Self-organizing Particle Swarm Optimization for Economic Generation Dispatch incorporating Wind Power

Dissertation submitted in the partial fulfilment for the award of the degree of

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CERTIFICATE

I hereby certify that the work which is being presented in the dissertation entitled **"Self-organizing Particle Swarm Optimization for Economic Generation Dispatch incorporating Wind Power"**, in partial fulfilment of the requirements for the award of degree of Master of Engineering in Power systems & Electric Drives submitted in Electrical & Instrumentation Engineering Department of Thapar University, Patiala, is an authentic record of my own work carried out under the guidance of **Ms. Manbir Kaur**, Associate Professor, EIED.

The matter presented in the dissertation has not been submitted for the award of any other degree of this or any other university.

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ABSTRACT

The focus of this dissertation is to explore the potential of energy savings through wind power source in coordination with thermal power generation to meet the losses and continuously varying load demand with due considerations to technical constraints imposed by units. The power output from thermal units is considered deterministic whereas wind power output is intermittent due to stochastic nature of wind speed. The intermittent wind power is modelled by discontinuous Weibull probability distribution function. The optimal generation allocation among thermal units and wind based units is based on the operating cost of thermal units and cost of wind power. The wind unit cost accounts for linearly incremental cost due to unused available wind power, penalty cost to account for overestimation and underestimation of wind power and direct cost pertaining to the issue of ownership of wind generators. The proposed optimization model is solved for ten and forty thermal units with valve point loading effect and two, five, one wind unit to meet 24 hour load demand using self-organizing particle swarm optimization technique that can handle the problem of convergence to sub-optimum solutions prematurely. B-coefficient method is used to include transmission losses. The results show that the total cost of system decreases as the wind power scheduling increases and hence the thermal fuel cost decreases. Self- organizing PSO (SOPSO) gives better results.

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LIST OF ABBREVIATIONS

ANN	Artificial Neural Network
AI	Artificial Intelligence
DED	Dynamic Economic Dispatch
DE	Differential Evolution
ELD	Economic Load Dispatch
EP	Evolutionary Programming
GA	Genetic Algorithm
HNN	Hopfield Neural Network
NG	No. of Thermal Generator
NW	No. of Wind Units
NR	Newton Raphson
NCED	Non-Convex Economic Dispatch
OPCDD	Optimic Control Dynamic Dispatch
PGSA	Plant Growth Simulation Algorithm
PSO	Particle Swarm Optimization
SQP	Sequential Quadratic Programming
SOHPSO	Self-Organizing Hierarchical Particle Swarm Optimization
SOPSO	Self-Organizing Particle Swarm Optimization
TVAC	Time-Varying Acceleration Coefficients
WECS	Wind Energy Conversion System

Chapter-1

Introduction

1.1 Overview

Electrical energy cannot be stored, but is generated from natural sources such as coal, oil, river water, marine tide, sun power, a radioactive matter etc. and is delivered as the demand arises. The challenging scenario of electricity sector in India reiterates the significance of least cost and clean generation approach. The power generation is expected to progress at a rate of 5% to 7% over a decade. Among the hydro, fossil fuel and innovative generation technologies, nearly 70% generation capacity is added through fossil fuel plants and 11% through innovative technologies. High efficiency thermal generation is challenged by coal ash content and greenhouse gas emissions. On the other hand, plant load factor of power producing innovative technologies is 15-20% and are expensive. However to shift the focus from financial benefit analysis of power generation to economic cost benefit analysis, sustainable energy resources, especially wind power is gaining importance and is suggested as an alternative to thermal power energy sources to save fast depleting fossil fuel and environment.

Economic Load Dispatch (ELD) technique is applied for allocating power generation among the committed units, so that the total generation cost of the system and transmission power losses, while satisfying the operational constraints. Although wind power is characterized as a variable power source on hourly basis, however due to its advantages like no production cost and clean energy, it offers an alternative to reduce the dependence on fossil fuel for generation [14].

In this dissertation, an economic power generation from wind power integrated with thermal power units is investigated. Due to uncertain nature of wind speed, the wind source is modelled using two parameter Weibull probability density function. Many other probability functions are mentioned in literature to model wind unit. The cost function of wind generator is augmented to incorporate the effect of uncertain nature of wind, variable output from wind power unit on hourly basis and the ownership of wind plant.

Over the past years, many classical optimization techniques, advanced heuristic search algorithms based on operational research and artificial intelligence concepts such as genetic algorithm (GA) [2], evolutionary programming (EP) [3], tabu search [20], simulated annealing, fuzzy logic, neural network [6], have been the choice of the researchers to solve constrained optimization problems with non-convex, discontinuous objective function, due to their certain attractive features such as simple concept, easy implementation, fast computation and robust search ability. In this thesis, Particle Swarm Optimization (PSO) [5] method is applied to economic generation from thermal units with non-smooth cost functions including valve- point effects and wind powered units due to its incomparable advantages of speed and precision [18]. The particle swarm optimization technique suffers from premature convergence which is overcome by using self-organizing particle swarm optimization and the proposed strategy shows the improvement in the results.

1.2 Literature Review

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 meet while satisfying all the constraints. Historically economic dispatch is being carried out since the year 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.

Happ H. H. [1] has presented comprehensive survey on economic dispatch. The survey covers the multi-area concepts in economic dispatch, Valve point loading, and optimal load flow.

X. Xia *et al.* [2] have presented the review on different techniques for Dynamic Load dispatch. The techniques presented were namely optimic control dynamic dispatch (OPCDD), dynamic economic dispatch (DED), artificial intelligence (AI).

El-Fergany A. A. [3] has presented an application of Genetic Algorithm (GA) to solve load dispatch problems with smooth and non-smooth fuel cost objective functions.

Sinha N. *et al.* [4] have presented evolutionary programming with various modifications for non-linear economic load dispatch problem. Evolutionary programs have been developed with adaptation based on an empirical learning rate.

James Kennedy *et al.* [5] have presented a concept for the optimization of nonlinear functions using particle swarm methodology. The evolution of several paradigms was outlined. Benchmark testing of the paradigm was described, and applications, including nonlinear function optimization and neural network training were proposed. The relationships between particle swarm optimization and both artificial life and genetic algorithms are described.

Amir Mohammadi *et al.* [6] have presented two methods for solving economic dispatch problems, namely Hopfield neural network and iteration method.

Zwe-Lee Gaing [7] has proposed particle swarm optimization (PSO) to solve the constrained dynamic economic dispatch (DED) problem in power system operation using stochastic methods.

Kwang Y. Lee *et al.* [8] have summarised the state of art particle swarm optimisation applications for resolving the economic dispatch (ED) problem. This paper focuses on the application of PSO techniques to the ED problems and describes their advantages and disadvantages in resolving the ED problems.

Chaturvedi K. T. *et al.* [9] have presented a novel hierarchical particle swarm optimization for the non-convex economic dispatch (NCED). The performance further improves when time-varying acceleration coefficients were included.

Victorie *et al.* [10] have implemented a hybridized PSO with sequential quadratic programming (SQP) to solve dynamic economic dispatch problem of generating units considering the valve-point effect.

Park *et al.* [11] have adopted a modified PSO (MPSO) incorporating dynamic search space reduction strategy to accelerate the optimization of economic dispatch problem by implementing heuristic treatment mechanism to handle the equality constraints and position adjustment strategy to handle the in equality constraints of ED problem.

Park *et al.* [12] have applied a chaotic particle swarm optimization for ED problem with valve point loading effect subjected to active power balance and power generation limit constraints. Chaotic logistic map based inertia weight variation in the velocity update equation avoids the premature convergence of PSO and helps to escape from local optimal point.

John Hetzer *et al.* [13] have presented a model including the WECS in the ED problem, and in addition to the classic economic dispatch factors, factors to account for both overestimation and underestimation of available wind power were included.

Mehdi Ghazavi Dozein *et al.* [14] have presented a new approach for Economic Dispatch (ED) problems incorporating wind power plant using Particle Swarm Optimization (PSO) method.

Singh S.N. *et al.* [15] have presented four versions of Particle Swarm Optimization (PSO) techniques for solving wind-thermal coordination problem. A pseudo code based algorithm was suggested to deal with the equality constraints of the problem for accelerating the optimization process.

Jadhav H. T. *et al.* [16] have presented the economic load dispatch (ELD) to meet the system load demand in an optimal manner considering wind power in power system using plant growth simulation algorithm (PGSA). Uncertain nature of wind power was included in study by using weibull probability distribution function. The errors in wind forecasting are taken in to account by adding costs such as overestimation cost and under estimation cost.

1.3 Scope of the Work

The main objectives of the present work are:

1) To study and investigate the mathematical models of thermal and wind generating units.
2) To formulate and solve economic dispatch for thermal units with valve point loading effect including wind units under the consideration of equality and inequality constraints using particle swarm optimization.
3) To improve the result of economic dispatch problem of all thermal and wind units with and without transmission losses by self-organising particle swarm optimization technique.

1.4 Organisation of the Dissertation

Chapter 1: The overview of the problem, brief literature review , scope of the work and organisation of the work carried out is summarised.

Chapter 2: It deliberates on the economic load dispatch model of thermal and wind system, and Weibull probability distribution function.

Chapter 3: It includes the overview of particle swarm optimization, its advantages, disadvantages, and self- organising particle swarm optimization.

Chapter 4: It includes the problem formulation and results obtained on the test problems are reported.

Chapter 5: In this chapter, the investigation is concluded with scope of future work.

Chapter- 2

Modelling of Thermal & Wind System

2.1 Introduction

Electrical energy cannot be stored, but is generated from natural sources such as coal, oil, river water, marine tide, sun power, a radioactive matter etc. and delivered as demand arises. A transmission system is used for the delivery of bulk power over considerable distances, and a distribution system is used for local deliveries. As shown in figure 2.1, an interconnected power system consist of mainly three parts: the generators which produce the electrical energy, the transmission lines which transmit it too far away places, and the loads which use it.

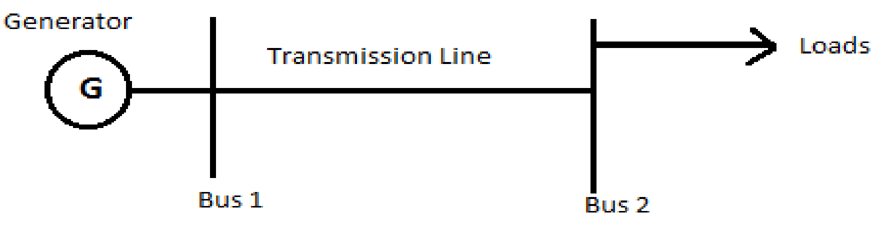


Figure 2.1 A Simplified Configuration of an Interconnected Power System.

The majority of generators in extant systems are of three types-nuclear, hydro, and fossil (coal, oil or gases). Nuclear plants tend to be operated at constant output levels and hydro plants have essentially no variable operating costs. Therefore, the components of cost that fall under the category of dispatching procedures are the costs of the fuel burnt in the fossil plants. The total cost of operation includes the fuel cost, costs of labour, supplies and maintenance. Figure 2.2 shows a simple model of a fossil plant. The power output of the fossil plant is increased sequentially by opening a set of valves at the inlet to its steam turbine.

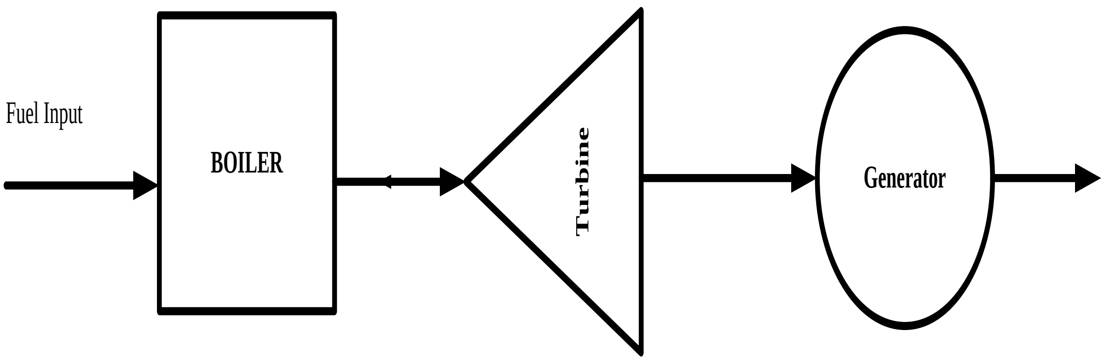


Figure 2.2 Simple Model of a Fossil Plant.

Electrical power systems are capable to produce sufficient electrical power to feed a bounded and certain range of load demand. The main aim of electric power utilities is to provide high-quality, reliable power supply to the consumers at the lowest possible cost while satisfying all the constraints imposed on the generating units. Thus, the Economic Load Dispatch technique is applied for allocating power generation among the committed units, so that the total generation cost of the system and also transmission power losses are minimized, while satisfying all the constraints.

2.2 Sources of Energy

Energy development is a field of endeavor focused on making available sufficient primary energy sources and secondary energy forms to meet the needs of society. Primarily the sources of the energy was taken from the nature itself like kinetic energy of water fall, energy taken from the sun as solar energy, thermal energy from coal fire etc. Due to the advancement of technology now we have plenty of other sources which can be classified as follows.

- Conventional Sources of energy.
- Non- conventional Sources of energy.

2.2.1 Conventional Sources of Energy

Energy that has been used from ancient times is known as conventional energy. Coal, natural gas, oil, and firewood are examples of conventional energy sources. (or usual) sources of energy (electricity) are coal, oil, wood, peat, uranium.

2.2.2 Non-Conventional Sources of Energy

Non-conventional sources of energy include:

- Solar power.
- Hydro-electric power (dams in rivers).
- Wind power.
- Tidal power.
- Ocean wave power.
- Geothermal power (heat from deep under the ground).
- Ocean thermal power (the difference in heat between shallow and deep water).
- Biomass (burning of vegetation to stop it producing methane).
- Biofuel (producing ethanol (petroleum) from plants.

Wind Energy is one of the safest energy technologies among innovative energy technologies. Wind industry has an outstanding health & safety record; in over 20 years of generation with more than 50,000 machines installed worldwide, no member of the public has ever been injured during the normal operation of a wind farm. Apart from generating electricity without causing injury wind energy has numerous other advantages. Wind energy is low risk, and the small unit size of each individual wind turbine (or wind scheme) also reduces the risk of technical failure or industrial action compared with larger generating units. It is more beneficial to produce electricity by wind rather than by fossil fuels and thus prevents the emission of greenhouse gases, including carbon and sulphur dioxides and nitrous oxide.

2.2.3 Wind Energy

The origin for Wind Energy is Sun. When sun ray falls on the earth, its surface gets heated up and as a consequence unevenly winds are formed. Kinetic energy in the wind can be used to run wind turbines but the output power depends upon the wind speed. Turbines generally require a wind in the range of 20km/hr.

2.2.4 Advantages of Wind Energy

With the increase in fuel prices, environmental concerns, and reduction in wind-turbine generating system cost, the integration of wind power generation in the power system having conventional power generators is increasing. Due to intermittency and unpredictable nature of wind, the wind power generation is not reliable and also it creates difficulty in the control of frequency and scheduling of generation. Some of the advantages of wind energy given below:

- Reducing dependence on fossil resources.
- Reducing greenhouse gas emissions and environmental protection.
- After the initial land and capital costs, there is essentially no cost involved in the production of power from wind energy conversion systems. Hence reducing the energy production cost.

2.3 Mathematical Model of Thermal system

For a given generating unit the various generating plant using equal incremental cost criteria. It is, however, unrealistic to neglect transmission losses particularly when long distance transmission of power is involved. A modern electric utility serves over a vast area of relatively low load density. The transmission losses may vary from 5 to 15% of total load. The power economic dispatch problem is defined so as to minimize the total operating cost of a power system while meeting the total load plus transmission losses within generator limits [17].

Mathematically, the optimization problem is defined as:

Minimize

$\sum_{i=1}^{NG} F_i(P_i)$ ………………………………………………………………………….. (2.1)

Subject to (i) the energy balance equation

$\sum_{i=1}^{NG} P_i = P_D + P_L$ ……………………………………………................................... (2.2)

(ii) and the inequality constraints

$P_i^{min} \leq P_i \leq P_i^{max} \qquad (i = 1,2, \dots, NG)$ ……………………………………………….. (2.3)

where,

P_D is load demand

P_i is real power generation and will act as decision variable

P_L is power transmission loss

NG is the number of generator unit.

Function $F_i(P_i)$ is the operating fuel cost of the ith unit and can be expressed in two ways:

1) Without valve point loading (Smooth cost function)
2) With valve point loading (Non-smooth cost function)

2.3.1 Without Valve Point Loading (Classical Smooth Fuel Cost Function)

Generally, the fuel cost of a thermal generation unit is considered as a second order polynomial function (quadratic function) as shown in figure 2.3. This is called classical and smooth cost function.

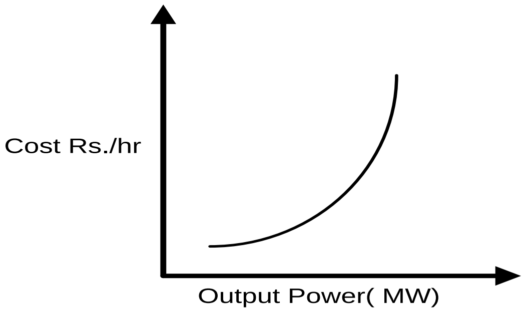


Figure 2.3 Fuel Cost for Thermal Units (Smooth quadratic function)

Mathematically, the cost curve can be expressed as:

$$F(P_i) = \sum_{i=1}^{NG}(a_i * P_i^2 + b_i * P_i + c_i \ \$/h \quad \ldots\ldots \quad (2.4)$$

where, a_i, b_i, c_i are cost coefficients of the ith unit.

2.3.2 Non-Smooth Fuel Cost Functions Including Valve-point Loading Effects

The generating units with multi-valve steam turbines exhibit a greater variation in the fuel cost functions. Since the valve point loading in a fossil fuel burning plant results in higher order nonlinearities and discontinuities in a heat-rate curve and in a cost function. Therefore, the cost function should be modified to consider the valve-point effects as given in equation 2.5. The valve-point loading effect has been modelled in as a recurring rectified sinusoidal function, shown in figure 2.4.

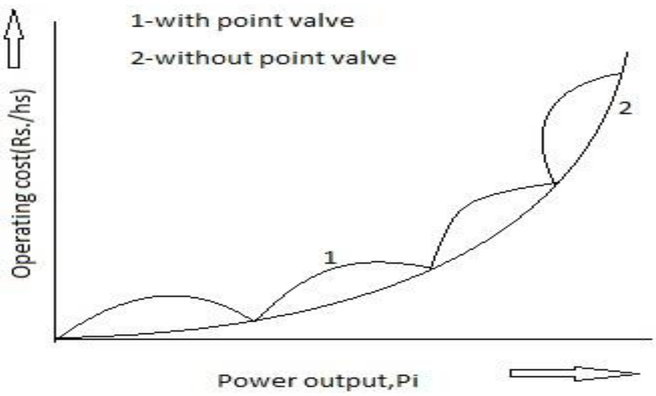


Figure 2.4 Fuel Cost Function with Valve Point Loading

Mathematically operating cost of thermal unit with valve point loadings is defined as:

$F(P_i) = \sum_{i=1}^{NG}(a_i * P_i^2 + b_i * P_i + c_i + |d_i * sin\{e_i * (P_i^{min} - P_i)|\$/h$……………….... (2.5)

subjected to:-

Energy balance equation

$\sum_{i=1}^{NG} P_i = P_D + P_L$……………………………………………………………………… (2.6)

The inequality constraints

$P_i^{min} \leq P_i \leq P_i^{max} \qquad (i = 1,2, \dots, NG)$……………………………………….. (2.7)

where, a_i, b_i, c_i are cost coefficients of the ith unit,

NG is the number of generator buses,

d_i, e_i are fuel cost coefficient of the ith unit with valve point effect.

2.3.3 Transmission Losses

The transmission losses increase with increase in distance between the two buses (e.g. between the unit and the load). The transmission losses may vary from 5 to 15 per cent of total load. The approximate methods of expressing transmission loss as a function of generator powers are through B-coefficients and it is given by Kron's loss formula. This method uses the fact that under normal operating condition, the transmission loss is quadratic in the injected bus real powers.

Using Kron's loss formula:

$P_L = B_{00} + \sum_i^{NG} B_{i0}P_{gj} + \sum_i^{NG}\sum_j^{NG} P_{gi}B_{ij}\, P_{gj}\ MW$………………………………….... (2.8)

where,

B_{00}, B_{i0}, B_{ij} are the loss coefficients which are constant under certain assumed conditions.

From equality constraint equation,

$\sum_{i=1}^{NG} P_i = P_D + P_L$……………………………………………………………………… (2.9)

can be rewritten considering transmission losses as:

$$P_d + \sum_{\substack{i=1\\ i\neq d}}^{NG} P_i = [\sum_{\substack{i=1\\ i\neq d}}^{NG}\sum_{\substack{j=1\\ j\neq d}}^{NG} P_iB_{ij}P_j + \sum_{\substack{j=1\\ j\neq d}}^{NG} P_j(B_{jd} + B_{dj})P_d + B_{dd}P_d^2 + \sum_{\substack{i=1\\ i\neq d}}^{NG} B_{i0}P_i + B_{d0}P_d + B_{00}] + P_D$$

(Assuming one generator as a slack/dependent generator) ………… (2.10)

Equation (2.10) can be simplified as:

$XP_d^2 + YP_d + Z = 0$……………………………………………………………….. (2.11)

where,

$X = B_{dd}$……………………………………………………………………………. (2.12)

$Y = \sum_{\substack{j=1\\ j\neq d}}^{NG} P_j(B_{jd} + B_{dj}) + B_{d0} - 1$.. (2.13)

$$Z = P_D + B_{00} + \sum_{\substack{i=1\\i\neq d}}^{NG} \sum_{\substack{j=1\\j\neq d}}^{NG} P_i B_{ij} P_j + \sum_{\substack{i=1\\i\neq d}}^{NG} B_{i0} P_i - \sum_{\substack{i=1\\i\neq d}}^{NG} P_i \quad \text{.... (2.14)}$$

The positive roots of the equation are obtained as:

$$P_d = \frac{-Y \pm \sqrt{Y^2} - 4XZ}{2X}, \text{ where } Y^2 - 4XZ \geq 0 \quad \text{(2.15)}$$

The positive values of roots, which lie within operating limits, are considered only, and then the fuel cost is computed. In case, transmissions losses are neglected, then coefficient of eq. (2.11) become

$$X=0,\ Y=-1 \text{ and } Z = P_D - \sum_{\substack{i=1\\i\neq d}}^{NG} P_i \quad \text{(2.16)}$$

The output of dependent generator,

$$P_d = Z \quad \text{(2.17)}$$

2.3.4 System Constraints

Broadly speaking there are two types of constraints

i) Equality constraints
ii) Inequality constraints

The inequality constraints are of two types (i) Hard type and, (ii) Soft type. The hard type are those which are definite and specific like the tapping range of an on-load tap changing transformer whereas soft type are those which have some flexibility associated with them like the nodal voltages and phase angles between the nodal voltages, etc. Soft inequality constraints have been very efficiently handled by penalty function methods.

2.3.4.1 Equality Constraints

To ensure real power balance, an equality constraint is imposed, i.e.

$$\sum_{i=1}^{NG} P_i = P_D + P_L \quad \text{(2.18)}$$

where,

P_D is the Load Demand

P_L is the transmission losses, which are approximated in terms of B-coefficients as

$$P_L = B_{00} + \sum_i^{NG} B_{i0} P_{gj} + \sum_i^{NG} \sum_j^{NG} P_{gi} B_{ij} P_{gj}\ MW \quad \text{(2.19)}$$

where,

P_{gi} and P_{gj} are the real power injection at the *i*th and *j*th buses, respectively.

B_{00}, B_{i0}, B_{ij} are the loss coefficients which are constant under certain assumed conditions.

2.3.4.2 Inequality Constraints

The inequality constraints imposed on generator output are

$$P_i^{min} \leq P_i \leq P_i^{max} \qquad (i = 1,2,\ldots,NG) \quad \text{(2.20)}$$

where, P_i^{min} is the lower limit, and P_i^{max} is the upper limit of generator output.

2.3.5 Constraint Handling Technique

In order to satisfy the power balance constraints, a generator is arbitrarily selected as a dependent generator d. $P_L = 0$ means transmission losses are neglected. $P_L \neq 0$ means transmission losses are considered. Output of dependent or slack generator is obtained from Eq. (2.11) and is given below:

$$P_d^j = \begin{cases} Z^j & ; \quad P_L = 0 \\ W^j & ; \quad P_L \neq 0 \end{cases} \quad (j = 1,2,\dots,L) \qquad (2.21)$$

where

$W^j = (-Y^j \pm \sqrt{(Y^j)^2 - 4XZ^j})/(2X)$, when $\left(Y^j\right)^2 - 4XZ^j \geq 0$

with $X = \begin{cases} 0 & ; \quad P_L = 0 \\ B_{dd} & ; \quad P_L \neq 0 \end{cases}$ ……… (2.22)

$$Y^j = \begin{cases} -1 & ; \quad P_L = 0 \\ \sum_{\substack{k=1 \\ k \neq d}}^{NG} P_k^j (B_{kd} + B_{dk}) + B_{d0} - 1 & ; \quad P_L \neq 0 \end{cases} \qquad (2.23)$$

$$Z^j = \begin{cases} P_D - \sum_{\substack{k=1 \\ k \neq d}}^{NG} P_k^j & ; \quad P_L = 0 \\ P_D + B_{00} + \sum_{\substack{k=1 \\ k \neq d}}^{NG} \sum_{\substack{l=1 \\ l \neq d}}^{NG} P_k^j B_{kl} P_l^i + \sum_{\substack{k=1 \\ k \neq d}}^{NG} B_{k0} P_k^j - \sum_{\substack{k=1 \\ k \neq d}}^{NG} P_k^j & ; \quad P_L \neq 0 \end{cases} \qquad (2.24)$$

Similarly, if the output of the dependent generator violates its limits, it is fixed using

$$P_i^j = \begin{cases} P_i^{min} & ; \quad P_i^j < P_i^{min} \\ P_i^{max} & ; \quad P_i^j > P_i^{max} \\ P_i^j & ; \quad P_i^{min} \leq P_i^j \leq P_i^{max} \end{cases} \quad (i = 1,2,\dots,NG;\ i \neq d;\ j = 1,2,\dots,L) \qquad (2.25)$$

And also if limits of dependent generator are violates then upgrade the other generation unit using Eq. given below:

If $P_d^j < P_d^{min}$ $then\ P_i^j - w \times rand()(P_i^{max} - P_i^{min})$ $(i = 1,2,\dots,NG;\ i \neq d)$……… (2.26)

If $P_d^j > P_d^{max}$ $then\ P_i^j + w \times rand()(P_i^{max} - P_i^{min})$ $(i = 1,2,\dots,NG;\ i \neq d)$……… (2.27)

where, *w* is some weighting factor nominally range [0,1].

After limiting the value of the dependent generator as above, a penalty term is introduced in the objective function Eq. (2.5) to penalize its fitness value. When so introduced, Eq. (2.5) is changed to the following generalized form:

$$f^j = F(P_i^j) + \varphi^j \quad (j = 1,2,\dots\dots,L) \qquad (2.28)$$

where,

Penalty factor is given by

$$\varphi^j = \begin{cases} \left(P_d^j - P_d^{min}\right)^2 & ; \; P_d^j < P_d^{min} \\ \left(P_d^{max} - P_d^j\right)^2 & ; \; P_d^j > P_d^{max} \\ 0 & ; \; P_d^{min} \le P_d^j \le P_d^{max} \end{cases} \qquad (2.29)$$

2.4 Mathematical Model of Wind System

The primary problem associated with the incorporation of wind power into the ED model is the future wind speed, which is the power source for the WECS, is an unknown at any given time. Because of the uncertainty of the wind energy available at any given time, factors for overestimation and underestimation of available wind energy must be included in the cost function of wind power plant [14]. Another factor ownership of wind power plant is considered in the cost function. The ELD model for wind power system can be formulated by considering different costs like direct cost of wind generators, overestimation and underestimation cost of available wind power [16].

Mathematically, the optimization problem is defined as:

Minimize:

$$C = \sum_{i=1}^{N} C_{w,i}(w_i) + \sum_{i=1}^{N} C_{p,wi}(W_{i,av} - w_i) + \sum_{i=1}^{N} C_{r,wi}(w_i - W_{i,av}) \qquad (2.30)$$

Subjected to:-

$$\sum_{i=1}^{NG} P_i + \sum_{i=1}^{N} W_i = P_D + P_{Loss} \qquad (2.31)$$

$$P_i^{min} \le P_i \le P_i^{max} \qquad (2.32)$$

$$0 \le w_i \le w_{r,i} \qquad (2.33)$$

where,

N: is the total number of wind-powered generators;

w_i: scheduled wind power from the *i*th wind-powered generator;

$W_{i,av}$: Available wind power from the *i*th wind-powered generator. This is a random variable, with a value range of $0 \le W_{i,av} \le w_r$.

$w_{r,i}$: rated wind power from the *i*th wind- powered generator;

$C_{w,i}$: cost function for the ith wind-powered generator. This factor will typically take form of a payment to the wind farm operator for the wind generated power actually used;

$C_{p,wi}$: Penalty cost function for not using all the available power from the *i*th wind-powered generator;

$C_{r,wi}$: Required reserve cost function, relating to uncertainty of wind power. This is effectively penalty associated with the overestimation of the available wind power;

2.4.1 Direct Cost for Wind-Powered Generator

The first term is direct cost for the power output from the wind-powered generator. This existence of this term will depend on the ownership of the wind- powered generators. If the generators are owned by the system operator, this term may not even exist however, if the system operator is paying for the wind power from the owner of the wind farm, a direct cost will be involved. A linear cost function will be assumed for the wind-generated power actually used as (2.34):

$$C_{w,i}(w_i) = d_i w_i \quad \ldots\ldots (2.34)$$

Where, d_i is the direct cost coefficient for the *i*th wind-powered generator

2.4.2 Cost Due to Underestimation of Wind Power

The second term represents the penalty cost for not using all the available power from the wind-powered generator. The cost associated with this term depends on who owns the wind-powered generators. This term will be zero if generators are owned by the system operator. This term linearly related to the difference between the available wind power and the actual wind power used. The penalty cost function will then take the following form [13]:

$$C_{P,w,i}(W_{i,av} - w_i) = k_{P,i}(W_{i,av} - w_i)$$

$$= k_{P,i} \int_{w_i}^{W_{ri}} (w - w_i) f_w(w) dw \quad \ldots\ldots (2.35)$$

Where,

$k_{P,i}$: Penalty cost (underestimation) coefficient for the *i*th wind generator;

$f_w(w)$: is probability density function of wind power output.

2.4.3 Cost Due to Overestimation of Wind Power

The third term of equation (2.30) relates to the price that must be paid for overestimation of the available wind power. The reserve requirement cost will be similar to the penalty cost (2.35), except that, in this case, it is a cost due to the available wind power being less than the scheduled wind power.

$$C_{r,w,i}(w_i - W_{i,av}) = k_{r,i}(w_i - W_{i,av})$$

$$= k_{r,i} \int_{0}^{w_i} (w_i - w) f_w(w) dw \quad \ldots\ldots (2.36)$$

where,$k_{r,i}$ is the reserve cost (overestimation) coefficient for the *i*th wind-powered generator.

2.5 Wind Speed and Probability Function

Scientific literature related to renewable energies that propose the use of a variety of probability distribution function (PDFs) to describe wind speed frequency distributions. The flexibility and usefulness of the PDFs is dependent upon the description of different wind regimes like high frequencies of null winds, unimodal, bimodal, bitangential regimes, etc.

2.5.1 Types of Distribution

There are many probability distributions that are applicable in many areas of study but we describe here some continuous frequency distribution function. These functions are relating to each other. Due to their close relationship with each other by changing the values of a parameter or keeping single parameter as a constant variable, we converts the whole distribution into another one. Some distribution functions are follows as:

- Normal Distribution

- Rayleigh Distribution
- Chi-square Distribution
- Weibull Distribution

2.5.1.1 Normal Distribution

The normal distribution was first discovered early in the 1667 while studying an important theoretical problem in emerging theory of probability. The normal distribution is the most reliable and best distribution to see any data whether it is normally distributed or not. With a certain condition the normal distribution is a subset of the weibull distribution. If we put k=3.2 the weibull distribution gives the shape of standard normal distribution.

$$f(v) = \frac{1}{\sigma\sqrt{2}} exp\left[-\frac{1}{2}\left(\frac{v_i-\overline{V}}{\sigma}\right)^2\right] \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \quad (2.37)$$

where,

σ is standard deviation

$\overline{V}$ is the mean speed

v_i variable speed vary from -∞ to +∞. But it is physically impossible for wind speed to be negative.

2.5.1.2 Rayleigh Distribution

Rayleigh distribution is also a subset of weibull distribution. Weibull distribution with shape factor k=2 gives the same shape of Rayleigh distribution. The Rayleigh probability density function is given as:

$$f(v) = \frac{\pi v_i}{2\overline{\overline{V}}^2} exp\left[-\frac{\pi}{4}\left(\frac{v_i}{\overline{\overline{V}}}\right)^2\right] \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \quad (2.38)$$

2.5.1.3 Chi-square Distribution

Some relationship exist between normal, Rayleigh, and weibull distributions. In case of normal distribution, when N(0,1) the normal distribution becomes the chi-square distribution. The probability density function for chi-square random variable is

$$f(v) = \frac{\pi v_i}{\overline{\overline{2m^2}}} exp\left[-\frac{\pi}{4}\left(\frac{v_i}{m}\right)^2\right] \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \quad (2.39)$$

where,

v_i is the wind speed

m is the mean velocity and average wind speed

2.5.1.4 Weibull Distribution

Weibull distribution is important, common and well known continuous distribution when estimating the wind power and energy, all over the world due to its versatility. This is only continuous distribution which is not derived from any other distribution. By keeping shape parameter k=1,2 and 3.6, the weibull distribution becomes exponential, Rayleigh, and normal distribution, respectively.

The wind speed variations for a particular place can be best described by the weibull pdf, with two parameters, the scale parameter (c) and the shape parameter (k).The probability of wind speed during any time interval is given by,

$$f_V(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{(k-1)} (e)^{-(vc)^k}, 0 < v < \infty \text{……………………………………………..} \quad (2.40)$$

Where

V: wind speed random variable;

v: wind speed;

c: scale factor at a given location (units of wind speed);

k: shape factor at a given location (dimensionless);

The shape parameter varied from 1.0 to 3.0 and the scale parameter ranged from 5 to 20 in [13]. In this thesis c=10 and *k*=2 is assumed.

In the probability distribution chart, f is plotted against v over a chosen time period, where [18]:

$$f = \frac{fraction\ of\ time\ wind\ speed\ in\ between\ v\ and\ (v+\Delta v)}{\Delta v} \text{..} \quad (2.41)$$

By definition of the probability function, probability that the wind speed will be between zero and infinity during that period is unity, i.e.:

$$\int_0^\infty f.dv = 1 \text{……………………………………………………………………..} \quad (2.42)$$

Figure 2.5 [18] is the plot of probability function f versus wind speed *v* for three different values of *k.*

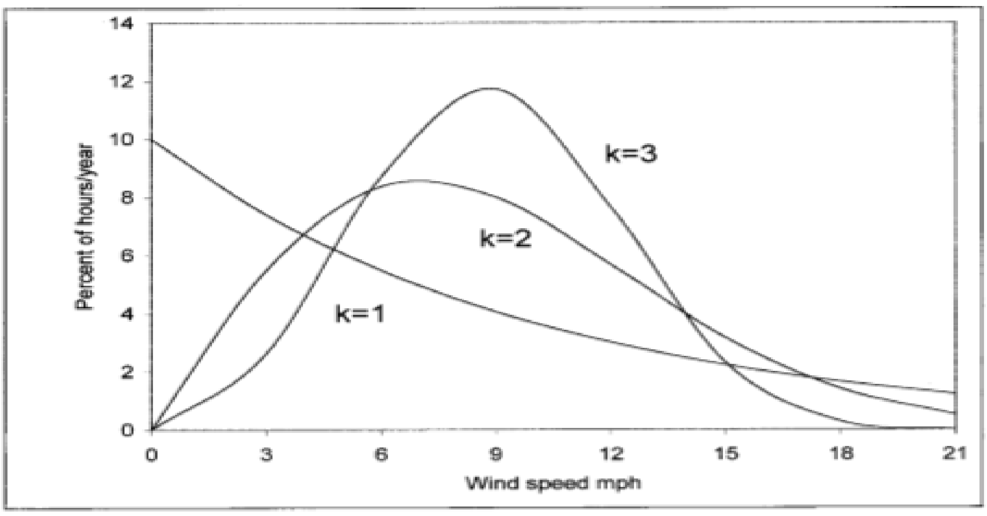


Figure 2.5 Weibull Probability Distribution Function with Scale Parameter c=10 and Shape Parameters k = 1, 2 and 3.

The curve on the left with k = 1 has a heavy bias to the left, where most days are windless (v=0). The curve on the right with k = 3 looks more like a normal bell shape distribution, where some days have high wind and equal number of days have low wind. The curve in the middle with k = 2 is a typical wind distribution found at most sites. In this distribution, more days have lower than the mean speed, while few days have high wind. The value of k determines the shape of the curve, hence is called the 'shape parameter'. The Weibull distribution with k = 1 is called the exponential distribution which is generally used in the reliability studies. For k>3, it approaches the normal distribution, often called the Gaussian or the bell-shape distribution.

k =1 makes it the exponential distribution, $f = \boldsymbol{\lambda} . \boldsymbol{e}^{-\boldsymbol{\lambda v}}$ where $\boldsymbol{\lambda}$=1/c

k = 2 makes it the Rayleigh distribution,$f = 2\lambda^2 . V . e^{-(\lambda V)^2}$, and

k > 3 makes it approach a normal bell-shape distribution.

Figure 2.6 shows the distribution curves corresponding to k = 2 with different values of c ranging from 8 to 16 mph (1 mph = 0.446 m/s). For greater values of c, the curves shift right to the higher wind speeds. That is, the higher the c, the more number of days has high winds. Since this shifts the distribution of hours at a higher speed scale, the c is called the scale parameter [18].

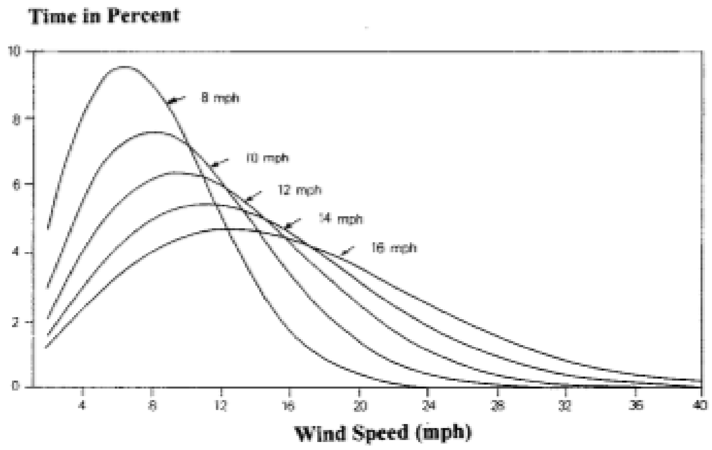


Figure 2.6 Weibull Probability Distribution with Shape Parameter k = 2 and the Scale Parameters Ranging from 8 to 16 miles per hour (mph).

For later use in conjunction with the wind power probability function, the Weibull PDF is given by:

$F_V(v) = \int_0^v f_V(\tau) d\tau = 1 - e^{-(v/c)^k}$ ………………………………………………….. (2.43)

The Weibull distribution function with a shape factor of 2 is also known as the Rayleigh distribution.

The advantages of the Weibull distribution are as follows:

1) It is a two- parameter distribution, which is more general than the single- parameter Rayleigh distribution, but less complicated than the five-parameter bivariate normal distribution;

2) It provides a good fit to observed wind speed data;

3) If the k and c parameters are known at one height, a methodology exists to find the corresponding parameters at another height. The characteristics of the wind depend on various factors like geography, topography, etc., and can be estimated by the observed frequency of wind speed in the target region.

2.6 Wind Power Formulation

The power generated by wind turbine expressed as a function of undisturbed wind velocity is given as in equation (2.44)

$$W = \rho A V^3 C_P \quad (2.44)$$

where,

ρ: is the air density in kilograms per cubic metre (kg/m^3);

A: is the swept rotor area in square metres (m^2);

V: is the wind speed in metres per second (m/s);

C_p: is the Power Coefficient of the turbine, defined as Power Output from turbine / Energy available in the wind;

For a given wind speed input, the output of the wind powered generator may be stated as

$$w = 0 \qquad v < v_i \; and \; v > v_0$$

$$w = w_r \frac{(v - v_i)}{(v_r - v_i)}, \qquad v_i \le v \le v_r$$

$$w = w_r \qquad v_r \le v \le v_0 \quad (2.45)$$

where,

v_i, v_0, v_r: are cut-in, cut out and rated wind velocity for wind turbine system respectively;

w: is the power output from wind-powered generator;

w_r: is the rated power of wind-powered generator;

Thus, WECS has:

1) No power output up to cut-in wind speed;

2) A linear power output relationship between cut-in and rated wind speed;

3) A constant rated power output between the rated wind speed and cut-out wind speed;

4) Once again has no power output with wind speeds greater than the cut-out wind speed;

Due to the fact that the WECS power output has a constant zero value below the cut-in wind speed and also above the cut- out wind speed, and due to the fact that the power output is constant between rated wind speed and cut-out wind speed, the power output random variable will be discrete in these ranges of wind speed. The WECS power output is a mixed random variable, which is continuous between values of zero and rated power, and is discrete at values of zero and rated power output.

If it is assumed that the wind speed has a given distribution, such as the Weibull, it is then necessary to convert that distribution to a wind power distribution.

$$W = T(V) = aV + b \quad (2.46)$$

and

$$f_W(w) = f_V[T^{-1}(w)]\left[\frac{dT^{-1}(w)}{dw}\right] = f_V\left(\frac{w-b}{a}\right)\left|\frac{1}{a}\right| \quad (2.47)$$

where,

T: a transformation, in general;

W: wind power random variable;

V: wind speed random variable;

w: wind power (a realization of the wind power random variable);

v: wind speed (a realization of the wind speed random variable).

The probability of wind power being zero, rated or in between zero and rated can be expressed respectively by (2.47), (2.48) and (2.49) using Eq. (2.42 and 2.44)

$$P_r\{W = 0\} = F_v(v_i) + (1 - F_v(v_0))$$
$$= 1 - exp\left(-\left(\frac{v_i}{c}\right)^k\right) + exp\left(-\left(\frac{v_o}{c}\right)^k\right) \quad (2.48)$$

$$P_r\{W = w_r\} = F_v(v_o) - F_v(v_r)$$
$$= exp\left(-\left(\frac{v_r}{c}\right)^k\right) - exp\left(-\left(\frac{v_o}{c}\right)^k\right) \quad (2.49)$$

To make the transformation from the wind speed random variable to the WECS power output random variable in the linear portion of the curve a bit less cumbersome, the following ratios are defined:

$\rho = \frac{w}{w_r}$ is the ratio of wind power output to rated wind power;

$l = \frac{v_r - v_i}{v_i}$ is the ratio of linear range of wind speed to cut-in wind speed.

Using Eq. (3.12), the Weibull PDF of the WECS power output random variable in the continuous range then takes the form

$$f_W(w) = \frac{klv_i}{c}\left(\frac{(1+\rho l)v_i}{c}\right)^{(k-1)} exp\left(-\left(\frac{(1+\rho l)v_i}{c}\right)^k\right) \quad (2.50)$$

It is assumed that the wind farm containing same type of wind turbines experience the same wind speeds. The equivalent rated capacity of entire wind farm is therefore assumed to be w_r. The forecasted wind power of wind farm is assumed to be $w_1 (0 \le w_1 \le w_r)$ and generated power is W_1 [16] .

$$C_{rwind}(w_1 - W_1) = k_r(w_1 - W_1)$$
$$= y_1 + y_2 \quad (2.51)$$

where,

$y_1 = w_1 P(W_1 = 0)$

$$= w_1 \left\{1 - exp\left(-\left(\frac{v_i}{c}\right)^k\right) + exp\left(-\left(\frac{v_o}{c}\right)^k\right)\right\} \quad (2.52)$$

$$y_2 = \int_0^{w_1} (w_1 - w) f_w(w) dw \quad (2.53)$$

Similarly, the equations for case of underestimation can be written as below

$C_{pwind}(W_1 - w_1) = k_p(W_1 - w_1)$

$$= y_3 + y_4 \quad (2.54)$$

where,

$y_3 = w_1 P(W_1 = w_r)$

$$= w_1 \left\{exp\left(-\left(\frac{v_r}{c}\right)^k\right) - exp\left(-\left(\frac{v_o}{c}\right)^k\right)\right\} \quad (2.55)$$

$$y_2 = \int_{w_1}^{w_r} (w - w_1) f_w(w) dw \quad (2.56)$$

Equation (2.53) and (2.56) are solved by using simple trapezoidal method.

2.7 Solution Methods for Economic Power Dispatch

A wide variety of technique has been reported to obtain solution of economic load dispatch problem. As it is an optimal problem, broadly optimization techniques are given as:-

1) Classical method
2) Evolutionary Techniques

2.7.1 Classical Method

i) Lambda-Iteration Method

The lambda iteration method is one of the methods used in solving the system lambda and optimal power dispatch of generators. Lambda is the variable introduced in solving constraint optimization problem and called a Lagrange multiplier. Lambda iteration method iteratively adjusts the system lambda and calculates for corresponding total power output contributed from all on-line units until one of the stopping criteria for iteration process is met. This method may slowly converge or yield an unacceptable result if the initial lambda and the method for updating the lambda are not properly selected.

ii) Gradient Method

The gradient method is an algorithm for the numerical solution of particular systems of linear equations, namely those whose matrix is symmetric and positive-definite. The conjugate gradient method is an iterative method, so it can be applied to sparse systems that are too large to be handled by direct methods such as the Cholesky decomposition. Such systems often arise when numerically solving partial differential equations.

iii) Newton Raphson Method

Newton method is a method for finding successively better approximations to the roots (or zeroes) of a real-valued function. The idea of the method is as follows: one starts with an initial guess which is reasonably close to the true root, then the function is approximated by its tangent line (which can be computed using the tools of calculus), and one computes the x-intercept of this tangent line (which is easily done with elementary algebra). This x-intercept will typically be a better approximation to the function's root than the original guess, and the method can be iterated.

2.7.2 Disadvantages of Classical Methods

- Conventional methods have failed to solve non-linear problems as they are sensitive to initial estimates and converge into local optimal solution and computational complexity.
- It has slow convergence of optimization problem.
- The conventional methods are facing problem to locate the optimal global solutions.
- Their execution time is very long and they cannot be applied to real-time power system operations.

2.7.3 Evolutionary Techniques

The term "Artificial Intelligence" (AI) is used to describe research into human-made systems that possess some of the essential properties of life. The conventional methods are not suitable for determining the global optimal solution of the ED problem with valve-point effects or prohibited operating zones. In order to make the numerical methods more convenient in solving the ED problem with non-convex, non-smooth and non-monotonically increasing incremental cost functions, artificial intelligent techniques such as artificial neural networks, stochastic optimization methods and hybrid methods have been used to solve the problem. This is due to its ability to find a global or near global optimal solution. The penalty based methods are commonly used in solving the ED problem by AI techniques [17].

i) Artificial Neural Network

Artificial neural network (ANN) is an emulation of biological neural system. A neural network consists of many massively neurons connected in a parallel manner. ANN can be classified in to several types according to the data type of inputs and training procedures. Hopfield neural network (HNN) is a single layer recursive neural network where all neurons are both input and output and they are connected with equal weights [2]. In applying the HNN to the DED problem, the minimization of cost function is equivalent to the search for a minimum energy function in HNN model, and the decision variables in the optimization problem are represented by the output of the neurons. The main drawback of the HNN is that, it converges slowly and normally takes a large numbers of iterations, also that the unsuitable sigmoid function may increase the computational time [7]. HNN has been used to solve DED problem only with smooth cost function.

ii) Genetic Algorithm

Genetic algorithm is a global search technique based on mechanics of natural genetics and natural selection. It is a general-purpose optimization algorithm that is distinguished from conventional optimization techniques by the use of concepts of population genetics to guide the optimization search. Instead of point-to-point search, GA searches from population to population. The advantages of GA over traditional techniques are: It needs only rough information of the objective function and places no restriction such as differentiability and convexity on the objective .The GA works with a set of solutions from one generation to the next, and thus making it less likely to converge on local minima. Basically GA consists of four steps i.e. representation, initialization, selection and reproduction with crossover and mutation.

iii) Evolutionary Programming

Evolutionary computing is an adaptive search technique based on the principle of genetics and natural selection. Evolutionary programming is a probabilistic, global search technique. It starts with a population of randomly generated candidate solutions and evolves towards better solutions over a number of generations and iterations. The main stages of this technique include initialization, mutation, and competition and selection [4].

iv) Particle Swarm Optimization

The PSO is a population based modern heuristic search method inspired by social behaviour of organisms such as fish schooling and bird flocking. It is a simple and powerful optimization tool which scatters random particles, i.e., solutions into the problem space. These particles, called swarms collect information from each other through an array constructed by their respective positions. The particles update their positions using the velocity of particles. Position and velocity are both updated in a heuristic manner using guidance from particles own experience and the experience of its neighbours [5].

v) Differential Evolution

Differential Evolution is a population-based stochastic function minimizer (or maximize) relating to evolutionary computation. DE combines simple arithmetic operators with the classical operators of recombination, mutation, and selection to evolve from a randomly generated starting population to a final solution.

Chapter 3

Particle Swarm Optimization

3.1 Introduction

Particle swarm optimization (PSO) [5] is a population based stochastic optimization technique developed by Eberhart and Kennedy in 1995, inspired by social behaviour of bird flocking or fish schooling. PSO shares many similarities with evolutionary computation techniques such as Genetic Algorithms (GA) [3]. The system is initialized with a population of random solutions and searches for optima by updating generations. However, unlike GA, PSO has no evolution operators such as crossover and mutation. In PSO, particles fly around in a multidimensional search space. During flight, each particle adjusts its position according to its own experience, and the experience of neighbouring particles, making use of the best position encountered by itself and its neighbours.

3.2 Representation of PSO

Let P and v represents a particle's coordinates (position) and its corresponding flight speed (velocity) in a search space. Therefore the jth particle is represented as $P_i = [P_{i1}, P_{i2}, \dots, P_{iNG}]$ in the NP-dimensional space. The best previous positions of each particle is recorded and represented as$Pb_i = [Pb_{i1}, Pb_{i2}, \dots, Pb_{iNG}]$. The index of the best particle among all the particles in the group is represented by the$[G_1, G_2, \dots, G_{NG}]$. The rate of the velocity for particle is represented as$v_i = [v_{i1}, v_{i2}, \dots, v_{iNP}]$.The modified velocity and position of each particle can be calculated using the current velocity and the distance from Pb_{ij} to G_j as shown in the following formula [17]

$$v_{ij}^{r+1} = w * v_{ij}^{r} + C_1 * R_1 * \left(Pb_{ij}^{r} - P_{ij}^{r}\right) + C_2 * R_2 * \left(G_j^{r} - P_{ij}^{r}\right) \quad (3.1)$$

$$P_{ij}^{r+1} = P_{ij}^{r} + v_{ij}^{r+1} \qquad (i = 1,2, \dots, NP;\ j = 1,2, \dots, NG) \quad (3.2)$$

where

NP is the number of particles in a group.

NG is the number of members in particles.

r is the pointer of iterations (generations).

w is the inertia weight factor

C_1 and C_2 are the acceleration constant.

R_1 and R_2 are uniform random values in the range [0,1].

v_{ij}^{r} is the velocity of jth member of ith particle at rth iteration, $V_j^{min} \leq v_{ij}^{r} \leq V_j^{max}$

P_{ij}^{r} is the current position of jth member of ith particle at rth iteration.

In this, the parameter V_j^{min} determined the resolution, or fitness, with which regions are to be searched between the present position and the target position. If V_j^{max} is too high, particles might fly past good solutions. If V_j^{max} is too small, particles may not explore sufficiently beyond local solutions. In many experiences with PSO, V_j^{max} was often set at 10-20% of the dynamic range of the variables on each dimension.

The constants C_1 and C_2 represent the weighting of the stochastic acceleration terms that pull each particle toward the Pb_{ij}^{r}, G_j^{r}positions. Low values allow particles to roam far from the target regions before being tugged back. On the other hand, high values result in abrupt movement toward, or past, target regions. Hence, the acceleration constants C_1 and C_2 were often set to be 2.0 according to past experiences.

Suitable selection of inertia weight w provides a balance between global and local explorations, thus requiring less iteration on average to find a sufficiently optimal solution. As originally developed, w often decreases linearly from about 0.9 to 0.4 during a run. In general, the inertia weight w is set according to the following equation.

$$w = w^{max} - \frac{w^{max} - w^{min}}{IT^{max}} \times IT \quad (3.3)$$

where

IT^{max} is the maximum number of iterations (generations)

IT is the current number of iterations.

Fig. 3.1 shows a concept of modification of a searching point by PSO [5] and Fig. 4.2 shows a searching concept with agents in a solution space. Each particle changes its current position using the integration of vectors as shown in Fig. 3.2

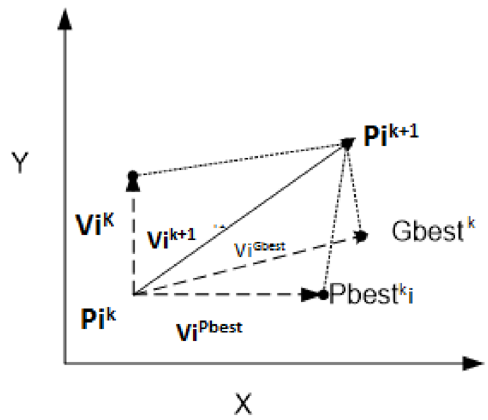


Figure 3.1 Concept of Modification of a Searching Point

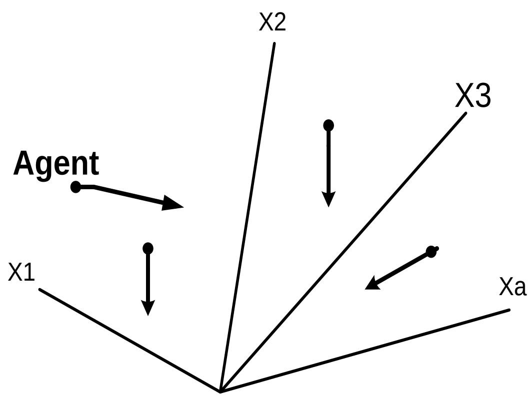


Figure 3.2 Searching Concept of Particles in a Solution Space by PSO

3.3 Problem Formulation Using PSO

The main objective function is to minimize the operating cost

$F(P_i) = \sum_{i=1}^{NG}(a_i * P_i^2 + b_i * P_i + c_i + |d_i * sin\{e_i * \left(P_i^{min} - P_i\right)\$/h$ .... (3.4)

Subject to:-

Energy balance equation

$\sum_{i=1}^{NG} P_i = P_D + P_L$ ……………………………………………………………………... (3.5)

The inequality constraints

$P_i^{min} \leq P_i \leq P_i^{max} \qquad (i = 1,2, \dots, NG)$……………………………………............. (3.6)

Where

a_i, b_i, c_i, d_i, e_i are cost coefficients of the ith unit

P_D is load demand

P_i is real power generation and will act as decision variable

P_L is power transmission loss

NG is the number of generator buses.

3.3.1 Representation of Swarm

The decision variables of the economic dispatch problems are real power generations; they are used to form the swarm. The set of real power output (P) of all the generators is represented as the position of the particle in the swarm. For a system with NG generators, the particle position is represented as a vector of length NG. If there are NP particles in the swarm, the complete swarm is represented as a matrix as below

$$Swarm = \begin{bmatrix} P_{11} & P_{12} & \dots & \dots & P_{1NG} \\ P_{21} & P_{22} & \dots & \dots & P_{2NG} \\ . & . & P_{ij} & \dots & . \\ . & . & \dots & \dots & . \\ P_{NP1} & P_{NP2} & \dots & \dots & P_{NPNG} \end{bmatrix}$$

Where P_{ij} is the jth position component of particle i and it represents the real power generation of generator j of the possible solution i.

3.3.2 Initialization of the Swarm

Each element of the swarm matrix is initialized randomly within the real power operating limits based on Eq. (3.6). The velocity of the particles are initialized randomly according to the following inequality

$V_j^{min} \leq V_{ij} \leq V_j^{max} \;\; (i = 1,2, \dots, NP; \;\; j = 1,2, \dots, NG)$……….………………………. (3.7)

This velocity-initialization scheme always guarantees to produce new particles satisfying real power operating limit constraints. The maximum velocity limit in the jth dimension is computed as:

$-0.5\, P_j^{min} \leq V_{ij} \leq +0.5 P_j^{max}$ .... (3.8)

3.3.3 Initialization of Population

The initial population comprises combinations of only the candidate dispatch solutions, which satisfy all the constraints and are feasible solutions of economic dispatch. It consists of P_i^j $(i = 1,2, \dots, NG; j = 1,2, \dots, L)$ trail parent individuals. The elements of a parent are the combinations of power outputs of the generating units, which are chosen randomly by a random ranging over$[P_i^{min}, P_i^{max}]$.

$$P_i^j = P_i^{min} + rand()\left(P_i^{max} - P_i^{min}\right) \; (i = 1,2, \dots, NG; j = 1,2, \dots, L) \quad (3.9)$$

Where rand () is uniform random number ranging from over [0, 1].

The elements of parent/offspring P_i^j may violate constraints Eq. (3.6). This violation is corrected by fixing them either at lower or upper limits as described below:

$$P_i^j = \begin{cases} P_i^{min}; \; P_i^j < P_i^{min} \\ P_i^{max}; \; P_i^j > P_i^{max} \\ P_i^j \; ; \; P_i^{min} \leq P_i^j \leq P_i^{max} \end{cases} \quad (i = 1,2, \dots, NG; j = 1,2, \dots, L) \quad (3.9a)$$

3.3.4 Evaluation of Objective Function

In order to satisfy the power balance constraints, a generator is arbitrarily selected as a dependent generator d. In this we are considering P_L=0 means transmission losses are neglected. Output of dependent or slack generator is given below

$$P_d^i = P_D + P_L - \sum_{\substack{k=1 \\ k \neq d}}^{NG} P_k^j \quad (j = 1,2, \dots, L) \quad (3.10)$$

Similarly, if the output of the dependent generator violates its limits, it is fixed using Eq. (3.9a). After limiting the value of the dependent generator as above, a penalty term is introduced in the objective function Eq. (3.4) to penalize its fitness value. When so introduced, Eq. (3.4) is changed to the following generalized form:

$$f^j = F\left(P_i^j\right) + \varphi^j \quad (j = 1,2, \dots, L) \quad (3.11)$$

where

Penalty factor is given by $\varphi^j = \begin{cases} (P_d^j - P_d^{min})^2 \; ; \; P_d^j < P_d^{min} \\ (P_d^{max} - P_d^j)^2 \; ; \; P_d^j > P_d^{max} \\ 0 \; ; \; P_d^{min} \leq P_d^j \leq P_d^{max} \end{cases}$ .... (3.11a)

3.3.5 Initialization of the Best Positions

In the strategy of PSO, the particle's best position, P_{ij}^{best} and global best position G_j^{best} are the key factors. The position with minimum objective function value is the particle's best position. The best position out of all the P_{ij}^{best} is taken as G_j^{best}.

3.3.6 Movement of the Particles

The particles in the swarm are accelerated to new positions by adding new velocities to their present positions. The new velocities are calculated using Eq. (3.1)

$$v_{ij}^{new} = w \times v_{ij} + c_1 \times rand() \times \left(P_{ij}^{best} - P_{ij}\right) + c_2 \times rand() \times \left(G_j^{best} - P_{ij}\right) \quad \ldots\ldots (3.12)$$

$$P_{ij}^{new} = P_{ij} + v_{ij}^{new} \quad (i = 1,2,\ldots,NP;\ j = 1,2,\ldots,NG) \quad \ldots\ldots (3.12a)$$

If any P_{ij} violates the real power operating limit constraints, it is clamped at the boundary value using Eq. (3.9a).

3.3.7 Updating the Best and the Worst positions

The particles are evaluated in the new position by objective function values. Then P_{ij}^{best} of particle j are updated. The best position out of all the new P_{ij}^{best} is taken as G_j^{best}. An objective value at $G_j^{best}$is saved asf_{best}.

3.3.8 Stopping Criterion

There are various criteria available to stop a stochastic optimization algorithm. In this maximum number of iterations is chosen as the stopping criterion.

3.4 Advantages of PSO

A PSO is a population-based evolutionary technique for resolving the non-smooth global optimization problems and has many key advantages as follows: „

- PSO is a derivative-free technique unlike other conventional technique.
- PSO is easy in its concept and coding implementation compared to other heuristic optimization techniques.
- PSO is less sensitivity to the nature of the objective function compared to the other conventional mathematical methods such as lambda iteration technique and other heuristic methods.
- PSO has limited number of parameters including only inertia weight factor and two acceleration coefficients in comparison with other competing heuristic optimization methods. Also, the impact of parameters to the solutions is considered to be less sensitive compared to other heuristic algorithms [8].
- It can also handle objective functions with stochastic nature and does not require a good initial solution to start its iteration process.
- PSO techniques can generate high-quality solutions within shorter calculation time and stable convergence characteristics than other stochastic methods [8].

3.5 Disadvantages of PSO

The major drawback of PSO is

- It has some limitations for real-time ED applications such as 5- minute dispatch considering network constraints since the PSO is also a variant of stochastic optimization techniques requiring relatively a longer computation time than mathematical approaches.

- It has the problems of dependency on initial point and parameters, difficulty in finding their optimal design parameters, and the stochastic characteristic of the final outputs.

3.6 Improved Particle Swarm Optimization

A novel parameter automation strategy called self-organizing hierarchical PSO (SOH_PSO) is applied in this thesis for the non-convex economic dispatch to address the problem of premature convergence. In this approach, the particle velocities are reinitialized whenever the population stick at local optima during the search. A relatively high value of the cognitive component (c_1) results in excessive wandering of particles while a higher value of the social component (c_1) causes premature convergence of particles [19]. Hence, time-varying acceleration coefficients (TVAC) [9] are employed to strike a proper balance between the cognitive and social component during the search. Integration of the TVAC with PSO for solving the practical economic dispatch problem has been found to avoid premature convergence during the early stages of the search and promote convergence towards the global optimum solution.

3.6.1 Concept of Time-Varying Acceleration Coefficients (TVAC)

In population-based optimization methods, the policy is to encourage the individuals to roam through the entire search space, during the initial part of the search, without clustering around local optima. During the latter stages, however convergence towards the global optima should be encouraged, to find the optimum solution efficiently. In TVAC, this is achieved by changing the acceleration coefficients and with time in such a manner that the cognitive component (c_1) is reduced while the social component (c_2) is increased as the search proceeds. A large cognitive component and small social component at the beginning, allows particles to move around the search space, instead of moving towards the population best prematurely. During the latter stage in optimization, a small cognitive component and a large social component allow the particles to converge to the global optima. The acceleration coefficients are expressed as [9]

$$c_1 = (c_{1f} - c_{1i})\frac{iter}{iter_{max}} + c_{1i} \quad (3.13)$$

$$c_2 = (c_{2f} - c_{2i})\frac{iter}{iter_{max}} + c_{2i} \quad (3.14)$$

where,

$c_{1f}, c_{1i}, c_{2f}, c_{2i}$ are initial and final values of cognitive and social acceleration factors, respectively.

Chapter 4

Problem Formulation and Results

4.1 Economic Dispatch Problem Formulation

The economic load dispatch problem for different type of thermal unit and with and without wind power unit is carried out with and without considering transmission losses for valve point loading function (non-smooth type).

4.1.1 Problem Formulation

The ED problem including wind can be described as an optimization (minimization) problem with objective function as formulated in chapter 2:

Minimize

$F_T = \sum_{k=1}^{T} \sum_{i=1}^{NG} C_i(P_i) = \sum_{k=1}^{T} \sum_{i=1}^{NT} F_i(P_i) + \sum_{k=1}^{T} \sum_{j=1}^{NW} F_j(P_{wj})$ .... (4.1)

where,

F_T Total generation cost,

$F_i(P_i)$ Cost function of *ith* thermal unit

$F_j(P_{wj})$ Cost function of *jth* wind unit

P_i Power generated from *ith* thermal unit

P_{wj} Scheduled power from *jth* wind unit

NG Total number of participating generating units

NT Number of thermal units

NW Number of wind-powered units

T Total time period

Subjected to:

$\sum_{i=1}^{NT} P_{ik} + \sum_{j=1}^{NW} Pw_{jk} = P_{Dk} + P_{Loss.k}$ .... (4.2)

$P_{ik}^{min} \leq P_{ik} \leq P_{ik}^{max}$ $\quad (k = 1,2, \ldots, T)$ .... (4.3)

$0 \leq Pw_{jk} \leq Pw_{r,jk}$ .... (4.4)

where,

P_{Dk} is the Load demand for *kth* time interval

$P_{Loss.k}$ is the transmission losses at *kth* time interval

$$P_d + \sum_{\substack{i=1 \\ i \neq d}}^{NG} P_i = [\sum_{\substack{i=1 \\ i \neq d}}^{NG} \sum_{\substack{j=1 \\ j \neq d}}^{NG} P_i B_{ij} P_j + \sum_{\substack{j=1 \\ j \neq d}}^{NG} P_j (B_{jd} + B_{dj}) P_d + B_{dd} P_d^2 + \sum_{\substack{i=1 \\ i \neq d}}^{NG} B_{i0} P_i + B_{d0} P_d + B_{00}] + P_D$$

The cost function of thermal system with valve point loading is modeled as:

$F(P_i) = \sum_{k=1}^{T} \sum_{i=1}^{NG} (a_i * P_i^2 + b_i * P_i + c_i + |d_i * sin\{e_i * (P_i^{min} - P_i)| \$/h$............ (4.5)

where,

a_i, b_i, c_i are cost coefficients of the ith unit,

NG is the number of generator buses,

d_i, e_i are fuel cost coefficient of the ith unit with valve point effect.

The cost function for wind system is modelled as:

$$F_j(P_{wj})=\sum_{j=1}^{NW} C_{w,j}(w_j) + \sum_{j=1}^{NW} C_{p,wj}(W_{j,av} - w_j) + \sum_{j=1}^{NW} C_{r,wj}(w_j - W_{j,av}) \quad (4.6)$$

where,

NW: is the total number of wind-powered generators;

w_j: scheduled wind power from the *j*th wind-powered generator;

$W_{j,av}$: Available wind power from the *j*th wind-powered generator.

$w_{r,j}$: rated wind power from the *j*th wind- powered generator;

$C_{w,j}$: cost function for the *jth* wind-powered generator.

$C_{p,wj}$: Penalty cost function for not using all the available power from the *j*th wind-powered generator;

$C_{r,wj}$: Required reserve cost function, relating to uncertainty of wind power.

All the three cost function of wind system given as

$$C_{w,j}(w_j) = d_j w_j \quad (4.7)$$

where, d_j is the direct cost coefficient for the *j*th wind-powered generator.

$$C_{P,w,j}(W_{j,av} - w_j) = k_{P,j}(W_{j,av} - w_j)$$

$$= k_{P,j} \int_{w_j}^{W_{rj}} (w - w_j) f_w(w) dw \quad (4.8)$$

where,

$k_{P,j}$: Penalty cost (underestimation) coefficient for the *j*th wind generator;

$f_w(w)$: is probability density function of wind power output.

$$C_{r,w,j}(w_j - W_{j,av}) = k_{r,j}(w_j - W_{j,av})$$

$$= k_{r,j} \int_0^{w_j} (w_j - w) f_w(w) dw \quad (4.9)$$

where,

$k_{r,j}$ is the reserve cost (overestimation) coefficient for the *j*th wind-powered generator.

And weibull density function is given as:

$$f_W(w) = \frac{klv_i}{c} \left(\frac{(1+\rho l)v_i}{c} \right)^{(k-1)} exp\left(- \left(\frac{(1+\rho l)v_i}{c} \right)^k \right) \quad (4.10)$$

where,

$\rho = \frac{w}{w_r}$ is the ratio of wind power output to rated wind power;

$l = \frac{v_r - v_i}{v_i}$ is the ratio of linear range of wind speed to cut-in wind speed.

4.1.2 Algorithm & Flowchart

1. Read data; viz. Cost Coefficients, a_i, b_i, c_i, d_i, e_i (i=1, 2… NT), dw_j, K_{pj}, K_{rj}, scale factor, shape factor (j=1,2,…NW), Convergence tolerance error, scaling factor, maximum allowed iterations, ITMAX, population size, L, and P_d^{min} and P_d^{min} (i=1, 2… NG), W_r, etc.

2. Set particle (bird) counter, i=0

   DO

3. Increment particle counter, i= i+1

4. Set generation counter, j=0,

   DO

5. Increment the generation counter, j= j+1

6. IF (j≠ d) THEN generate the position of particle P_{ij} and velocity of particle V_{ij}

7. Initialize $P_{ij}^{best} = P_{ij}$

   WHILE (j < NP)

8. Compute P_{id} using Eq. (3.10), check limits and adjust using Eq. (3.9a). Then compute penalty factor, $\varphi_i and\ f_i$ using Eq. (3.11a) and (4.1).

9. Initialize $f_i^{best} = f_i$

   WHILE (i < NP)

10. Set particle counter, i=1, $f^{global} = f_i^{best}$

    DO

11. Increment particle counter, i=i+1

12. IF $\left(f_i^{best} < f^{global} \right)$ THEN set $f^{global} = f_i^{best}$and $G_j^{best} = P_{ij}^{best}$ $(j = 1,2, \dots, NG)$

    WHILE (i < NP)

13. Set iteration counter, IT=0

    DO

14. Increment iteration counter, IT=IT+1

15. Compute w using Eq. (3.3)

16. Set particle (bird) counter, i=0

    DO

17. Increment particle counter, i=i+1

18. Set generation counter, j=0

    DO

19. Increment the generation counter, j=j+1

20. IF (j ≠ d) THEN generate the velocity of particle

21. Compute v_{ij}^{new} using Eq. (3.12)

22. IF ($v_{ij}^{new} > v_j^{max}$) THEN update ($v_{ij}^{new} = v_j^{max}$)

23. IF ($v_{ij}^{new} < v_j^{min}$) THEN update ($v_{ij}^{new} = v_j^{min}$)

24. Compute $P_{ij}^{new} = P_{ij} + v_{ij}^{new}$

WHILE (j < NG)

25. Compute P_{id}^{new} using Eq. (2.21), check limits and adjust using Eq. (3.9a). Then Compute penalty factor, $\varphi_i and\ f_i^{new}$ using Eq. (3.11a) and (3.11).

26. IF ($f_i^{new} < f_i^{best}$) THEN set $f_i^{best} = f_i^{new}$ and $P_{ij}^{best} = P_{ij}^{new}$ $(j = 1,2, \ldots, NG)$

WHILE (i < NP)

27. Set particle counter, i = 1, $f^{min} = f_i^{best}$

DO

28. Increment particle counter, j=j+1

29. IF ($f_i^{best} < f^{min}$) THEN set $f^{min} = f_i^{best}$ and $P_j^{min} = P_{ij}^{best}$ $(j = 1,2, \ldots, NG)$

WHILE (i < NP)

30. IF $|f_{min} - f^{global}| \leq error$ THEN STOP

31. Set particle counter, i=0

DO

32. Increment particle counter, i=i+1

33. Set generation counter, j=0

DO

34. Increment the generation counter, j=j+1

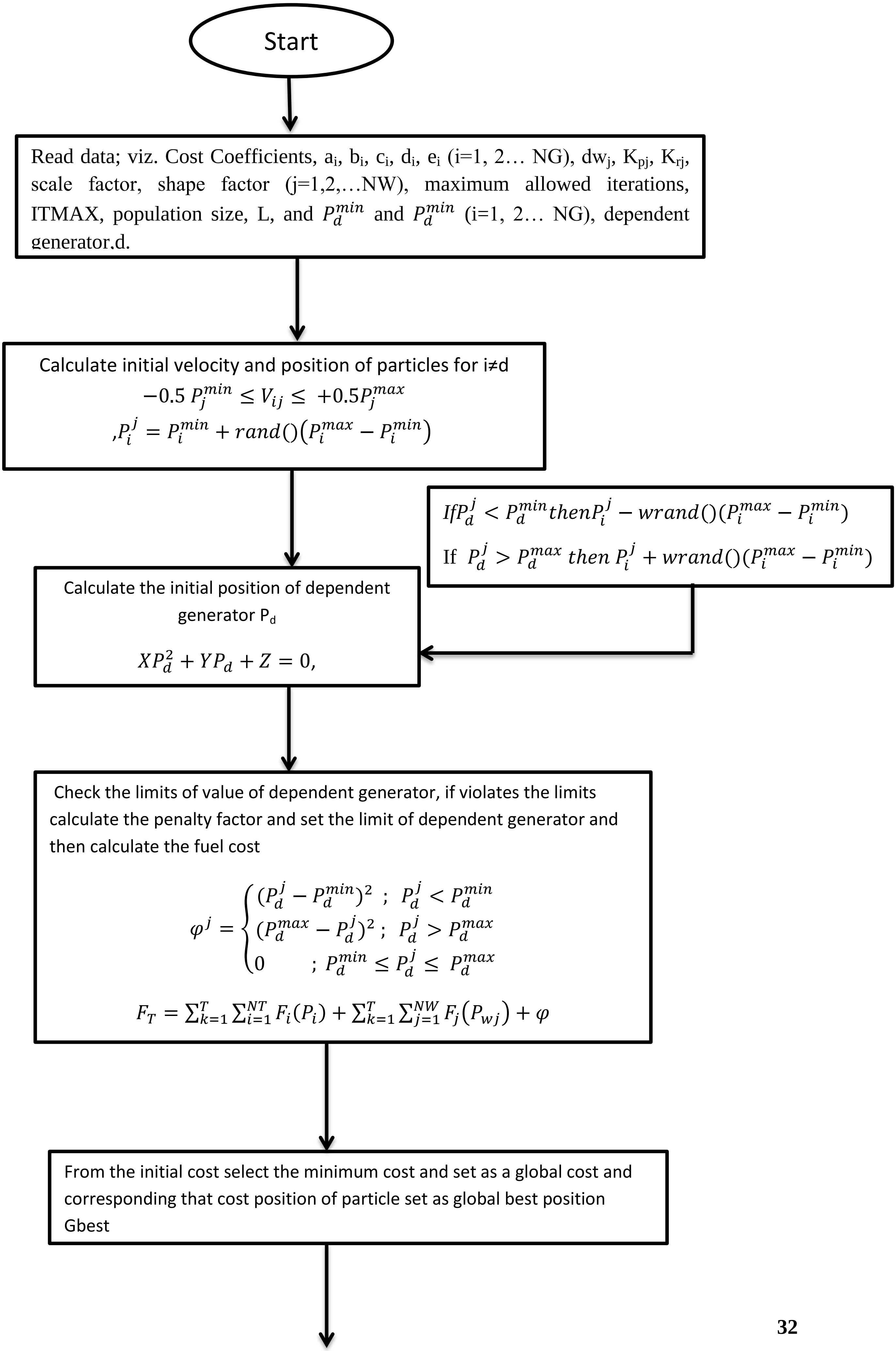
35. Set $v_{ij} = v_{ij}^{new}$

WHILE (j < NG)

36. IF ($f^{min} < f^{global}$) THEN set $f^{global} = f^{min}$

WHILE (IT < IT^{MAX})

37. STOP



Start
Read data; viz. Cost Coefficients, a_i, b_i, c_i, d_i, e_i (i=1, 2… NG), dw_j, K_{pj}, K_{rj}, scale factor, shape factor (j=1,2,…NW), maximum allowed iterations, ITMAX, population size, L, and P_d^{min} and P_d^{min} (i=1, 2… NG), dependent generator.d.
Calculate initial velocity and position of particles for i≠d
$-0.5\, P_j^{min} \leq V_{ij} \leq +0.5 P_j^{max}$
$,P_i^j = P_i^{min} + rand()\left(P_i^{max} - P_i^{min}\right)$
$If P_d^j < P_d^{min} then P_i^j - wrand()(P_i^{max} - P_i^{min})$
If $P_d^j > P_d^{max}$ $then\ P_i^j + wrand()(P_i^{max} - P_i^{min})$
Calculate the initial position of dependent generator P_d
$XP_d^2 + YP_d + Z = 0,$
Check the limits of value of dependent generator, if violates the limits calculate the penalty factor and set the limit of dependent generator and then calculate the fuel cost
$\varphi^j = \begin{cases} (P_d^j - P_d^{min})^2 \ ; \ P_d^j < P_d^{min} \\ (P_d^{max} - P_d^j)^2 \ ; \ P_d^j > P_d^{max} \\ 0 \qquad ; \ P_d^{min} \leq P_d^j \leq P_d^{max} \end{cases}$
$F_T = \sum_{k=1}^{T} \sum_{i=1}^{NT} F_i(P_i) + \sum_{k=1}^{T} \sum_{j=1}^{NW} F_j\left(P_{wj}\right) + \varphi$
From the initial cost select the minimum cost and set as a global cost and corresponding that cost position of particle set as global best position Gbest

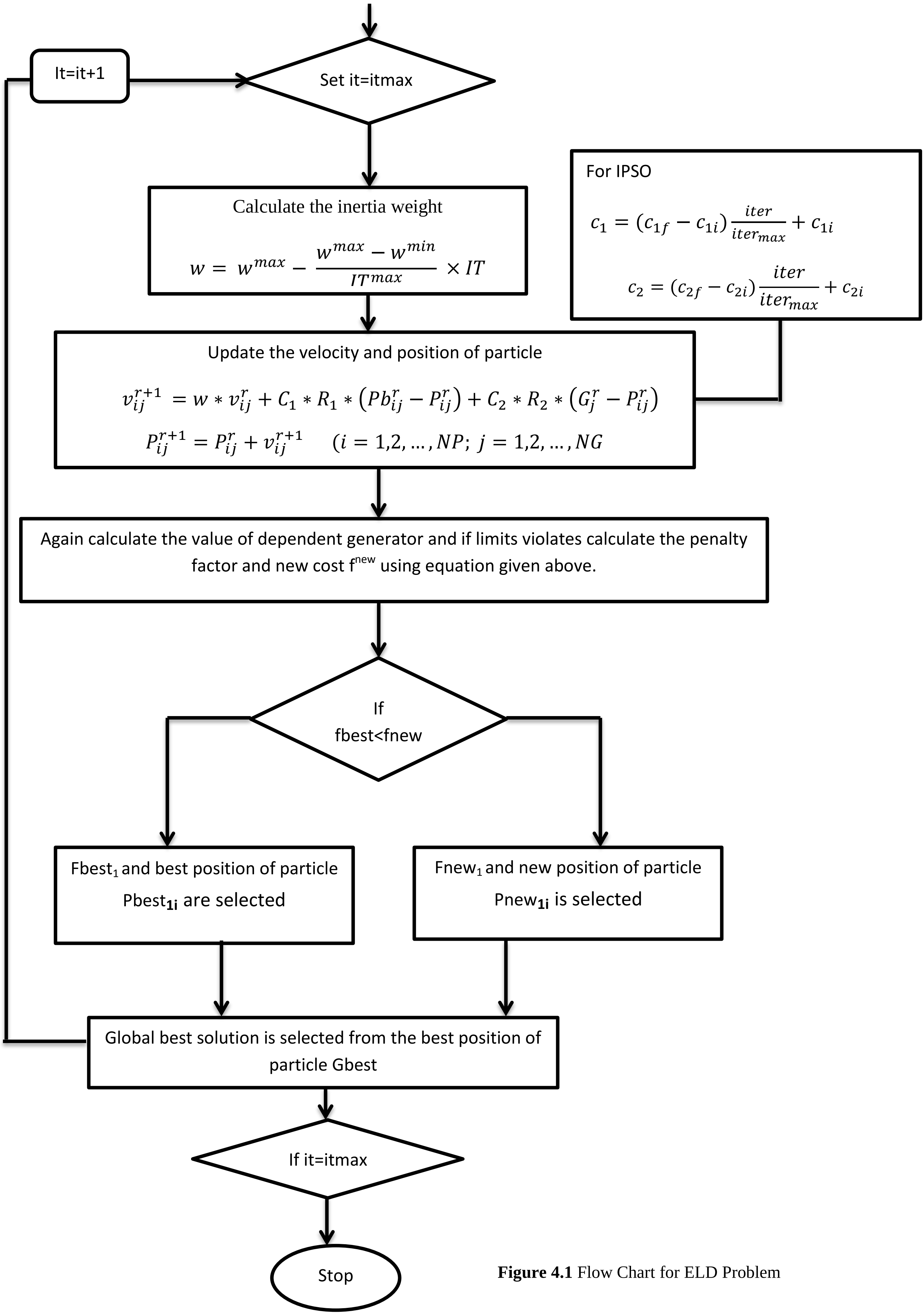


Figure 4.1 Flow Chart for ELD Problem

4.1.3 Test Problem 1_Without losses_12 Unit System

The economic load dispatch problem is applied on 10 unit thermal system with and without wind power unit for 24 hour load demand without considering losses using particle swarm optimization technique (PSO). The same problem is check by using self- organising PSO (SOPSO). The data of cost coefficients and operating ranges for thermal generators and load data for 24 hours are given in appendix 1. For PSO, with population size of 10, acceleration coefficient c_1 and c_2=2 are considered and for SOPSO the acceleration coefficients c_{1i}= 2.5, c_{1f}= c_2i= 0.2, c_{2f}= 2.2 is considered. The economic load dispatch problem is run for 100 iterations.

4.1.3.1 Case1_Test Problem 1_Results

Simulation results for 10 thermal units only using PSO and SOPSO are reported in table 4.1

Table 4.1: Result of Case1_Test problem1 for 24 hour

HOUR	PSO ($/hr.)	SOPSO ($/hr.)
1	28965.54791	28892.9959
2	30774.28071	30041.64921
3	33890.3691	33676.11953
4	36938.30781	37193.77431
5	39380.12778	38603.54551
6	42101.0906	42005.85838
7	43971.13245	43866.35926
8	45669.43299	45674.72705
9	48942.50498	48667.93439
10	52931.61645	51809.77769
11	54598.09022	53510.64725
12	55712.43246	55891.46709
13	52393.77434	52371.03683
14	48435.37039	48742.08971
15	45492.47389	45645.35033
16	40307.64791	40137.67012
17	38706.83855	38223.30763
18	41410.30147	42321.27725
19	45800.05611	45411.23719
20	51924.66515	52136.12831
21	49052.3842	49129.98542
22	42437.0519	42422.61259
23	35577.63783	35704.77828

24	31907.02501	32312.24315
Total Cost ($)	1037320.16	1034393
CPU Time (sec)	9.569297	8.328463

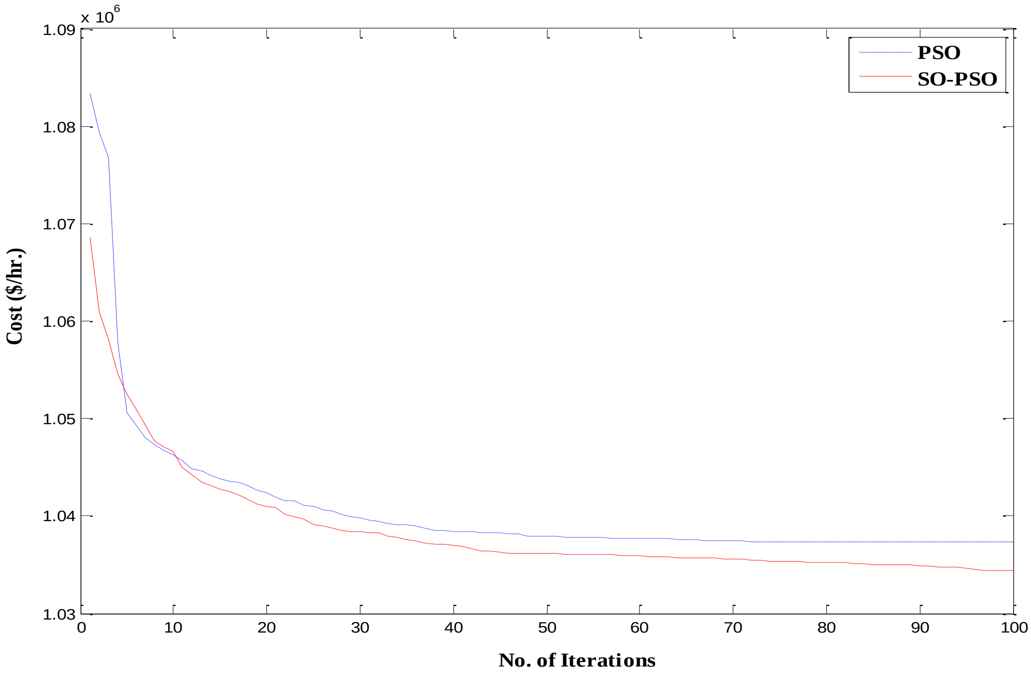


Figure 4.2 Convergence Curve for Case1_Test Problem1

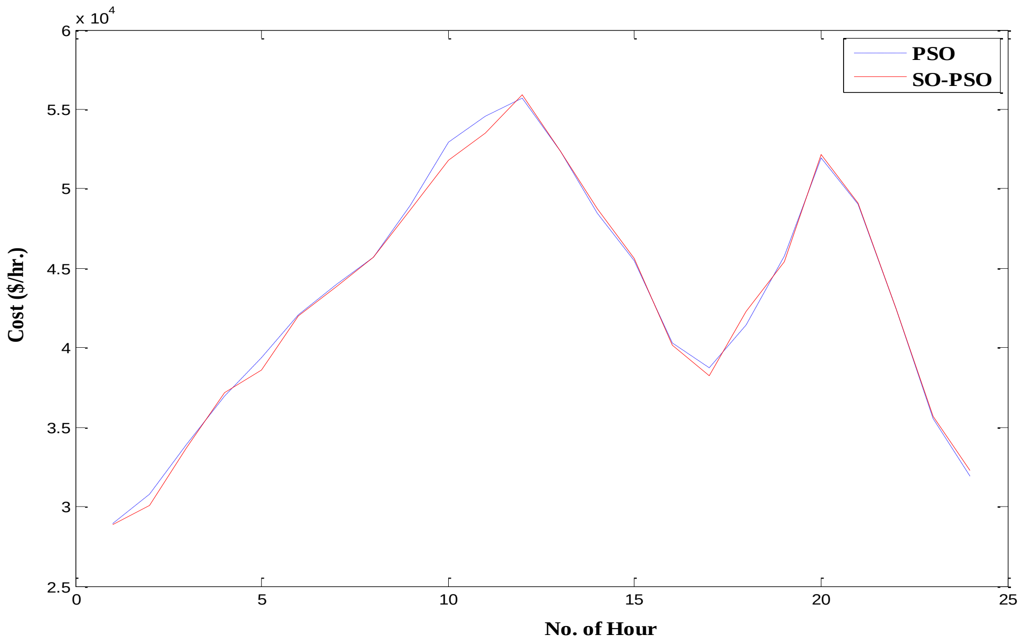


Figure 4.3 Cost-Load Curve for Case1_Test Problem1

It is observed from above table and graph that total cost (TC)of ten unit system for SOPSO is 1034393$ for a 24 hour scheduling correspondence to its load demand which is lower than PSO TC. The CPU time is fast in case of SOPSO i.e. 8.328463 sec for 100 iterations than PSO.

4.1.3.2 Case2_Test Problem1_Results

Results for ten thermal units including two wind power units. The wind speed is known for 24 hours and the data is given in appendix 1.

Table 4.2: Result of Case2_Test problem1 for 24 hour

HOUR	Without Wind power unit ($/hr.)	With Wind power unit ($/hr.)	
		Private sector	System operator
1	28743.29651	28424.0802	28602.5806
2	30716.33983	29962.343	29474.0381
3	34593.4989	32687.3346	32977.2052
4	37212.94618	36606.5296	36102.3226
5	38537.7949	38677.7466	38533.8459
6	42109.69859	42375.245	41040.363
7	43795.38474	42785.8781	42136.2143
8	45404.99307	45863.1769	44968.4535
9	48768.97473	48756.7004	47732.7681
10	52608.45545	52745.8388	51266.4312
11	53947.87754	53187.9264	53244.2377
12	55863.96374	54330.686	54468.3477
13	52317.6037	50870.5744	50467.1816
14	48943.36974	47932.6266	48151.7781
15	44850.93469	44877.5754	44733.4244
16	40866.92037	39125.8882	39702.0611
17	38706.8038	37912.478	37957.4649
18	42166.37135	41551.4975	41463.0774
19	45296.66141	44374.4993	44117.6022
20	52294.75597	52725.4526	52166.3221
21	48530.06993	50213.1466	48889.3595
22	42011.9542	42468.2403	41898.2633
23	35310.9404	35769.0595	35187.7232
24	31709.04	33338.8755	32659.2683
Total Cost $	1035308.65	1027563.399	1017940.334

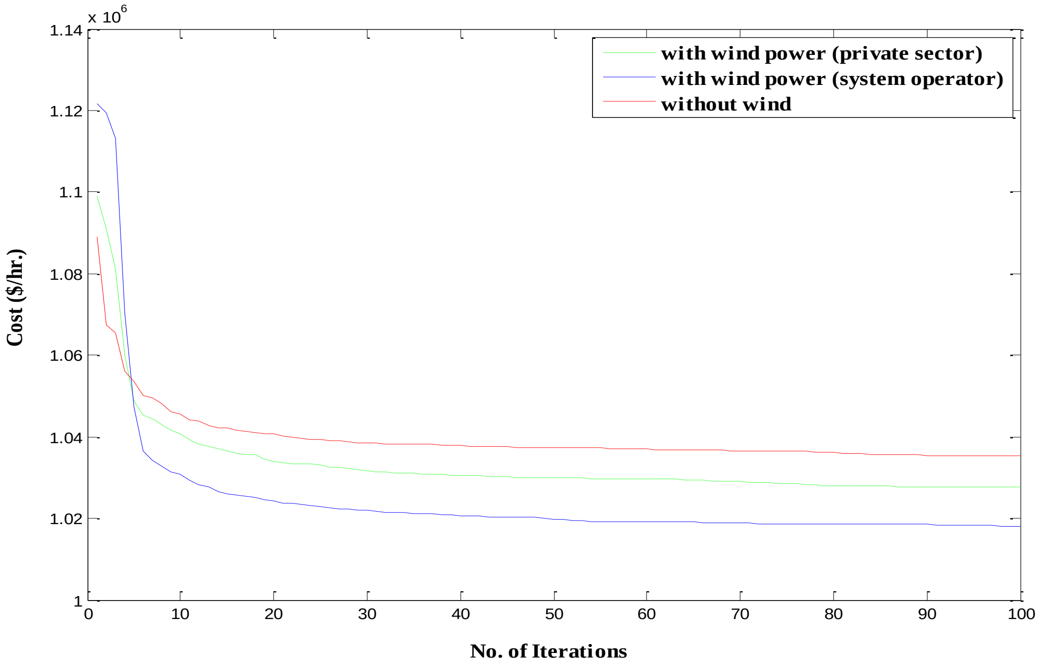


Figure 4.4 Convergence Curve for Case2_Test Problem1

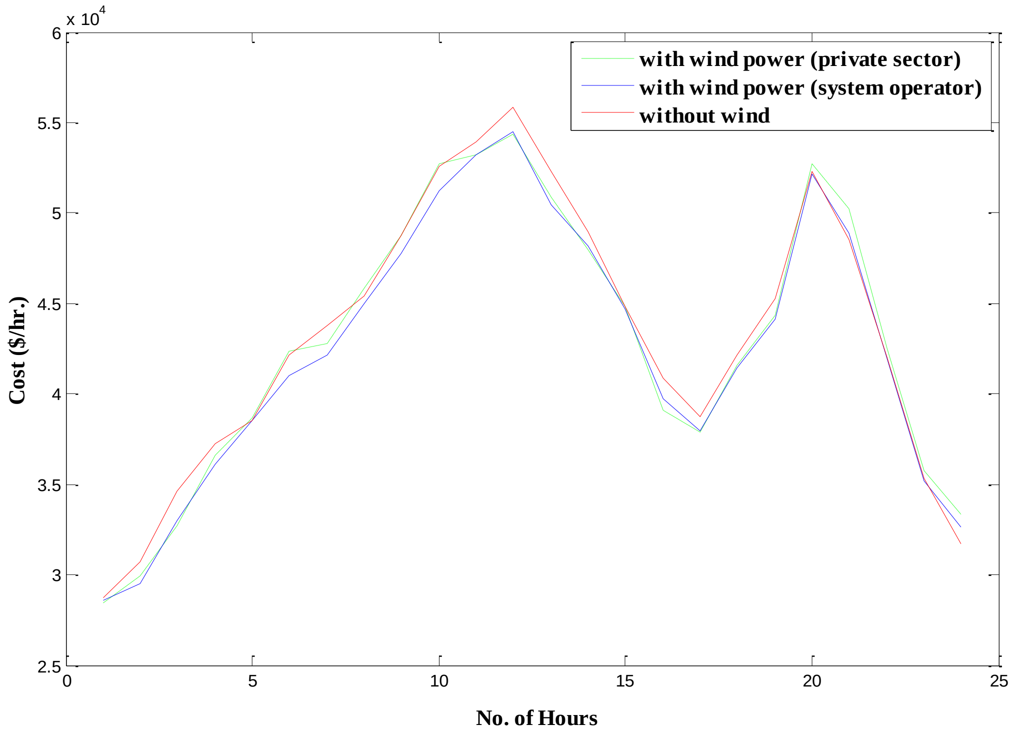


Figure 4.5 Cost-Load Curve for Case2_Test Problem1

It is observed from above table and graph that TC during power generation through thermal units are found to be more than the case when wind power units are used along with the thermal units and also if wind power unit owned by system operator, total cost can be decreased mother than when private sector is owner of wind power unit.

4.1.3.3 Case3_Test Problem1_Results

Results for ten thermal unit including two wind power plants which have assumed similar to wind power unit given in Appendix 1 using SO_PSO with wind power generated randomly within the limits.

Table 4.3: Result of Case3_Test problem1 for 24 hour

HOUR	Without Wind power unit ($/hr.)	With Wind power unit ($/hr.)	
		Private sector	System operator
1	28839.88806	27882.969	27900.48891
2	31171.72803	29756.3192	29431.51017
3	34258.58065	33493.8984	32379.46821
4	37334.12855	35809.67	35670.45526
5	39083.9246	36861.9318	37139.12423
6	42281.34037	40768.0041	40494.99678
7	43854.73817	42696.0149	41925.32891
8	45626.40923	43938.0767	43730.36984
9	48873.85272	47222.0142	47248.3437
10	51801.54462	51034.7103	50631.7478
11	53893.52653	52810.7718	52161.55913
12	55946.26056	54102.2537	54170.13889
13	52132.28339	50701.9867	50986.7452
14	48962.97838	47566.7189	47436.56062
15	45602.60879	44977.0351	44445.5598
16	40382.29802	38882.1129	38984.21165
17	38411.54935	36906.6557	37364.75319
18	42577.63641	40370.6327	40924.88088
19	45009.09888	44264.2556	43780.98922
20	52252.46181	50054.7959	50883.13041
21	48990.23826	47439.8961	47866.5395
22	41587.80703	40443.5838	40258.63666
23	34980.70817	34112.2966	33694.87747
24	32140.23163	30766.9859	30522.03034
Total Cost ($.)	1035995.822	1002863.59	1000032.447

Table 4.4: Real Power Generation of 10 +2 Units (Thermal and Wind Units) (Private Sector)

Load	**1 (MW)**	**2 (MW)**	**3 (MW)**	**4 (MW)**	**5 (MW)**	**6 (MW)**	**7 (MW)**	**8 (MW)**	**9 (MW)**	**10 (MW)**	**1 (MW)**	**2 (MW)**
1036	303.2	135	73	71.37	73	57	93.06	85.31	20	55	35	35
1110	303.2	135	73	81.16	73	125.44	56.56	85.50	52.05	55	35	35
1258	301.6	210.7	86.70	63.17	83.14	129.81	107.95	108.2	65.30	55	16.68	29.68
1406	153.9	396.9	316.83	60	172.78	57	56.54	47	20	55	35	35
1480	456.4	135	297.56	60	73	135.93	130	47	20	55	35	35
1628	226.6	309.5	292.16	119.83	171.97	120.87	93.59	120	48.33	55	35	35
1702	306.0	311.2	299.31	185.57	73.32	144.45	130	47	80	55	35	35
1776	226.6	309.5	285.72	176.56	222.59	159.97	129.99	119.9	20	55	35	35
1924	379.8	396.7	340	167.06	122.95	122.45	129.91	120	20	55	35	35
2072	379.8	460	340	155.47	222.59	160	130	47	52.05	55	35	35
2146	379.8	396.7	297.39	300	243	146.93	129.99	47	80	55	35	35
2220	456.4	396.6	340	300	172.74	127.28	130	120	51.84	55	35	35
2072	379.8	396.7	313.98	241.29	243	142.99	130	47	52.05	55	35	35
1924	317.7	313.0	285.35	262.56	243	160	130	47	41.91	55	33.33	35
1776	458.3	442.2	294.66	139.66	74.54	60.61	72.03	102.0	38.24	55	11.72	26.86
1554	379.7	310.2	190.58	123.6	103.40	123.43	130	47	21.01	55	35	35
1480	379.	135	296.90	60	174.23	122.35	120.26	47	20	55	35	35
1628	226.5	309.5	323.25	119.56	172.72	122.46	130	47	51.88	55	35	35
1776	149.8	394.7	296.59	175.54	222.42	159.04	130	47	75.74	55	35	35
2072	456.4	396.8	309.81	241.24	222.60	123.0	130	47	20	55	35	35
1924	226.6	396.7	325.60	241.32	232.26	147.89	129.58	47	51.90	55	35	35
1628	303.2	396.7	205.15	60	172.73	160	130	47	28.06	55	35	35
1332	456.4	135	73	60	73	139.50	130	120	20	55	35	35
1184	150.0	396.8	87.293	60	73	57	129.59	85.31	20	55	35	35

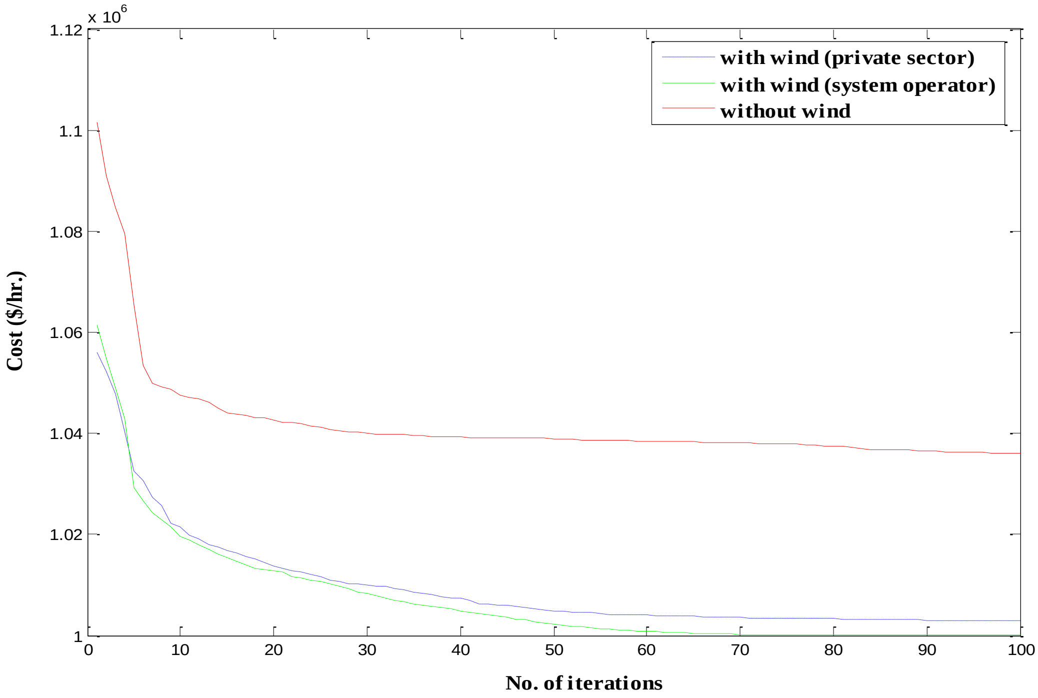


Figure 4.6 Convergence Curve for Case3_Test Problem1

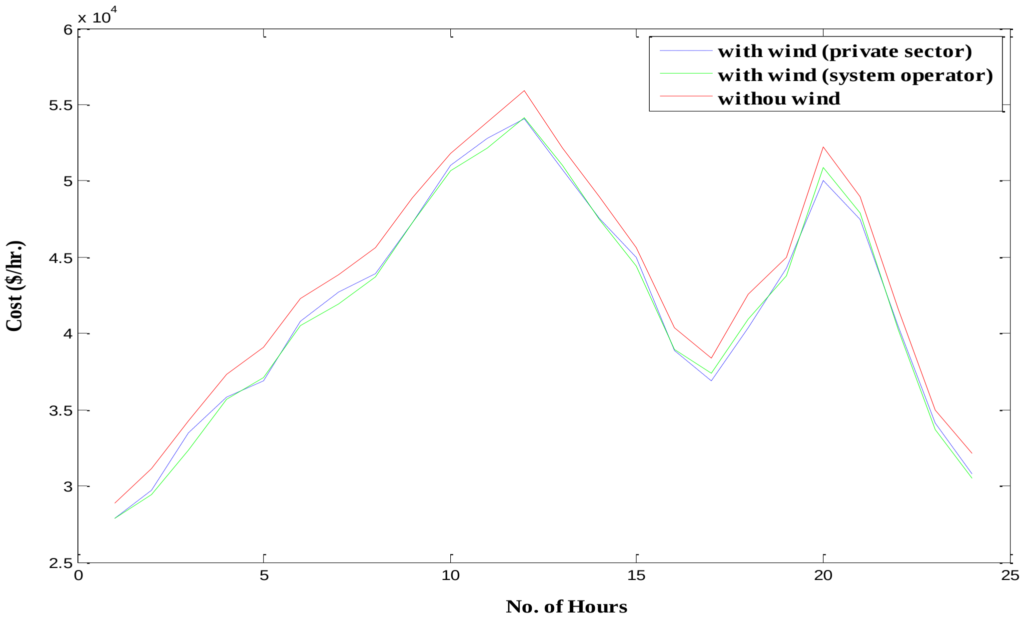


Figure 4.7 Cost-Load Curve for Case3_Test Problem1

It is observed from above table and graph that TC (1035995.822) during power generation through thermal units are found to be more than the TC (1002863.59) when wind power units are used along with the thermal units and also if wind power unit owned by system operator, total cost can be decreased mother than when private sector is owner of wind power unit.

4.1.4 Test Problem 2_Without losses_ 45 Unit System

Economic load dispatch problem is solved for 40 thermal units with 5 wind power units for 24 hour load demand using SO-PSO. The cost coefficient and operating ranges data and load demand data for 24 hour is given in Appendix 2. For SO_PSO c1i= 2.5, c1f= c2i= 0.2, c2f= 2.2 are considered.

4.1.4.1 Case1_Test Problem2_Results

Results for forty thermal unit including five wind power units which have assumed similar to wind power units are given in Appendix 1 using SO_PSO with wind power generated randomly within the operating range.

Table 4.5: Result of Case1_Test problem2 for 24 hour

HOUR	Without Wind power unit ($/hr.)	With Wind power unit ($/hr.)	
		Private sector	System operator
1	98985.38741	99301.8607	91656.96705
2	94557.72122	90663.4084	94257.49975
3	107997.9818	105673.308	103206.3678
4	109218.5207	111162.489	104503.0965
5	128281.8136	126169.21	116459.7295
6	125523.9397	125214.405	119313.6781
7	130711.7775	116446.121	117507.4883
8	136032.1092	121732.007	126495.4879
9	133966.7353	127178.752	127514.1299
10	135846.0182	123619.21	129404.6138
11	132204.8666	129925.526	124066.8412
12	133424.8878	133893.325	125429.5504
13	128084.6322	126201.656	127646.6003
14	137540.8771	127812.19	125634.9905
15	127302.3553	133926.62	126159.9991
16	113301.3843	108176.013	108623.5065
17	110166.6305	107828.429	106905.6736
18	115852.5363	105213.873	108226.2251
19	134676.2463	127004.549	123551.6145
20	141798.4095	127254.704	140702.3741
21	135821.638	124494.377	131486.2557
22	125054.9145	118292.75	125689.3243
23	101657.5022	91970.4848	104956.0945

24	102651.8346	105738.015	103713.9263
Total Cost ($/hr.)	2940660.72	2814893.282	2813112.035

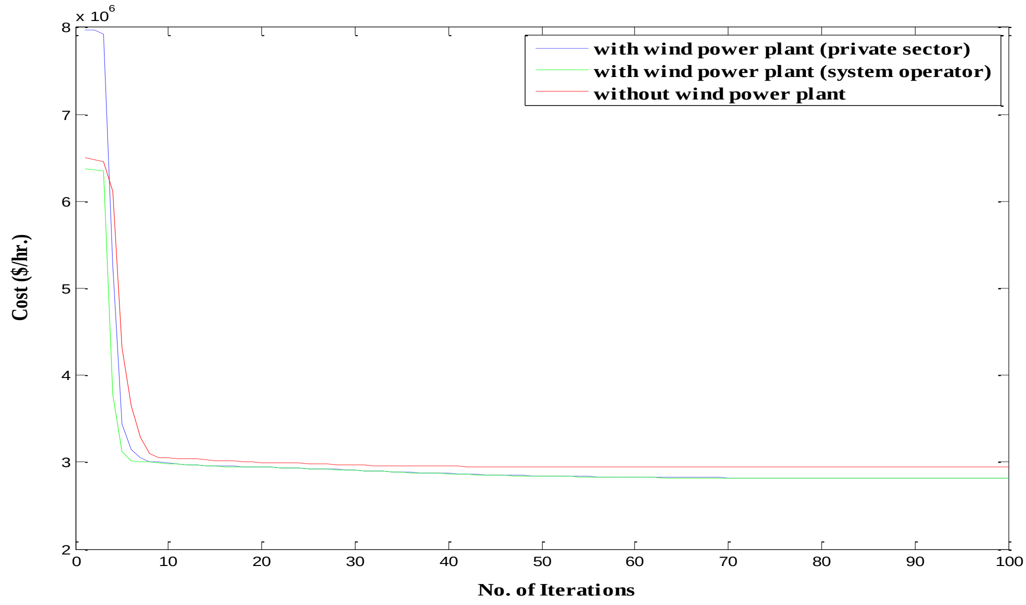


Figure 4.8 Convergence Curve for Case1_Test Problem2

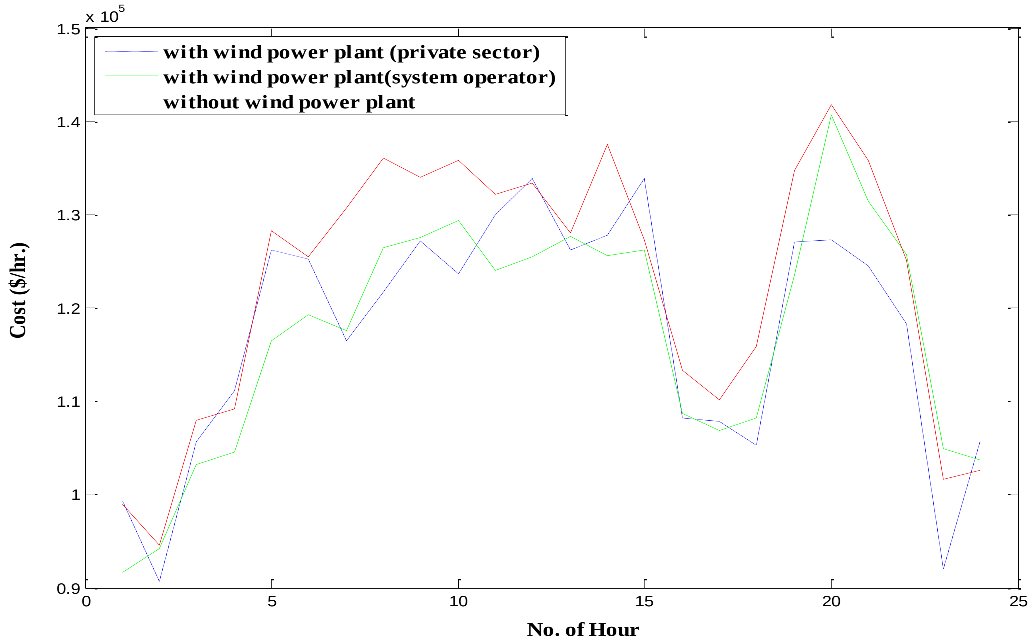


Figure 4.9 Cost-Load Curve for Case1_Test Problem2

It is observed from above table and graph that TC for forty thermal units are found to be more than the TC when five wind power units are used along with forty thermal units and also if wind power unit owned by system operator, total cost can be decreased mother than when private sector is owner of wind power unit.

4.1.4.2 Case2_Test Problem2_Results

Simulation results for forty thermal unit including five wind power units which have assumed similar to wind power units are given in Appendix 2using SOPSO with wind speed known. Wind speed data for 24 hour given in Appendix 1.

Table 4.6: Result of Case2_Test problem2 for 24 hour

HOUR	Without Wind power unit ($/hr.)	With Wind power unit ($/hr.)	
		Private sector	System operator
1	92605.05941	92741.6796	96263.50169
2	123310.6199	95977.8321	99810.55123
3	106476.5709	106673.251	110589.4533
4	107906.2363	107018.688	109091.578
5	126716.5606	129054.419	122862.3697
6	127063.5031	125322.644	121391.9583
7	125507.5912	122232.723	127925.3894
8	130460.2545	129702.776	125773.3601
9	133955.3988	136749.849	129670.902
10	136226.0686	131399.583	136829.8753
11	137255.9866	126241.164	129028.9774
12	137885.7927	134150.481	142780.9718
13	134016.2699	137790.693	135028.2515
14	130770.0236	134233.857	126623.5753
15	131937.8583	129897.368	129445.6403
16	109311.2974	117094.365	107080.249
17	108163.1126	108174.671	109233.9417
18	110756.0642	112428.206	113555.2491
19	125591.2582	125989.874	125832.9095
20	128526.0634	138065.267	131541.5121
21	131426.8468	141286.903	127923.7449
22	125841.6504	125499.385	128772.1049
23	98786.65389	111377.691	98045.19088
24	94948.73742	111183.857	99180.00646
Total Cost ($)	2949287.227	2915445.479	2884281.264

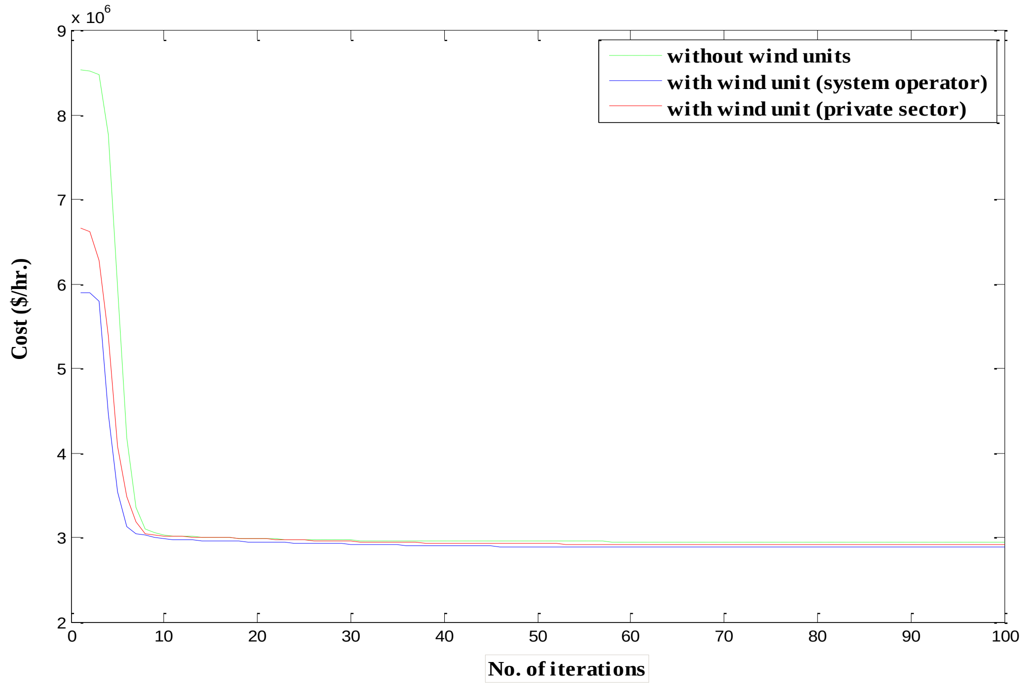


Figure 4.10 Convergence Curve for Case2_Test Problem2

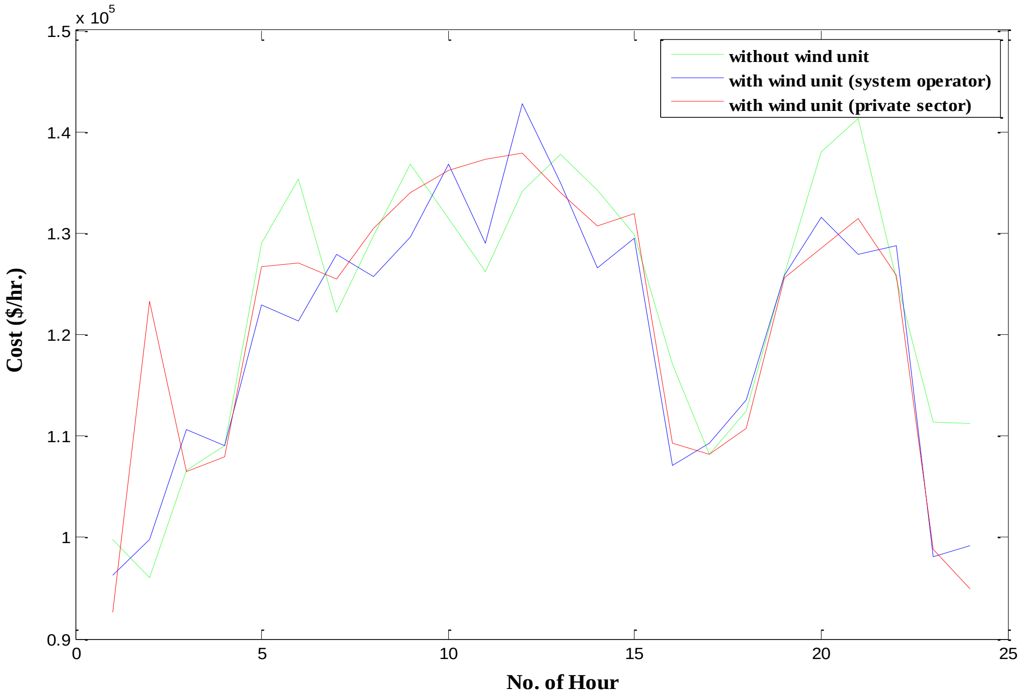


Figure 4.11 Cost-Load Curve for Case2_Test Problem2

It is observed from above table and graph that TC for forty thermal units are found to be more than the TC when five wind power units with wind speed known are used along with the thermal units and also if wind power unit owned by system operator, total cost can be decreased mother than when private sector is owner of wind power unit.

4.1.5 Test Problem 3_With Losses

The economic load dispatch problem is applied on 10 unit thermal systems with and without wind power unit for 24 hour load demand with considering losses using particle swarm optimization technique and by using SOPSO. The cost coefficient and operating ranges data and B-Coefficient data is given in Appendix 3. The load data for 24 hour is taken from Appendix 1.

4.1.5.1 Case1_Test problem 3_Results

Simulation results for considering thermal units only using PSO and SOPSO are given in table 4.7.

Table 4.7: Result of Case1_Test problem3 for 24 hour

HOUR	PSO ($/hr.)	PSO P_{Loss} (MW)	SOPSO ($/hr.)	SOPSO P_{Loss} (MW)
1	57029.62	22.27375	56923.24	22.46176
2	61085.66	28.51222	60954.55	25.78094
3	69297.86	32.31301	70133.9	30.79013
4	76876.52	41.28372	77084.91	40.58268
5	81190.54	45.25448	80698.12	46.22542
6	88912.4	57.13795	88995.08	59.00678
7	94287.54	61.23195	94004.71	62.65629
8	98672.86	66.28601	98010.08	68.56288
9	110427.8	77.42334	106801.3	81.06396
10	118989.7	87.84271	116622.8	91.24454
11	124226.4	96.96502	122658.5	96.77886
12	129049.7	102.449	129203.3	96.77886
13	116637.4	91.55724	116714.6	91.679
14	106859.2	80.93683	106951.5	79.57195
15	98015.67	68.26196	97982.81	69.8954
16	85109.5	51.60564	85609.61	50.71719
17	80870.96	46.50767	80744.88	46.28015
18	89378.38	56.80492	88934.82	58.68854
19	101581.3	64.75201	98608.81	65.25809
20	116606.3	91.81507	116606.3	91.38952
21	110024.9	75.26894	106844	81.22624
22	89535.3	56.69235	90605.29	54.79665
23	75536.6	56.69235	72981.26	36.91397

24	64842.6	29.06714	65067.48	28.9052
Total	2245045	1488.935	2229742	1477.255
CPU time (sec)	14.05125		12.97976	

Table 4.8: Real Power Generation of 10 Thermal Units (PSO)

1 (MW)	**2 (MW)**	**3 (MW)**	**4 (MW)**	**5 (MW)**	**6 (MW)**	**7 (MW)**	**8 (MW)**	**9 (MW)**	**10 (MW)**
23.47	80	60.53	20	59.51	70	151.20	135.10	213.37	244.91
13.61	53.24	47	38.55	53.19	70	69.66	70	383.87	339.62
45.32	47.83	69.61	58.31	50	77.42	176.98	319.08	295.72	150
41.41	38.02	58.77	130	56.99	70	169.21	224.33	345.08	313.44
11.80	78.31	101.88	109.36	50	70.584	164.39	297.36	321.23	320.50
54.17	56.40	66.99	80.54	55.14	70	224.93	340	368.14	368.60
52.92	64.93	101.72	82.46	73.84	127.94	273.77	217.13	298.78	470
54.42	67.78	99.87	130	71.87	130.06	203.63	267.84	380.12	436.66
141.02	76.56	75.69	92.99	158.51	212.20	190.62	254.40	448.29	349.82
166.82	75.37	112.39	103.08	156.21	202.87	260.22	306.17	361.19	415.47
54.86	80	90.11	130	68.052	240	300	340	470	470
52.39	80	120	130	159.47	200.63	300	340	470	470
53.50	80	120	130	88.12	112.19	300	340	470	470
53.01	80	74.70	130	62.43	70	255.02	340	470	470
48.46	78.74	47	108.81	61.86	70	300	306.57	470	352.80
53.37	25.69	51.79	31.95	106.34	105.51	300	226.34	333.25	371.31
38.38	80	109.06	80.95	50	70	179.48	209.32	434.05	275.24
10.37	80	101.27	72.43	50	70	201.75	317.96	312.13	470
52.37	80	120	120	145.10	108.44	270	340	135	470
54.78	80	120	130	93.62	105.46	300	340	470	470
86.17	55.37	97.45	106.33	146.48	196.86	252.35	284.43	406.22	367.56
48.38	69.88	60.46	120	53.06	77.67	227.75	306.02	438.04	282.66
48.38	69.88	60.46	120	53.06	77.67	227.75	306.02	438.04	282.66
38.77	31.53	47	71.85	50	70	177.56	220.66	355.68	150

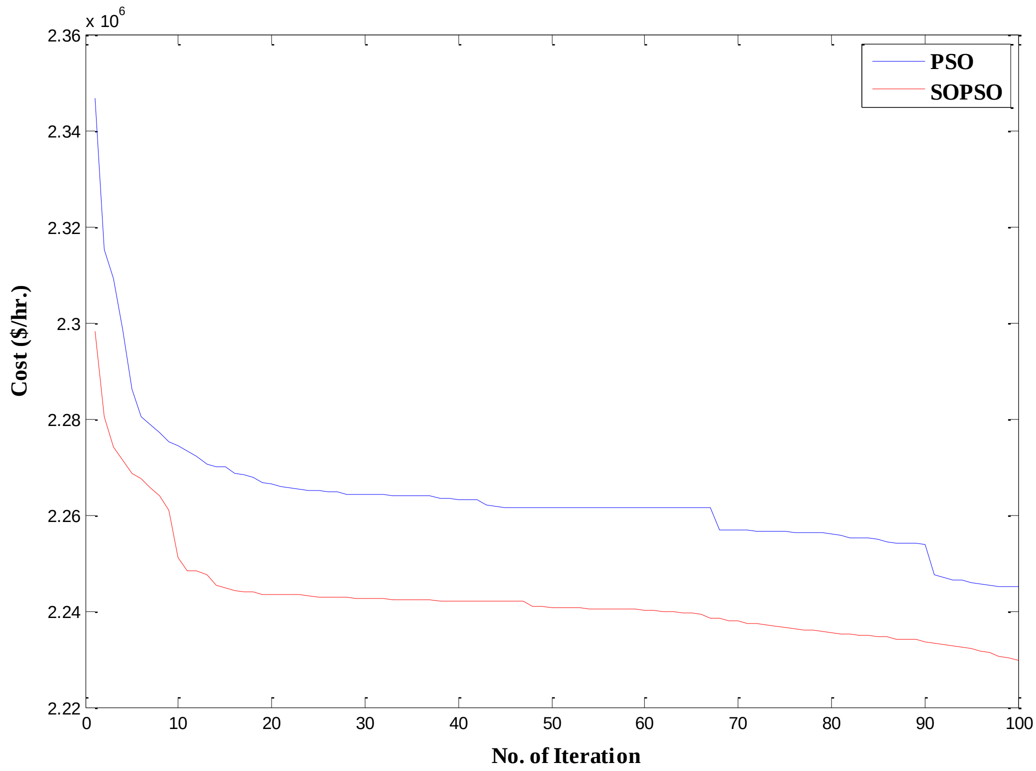


Figure 4.12 Convergence Curve for Case1_Test Problem3

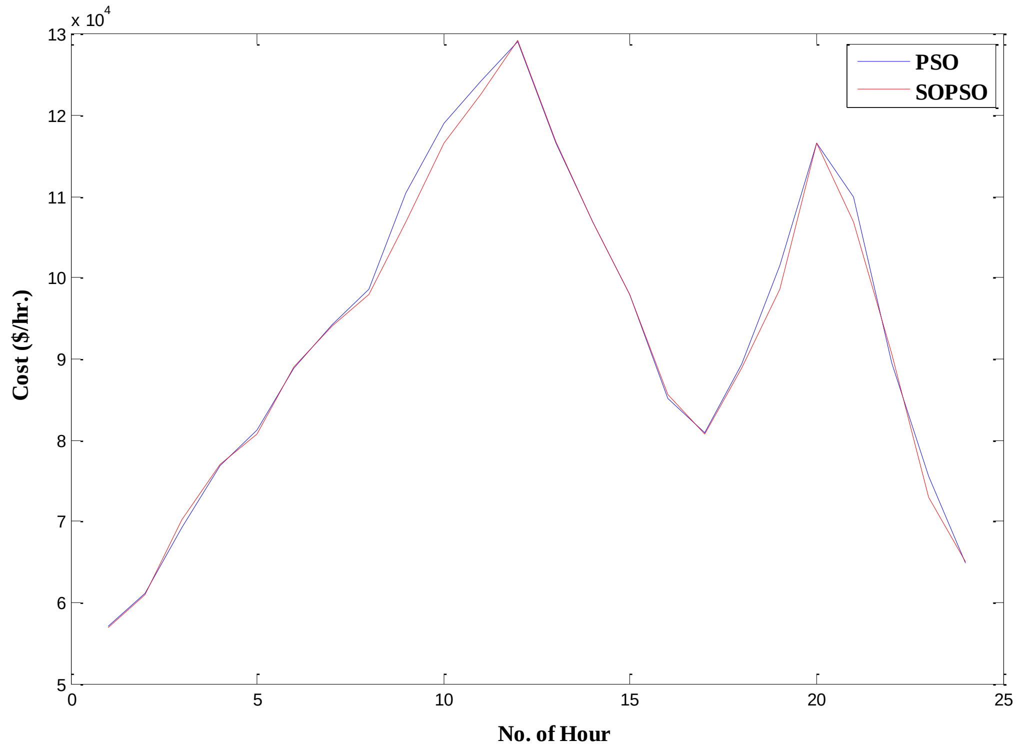


Figure 4.13 Cost-Load Curve for Case1_Test Problem3.

It is observed from above table and graph that total cost (TC) of ten unit system including losses for SOPSO is 2229742 $ for a 24 hour scheduling lower than PSO TC 2245045$. the total transmission losses are less in case of self-organising PSO i.e. 1477.255 MW than PSO. The CPU time is fast in case of SOPSO i.e. 12.97976 sec for 100 iterations than PSO.

4.1.5.2 Case2_Test Problem3_Results

Simulation results for 10 thermal units including one wind power units using SOPSO with wind power generated randomly within the operating range. The parameter for wind power unit is taken from Appendix 1.

Table 4.9: Result of Case2_Test problem3 for 24 hour

HOUR	Without Wind power unit ($/hr.)	P_{Loss} (MW)	With Wind power unit ($/hr.)		With Wind power unit losses P_{Loss} (MW)	
			Private sector	System operator	Private Sector	System Operator
1	56999.25585	21.73830868	55503.3283	55586.41328	21.05781931	19.73170013
2	60513.67898	26.87767495	59425.6093	58866.05806	22.88206415	24.05717998
3	68278.81242	34.71423254	66956.0348	66633.42956	30.98703101	31.73657191
4	77677.39579	40.56130505	74887.7194	74390.61416	38.71045268	39.99576445
5	81205.31442	46.60524563	78464.2658	78703.44057	44.72627861	44.13203212
6	89432.63398	57.09613926	87533.3176	87411.98379	53.35873024	54.1596325
7	93198.81678	62.15196117	92071.6035	91384.61675	57.25277181	59.02066667
8	98227.72804	67.70230285	96055.5263	95568.88503	65.23545797	67.32647706
9	106732.0628	80.3928989	104568.767	104758.2255	78.37113809	78.48229504
10	118691.6769	91.13981805	114381.129	114966.3717	89.17885261	83.40624824
11	122427.0897	97.03367886	120723.145	119763.8438	94.09450496	94.62417192
12	129445.2826	102.4721871	126004.624	125966.1708	99.61767497	99.91573321
13	117468.4863	91.56800623	114322.283	114405.7052	88.93149477	88.67934571
14	108043.0062	80.33125752	104851.789	104696.0184	78.25582978	78.24483708
15	97631.04291	68.64399197	95931.1706	95713.29538	65.61068862	67.20610259
16	84690.74138	52.79390986	82784.5006	83086.74005	51.86267224	48.94020323
17	83122.12472	52.79390986	80244.5068	78522.09295	43.6091337	44.1229352
18	88632.197	58.41573388	86965.7564	86867.27143	55.02668254	53.79709027
19	98291.54628	68.30711741	97965.9615	95827.70418	62.72913825	65.40196762
20	117030.234	91.03638166	114336.684	116078.4944	89.07001734	86.05848501
21	107013.9273	79.36035124	104973.5	105450.7485	78.00506396	76.94325344
22	89413.95566	55.76511546	86834.3203	87734.33552	56.21473512	51.83368498
23	75003.54131	55.76511546	70397.3569	71526.43798	36.13835854	34.29756331
24	64259.84845	31.28449179	62652.4368	63232.4922	28.29257974	27.91855684
Total	2233430	1514.551	2178835.336	2177141.389	1429.21917	1420.032499

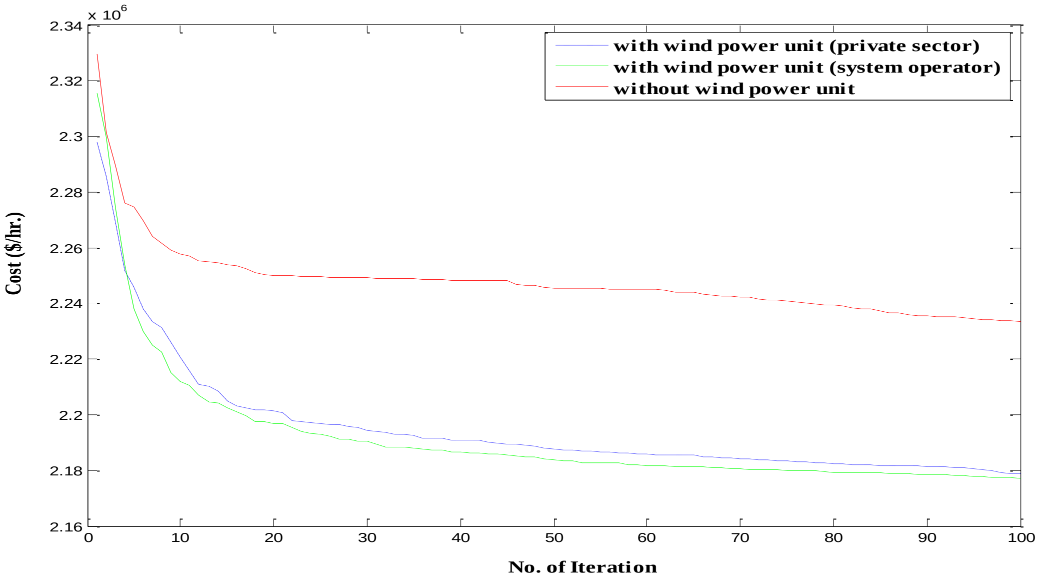


Figure 4.14 Convergence Curve for Case2_Test Problem3

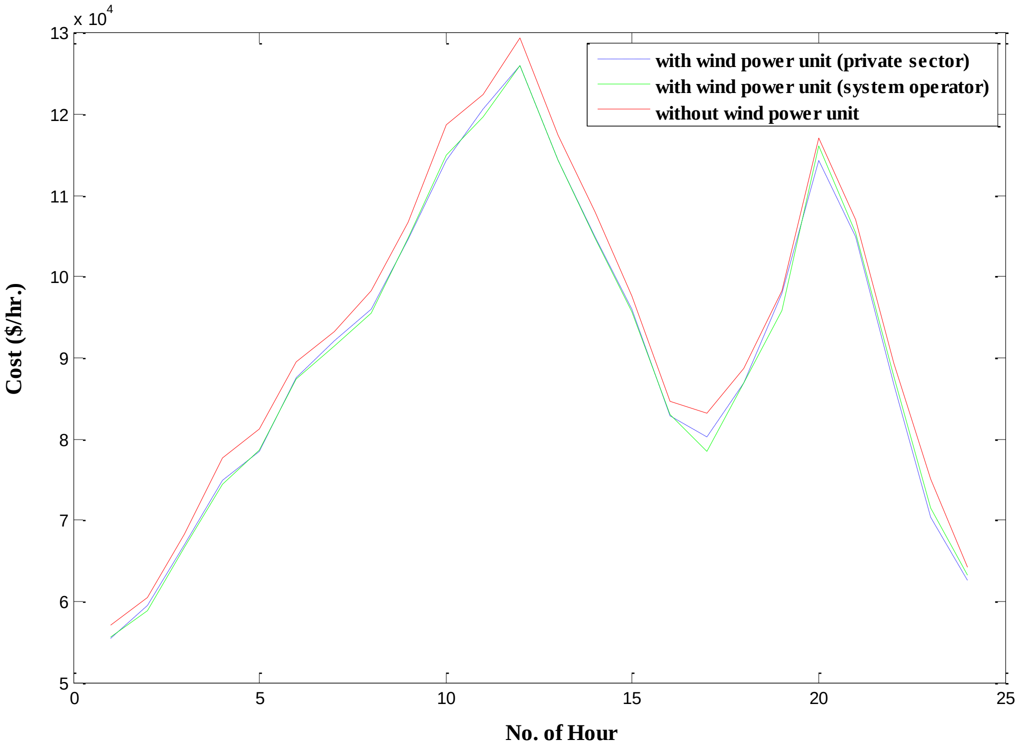


Figure 4.15 Cost-Load Curve for Case2_Test Problem3.

It is observed from above table and graph that TC for ten thermal units i.e. 2233430 are found to be more than the TC (2178835.336) when one wind power units are used along with ten thermal units and also if wind power unit owned by system operator, total cost can be decreased mother than when private sector is owner of wind power unit. The total transmission losses are also decreased when wind power unit is incorporate with thermal units.

4.1.5.3 Case3_Test Problem2_Results

Simulation results for 10 thermal units including one wind power units using SO_PSO with wind speed known. The parameters for wind power unit are taken from Appendix 1. Wind speed data for 24 hour given in Appendix 3. The simulation is carried out for 100 iterations and 10 population size.

Table 4.10: Result of Case3_Test problem2 for 24 hour

HOUR	Without Wind power unit ($/hr.)	P_{Loss} (MW)	With Wind power unit ($/hr.)		With Wind power unit losses P_{Loss} (MW)	
			Private sector	System operator	Private Sector	System Operator
1	57263.57	21.72973	57552.65	56888.94	22.79446	21.98970432
2	60763.72	26.15021	62374.8	61104.3358	24.44291	24.27602912
3	68865.81	33.14933	68971.8	67653.1335	30.2968	32.77651899
4	76639.35	42.71472	76586.85	73676.8611	42.81464	42.05952508
5	82000.24	45.37943	75962.24	75583.197	44.15017	44.38480672
6	88873.57	58.26429	91014.64	83383.7466	53.60405	44.38480672
7	93097.74	62.75631	93845.79	93424.8707	62.3699	63.00441879
8	98376.7	65.22839	98349.63	97733.7038	67.64809	69.69056703
9	107352.8	78.51143	107274.6	106548.483	81.93923	82.07404243
10	117501.3	91.66242	117075.9	117819.808	91.62775	88.67086901
11	122650	97.15999	122945.6	122396.67	96.92445	97.05326216
12	129448.7	102.5448	129385	128874.6	102.1856	102.375651
13	116667.8	91.61728	117075.4	116603.99	91.61553	91.75828306
14	106934.9	81.1404	107060.5	107004.799	81.77195	79.68155505
15	97443.37	69.41932	97891.32	97930.1169	69.94767	69.32429831
16	85202.48	50.88112	79411.74	81888.1797	69.94767	48.67921541
17	81696.29	45.20171	75962.24	75583.197	44.89557	44.7754447
18	89225.83	57.16317	89366.6	83383.7466	55.90242	44.7754447
19	97584.35	69.3996	97687.26	97362.5878	69.73268	69.35505308
20	117258.7	91.37137	116300.7	117123.448	90.59757	88.74867493
21	106723.9	81.22788	105947.8	105931.999	80.63615	79.26559254
22	89822.92	57.06622	88439.02	84132.5279	55.92315	79.26559254
23	72706.14	35.05855	71722.25	71139.4859	37.42055	34.79577502
24	64705.93	29.18922	64659.07	64292.2929	28.23828	27.82269669
Total	2228806	1483.987	2212864	2187464.72	1497.427	1470.987827

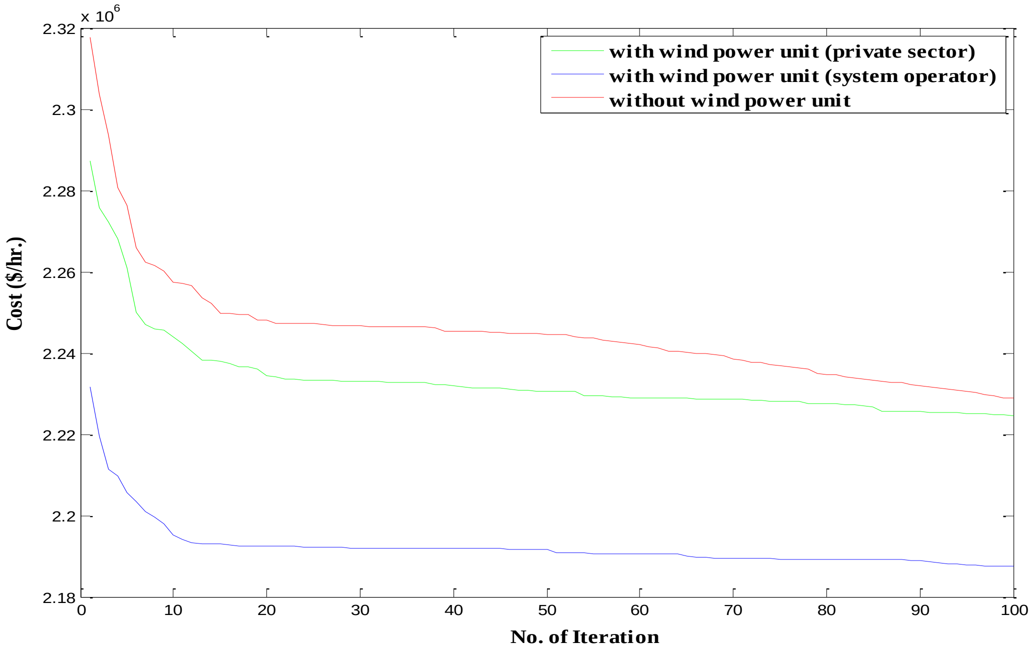


Figure 4.16 Convergence Curve for Case3_Test Problem3

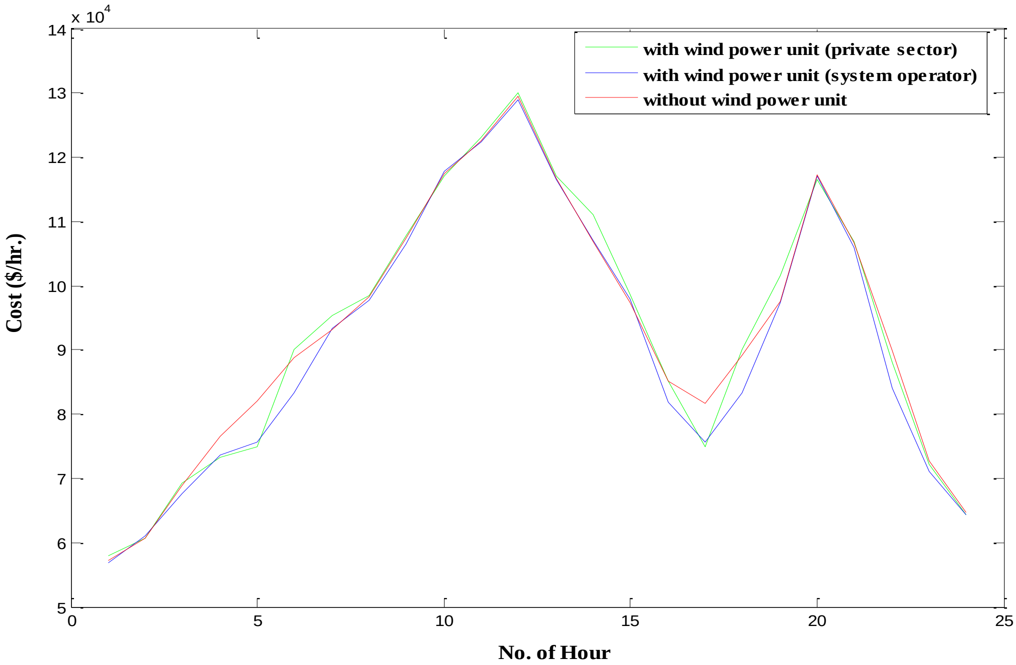


Figure 4.17 Cost-Load Curve for Case3_Test Problem3.

It is observed from above table and graph that TC for ten thermal units i.e. 2228806 are found to be more than the TC (2212864) when one wind power units are used along with ten thermal units and also if wind power unit owned by system operator, total cost can be decreased mother than when private sector is owner of wind power unit.

Chapter 5

Conclusion and Future Scope

5.1 Conclusion

Particle swarm optimisation (PSO) technique is applied to economic power generation for ten and forty thermal units with valve point loading effect. This dissertation develops a model to include wind power units in the Economic Dispatch (ED) problems. The uncertain nature of the wind speed is represented by the Weibull PDF. Classical PSO is improved using dynamically varying and acceleration coefficients and is successfully employed to solve power economic generation problem incorporating wind power units.

In this dissertation, particle swarm optimisation and self-organising particle swarm optimisation is applied to ten thermal generator system with and without two wind power units and 40-generator with and without five wind power units and 10-generator including losses with and without wind power units. The comparative simulations with and without wind power units, illustrate that wind power plants have powerful performance in total power production and can reduce total cost in power systems. Also, if wind power units owned by system operator, total cost can be decreased more than when private sector is owner of wind power units.

5.2 Future Scope

1. Sensitive analysis for the control parameters of PSO like acceleration factor, inertial weights.
2. Multi objective Particle swarm optimization (MOPSO) algorithm can be used to solve the problem.

Publications

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APPENDIX -1

1. Input Data for Ten Thermal generating unit [10]

UNIT	a_i	b_i	c_i	e_i	f_i	$P_i^{min}(MW)$	$P_i^{max}(MW)$
Gen1	0.00043	21.60	958.20	450	0.041	150	470
Gen 2	0.00063	21.05	1313.6	600	0.036	135	460
Gen 3	0.00039	20.81	604.97	320	0.028	73	340
Gen 4	0.00070	23.90	471.60	260	0.052	60	300
Gen 5	0.00079	21.62	480.29	280	0.063	73	243
Gen 6	0.00056	17.87	601.75	310	0.048	57	160
Gen 7	0.00211	16.51	502.70	300	0.086	20	130
Gen 8	0.00480	23.23	639.40	340	0.082	47	120
Gen 9	0.10908	19.58	455.60	270	0.098	20	80
Gen 10	0.00951	22.54	692.40	380	0.094	55	55

2. Parameters of Wind power plant [14]

P_j^{min} (Mw)	P_i^{max} (MW)	V_i(m/s)	V_r(m/s)	V_o(m/s)	K_r	K_p	d
0	35	5	15	45	1	1	1.12

3. Ten unit 24 hour Load demand [14]

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

4. Wind Speed for 24 Hour [22]

HOUR	V_i(m/s)	HOUR	V_i(m/s)	HOUR	V_i(m/s)
1	10	**9**	11	**17**	11
2	13	**10**	8	**18**	10
3	15	**11**	14	**19**	12
4	12	**12**	16	**20**	6
5	10	**13**	17	**21**	3
6	7	**14**	14	**22**	8
7	15	**15**	13	**23**	6
8	7	**16**	13	**24**	2

APPENDIX-2

1. **Input Data for 40 Thermal units** [4]

UNIT	a_i	b_i	c_i	e_i	f_i	$P_i^{min}(MW)$	$P_i^{max}(MW)$
GEN1	0.0069	6.73	94.705	100	0.084	36	114
GEN 2	0.0069	6.73	94.705	100	0.084	36	114
GEN 3	0.02028	7.07	309.54	100	0.084	60	120
GEN 4	0.00942	8.18	369.03	150	0.063	80	190
GEN 5	0.0114	5.35	148.89	120	0.077	47	97
GEN 6	0.01142	8.05	222.33	100	0.084	68	140
GEN 7	0.00357	8.03	287.71	200	0.042	110	300
GEN 8	0.00492	6.99	391.98	200	0.042	135	300
GEN 9	0.00573	6.6	455.76	200	0.042	135	300
GEN 10	0.00605	12.9	722.82	200	0.042	130	300
GEN 11	0.00515	12.9	635.2	200	0.042	94	375
GEN 12	0.00569	12.8	654.69	200	0.042	94	375
GEN 13	0.00421	12.5	913.4	300	0.035	125	500
GEN 14	0.00752	8.84	1760.4	300	0.035	125	500
GEN 15	0.00708	9.15	1728.3	300	0.035	125	500
GEN 16	0.00708	9.15	1728.3	300	0.035	125	500
GEN 17	0.00313	7.97	647.85	300	0.035	220	500
GEN 18	0.00313	7.95	649.69	300	0.035	220	500
GEN 19	0.00313	7.97	647.83	300	0.035	242	550
GEN 20	0.00313	7.97	647.81	300	0.035	242	550
GEN 21	0.00298	6.63	785.96	300	0.035	254	550
GEN 22	0.00298	6.63	785.96	300	0.035	254	550
GEN 23	0.00284	6.66	794.53	300	0.035	254	550
GEN 24	0.00284	6.66	794.53	300	0.035	254	550
GEN 25	0.00277	7.1	801.32	300	0.035	254	550
GEN 26	0.00277	7.1	801.32	300	0.035	254	550
GEN 27	0.52124	3.33	1055.1	120	0.077	10	150
GEN 28	0.52124	3.33	1055.1	120	0.077	10	150
GEN 29	0.52124	3.33	1055.1	120	0.077	10	150
GEN 30	0.0114	5.35	148.89	120	0.077	47	97

GEN 31	0.0016	6.43	222.92	150	0.063	60	190
GEN 32	0.0016	6.43	222.92	150	0.063	60	190
GEN 33	0.0016	6.43	222.92	150	0.063	60	190
GEN 34	0.0001	8.95	107.87	200	0.042	90	200
GEN 35	0.0001	8.62	116.58	200	0.042	90	200
GEN 36	0.0001	8.62	116.58	200	0.042	90	200
GEN 37	0.0161	5.88	307.45	80	0.098	25	110
GEN 38	0.0161	5.88	307.45	80	0.098	25	110
GEN 39	0.0161	5.88	307.45	80	0.098	25	110
GEN 40	0.00313	7.97	647.83	300	0.035	242	550

2. Forty unit 24 hour Load demand [14]

HOUR	P_D **(MW)**	**HOUR**	P_D **(MW)**	**HOUR**	P_D **(MW)**
1	7036	**9**	9924	**17**	8480
2	7110	**10**	10072	**18**	8628
3	8258	**11**	10146	**19**	9776
4	8406	**12**	10220	**20**	10072
5	9480	**13**	10072	**21**	9924
6	9628	**14**	9924	**22**	9628
7	9702	**15**	9776	**23**	7332
8	9776	**16**	8554	**24**	7184

APPENDIX-3

1. **Cost coefficient data for Ten thermal Generating units** [21]

UNIT	a_i	b_i	c_i	e_i	f_i	$P_i^{min}(MW)$	$P_i^{max}(MW)$
Gen1	0.12951	40.5407	1000.403	33	0.0174	10	55
Gen 2	0.10908	39.5804	950.606	25	0.0178	20	80
Gen 3	0.12511	36.5104	900.705	32	0.0162	47	120
Gen 4	0.12111	39.5104	800.705	30	0.0168	20	130
Gen 5	0.15247	38.5390	756.799	30	0.0148	50	160
Gen 6	0.10587	46.1592	451.325	20	0.0163	70	240
Gen 7	0.03546	38.3055	1243.531	20	0.0152	60	300
Gen 8	0.02803	40.3965	1049.998	30	0.0128	70	340
Gen 9	0.02111	36.3278	1658.569	60	0.0136	135	470
Gen 10	0.01799	38.2704	1356.659	40	0.0141	150	470

2. **B-Coefficient data [21]:**

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

3. **Wind Speed for 24 Hour [22]**

HOUR	V_i(m/s)	HOUR	V_i(m/s)	HOUR	V_i(m/s)
1	5	**9**	3.61	**17**	4.44
2	5.5	**10**	4.17	**18**	4.72
3	5.83	**11**	4.44	**19**	6.11
4	5.28	**12**	5.28	**20**	7.5
5	4.44	**13**	5	**21**	8.88

6	3.89	**14**	4.72	**22**	8.88
7	3.89	**15**	4.44	**23**	8.88
8	3.61	**16**	4.44	**24**	8.88

4. Wind Speed for 24 Hour

HOUR	V_i**(m/s)**	**HOUR**	V_i**(m/s)**	**HOUR**	V_i**(m/s)**
1	10	**9**	11	**17**	11
2	13	**10**	8	**18**	10
3	15	**11**	14	**19**	12
4	12	**12**	16	**20**	6
5	10	**13**	17	**21**	3
6	7	**14**	14	**22**	8
7	15	**15**	13	**23**	6
8	7	**16**	13	**24**	2