UNIVERSITY OF SOUTHAMPTON

FACULTY OF ENGINEERING, SCIENCE AND MATHEMATICS

School of Electronics and Computer Science

Solving Dynamic Economic Dispatch problems using Pattern Search based methods with particular focus on the West Doha Power Station in Kuwait

by

Jamal Al-Sumait

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ABSTRACT

FACULTY OF ENGINEERING AND APPLIED SCIENCE
School of Electronics and Computer Science

by Jamal S. Alsumait

This thesis is concerned with Dynamic Economic Dispatch (DED) problems, in particular in the context of the current and future needs of the electrical power system in the State of Kuwait. General Economic Dispatch (ED) issues are addressed, under both static and dynamic conditions, with valve-point effects accounted for. Improvements have been achieved in terms of lower fuel costs, but also more efficient and reliable simulation algorithms. The existing ED/DED models have been improved in various ways and enhanced by developing and incorporating two renewable energy sources; namely wind energy and solar energy. These two have been identified as most relevant to the power system investigated. The models developed are general and can be adjusted to represent many practical systems.

The Economic Dispatch problem had been formulated and solved as a constrained optimisation and a particular technique selected for this purpose – not explored before – was a Pattern Search (PS) algorithm. For illustrative purposes, the proposed PS technique had been applied to various test systems to validate its effectiveness. Furthermore, convergence characteristics and robustness of the method had been assessed through comparison with results reported in literature. The PS technique was found to be very competitive in terms of its overall performance. Variations of the technique have also been explored, in particular a hybrid formulation exploiting Genetic Algorithm (GA), Pattern Search (PS) and Sequential Quadratic Programming, and advantages of such a combined technique reported.

A DED model for the West Doha Power Station (WDPS) in Kuwait has been developed and the penetration of renewable energy resources to this model has been discussed. The DED model was then solved using the PS method developed in this thesis to achieve the optimal dispatch with the aim to minimise fuel costs in WDPS. Considerable potential savings in electric power production of WDPS have been identified and thus the benefits of deploying renewable energy in Kuwaiti electric system demonstrated.

KEY WORDS

Economic Dispatch (ED), Dynamic Economic Dispatch (DED), Valve-Point effect, Direct Search (DS), Pattern Search (PS), Evolutionary Algorithm (EA), Sequential Quadratic Programming (SQP), Renewable Energy (RE).

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Nomenclature

F	system's overall fuel cost function
E	system's overall emission cost function
$F(P_{gi})$	fuel cost function of generator P_{gi}
N	number of generators in the system
$a_i,\ b_i,\ c_i$	constants of fuel function of generator i
$e_i,\ f_i$	constants of valve-point effect of generator i
P_{gi}	the active power generation of generator i
P_D	the total power system demand
P_L	the total system transmission losses
$P_{gi(\min)}$	the minimum limit on active power generation of generator i
$P_{gi(\max)}$	the maximum limit on active power generation of generator i
N_s	the set of generators in the system
M	the number of hours in a day (DED)
UR_i	the ramp-up rate limits of the i th generator (DED)
DR_i	the ramp-down rate limits of the i th generator (DED)
$G(t_{jk})$	transmission cost of line t_{jk}
t_{jk}	economic flow on tie line from area j to k
α_m	set of generating units in area m
β_m	set of tie lines in area m
$t_{jk(\min)}$	the minimum limit on active power generation of generator i
$t_{jk(\max)}$	the maximum limit on active power generation of generator i
w	the weighting factor
B	the matrix of loss coefficients

DECLARATION OF AUTHORSHIP

I, Jamal S. F. Al-Sumait, declare that the thesis entitled:

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and the work presented in the thesis are both my own, and have been generated by me as the result of my own original research. I confirm that:

- this work was done wholly or mainly while in candidature for a research degree at this University;
- where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
- where I have consulted the published work of others, this is always clearly attributed;
- where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
- I have acknowledged all main sources of help;
- where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
- parts of this work have been published as:

1) Alsumait, J. S., Sykulski, J. K. and Alothman, A. K. (2007) Application of Pattern Search Method to Power System Economic Load Dispatch. In: *Third IASTED Asian Conference Power and Energy Systems*, 2-4 April 2007, Phuket, Thailand.

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1 Introduction

Shortage of energy resources, increasing power generation costs, ever-growing demand for electric energy and the global concern regarding environmental pollution necessitate optimal economic dispatch (ED) and the introduction of renewable energy (RE) in modern power systems. The main objective of ED is to reduce the total power generation cost while satisfying various (equality and inequality) constraints, whereas the goal of RE generation is to produce cheap and environmentally friendlier energy. Various aspects of ED problems and different models of RE generation systems are reviewed in this section to provide background for the work that has been done by the author of this report.

1.1 Summary of the work

When I decided to undertake my PhD studies in 2005, I committed myself to conduct my research for the benefit of my country Kuwait. By early 2006, Kuwait was already facing a serious problem with electric power production which could not meet the electric power demand of the country. In summer 2006, a scheduled electric power-cut programme was implemented to prevent electric power over-loading. It was also the requirement of my sponsors that I pursue studies which were likely to assist the electricity industry in Kuwait. The scope of this work was developed under these special circumstances.

The first step that I took was to consider the usage of Economic Dispatch (ED) to reduce the fuel cost of electrical production by allocating the most economic dispatch for the generators. Since ED is a minimization problem, a reliable search method had to be chosen for finding global or near global solutions. After intensive review of the literature, the Pattern Search method, which is one of the Direct Search (DS) algorithms, was selected to be the primary solver for the ED problem. This choice was encouraged by the reports of overall good performance of this method reported by several researchers; moreover, the method had not been used before in the context of solving ED problems, thus the project I was about to undertake promised clear aspects of novelty. Consequently, I implemented the PS algorithm to solve most of ED problem cases described in the literature to verify and assess its performance. After comparing with results of other search algorithms reported in the literature, the PS had proven to be a reliable search method and actually produced better results in most cases considered. The most important characteristic of PS was that it outperformed other methods in computational time. The need for a fast ED problem solver is essential for the last part of the research, in which the algorithm would be used for solving the ED problem of West Doha Power Station (WDPS) in Kuwait. The ever changing hourly load demand in WDPS necessitates the presence of a quick dispatch scheduling technique and the fast execution time of PS makes it the appropriate candidate for this task. However, the PS method has one drawback that makes it inferior when compared with other heuristic methods, such as Genetic Algorithms (GA) or Particle Swarm Optimization (PSO), and that is the need of a good starting point. PS is sensitive to the initial guess that the user must supply, to initiate the search, and the final result depends on the quality of the starting point.

To overcome this drawback of the PS technique, a number of scenarios were investigated using a hybrid approach that is a combination of various search techniques. Of such combinations, the hybrid GA-PS-SQP algorithm was identified as superior as it eliminated the need for a starting point and it reduced the computational times substantially. This was beneficial as in the initial stages of this work the PS was executed 100 times with 100 random starting points to reach the global or near global solution. Such procedure consumed substantial amount of computational time in many of the study cases. The need to reduce the computational time of the PS algorithm was therefore considered as essential and the usage of the hybrid method succeeded in reducing the time by cutting the number of executions to only one run.

To make the ED approach more relevant to practical situations, a Dynamic Economic Dispatch (DED) problem was formulated. The DED approach solves the ED model for a period of 24 hours which is closer to real life conditions in power stations. Moreover, the DED allows for more constraints which may be added to the model to represent properly the changing operation situations of the generators. The additional constraints are the unit’s ramp-up and ramp-down, which limit the change in the generator production in case of any increase/decrease in the load demand. Furthermore, an improved DED model was developed to assure the continuity of the electric power production after the 24th hour. The improved algorithm guarantees that the transition between the 24th hour of operation and the 25th (1st hour of next day) is within the limits and constraints of the DED problem; this feature was not found in the literature.

Finally, with the aim to reduce the usage of fossil fuels in the production of electric power in Kuwait, renewable energy resources were considered. Solar and wind energy systems were investigated as candidates for deployment in the Kuwaiti electrical system. The Maximum Power Point Traction (MPPT) circuits for solar and wind energy systems were studied for optimal power production. Unfortunately, only the solar energy system was ultimately implemented in the final stage of this work. The decision against deployment of wind power systems was made due to the lack of some essential data about the wind turbines and the barely sufficient wind speeds in Kuwait.

The West Doha Power Station (WDPS) in Kuwait was chosen to be the real life study case for this work. Professional regression software called DataFit was used to develop a DED model for the proposed combined thermal/solar system for the WDPS electrical system. The DED model was then solved using the developed PS algorithm to find the optimal or near optimal dispatch solutions for the generators of WDPS. The results of this work show that substantial savings in fuel costs could be achieved and the concept of deployment of solar energy in Kuwaiti electric power system is realistic and potentially beneficial.

1.2 Economic Dispatch (ED)

Solving the economic dispatch (ED) problems has been an essential task for researchers since 1920s due to their importance in electrical power systems. Over the years, substantial improvements have been applied to the ED and different algorithms have been proposed to solve this problem. The problem initially arose when engineers had concerned themselves with the question of how to properly divide the load amongst the generating units available [1]. At the beginning, various simplistic methods were used, such as “the base load” and “best point loading” [1]. A breakthrough in mathematical formulation was achieved in early 60s of last century by Carpentier of Electricite de France who treated the entire network in an exact manner and as a nonlinear optimization problem [1]. The essential role of ED has been demonstrated by the implementation of the method by most individual utilities and power pools for both providing base points and participation factors for Automatic Generation Control (AGC) and for off-line or breakdown studies [1].

The mission of finding the best combination of the units’ power generation to minimize the total cost is considered as one of the important tasks for system control engineers. Moreover, the addition of the environmental aspect to the ED increases the significance of the solution and puts it in a broader context. As a result, ED problems have been investigated and appropriate methods developed for a long time by many researchers. The main goal of most studies was to find the optimal power flow procedure which consists of methods that utilize load flow techniques for the purpose of ED [2]. Although the models and constraints may differ in these studies, the ultimate objective has always been the same. For example, some researchers have used the ac load flow model while others have employed the dc load model. Decreasing the cost of the generation of electrical power and improving the environmental emission index are the concrete results of solving such problems. For more details about the historical development and importance of the ED the reader is referred to the comprehensive surveys [1, 2].

Due to the importance of the ED problem, several conferences, societies and groups have been interested in investigating, solving and publishing the outcome of the research done in the area. The recent examples include the American Power Conference, Chicago [3] and the 14th International Conference on Nuclear Engineering [4]. The Engineering and Scientific Research Groups [5] and the Electric Utility Investor Relations Group in New York City are two examples of large communities of engineers and officials trying to find a solution to minimize the cost of electrical power generation. Finally, the IEEE Power Engineering Society [6] and the American Public Power Association (APPA) [7] are two technical bodies that have a huge concern for the ED. As evidence of the importance of the problem, the reader may refer to the reply letters sent by APPA and Edison Electric Institute to the Office of Electricity Delivery and Energy Reliability in the United State Department of Energy regarding a governmental act imposing the essential role of ED in electrical power systems [8, 9].

A wide variety of optimization techniques have been applied to solving ED problems. Some of these techniques are based on classical optimization methods while others use artificial intelligence or heuristic algorithms. Many references present the application of classical optimization methods, such as linear programming or quadratic programming [10, 11]. Such classical methods are highly sensitive to starting points and often converge to local optimum or diverge altogether. Linear programming methods are fast and reliable but have a disadvantage associated with the piecewise linear cost approximation. Non-linear programming methods have known problems of convergence and algorithmic complexity. Newton based algorithms have difficulty in handling a large number of inequality constraints [12]. The evolutionary based approach in [12] was developed using Particle Swarm Optimization (PSO) technique to solve the ED with security constraints. The algorithm was tested on three benchmark systems, i.e. IEEE 14 bus, IEEE 30 bus and IEEE 57 bus systems. The results were compared with Linear Programming (LP), Quadratic Programming (QP) and Genetic Algorithm (GA), respectively, and the authors concluded that their method is faster than the other algorithms in the literature. Methods based on artificial intelligence techniques, such as artificial neural networks, have also been applied successfully and are reported [13, 14].

A new approach using Hopfield neural networks for solving the ED problem with transmission capacity constraints was proposed in [14]. The authors discussed a new mapping technique for quadratic 0-1 programming problems with linear equality and inequality constraints. Moreover, the special methodology improved the performance of Hopfield neural networks for solving combinatorial optimization problems. The proposed method in [14] has achieved efficient and accurate solutions for two-area power systems with 3, 4, 40 and 120 units. Finally, the genetic algorithm method was presented in [15], where the authors used a pattern recognition technique to assess dynamic security. Then they added linear classifiers to determine the system stability in addition to the other system stability and operational constraints.

More recently, heuristic search techniques – such as particle swarm optimization (PSO) [16-18] – have also been considered in the context of ED. In addition, differential evolution algorithms were implemented to solve the ED problem [19-21]. Differential evolution (DE) is a stochastic search based method, which offers a simple structure, good convergence, versatility and robustness. However, DE's fast convergence might lead the direction of the search toward a local optimal and premature solution. Finally, the use of harmony search (HS) method to find the global or near global solution for the ED problem can be found in [22, 23]. HS is considered a stochastic random search method, which does not need any information about the derivative. Nevertheless, HS has some insufficiencies associated with the premature convergence in its performance.

1.3 Hybrid Economic dispatch

In the pursuit of the optimal solution, hybrid methods have been investigated and developed by many researchers. In [24], the authors used the conventional Lagrangian relaxation approach, where the first order gradient method and multi-pass dynamic programming were combined together. Moreover, the authors stated that the proposed method has no restrictions on generator cost function and that it performs a direct search of the feasible solution at each step.

The use of two hybrid techniques based on Genetic Algorithm (GA) and Simulated Annealing (SA) to evaluate the trade-off between fuel cost and environmental impact in ED was presented in [25]. The authors combined the total emission of the individual pollutants into a criterion via the use of relative weights in the main objective function. A two-phase GA approach to solve the economic and emission dispatch was proposed in [26]. In the first phase the authors searched for the incremental cost factor using binary coded GA. Then the best solution of the first phase was taken as the initial condition in the second phase. The results were compared with other methods and were considered equally reliable and promising. However, the constraints for security and ramp rate were not included in the modelling of the system. In [27], the authors introduced hybrid evolutionary algorithms to solve the ED problem with valve-point effect (the valve-point effect explanation and definition will be presented later in this section) , i.e. Particle Swarm Optimization (PSO) and Sequential Quadratic Programming (SQP). They used PSO as the main optimizer of the objective function and SQP as the fine tuner for every improvement in the solution of the PSO run.

Another hybrid approach with different heuristic methods was implemented in [28]. The Differential Evolution (DE) and the Sequential Quadratic Programming (SQP) were combined into a single algorithm that is able to solve the ED problem. The algorithm was used on 13 and 40 thermal units whose incremental fuel cost function contains the valve-point loading effect. Another interesting article showing the importance of the usage of hybrid algorithms is presented in [29]. The authors combined three evolutionary methods to solve a fuzzy modelled Unit Commitment Problem (UCP). The three methods are Tabu Search (TS), Particle Swarm Optimization (PSO) and Sequential Quadratic Programming (SQP) or simply hybrid TS-PSO-SQP. TS is used to solve the combinatorial sub-problem of the UCP. Then the non-linear programming sub-problem of the UCP is solved using the hybrid PSO-QSP technique.

1.4 Dynamic Economic Dispatch

For a more advanced treatment of ED, researchers have been investigating and solving the Dynamic Economic Dispatch (DED) problem. The addition of certain periods of time in which the traditional ED is scheduled and operated, and the variation of the load demands over this period of time, has made the dynamic economic dispatch a more realistic representation of practical conditions. The introduction of the ramp-up and ramp-down constraints in DED has added an important aspect to the formulation.

Furthermore, the concern about air pollution has also been taken into consideration. The combined dynamic economic and emission dispatch has been addressed as a result of increased awareness of the need to reduce of harmful gases in the atmosphere.

The DED was introduced in 1971 by Bechert and Kwanty [30]. The authors overcame the drawbacks of applying static optimization methods by combining economic load allocation and an additional control action. This combination was called the dynamic optimal control and considered to be the foundation in the of DED problem formulation. Many researchers followed this approach and proposed several modifications and additions to the original formulation. Ross and Kim introduced a set of procedures and algorithms that protect the generation units from over responding to the change of the predicted load [31]. The authors split the large problem into smaller sub-problems, and then they solve each sub-problem using forward dynamic programming. Moreover, the author of [32] proposed a particle swarm optimization (PSO) method to solve DED, in which the ramp rate limits, prohibited zones constraints and the non-smooth cost functions were taken into consideration. A comparison between the proposed method and genetic algorithm (GA) was made to verify the quality of the algorithm. In the most recent publication, a new multiple tabu search algorithm (MTS) was presented and discussed [33]. The authors have considered most of the DED problem constraints, such as load demand, spinning reserve capacity, ramp rate limits and prohibited zones. The results of this novel algorithm were compared with PSO, ordinary tabu search, GA and simulated annealing (SA) methods to prove the applicability and the superiority of MTS in DED problems.

The work in this project regarding the DED problem has been conducted in the context of the following two journal papers. First, the authors of [34] used the simulated annealing (SA) method to solve the DED problem on a model that consists of five unit generators with non-smooth fuel cost functions. The unit ramp constraints for the five units were observed and maintained throughout the period of 24 hours and the results were assumed to be global or near global. However, the authors admitted that the computing times were long and they suggested parallel processing as a solution. In the second paper, Basu [35] solved the Dynamic Economic Emission Dispatch (DEED) problem using evolutionary programming based fuzzy satisfying method. Moreover, the author treated the optimization problem as a minimax where the cost and the emission are competing to be the priority function by a decision maker (DM). Although the author has listed the achieved optimal or near optimal total cost solutions, but unfortunately the outputs of each unit for the period of 24 hours were not presented, as it was done in [34]. In addition, the solution of the DED problem presented in [34] has not taken into consideration the consistency of the unit ramp constraints for all of the units in operation during the transaction time between one 24 hours period to another. In other words, to avoid violating the unit ramp constrains after a period of 24 hours, the controller must shut down the whole power system and restart it again. To rectify this drawback, the author of this thesis improved his algorithm and has made the necessary adjustments to ensure the constancy of the unit ramp constraints during the transaction time.

1.5 Pattern Search Method

Recently, a particular family of global optimization methods, originally introduced and developed by researchers in 1960 [36], has received great attention, namely the Direct Search methods. Direct Search methods are simply structured to explore a set of points, around the current position, looking for a point that has smaller objective value than the current one. This family includes Pattern Search (PS) algorithms, Simplex Methods (SM) (different from the simplex used in linear programming), Powell's Method and others [37].

The Direct Search methods, in contrast to more standard optimization methods, are often called derivative-free as they do not require any information about the gradient or higher derivatives of the objective function to search for an optimal solution. Therefore Direct Search methods may very well be used to solve non-continuous, non-differentiable and multimodal (i.e. multiple local optima) optimization problems. Since the ED is one of such problems, then the proposed method appears to be a good candidate to tackle the ED tasks.

One of the main objectives of this study is to introduce the use of Pattern Search (PS) optimization technique to the subject of power system ED. In this report, the PS method has been employed to solve many different cases of the ED problem with a valve-point effect. A valve-point effect is the rippling effect added to the generating unit curve when each steam admission valve in a turbine starts to open. Moreover, to assure accurate results for this model, an additional term representing the valve-point effect should be added to the cost function [38]. Furthermore, the inclusion of valve-point loading effect makes the modelling of the incremental fuel cost function of the generators more practical [27]. The addition of the valve-point effect poses a more challenging task to the proposed method since it increases the non-linearity of the search space as well as the number of local minima. Probably the most complete definition for the "valve-point effect" phenomenon can be quoted from [39, 40] as "the ripples in the input-output curve in the thin line express the result of the sharp increase in losses due to wire drawing effects which occur as each steam admission valve starts to open" (see Figure 1).

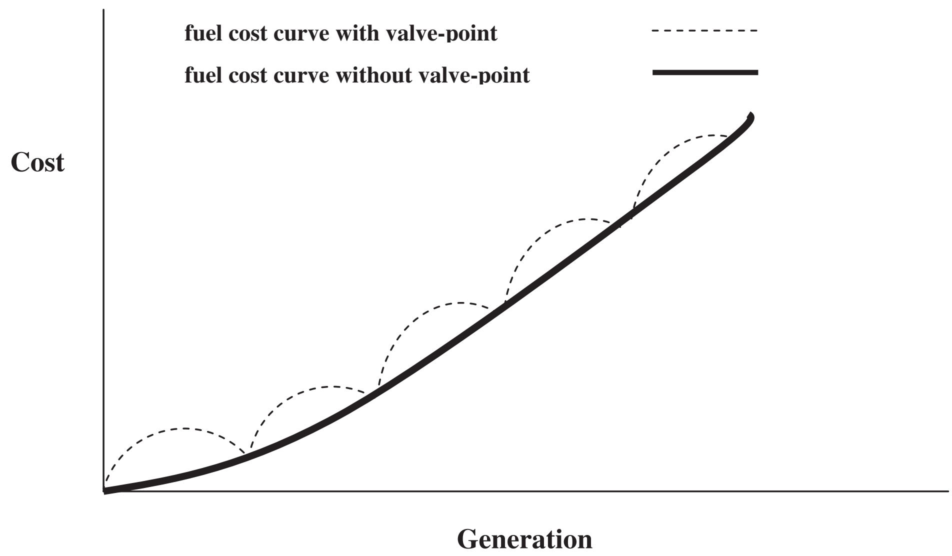

Figure 1: Valve Point Effect

The numerous different cases to consider within the ED problem are diverse. These cases include different number of units of operation, i.e. 3, 10, 13, 40, … , etc, the multi-area ED with tie lines, the quadratic cost function for the operation units, the inclusion of losses in the model, the implementation of the valve-point effect or ignoring it, and the combination of the ED and the environment emission index. In this report, the implementation of the PS to solve many such cases is described. This approach had never been used before to solve the stated problem. As will be shown, the proposed method is reliable and very competitive compared with the other well known heuristics algorithms such as GA, PSO, Evolutionary Programming (EP) and others. As a result, the proposed method could be considered as one of the heuristics methods that exhibit reliability of solving optimization problems with non-linear objective functions, non-linear equality/non-equality constraints and security constraints such as exist in ED. However, as in the case of all other heuristic methods, the performance of PS is dependent upon and sensitive to the starting point. To eliminate the reliance of PS on the initial guess, a new hybrid method has been proposed and elaborated in Chapter 4. The implementation of PS to solve multi-objective optimization problems has been considered in this report, since these kinds of problems have important applications in electrical power systems.

Moreover, the Dynamic Economic Dispatch is introduced in Chapter 5 to make the treatment more general and practical. Finally, the ED problem has been extended to include renewable energy (RE) sources and this is considered to be the final goal of this project.

1.6 Renewable Energy (RE)

The interest in renewable energy (RE), as an alternative electric power source, began in 1973 during the oil crisis. Countries with limited fossil fuel resources and totally dependent on importing oil from producing states started the search for other means to insure the continuity of electric power supply. Moreover, the officials of many of these countries had eliminated nuclear power plants from their list of nominated alternative power sources because of public pressure. As a result, RE sources were the most eligible candidates due to their availability, safety and friendliness to the environment. Wind energy was the most appropriate energy substitute, while photovoltaic sources came in second. Thirty five years of research and development since the oil crisis has led some countries to have tremendous success in RE production. Denmark and Germany are two examples that successfully introduced RE in their electric power systems and lessened their dependency on fossil fuel.

Denmark is the world’s leading country in RE integration in its electric power generation systems. It started investigating the possibilities of finding other electric power sources in the mid 1970s. The oil crisis debacle was taken seriously after the country experienced a devastating economic deficit. Furthermore, the country’s options were limited due to the absence of any national fossil-fuel resource. Public pressure in opposing the construction of nuclear power plants did not help resolve the problem either. Consequently, Denmark turned towards RE as a last resort, and has become, since early 1980s, the world leading supporter and developer of RE.

Denmark’s main objectives for using the RE were energy security, self-sufficiency and efficiency. To achieve those objectives, many national energy plans were developed with the cooperation of various organizations in Denmark. They organized grassroots movements in Denmark that successfully imposed the wind sector in the primary agenda, as the most eligible and promising alternative RE source for electric power [41].

Denmark had to overcome many obstacles in the process of deploying wind turbines in the power energy industry. The most important obstacle was the monopoly market of energy research in institutions. Public lobbying was successful in shifting the research from fossil fuel to wind turbines. As a result, many comprehensive energy plans were developed periodically (every 2-5 years) since 1976, along with new objectives and the means to achieve them. Also, the attitude of the public was gradually changed by allowing them direct investment in wind turbines. This was done through the Feed-In Tariff act in the 1993. Under FIT regulations, the utility is compelled to purchase wind-generated electricity at a rate that equals 85% of the price paid by consumers. In addition, FIT motivated the wind energy industries to invest more in improving wind turbines, and spreading out the technology throughout population. The continuous refinement and development of wind turbines lead to an astonishing success. It was able to reduce the cost of producing 1 kWh of wind power by 80%. In 2001, FIT was modified and the utility was obliged to pay full market price for wind generated electricity producers.

Nowadays, Denmark produces 23% of its electric power from both inshore and offshore wind turbines. By the year 2015, it is expected that the wind turbines will be responsible for supplying 35% of the country's total power demand [42]. Germany comes second to Denmark in RE production. It produces more than 22 GW of wind power every year, and its target is to have 36 GW (15% of Germany electricity consumption) produced by wind by 2015. As of the end of 2007, more than 19,000 wind turbines were installed and operated in Germany, and the total capacity of these wind turbines reached 20,090 MW [42]. Germany's RE strategy was also sparked by the 1973 oil crisis. Since then, every successive government made RE a top priority. Germany's Green Party suggested the FIT law in the 1980's at first, and it became a law in 1993. All governments that have come to power from 1980s till the 2000 had added some improvements to the FIT making it more attractive for the general public. In 2000, the Renewable Energy Sources Act (RESA) replaced FIT. New modifications in the compensation rates and the long term contracts (20-30 years) were the main features of RESA [41].

Germany also utilizes solar energy in its electric power generation. The use of photovoltaic energy was primarily for central and water heating. At first, the Germans were not enthusiastic about the use of photovoltaic energy due to its high price and its inefficiency. However, public awareness programs regarding the environment, the developments in solar energy industry and the RESA implementation led to the reinstatement of confidence in photovoltaic cells. In fact the number of photovoltaic devices installed in residential houses and commercial buildings rose from 29,000 to 330,000 units between the year 2000 and 2007 [43]. A very interesting example of the success of deploying solar energy in Germany was reported in an article entitled "Germany goes for solar" [43], which was written by Michael Gross, who is a science writer based in Oxford. Gross reported that photovoltaic cells were installed in the house of Franz Alt, a widely known writer and commentator since 1993 (when FIT was legislated). In 2001, one year after RESA, Alt increased his power generation capacity from 4.8 kW to 8.8 kW. The remarkable outcomes of this example were that the cells provided hot water for 225 days per year. In addition, the cells delivered between 6000 kWh to 7000 kWh (equals to twice the average power that German family consumes per year) of solar electricity per year. Moreover, Alt gained 3000 to 3500 Euros per year from selling the excess energy back to the utility. Finally, the installed photovoltaic set saved around six tones of CO_2 each year [43].

1.7 Renewable Energy and Economic Dispatch

Due to the continuing increase of oil prices, the depletion of fuel resources, ever growing demand for electrical power, and the global concern for the air pollution and the environmental protection, the use of the renewable energy (RE) resources has caught the attention of researchers in recent years. Such resources are considered environmentally friendly and have no or insignificant operational cost. In addition, power generation utilizing RE resources has been found reliable and could lead to considerable drop in the total cost of any power system, if properly scheduled and operated. However, the penetration of such power generation into the utility system may violate some security constraints of the ED model of that system, due to the intermittent and unpredictable nature of these resources. As a result, a modified system modelling and more security constraints must be added to the conventional ED formulation in order to prevent any mishaps in the operation process.

Many countries embarked on a mission to find alternative sources for electrical power generation and invested heavily in RE resources subject to natural climate conditions. For example, Taiwan has been developing the wind power generation due to the windy conditions in the country. The production of 1200-1300 MW of wind generation power from wind farms study in Taiwan was shown in [44], which has made the wind energy as one of the most promising RE sources in the country. Another example of the countries that have huge interest in RE resources is Portugal. The development and the instalment of a wind generation dispatch centres in the Portuguese power system were proposed in [45]. The purpose of these centres is to monitor and control several wind parks and then communicate with the transmission system operator or the distribution system operator to supply the required wind power penetration into the grid.

A combination of hydro, wind and solar power generation systems, which will be penetrated into the Taiwan's utility, was presented in [46]. The use of three different RE resources was seen as promising and challenging at the same time. The overall system is very complicated and the authors considered all the security constraints regarding hydro, wind and solar systems. However, if properly developed, the proposed system in [46] could become very useful and practical for countries that have the three kinds of RE resources. One of the most ambitious plans for using the wind energy as a source for electric power has been proposed by an Irish RE firm in which the construction of a "Supergrid" of offshore wind farms between European countries was proposed. The "Supergrid" would consist of 2000 turbines that could produce 10GW of cheap and environmentally friendly electricity. This is about 1.2% of the total electric power generation consumed by European countries (electric power for 6 million homes) [47]. The authors have pointed out that one of the main advantages of this project is to "smooth out" the unpredictability of the wind generation by aggregating it throughout the widespread geographical areas of Europe.

The geographical location and climate of the State of Kuwait provide sufficient motivation for the use of RE resources in the production of electric power. Solar energy is available all year long, and the wind strength is just about adequate most of the year for commercial electric power production. As an oil producing country, more than 90% of Kuwait revenue comes from selling oil and with prices of oil exceeding $70 per barrel, at the time of writing this report, the use of crude oil to produce electrical power is considered as a waste of money. Moreover, the oil reserves of the State of Kuwait are decreasing year by year due to the limited amount of oil and the shortage of new oil discoveries in the country. As a result, the interest of the Kuwaiti officials in finding alternative sources of electric power has risen in recent years. Although there are no specific plans for any kind of RE plants in Kuwait, it is not too late to start a process of introducing RE generation into the Kuwaiti electric power system. The concern about finding other means of energy generations, e.g. renewable energy, has been recurring in the meetings of the Organization of the Petroleum Exporting Countries (OPEC) for years, and the announcement of the $300 million dollars budget for RE research and development in 2007 is considered an indication of the future interests of OPEC in this area [48].

To maximize the outcome of RE systems, the implementation of ED on combined thermal and RE systems was investigated by many researchers worldwide. Although the effort was limited to small systems or local cases, the results were encouraging and can be considered a successful start to larger systems. Many different models were proposed in the literature. The diversity between these models was wide according to the size of the system and the nature of RE resources that have been used. Different assumptions were proposed and new constraints were developed to match the specific nature of each model. Explanations of some of the models in the literature are presented in the next paragraphs. In this project, a redefinition of the ED problem to be applicable to hybrid ED-RE system is considered. All security constrains should be maintained to assure the safety in the operation process.

The authors of [44] presented two scenarios for hybrid wind-thermal power system. In scenario one, the authors assumed the wind generators to be owned by the public utility; whereas in scenario two it is owned by private sector under guaranteed contract with the public utility. Moreover, the authors implemented an extension of the direct search method (DSM) to solve the hybrid wind-thermal power system ED problem. The variation of the load demand and selling prices for one of the Taiwan's power system were covered intensively in scenario one and scenario two, respectively. Another wind-thermal system was investigated in [49], where the authors proposed a modified multi-objective particle swarm optimization (MOPSO) algorithm to minimize both the system level of risk and operational cost. Furthermore, the system risk level is expected when wind generation is penetrated into the traditional utility grid, and this risk level is produced by the un-predictability of the wind power. In addition, the authors have used several fuzzy membership functions, both linear and quadratic, to indicated system security levels to represent the wind penetration and wind power cost.

An operational optimization strategy for defining the production of wind generation for the Portuguese Power system is described in [45]. The authors have assumed that the information regarding a short term wind speed forecast for individual wind turbine is available. Moreover, the authors have suggested the creation of a new control centre for monitoring and controlling the wind park and they have called it the Wind Park Dispatch Centre. At the same time, secure communication links between the Wind Park Dispatch

Centre and the distribution system operator or the transmission system operator must be established, to observe the proper process of injection the wind park generation power into the transmission network or the distribution grid. The authors of [45] have divided the problem into two sub-problems, first they have solved a unit commitment problem then they have treated the problem as a technical dispatch. The results in [45] give the wind park controller a clear view over the commitment of the wind turbines and the active and reactive power production.

Warsono and Ozveren have used a Direct Search Method (DSM) for solving an Economic Dispatch (ED) problem that has combined the conventional ED problem with RE generation in [50]. Furthermore, the unpredictability of the output of the RE resources has forced the authors to add more reserves to compensate for the power shortage by the wind park. The authors have investigated two approaches that they have called “Negative Load” and “Inclusive” to represent the wind generation. In the “Negative Load” approach, the authors have treated the wind forecast as negative load, in other words, they have reduced the load demand by the forecasted wind power, which eventually produced a new load demand; whereas in the “Inclusive” approach the wind turbine generation was included in the calculation and the authors have suggested that the maximization of the usage of the wind output is needed in order to reduce emissions. Unfortunately, in the discussion part of their report, the authors of [50] have concluded that the DSM results for solving the “inclusive” approach were not reliable, because different results were produced when they have repeated the simulation.

A new ED model that includes a Wind Energy Conversion System (WECS) was developed in [51] to be implemented in a hybrid fuel-wind power generation system. The authors used a Weibull probability density function [52] to estimate wind speed instead of short term forecasting of weather conditions. Then they transformed the wind speed distributions to wind power distributions using the linear wind power equation. Moreover, the authors presented a general ED model that can be used in all situations, regardless of who owns the wind generation facilities. A two-fuel and two-wind generator system was used in [51] and the analysis section of the paper covered many cases of coefficient alteration that the proposed model depends on, i.e. the reserve cost for overestimation the wind energy and the penalty cost for underestimating the wind energy. Chen [53] presented a hybrid algorithm which coordinates the wind and thermal generation scheduling problem for operating an isolated hybrid power system reliably and efficiently. The author tested his method on ten thermal units and hybrid ten thermal with an equivalent wind generators systems to illustrate the merits of the proposed algorithm, and presented a diverse range of results for many different cases under various conditions that the hybrid power system may operate in. In addition, the author implemented his model in the Peng-Hu power system in Taiwan and concluded that the increase of wind turbine generators will lead to significant annual saving in the operational costs.

The combination of thermal, hydro, wind and solar energy system was presented in [46], where the authors used a fuzzy optimization approach to consider the forecast hourly load, available water, wind speed and solar radiation errors. Furthermore, the emission constraint was taken into account in the generation scheduling problem by the authors to make the model friendlier to the environmental. However, the authors have not considered system configuration and line impedances, due to their emphasis on the short-term generation scheduling problem for the wind and solar energy system. A new levels of wind generation penetration scheduling was presented in [54] to improve the economic, environmental and security constraint performance of a power system. The authors have employed a dynamic programming technique with backtracking on IEEE30 bus system over a period of one week to present the optimal level of wind generation allowed to penetrate the electric power system. Moreover, the authors have concluded that up to 5.73% of wind generation penetration into the utility will lead to 8% of drop in the total cost of power generation in the power system.

1.8 The context of the research and proposed elements of novelty

As argued in this introduction, the Economic Dispatch is a very important component of a decision-making process to make the production of electrical power as efficient and economically advantageous as possible. Research in this area has been conducted for decades and various models and techniques have been proposed. The motivation for this particular research project had come from three directions. First, it was recognised that although significant progress had been made, there were still some questions unanswered and some scope for further fundamental developments in the basic formulation of the ED problem. In particular, the renewable energy aspect needed further investigation and the Dynamic Economic Dispatch required an enhanced treatment. Secondly, it was noted that some optimization techniques attracted significant attention in recent years but had not been tried in the context of the Economic Dispatch. The Pattern Search (PS) method was identified as worth careful consideration in the hope of achieving better performance and more reliable results. The technique was subsequently implemented and extended to include a hybrid formulation, to alleviate some of the drawbacks of the pure PS approach. Finally, the ultimate aim of this research has always been to advance the technology for the benefit of my home country, the State of Kuwait, and to address the urgent needs of its electricity sector. The author believes that elements of novelty may be found in all three areas mentioned above in the forthcoming sections throughout this report.

1.9 Aims and objectives of the thesis

The overall aim of this research is to advance the knowledge, understanding and modelling capabilities of the Economic Dispatch (including Dynamic Economic Dispatch, DED) through the use of modern optimisation techniques and in the context of practical implementation in the electricity system of the State of Kuwait.

The objectives may be formulated as follows:

1. Consider, investigate and enhance the basic definitions of the Economic Dispatch and Dynamic Economic Dispatch in the context of Renewable Energy (RE) sources, including wind and solar power, and in view of possible benefits for the particular implementations in the State of Kuwait.
2. Introduce, develop and implement the Pattern Search (PS) technique for the ED and DED problems; compare its performance with existing techniques, identify advantages and drawbacks, draw conclusions regarding its usefulness for solving ED problems.
3. Conduct a thorough verification of the proposed technique for a number of cases, varying the number of units, etc.
4. Modify and enhance the technique to improve its performance.
5. Introduce and develop appropriate models for wind farms and solar power sources which could be used in the ED and DED models.
6. Investigate in detail the case of the West Doha Power Station in Kuwait using methods and techniques developed in this project, produce practical recommendations for the operation of this station.
7. Draw conclusions and generate recommendations for the benefit of the electricity sector in the State of Kuwait.

2 Economic dispatch

In this chapter, a description of the ED problem is presented in detail, and a brief explanation of the Pattern Search method is provided. The objective of this chapter is to make it easier for the reader to follow the arguments of the rest of the thesis.

2.1 Problem Formulation

Different formulations of the ED problem exist; this sub-section has been organised and divided according to the type of ED considered. It should be noted that the system losses have been ignored for test cases 3-I and 3-III to 3-V for the sake of simplicity, but are included in all other cases in this report.

2.1.1 General Formulation (Economic Dispatch with valve-point loading)

The traditional formulation of the ED problem is a minimization of summation of the fuel costs of the individual dispatchable generators, subject to the real power balanced with the total load demand, as well as the limits on generators outputs. In mathematical form the problem can be stated as [55]:

$$F = \sum_{i=1}^{N} F_i(P_i) \tag{2.1}$$

with the incremental fuel cost functions of the generation units with valve-point loading represented as:

$$F_i(P_i) = a_i P_i^2 + b_i P_i + c_i + \left| e_i \sin\left(f_i\left(P_{gi(\min)} - P_i\right)\right)\right| \tag{2.2}$$

subject to

$$\sum_{i=1}^{N} P_{gi} = P_D + P_L \tag{2.3}$$

$$P_{gi(\min)} \langle P_{gi} \langle P_{gi(\max)} \quad ,i \in N_s \tag{2.4}$$

where

F system's overall cost function

$F(P_{gi})$ fuel cost function of generator P_{gi}

N number of generators in the system

$a_i,\ b_i,\ c_i$ constants of fuel function of generator i

$e_i, \ f_i$ constants of valve-point effect of generator *i*

P_{gi} the active power generation of generator *i*

P_D the total power system demand

P_L the total system transmission losses

$P_{gi(\min)}$ the minimum limit on active power generation of generator *i*

$P_{gi(\max)}$ the maximum limit on active power generation of generator *i*

N_s the set of generators in the system

The sinusoidal term added to the fuel cost function which models the valve-point effect introduces ripples to heat-rate curve, thus introducing more local minima to the search space.

2.1.2 Multi Area Economic Dispatch (MAED)

In a multi-area ED problem, the objective is to determine the most economical generation level in a given area and the power interchange between the areas that minimize the overall operation cost while satisfying a set of constraints [56]:

$$\min\left[\sum F(P_{gi}) + \sum G(t_{jk})\right] \tag{2.5}$$

subject to

$$\sum_{i\in\alpha_m} P_{gi} + \sum_{j\in\beta_m} t_{kj} - \sum_{j\in\beta_m} t_{jk} - D_m = 0 \tag{2.6}$$

$$P_{gi(\min)} \le P_{gi} \le P_{gi(\max)} \tag{2.7}$$

$$t_{jk(\min)} \le t_{jk} \le t_{jk(\max)} \tag{2.8}$$

where:

$F(P_{gi})$ fuel cost function of generator P_{gi}

$G(t_{jk})$ transmission cost of line t_{jk}

t_{jk} economic flow on tie line from area j to k

α_m set of generating units in area m

β_m set of tie lines in area m

P_{gi} the active power generation of generator number i

D_m the total load demand of area m

$t_{jk(\min)}$ the minimum limit on active power generation of generator i

$t_{jk(\max)}$ the maximum limit on active power generation of generator i

2.1.3 Combined Economic and Emission Dispatch (CEED)

The primary objective of ED can be extended to take into account the environmental impact of power generation due to the emission of different pollutants that could inflict harm on the environment [57, 58]. The emission cost function, just like the fuel cost function in traditional ED, is modelled as a second order polynomial

$$E = \sum_{i=1}^{N} d_i P_{gi}^2 + h_i P_{gi} + u_i \quad \text{(kg/h)} \tag{2.9}$$

where d_i, h_i and u_i are emission coefficients of generator i. Thus the overall objective function for the combined emission–economic dispatch is:

$$\min\left[\, w\, F + (1-w)\, E\right] \tag{2.10}$$

where w is a weighting factor, $w \in [0,...1]$, which represents the relative importance or the trade-off between the fuel cost functions F and the emission cost functions E. The objective function of equation (2.10) is minimized subject to the constraints given by equations (2.3) and (2.4), where the transmission losses are given by:

$$P_L \approx \sum_{n=1}^{N} \sum_{k=1}^{N} P_{gn} B_{n,k} P_{gk} \tag{2.11}$$

where B is a matrix of loss coefficients and P_{gn} and P_{gk} are the active power generation of generator n and k respectively.

2.1.4 Cubic Cost Function Economic Dispatch (CCFED)

Traditionally, the cost function of the generating units is approximated as a quadratic function. A crucial issue in ED studies is to determine the order and approximate the coefficients of the polynomial used to model the fuel cost function [59]. This issue is particularly important in terms of reducing the error between the approximated polynomial, along with its coefficients, and the actual operating cost. According to [59, 60], a third order (cubic) polynomial is realistic to model the operating cost. For a generating unit with non-monotonically increasing cost curves a cubic polynomial is usually used to obtain accurate dispatch results [61]. The third order polynomial function is expressed as

$$F_i(P_{gi}) = \alpha_{i,1}P_{gi}^3 + \alpha_{i,2}P_{gi}^2 + \alpha_{i,3}P_{gi} + \alpha_{i,4} \tag{2.12}$$

subject to

$$\sum_{i=1}^{N} P_{gi} = P_D + P_L \tag{2.13}$$

$$P_{gi(\min)} \langle\, P_{gi} \,\langle\, P_{gi(\max)} \quad ,i \in N_s \tag{2.14}$$

where $\alpha_{i,1}, \alpha_{i,2}, \alpha_{i,3}$ and $\alpha_{i,4}$ are the coefficients of the cubic fuel cost function.

2.1.5 Dynamic Economic Dispatch (DED)

The formulation of the dynamic economic dispatch consists of the traditional formulation of the ED scheduled over a period of time and has to satisfy certain system bounds and operational constraints. In this sub-section, the formulation of the dynamic economic dispatch is presented and the addition of emission index is also considered hence the overall picture of this formulation can be completed. The objective function of the ordinary DED is as follows:

$$f_1 = F = \sum_{m=1}^{M}\sum_{i=1}^{N} F_{im}(P_{im}) \tag{2.15}$$

with the incremental fuel cost functions of the generation units with valve-point loading represented as:

$$F_{im}(P_{im}) = a_i P_{im}^2 + b_i P_{im} + c_i + \left| e_i \sin(f_i(P_{i\min} - P_{im})) \right| \tag{2.16}$$

where a_i, b_i, c_i, e_i, f_i are the cost coefficients of i^{th} unit, P_{im} is the output power of i^{th} unit at time m, $P_{i\,min}$ is the lower generation bound for i^{th} unit, N is the number of generation units, M is the number of hours in the time horizon.

If the emission index is considered, then the following additional term should be added to the formulation:

$$f_2 = E = \sum_{m=1}^{M} \sum_{i=1}^{N} E_{im}(P_{im}) \tag{2.17}$$

and the amount of emission of each generator can be expressed by

$$E_{im}(P_{im}) = \alpha_i P_{im}^2 + \beta_i P_{im} + \gamma_i + \eta_i \exp(\delta_i P_{im}) \tag{2.18}$$

so the following term is considered as the objective function to combined economic and emission dispatch, therefore the minimization problem is represented as

$$Min\ (f_1 + f_2) = Min\ (F + E) \tag{2.19}$$

subject to

real power balance

$$\sum_{i=1}^{N} P_{im} = P_{Dm} + P_{Lm} \tag{2.20}$$

real power operation limits

$$P_{i(\min)} \langle\ P_{im} \ \langle\ P_{i(\max)} \quad , i \in N_s, m \in M \tag{2.21}$$

generating unit ramp rate limits

$$\begin{aligned} P_{im} - P_{i(m-1)} &\le UR_i \qquad i \in N, m \in M \\ P_{i(m-1)} - P_{im} &\le DR_i \qquad i \in N, m \in M \end{aligned} \tag{2.22}$$

where P_{Dm} is the load demand at time m, P_{Lm} is the transmission line losses at time m, $P_{i(\max)}$ is the upper generation bound for i^{th} unit, and UR_i and DR_i are the ramp-up and ramp-down rate limits of the i^{th} generator, respectively.

2.2 System losses representation

It is important to mention at this stage that the *B*-coefficients, as found for example in (2.11), or loss coefficients, have been adopted for the modelling of the system losses in the previous formulations. The representation using *B*-coefficients is suitable for interpretation of the real power system losses under certain conditions. If the actual operating conditions are close to the base case, where B-constants were computed, then the B-coefficients method should compute the system losses with reasonably high accuracy [62, 63]. In other words, the use of constant values for the loss coefficients in the equation for transmission losses yields good results when the coefficients are calculated for some average operating condition and extremely wide shifts of load between plants, or in the total load, do not occur. In practice, large systems are represented by calculations based on just one set of loss coefficients which are sufficiently accurate throughout the daily variations of load on the system [63].

2.3 Pattern Search Method

The Pattern Search (PS) optimization routine is an evolutionary technique that is suitable to solve a variety of optimization problems that lie outside the scope of standard optimization methods. Generally, PS has the advantage of being very simple in concept, easy to implement and computationally efficient. Unlike other heuristic algorithms, such as genetic algorithms [64, 65], PS possesses a flexible and well-balanced operator to enhance and adapt the global and fine tune local search. A useful review of direct search methods for unconstrained optimization is presented in [37], where the authors give a modern perspective on the classical family of derivative-free algorithms, focusing on the development of direct search methods.

The Pattern Search (PS) algorithm proceeds by computing a sequence of points that may or may not approach the optimal value. The algorithm starts by establishing a set of points called a mesh, around the given point. This current point could be the initial starting point supplied by the user or it could be computed from the previous step of the algorithm. The mesh is formed by adding the current point to a scalar multiple of a set of vectors called a pattern. If a point in the mesh is found to improve the objective function at the current point, the new point becomes the current point at the next iteration.

The details of the above process are as follows. First, the Pattern Search begins at the initial point X_0 that is given as a starting point by the user. At the first iteration, with a scalar equal to 1 called the mesh size, the pattern vectors are constructed as [1 0], [0 1], [−1 0] and [0 −1]; they may be called the direction vectors. Then the Pattern Search algorithm adds the direction vectors to the initial point X_0 to compute the following mesh points:

$$X_0 + [1 \;\; 0]$$

$$X_0 + [0 \;\; 1]$$

$$X_0 + [-1 \;\; 0]$$

$$X_0 + [0 \;\; -1]$$

Figure 2 illustrates the formation of the mesh and pattern vectors. The algorithm computes the objective function at the mesh points in the order shown.

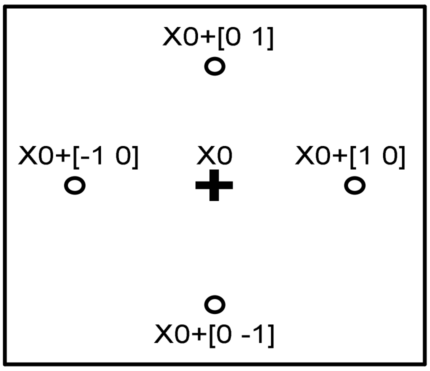

Figure 2: PS Mesh points and the Pattern

The algorithm polls the mesh points by computing their objective function values until it finds the one with a value smaller than the objective function value of X_0. If there is such a point, then the poll is successful and the algorithm sets this point as equal to X_1.

After a successful poll, the algorithm proceeds to the second iteration and multiplies the current mesh size by 2 (this is called the expansion factor and normally has a default value of 2). The mesh at iteration two contains the following points: X_1+2*[1 0], X_1+2*[0 1], X_1 +2*[−1 0] and X_1+2*[0 −1]. The algorithm polls the mesh points until it finds the one whose value is smaller than the objective function value of X_1. The first such point it finds is called X_2, and the poll is successful. Because the poll is successful, the algorithm multiplies the current mesh size by 2 to get a mesh size of 4 at the third iteration because the expansion factor equals 2.

Secondly, if iteration 3 (mesh size = 4) ends up being an unsuccessful poll, i.e. none of the mesh points have a smaller objective function value than the value at X_2, the algorithm does not change the current point at the next iteration; that is $X_3 = X_2$. At the next iteration, the algorithm multiplies the current mesh size by 0.5, a contraction factor, so that the mesh size at the next iteration is smaller. The algorithm then polls with a smaller mesh size.

The Pattern search optimization algorithm will repeat the illustrated steps until it finds the optimal solution for the minimization of the objective function. The algorithm stops when any of the following conditions occurs:

- The mesh size is less than mesh tolerance.
- The number of iterations performed by the algorithm exceeds a predefined value.
- The total number of objective function evaluations performed by the algorithm reaches a pre-set maximum number of function evaluations.
- The distance between the point found at one successful poll and the point found at the next successful poll is less than a set tolerance.
- The change in the objective function from one successful poll to the next successful poll is less than a function tolerance.

All the parameters involved in the Pattern Search optimization algorithm can be pre-defined subject to the nature of the problem being solved (see Figure 3 for illustrative explanation of how the PS works).

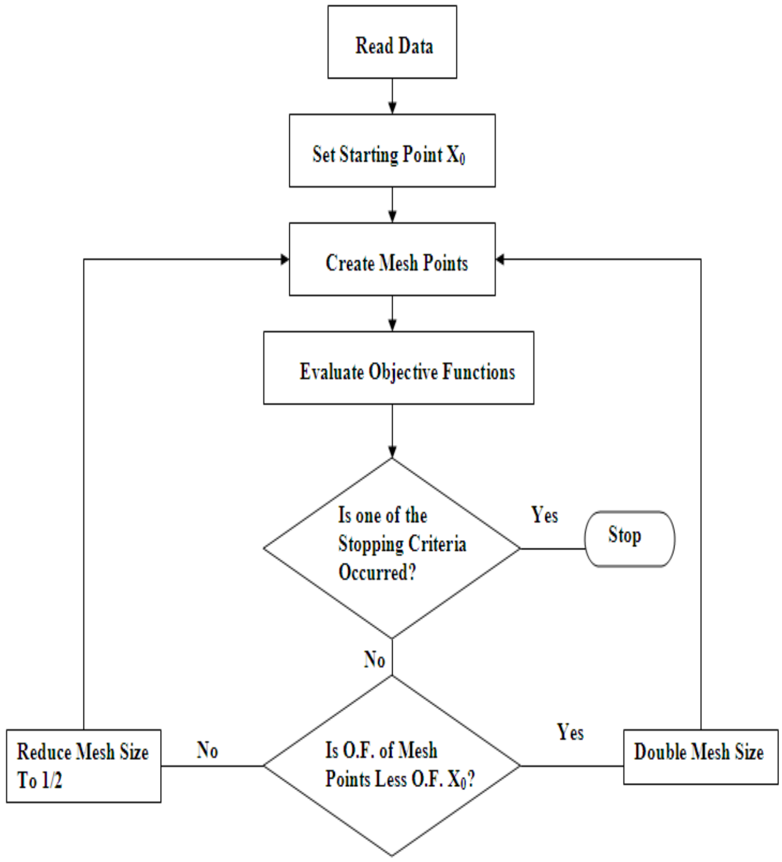

Figure 3: Flow Chart of PS

2.4 Constraints handling

Many ideas were suggested to ensure that the solution satisfies the constraints [66]. The lack of specific information related to first order derivatives is considered the only weakness in the nonlinear constraints handling procedure. Although many systematic methods have been employed to handle the nonlinear constraints, the augmented Lagrangian approach, which has been utilized by pattern search method, has overcome such shortcomings. Lewis and Torczon [67] stated that, despite the absence of an explicit estimation of any derivatives (a characteristic of pattern search methods), pattern search augmented Lagrangian approach exhibits all of the first-order convergence properties of the original algorithm advocated by Conn, Gould, and Toint [68, 69]. The authors in [67] were able to overcome this drawback by proceeding with successive, inexact minimization of the augmented Lagrangian via a pattern search method, even without knowing exactly how inexact the minimization is. As a result, the size of the problem has increased by introducing new parameters.

Augmented Lagrangian Pattern Search (ALPS) proceeds to solve a nonlinear optimization problem with nonlinear constraints, linear constraints and bounds [67, 70-72]. The variables' bounds and linear constraints are handled separately from nonlinear constraints, where a sub-problem is constructed and solved (having the objective function and nonlinear constraint function) using the Lagrangian and the penalty factors. Such sub-problem is minimized using a pattern search method, so that the linear constraints and bounds are satisfied. ALPS starts with an initial value for the penalty parameter, where the PS algorithm minimizes a series of the subproblems, which estimates the original problem. If the required accuracy and feasibility conditions are met, then the Lagrangian estimates are updated. If not, a penalty factor is added to the penalty parameter. This in turns leads to a new formation of a subproblem and ultimately results in a new minimization problem. The above steps are repeated until one of the stopping criteria is reached. For more explanation on how PS handles constraints refer to [67, 69, 73].

2.5 Pareto Front and Test Cases

One of the most ambiguous aspects in an optimization process is the confidence in the result that the algorithm has produced. The user of any method of optimization implicitly assumes that his/her results are an optimal or a near optimal solution, but this assumption requires some justification. Many researchers simply compare their results with what has been reported in the literature. Others verify their methods using standard benchmark problems or test functions. In this thesis, the notion of a Pareto Front and two simple test cases have been used to increase the confidence in the results of the PS algorithm for solving ED problems.

2.5.1 Pareto Front (PF)

The presence of the Pareto Front (PF), or Pareto Optimal Front, adds a constructive feature to multi objective optimisation. The solutions of multi-objective optimisation problems are usually conflicting and the final decision often necessities a trade off between the objective functions. The Pareto Front formulation gives the researcher a clearer view of the final result of a multi objectives optimisation process and makes the choice of a suitable final solution easier. For example, if there is an optimization problem with two objective functions, say f_1 and f_2, and the minima are sought for both functions, the final result may not be unique in a sense that f_1 and f_2 cannot achieve optimum simultaneously. Thus a trade off between the two objective functions must be established. Figure 4 shows several possible solutions of the problem and the Pareto Optimal Front – represented by the black line – which contains all possible optimal solutions (optimal in a pareto sense). The solutions that lie on PF may be described as points that are not strictly dominated by any other solution. For example, let points *A* and *B* represent two possible solutions located on the PF; both are therefore pareto optimal. The final choice between the solutions depends on the relative importance of the objective functions f_1 and f_2. If the first objective function were assumed to have more impact in this problem, point B would be selected as a preferred solution, because $f_1(B) < f_1(A)$. On the other hand, point *A* would be chosen as a better optimal solution if the second objective function were more important. The focus on points *A* and *B* was for illustrative purpose only and does not mean that these are the only PF solutions. In fact, all blue circles are considered pareto optimal and the final choice of the solution is subject to the weights applied to both objective functions.

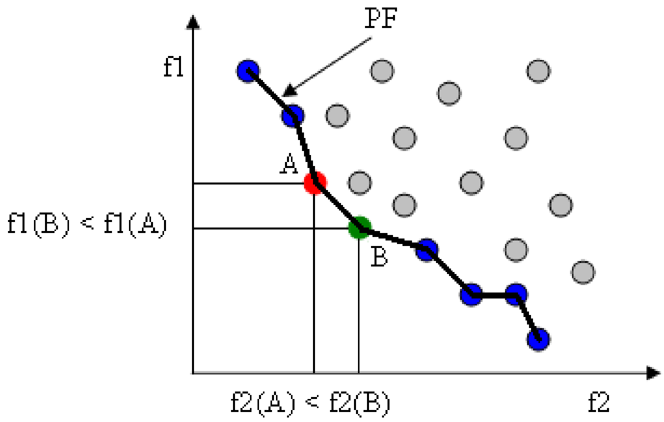

Figure 4: Pareto Front

In this report, the PF was implemented in cases of multi objective functions, as described in sub-sections 3.4.2 and 5.2. In these two cases, the PF was used to produce a set of solutions that depend on the importance of the fuel cost or the emission associated with the electric power generation. In most of this report, the fuel cost and emission were weighted equally (weighting factor (w) = 0.5), but when the PF was used, the weighting factor was varied from 0.1 to 0.9. As a result, different solutions were produced according to the choice of the weighing factor and depending on whether it was in favour of the fuel cost or the emission. From Equation (2.10), if the weighting factor is set below 0.5, this means that the emission has more weight in the final solution than the fuel cost. On the contrary, the fuel cost would have more impact on the optimal solution if the weighting factor was assigned a value that is greater than 0.5.

2.5.2 Simple Test Cases

Two simple test cases were used as benchmark models for the PS algorithm. The main objective of this experiment was to increase confidence in the PS solutions. Moreover, the optimal solution in multi-objective optimization problems may not be unique. The presence of two or more objective functions increases the range of possible pareto optimal solutions and the final choice is often a subjective decision. A trade-off relationship between the objective functions must be established. This trade-off may be developed by assigning different weighting factors to each objective function. The objective functions relevant to the ED problem in hand are the fuel cost and emission. The Pareto Fronts for the test cases were computed and compared with the trade-off relationship of the two objective functions. Both the PF and the different optimal solutions were plotted on the test cases graphs. The results and graphs of this experiment are described in Appendix B.

2.6 Economic Dispatch Model

In order to increase confidence in the PS method, the following numerical experiment was undertaken. The whole space of the economic dispatch model was explored and the results of the algorithm were placed in this space to assess the quality of the PS solution. The economic dispatch problem's search space lies in the first quadrant and, with the fuel cost and emissions as objective functions, the global or near global minima should be on the Pareto Optimal Front in the lower left 'corner' of the space (similar to the two simple test cases).

As may be seen in Figure 5, the whole search space of the ED problem is huge and has been established using initially 5 million random points. Since the global or near global minima will eventually be found in the lower left corner of this space, the search was focused in that area. The number of random points was thus increased to 50 million as illustrated in Figure 6. Then the PS algorithm was executed 100 times and the solutions added to Figure 6. It can be seen that even with 50 million points the proper shape of the Pareto Front still has not been fully captured, while the PS algorithm appears to have found solutions better than the random search.

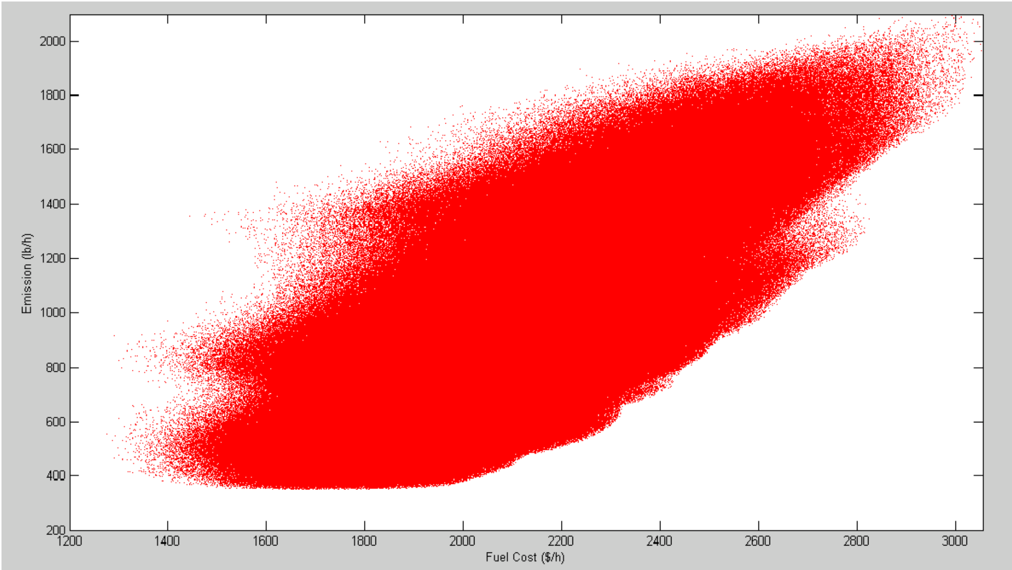

Figure 5: ED problem space

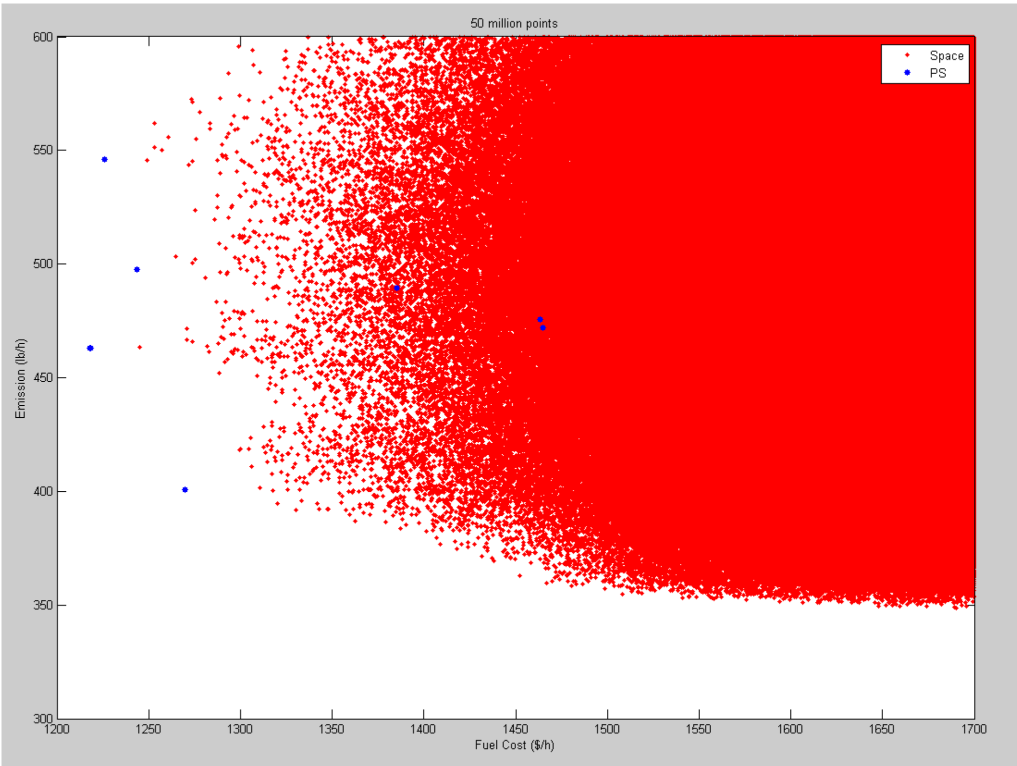

Figure 6: ED problem space (50 million points)

The number of random points used to plot the ED space was further increased gradually from 50 million to 6 billion (see Figures 7 to 9). The shape of the 'edge' of the lower left corner area of the ED problem was no longer changing so it could be considered a reasonable approximation of the Optimal Pareto Front. As can also be seen from the Figures – and this was in fact the main purpose of this 'experiment' – the Pattern Search algorithm has produced remarkably accurate estimates of the Pareto Front. To be more precise, it was found that between 65-85% of the 100 solutions generated by PS for the ED problem were optimal or near optimal. Furthermore, the least accurate solutions were produced only 3-5% of the time. These findings demonstrate that PS is indeed a reliable algorithm for solving the ED problem and its final results could be confidently considered as the optimal or near optimal solutions.

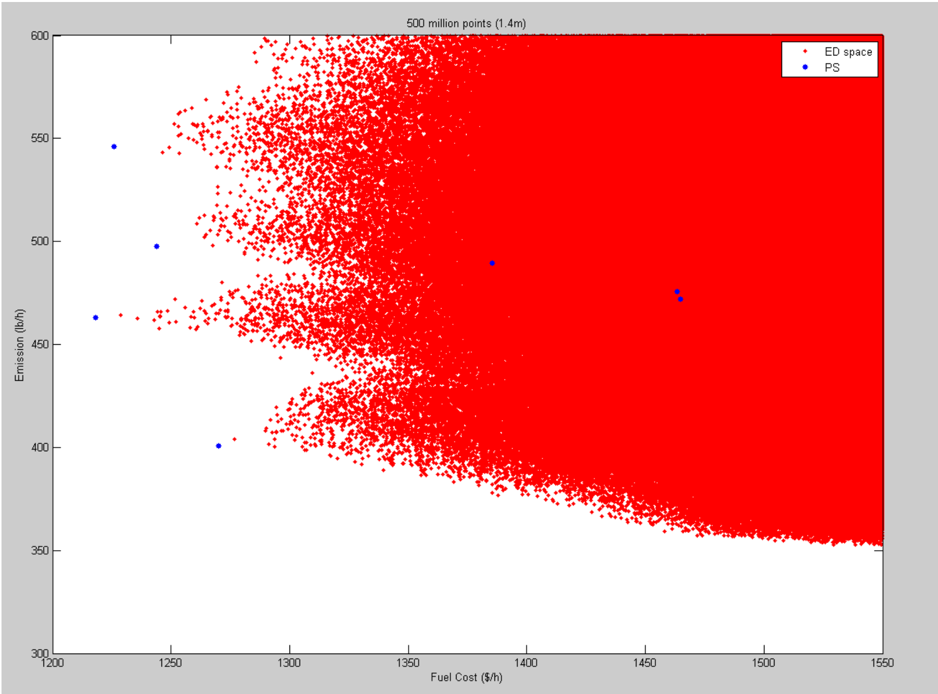

Figure 7: ED space (500 million points)

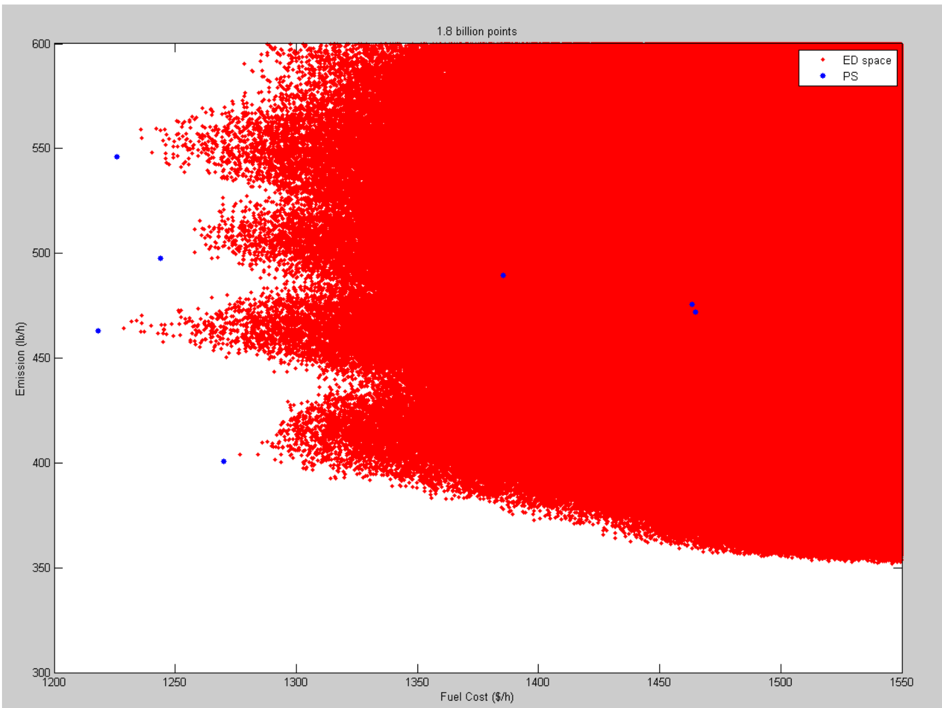

Figure 8: ED space (1.8 billion points)

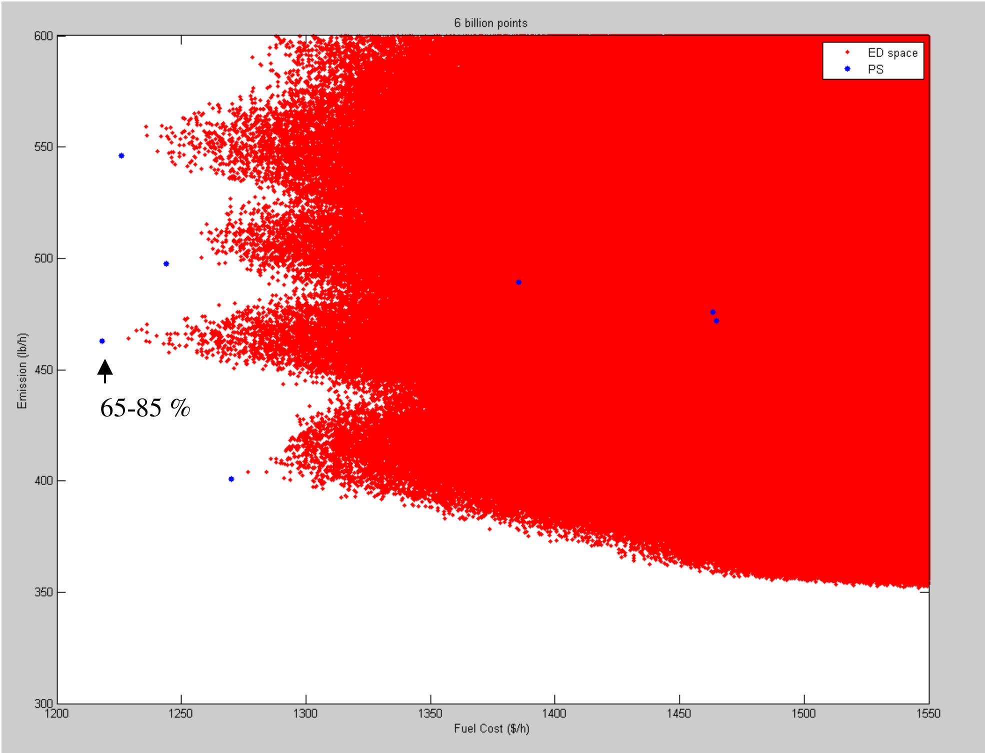

Figure 9: ED space (6 billion points)

3 Numerical Results

In order to assess the effectiveness and robustness of the proposed Pattern Search method, several test cases of ED have been considered, and some of these cases contain the valve-point effect. For simplicity, transmission losses are ignored in some of the cases (P_L in Equation 2.3 is set to zero). The non-linear minimization problem formulation of all test cases has been solved using the predefined function pattern search incorporated in the GA & DS toolbox of Matlab . This function implements the Pattern Search algorithm described in Section 2.3. The cost coefficients of the fuel cost and the combined objective function for the considered test cases were coded in Matlab environment. The test cases differ in the number of generating units, the cost function objective function and the number of areas of units operation.

Initially, several runs have been carried out with different values of the key parameters of PS, such as the initial mesh size and the mesh expansion and contraction factors. In this study, the mesh size and the mesh expansion and contraction factors are selected as 1, 2 and 0.5 respectively. In addition, a vector of initial points, i.e. X_0, was randomly generated (each initial point is bounded within the generators limits) to provide an initial guess for the PS to proceed. As for the stopping criteria, all tolerances were set to 10^{-6} and the maximum number of iterations and function evaluations were set to 1000. Runs in cases 3-I to 3-VI have been conducted on a modest 1GHz Pentium 3 processor with 256 MB of RAM laptop computer, all the rest of the cases have been conducted on 3.4 GHz Pentium(R) 2 GB of RAM desktop computer, so the comparisons of computing times with those given in literature should be fair.

3.1 Three Generating Units

In this subsection, two test cases consist of three generating units with quadratic cost function combined with the effects of valve-point loading included. In Case 3-I the system transmission losses were ignored, whereas in Case 3-II the losses were added to the system formulation.

3.1.1 Case 3-I: Three Generators Units (ED without losses)

The units' data (upper and lower bounds) along with the cost coefficients for the fuel cost (*a, b, c, e* and *f*) for the three generators with valve-point loadings are given in [55, 74].

The Pattern Search algorithm has been executed 100 times with different starting points to assess its performance and effectiveness. The solutions obtained using the PS method and the execution times for the 100 runs were compared with the outcome of other evolutionary methods, for example Genetic Algorithm (GA) and Evolutionary Programming (EP), applied to the same test system in [74]. The comparison of performance of PS with the other methods is in terms of dispatching costs and convergence speed.

Table 1 shows the optimal solutions determined by PS for the three units while the execution time and cost comparisons are shown in Table 2. The names of methods mentioned in Table 2 are Genetic Algorithm (GAB & GAF), Classic Evolutionary Programming (CEP), Fast Evolutionary Programming (FEP), Mean Fast Evolutionary Programming (MFEP), Improved Fast Evolutionary Programming (IFEP) and Pattern Search (PS).

Table 1: Generator loading and fuel cost determined By PS with total load demand of 850 MW

Generator	Generator Production (MW)
P_{g1}	300.27
P_{g2}	149.73
P_{g3}	399.99
$\Sigma P_{gi} =$ 850 MW	Total cost: 8234.1 $/h

Table 2: Comparison of PS and EP

Evolution Method	Mean time (s)	Best time (s)	Mean cost ($/h)	Maximum cost ($/h)	Minimum cost ($/h)
GAB	35.80	32.46	------	------	8234.08
GAF	24.65	23.03	------	------	8234.07
CEP	20.46	18.35	8235.9	8241.8	8234.07
FEP	4.45	3.79	8234.2	8241.8	8234.07
MFEB	8.00	6.31	8234.7	8241.8	8234.08
IFEP	6.78	6.11	8234.2	8234.5	8234.07
PS	0.81	0.62	8352.4	8453.0	8234.05

All methods give a similar ‘best’ solution, whereas ‘mean’ and ‘maximum’ costs differ. The PS algorithm is significantly faster than methods described in [74].

The convergence of the PS algorithm is shown in Figure 10, where only about 22 iterations were needed to find the optimal solution. However, PS may be allowed to continue the search in the neighbourhood of the optimal point to increase the confidence in the result. PS stops after 44 more iteration and returns the optimal value.

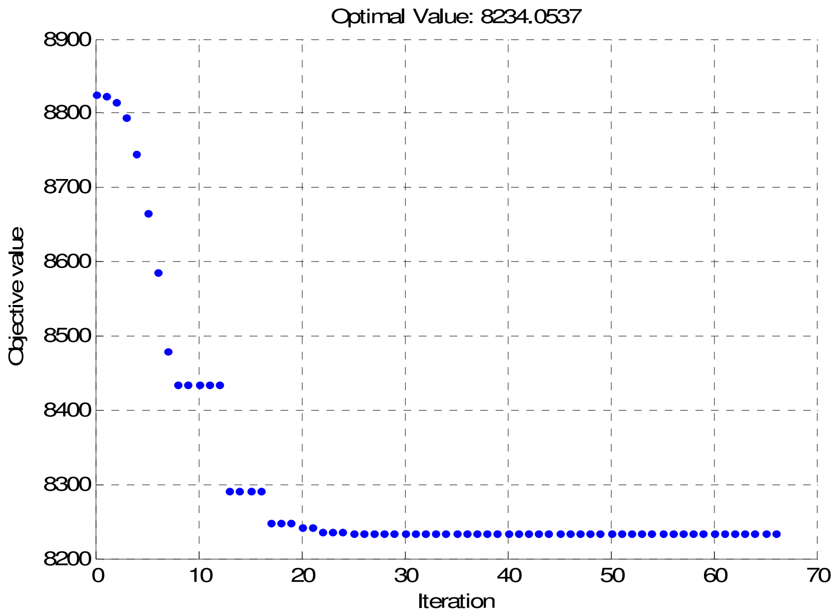

Figure 10: Convergence of PS (Case 3-I)

Figure 11 depicts the mesh size throughout the convergence process. It is apparent that the mesh size decreases until the algorithm terminates, in this case at a mesh size of $1.5259*10^{-5}$ which is more than the stopping criteria, thus indicating that this particular run did not terminate using the mesh size tolerance. Figure 11 shows that for the first 8 iterations the poll was successful since the mesh size keeps increasing as the algorithm had to expand the scope of the search. This is accomplished by multiplying the current mesh size by the expansion factor, in this study taken as 2. This scenario continued until iteration number 8 when the mesh size reached 256. At iteration number 9 the mesh size decreased by half due to multiplying the current mesh size by the contracting factor, indicating an unsuccessful poll in the previous iteration. This process continues until reaching one of the termination criteria.

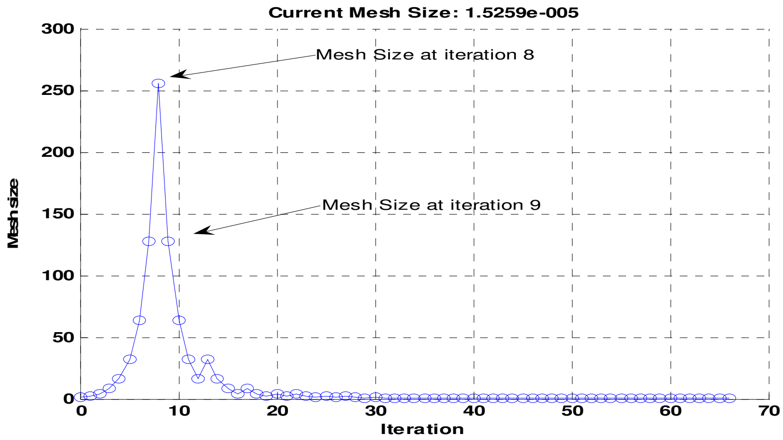

Figure 11: Mesh Size-linear scale (Case 3-I)

It is worth mentioning that the mean and the maximum costs are higher than those of the other methods, and this is a certain drawback of the performance of PS in this test. Moreover, it has been observed that the algorithm is quite sensitive to the initial (starting) point and how far it is from the global optimal solution. Figure 12 illustrates the sensitivity of PS where a hundred solutions were obtained by PS with different initial values. The optimal solution has been reached a number of times for initial points around run number 80. The total execution time for the 100 runs was 80.75 sec. Other quality answers occurred for runs between 32 to 40 and 84 to 100. However, there were also several less successful results as illustrated in Figure 12.

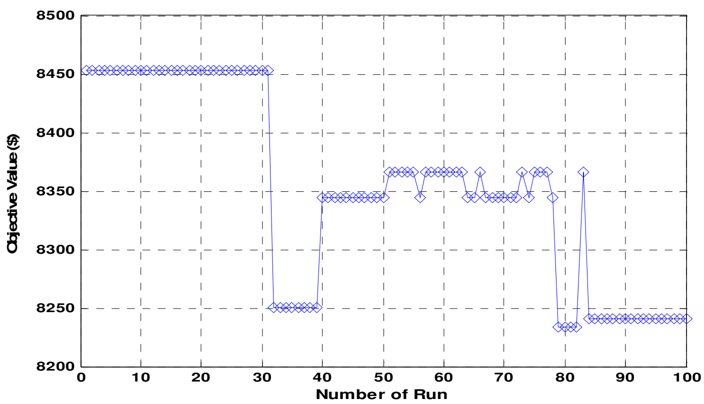

Figure 12: Objective Function Value for 100 different Starting Points (Case 3-I)

3.1.2 Case 3-II: Three Generators systems (ED with losses)

In this case, we considered a test system containing three generators with transmission losses as reported in [65]. The results of the optimal generation for each generator and the optimal fuel cost are compared with the result of the Hybrid Stochastic

Search (HSS) method presented in [75] and those obtained from the conventional method obtained in [65].

The results obtained from PS are shown in Table 3. The results were compared with other methods reported in [75] and PS produced better results than the conventional method and HSS in terms of total power generating cost and system losses. The total demand of the generators is 210 MW.

Table 3: Comparison CM, HSS and PS

Generator	Conventional Method	HSS	PS
P_{g1} (MW)	60.27	73.66	75.50
P_{g2} (MW)	79.45	69.98	75.10
P_{g3} (MW)	80.15	75.18	67.95
Cost ($/h)	3168.6	3164.5	3160.9
Losses	9.865	8.820	8.541

In Figure 13, we can see the final best point of the optimal solution of the generating units for the proposed problem. In addition, we executed the algorithm for 100 different starting points, and the results of these runs are shown in Figure 14. It can be seen that the optimal solution was achieved in the 25th run and all other solutions were within a range of 2.4% of the optimal solution. In this case, PS demonstrated that it has the ability to produce quality solutions for the ED problem regardless of the starting point.

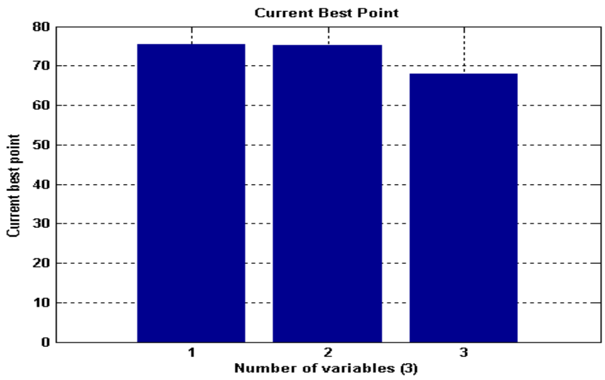

Figure 13: Best Point (Case 3-II)

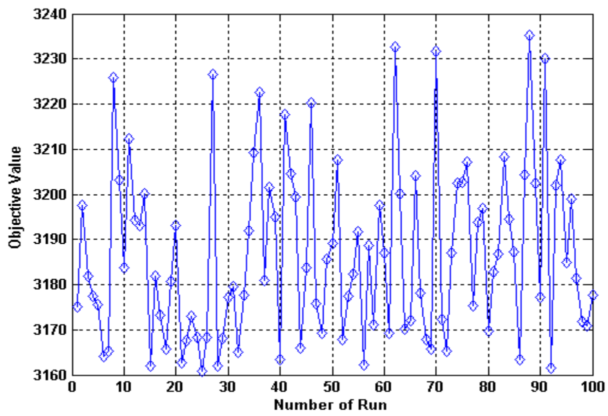

Figure 14: Objective Function Value for 100 Different Starting Points (Case 3-II)

3.2 Case 3-III: Thirteen Generating Units

This test assumes 13 generating units with a quadratic cost function combined with the effects of valve-point loading. The units data (upper and lower bounds) and cost coefficients for the fuel cost (*a, b, c, e* and *f*) for the 13 generators with valve-point loading are given in [74, 76].

The Pattern Search algorithm has been executed 50 times with different starting points and similar comparisons as for Case 3-I are summarized by Tables 4 and 5. The results for all the 'EP' methods are taken from [74, 76].

Table 4: Generator loading and fuel cost determined by PS with total load demand of 1800 MW

Generator	Generator Production (MW)
P_{g1}	538.56
P_{g2}	224.64
P_{g3}	149.85
P_{g4}	109.87
P_{g5}	109.87
P_{g6}	109.87
P_{g7}	109.87
P_{g8}	109.87
P_{g9}	109.87
P_{g10}	77.47
P_{g11}	40.22
P_{g12}	55.03
P_{g13}	55.03
ΣP_{gi} = 1800 MW	Total cost: 17969 $/h

Table 5: Comparison of PS and EP

Evolution Method	Mean time (s)	Best time (s)	Mean cost ($/h)	Maximum cost ($/h)	Minimum cost ($/h)
CEP	294.96	293.41	18190	18404	18048
FEP	168.11	166.43	18200	18453	18018
MFEP	317.12	315.98	18192	18416	18028
IFEP	157.43	156.81	18127	18267	17994
PS	5.88	1. 65	18088	18233	17969

In this case the results of the PS method are better than all other algorithms in terms of all costs: minimum, mean and maximum, while at the same time offering significant saving in computing times.

The convergence of the PS algorithm is shown in Figure 15. As before, the search continues beyond the 70 iterations (when the optimal solution has been reached) to improve the confidence in the result. A total of 122 iterations have been performed.

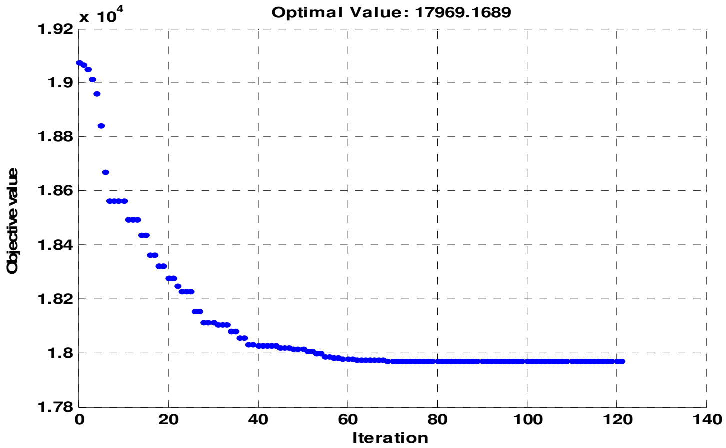

Figure 15: Convergence of PS (Case 3-III)

The dynamics of the mesh size is depicted by Figure 16. As before, the initial polling is successful leading to mesh size increases, whereas subsequently the mesh size is being reduced (with the exception of iterations 11 and 23) indicating unsuccessful polls. As for Case 3-I, the termination criteria for the mesh size has not been reached.

Although the PS has achieved the ‘best’ optimum only on three occasions out of 50 runs (see Figure 17), the overall minimum and mean costs are still better than those obtained by other methods. The total execution time for 50 runs is 294.06 s, which is comparable to just one run using the other techniques.

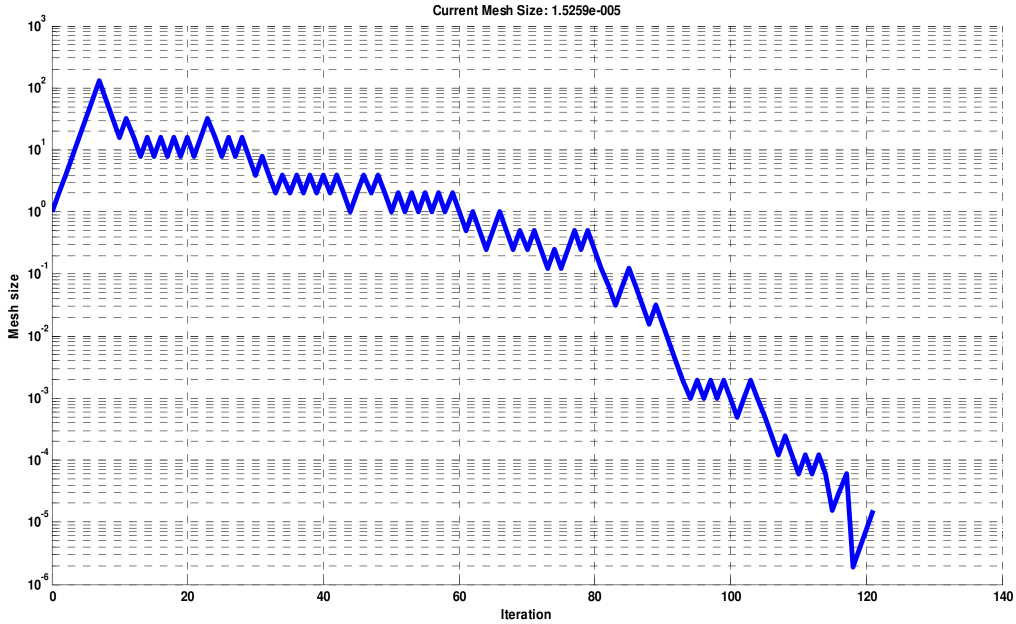

Figure 16: Mesh Size-log scale (Case 3-III)

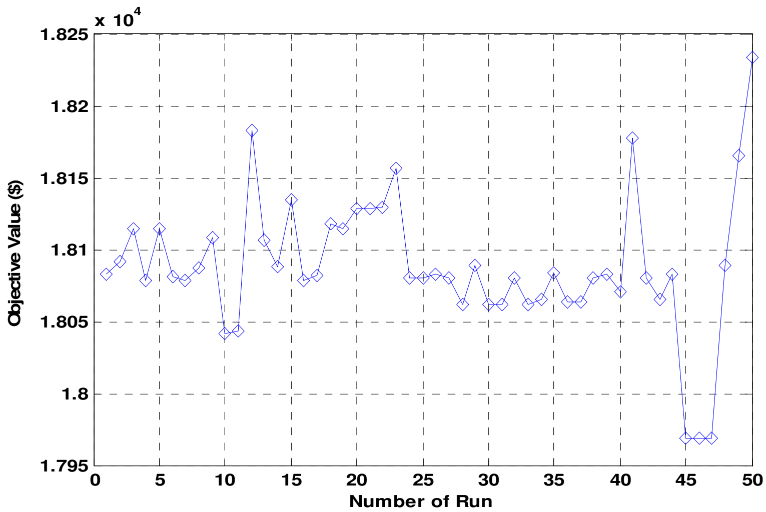

Figure 17: Objective Function Value for 50 different Starting Point (Case 3-III)

3.3 Case 3-IV: Forty Generating Units

This test case consists of 40 generating units with quadratic cost function combined with the effects of valve-point loading, with full data given in [74, 77].

The Pattern Search algorithm has been executed for a hundred times with different starting points and results and comparisons with other methods are given in Tables 6 and 7, respectively.

Table 6: Generator loading and fuel cost determined by PS with total load demand of 10500 MW

Generator	Generator Production (MW)	Generator	Generator Production (MW)
P_{g1}	110.81	P_{g21}	523.28
P_{g2}	110.81	P_{g22}	523.28
P_{g3}	97.402	P_{g23}	523.28
P_{g4}	179.73	P_{g24}	523.28
P_{g5}	92.707	P_{g25}	523.28
P_{g6}	140.00	P_{g26}	523.28
P_{g7}	259.60	P_{g27}	10.000
P_{g8}	284.60	P_{g28}	10.000
P_{g9}	284.60	P_{g29}	10.000
P_{g10}	130.00	P_{g30}	87.800
P_{g11}	168.80	P_{g31}	189.99
P_{g12}	168.80	P_{g32}	189.99
P_{g13}	214.76	P_{g33}	189.99
P_{g14}	304.52	P_{g34}	164.80
P_{g15}	394.28	P_{g35}	164.80
P_{g16}	394.28	P_{g36}	164.80
P_{g17}	489.28	P_{g37}	109.99
P_{g18}	489.28	P_{g38}	109.99
P_{g19}	511.28	P_{g39}	109.99
P_{g20}	511.28	P_{g40}	511.28
Total cost:	121415 \$/h	ΣP_{gi} =	10500 MW

Table 7: Comparison of PS and EP

Evolution Method	Mean time (s)	Best time (s)	Mean cost (\$/h)	Maximum cost (\$/h)	Minimum cost (\$/h)
CEP	1956.9	1955.2	124793	126902	123488
FEP	1039.1	1037.9	124119	127245	122679
MFEP	2196.1	2194.7	123489	124356	122647
IFEP	1167.4	1165.7	123382	125740	122624
PS	42.98	12.66	122332	125486	121415

Figures 18 to 20 show the convergence of the objective function, changes to mesh size and quality of the optimum depending on the starting point. The tendencies and the properties of the algorithm are similar to those observed when studying Case 3-II. Overall, the PS method provides the best minimum and mean costs of all the methods compared at significant savings of computational effort. These short computing times allow for more cases to be studied with the aim of increasing the confidence in the final solution.

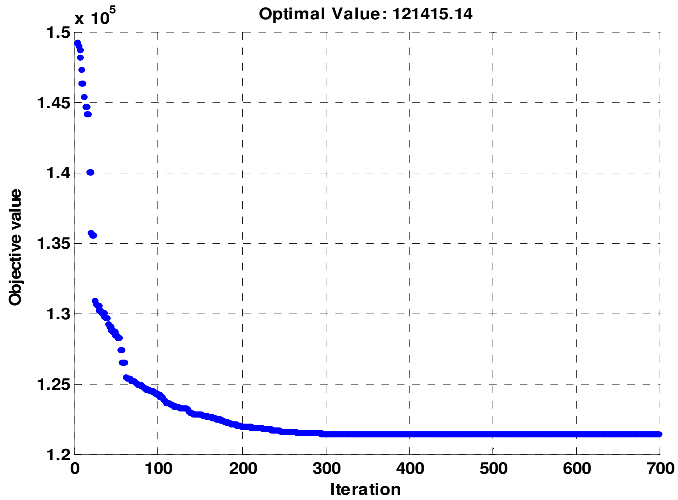

Figure 18: Convergence of PS (Case 3-IV)

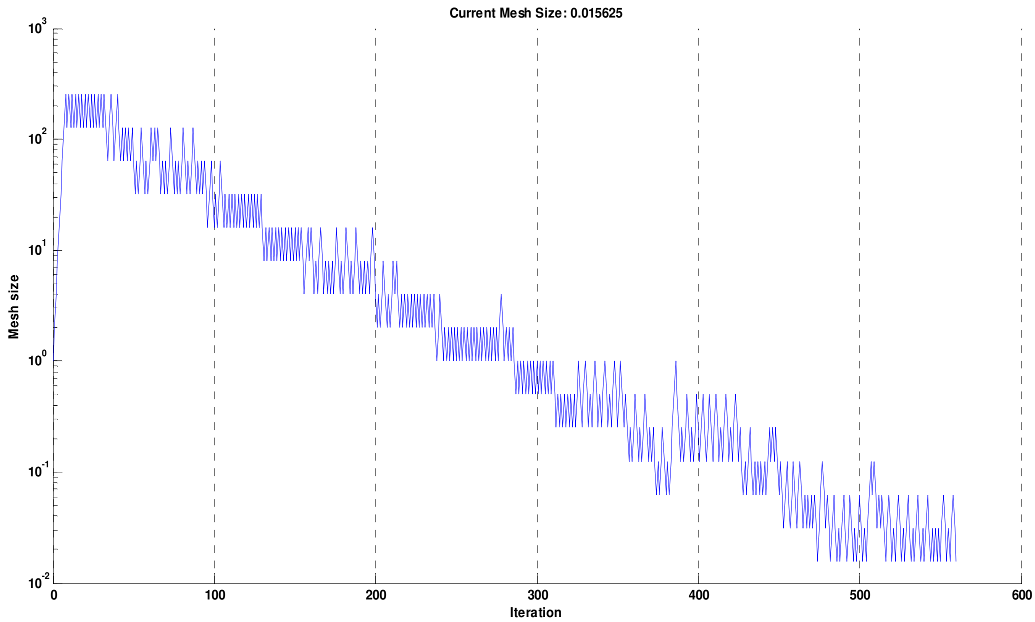

Figure 19: Mesh Size-log scale (Case 3-IV)

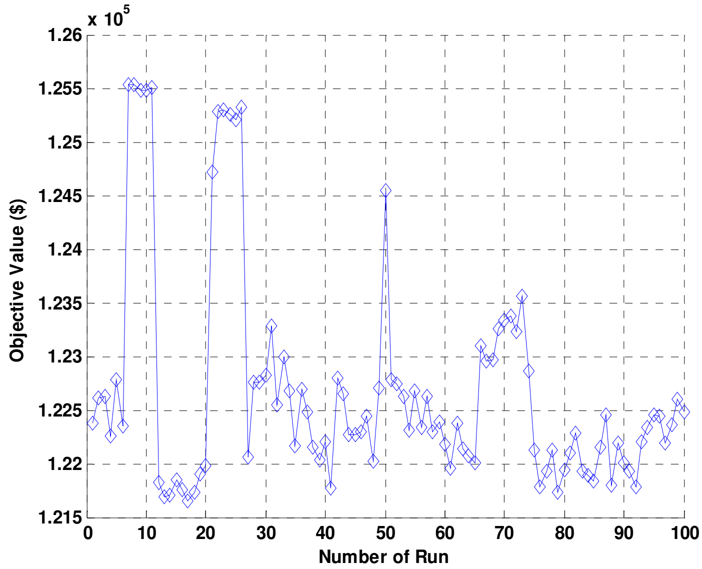

Figure 20: Objective Function Value for 100 different Starting Point (Case 3-IV)

3.4 Combined ED with Emission (CEED)

Due to global concern regarding the environment, the addition of the emission index as a second objective function in ED formulation has become essential and widely implemented in the literature. The economic and emission dispatch (CEED) subsection is divided into two cases; Case 3-V solves CEED without the inclusion of the transmission losses, while Case 3-VI considers the transmission losses in the CEED formulation.

3.4.1 Case 3-V: (CEED without losses)

Case 3-V consists of six generators described in [75] and combines the normal ED with the Emission index to form a multi objective minimization problem. The two problems can be treated separately as a minimization of the operating cost and as an emission reduction. The results of PS are compared with those obtained in [75] regarding the operating cost and the emission index and they are listed in Tables 8 and 9, respectively. It can be seen that PS has come up with a better operating cost than the Linear Programming (LP) and the Hybrid Stochastic Search (HSS) methods. However, the PS result in the emission index is less than LP, but it did not reach the HSS result. The increase in the emission index is a result of the reduction of the operating cost, and that is acceptable if we look at the problem from an economic point of view. The total operating demands for the operating cost and the emission index are both set to 2860 MW.

Table 8: Comparison of LP, HSS and PS in Operating Cost

Generator	LP	HSS	PS
P_{g1} (GW)	0.15	0.1137	0.1124
P_{g2} (GW)	0.30	0.3023	0.3020
P_{g3} (GW)	0.55	0.5297	0.5311
P_{g4} (GW)	1.05	1.0194	1.0207
P_{g5} (GW)	0.46	0.5328	0.5311
P_{g6} (GW)	0.35	0.3621	0.3624
Operating Cost ($/h)	606.31	605.89	605.87

Table 9: Comparison of LP, HSS and PS in Emission Index

Generator	LP	HSS	PS
P_{g1} (GW)	0.40	0.4095	0.4095
P_{g2} (GW)	0.45	0.4626	0.4625
P_{g3} (GW)	0.55	0.5426	0.5428
P_{g4} (GW)	0.40	0.3884	0.3885
P_{g5} (GW)	0.55	0.5427	0.5428
P_{g6} (GW)	0.50	0.5142	0.5141
Emission index	0.1942	0.1939	0.1942

The operating cost and the emission cost functions were coded in a single Matlab program, but the algorithm was designed in such a way that the costs were treated separately. The minimizations of the operation cost and of the emission costs were executed simultaneously, and then the final results of both operations were added to get the final solution. It took 100 iterations and 53.31 seconds for the PS to reach the optimal solution for both problems. The optimal solution convergence and the mesh size reduction are shown in Figures 21 and 22, respectively.

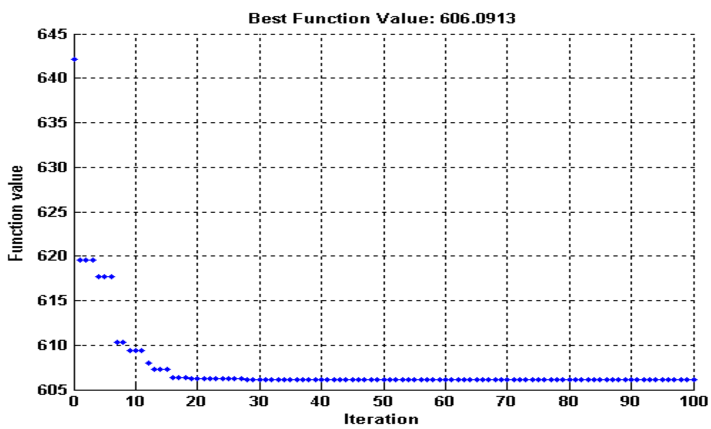

Figure 21: Convergence of PS (Case 3-V)

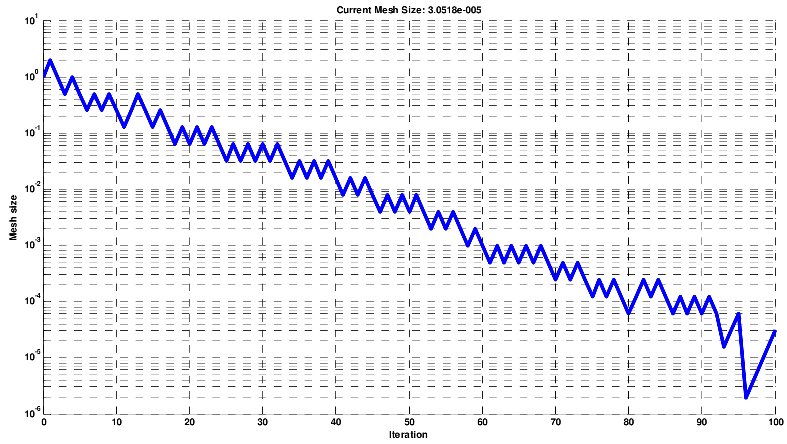

Figure 22: Mesh Size-log scale (Case 3-V)

In addition, the PS tool box in Matlab has a function that can plot the best solution points for all iterations, and the user can see these solutions and how they change as the search of the optimal solution advances. Finally, PS saves the best points for the optimal solution for both the operating cost and the emission index problems and plots it. This feature is illustrated in Figures 23 and 24, respectively.

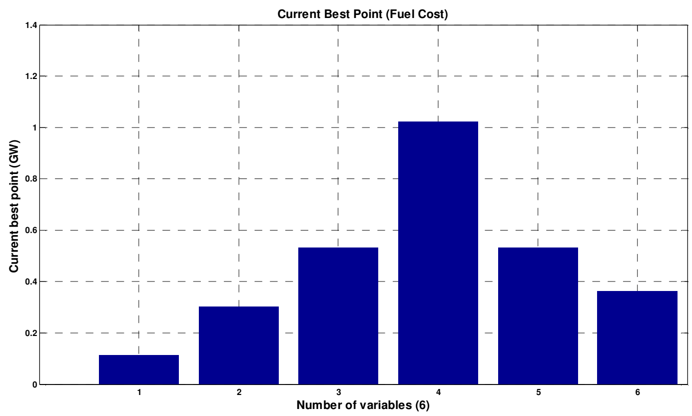

Figure 23: Best Point for Fuel Cost (Case 3-V)

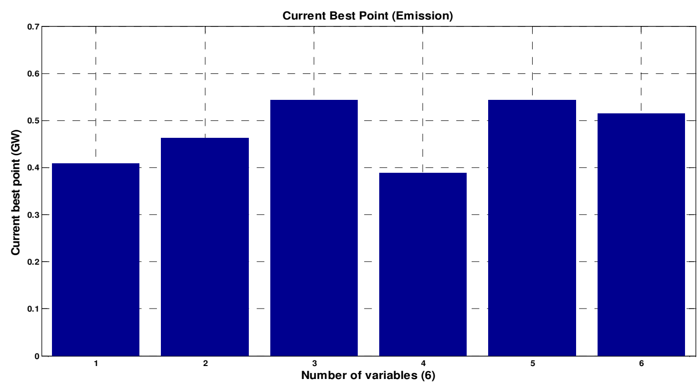

Figure 24: Best Point for Emission (Case 3-V)

3.4.2 Case 3-VI: ED with Emission (with losses)

In this combined environmental economic dispatch case, a six-generator system is considered. Information about the generators' fuel cost, NO_x emission functions, the *B* matrix, loss coefficients, and the operating limits are detailed in [78]. The total load demand is set to 700 MW, and the weighting factor (trade off between the two objective functions) is 0.5.

The PS results for the line losses, emission, fuel cost, total cost, and computation time are presented and compared with results of other heuristic methods (Genetic Algorithms & Evolutionary Programming from [79, 80]) in Table 10. It can be seen that the PS has reached the best total and fuel costs, and also has produced the best time of computation compared with the other methods. In addition, PS had the third best results in line losses and emissions. The convergence of the PS needs only 40 iterations and 2.05 seconds to reach the optimal solution, which are significantly less than EP and GA.

Table 10: Comparison of PS and other heuristic methods

Generator	Optimization Techniques				
	IFEP	FEP	CEP	FCGA	PS
P_{g1} (MW)	77.142	77.358	77.274	80.160	77.432
P_{g2} (MW)	49.925	49.669	49.639	53.710	48.894
P_{g3} (MW)	48.764	48.316	48.535	40.930	48.516
P_{g4} (MW)	103.49	104.37	103.53	116.23	104.57
P_{g5} (MW)	259.81	260.66	260.70	251.20	260.86
P_{g6} (MW)	191.83	190.47	191.23	190.62	190.67
Line losses (MW)	30.949	30.849	30.901	32.850	30.945
Emission (kg/h)	530.52	532.50	524.49	527.46	528.33
Fuel cost ($/h)	38214	38214	38216	38408	38208
Total cost ($/h)	19369	19369	19369	19468	19368
Computation time (s)	3.874	1.598	4.48	-	2.05
No. of iteration	57	65	77	-	40

3.5 Case 3-VII: Multi Areas Economic Dispatch (MAED)

The multi area ED problem considered consists of four areas with tie lines connecting these areas. Each area contains four generation units. Note that quadratic cost functions are used to model the cost of generation $F(P_{gi})$, but the tie lines transmission costs, $G(t_{jk})$, are assumed to be linear functions of the power transfer. The generators' data and the tie lines coefficients along with their limits are all given in reference [56].

Different heuristic methods such as PSO and EP have been applied to the same problem and results reported in [79, 80]. The results using the PS and the other methods are shown in Tables 11 and 12. The optimal solution obtained by PS is obviously better than those obtained by various EP algorithms and slightly less than the result obtained by NFP (Network Flow Programming [56]), which is not heuristic in nature. In addition, the computation time of PS is less than execution times of the variants of EP.

Table 11: Comparison of PS and other heuristic methods (16 generators)

Generator		Optimization techniques				
		IFEP	FEP	CEP	NFP	PS
Area 1 Demand 400 MW	P_{g1} (MW)	149.99	149.99	150.00	150.00	150.00
	P_{g2} (MW)	99.986	99.968	100.00	100.00	100.00
	P_{g3} (MW)	68.270	67.017	68.826	66.970	66.971
	P_{g4} (MW)	99.940	99.774	99.985	100.00	100.00
Area 2 Demand 200 MW	P_{g5} (MW)	56.349	57.181	56.373	56.970	56.972
	P_{g6} (MW)	96.753	95.554	93.519	96.250	96.252
	P_{g7} (MW)	41.264	41.736	42.546	41.870	41.872
	P_{g8} (MW)	72.586	72.748	72.647	72.520	72.522
Area 3 Demand 350 MW	P_{g9} (MW)	50.003	50.030	50.000	50.000	50.002
	P_{g10} (MW)	35.985	36.552	36.399	36.270	36.272
	P_{g11} (MW)	38.012	38.413	38.323	38.490	38.492
	P_{g12} (MW)	37.426	37.001	36.903	37.320	37.322
Area 4 Demand 300 MW	P_{g13} (MW)	149.99	149.99	50.000	150.00	150.00
	P_{g14} (MW)	99.964	99.995	100.00	100.00	100.00
	P_{g15} (MW)	57.601	57.568	56.648	57.050	57.051
	P_{g16} (MW)	95.874	96.482	95.826	96.270	96.271

Table 12: Comparison of PS and other heuristic methods (tie lines)

Area		Tie lines values (MW)				
From	To	IFEP	FEP	CEP	NFP	PS
1	2	00.094	00.062	00.000	00.000	00.000
1	3	18.649	18.241	19.587	18.180	18.181
1	4	00.000	00.000	00.000	00.000	00.000
2	1	00.018	00.000	00.018	00.000	00.000
2	3	69.997	69.790	68.861	69.730	69.730
2	4	00.000	00.000	00.000	00.000	00.000
3	1	00.000	00.000	00.000	00.000	00.000
3	2	00.000	00.000	00.000	00.000	00.000
3	4	00.000	00.000	00.000	00.000	00.000
4	1	00.549	01.548	00.758	01.210	01.210
4	2	02.951	02.509	01.789	02.110	02.111
4	3	99.927	99.974	99.927	100.00	100.00
Total cost ($/h)		7337.51	7337.52	7337.75	7337.00	7336.98
Computation time(s)		23.97	7.47	7.82/11.49	-	5.77
Population size		100	100	100	-	-
No. of iterations		585	645	758/920	-	1225

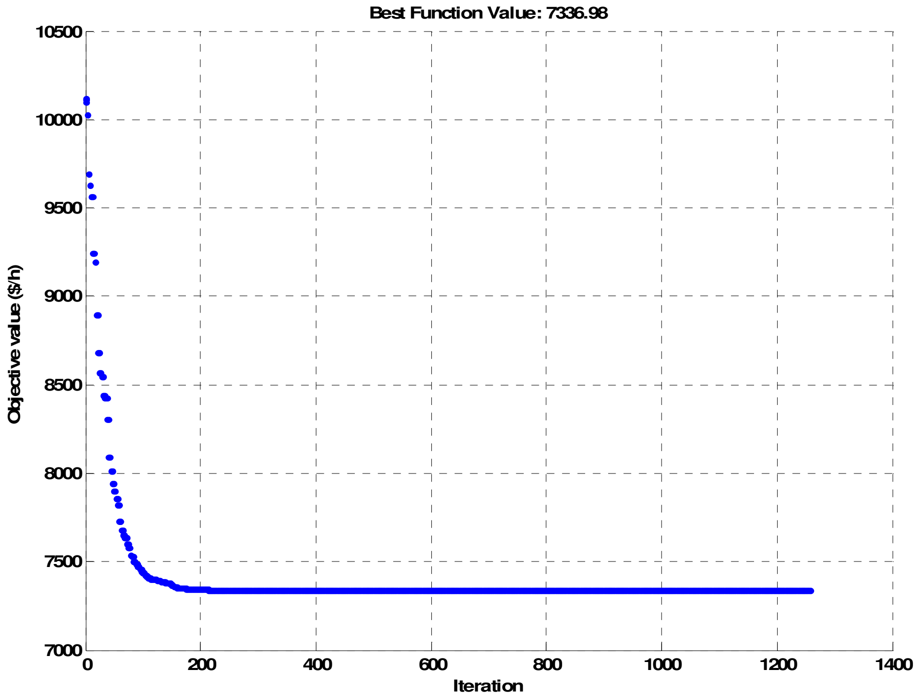

Figure 25: Convergence of PS for MAED (Case 3-VII)

As illustrated in Figure 25, PS has located the optimal solution after only 200 iterations, but it continues the computation and refining the result. Figure 26 shows the mesh size expansion and contraction behaviour during the PS search for the global minimum.

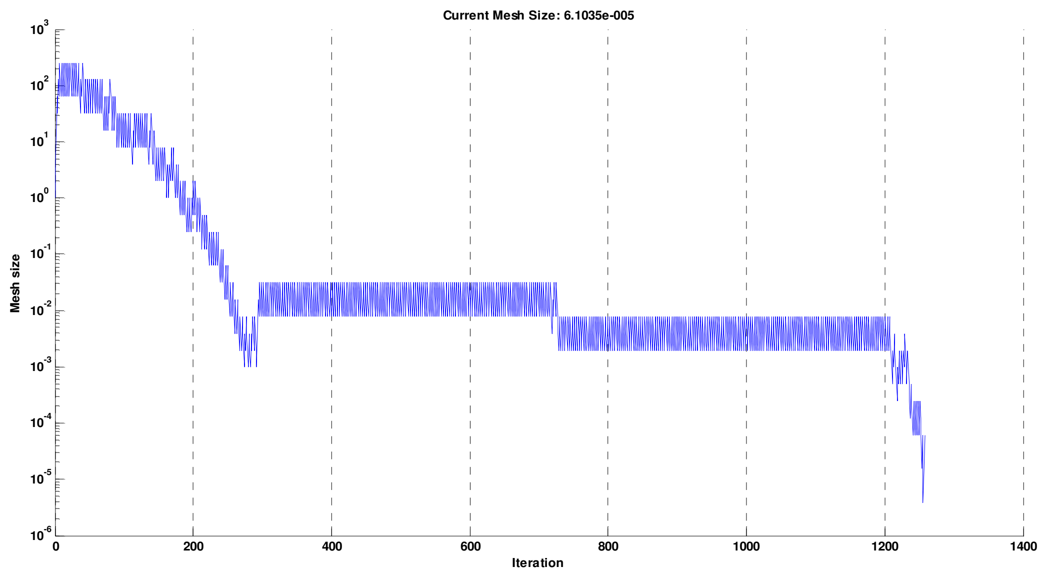

Figure 26: Mesh size-log scale (Case 3-VII)

3.6 Case 3-VIII: Cubic Cost Function Economic Dispatch (CCFED)

According to [59], it is an industry practice to adopt a cubic polynomial for modelling fuel costs of generation units. This is particularly important in situations with generation units having non-monotonically increasing incremental curves [61]. In this case, a three-generator system is considered with third order cost functions. Information about the generators' fuel cost coefficients, the *B* matrix, loss coefficients and the operating limits are detailed in [60].

The optimal solution of PS is given in Table 13 along with the results obtained by conventional Dynamic Programming (DP) from [60] for comparison purposes. Clearly, the PS has converged to a better solution, while the execution time is less than one second. Also, the reduction in line loses has reached 7.17%, which can be considered as significant improvement.

Table 13: Comparison of PS and DP with total demand 1400 MW

Generator	Optimization Technique	
	DP	PS
P_{g1} (MW)	360.2	372.3
P_{g2} (MW)	406.4	356.0
P_{g3} (MW)	676.8	712.0
Line losses (MW)	43.40	40.29
Fuel cost ($/h)	6642	6639
Computation time (s)	-	0.619
No. of iterations	5	6

3.7 Investigation regarding the required number of runs

It will have been noticed by the reader that in most cases the PS algorithm was executed 100 times. The purpose of running an algorithm many times – routinely done by most researchers as reported in the literature – is to prevent the entrapment of the optimizer in local minima. Thus a common approach is to run the algorithm for 100 times and then report the maximum, mean and minimum results. However, an interesting question arises: do we really need 100 runs to reach a satisfactory result and what is the actual typical number of executions to achieve sufficient level of confidence? These questions prompted a small investigation as reported below.

The methodology adopted involved executing PS for a different number of runs until it reaches its final solution; the selected numbers of runs were 10, 15, 20, 40, 70 and 100.

All results were saved and examined. Comparison tables between minimum, maximum, mean fuel costs, and total computational times for each case were generated. In addition, illustrative graphs were drawn for every case to facilitate comparisons.

3.7.1 Three generators without losses

In this case, the optimal solution was obtained after only 20 runs, which lead to computational time savings of 81% (in comparison with the 'standard' case of 100 runs). Table 14 presents detailed results for this case. The fuel cost and computational time for all different number of runs considered are illustrated in Figures 27 and 28.

Table 14: Cost and time as functions of the number of runs (3 generators without losses)

Case	Runs	10	15	20	40	70	100
3 Gen without losses	Min Cost ($/h)	8241.2	8241.2	8234.1	8234.1	8234.1	8234.1
	Max Cost ($/h)	8453.0	8453.0	8453.0	8453.0	84530	8712.1
	Mean Cost ($/h)	8335.5	8338.2	8344.9	8359.7	83613	8370.2
	Total Time (s)	3.37	4.25	4.94	9.06	13.78	22.14

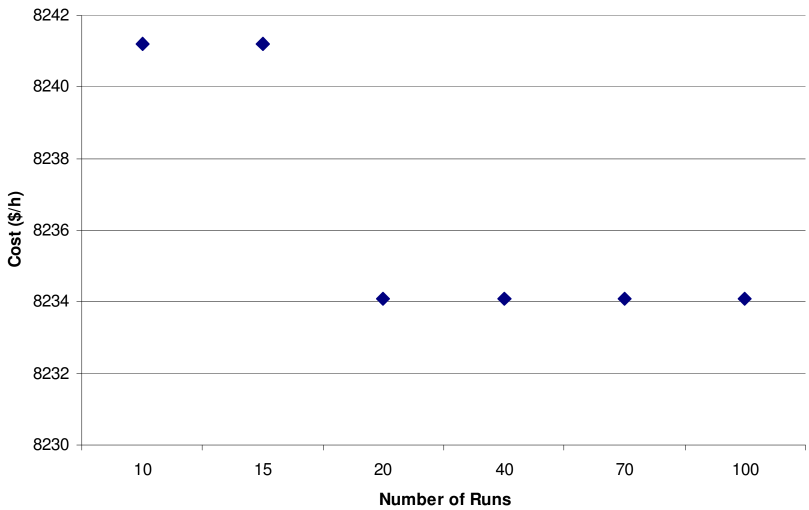

Figure 27: Number of runs to find the minimum cost (3 generators without losses)

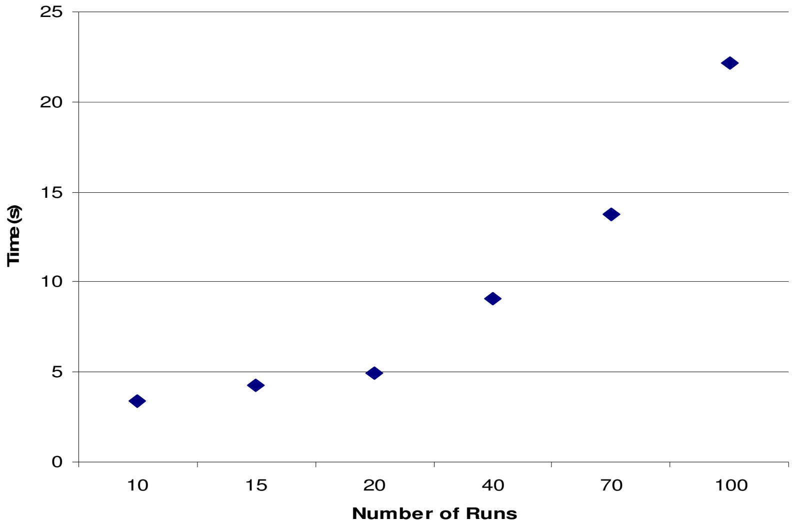

Figure 28: Total time needed to execute a given number of runs (3 Generators without losses)

3.7.2 Three generators with losses

The number of runs needed to produce a reliable global or near global solution was 40 runs in this case and the savings in computational time was 24.2% of the total time. Table 15 and Figures 29 and 30 present the detailed outcome.

Table 15: Cost and time as functions of the number of runs (3 generators with losses)

Case \ Runs		10	15	20	40	70	100
3 Gen with losses	Min Cost ($/h)	3164.9	3160.9	3161.0	3160.8	3160.9	3160.8
	Max Cost ($/h)	3240.8	3240.3	3240.3	3240.9	3240.8	3240.6
	Mean Cost ($/h)	3202.7	3213.8	3214.7	3219.8	3219.6	3213.2
	Time (s)	35.22	26.33	42.77	113.67	96.56	150.02

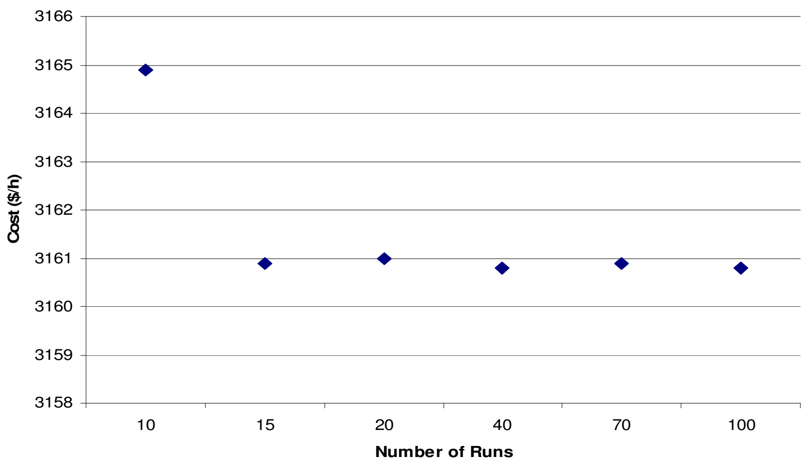

Figure 29: Number of runs to find the minimum cost (3 generators with losses)

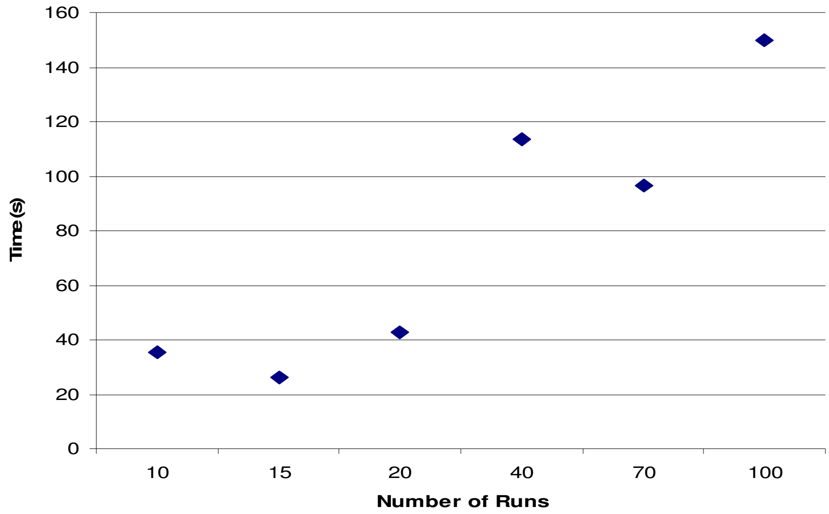

Figure 30: Total time needed to execute a given number of runs (3 generators with losses)

3.7.3 Thirteen generators without losses

Only 40 runs were needed, instead of 100, to reach the exact final solution, thus the saving in time exceeded 67%. The detailed findings of this case can be found in Table 16 and Figures 31 and 32.

Table 16: Cost and time as functions of the number of runs (13 generators without losses)

Case	Runs	10	15	20	40	70	100
13 Gen without losses	Min Cost ($/h)	18047	18063	18046	17969	17969	17969
	Max Cost ($/h)	18351	18416	18391	19535	18416	19533
	Mean Cost ($/h)	18175	18217	18167	18236	18172	18188
	Time (s)	22	37.36	47.27	77.09	144.77	234.45

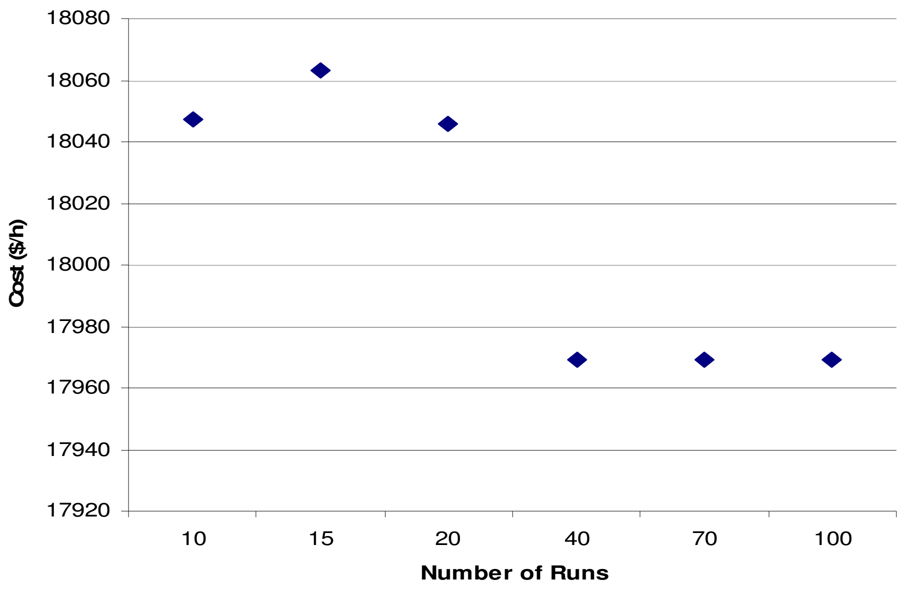

Figure 31: Number of runs to find the minimum cost (13 generator without losses)

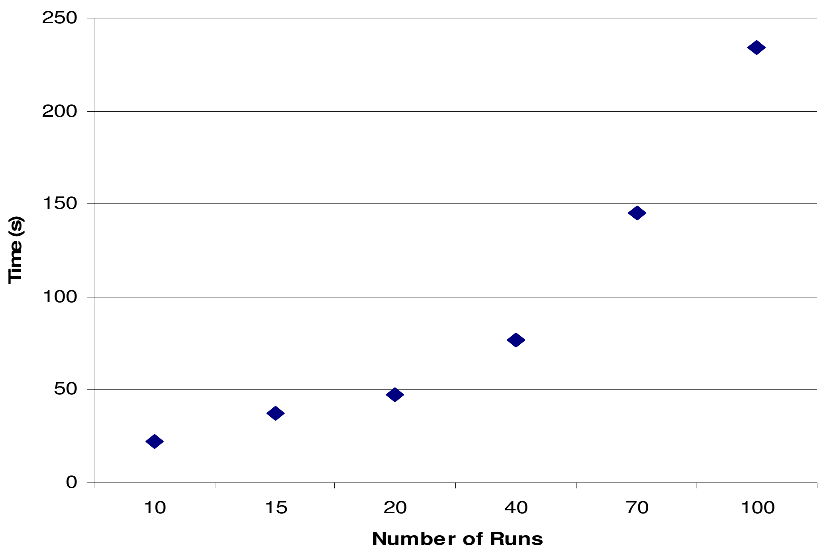

Figure 32: Total time needed to execute a given number of runs (13 generators without losses)

3.7.4 Forty generators without losses

In this case, the PS needed only 20 runs to produce a quality solution (with only 1 $/h more than the optimal solution produced by the 100 runs) and the savings in computational time have exceeded 80%. Table 17 lists all the results and Figures 33 and 34 illustrate the findings.

Table 17: Cost and time as functions of the number of runs (40 generators without losses)

Case	Runs	10	15	20	40	70	100
40 Gen without losses	Min Cost ($/h)	121475	121521	121469	121469	121469	121468
	Max Cost ($/h)	125484	122913	122635	125491	125486	125491
	Mean Cost ($/h)	122293	122170	121750	122530	122455	122224
	Time (s)	111.92	244.7	265.39	501.17	936.64	1344.25

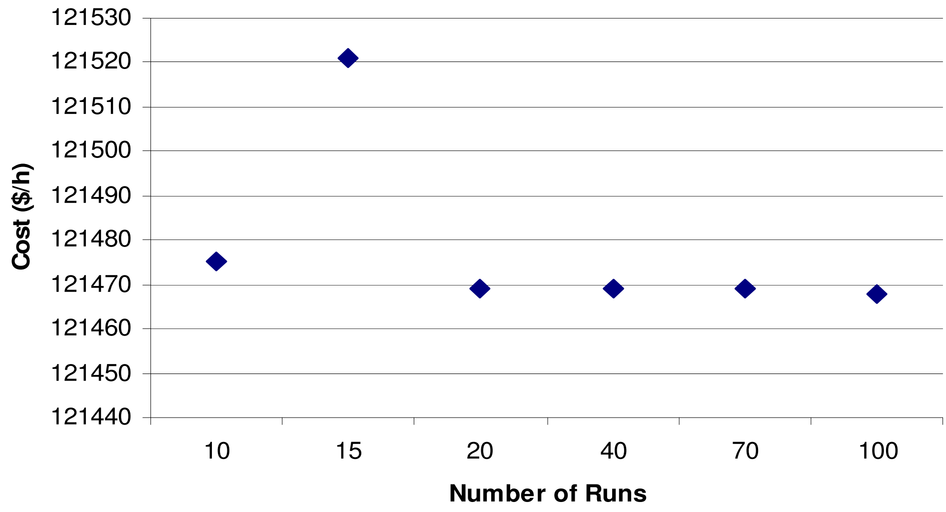

Figure 33: Number of runs to find the minimum cost (40 generators without losses)

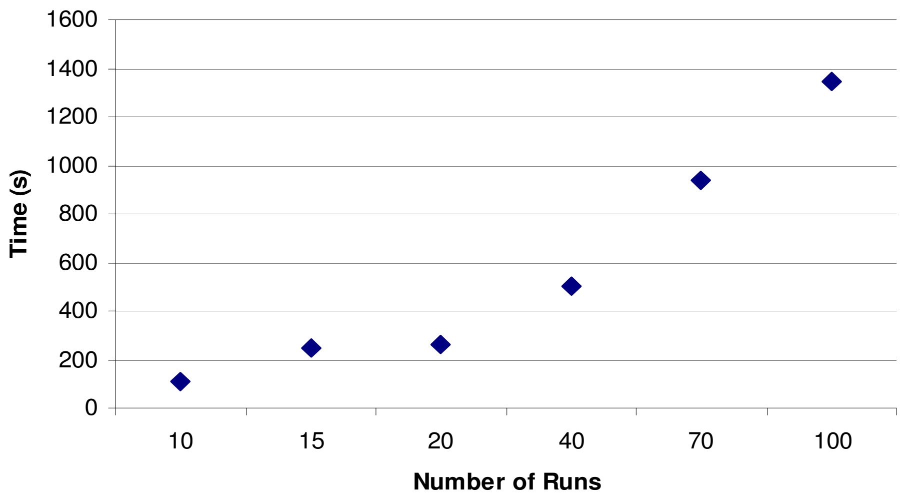

Figure 34: Total time needed to execute a given number of runs (40 generators without losses)

3.7.5 ED & EM with losses

In this case only 40 runs were needed to achieve an optimal solution and 38.6% of computational time was saved (see Table 18 and Figures 35 and 36 for more details).

Table 18: Cost and time as functions of the number of runs (ED & EM with losses)

Case	Runs	10	15	20	40	70	100
ED & EM with losses	Min Cost ($/h)	19514	19543	19757	19382	19423	19449
	Max Cost ($/h)	22767	22171	22595	23588	23332	23636
	Mean Cost ($/h)	20637	20655	2.0805	20963	20678	20863
	Time (s)	39.17	45.66	65.30	174.61	302.87	462.02

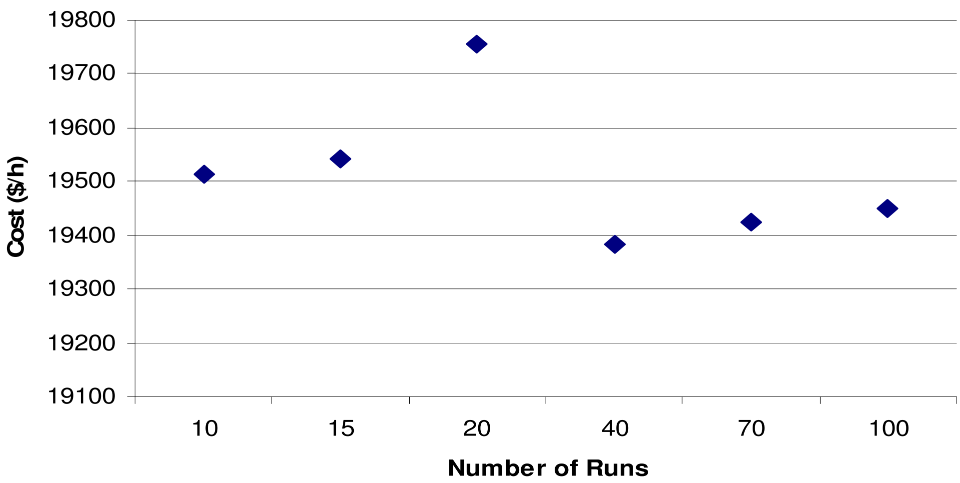

Figure 35: Number of runs to find the minimum cost (ED&EM with losses)

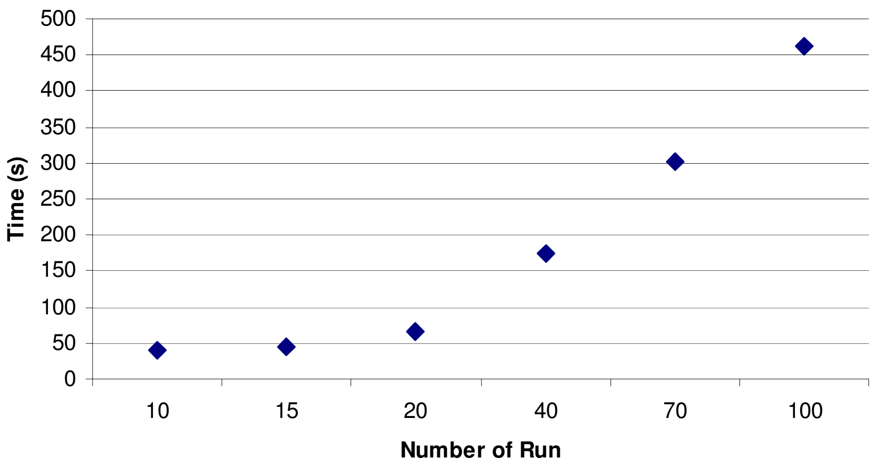

Figure 36: Total time needed to execute a given number of runs (ED&EM with losses)

3.7.6 MAED

In the MEAD case, all trial runs may be considered as possible optimal solutions since they lie within a range of 3.8 $/h (about 0.05% off the optimal solution). The results of the MAED case are listed in Table 19 and drawn as Figures 37 and 38.

Table 19: Cost and time as functions of the number of runs (MAED)

Case \ Runs		10	15	20	40	70	100
MAED	Min Cost ($/h)	7342.9	7339.6	7341.0	7340.0	7339.1	7340.1
	Max Cost ($/h)	7409.8	7404.7	7404.7	7448.1	7448.1	7437.5
	Mean Cost ($/h)	7377.1	7376.2	7372.9	7374.1	7373.0	7373.5
	Time (s)	268.8	382.4	404.5	822.2	1676.2	2347.9

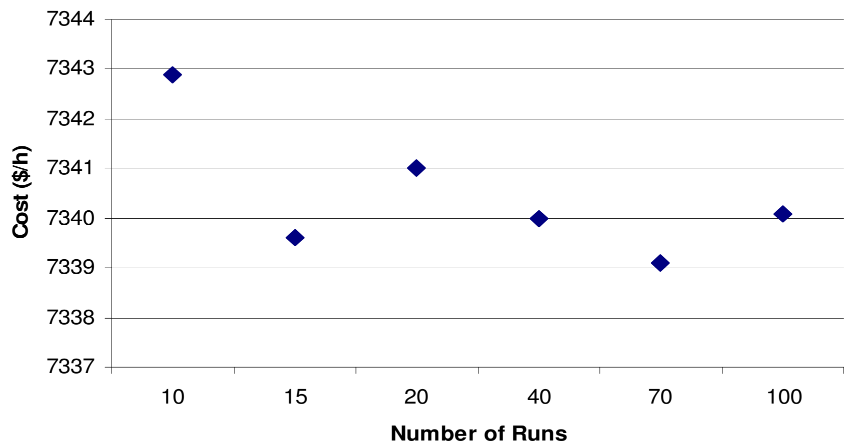

Figure 37: Number of runs to find the minimum cost (MEAD)

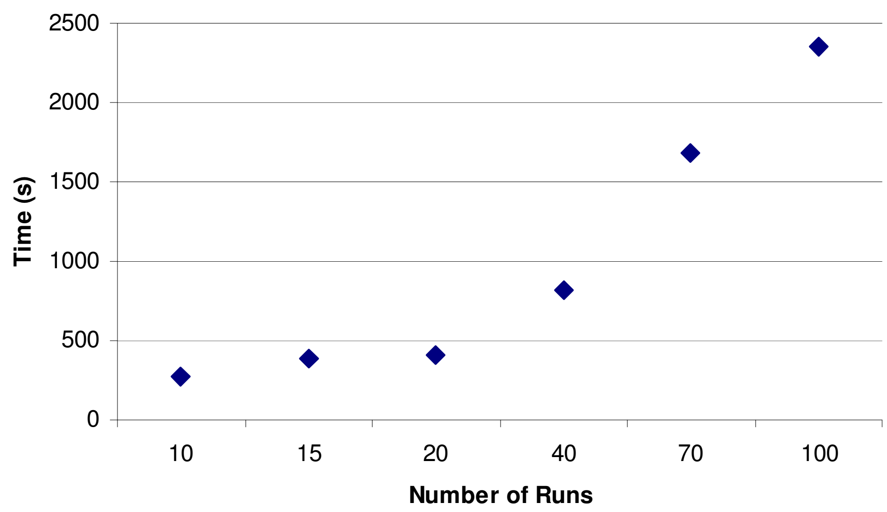

Figure 38: Total time needed to execute a given number of runs (MEAD)

3.7.7 Remarks

The outcome of this investigation demonstrates that the PS algorithm does not really need to be executed 100 times in order to produce quality solutions; the number of required runs, however, is problem dependent. In the cases studied the highest number of executions needed was 40, but in some cases was only 20, suggesting that the commonly used number of 100 is too conservative leading to excessive computational times.

3.8 Conclusion

In this chapter, the PS was used to solve different cases of the ED problem. The cases varied from a simple three generators system to much complex problems such as the forty generators and the multi area economic dispatch systems. Moreover, the valve-point effect and the emission were also considered in some cases of the ED model. The results obtained through our approach were compared with the methods reported in the literature. PS outperformed all of the other methods (except FEP) in terms of the computational time, while improving or matching the fuel cost. PS has reduced the computational time of solving the ED problem substantially by saving up to 90% of the execution time in some cases. This feature, low computational cost, of PS was the main reason for choosing the method for the final real life case of WDPS in Kuwait. In addition, a study of the number of runs needed for PS to reach the optimal or near optimal solution was conducted in this chapter. The outcome of this study showed that PS needs 20 to 40 runs, instead of 100 as reported in the literature, to produce its optimum solution. Finally, the extensive examination of PS in this chapter had increased the confidence in the algorithm and the usage of PS as the primary solver for the final model was decided with a great trust in its capability.

4 Solving Economic dispatch problem using Hybrid Methods

Due to the observed sensitivity of the PS to the initial guess, a new hybrid method was developed in this project to overcome this drawback. The need for an initial guess for the starting point was eliminated by the introduction of the Genetic Algorithm (GA) method, which operates on a population of initial points generated automatically by the algorithm. Moreover, the algorithm has become more automated and it does not need the user to supply the initial point to start searching for the solution. This feature has led to the reduction of the time of finding suitable starting point for PS.

The main objective of this chapter is to introduce a hybrid method that combines the Genetic Algorithm (GA), Pattern Search (PS) and Sequential Quadratic Programming (SQP) – referred to as the hybrid GA-PS-SQP method – in the context of power system economic load dispatch problem with a valve-point effect. The algorithm was constructed to operate as follows: first, the GA algorithm is used to solve the initial stage of the process and produce a starting point, then the hybrid PS-QP is employed as a fine tuner combination to produce the final solution. For simplicity, transmission losses are ignored in several test cases (P_L in Equation 3 is set to zero), but included in some. The non-linear minimization problem formulation of all test cases has been solved using the predefined functions *ga*, *patternsearch* and *fmincon* incorporated into the GA & DS toolbox of Matlab [73].

4.1 Three Generating Units

In this section, PS has been implemented to study two different cases of three generating units. First, the system losses were neglected, but in the second case the system losses were considered.

4.1.1 Case 4-I: Three Generators system (without losses)

Three generating units have been modelled using a quadratic cost function and with the effects of the valve point loading included. All data (upper and lower bounds for the units and fuel cost coefficients a, b, c, e, and f in the model formulation from sub-section 2.1.1) are taken from [55, 74].

The hybrid GA-PS-SQP algorithm has been executed 100 times to study its performance and effectiveness. The execution times have been compared with other evolutionary methods, such as Genetic Algorithm (GA), Evolutionary Programming (EP) and Particle Swarm Optimization (PSO), presented in [27]. Moreover, previous results from the implementation of the Patter Search (PS) method in ED problems have also been added [81]. This numerical experiment compares the performance of the proposed hybrid algorithm with the other methods in terms of the dispatching cost and the speed of convergence. Table 20 shows the optimal solutions determined by the different methods, whereas the execution times and cost comparison are shown in Table 21.

Table 20: Generator loading and fuel costs with the total load demand of 850 MW

Method	P_{g1} (MW)	P_{g2} (MW)	P_{g3} (MW)	P_D (MW)
GA	398.7	399.6	50.1	848.4
EP	300.3	400.0	149.7	850.0
EP-SQP	300.3	400.0	149.7	850.0
PSO	300.3	400.0	149.7	850.0
PSO-SQP	300.3	400.0	149.7	850.0
PS	300.3	399.9	149.7	850.0
GA-PS-SQP	300.3	400.0	149.7	850.0

Table 21: Comparisons of execution times and costs

Method	Mean time (s)	Best cost ($/h)	Mean cost ($/h)
GA	35.80	8222.1	8234.7
EP	6.78	8234.1	8234.2
EP-SQP	5.12	8234.1	8234.1
PSO	4.37	8234.1	8234.7
PSO-SQP	3.37	8234.1	8234.1
PS	0.81	8234.1	8352.4
GA-PS-SQP	15.67	8234.1	8292.7

All methods (except GA) give an almost identical 'best' solution, whereas 'mean' costs differ slightly. The GA has not met the demand constraint of 850 MW, which explains the difference in the best cost result. The mean execution time for the proposed hybrid method is worse than for the other methods, except for GA, due to three consecutive searches being applied when seeking the best solution. However, the best-cost time was only 3.2 seconds and the smallest recorded time for 100 runs was 3.13 seconds. Figures 39 and 40 compare the results of the methods in terms of the minimum cost and the best execution time, respectively. Further investigations regarding the performance of the propose hybrid method were conducted and the results are described in Section 4.6.

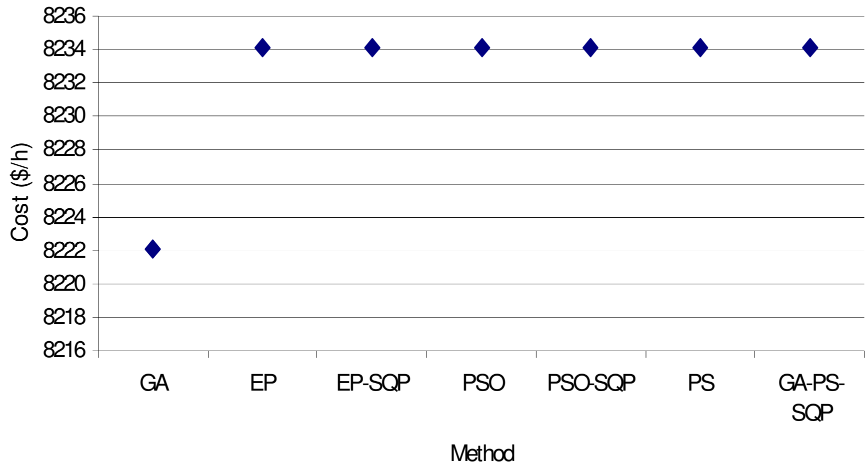

Figure 39: Minimum cost comparison

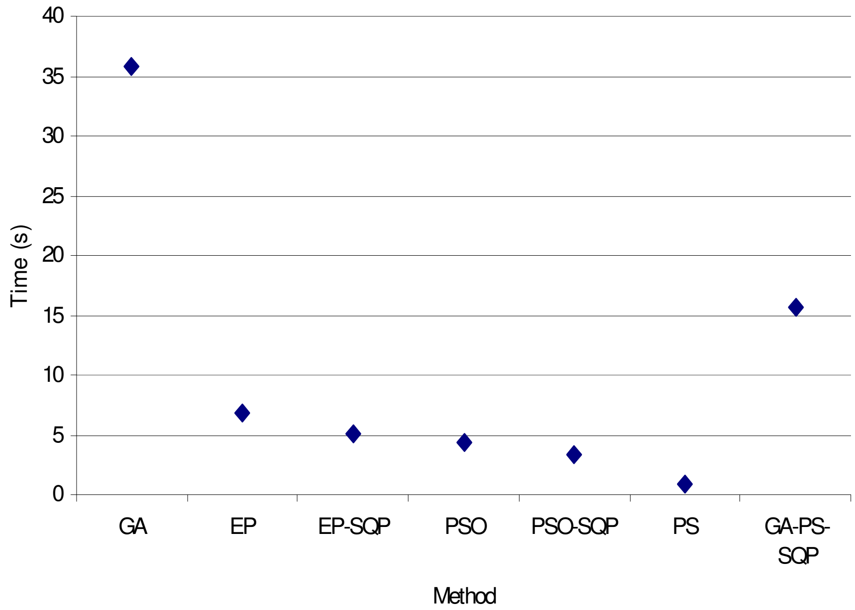

Figure 40: Mean execution time comparison

Figure 41 illustrates the results for one hundred runs using the hybrid algorithm. As can be seen, the optimal solution has been reached on a number of occasions. Furthermore, the results obtained using this algorithm fluctuate between 8460 and 8234, which means that all solutions are within 3% of the best result and thus from the practical point of view they may all be considered as successful. The hybrid search resulted in this quite narrow error band thanks to the application of PS and SQP, which can therefore be considered as sufficient fine tuning mechanisms following the initial GA search. For GA, the population size, migration rate and cross-over rate were set to 100, 0.76 and 0.4, respectively, and the stopping criteria are set to the default parameters found in Matlab's GA toolbox. The parameters of PS were stated previously.

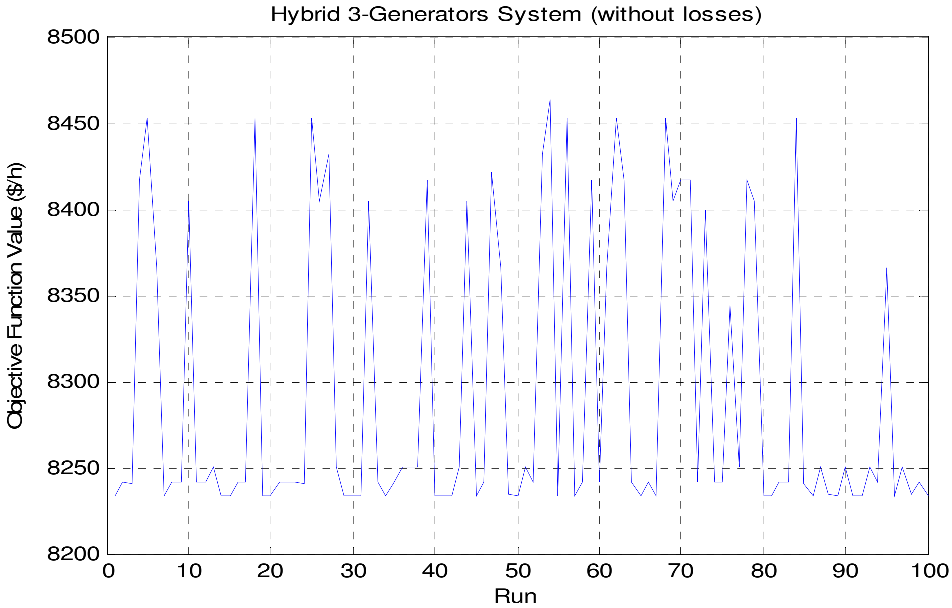

Figure 41: Objective function value for 100 runs (Case 4-I)

4.1.2 Case 4-II: Three Generating Units (with losses)

In this case, we considered a test system containing three generators with transmission losses that was reported in [74]. The results of the optimal generation for each generator and the optimal fuel cost are compared with the result of HSS method presented in [75] and those obtained from the conventional method obtained in [74]. Moreover, the generation losses values were also compared with results presented in the literature.

The results of the proposed hybrid method are listed in Table 22. The GA-PS-SQP algorithm has outperformed the other methods in terms of total production cost and power system losses. Moreover, the algorithm has overcome the previous drawback of the need to supply a good initial point in order to reach its global or near global solution.

Table 22: Total cost and system losses comparison

Generator	Conventional Method	HSS	PS	GA-PS-SQP
P_{g1} (MW)	60.2677	73.66	75.4993	77.2881
P_{g2} (MW)	79.4462	69.98	75.0931	74.6855
P_{g3} (MW)	80.1503	75.18	67.9488	66.4564
Cost ($/h)	3168.623	3164.504	3160.852	3160.774
Losses (MW)	9.865	8.820	8.541	8.429

Figures 42 and 43 illustrate the better performance of the proposed method in terms of the reduction of the total power generation cost and the drop in the system losses.

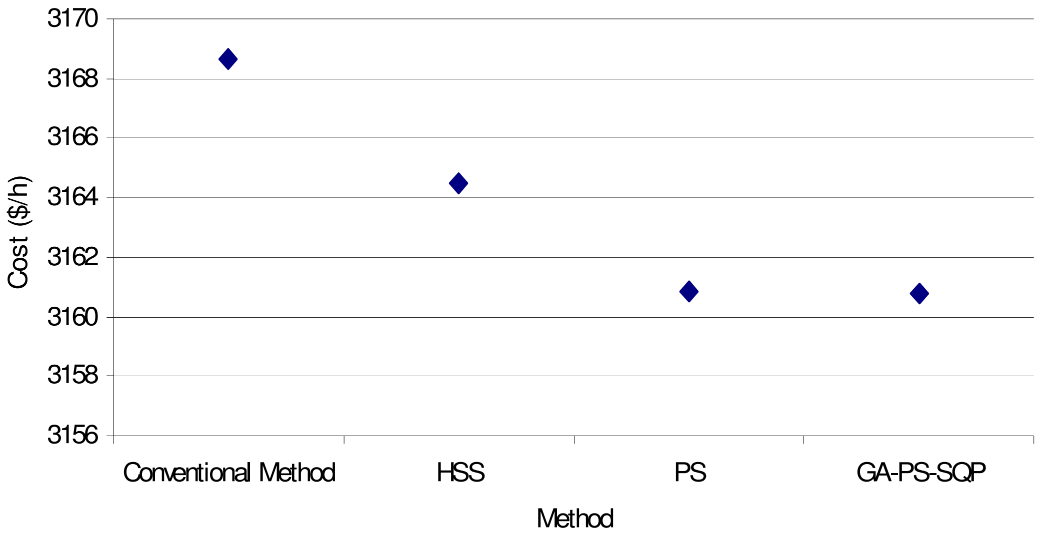

Figure 42: Total cost comparison Case 4-II

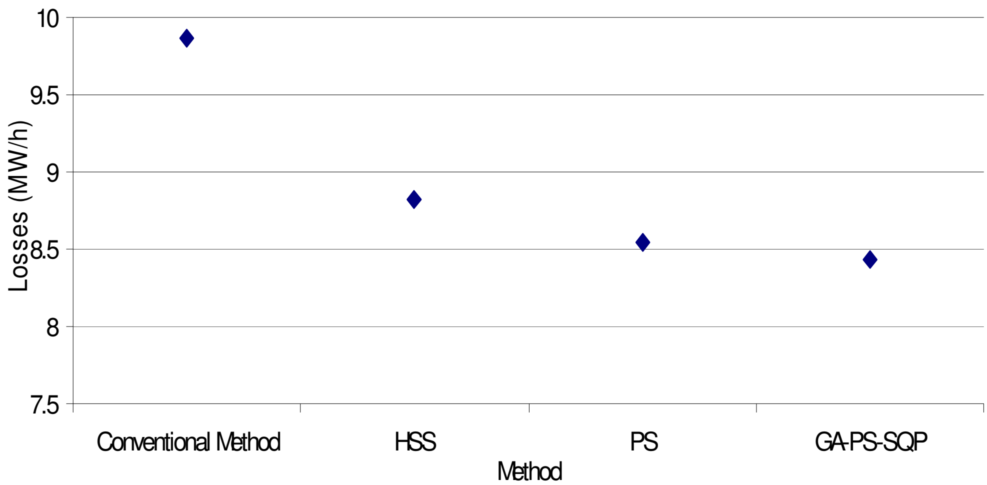

Figure 43: System losses comparison Case 4-II

4.2 Case 4-III: Thirteen Generating Units

In this test there are 13-generating units, while quadratic cost functions combined with the effects of valve point loading have been used as before. All data for the 13 generators may be found in [74, 76] and the load demand is 1800 MW. The GA-PS-SQP algorithm has been executed 100 times. Similar comparisons as for Case 4-I are summarized by Tables 23 and 24 and Figures 44 and 54. The results for the other methods are taken from [27] and [81].

Table 23: Generator loading and fuel cost determined by the GA-PS-SQP hybrid method with total load demand of 1800 MW

Generator	Unit Generation (MW)
P_{g1}	628.31
P_{g2}	148.50
P_{g3}	224.03
P_{g4}	109.75
P_{g5}	109.85
P_{g6}	60.000
P_{g7}	109.86
P_{g8}	109.83
P_{g9}	109.86
P_{g10}	40.000
P_{g11}	40.000
P_{g12}	55.000
P_{g13}	55.000
Total cost: ($/h) =	17964

Table 24: Comparison of GA-PS-QSP with PS, GA and EP

Evolution Method	Mean time (s)	Minimum cost ($/h)	Mean cost ($/h)
EP	157.43	17994	18127
EP-SQP	121.93	17991	18107
PSO	77.37	18031	18206
PSO-SQP	33.97	17970	18030
PS	5.88	17969	18089
GA- PS- SQP	10.55	17964	18227

The GA-PS-QSP hybrid method performance surpasses all other algorithms in terms of achieving the best minimum cost (although differences are quite small), while at the same time offering significant saving in computing times – except for the PS method (see also Figures 44 and 54). It appears that the proposed algorithm performs better as the problem becomes larger and more complex (6 generators and more). The migration and cross-over rates for GA have been changed in this case to 0.64 and 0.3, respectively, whereas the population size is the same as in the previous case. For the record, the best solution time and the minimum time for the 100 runs were 11.06s and 6.77s, respectively.

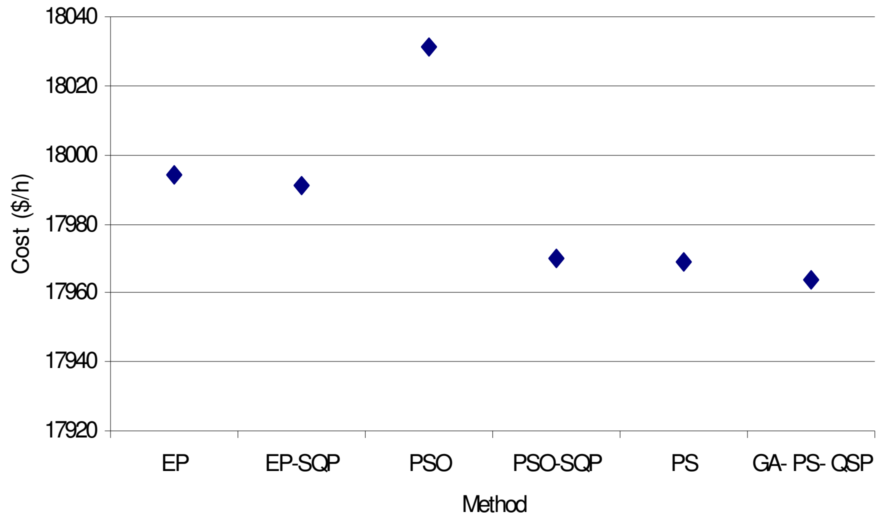

Figure 44: Minimum cost comparison (Case 4-III)

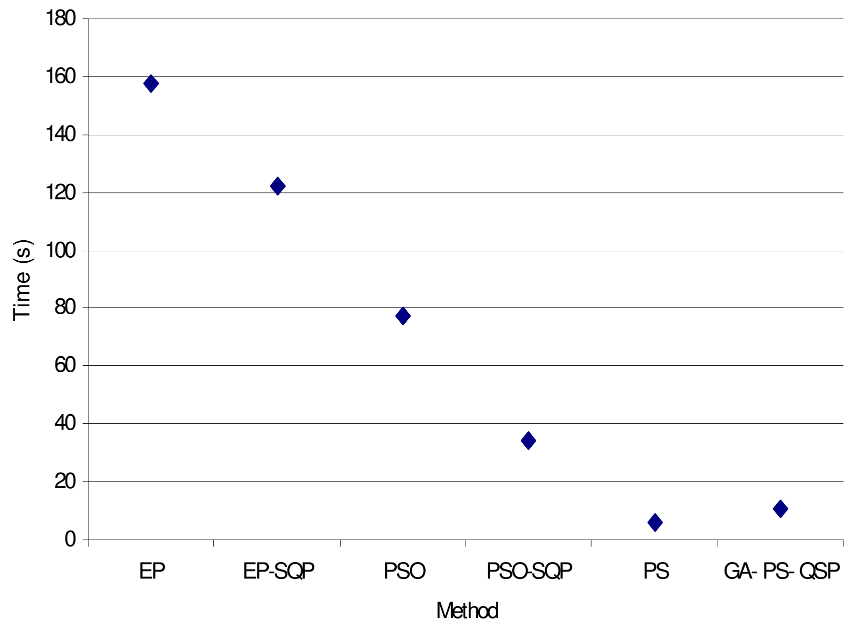

Figure 45: Best execution time comparison (Case 4-III)

The proposed hybrid method has generated very satisfactory solutions, all 100 being within 2.3% of the best result. The maximum cost and the total execution time for the 100 runs were 18392 $/h and 1054.9 s, respectively.

4.3 Case 4-IV: Forty Generating Units

The final test case consists of 40 generating units with full data given in [74, 77]. The GA-PS-SQP algorithm has been executed a hundred times and the results and comparison with other methods are given in Tables 25 and 26, respectively, while Figures 46 and 47 show the comparison of costs and best times for all methods. The load demand is 10500 MW.

Table 25: Generator loadings and fuel costs determined by GA-PS-SQP (Case 4-IV)

Generator	Generator Production (MW)	Generator	Generator Production (MW)	Generator	Generator Production (MW)	Generator	Generator Production (MW)
P_{g1}	110.97	P_{g11}	168.80	P_{g21}	523.28	P_{g31}	190.00
P_{g2}	111.02	P_{g12}	168.80	P_{g22}	523.28	P_{g32}	190.00
P_{g3}	120.00	P_{g13}	214.76	P_{g23}	523.28	P_{g33}	190.00
P_{g4}	179.73	P_{g14}	394.28	P_{g24}	523.28	P_{g34}	164.80
P_{g5}	88.27	P_{g15}	304.52	P_{g25}	523.28	P_{g35}	200.00
P_{g6}	140.00	P_{g16}	304.52	P_{g26}	523.28	P_{g36}	200.00
P_{g7}	259.60	P_{g17}	489.28	P_{g27}	10.000	P_{g37}	110.00
P_{g8}	284.60	P_{g18}	489.28	P_{g28}	10.000	P_{g38}	110.00
P_{g9}	284.60	P_{g19}	511.28	P_{g29}	10.000	P_{g39}	110.00
P_{g10}	130.00	P_{g20}	511.28	P_{g30}	88.660	P_{g40}	511.28
ΣP_{gi} = 10500 MW				Total cost: $121458.14			

Table 26: Comparison of GA-PS-SQP with PS, GA and EP (Case 4-IV)

Method	Mean time (s)	Minimum cost ($/h)	Mean cost ($/h)
EP	1167.35	122624	123382
EP-SQP	997.73	122324	122379
PSO	933.39	123930	124154
PSO-SQP	733.97	122094	122245
PS	42.98	121415	122333
GA-PS-SQP	44.68	121457	121953

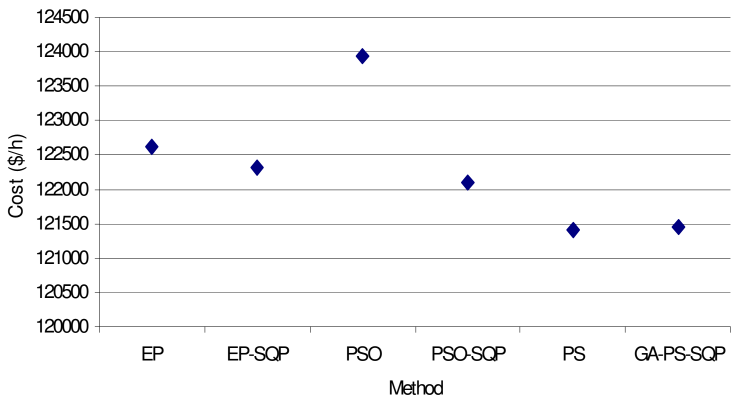

Figure 46: Cost Comparison (Case 4-IV)

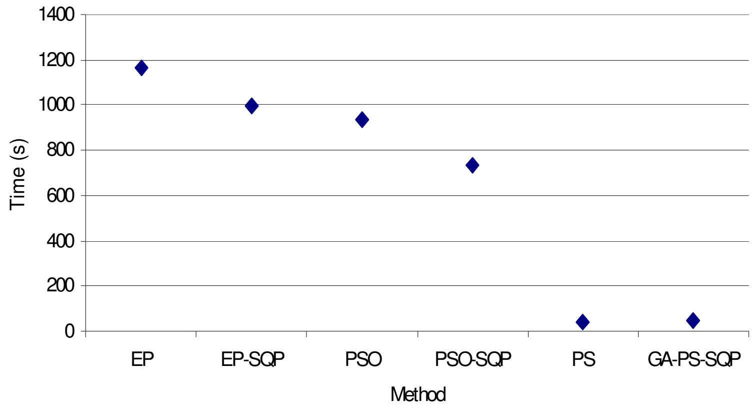

Figure 47: Best times comparison (Case 4-IV)

Figure 48 illustrates the quality of the optimum depending on the starting point provided by the hybrid GA-PS to the SQP algorithm. The tendencies and the properties of the algorithm are similar to those observed when studying Case 4-II. Overall, the proposed hybrid method yields the best mean cost of all the methods compared, at significant savings of computational effort. These short computing times allow for more cases to be studied with the aim of increasing the confidence in the final solution. In addition, all results from the 100 runs are within 1% of the best value. It may therefore be concluded that the first stage (i.e. the outcome of the PS) provides a good starting point to the final search method to ensure that all results are global or near global solutions. In this case the migration rate, cross-over rate and population size are the same as for Case 4-II, and the total computation time for 100 runs is 4467.64 s.

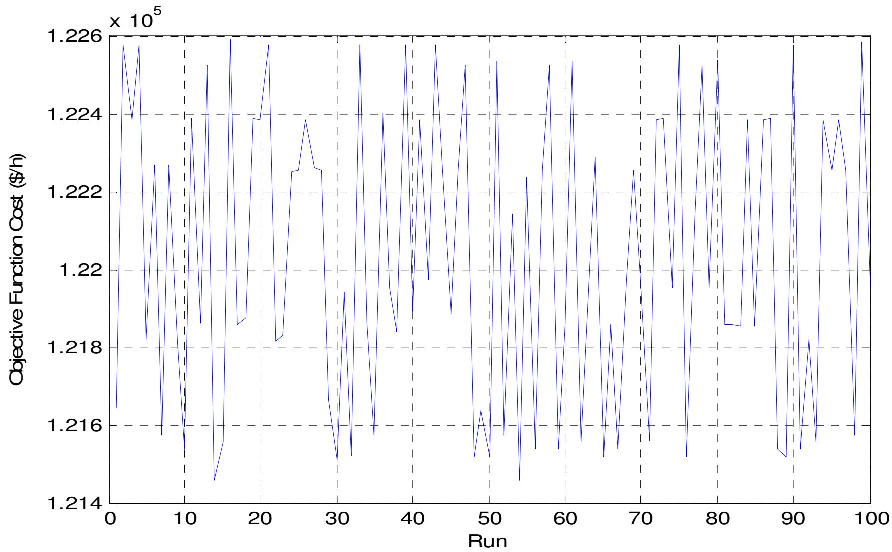

Figure 48: Objective function values for 100 different starting points (Case 4-IV)

One of the identified advantages of combining the three techniques into a hybrid GA-PS-SQP is to do with the removal of the requirement of providing an initial (starting) point for the algorithm to commence the search. The PS technique on its own, successfully implemented and reported in [81], relies on a good initial 'guess' making the technique more susceptible to getting trapped in local minima. In the proposed hybrid method, the initial search based on the use of the GA does not require the user to provide such a starting value as the search is performed automatically. The tests undertaken have confirmed that this indeed makes the whole optimization process more robust and explains why the error bound of all solutions is now so narrow, much better than when using the other techniques.

4.4 Case 4-V: Six Generating Units (with emission and losses)

In this combined environmental economic dispatch case, a six-generator system is considered. Information about the generators' fuel cost, NO_x emission functions, the B matrix, loss coefficients, and the operating limits are detailed in [78]. The total load demand is set to 700 MW, and the weighting factor is 0.5.

The PS results in terms of the line losses, emission, fuel cost, total cost, and computation time are presented and compared with results of other heuristic methods (Genetic Algorithms, Evolutionary Programming and Pattern Search) from [79, 80, 82] in Table 27. The proposed algorithm has taken more time to reach its optimal solution than the other methods. However, the proposed algorithm has produced the lowest total cost. The nature of the proposed method necessities the increase of computation times, because it runs three methods in sequence.

The total cost of power production and the computation time comparisons between the proposed method and other algorithms in the literature are shown in Figures 49 and 50, respectively.

Table 27: Losses, Emission, Total Cost and Computation Time Comparison

Generator	Optimization Techniques					
	IFEP	FEP	CEP	FCGA	PS	GA-PS-SQP
P_{g1} (MW)	077.142	077.358	077.274	080.16	77.4318	74.7285
P_{g2} (MW)	049.925	049.669	049.639	053.71	048.894	50.9223
P_{g3} (MW)	048.764	048.316	048.535	040.93	048.516	49.1058
P_{g4} (MW)	103.486	104.369	103.525	116.23	104.568	104.446
P_{g5} (MW)	259.805	260.663	260.695	251.20	260.863	263.233
P_{g6} (MW)	191.828	190.473	191.233	190.62	190.672	188.774
Line losses (MW)	30.949	30.849	30.901	32.850	30.945	31.2108
Emission (kg/h)	530.5164	532.505	524.49	527.46	528.33	529.369
Fuel cost ($/h)	38214.02	38214.2	38216.47	38408.8	38208.6	38203.4
Total cost ($/h)	19369.84	19369.9	19369.84	19468.1	19368.5	19366.4
Computation time (s)	3.874	1.598	4.48	-	2.05	26.67
No. of iteration	57	65	77	-	40	-

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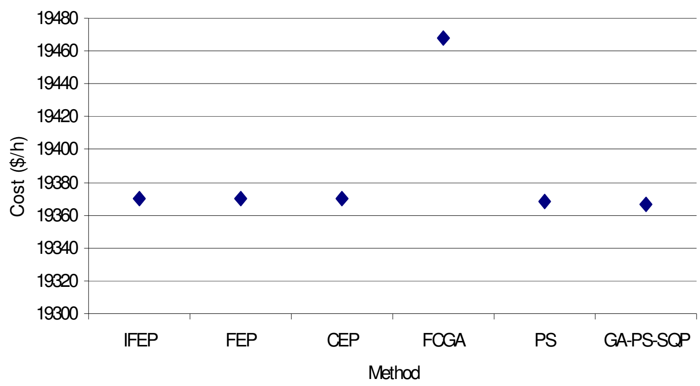


Figure 49: Total Cost Comparison Case V

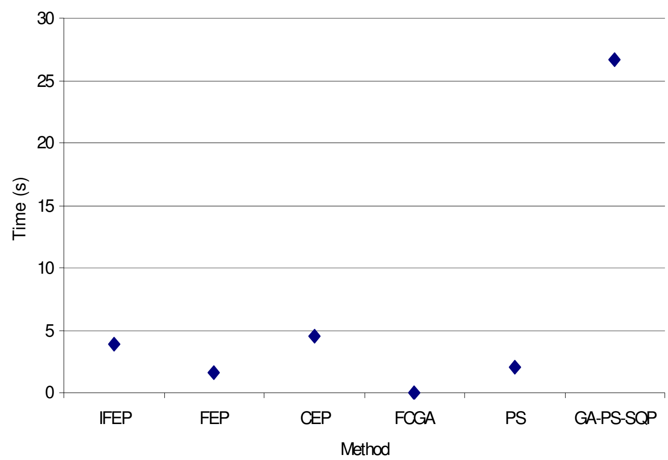


Figure 50: Computation Time Comparison Case V

4.5 Case 4-VI: Multi Area Economic Dispatch (MAED)

The multi area ED problem considered consists of four areas with tie lines connecting these areas. Each area contains four generation units. Note that quadratic cost functions are used to model the cost of generation $F(P_{gi})$, but the tie lines transmission costs, $G(T_{jk})$, are assumed to be linear functions of the power transfer (MAED model is presented in sub-section 2.1.2). The generators' data and the tie lines coefficients along with their limits are all given in reference [56].

Different heuristic methods such as PSO, EP and PS have been applied to the same problem and results reported in [79, 80, 82]. The results using the PS and the other methods are shown in Tables 28 and 29. Like in the previous case the proposed algorithm has taken more time to solve and, since this case is more complicated in nature than other hybrid cases, the large difference in computation times is clearly noticeable.

Table 28: Generator Productions

Generator		Optimization techniques					
		IFEP	FEP	CEP	NFP	PS	GA-PS-SQP
Area 1 Demand 400 MW	P_{g1} (MW)	149.998	149.997	150.000	150.000	150.000	150.000
	P_{g2} (MW)	099.986	099.968	100.000	100.000	100.000	100.000
	P_{g3} (MW)	068.270	067.017	068.826	066.970	066.971	67.0078
	P_{g4} (MW)	099.940	099.774	099.985	100.000	100.000	100.000
Area 2 Demand 200 MW	P_{g5} (MW)	056.349	057.181	056.373	056.970	56.9718	57.0085
	P_{g6} (MW)	096.753	095.554	093.519	096.250	96.2518	96.2605
	P_{g7} (MW)	041.264	041.736	042.546	041.870	41.8718	41.8786
	P_{g8} (MW)	072.586	072.748	072.647	072.520	72.5218	72.5070
Area 3 Demand 350 MW	P_{g9} (MW)	050.003	050.030	050.000	050.000	050.002	50.0000
	P_{g10} (MW)	035.985	036.552	036.399	036.270	036.272	36.2541
	P_{g11} (MW)	038.012	038.413	038.323	038.490	038.492	38.5041
	P_{g12} (MW)	037.426	037.001	036.903	037.320	037.322	37.3112
Area 4 Demand 300 MW	P_{g13} (MW)	149.988	149.986	150.000	150.000	150.000	150.0000
	P_{g14} (MW)	099.964	099.995	100.000	100.000	100.000	100.0000
	P_{g15} (MW)	057.601	057.568	056.648	057.050	057.051	57.0081
	P_{g16} (MW)	095.874	096.482	095.826	096.270	096.271	96.2600

Table 29: Tie Lines and Total Cost Comparison

Area		Tie lines values (MW)					
From	To	IFEP	FEP	CEP	NFP	PS	GA-PS-SQP
1	2	00.094	00.062	00.000	00.000	00.000	00.000
1	3	18.649	18.241	19.587	18.180	18.180	20.276
1	4	00.000	00.000	00.000	00.000	00.000	00.000
2	1	00.018	00.000	00.018	00.000	00.000	00.000
2	3	69.997	69.790	68.861	69.730	69.730	67.655
2	4	00.000	00.000	00.000	00.000	00.000	00.000
3	1	00.000	00.000	00.000	00.000	00.000	00.000
3	2	00.000	00.000	00.000	00.000	00.000	00.000
3	4	00.000	00.000	00.000	00.000	00.000	00.000
4	1	00.549	1.548	00.758	01.210	01.210	03.268
4	2	02.951	02.509	01.789	02.110	02.111	00.000
4	3	99.927	99.974	99.927	100.00	100.00	100.00
Total Cost ($/h)		7337.51	7337.52	7337.75	7337.00	7336.98	7337.01
Computational Time (s)		23.97	7.47	7.82/11.49	-	5.77	61.25
Population size		100	100	100	-	-	100
No. of Iterations		585	645	758/920	-	1225	-

Figure 51 shows the competitiveness of the proposed method with NFP and PS in terms of reduction of the total cost of the four areas generation production. The comparison of the computation times is illustrated in Figure 52.

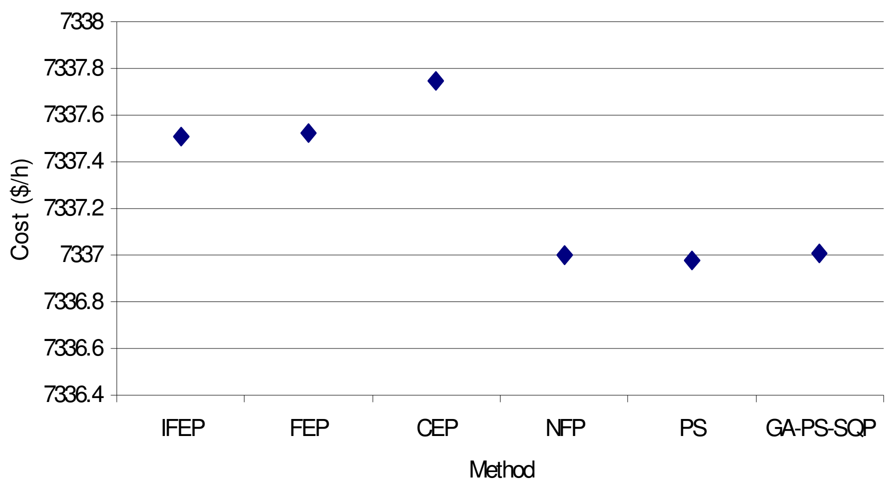


Figure 51: Total Cost Comparison Case 4-VI

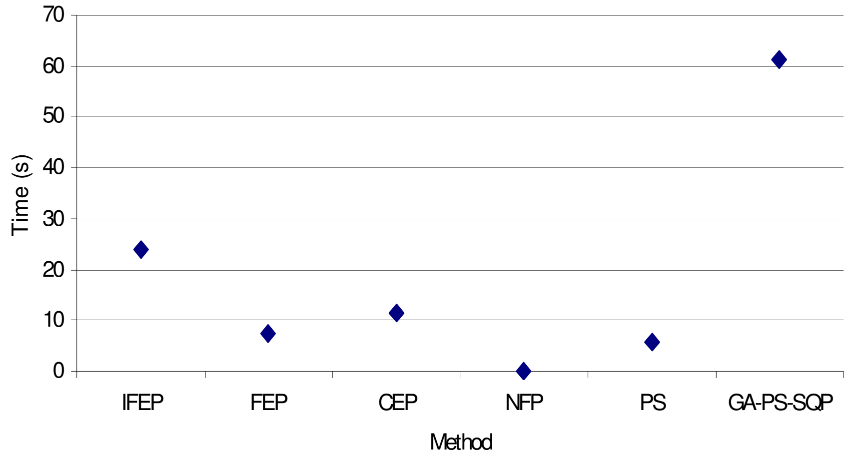


Figure 52: Computation Time Comparison Case 4-VI

It should be noted that the proposed hybrid method produced the final result in a single run, whereas PS needed 100 runs to find a proper starting point that led to its solution. As a result the total execution time for the PS method (402 s in case 4-V and 1473.6 s in case 4-VI) should be considered as the sum of the 100 runs. In this case, the comparison of the execution times shows that the proposed hybrid method has led to a significant saving in computation time. As a result, an investigation in the execution times of all of the hybrid cases has been conducted to emphasize the savings in computational time.

4.6 Further investigations using the proposed hybrid method

The main reason for introducing the hybrid method was to alleviate the main drawback of the PS algorithm, that is the need to independently generate the initial (starting) point to trigger the optimisation search. The proposed hybrid method indeed removes such requirement as the initial point is generated automatically and the results are no longer sensitive to the starting point as the need for it is avoided. However, the comparisons of the previous section appear to suggest that the computing times of the hybrid method are longer, sometimes significantly longer, and this aspect of the comparison requires further analysis.

It has already been mentioned that the common approach in literature, and thus also adopted in the project, is to execute the PS algorithm 100 times with random starting points and choose the best solution – this increases the confidence in the result. It has already been suggested in Section 3.7 that this seems to be a rather conservative approach as typically between 20 and 40 runs are sufficient to achieve good solutions for the problems studied. Notwithstanding, the 100 executions appears to be a well established practice. Thus a fairer comparison would be to take the total time of 100 runs of the PS method rather than a time of a single run. This prompted the following investigation and an alternative comparison of computing times.

For the purpose of this analysis the following runs were executed:

a) Calculations using the PS method with 100 runs,

b) Calculations using the hybrid method with 100 runs,

c) Calculations using the hybrid method with 1 run.

These calculations were applied again to the cases of 3, 13 and 40 generators discussed before, as well as to the ED & EM and MAED cases, and the results are discussed below.

4.6.1 Three Generators

The results are summarised in Table 30 and Figures 53 and 54. The quality of the optimum is the same for all three calculations, thus there appears to be no need to apply the hybrid algorithm more than once. The total time of the hybrid method is therefore reduced by 35.9% compared with the 'full' run (100 executions) of the PS algorithm. Thus the hybrid algorithm offers a double benefit: no need to generate (or 'guess') the starting point and shorter overall computing time.

Table 30: Comparison between PS and Hybrid Method (3 generators)

Method	Number of runs	Minimum Fuel Cost ($/h)	Total Computational Time (s)
PS	100	8234.1	22.14
Hybrid first trial	100	8234.1	1032.3
Hybrid second trial	1	8234.1	14.2

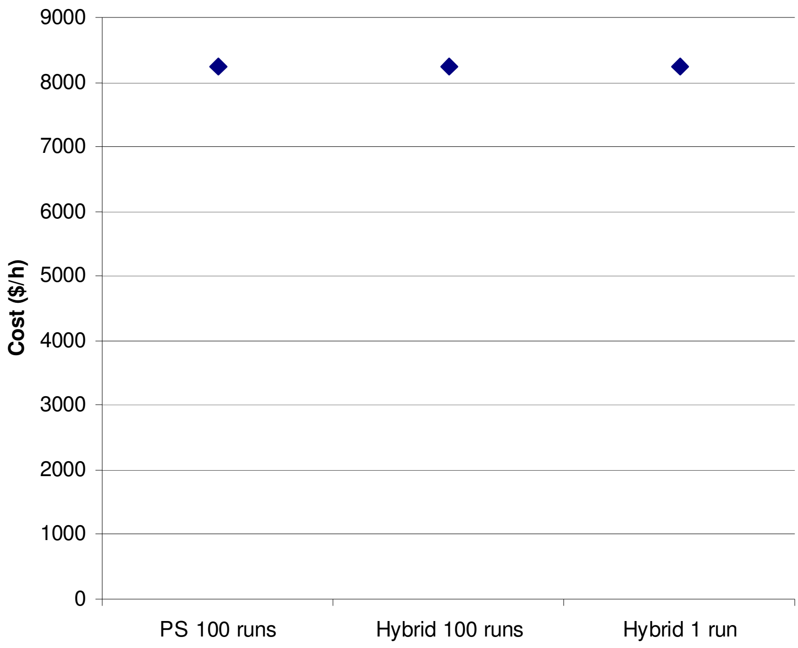


Figure 53: Fuel cost comparison (3 generators)

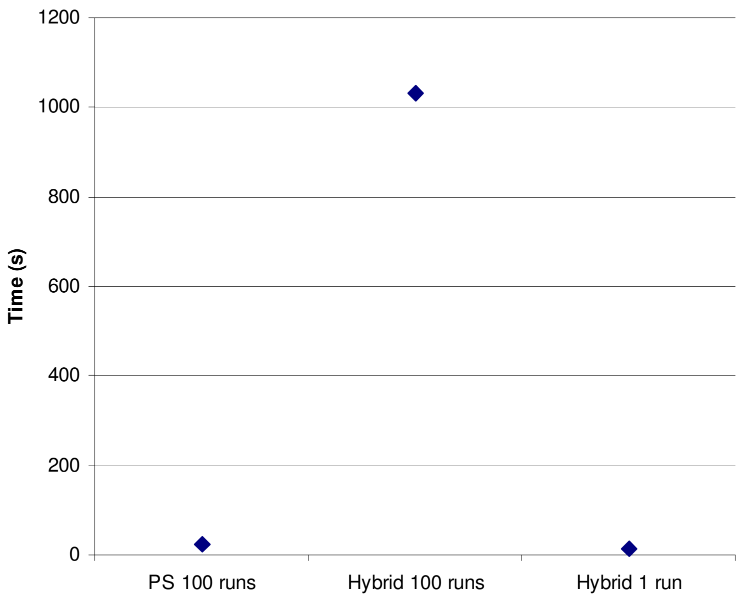


Figure 54: Computation time comparison (3 generators)

4.6.2 Thirteen Generators

As demonstrated by Table 31 and Figures 55 and 56, the 'single run' Hybrid Method offers a significant reduction of overall computing times (by about 87%), while the quality of the final optimum is preserved (within 1% of the value achieved by the PS).

Table 31: Comparison between PS and Hybrid Method (13 generators)

Method	Number of runs	Minimum Fuel Cost ($/h)	Total Computational Time (s)
PS	100	17969	455.7
Hybrid first trial	100	17964	1054.9
Hybrid second trial	1	18153	58.67

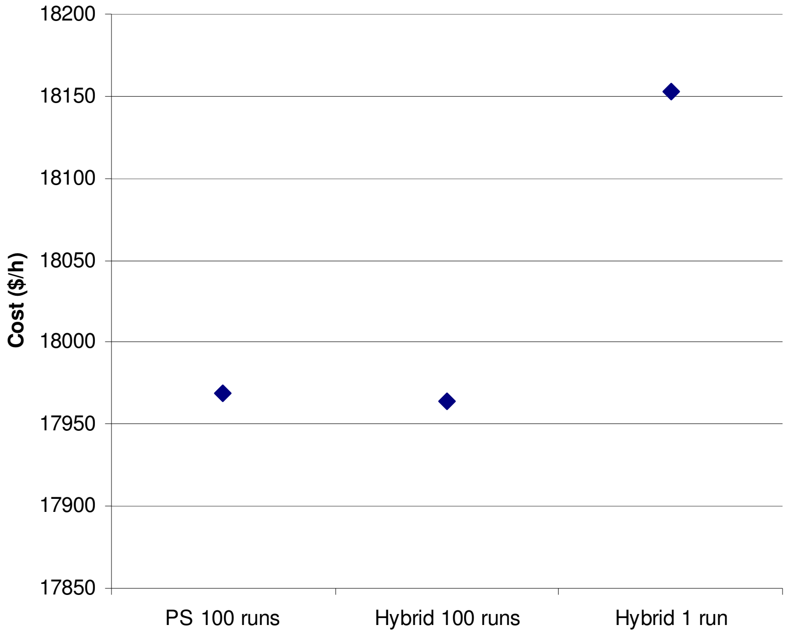


Figure 55: Fuel cost comparison (13 generators)

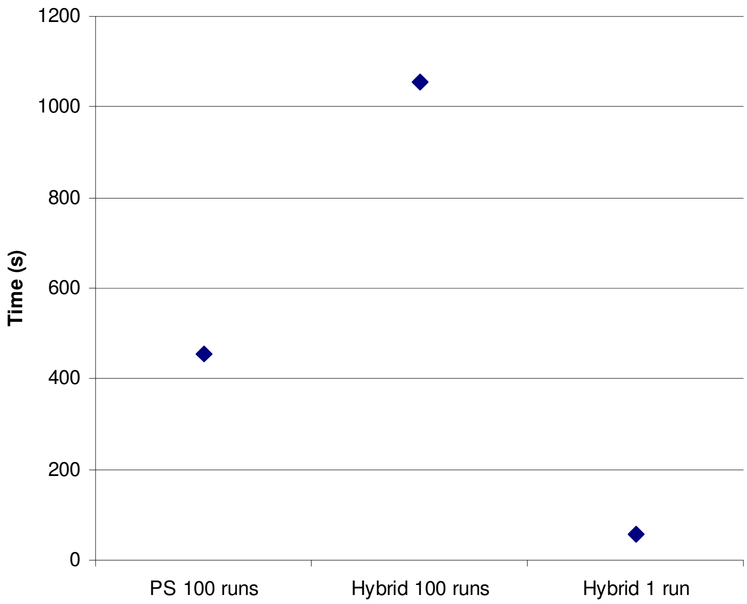


Figure 56: Computational time comparison (13 generators)

4.6.3 Forty generators

The results (Table 32 and Figures 57 and 58) are even more encouraging, showing a high quality answer from the one run of the Hybrid Method (within 0.02% of the PS generated value) and a massive saving in computing times (by 96.6%).

Table 32: Comparison between PS and Hybrid Method (40 generators)

Method	Number of runs	Minimum Fuel Cost ($/h)	Total Computational Time (s)
PS	100	121416	4298.3
Hybrid first trial	100	121460	4467.6
Hybrid second trial	1	121670	147.9

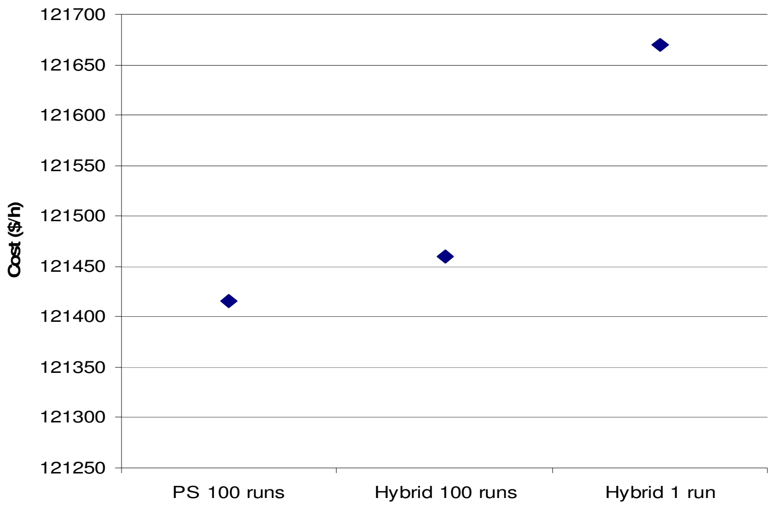


Figure 57: Fuel cost comparison (40 generators)

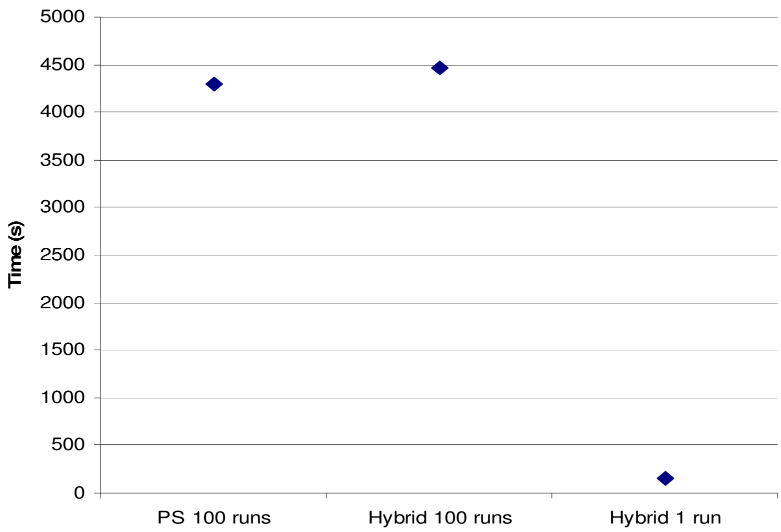


Figure 58: Computational time comparison (40 generators)

4.6.4 ED & EM

In the case of combined economic dispatch and emission problem, as demonstrated in Table 33 and Figures 59 and 60, the savings in computational time continue to be enormous – the Hybrid method only needs 1/20 of the time required by the 100 runs of the PS. Moreover, in this particular case, the Hybrid Method has actually found a better optimum.

Table 33: Comparison between PS and Hybrid Method (ED&EM)

Method	Number of runs	Minimum Fuel Cost ($/h)	Total Computational Time (s)
PS	100	19369	402
Hybrid first trial	100	19366	3012.5
Hybrid second trial	1	19366	19.1

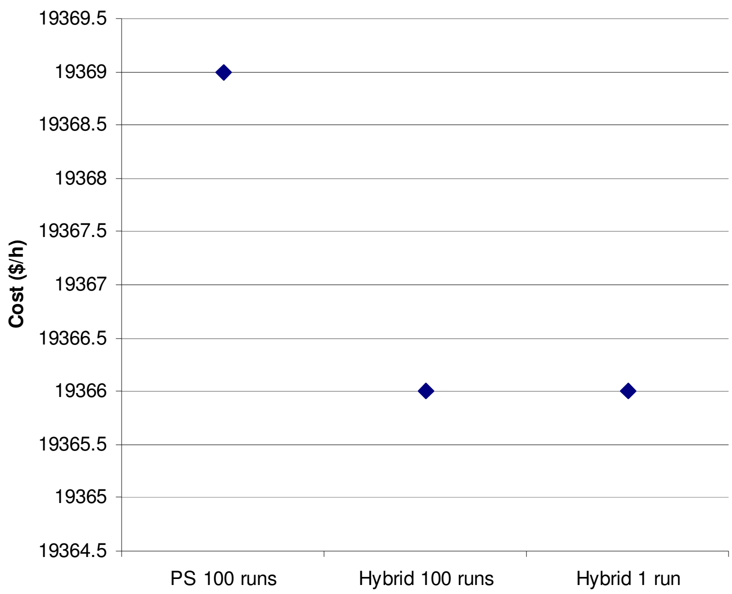


Figure 59: Fuel cost comparison (ED&EM)

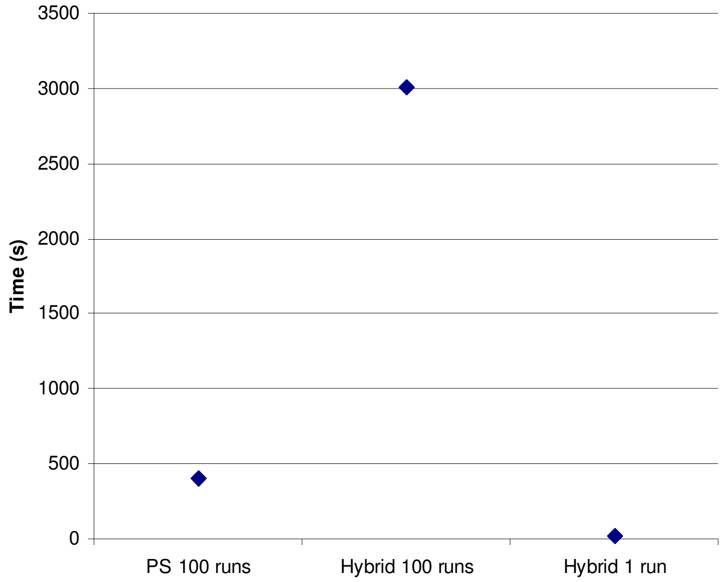


Figure 60: Computational time comparison (ED&EM)

4.6.5 MAED

The final system considered was the multi-area economic dispatch. As expected (Table 34 and Figures 61 and 62), the proposed hybrid method matched the minimum fuel cost obtained by PS and outperformed it in terms of execution time by a considerable margin (92.4%).

Table 34: Comparison between PS and Hybrid Method (MAED)

Method	Number of runs	Minimum Fuel Cost ($/h)	Total Computational Time (s)
PS	100	7337	1473.6
Hybrid first trial	100	7337	8321.4
Hybrid second trial	1	7337	141.4

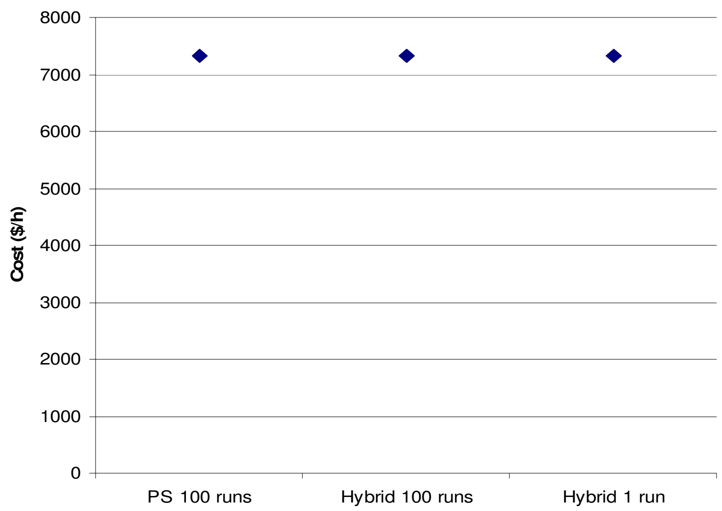


Figure 61: Fuel cost comparison (MAED)

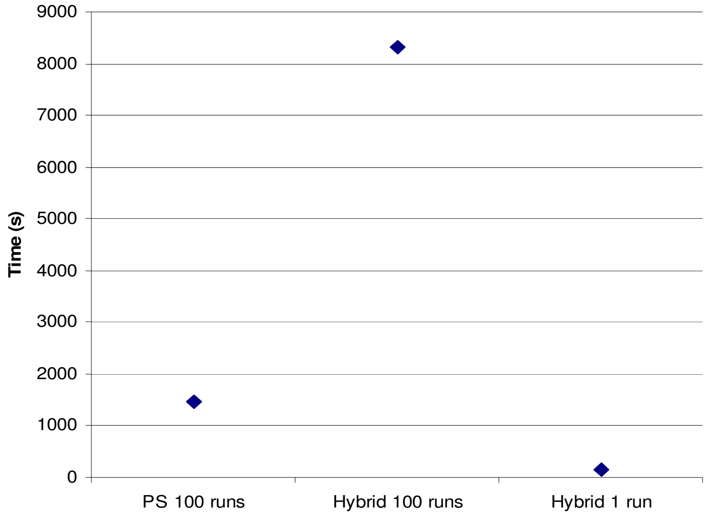


Figure 62: Computational time comparison (MAED)

4.6.6 Conclusion

The conclusion from this section is that the hybrid method is beneficial in two respects; it produces a high quality answer without the need of specifying (or guessing) the starting point and achieves the solution in shorter (or much shorter) time. The comparisons need to be done carefully as the PS algorithm necessitates multiple executions using several starting points (usually 100, commonly adopted in literature), whereas it is usually sufficient to apply the hybrid method only once. The short computing times, however, would allow for multiple executions of the hybrid method as well (with the purpose of further increasing the confidence in results), whereas it has been shown in this report (see section 0) that fewer than 100 runs would often be sufficient, depending on the problem in hand. These observations need to be borne in mind when making comparisons.

5 Dynamic Economic Dispatch (DED)

In this chapter, a more generalized form of the Economic Dispatch (ED) problem is introduced and investigated, namely the Dynamic Economic Dispatch (DED) formulation which solves the ED problem for twenty four hours with different load demand in each hour. The changing load demand throughout a twenty four hour period reflects realistic situations that the control engineers in power plants usually encounter. However, the addition of new constraints in the DED formulation increases the complexity of the model and makes solving the DED problem more challenging than the ordinary ED. For example, the addition of the generation unit ramp rate limits, which restrict the change of the production of power in generating units between the hours of operation, makes it more difficult to find the path to the optimal solution. It should be noted that the problem formulation presented in section 2.1.5 is adapted throughout Chapter 5.

Chapter 5 is divided into three main sections; Section 5.1 covers the DED problem with fuel cost only, Section 5.2 solves the DED problem with fuel cost and emission, and Section 5.3 introduces an improved algorithm to solve the same DED problem as in Section 5.2.

5.1 Case 5-I: Dynamic Economic Dispatch (Fuel Cost only)

In this case, the system consists of five power generation units and the data, transmission loss formula coefficients and load demand for twenty four hours are listed in Tables 35 and 36, respectively, whereas the transmission loss formula coefficients are:

$$B = \begin{bmatrix} 0.000049 & 0.000014 & 0.000015 & 0.000015 & 0.000020 \\ 0.000014 & 0.000045 & 0.000016 & 0.000020 & 0.000018 \\ 0.000015 & 0.000016 & 0.000039 & 0.000010 & 0.000012 \\ 0.000015 & 0.000020 & 0.000010 & 0.000040 & 0.000014 \\ 0.000020 & 0.000018 & 0.000012 & 0.000014 & 0.000035 \end{bmatrix} \tag{5.1}$$

Table 35: Data for the five units system

Quantities	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5
a_i (\$/h)	25	60	100	120	40
b_i (\$/MWh)	2.0	1.8	2.1	2.0	1.8
c_i (\$/(MW)^{2}h)	0.0080	0.0030	0.0012	0.0010	0.0015
e_i (\$/h)	100	140	160	180	200
f_i (1/MW)	0.042	0.040	0.038	0.037	0.035
$P_{i\,\min}$ (MW)	10	20	30	40	50
$P_{i\,\max}$ (MW)	75	125	175	250	300
UR (MW/h)	30	30	40	50	50
DR (MW/h)	30	30	40	50	50

Table 36: Load demand for 24 hours

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

The authors of [34] used a Simulated Annealing (SA) technique to solve the DED problem. The PS method has now been applied to the above system. A comparison of best fuel costs and best run times for the two methods, and the power generating units production levels, are given in Tables 37 and 38, respectively. It can be seen that the PS achieves a better optimum (lower fuel cost) than the SA and in a shorter time (a 23% reduction in computing time has been observed).

However, it should be mentioned that there is a common weakness in both SA and PS when applied to DED problems. From the practical point of view, the algorithms should be able to maintain all constraints after the last hour as it goes to hour number one on the next day, but this has not always happened in this formulation. Hence some generators would need to be shut down and restarted again every day. To clarify this shortcoming, some of the cells in Table 38 are highlighted. It can be seen in Table 38 that units 2 and 5 have in fact violated the generating unit ramp rate limits. To rectify this problem, an improved algorithm has been developed and is reported later in Section 5.3.

Table 37: Comparison between SA & PS

Method	SA	PS
Best Fuel Cost ($/day)	47,356	46,530
Best Run Time (s)	351.98	272.2

Table 38: Power production of generators for 24 hours

Hour No.	P_1 (MW)	P_2 (MW)	P_3 (MW)	P_4 (MW)	P_5 (MW)
1	24.906	21.200	75.570	77.970	214.07
2	10.127	20.011	112.695	66.783	229.57
3	10.000	20.000	112.673	107.675	229.52
4	40.000	28.854	112.673	124.908	229.52
5	57.127	40.350	112.673	124.908	229.52
6	74.990	70.290	112.798	128.204	229.52
7	72.974	90.794	112.798	128.204	229.52
8	72.457	88.052	112.799	160.204	229.52
9	49.623	98.539	112.673	209.815	229.52
10	64.011	98.540	112.673	209.815	229.52
11	48.365	98.540	144.674	209.816	229.52
12	68.948	98.540	144.674	209.816	229.52
13	63.819	98.540	144.67	177.816	229.52
14	65.578	114.54	112.67	177.816	229.52
15	60.739	114.54	80.67	177.816	229.52
16	30.739	86.402	112.673	127.816	229.52
17	40.238	86.402	112.673	95.816	229.52
18	50.207	98.540	112.673	124.91	229.52
19	75.000	98.540	112.673	147.32	229.52
20	75.000	100.02	112.673	197.32	229.52
21	75.000	98.540	112.673	174.06	229.52
22	60.784	82.540	145.673	126.06	197.52
23	36.140	75.376	113.673	142.06	165.52
24	50.871	91.377	81.673	110.06	133.52

Figures 63 and 64 illustrate the comparison between the two methods concerning the fuel cost and run time, respectively (based on Table 37). In addition, detailed information regarding the system's power losses every hour of the day, total losses and the percentage of the total losses are given in Table 39. One of the main objectives of the proposed method is to reduce the generating power losses in the system, which will lead to minimizing the total cost. Implementing PS has led to the reduction of the total losses by 192.2059 MW (about 1.32%).

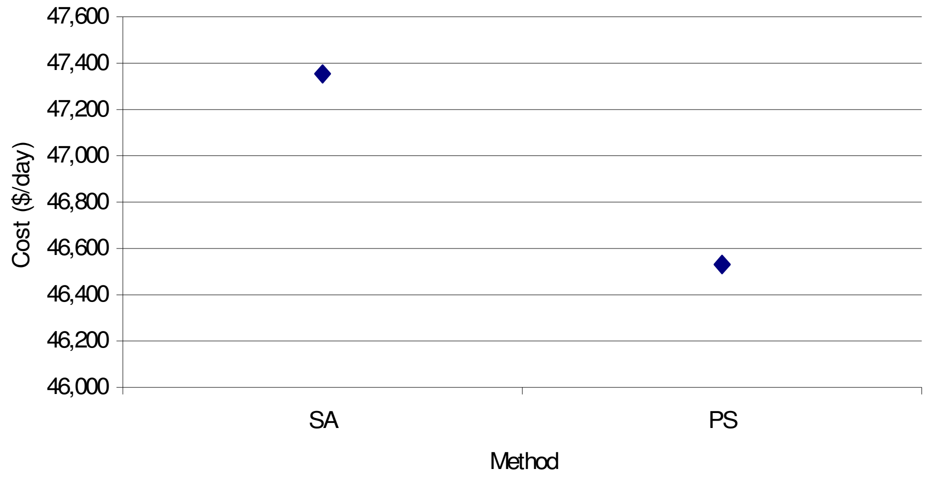


Figure 63: Fuel cost comparison

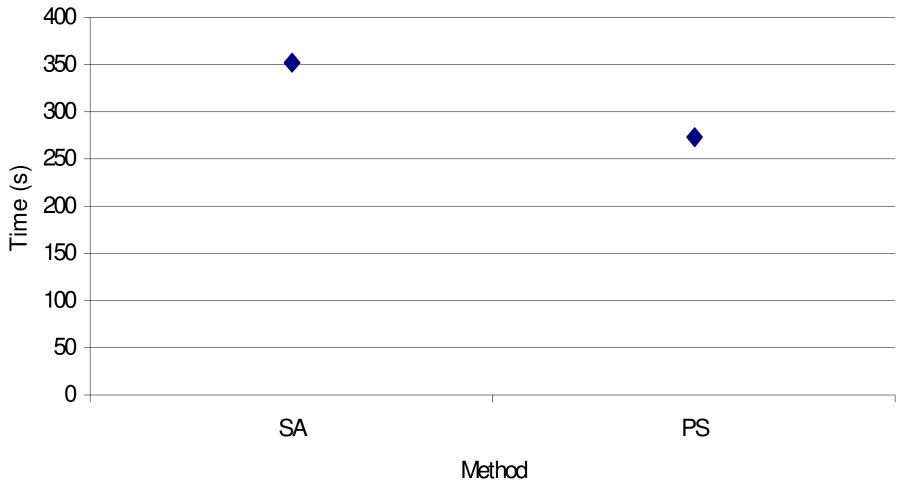


Figure 64: Run time comparison

Table 39: Power losses for 24 hours

Hour No.	Power Losses (MW)	Hour No.	Power Losses (MW)
1	3.717	13	10.366
2	4.186	14	10.127
3	4.868	15	9.288
4	5.955	16	7.150
5	6.578	17	6.649
6	7.803	18	7.847
7	8.290	19	9.049
8	9.032	20	10.53
9	10.168	21	9.791
10	10.559	22	7.575
11	10.914	23	5.767
12	11.497	24	4.499
Total Losses = 192.21 (MW)		Percentage of losses = 1.32%	

5.2 Case 5-II: Dynamic Economic Dispatch (Fuel and Emission)

In this case, the system consists of five power generation units and the system data, transmission loss formula coefficients, and load demand for twenty four hours were taken from [35]. The transmission loss formula coefficients and the load demand for twenty four hours are the same as in Case 5-I, see Equation (5.1) and Table 36, respectively. Furthermore, the data of the system is given in Table 40.

Table 40: System data for Case 5-II

Quantities	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5
a (\$/h)	25	60	100	120	40
b (\$/MWh)	2.0	1.8	2.1	2.0	1.8
c (\$/(MW)^{2}h)	0.0080	0.0030	0.0012	0.0010	0.0015
d (\$/h)	100	140	160	180	200
e (rad/MW)	0.042	0.040	0.038	0.037	0.035
α (lb/h)	80	50	60	45	30
β (lb/MWh)	-0.805	-0.555	-1.355	-0.600	-0.555
γ (lb/MW^{2}h)	0.0180	0.0150	0.0105	0.0080	0.0120
η (lb/h)	0.6550	0.5773	0.4968	0.4860	0.5035
δ (1/MW)	0.02846	0.02446	0.02270	0.01948	0.02075
$P_{i\ min}$ (MW)	10	20	30	40	50
$P_{i\ max}$ (MW)	75	125	175	250	300
UR (MW/h)	30	30	40	50	50
DR (MW/h)	30	30	40	50	50

In this case, two approaches were attempted. The first technique solves the DED with a combined objective function. In other words, the fuel cost and the emission are combined into one objective function and then minimized. The second procedure solves the fuel cost and emission separately. It should be mentioned that no weighting factors were assigned to this minimization problem, and the algorithm's default weighting factor was 0.5. (See sub-section 2.1.3 for definition of the weighting factor.)

5.2.1 Solving DED with combined objective functions

Table 41 lists all the outputs of the five generators for the period of 24 hours. Moreover, the load demand and the unit ramp constraints are maintained throughout. The total fuel cost and the emission index produced by PS are \$47,911 per day and 18,927 *lb* / day, respectively. From Figures 65 and 66, it can be easily seen that PS yields the lowest overall fuel cost and the lowest emission index compared to Evolutionary Programming (EP) and Simulated Annealing SA. The results show that PS has successfully reduced the fuel cost by approximately 1.47% and prevented an estimated 10.53% of the emission that EP calculated. Furthermore, calculated reductions of 1.46% and 10.67% in fuel cost and emission, respectively, have made PS superior to SA.

Table 41: Power production of generators for 24 hours

Hour No.	P_1 (MW)	P_2 (MW)	P_3 (MW)	P_4 (MW)	P_5 (MW)
1	16.927	86.655	59.803	180.54	69.929
2	46.927	98.540	34.315	209.81	50.000
3	75.000	98.540	46.925	209.81	50.000
4	75.000	98.540	86.925	209.81	65.937
5	75.000	98.540	112.67	209.81	68.732
6	75.000	98.540	113.78	209.81	118.73
7	73.574	98.540	112.66	209.81	139.73
8	70.320	98.540	112.66	209.81	171.73
9	74.206	98.540	145.66	209.81	171.73
10	74.961	104.40	174.97	209.81	150.17
11	74.923	98.556	174.98	209.81	172.48
12	63.544	98.556	174.98	209.81	204.48
13	58.467	98.556	174.98	209.81	172.48
14	60.132	114.56	174.98	209.81	140.48
15	55.194	114.56	142.98	209.81	140.48
16	43.254	98.558	110.98	177.81	156.48
17	52.662	98.558	110.98	145.81	156.48
18	71.799	98.558	142.98	145.81	156.48
19	75.000	98.540	175.00	174.54	139.75
20	75.000	114.78	175.00	209.81	139.76
21	75.000	98.540	166.52	209.81	139.76
22	60.946	82.540	135.52	177.81	155.76
23	53.984	98.540	112.67	127.81	139.76
24	36.844	98.540	80.673	159.81	91.760

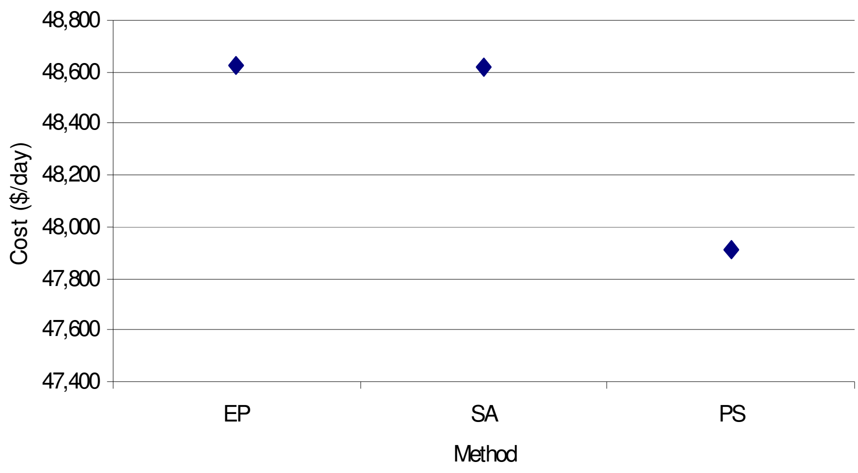


Figure 65: Fuel cost comparison

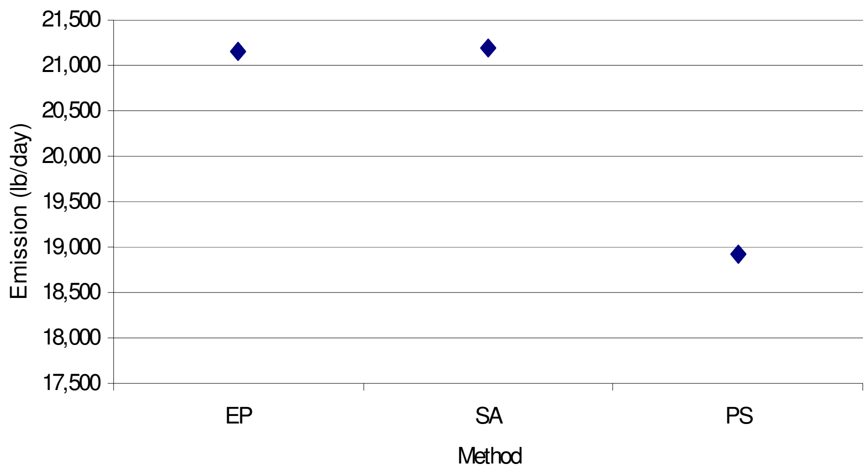


Figure 66: Emission comparison

Table 42: Power losses for 24 hours

Hour No.	Power Losses (MW)	Hour No.	Power Losses (MW)
1	3.856	13	10.30
2	4.598	14	9.970
3	5.280	15	9.032
4	6.217	16	7.092
5	6.761	17	6.501
6	7.869	18	7.638
7	8.317	19	8.838
8	9.062	20	10.36
9	9.949	21	9.638
10	10.32	22	7.584
11	10.76	23	5.773
12	11.38	24	4.632
Total Losses = 191.73 (MW)		Percentage of losses = 1.32 %	

Table 42 shows the losses of the five generators every hour of the 24 hour period of operation. In addition, the total losses of the system and the percentage of these losses in terms of the total generation of the units are also presented. It is worth mentioning that the default weighting factor of 0.5 was used in this part of the report.

5.2.2 Solving DED with separated objective functions

In this sub-section the DED problem was solved twice with each objective function separately. The total fuel cost obtained from PS is $46,530 per day, compared to $46,777 found by the EP algorithm. There would, however, be an emission increase of about 1.2% if the PS solution were adopted instead of EP (see Table 43 for details). (As a reminder, though, the PS has produced better results in the combined objective functions case, as reported in Section 5.2.1). Further trials were carried out but no improvement in the emission index was achieved. Figures 67 and 68 illustrate the comparison between PS and EP in fuel cost and emission.

Table 43: Results of separated objective functions

	EP	PS
Fuel Cost ($/day)	46,777	46,530
Emission (*lb* /day)	17,966	18,192
Run Time (s)	---	294.94

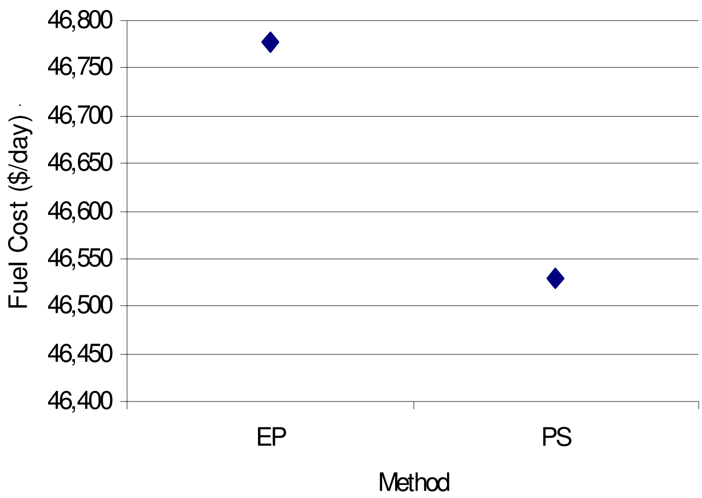


Figure 67: Fuel cost comparison (separated objective functions)

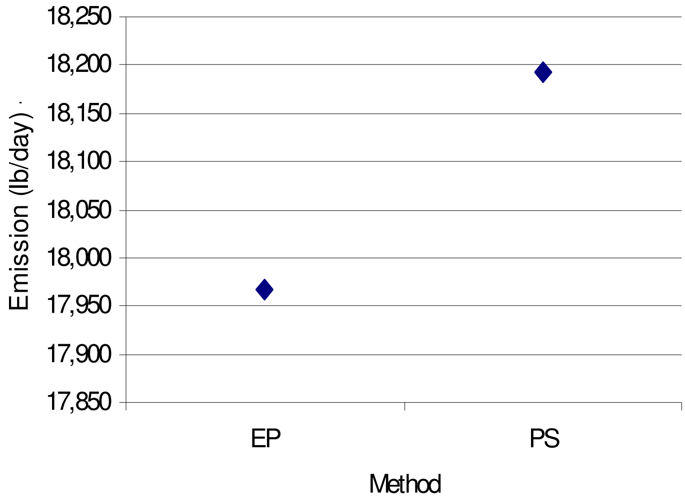


Figure 68: Emission comparison (separated objective functions)

5.3 Case 5-III: Dynamic Economic Dispatch (an improved algorithm)

The method used initially in this study, based on [34] and reported above, did not consider the unit ramp rate constraint after the end of the 24th hour and the beginning of the next day. To overcome this weakness, an improved version of the algorithm, capable of eliminating this drawback of violating the unit ramp constraint, was developed and results are presented in this section of the report. The improved algorithm guarantees the consistency of the unit ramp rate for the next day of the units operation. The implementation of this improved version of the algorithm has been carried on the combined dynamic economic emission fuel (DEED) problem mentioned in Section 5.2.1.

The improvements that were incorporated into the original algorithm are summarized in the following: 1) the interconnection between the last hour and the next first hour, 2) the redefinition of the upper and lower limits. The first improvement of the algorithm ensures that the 1st and the 24th hours' unit ramp rate constraints are maintained. However, the addition of this improvement has led to an increase of the computation time, and this has instigated the second feature.

As for the second improvement, the algorithm's upper and lower bounds were redefined to reduce the computing times. Since the DED has unit ramp rates constraints, the improved algorithm was programmed so that when it starts searching, new upper and lower limits are defined in accordance with the units' ramp-up and ramp-down limits. As a result, the improved algorithm does not need to search the whole range between the upper and lower limits of the generator; instead the redefined range of search is set by the units' ramp-up and ramp-down bounds. A Matlab code for the improved algorithm is attached as Appendix C.

Table 44 illustrates the outcome for the five units over the 24 hours operation time. It can be seen that none of the unit ramp rate constraint have been violated. In other words, the units can be operated after the 24th hour to the 1st in the next day without the need to be concerned about the unit ramp rate limits of the units. As already explained this extends the original treatment proposed in [34] (for a complete picture please refer to Table 3 in [34]).

Table 44: Power production os generators for 24 hours

Hour No.	P_1 (MW)	P_2 (MW)	P_3 (MW)	P_4 (MW)	P_5 (MW)
1	16.8272	36.051	107.190	102.65	150.75
2	41.5366	20.000	112.673	124.91	139.76
3	58.7964	43.480	112.673	124.91	139.76
4	75.0000	73.480	122.627	124.91	139.76
5	75.0000	98.540	126.239	124.91	139.76
6	75.0000	98.540	166.239	136.08	139.76
7	75.0000	98.540	175.000	145.78	139.76
8	75.0000	98.540	175.000	174.54	139.76
9	75.0000	100.34	175.000	209.82	139.76
10	75.0000	114.78	175.000	209.82	139.76
11	75.0000	125.00	175.000	209.82	146.04
12	75.0000	125.00	175.000	209.82	166.63
13	75.0000	114.78	175.000	209.82	139.76
14	75.0000	100.23	175.000	209.92	139.76
15	75.0000	102.50	135.893	209.83	139.77
16	62.0234	86.499	168.89	177.83	91.77
17	46.0234	88.296	168.89	177.83	83.51
18	16.0234	98.540	157.98	209.82	133.51
19	39.8480	98.540	175.00	209.82	139.76
20	69.8480	119.96	175.00	209.82	139.76
21	46.2456	119.96	142.00	209.82	171.76
22	33.2429	103.95	110.00	177.82	187.76
23	33.50	87.95	78.00	193.81	139.76
24	12.52	65.80	105.50	143.90	139.76

Table 45 shows a comparison between the proposed method and the results of EP and SA reported in [35]. Figures 69 and 70 present the comparison between PS, EP and SA in terms of fuel costs and emissions, respectively. The PS results offer the lowest fuel costs and emissions, compared to EP and SA, with reductions reaching 1.47% and 10.52% in terms of fuel cost and emission, respectively. However, the computing times increased to 514.25 s, from 294.94 s in Section 5.2.2, due to additional constraints and other modifications that were necessary in the improved version of the algorithm.

Table 45: Comparison between EP, SA and PS

	EP	SA	PS
Fuel cost ($/day)	48,628	48,621	47,911
Emission (*lb* /day)	21,154	21,188	18,927
Run time (s)	---	--	514.25

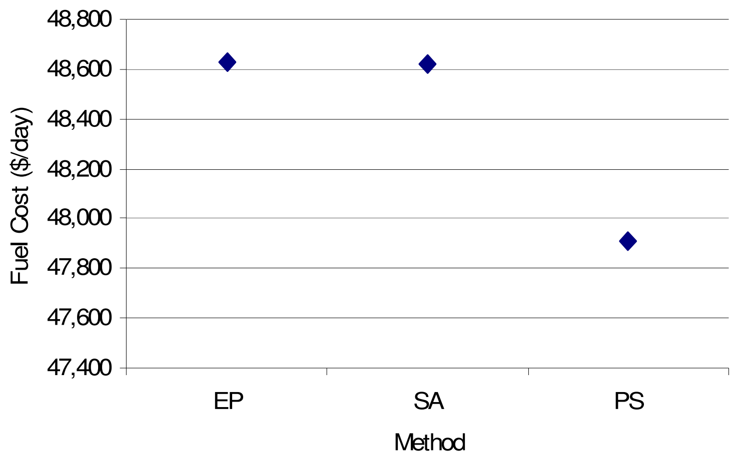


Figure 69: Fuel cost comparison (improved algorithm)

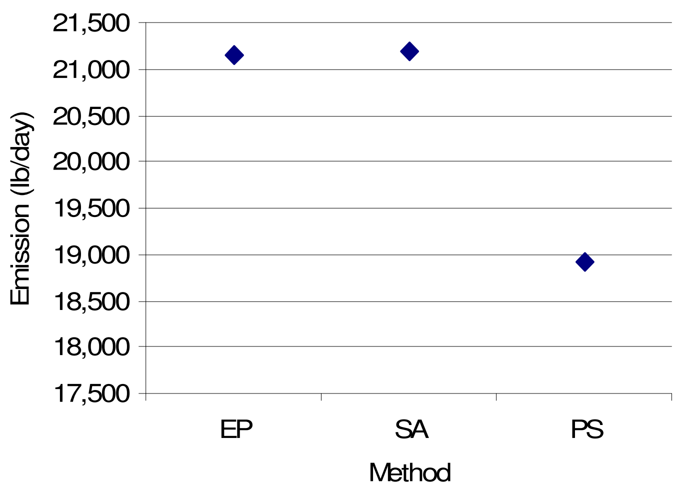


Figure 70: Emission comparison (improved algorithm)

6 Renewable Energy and Regression Methods

The introduction of renewable energy (RE) to the Kuwaiti electrical power system is unprecedented and challenging due to the absence of any existing RE plants or future projects. However, the need to introduce RE sources, to compensate for the electric power shortages in Kuwait, appears to be essential. Two main RE sources are available in Kuwait all year round with potentially sufficient supply for electrical power production, namely solar and wind. It was the requirement of my sponsors, and therefore one of the objectives of this thesis, that I consider the principles, fundamental properties, practical implementation issues and their relevance to the Economic Dispatch in the context of their impact on the installations in the State of Kuwait. To achieve these goals – and as agreed with my sponsors – I considered the RE issues using an example of the existing Thermal West Doha power station (WDPS) in Kuwait. A brief general description of solar, wind and thermal energy systems is presented in this chapter, followed by a more practical and focused analysis of a possible implementation at WDPS in the next Chapter 7.

6.1 Introduction

The need for electric power generation has peaked worldwide. Many existing power plants are incapable of satisfying the demand. The addition of renewable energy (RE) systems to the existing power plants is therefore desired more than ever. However, the RE penetration into current power systems results in many violations of security constraints due to its unpredictability and intermittency. To assist in finding ways to overcome this obstacle, researchers have developed hybrid models that combine traditional thermal generation with one or more RE systems. Moreover, the need to enhance the Economic Dispatch (ED) formulation to include RE systems using such hybrid models has become more important. The introduction of RE has a potential of increasing power production efficiency and reducing costs and emissions of power generation.

Many countries have begun deploying RE sources in their electric power systems, while other are considering the different options available. Kuwait is one of the countries that has been concerned about the development and the deployment of RE and in 2009 hosted a major international conference in this area with over four thousand participants [83]. The author of this report realizes the possibility of conducting his future research in the area of deploying RE for the State of Kuwait, and hopes to take advantage of this opportunity.

There is an electrical power crisis in the State of Kuwait. For the last three years, especially in the summer season, the State has faced the challenge of increasing demand for electrical power exceeding the production capacity. Moreover, the recommendations of the Ministry of Electricity and Water officials in 1994, that urged the Kuwaiti government to provide additional sources of electrical power before the year 2006, were faced with bureaucracy and shortage of funds. As a result, the Kuwaiti government has recently become very interested and started exploring new strategies to overcome this nationwide problem. One of these strategies is a well organized public awareness program called "TARSHEED", which can be translated to "Rationalization", in which the government addresses the public to save electricity and water during the summer critical times. The "TARSHEED" campaign scored a huge success in preventing an inevitable load shedding from taking place in the summer of 2007.

Another aspect that the Kuwaiti government has been interested in is the usage of RE to compensate the shortage of the electrical power from the existing power plants in the country. In addition, the massive increase of oil prices in recent years, and the ever decreasing oil reserves in the country, made the investment in the RE area a more feasible approach in the minds of the Kuwaiti government officials. Finally, the subject of RE was investigated in the OPEC meeting in 2007 and the oil producing countries pledged to contribute in the RE area. Therefore, the Kuwaiti government has assigned a $300 million budget for research in the area of RE to show its support in this promising field.

6.2 Solar Energy system

The location of Kuwait gives a great advantage for the usage of the solar energy in the production of electrical power. The shining sun is present in Kuwait most of the year with intensity more than sufficient for electrical power production. The Kuwaiti government has shown a great interest in investing in solar energy, yet no physical project has been implemented.

The Electrical Engineering Department in the Technological Studies College (TSC) in Kuwait started exploring the RE field a few years ago. Many members of staff in the department have established projects regarding RE sources implementation in the electrical power system of Kuwait. Furthermore, the work of Ahmed et al. [84] was the basis for the development of the solar system, which is illustrated in Figure 71 and will be used later in the DED model. The experiment was simulated in Matlab Simulink for a small size model (1 kW capacity) to achieve the Maximum Power Point Traction (MPPT). In other words, the main challenge facing the researchers in RE power sources designs was the extraction of the maximum power of the source all of the time under varying conditions of the day. The criteria that the RE system should adapt is that even with bad conditions the model should be able to deliver maximum power available at that instant of time. In the case of a solar energy system, the maximum power should be obtained irrespective of the Sun intensity. The proposed solar energy system guarantees the MPPT for all levels of Sun irradiation. The solar model does that by tracking the point that delivers the maximum power each time the intensity of the Sun changes. This point can be seen in Figure 72 for different Sun intensities. The success of the small size model had encouraged us to modify the rating to make it suitable for implementation in the final real life case of West Doha Power Station (WDPS).

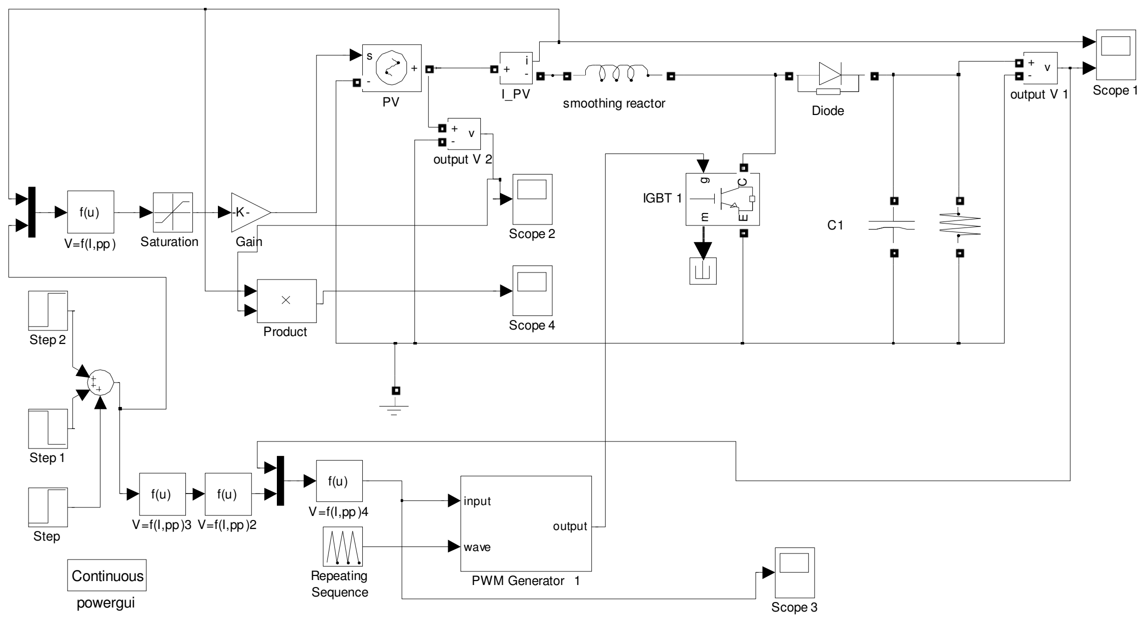


Figure 71: PV Model (Matlab-Simulink)

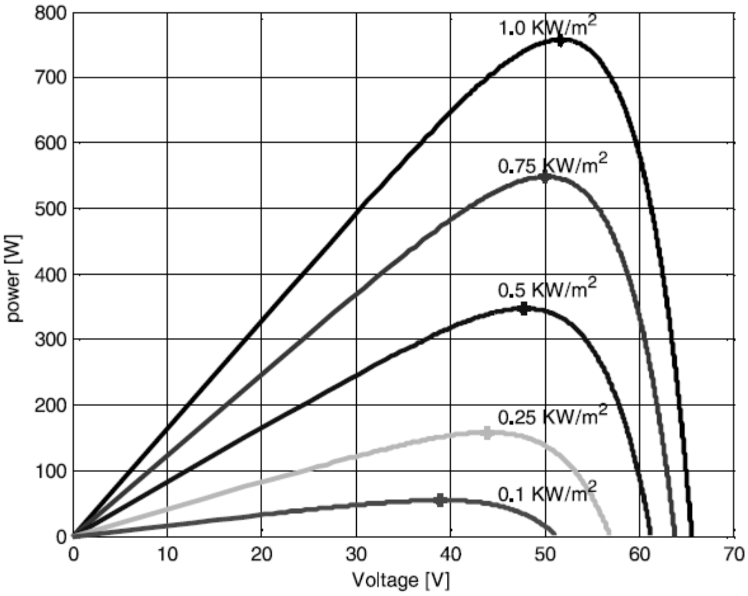


Figure 72: P-V Characteristics of PV model [85]

The solar model can obtain MPPT at all conditions through maintaining the predetermined relationship between the operation voltage/current and the open circuit voltage/short circuit current. In most PV models, an approximately constant ratio is sustained between the voltage at maximum power point for different irradiation levels and the open circuit voltage. The same applies for the current at the maximum power point for different intensity levels to the short circuit current ratio; it is also constant [84, 86, 87]. Moreover, the open circuit voltage/short circuit current of an unloaded photo cell within the power producing array are measured periodically. The operating voltage/current of the power producing array are then set to the required values, which correspond to maximum power [84].

The solar model can be divided into two parts for simplification. The first part is the PV cells circuit and it consists of the input step functions representing the Sun intensities, its governing function supplied by the manufacturer of the cells, and its output current and voltage (see the left hand side of Figure 71). The second part is the control scheme of the model. It consists of a controlled voltage source, smoothing reactor, diode, capacitor, resistor, and electronic switch (IBJT) (see the middle and right hand side of Figure 71). The extra elements in the PV model are used to produce an appropriate switching sequence for the electronic switch that guarantees the MPPT. The duty cycle of the IBJT is controlled by a Pulse Width Modulator (PWM), whose input consists of the output voltage of the PV circuit and an electric representation of the Sun intensities. The PWM generates a sequence of triggering pulses to set up the duty cycles that assure the optimal operation of the IBJT.

Figure 73 shows the PV cells output current, which varies according to the Sun intensity. The PV cells are designed to produce a larger current in case of high Sun radiation. However, any obstacle that prevents or shades this radiation from reaching the PV cells will lead to a decrease of the produced current. The output voltage of the PV cells is shown in Figure 74. The PV circuit output voltage is illustrated in Figure 75. When compared to the PV cell's output voltage, the PV circuit output voltage is smoother with less fluctuations and it was amplified due to the boost configuration of the electronic switch (IBJT). The addition of the transistor may increase the cost of the circuit, but it is essential for obtaining the MPPT. The trade off between achieving the MPPT and minimizing the cost of the model is in favour of the first. The Sun intensities were set to multiple step functions that have different values. Furthermore, the combination of these step functions produced different Sun intensity every second in the simulation (see Figure 76). The steps were 1, -0.5, and 0.25. The different Sun radiations represent the presence of shadows, clouds, dust storms, etc. Finally, the output power of the PV cells is illustrated in Figure 77, and it is the product of the PV cells output current and voltage.

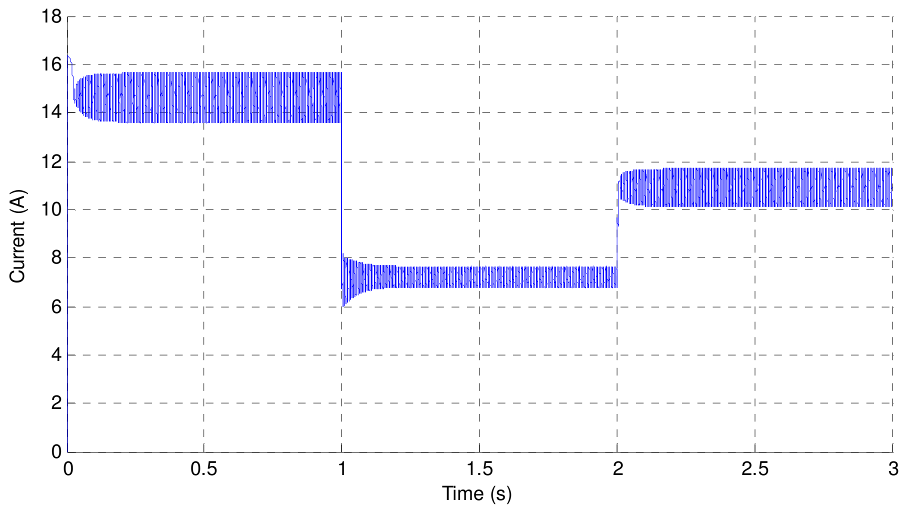


Figure 73: PV cells (output current)

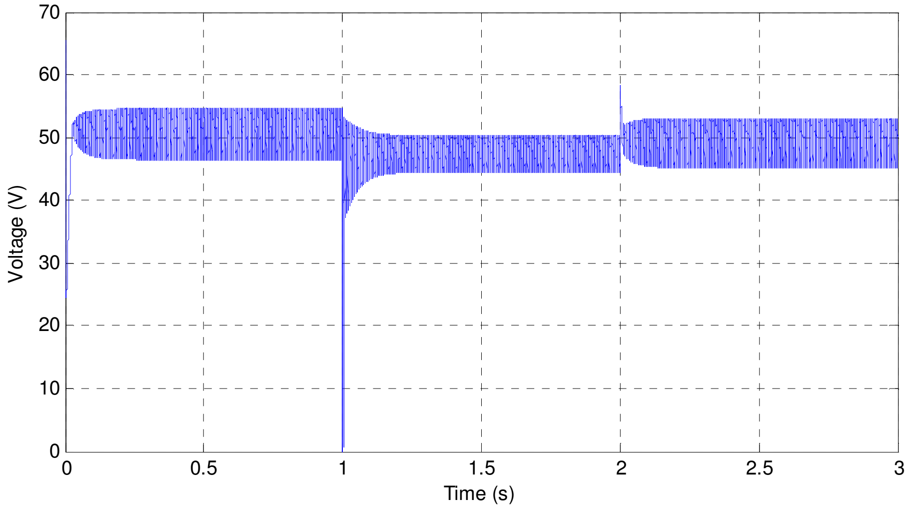


Figure 74: PV cells (output voltage)

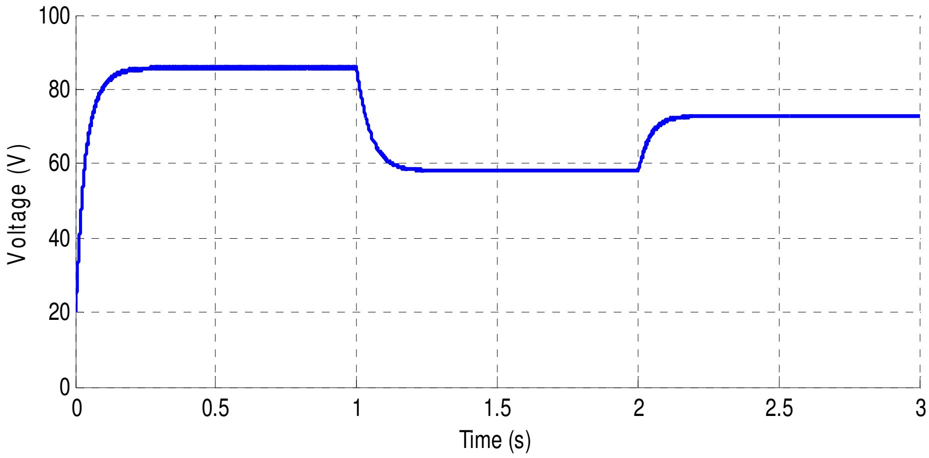


Figure 75: PV circuit (output voltage)

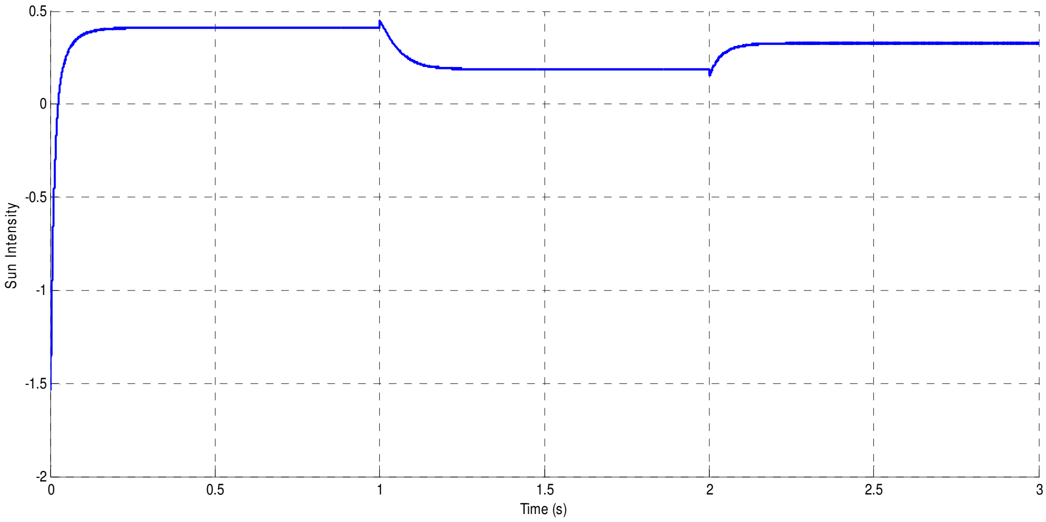


Figure 76: PV circuit (Sun intensity level)

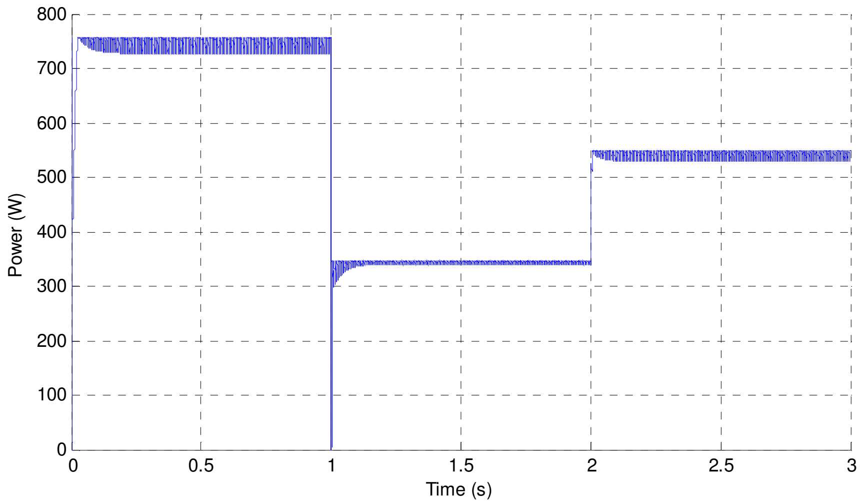


Figure 77: PV cells (output power)

Other obstacles facing the deployment of solar energy sources include extensive heat and dust storms in the summer. With temperatures that might exceed 50C^o in the summer in Kuwait, the photovoltaic cells and arrays should have special specification to overcome the over-heating problem and operate properly. Moreover, Kuwait's geographical position in a region that has dust storms in the summer makes it very hard to maintain sufficient operation of photovoltaic cells. The particles of sand from the dust storms will inevitably prevent Sun rays and cover the photovoltaic arrays with an isolation layer that will decrease its functionality. However, with proper heavy duty heat resistance designs and daily/hourly maintenance plans, the introduction of the solar energy system should become a reality and will be beneficial in Kuwait.

6.3 Wind Energy system

The wind energy comes second to the solar energy in Kuwait as a potential renewable energy source. From the data collected by the Kuwait Institute for Scientific Research (KISR) over a period of ten years (1996-2005), the average wind speed (5.0 m/s) meets the minimum requirements for the usage of wind power in the production of electrical power in Kuwait. As a result, the interest in employing the wind energy as an alternative source of electricity has risen and serious planning for using this RE source has started. In this section, the wind energy model is presented and a brief explanation about how it functions.

Due to some limitations in simulating generators in Matlab, the wind model was developed using software called PSIM (version 8), which is compatible with Matlab. The compatibility between the two powerful packages was essential as the final DED problem was to be solved by a PS algorithm available in one of Matlab tool boxes. PISM 8 has a “SimCoupler” file command that enables Matlab Simulink tool box to call any file in PSIM 8. This useful feature gives the electric power designers a flexibility to built their models in PSIM 8 and call them through Matlab codes. PISM 8 is powerful software for electric power circuits’ simulation and contains a large number of electrical elements and components. In addition, PSIM 8 offers many types of generators with more design parameters for better simulation results. It should be mentioned that PSIM 8 was used to build the solar energy model as well and it will be presented in Section 7.3.

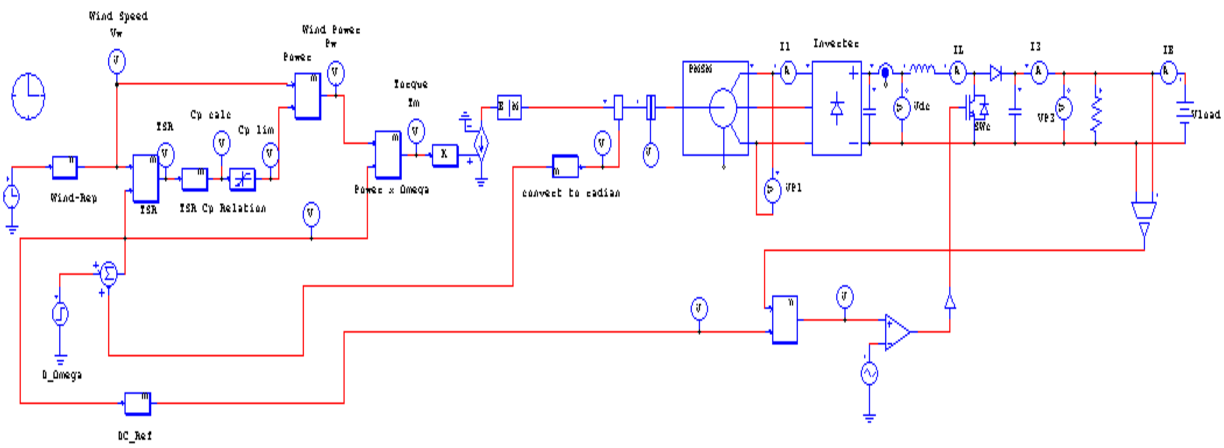


Figure 78: Wind turbine model

A mini wind energy system was developed by the EE Department in TSC of Kuwait that represents a single wind turbine model for the production of electrical power [84]. The adaptation of this wind model for the final hybrid system was made because of its practicality and applicability for Kuwaiti electrical system. Nevertheless, the mini model needs some modifications of its ratings to make it compatible for the real life case of WDPS, as described in the next chapter.

The wind energy system is governed by Equation 6.1 describing the mechanical power captured by the wind turbine blades which drives the electrical generator.

$$P = \frac{1}{2} \rho A C_p V^3 \tag{6.1}$$

where

ρ is the air density (kg/m^3)

A is the area swept by the rotor blades (m^2)

V is the velocity of the air (m/s), and

C_P is the power coefficient of the wind turbine.

In theory, the maximum that C_p can achieve is 0.59 [85] and the practical range is between 0.4 and 0.5. The expression of C_p came from the up-stream and down-stream wind speed that penetrates the turbine's blades. Moreover, another important term in wind turbine energy designs that correlates with C_p is the Tip Speed Ratio (TSR), which can be defined as the linear speed of the tip of the turbine's blades to the wind speed. An expression that represents the TSR is stated in Equation 6.2.

$$TSR = \frac{\omega_m R}{V} \tag{6.2}$$

where

ω_m is the angular velocity of the wind turbine blades, and

R is the radius of the wind turbine.

Figure 79 depicts the correlation between C_p and TSR for different types of wind turbines. It can be seen from the figure that at a certain TSR, called optimal TSR, the efficiency of the rotor is at its maximum. Moreover, the MPPT could be achieved if the turbine speed was controlled in such way that it would follow the optimal TSR. As explained in Section 6.2 for the solar system, the MPPT must be maintained by the wind turbine model for all different speeds of the wind to maximize the output power. The authors of [84] have presented a mathematical solution that does not depend on wind speed measurement and relies on the relationship between the turbine speed and the rectified DC voltage. The details of the control scheme, which has been used for the wind energy model, are out of the scope of this report and were presented in [84]. In short, the proposed control scheme maintains the turbine speed in accordance with the ideal TSR of the blades to guarantee the MPPT of the wind model.

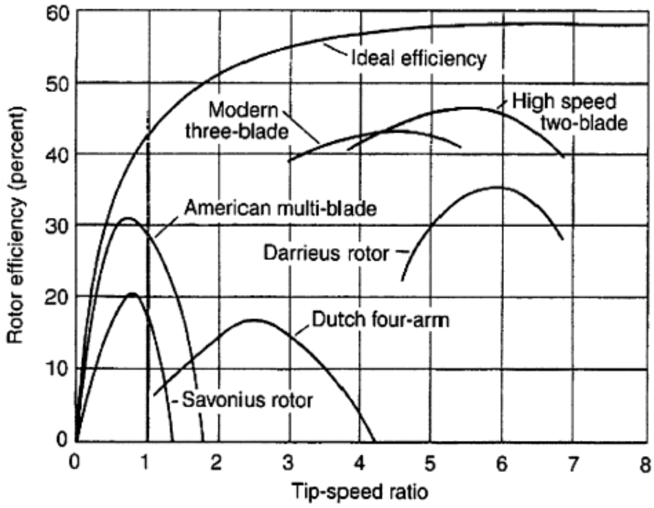


Figure 79: *Cp* and TSR corelation graph for different wind turbines [85]

Figure 80 illustrates the gradual rectification and amplification of the output voltages of the permanent magnet synchronous machine (PMSM). VP1 is the output voltage of the PMSM and it is fluctuating in accordance with the rpm of the PMSM. An inverter, a half wave rectifier, was used to rectify the signal and Vdc is produced. Finally, an IBJT switch was utilized in a boost configuration to achieve the MPPT condition of the wind energy system. As seen in Figure 80 the output voltage (VP3) is constant and it is amplified to reach its maximum point. It is necessary that the output power of the wind turbine is constant; otherwise any fluctuation in the signal would inject harmful harmonics in the grid.

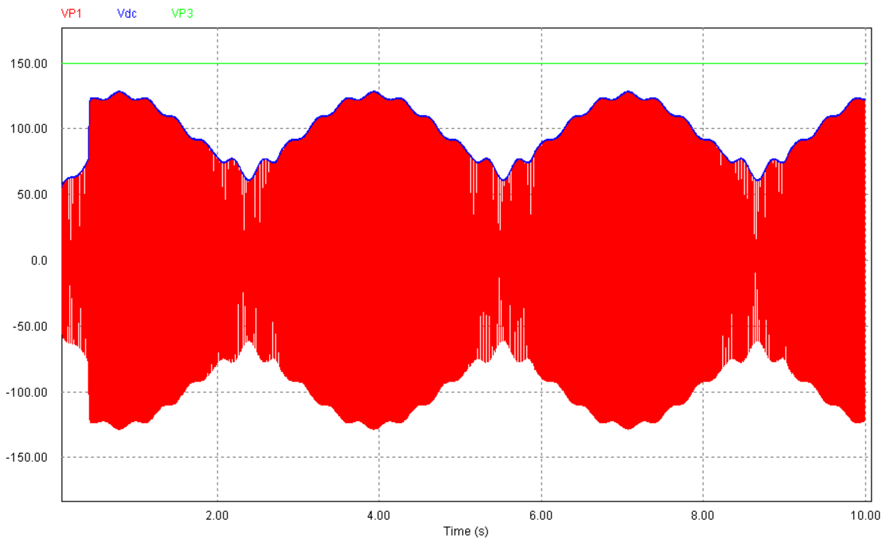


Figure 80: Wind turbine system voltages (V)

6.4 The combined System

The final hybrid system, which consists of solar, wind and thermal models, is presented in this section. The main purpose of adding renewable energy sources to the existing thermal system is to compensate for the electric power shortage in Kuwait. However, the proposed solar and wind systems do not currently meet the practical ratings of the WDPS load demand. A modification in the output power ratings for both systems has to be made and this will be presented in Chapter 7.

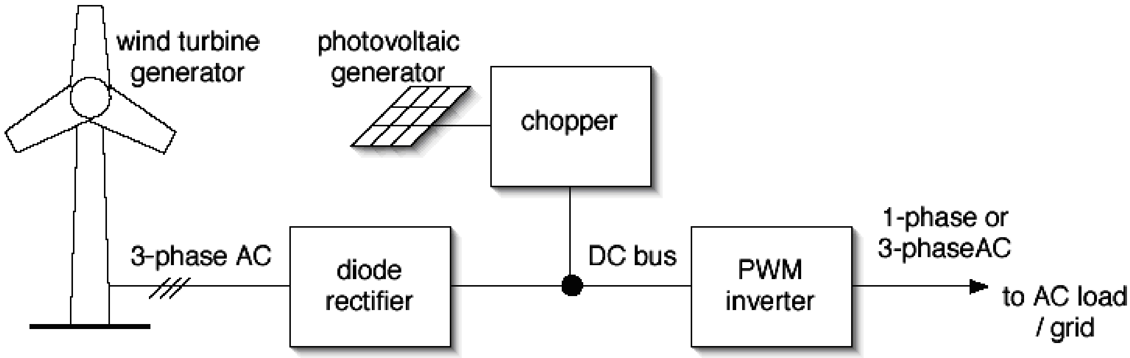


Figure 81: The hybrid Wind-Solar-Thermal system

The target combined solar and wind power production is 10% of the peak load demand of WDPS (approximately 200 MW) and it is divided equally between the two RE sources. A schematic drawing of the hybrid system is presented in Figure 81. The details of the thermal (WDPS steam turbines) system are presented in Chapter 7.

6.5 Regression Methods

The economic dispatch (ED) problem is simply a minimization problem for the fuel cost of the production of electric power and is governed by a number of constraints and limits. In other words, ED describes the relationship between fuel cost and power production. The ED model in most of the literature is approximated as a 2^{nd} order polynomial with many constraints and limits (see Section 2.1.1). Furthermore, the dynamic economic dispatch (DED) problem is the normal ED but it is repeated every hour for different load demands. The addition of the units' ramp-up and ramp-down (UR and DR) constraints to DED model is in fact the only difference that distinguishes the DED from the ED problems. The outcome of the regression method will be used in the DED modelling of WDPS.

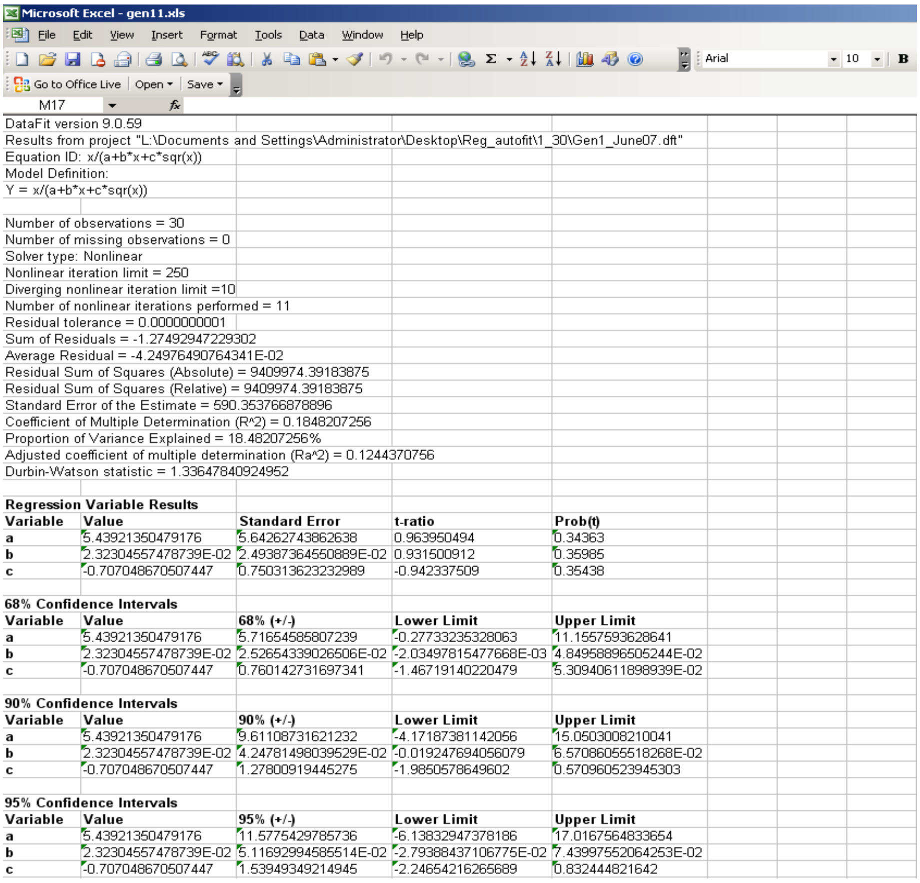
To solve the DED model for the problem in this project, first a DED model for the WDPS electric power system must be developed. Such a model has to be developed in accordance with the data that were collected from the operation section in WDPS and the cost evaluation department in MEW (detailed data is presented in Section 7.2). Moreover, the model must represent the real relationship between power production and fuel cost as accurately as possible. Due to the absence of any previous DED or ED models for WDPS, regression methods had to be used for the development of an appropriate representation of the production/cost relationship.

First, I tried to develop a similar expression as in the literature (2^{nd} order polynomial). The function (polyfit) in Matlab was used to find an appropriate expression, but the mean square error of the resulted formula was huge and this option was discarded. Secondly, the order of the polynomial was reduced to 1^{st} order, but again the trial was unsuccessful. Finally, a 3^{rd} order polynomial was tested, but the error was more than in the previous 2 trials. Thus the Matlab regression methods were abandoned and the search for alternative regression methods begun.

Ultimately, a professional software package called “DataFit”, developed by Oakdale Engineering, was used to develop an accurate expression to represent the relationship between production and cost of WDPS. A sample from the data collected was fed to the software, which produced more than 290 possible expressions and ranked them from the best fit to the worst one. The criteria used in choosing candidates for the final selection were the monotonic nature and the lowest standard errors of these expressions. The final round of elimination resulted in 6 different expressions, which were all monotonic but differed in terms of their order and the standard error. The expressions are shown in Table 46. A sample of the data sheet, which “DataFit” produces and shows the standard errors of the expressions, is presented in Figure 82.

Table 46: Regression method results

Expression 1	1/(a+b*x+c*x2)
Expression 2	x/(a+b*x+c*$x^{1/2}$)
Expression 3	a*(x-b)
Expression 4	a*xb
Expression 5	a*(1+x)b
Expression 6	x/(a*x+b)



Microsoft Excel - gen11.xls

DataFit version 9.0.59
Results from project "L:\Documents and Settings\Administrator\Desktop\Reg_autofit\1_30\Gen1_June07.dft"
Equation ID: x/(a+b*x+c*sqr(x))
Model Definition:
Y = x/(a+b*x+c*sqr(x))

Number of observations = 30
Number of missing observations = 0
Solver type: Nonlinear
Nonlinear iteration limit = 250
Diverging nonlinear iteration limit =10
Number of nonlinear iterations performed = 11
Residual tolerance = 0.0000000001
Sum of Residuals = -1.27492947229302
Average Residual = -4.24976490764341E-02
Residual Sum of Squares (Absolute) = 9409974.39183875
Residual Sum of Squares (Relative) = 9409974.39183875
Standard Error of the Estimate = 590.353766878896
Coefficient of Multiple Determination (R^2) = 0.1848207256
Proportion of Variance Explained = 18.48207256%
Adjusted coefficient of multiple determination (Ra^2) = 0.1244370756
Durbin-Watson statistic = 1.33647840924952

Regression Variable Results

Variable	Value	Standard Error	t-ratio	Prob(t)
a	5.43921350479176	5.64262743862638	0.963950494	0.34363
b	2.32304557478739E-02	2.49387364550889E-02	0.931500912	0.35985
c	-0.707048670507447	0.750313623232989	-0.942337509	0.35438

68% Confidence Intervals

Variable	Value	68% (+/-)	Lower Limit	Upper Limit
a	5.43921350479176	5.71654585807239	-0.27733235328063	11.1557593628641
b	2.32304557478739E-02	2.52654339026506E-02	-2.03497815477668E-03	4.84958896505244E-02
c	-0.707048670507447	0.760142731697341	-1.46719140220479	5.30940611898939E-02

90% Confidence Intervals

Variable	Value	90% (+/-)	Lower Limit	Upper Limit
a	5.43921350479176	9.61108731621232	-4.17187381142056	15.0503008210041
b	2.32304557478739E-02	4.24781498039529E-02	-0.019247694056079	6.57086055518268E-02
c	-0.707048670507447	1.27800919445275	-1.9850578649602	0.570960523945303

95% Confidence Intervals

Variable	Value	95% (+/-)	Lower Limit	Upper Limit
a	5.43921350479176	11.5775429785736	-6.13832947378186	17.0167564833654
b	2.32304557478739E-02	5.11692994585514E-02	-2.79388437106775E-02	7.43997552064253E-02
c	-0.707048670507447	1.53949349214945	-2.24654216265689	0.832444821642

Figure 82: Regression software "DataFit" data sheet

After intensive tests and eliminations, expression number 2 was chosen to be the final representation for the relation between production and cost in WDPS:

$$F(x) = \frac{x}{a + bx + c\sqrt{x}} \quad (6.3)$$

Expression 1 had performed very well and was a nominee until the end, but the percentage of correct answers was less than that achieved by Expression 2. On the other hand, although the execution of Expression 3 was successful, it produced unfeasible results. The other expressions (4-6) did not work properly and were eliminated early during further tests. It should be mentioned that the regression method was used to produce an expression that represents the relationship between production of electric power and cost only, whereas the total cost of electric power production, which MEW calculates every year, includes an additional fixed cost.

The fixed cost was determined from all kinds of expenses (omitting fuel cost) stated in the final auditing report that was issued by MEW for the fiscal year 2007/2008. The report included wages, pensions, spare parts cost, maintenance, operation, etc. As a result, an extra term (d) was added to the final expression (6.3) to represent the fixed cost. Furthermore, the total fixed cost (KD 41853189) was divided equally by the number of generators and by the number of hours in a year (d = 41853189 / 8 / 8760 = 597.220 KD/Generator/hr). The fixed cost was calculated in every hour of operation for all of the generators. This procedure was necessary because the final cost of electric power production in Kuwait includes the fixed cost in its computations. Adding up the fixed cost to the DED model represents the actual cost evaluation scenario that is applied in WDPS.

The ED problem model for WDPS can therefore be presented as follows:

$$F = \sum_{m=1}^{M} \sum_{i=1}^{N} F_{im}(P_{im}) \tag{6.4}$$

$$F_{im}(P_{im}) = \frac{P_i}{a_{im} + b_{im}P_{im} + c_{im}P_{im}^{1/2}} + d_{im} \tag{6.5}$$

subject to:

Real power balance:

$$\sum_{i=1}^{N} P_{im} = P_{Dm} + P_{Lm} \qquad i \in N, m \in M \tag{6.6}$$

Real power operation limits:

$$P_{i\min} \langle \; P_i \; \langle \; P_{i\max} \qquad i \in N, m \in M \tag{6.7}$$

Generating units' ramp rate limits:

$$\begin{aligned} P_{im} - P_{i(m-1)} &\leq UR_i \\ P_{i(m-1)} - P_{im} &\leq DR_i \qquad i \in N, m \in M \end{aligned} \tag{6.8}$$

where a_i, b_i and c_i are the cost coefficients of i^{th} unit, d is the fixed cost of power production, P_i is the output power of i^{th} unit, P_D is the load demand, P_L is power losses, $P_{i\min}$ is the lower generation bound for i^{th} unit, $P_{i\max}$ is the upper generation bound for i^{th} unit, UR and DR are the units ramp-up and ramp-down rate limits, respectively, M is the operation hour and N is the number of generation units. The cost coefficients produced by the regression method are listed in Table 47. It should be mentioned that P_L has been assumed to be zero for simplicity.

Table 47: Coefficients of the regression method

a (h/KD)	5.4392	-0.2849	0.9405	0.3072	1.3107	1.5014	1.9956	0.5088
b (10^{-3}) (h/KD MW)	23.24	-1.40	3.93	1.14	5.43	6.33	8.63	1.87
c (10^{-2}) (h/KD $(MW)^{1/2}$)	-70.7	4.40	-11.76	-3.35	-16.47	-19.1	-25.84	-5.7
d (KD/hr)	597.22	597.22	597.22	597.22	597.22	597.22	597.22	597.22

At this stage of my research, the DED model for WDPS was ready for testing. The upper and lower limits of the generators, the units' ramp-up and ramp-down and the hourly load demands were provided by the chief engineer in the operation section in WDPS. The complete data for DED system for WDPS is listed in Table 48 and the average load demands are stated in Table 49. It should be mentioned that the average load demands for the months of June, July, August, and September of 2007 had to be taken to generalize the final DED model of WDPS.

Table 48: WDPS Data

	Gen 1	Gen 2	Gen 3	Gen 4	Gen 5	Gen 6	Gen 7	Gen 8
a (h/KD)	5.4392	-0.2849	0.9405	0.3072	1.3107	1.5014	1.9956	0.5088
b (10^{-3}) (h/KD MW)	23.24	-1.40	3.93	1.14	5.43	6.33	8.63	1.87
c (10^{-2}) (h/KD $(MW)^{1/2}$)	-70.7	4.40	-11.76	-3.35	-16.47	-19.1	-25.84	-5.7
d (KD/hr)	597.22	597.22	597.22	597.22	597.22	597.22	597.22	597.22
$P_{i\max}$ (MW)	300	300	300	300	300	300	300	300
$P_{i\min}$ (MW)	80	80	80	80	80	80	80	80
UR (MW/hr)	45	45	45	45	45	45	45	45
DR (MW/hr)	45	45	45	45	45	45	45	45

Table 49: Average load demand of WDPS

Time (h)	Load (MW)	Time (h)	Load (MW)	Time (h)	Load (MW)	Time (h)	Load (MW)
1	1783	7	1470	13	1935	19	1893
2	1733	8	1527	14	1990	20	1913
3	1684	9	1584	15	2045	21	1933
4	1636	10	1702	16	2015	22	1911
5	1588	11	1820	17	1985	23	1890
6	1538	12	1878	18	1939	24	1816

7 Dynamic Economic Dispatch for the West Doha Power Station

Kuwait has six electric power stations, and they are Doha (West and East), Azzour (North and South), Shuaibah, and finally Sabeyah power station. Two of these power stations (South Azzour and Shuaibah) were damaged and were taken out of service during the Gulf war in 1990, which led to the decrease of electric power supply in Kuwait. The Ministry of Electricity and Water (MEW) had been planning on fixing the damaged stations and returning them to service again, but in 2002 was faced with strong opposition from the Kuwaiti parliament on the basis of procedural mistakes. MEW managed to obtain all necessary approvals later for the South Azzour power station and it went back to service in mid 2005 with a capacity of 1000 MW. The next power station planned to enter the service is north Azzour in 2013 with a capacity of 1500 MW. The power stations in Kuwait are steam turbine operated (except Sabeyah), which led designers of these stations to choose their locations to be as near as possible to the sea. Besides producing electric power to the country, the six stations also supply Kuwait with water. The need for more power stations to compensate the shortage in electric power in Kuwait was recognized more than a decade ago, but limited action has been taken by the government of Kuwait to meet the increased demand.

Recently, the MEW Minister's assistant for planning and training, Dr Meshan Alotaibi, held a press conference on the 18th of February 2010 and stated that the next expected peak electric power demand in Kuwait will be 10700 MW, whereas the total electric power capacity of the six power stations is 11300 MW. This implies that the difference between the production and the demand of electric power is less than the desired reserve electric power of 15% of total production. As a result, the electric power system of Kuwait will operate under critical conditions in summer 2010 and it will be vulnerable in case one of the units goes out of service for whatever reason.

7.1 Background about WDPS

The completion of West Doha Power Station (WDPS) in 1984 added significant support to the Kuwaiti electrical power system (Figure 83). The 2400 MW generating capacity of the station has supplied in many occasions up to 40% of the total electrical power demand in Kuwait. WDPS is situated in the Doha area, which is located about 15 km west of Kuwait city. Moreover, WDPS consists of eight steam generating units of 300 MW

(Figure 84) and 16 distillation units. The generated power is pumped into the Kuwaiti national grid through 6 overhead line feeders after stepping it up to a voltage of 275 KV.

Figure 83: WDPS in Kuwait

Figure 84: 300 MW Steam Turbine of WDPS

WDPS administration falls under the deputy secretary assistant for power stations in the MEW, and it is headed by a general manager and seven head sections. The most important section in WDPS is the operation section, which is responsible for running and observing the daily operation of the electrical and distillation units. In addition, the operation section is accountable for the isolation of electrical and mechanical machinery in case of emergencies and maintenance. Most of the data that has been used in this report was supplied by the operation section and the most appreciated advice and interpolations of the data were also provided by the staff of this section. The rest of the WDPS sections are instruments maintenance IMD, mechanical maintenance MMD, electrical maintenance EMD, planning, chemical, and training. Combined with operation section, these sections are responsible for the daily operation of the power station.

7.2 Data for WDPS

First of all, the assistance and cooperation of the manager, head sections and engineers of WDPS are mostly appreciated. Moreover, the efforts of the employees of the cost evaluation and budget departments in MEW headquarters that were involved in providing many crucial data for this research are also acknowledged. Although most of the data was classified as confidential, the MEW employees had provided access to all necessary information which allowed photo and electronic copies to be made for personal referencing. This cooperation made conducting this research easier and the outcomes more accurate.

7.2.1 WDPS data acquisition

The data that was collected from WDPS is considered the core of this section of the report. It is very important to give an explanation of the nature of this data and how it was collected and used. The data received was for the fiscal year 2007/2008, which in Kuwait starts in April and ends in March. The collected data consists of:

a) Daily total power production of the 8 generators from April 2007 till March 2008.
b) The load demand of the 1st and 15th day of each month from April 2007 till March 2008.
c) The daily quantities of Heavy Fuel Oil (HFO) used for each generator.
d) The daily quantities of Natural Gas (NG) used for each generator.
e) The upper and lower limits of the generators.
f) The units' ramp-up and ramp-down constraints.

First, the data was mainly collected, organized, and preserved in the Operation Section of WDPS. The head of the Operation Section has personally confirmed that 95% of the data is accurate and thus trustworthy for research purposes. Although it was initially very hard to obtain any information from the operation section due to confidentiality reasons, promises of secrecy were eventually made and all necessary data were collected.

Secondly, the collected data was not in the form suitable for the dynamic economic dispatch (DED). In DED problems the hourly load demand is needed, whereas the operation section technicians recorded the load demand every two hours (12 readings per day). An interpolation procedure was used to predict the appropriate load demand in between any two recorded readings.

Finally, the operation section staff have recorded the daily total power production of the 8 generators. As it was essential to have the hourly power production to find the relationship between production and cost within 24 hours, a problem arose how to estimate the production of each generator every hour of the day. The following procedure was applied. A percentage vector was calculated by dividing the 24 load demands by their sum. Then the total production of each generator was multiplied by this percentage vector. The result was 24 production quantities that were evaluated according to the percentage vector and they represent the estimated hourly production of the generators. The same procedure has been applied to the calculated total fuel costs to obtain the hourly fuel cost of every power production within the 24 hours. In short, the hourly power production and its fuel cost for the 8 generators were obtained for every day in the fiscal year 07/08.

7.2.2 MEW Cost Evaluation Department data

The costs of Heavy Fuel Oil (HFO) and Natural Gas (NG) were obtained from the cost evaluation department in MEW headquarter. The costs of HFO and NG are subject to change every month. The purchasing department in MEW states the prices that the ministry had bought the HFO and NG from Kuwait Oil Company (KOC) every month, and the fuel cost is then calculated accordingly. There are two more different fuels that the ministry buys (crude oil and gas oil), but they were not used in WDPS and are thus irrelevant in this research. In addition, the total costs and quantities of HFO and NG for the fiscal year 07/08 were also obtained from the budget department in MEW for cross checking and approval. The figures were matched and confidence in the data was achieved. Due to the confidentiality of the data and the secrecy promises that were made, the details of the data had to be withheld from this report.

Every year, the Cost Evaluation department issues a detailed report regarding all operational costs of all the power stations in Kuwait. The WDPS costs report for the fiscal year 07/08 was obtained from the Cost Evaluation department and it contains all kinds of costs of the production of electricity and water from WDPS. Regarding electricity, the report had distinguished between fuel cost and all other costs, which were considered as a fixed cost in Section 6.5. The report gives a lump sum figure for the fuel cost and it states that the cost of fuel used for electric power production is 62% of the total cost, whereas the rest of the report gives detailed costs of the operation, maintenance, wages, pensions, depreciation of assets, spare parts, etc. Moreover, the final outcome of the report, regarding electricity, is the cost of one kilowatt of power and that was 0.01959 KD/kW for the fiscal year 07/08.

7.2.3 WDPS data manipulation

The data obtained from WDPS operation department was fed first to an excel sheet. For every day in fiscal year 07/08 a row had been assigned that contains the date, the total production, HFO quantity, HFO price, NG quantity, NG price, and the total fuel cost. The quantities of HFO and NG were multiplied by their prices of the month and then added together to get the total fuel cost. Since WDPS operates 16 distillation units from the generated power of the 8 steam turbines, a standard 62% of the total fuel cost is assigned by MEW as the cost of electric power production. As a result, the total fuel cost of the electric power production in WDPS is recalculated again according to the same percentage.

The data was fed to 12 Matlab codes for every month of 07/08 to sort the information of each generator and to find an expression that represents their behaviours. Each Matlab code contains the monthly data of every generator arranged in terms of its production and fuel cost. Then, Matlab's regression method was used to obtain the relationship between the production and cost of the 8 generators. Unfortunately, the regression method produced solutions that had unacceptably large mean square errors, so it was discarded and an alternative approach was sought.

Professional software called "DataFit" was eventually used to solve the problem of finding suitable expressions for the production/cost relation (refer to Section 6.5). Moreover, DataFit produced many polynomial solutions that had different orders and varying standard errors. Extensive tests were conducted to eliminate undesirable solutions and narrow the selection to the best fit and small standard error solutions.

In DED, the operation's scope of the problem is 24 hours. Thus, the formula to represent the relation between production and cost must be developed in accordance with this time frame. Since every month involves a different fuel cost, the computations must be conducted for each month separately. The behaviour of the production/cost in one month is different than the behaviour in other months. Furthermore, the averages of the fuel costs, the total power production, and the load demands for every month were calculated and used in obtaining the final expression of the production and cost relation. This approximation made the results of the regression method suitable for application in every day of the month.

There was a massive amount of data in hand and significant effort was needed to ensure that the best solution was to be obtained. For example, every month there were 8 generators, 24 power productions quantities, and 24 fuel costs for 30/31 days. The data of each month was arranged in arrays to make it easier to locate and call any required information. To start the regression method, the supply of the power production and its fuel cost for one generator for all of the days in the month were needed. Next, the specific data was fed to the regression method. As a result there were more than 290 formulae that express the correlation between the production and fuel cost of the specified generator. This procedure had to be repeated for all the generators in each month to produce 8 expressions. Lastly, the process had to be applied 12 times to have solutions for the whole year. Furthermore, each generator had slightly different behaviour than the others due to operation and/or manufacture differences. After 26 years of operation the differences in the behaviour of the generators were considerable.

There are operational data for 12 months, which increased the size of the available information. If not treated properly, the massive amount of data might be confusing and misleading. To narrow down the scope of the research, only June, July, August, and September of 2007 were chosen as test cases in this report. The generalization of the outcome of the regression method will be made after the demonstration of the practicality of the results for those 4 months. There are two main reasons for concentrating on the above 4 months. First, the peak of the load demand in Kuwait occurs every year from mid May till the end of September. Secondly, only during those months all of the 8 generators were in operation mode, whereas in other months, one, two, or three generators were out of service due to maintenance scheduling. Moreover, the regression method was applied on June's data first to produce a formula that expresses the production and cost relationship. The first, tenth, and twentieth hour's data of the 8 generators in June were fed to the regression algorithm and three different solutions for each generator were produced. The purpose of choosing 3 different hours was to make sure that the behaviour of the generators was maintained throughout the different load demands of the day. In addition, if the results of the first hour had not applied to the other months (July, August and September), alternative results were available to be used. The detailed results of the regression method are presented in Section 6.5.

The expression that resulted from the regression method for the first hour of operation in June was used in the DED algorithm for the WDPS system. Moreover, PS was implemented to solve the DED problem and to produce the proper dispatch that would decrease the fuel cost. The results were promising and managed to reduce June's fuel cost in WDPS by a considerable percentage. Then the same expression was used for July, August and September and once again all the results yielded lower fuel costs than the average fuel cost of the month. Due to the success of the developed expression in the chosen four months, a generalization of this expression for the rest of the months had been made. In addition, it was concluded that the developed expression is the first and most accurate representation of the relationship between the production and the cost of electric power in WDPS. Finally, the average of the load demands for the 4 months was calculated for the compilation of the DED model.

The final step was to add the developed solar and wind energy systems to the DED model of WDPS. The outcome of both RE systems would be added in the form of a power balance constraint to DED. Moreover, RE sources were designed to deliver up to 100 MW of electric power capacity and this would reduce the total production of the thermal system by about 10%. Further reduction in fuel cost is expected from solving the DED problem of WDPS. As a result, considerable reductions in the fuel and the total costs of the production of electric power in WDPS are anticipated.

7.3 New rating for the Solar Energy System

In Section 6.2, the solar energy model was presented with the MPPT criteria applied to optimise the output. The rating of the model was small and for experimental use only. The need for increasing the rating of the solar energy system was therefore essential at that stage of the research, since the rating of the model must fit the real life case specifications. Thus, the solar system model was modified to a new rating of 1 MW per one array of photovoltaic modules. Moreover, the new rating was achieved by increasing both the modules' output power and the number of modules per array. A Sanyo HIP-205BA 19 photovoltaic module was chosen for the final solar energy system design. Every module has an output power of 205 W and the number of modules needed for the new rating was calculated by dividing the desired new rating (1 MW) by the output power of the chosen module. As a result, the total number of modules needed for an output power of 1 MW was 4880 modules. Furthermore, the photovoltaic final array arrangement was chosen to be 80 modules in parallel ($N_p = 80$) and 61 modules in series ($N_s = 61$). The length and the width of the selected module are 1319 mm and 880 mm, respectively. Thus, the dimension of the 1 MW PV array is approximately 5666 m^2 (0.00567 Km^2).

In this report, the initial plans assumed the deployment of the solar energy system in WDPS at a level to produce approximately 5% of the total load demand in peak times (approx. 100 MW). This would require 100 arrays of photovoltaic modules mentioned above and an open area of 0.567 km^2. Additional areas would be needed for the roads and accompanying equipment, which makes the total area for the PV plant of about 0.65 km^2. It should be mentioned that the largest PV plant in the world is in Spain and its output power is 60 MW, which makes the proposed 100 MW PV plant in WDPS an unprecedented and ambitious design. As for future plans, the government of Kuwait has declared that by the year 2020 RE resources will produce 20% of the electric power of the country. The consideration of increasing the employment of solar energy in WDPS is the main objective for future research.

7.4 New rating for the Wind Energy System

As in Section 6.3, the rating of the wind energy system developed previously had to be modified to be applicable to the real life case of WDPS. The new ratings have been calculated according to the specifications of the SIEMENS 3.6 MW wind turbine. The initial objective power rating of the wind energy system is 100 MW (5% of the peak load demand in WDPS), which means that 28 SIEMENS 3.6 MW turbines are required. Unfortunately no details of the SIEMENS 3.6 MW wind turbine generator were available for the simulation part of this research. A request for relevant data was made to the official of SIEMENS on the 3rd of February 2010 and up to the date of writing this report no reply has been received. There were two avenues available to continue this research. First, the wind energy part of the research could be omitted and only the solar energy used in the simulation. Secondly, an approximation of the wind power could be determined from the mini scale wind turbine model presented in 6.3 and then applied to the real life case of WDPS. After evaluating both options, in consultation with the sponsors of this research and as a result of some further findings regarding availability of wind power in

Kuwait (see below), the first path was chosen, although further comments are provided at the end of this section.

In the meantime, more research had been conducted on wind power and a new perspective was reached regarding the potential usage of this type of renewable energy in the electric power system of Kuwait. The main conclusion from this investigation was that the potential advantages of deploying the wind power in Kuwait are more than questionable. It was found that the average wind speeds in Kuwait from the year 1996 till 2005 of 5.0 m/s, as supplied by KISR, are barely sufficient for the minimum operation of any wind turbine. The rated wind speed, at which the rated power of a typical turbine is obtained, was found to be in the range of 11-15 m/s. This means that in Kuwait a wind turbine would only be able to produce on average 3.7-9.3 % of rated power (see Table 50). The wind turbines already installed in the USA, UK, Denmark and Germany are reported to have been producing in practice on average between 12.7% and 24.1% of their rated power despite much more favourable wind conditions [88]. Another study conducted in Iraq [85] (the northern neighbour of Kuwait) quoted the highest monthly average wind speed in Iraq to be 5.5 m/s for an 8 years period. Interestingly, the authors stated that the highest wind speed was in Basrah, which is an Iraqi city nearest to Kuwait, and it was in the month of July. However, the wind turbine power results showed a modest performance instead of the authors' assumption that the system operated at a maximum output (rated wind speed was reported as 13 m/s !) [89].

Table 50: Wind turbine models data [88].

model	capacity	blade length*	hub ht†	total ht	area swept by blades	rpm range	max blade tip speed‡	rated wind speed§
GE 1.5s	1.5 MW	35.25 m	64.7 m	99.95 m	3,904 m^2	11.1-22.2	183 mph	12 m/s
GE 1.5sle	1.5 MW	38.5 m	80 m	118.5 m	4,657 m^2	-	-	14 m/s
Vestas V82	1.65 MW	41 m	70 m	111 m	5,281 m^2	14.4	138 mph	13 m/s
Vestas V90	1.8 MW	45 m	80 m	125 m	6,362 m^2	8.8-14.9	157 mph	11 m/s
Vestas V100	2.75 MW	50 m	80 m	130 m	7,854 m^2	7.2-15.3	179 mph	15 m/s
Vestas V90	3.0 MW	45 m	80 m	125 m	6,362 m^2	9-19	200 mph	15 m/s
Gamesa G87	2.0 MW	43.5 m	78 m	121.5 m	5,945 m^2	9/19	194 mph	13.5 m/s
Siemens	2.3 MW	46.5 m	80 m	126.5 m	6,793 m^2	6-16	169 mph	13-14 m/s
Bonus (Siemens)	1.3 MW	31 m	68 m	99 m	3,019 m^2	13/19	138 mph	14 m/s
Bonus (Siemens)	2.0 MW	38 m (125 ft)	60 m (197 ft)	98 m (322 ft)	4,536 m^2	11/17	151 mph	15 m/s
Bonus (Siemens)	2.3 MW	41.2 m	80 m	121.2 m	5,333 m^2	11/17	164 mph	15 m/s
Suzlon 950	0.95 MW	32 m	65 m	97 m	3,217 m^2	13.9/20.8	156 mph	11 m/s

Suzlon S64	1.25 MW	32 m	73 m	105 m	3,217 m^2	13.9/20.8	156 mph	12 m/s

*This figure is actually half the rotor diameter. The blade itself may be about a meter shorter, because it is attached to a large hub.
†Hub (tower) heights may vary; the more commonly used sizes are presented.
‡Rotor diameter (m) × π × rpm ÷ 26.82
§The rated, or nominal, wind speed is the speed at which the turbine produces power at its full capacity. For example the GE 1.5s does not generate 1.5 MW of power until the wind is blowing steadily at 27 mph or more. As the wind falls below that, power production falls exponentially.

The major disadvantage of wind power is its cost. One of the main practical outcomes – and thus a prime objective – of this thesis is to minimize the cost of electrical power production in Kuwait by developing and solving the ED problem. Moreover, the electric power production in Kuwait is costing the government of Kuwait about 0.020 KD/kW and it sells it for only 0.002 KD/kW. Production of electricity is considered as the most expensive commodity that the government offers to the population of Kuwait. So, adding another expensive low efficiency source of electric power would probably be unwise and probably not a sound technical solution. Wind power has been always considered an overpriced and inefficient source of electric power and many wind farm plans have been cancelled, decommissioned, halted or ended in Denmark, Netherlands, Ireland, and Spain for this reason [88]. However, one might argue that wind power is clean and environmentally friendly energy. This is true, of course, but the money that is going to be wasted by investing in an inefficient and expensive source of energy could be used in installing more filters to the fossil fuel systems, or insulate buildings better to reduce CO_2 [88]. In addition, Denmark, one of the world leading countries in wind power, has not been able to reduce the emission of greenhouse gases considerably between 1991 and 2004, according to the National Environmental Research Institute in Denmark [90]. (See Table 51)

Table 51: Danish greenhouse emission 1991-2004 [90]

	Base year	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
Emission and removals, Kyoto-protocol (CO2-equivalents [1000 Gg])	69.3	79.6	73.4	75.6	79.0	76.3	89.6	79.9	75.9	72.7	68.1	69.6	68.8	74.0	68.0
Changes compared to base year (CO2-equivalents [1000 Gg])	--	10.3	4.1	6.3	9.7	7.0	20.3	10,6	6.6	3.4	-1.2	0.3	-0.5	4.6	-1.4
Changes compared to base year (%)	--	15	6	9	14	10	29	15	9	5	-2	0	-1	7	-2

In conclusion, the research done on wind energy usage in countries which have over 20 years of wind power experience has led to the decision of discarding the wind power as a potential renewable source in Kuwait for the time being. Wind speeds have been found insufficient in Kuwait and the low efficiency and high cost of wind power have made the choice of deploying this type of energy source in Kuwait simply not feasible. In other words, Kuwait is not ready for wind power yet. Moreover, the lack of some crucial data for the simulation of the wind turbine generator has forced the cancelation of further research in considering wind power for the WDPS power station. This does not mean that wind power has not received the proper attention by the government of Kuwait or the author of this report. The wind power implementation in Kuwait will be left for future research when better circumstances are present. Moreover, the techniques developed in this thesis will be available for the wind power to be easily added to the Economic Dispatch model if or when required.

7.5 Implementation of Economic Dispatch

In this final part of the research, the hybrid solar-thermal model of WDPS is considered for implementation as an economic dispatch problem. The goal of implementing ED for the hybrid system is to minimize the fuel cost of the production of electric power in Kuwait. The absence of any scientific strategies for the electric dispatch in Kuwait requires further research in ED area and the development of daily/hourly dispatch criteria to overcome the excessive cost of electrical power production. Moreover, the addition of renewable energy sources to Kuwaiti electrical power system is also a desired objective by the Kuwaiti government. Low cost production, environment friendly energy and the availability of renewable energy sources are the main features that attracted the officials of MEW in Kuwait. As discussed in Section 7.4, the wind power was eliminated from the final model and only solar energy was used as a renewable energy source. The final hybrid system consists of the thermal and solar electric power systems. The solar energy system was developed earlier and it was designed to produce 5% of the peak load demand in WDPS (see Section 7.3). This percentage can be increased in future research opportunities and the goal of 20% of renewable energy power in 2020 can be achieved if proper plans and designs are prepared by the Kuwaiti government or private investors.

7.5.1 Implementations in June, July, August, and September 2007

The proposed model was first implemented in the four months that have the generators in full operational mode at WDPS. The selected four months were June, July, August, and September of 2007. The proposed model was solved by PS to find the optimal or near optimal solution for the DED problem of WDPS. The Sun intensity was varied to show the effectiveness of shadings, clouds or dust storms that might affect the photovoltaic operation. For testing purposes only, two Sun intensities were chosen to minimise the computational time and memory requirements. More Sun irradiations are added in the generalized model of DED for the WDPS case, which is presented in the next section. The results of the proposed model were compared with the average daily fuel costs to verify the effectiveness of the proposed algorithm and to show the savings that could have been made in electric power production at WDPS. Table 52 lists all the results of the proposed model and shows the effect of the implementation of DED and the solar energy in reducing the fuel cost. Although the percentages vary from one month to another, the gradual savings in each month separately show a constancy pattern. Solving the DED of WDPS has added a substantial amount of savings in fuel cost and had met all constrains and load demands of the minimization problem.

Table 52: Results of proposed model for June, July, August, and September 2007

	June 07	July 07	August 07	September 07
Average Fuel Cost KD/day	709884.240	747140.950	718475.690	755957.890
Proposed DED model Fuel Cost KD/day	502432.619	535105.724	560273.619	464868.367
Savings %	29.22	28.38	22.02	38.51
Proposed DED model + Solar (0.4 intensity) Fuel Cost KD/day	475511.984	507199.734	525378.579	451158.234
Savings %	33.02	32.11	26.88	40.32
Proposed DED model + Solar (0.8 intensity) Fuel Cost KD/day	451786.542	464704.667	495263.174	416904.840
Savings %	36.36	37.80	31.07	44.85

7.5.2 The Generalized DED Model for WDPS

In the sub-section 7.5.1 the DED model was tested four times (June, July, August, and September 2007) and in all cases the results showed considerable savings in fuel cost. In addition, all the constraints were sustained and the hourly load demands were met. As a result, the DED model for WDPS was shown to be an accurate representation for the relationship between fuel cost and electric power production in WDPS. In this sub-section, a generalized DED model, which was developed from the average interpolation of the chosen four months' data, is presented. Since the DED model requires hourly load demands, the average load demands for June, July, August and September of 2007 were calculated and fed to the proposed algorithm. Furthermore, the average daily electric power fuel costs for the four months were calculated and considered as a reference for demonstrating the savings. The operation of the solar energy system was simulated in a time period of twelve hours (average daylight duration in Kuwait), which lasts from 6 am to 6 pm. Lastly, the generalized DED model was tested on the solar/thermal system and all descriptive results and graphs are included in this report. It should be mentioned that the proposed DED model for the WDPS system is the first and only mathematical interpretation for WDPS' fuel costs and electric power production correlations.

The proposed algorithm was executed for different Sun intensities to simulate the different operation conditions. The solar system output power was fed to the load balance constraint, Equation 6.6, as a negative quantity to reduce the electric power needed from the thermal system. Furthermore, any reduction in the electric power of the thermal system will minimize the fuel cost and consequently the electric power production cost will be reduced in WDPS. This is the main motivation behind the implementation of the solar energy system, in addition to the argument that it is an environment friendly energy. Table 53 lists the power productions of the solar energy system for different Sun intensities and Figure 85 illustrates the gradual increase of electric power production in PV cells according to the Sun intensities. The desired solar energy system output power of 5% of the peak load demand of WDPS, 100 MW, is almost met at 100% Sun intensity.

Table 53: Power production from solar energy system

Sun Intensity (%)	Solar system power production (MW)
20	15.995
40	35.246
60	55.749
80	77.064
100	98.987

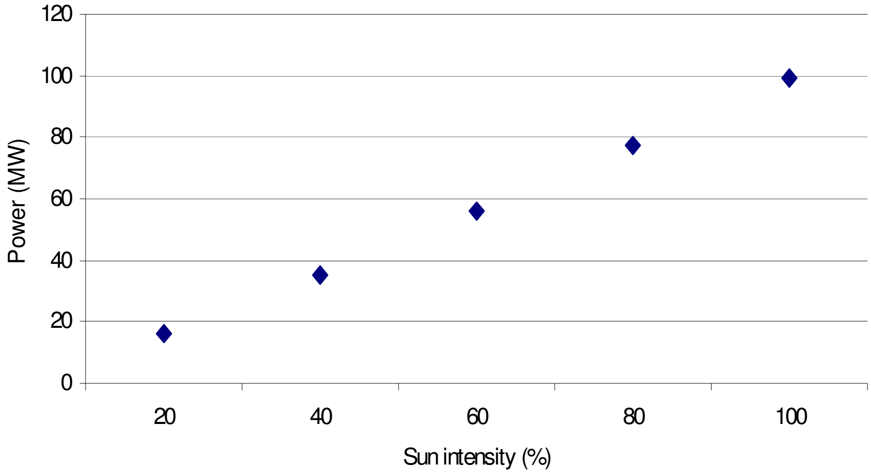


Figure 85: Power production from solar energy system

The results of the generalized DED model for maximum operation condition (max Sun intensity) are presented in Table 54. To prove the effectiveness of the proposed DED model and the implementation of the solar energy, the results were compared to the average fuel cost of June-September 2007. The results of the proposed DED model show the considerable amount of savings from the execution of the proposed DED model alone, 26.33% savings. Moreover, the penetration of the solar energy system in the thermal system has also reduced the cost of electrical power production in WDPS by an additional 7.48%. Although the solar energy system was designed to produce 5% of the peak load demand, the maximum operation of the system during the period that contains the highest load demands, 11 am to 6 pm, has increased the savings up to 33.81%.

Table 54: Results of the proposed DED with the solar energy system

	Fuel cost KD/day	Savings (%)
WDPS average (June-Sep)	732864	----
Proposed DED model	539932.048	26.33
Proposed DED model + solar (maximum operation condition)	485088.255	33.81

The proposed algorithm dispatch for the 100% Sun intensity is listed in Table 55. The improvement that has been done to the DED algorithm in Section 5.3 can be easily seen at the first and last rows of Table 55. The proposed algorithm maintained the units ramp-up and ramp-down constraints between the 24th hour and 25th hour, which is the 1st hour of next day, for all the cases in this sub-section. The solar energy system output powers sustain the MPPT, described in Section 6.2, during the simulation and the graphical representation of the maximum Sun intensity condition output power is illustrated in Figure 86.

Table 55: The dispatch of the proposed DED for maximum operation condition

Hour	Gen 1 (MW)	Gen 2 (MW)	Gen 3 (MW)	Gen 4 (MW)	Gen 5 (MW)	Gen 6 (MW)	Gen 7 (MW)	Gen 8 (MW)
1	140.60	224.59	300.00	299.99	300.00	105.46	111.87	300.00
2	158.56	192.66	300.00	267.99	300.00	102.23	111.87	300.00
3	164.55	192.66	300.00	235.99	300.00	106.74	115.87	268.00
4	148.48	192.66	300.00	203.49	300.00	107.31	115.87	268.00
5	133.24	192.66	300.00	171.49	300.00	107.31	114.81	268.00
6	112.00	192.67	300.00	127.42	300.00	107.31	130.81	268.00
7	111.64	188.15	300.00	82.42	300.00	80.00	85.81	223.00
8	138.40	220.31	300.00	80.00	300.00	102.33	108.97	178.00
9	151.08	250.21	300.00	82.53	300.00	128.33	126.30	146.36
10	159.08	278.21	300.00	110.03	300.00	131.83	141.69	182.17
11	163.60	284.24	300.00	155.03	300.00	144.80	146.17	227.17
12	161.55	277.71	300.00	189.12	300.00	136.80	141.15	272.17
13	158.91	271.03	300.00	234.12	300.00	134.42	137.54	300.00
14	158.93	271.53	300.00	279.12	300.00	143.37	138.06	300.00
15	164.96	288.34	300.00	300.00	300.00	145.66	147.06	300.00
16	160.28	275.40	300.00	300.00	300.00	136.89	143.44	300.00
17	153.00	262.84	300.00	300.00	300.00	127.55	142.62	300.00
18	147.60	249.53	300.00	300.00	300.00	121.16	121.51	300.00
19	157.81	267.20	300.00	300.00	300.00	132.05	135.44	300.00
20	160.40	275.01	300.00	300.00	300.00	137.14	139.95	300.00
21	162.44	285.87	300.00	300.00	300.00	140.25	143.95	300.00
22	158.11	276.46	300.00	300.00	300.00	135.62	141.00	300.00
23	155.07	262.90	300.00	300.00	300.00	134.78	137.25	300.00
24	147.44	241.36	300.00	300.00	300.00	113.07	114.32	300.00

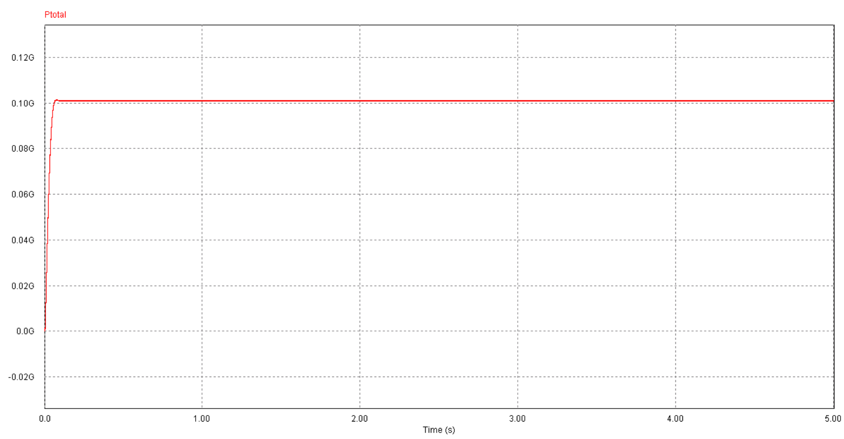


Figure 86: Solar system output power (W) (max Sun intensity)

After executing the proposed algorithm for different Sun intensities, informative data is produced for the implementation of the algorithm in any operation condition. It is easier now to simulate any climate condition that would affect the operation of the solar energy system. The wide range of solutions in hand could represent whether the operation condition is cloudy, partially cloudy, light dust storm, heavy dust storm, etc. The proposed DED model has produced the amount of electric power output from the solar energy for seven deferent intensities and any operation condition of the solar energy system could simulated by combining two or more of these outputs. For example, if the solar energy system is operating in a clear atmosphere, the electric power output is assigned the max Sun intensity result. Moreover, if light clouds or dust storms were present then the Sun intensity index would be reduced to 60% or 80%, which would lead to a reduction in the output power of the solar energy system. Heavy clouds and dust storms would therefore be assigned the lowest Sun intensities of 20% or 40%. For simplicity, the maximum operation conditions of the solar energy system for twelve operation hours and the penetration of the produced maximum output power of the solar energy system into WDPS power system were assumed. Nevertheless, the proposed algorithm was executed for mixed Sun intensities to clarify the effect of climate conditions on the solar energy system. Table 56 contains the results of the proposed algorithm for an operation condition of two hours light dust storm, eight hours of sunny sky and two hours of heavy clouds. Table 57 lists the proposed dispatch for this experimental operation condition.

Table 56: Fuel cost of the proposed DED model with mixed operation conditions

	Cost KD/day	Savings (%)
Proposed DED model + Solar (mixed operation conditions)	489581.412	33.19

Table 57: The dispatch of the proposed DED model with mixed operation conditions

Hour	Gen 1 (MW)	Gen 2 (MW)	Gen 3 (MW)	Gen 4 (MW)	Gen 5 (MW)	Gen 6 (MW)	Gen 7 (MW)	Gen 8 (MW)
1	112.28	230.50	296.53	296.22	296.58	144.53	113.96	291.90
2	130.28	230.50	296.53	296.22	296.64	108.49	82.74	291.90
3	144.27	198.50	296.53	296.22	296.64	104.49	87.25	259.89
4	144.20	198.50	296.53	264.22	296.64	104.49	103.82	227.39
5	144.20	198.50	296.53	232.22	296.65	105.25	118.75	195.39
6	115.46	198.50	296.53	232.22	296.66	101.25	134.25	163.33
7	121.73	196.40	300.00	187.22	300.00	80.00	89.25	118.33
8	142.30	228.43	300.00	142.22	300.00	116.00	114.39	106.59
9	152.99	254.46	300.00	97.37	300.00	124.54	129.85	125.61
10	159.42	273.19	300.00	125.72	300.00	135.76	138.31	170.61
11	162.42	279.70	300.00	170.72	300.00	145.75	146.81	215.61
12	159.11	271.61	300.00	214.57	300.00	134.77	137.84	260.61
13	155.12	260.88	300.00	259.57	300.00	128.26	132.19	300.00
14	156.85	268.82	300.00	300.00	300.00	130.87	134.47	300.00

15	164.98	288.32	300.00	300.00	300.00	145.71	147.00	300.00
16	160.28	275.39	300.00	300.00	300.00	136.86	143.49	300.00
17	165.57	289.83	300.00	300.00	300.00	146.37	147.99	300.00
18	153.11	274.03	300.00	300.00	300.00	140.38	136.04	300.00
19	156.93	269.12	300.00	300.00	300.00	131.76	134.70	300.00
20	159.94	276.61	300.00	300.00	300.00	136.26	139.70	300.00
21	162.94	281.64	300.00	300.00	300.00	144.22	143.70	300.00
22	158.12	271.64	300.00	300.00	300.00	139.96	141.48	300.00
23	155.07	269.61	300.00	300.00	300.00	133.18	132.13	300.00
24	149.79	230.13	300.00	300.00	300.00	120.49	115.79	300.00

7.6 Modified Solar Energy System

The desired output power of all RE sources that was declared previously was 10% of the maximum load demand in WDPS (200 MW). However, since the preliminary design assumed the solar energy system producing 5% of the maximum load demand and due to the decision not to use the wind energy system (see Section 7.4), a modified solar system was needed to achieve the desired RE output power. Hence the same PV cells, described in Section 7.3, were used in the modified system while the number of modules was doubled. The modified solar energy system has the capability of producing around 200 MW of clean and environmental friendly electric power.

As in the previous section, the proposed model was executed for different Sun intensities to represent the different operation conditions. The output powers of the solar energy system for the different Sun intensities are shown in Table 58 and Figure 87 The amount of power produced by the solar energy system is sufficient now to meet the desired RE output power, which is nearly met at maximum Sun intensity condition. As a result, the maximum power operation condition is also assumed in this sub-section. The results of the proposed DED under the maximum operating condition of the modified solar energy system are listed in Table 59. The proposed DED model has produced the optimal or near optimal solution with fuel cost savings up to 37.68% when compared to the reported average daily fuel cost in WDPS. Moreover, the proposed algorithm has succeeded in meeting the load demands and satisfying all the constraints. The continuity of the algorithm operation is guaranteed to follow smoothly to the next day without any violations in the units' ramp rate constraints as demonstrated by Table 60.

Table 58: Power production from modified solar energy system

Sun Intensity (%)	PV cells power production (MW)
20	31.990
40	70.492
60	111.50
80	154.13
100	197.97

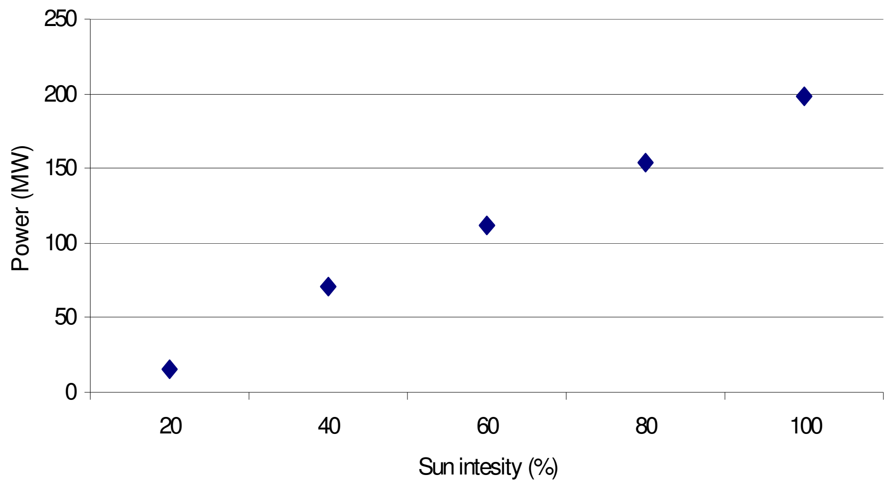


Figure 87: Power production from modified solar energy system

Table 59: Results of the proposed DED with the modified solar energy system

	Cost KD/day	Savings (%)
Proposed DED model + solar (maximum operation condition)	456700.769	37.68

Table 60: The dispatch of the proposed DED for maximum operation condition (modified solar system)

Hour	Gen 1 (MW)	Gen 2 (MW)	Gen 3 (MW)	Gen 4 (MW)	Gen 5 (MW)	Gen 6 (MW)	Gen 7 (MW)	Gen 8 (MW)
1	141.98	227.65	300.00	300.00	105.33	107.54	300.00	300.00
2	127.69	218.41	300.00	300.00	96.00	91.20	300.00	300.00
3	123.61	201.27	300.00	275.80	93.84	89.28	300.00	300.00
4	128.63	204.29	300.00	230.80	84.45	87.62	300.00	300.00
5	128.60	211.46	300.00	185.80	80.01	81.62	300.00	300.00
6	133.06	201.76	300.00	140.80	80.01	82.56	300.00	300.00
7	88.06	156.76	255.00	95.80	80.00	80.00	261.40	255.00
8	97.95	181.08	300.00	80.00	80.00	80.00	300.00	210.00
9	135.00	214.16	300.00	80.00	94.42	97.24	300.00	165.00
10	152.99	254.76	300.00	89.72	129.55	130.46	300.00	146.55
11	160.99	277.67	300.00	118.77	138.74	134.31	300.00	191.55
12	160.41	274.95	300.00	133.33	137.27	137.01	300.00	236.55
13	160.90	276.46	300.00	142.28	138.25	137.58	300.00	281.55
14	160.90	276.46	300.00	176.34	140.74	137.58	300.00	300.00
15	162.18	280.48	300.00	221.34	141.29	141.75	300.00	300.00
16	149.40	260.01	300.00	266.34	116.89	124.39	300.00	300.00

17	139.17	237.02	300.00	300.00	101.20	109.64	300.00	300.00
18	135.11	214.16	300.00	300.00	94.56	97.00	300.00	300.00
19	160.11	259.16	300.00	300.00	136.68	136.55	300.00	300.00
20	160.13	277.64	300.00	300.00	137.68	137.05	300.00	300.00
21	163.15	284.10	300.00	300.00	142.22	143.03	300.00	300.00
22	158.45	272.48	300.00	300.00	140.03	140.24	300.00	300.00
23	155.56	271.76	300.00	300.00	133.43	129.24	300.00	300.00
24	151.55	232.27	300.00	300.00	121.17	111.21	300.00	300.00

The levels of the output power of the modified solar energy system vary according to the Sun intensities and simulating different working conditions relies totally on those powers. For example, the solar energy system output power for the maximum Sun intensity condition is illustrated in Figure 88. Experimental operational conditions for the solar energy system were simulated to demonstrate the effectiveness of the proposed DED model. The operating conditions were assumed to be three hours of a partially cloudy morning, eight hours of sunny sky and one hour of a strong dust storm. The partially cloudy, sunny and the storm operation conditions were given 60%, 100% and 20% of Sun intensities' corresponding solar energy system output powers, respectively. The outcomes of this simulated operation conditions are listed in Table 61 and the DED model proposed dispatch is given in Table 62. Once again the proposed DED model has shown its capability of handling any kind of operating conditions and has produced solutions with a substantial savings in fuel cost.

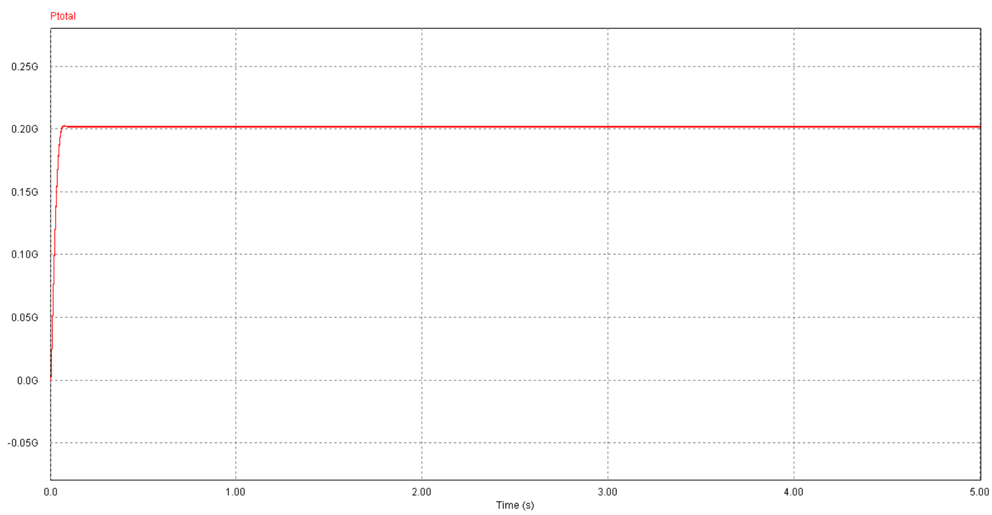


Figure 88: Modified solar energy system output power (W) (max Sun intensity)

Table 61: Fuel cost of the proposed DED model with mixed operation conditions

	Cost KD/day	Savings (%)
Proposed DED model + solar (mixed operation conditions)	468967.580	36.01

Table 62: The dispatch of the proposed DED model with mixed operation conditions

Hour	Gen 1 (MW)	Gen 2 (MW)	Gen 3 (MW)	Gen 4 (MW)	Gen 5 (MW)	Gen 6 (MW)	Gen 7 (MW)	Gen 8 (MW)
1	143.06	230.01	94.34	300.00	300.00	300.00	115.08	300.00
2	127.82	213.83	80.01	300.00	300.00	300.00	111.64	300.00
3	117.79	202.00	80.00	300.00	300.00	300.00	84.00	300.00
4	121.17	198.00	80.00	288.81	300.00	300.00	92.82	255.00
5	129.89	200.50	80.00	277.36	300.00	300.00	89.76	210.00
6	127.94	218.14	80.00	248.36	300.00	300.00	98.76	165.00
7	95.14	180.01	80.00	203.36	300.00	300.00	80.00	120.00
8	140.14	225.01	92.00	158.36	300.00	300.00	113.23	86.77
9	151.12	248.87	116.55	113.36	300.00	300.00	125.86	116.54
10	155.18	259.90	116.55	102.37	300.00	300.00	131.50	138.54
11	158.18	287.71	134.55	134.37	300.00	300.00	139.50	167.72
12	158.71	274.85	127.93	165.81	300.00	300.00	139.50	212.72
13	156.68	264.71	120.06	203.63	300.00	300.00	134.23	257.72
14	152.82	250.23	111.72	248.63	300.00	300.00	128.62	300.00
15	152.83	259.20	112.73	293.63	300.00	300.00	128.64	300.00
16	145.43	241.58	99.69	300.00	300.00	300.00	130.33	300.00
17	140.51	238.71	96.35	300.00	300.00	300.00	111.46	300.00
18	166.25	270.71	136.35	300.00	300.00	300.00	133.50	300.00
19	158.71	270.94	124.73	300.00	300.00	300.00	138.12	300.00
20	161.35	278.51	131.03	300.00	300.00	300.00	141.60	300.00
21	163.39	284.51	139.00	300.00	300.00	300.00	145.60	300.00
22	158.95	279.89	128.90	300.00	300.00	300.00	143.46	300.00
23	156.93	271.89	122.28	300.00	300.00	300.00	138.90	300.00
24	150.94	248.39	93.77	300.00	300.00	300.00	123.10	300.00

7.7 Conclusion

Two solar energy systems with deferent output power capabilities were developed and tested in this chapter. These two solar energy systems were implemented with different output Sun intensities to simulate the different operation conditions that the systems may face in real life situations. The proposed DED model was executed for two deferent cases of operating conditions. The results show that the proposed DED model succeeded in achieving the optimal or near optimal solutions in two different cases. In addition, the DED model has managed to decrease the fuel cost in WDPS significantly. All load demands and constraints were met in the implementation of the proposed DED model and the smooth transaction to the next day of operation was guaranteed. In short, the first accurate representation of the correlation between the power production and fuel cost in

WDPS in Kuwait has been tested in this chapter and the results demonstrate the effectiveness of the proposed DED model for real life implementation.

8 Conclusions

This report introduces a new approach based on Pattern Search (PS) algorithm to study power system Economic Dispatch problems with valve-point and dynamic effects, formulated as a constrained optimisation problem. The proposed method has been applied to several test cases and compared with Evolutionary Programming (EP), Hybrid Stochastic Search (HSS), Genetic Algorithm (GA) and Simulated Annealing (SA). The results suggest that PS outperforms the other methods in terms of a better optimal solution and significant reduction of computing times in most of the cases. On the other hand, the PS is more sensitive to the initial guess and appears to rely on how close the given initial point is to the global solution. This makes the PS method possibly more susceptible to getting trapped in local minima. However, the much improved speed of computation allows for additional searches to be made to increase the confidence in the solution. To overcome the problem of the need for the initial guess, hybrid methods were introduced. A combined GA-PS-SQP (Genetic Algorithm – Pattern Search – Sequential Quadratic Programming) hybrid algorithm was developed and used to solve all the cases in this report; it was found that such formulation led to substantial savings in computing times. Furthermore, PS was also used to solve the Dynamic Economic Dispatch problems. Two particular modifications were added to enhance the performance of the proposed algorithm and the results, when compared to other methods from the literature, have shown great quality in terms of lower fuel costs and shorter execution times. Overall, the PS algorithm was shown to be very helpful in studying optimisation problems in power systems and was therefore assumed to be the primary solver for the final DED model developed in this work.

The correlation between the fuel cost and electric power production in West Doha Power Station (WDPS) was studied. The first, and to date the only, formulation that represents this correlation was produced and tested for its accuracy and applicability as a DED model for WDPS. The results demonstrate that the developed DED model offers potentially huge savings in fuel costs, while complying with all constrains and limits. The proposed DED model can therefore be considered as an adequate interpretation of the fuel cost and power production relationship in WDPS.

The introduction of renewable energy (RE) to the electric power system in Kuwait was investigated and implemented in the models. Solar and wind energy systems were chosen as the most promising resources in the particular circumstances of Kuwait. The solar energy system was found to be suitable for deployment due to its commercial power production capability. On the other hand, the study of wind energy system has revealed that wind speed in Kuwait is insufficient for adequate wind power production. The addition of RE sources was planned to produce 200 MW, which would reduce the total power production cost in WDPS by minimizing the fossil fuel consumption. However, as a decision was made not to pursue wind power in this study, as a consequence of insufficient natural resources due to climatic conditions, a modified solar energy system was designed to meet the desired RE power production. Furthermore, the Maximum Power Point Traction (MPPT) technique was used to ensure the optimal power production of the RE sources. The output power of the RE sources was applied as the power balance constraint in the DED model of WDPS.

Lastly, the proposed DED model was tested on the hybrid solar/thermal system using PS as the solver. Two different cases of operating conditions were designed for both solar energy systems, intended to simulate the typical conditions in Kuwait. The results of the proposed DED model showed a considerable amount of potential savings in the cost of electrical power production in WDPS (up to 26%). Moreover, the addition of RE sources to the existing thermal system in WDPS has the potential to increase the savings in electric power cost by 11%.

In conclusion, the research conducted within this PhD has considered both the general issues of the Economic Dispatch and the more particular aspects applicable to the peculiar requirements of the Kuwaiti electricity systems. In terms of scientific achievements, this work is a step forward in the understanding, description, formulation and analysis of the relationships which exist between different components of the power system from the point of view of its economics. The Dynamic Economic Dispatch (DED) approach has been made more consistent and ways of introducing renewable energy (RE) sources into the model have been explored. Pattern Search based methods have been employed in a novel way to provide an efficient and reliable tool for simulation.

Throughout this work the electricity system in Kuwait has been used both as an example and a particular object for improvement. This was also necessary to satisfy the sponsors of this research. The special climatic conditions of Kuwait imposed particular solutions while one of the objectives of the thesis was to offer solutions potentially beneficial to the State of Kuwait. The penetration of RE sources into the Kuwaiti electric power system had never been investigated on the scale undertaken in this report. For example, the design of solar systems for commercial power production and the integration of RE sources with the Kuwaiti utilities are considered in this thesis for the first time.

Finally, particular attention was paid to modelling and improving the operation of the West Doha Power Station (WDPS), considered in the thesis as a case study. The proposed DED model of WDPS is the first and has been shown to be a very accurate interpolation of the fuel cost and electric power production relationship. The substantial potential savings in the power production of WDPS, while meeting all constraints and limits of the optimisation problem, is considered a significant outcome of the work. Moreover, the Pattern Search based methods, applied in this research, have never been used before in the context of DED problems, while the modifications that have been added to enhance the performance of DED are also considered significant.

Overall, it is believed that all objectives, as formulated in Sections 1.8 and 1.9 of this report, have been achieved.

Future Work

Regarding extending this work and future follow-up developments, the addition of the emission index to the proposed DED model is probably the most appropriate next step to be taken. The importance of the environmental protection has risen recently. After the Kyoto convention and the declaration of the Kyoto Protocol Treaty in 2005, the world's attention turned towards the collective emissions of greenhouse gases that the industrial nations produce every year. Moreover, a reduction in the emission was demanded urgently by the United Nations officials. The addition of the emission index to the proposed DED model of WDPS would be a positive step towards protecting the environment.

Kuwait has plans to employ RE sources to substitute up to 20% (by 2020) of its electric power production that is currently totally relying on fossil fuel and Natural Gas. The task of designing a DED model for the whole Kuwaiti electric power system to produce 20% of Kuwait electric power production from RE sources is my ambition after concluding my PhD degree. Moreover, the addition of other RE sources, such as wind, fuel cells and sea wave movements, as possible clean and environmental friendly alternatives for the power production in Kuwait, should also be investigated in the future.

Appendix A

Publications:

2010

Alsumait, J. S., Sykulski, J. K. and Al-Othman, A. K. (2010) A hybrid GA–PS–SQP method to solve power system valve-point economic dispatch problems. *Applied Energy - Elsevier*, 87 (5). pp. 1773-1781. ISSN 0306-2619

Al-Sumait, J., Qasem, M., Sykulski, J. K. and Al-Othman, A. K. (2010) An improved Pattern Search based algorithm to solve the Dynamic Economic Dispatch problem with valve-point effect. *Energy Conversion and Management*, 51 . pp. 2062-2067. ISSN 0196-8904

2009

Alsumait, J. S., Sykulski, J. K. (2009) Solving Economic Dispatch Problem using Hybrid GA-PS-SQP Method. In: *EUROCON 2009*, proceedings pages: 352-356, 18-23 May 2009, Saint Petersburg Russia.

2008

Al-Sumait, J. S., Sykulski, J. K. and Al-Othman, A. K. (2008) Solution of Different Types of Economic Load Dispatch Problems Using a Pattern Search Method. *Electric Power Components and Systems*, 36 (3). pp. 250-265. ISSN 1532-5008

2007

Alsumait, J. S., Sykulski, J. K. and Alothman, A. K. (2007) Application of Pattern Search Method to Power System Economic Load Dispatch. In: *Third IASTED Asian Conference Power and Energy Systems*, 2-4 April 2007, Phuket, Thailand.

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Appendix B

1) The Circle Plane:

In this test case a standard circle plane model has been used to be solved by PS to find the minimum points of a circle. It is clear that the minimum points of a circle in the first quadrant are those in the lower left side of the circle. This test case consists of a circle centred at point (10, 10) with a radius of 7. The test case has been treated as a multi objective functions in which x is denoted as objective function 1 and y is denoted as objective function 2. The model multi objective function is:

$$(x-a)^2 + (y-b)^2 = r^2$$

where $a = b = 10$ (centre point), and $r = 7$ (radius).

PS has been implemented to minimize the multi objective function of the test case. Moreover, the PF has been added to the model to show the trade off between the two objective functions. The results are shown in Figure 89.

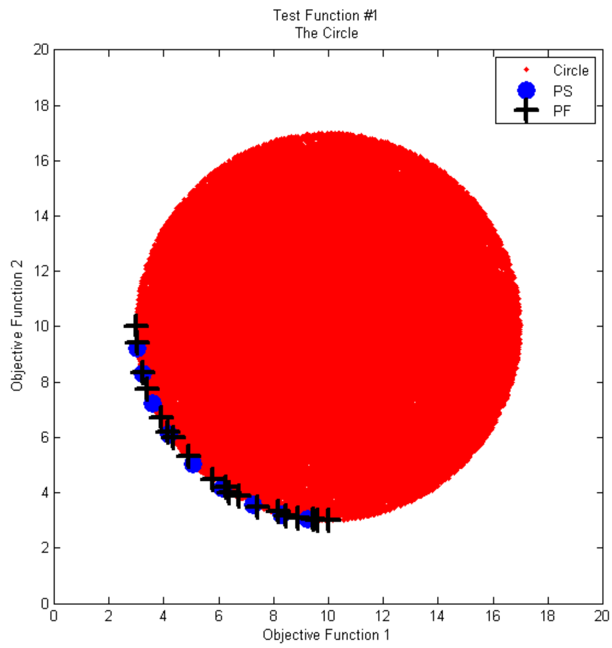

Figure 89: Test Case 1

It can be easily shown that PS has successfully located the minimum solutions in the lower left side of the standard circle (blue circles). In addition, the PF for this test case is also illustrated in Figure 89 (black plus signs). The trade off relation between the first and second objective functions ranges from 0.1 to 0.9.

2) The Ellipse Plane:

In this test case, PS was implemented on a standard ellipse plane to find its minimum points. The equation of the ellipse is as follows:

$$X(t) = X_c + a\cos t\,\cos\phi - b\sin t\,\sin\phi$$

$$Y(t) = Y_c + a\cos t\,\sin\phi + b\sin t\,\cos\phi$$

where $(X_c\ ,\ Y_c) = (5\ ,\ 5)$ is the centre of the ellipse, and a (= 5) and b (= 4) are the major and minor radiuses, respectively. The major and minor radiuses were changed randomly to produce the ellipse plane. The results of PS and the PF were plotted on the ellipse plane to illustrate the quality of solutions (See Figure 90).

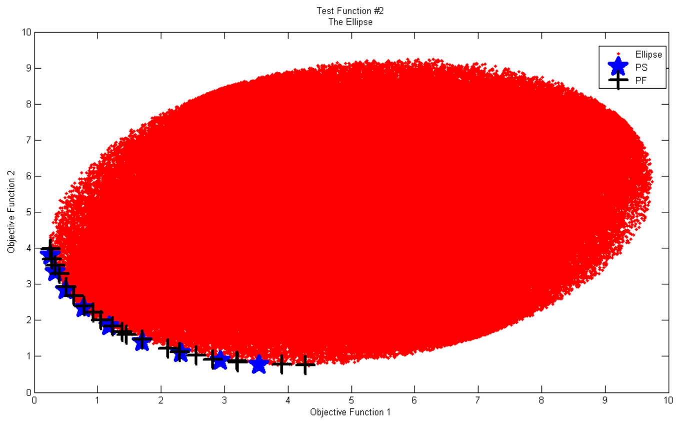

Figure 90: Test Case 2

PS has succeeded in obtaining the optimal minimum of the ellipse which is located in the lower left side. Furthermore, the PF supplies a wide rage of possible optimal or near optimal solutions and it is up to the nature of the problem in hand that on of these solutions is selected.

Appendix C

Matlab code for the Dynamic Economic Dispatch problem (the improved version in Sec. 5.3)

1) Main Code

```
%Main code for the improved algorithm in DED chapter
clear all;

global ploss;
global M; % total emission
global F1;  % The Total Cost = fuel + emission
global fuel emission;

%Setting key reference parameters for testing
acceptableFuelFraction = .0002;
acceptableEmissionFraction = .0002;
bestFuel = 48621;
bestEmission = 21189;

%Setting the inequality vectors A . X <= b
A=[];
b=[30 30 40 50 50 30 30 40 50 50]';% this UR and DR in eq 5 in the paper

%Setting the equality vectors Aeq . X = beq
Aeq=[];
beq=[];

%Setting the lower(lb) and upper(ub) limits eq 4 in the paper
lb=[10 20 30 40 50]';
ub=[75 125 175 250 300]';
limits = [30 30 40 50 50];
minPower =[410 435 475 530 558 608 626 654 690 704 720 740 ...
           704 690 654 580 558 608 654 704 680 605 527 463]';

%nuber of variables
n=5;

%Setting the options for the PS tool box
options = psoptimset('MeshExpansion',2,'MaxFunEvals',10000*n,...
           'PollMethod','gpspositivebasis2n','CompletePoll','on',...
           'PollingOrder','success','MeshAccelerator','on',...
           'PenaltyFactor',100,'InitialPenalty',50,...
           'MeshContraction',0.5,'TolMesh',1e-006,'TolBind',1e-003,...
           'TolFun',1e-6, 'Display', 'off');

%initialization of the generators output
X=zeros(24,5);

%starting the algorithm calculations
successfullRuns = 0;
unsuccessfullRuns = 0;
minFVAL = inf;
for runIndex = 1: 100  %setting the number of algorithm runs
    t=cputime;         %saving the algorithm starting time
    fprintf('Run number: %d\n\n', runIndex);
    successful = 1;
    M = 1;
    FVAL = [];
    fuel1 = [];
```

```
    emission1 = [];
    x0=[10 20 30 40 50];
    x0 = x0 + rand(1, size(x0, 2)) .* (ub - lb)'; %setting the random
starting point

    EXITFLAG = 0;
    itt = 0;

%Calling PS to solve the problem for the first hour
    while (EXITFLAG == 0 && itt < 10)
        [X(M,:),FVAL(M),EXITFLAG,OUT] =
patternsearch(@objfunc,x0,[],[],[],[],lb,ub,@nlcon,options);
        x0 = X(M, :); %saving the solution of PS
        itt = itt+ 1;
    end
    fuel1(M)=fuel; %saving the fuel cost returned from the function
    emission1(M)=emission;  %saving the emission returned from the
function

%first improvement:(first hour)
%changing the upper and lower limits according to the unit up and down
%rates
    result = (X(M, :)' + limits') <= ub;
    ub1 = (X(M, :)' + limits') .* result;
    indeces = find(ub1 == 0);
    ub1(indeces) = ub(indeces);
    result = (X(M, :)' - limits') >= lb;
    lb1 = (X(M, :)' - limits') .* result;
    indeces = find(lb1 == 0);
    lb1(indeces) = lb(indeces);
    x0 = X(M, :);
    count = 1;
    fprintf('Finsihed with hour %d, and the exitflag was: %d\n', count,
EXITFLAG);

%Calling PS to solve the problem for the hours 2 to 24
    for M=2:24
        EXITFLAG = 0;
        itt = 0;
        while (EXITFLAG == 0 && itt < 10)
            [X(M,:),FVAL(M),EXITFLAG,OUT] =
patternsearch(@objfunc,x0,[],[],[],[],lb1,ub1,@nlcon,options);
            x0 = X(M, :);
            itt = itt + 1;
        end

%first improvement:(hours 2 to 24)
%changing the upper and lower limits according to the unit up and down
%rates
        result = (X(M, :)' + limits') <= ub;
        ub1 = (X(M, :)' + limits') .* result;
        indeces = find(ub1 == 0);
        ub1(indeces) = ub(indeces);
        result = (X(M, :)' - limits') >= lb;
        lb1 = (X(M, :)' - limits') .* result;
        indeces = find(lb1 == 0);
        lb1(indeces) = lb(indeces);
        count = count + 1;
        fuel1(M) = fuel;  %saving the fuel cost returned from the
function
        emission1(M) = emission;  %saving the emission returned from the
function
        x0 = X(M, :);
```

```
        fprintf('Finsihed with hour %d, and the exitflag was: %d\n',
count, EXITFLAG);

%second improvement:
%the algoritm checks the unit up and down constraints of the last
%hour (24th) with the first hour of next day
        if (M == 23)
            tempUB = ub1 + limits';
            result = tempUB <= ub;
            checkUB = tempUB .* result;
            indeces = find(checkUB == 0);
            checkUB(indeces) = ub(indeces);
            if (sum(checkUB < X(1, :)') ~= 0)
                successful = 0;
                fprintf('Upper bound cannot be met\n');
                break;
            end
            tempLB = lb1 - limits';
            result = tempLB >= lb;
            checkLB = tempLB .* result;
            indeces = find(checkLB == 0);
            checkLB(indeces) = lb(indeces);
            if (sum(checkLB > X(1, :)' ~= 0))
                successful = 0;
                fprintf('Lower bound cannot be met\n');
                break;
            end
            maxUB = X(1, :)' + limits';
            result = ub1 > maxUB;
            tempUB = maxUB .* result;
            indeces = find(result == 0);
            tempUB(indeces) = ub1(indeces);
            ub1 = tempUB;

            minLB = X(1, :)' - limits';
            result = lb1 < minLB;
            tempLB = minLB .* result;
            indeces = find(result == 0);
            tempLB(indeces) = lb1(indeces);
            lb1 = tempLB;
            ub1;
            lb1;
            X(1, :);
        end
        if (EXITFLAG == -2)
            fprintf('Could not find a good point. \n');
            successful = 0;
            break;
        end
    end
%saving the final solution
    if (successful == 1)
        sumf = sum(fuel1);
        sume = sum(emission1);
        sumt = sum(FVAL);
        if (sumt < minFVAL)
            minFVAL = sumt;
            minFuel = sumf;
            minEmission = sume;
            minX = X;
            minT = cputime - t;
            fprintf('This one is better than the minimum!!!!!\n');
        else
            fprintf('This one is not better than the minimum\n');
```

```
        end
%display the results
        fprintf('The total fuel is: %f\nThe total emissions is: %f\nThe 
total cost is: %f\n', ...
                sumf, sume, sumt);
        fprintf('The time it took for %d runs is: %f\n', M, minT);

        totalPower = sum(X, 2);
        comparison = [totalPower minPower totalPower - minPower];
        Check(X, limits);
    end
end
```

2) Objective Functions Code

```
%solve the objective functions f1 and f2 (eq 1 and 2) in the paper

function F1 = objfunc(x)

global fuel emission F1;

%Number of Generators:
N=5;

%Fuel Coast Coefficients
a=[25 60 100 120 40];
b=[2 1.8 2.1 2 1.8];
c=[8 3 1.2 1 1.5]*1E-3;
d=[100 140 160 180 200];
e=[42 40 38 37 35]*1E-3;

%Emission coefficients
al=[80 50 60 45 30];
be=[-0.805 -0.555 -1.355 -0.6 -0.555];
ga=[18 15 10.5 8 12]*1E-3;
nu=[0.655 0.5773 0.4968 0.486 0.5035];
delt=[0.02846 0.02446 0.0227 0.01948 0.02075];

%Lower limits
lb=[10 20 30 40 50];

f1 = a + b .* x + c .* (x .^ 2) + abs(d .* sin(e .* (lb - x)));
f2 = al + be .* x + ga .* (x .^ 2) + nu .* exp(delt .* x);

%Calculating the fuel cost and emission
fuel=sum(f1);
emission=sum(f2);

%calculating the total cost
F1=fuel+emission;
```

3) Non Linear Constraints Code (system losses)

```
%Solve the non linear equality constraint (system losses)

function [c, ceq] = nlcon(x)
global ploss;
global ceq;
global M;
```

```
%setting the 24 load demmands of the day
loaddem=[410 435 475 530 558 608 626 654 690 704 720 740 ...
        704 690 654 580 558 608 654 704 680 605 527 463];

%setting the loss matrix B, B0, and B00
B=[49 14 15 15 20; ...
   14 45 16 20 18; ...
   15 16 39 10 12; ...
   15 20 10 40 14; ...
   20 18 12 14 35]*1E-6;

%No inequalty non linear constraint
c=[];

%solving for equality non linear constraint for 24 hours
ploss=x*B*x';
ceq = [( sum(x))- loaddem(M) - ploss];
```

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