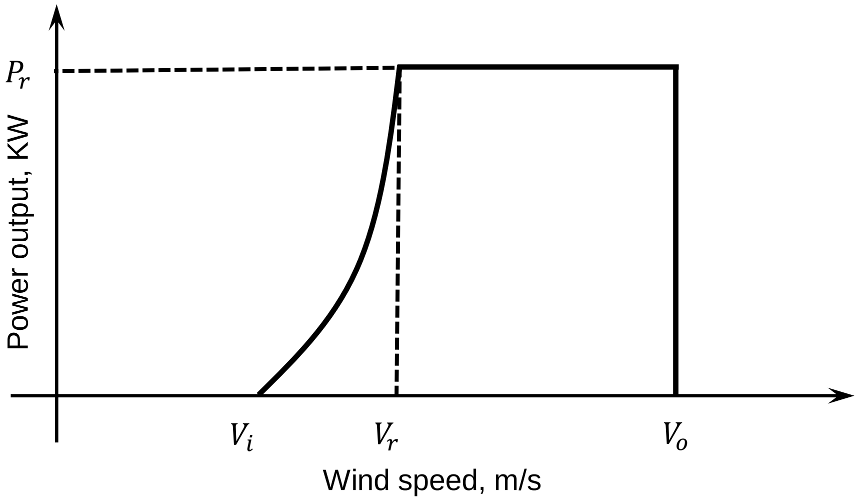

Figure 3-9: Power curve of a wind turbine

The above power curve shows the relationship between the output power generated by the wind turbine and the wind speed. Below the cut-in speed V_i, the wind turbine remains shut down because of the power in the wind is too low to produce useful energy. Once the wind speed exceeds the cut-in speed, the power output increases following the cubic relationship with the wind speed modified by the variations in C_p until the rated speed V_r of wind is reached. Above the rated wind speed the aerodynamic rotor is arranged and designed to limit the mechanical power extracted from wind and reducing the mechanical loads on the turbine shaft. After that, if the wind speed exceeds the cut-out speed V_o, the turbine is shut down [53].

The output of the wind turbine with a given wind speed input may be stated as [53]:

$$P_w = 0\,, \qquad\qquad for\;\; V < V_i \; and \; V > V_0 \tag{21}$$

$$P_w = \frac{1}{2} C_p \times \xi \times A \times V^3, \qquad\qquad for\;\; V_i \le V \le V_r \tag{22}$$

$$P_w = P_r\,, \qquad\qquad for\;\; V_r \le V \le V_o \tag{23}$$

Because of the uncertainty of the available wind speed at any given time, factors for overestimation and underestimation of available wind power are used in the mathematical model, that can be calculated based on the difference between expected wind power $\hat{P}_{w,f}$ and available wind power $P_{w.f}$ [54].

The mathematical model of wind power source for economic dispatch will also include direct cost for the wind power to represent the payment of the operator for wind power to the wind farm owner. Therefore, the total electrical energy cost related to the overestimation and underestimation should be considered in the evaluation. In addition, the direct electrical energy cost of wind power generators is very significant and it should be added to the thermal electrical energy cost in wind-thermal power plants [28].

The direct cost for wind power can be given by [28, 54]:

$$DC_w = \sum_{f=1}^{NF} \sum_{w=1}^{NW} C_{w.f} P_{w.f} \quad \$/h \tag{24}$$

The factor for overestimation can be described as if a certain amount of wind power is assumed and that power is not available at the assumed time, power must be purchased from an alternate source, or loads must be shed [28, 54].

$$OS_w = \sum_{f=1}^{NF} \sum_{w=1}^{NW} C_{\mathrm{os},w.f} \left(\hat{P}_{w.f} - P_{w.f}\right) \quad \$/h \tag{25}$$

The underestimation factor can be explained as that if the available wind power is actually more than what was assumed the power will be wasted and it is reasonable for the system operator to pay a cost to the wind power producer for the waste of available capacity [28, 54].

$$US_w = \sum_{f=1}^{NF}\sum_{w=1}^{NW} C_{\mathrm{us,w}.f}\left(P_{w.f} - \hat{P}_{w.f}\right) \qquad \$/h \tag{26}$$

Consequently, the wind generation cost in $\$/hour$ will be:

$$C_{\mathrm{w}} = DC_w + OS_w + US_w \tag{27}$$

or

$$C_{\mathrm{w}} = \sum_{f=1}^{NF}\sum_{w=1}^{NW}[C_{\mathrm{w}.f}\, P_{w.f} + C_{\mathrm{os,w}.f}(\hat{P}_{w.f} - P_{w.f}) + C_{\mathrm{us,w}.f}(P_{w.f}-\hat{P}_{w.f})] \tag{28}$$

The additional wind power can be handled in different ways; one way is to sell the surplus power to other utilities, or by a fast dispatch and automatic generation control (AGC), the output of non-wind generators (thermal generators) must be reduced correspondingly. If these ways cannot be achieved a dummy load resistors can be used to dissipate the additional energy [28].

These practicalities can be modeled by underestimation penalty cost function. From the perspective of the system operator, determining the optimal generation of wind power generators and system total demand are key factors to reduce the overestimation and underestimation of wind generator output [28].

3.4. CONSTRAINS

Constrains can be divided into equality and inequality constrains. Inequality constrains includes generators physical limits which are upper, lower, prohibited zones and ramp rate limits.

Equality constrain is the power balance between load and the generated power from both thermal and wind generation units.

3.4.1. Generators Limits

Each of the generators has its own generation capacity, which cannot be exceeded at any time. Synchronous generators rated by the maximum MVA output at certain voltage and power factor, which is usually between 0.85 to 0.9 lagging. The maximum and minimum active power output is limited by the prime mover capabilities [55].

Minimum and maximum power limits of generator i are given by:

$$P_{Gi}^{min} \leq P_{Gi} \leq P_{Gi}^{max} \tag{29}$$

The reactive power output of a synchronous generator is limited due to three factors: armature current limit, field current limit and end region heating limit. Figure 3-10 shows the capability curve of a synchronous generator [55].

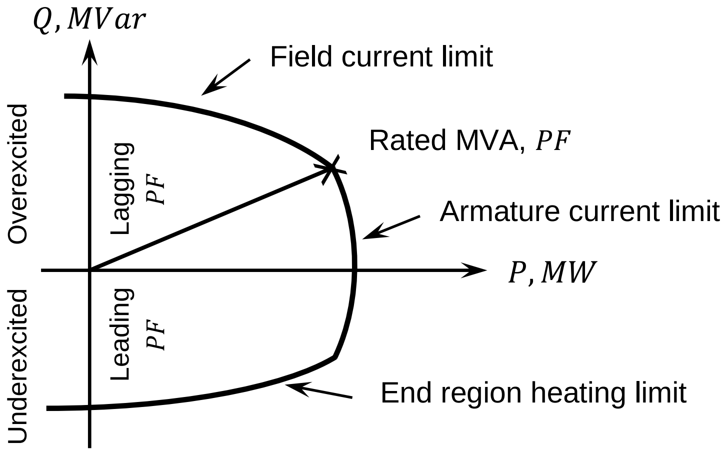

Figure 3-10: Capability curve of a synchronous generator

A typical thermal unit may possibly have a steam valve in operation, or a vibration in a shaft bearing. These cause a discontinuity and interference in input/output curve sections. This called prohibited zones, as shown in Figure 3-11. In practical operation of a thermal unit, changing the power output must stay within all capacity limits and avoid the unit from operating in the prohibited zones [5].

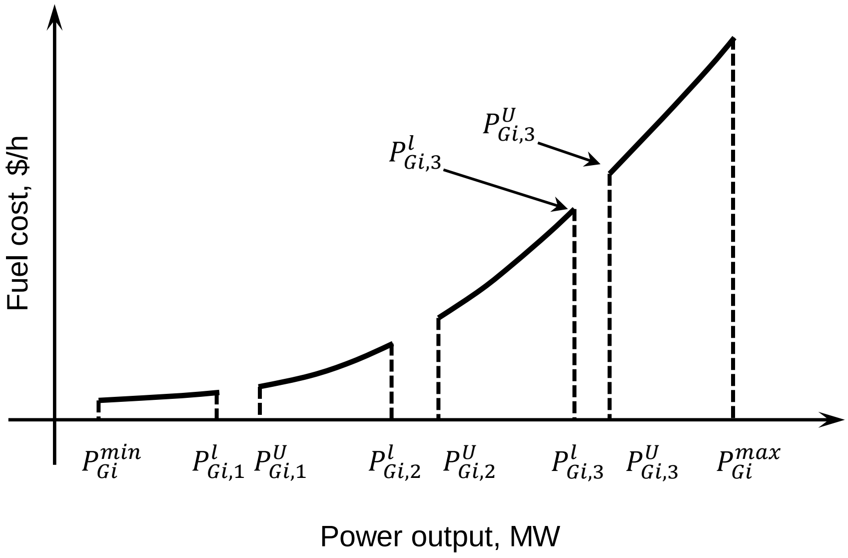

Figure 3-11: Operating cost curve including upper, lower limits and prohibited operating zones

Minimum, maximum power limits and prohibited zones of generator i are given by [4]:

$$\begin{cases} P^{min}_{Gi} \leq P_{Gi} \leq P^{l}_{Gi} \\ P^{U}_{Gi,j-1} \leq P_{Gi} \leq P^{l}_{Gi,j} \\ P^{U}_{Gi,Zi} \leq P_{Gi} \leq P^{max}_{Gi} \end{cases} \qquad i = 1,2 \ldots NG,\ j = 1,2 \ldots z \tag{30}$$

The power output of a practical generator cannot be adjusted instantaneously without limits. The operating range of all operating units is constrained by limits during each dispatch period. These limits are called ramp rate limits. Consequently, the following dispatch output of a generator should be limited between the constraints of up and down ramp rates [5].Therefore, for generator i, the real power generated P_{Gi} in any certain time may not exceed the real power of the previous time interval P^{0}_{Gi} by more than up ramp rate limit UR_i and not less than the real power of the previous interval by more than down ramp rate limit DR_i of the generator.

Ramp rate limits of generator i are given by [5]:

$$\max\left(P_{Gi}^{min}, P_{Gi}^{0} - DR_i\right) < P_{Gi} < \min(P_{Gi}^{max}, P_{Gi}^{0} + UR_i) \tag{31}$$

3.4.2. Power Balance Including Losses and Wind power

The total real power output of all thermal and wind generators must always be equal to the sum of the real power demands and the total system real power losses.

$$P_{GT} = \sum_{i=1}^{NG} P_{Gi} + \sum_{f=1}^{NF} \sum_{w=1}^{NW} P_{w.f} = P_D + P_l \tag{32}$$

3.4.3. Loss Formula and B-Matrix

Power plants in a power system are spread out geographically. Transmission network losses must be considered to accomplish a true economic dispatch solution. Total network loss is expressed as a function of unit generations. To calculate network losses, Kron's approximate formula is commonly used by the power utility industry. Total transmission network real power loss in the system is given by Kron's formula [51]:

$$P_l = \sum_{i=1}^{NG} \sum_{j=1}^{NG} P_{Gi} B_{ij} P_{Gj} + \sum_{i=1}^{NG} B_{oj} P_{Gi} + B_{oo} \tag{33}$$

3.4.4. Dynamic Economic Dispatch

Dynamic economic dispatch is an extension of conventional economic dispatch problem which takes into account the ramp rate limits on of the generation units. Solving dynamic economic dispatch problem is carried out by dividing the entire dispatch period to small time periods and solving the conventional economic dispatch of each small time period [34].

3.5. MATHEMATICAL REPRESENTATION

The economic dispatch problem is a nonlinear problem with equality and non-equality constrains, it can be considered as a part of unit commitment problem.

The solution can be obtained by various methods. The aim is to obtain an optimum solution to give minimum cost and/or emission and satisfying all constrains.

By solving economic dispatch problem the optimal solution is obtained while satisfying number of constrains, which are:

- **Balance of power:** total power output of all generators must equal the total power demand plus transmission losses.
- **Generators limits:** Minimum and maximum power limits, ramp rate limit and prohibited zones.

3.5.1. Objective Function

The total operating cost for thermal generating units (C_g) in $\$/hour$ and total emission (E_T) in $kg/hour$ are given by:

$$Cost(C_g) = \sum_{i=1}^{NG} C_i(P_{Gi}) \tag{34}$$

$$Emission(E_T) = \sum_{i=1}^{NG} E_i(P_{Gi}) \tag{35}$$

Total operating cost of committed generators (C_T) including wind generating units is given by:

$$Cost(C_T) = \sum_{i=1}^{NG} C_g + C_{\mathrm{w}} \tag{36}$$

For dynamic economic dispatch, the total operating cost and emission become [34]:

$$C_g = \sum_{t=1}^{\mathcal{T}} \sum_{i=1}^{NG} C_i(P_{Gi}) \tag{37}$$

$$E_T = \sum_{t=1}^{\mathcal{T}} \sum_{i=1}^{NG} E_i(P_{Gi}) \tag{38}$$

where $\mathcal{T}$ is the number of dispatch hours.

3.5.2. Solving Economic Dispatch Problem

Solution of economic dispatch problem is obtained by obtaining the minimum value of the objective function. The objective function can be the total generation cost. If emission levels are considered, the objective function will be a combination of both cost and emission. In this case the solution can be minimizing total cost only, or minimizing total emission only or minimizing both total cost and emission.

Equality and inequality constrains should be taken in count when solving economic dispatch problem. Equality constrain is the power balance and the inequality constrains are the generator power limits.

The objective function which is the sum of total generating cost and total emission is given by:

$$f_T = C_T + r \times E_T \tag{39}$$

Where r is the weight factor between cost and emission. Setting $r = 0$, then the emission is not considered.

For combined economic emission dispatch problem, the solution obtained by minimizing both cost and emission functions. A proper value of r can be obtained by the ratio between the maximum fuel cost and the maximum emission [6], and given as:

$$r_i = \frac{C_i(P_{Gi}^{max})}{E_i(P_{Gi}^{max})} = \frac{\alpha_i + \beta_i P_{Gi}^{max} + \gamma_i P_{Gi}^{max\,2} + \left|\eta_i \sin(\chi_i (P_{Gi}^{min} - P_{Gi}^{max})\right|}{a_i + b_i P_{Gi}^{max} + c_i P_{Gi}^{max\,2} + d_i \exp(\delta_i P_{Gi}^{max})} \tag{40}$$

The equality constrain of economic dispatch problem is the power balance. Power balance means that the total power generated should equal the total demand plus the total system losses as given in equation (32) and can be rewritten as:

$$P_D + P_l - \sum_{i=1}^{NG} P_{Gi} + \sum_{f=1}^{NF} \sum_{w=1}^{NW} P_{w.f} = 0 \tag{41}$$

The inequality constrains of economic dispatch problem are the generator minimum and maximum power, prohibited zones and ramp rate limits given in equations (30) and (31).

In summary, the economic dispatch is to solve the following nonlinear constrained optimization problem:

Minimize

$$f_T \tag{42}$$

Subject to:

$$P_D + P_l - \sum_{i=1}^{NG} P_{Gi} + \sum_{f=1}^{\mathrm{NF}} \sum_{w=1}^{\mathrm{NW}} P_{w.f} = 0 \tag{43}$$

$$\max\left(P_{Gi}^{min}, P_{Gi}^{0} - DR_i\right) < P_{Gi} < min(P_{Gi}^{max}, P_{Gi}^{0} + UR_i), \quad i = 1,2 \ldots NG \tag{44}$$

$$\begin{cases} P_{Gi}^{min} \le P_{Gi} \le P_{Gi}^{l} \\ P_{Gi,j-1}^{U} \le P_{Gi} \le P_{Gi,j}^{l} \\ P_{Gi,Zi}^{U} \le P_{Gi} \le P_{Gi}^{max} \end{cases} \qquad i = 1,2 \ldots NG, \; j = 1,2 \ldots z \tag{45}$$

Mathematical model and formulation of economic dispatch problem has been presented in this chapter, considering both emission and wind power. In the next chapter, fractal search and stochastic fractal search are discussed.

4

STOCHASTIC FRACTAL SEARCH

4.1. INTRODUCTION

Stochastic fractal search algorithm is one of the latest metaheuristic global optimization algorithms that has been proposed by Salimi, Hamid in 2015. As in the case of most of the nature-inspired evolutionary algorisms, stochastic fractal search imitates a natural behavior, which is inspired by the natural phenomenon of growth by using the mathematic concept of fractal. The particles in the stochastic fractal search algorithm explore the search space more efficiently using the diffusion property, which is implemented commonly in random fractals [2].

Metaheuristics have two main properties: exploitation (intensification) property and exploration (diversification) property. The exploitation property is searching around the current best solutions, and selecting the best candidates or solutions. The exploration property investigates the efficiency of the algorithm in exploring the search space, usually by the randomization method.

All procedures in the stochastic fractal search algorithm are divided into two processes; diffusing process and updating process. In the diffusing process, the chance of finding the global minimum is increased. Each particle diffuses around its current position. In the updating process, the problem space is exploring efficiently, it uses some random methods as updating processes [2].

4.2. FRACTAL SEARCH

Fractal is a natural phenomenon that indicates the property of an object or quantity or a mathematical set that exhibits a repeating pattern (a self-similar structure) that displays on all scales. Based on the fractal characteristics, the stochastic fractal search metaheuristic algorithm inspires random fractals grown by diffusion limited aggregation (DLA) method concept as a successful search algorithm in both accuracy and time consumption. The diffusion limited aggregation is the process by which particles experiencing a random walk due to Brownian motion cluster together to form aggregates of such particles [2].

Random fractals can be generated by modifying the iteration process by means of stochastic rules. Stochastic fractal search employs a random walk to simulate the diffusion process, where the diffusing particle remains attached to the seed particle which creates it. This process is repeated until a cluster is formed [2].

4.3. STOCHASTIC FRACTAL SEARCH

There are two main processes that take place in the stochastic fractal search algorithm: the diffusion process and the updating process. In the former one, each particle diffuses around its present position to assure exploitation property. This diffusion prevents of being trapped in the local minima and improves the chance of finding the global minima. In the second process, the algorithm simulates how a point in a group updates its position based on the positions of other points in the group [2].

The stochastic fractal search considers a static diffusion process. i.e., the best generated particle from the diffusing process is the only particle that is considered, and the rest of the particles are ignored. In addition to efficient exploration of the problem space, stochastic fractal search uses some random methods as updating processes [2].

To create new particles from the diffusion procedure, stochastic fractal search uses the Gaussian statistical methods, where the Gaussian distribution is the random walk used in the DLA growth process of stochastic fractal search [2].

If ε and ε' are uniformly distributed random numbers restricted to [0,1], BP is the position of the best point, $\mathrm{P_i}$ is the ith point in the group, then a series of Gaussian walks ($\mathrm{GW_1}$ and $\mathrm{GW_2}$) participating in the diffusion process are described by the following two equations:

$$\mathrm{GW_1} = \mathrm{Gaussian}\ (\mu_{\mathrm{BP}}, \sigma) + (\varepsilon \times \mathrm{BP} - \varepsilon' \times \mathrm{P_i}) \tag{46}$$

$$\mathrm{GW_2} = \mathrm{Gaussian}\ (\mu_{\mathrm{P}}, \sigma) \tag{47}$$

Where μ_{BP}, μ_{P} and σ are the Gaussian means and standard deviation of (46) and (47): $\mu_{\mathrm{BP}} = |BP|$, and $\mu_{\mathrm{P}} = |\mathrm{P_i}|$. If g indicates the generation number, the standard deviation in the above equations is computed as follows:

$$\sigma = \left| \frac{\log(\mathrm{g})}{\mathrm{g}} \times (\mathrm{P_i} - \mathrm{BP}) \right| \tag{48}$$

For a D-dimensional global optimization problem, each denoted individual is considered to solve the problem has been built based on a D-dimensional vector. During the initialization stage, each point is initialized randomly based on minimum and maximum bounds. If UB and LB indicate, respectively, the vectors of upper and the lower bounds of a problem, the initialization equation of the jth point, $\mathrm{P_j}$, is expressed as follows:

$$\mathrm{P_j} = \mathrm{LB} + \varepsilon \times (\mathrm{UB} - \mathrm{LB}) \tag{49}$$

After initializing all points, the fitness function of each point is evaluated to achieve the best point (BP) among all points. To exploit problem search space, consistent with the exploitation property in the diffusion procedure, all points wander around their current position.

Due to the exploration property, stochastic fractal search uses two statistical procedures to increase the better space exploration. The first procedure is carried out on each individual vector index, while the second procedure is then carried out to all points. First of all, the first procedure rank all points based on the value of the fitness function. Each point i in the group is then assigned a probability value $(\mathrm{P}_{\mathrm{ai}})$ which abides by a simple uniform distribution, which is given by:

$$\mathrm{P}_{\mathrm{ai}} = \frac{\mathrm{rank}(\mathrm{P}_{\mathrm{i}})}{\mathrm{N}} \tag{50}$$

Where $\mathrm{rank}\,(\mathrm{P}_{\mathrm{i}})$ is the rank of point P_{i} among the other points in the group, and N is the number of all points in the group. Equation (50) indicates that the better the point, the higher the probability. For each point P in group, based on whether or not the condition $\mathrm{P}_{\mathrm{ai}} < \varepsilon$ is satisfied, the jth component of P_{i}, is updated according to the next equation, otherwise it remains unchanged.

$$\mathrm{P'}_{\mathrm{i}}(\mathrm{j}) = \mathrm{P}_{\mathrm{r}}(\mathrm{j}) - \varepsilon \times (\mathrm{P}_{\mathrm{t}}(\mathrm{j}) - \mathrm{P}_{\mathrm{i}}(\mathrm{j})) \tag{51}$$

Where $\mathrm{P'}_{\mathrm{i}}(\mathrm{j})$ is the new modified position of P_{i}, P_{r} and P_{t} are randomly selected points in the group, ε is a random number selected from the uniform distribution in the continuous space [0, 1].

From previous discussion, it can be noted that the first statistical procedure is carried out on the components of the points. To improve the quality of exploration and satisfy the diversification property, the second statistical procedure, on the other hand, modifies the position of a point considering the position of other points in the group.

Once again, before initiating the second statistical procedure, all points obtained from the first statistical procedure are ranked based on equation 50. Similar to the first statistical process, if the condition $\mathrm{P_{ai}} < \varepsilon$ is held for a new point$\mathrm{P'_i}$, the current position of $\mathrm{P'_i}$ is modified according to equations given below. Otherwise no update occurs.

$$\mathrm{P''_i} = \mathrm{P'_i} - \Psi \times (\mathrm{P'_i} - \mathrm{BP}) \qquad \Psi \leq 0.5 \tag{52}$$

$$\mathrm{P''_i} = \mathrm{P'_i} - \Psi \times (\mathrm{P'_i} - \mathrm{P'_r}) \qquad \Psi > 0.5 \tag{53}$$

Where $\mathrm{P'_r}$ and $\mathrm{P'_t}$ are randomly selected points obtained from the first procedure, and Ψ are random numbers generated by the Gaussian normal distribution. The new point $\mathrm{P''_i}$ replaced $\mathrm{P'_i}$ if its fitness function value is better than $\mathrm{P'_i}$.

The flowchart of the stochastic fractal search algorithm is shown in Figure 4-1.

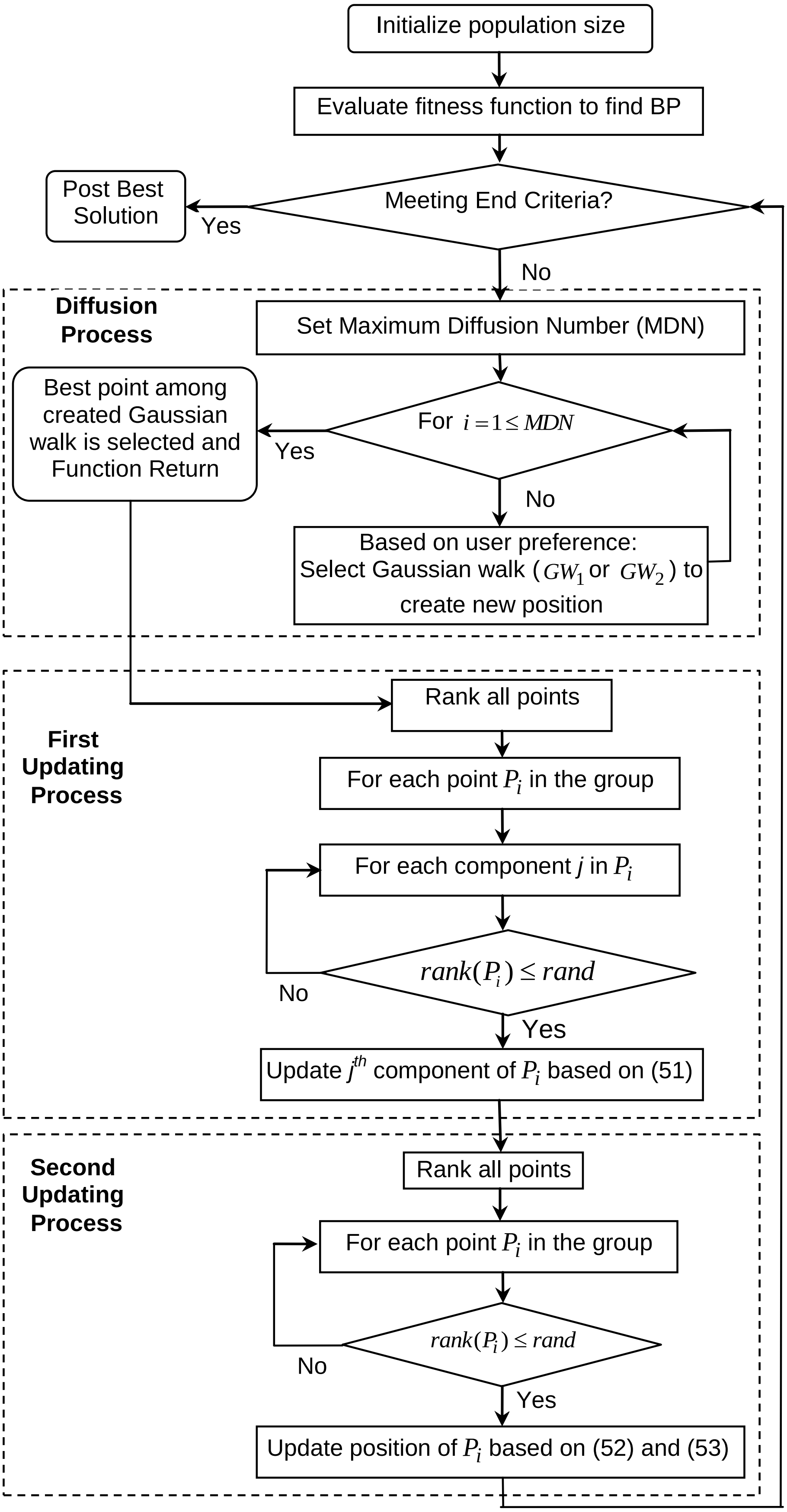

Figure 4-1: Stochastic fractal search flowchart

The pseudo algorithm of the SFS is as follows [2]:

```
 "Initialize a population of N points
   While g < maximum generation or (stop criterion) Do
 {
     For each Point $P_i$ in the system Do
     {
         Call Diffusion Process with the following process:
         {
             q = (maximum considered number of diffusion).
             For j = 1 to q Do
             {
                 If (user uses Gaussian walk to solve the problem)
                 {
                 Create a new point based on Eq. (46).
               }
               Else (user uses another Gaussian walks to solve the problem)
               {
                 Create a new point based on Eq. (47).
               }
           }
         }
     }
         Call Updating Process with the following process
         {
             First Updating Process:
             First, all points are ranked based on Eq. (50).
             For each Point $P_i$ in the system Do
               {
                 For each component j in $P_i$ Do
                   {
                   If rand [0, 1] $\geq$ $Pa_i$
                     {
                       Update the component j in $P_i$ based on Eq. (51).
                     }
                   Else
                   {
                       Do nothing.
                   }
             }
             Second Updating Process:
             Once again, all points obtained by the first update process are ranked based on
             Eq. (50).
             For each new point $P_i$ in the system Do
               {
                   If rand [0, 1] $\geq$ $Pa_i$'
                 {
                   Update the position based on Eq. (52) and Eq. (53).
                 }
                 Else
                 {
                   Do nothing.
                 }
           }
     }
}"
```

5

SIMULATION RESULTS AND DISCUSSIONS

5.1. SYSTEMS UNDER STUDY

In the present work various power systems have been studied and solutions using SFS was obtained. The systems can be categorized into four scenarios, each one of them has different cases as follows:

1. First scenario: cost only is considered without emission or wind power. There are four cases in this scenario:
    a. **6 unit system** with quadratic cost function. Valve-point effect is not considered but losses and prohibited zones are taken into account.
    b. **13 unit system** with quadratic cost function. Valve-point effect is considered but losses are not considered in this case.
    c. **40 unit system**: quadratic cost function only is considered and ignoring any other factors.
    d. **40 unit system** with quadratic cost function. Valve-point effect is considered but transmission losses are neglected.
2. The second scenario: cost and emission are considered without wind power. There are four cases in this scenario:

a. **6 unit system** with quadratic cost and emission function. Valve-point effect and transmission losses are not considered.

b. **10 unit system** with quadratic cost and emission function. Valve-point effect and transmission losses are considered.

c. **11 unit system**: quadratic cost and emission function are considered. Transmission losses are not considered.

d. **40 unit system** with quadratic cost and emission function. Valve-point effect is considered but transmission losses are not considered.

3. In the third scenario, cost emission and wind power are considered; there is one system in this scenario. The study of the system can be divided in to two cases:

a. First case, **6 thermal unit system**: the studied system considers emission and cost. Wind power is ignored in the system.

b. In the second case **three wind generators are placed in the system and three thermal generating units are removed**. The cost and emission are taken into account.

4. The forth scenario is dynamic economic dispatch. Two cases are studied in this scenario:

a. Case 1: **5 unit system**, where cost, transmission losses and valve-point effect are considered.

b. Case 2: **10 unit system**, which include cost only. Valve-point effect and transmission losses are neglected.

5.2. CONSIDERING COST

5.2.1. Case 1: 6 Unit System

This system includes six thermal generation units, which have the cost coefficients and limits presented in Table 5-1, ramp rate limits and prohibited zones presented in Table 5-2. The system contains 26 buses and 46 transmission lines, and the load demand is 1263 MW [4], the results obtained are compared with the corresponding genetic algorithm results as well as particle swarm optimization results.

Table 5-1: Generators cost-coefficients and limits of the 6-unit system

Unit	α_i	β_i	γ_i	P_{Gi}^{min}	P_{Gi}^{max}
i	*\$/h*	*\$/MWh*	*\$/MW²h*	*MW*	*MW*
1	240	7.00	0.0070	100	500
2	200	10.0	0.0095	50	200
3	220	8.50	0.0090	80	300
4	200	11.0	0.0090	50	150
5	220	10.5	0.0080	50	200
6	190	12.0	0.0075	50	120

Table 5-2: Ramp rate limits and prohibited zones of the 6-unit system

Unit	P_{Gi}^{0}	UR_i	DR_i	Prohibited zones
i	*MW*	*MW/h*	*MW/h*	*MW*
1	440	80	120	[210 240][350 380]
2	170	50	90	[90 110][140 160]
3	200	65	100	[150 170][210 240]
4	150	50	90	[80 90]110 120]
5	190	50	90	[90 110][140 150]
6	110	50	90	[75 85][100 105]

Loss coefficients of this 6-unit system are given by the following B-matrix:

$$B_{ij} = \begin{bmatrix} 0.17 & 0.12 & 0.07 & -0.01 & -0.05 & -0.02 \\ 0.12 & 0.14 & 0.09 & 0.01 & -0.06 & -0.01 \\ 0.07 & 0.09 & 0.31 & 0.00 & -0.1 & -0.06 \\ -0.01 & -0.06 & 0.00 & 0.24 & -0.06 & -0.08 \\ -0.05 & -0.06 & -0.10 & -0.06 & 1.29 & -0.02 \\ 0.02 & -0.01 & -0.06 & -0.08 & -0.02 & 1.5 \end{bmatrix} \times 10^{-3}$$

$$B_{io} = [-0.3908 \quad -0.1297 \quad 0.7047 \quad 0.0591 \quad 0.2161 - 0.6635] \times 10^{-3}$$

$$B_{oo} = 0.0056$$

Table 5-3 presents the optimal values obtained by solving the optimization problem using stochastic fractal search, genetic algorithm and particle swarm optimization.

Table 5-3: Optimal solution of the 6-unit system

P_{Gi}	Optimization Method		
MW	GA	PSO	SFS
P_{G1}	474.81	447.50	**448.0000**
P_{G2}	178.64	173.32	**172.7072**
P_{G3}	262.21	263.47	**263.3454**
P_{G4}	134.28	139.06	**139.8460**
P_{G5}	151.90	165.48	**164.3151**
P_{G6}	74.18	87.13	**87.7195**
P_L	13.022	12.958	**12.9334**
P_{GT}	1276.03	1276.01	**1275.93**
C_T **[$/h]**	15459	15450	**15450**

In the first studied system, the solution obtained regarding the cost using stochastic fractal search is $15450/h, which is the same as the solution obtained by particle swarm optimization and lower than genetic algorithm, but the power losses is 12.9334 MW, which is lower than the results of both methods. This shows the effectiveness and the ability of stochastic fractal search algorithm in solving economic dispatch problem including generator limits and transmission losses.

5.2.2. Case 2: 13 Unit System

The system consists of 13 thermal generating units with total load demand of 1800 MW. The losses are not considered in this case. Study cost coefficients, generators limits and valve effect coefficient are shown in Table 5-4 [26].

Table 5-5 shows the optimal solution obtained by stochastic fractal search and other solution methods. The total cost obtained by stochastic fractal search is $17933/h, which is lower than deferential evolution solution by $26.18/h and lower than sequential quadratic programming solution by $5.52/h.

Table 5-4: Cost coefficients, generators limits and valve effect coefficients of the 13-unit system

Unit	α_i	β_i	γ_i	P_{Gi}^{min}	P_{Gi}^{max}	η_i	χ_i
i	*\$/h*	*\$/MWh*	*\$/MW²h*	*MW*	*MW*	*\$/h*	*Rad/MWh*
1	550	8.10	0.00028	0	680	300	0.035
2	309	8.10	0.0005	0	360	200	0.042
3	307	8.10	0.00056	0	360	150	0.042
4	240	7.74	0.00324	60	180	150	0.063
5	240	7.74	0.00324	60	180	150	0.063
6	240	7.74	0.00324	60	180	150	0.063
7	240	7.74	0.00324	60	180	150	0.063
8	240	7.74	0.00324	60	180	150	0.063
9	240	7.74	0.00324	60	180	150	0.063
10	126	7.74	0.00284	40	120	100	0.084
11	126	8.60	0.00284	40	120	100	0.084
12	126	8.60	0.00284	55	120	100	0.084
13	126	8.60	0.00284	55	120	100	0.084

Table 5-5: Optimal solution of the 13-unit system

P_{Gi}	Optimization Method		
MW	DE	DEC-SQP	SFS
P_{G1}	——————	526.1823	**515.2944**
P_{G2}	——————	252.1857	**258.5680**
P_{G3}	——————	257.9200	**223.3036**
P_{G4}	——————	78.2586	**101.0292**
P_{G5}	——————	84.4892	**99.62523**
P_{G6}	——————	89.6198	**102.4947**
P_{G7}	——————	88.0880	**104.6944**
P_{G8}	——————	101.1571	**103.6471**
P_{G9}	——————	132.0983	**100.9663**
P_{G10}	——————	40.0007	**40.09425**
P_{G11}	——————	40.0000	**40.12567**
P_{G12}	——————	55.0000	**55.00022**
P_{G13}	——————	50.0000	**55.15642**
P_L	0	0	**0**
P_{GT}	1800	1800	**1800**
C_T **[\$/h]**	17959.609	17938.952	**17933.429**

5.2.3. Case 3: 40 Unit System

This system consists of 40 generation units. The units are a mix of oil, gas, coal, diesel, and combined cycle units. Total demand of the system is 8550 MW, generator cost coefficients and limits are given in Table 5-6 [27].Transmission losses are neglected. Solution using SFS is also given in Table 5-6. The reference paper uses modified particle swarm optimization technique to solve economic dispatch problem.

Table 5-6: Cost coefficients, generators limits and SFS solutiotion of the 40-unit system

Unit	α_i	β_i	γ_i	P_{Gi}^{min}	P_{Gi}^{max}	SFS
i	$\$/h$	$\$/MWh$	$\$/MW^2h$	*MW*	*MW*	*MW*
1	170.4\`4	8.336	0.03073	40	80	**73.5038**
2	309.54	7.0706	0.02028	60	120	**119.9986**
3	369.03	8.1817	0.00942	80	190	**189.9996**
4	135.48	6.9467	0.08482	24	42	**34.9770**
5	135.19	6.5595	0.09693	26	42	**32.6788**
6	222.33	8.0543	0.01142	68	140	**139.9993**
7	287.71	8.0323	0.00357	110	300	**299.9998**
8	391.98	6.999	0.00492	135	300	**299.9997**
9	455.76	6.602	0.00573	135	300	**292.9024**
10	722.82	12.908	0.00605	130	300	**130.0008**
11	635.2	12.986	0.00515	94	375	**94.0008**
12	654.69	12.796	0.00569	94	375	**94.0027**
13	913.4	12.501	0.00421	125	500	**125.0002**
14	1760.4	8.8412	0.00752	125	500	**266.9111**
15	1728.3	9.1575	0.00708	125	500	**262.0069**
16	1728.3	9.1575	0.00708	125	500	**269.6199**
17	1728.3	9.1575	0.00708	125	500	**261.8901**
18	647.85	7.9691	0.00313	220	500	**499.9998**
19	649.69	7.955	0.00313	220	500	**440.9808**
20	647.83	7.9691	0.00313	242	550	**549.9990**
21	647.83	7.9691	0.00313	242	550	**549.9993**
22	785.96	6.6313	0.00298	254	550	**550.0000**
23	785.96	6.6313	0.00298	254	550	**549.9996**
24	794.53	6.6611	0.00284	254	550	**546.4674**
25	794.53	6.6611	0.00284	254	550	**549.9994**
26	801.32	7.1032	0.00277	254	550	**546.2601**
27	801.32	7.1032	0.00277	254	550	**532.8674**
28	1055.1	3.3353	0.52124	10	150	**14.8896**
29	1055.1	3.3353	0.52124	10	150	**10.0100**
30	1055.1	3.3353	0.52124	10	150	**10.0051**
31	1207.8	13.052	0.25098	20	70	**20.0002**
32	810.79	21.887	0.16766	20	70	**20.0027**
33	1247.7	10.244	0.2635	20	70	**20.0003**
34	1219.2	8.3707	0.30575	20	70	**20.0000**
35	641.43	26.258	0.18362	18	60	**18.0002**
36	1112.8	9.6956	0.32563	18	60	**18.0001**
37	1044.4	7.1633	0.33722	20	60	**20.0271**
38	832.24	16.339	0.23915	25	60	**25.0000**
39	832.24	16.339	0.23915	25	60	**25.0003**
40	1035.2	16.339	0.23915	25	60	**25.0001**

Results obtained using stochastic fractal search and those obtained by particle swarm optimization are shown in Table 5-7. The results show that the total cost obtained using the new technique is approximately lower by $1400/h.

Table 5-7: Optimal solution of the 40-unit System

		PSO	SFS
P_L	MW	0	**0**
P_{GT}	MW	8550	**8550**
C_T	$\$/h$	116943	**115470**

5.2.4. Case 4: 40 Unit System With Valve-Point Effect

This system consists of 40 generation units, with valve-point effect. Total load demand is equal to 10500 MW.

Table 5-8 shows the optimal solution obtained by stochastic fractal search and other solution methods, the solution obtained using stochastic fractal search is $120340/h, which is lower than the solution obtained by sequential quadratic programming solution by $1401/h and lower than deferential evolution solution by $1560/h, so that the obtained solution using stochastic fractal search is the lowest.

Table 5-8: Optimal solutions of the 40-unit system including valve-point effect

P	Optimization Method		
MW	DE	DEC-SQP	SFS
P_L	0	0	**0**
P_{GT}	10500	10500	**10500**
C_T **[$/h]**	121900	121741	**120340**

Table 5-9 shows quadratic cost coefficients of generators including valve-point effect coefficients. Transmission losses are not considered [26]. The optimal SFS solution is also given in Table 5-9.

Table 5-9: Cost coefficients, generators limits, valve effect coefficients and SFS solution of the 40-unit system

Unit	α_i	β_i	γ_i	P_{Gi}^{min}	P_{Gi}^{max}	η_i	χ_i	SFS
i	$\$/h$	$\$/MWh$	$\$/MW^2h$	MW	MW	$\$/h$	Rad/MW	MW
1	94.705	6.73	0.00690	36	114	100	0.084	**113.9098**
2	94.705	6.73	0.00690	36	114	100	0.084	**113.9247**
3	309.54	7.07	0.02028	60	120	100	0.084	**98.0009**
4	369.03	8.18	0.00942	80	190	150	0.63	**157.9259**
5	148.89	5.35	0.01140	47	97	120	0.077	**96.9895**
6	222.33	8.05	0.01142	68	140	200	0.084	**107.7687**
7	278.71	8.03	0.00357	110	300	200	0.042	**299.3204**
8	391.98	6.99	0.00492	135	300	200	0.042	**256.3926**
9	455.76	6.60	0.00573	135	300	200	0.042	**299.6428**
10	722.82	12.90	0.00605	130	300	200	0.042	**130.0150**
11	635.20	12.90	0.00515	94	375	200	0.042	**94.2499**
12	654.69	12.80	0.00539	94	375	200	0.042	**94.5931**
13	913.40	12.50	0.00421	125	500	300	0.035	**196.1035**
14	1760.4	8.84	0.00752	125	500	300	0.035	**386.4045**
15	1728.3	9.15	0.00708	125	500	300	0.035	**374.5277**
16	1728.3	9.15	0.00708	125	500	300	0.035	**310.0143**
17	647.85	7.97	0.00313	220	500	300	0.035	**489.3796**
18	649.69	7.95	0.00313	220	500	300	0.035	**461.9662**
19	647.83	7.97	0.00313	242	550	300	0.035	**545.5149**
20	647.81	7.97	0.00313	242	550	300	0.035	**513.0920**
21	785.96	6.63	0.00298	254	550	300	0.035	**549.7983**
22	785.96	6.63	0.00298	254	550	300	0.035	**523.5309**
23	794.53	6.66	0.00284	254	550	300	0.035	**549.7741**
24	794.53	6.66	0.00284	254	550	300	0.035	**549.9140**
25	801.32	7.10	0.00277	254	550	300	0.035	**548.3053**
26	801.32	7.10	0.00277	254	550	300	0.035	**541.3216**
27	1055.1	3.33	0.52124	10	150	120	0.077	**39.7752**
28	1055.1	3.33	0.52124	10	150	120	0.077	**10.2137**
29	1055.1	3.33	0.52124	10	150	120	0.077	**10.0790**
30	148.89	5.35	0.01140	47	97	120	0.077	**75.5158**
31	222.92	6.43	0.00160	60	190	150	0.063	**181.7705**
32	222.92	6.43	0.00160	60	190	150	0.063	**189.9689**
33	222.92	6.43	0.00160	60	190	150	0.063	**189.9558**
34	107.87	8.95	0.00010	90	200	200	0.042	**199.2706**
35	116.58	8.62	0.00010	90	200	200	0.042	**183.3559**
36	116.58	8.62	0.00010	90	200	200	0.042	**199.67714**
37	307.45	5.88	0.01610	25	110	80	0.098	**109.5170**
38	307.45	5.88	0.01610	25	110	80	0.098	**108.6019**
39	307.45	5.88	0.01610	25	110	80	0.098	**109.8282**
40	647.83	7.97	0.00313	242	550	300	0.035	**490.0961**

5.3. CONSIDERING COST AND EMISSION

5.3.1. Case 1: 6 Unit System

The system consists of 6 generators, cost coefficients and generators limits are shown in Table 5-10. Emission coefficients are shown in Table 5-11. Total load demand is 1000 MW [6]. A comparison of the results between SFS and gravitational search algorithm solution is made.

Table 5-10: Cost coefficients and generators limits of the 6-unit system

Unit	α_i	β_i	γ_i	P_{Gi}^{min}	P_{Gi}^{max}
i	$\$/h$	$\$/MWh$	$\$/MW^2h$	*MW*	*MW*
1	756.800	38.540	0.1525	10	125
2	451.325	46.160	0.1060	10	150
3	1050.00	40.400	0.0280	35	225
4	1243.53	38.310	0.0355	35	210
5	1658.57	36.328	0.0211	130	325
6	1356.66	38.270	0.0180	125	315

Table 5-11: Emission coefficients of the 6-unit system

Unit	a_i	b_i	c_i
i	*kg/h*	*kg/MWh*	kg/MW^2h
1	13.860	0.3300	0.0042
2	13.860	0.3300	0.0042
3	40.267	-0.5455	0.0068
4	40.267	-0.5455	0.0068
5	42.900	-0.5112	0.0046
6	42.900	-0.5112	0.0046

Tables 5-12 and 5-13 show the optimal values obtained by solving the optimization problem using stochastic fractal search and other methods. The solution obtained is lower than other techniques solution. Solution obtained using stochastic fractal search is \$51252/h, which is lower than the solution obtained by genetic algorithm and differential evolution solution by \$10/h and lower than particle swarm optimization solution by \$17/h.

Comparing the result with gravitation search algorithm result we have $3/h lower cost and approximately the same emission rate. But comparing SFS with, λ- iteration method, much lower cost of $12/h is obtained and the emission rates are reduced by 1.5 kg/h. By using this method we have a lower fuel cost and emission rates.

Table 5-12: Optimal Solution of the 6-unit System using SFS

P_{Gi}	Optimization Method
MW	SFS
P_{G1}	**80.89420**
P_{G2}	**80.63590**
P_{G3}	**165.6298**
P_{G4}	**164.4522**
P_{G5}	**254.5702**
P_{G6}	**253.8177**
P_L	**0**
P_{GT}	**1000**
E_T **[kg/h]**	**827.1086**
C_T **[$/h]**	**51252.35**

Table 5-13: Comparison of the results for the 6-unit System

Optimization Method	E_T	C_T
	kg/h	*$/h*
λ - iteration	828.720	51264.6
Recursive	828.715	51264.5
PSO	828.863	51269.6
DE	828.715	51264.6
Simplified recursive	828.715	51264.6
GA similarity	827.261	51262.3
GSA	827.138	51255.7
SFS	**827.109**	**51252.0**

5.3.2. Case 2: 10 Unit System

The system consists of 10 generation units with load demand of 2000 MW. Quadratic cost coefficients and generators limits are shown in Table 5-14. Emission coefficients and valve effect coefficient are shown in Table 5-15. [6]. The results obtained are compared with gravitational search algorithm results.

Table 5-14: Cost coefficients and generators limits of the 10-unit system

Unit	α_i	β_i	γ_i	P_{Gi}^{min}	P_{Gi}^{max}
i	*$/h*	*$/MWh*	*$/MW²h*	*MW*	*MW*
1	1000.403	40.5407	0.12951	10	55
2	950.6060	39.5804	0.10908	20	80
3	900.7050	36.5104	0.12511	47	120
4	800.7050	39.5104	0.12111	20	130
5	756.7990	38.5390	0.15247	50	160
6	451.325	46.1592	0.10587	70	240
7	1243.531	38.3055	0.03546	60	300
8	1049.998	40.3965	0.02803	70	340
9	1658.569	36.3278	0.02111	135	470
10	1356.659	38.2704	0.01799	150	470

Table 5-15: Emission and valve effect coefficients of the 10-unit system

Unit	a_i	b_i	c_i	η_i	χ_i	d_i	δ_i
i	*lb/h*	*lb/MWh*	*lb/MW²h*	*$/h*	*Rad/MWh*	*lb/h*	*1/MW*
1	360.0012	-3.9864	0.04702	33	0.0174	0.25475	0.01234
2	350.0056	-39524	0.04652	25	0.0178	0.25475	0.01234
3	330.0056	-3.9023	0.04652	32	0.0162	0.25163	0.01215
4	330.0056	-3.9023	0.04652	30	0.0168	0.25163	0.01215
5	13.85930	0.3277	0.00420	30	0.0148	0.24970	0.01200
6	13.85930	0.3277	0.00420	20	0.0163	0.24970	0.01200
7	40.26690	-0.5455	0.00680	20	0.0152	0.24800	0.01290
8	40.26690	-0.5455	0.00680	30	0.0128	0.24990	0.01203
9	42.89550	-0.5112	0.00460	60	0.0136	0.25470	0.01234
10	42.89550	-0.5112	0.00460	40	0.0141	0.25470	0.01234

Loss coefficients of this 10-unit system are given by the following B-matrix:

$$B_{ij} = \begin{bmatrix} 49 & 14 & 15 & 15 & 16 & 17 & 17 & 18 & 19 & 20 \\ 14 & 45 & 16 & 16 & 17 & 15 & 15 & 16 & 18 & 18 \\ 15 & 16 & 39 & 10 & 12 & 12 & 14 & 14 & 16 & 16 \\ 15 & 16 & 10 & 40 & 14 & 10 & 11 & 12 & 14 & 15 \\ 16 & 17 & 12 & 14 & 35 & 11 & 13 & 13 & 15 & 16 \\ 17 & 15 & 12 & 10 & 11 & 36 & 12 & 12 & 14 & 15 \\ 17 & 15 & 14 & 11 & 13 & 12 & 38 & 16 & 16 & 18 \\ 18 & 16 & 14 & 12 & 13 & 12 & 16 & 40 & 15 & 16 \\ 19 & 18 & 16 & 14 & 15 & 14 & 16 & 15 & 42 & 19 \\ 20 & 18 & 16 & 15 & 16 & 15 & 18 & 16 & 19 & 44 \end{bmatrix} \times 10^{-6}$$

$$B_{io} = [0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0]$$

$$B_{oo} = 0$$

Table 5-16 shows optimal solution obtained by SFS and other solution methods. Comparing the SFS results, with results of other algorithms, shows that a lower cost than all other methods with almost the same emission rates.

Table 5-16: Optimal solution of the 10-unit system

P_{Gi}	Optimization Method					
MW	MODE	PDE	NSGA	SPEA	GSA	SFS
P_{G1}	54.95	54.96	51.95	52.96	54.9992	**54.4804**
P_{G2}	74.58	79.38	67.26	72.81	79.9586	**80.0000**
P_{G3}	79.43	83.98	73.69	78.11	79.4341	**84.9712**
P_{G4}	80.69	86.59	91.36	83.61	85.0000	**83.5194**
P_{G5}	136.86	144.44	134.05	137.24	142.1063	**138.037**
P_{G6}	172.64	165.78	174.95	172.92	166.5670	**165.902**
P_{G7}	283.82	283.21	289.43	287.20	292.8749	**299.399**
P_{G8}	316.34	312.77	314.06	326.40	313.2387	**315.436**
P_{G9}	448.59	440.11	455.70	448.88	441.1775	**429.956**
P_{G10}	436.43	432.68	431.81	423.90	428.6306	**432.211**
P_{GT}	2084.3	2083.9	2084.26	2084.03	2083.99	**2083.92**
E_T **[lb/h]**	4124.9	4111.4	4130.2	4109.1	4111.4	**4118.4**
C_T **[\$/h]**	113480	113510	113540	113520	113490	**113400**

5.3.3. Case 3: 11 Unit System

The system consists of 11 generating units. Quadratic cost coefficients and generators limits are shown in Table 5-17.Emission coefficients are shown in Table 5-18. Total Demand is 2500 MW [6].

Table 5-17: Cost coefficients and generators limits of the 11-unit system

Unit	α_i	β_i	γ_i	P_{Gi}^{min}	P_{Gi}^{max}
i	$\$/h$	$\$/MWh$	$\$/MW^2h$	MW	MW
1	0.00762	192.699	387.85	20	250
2	0.00838	211.969	441.62	20	210
3	0.00523	219.196	422.57	20	250
4	0.00140	201.983	552.50	60	300
5	0.00154	212.181	557.75	20	210
6	0.00177	191.528	562.18	60	300
7	0.00195	210.681	568.39	20	215
8	0.00106	199.138	682.93	100	455
9	0.00117	199.802	741.22	100	455
10	0.00089	212.352	617.83	110	460
11	0.00098	210.487	674.61	110	465

Table 5-18: Emission coefficients of the 11-unit system

Unit	a_i	b_i	c_i
i	*kg/h*	*kg/MWh*	*kg/MW^{2}h*
1	33.93	-0.67767	0.00419
2	24.62	-0.69044	0.00461
3	33.93	-0.67767	0.00419
4	27.14	-0.54551	0.00683
5	24.15	-0.40060	0.00751
6	37.14	-0.54551	0.00683
7	24.15	-0.40006	0.00751
8	30.45	-0.51116	0.00355
9	25.59	-0.56228	0.00417
10	30.45	-0.41116	0.00355
11	25.59	-0.56228	0.00417

Tables 5-19 and 5-20 show the optimal solutions obtained by solving the optimization problem using stochastic fractal search and other solution methods. Using the new technique, it can be noticed that low cost and low emission rates are obtained. Comparing with gravitational search algorithm, $4/h lower cost and 17 kg/h lower emission rate are obtained. Moreover, the solution obtained using SFS is lower than other techniques solutions by approximately $7/h lower cost and 18 kg/h lower emission rate.

Table 5-19: Optimal solution of the 11-unit system using SFS

P_{Gi}	Optimization Method
MW	SFS
P_{G1}	**130.7778**
P_{G2}	**110.8997**
P_{G3}	**153.2003**
P_{G4}	**208.7158**
P_{G5}	**167.7840**
P_{G6}	**203.2996**
P_{G7}	**1663755**
P_{G8}	**363.4619**
P_{G9}	**320.2738**
P_{G10}	**353.0403**
P_{G11}	**322.1713**
P_L	**0**
P_{GT}	**2500**
E_T ***[kg/h]***	**1985.23**
C_T ***[\$/h]***	**12418.41**

Table 5-20: Comparison of the results for the 11-unit system

Optimization Method	E_T	C_T
	kg/h	*$/h*
λ- iteration	2003.301	12424.94
Recursive	2003.300	12424.94
PSO	2003.720	12428.63
DE	2003.350	12425.06
Simplified recursive	2003.300	12424.94
GA similarity	2003.030	12423.77
GSA	2002.949	12422.66
SFS	**1985.231**	**12418.41**

5.3.4. Case 4: 40 Unit System

The system consists of 40 generation units with total demand of 10500 MW. Quadratic cost coefficients, generators limits and emission coefficients are given in Table 5-23 [6].

Table 5-21 presents the optimal solutions obtained by all methods and Table 5-22 shows the solution obtained using SFS.

Table 5-21: Optimal solution of the 40-unit system

	Optimization Method					
	MODE	PDE	NSGA	SPEA	GSA	SFS
P_{GT}	10500	10500	10500	10500	10500	10500
E_T **[Ton/h]**	211190	211770	210950	211100	210930	**182343.6**
C_T **[$/h]**	125790	125730	125830	125810	125780	**124590**

Table 5-22: Optimal solution of the 40-unit System using SFS

P_{Gi} *[MW]*	SFS	P_{Gi} *[MW]*	SFS	P_{Gi} *[MW]*	SFS	P_{Gi} *[MW]*	SFS
P_{G1}	113.8665	P_{G11}	295.3845	P_{G21}	444.5625	P_{G31}	175.6489
P_{G2}	113.9777	P_{G12}	298.0532	P_{G22}	439.5840	P_{G32}	174.4711
P_{G3}	119.4605	P_{G13}	432.8162	P_{G23}	441.3943	P_{G33}	175.4764
P_{G4}	144.4912	P_{G14}	431.4881	P_{G24}	445.5711	P_{G34}	173.1724
P_{G5}	96.9683	P_{G15}	423.1698	P_{G25}	439.9883	P_{G35}	199.9691
P_{G6}	122.8907	P_{G16}	423.5865	P_{G26}	463.1519	P_{G36}	199.8800
P_{G7}	295.9641	P_{G17}	441.2563	P_{G27}	25.1624	P_{G37}	101.6913
P_{G8}	297.8583	P_{G18}	442.3444	P_{G28}	26.6369	P_{G38}	101.3996
P_{G9}	281.7908	P_{G19}	444.3756	P_{G29}	26.5788	P_{G39}	101.0322
P_{G10}	140.9844	P_{G20}	438.8891	P_{G30}	95.5949	P_{G40}	449.4179

Table 5-23: Cost, emission and valve effect coefficients and generators limits of the 40-unit system

Unit	α_i	β_i	γ_i	P_{Gi}^{min}	P_{Gi}^{max}	a_i	b_i	c_i	η_i	χ_i	d_i	δ_i
i	\$/h	\$/MWh	$\$/MW^2h$	MW	MW	Ton/h	Ton/MWh	Ton/MW^2h	\$/h	Rad/MWh	Ton/h	1/MW
1	94.705	6.73	0.00690	36	114	60	-2.22	0.0480	100	0.084	1.3100	0.05690
2	94.705	6.73	0.00690	36	114	60	-2.22	0.0480	100	0.084	1.3100	0.05690
3	309.54	7.07	0.02028	60	120	100	-2.36	0.0762	100	0.084	1.3100	0.05690
4	369.03	8.18	0.00942	80	190	120	-3.14	0.0540	150	0.063	0.9142	0.04540
5	148.89	5.35	0.01140	47	97	50	-1.89	0.0850	120	0.077	0.9936	0.04060
6	222.33	8.05	0.01142	68	140	80	-3.08	0.0854	200	0.084	1.3100	0.5690
7	278.71	8.03	0.00357	110	300	100	-3.06	0.0242	200	0.042	0.6550	0.02846
8	391.98	6.99	0.00492	135	300	130	-2.32	0.0310	200	0.042	0.6550	0.02846
9	455.76	6.60	0.00573	135	300	150	-2.11	0.0335	200	0.042	0.6550	0.02846
10	722.82	12.90	0.00605	130	300	280	-4.34	0.4250	200	0.042	0.6550	0.02846
11	635.20	12.90	0.00515	94	375	220	-4.34	0.0322	200	0.042	0.6550	0.02846
12	654.69	12.80	0.00539	94	375	225	-4.28	0.0338	200	0.042	0.6550	0.02846
13	913.40	12.50	0.00421	125	500	300	-4.18	0.0296	300	0.035	0.5035	0.02075
14	1760.4	8.84	0.00752	125	500	520	-3.34	0.0512	300	0.035	0.5035	0.02075
15	1760.4	8.84	0.00752	125	500	510	-3.55	0.0496	300	0.035	0.5035	0.02075
16	1760.4	8.84	0.00752	125	500	510	-3.55	0.0496	300	0.035	0.5035	0.02075
17	647.85	7.97	0.00313	220	500	220	-2.68	0.0151	300	0.035	0.5035	0.02075
18	649.69	7.95	0.00313	220	500	222	-2.66	0.0151	300	0.035	0.5035	0.02075
19	647.83	7.97	0.00313	242	550	220	-2.68	0.0151	300	0.035	0.5035	0.02075
20	647.81	7.97	0.00313	242	550	220	-2.68	0.0151	300	0.035	0.5035	0.02075
21	785.96	6.63	0.00298	254	550	290	-2.22	0.0145	300	0.035	0.5035	0.02075
22	785.96	6.63	0.00298	254	550	285	-2.22	0.0145	300	0.035	0.5035	0.02075
23	794.53	6.66	0.00284	254	550	295	-2.26	0.0138	300	0.035	0.5035	0.02075
24	794.53	6.66	0.00284	254	550	295	-2.26	0.0138	300	0.035	0.5035	0.02075
25	801.32	7.10	0.00277	254	550	310	-2.42	0.0132	300	0.035	0.5035	0.02075
26	801.32	7.10	0.00277	254	550	310	-2.42	0.0132	300	0.035	0.5035	0.02075
27	1055.1	3.33	0.52124	10	150	360	-1.11	1.8420	120	0.077	0.9936	0.04060
28	1055.1	3.33	0.52124	10	150	360	-1.11	1.8420	120	0.077	0.9936	0.04060
29	1055.1	3.33	0.52124	10	150	360	-1.11	1.8420	120	0.077	0.9936	0.04060
30	148.89	5.35	0.01140	47	97	50	-1.89	0.0850	120	0.077	0.9936	0.04060
31	222.92	6.43	0.00160	60	190	80	-2.08	0.012	150	0.063	0.9142	0.04540
32	222.92	6.43	0.00160	60	190	80	-2.08	0.012	150	0.063	0.9142	0.04540
33	222.92	6.43	0.00160	60	190	80	-2.08	0.012	150	0.063	0.9142	0.04540
34	107.87	8.95	0.00010	90	200	65	-3.48	0.0012	200	0.042	0.6550	0.02846
35	116.58	8.62	0.00010	90	200	70	-3.24	0.0012	200	0.042	0.6550	0.02846
36	116.58	8.62	0.00010	90	200	70	-3.24	0.0012	200	0.042	0.6550	0.02846
37	307.45	5.88	0.01610	25	110	100	-1.98	0.0950	80	0.098	4.4200	0.06770
38	307.45	5.88	0.01610	25	110	100	-1.98	0.0950	80	0.098	4.4200	0.06770
39	307.45	5.88	0.01610	25	110	100	-1.98	0.0950	80	0.098	1.4200	0.06770
40	647.83	7.97	0.00313	242	550	220	-2.68	0.0151	300	0.035	0.5035	0.02075

5.4. CONSIDERING COST, EMISSION AND WIND POWER

The system consists of 6-thermal unit generators. Cost and emission coefficients are given in Table 5-24 and Table 5-25. In this study thermal generators 1, 2 and 6 replaced by wind generators rated 500 KW, 600 KW and 600 KW, respectively. The total load demand is 2834 KW [28]. The solutions obtained using stochastic fractal search is compared with the solutions in [28], which used a modified teaching learning technique.

The direct electrical energy cost, over estimation and under estimation electrical energy cost coefficients are set to \$120/MWh, \$30/MWh and \$30/MWh, respectively [28].

Table 5-24: Cost coefficients of the 6-unit system

Unit	α_i	β_i	γ_i
i	*\$/h*	*\$/MWh*	*\$/MW²h*
1	10	200	100
2	10	150	120
3	20	180	40
4	10	100	60
5	20	180	40
6	10	150	100

Table 5-25: Emission and valve effect coefficients of the 6-unit system

Unit	a_i	b_i	c_i	d_i	δ_i
i	*kg/h*	*kg/MWh*	*kg/MW²h*	*kg/h*	*1/MW*
1	40.91	-55.54	64.90	0.200	2.857
2	25.43	-60.47	56.38	0.500	3.333
3	42.58	-50.94	45.86	0.001	8.000
4	43.26	-35.60	33.80	2.000	2.000
5	42.58	-50.94	45.86	0.001	8.000
6	61.31	-55.55	51.51	0.010	6.667

5.4.1. Case 1: Solution Without Wind Power

Table 5-26 shows the solutions obtained using stochastic fractal search technique without wind power and setting value of r equals to zero (minimizing cost only).

Comparing the results obtained by stochastic fractal search with those obtained by modified teaching learning algorithm, gives the same cost value $600.111.

By changing the value of r, we can obtain another two different solutions:

- Minimizing emission: cost of $637.7925 and emission of 0.1764 ton
- Minimizing both cost and emission: cost of $601.8331 and emission: 0.1990 ton

Table 5-26: Optimal solution of the 6-unit system without wind power

P_{Gi}	Optimization Method
KW	SFS
P_{G1}	109.7225
P_{G2}	299.7688
P_{G3}	524.3063
P_{G4}	1016.204
P_{G5}	524.3064
P_{G6}	359.6916
P_L	0
P_{GT}	2834
E_T [Ton/h]	**0.2221**
C_T [$/h]	**600.111**

5.4.2. Case 2: Solution Including Wind Power

In Table 5-27, three different solutions are obtained using stochastic fractal search. With the value of r is changed to obtain different solution each time. Comparing the results with modified teaching learning algorithm results is given in Table 5-28. Solutions two and three give the same emission, but with lower cost. Solution one gives higher emission rate using stochastic fractal search, but lower cost.

Comparing the total cost of SFS with wind generators, it can be seen from SFS results that when replacing three thermal generators, with three wind generators, the results give $100/h lower cost, which is almost 17% of the total cost in the system. The emission rates also reduced by 0.1 Ton/h, which is about 50%.

Table 5-27: Optimal solution of the 6-unit system including wind power

P_{Gi}	Optimization Method		
KW	SFS		
Sol #	Solution.1	Solution.2	Solution.3
P_{G1}	245.0	244.5	244.9
P_{G2}	409.4	404.9	419.2
P_{G3}	347.0	363.3	593.6
P_{G4}	951.1	912.5	459.9
P_{G5}	352.3	379.1	586.5
P_{G6}	529.2	529.7	529.8
P_L	0	0	0
P_{GT}	2834	2834	2834
E_T [Ton/h]	**0.1234**	**0.1214**	**0.1063**
C_T [\$/h]	**487.7265**	**488.3771**	**504.9832**

Table 5-28: Optimal solutions of the 6-unit system including wind power

Optimization Method	E_T	C_T
	Ton/h	*\$/h*
SFS solutions	**0.1234**	**487.7265**
	0.1214	**488.3771**
	0.1063	**504.9832**
MTLA solutions	0.1215	488.2176
	0.1214	488.6965
	0.1063	505.3883

5.5. DYNAMIC ECONOMIC DISPATCH

In dynamic economic dispatch, a period of 24 hours is considered. Each hour has certain load demand and a corresponding solution for each hour is obtained. The total cost is calculated by the sum of the costs in each hour. Ramp rate limit is important factor in this study. Two systems have been studied.

5.5.1. Case 1: 5 Unit System

System 1: Cost and losses are considered including valve-point effect for 5 thermal units, that has the following data shown in Table 5-29 and 5-30 [34, 56].

Table 5-29: Cost coefficients, generators limits, ramp rates and valve effect coefficients of the 5-unit system

Unit	α_i	β_i	γ_i	P_{Gi}^{min}	P_{Gi}^{max}	η_i	χ_i	UR_i	DR_i
i	*$/h*	*$/MWh*	*$/MW²h*	*MW*	*MW*	*$/h*	*Rad/MWh*	*MW/h*	*MW/h*
1	25	2.0	0.0080	10	75	100	0.042	30	30
2	60	1.8	0.0030	20	125	140	0.040	30	30
3	100	2.1	0.0012	30	175	160	0.038	40	40
4	120	2.0	0.0010	40	250	180	0.037	50	50
5	40	1.8	0.0015	50	300	200	0.035	50	50

$$B_{ij} = \begin{bmatrix} 49 & 14 & 15 & 15 & 20 \\ 14 & 45 & 16 & 20 & 18 \\ 15 & 16 & 39 & 10 & 12 \\ 15 & 20 & 10 & 40 & 14 \\ 20 & 18 & 12 & 14 & 35 \end{bmatrix} \times 10^{-6}$$

$$B_{io} = [0 \quad 0 \quad 0 \quad 0 \quad 0]$$

$$B_{oo} = 0$$

The load demand in 24 h period is shown in Table 5-30.

Table 5-30: Load demand for 24 h of the 5-unit system

Time	Load
h	*MW*
1	410
2	435
3	475
4	530
5	558
6	608
7	626
8	654
9	690
10	704
11	720
12	740
13	704
14	690
15	654
16	580
17	558
18	608
19	654
20	704
21	680
22	605
23	527
24	463

The total cost obtained using stochastic fractal search is $40122 for the 24 hour period as shown in Table 5-31. The solutions obtained using other two techniques, seeker optimization algorithm and sequential quadratic programming, are shown in Table 5-32. Comparing the solution obtained using SFS with SOA solution, $2466 lower cost is obtained. Moreover, the solution obtained using SFS is lower than SOA-SQP solution by $579.

Table 5-31: Optimal solutions of the 5-unit system using SFS

Time	Load	P_{G1}	P_{G2}	P_{G3}	P_{G4}	P_{G5}	P_L	Cost
h	*MW*	*MW*	*MW*	*MW*	*MW*	*MW*	*MW*	*$/h*
1	410	15.6235	71.0956	63.2422	117.6855	145.9588	3.6056	**1202.9**
2	435	16.2198	72.935	71.0552	127.4069	151.4267	4.0436	**1260.1**
3	475	18.0725	79.5119	79.1652	142.9912	160.0812	4.8220	**1352.6**
4	530	20.4917	85.301	99.1549	157.0249	173.9848	5.9573	**1482.1**
5	558	21.2456	91.1124	103.1600	171.9998	177.109	6.6269	**1548.9**
6	608	23.6971	96.0931	118.5535	185.7833	191.7183	7.8453	**1669.7**
7	626	25.0163	97.1042	125.8175	191.1269	195.235	8.3000	**1713.7**
8	654	26.2081	100.8749	131.2778	201.8107	202.9014	9.0729	**1782.7**
9	690	27.0603	107.0659	143.392	207.483	215.086	10.0872	**1872.5**
10	704	27.5304	107.1357	149.1451	217.6733	213.0161	10.5005	**1907.5**
11	720	29.0407	107.8755	151.2633	226.1561	216.661	10.9965	**1947.9**
12	740	29.9456	110.1877	156.9594	230.554	223.9664	11.613	**1998.7**
13	704	26.7123	105.8791	146.4549	220.0822	215.3901	10.5185	**1907.6**
14	690	28.5668	102.8044	144.492	213.6945	210.5201	10.0778	**1872.4**
15	654	25.8361	99.7957	134.0199	200.5522	202.8542	9.0581	**1782.8**
16	580	22.8203	92.1897	109.1687	177.4265	185.5437	7.1488	**1601.8**
17	558	21.3753	89.562	104.4746	168.2293	180.9728	6.6139	**1548.8**
18	608	24.9208	94.9945	117.9843	186.5232	191.4194	7.8421	**1669.7**
19	654	25.5204	99.9084	131.3958	201.9494	201.2999	9.0739	**1782.7**
20	704	27.9375	105.0274	148.0066	217.6056	215.9224	10.4995	**1907.6**
21	680	27.7815	103.9252	140.0752	203.5158	214.4916	9.7894	**1847.5**
22	605	24.0115	96.5422	116.4111	185.3175	190.4923	7.7746	**1662.4**
23	527	20.2413	83.9092	97.2500	159.0847	172.4118	5.8970	**1474.9**
24	463	17.9778	78.7928	75.6125	137.1786	158.0237	4.5854	**1324.7**

Table 5-32: Optimal solutions of the 5-unit system

	Optimization Method		
	SOA	SOA-SQP	SFS
P_{GT}	14577	14577	14577
C_T **[$/h]**	42588	40701	**40122**

5.5.2. Case 2: 10 Unit System

System 2: Cost only is considered including valve-point effect for 10 thermal units. Losses are neglected. The used data is given in Table 5-33 and 5-34 [34, 56].

Table 5-33: Cost coefficients, generators limits, ramp rates and valve effect coefficients of the 10-unit system

Unit	α_i	β_i	γ_i	P_{Gi}^{min}	P_{Gi}^{max}	η_i	χ_i	UR_i	DR_i
i	*\$/h*	*\$/MWh*	*\$/MW²h*	*MW*	*MW*	*\$/h*	Rad/MWh	*MW/h*	*MW/h*
1	958.20	21.60	0.00043	150	470	450	0.041	80	80
2	1313.6	21.05	0.00063	135	460	600	0.036	80	80
3	604.97	20.81	0.00039	73	340	320	0.028	80	80
4	471.60	23.90	0.00070	60	300	260	0.052	50	50
5	480.29	21.62	0.00079	73	243	280	0.063	50	50
6	601.75	17.87	0.00056	57	160	310	0.048	50	50
7	502.70	16.51	0.00211	20	130	300	0.086	30	30
8	639.40	23.23	0.00480	47	120	340	0.082	30	30
9	455.60	19.58	0.10908	20	80	270	0.098	30	30
10	692.40	22.54	0.00951	55	55	380	0.094	30	30

Table 5-34: Load demand for 24 h of the 10-unit system

Time	Load
h	*MW*
1	1036
2	1110
3	1258
4	1406
5	1480
6	1628
7	1702
8	1776
9	1924
10	2072
11	2146
12	2220
13	2072
14	1924
15	1776
16	1554
17	1480
18	1628
19	1776
20	2072
21	1924
22	1628
23	1332
24	1184

The solution using stochastic fractal search is lower than other two methods as shown in Table 5-35. Comparing the solution obtained using SFS with SOA solution, $20823 lower cost is obtained. Furthermore, the solution obtained using SFS is lower than SOA-SQP solution by $18338.

Table 5-35: Optimal solutions of the 10-unit system

	Optimization Method		
	SOA	SOA-SQP	SFS
P_{GT}	40108	40108	40108
C_T ***[$/h]***	1023945	1021460	**1003122**

For 24 hour period, the load demand in each hour, the generation power of each generator, the generation cost of each hour and the total generation cost are shown in Table 5-36.

In this chapter, Results have shown that the optimal SFS solution reduces the system production costs, losses and emissions. Different scenarios have been studied including generators power limits (lower, upper, ramp rate limits and prohibited zones), transmission network losses and wind power.

Table 5-36: Load demand, generation of each generator, the generation cost and the total generation cost of the 10-unit system

	Unit *i*	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	Cost *$*
Time *h*	Load *MW*											
1	1036	168.2708	167.6621	122.2823	60.3785	105.4351	159.7601	129.9888	47.0831	20.1393	55	28061
2	1110	151.0105	192.4011	195.2413	60.0802	97.0536	159.9514	129.8949	47.6093	21.7577	55	29604
3	1258	157.5592	270.6065	274.9329	61.6558	79.8158	159.9353	129.8685	47.7422	20.8839	55	32732
4	1406	150.7784	342.0023	338.9157	60.0566	102.5912	159.5693	129.9283	47.0473	20.1108	55	35879
5	1480	159.9461	411.4711	339.0698	66.0190	90.8449	159.9061	129.4954	48.0809	20.1666	55	37488
6	1628	238.0605	443.8701	339.461	73.7340	119.2957	159.3474	129.9138	48.4080	20.9095	55	40724
7	1702	287.3698	458.3647	339.9698	60.2767	145.4623	158.0753	129.9979	47.2631	20.2204	55	42307
8	1776	329.0886	457.3369	338.4007	69.3255	169.0889	159.7280	129.3802	48.0533	20.5979	55	43945
9	1924	408.5110	458.6786	339.7115	70.3724	209.9781	159.9786	128.8438	61.2173	30.6686	55	47243
10	2072	469.5918	456.3577	339.4888	107.2681	237.4716	159.7002	129.7193	80.2089	37.1936	55	50644
11	2146	469.5262	457.9141	334.8218	146.5394	239.7108	159.9669	129.9470	100.2495	52.3242	55	52508
12	2220	467.5777	458.8830	339.1045	189.9091	240.6141	159.5401	129.8171	118.7701	60.7843	55	54353
13	2072	443.8162	459.2572	339.5031	140.3219	223.3943	159.9742	129.9305	89.88629	30.9398	55	50698
14	1924	398.9478	458.8723	339.8961	90.3640	211.0266	159.9159	129.9727	59.9660	20.0386	55	47248
15	1776	343.7598	444.8537	339.6653	60.0585	175.6581	159.9070	129.9744	47.0158	20.1074	55	43922
16	1554	266.5002	377.9203	306.7345	60.3237	129.8107	159.9157	129.9736	47.3678	20.4535	55	39116
17	1480	188.7146	389.5759	339.0332	60.2930	90.3124	159.6923	129.9015	47.3180	20.1528	55	37475
18	1628	239.9063	459.0291	339.9889	60.0091	116.9672	159.9581	129.9720	47.0581	20.1112	55	40684
19	1776	315.9088	457.2025	339.9864	92.2765	159.3735	159.9322	128.8744	47.4161	20.0294	55	43992
20	2072	450.3295	459.7928	339.3997	142.2090	209.3073	159.5107	129.9110	77.1859	49.5264	55	50796
21	1924	395.8138	459.2357	339.9322	101.0224	209.2991	159.8000	129.9044	53.1765	20.8158	55	47260
22	1628	317.2320	381.8098	296.7491	60.2300	159.9333	159.9943	129.7904	47.1796	20.0813	55	40739
23	1332	238.0917	302.9880	218.4582	60.4082	117.2001	150.7001	121.8937	47.1453	20.1146	55	34441
24	1184	165.8209	250.9173	248.1070	60.1399	77.7911	128.2069	129.9136	47.4405	20.6628	55	31263
Total load **40108**												**Total cost** **1003122**

6

CONCLOUSIN AND FUTURE WORK

6.1. CONCLUSION

Due to the importance of economic dispatch in power systems, a new approach has been introduced to solve combined economic emission dispatch including wind power. The SFS algorithm, which is one of the latest global optimization algorithms, is a promising algorithm and outperforms some existing well known metaheuristic algorithms.

Results have revealed that the optimal SFS-based optimal solution significantly reduces the system production costs. Results also have shown that the optimal solutions obtained using the SFS algorithm which performs better than some commonly used global optimization techniques, such as GA and PSO since a lower cost has been obtained.

The algorithm has been applied to different test systems with different number of generators; 6, 10, 11, 13 and 40 generating units, including emission, thermal generators constrains, transmission losses and wind power. The obtained solution using SFS regarding both cost and emission was lower compared to other solution methods.

In the first scenario, considering only the cost as an objective function, the solution obtained using SFS was the same as the PSO solution and lower than GA solution for the six unit system. In this case, all generators limits (lower, upper, ramp rate limits and prohibited zones) are included. Transmission losses are also considered. This shows the ability of SFS in solving an economic dispatch problem. In the second, third and fourth cases with 13 and 40 generating units (with and without valve-point effect), the solution obtained using SFS was lower than other solution methods; PSO, DE and SQP.

In the second scenario a combined economic-emission dispatch was studied for 6, 10, 11and 40. In all cases the obtained solution regarding both cost and emission rates using SFS was lower than all other optimization methods solutions, except in the second case, the emission rates were slightly higher than other solution methods.

In case of using wind power effectively, the emission rates and total cost are reduced. This shows that benefits of using wind power as an energy source with no emission and greenhouse gases. It delivers power with minimal impact on the environment. Wind power can also be cost-effective compared to traditional power sources such as fossil fuel, natural gas and coal as in our studied case.

Dynamic economic dispatch has been studied in the fourth scenario for 5 and 10 generating units, and the results have shown the superiority of SFS, as the solution obtained using SFS was lower than SOA and SQP solutions in both cases.

The proposed algorithm has achieved faster and near global optimal solution compared to the other approaches. This shows the ability of this new technique in solving nonlinear constrained optimization problem.

6.2. FUTURE WORK

Even though transmission losses, generation limits have been studied in this thesis in solving realistic economic dispatch problem. Additional constrains in power system must be considered when solving this problem, such as line flow constrains, which is defined as each transmission line has its maximum power transfer capability and the power flow in each transmission line must not exceed this value. Moreover reactive power, voltage magnitude and angle must be taken into count.

Another important factor is the spinning reserve, which can be explained as the extra generating capacity that is available by increasing the power output of generators, which are already connected to the power system. Furthermore, accurate wind generation mathematical representation can be considered.

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عويس، زيد باسل. التشغيل الاقتصادي-البيئي والذي يتضمن قدرة الرياح باستخدام خوارزمية البحث الكسري العشوائي. قسم هندسة القوى الكهربائية، جامعة اليرموك، ٢٠١٦ (المشرف: أ.د موفق العموش).

الملخص

التشغيل الاقتصادي هو أحد المشاكل الرئيسية في أنظمة الطاقة الكهربائية .ويمكن تعريفه على أنه إيجاد الحل الأمثل لتوزيع الأحمال الكهربائية للحصول على الحد الأدنى من تكاليف التشغيل و الإنتاج مع التقيد باستطاعات وحدات التوليد الكهربائية وخسائر النقل و التأثيرات البيئية.

التشغيل الاقتصادي هو تشغيل المولدات الكهربائية لإنتاج الطاقة الكهربائية بأقل تكلفة ممكنة و تقديم خدمة موثوقة للمستهلكين، مع الأخذ بعين الاعتبار أي حدود تشغيلية لوحدات توليد الطاقة الكهربائية ونظام النقل. كما يجب النظر في العديد من الاعتبارات في حل مشكلة التشغيل الاقتصادي، مثل استطاعات مولدات الكهرباء و الحمل الكهربائي و استطاعات خطوط النقل و الخسائر في النظام الكهربائي وانبعاثات الغازات.

لقد استخدمت العديد من الأساليب لحل مسألة التشغيل الاقتصادي في السنوات الأخيرة .و قد تم تاريخياً استخدام عدد كبير من الطرق لإيجاد الحل الأمثل لمسألة التشغيل الاقتصادي .إذ ويمكن تصنيف هذه الأساليب إلى طرق كلاسيكية وخوارزميات الأدلة العليا. ولأن مسألة التشغيل الاقتصادي مسألة غير خطية ، وتتضمن عدداً كبيراً من القيود فإن الطرق التقليدية عادة ما تعطي الحلول الأمثلية المحلية ولم تضمن حلا شاملاً.

إن خوارزمية البحث الكسري العشوائي (Stochastic Fractal Search) هي واحدة من أحدث الخوارزميات وقد قدمت في عام ٢٠١٥، تلك التي يمكن استخدامها لحل مشكلة التشغيل الاقتصادي بشكل فعَال .إن حل مشكلة التشغيل الاقتصادي تشمل الخصائص غير الخطية لمولدات الكهرباء مثل اقتران التكلفة الكهربائية و حدود المناطق المحظورة التي سيتم النظر فيها عند حل المشكلة باستخدام الخوارزمية المقترحة.

وينبغي النظر في عامل مهم آخر وهو معدلات انبعاث الغازات من وحدات توليد الكهرباء عند حل مشكلة التشغيل الاقتصادي و التي يمكن أيضا أن يتم تخفيضها للحصول على تأثيرات بيئية أقل في استخدام الوقود الأحفوري.

وقد أظهرت نتائج هذه الخوارزمية أداء أفضل في إيجاد حل شامل، مع أقل عدد من التكرارات و وقتا أقل مقارنة مع حلول الخوارزميات الأخرى .إن مقارنة نتائج خوارزمية البحث الكسري العشوائي مع خوارزميات أخرى مثل الخوارزمية الجينية يثبت فعالية هذه الخوارزمية. في النظام الأول الذي تم دراسته، تم خفض خسائرنظام النقل بمقدار ٢٤,٦ ك.و.س. وفي النظام الثاني والذي يتكون من ١٣ مولد حراري، تم تقليل التكلفة بمقدار ٥,٥ $/ساعة. وأظهرت النتائج أن حل الخوارزمية المقترحة يتفوق على غيره من حلول الخوارزميات الأخرى. و ذلك عن طريق الحصول على حل أفضل و أمثل، كما يمكن خفض تكاليف الإنتاج والتشغيل بدرجة كبيرة.

كلمات مفتاحية: التشغيل الاقصادي، التشغيل البيئي، التشغيل الاقتصادي-البيئي، خوارزميات تطورية، الحل الأمثل الشامل، خوارزميات البحث العليا، طاقة الرياح، خوارزمية البحث الكسري العشوائي، خسائر النقل.