

# SOLVING ECONOMIC DISPATCH PROBLEM USING PARTICLE SWARM OPTIMIZATION

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## ABSTRACT

This project presents a new approach to solve Economic Dispatch (ED) using Particle Swarm Optimization (PSO) technique with consideration of several generators constraints to search the optimal solution and the minimum of total generation operating cost. Conventional optimization methods assume generator cost curves to be continuous and monotonically increasing, but modern generators have a variety of nonlinearities in their cost curves making this assumption inaccurate, and the resulting approximate dispatches cause a lot of revenue loss. In PSO technique, the movement of a particle is governed by three behaviors namely, inertial, cognitive, and social. The cognitive behavior helps the particle to remember its previously visited best position. This technique helps to explore the search space very effectively. The proposed method considers the nonlinear characteristics of a generator such as ramp rate limits, power balance constraints with maximum and minimum operating limits and prohibited operating zone for actual power system operation. The practicality of the proposed method was demonstrated for different cases on 6-unit generation system and 15-unit generation system based on IEEE standard operation. The PSO algorithms with the proposed objective function are being considered efficient in solving this kind of models. Also, PSO has been successfully applied in many complex optimization problems in power systems. The proposed function approach was first tested on some less complex systems and then the effectiveness of the PSO was compared with the research studies from several references of studied papers.

## ABSTRAK

Projek ini membentangkan satu kaedah baru untuk menyelesaikan masalah *Economic Dispatch (ED)* menggunakan teknik *Particle Swarm Optimization (PSO)* dengan mempertimbangkan beberapa kekangan mesin janakuasa sehingga memperoleh penyelesaian yang optimum dan mendapat nilai minimum keseluruhan kos operasi penjanaan kuasa. Kaedah penyelesaian konvensional menganggap keluk/graf kos operasi penjanaan adalah malar dan sentiasa meningkat, tetapi mesin janakuasa moden sebenarnya mempunyai pelbagai ketidakseimbangan dalam keluk/graf kos operasi penjanaan-kuasa. Andaian tersebut adalah tidak tepat dan apa yang berlaku menyebabkan penjanaan membazirkan banyak kuasa. Dalam teknik *PSO*, pergerakan partikal zarah dikawal oleh tiga tindakan iaitu inersia, kognitif, dan sosial. Tindakan kognitif membantu partikal mengingat kedudukan terbaik pernah dilawatinya iaitu titik minimum atau maksimum. Teknik ini membantu untuk meneroka ruang carian penyelesaian dengan sangat berkesan. Teknik ini akan mengambilkira ciri-ciri ketidakseimbangan dalam mesin penjana kuasa seperti had-had kadar lajukan penjanaan, keseimbangan kuasa janaan dengan had maksimum minimum dan juga zon operasi yang dilarang dalam penjanaan dengan menggunakan rumus fungsi objektif yang dicadangkan. Teknik yang dicadangkan ini akan ditunjukkan untuk kes penjanaan sistem penjanaan 6-unit dan sistem penjanaan 15-unit berdasarkan operasi standard IEEE. Teknik *PSO* dengan rumus fungsi objektif dicadangkan adalah cekap dalam menyelesaikan model ujian tersebut. Teknik *PSO* juga telah berjaya menyelesaikan banyak masalah untuk mencari penyelesaian optimum yang kompleks dalam sistem penjanaan kuasa. Rumus fungsi objektif yang dicadangkan akan mula diuji mengenai beberapa model yang mudah dan ykemudian yang lebih kompleks. Keberkesanan teknik *PSO* kemudian akan dibandingkan dengan kajian penyelidikan dari beberapa rujukan.

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## **CHAPTER 1**

### **INTRODUCTION**

#### **1.1 Project History**

This project proposed the techniques of the Particle Swarm Optimization (PSO) method with proposed function which can be used to solve the Economic Dispatch (ED) problem and minimize the total cost of generating units with considerations several constraints which will be discussed in the next chapter.

The ED has the objective of generation allocation of the power generators, in such a manner that the generations cost is minimized while all operating constraints are satisfied. Conventional optimization methods assume generator cost curves to be continuous and monotonically increasing, but modern generators have a variety of nonlinearities in their cost curves making this assumption inaccurate, and the resulting approximate dispatches cause a lot of revenue loss. Evolutionary methods like PSO perform better for such problems.

Conventionally in ED problems, the cost function for generating units has been approximated as a quadratic function. The lambda-iteration method, base point and participation factors method and gradient method have been employed to solve the ED problem. Practically these cost functions of modern power generation units are highly nonlinear, and discrete in nature. Hence, these classical calculations based algorithms failed to solve these ED problems. The Dynamic Programming (DP) method has no restrictions on the nature of cost curves. It could generate global

solutions even for the nonlinear and discrete cost curves of the generation units but it has the drawback of '*curse of dimensionality*', that worsens for large scale problems, leading to extremely high computation time [6].

PSO algorithms can be considered efficient to solve the non-linear model of mathematical Economic Power Dispatch. Also, PSO has been successfully applied in many complex optimization problems in power systems. The PSO method has been used successfully meeting all constraints and compared with the classical optimization techniques such as genetic algorithms (GA), and evolutionary programming (EP).

Many of these older techniques have too much complexity and converge slowly but the Optimal Power Flow (OPF) obtained using PSO can be considered very well results. The results will indicate the applicability of the proposed method to the practical ED problem. Traditionally, fuel cost function of a generator is represented by single quadratic function with ED problems with quadratic cost functions are well solved by gradient-based optimization methods [4]

## 1.2 Project Objective

The Economic Dispatch (ED) problem of power generation involves allocation of power generation to different thermal units' diverse equality and in equality constraints. Particle Swarm Optimization (PSO) is algorithm model on swarm intelligence that finds a solution to an optimization problem in a search space or model and predicts social behavior in presents as objectives. The objective of the project is to minimize the total cost of generating unit with consideration of the practical operation constraints of generators. The purposes of the project include:

- (i) To study and solve ED Problem using PSO technique based on IEEE standard power generations systems (6-generation units and 15-generation units)
- (ii) To minimize the generations total cost while satisfying the load demand with consideration practical operation constraints of generating units.

- (iii) To simulate and demonstrate capability of PSO techniques to find the global solution for the optimal dispatch of power generation PSO techniques using MATLAB software.

### 1.3 Scope of Project

In this project, the focus will be concentrated on the controlling the committed generators' output such as the generation cost is minimized while satisfying the power demand and other constraints. As power demand increase and power generations cost booms in recent years, saving the operation costs of power system become an important issues. One of the choices is to operate generators to be more efficient and economically [4].

Traditionally, cost function of a generator is represented by single quadratic function. Economic Dispatch problems with quadratic cost functions are well solved by gradient based optimization method for example *Lagrangian* multiplier or Newton type method which are only suitable for fuel-cost curve with a linear and monotonically increasing functions. However in order to improve the accuracy of solution in ED problem studies, it requires a more accurate representation of cost function.

Therefore, the project's scope will cover several problems of power generations such as the piecewise quadratic cost function, generations levels between the minimum and maximum limits, power balance constraints, ramp rate limits, prohibited operating zones (POZ) and the line limits constraints. As a result, conventional optimization techniques are no longer the best choice as the new optimization techniques with consideration of constraints is discovered.

## 1.4 Report Structure

Chapter two will review about the Economic Dispatch (ED) Problems of power generating units which has always occupied an important position in the electric power industry. ED can be present a computational process where the total required generation is distributed among the generation units in operation, by minimizing the selected cost criterion, subject to load and operational constraints. The section of this chapter also explains about the Optimal Power Flow problems and Particle Swarm Optimization (PSO) technique which is quite similar to genetic algorithm and evolutionary algorithms.

Chapter three discussed about the method on how to use Particle Swarm Optimization techniques to solve the Economic Dispatch problems. Mathematical formulation of economic dispatch problem is reviewed briefly in this section. The PSO algorithm is outlined in this section and the proposed algorithm is presented.

Chapter four presents experimental results and the discussion about end result obtained from the simulation. The focus will be given on the analyzed data which converging to the optimal solutions. PSO searches for optimal solution via intersection with individual within a swarm population [4].

Chapter five draws conclusion for the experiment work on PSO technique to solve the ED problems. The results of the study clearly demonstrate the capability and effectiveness of the approaches. As the results will prove the promising of PSO techniques, there are great potentials for applying the proposed approaches to the various ED problems with more sophisticated constraints.

## **CHAPTER 2**

### **LITERATURE REVIEW**

#### **2.1 Common System of Electric Power**

Starting from very small utility networks, electric utilities have grown billion times larger. Now, electric power systems became widespread and complex in nature. From its birth to present, power system networks and utilities have gone through various stages of evolution. For the last one hundred years electric power systems operated as regulated dominations. In a regulated monopoly, an electric power system can be divided into four main functional zones; generation, transmission, distribution and retail service.

- a) Generation – generation is the conversion of electric energy from other forms of energy like chemical (gas, coal, and hydrogen), nuclear, solar, hydro energy, geothermal energy, wind and wave energy.
- b) Transmission – transmission is the transfer of bulk electric energy from one place to another through some transmission network. It connects the generator network and distribution network.
- c) Distribution – distribution is the process of delivering electric power from the local network to the consumers.
- d) Retail Service – retail service can broadly called retail customer service. Its main function is measuring and billing customers for the power delivered.

In a regulated monopoly, these four functional blocks are controlled by one single entity. As today's power system networks are very large in production volume and geographical area, their operation became a complex phenomenon which does not only depend on the state of technology but also on complex issues like economy, social advancement, environmental impact and political decisions.

In traditional monopoly, one company is allowed to generate, transmits and distribute electrical power to the consumers in one jurisdiction. The service area is primarily determined by political map and jurisdiction. In some cases, distribution is divided among two or more electric utilities, e.g. City Corporation or other private distribution companies. Price of electricity is determined by the same utility which is justified by cost of generation, transmission and distribution.

Electric power systems in the early days were developed on the concept of natural monopoly. Natural monopoly occurs if the production costs decrease as the output grows larger. Before 1990s, all power systems in the world were running as vertically integrated monopoly system. Later it was realized that the electric power industry was not necessarily a natural monopoly at least when it came to generating electricity. It was proven that open access and competition in business lowers the unit price. The same is believed to happen in electric power industry.

Therefore, bringing competition in power sector in generation and retail consumer level became essential. The regulatory process and lack of competition gave electric utility no incentive to improve on yesterday's performance or to take risk on new ideas that might increase customer value. The main argument used to support deregulation is that a free market promotes efficiency. In a regulated environment, for example, wholesale and retail electricity power prices are calculated based on a utility's costs. If a utility invests in what turns out to be an uneconomical project, it can still add the costs of the investment to the price it charges for electricity. Thus, the risks and economic consequences of a poor investment are passed to the electricity customer. Competition will encourage new technologies for generating electricity with better efficiency and inefficient generating plants will die out.

In many of the countries where electric utility deregulation first occurred e.g. Argentina, England, the government was privatizing the industry. By deregulating i.e. by privatizing the power sector, government can withdraw huge amount of money. It has also been proved in many cases that a private organization can serve better than a government organization. Competitions also increase customer focus. Another reason for deregulation is to give customer a meaningful choice to select their supplier, although the term ‘customer’ is confined only to bulk or retail buyer.

## **2.2 Energy Management System**

The operational planning of the power system involves the best utilization of the available energy resources subjected to various constraints to transfer electrical energy from generating stations to the consumers with maximum safety of personal/equipment without interruption of supply at minimum cost. In modern complex and highly interconnected power systems, the operational planning involves steps such as load forecasting, unit commitment, economic dispatch, maintenance of system frequency and declared voltage levels as well as interchanges among the interconnected systems in power pools [33].

The generation of the power system as we know it today had its origin in the need for electric utility companies to operate their generators as economically as possible. To operate the system as economically as possible requires that the characteristics of all generating units be available so that the most efficient units could be dispatched properly along with the less efficient.

In addition, there is a requirement that the on/off scheduling of generators units be done in an efficient manner as well. The scheduling of generators with limited fuel or water supplies is incorporated in energy management systems. This allows operators to further reduce the cost of operation by taking advantage of cheaper fuels or hydropower. In the environment where cost minimizations not only the objective, profit maximization is the also the concern. Fast and accurate economic dispatch solution is one of the requirements in the scenario as well [13].



### 2.3 Economic Dispatch (ED)

EPAct defines “Economic Dispatch” by means of, “*The operation of generation facilities to produce energy at the lowest cost to reliably serve consumers, recognizing any operational limits of generation and transmission facilities.*” [EPAct 2005, Sec. 1234 (b)]. Demand of the power keeps increasing and the energy cost swing over years.

Economic dispatch is generation allocation problem and defined as the process of calculating the generation of the generating units so that the system load is supplied entirely and most economically subject to the satisfaction of the constraints. Historically economic dispatch is being carried out since 1920. It was the time when engineers were concerned with the problem of economic allocation of generation or the proper division of the load among the generating units available.

Prior to 1930, the methods in use includes: the base load method and best point loading. It was recognized as early as 1930, that the incremental method, later known as the equal incremental method, yielded the most economic results. The analogue computer was developed to solve the coordination equations. A transmission loss penalty factor computer was developed in 1954. An electronic differential analyzer was developed and used in ED for both offline and on-line use by 1955. The digital computer was investigated in 1954 for ED and is being used to date [33].

Researchers still keep looking for the best solution to saving the operation costs of power generations. Generators must be operational efficiently and economically. The objective of solving the Economic Dispatch (ED) problem is controlling the generators’ output so the total cost is minimized while sustaining the power demand and other constraints.

## 2.4 Basic Formulation for Economic Dispatch

The objective of ED is to simultaneously minimize the generation cost rate and to meet the load demand of a power system over some appropriate period while satisfying various generators constraints which have been discussed later. To solve ED problem, the basic constrained optimization problem at specific operating interval can be modified as

$$\text{Min } F_T = \sum_{i=1}^n F_i(P_i) \quad (2.1)$$

where  $F_T$  the total fuel is cost;  $F_i(P_i)$  and  $P_i$  are the cost function and the real power output of generator  $i$ , respectively;  $n$  is the number of committed generators.

The fuel cost of each generator is usually presented by a single quadratic cost function which is expressed as in (2.2) :

$$\sum_{i=1}^n F_i(P_i) = \alpha_i + \beta_i P_i + \gamma_i P_i^2 \quad (2.2)$$

where  $\alpha_i$ ,  $\beta_i$  and  $\gamma_i$  denote the cost coefficients of the  $i$ -th generator. In case of using multiple fuels for a generator, the cost function is modeled as below:-

$$F_i(P_i) = \begin{cases} \alpha_{i1} + \beta_{i1} P_i + \gamma_{i1} P_i^2 & P_{i,b1} \leq P_i \leq P_{i,u1} \\ \alpha_{i2} + \beta_{i2} P_i + \gamma_{i2} P_i^2 & P_{i,b2} \leq P_i \leq P_{i,u2} \\ \vdots & \\ \alpha_{ik} + \beta_{ik} P_i + \gamma_{ik} P_i^2 & P_{i,bk} \leq P_i \leq P_{i,uk} \end{cases} \quad (2.3)$$

where  $\alpha_{ik}$ ,  $\beta_{ik}$  and  $\gamma_{ik}$  are the  $k$ -th fuel cost coefficients of unit and  $P_i$  considered as the power of  $i$ -th generating unit.

## 2.5 ED with losses consideration

When transmission distance is very small and load density is very high, transmission losses may be neglected and the optimal dispatch of generation is achieved with all plants operating at equal incremental production cost. However, in large interconnected network where power is transmitted over a long distances with low density areas, transmission losses are major factor and affect the optimum dispatch of generation.

One common practice for including the effect of transmission losses is to express the total transmission loss as a quadratic function of the generator power outputs [8]. The simplest quadratic form is

$$P_L = \sum_{i=1}^{n_g} \sum_{j=1}^{n_g} P_i B_{ij} P_j \quad (2.4)$$

A more general formula containing a linear term and constant term, referred to Kron's loss formula as in (2.5):

$$P_L = \sum_{i=1}^{n_g} \sum_{j=1}^{n_g} P_i B_{ij} P_j + \sum_{i=1}^{n_g} B_{0i} P_i + B_{00} \quad (2.5)$$

$B_{ij}$  are called the loss coefficients or B-coefficient, which are assumed to be constant for a base range of loads, and reasonable accuracy is expected when actual operating conditions are close to the base case conditions used to compute the coefficients. The economic dispatch problem is to minimize the overall generation cost, which will be discussed next with the other constraints.

## 2.6 Practical Operation Constraints of Generator

In order to solve the ED problem, the unit generation outputs are usually assumed to be adjusted smoothly and instantaneously. The most appropriate way to solve the

problem is economic dispatch generation output unit is commonly supposed that are arranged uniformly.

Practically, the operating range of all online units is restricted by their Power Generation Limits, Ramp Rate Limits (RRL), Prohibited Operating Zone (POZ), the limit of the power generation, the balance constraints and the transmission with losses consideration as previously explained. Hence all the constraints stated must be taken into account to achieve true economic operation.

### 2.6.1 Ramp Rate Limit (RRL)

Output power of each generator is limited to increase and decrease to a constant quality of power over a certain time interval due to the physical limitation of generators. The inequality constraints due to RRL for unit generation changes are given :-

- 1) as generation increases

$$P_i - P_i^0 \leq UR_i \quad (2.6)$$

- 2) as generation decreases

$$P_i - P_i^0 \leq DR_i \quad (2.7)$$

where is  $P_i$  the current output power, and  $P_i^0$  is the previous output power.  $UR_i$  is the up ramp limit of the  $i$ -th generator (MW/time-period); and  $DR_i$  is the down ramp limit of the  $i$ -th generator (MW/time period).

### 2.6.2 Prohibited Operating Zone (POZ)

A generation's unit may have prohibited operating zone due to the physical limitations of power plant components (e.g. vibrations in a shaft bearing are amplified in a certain operating region). For a prohibited zone, the unit can only operate above or below the zone. In practical operation, adjusting the generation

output  $P_i$  of a unit must avoid unit operation in the prohibited zones. These two disjoint regions form a non-convex set.

The feasible operating zones of unit  $i$  can be described as follows:

$$P_i^{\min} \leq P_i \leq P_{i,1}^l \quad (2.8)$$

$$P_{i,j-1}^u \leq P_i \leq P_{i,j}^l, j = 2, 3, \dots, n_i \quad (2.9)$$

$$P_{i,n_i}^u \leq P_i \leq P_{i,1}^{\max} \quad (2.10)$$

Where:

$j$	Number of prohibited zones of unit $i$ .
$P_i$	Output power of generator $i$
$P_i^{\min}$	Minimum power output limit of generator $i$
$P_i^{\max}$	Maximum power output limit of generator $i$
$P_{i,j}^l$ & $P_{i,n_i}^u$	Lower and upper boundaries of prohibited operation zone $j$

### 2.6.3 Generation Limit Constraints

Power generation for each generator should locate between the upper and lower limits; the following inequality constraint for each generator should be satisfied.

$$P_{i,\min} \leq P_i \leq P_{i,\max} \quad (2.11)$$

Where:

$P_i$	Output power of generator $i$ (MW)
$P_{i,\min}$	Minimum power output limit of generator $i$
$P_{i,\max}$	Maximum power output limit of generator $i$

#### 2.6.4 Balance Constraints

The total output power generation is the sum of the total power demand and total power losses. Hence the total output power is shown in Equation 2.12 below:

$$P_{Loss} + P_D - \sum_{i=1}^n P_i = 0 \quad (2.12)$$

and Equation 2.13 shows Error in MW:

$$Error = \left| \sum_{i=1}^n P_i - P_{Loss} - P_D \right| \quad (2.13)$$

Where:

$P_{Loss}$	Total active power losses of the network (MW)
$P_D$	Total average demand forecast for the dispatch period (MW)
$P_i$	Output power of generator $i$ for dispatched hour (MW)

#### 2.7 Evaluation function

The quality of each individual particle in the swarm is found using a fitness function called evaluation function. The popular penalty function method employs functions to reduce the fitness of the particle in proportion to the magnitude of the constraint violation. The penalty parameters are chosen carefully to distinguish between feasible and infeasible solution [10]

The evaluation functions for evaluating the fitness of each individual in the population. In order to emphasize the “best” chromosome and speed up convergence of the iteration procedure, the evaluation value is normalized into the range closing to the zero value.

The evaluation function  $f(P_i)$  is defined to minimize the non-smooth cost function given by Equation (2.1) for a given load demand  $P_D$  while satisfying the constraints given Equation (2.11) and Equation (2.13) as

$$f(P_i) = \sum_{i=1}^N F_i(P_i) + \alpha \left[ \sum_{i=1}^N P_i - (P_D + P_{Loss}) \right]^2 + \beta \left[ \sum_k^{n_i} P_i (violation)_k \right]^2 \quad (2.14)$$

where  $\alpha$  is the penalty parameter for not satisfying load demand and  $\beta$  represents the penalty for a unit loading falling within a prohibited operating zone. Basically, several constraints will be taken into account to satisfy the actual operations of the generators.

## 2.8 Optimal Power Flow Optimization

The optimal power flow procedure consists of methods of utilizing load flow techniques for the purpose of Economic Dispatch (ED). Some of the researchers before used the ac load flow model and others have used the dc load flow model. Then later it is based on the Power Quality decomposition and then using term optimization techniques. The ac optimal load flow problem on the other hand consists of finding the active and reactive power output and the voltage magnitudes at any generator unit, in order to minimize the operating cost while meeting various security constraints. Security constrained dispatch involves those dispatch activities which are constrained to respect selected system security limits. In general, optimal power flow requires use of network modeling as well as resource modeling and naturally results in higher system costs [11].

One type of bus in power flow was the voltage controlled bus, where the real power generation and voltage magnitude were specified. The power flow solution provided the voltage phase angle and the reactive power generation in practical power system, the power plants are not located at the same distance from the center of loads and their fuel costs are different. Also, under normal operating conditions the generation capacity is more than the total load demand and losses. Thus there are many options for scheduling generation. [8]

In an interconnected power system, the objective is to find the real power scheduling of each power plant in such way to minimize the operating cost. This means that the generator's real and reactive powers are allowed to vary within the certain limits so as to meet a particular load demand with minimum fuel cost. This is called optimal power flow (OPF) problem. The OPF is used to optimize the power flow solution of large scale power system. This done by minimizing the selected objective functions while maintaining acceptable system performances in terms of generator capability limits and the output of the compensating devices. [8] The objective functions, also known as cost functions, may present economic costs, system securities or other objectives. The OPF has been studied by many researchers and many algorithms using different objectives functions and methods have been presented.

## 2.9 Nonlinear Function Optimization

Nonlinear function optimization is an important tool in computer aided design and is part of broader class of optimization called nonlinear programming. The underlying theory and computational methods are discussed in many books. The basic goal is minimization of some nonlinear objective cost function subject to nonlinear equality and inequality constraints. [8]

### 2.9.1 Unconstrained Parameter Optimization

The mathematical tools that are used to solve unconstrained parameter optimization problems come directly from multivariable calculus. The necessary condition to minimize the cost function

$$f(x_1, x_2, \dots, x_n) \quad (2.15)$$

is obtained by setting derivative of  $f$  with respect to the variables equal to zero, i.e

$$\frac{\partial f}{\partial x_i} = 0 \quad i = 1, \dots, n \quad (2.16)$$



or

$$\nabla f = \mathbf{0} \quad (2.17)$$

where

$$\nabla f = \frac{\partial f}{\partial x_1}, \frac{\partial f}{\partial x_2}, \dots, \frac{\partial f}{\partial x_n} \quad (2.18)$$

which is known as the gradient vector. The terms associated with the second derivatives is given

$$H = \frac{\partial^2 f}{\partial x_i \partial x_j} \quad (2.19)$$

The previous equation results in a symmetric matrix called *Hessian* matrix of the function. Once derivative of  $f$  is vanished at local extrema  $(\hat{x}_1, \hat{x}_2, \dots, \hat{x}_n)$ , for  $f$  to have the relative minimum, the Hessian matrix evaluated at  $(\hat{x}_1, \hat{x}_2, \dots, \hat{x}_n)$  must be a positive definite matrix. This condition requires that all eigenvalues of the Hessian matrix evaluated at  $(\hat{x}_1, \hat{x}_2, \dots, \hat{x}_n)$  be positive.

In summary, the unconstrained minimum of a function is found by setting its partial derivative (with no respect to the parameters may be varied) equal to zero and solving for the parameters values. Among the sets of parameters values obtained, those at which the matrix of second partial derivatives of the cost function is positive are local minima. If there is a single local minimum, it is also the global minimum; otherwise, the cost function must be evaluated at each of the local minima to determine which one is the global minimum. [8]

### 2.9.2 Equality Constrained Optimization

This type of problem arises when there are functional dependencies among the parameters to be chosen. The problem is to minimize the cost function [8]. The problem is to minimize the cost function (2.1) subject to the equality constraints

$$g_i(x_1, x_2, \dots, x_n) = 0 \quad i = 1, 2, \dots, k \quad (2.20)$$

Such problems may be solved by the *Lagrange* multiplier method. This provides an augmented cost function by introducing  $k$ -vector  $\lambda$  of undetermined quantities. The unconstrained cost function becomes

$$\mathcal{L} = f + \sum_{i=1}^k \lambda_i g_i \quad (2.21)$$

The resulting necessary conditions for constrained local minima of  $\mathcal{L}$  are the following:-

$$\frac{\partial \mathcal{L}}{\partial x_i} = \frac{\partial f}{\partial x_i} + \sum_{i=1}^k \lambda_i \frac{\partial g_i}{\partial x_i} = 0 \quad (2.22)$$

$$\frac{\partial \mathcal{L}}{\partial x_i} = g_i = 0 \quad (2.23)$$

Note that equation (2.9) is simply original constraints.

### 2.9.3 Inequality Constraints Optimization

Practical optimization problem contain inequality constraints as well as equality constraints. The problem is to minimize the cost function

$$f(x_1, x_2, \dots, x_n) \quad (2.24)$$

subject to the equality constraints

$$g_i(x_1, x_2, \dots, x_n) = 0 \quad i = 1, 2, \dots, k \quad (2.25)$$

and the inequality constraints

$$u_j(x_1, x_2, \dots, x_n) \leq 0 \quad j = 1, 2, \dots, m \quad (2.26)$$

The *Langrange* multiplier is extended to include the in equality constraints by introducing  $m$ -vector  $\mu$  of undetermined quantities. The unconstrained cost function becomes

$$\mathcal{L} = f + \sum_{i=1}^k \lambda_i g_i + \sum_{j=1}^m \mu_j u_j \quad (2.27)$$

The resulting necessary conditions for constrained local minima of  $\mathcal{L}$  are the following:

$$\frac{\partial \mathcal{L}}{\partial x_i} = 0 \quad i = 1, \dots, n \quad (2.28)$$

$$\frac{\partial \mathcal{L}}{\partial \lambda_i} = g_i = 0 \quad i = 1, \dots, k \quad (2.29)$$

$$\frac{\partial \mathcal{L}}{\partial \mu_j} = u_j \leq 0 \quad j = 1, \dots, m \quad (2.30)$$

$$\mu_j u_j = 0 \text{ \& \; } \mu_j > 0 \quad j = 1, \dots, m \quad (2.31)$$

Note that Equation (2.15) is simply the original equality constraints. Suppose  $(\hat{x}_1, \hat{x}_2, \dots, \hat{x}_n)$  is a relative minimum. The in equality constraints (2.16) is said to be inactive if strict inequality holds at  $(\hat{x}_1, \hat{x}_2, \dots, \hat{x}_n)$  and  $\mu_j = 0$ . On the other hand, when strict equality holds, the constraint is active at this point, (i.e, if the constraint  $\mu_j u_j(\hat{x}_1, \hat{x}_2, \dots, \hat{x}_n) = 0$  and  $\mu_j > 0$ . This is known as the *Kuhn-Tucker* necessary condition.

## **2.10 Power generation optimization techniques**

One way to solve the ED problems with quadratic cost functions is by gradient-based optimization methods, for example Newton-type methods which are only suitable for fuel-cost curve with linear and monotonically increasing functions [4]. To improve more accurate solution in ED problem requires a more precise representation of cost function. Therefore, piecewise quadratic cost functions discovered in representing multiple options. However, ED problems with multiple-unit and piecewise quadratic cost functions will occur many local extreme points [4]. As a result, conventional optimization techniques are no longer the finest choice since they may fail to locate the optimal solution and result in considerable errors.

Recently, the advances in computation found a better solution of complex problems have led to using stochastic optimization techniques, such as evolutionary algorithm, differential evolution, Genetic Algorithm (GA), Artificial Bee Colony (ABC) and etc., for solving ED problems. One of them is Particle Swarm Optimization (PSO) method which is inspired from fish schooling and birds flocking [3]. It is a powerful method yet simple optimization algorithm that can perform extensive exploration of the problem space. Besides, it does not rely on derivative information to guide the search toward the problem solution. PSO and some of its variants have been proposed and successfully apply to ED problems with piecewise quadratic cost functions.

## **2.11 Particle Swarm Optimization (PSO)**

PSO is a population based stochastic optimization technique developed by Dr. Ebehart and Dr. Kennedy in 1995 inspired by social behavior of bird flocking or fish schooling [3]. PSO and evolutionary computation techniques such as Genetic Algorithms (GA) share many similarities. The system is initialized with a population of random solutions and searches for optima by updating generations. However, PSO has no evolution operators such as crossover and mutation different with GA. In PSO, the potential solutions, called ‘particles’, fly through the problem space by following the current optimum particles[7].

PSO searches for optimal solutions via interaction with individuals within a swarm of population. Particle is made of two parts, the position and velocity. Position represents the objective variable and velocity is the step size a particle attempt to move in next turn. A particle represents a potential or candidate solution of the problem. The particles are responsible for searching the solutions within the multidimensional problem space according to two major operations, velocity and position updating rules. Each particle moves toward the optimal point by adding velocity to its position. Updating rules of position will be the major function of PSO with consideration the  $d$ -th dimension.

### 2.11.1 Nature of PSO

Originally, these began to develop computer software simulations of birds flocking around food sources and then later realized how well their algorithms worked on optimization problems. Particle Swarm Optimization might sound complicated, but it is a very simple algorithm. Suppose the following scenario a group of birds is randomly searching food in an area. There is only one piece of food in the area being searched. All the birds do not know where the food is. But they know how far the food is in every each iteration. Over a number of iterations, a group of variables have their values adjusted closer to the member whose value is closest to the target at any given moment [3].

The effective one is to follow the bird, which is nearest to the food. PSO learned from the scenario and used it to solve the optimization problems. In PSO, each single solution is a bird in the search space call as particle. All of particles have fitness values, which are evaluated by the fitness function to be optimized, and have velocities, which direct the flying of the particles. The particles fly through the problem space by following the current optimum particles.

PSO is initialized with a group of random particles (solutions) and then searches for optimal by updating generations. In each every iteration, each particle is updated by following two "best" values. The first one is the best solution (fitness) it has achieved so far. The fitness value is also stored. This value is called personal best (*Pbest*). Another "best" value that is tracked by the particle swarm optimizer is the

best value, obtained so far by any particle in the population. This best value is a global best and called global best (*Gbest*). When a particle takes part of the population as its topological neighbors, the best value is a local best and is called p-best. The 'Figure 2.1' and 'Figure 2.2' shows the nature of PSO method:



**Figure 2.1:** Example on the flock of bird in nature



**Figure 2.2** Example on the school of fish in nature

### 2.11.2 PSO Algorithm

In PSO, suppose that the target problem has ‘ $n$ ’ dimensions and a population of particles, which encode solutions to the problem, move in the search space in an attempt to uncover better solutions. Each particle has a position vector of  $X_i$  and a velocity vector  $V_i$ . The position vector  $X_i$  and the velocity vector  $V_i$  of the  $i$ -th particle in the  $n$ -dimensional search space can be represented as  $X_i = (x_{i1}, x_{i2}, \dots, x_{in})$  and  $V_i = (v_{i1}, v_{i2}, \dots, v_{in})$  respectively. Each particle has a memory of the best position in the search space that it has found so far ( $Pbest_i$ ), and knows the best location found to date by all the particles in the swarm ( $Gbest$ ). Let  $Pbest = (x_{i1}^{Pbest}, x_{i2}^{Pbest}, \dots, x_{in}^{Pbest})$  and  $Gbest = (x_1^{Gbest}, x_2^{Gbest}, \dots, x_n^{Gbest})$  be the best position of the individual  $i$  and all the individuals so far, respectively.

At each step, the velocity of the  $i$ -th particle will be updated according to the following equation in the PSO algorithm as in (2.32):

$$V_i^{k+1} = \omega V_i^k + c_1 r_1 \times (Pbest_i^k - x_i^k) + c_2 r_2 \times (Gbest^k - x_i^k) \quad (2.32)$$

Where:

$V_i^k$	Velocity of individual $i$ at iteration $k$
$\omega$	Weight parameter
$c_1, c_2$	Weight factors
$r_1, r_2$	Random numbers between 0 and 1
$x_i^k$	Position of individual $i$ until iteration $k$
$Pbest_i^k$	Best position of individual $i$ until iteration $k$
$Gbest^k$	Best position of group $i$ until iteration $k$

The updating of position is given by:

$$x_{id}^{(t+1)} = x_{id}^{(t)} + v_{id}^{(t+1)} \quad (2.33)$$

Where:

$t$	Iteration count
$i$	Index of the particle
$x_{id}^{(t+1)}$	Position among the $d$ -th dimension of the $i$ -th particle at iteration $t$
$v_{id}^{(t+1)}$	Velocity among the $d$ -th dimension of the $i$ -th particle at iteration $t$

In this velocity updating process, the acceleration coefficients  $c_1$ ,  $c_2$  and the inertia weight  $\omega$  are predefined and  $r_1$ ,  $r_2$  are uniformly generated random numbers in the range of  $[0, 1]$ . In general, the inertia weight  $\omega$  is set according to the following equation:

$$\omega = \omega_{\max} - \frac{\omega_{\max} - \omega_{\min}}{Iter_{\max}} \times Iter \quad (2.34)$$

Where:

$\omega_{\max}, \omega_{\min}$	initial and final inertia parameter weights,
$Iter_{\max}$	maximum iteration number,
$Iter$	Iter current iteration number.

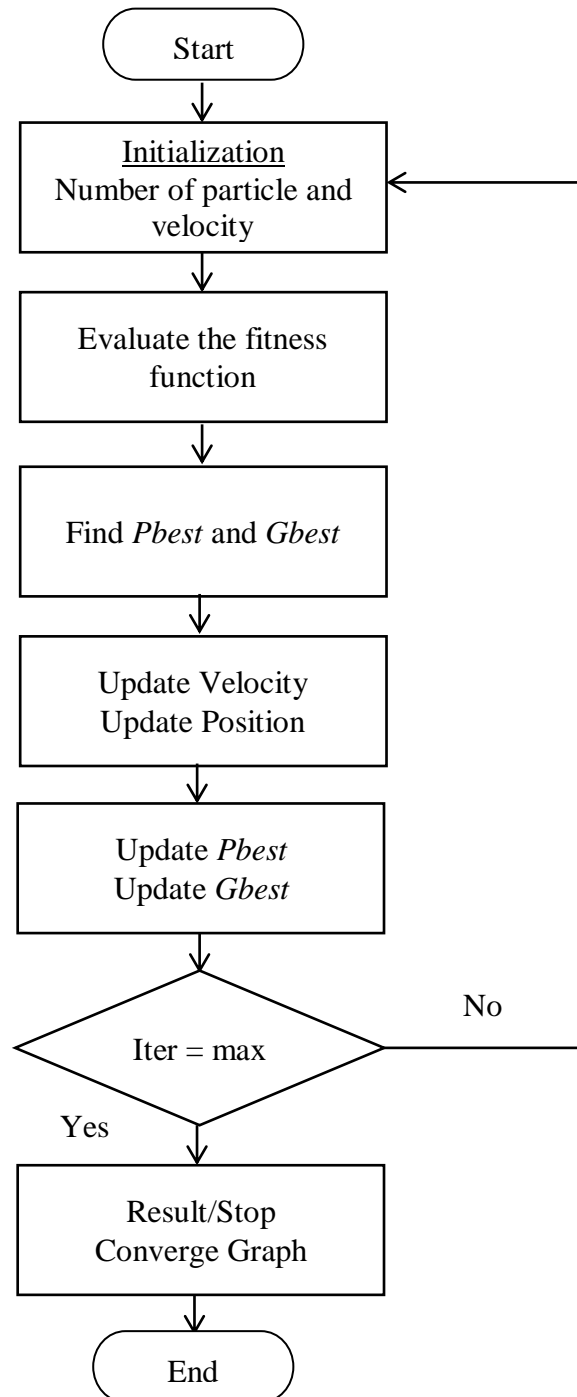
### 2.11.3 General Flowchart of PSO

Flowchart below shows the solution of PSO to obtain an optimum solution. The flowchart used in analysing, designing, documenting or managing a process operation of PSO. From the flowchart of PSO, it help visualize what is going on the thus help to understand the process and may also find weaknesses, obstacles and other features that are not clear in it. This technique allows finding the responsibility



to perform an achievement or make a right choice, showing the responsibility of each organizational unit for different part of a single process.

Figure 2.3 shows the general flowchart of PSO:



**Figure 2.3:** General Flow Chart of Basic PSO

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