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AN ALTERNATIVE METHOD TO SOLVE COMBINED ECONOMIC EMISSION DISPATCH PROBLEMS USING FLOWER POLLINATION ALGORITHM

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Thesis submitted in fulfilment of the requirements for the award of the degree of Master of Engineering in Electrical (Power Systems)

Faculty of Electrical & Electronics Engineering
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ABSTRACT

Flower Pollination Algorithm (FPA) is a new biologically inspired meta-heuristic optimization technique based the pollination process of flowers. FPA mimics the flower pollination characteristics in order to survival by the fittest. This research presents implementation of FPA optimization in solving Combined Economic Emission Dispatch (CEED) problems in power system which minimize total generation cost by minimizing fuel cost and emission. Increasing in power demand requires effective solution to provide sufficient electricity to customer with minimum cost of operation at the same time considering emission. CEED actually is a multi-objective problem and need complex programming to solve it. The problem becomes complicated when there is practical constraints to be considered as well. To simplify the programming, objective of economic dispatch (ED) and emission dispatch (EmD) are combined into a single function by price penalty factor and analysed using weighted sum method to choose the best compromising result. In this research, the valve point loading effect problem in power system also will be considered. The proposed algorithm are tested on four different test systems which are: 6-generating unit and 11-generating unit without valve point effect with no transmission loss, 10-generating unit with having valve point effect and transmission loss, and lastly 40-generating unit with having valve point effect without transmission loss. The results of these four different test cases were compared with the optimization techniques reported in recent literature in order to observe the effectiveness of FPA. Result shows FPA able to perform better than other algorithms by having minimum fuel cost and emission.

ABSTRAK

Algoritma adalah salah satu usaha dalam bidang sains komputer yang semakin pesat digunakan dalam pelbagai aplikasi untuk menyelesaikan masalah matematik yang kompleks. *Flower Pollination Algorithm (FPA)* adalah antara algoritma yang diciptakan baru-baru ini dimana inspirasi ideanya berdasarkan sifat biologi proses pendebungaan. Ciri-ciri daya kewujudan bunga atau kejayaan dalam proses pendebungaan untuk mengekalkan kewujudan bunga daripada pupus diubahsuai menjadi formula matematik yang menghasilkan teknik *FPA* ini. Sehubungan itu, kajian ini mengaplikasikan kaedah *FPA* untuk menyelesaikan masalah dalam *Combined Economic Emission Dispatch (CEED)*. *CEED* merupakan proses dalam sistem kuasa untuk mengagihkan kuasa setiap unit penjana supaya mencapai pengagihan yang optimum bagi mengurangkan kos bahan api dan jumlah pembebasan bahan pencemaran udara kepada minimum. *CEED* sebenarnya proses yang melibatkan dua objektif yang berbeza dimana memerlukan pengaturcaraan computer yang kompleks. Masalah ini menjadi semakin komplikasi apabila perlu menitikberatkan masalah praktikal dalam CEED. Untuk memudahkan pengaturcaraan komputer, kedua-dua objektif ini disatukan dengan menggunakan kaedah *price penalty factor*. Keputusan optimum nilai kos bahan api dan jumlah bahan pencemaran yang dibebaskan dipilih secara stokastik dan menggunakan kaedah *weighted sum method*. Selain itu, masalah praktikal sistem kuasa iaitu *valve-point loading effect* turut dititikberatkan dalam kajian ini. Untuk mengenalpasti keberkesanan teknik *FPA* ini dalam menyelesaikan masalah *CEED*, pelbagai kes ujian dijalankan. Nilai yang diperolehi dari kes-kes ujian menggunakan teknik *FPA* ini turut dibandingkan dengan nilai-nilai dari teknik lain yang dibentangkan oleh para penyelidik dari seluruh dunia. Kesimpulanya, *FPA* ternyata amat berkesan dengan menghasilkan kos bahan api dan jumlah bahan pencemaran yang minimum berbanding teknik-teknik yang lain.

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LIST OF SYMBOLS

FT	Total generating fuel cost
N	Number of generating units
F_i	Generating cost of each unit i
P_{Gi}	Power generated by each unit i
$F(P_{Gi})$	Total fuel cost
a_i, b_i and c_i	Cost coefficients for i^{th} generator
$P_{Gi}^{\min}$	Minimum loading limit
$P_{Gi}^{\max}$	Maximum output limit of a generator
Emi_T	Total generating emission
Emi_i	Generating emission of each unit *i*
$Emi(P_{Gi})$	Total emission
α_i, β_i and γ_i	Emission coefficients for i^{th} generator
P_d	Power demand
P_{loss}	Transmission loss
P_{Gj}	The output generation of unit *j* (MW)
B_{ij}	The *ij-th* element of the loss coefficient square matrix
B_{i0}	The *i-th* element of the loss coefficient
B_{00}	The loss coefficient constant
d_i and e_i	Cost coefficients for i^{th} unit with valve point loading effect
η_i and δ_i	Emission coefficients for i^{th} generator with valve point loading effect
T	Optimal cost of generation
w_i.	Weighting factor
h_i	Price penalty factor

N_p	Population of flower
p	Switch probability
x_i^t	Solution vector x_i at iteration t
L	Step size which uses Lévy distribution for L > 0
$\Gamma(\lambda)$	Standard gamma function
x_j^t and x_k^t	Pollen from the same plant species but different flower
x	Solutions for CEED
P	Power output for each generating unit
$P_j^{\min}$	Lower limits of the inequality constraint of objective function
$P_j^{\max}$	Upper limits of the inequality constraint of objective function
X_{best}	The current best feasible solution
λ	Distribution factor
K	The multiplication factor selected in the range [0,1]
X_i^{new}	New solution
X_j^{old} and X_k^{old}	Different flowers from the same plant type
g_*	Current best solution
F	Scaling factor selected in the range [0,1]

LIST OF ABBREVIATIONS

ABC	Artificial Bee Colony
BCS	Best Compromising Solution
BI	Biologically Inspired
Btu	British Thermal Unit
CE	Controlled Elitism
CEED	Combined Economic Emission Dispatch
CLIM	Classical Lambda Iteration Method
CO_2	Carbon Dioxide
CSA	Cuckoo Search Algorithm
DCD	Dynamic Crowding Distance
DE	Differential Evolution
DED	Dynamic Economic Dispatch
DEED	Cynamic Economic Emission Dispatch
DP	Dynamic Programming
ED	Economic Dispatch
EED	Economic Environmental Dispatch
EmD	Emission Dispatch
EP	Evolutionary Programming
FPA	Flower Pollination Algorithm
GA	Genetic Algorithm
GSA	Gravitational Search Algorithm
GSOMP	Group search optimizer with multiple producers
GWO	Grey Wolf Optimizer
IEEE	Institute of Electrical and Electronics Engineers

IFEP	Improved Fast Evolutionary Programming
LP	Linear Programming
MNSGA-II	Modified nondominating sorting genetic algorithm
MODE	Multiobjective Differential Evolution .
MOEA	Multiobjective Evolutionary Algorithm
MOO	Multiobjective Optimization
MOOP	Multiobjective Optimization Problem
MOPSO	Multiobjective particle swarm optimization
MPSO	Modified Particle Swarm Optimization
MW	Mega Watt
NO_x	Nitrogen Oxide
NPGA	Niched pareto genetic Algorithm
NSGA	Nondominating sorting genetic algorithm
NSGA-II	Nondominating sorting genetic algorithm II
PAES	Pareto Archieved Evolution Strategy
PDE	Pareto Differential Evolution
PF	Penalty Factor
POZ	Prohibited Operating Zone
PSO	Particle Swarm Optimization
QP	Quadratic Programming
SA	Simulated Annealing
SO_2	Sulphur Dioxide
SPEA	Strength Pareto Evolutionary Algorithm
SQP	Sequential quadratic programming
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Power system is one of the important industries that plays vital role in today's modernised world. It is very obvious that people are consuming electricity every day and every second. Without it, people may face many consequences in terms of financial loss, life, facilities, works and etc. Due to the improving lifestyle of human beings and development in technology, contributes the demands for the power also consequently arises. To combat this situation, more numbers of power generating units and improvement in power generation technology needed. In power system, it should be understood that there will be huge damage or instability in system performance if each power generating units running in maximum capability of capacity every day in the purpose to meet the load demand. Hence, Economic dispatch was introduced and implemented in power system engineering. Economic Dispatch (ED) is the scheduling of generators to minimize the total operating cost and to meet load demand of the power system over some appropriate period while satisfying various equality and inequality constraint (Sulaiman, 2013)(A.J. Wood, 1996). The ED basically considers the load balance constraint besides the generating capacity limits. However, in practical ED, ramp rate limits as well as prohibited operating zones (POZ), valve point effects, and multi-fuel option must take into the account.

Due to the set-up of large number of fossil-fuelled plant to meet the increasing load demand, results increases in the emission of pollutants such as sulphur dioxides(SO_2), nitrogen oxides (NO_x)and carbon dioxide(CO_2) (Yalçınöz & Altun, n.d.). Generating the power by minimum fuel cost as in ED does not promise minimum emission of harmful substances to air (Guvenc, 2010). The question that concerns environmental protection and the methods of eliminating or reducing pollutant from power plant always been raised to the power energy industry especially since the passage of the Clean Air Act Amendments in November, 1990, utility management gives the highest priority on environmental constraints (Resek et al., 1995). SO_2 and NO_x are the two mostly emitted pollutants in power plant. SO_2 is emitted dependent to the amount of fuel burned whereas the emission of NO_x is more complex. Hence, besides in minimizing the total generating cost, reduction of emission also emphasized since the emitted pollutants are very harmful to the human beings and environment (Balamurugan & Subramanian, 2008). The both objectives which are minimizing fuel cost and emission are combined in this research to make it as single objective which called combined economic and emission dispatch (CEED). This was done by introducing price penalty factor that converts this bi-objective function into single where the objective will be minimizing the total cost of economic dispatch and emission (Venkatesh, Gnanadass, & Padhy, 2003).

Many conventional and nonconventional optimization techniques available in literature are applied to solve the problem in CEED. In early of economic dispatch study, the basic mathematical method was used to solve ED problem which is Langrange Multiplier method in which the cost function is augmented by the equality constraints. Following it, this method was extended by considering inequality constraints through a technique called Kuhn Tucker method (Hassan, 2007) when modern unit's characteristics inherently highly nonlinear which is with valve-point loading effect, ramp rate limits etc. Quadratic linear programming, Mathematical linear programming, dynamic programming are the conventional methods that used to solve CEED problem. However, conventional method failed to solve the problem because they have the drawbacks of multiple local minimum points in the cost function. Conventional methods usually have simple mathematical model and high search speed. But, it will use approximation to search for the algorithms that have the required characteristics. This may cause to suboptimal operation and huge revenue loss over time.

Overcoming highly nonlinear characteristics of the units requires highly robust algorithms to avoid multiple local minimum points since the conventional method fail to solve as mentioned. Respect to this, stochastic search algorithms like Genetic Algorithm (GA) (Kumar, Parmar, & Dahiya, 2012), Artificial Bee Colony (ABC) (Aydin, Özyön, Yaşar, & Liao, 2014), Particle Swarm Optimization (PSO) (Thakur, Sem, Saini, & Sharma, 2006), Simulated Annealing (SA)(Basu, 2005) , Differential Evolution (DE) (Bhattacharya & Chattopadhyay, 2011), Cuckoo Search Algorithm (CSA) (Thi, Thao, & Thang, 2014), Grey Wolf Optimizer (GWO) (L. I. Wong, Sulaiman, Mohamed, & Hong, 2014) and etc. introduced in some literature to solve ED and CEED problems and no doubt that it was proved to be very efficient in solving highly nonlinear problems than conventional method. However, not all heuristic optimization technique able to provide global optimum solution but they are able to solve with fast and convergent.

Apart from that, this research presents implementation of recently proposed optimization technique, Flower Pollination Algorithm (FPA) developed by Xin-She Yang in year 2012 (Xin-She, Y., 2012). The main objective of the combined economic emission dispatch is to minimize the total cost of generation by decreasing the fuel cost and pollution emission. The proposed optimization technique in this project will be used to find optimal combination of power generation units that minimizes the total fuel cost as well as the emission. FPA was expected to give satisfaction optimal result on solving non-convex CEED problems.

1.2 PROBLEM STATEMENT

Nowadays, people are very dependent on electricity. Increasing in power demand and limited generation of power to supply to the consumer can disturb the continuous power supply to the customer which causes dissatisfaction to the customer. To meet the load demand, generating power with maximum limit continuously also can bring disruption to the power generating unit. This situation will lead to financial losses to the power generation developer as well as could not meet the load demand of customer. Hence, optimal combination of power generating units must be achieved which minimizes the total fuel cost by considering the equality and inequality constraints.

Consequently, in this modern and fast developing world human being also ignored to consider the consequences that might happen to the environment cause by their activities. In power system, huge increases in thermal power plant which mainly using combustion of fossil-fuels cause emission of harmful pollutants such as sulphur dioxide (SO_2), nitrogen oxide (NO_x) and carbon dioxide (CO_2) . So, environmental friendly power generating plants must be implemented to save the world from being polluted.

It should be bear in mind that in practical power system, the process of generation of power is not as smooth as theoretical which is linear. There are non-linear problems which need to be considered as well where it is more complex compare to linear problem in terms of mathematical formulation. The examples of nonlinear problem of power system include valve point loading effect, prohibited operating zone, ramp rate limits and so on.

Fast develop in software programming lead to many inventions on algorithm to solve complex mathematical function. The non-stop development from day to day which solves algorithm's previous weakness makes the researches on new developed algorithm on various field conducted to validate its effectiveness. Hence, FPA incorporated to solve non-convex CEED problems in power system.

1.3 OBJECTIVES

The objective of this research is to determine the optimize combined economic emission dispatch of the power generation in order to achieve the minimization of the operating cost as well as the emission level.

In order to achieve this objective, the following sub-objectives are as follows:

(i) To incorporate FPA to determine the optimal power generation schedule for the online generating units over a time horizon with consideration of nonlinear problems.

(ii) To associate price penalty factor and weighting function method in order to combine multiobjective into single objective function.

(iii) To compare the obtained results of proposed method with reviewed methods.

1.4 SCOPE OF PROJECT

The scope of this project can be broken down into several sub-tasks:

i. This research mainly focuses on solving cost and emission functions which have linear constraints consists generation capacity constraints (equality constraint) and power balance constraints (inequality constraint) in thermal power plant. To be more practical, the nonlinear problem which is valve-point loading effect also considered. Whereas, only Nitrogen Oxides (NO_x) covered for the part of emission.

ii. There are four test cases that used to conduct in this research. Firstly, test case with 6-unit test system which considers load demand of 1000 MW without transmission loss and valve point loading effect. Secondly, the test case that considers both transmission loss and valve point loading effect is 10-unit test system with 2000 MW. Followed by 11-unit test system with load demand of 2500 MW without considering transmission loss and valve point loading effect. And lastly, 40-unit test system with 10500 MW load demand by considering practical constraint without transmission loss chosen.

1.5 THESIS ORGANIZATION

This thesis consists of five chapters. Chapter 1 introduces the early research on this title, the problem statements, objectives of this research, scope for this research and organization of the thesis.

In Chapter 2, the survey and study on literature that related to this research are deeply explained and presented so that the knowledge on the research conducted is wider and further development of this research could be identified.

In Chapter 3, the implementation of Flower Pollination Algorithm on Combined Economic Emission Dispatch, problem formulation for basic economic dispatch and basic emission dispatch, function for nonlinear problems in economic dispatch and emission dispatch, mathematical formula for both with and without nonlinear problems in Combined Economic Emission Dispatch and formulation of Flower Pollination Algorithm are presented.

Chapter 4 analyse and discuss the results of implementation of Flower Pollination Algorithm on Combined Economic Emission Dispatch which tested on various test cases.

Chapter 5 conclude the thesis.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter presents the review of Combined Economic Emission Dispatch in power generation plant, the fundamentals of optimization techniques proposed by the researchers so far and ideas of these optimization techniques was used to apply in power system engineering especially in solving CEED problems.

2.2 ELECTRICAL POWER SYSTEM

2.2.1 Thermal power generation and its characteristics

Thermal power generation unit is the largest provider of electricity in power system because of flexibility in using different type of fuel for combustion. The basic thermal unit can be divided into three main components which are boiler, turbine, and generator. The boiler in thermal unit will burn the fuel which can be consisted any type to generate steam. The steam will initiate the turbine in the system to rotate or in other word converts the natural energy (steam) to mechanical power. Turbine is coupled to generator where the rotation of the turbine automatically initiates the generator to operate.

There are also other components in thermal unit such as fans and pumps that needs supply of electric. Hence, the net power is equal to total generated power minus auxiliary power consumed. The input for this thermal unit is fuel that will be boiled in boiler which can be consists of any kind. Therefore, the unit also varies such as dollar per hour, tons of coal per hour, millions of cubic feet of natural gas per hour or British thermal unit (Btu). Whereas, output of thermal unit is always in unit of power, MW/h.

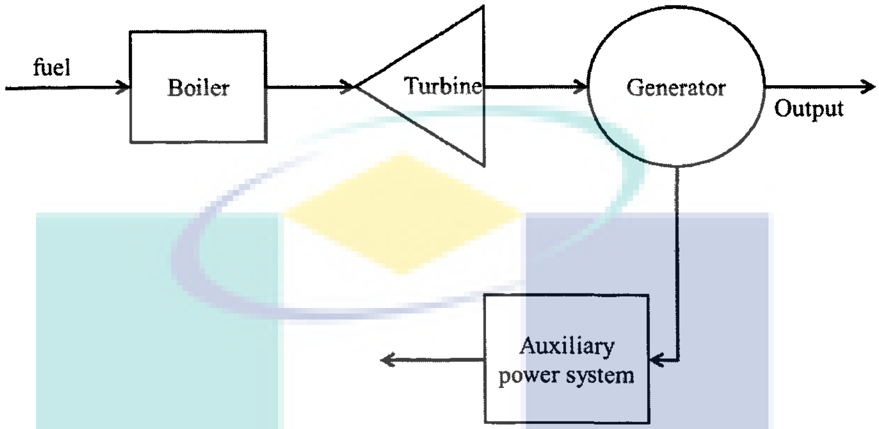

Figure 2.1. Schematic diagram of basic thermal unit

Source: Kaushal & Ahamad (2015)

The input-output characteristic of a thermal unit is mainly based on the variable costs of the unit, mainly fuel cost, and the fixed costs such as employees' wages are not included in the characteristic function (also known as cost function). Figure 2.1 shows a typical input-output characteristic of a thermal unit.

The incremental heat rate characteristic for a thermal unit is defined as the derivative (slope) of the input-output characteristic. This characteristic is the most important one for the operator of the power system and it is widely used by the dispatchers in order to economically dispatch the unit and the power system. The linear function (or straight curve) is the best approximation to present the heat rate characteristic. This function can be converted to incremental fuel cost characteristic by multiplying the incremental heat rate by the equivalent fuel cost.

Because of the technical limitations, the thermal units have some capacity constraints. Unit capacity constraints are mostly related to upper and lower generation limits of thermal units. The results from heat rate tests may deviate from the result from design calculation. The design calculation usually gives a smooth characteristic function. However, the data from tests does not make a smooth curve, especially in the large thermal units. These set of un-smoothness on the characteristic curve are more severe in the large thermal units and they are caused by several operational constraints. One of the most common operational constraints which affect the smoothness of the characteristic curve is called the valve-point effect.(Keshmiri, 2011)

2.3 SIMPLE ECONOMIC DISPATCH

2.3.1 Conventional Method

B.H. Chowdhury ans S. Rahman defined economic dispatch as the process of allocating generation levels to the generating units in the mix, so that the system load may be supplied entirely and more economically. They reviewed the works on economic dispatch from year 1977 to 1988 (Chowdhury & Rahman, 1990). The objective of ED problem, pertains to the optimum generation scheduling of available generating units in a power system, is to minimize the cost of generation subjected to system constraints such as power balance, generator capacity limit etc (Kirchmayer L. K., 1958).

According to Happ, work on economic dispatch dates back to as far as the 1920's or even earlier. Prior to 1930, various method were used such as the "base load method" (loading of most efficient generator unit at maximum capacity followed by second unit) and "best point loading" (loading of generator units at lowest heat rate point start with the most efficient one). Later, he discovered that the incremental method or also known as equal incremental method gives the best result for economic diaptch at 1930 (Happ, 1977).

In (Wood A. J. and Wollenberg B. F., 1996), they presented various conventional methods such as Lambda iteration, Base point participation factor, Gradient method and Newton method to solve simple ED problem. Although these techniques are easy and simple to implement, but it has disadvantages such as slow convergence, only can solve linear problems, cannot accommodate larger number of units and complex cost functions, difficulty on getting optimum result and difficulty with handling a large number of inequality constraints.

Later, there is revolution in conventional method by implementing mathematical programming where the cost function of each generating unit is represented by simple quadratic function based on several optimization techniques, such as Dynamic Programming (DP), Linear Programming (LP), Quadratic Programming (QP), Homogeneous LP and Nonlinear programming techniques. However, these classical optimization methods are highly sensitive to starting points and often converge to local optimum or diverge altogether. All these conventional methods require the generator cost curves to be continuous functions, which is not possible in the case of practical situations. Also these methods have oscillating tendency in large scale mixed generating unit systems leading to high computation time (Rajkumar M, 2014).

These dispatch methods and strategies increased in complexity and ability as new generator technology and computers were introduced, leading to today, where current dispatch strategies can operate numerous types of generators with a variety of operational constraints. Current strategies utilize numerous optimization techniques and can perform economic dispatch for systems that have generator constraints, non-smooth or non-convex cost functions and emission constraints.

2.4 ECONOMIC DISPATCH WITH NONLINEARITIES

The cost function of power system is not as smooth as linear because of the discontinuities caused by practical constraints such as valve-point loading effect. This non-linearity handled effectively by using various stochastic search algorithms.

2.4.1 Economic Dispatch with Valve Point Loading Effect

(Liang & Glover, 1992) have applied dynamic programming (DP) method for solving nonlinear and discontinuous ED problem. They also implemented zoom feature in order to converge to the economic dispatch solution with low computer time and storage requirements. DP works with the unit input-output information directly by enumerating all possible solutions. It consists of evaluating the problem in stages corresponding to each unit for choosing the optimal allocation for a unit. It gives an optimum solution for smaller systems. But as the number of generating units and the constraints of the system increases, it is difficult in DP method to generate and manage the larger number of entries in the discrete tables. Therefore, when the number of generating units and scheduled power range increases, DP method fails. In other words, DP method suffers from the curse of dimensionality.

(Walters & Sheble, 1993) solve the ED problem which have valve-point discontinuities by using genetic algorithm (GA). The algorithm utilizes payoff information of an objective function determine optimality. Hence, any type of unit characteristic cost curve may be used with adjustments only to the objective function. The result obtained from implementing GA in economic dispatch also compared with DP by Walters & Sheble. GA yields solutions which are very near optimal, but need long computation time when solving large scale optimization problems.

(K. P. Wong & Fung, 1993) implemented Simulated Annealing (SA) to determine the global or near global optimum dispatch solution. The SA method employs a probabilistic approach in accepting candidate solutions in its solution process such that it can 'jump' out of the local optimum solutions. Wong and Fung validated the algorithm by comparing with DP which have zoom feature. SA has advantages such as independent solution process of objective function, stable convergence property with inequality constraints, optimal solution, eliminates the process of evaluation of Lagrange multipliers and penalty factors, and low computer memory required. However, SA based algorithm is difficult to tune the related control parameters of the annealing schedule and may be too slow when applied to a practical power system

(H. T. Yang, Yang, & Huang, 1996) proposed Evolutionary Programming (EP) to solve ED for units with non-smooth fuel cost functions. The EP implementation is capable on solving the ED with any type of fuel cost functions, analytical or empirical curves, as well as obtaining the global or near global minimum solution considering transmission losses or not within reasonable execution time. With EP, the computational time can be saved because no essential of encoding and decoding schemes as in GA.

Author compared the execution result with DP, SA and GA and validated EP as powerful algorithm which solves ED by avoids entrapping in local optimal solutions and also solved power balance problem that appear in GA.

(Lin, Cheng, & Tsay, 2002) applied their proposed method, Tabu Search on solving ED with multiple minima. It usually reaches local minima since a single candidate solution is used to generate off-springs. Getting trapped in the local minima points is avoided in this method by using an adaptive size for the Tabu list. A number of searches are carried out inside in each of the iterations of the algorithm and the best solution point is fixed. Also the different individuals are ranked by a sorting algorithm in descending order according to their fitness scored. This ensured the optimum solution to the constrained problem. But the search space which is large for larger systems occupies more computer memory and thus sometimes is difficult to get converged.

PSO is another modern heuristic optimization technique which has been applied by (Park, Lee, Shin, & Lee, 2005) to solve the nonlinear ED problems. The algorithm mimics the nature behaviour of swarm of bird or fish schooling. PSO have been applied in many field due to its extraordinary strength such as simple concept, easy implementation, robustness to control parameters, and computational efficiency if compared with other mathematical algorithm and heuristic techniques. Velocity update and position update are the two basic operations to obtain the solution of optimization problems. However, the main drawback of PSO is its premature convergence, if the problem has multiple local minima. In the review paper, Park et.al proposed an improved PSO which named modified PSO (MPSO). The modification focuses on the treatment of the equality and inequality constraints when modifying each individual's search. It has provided the global solution satisfying the constraints with a very high probability for the ED problems with smooth cost functions.

An improved fast EP (IFEP) search technique presented by (Ravi, Chakrabarti, & Choudhuri, 2006) to solve extremely challenging nonconvex ED problem with transmission losses involving variations of consumer load patterns. Author compared the result obtained from IFEP with classical lambda iteration method (CLIM). The improved fast EP approach can provide better optimal solutions than those of classical lambda iteration method. But it takes comparatively larger computational time. Besides, this time also depends on the network configuration and load pattern.

There are many more modern heuristic optimization technique presented to solve economic dispatch problem other than DP, GA, SA, EP, Tabu Search and PSO especially in order to overcome non-linearity problem of ED. To overcome the weakness of an algorithm, researcher also tried to improve the algorithm to better such as MPSO and IFEP as mentioned above. Although these heuristic methods do not always guarantee discovering the global optimal solution in finite time, they often provide a fast and reasonable solution (suboptimal nearly global optimal). In addition, simulation time is longer to obtain the solution for such problems.

For instance, (X. S. Yang, Hosseini, & Gandomi, 2012) proposed firefly algorithm (FA) to solve nonconvex ED problem. Author validated the superiority of the FA on solving nonconvex ED which gives quality and reliability solution. However, FA doesn't implemented to solve more practical constraints and large scale generating unit.

Following it, cuckoo search algorithm, (CSA) implemented by (Serapião, 2013) to sove ED. According to author, population-based optimization techniques are more effective than the gradient techniques in finding the global minimum. At the same time, they have been preferred in many applications, because metaheuristics approaches allow the insertion of constraints in a smoother manner. CSA with having Lévy flight has a good balance of intensive local search strategy and an efficient exploration of the whole search space which cause it an efficient algorithm. With the result performed by author, FA did not satisfy the power balance equality constraint and CSA proved to perform better than FA and ABC. However, author did not apply higher test system to observe the effectiveness and stability of CSA in solving the ED problem.

(Dubey, Pandit, & Panigrahi, 2015) applied modified flower pollination algorithm (MFPA) to solve ED problem recently. According to author, application of FPA for practical power system problems has not yet been reported. MFPA developed by making the local pollination operation of FPA more effective through a user-controlled scaling factor and adding an additional intensive exploitation phase to carry out exhaustive search through the solution domain to achieve the best solution. Author compared with CSA and GSA and found MFPA gives superior solution quality and better convergence characteristic.

On the other hand, hybrid methods which is combining two or more optimization methods also plays vital role in effectively solving ED problem. Fr example, hybrid method which were introduced by (Dos Santos Coelho & Viviana Cocco, 2006). This method combines the DE algorithm with the generator of chaos sequences and Sequential QP (SQP) technique to optimize the performance of ED problems, and provides a good solution, even when the problem begins with many local optimal solutions. The SQP's local search property is used to find a final solution. The combined method produces better quality solutions than the ones found by these techniques when applied separately.

Many combined method have been applied in ED problems following it which gives satisfaction result. Combining method need more studies on optimization techniques need to be carried out and the application is complex compare to non hybrid methods.

2.5 COMBINED ECONOMIC EMISSION DISPATCH

The early work on combined economic emission dispatch initiated by (Gent & Lamont, 1972) entitled minimum-emission dispatch. They developed a program for on-line steam unit dispatch that results in the minimizing of NOx emission. They produce a unique mathematical representation of the steam generating units coupled with a Newton-Raphson convergence technique for dispatch produces base points and participation factors for any load level and any unit configuration.

(Brodsky & Hahn, 1986) introduced single-objective problem by treating emission as a constraint in order to reduce the complexity of economic emission dispatch problem. This formulation has a severe difficulty to obtain the relation between cost and emission.

Later, the CEED problem was converted to a single-objective problem by linear combination of different objectives as a weighted sum method by (R.Ramanathan, 1994). This method can be varying the weights in order to obtain a set of Pareto-optimal solutions. Unfortunately, this method cannot be implemented in problems having a nonconvex Pareto-optimal front. Hence, the ε-constraint method was presented by (Hsiao, Chiang, Liu, & Chen, 1994) to overcome this problem. This method optimizes the most preferred objective and considered the other objectives as constraints bounded by some allowable levels ε. However, the weaknesses of this approach are that it is time-consuming and tends to find weakly non-dominated solutions.

The other direction is to handle both objectives simultaneously as competing objectives instead of simplifying the MOOP to a single-objective problem. A fuzzy MOO technique for EED problem was proposed by (Srinivasan, Chang, & Liew, 1994). However, the solutions produced are sub-optimal and the algorithm does not provide a systematic framework for directing the search towards Pareto-optimal front. (Farag, Al-Baiyat, & Cheng, 1995) proposed a LP based optimization method to solve Economic Emission Dispatch (EED) problem in which only one objective is considered at a time to simplify the problem. However, this method may require high computational time. Furthermore, this approach does not give precise information about trade-off relations between cost and emission.

(Srinivasan & Tettamanzi, 1997) have proposed an EA based approach evaluating the economic impacts of environmental dispatching and fuel switching. However, some non-dominated solutions may be lost during the search process while some dominated solutions may be misclassified as non-dominated ones due to the selection process adopted.

Deb (2001) presented various MOEAs which are used to eliminate many difficulties in the classical MOO methods. Because, population of solutions is used in their search and multiple Pareto-optimal solutions can be found in one single simulation run. Some of the popular MOEAs are NSGA, NPGA, SPEA, NSGA-II, PAES etc.

(M. A. Abido, 2001) has applied NSGA for EED optimization problem. The proposed approach employs a diverse-preserving technique to overcome the premature convergence and search bias problems. In addition, the non-dominated solutions in the obtained Pareto-optimal set are well distributed and have satisfactory diverse characteristics. A hierarchical clustering technique is also imposed to provide the decision maker with a representative and manageable Pareto-optimal set.

NSGA suffers from computational complexity, lack of elitism and the need for specifying the sharing parameter. To overcome the three difficulties (Deb, Pratap, Agarwal, & Meyarivan, 2002) presented an improved version of NSGA known as NSGA-II, which resolves CEED problems and uses elitism to create a diverse Pareto-optimal front. The proposed NSGA-II is maintains a better spread of solutions and converges better in the obtained non-dominated front compared to two other elitist MOEAs such as SPEA and PAES.

(M. a. Abido, 2009) has proposed Multi-Objective PSO (MOPSO) technique to solve the CEED problem. A clustering algorithm to manage the size of the Pareto-optimal set and fuzzy-based mechanism to extract the best compromise solution is imposed. (Wu, Wang, Yuan, & Zhou, 2010) proposed MODE algorithm with an external elitist archive to retain non-dominated solutions found during the evolutionary process. In order to preserve the diversity of Pareto-optimality, a crowding entropy diversity measure is proposed. In addition, fuzzy set theory is employed to extract the best compromise solution. The capability of MODE approach is to generate well distributed Pareto solutions of EED problems. However, most of the MODE algorithms still have premature convergence problem and they lack a mechanism to deal with the complicated constraints of EED problem. Hence, (Lu, Zhou, Qin, Wang, & Zhang, 2011) proposed an enhanced MODE algorithm to solve the EED problem. This algorithm focuses on preventing premature convergence and handling the complicated constraints with efficiency.

Furthermore, (Dhanalakshmi, Kannan, Mahadevan, & Baskar, 2011) have incorporated DCD and CE into NSGA-II and named as MNSGA-II to improve the uniform diversity as well as lateral diversity of the obtained non-dominated solutions. This algorithm has been used to solve the CEED problem to improve convergence, diversity and robustness. Moreover, four different performance metrics are used to evaluate the different approaches. In addition, Technique for Order Preference by

Similarity to Ideal Solution (TOPSIS) method is employed to identify the best compromise solution. But the practical ED problem constraints such as valve-point effect, POZ and ramp rate limit are not considered in the CEED problem.

2.6 COMBINED ECONOMIC EMISSION DISPATCH WITH NONLINEARITIES

Many references for the nonlinearities consider single-objective function to solve combine economic emission dispatch problem. Combined Economic Emission Dispatch also can be solved by maintained the mathematical function as multi-objective. However, formulation and parameter need to be tuned by method of combining the multi-objective into single is much simple and easier.

(Yokoyama, Bae, Morita, & Sasaki, 1987) have proposed ε-constraint method, which is designed to obtain Pareto-optimal solutions based on optimization of one objective function while treating the other objectives as constraints bound by some allowable range ε_i. The problem is repeatedly solved for different values of ε_i to generate the entire Pareto set. The main strength of this approach is that it can be used for any arbitrary problem with either convex or non-convex objective space. The most obvious weakness of this approach is that it is time consuming and the coding of the objective functions may be difficult or even impossible for certain problems, particularly if there are too many objectives

Weighted sum method presented by (R.Ramanathan, 1994) is the most common approach to multi-objective optimization problem (MOOP). This method scalar a set of objectives into a single-objective by pre-multiplying each objective with a user supplied weight. After the objectives are normalized, a composite objective function is formed by summing the weighted normalized objectives thereby the MOOP is converted into a Single objective optimization problem (SOOP). The main strength of this method is that it can be applied to generate a strongly non-dominated solution that can be used as an initial solution for other techniques. Its main weakness is the difficulty to determine the appropriate weights when we do not have enough information about the problem.

(Alrashidi, 2008) presented on the impact of loading conditions on the emission and economic dispatch problem uses weighting functions on the double objective of emission and fuel cost. It provides a simple way of addressing the equality constraint. The rule guiding the application of the weights to the objectives is not explicitly shown. Also this method is not applied to the CEED rather it optimizes the objectives independently

(Singh & Dhillon, 2009) presented solving formulated EED problem using weighting method to generate non-inferior solutions which allows explicit trade-offs between objective levels for each non-inferior solution. Exploiting fuzzy decision making theory, membership functions relating to objectives are defined those play a vital role to find the 'best alternative' among the non-inferior solutions. To access the indifference band, interaction with the decision maker is obtained via cardinal priority ranking of the objectives. The advantage of the proposed method by Singh and Dhillon is it provides interface between the decision maker and the mathematical model through cardinal priority ranking.

(Güvenç, Sönmez, Duman, & Yörükeren, 2012) applies the Gravitational Search Algorithm method to solve the multi-objective economic and environmental dispatch problem using the penalty factor approach. It is superior in comparison to the other heuristic methods and more efficient.

(Rajasomashekar & Aravindhababu, 2012) encompasses a solution strategy using BBO with a view of obtaining the BCS for EED problem to explore its applicability for emerging power systems. In this paper, author used a new modified strategy by proposing new mathematical formula for best compromising solution by eliminates the price penalty factor in objective function, and assigned weighting factor. They modified through normalizing the fuel cost and emission components with a view to provide relatively equal significance to both the objectives. It has been found that the proposed strategy only requires minimum solution runs to obtain the best compromise solution.

In (Mishra & Pandit, 2013), the authors also solved CEED problem with weighted sum method using Particle Swarm Optimization by generating sets of the

Pareto- optimal solutions. These solutions provide many alternate dispatch options for reducing conflicting objectives like cost and harmful gases. Author used fuzzy membership function based ranking which also known as cardinal priority ranking to identify the best compromise solution.The projected method is initiate to be consistent in producing feasible and superior solution. At the same time, the obtained results from this paper are found to be better than available in previous literature. However, there are many techniques proved to be perform better than PSO where this weighted sum method can be impose on other techniques too.

CSA also applied to solve CEED problems by (Thi et al., 2014) since the technique have superior performance in solving ED problem previously as mentioned. The optimal solution from CSA in this paper compared with other methods such as tabu search, NSGA-II and BBO has indicated that CSA is a very efficient method for solving CEED problem. Again, population based metaheuristic technique proved to perform better with CEED too. But the authors did not implement non convex problem in this paper to show the efficiency of CSA towards solving discontinuities in objective function.

2.7 SUMMARY

As in this research, thermal power plant taken into the account because according to (Keshmiri, 2011) thermal power generation units are the main provider of the power in power system since they have flexibility in using different kinds of fuel. The incremental heat rate characteristic is the most important one for the operator of the power system and it is widely used by the dispatchers in order to economically dispatch the unit and the power system.

(Rajkumar M, 2014) stated that all conventional methods require the generator cost curves to be continuous functions, which is not possible in the case of practical situations. Also these methods have oscillating tendency in large scale mixed generating unit systems leading to high computation time. These lead to introduction of heuristic optimization techniques which solve nonlinearities problems such as in (Lin et al., 2002), (Serapião, 2013) and (Dubey et al., 2015).

There are some heuristic optimization techniques which need yet to be applied in combined economic emission dispatch to test it's performance efficiency in bi-objective and nonlinearities problem. As in (Dubey et al., 2015), FPA not yet applied in combined economic emission dispatch problem. Combined economic emission dispatch since is bi-objective problem, it can be solved either through multiobjective solving method (Lu et al., 2011) or convert into single objective (R.Ramanathan, 1994). Price Penalty Factor used to convert bi-objective into single objective as in (Güvenç et al., 2012) which have effective solutions. In order to compare the value with reference techniques, weighted sum method can be used in order to obtain the result close to reference values as in (R.Ramanathan, 1994). However, it is difficult to set weights value unless by try and error which defines a set of solutions from weight value of 0 until 1.

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

Economic Dispatch (ED) is a solution in power system to allocate suitable amount of generated power in generating units which meet the active load demand by considering the constraints. ED achieved by optimizing the cost function of generation. Unfortunately, urges from Clean Air Act Amendments (Resek et al., 1995) towards consideration of emission imposes great challenge to power system industry to optimize the emission as well in conjunction with generation cost. Besides, high non-linearity of the power system also another challenge in ED to formulate the mathematical function which is more complex compare with the conventional. In this chapter, the form of Combined Economic Emission Dispatch (CEED) to solve the two main objectives as well as the non-linearity problems of this research is discussed. Following it, the idea on solving CEED is introduced. General speaking, Flower Pollination Algorithm (FPA) is approached to efficiently allocate the generating units to solve nonlinear CEED with valve point loading effect and transmission losses. The overall processs illustrated in Figure 3.1.

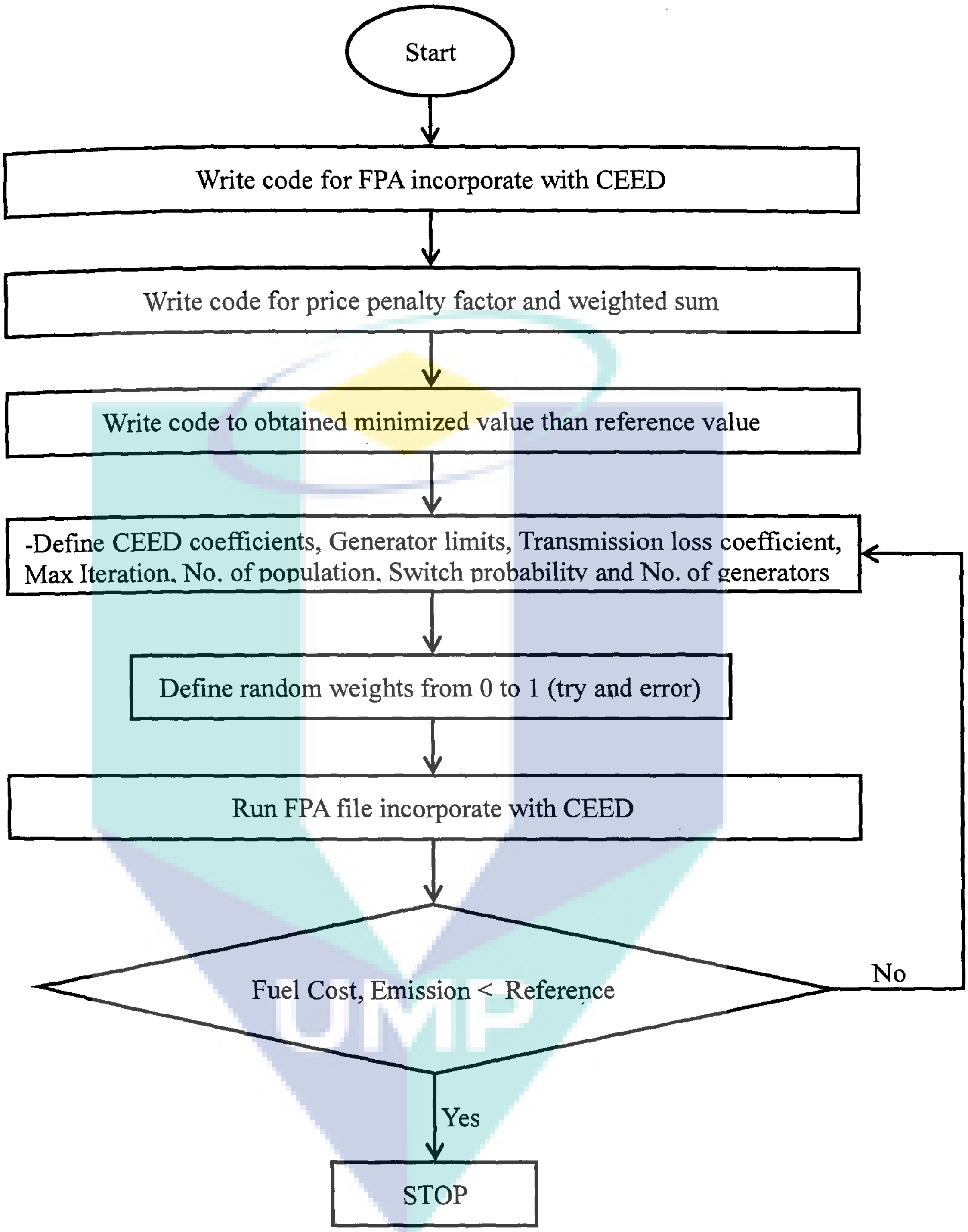

Figure 3.1. General flow chart of methodology

3.2 ECONOMIC DISPATCH

The ED is the process of allocating generation levels to the generating units, so that the system load is meets the load demand economically. Minimizing expenses of generation cost in an interconnected system is vital. Since the objective of ED is to minimise the overall cost of generation, the method of ED for generating units at different loads must have total fuel cost at the minimum point.

In a typical power system, multiple generators are implemented to provide enough total output to satisfy a given total consumer demand. Each of these generating stations can, and usually does, have a unique cost-per-hour characteristic for its output operating range. A station has incremental operating costs for fuel and maintenance; and fixed costs associated with the station itself that can be quite considerable in the case of a nuclear power plant, for example. Things get even more complicated when utilities try to account for transmission line losses, and the seasonal changes associated with hydroelectric plants.

3.2.1 Conventional Formulation of the Economic Dispatch

The main objective of ED is to minimize the total fuel generation cost function which formulated as

$$Min\ F_T = Min \sum_{i=1}^{N} F_i(P_{Gi}) \tag{3.1}$$

where F_T is total generating fuel cost given by $F_T = F_1 + F_2 + ... + F_N$, N is number of generating units, F_i is generating cost of each unit *i*, and P_{Gi} is the power generated by each unit *i*.

The operating cost of the plant has the form shown in Figure 3.2. For dispatching purposes, this cost is usually approximated by one or more quadratic segments. So, the fuel cost curve in the active power generation, takes up a quadratic form with the total fuel cost $F(P_{Gi})$ in (\$/h), given as:

$$F(P_{Gi}) = \sum_{i=1}^{N}(a_i P_{Gi}^2 + b_i P_{Gi} + c_i) \tag{3.2}$$

where a_i, b_i and c_i are cost coefficients for i^{th} generator.

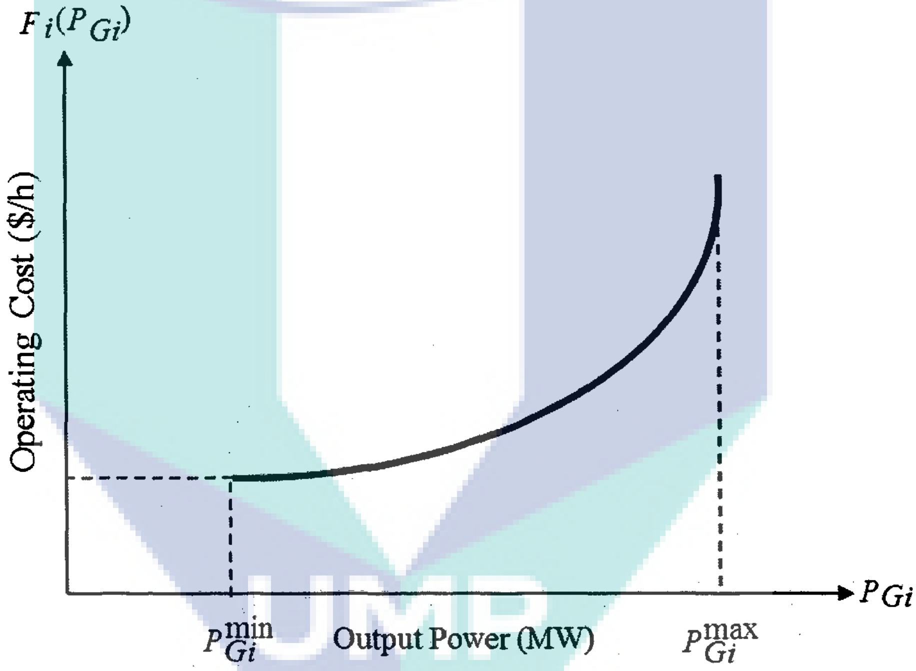

Figure 3.2. Operating cost curve of thermal generator

Source: Hassan (2007)

By refer to the Figure 3.2, P_{Gi}^{min} is the minimum loading limit and P_{Gi}^{max} is the maximum output limit of a generator. When it have violated by performing out of the curve, operating the unit will be uneconomical or technically infeasible.

The fuel cost curve may have a number of discontinuities. The discontinuities occur when the output power is extended by using additional boilers, steam condensers, or other equipment. They may also appear if the cost represents the operation of an entire power station, and hence cost has discontinuities on paralleling of generators. Within the continuity range the incremental fuel cost may be expressed by a number of short line segments or piece-wise linearization.

3.3 EMISSION DISPATCH

Emission Dispatch (EmD) is a second main objective of this research to minimize the total emissions by satisfies the allowable emission limit. The power generation from thermal power plant by combustion of fossil fuel releases several contaminants, such as Sulphur Oxides, Nitrogen Oxides and Carbon Dioxide, into the atmosphere (Talaq, Ferial, & El-Hawary, 1994). The two primary emissions from power plant that highly concerned in dispatching perspective are sulphur oxides (SO_x) and nitrogen oxides (NO_x). This research only focuses on minimizing NO_x. In power plant, there are two sources of nitrogen that combine with oxygen from the fuel and the combustion air to produce NO_x. The first source is nitrogen in the air that produces an emission called thermal NO_x. The second source is nitrogen in the fuel that produces an emission called fuel NO_x. The total NO_x produced during combustion is the sum of the thermal NO_x and fuel NO_x. In coal, there is no apparent correlation between the amount of fuel-bound nitrogen and the fuel NO_x produced (Basu, 2011a).

3.3.1 Conventional Formulation of the Emission Dispatch

ED introduced in order to minimize the total emission which expressed as

$$Min\ Emi_T = Min \sum_{i=1}^{N} Emi_i(P_{Gi}) \tag{3.3}$$

where Emi_T is total generating emission given by $Emi_T = Emi_1 + Emi_2 + ... + Emi_N$, N is number of generating units, Emi_i is generating emission of each unit i, and P_{Gi} is the power generated by each unit i.

The quadratic function of total emission $Emi(P_{Gi})$ in (Kg/h) can be defined as

$$Emi(P_{Gi}) = \sum_{i=1}^{N} (\alpha_i P_{Gi}^2 + \beta_i P_{Gi} + \gamma_i) \tag{3.4}$$

where α_i, β_i and γ_i are emission coefficients for i^{th} generator. The cost curve of emission is as illustrated in Figure 3.3.

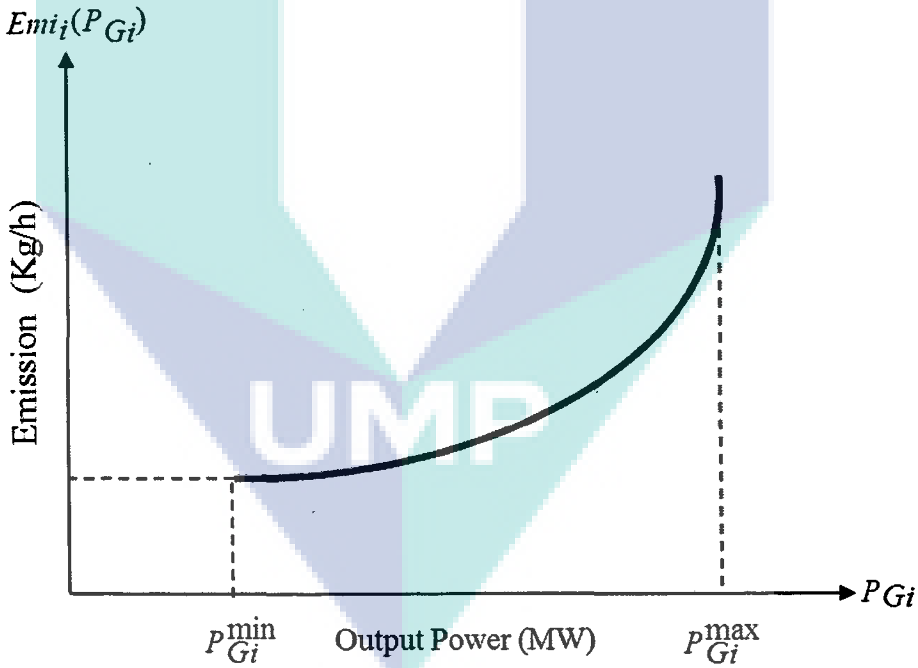

Figure 3.3. Emission curve of thermal generator

3.4 CONSTRAINTS

The power system has to satisfy several constraints while in operation. These can be broadly divided into two types. The first of these formed due to the necessity for the system to satisfy load balance and are called equality constraints. In addition, a number of other constraints due to physical and operational limitations of the units and components in economic scheduling defined as inequality constraints.

3.4.1 Equality Constraints

Also known as power balanced constraint where the total generated power must cover the total load demand and transmission losses which can be defined as

$$\sum_{i=1}^{N} P_{Gi} - P_d - P_{loss} = 0, \qquad i=1, 2, \ldots, N \qquad (3.5)$$

3.4.2 Inequality Constraints

Inequality constraint also referred as generator capacity constraint. For stable operation, the real power output of each generator is restricted by lower and upper limits as follows:

$$P_{Gi}^{min} \le P_{Gi} \le P_{Gi}^{max}, \qquad i=1,2,\ldots,N \qquad (3.6)$$

3.5 FORMULATION FOR TRANSMISSION LOSS

Transmission losses may be neglected when transmission losses are very small but in a large interconnected network where power is transmitted over long distances, transmission losses are a major factor and affect the optimum dispatch of generation.

The economic load dispatch problem considering the transmission power loss P_{loss} for the objective function is thus formulated as

$$P_{loss} = \sum_{i=1}^{N} \sum_{j=1}^{N} P_{Gi} B_{ij} P_{Gj} \tag{3.7}$$

Or in more complex form formulated as

$$P_{loss} = \sum_{i=1}^{N} \sum_{j=1}^{N} P_{Gi} B_{ij} P_{Gj} + \sum_{i=1}^{N} B_{i0} P_{Gi} + B_{00} \tag{3.8}$$

where,

P_{Gj} = the output generation of unit j (MW).

B_{ij} = the *ij-th* element of the loss coefficient square matrix.

B_{i0} = the *i-th* element of the loss coefficient.

B_{00} = the loss coefficient constant.

3.6 FORMULATION FOR PRACTICAL CONSTRAINTS OF GENERATOR

3.6.1 Valve Point Loading Effect

The input-output characteristics (or cost functions) of a generator are approximated using quadratic or piecewise quadratic function, under the assumption that the incremental cost curves of the units are monotonically increasing piecewise-linear functions. However, real input-output characteristics display higher-order nonlinearities and discontinuities due to valve-point loading in fossil fuel burning plant. The valve-point loading effect has been modelled in as a recurring rectified sinusoidal function, such as the one show in Figure 3.4 (Kothari D. P. and Dhillon J. S., 2011).

The generating units with multi-valve steam turbines exhibit a greater variation in the fuel cost functions. The valve-point effects introduce ripples in the heat-rate curves.

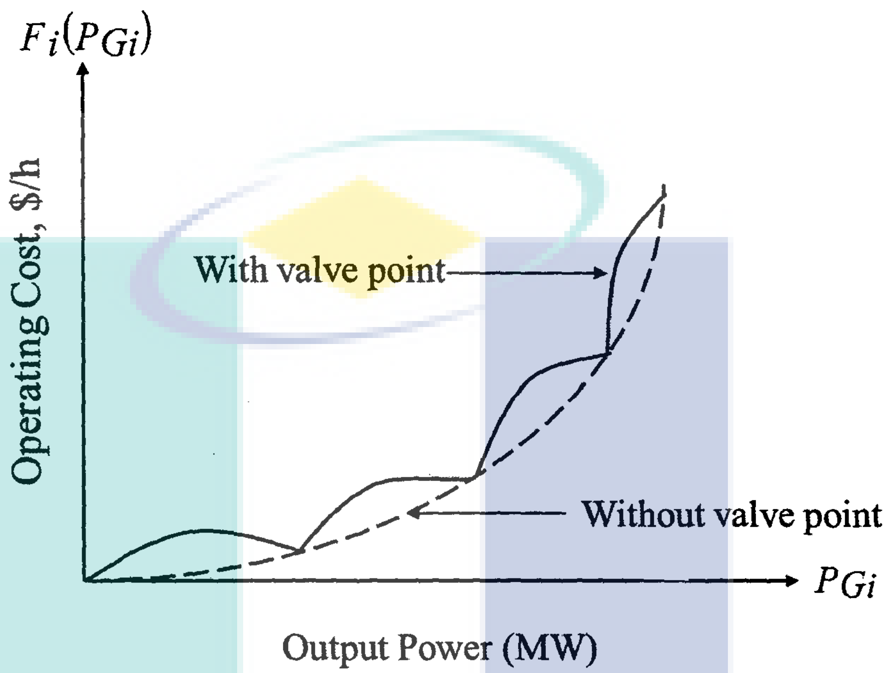

Figure 3.4. Operating cost curve with valve point loading effect

Source: Kothari D. P. and Dhillon J. S. (2011)

The cost function with considering valve point loading effects can be expressed as

$$F(P_{Gi}) = \sum_{i=1}^{N} \left[a_i P_{Gi}^2 + b_i P_{Gi} + c_i + \left| d_i \sin\{e_i (P_{Gi}^{\min} - P_{Gi})\} \right| \right] \tag{3.9}$$

Where a_i, b_i, c_i, d_i and e_i are cost coefficients for i^{th} unit with valve point loading effect.

For emission function with valve point loading effect, the mathematical formula expressed as

$$Emi(P_{Gi}) = \sum_{i=1}^{N} [\alpha_i P_{Gi}^2 + \beta_i P_{Gi} + \gamma_i + \eta_i \exp(\delta_i P_{Gi})] \tag{3.10}$$

where α_i, β_i, γ_i, η_i and δ_i are emission coefficients for i^{th} generator with valve point loading effect.

3.7 COMBINED ECONOMIC EMISSION DISPATCH

The CEED seeks a balance between cost and emission. The ED and EmD problem are conflicting in nature as the ED reduces the total fuel cost of the system, without any concern about the rate of emission. EmD, on the contrary, reduces the total emission from the system, which generally causes an increase in the system operating cost. As CEED seeks a balance between the fuel cost and emission hazards simultaneously, therefore this problem may be considered as a multi-objective optimization problem. The above mentioned multi-objective optimization can be solved using Fuzzy set theory along with any conventional optimization techniques, weighted sum method and many other techniques. In this paper, the CEED solved using weighting function and cardinal priority ranking method (Emmanuel Dartey Manteaw, 2012) to normalizing the fuel cost and emission components with a view to provide relatively equal significance to both the objectives.

3.7.1 Conventional Formulation for Combined Economic Emission Dispatch

The optimal generating cost actually is sum of minimized fuel cost and minimized emission

$$MinT = Min \sum_{i=1}^{N} [F(P_{Gi}), Emi(P_{Gi})] \tag{3.11}$$

where T is the optimal cost of generation. $F(P_{Gi})$ and $Emi(P_{Gi})$ are total fuel cost and emission costs of generators, respectively. N represents the number of generators connected in the network.

3.7.1.1 Weighted Sum Method

The weighted sum method applied in this research in order to converts the multi-objective problem into single objective function and to obtain result close to reference value. This approach tend to give satisfy results when solved using different values of w_i. Hence, the formulation of objective function with weighting function expressed as:

$$T = w_1 * F(P_{Gi}) + w_2 * Emi(P_{Gi}) \qquad (3.12)$$

Where $\sum_{i=1}^{N} w_i = 1$; N=Number of objectives.

When the value of w_1 is 1 and w_2=0, the objective function represents fuel cost of generation function. Whereas when w_1 is equal to 0 and w_2 is 1, the objective function represents emission function only. It is very difficult to make a solution that will give the best compromising solution (BCS) which lie nearer to both of the best solution due to the independent characteristic of both objective functions. The fuel cost increases and the emission cost decreases when w_1 is reduced in steps from 1 to 0. The problem becomes purely CEED that minimizes only the emissions when w_1 is equal to 0.

The formulated CEED problem is solved using the weighting method to generate non inferior solutions which allows explicit trade-offs between objective levels for each non inferiors solution. (Kothari D. P. and Dhillon J. S., 2011).

3.7.1.2 Price Penalty Factor

The bi-objective method convert to single objective method by introducing price penalty factor where it will converts emission to emission cost in order to minimize total cost of CEED. Belows are the problem formulation for price penalty factor, h_i :

$$T = w_1 * F(P_{Gi}) + w_2 * h_i * Emi(P_{Gi}) \tag{3.13}$$

The price penalty factor is ratio between fuel cost and emission of corresponding generator (Gnanadass, Padhy, & Manivannan, 2004). There are research carry out to determine the suitable generator capacity to obtain ratio of price penalty factor which gives effective resut. According to (Krishnamurthy & Tzoneva, 2013), Min-Max generator capacity gives the better optimization solution compare with Max-Max, Min-Min and Max-Min. Hence, in this research, Min-Max price penalty factor have been implemented and the equation expressed as below:

$$\begin{aligned} h_i &= \frac{F(P_{Gi}^{\min})}{Emi(P_{Gi}^{\max})} \\ &= \frac{a_i P_{Gi\min}^2 + b_i P_{Gi\min} + c_i + \left| d_i \sin\{e_i (P_{Gi\min} - P_{Gi\min})\} \right|}{\alpha_i P_{Gi\max}^2 + \beta_i P_{Gi\max} + \gamma_i + \eta_i \exp(\delta_i P_{Gi\max})} \end{aligned} \tag{3.14}$$

The following steps are used to find the price penalty factor for a particular load demand.

1. Find the ratio between minimum fuel cost and maximum emission of each generator.
2. Arrange the values of price penalty factor in ascending order.
3. Add the maximum capacity of each unit ($P_{Gi}^{\max}$) one at a time, starting from the smallest h_i unit until $P_{Gi}^{\max} \geq$ Pd.
4. At this stage, h_i associated with the last unit in the process is the price penalty factor *h* for the given load.

3.8 FLOWER POLLINATION ALGORITHM

Flower Pollination Algorithm (FPA) is a new biologically-inspired (BI) meta-heuristic optimization technique developed by Xin-She Yang at 2012 (Xin-She, Y., 2012). The inspiration of pollination process of the plant in nature became main idea on develop FPA by the author. Flower pollination actually is reproduction activity of flower where the pollen of the flower mostly will be transferred via transfer agent which also called pollinators. Significantly, pollination can occur in two ways which are abiotic and biotic. Abiotic process is a pollination process which does not require pollinators to transfer the pollens. Usually, the transfer agents for abiotic process are wind or diffusion method of the flower plant itself. On the other hand, biotic process needs help of pollinators such as insects and animals to transfer the pollen for the purpose of reproduction of flower plant.

For biotic process, pollinators will visit the flower species that it was attracted by bypassing other flower species. This selective method by pollinators considered as flower constancy. Flower constancy has benefits on reproducing more of the same flower species since the flower pollen will be highly transferred. On the contrary, pollinators receive their benefits with just using their bounded memory and minimum cost of learning and exploring, they can be sure with the availability of nectar in that specific flower.

There are two types of pollination which are self-pollination and cross-pollination. Cross pollination or in other word allogamy, can be defined as pollen from one plant to fertilize the flower of another plant. Meanwhile, self-pollination occurs in case when there are no reliable pollinators, pollen from the same flower or different flower of the same plant to fertilize one flower.

Global pollination took place when there is long distance cross pollination occur via biotic process. Large jump or fly distance steps involved in global pollination with respect to the Lévy distribution by pollinators that copy the behaviour of Lévy flight (Xin-She, Y., 2012)(Pavlyukevich, 2007). In addition, flower constancy also connected using similarity or difference between two flowers as an increment step in reproduction due to nature attraction of pollinators towards exclusive flowers.

Due to the basic features of pollination process, flower constancy and pollinator behaviour, Yang developed FPA by respect to the four basic rules as below (Xin-She, Y., 2012) :

Rule 1: The global pollination process occurs through biotic and cross-pollination with pollinators that copying behaviour of Lévy flight.

Rule 2:Local pollination consists of abiotic and self-pollination.

Rule 3:Reproduction probability takes the preferences of flower constancy which is proportional to the similarity of two flowers involved.

Rule 4:Switch probability that constrained from 0 to 1 is used to control local pollination and global pollination. Local pollination has higher percentage in switch probability due to nature obstacles during the process of pollination.

For the first rule, the mathematical formula is formulated as below

$$x_i^{t+1} = x_i^t + L(x_i^t - g_*) \tag{3.15}$$

where x_i^t is the solution vector x_i at iteration t, and g_* is the current best solution which represent the most fittest. Whereas, L is the step size which uses Lévy distribution for L > 0, to represent the nature of long distance pollination by pollinators respect to the Lévy flight behaviour. Lévy distribution mathematically can be describe as

$$L \sim \frac{\lambda\Gamma(\lambda)\sin(\pi\lambda/2)}{\pi}\frac{1}{s^{1+\lambda}}, \qquad (s >> s_0 > 0). \tag{3.16}$$

In his function, $\Gamma(\lambda)$ stand for standard gamma function and only applicable when the step is large, s>0. At the same time the λ was pre-set to 1.5 (Xin-She, Y., 2012).

For the rule 2 which is for local pollination and flower constancy which is rule 3, the formulated mathematical function is

$$x_i^{t+1} = x_i^t + \in (x_j^t - x_k^t), \quad (3.17)$$

where x_j^t and x_k^t are represents pollen from the same plant species but different flower with $\in$ from distribution [0,1].

According to the rule 4 where the switch probability p is used to control the local pollination and global pollination. To initialize the switch probability, it can be set to equal value which is 0.5 then heuristically adjust the parameter which gives better performance.

3.9 FLOWER POLLINATION ALGORITHM FOR COMBINED ECONOMIC EMISSION DISPATCH

To initialize the simulation, population of the flower, N_p need to be defined. Population of the flower where $x = [x_1, x_2, ..., x_{Np}]$ in this paper represents the solutions for CEED which are $x_i = [P_{i1}, P_{i2}, ..., P_{ij}, P_{iN}]$. P is power output for each generating unit. The initialization mathematical function of FPA works as below

$$P_{ij} = P_j^{min} + rand * (P_j^{max} - P_j^{min}) \quad (3.18)$$

Uniformly distributed random number which lie between [0,1] is generated for the rand function in the formula. Whereas, $P_j^{\min}$ and $P_j^{\max}$ is the lower limits and upper limits of the inequality constraint of objective function that need to be defined. By adding the objective function which is minimizing total cost, Eq. (3.11) which also minimizes fuel cost and emission, fitness function is defined to find the current best feasible solution X_{best}.

Next, the switch probability needs to be set as $P \in [0,1]$ and the total number of iteration so that the simulation can meet the stopping criteria. Insect carrying pollen may travel over long distances by taking big steps and can cause cross-pollination. The travel of pollinators can be approximated by Lévy distribution. The new solution is computed on the basis of previous best flower via Lévy flight. When $rand_1$ > switch probability, new best solution will be computed with implementation of Lévy flight (global search) formulation as below. Otherwise new population member is generated through local search.

$$X_i^{new} = X_i^{old} + \Delta X_i^{new} \tag{3.19}$$

$$\Delta X_i^{new} = \left(X_i^{old} - X_{best}\right) \times L(\lambda) \tag{3.20}$$

The parameter $L(\lambda)$ is a step size, which represents the strength of pollination. Levy flight distribution is used to represent this step size, and λ is the distribution factor. The distribution factor of Lévy flight is maintained 1.5 and the multiplication factor in the range [0,1] respectively thorough the simulation for this paper (Dubey et al., 2015). The Lévy flight calculate as

$$L(\lambda) = K \times \varphi \times \frac{\sigma_x(\lambda)}{\sigma_y(\lambda)} \tag{3.21}$$

where K is the multiplication factor selected in the range [0,1].

$$\varphi = \frac{rand\, n_1}{|rand\, n_2|^{1/\lambda}} \tag{3.22}$$

where *rand n1* and *rand n2* are normally distributed d-dimensional random numbers. The values of $\sigma_1(\lambda)$ and $\sigma_2(\lambda)$ are given by

$$\sigma_1(\lambda) = \left[\Gamma(1+\lambda) \times \sin(\pi\lambda/2) / \Gamma\left(\frac{1+\lambda}{2}\right) \times \lambda \times 2^{\left(\frac{\lambda-1}{2}\right)}\right] \tag{3.23}$$

$$\sigma_2(\lambda) = 1 \tag{3.24}$$

Γ is the gamma distribution applicable for larger step size. The variables of new solution have to be satisfying the lower and upper operating limits as below.

$$X_i^{new} = \begin{cases} P_i^{\min} & if\ X_i^{new} < P_i^{\min} \\ P_i^{\max} & if\ X_i^{new} > P_i^{\max} \\ X_i & otherwise \end{cases} \tag{3.25}$$

Next, new solution will be generated by flower constancy which also called local pollination, can be expressed as,

$$X_i^{new} = X_i^{old} + F\left(X_j^{old} - X_k^{old}\right) \tag{3.26}$$

where X_j^{old} and X_k^{old} are different flowers from the same plant type. Therefore X_j^{old} and X_k^{old} are selected from the same population. F is a scaling factor selected in the range [0,1] to control the mutation taking place during local pollination. The value of F can be controlled to improve local search and achieve fast convergence. In this research, the F set as random value, *rand* so that it optimizes for each different case.

Additionally, the solution for the FPA also defined to obey the equality constraint rule as in Eq. (3.5). At the same time for equality constraint, the penalty factor PF implemented in objective functions when it is violated. The implementation of PF is as follows

$$F = (F) + PF * abs[(\Sigma_{i=1}^{N} P_{Gi}) - P_D - P_{loss}] \tag{3.27}$$

$$Emi = (Emi) + PF * abs[(\Sigma_{i=1}^{N} P_{Gi}) - P_D - P_{loss}] \tag{3.28}$$

The algorithm will come to the stop point when predefined maximum number of iteration reached.

The simulation repeated with same parameters by varying w_1 from 1 and w_2 from 0 to w_1=0 and w_2=1 with step size of 0.1. For more precise result, the whole process repeated by decreasing the step size of w_1 to 0.01, 0.001 and so on simultaneously until there is no changes on result. For example, if the value of w is with 4 decimal values, the run time cycle will be 4 times with 11 run time by step size 0.1, 0.01, 0.001 ad 0.0001 in each cycle respectively. The best result of each cycle which is best compromising result nearest to the compared value from literature is chose to bring the *w* value to next cycle. The method although is try and error but it is systematically applied.

From the results tabulated, the minimum fuel cost, emission or both fuel cost and emission compare with reference value chosen as the best combined objective result.

The pseudo code of Flower Pollination Algorithm (FPA) which used to simulate in MATLAB to solve the problem of combined economic emission dispatch (CEED) function presented in Figure 3.5. Simultaneously, the overall process of FPA in solving CEED as explained above simplified and presented in the form of flow chart in Figure 3.6.

Initialize the population of flower, n with predefined min and max of function limits

Calculate the fitness of each flower and find the best solution g_*

Define switch probability $p \in [0,1]$ **(Rule 4)**

while (t<Max number of iterations)

for i=1:n

if rand<p,

Define the step vector which respects Levy distribution, L

$x_i^{t+1} = x_i^t + L(x_i^t - g_*)$

(Rule 1)

else

Describe $\in$ from a uniform distribution in [0, 1]

J and K will be randomly chosen among the solutions

$x_i^{t+1} = x_i^t + \in (x_j^t - x_k^t)$ ***(Rule 2 and 3)***

end if

Evaluate new solutions

Update the better new solutions in the population

end for

Find the current best solution g_*

end while

Figure 3.5. Pseudo code of Flower Pollination Algorithm

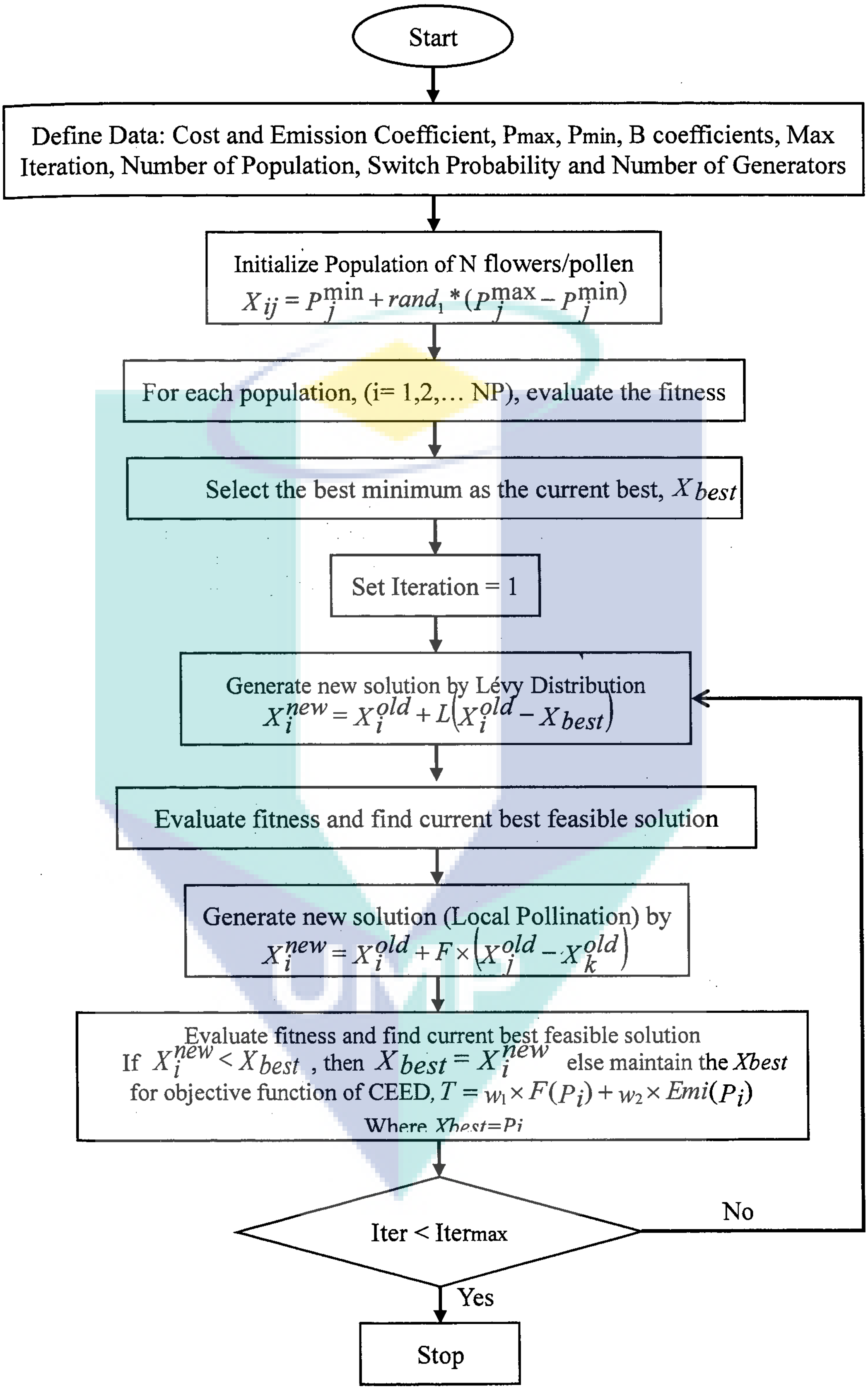

Figure 3.6. Flow Chart of FPA for CEED

3.10 SUMMARY

For this research, combined economic emission dispatch problems solved by using Flower Pollination Algorithm which is modern heuristic optimization technique. For non-linearities, only valve point loading effect considered because it is the major practical constraint that influence much on optimal power dispatch. Due to make the complex mathematical formula to simple, weighting function and price penalty factor was added because it is easy to tune and optimal result as expected could be gained. Decision made by chosing the best minimum fuel cost and emission obtained by comparing with reference value.

CHAPTER 4

RESULT AND ANALYSIS

4.1 INTRODUCTION

The data that collected from the simulation of this research is discussed in this chapter to show the efficiency of implementation of Flower Pollination Algorithm (FPA) on solving Combined Economic Emission Dispatch (CEED) problems. To make it more realistic, other than considering equality and inequality constraints of thermal power plant, the non-linearity characteristics which is valve point loading effect also taken into the account. MATLAB R2011b used to program the problem of this research.

4.2 TEST SYSTEMS

There are four test system, 6-generating unit, 10- generating unit, 11-generating unit and 40 generating unit, implemented in this research to validate the proposed FPA technique on solving CEED problems. For each case, different power load demands have been set to observe the stability of proposed technique. In every case, the weighting function and price penalty factor method also implemented to select the best optimum result according to the objective function which minimum than the comparison value.

Table 4.1
Specifications of test systems

Test Systems	Transmission Loss	Valve Point Loading Effect	Power Demand
6 generating unit	No	No	1000 MW
10 generating unit	Have	Have	2000 MW
11 generating unit	No	No	2500 MW
40 generating unit	No	Have	10500 MW

4.2.1 Case 1: 6-unit Test System

This test case consists of 6 generating unit where the fuel cost coefficients, emission coefficients and generator capacity limit are taken from (Balamurugan & Subramanian, 2007). Balamurugan clearly specified that the coeffiecients provided is for 6 unit test case which ignores the transmission losses for the system and doesn't count practical problems of power system. Meanwhile, his data which referred for this test system have been validated with the data from the techniques he compared and it shares the same as presented by Balamurugan. Moreover, the data for CEED problem is limited and the data value is same for almost all CEED papers reviewed. The power demand of this test system was set to 1000 MW. The unit data is presented in Table 4.2 and 4.3.

Table 4.4 until Table 4.8 presents the result obtained for this test system by using proposed technique of this paper with implementation of price penalty factor and weighted sum method to choose the best compromising result with minimum than comparison value. For the optimization purpose, the parameter of the technique set as N_p =40 and p=0.2 with iteration=1000. The convergence characteristics of proposed FPA are presented in Figure 4.5 for number of population and Figure 4.6 for switch probability. The result also compared with other heuristic optimization techniques based literature in Table 4.9 to show the strength of the proposed technique.

Based on the Table 4.9, it is not deniable that FPA gives the best result in solving CEED problems for six generating unit by minimize both fuel cost and emission.

Table 4.2
Fuel cost coefficients and generation limits for six generator system

Generator	$P_i$min **(MW)**	$P_i$max **(MW)**	a_i **($/MW²h)**	b_i **($/MWh)**	c_i **($/h)**
1	10	125	0.1525	38.540	756.800
2	10	150	0.1060	46.160	451.325
3	35	225	0.0280	40.400	1050.000
4	35	210	0.0355	38.310	1243.530
5	130	325	0.0211	36.328	1658.570
6	125	315	0.0180	38.270	1356.660

Table 4.3
Emission coefficients for six generator system

α_i **(kg/MW²h)**	β_i **(kg/MWh)**	γ_i **(kg/h)**
0.0042	0.3300	13.860
0.0042	0.3300	13.860
0.0068	-0.5455	40.267
0.0068	-0.5455	40.267
0.0046	-0.5112	42.900
0.0046	-0.5112	42.900

Table 4.4
Showing result for *w* in one decimal value of six generator system with load demand of 1000 MW

Weighting Factors		**Fuel Cost (\$/h)**	**Emission (kg/h)**
w_1	w_2	**F**	**E**
1	0	50365.29	976.2445
0.9	0.1	50365.46	973.1722
0.8	0.2	50366.13	969.4922
0.7	0.3	50367.65	964.9987
0.6	0.4	50370.72	959.3779
0.5	0.5	50376.74	952.1232
0.4	0.6	50388.91	942.3532
0.3	0.7	50415.54	928.3655
0.2	0.8	50484.42	906.3287
0.1	**0.9**	**50739.4**	**865.3696**
0	1	53530.13	784.6346

Table 4.4 shows the results obtained by varying weighting function in order to find the best compromising solution. By observing the pattern of the result obtained from the above table, when w_1 is 1 and w_2 is 0, the optimization tends to minimize fuel cost rather than emission. Whereas, when w_1 is 0 and w_2 is 1, it minimizes emission. The best result was chosen by try and error method where the result laid close to comparison value and still able to minimize, which are fuel cost is 50739.4 \$/h and emission 865.3696 kg/h. The Figure 4.1 illustrates the trade-off plot of the results in Fuel cost versus Emission. Most of the points are laying more on minimum fuel cost but high emission value. However, the point which is w_1=0.1 and w_2=0.9 gives approximately balance in minimizing fuel cost and emission.

When doing comparison with other optimization techniques as showed in Table 4.9, this obtained value still not satisfying and can be improved. To get almost fine result to win the compared values of fuel cost and emission of other author's, the weighting function value specified by adding decimal values.

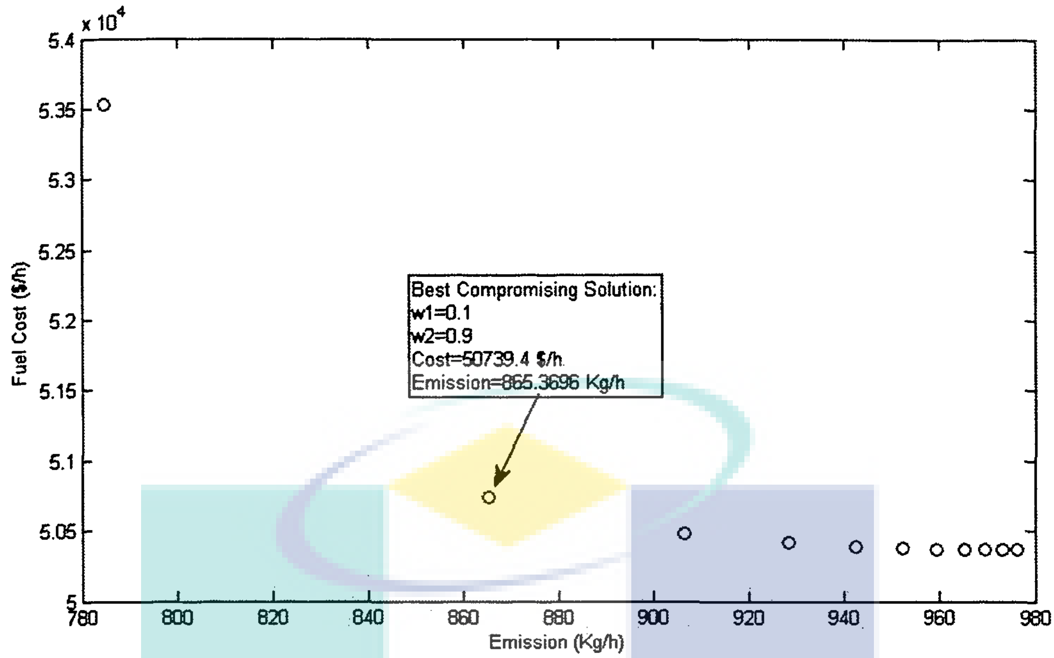

Figure 4.1. Trade-off result using weighted sum method by one decimal value step size for six generator system with 1000 MW load demand

For the following, the weighting function value was added with one more decimal place which means the step size will be 0.01. Because the previous best compromising result lays at w_1=0.1 and w_2=0.9, this will set as highest weighting function in this second stage meanwhile w_1=0 and w_2=1 set as lowest. When look at the comparison values, the fuel cost and emission result of reviewed paper also underlying within this weighting function value which is in between 50739.4 $/h and 53530.13 $/h for fuel cost, 865.3696 kg/h and 784.6346 kg/h for emission.

Table 4.5
Showing result for w in two decimal value of six generator system with load demand of 1000 MW

Weighting Factors		Fuel Cost ($/h)	Emission (kg/h)
w_1	w_2	F	E
0.1	0.9	50739.40	865.3696
0.09	0.91	50798.08	859.222
0.08	0.92	50870.58	852.5016
0.07	0.93	50961.61	845.1408
0.06	0.94	51078.04	837.074
0.05	**0.95**	**51230.28**	**828.2516**
0.04	0.96	51434.72	818.6739
0.03	0.97	51718.44	808.4686
0.02	0.98	52128.99	798.0791
0.01	0.99	52757.04	788.7552
0	1	53530.13	784.6346

Hence, from the Table 4.4, the results optimized more specifically. According to weighted function method, the best suitable weighted function picked based on try and error is w_1=0.05 and w_2=0.95 with fuel cost 51230.28 $/h and emission 828.2516 kg/h. The Figure 4.2 illustrates the distribution of results in between w_1=0.1, w_2=0.9 and w_1=0, w_2=1.

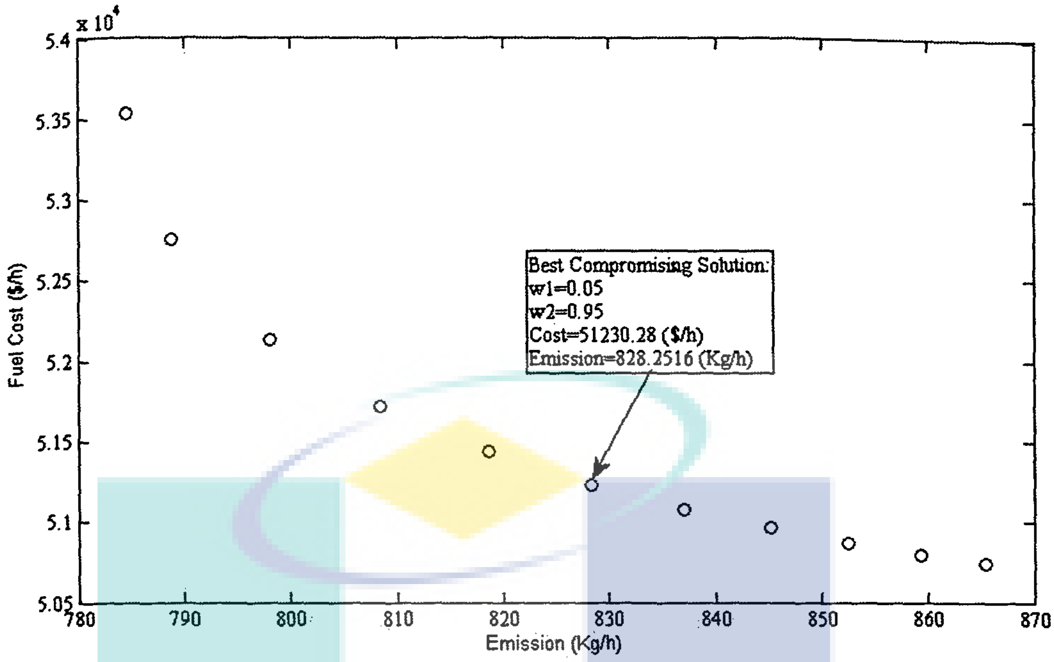

Figure 4.2. Trade-off result using weighted sum method by two decimal value step size for six generator system with 1000 MW load demand

The result with weighted function above has minimum fuel cost than compared fuel cost but higher emission than compared emission of other optimization techniques. This indicates, the w_1 value should be decreased and w_2 should be increased since both objectives functions are independent of each other. Hence, in this third stage, step size is set more specifically than previous which is 0.001. w_1 and w_2 are taken between 0.05 to 0.04 and 0.95 to 0.96 respectively since the reviewed results also lay in between this value of fuel cost and emission. Reviewed result can be referred as in Table 4.9.

Table 4.6
Showing result for *w* in three decimal value of six generator system with load demand of 1000 MW

Weighting Factors		**Fuel Cost ($/h)**	**Emission (kg/h)**
w_1	w_2	F	E
0.05	0.95	51230.28	828.2516
0.049	**0.951**	**51248.03**	**827.327**
0.048	0.952	51266.32	826.3949
0.047	0.953	51285.17	825.4553
0.046	0.954	51304.59	824.5081
0.045	0.955	51324.62	823.5535
0.044	0.956	51345.27	822.5917
0.043	0.957	51366.58	821.6226
0.042	0.958	51388.57	820.6466
0.041	0.959	51411.28	819.6636
0.04	0.96	51434.72	818.6739

By refer to the Table 4.5, the results optimized more specifically than previous stage. In short, the best fuel cost obtained for this stage is 51248.03 $/h and 827.327 kg/h for emission where belongs to the weighting function w_1=0.049 and w_2=0.951. In Figure 4.3, it can be observed that the results almost evenly distributed when the step size set to be specific.

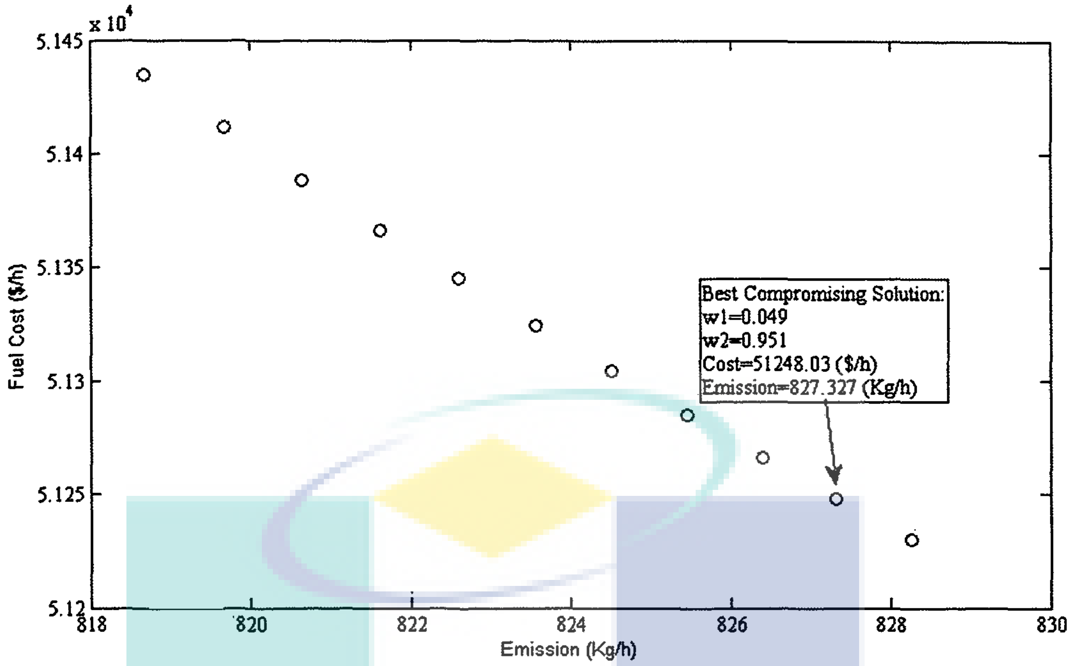

Figure 4.3. Trade-off result using weighted sum method by three decimal value step size for six generator system with 1000 MW load demand

The best compromising result obtained at stage three is quite very near to the comparison values. The fuel cost of this research beats the compared values but yet need minimization of emission although the difference between the values obtained from this research and compared values is small. In order to achieve the best compromising result, the step size reduced again to 0.0001 at this stage. The range of weighting function chose in between 0.049 and 0.048 for w_1 as well as 0.951 and 0.952 for w_2.

Table 4.7
Showing result for *w* in four decimal value of six generator system with load demand of 1000 MW

Weighting Factors		Fuel Cost ($/h)	Emission (kg/h)
w_1	w_2	F	E
0.049	0.951	51248.03	827.327
0.0489	0.9511	51249.84	827.2342
0.0488	0.9512	51251.65	827.1412
0.0487	**0.9513**	**51253.46**	**827.0482**
0.0486	0.9514	51255.28	826.9551
0.0485	0.9515	51257.11	826.8619
0.0484	0.9516	51258.94	826.7687
0.0483	0.9517	51260.78	826.6754
0.0482	0.9518	51262.62	826.582
0.0481	0.9519	51264.47	826.4885
0.048	0.952	51266.32	826.3949

From the Table 4.7, the best compromising result of this stage achieved minimum than comparison value where fuel cost is **51253.46 $/h** and emission **827.0482 kg/h** at weighting function w_1=**0.0487** and w_2=**0.9513**. This weighting function although uses try and error method but it was systematically conducted to obtained the result nearest to the comparison value. The further details for this result tabulated in Table 4.8. At the same time when observe Figure 4.4, the result of this stage distributed evenly which means FPA optimize the objective function at stable condition along the simulation.

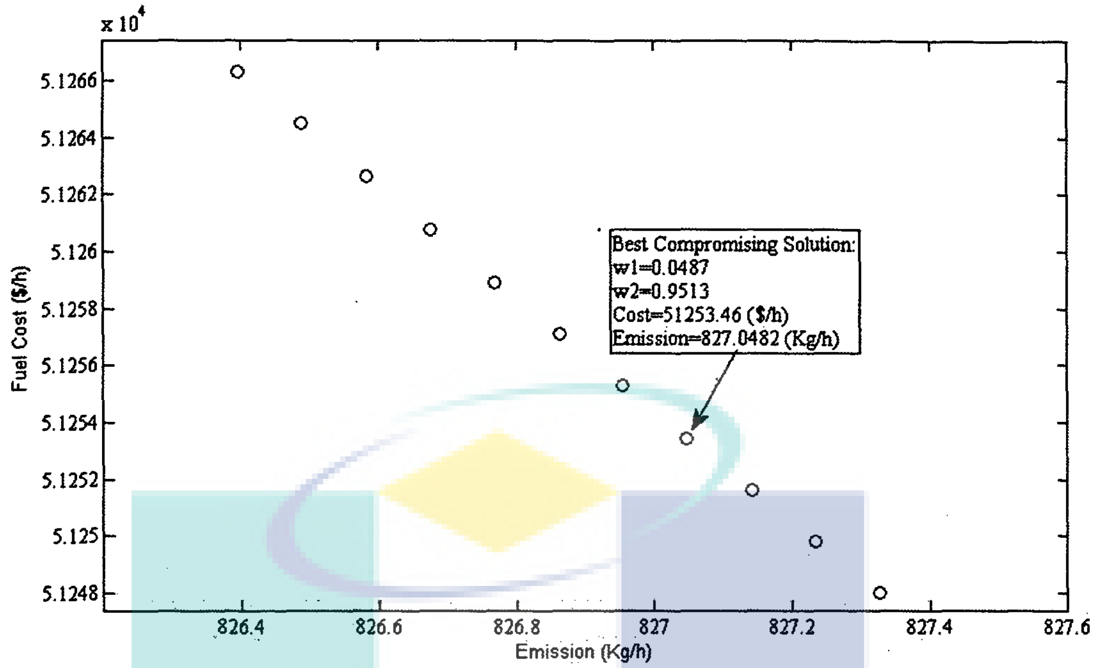

Figure 4.4. Trade-off result using weighted sum method by four decimal value step size for six generator system with 1000 MW load demand

Table 4.8
Best Compromising result for six generator system with load demand of 1000 MW

Unit (MW)	**Proposed FPA**
P1	80.95475
P2	80.71223
P3	165.443
P4	164.2797
P5	255.1399
P6	253.4704
Fuel cost ($/h)	**51253.46**
Emission (kg/h)	**827.0482**

Table 4.9
Comparison of the results for test case 1

Methods	Cost ($/h)	Emission (kg/h)
γ **-iteration** (Balamurugan & Subramanian, 2007)	51264.6	828.720
Recursive (Balamurugan & Subramanian, 2007)	51264.5	828.715
PSO (Balamurugan & Subramanian, 2007)	51269.6	828.863
DE (Balamurugan & Subramanian, 2007)	51264.6	828.715
Simplified Recursive (Balamurugan & Subramanian, 2007)	51264.6	828.715
GA similarity (Guvenc, 2010)	51262.31	827.2612
GSA (Güvenç et al., 2012)	51255.79	827.1380
Proposed FPA	**51253.46**	**827.0482**

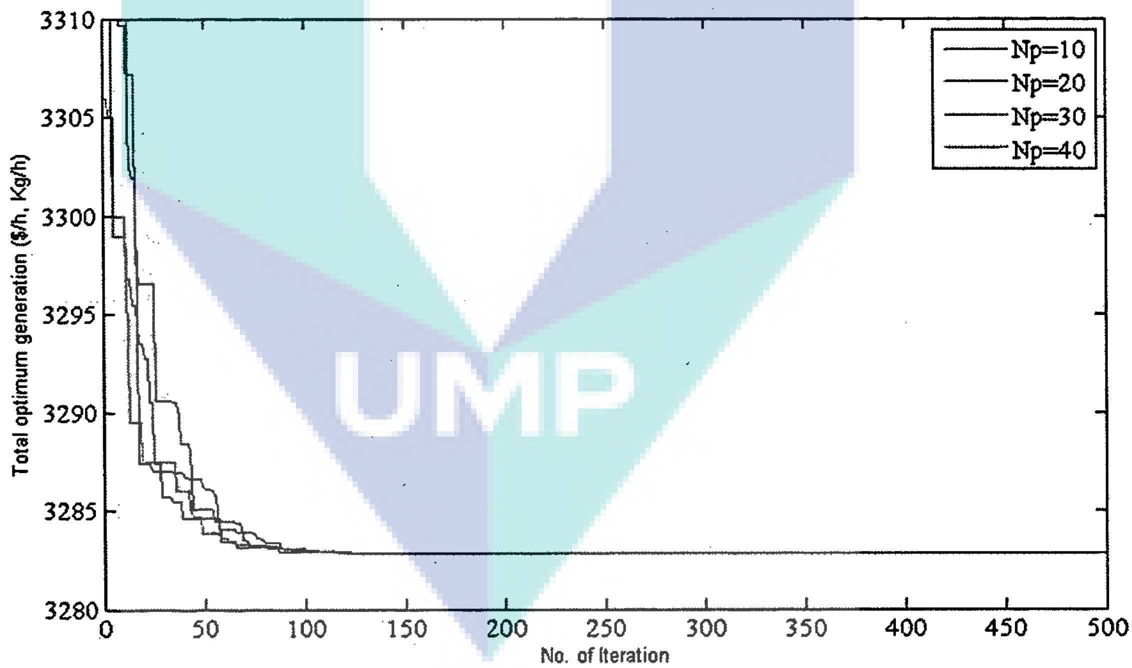

Figure 4.5. Convergence characteristics of proposed FPA with different number of population for test case 1

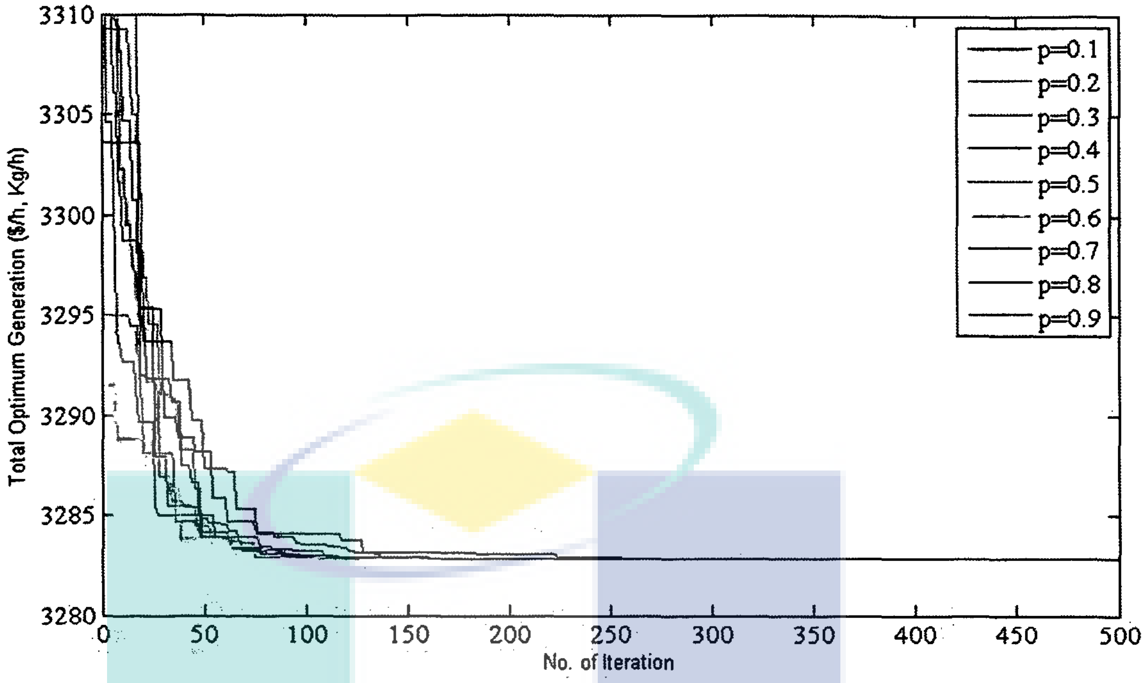

Figure 4.6. Convergence characteristics for proposed FPA with different switch probability for test case 1

According to the Table 4.9, proposed FPA is proven to obtain best minimized fuel cost and emission value compare with other reviewed optimization techniques. The convergence characteristic of proposed FPA presented in Figure 4.5 with different number of population and fixed p=0.2, shows ***Np*=40** has best convergence characteristic where it started to converge when number of iteration is 116 although the maximum limit set as 1000. At the same time, as in Figure 4.6, ***p*=0.2** with fixed *Np*=40 has the best convergence characteristic for proposed FPA performance in this test case by obtaining the minimum value when the iteration reach 118.

In the nutshell, for six generator system with power load demand of 1000 MW, proposed FPA able to perform effectively by giving minimum fuel cost and emission. Besides, it also has faster convergence where the minimum objective value is reach at minimum number of iteration.

4.2.2 Case 2: 10-unit Test System

A 10 generating unit test system applied in this test case. This test case gives the priority on solving CEED problem which contain valve-point loading effect using proposed FPA optimization technique. Besides, the transmission losses also considered. The unit data which are fuel cost coefficients, emission coefficients, generator capacity limit and B-matrix loss formula are taken from (Basu, 2011a). The data taken from Basu because he provided full data include for transmission loss with considering valve point loading effect. Moreover, the data for CEED with transmission loss and practical constraint are very limited. Following it, the power demand was tune to 2000 MW. At the same time, the unit data is presented in Table 4.10 and 4.11 except B-matrix loss formula data which attached at Appendix.

Table 4.12 until Table 4.15 presents the result obtained for this test system by using proposed technique of this paper with implementation of price penalty factor and weighted sum method to choose the best compromising result which is minimum than comparison value. For the optimization purpose, the parameter of the technique set as N_p =30 and p=0.6 with iteration=1000. The convergence characteristics of proposed FPA are presented in Figure 4.10 for number of population and Figure 4.11 for switch probability. The result also compared with other heuristic optimization techniques based literature in Table 4.16 to show the strength of the proposed technique.

Based on the Table 4.16, proposed FPA performed convincing result in solving CEED problems with valve-point loading effect and transmission losses for ten generating unit if compared with other optimization techniques.

Table 4.10
Fuel cost coefficients and generation limits for ten generator system

Generator	$P_i$min (MW)	$P_i$max (MW)	a_i (\$/MW²h)	b_i (\$/MWh)	c_i (\$/h)	d_i (\$/h)	e_i (rad/MW)
1	10	55	0.12951	40.5407	1000.403	33	0.0174
2	20	80	0.10908	39.5804	950.606	25	0.0178
3	47	120	0.12511	36.5104	900.705	32	0.0162
4	20	130	0.12111	39.5104	800.705	30	0.0168
5	50	160	0.15247	38.5390	756.799	30	0.0148
6	70	240	0.10587	46.1592	451.325	20	0.0163
7	60	300	0.03546	38.3055	1243.531	20	0.0152
8	70	340	0.02803	40.3965	1049.998	30	0.0128
9	135	470	0.02111	36.3278	1658.569	60	0.0136
10	150	470	0.01799	38.2704	1356.659	40	0.0141

Table 4.11
Emission coefficients for ten generator system

α_i (lb/MW²h)	β_i (lb/MWh)	γ_i (lb/h)	η_i (lb/h)	δ_i (1/MW)
0.04702	−3.9864	360.0012	0.25475	0.01234
0.04652	−3.9524	350.0056	0.25475	0.01234
0.04652	−3.9023	330.0056	0.25163	0.01215
0.04652	−3.9023	330.0056	0.25163	0.01215
0.00420	0.3277	13.8593	0.24970	0.01200
0.00420	0.3277	13.8593	0.24970	0.01200
0.00680	−0.5455	40.2669	0.24800	0.01290
0.00680	−0.5455	40.2669	0.24990	0.01203
0.00460	−0.5112	42.8955	0.25470	0.01234
0.00460	−0.5112	42.8955	0.25470	0.01234

Table 4.12
Showing result for w in one decimal value of ten generator system with load demand of 2000 MW

Weighting Factors		Fuel Cost ($/h)	Emission (lb/h)
w_1	w_2	F	E
1	0	111546.99	4522.758
0.9	0.1	111515.11	4565.100
0.8	0.2	111512.40	4555.544
0.7	0.3	111533.21	4518.099
0.6	0.4	111530.46	4537.198
0.5	0.5	111550.79	4492.917
0.4	0.6	111629.17	4453.653
0.3	0.7	111677.54	4431.812
0.2	0.8	112080.52	4317.643
0.1	**0.9**	**113331.09**	**4135.402**
0	1	116345.02	3935.624

Table 4.12 presents the results obtained by varying weighting function in order to find the best compromising solution which lays near comparison value. As usual, tuning w_1=1 and w_2=0, the optimization tends to minimize fuel cost rather than emission and vice versa when w_1=0 and w_2=1. The best result was chosen try and error base by picking the weight factor which gives result near to the compare value, where fuel cost is 113331.09 $/h and emission 4135.402 lb/h. The Figure 4.7 illustrates the trade-off plot of the results in Fuel cost versus Emission. Most of the points are laying more on minimum fuel cost but high emission value. However, the point which is w_1=1 and w_2=0.9 gives approximately balance in minimizing fuel cost and emission.

However, when doing comparison with other optimization techniques as showed in Table 4.16, this obtained value still not as expected and can be optimized further. To get almost accurate result to cross the compared values of fuel cost and emission of other author's, the weighting function value specified by adding decimal values.

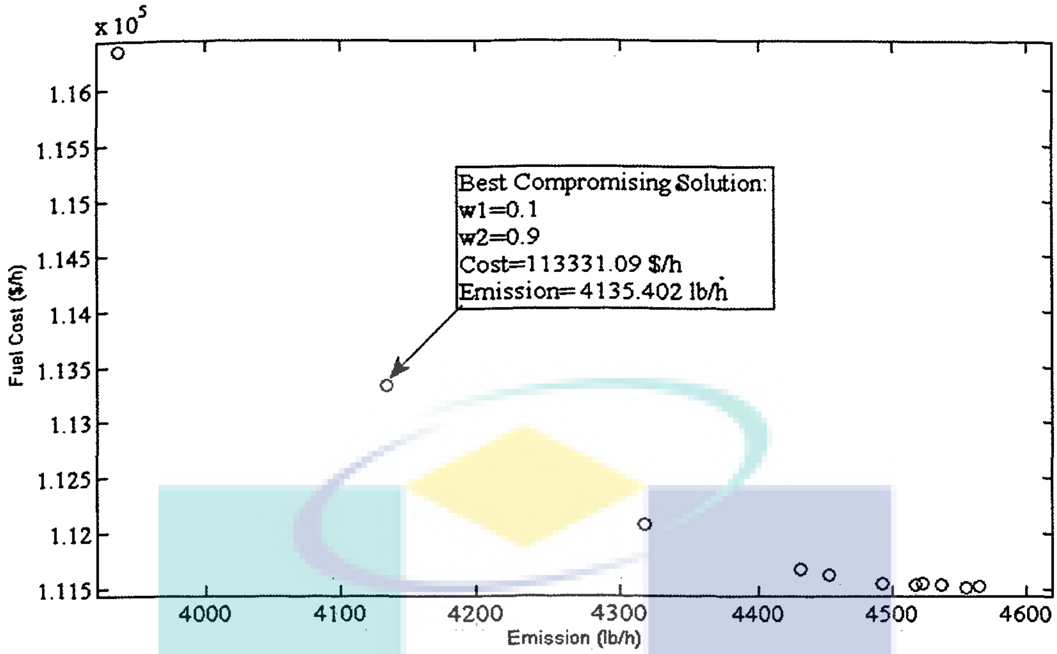

Figure 4.7. Trade-off result using weighted sum method by one decimal value step size for ten generator system with 2000 MW load demand

For the following, the weighting function value was added with one more decimal place which means the step size will be 0.01. Because the previous best compromising result lays at w_1=0.1 and w_2=0.9, in this second stage weighting function set as highest and w_1=0 and w_2=1 set as lowest. When look at the comparison values, the fuel cost and emission result of reviewed paper also underlying within this weighting function value which is in between 113331.09 $/h and 116345.02 $/h for fuel cost, 4135.402 lb/h and 3935.624 lb/h for emission.

Table 4.13
Showing result for *w* in two decimal value of ten generator system with load demand of 2000 MW

Weighting Factors		Fuel Cost ($/h)	Emission (lb/h)
w_1	w_2	F.	E
0.1	**0.9**	**113331.09**	**4135.402**
0.09	0.91	113687.57	4101.41
0.08	0.92	113754.17	4096.88
0.07	0.93	114286.92	4048.15
0.06	0.94	114439.64	4041.68
0.05	0.95	115069.90	3992.12
0.04	0.96	115692.08	3964.28
0.03	0.97	116252.29	3939.25
0.02	0.98	116256.28	3944.41
0.01	0.99	116311.45	3944.58
0	1	116345.02	3935.62

Hence, from the Table 4.13, the results optimized more specifically. In this case, the best compromising value picked where the value almost near to the reviewed values of minimum fuel cost and emission of other author. So, Fuel cost with 113331.09 $/h and emission 4135.402 lb/h with w_1=0.1 and w_2=0.9 was used to try to minimized further.

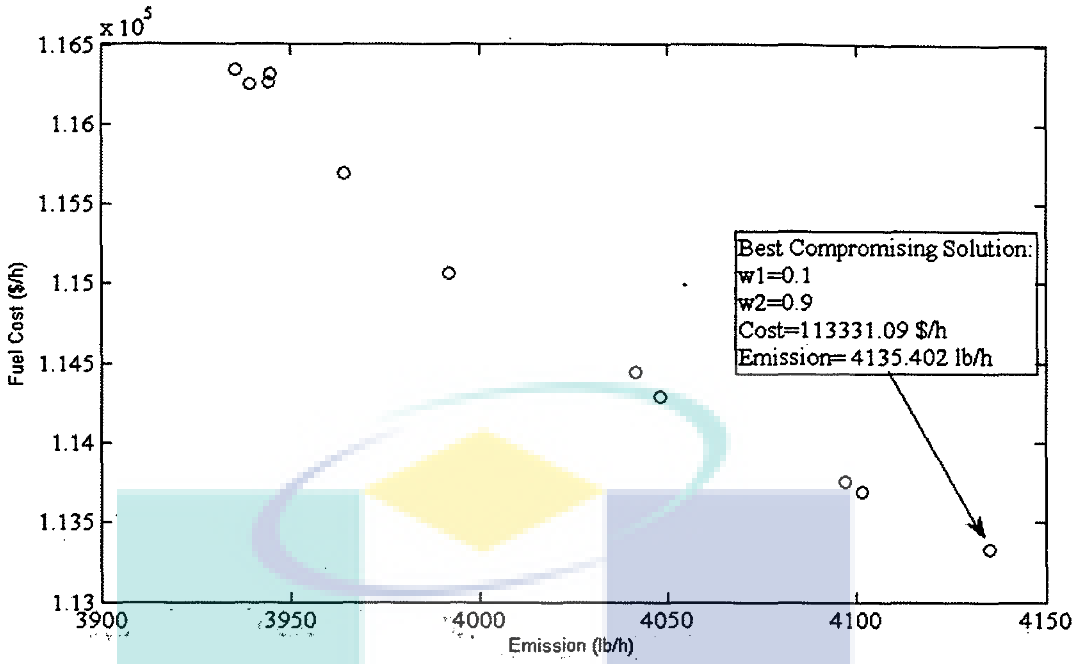

Figure 4.8. Trade-off result using weighted sum method by two decimal value step size for ten generator system with 2000 MW load demand

The Figure 4.8 illustrates the distribution of results in between w_1=0.1, w_2=0.9 and w_1=0, w_2=1. There are few results appear to be randomly distributed in the figure above which shows the proposed technique become slightly not stable when there is transmission load and valve point loading effect applied. However, the random distribution is due to random values that appear inside each sets of number of population which is predefined in this test case as 30. When 1000 iteration runs in simulation, the value is optimized for each set of population thorough the iteration meet the maximum as defined.

The optimized value of fuel cost and emission in this stage has minimum fuel cost than compared fuel cost but higher emission than compared emission of other optimization techniques. This indicates, the w_1 value should be decreased and w_2 should be increased since both objectives functions are independent of each other. Hence, in this third stage, step size is set more specifically than previous which is 0.001. w_1 and w_2 are taken between 0.09 to 0.1 and 0.9 to 0.91 respectively since the reviewed results also lay in between this value of fuel cost and emission. Reviewed result can be referred as in Table 4.16.

Table 4.14
Showing result for *w* in three decimal value of ten generator system with load demand of 2000 MW

Weighting Factors		**Fuel Cost (\$/h)**	**Emission (lb/h)**
w_1	w_2	F	E
0.1	0.9	113331.09	4135.402
0.099	0.901	113383.56	4123.045
0.098	0.902	113394.92	4132.879
0.097	0.903	113372.48	4130.928
0.096	0.904	113366.96	4123.389
0.095	0.905	113468.27	4123.044
0.094	0.906	113436.94	4117.596
0.093	0.907	113460.49	4116.188
0.092	**0.908**	**113476.27**	**4109.656**
0.091	0.909	113535.41	4103.050
0.09	0.91	113687.57	4101.406

By refer to the Table 4.14, the results optimized more specifically than previous stage. In short, the best fuel cost obtained for this stage is **113476.27 \$/h** and **4109.656 lb/h** for emission where belongs to the weighting function w_1=**0.092** and w_2=**0.908**. In Figure 4.9, it can be observed that the results are randomly distributed due to unstable characteristic of proposed FPA towards solving CEED with transmission loss and valve-point loading effect.

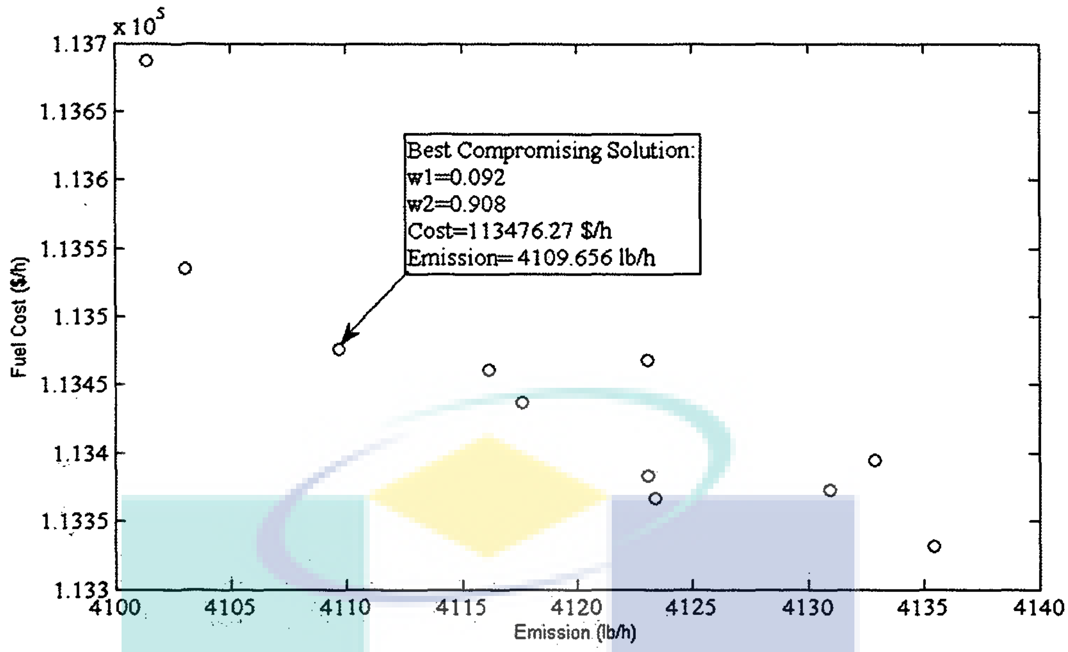

Figure 4.9. Trade-off result using weighted sum method by three decimal value step size for ten generator system with 2000 MW load demand

Table 4.15
Best Compromising result for ten generator system with load demand of 2000 MW

Unit (MW)	**Proposed FPA**
P1	54.97525
P2	79.65537
P3	85.42218
P4	84.93857
P5	141.9827
P6	165.8223
P7	294.5426
P8	312.6769
P9	430.9547
P10	432.882
Transmission loss	83.8526
Fuel cost ($/h)	**113476.27**
Emission (lb/h)	**4109.656**

Table 4.16
Comparison of the results for test case 2

Methods	Cost ($/h)	Emission (lb/h)
MODE(Basu, 2011a)	113480	4124.90
PDE(Basu, 2011a)	113510	4111.40
NSGA-II (Basu, 2011a)	113540	4130.20
SPEA 2 (Basu, 2011a)	113520	4109.10
GSA (Güvenç et al., 2012)	113490	4111.40
Proposed FPA	**113476.27**	**4109.656**

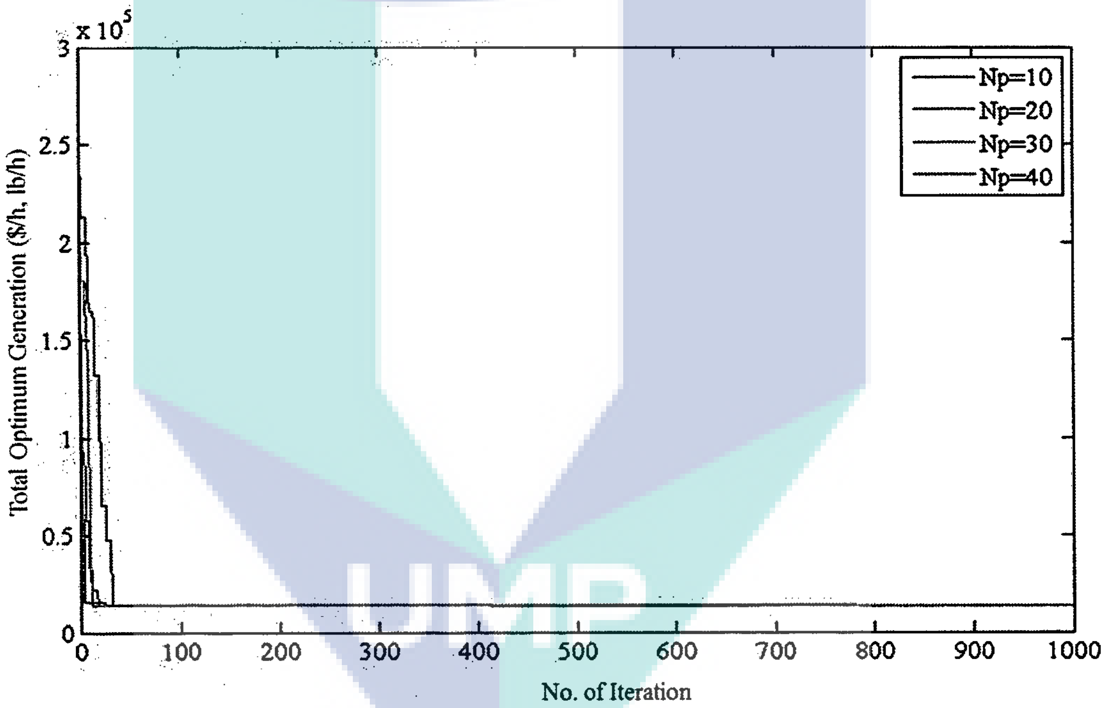

Figure 4.10. Convergence characteristics of proposed FPA with different number of population for test case 2

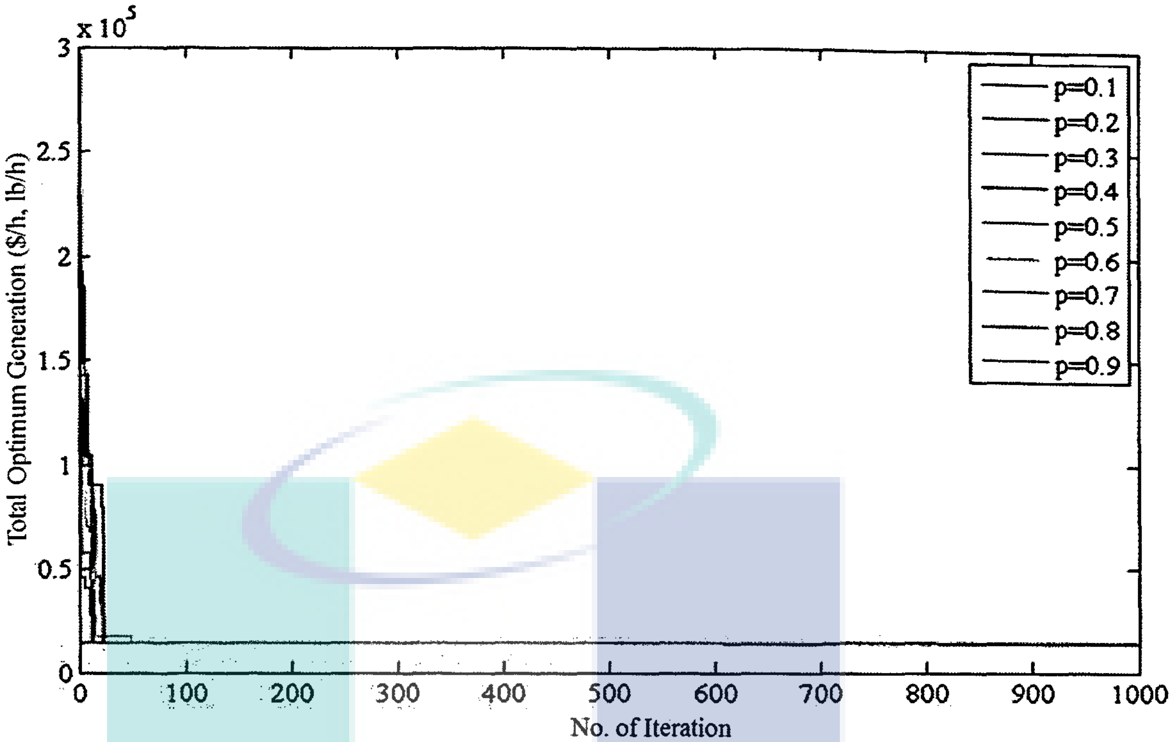

Figure 4.11. Convergence characteristics for proposed FPA with different switch probability for test case 2

According to the Table 4.16, proposed FPA is proven to obtain best minimized fuel cost and second best emission value compare with other reviewed optimization techniques. The convergence characteristic of proposed FPA presented in Figure 4.10 with different number of population shows ***Np*=30** has best convergence characteristic where it started to converge when number of iteration is 434 although the maximum limit set as 1000. At the same time, as in Figure 4.11, ***p*=0.6** has the best convergence characteristic for proposed FPA performance in this test case by obtaining the minimum value when the iteration reach 853.

In short, for ten generator system with power load demand of 2000 MW, proposed FPA able to perform effectively by giving convincing fuel cost and emission. However, the proposed technique seems unstable when need to solve CEED problem with considering transmission limit and valve-point loading effect.

4.2.3 Case 3: 11-unit Test System

This test case consists of 11 generating unit where the fuel cost coefficients, emission coefficients and generator capacity limit are taken from (Balamurugan & Subramanian, 2007). The data presented by Balamurugan was taken because his paper compared with few optimization techniques for CEED which shares the same data table. He also precisely explained and the data given is complete. This case ignores the transmission losses for the system and doesn't count practical problems of power system. The power demand was set to 2500 MW. The unit data is presented in Table 4.17 and 4.18.

Table 4.19 and Table 4.20 presents the result obtained for this test system by using proposed technique of this paper with implementation of price penalty factor and weighting sum method to choose the best compromising result. For the optimization purpose, the parameter of the technique set as N_p =20 and p=0.3 with iteration=1000. The convergence characteristics of proposed FPA are presented in Figure 4.13 for number of population and Figure 4.14 for switch probability. The result also compared with other heuristic optimization techniques based literature in Table 4.21 to show the strength of the proposed technique.

Based on the Table 4.21, proposed FPA proved to gives the best optimum result in solving CEED problems for eleven generating unit by minimize both fuel cost and emission.

Table 4.17
Fuel cost coefficients and generation limits for eleven generator system

Generator	P_i min (MW)	P_i max (MW)	a_i ($/MW²h)	b_i ($/MWh)	c_i ($/h)
1	20	250	0.00762	1.92699	387.85
2	20	210	0.00838	2.11969	441.62
3	20	250	0.00523	2.19196	422.57
4	60	300	0.0014	2.01983	552.5
5	20	210	0.00154	2.22181	557.75
6	60	300	0.00177	1.91528	562.18
7	20	215	0.00195	2.10681	568.39
8	100	455	0.00106	1.99138	682.93
9	100	455	0.00117	1.99802	741.22
10	110	460	0.00089	2.12352	617.83
11	110	465	0.00098	2.10487	674.61

Table 4.18
Emission coefficients for eleven generator system

α_i (kg/MW²h)	β_i (kg/MWh)	γ_i (kg/h)
0.00419	-0.67767	33.93
0.00461	-0.69044	24.62
0.00419	-0.67767	33.93
0.00683	-0.54551	27.14
0.00751	-0.4006	24.15
0.00683	-0.54551	27.14
0.00751	-0.40006	24.15
0.00355	-0.51116	30.45
0.00417	-0.56228	25.59
0.00355	-0.41116	30.45
0.00417	-0.56228	25.59

Table 4.19
Showing result for *w* in one decimal value of eleven generator system with load demand of 2500 MW

Weighting Factors		**Fuel Cost ($/h)**	**Emission (kg/h)**
w_1	w_2	F	E
1	0	12274.40	2540.4254
0.9	0.1	12282.91	2376.0153
0.8	0.2	12307.77	2235.1092
0.7	0.3	12349.69	2109.4733
0.6	**0.4**	**12410.30**	**1997.0726**
0.5	0.5	12491.67	1897.7812
0.4	0.6	12596.35	1812.2942
0.3	0.7	12727.475	1741.8471
0.2	0.8	12888.99	1688.1747
0.1	0.9	13039.49'	1660.0123
0	1	13045.13	1659.5122

Table 4.19 shows the results obtained by varying weighting function in order to find the best compromising solution need in the purpose to compare with other optimization technique's results. The result of weighting function w_1**=0.6** and w_2**=0.4** have better solution which wins over the other optimization techniques for both objective functions where fuel cost is **12410.30 $/h** and emission **1997.0726 kg/h**.

The efficiency of the proposed FPA need to be validate therefore selected result based on systematic try and error method for weighting function which crossed the compared results undoubtedly need to be chose as best compromising result of this case. The Figure 4.12 illustrates the trade-off plot of the results in Fuel Cost versus Emission. Although this is first phase of simulation run with one decimal point for weighting function method, but the results approximately well distributed and optimized simultaneously.

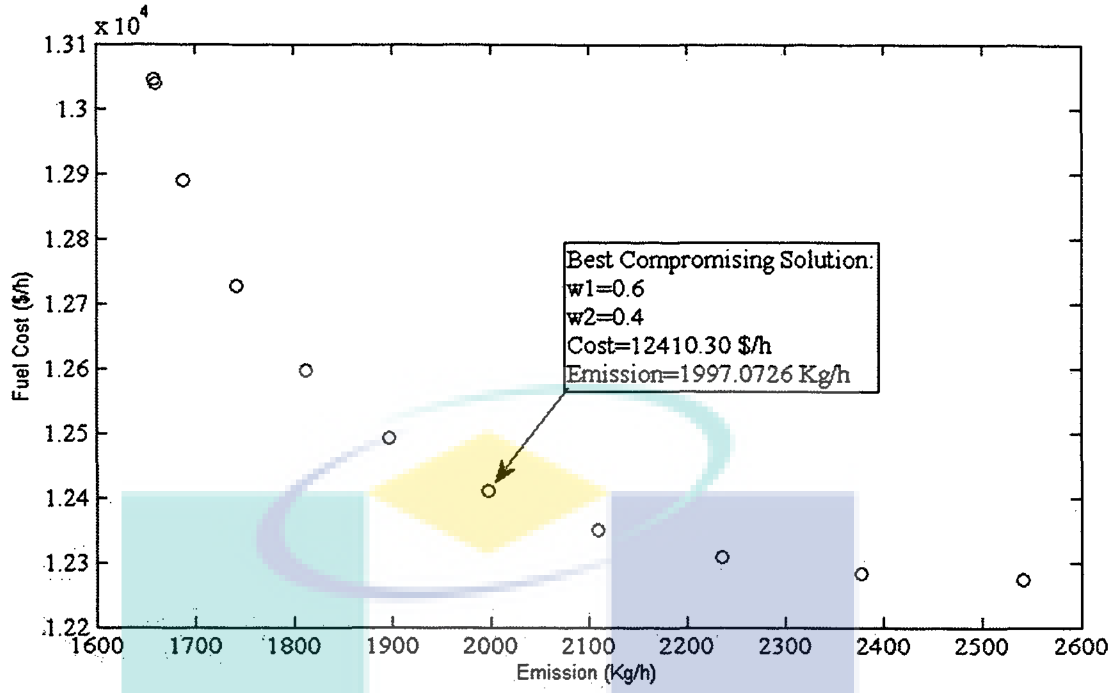

Figure 4.12. Trade-off result using weighted sum method by one decimal value step size for eleven generator system with 2500 MW load demand

Table 4.20
Best Compromising result for eleven generator system with load demand of 2500 MW

Unit (MW)	**Proposed FPA**
P1	128.6422
P2	108.9203
P3	150.4499
P4	209.8188
P5	167.9977
P6	205.8083
P7	166.3365
P8	365.3393
P9	320.4089
P10	353.887
P11	322.3912
Fuel cost ($/h)	**12410.30**
Emission (kg/h)	**1997.0726**

Table 4.21
Comparison of the results for test case 3

Methods	Cost ($/h)	Emission (kg/h)
γ**-iteration** (Balamurugan & Subramanian, 2007)	12424.94	2003.301
Recursive (Balamurugan & Subramanian, 2007)	12424.94	2003.300
PSO (Balamurugan & Subramanian, 2007)	12428.63	2003.720
DE (Balamurugan & Subramanian, 2007)	12425.06	2003.350
Simplified Recursive (Balamurugan & Subramanian, 2007)	12424.94	2003.300
GA similarity (Guvenc, 2010)	12423.77	2003.030
GSA (Güvenç et al., 2012)	12422.66	2002.949
Proposed FPA	**12410.30**	**1997.0726**

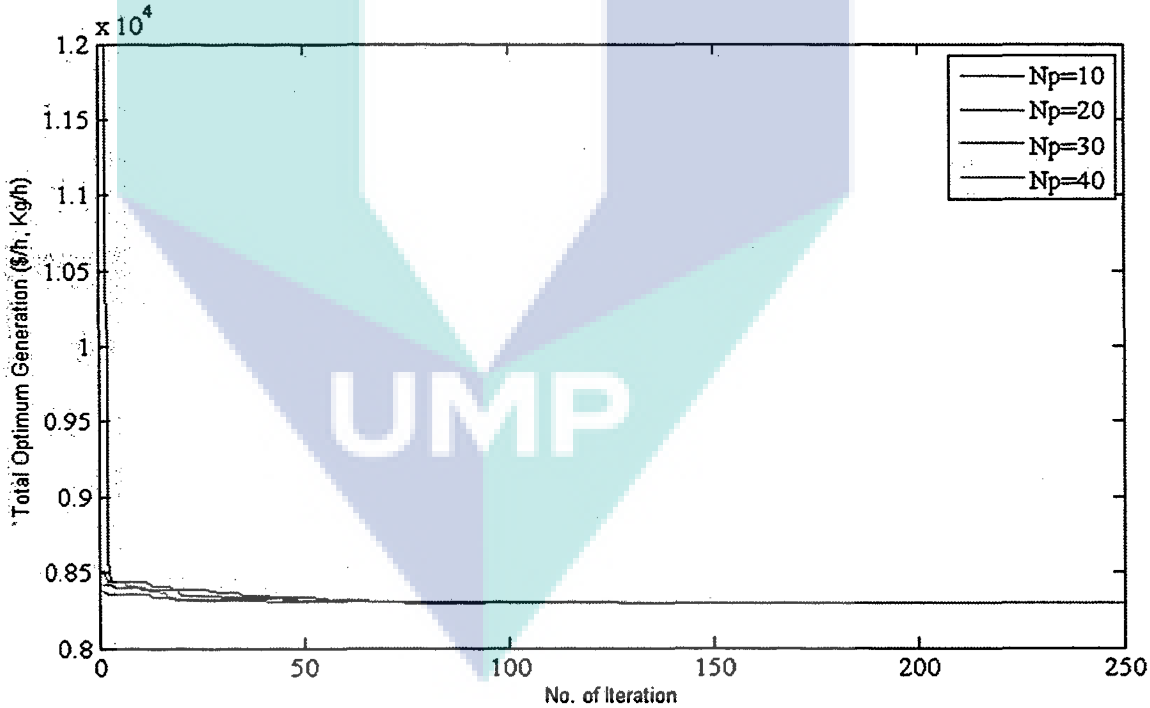

Figure 4.13. Convergence characteristics of proposed FPA with different number of population for test case 3

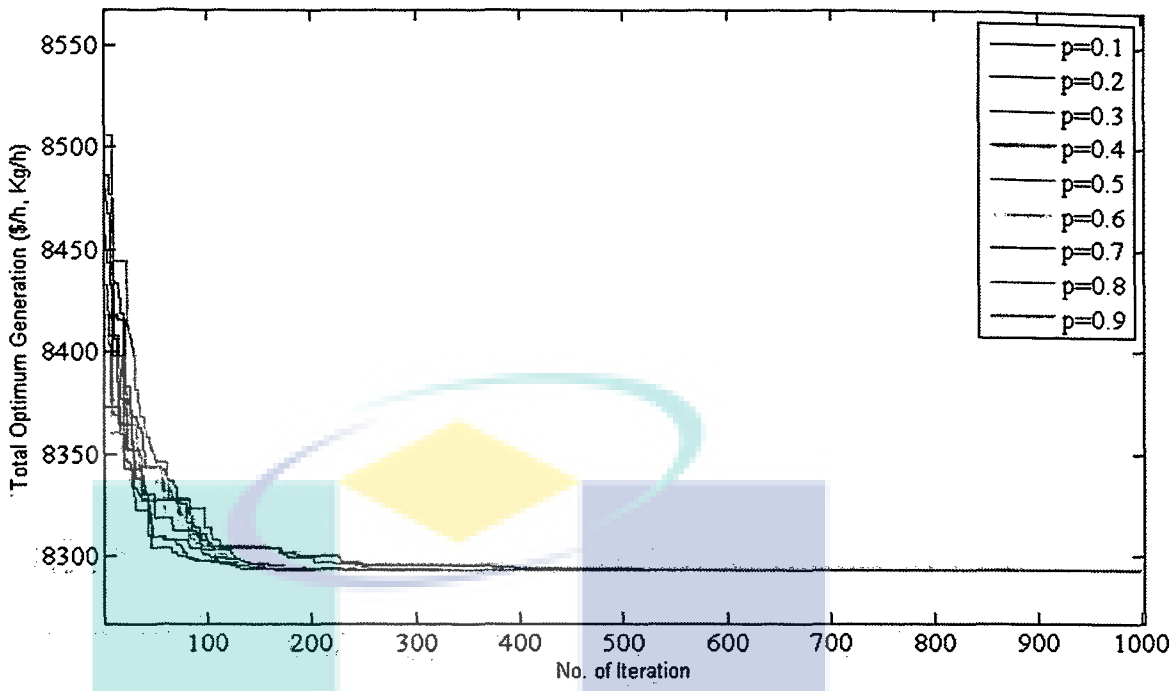

Figure 4.14. Convergence characteristics for proposed FPA with different switch probability for test case 3

As compared in Table 4.21, proposed FPA is proven to obtain best minimized fuel cost and emission value than other reviewed optimization techniques. The convergence characteristic of proposed FPA presented in Figure 4.13 with different number of population shows ***Np*=20** has best convergence characteristic for this case where it started to converge when number of iteration is 227 although the maximum limit set as 1000. At the same time, as in Figure 4.14, ***p*=0.3** has the best convergence characteristic for proposed FPA performance by obtaining the minimum value when the iteration reach 248.

In short, for eleven generator system with power load demand of 2500 MW, proposed FPA able to perform effectively by giving minimum fuel cost and emission. Besides, it also has faster convergence where the minimum objective value is reach at minimum number of iteration.

4.2.4 Case 4: 40-unit Test System

This test case consists of 40 generating unit where the fuel cost coefficients, emission coefficients and generator capacity limit are referred from (Basu, 2011a). Basu test case data was chosen because his data given was complete and explained detail. Moreover, the data for CEED are very limited and almost all shares same data for CEED problems of thermal power plant. Because the system practiced is large unit test system, this case neglects the transmission losses but considers practical problems of power system which is valve-point loading effect. The power demand was set to 10500 MW meanwhile unit data is presented in Table 4.22 and 4.23.

Table 4.24 until Table 4.26 presents the result obtained for this test system by using proposed technique of this paper with implementation of price penalty factor and weighted sum method to choose the best compromising result. For the optimization purpose, the parameter of the technique set as N_p =30 and p=0.4 with iteration=10000. The convergence characteristics of proposed FPA are presented in Figure 4.17 for number of population and Figure 4.18 for switch probability. The result also compared with other heuristic optimization techniques based literature in Table 4.27 to show the strength of the proposed technique.

Based on the Table 4.27, it is not deniable that FPA gives the outstanding result in solving CEED problems for forty generating unit by minimize both fuel cost and emission.

Table 4.22
Fuel cost coefficients and generation limits for forty generator system

Generator	P_i min (MW)	P_i max (MW)	a_i ($/MW²h)	b_i ($/MWh)	c_i ($/h)	d_i ($/h)	e_i (rad/MW)
1	36	114	0.0069	6.73	94.705	100	0.084
2	36	114	0.0069	6.73	94.705	100	0.084
3	60	120	0.02028	7.07	309.54	100	0.084
4	80	190	0.00942	8.18	369.03	150	0.063
5	47	97	0.0114	5.35	148.89	120	0.077
6	68	140	0.01142	8.05	222.33	100	0.084
7	110	300	0.00357	8.03	287.71	200	0.042
8	135	300	0.00492	6.99	391.98	200	0.042
9	135	300	0.00573	6.6	455.76	200	0.042
10	130	300	0.00605	12.9	722.82	200	0.042
11	94	375	0.00515	12.9	635.2	200	0.042
12	94	375	0.00569	12.8	654.69	200	0.042
13	125	500	0.00421	12.5	913.4	300	0.035
14	125	500	0.00752	8.84	1760.4	300	0.035
15	125	500	0.00752	8.84	1760.4	300	0.035
16	125	500	0.00752	8.84	1760.4	300	0.035
17	220	500	0.00313	7.97	647.85	300	0.035
18	220	500	0.00313	7.95	649.69	300	0.035
19	242	550	0.00313	7.97	647.83	300	0.035
20	242	550	0.00313	7.97	647.81	300	0.035
21	254	550	0.00298	6.63	785.96	300	0.035
22	254	550	0.00298	6.63	785.96	300	0.035
23	254	550	0.00284	6.66	794.53	300	0.035
24	254	550	0.00284	6.66	794.53	300	0.035
25	254	550	0.00277	7.1	801.32	300	0.035
26	254	550	0.00277	7.1	801.32	300	0.035
27	10	150	0.52124	3.33	1055.1	120	0.077
28	10	150	0.52124	3.33	1055.1	120	0.077
29	10	150	0.52124	3.33	1055.1	120	0.077
30	47	97	0.0114	5.35	148.89	120	0.077
31	60	190	0.0016	6.43	222.92	150	0.063
32	60	190	0.0016	6.43	222.92	150	0.063
33	60	190	0.0016	6.43	222.92	150	0.063
34	90	200	0.0001	8.95	107.87	200	0.042
35	90	200	0.0001	8.62	116.58	200	0.042
36	90	200	0.0001	8.62	116.58	200	0.042
37	25	110	0.0161	5.88	307.45	80	0.098
38	25	110	0.0161	5.88	307.45	80	0.098
39	25	110	0.0161	5.88	307.45	80	0.098
40	242	550	0.00313	7.97	647.83	300	0.035

Table 4.23
Emission coefficients for forty generator system

Generator	α_i (ton/MW²h)	β_i (ton/MWh)	γ_i (ton/h)	η_i (ton/h)	δ_i (1/MW)
1	0.0480	−2.22	60	1.3100	0.05690
2	0.0480	−2.22	60	1.3100	0.05690
3	0.0762	−2.36	100	1.3100	0.05690
4	0.0540	−3.14	120	0.9142	0.04540
5	0.0850	−1.89	50	0.9936	0.04060
6	0.0854	−3.08	80	1.3100	0.05690
7	0.0242	−3.06	100	0.6550	0.02846
8	0.0310	−2.32	130	0.6550	0.02846
9	0.0335	−2.11	150	0.6550	0.02846
10	0.4250	−4.34	280	0.6550	0.02846
11	0.0322	−4.34	220	0.6550	0.02846
12	0.0338	−4.28	225	0.6550	0.02846
13	0.0296	−4.18	300	0.5035	0.02075
14	0.0512	−3.34	520	0.5035	0.02075
15	0.0496	−3.55	510	0.5035	0.02075
16	0.0496	−3.55	510	0.5035	0.02075
17	0.0151	−2.68	220	0.5035	0.02075
18	0.0151	−2.66	222	0.5035	0.02075
19	0.0151	−2.68	220	0.5035	0.02075
20	0.0151	−2.68	220	0.5035	0.02075
21	0.0145	−2.22	290	0.5035	0.02075
22	0.0145	−2.22	285	0.5035	0.02075
23	0.0138	−2.26	295	0.5035	0.02075
24	0.0138	−2.26	295	0.5035	0.02075
25	0.0132	−2.42	310	0.5035	0.02075
26	0.0132	−2.42	310	0.5035	0.02075
27	1.8420	−1.11	360	0.9936	0.04060
28	1.8420	−1.11	360	0.9936	0.04060
29	1.8420	−1.11	360	0.9936	0.04060
30	0.0850	−1.89	50	0.9936	0.04060
31	0.0121	−2.08	80	0.9142	0.04540
32	0.0121	−2.08	80	0.9142	0.04540
33	0.0121	−2.08	80	0.9142	0.04540
34	0.0012	−3.48	65	0.6550	0.02846
35	0.0012	−3.24	70	0.6550	0.02846
36	0.0012	−3.24	70	0.6550	0.02846
37	0.0950	−1.98	100	1.4200	0.06770
38	0.0950	−1.98	100	1.4200	0.06770
39	0.0950	−1.98	100	1.4200	0.06770
40	0.0151	−2.68	220	0.5035	0.02075

Table 4.24
Showing result for *w* in one decimal value of forty generator system with load demand of 10500 MW

Weighting Factors		**Fuel Cost ($/h)**	**Emission (ton/h)**
w_1	w_2	F	E
1	0	121779.82	361705.11
0.9	**0.1**	**125850.83**	**193780.07**
0.8	0.2	128065.20	180714.84
0.7	0.3	128939.99	177931.14
0.6	0.4	129346.82	177159.52
0.5	0.5	129591.21	176879.00
0.4	0.6	129695.66	176778.65
0.3	0.7	129776.79	176728.32
0.2	0.8	129847.92	176725.46
0.1	0.9	129925.31	176695.46
0	1	129956.68	176693.38

Table 4.24 shows the results obtained by varying weighting function in order to find the best compromising solution. The best result where fuel cost is 125850.83 $/h and emission 193780.07 ton/h was chosen by try and error method for weighting function which systematically done with close to comparison value since all the displayed result at the above table are optimized results. The Figure 4.15 illustrates the trade-off plot of the results in Fuel Cost versus Emission. Most of the points are laying more on minimum emission but high fuel cost value. However, the point which is w_1=0.9 and w_2=0.1 gives approximately balance in minimizing fuel cost and emission.

Unfortunately, when doing comparison with other optimization techniques as showed in Table 4.26, this obtained value still not satisfying especially in terms of fuel cost and can be improved. To get almost close result to the compared values of fuel cost and emission of other author's, the weighting function value specified by adding decimal values.

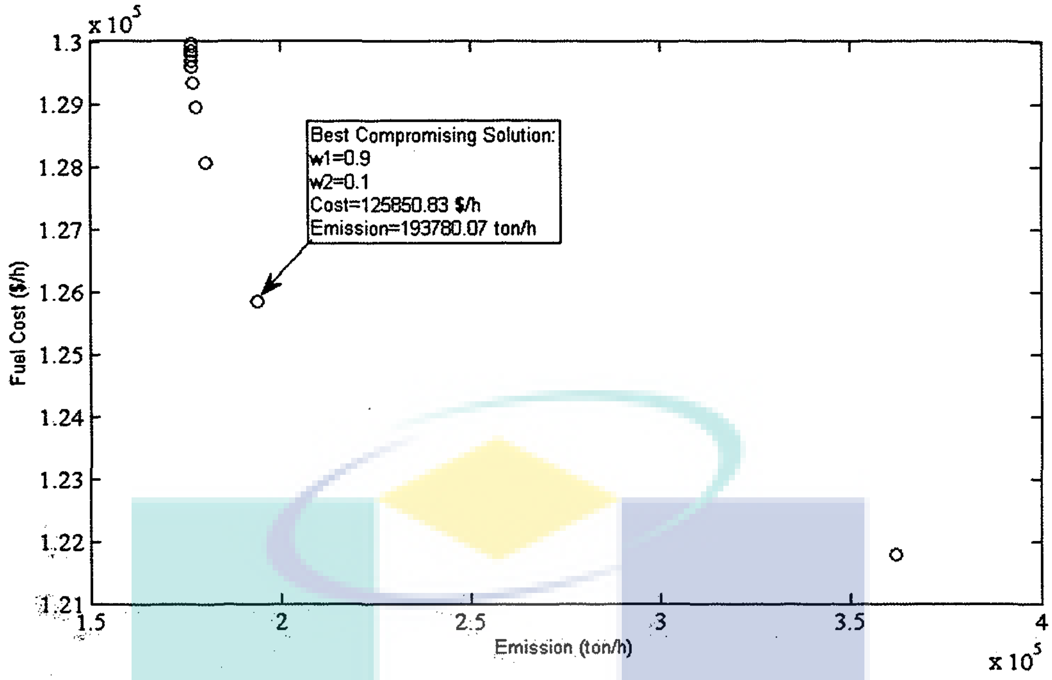

Figure 4.15. Trade-off result using weighted sum method by one decimal value step size for forty generator system with 10500 MW load demand

For the following, the weighting function value was added with one more decimal place which means the step size will be 0.01. Because the previous best compromising result lays at w_1=0.9 and w_2=0.1, in this second stage weighting function set as lowest and w_1=1 and w_2=0 set as highest. When look at the comparison values, the fuel cost and emission result of reviewed paper also underlying within this weighting function value which is in between 121779.82 $/h and 125850.83 $/h for fuel cost, 361705.11 ton/h and 193780.07 ton/h for emission.

Table 4.25
Showing result for *w* in two decimal value of forty generator system with load demand of 10500 MW

Weighting Factors		Fuel Cost ($/h)	Emission (ton/h)
w_1	w_2	F	E
1	0	121779.82	361705.11
0.99	0.01	122850.46	293602.89
0.98	0.02	123848.25	251991.30
0.97	0.03	124386.45	231398.35
0.96	0.04	124629.44	223592.41
0.95	0.05	125667.10	195624.75
0.94	0.06	125669.53	195535.50
0.93	**0.07**	**125573.14**	**198016.74**
0.92	0.08	125731.95	195985.73
0.91	0.09	125706.95	195168.18
0.9	0.1	125850.83	193780.07

Hence, from the Table 4.25, the results optimized more specifically. In this case, there are five set of results which have both minimum fuel cost and emission than compared values. Among the five sets, the set of result which have the minimum total cost of generation have been determined as best compromising result for this test case. So, Fuel cost with **125573.14 $/h** and emission **198016.7416 ton/h** with w_1**=0.93** and w_2**=0.07** was chosen. The Figure 4.16 illustrates the distribution of results in between w_1=1, w_2=0 and w_1=0.9, w_2=0.1.

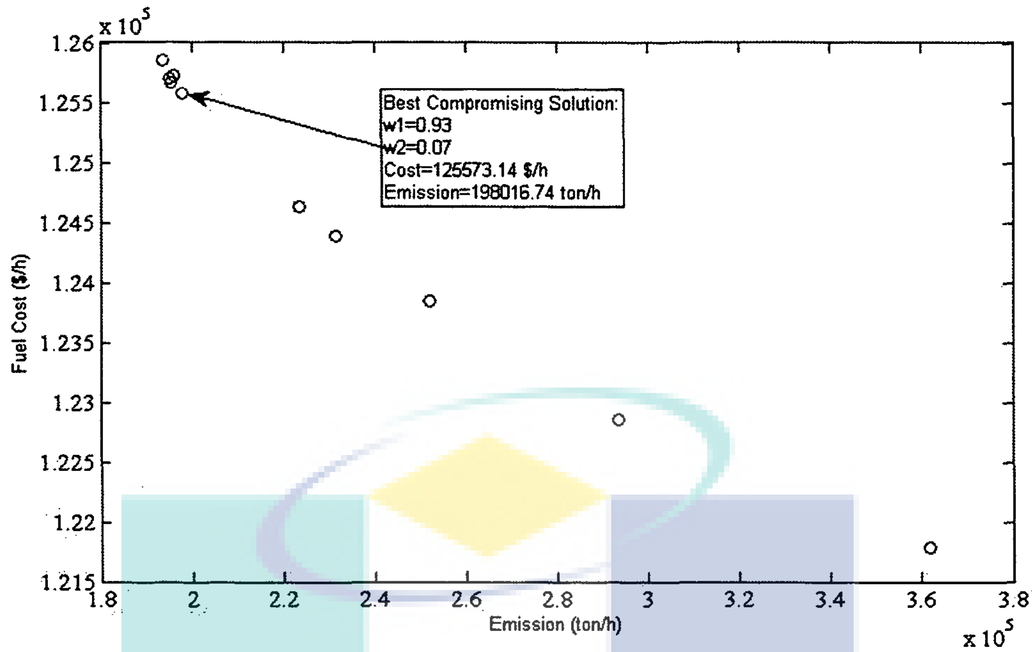

Figure 4.16. Trade-off result using weighted sum method by two decimal value step size for forty generator system with 10500 MW load demand

From the graph, it is clear that proposed FPA optimizes the objective function with stable. The further detail which is generated power for each unit presented in Table 4.26. Meanwhile, the comparison result presented in Table 4.27.

Table 4.26
Best Compromising result for forty generator system with load demand of 10500 MW

Unit (MW)	Proposed FPA
P1	113.9998
P2	113.9999
P3	120
P4	179.733
P5	96.9999
P6	139.9997
P7	300
P8	284.5997
P9	284.5999
P10	204.7996
P11	318.3977
P12	318.3986
P13	394.2794
P14	394.2794
P15	394.2794
P16	394.2794
P17	489.2646
P18	489.278
P19	421.5196
P20	421.5197
P21	433.5198
P22	433.5196
P23	433.5196
P24	433.5197
P25	433.5197
P26	433.5197
P27	10
P28	10
P29	10
P30	97
P31	189.9995
P32	166.1373
P33	189.9983
P34	200
P35	200
P36	200
P37	109.9999
P38	110
P39	110
P40	421.5196
Fuel cost ($/h)	**125573.1376**
Emission (ton/h)	**198016.7426**

Table 4.27
Comparison of the results for test case 4

Methods	Cost ($/h)	Emission (ton/h)
MODE(Basu, 2011a)	1.2579 x 10^5	2.1119 x 10^5
PDE(Basu, 2011a)	1.2573 x 10^5	2.1177 x 10^5
NSGA-II (Basu, 2011a)	1.2583 x 10^5	2.1095 x 10^5
SPEA 2 (Basu, 2011a)	1.2581 x 10^5	2.111 x 10^5
GSA (Güvenç et al., 2012)	1.2578 x 10^5	2.1093 x 10^5
Proposed FPA	**1.2557 x 10^5**	**1.9802 x 10^5**

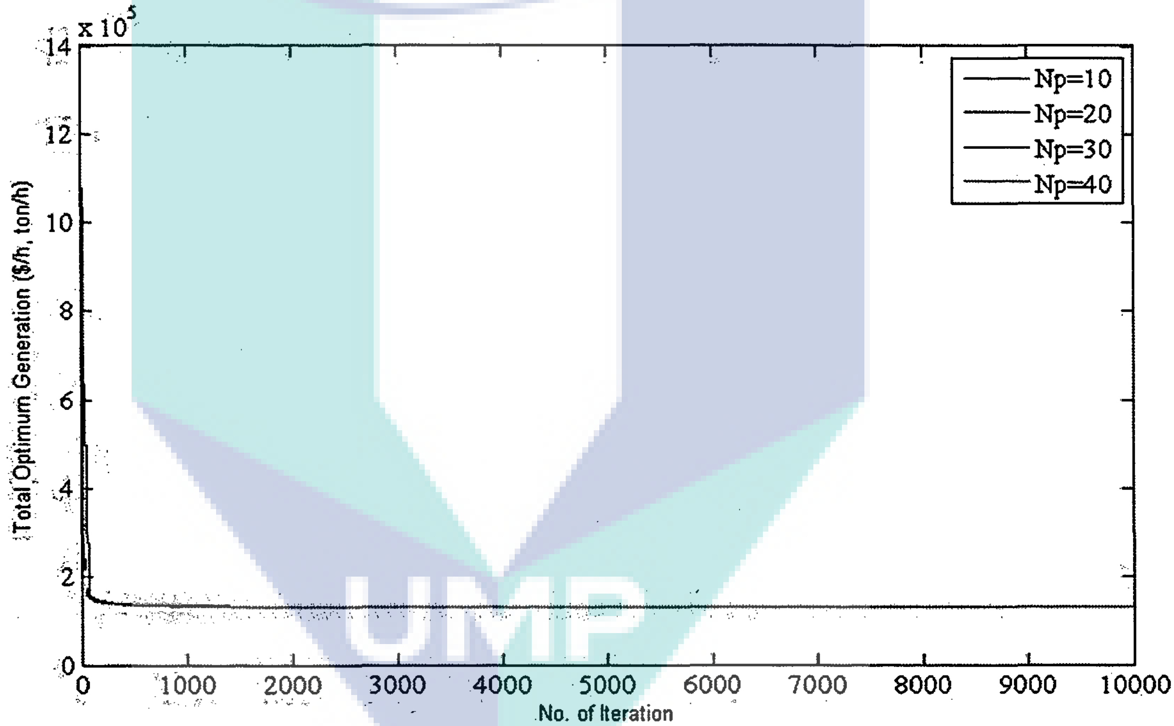

Figure 4.17. Convergence characteristics of proposed FPA with different number of population for test case 4

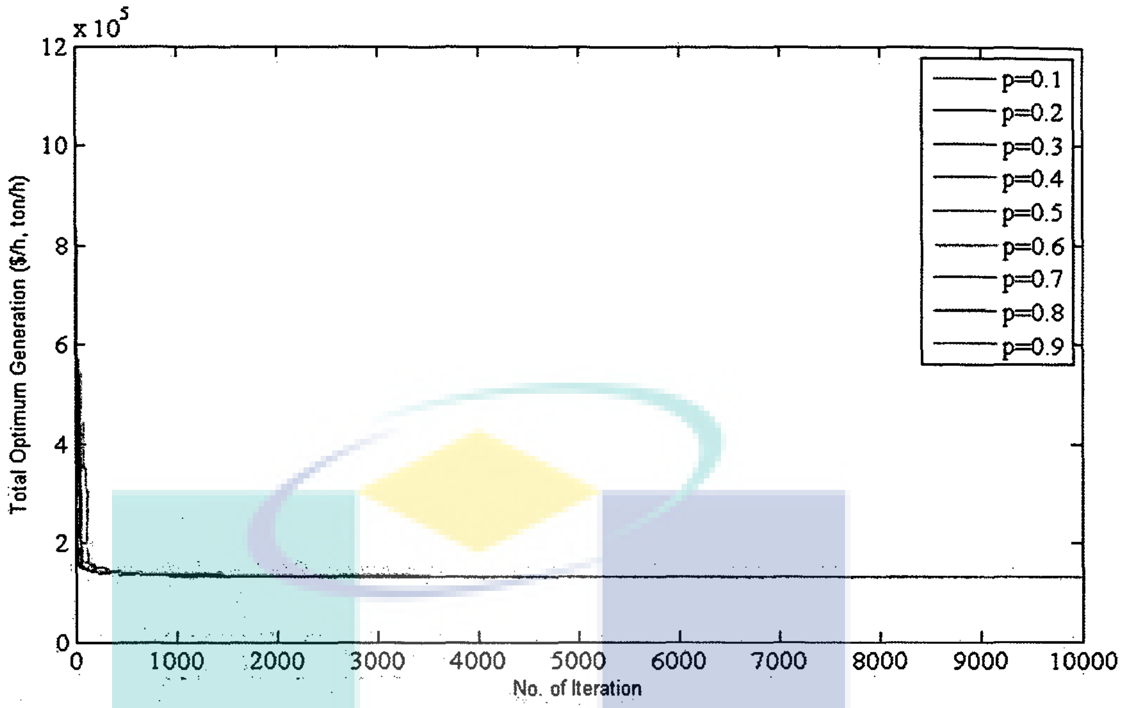

Figure 4.18. Convergence characteristics for proposed FPA with different switch probability for test case 4

According to the Table 4.27, proposed FPA is proven to obtain best minimized fuel cost and emission value compare with other reviewed optimization techniques. The convergence characteristic of proposed FPA presented in Figure 4.17 with different number of population shows ***Np*****=30** has best convergence characteristic where it started to converge when number of iteration is 6612 with the maximum limit set as 10000. At the same time, as in Figure 4.18, ***p*****=0.4** has the best convergence characteristic for proposed FPA performance in this test case by obtaining the minimum value when the iteration reach 6726.

In the nutshell, for forty generator system with power load demand of 10500 MW, proposed FPA able to perform effectively by giving minimum fuel cost and emission. Besides, it also has faster convergence where the minimum objective value is reach at minimum number of iteration.

4.3 SUMMARY

Generally, nature-inspired optimization techniques performed quite well in various applications with competent results. Again through this research, the efficiency of FPA on CEED bi-objective problem proved giving satisfactory result by outperformed all the test cases. Variation in loadings level validated the efficiency of FPA solving both linear and nonlinear cases of CEED. On the other hand, FPA also managed to obtained better result for complex problem of CEED which is as in test case 2 with only slight difference for the best value. In short, FPA can be said have following strengths include better ability to reach near global optimal solution, quality solutions, stable convergence characteristic and simple to implement due to acceptable control parameters.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

This topic covers the summary of this whole research, its contribution and the future work that can be developed from this work.

In this research, a new approach which is FPA has been used to solve bi-objective problem of CEED. This new optimization technique validated using six generating unit test system, ten generating unit test system, eleven generating unit test system and forty generating unit test system. The comparison results obtained from the optimization techniques shows the efficiency of this new proposed method in addressing the CEED problem.

For the six generating unit test system, the power demand of the system was subjected to 1000MW. With the aid of the price penalty factor and the classical weighted sum method, the Combined Economic and Emission dispatch was deduced for the various loading levels. The proposed FPA optimization technique performed very well and had outstanding results for basic system of CEED when evaluated against γ-iteration, Recursive, PSO, DE, Simplified Recursive, GA Similarity and Gravitational Search Algorithm.

The ten generating unit test system was subjected to 2000MW of power demand with considering transmission losses and non-linear characteristics of practical power system which is valve-point loading effect. By using the classical weighted sum and price penalty factor, the CEED was deduced for the various loading levels, The FPA performed well in CEED by obtained outstanding value for fuel cost and convincing value for emission compared with MODE, PDE, NSGA-II, SPEA 2 and GSA.

The eleven generator test system was subjected to 2500MW power demand. Again the proposed FPA technique proven to perform well by minimizing both fuel cost and emission when compared with same techniques as in six generating test system.

Moreover, for forty generator test system which subjected to 10500MW of power demand with considering valve point loading effect, the proposed FPA technique have excellent result in solving CEED problems. It minimizes both fuel cost and emission when compared with same techniques as in ten generating unit test system.

The variation of different types of test systems was done to show that the proposed optimization method has a stable behavior independent of the linear and non-linear characteristic of system, size of the system, does not converge to local optima and also has feasible solutions.

However, this method have its weakness which is has high computational time and try and error which requires many run time for weighted sum method. To overcome the problems, the further research has been proposed as well.

5.2 CONTRIBUTION

The contributions of this research towards CEED can summarize as follows:

i. A newly introduced optimization technique, FPA utilized to solve linear and nonlinear problems of CEED. Previously as viewed in various literatures, there is no any implementation of FPA technique yet on CEED.As expected, this technique proved to have outstanding ability on solving the problem which is worth to develop more so that it's talent can be identified which might useful to solve many other cases.

ii. In terms of objective achievement, this research successfully presented outperformed results in most cases by giving optimum minimum solution for fuel cost and emission. The reduction of cost brings not only benefits for power industry in term of profits but also manage the critical situations by dispatching the load according to it demand without affecting the reliability of generators.

iii. Implementation of weighted sum method and price penalty factor on multi-objective function gives best compromising solution to the problem. However, sometime single implementation of the method will not work out when need to compare it with reviewed results. Hence, in this research the both method was carried to find best compromising solution which sits near to the reviewed value. The combination gives the results that fulfil the expectation.

5.3 AREAS FOR FUTURE RESEARCH

Implementation of FPA in CEED opens the new framework for further development of this research area. Hence, few suggestions listed as below.

i. Improving the quality, efficiency and robustness of the technique by proposing hybrid, combine or improve the original version.
ii. Effective multi-objective method to solve the problem in simple way such as application of pareto optimal front which can reduce the run time and avoids try and error.
iii. Employment on solving further solution such as unit commitment, dynamic dispatch and reactive power scheduling.
iv. Consideration of other types of power system such as hydro, wind and solar as well as emission with sulphur oxide and carbon dioxide.

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APPENDIX A
B-LOSS COEFFICIENTS OF TEN GENERATING UNIT FOR TEST CASE 3

$$B=\begin{bmatrix}
0.000049 & 0.000014 & 0.000015 & 0.000015 & 0.000016 & 0.000017 & 0.000017 & 0.000018 & 0.000019 & 0.000020 \\
0.000014 & 0.000045 & 0.000016 & 0.000016 & 0.000017 & 0.000015 & 0.000015 & 0.000016 & 0.000018 & 0.000018 \\
0.000015 & 0.000016 & 0.000039 & 0.000010 & 0.000012 & 0.000012 & 0.000014 & 0.000014 & 0.000016 & 0.000016 \\
0.000015 & 0.000016 & 0.000010 & 0.000040 & 0.000014 & 0.000010 & 0.000011 & 0.000012 & 0.000014 & 0.000015 \\
0.000016 & 0.000017 & 0.000012 & 0.000014 & 0.000035 & 0.000011 & 0.000013 & 0.000013 & 0.000015 & 0.000016 \\
0.000017 & 0.000015 & 0.000012 & 0.000010 & 0.000011 & 0.000036 & 0.000012 & 0.000012 & 0.000014 & 0.000015 \\
0.000017 & 0.000015 & 0.000014 & 0.000011 & 0.000013 & 0.000012 & 0.000038 & 0.000016 & 0.000016 & 0.000018 \\
0.000018 & 0.000016 & 0.000014 & 0.000012 & 0.000013 & 0.000012 & 0.000016 & 0.000040 & 0.000015 & 0.000016 \\
0.000019 & 0.000018 & 0.000016 & 0.000014 & 0.000015 & 0.000014 & 0.000016 & 0.000015 & 0.000042 & 0.000019 \\
0.000020 & 0.000018 & 0.000016 & 0.000015 & 0.000016 & 0.000015 & 0.000018 & 0.000016 & 0.000019 & 0.000044
\end{bmatrix}$$

APPENDIX B

COMPARISON TABLE OF VARIOUS OPTIMIZATION TECHNIQUES FOR TEST CASE 2

Unit (MW)	MODE(Basu, 2011a)	PDE(Basu, 2011a)	NSGA-II(Basu, 2011a)	SPEA 2(Basu, 2011a)	GSA(Güvenç et al., 2012)	**Proposed FPA**
P1	54.9487	54.9853	51.9515	52.9761	54.9992	**54.97525**
P2	74.5821	79.3803	67.2584	72.8130	79.9586	**79.65537**
P3	79.4294	83.9842	73.6879	78.1128	79.4341	**85.42218**
P4	80.6875	86.5942	91.3554	83.6088	85.0000	**84.93857**
P5	136.8551	144.4386	134.0522	137.2432	142.1063	**141.9827**
P6	172.6393	165.7756	174.9504	172.9188	166.5670	**165.8223**
P7	283.8233	283.2122	289.4350	287.2023	292.8749	**294.5426**
P8	316.3407	312.7709	314.0556	326.4023	313.2387	**312.6769**
P9	448.5923	440.1135	455.6978	448.8814	441.1775	**430.9547**
P10	436.4287	432.6783	431.8054	423.9025	428.6306	**432.882**
Fuel cost ($/h)	1.1348×10^5	1.1351×10^5	1.1354×10^5	1.1352×10^5	1.1349×10^5	**113476.27**
Emission (Kg/h)	4124.9	4111.4	4130.2	4109.1	4111.4	**4109.656**

APPENDIX C

COMPARISON TABLE OF VARIOUS OPTIMIZATION TECNIQUES FOR TEST CASE 4

Unit (MW)	MODE(Basu, 2011b)	PDE(Basu, 2011b)	NSGA-II(Basu, 2011b)	SPEA 2(Basu, 2011b)	GSA(Güvenç et al., 2012)	Proposed FPA
P1	113.5295	112.1549	113.8685	113.9694	113.9989	113.9998
P2	114.0000	113.9431	113.6381	114.0000	113.9896	113.9999
P3	120.0000	120.0000	120.0000	119.8719	119.9995	120
P4	179.8015	180.2647	180.7887	179.9284	179.7857	179.733
P5	96.7716	97.0000	97.0000	97.0000	97.0000	96.9999
P6	139.2760	140.0000	140.0000	139.2721	139.0128	139.9997
P7	300.0000	299.8829	300.0000	300.0000	299.9885	300
P8	298.9193	300.0000	299.0084	298.2706	300.0000	284.5997
P9	290.7737	289.8915	288.8890	290.5228	296.2025	284.5999
P10	130.9025	130.5725	131.6132	131.4832	130.3850	204.7996
P11	244.7349	244.1003	246.5128	244.6704	245.4775	318.3977
P12	317.8218	318.2840	318.8748	317.2003	318.2101	318.3986
P13	395.3846	394.7833	395.7224	394.7357	394.6257	394.2794
P14	394.4692	394.2187	394.1369	394.6223	395.2016	394.2794
P15	305.8104	305.9616	305.5781	304.7271	306.0014	394.2794
P16	394.8229	394.1321	394.6968	394.7289	395.1005	394.2794
P17	487.9872	489.3040	489.4234	487.9857	489.2569	489.2646
P18	489.1751	489.6419	488.2701	488.5321	488.7598	489.278
P19	500.5265	499.9835	500.8000	501.1683	499.2320	421.5196
P20	457.0072	455.4160	455.2006	456.4324	455.2821	421.5197
P21	434.6068	435.2845	434.6639	434.7887	433.4520	433.5198
P22	434.5310	433.7311	434.1500	434.3937	433.8125	433.5196
P23	444.6732	446.2496	445.8385	445.0772	445.5136	433.5196
P24	452.0332	451.8828	450.7509	451.8970	452.0547	433.5197
P25	492.7831	493.2259	491.2745	492.3946	492.8864	433.5197
P26	436.3347	434.7492	436.3418	436.9926	433.3695	433.5197
P27	10.0000	11.8064	11.2457	10.7784	10.0026	10
P28	10.3901	10.7536	10.0000	10.2955	10.0246	10
P29	12.3149	10.3053	12.0714	13.7018	10.0125	10
P30	96.9050	97.0000	97.0000	96.2431	96.9125	97
P31	189.7727	190.0000	189.4826	190.0000	189.9689	189.9995
P32	174.2324	175.3065	174.7971	174.2163	175.0000	166.1373
P33	190.0000	190.0000	189.2845	190.0000	189.0181	189.9983
P34	199.6506	200.0000	200.0000	200.0000	200.0000	200
P35	199.8662	200.0000	199.9138	200.0000	200.0000	200
P36	200.0000	200.0000	199.5066	200.0000	199.9978	200
P37	110.0000	109.9412	108.3061	110.0000	109.9969	109.9999
P38	109.9454	109.8823	110.0000	109.6912	109.0126	110
P39	108.1786	108.9686	109.7899	108.5560	109.4560	110
P40	422.0682	421.3778	421.5609	421.8521	421.9987	421.5196
Fuel cost ($/h)	1.2579×10^5	1.2573×10^5	1.2583×10^5	1.2581×10^5	1.2578×10^5	**125573.1376**
Emission (Kg/h)	2.1119×10^5	2.1177×10^5	2.1095×10^5	2.111×10^5	2.1093×10^5	**198016.7426**

APPENDIX D
LIST OF PUBLICATIONS

Hong Mee Song, Mohd Herwan Sulaiman, Mohd Rusllim Mohamed, *An Application of Flower Pollination Algorithm to Solve Combined Economic Emission Dispatch by Considering Valve-Point Loading Effect*, International Review on Modelling and Simulations (IREMOS), Vol 8, No. 4, pp. 427-435 (2015). Abs./Ind.: SCOPUS.

Hong Mee Song, Mohd Herwan Sulaiman, Mohd Rusllim Mohamed, An Application of Grey Wolf Optimizer for Solving Combined Economic Emission Dispatch Problems, International Review on Modelling and Simulations (IREMOS), Vol 7, No. 5, pp. 838-844 (2014). Abs./Ind.: SCOPUS.

Wong Lo Ing, **Hong Mee Song**, Mohd Herwan Sulaiman, Mohd Rusllim Mohamed, *Grey Wolf Optimizer for Economic Dispatch*, PECON 2014, Kuching, Sarawak.

Hong Mee Song, Mohd Herwan Sulaiman, Mohd Rusllim Mohamed, *Grey Wolf Optimizer Technique to Solve Combined Economic Emission Dispatch (CEED) Problem*, The Asian Conference on Society, Education & Technology 2014 (ACSET 2014), Osaka, Japan, 28 October - 2 November 2014.

M. S. Hong, M. H. Sulaiman, M. R. Mohamed, L. I. Wong, *Comparative Study of Economic Dispatch by Using Various Optimization Techniques*, 2nd Power and Energy Conversion Symposium, (PECS) 2014, Utem, Melaka, 12 May 2014.