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FACULTY OF ENGINEERING

DEPARTMENT OF ELECTRICAL AND INFORMATION ENGINEEERING

UNCERTAINTY TREATMENT IN ECONOMIC DISPATCH WITH RENEWABLE ENERGY

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By

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Project report submitted in partial fulfilment of the requirement for the award of the degree of

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DEDICATION

I dedicate this work to my mother, who has sacrificed a lot to see me through my studies.

ACKNOWLEDGEMENT

I would like to sincerely thank my supervisor, Mr Musau, for his professional guidance and continuous support and belief in this work throughout the lifetime of this project. His vast knowledge in Renewable energy has been inspiring. Without his consistent guidance and encouragement, the accomplishment of this study would not have been possible.

It is my great pleasure to express sincere gratitude to all staff and students of department of electrical engineering, University of Nairobi, for their continuous support.

ABSTRACT

Increasing environmental concerns due to emissions from fossil fuel driven power plants has led to focusing on developing alternative sources of power. Renewable energy has therefore received a lot of attention due to it merits over the conventional methods of generating electricity. However, the main challenge of integration of renewable energy is its uncertainty. The availability of wind and solar power is highly dependent on the weather conditions which are variable. For consumers to be supplied reliably, uncertainty of these renewable sources should be minimized.

In this project, a genetic algorithm has been developed and applied in the treating of uncertainties in an economic dispatch with renewable energy sources. Economic Dispatch (ED) problem considering wind and solar is formulated. The cost functions of wind and solar is divided into three parts. Renewable energy is given the first priority then the thermal plants can supply the remaining demand after all renewable energy has been utilized. PSO algorithm is then applied to obtain an allocation of generation output to thermal units in the system to meet system load and achieve minimum operation cost. Uncertainty is treated by charging varying costs due to over generation and under generation depending on the discrepancy of the predicted and the actual available power.

The developed PSO algorithm has been tested on a 6 unit IEEE 30-bus network at 30% and 50% penetration level of Renewable Energy and the results obtained were satisfactory. At low uncertainty values at 50% penetration the cost of supplying a load of 300MW is 735.15$ while for the same demand at 30% penetration level generation cost is 766.243$. When the level of discrepancy between predicted and the available power increases, the cost of generation for a load of 300MW at 50% penetration is1433.16$ while at 30% penetration of renewable resources the cost of supplying the same load of 300MW is 1316.2$. The results showed that renewable sources can be integrated into the conventional power plants. Uncertainty can be highly reduced by accurate forecasts. This is achieved by use of modelled data and onsite monitoring.

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LIST OF ABBREVIATIONS

ED: Economic Dispatch

RE: Renewable Energy

WPGs: Wind Power Generators

PVs: Photovoltaic Power Generators

DFIGs: Doubly Fed Induction Generators

RES: Renewable Energy Sources

WECs: Wind Energy Conversion Systems

AGC: Automatic Generation Control

PSO: Particle Swarm Optimization

GA: Genetic Algorithm

SA: Simulated Annealing

TS: Tabu search

LP: Linear Programming

OPF: Optimal Power Flow

IEEE: Institute of Electrical and Electronic Engineering

DSR: Diffuse Solar Radiation

CHAPTER 1: UNCERTAINTY TREATMENT IN ECONOMIC DISPATCH WITH RENEWABLE ENERGY

1.1. Definition of Terms

a. Uncertainty

Uncertainty is the (changefulness) unpredictability, inaccuracy, variability.

Uncertainty is a state for all the power system components, and the objective environment, where it is impossible to exactly describe the existing state, a future outcome, or more than one possible outcome due to limited knowledge. Due to uncertainty, the power system can suffer potential safety issues as well as economic loss. Mitigating the uncertainty is therefore desirable, therefore an important research topic [42]. Uncertainties in power systems occur in two forms:

i. Uncertainty in a mathematical sense, which means difference between measured, estimated values and true values; includes errors in observation or calculation
ii. Sources of uncertainty including; generation availability, load requirements, unplanned outages, transmission capacity market rules, fuel price, energy price, market forces, weather and other interruptions [1]

b. Treatment

Treatment is the manner of handling or dealing with something. It is the use of a process to give particular properties to something.

It aims to describe the variation of information under conditions that are hypothesized to reflect the variation.

c. Economic Dispatch

Economic dispatch is the determination of the optimal output of a number of electricity generating facilities to meet the system load at the lowest possible cost subject to generation, transmission and operational constraints [39].

d. Renewable Energy

Renewable energy is that which comes from resources that are replenished on human timescales. Examples of these renewable sources include sun, wind, water, ocean tides, earth’s heat and plants.

This study is interested in two types of renewable energy: wind and solar since they have enormous resource potential and face similar challenges to wide spread deployments.

e. Wind Energy

Wind is the flow of gases on large scale. It is caused by solar energy falling on water bodies which then causes air to warm and rise, which in turn generates surface winds. The wind has been used by humans for thousands of years to carry ships across ocean.

Recently wind has been harnessed by use of wind turbines to produce electricity. It is the fastest growing renewable energy source since it is abundant in nature.

f. Solar Energy

Solar energy is the energy produced by solar radiation directly or in diffuse way in the atmosphere. It is the cleanest and the most abundant in nature.

The solar source of energy is inexhaustible and free from pollution fumes.

This energy can be used to heat water, and the steam produced used to drive turbines, provide light or generate electricity directly.

1.2. Introduction

The need to reduce greenhouse gas emission has led to shifting attention towards more environmentally friendly and sustainable energy sources. The projection is therefore the use of renewable energy sources is expected to rise in future due to these environmental pressures. There have been universal agreements such as Kyoto protocol which has obligated ratifying nations to reduce greenhouse gas emissions.

Alternative energy sources such as wind and solar have received increased attention in the recent years due their green nature (do not emit greenhouse gases). However, these renewable energy sources tend to be highly variable. Output of solar and wind energy sources are highly dependent on prevailing weather conditions. These weather patterns may not match the load profile or the market demand. Integrating renewables in energy markets will therefore require special considerations and new methods of allocating its output.

Due to large variability of Renewable Energy sources, to reliably supply a load they are integrated with non-conventional generators (making hybrid networks). This is because stand-alone renewable energy generators might not match the load profile due its dependence on weather conditions. The power generated by these renewable energy generators take the highest priority in meeting the load demand, leaving the conventional generating units to meet the remaining net demand.

1.3. Problem Statement

The increase in penetration of renewable energy sources with their stochastic nature has led to introduction of new types of uncertainties into power systems, hence the need to study these uncertainties; their effects and how to deal with them in a power system, while ensuring security and reliability.

1.4. Project Objectives

1. To study uncertainties present in a power system.
2. To analyse the effects of uncertainties in a power system.
3. To study the effect of introducing renewable energy sources on the power system uncertainties.
4. To determine how to deal with uncertainties in a power system.

1.5. Project Questions

This project will attempt to answer the following questions:

1) What are the uncertainties present in the operation of Power Systems?
2) What are the uncertainties that are introduced to the power system by the introduction of renewable energy sources?
3) How to handle uncertainties in a Power System?

CHAPTER 2: LITERATURE REVIEW

2.1 Uncertainty

Uncertainty is the difference between a measured, estimated or calculated value and the true value. Uncertainty includes errors in observation and calculation. In a power system the sources of uncertainty are varied. They include; Generation availability, Transmission capacity, Load requirements, Market forces, Fuel prices and Forces of nature such as extreme weather. These uncertainties may affect planning and operations both in the short-term and long-term.

Power system exhibit numerous parameters and phenomena that are either nondeterministic or dependent on so many diverse factors that may not be predicted with accuracy. Uncertain problems in power systems operations include:

Uncertainty Load Analysis

Power demands are inherently uncertain. Consider the variability of the electricity consumption of a single residential customer; it depends on the presence at home of the family members and on the time of use of high - power appliances, which is subject to high uncertainty [1]. Probabilistic analysis and fuzzy theory can be used to analyse the uncertainty. Different probability distribution functions may be selected for the different kinds of uncertainty load. The commonly used distribution functions are:

Normal Distribution

The general formula for the probability density function of the normal distribution for uncertain load P_D is

$$f(P_D) = \frac{e^{\frac{(P_D-u)^2}{2\sigma^2}}}{\sigma\sqrt{2\pi}} \text{ .... (1)} \quad -\infty \leq P_D \leq \infty \quad 2.10$$

$$\sigma > 0$$

Where;

P_D: is the uncertain load

u: The mean value of the uncertain load

σ: The standard deviation of the uncertain load

Lognormal Distribution

This is a continuous distribution in which the logarithm of a variable has a normal distribution. It results if the variable is a product of a large number of independent identically distributed variables. This is due to the distribution having one or more shape parameters. Shape parameters allow a distribution to take on a variety of shapes, depending on the value of the shape parameter. These distributions are particularly useful in modelling applications since they are flexible enough to model a variety of uncertainty load data sets. The following is the equation of the lognormal distribution for uncertain load P_D.

$$f(P_D) = \frac{e^{-(\ln(P_D-u)/m)^2}}{\sigma(P_D-u)\sqrt{2\pi}} \qquad P_D \geq u \qquad 2.11$$

$$\sigma > 0$$

Where

m : The scale parameter

ln: The natural logarithm

Exponential Distribution

The formula for the probability density function of the exponential distribution for uncertain load P_D is

$$f(P_D) = \frac{e^{-\frac{P_D-u}{b}}}{b} \qquad 2.12$$

$$P_D \geq u$$

$$b > 0$$

Where

b: The scale parameter

Beta Distribution

The general formula for the probability density function of the beta distribution for uncertain load P_D is given by

$$f(P_D) = \frac{(P_D-u)^{a-1}(c-P_D)^{b-1}}{\beta(a,b)(c-d)^{a+b-1}} = \frac{\Gamma(a+b)(P_D-d)^{a-1}(c-P_D)^{b-1}}{\Gamma(a)(b)(c-d)^{a+b-1}} \qquad 2.13$$

$$d \leq P_D \leq c$$

$$a > 0$$

$$b > 0$$

Where,

a ,b : The shape parameters

c : The upper bound

d : The lower bound

β (a b): The beta function

Gamma Distribution

The general formula for the probability density function of the gamma distribution for uncertain load P_D is

$$f(P_D) = \frac{(P_D - u)^{a-1}}{b^a \Gamma(a)} \; e^{-(\frac{P_D - u}{b})} \qquad 2.14$$

Where a is the shape parameter, μ is the location parameter, *b* is the scale parameter, and Γ is the gamma function which can be expressed as,

$$\Gamma(a) = \int_0^\infty t^{a-1} e^{-1} dt \qquad 2.15$$

Gumbel Distribution

The Gumbel distribution is also referred to as the extreme value type I distribution. It has two forms. One is based on the smallest extreme, and the other is based on the largest extreme. We call these the minimum and maximum cases, respectively. The general formula for the probability density function of the Gumbel (maximum) distribution for uncertain load P_D is

$$f(P_D) = \frac{1}{b} e^{\left(\frac{u - P_D}{b}\right)} e^{-e^{(\frac{u - P_D}{b})}} \qquad 2.16$$

$$-\infty \leq P_D \leq \infty$$

$$b > 0$$

Chi - Square Distribution

The chi - square distribution results when *v* independent variables with standard normal distributions are squared and summed. The formula for the probability density function of the chi -square distribution for uncertain load P_D is

$$f(P_D) = \frac{P_D^{\frac{v}{2}-1}}{2^{\frac{v}{2}}\Gamma(\frac{v}{2})} \quad e^{-\frac{P_D}{2}} \qquad 2.17$$

$$P_D \geq 0$$

Weibull Distribution

The formula for the probability density function of the Weibull distribution for uncertain load is P_D

$$f(\mathrm{P_D}) = \frac{\mathrm{a(P_{D-u})^{a-1}}}{\mathrm{b^a}} \ \mathrm{e}^{-\frac{\mathrm{(P_D-u)^a}}{\mathrm{b}}} \qquad 2.18$$

$P_D \geq u$ 2.22

$a > 0$ 2.22

$b > 0$ 2.22

Where *a* is the shape parameter, μ is the location parameter, and *b* is the scale parameter.

2.2 Inaccurate fuel cost.

The inaccuracies in the cost functions for steady - state operation are caused by the limited accuracy of the determination of the thermal dynamic performance, changing cooling water temperatures, changing calorific values and contamination, erosion, and attrition in boiler and turbine. These deviations lead to inaccurate values for heat inputs and fuel prices [1]. Similar to the uncertain load, the cost functions of generating units can also be expressed in the form of intervals.

$$F_{Min}(P_{Gi}) \leq F(P_{Gi}) \leq F_{Max}(P_{Gi}) \qquad 2.19$$

2.3 Uncertainty Power Flow Analysis

In power flow analysis, the input variables to the power flow problem are assumed to be deterministically known. The practical operation conditions with uncertainty factors are not considered. Consequently, the power flow results may not reflect the real status of system operation. This limitation can be mitigated if a probabilistic approach or a fuzzy approach is applied.

2.4 Probabilistic Power Flow

The standard form of the load flow equations in rectangular form is:

$P_i = P_{Gi} - P_{Di} = \sum_j Y_{ij}V_iV_j \cos(\theta_i - \theta_j - \delta_{ij})$ 2.20

$Q_i = Q_{Gi} - Q_{Di} = \sum_j Y_{ij}V_iV_j \sin(\theta_i - \theta_j - \delta_{ij})$ 2.21

where

i , j : The bus number

P_i : The net real power injection

Q_i : The net reactive power injection

V : The magnitude of the bus voltage

θ : The phase angle of the bus voltage

Y_{ij} : The magnitude of the i - j th element of the admittance matrix

δ_{ij} : The angle of the i - j th element of the admittance matrix

2.5 Unit Commitment with Uncertainties

The economy of unit commitment of power systems is influenced by approximations in the operation planning methods and by the inaccuracies and uncertainties of input data. However, most of the prior work on the unit commitment problem uses a deterministic formulation neglecting the uncertainties [1].

The uncertain load can be expressed as normal distribution with a specific correlation structure. Thus we use a chance -constrained optimization (CCO) formulation for the UCP assuming that the hourly loads follow a multivariate normal distribution. The CCO formulation falls into a class of optimization procedures known as stochastic programming in which the solution methods take into consideration the randomness in input parameters

2.6 Effects of Uncertainties in a Power System

Uncertainties present in a power system has affected planning and operation in the following aspects:

[1] Entry of new energy producing/trading participants

[2] Increases in regional and intraregional power transactions

[3] New types and numbers of generation resources

Integration of Renewable Energy

Renewable sources of energy help in mitigating global warming as well as greenhouse gas emission. Moreover, they are also readily available for an area affected by war or natural disasters. Therefore with increasing concern of environmental protection and continuous depletion of fossil fuels with ever rising demand for electricity, renewable energy sources are widely encouraged to be integrated into the already existing conventional units. The hybrid power system can be represented by the figure 2.1 shown below.

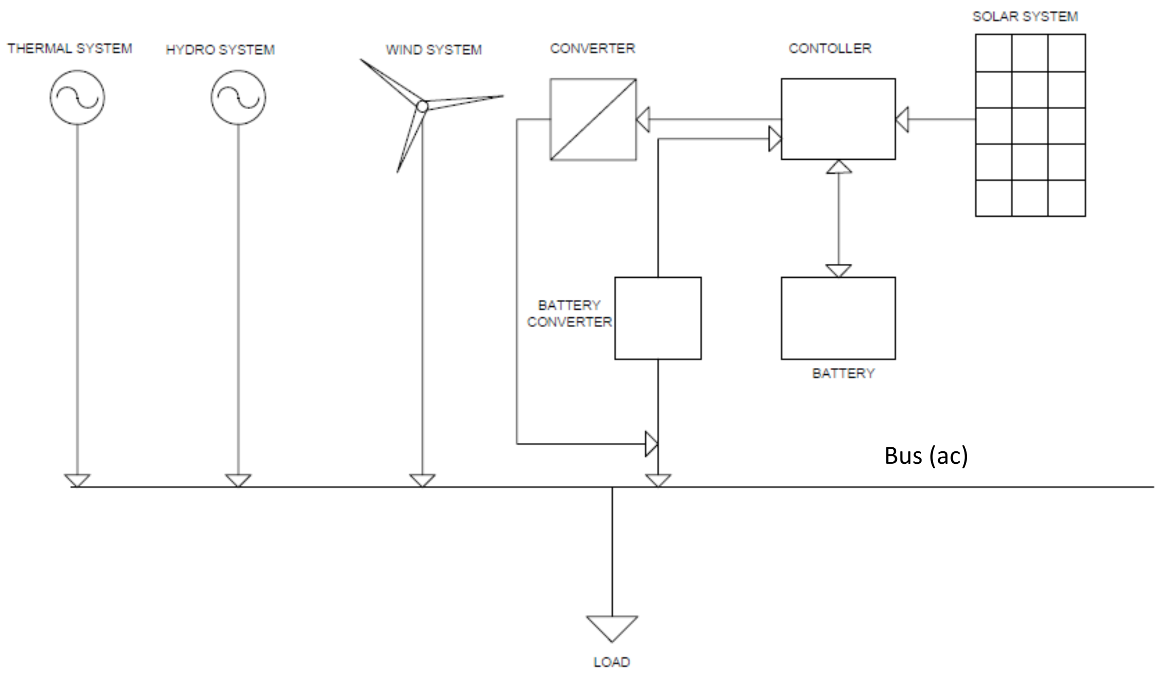

Figure 2.1 Hybrid Power System

In a practical hybrid power system uncertainty not only exists in the energy sources and loads but also in the manner in which the system is managed and operated.

2.7 Uncertainties Introduced by Renewable Energy into a Power System

Although the output of any power plant is variable and unpredictable to a certain level, wind and solar generation exhibit these characteristics at a higher degree. Without storage, limited control in variability implies a likelihood that an individual plant could be unavailable when needed that is significantly higher than in conventional plants.

Solar power has the advantage of being mostly coincidental with the periods of high electricity demand while wind production may happen at any time and, as reported in most systems predominantly at night, when demand is lowest. Both wind and solar generation have virtually no variable operating costs.

Intermittent generation add new challenges to system operation and capacity expansion of power system.

Wind Power

Wind is caused when air moves from an area of high pressure to areas of low pressure. The difference in pressure between the two areas determines the strength of wind. Since the equator is constantly hot and the poles are cold, there is a general pattern to air circulation on the surface of Earth. In many areas the wind usually blows from the same direction. Wind speed can be measured using an anemometer while direction of wind is indicated by a wind vane.

Wind is the most predominantly used technology world-wide, amongst renewable energy sources, to generate electricity. Wind turbines work by converting the kinetic energy in the wind first into rotational kinetic energy in the turbine and then electrical energy. The energy available for conversion mainly depends on the wind speed and the swept area of the turbine. It is one of the fastest growing fields of the renewable energy sources. Wind farms are already in their large-scale with a single turbine capacity ranged from 10 to 15 MW. Several countries have achieved relatively high levels of wind power penetration such as 39% of electricity production in Denmark, 18% in Portugal, 16% in Spain, 14% in Ireland and 9% in Germany as at 2010. The global installed capacity of wind as shown by the statistics below show that it has experienced steady continuous growth over the years;

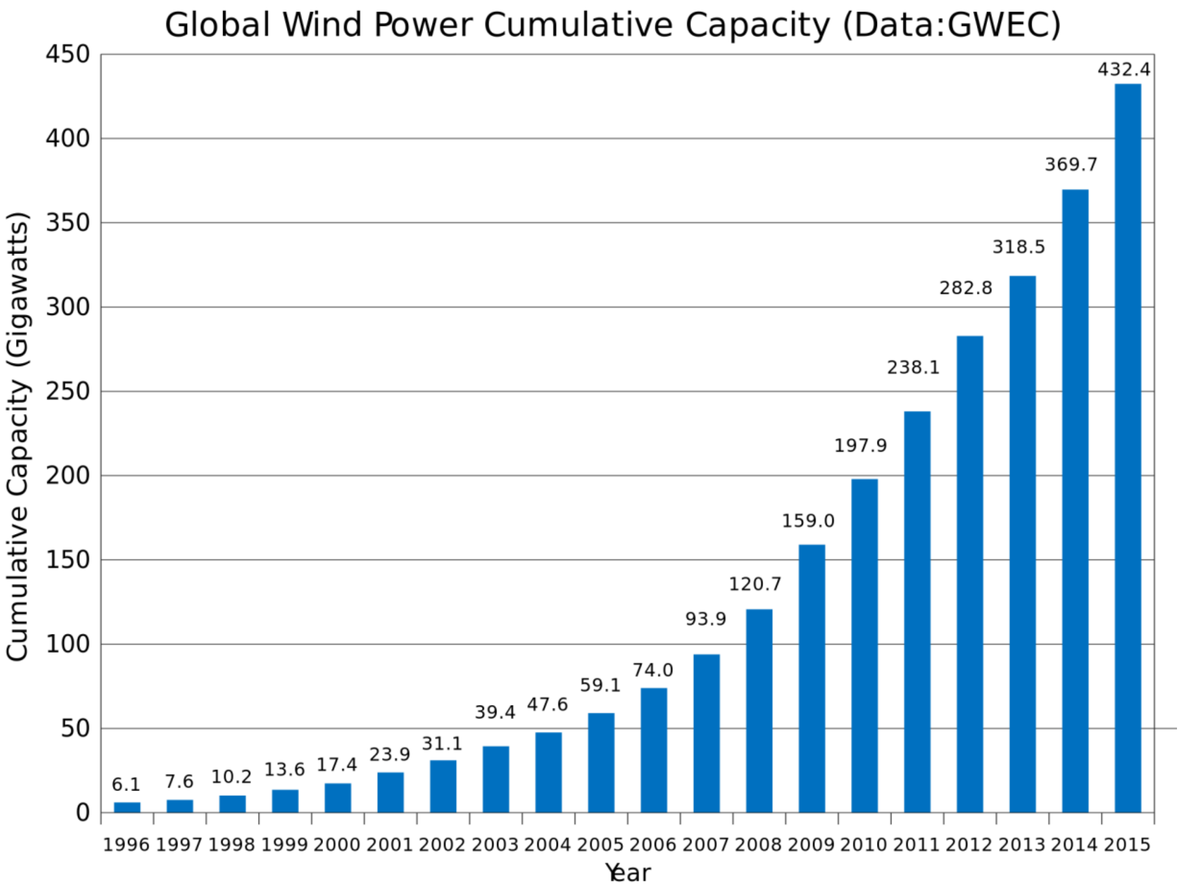

Figure 2.2 Global Cumulative Wind Power Capacity [31]

Wind power systems convert the movement of air into electricity by means of a rotating turbine and a generator. There are two types of Wind generators, namely:

- On-shore
- Off-shore

These wind turbines sit on top of towers taking advantage of stronger and less turbulent winds at 100ft (30m) or more above ground. Modern large wind turbines generally have three blades and sit on top of towers ranging 150ft tall for onshore turbines to 300ft for offshore Wind-turbine captures the wind energy by its blades and then transform the wind energy to the mechanical wheel torque that act on the wheel hub.

The conversion of wind energy captured to mechanical output power P_m can be expressed as follows:

$$P = \frac{1}{2}\rho A V^3 C_P \qquad 2.23$$

Where, ρ is the air density (kg/m^3), A is the area in (m^2) swept by the wind turbine blade, V_w is the head-on wind speed (m/s), C_p is an efficiency coefficient of wind energy converting to mechanical energy (C_{pmax}=0.59), also known as the Beltz limit, can only convert 59.3% of kinetic energy of wind into mechanical energy turning the rotor.

Wind Stochastic Model

In order to be able to characterize the stochastic nature of wind speed so as to be able to analyse the problem with numerical results, Weibull probability density function, (pdf) is utilized to represent their stochastic nature. Wind speed distribution for selected sites and the power output characteristics of the chosen wind turbine are factors that affect the wind power generated. Prior research has shown that the wind speed profile at a given chosen site closely follow a Weibull distribution [6] [24]. The pdf for a Weibull distribution is given by the following equation.

$$f_v(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} e^{-(v/c)^k} \qquad 2.24$$

Where,

V wind speed random variable

v wind speed (m/s)

k shape factor at a given location (dimensionless)

c scale factor at a given location

Weibull distribution function has advantages in that; It has been shown to provide a good fit to observed wind speed data and also 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.

It can be estimated by the observed frequency of wind speed in the target region that the output power of a wind turbine is dependent on the wind speed at the site as well as the parameters of the power performance curve. Therefore, once the Weibull pdf is generated for a specific time segment, the output power during the different states can calculated for this segment as per the equation shown below.

$$w = \begin{cases} 0 & 0 \le v \le v_i \\ w_r * \frac{(v - v_i)}{(v_r - v_i)} & v_i \le v \le v_r \\ 0 & v_0 \le v \end{cases} \qquad 2.25$$

Where;

w Wind power generator (WPG) output power

w_r WPG rated power

v_i Cut-in wind speed

v_o Cut out wind speed

v_r Rated wind speed

The output power of wind turbine can be obtained using equations by the application of the transformation theorem.

$$f(w) = \begin{cases} \left(\frac{klv_i}{c}\right)\left(\frac{(1+\rho)v_i}{c}\right)^{k-1} exp\left(-\left(\frac{(1+\rho l)v_i}{c}\right)^k\right) \ for\ 0 < w < w_r \\ 1 - exp\left[-\left(\frac{v_i}{c}\right)^k\right] + exp\left[-\left(\frac{v_o}{c}\right)^k\right] \quad w = 0 \\ exp\left[-\left(\frac{v_r}{c}\right)^k\right] - exp\left[-\left(\frac{v_o}{c}\right)^k\right] \quad w = w_r \end{cases} \qquad 2.26$$

Where $\rho = \frac{w}{w_r}$ and $l = \frac{v_r - v_i}{v_r}$

The captured wind power can be represented on a power curve shown below;

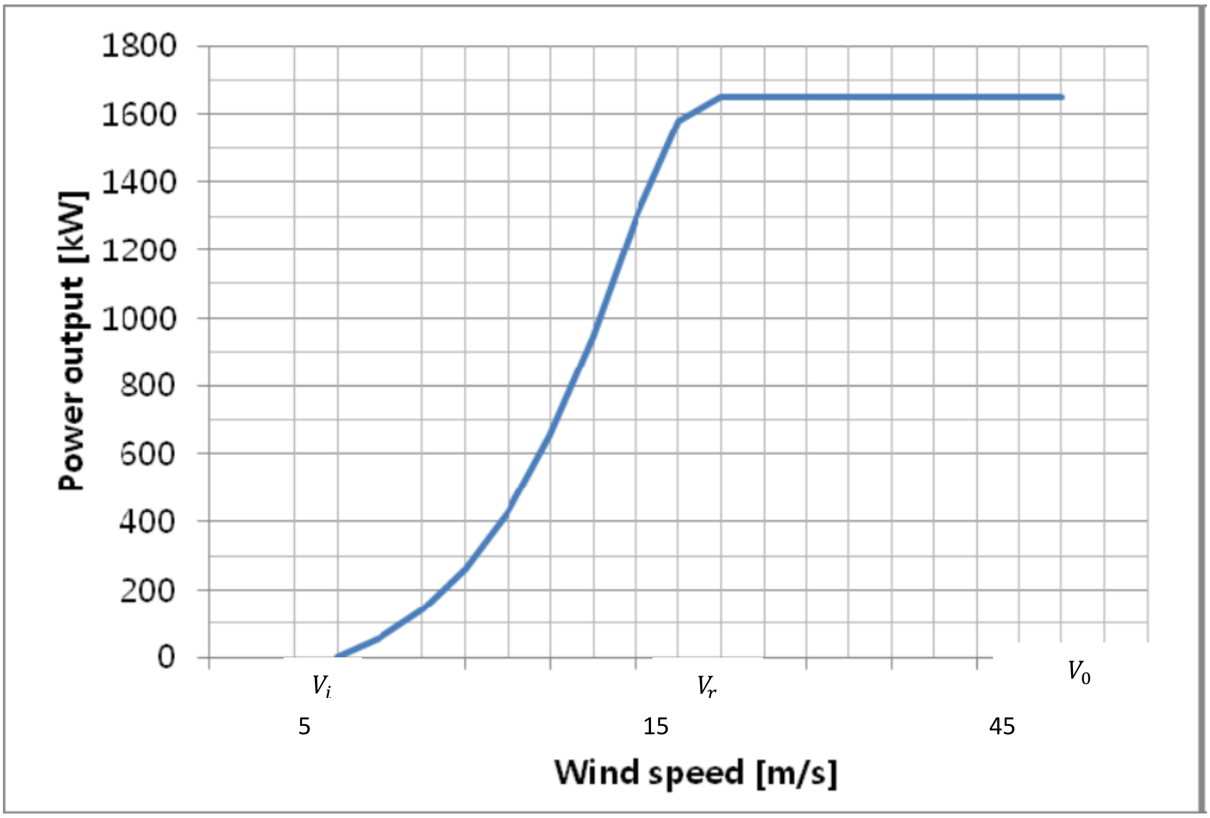

Figure 2.3 Wind Power Curve [29]

Solar Power

Solar power is clean green electricity that is generated either from direct conversion of sunlight or from heat from the sun. Solar power is produced by collecting sunlight and converting it to electricity. Electricity generated depends on the solar irradiance. Solar irradiance flux density is measured by use of a pyranometer. There are two technologies that have been developed for conversion of solar energy into electricity. These are Photovoltaic cells (PVs) and solar thermal systems.

Solar Photovoltaic (PV) technology converts the electromagnetic energy in sunlight directly into direct current (DC) through use of modified silicon (Crystalline Silicon). It can use both Diffuse Solar Radiation (DSR) and Direct Normal Irradiance (DNI) [6]. It is the most popular technology as it does not require larger plant sizes to achieve economies of scale and is often deployed as distributed generation. It uses DC-AC convertor for grid interface. However it can serve DC loads without the need of a convertor.

When a group of cells are joined together they form a module and modules may be connected into an array. These cells, modules and arrays can provide electricity up to several MW, the size of a large power plant.

Solar thermal Systems depend on intermediate conversion of solar energy into thermal energy in form of steam, which in turn is used to drive a generator. Solar thermal systems can be implemented using either of the two available techniques.

These techniques are; large parabolic trough reflectors (mirrors) and Solar power towers where a central receiver is mounted on top of a tower which concentrating mirrors track the sun while concentrating the light to a receiver where the energy is absorbed by a heat transfer medium.

The use of solar power globally has increased steadily over the years as witnessed by the statistics shown below;

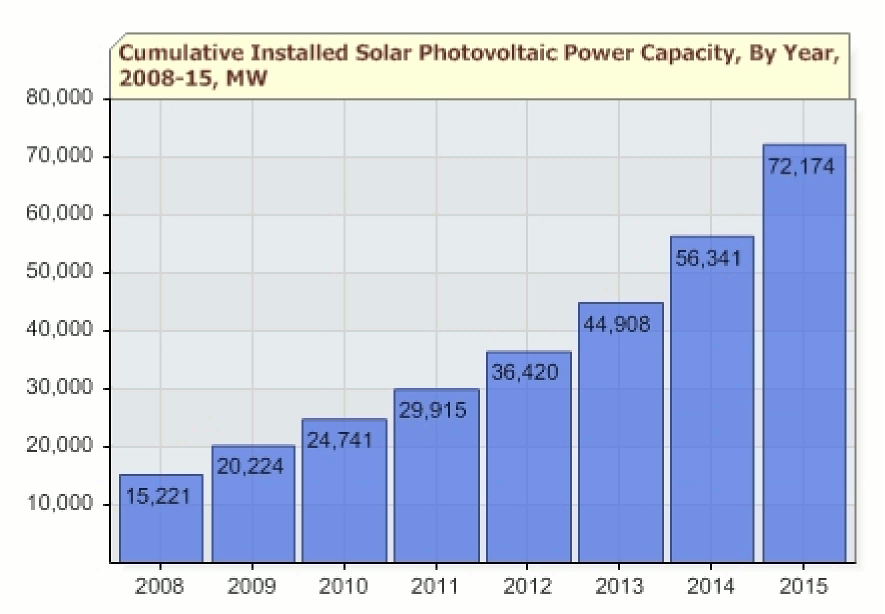

Figure 2.4 Cumulative Installed PV Power Capacity by year 2015 [31]

PV STOCHASTIC MODEL

The amount of solar radiation that reaches the earth's surface depends on the geographical location (latitude and altitude), position of sun in the sky, which varies from month to month and on the weather conditions (e.g. cloud cover). To account for the difference between the values of solar radiation measured outside the atmosphere and on earthly surface an hourly clearness index, k_t, has been defined as the ratio of the irradiance on a horizontal plane, I_t $[kW/m^2]$, to the extra-terrestrial total solar irradiance I_o kW/m^2 [6].

$$k_t = \frac{I_t}{I_0} \quad 2.27$$

The clearness index pdf is utilized to model the hourly solar irradiance

$$f_{kt}(k_t) = c'\left(1 - \frac{k_t}{k_{tmax}}\right)\exp(\lambda k_t) \quad 2.28$$

Where c' and λ are functions of maximum value of clearness index k_{tmax}, and the mean value of clearness indexk_{tm}. If the probability density function $f_{kt}(k_t)$ for the random variable is known, it is possible to obtain its value for pv, $f_{pv}(pv)$,by applying the fundamental theorem for function of a random variable. The probability density function $f_{pv}(pv)$ has four different expressions but only two have physical meaning, if T>0 and T'<0

$$f_{pv}(pv) = \begin{cases} \frac{c'(k_{tmax} - 0.5(\alpha + \alpha'))}{k_{tmax} A_c T' \alpha'} \exp\frac{\lambda(\alpha + \alpha')}{2} & if\ P_{pv} \epsilon [0, P_{pv}(k_{tu}) \\ 0 & , otherwie \end{cases} \quad 2.29$$

$$\alpha = \frac{T}{T'}$$

$$\alpha' = \sqrt{\alpha^2 - 4\frac{pv}{\eta . T' . A_{pv}}}$$

Where, A_{pv} is the array surface area $[m^2]$, η is the efficiency of the PVs.

The power output of a PV module can therefore be calculated as;

$$P_{sj} = I_{Tj} \eta A_{pv} \quad 2.30$$

where;

I_{Tj} is the solar incident radiation

η is the PV system efficiency

$\eta = \eta_m \eta_{pc} p_f$

$\eta_m = \eta_r\{1 - \beta(T_c \text{-} T_r)\}$

Where η_r is the module reference efficiency, η_{pc} is the efficiency of power tracking equipment which is equal to 1 if a perfect maximum power tracking equipment is used.

p_f is the packing factor which is the ratio of the total area of the solar cell to the area of the module β is the array efficiency temperature coefficient, T_r is the reference temperature for the cell efficiency and T_c is the average cell temperature. [34]

2.8 Economic Dispatch

Economic dispatch is the operation of power generation facilities to produce energy at the lowest cost while meeting load demand and spinning reserve requirements, recognizing any operational limits (constraints) of generation and transmission facilities of a power system.
The primary objective of the ED problem is to determine the optimal combination of power outputs of all generating units so as to meet the required load demand at minimum operating cost while satisfying system equality and inequality constraints [39].
It can be mathematically expressed as follows;

$$\text{Minimize } F_T = \sum_{i=1}^{n} F_i(P_i) \qquad 2.31$$

Where,
F_T: Total generation cost

n: number of generators

P_i: Real power generation of i_{th} generator

$F_i(P_i)$: Generation cost for P_i

This minimization is done subject to a number of power systems network equality and inequality constraints.

Renewable energy generation sources, such as solar and wind have become attractive alternatives to fossil plants, due to ever increasing costs of fossil fuel prices and the fact that at one time they will be exhausted coupled with environmental concerns.
These have therefore made it necessary to include renewable energy sources into classical economic dispatch problem. The uncertain nature of renewable sources makes classical economic dispatch problem become stochastic in nature. There are two fundamental components in economic dispatch:

- Planning for tomorrow’s dispatch
- Dispatching the power system today

a. Planning for Tomorrow’s Dispatch

This involves scheduling generating units for each hour of the next day’s dispatch based on;

- ✓ Forecast load for the next day
- ✓ Generating units to be running and available for dispatch the next day
- ✓ Recognizing each generating unit’s operating limit, including its:
  - Maximum and minimum generation levels
  - Ramp rate (how quickly the generator’s output can be changed)
  - Minimum amount of time the generator must run
  - Minimum amount of time the generator must stay off once turned off

- ✓ Recognizing generating unit characteristics, including:
  - Cost of generating, which depends on:
    - Its efficiency (heat rate)
    - Its variable operating costs (fuel and non-fuel)
  - Variable cost of environmental compliance
  - Start-up costs

- ✓ Reliability Assessment

  This is involves analysing whether the forecasted load and the transmission conditions in the area so as to ensure that the generated dispatch is able to meet the load. If the scheduled dispatch is not feasible within the limits of the transmission system, it is revised.

b. Dispatching the Power System Today

This involves monitoring the load and generation so as to ensure balance of supply and demand (including losses in the system).

Typically this monitoring is performed by the transmission operator.

The process of dispatching power today involves the following functions:

- ❖ Monitoring and maintaining required system frequency at 50Hz dispatch, using Automatic Generation Control (AGC)

- ❖ Keeping voltage levels within reliability ranges
- ❖ Taking corrective action, when needed, by:
    - Limiting new power flow schedules
    - Curtailing existing power flow schedules
    - Changing the dispatch
    - Load shedding

2.9 Uncertainties in Renewable Energy

Uncertainty is the difference between a measured, estimated or calculated value and the true value. Uncertainty includes errors in observation and calculation. In a power system the sources of uncertainty are varied. Power systems are always affected by huge number of uncertainties [42]. These uncertainties include:

a) Generation availability
b) Transmission capacity
c) Load requirements
d) Market forces
e) Fuel prices
f) Forces of nature such as extreme weather
g) Technological developments
h) Regulatory uncertainties. New reliability standards (environmental policies)

These uncertainties may affect planning and operations of power systems both in the short-term and long-term. Increase in Renewable energies (solar and wind) integration into power system comes with its associated uncertainties. The uncertainties associated with these renewable energies include:

[1] Generation availability
[2] Transmission capacity
[3] Forecast inaccuracy
[4] Technological developments
[5] Regulatory uncertainties. New reliability standards (environmental policies)

Conventional thermal power plants exhibit certainty of generation and can deliver the required power when needed. Thus, they are identified as dispatchable power plants. However generators based on renewable resources such as wind and solar inherit the uncertainty of generation by virtue of their variable primary energy source. This uncertainty poses a significant barrier for wind and solar power, restricting its widespread use. However, the importance of renewable energy as a non-polluting generation option, measures to overcome such barriers need to be studied.

2.10 Modelling of uncertainties

Energy system studies include a wide range of issues from short term i.e real-time hourly, daily to long term issues i.e planning or policy making. Decision making chain is fed by input parameters which are normally subject to uncertainties. Uncertain parameters in power system studies can be generally classified into two categories [4];

i. Technical parameters: These parameters are categorized in two classes, topological parameters and operational parameters.

   The topological parameters are those related to network topologies like failure or forced outage of lines, generators or metering devices while operational parameters are tied with operating decisions like demand or generation values in power systems.

ii. Economical parameters: these are the parameters that affect the economical indices. Examples include; uncertainty in fuel supply, costs of production, business taxes, labour and raw materials. Issues like regulation or deregulation, environmental policies, economic growth and interest rates are also analysed. All of these parameters are subject to uncertainties and should be correctly addressed in economic studies. [4]

Uncertainty modelling techniques

Various methods have been developed to deal with uncertain parameters. The difference between these methods is the technique used to describe uncertainty of input parameters. For example, fuzzy method use membership functions to describe an uncertain parameter while the stochastic methods use probability density function. However, the objective of each one of them is to quantify the effect of input parameters on model’s outputs. Some of these methods include:

1) Probabilistic approach: It is assumed that the input parameters of the model are random variables with a known probability density function (pdf).
2) Possibilistic approach: The input parameters of the model are described using the membership function of input parameters.

3) Hybrid possibilistic-probabilistic approaches: both random and possibilistic parameters are present in the model.
4) Robust optimization: The uncertainty sets are used for describing the uncertainty of input parameters. Using this technique, the obtained decisions remain optimal for the worst-case realization of the uncertain parameter within a given set.
5) Interval analysis: It is assumed that the uncertain parameters are taking value from a known interval. It is somehow similar to the probabilistic modelling with a uniform PDF. This method finds the bounds of output variables.
6) Information gap decision theory: In this method, no pdf or membership function is available for input parameters. It is based on the difference between what is known and what is vital to be known by quantification of severe lack of information in decision making process. [4]

2.11 Effects of Uncertainties on a Power System

a) Stability

Power system stability is its ability to maintain synchronism when subjected to severe disturbance. System stability is largely attributed with faults in a network. These faults may include; tripping of transmission lines, loss of production capacity or short circuits.
These failures disrupt the balance of power (active and reactive). The imbalance and re-distribution of real and reactive power in a network may force the voltage to vary beyond the stable regions.
With high penetration of variable renewable energy sources (solar and wind), sudden disconnection of an entire solar or wind farm at full generation, the power system will lose the production capacity. Unless the remaining power plants have enough ‘spinning reserve’ to compensate for the loss in a short time, large frequency and voltage drops will occur and possibly followed by a complete loss of power.
To avoid these, the new generation of wind generators should be able to ‘ride through’ during disturbances and faults to avoid total disconnection from the grid. To ensure system stability it is important for the wind turbine to restore normal operation in an appropriate way within the shortest time. This focuses on different types of turbine technology and supporting the system voltage with reactive power compensation devices.

b) Security

Power system security is the ability of the system to withstand disturbances without causing a breakdown of the power system. It is the power system ability to operate at a point remaining within acceptable ranges, given the probabilities of changes in the system (contingencies) and its environment. Customer interruption can occur because of:

- ❖ Insufficient active power reserve leading to load shedding.
- ❖ Grid congestion (overloaded lines) that require disconnection of loads to avoiding cascading faults.
- ❖ Bus bar voltages getting out of permitted ranges leading to load disconnection.
- ❖ System running into stability problems (frequency stability, voltage stability, transient stability) leading to wide area load disconnections or even a black-out.

Renewable energy systems can improve some aspects of security, but they will not lead to complete removal of all types of security problems, in fact new problems will most certainly arise. Some of the security aspects of the power system improved by introduction of renewable energy include;

1. Renewable energy increases the diversity of a power system making it less sensitive to some types of disturbances. Dependence on a single supplier is always discouraged since any disturbance from the sole supplier will affect the whole network.
2. Renewable energy provides security of supply because its energy sources are based on energy flows in contrast to fossil fuels which are based on resources whose stocks can be depleted in the long run. Renewable energy therefore can sustain energy flow for a longer term since its resources are continuously replenished on human timescales.
3. Renewable energy sources in most cases are less concentrated; they are almost available in all countries. This reduces the risk of one country exerting pressure on other countries and dictating the prices. Furthermore, studies have shown that energy independence is credited with improving security.

Some of the security challenges in a power system that come along with renewable energy sources include;

1. Renewable energy is often faced with difficulties with regards to reliability in terms of the generation, planning and scheduling of the supply of electricity. There is always a lack of confidence by the utility operators in the system’s capability to meet peak demands. Intermittent generation associated with RE will increase the level of

uncertainty and therefore the need for a reserve capacity, both spinning and non-spinning reserves, of the power system which in turn increases the generation costs.

2. The variability and the unpredictability of wind and solar power can cause a power imbalance on the grid. Their output power may not be available to meet the demand when needed, while there could be an excess when the demand is low, thereby causing an upset on the grid.
3. Renewable energy sources are very unpredictable, and their generation varies with time scales ranging from seconds, minutes to hours. To ensure security and reliability to consumers, therefore require large reserves both spinning and non-spinning hence increasing the generation cost per unit.

c) Load Flow

The power flow is fundamental to power system analysis, to system planning.
The power flow problem is the computation of voltage magnitude and phase angle at each bus in a power system under balanced three-phase steady-state conditions.
For every bus i = 1. . . . . n in the network, let V_i denote the voltage magnitude, $\emptyset_i$ the voltage angle, P_i the net real power injection, and Q_i the net reactive power injection [7].
The power flow equations to be satisfied are:

$$P_i = V_i \sum_{k=1}^{n} V_k (G_{ik} \cos(\emptyset_i - \emptyset_k) + B_{ik} \sin(\emptyset_i - \emptyset_k) \qquad 2.32$$

$$Q_i = V_i \sum_{k=1}^{n} V_k (G_{ik} \cos(\emptyset_i - \emptyset_k) - B_{ik} \sin(\emptyset_i - \emptyset_k) \qquad 2.33$$

$$P_i^{net} = -P_i^D + P_i^{w/pv}$$
$$Q_i^{net} = -Q_i^D + Q_i^{w/pv}$$

Where G_{ik} and B_{ik} are real and imaginary parts of the entry in the network admittance matrix respectively.
P_i^{net}, Q_i^{net} are the net injected active and reactive power to bus i, respectively.
$P_i^{w/pv}$ and $Q_i^{w/pv}$ are the active and reactive power of wind turbine and PV cells in bus i.

Wind and solar generation introduces high variability into sub-transmission networks influencing statistical characteristics of voltages and power flows. Interconnections within sub-transmission networks further complicate power flow patterns induced by RE sources especially when wind and solar farms are distributed. Wind-farm operators are required to regulate the voltage at their point-of-interconnection however, the requirement does not ensure voltages throughout the network are well-behaved. Some of the effects of RE power in power system include:

a. RE power generation at multiple nodes can create unanticipated power flow patterns within the sub-transmission network. This may result in line congestion at power production levels that are below the rated capacity of the farms.
b. The variability inherent in the power produced by distributed wind and solar farms can lead to reactive power requirements that may adversely affect bus voltages and transformer tapping.
c. Can lead to bi-directional flows in distribution networks that were designed for unidirectional operation.
d. When voltage controls are not carefully coordinated, voltage regulating transformers may undergo excessive tapping, leading to a significant increase in maintenance costs.

d) Power Quality

Power quality components of a power system comprise of flickers, harmonic distortions, voltage imbalance, voltage sag and voltage swells.

The degree of deviation from the normal sinusoidal voltage and current waveforms in power system network determines the quality of the power transmitted on the grid. The level of tolerance of power quality depends on the kind of load installed by the customer.

RE unlike other conventional sources of energy, introduce real power variations into the grid. These power variations cause voltage variations with consequences to power system and the customers. Variable speed wind generators, made of doubly fed induction generator (DFIG) and synchronous generators, require power converters to achieve controllable grid integration. These converters introduce harmonics. Effects of these harmonics on the power system include:

a. Excessive heating of equipment which decreases their lifetime.

b. Increase line losses

c. Sub-harmonics could cause flickers that result in an uncomfortable visual effect on the eyes, core saturation of transformers and thermal aging of induction motors.

e) Phase Imbalance

Integrating renewable energy in three-phase distribution systems can also develop acute phase imbalance as a majority of PV sources are connected in the form of single-phase units. These imbalances could lead to unbalanced voltage profiles among phases and shift the neutral point voltage to an unacceptable and unsafe value. A severe phase imbalance due to PV integration, exceeding 6% was reported in Freiburg, Germany while the utility standard is to keep the unbalanced condition within 2.5%.

An unbalanced three-phase condition could also influence various instability problems and also lead to higher network losses. [33]

2.12 How to Reduce Uncertainty of Renewable Energy

Renewable energy is uncertain. Its availability varies as a function of prevailing weather conditions. It varies on time scales of seconds, minutes, hours, and days to months. The amount of power generated by solar depends on solar irradiance while power generated by wind generators vary depending on the wind speed profile.

With solar photovoltaic (PV) and wind turbine projects, the main risk is quantifying the expected annual energy production and uncertainty. Modelled reference data sources lack the accuracy to sufficiently mitigate the energy production risk for larger projects. Wind forecasts for example, typically have errors in the range of 15% to 20% mean absolute error (MAE) for a single wind plant. For long, the industry has relied on modelled data to estimate the on-site solar and wind resources. Large-scale wind integration studies have demonstrated that using day a head forecasts for unit commitment improves system operation by reducing overall operating costs, reducing unserved energy while maintaining required levels of system reliability.

Uncertainty in energy estimates can therefore be significantly reduced by on-site monitoring and an in- depth analysis of all available data sources. The quality of on-site solar and wind measurements is affected by the level of diligence taken in the design and implementation of the monitoring program. [14]

Studies have shown that uncertainty in power generation from RE sources can be greatly reduced by using on-site solar and wind measurements. To demonstrate how solar irradiance data affects uncertainty in energy production estimates, a case study was conducted for 11 sites in the U.S. using modelled and measured data [14]. Therefore in order to overcome uncertainty, market operator has to incur an additional expense to forecast wind energy supply and carry increased online reserves. It is also noted that an increase in numbers of wind farms reduces the uncertainty due to spatial smoothing effect [2].

On-site data was collected with LI-200 pyranometers with each site having a period of record of a year or more, while the satellite-modelled data with a 13-year period of record was selected as the long-term reference data source.

A comparison of the resulting energy uncertainty estimates shows how confidence can be increased and uncertainty decreased by incorporating data from on-site instrumentation. On average, on-site monitoring reduced the project's expected uncertainty from 9.2% to 5.7% as shown by figure 2.3 below

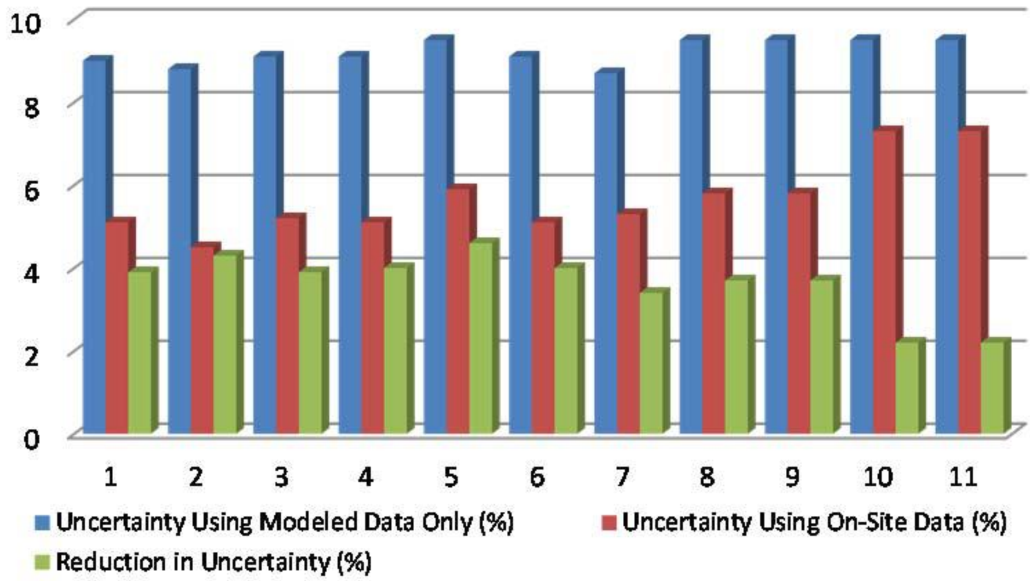

Figure 2.5: Difference in Energy Production Uncertainty using Modelled Data and On-Site Data [14]

2.13 Problem Formulation of Uncertainty Treatment in Economic Dispatch with Renewable Energy

Economic Dispatch

The primary objective of any ED problem is to reduce the total fuel cost by satisfying all constraints.

2.13.1 Cost Function of thermal generators

Thermal generation cost function is a quadratic approximation of the incremental cost curves that could include the operation maintenance cost and is of the form given by equation (2.34) as shown below;

$F_c(P_{Gi}) = (a_i + b\ _iP_{Gi} + c_iP_{Gi}^2)$ 2.34

Where

a_i, $b\ _i$ and ci are the cost coefficients of i^{th}hermal generator

F_c is the fuel cost for the i^{th} conventional generator

P_{Gi} is the real power generated from i^{th} thermal generator

2.13.2 Operational Cost Function for Wind Power Plant

The objective function of a wind power generator is:

$$C(w_i) = C_{wi}(w_i) + C_{p,wi}(W_{i,av} - w_i) + C_{r,wi}(w_i - W_{i,av}) \quad 2.35$$

Where;

$C(w_i)$ is cost of wind energy generation

w_i is the scheduled output of the ith wind farm

The equation is divided into three parts;

The first part is the cost function representing the cost based on wind speed profile. Where the cost coefficient is multiplied by Weibull pdf of wind power,$f_w(w)$, and is represented by:

$$C_{wi}(w_i) = d_if_w(w)w_i \quad 2.36$$

Where $d_i$is the direct cost coefficient for i^{th}wind farm.

The second part is the penalty for not using all the available wind power. In the case of underestimation, available wind power is actually more than what was assumed and that power will be wasted. The penalty cost for not using all the available wind power will be 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

$$C_{p,wi} = k_{p,wi}(W_{i,av} - w_i) = k_{p,wi}\int_{w_i}^{w_{ri}} (w - w_i)f_w(w)dw \quad 2.37$$

Where;

$k_{p,wi}$ is the penalty cost coefficient for over generation by i^{th}wind farm

$w_{i\,av}$ is actual or available wind power

w_{ri} is the rated or expected wind power output

The third part is the penalty reserve requirement cost which is due to that the actual or available wind power is less than the scheduled wind power. The difference between the available wind power and the scheduled wind power, multiplied by the wind power output probability function is linearly related to the reserve cost and is given by;

$$C_{r,wi} = k_{r,wi}\left(w_i - W_{i,av}\right) = k_{r,wi}\int_0^{wi}(w_i - w)f_w(w)dw \qquad 2.38$$

Where;

$k_{r,wi}$ is the reserve cost coefficient for under generation of i^{th} wind farm

2.13.3 Operational Cost Function for Solar Power Plant

The operating cost of PV power plant also includes three parts just like the wind power plant. The cost function equation is given as;

$$C(p_{s\,i}) = C_{pvi}(pv_i) + C_{p,pvi}\left(PV_{i,av} - pv_i\right) + C_{r,pvi}\left(pv_i - PV_{i,av}\right) \qquad 2.39$$

The first part is the weighted cost function which represents the cost based on solar irradiance profile. This is expressed as

$$C_{pvi}(pv_i) = h_i f_{pv}(pv)(p_{vi}) \qquad 2.40$$

Where h_i, and pv_i are the cost coefficient and the scheduled output from i^{th} PV plant respectively.

The second part is penalty for not using all available solar power. It can be formulated as:

$$C_{p,pvi} = k_{P,pvi}\left(PV_{i,av} - pv_i\right) = k_{P,pvi}\int_{pvi}^{pv_{max}}(pv - pv_i)\, f_{pv}(pv)dpv \qquad 2.41$$

Where;

$k_{p,pvi}$ the penalty cost coefficient for over generation of i^{th} PV plant

$pv_{ij,av}$ is the actual or available PV power from the i^{th} PV power plant which is a random variable

$pv(k_{tmax})$ is the maximum output of i^{th} PV plant

The third part is the penalty reserve requirement cost if the available PV power is less than the scheduled PV power and can be given modelled as;

$$C_{r,pvi} = k_{r,pvi}\left(pv_{i,av} - PV_i\right) = k_{r,pvi}\int_0^{pv_i}(pv_i - pv)\, f_{pv}(pv)dpv \qquad 2.42$$

Where;

$k_{r,pvi}$ is the reserve cost coefficient for under generation of the i^{th} PV generator

2.13.4 The overall Formulation of economic dispatch including solar and wind

$$C_{T,g} = \sum_{i=1}^{N} F_c(P_{Gi}) + \sum_{i=1}^{M} C_{wi} + \sum_{i=1}^{n} C_{si} \qquad 2.43$$

$$C_{T,g} = \sum_{i=1}^{N} F_C\,(P_{Gi}) + \sum_{i=1}^{M} C_{wi} + \sum_{i=1}^{M} C_{P,wi} + \sum_{i=1}^{n} C_{si} + \sum_{i=1}^{n} C_{p,si} \qquad 2.44$$

Where; N, M, n; is the number of generators (thermal, wind, solar) respectively.

$C_{P,wi}$ is the penalty for under/over generation by from wind generators

$C_{p,si}$ is the penalty for under/over generation by from wind generators

2.14 Constraints

There are various system equality and inequality constraints which are taken into account while optimizing the objective functions. The following are the constraints taken into account in this study:

a) Generation capacity

$$P_{Gi\,min} \leq P_{Gi} \leq P_{Gi\,\max} \qquad 2.45$$

Power generated from thermal generators has a minimum value for efficient operation and maximum permissible power limits of the generator.

$$0 \leq w_i \leq w_{ri} \qquad 2.46$$

Power generated by wind turbines is a function of wind; varies from zero (times of no wind blowing) to maximum value of the installed wind turbine (generator).

$$0 \leq pv_i \leq pv_{max} \qquad 2.47$$

Similarly power generated from solar varies from zero (times of no sun; say night) to a maximum value of installed capacity. This value is always variable varying from zero; when there is no wind blowing to maximum value as per the ratings of the wind turbine. Similarly solar power also varies from zero say at night to a maximum value as dictated by the solar panel.

b) Power balance (demand and losses)

The total real power generation by each generating unit must balance the predicted real power demand plus the real power losses.

Power generating stations, usually are spread out over large geographical areas, transmission network losses must therefore be taken into account to achieve true economic dispatch.

Power loss can occur anywhere before the power reaches load to meet the demand. Any shortage in the generated power will cause shortage in feeding the load demand which may cause many problems for the system and loads.

Network losses can be determined using either Penalty factors method or the *B* coefficients method. In this study, loss coefficient method is used. B matrix also known as the transmission loss coefficients matrix, which is a square matrix with a dimension of n×n where n is the number of generation units in the system is used.

The function of calculating Power loss as the transmission loss through B-matrix is given by the equation below.

$$P_{loss} = \sum_{i=1}^{n} \sum_{j=1}^{n} P_i B_{ij} P_j \qquad 2.48$$

Therefore, total thermal, wind and PV power must match the total load demand P_D and the total power lossP_l, thus:

$$\sum_{i=1}^{N} P_i + \sum_{i=1}^{M} W_i + \sum_{i=1}^{n} PV_i = P_D + P_l \qquad 2.49$$

c) Active power loss is positive

$$P_L > 0 \qquad 2.50$$

d) Dispatched amount of renewable power is limited to some fraction, (x) of the total actual power demand

$$(P_s + P_w) \leq xP_D \qquad 2.51$$

The renewable power used for dispatch should not exceed the 30% of total power demand, hence the equation 2.51 becomes;

$$(P_s + P_w) \leq 0.3P_D \qquad 2.52$$

2.15 Uncertainty Treatment

Uncertainty is the difference between the estimated or calculated value and the true (actual) value. In a power system the sources of uncertainty are varied [42]. Generation availability from the renewable sources is one of the main sources of uncertainty in power systems.

Power generated from solar varies as a function of solar irradiance at given place while wind power varies as a function of wind speed. For planning of operation of a power system purposes, solar and wind power is predicted from the weather forecast data. The predicted values do not always exactly match the actual values. In most cases a small discrepancy is witnessed. This discrepancy should always be kept as little as possible.

Wind power depends on the predicted wind speed whereas solar power depends on the predicted solar irradiance. For effective planning of the power system the predicted values should closely match the actual values available at a given point in time. To ensure this, the cost function of wind and solar generators should be designed in such a way that the penalty for discrepancy between the predicted and the actual available power (penalty for over-generation and under-generation) should be increasing progressively with increase in the difference between the two values, with zero penalty cost when the two are the exactly the same. From the cost functions of wind and solar as shown in the equations below;

Cost of wind generator

Wind_Cost= (C_{wj}(wind_a)) + abs (C_{rwj}(wind_a-wind_p)) + abs (C_{pwj}(wind_p-wind_a)) 2.60

This then simplifies into;

Wind_Fuel_Cost = (Cwj (wind_a)) + Crwj (dw) + Cpwj *dw 2.61

Where; wind_a: is the wind power available

Wind_p: is the wind power predicted

dw: is the absolute value of the difference between the predicted and the actual values of wind power.

The following scales of charging for the penalties of over-generation and under-generation was designed for wind energy conversion system:

Cost of Wind Generator

Cwj = Wind Cost coefficient. Set at Cwj= 1.5

Crwj = Cost Coefficient due to over-generation

Cpwj = Cost Coefficient due to under-generation

dw = absolute (solar_available - solar_predicted)

For dw <= 5

Crwj = 1.5

Cpwj = 3

For dw <= 10

Crwj = 2

Cpwj = 4

For dw <= 15

Crwj = 3

Cpwj = 6

For dw <= 20

Crwj = 4.5

Cpwj = 6.5

For dw >= 20

Crwj = 7 Cpwj = 8.5

Cost of Solar Generator

Solar Cost = (Cpvi *(solar_a)) + abs(Cppvi *(solar_a-solar_p)) + abs(Crpvi *(solar_a-solar_p)) 2.62

This then simplifies to;

Solar_Fuel_Cost = (Cpvi *(solar_a)) + Cppvi * ds+ Crpvi *ds 2.63

Where; Cpvi: Solar Cost coefficient, set as Cpvi= 2.5

Cppvi: Cost Coefficient due to over-generation

Crpvi: Cost Coefficient due to under-generation

solar_a: is the solar power available

solar_p: is the solar power predicted

ds = absolute(solar_a – solar predicted)

For ds <= 5

Cppvi = 1.5 Crpvi = 3.0

For ds <= 10

Cppvi = 2.5 Crpvi = 4.0

For ds <= 15

Cppvi = 5.5 Crpvi = 6.0

For ds <= 20

Cppvi = 6.5 Crpvi = 7.5

For ds >= 20

Cppvi = 8.0 Crpvi = 8.5

CHAPTER 3: METHODOLOGY

3.1 Optimization Methods in ED Problem

Optimization is the art of finding the best solution under the prevailing constraints in the power system. Constrained optimization problems, especially nonlinear optimization problems, where objective functions are minimized under given constraints, are very important and frequently appear in the real world [40].

Studies about the optimization and sizing of hybrid renewable energy systems have increased tremendously since the recent popular utilization of renewable energy sources. Mathematical optimization involves maximizing or minimizing an objective function while meeting a set of constraints. The main modelling approaches that are commonly used are: deterministic, stochastic, hybrid, and IT-driven models. With integration of RE in to the power systems, the main aim of optimization algorithms is to obtain a solution that minimizes costs as well as ensuring system reliability and security by minimizing uncertainties of RE.

Optimization techniques can be broadly classified into three categories:

a. **Conventional methods**

   These incude:

Linear Programming (LP)

It is used to linearize nonlinear optimization problems so that objective functions and constraints of power system optimization problems have linear forms. LP is widely used to solve security-constrained economic dispatch, optimal power flow and steady-state security.

Nonlinear Programming (NLP)

Most power system problems are nonlinear. Therefore nonlinear programming techniques can easily handle power system problems. While solving a NLP problem, the first thing is to choose a search direction in the iterative procedure, which is determined by the first partial derivative of the equation. NLP-based methods have higher accuracy than LP-based approaches, and also have global convergence.

Quadratic Programming (QP)

This is a special form of NLP. The objective function of the QP optimization model is quadratic but the constraints are in linear form. The most-used objective function is the generator cost function, which generally is a quadratic.

Newton's Method

Newton's method requires the computation of the second-order partial derivatives of the power-flow equations. It is also known as the second-order method. The necessary conditions of optimality are the Kuhn-Tucker conditions.

Network Flow Programming (NFP)

Network flow programming (NFP) is a special form of LP. It is characterised by speed and simplicity in calculation. It is efficient for solving security-constrained economic dispatch, multi-area systems economic dispatch, and optimal reconfiguration of an electric distribution network.

b. Non-quantity approaches to address uncertainties in objectives and constraints

These include: Probabilistic optimization, Fuzzy set applications, Analytic hierarchical process (AHP)

The Fuzzy Set Theory

Data and parameters used in power system operations are usually derived from many sources, with a wide variance in their accuracy. Insufficient information may generate an uncertain region of decisions. To account for the uncertainties in information and goals related to multiple and usually conflicting objectives in power system optimization, the use of probability theory, fuzzy set theory, and analytic hierarchical process (AHP) play a significant role in decision making.

c. Intelligence search method

Neural network (NN)

The optimization Neural Network changes the solution of an optimization problem into an equilibrium point of a nonlinear dynamic system, and changes the optimal criterion into energy functions for dynamic systems. Its parallel computational makes it superior to traditional optimization methods.

Evolutionary Algorithms (EAs)

Natural evolution is a population-based optimization process. They are artificial intelligence methods for optimization based on the mechanics of natural selection, such as mutation, recombination, reproduction, crossover and selection. EAs include; GA, Simulated Annealing and Evolutionary Programming (EP).

Simulated Annealing

Simulated annealing finds optima in a way analogous to the reaching of minimum energy configurations in metal annealing. The working principle is borrowed from metallurgy: a piece of metal is heated and then the metal is left to cool slowly. The slow and regular cooling of the metal allows the atoms to slide progressively toward their most stable, minimal energy positions. Rapid cooling would have "frozen" them in whatever position they happened to be at that time. The resulting structure of the metal from gradual cooling is therefore stronger and more stable.

Genetic Algorithm (GA)

GA is a multi-objective optimization technique based on principles inspired from the genetic and evolution mechanisms observed in natural systems and populations of living organisms. It evolves a population of individuals towards better individuals through some genetic operators; selection, crossover and mutation. It mimics the natural selection process of nature. Each individual in a population has a set of properties which can be altered.

Evolution starts from a population of randomly generated individuals and it is iterative. The algorithm identifies individuals with the optimizing fitness values. Individuals with lower fitness naturally get discarded. Normally, solutions are represented in binary as strings of 0s and 1s. Although GA always guarantees convergence, there is no absolute assurance that a genetic algorithm will find a global optimum. It also does not have a constant optimization response time.

Particle Swarm Optimization (PSO)

Particle swarm optimization is a population based stochastic optimization technique based on the movement and intelligence of swarms. It was developed by Dr. Eberhart and Dr. Kennedy in 1995. It is inspired by social behaviour of group of creatures that has this relative behaviour, for example, bee swarm, fish school and bird flock. PSO exploits a population, called a *swarm*, of potential solutions, called *particles*, which are modified after every iteration of the algorithm [11]. Particle Swarm Optimization is an approach to problems whose solutions can be represented as a point in an n-dimensional solution space. A number of *particles* are randomly set into motion through this space. At each iteration, they observe the "fitness" of themselves and their neighbours and "emulate" successful neighbours (whose current position represents a better solution to the problem than theirs) by moving towards them [11].

Tabu search (TS)

Tabu search is an iterative search algorithm, characterized by the use of a flexible memory. It is a heuristic procedure that employs dynamically generated constraints to guide the search for optimum solutions. Tabu search is able to eliminate local minima and to search areas beyond a local minimum. It does this through an evaluation function that chooses the highest evaluation solution per iteration. This means moving to the best admissible solution in the neighbourhood of the current solution in terms of the objective value and tabu restrictions. The evaluation function selects the move that produces the most improvement in the objective function.

3.2 SUMMARY OF METHODOLOGIES

After reviewing several methodologies available for optimization, Particle Swarm Optimization (PSO) method algorithm was chosen to solve Uncertainty Treatment in Economic Dispatch with RE problem. This was arrived because of its advantages which include; it can be easily programmed, faster in convergence, its simple concept and mostly provides a better solution. In PSO, only gbest gives out the information to others. It is a one - way information sharing mechanism. The evolution only looks for the best solution therefore tend to converge to the best solution quickly.

3.3 REVIEW OF PARTICLE SWARM OPTIMIZATION

PSO exploits a population, called a *swarm*, of potential solutions, called *particles*, which are modified after every iteration of the algorithm [11]. Particle Swarm Optimization is an approach to problems whose solutions can be represented as a point in an n-dimensional solution space. A number of *particles* are randomly set into motion through this space. After each iteration, they observe the "fitness" of themselves and their neighbours and "emulate" successful neighbours (whose current position represents a better solution to the problem than theirs) by moving towards them [11].

In PSO manipulation of swarm differs significantly from that of Evolutionary Algorithms such as GA, in that it promotes a cooperative rather than a competitive model.
PSO uses an adaptable velocity vector for each particle, which shifts its position after every iteration of the algorithm. Particles move towards promising regions of the search space by

exploiting information springing from their own experience during the search, as well as the experience of other particles. A separate memory is therefore is used where each particle stores the best position it has ever visited in the search space.

PSO algorithm has other advantages such as robustness, efficiency, as well as suitability for parallel computing. Therefore, PSO algorithm is a unique and attractive approach for real-world design optimization in ED problem.

The basic PSO algorithm consists of three steps, namely: generating particles' positions and velocities, velocity update, and finally, position update [38].

3.3.1 Generating Particles' Positions

In a physical -dimensional search space let the position and velocity of individual be defined as;

$X_i = (X_{i1}, \dots \dots \dots \dots, X_{in})$: Position of individual i

$V_i = (V_{i1}, \dots \dots \dots \dots, V_{in})$: Velocity of individual i

In the PSO algorithm let the following equations be the best position of individual and its neighbours' best position so far.

$P_{besti} = (X_{i1}P_{best}, \dots \dots \dots \dots, X_{in}P_{best})$: Best position of individual i

$G_{besti} = (X_{i1}G_{best}, \dots \dots \dots \dots, X_{in}G_{best})$: Global best position

3.3.2 Updating Velocity of Individuals

Velocity of individual particle is modified under the following equation:

$$V_i^{k+1} = w_i^k + c_1 r_1 * \left(P_{besti}^k - X_i^k\right) + c_2 r_2 * \left(G_{besti}^k - X_i^k\right) \qquad 3.10$$

Where;

V_i^k is the velocity of individual i at iteration k

w: inertia weighting factor

$c_1,\ c_2$: weighting factors

$r_1,\ r_2$: random uniform numbers between 0 and 1

P_{besti}^k: best position of individual i until iteration k

G_{besti}^k: best position of the group until iteration i.

X_i^k: position of individual i at iteration k

3.3.3 Updating Position of Individuals

Individual particles move from the current position to the next one by the modified velocity according to the following equation:

$$X_i^{k+1} = X_i^k + V_i^{k+1} \qquad 3.11$$

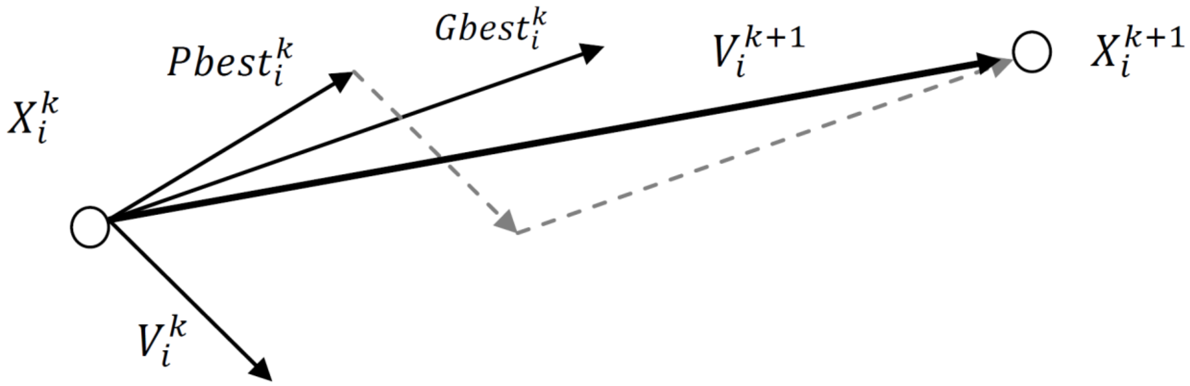

Figure 2.6 PSO mechanism [11]

The key parameters of PSO in the velocity update equation are;

The momentum component, where the inertial constant w, controls how much the particle remembers its previous velocity. Suitable selection of inertia weight w provides a balance between global and local explorations, thus requiring less iteration on average to find optimal solution. As originally developed, it decreases linearly from about 0.9 to 0.4 during a run [41].

Cognitive component, here the acceleration constantc_1, controls how much the particle heads toward its personal best position. Social component, draws the particle toward swarm's best ever position, the acceleration constant c_2 controls this tendency. A good selection of the inertia weighting factor provides a balance between global and local exploration and results in fewer iterations on average to find an optimal solution. Its value is set according to the following equation;

$$w = w_{max} - \frac{w_{max} - w_{min}}{iter_{max}} * iter \qquad 3.12$$

Where; $iter_{max}$ is the maximum iteration number (generations) and $iter$ is the current iteration number. A particle goes to a direction computed from the best visited position and the best visited position of all particles in the swarm.

3.4 Implementation of PSO

The Particle Swarm algorithm is implemented by searching the generation of power plants within generator constraint. That is any possible value within the maximum and minimum value of power that can be generated by the power plant. The parameters of PSO can be represented in the ED problem as shown below;

Swarm: All possible generation from power plant

Particle: An individual power generation (solution) particles are members of a swarm.

Velocity: Rate of change from one possible solution to another in iteration.

Dimension: Number of generating units against the number of possible generations from each unit.

3.5 Stopping Criterion

Once the PSO Algorithm is started it cannot run forever, it must come to stop when the best solution is achieved. Various criteria are available to terminate the optimization algorithm. When maximum number of iteration is reached. When acceptable solution has been found (when no improvement is observed over a number of iterations)

3.6 Proposed PSO Algorithm for Uncertainty treatment in ED with RE

Step 1: Read data; thermal cost coefficients, maximum allowed iterations, population size, minimum power from each generatorP_i^{min}, maximum power from each generatorP_i^{max} where i is the number of generator. Read values of the total demand on the power system, values of available renewable energy versus the predicted values of RE.

Step 2: From the demand subtract the available amount of power from wind and solar.

$$P_{Thermal} = P_{Demand} - (P_{Wind} + P_{Solar})$$

Step 3: Initialize randomly the real power generation P_{gi} of the population according to the limit of each unit including the individual dimensions, searching points and velocities. These initial individuals must be feasible candidate solution that satisfies the practical operation constraints. In a dimensional optimization problem, the position of i^{th} particle is an array of $[I \times N]$. The position and velocity of particles take the forms shown below

$$X_i = [X_{i1}, X_{12}, \dots \dots \dots \dots \dots, X_{iN}]$$

$$V_i = [V_{i1}, V_{i2}, \dots \dots \dots, V_{iN}]$$

Step 4: To each individual P_g of the population, use the B-coefficient loss-formula to calculate the transmission lossP_L.

Step 5: Calculate the value of objective function for each particle's position. Compare each individual's evaluation value with its Pbest. The best evaluation value among Pbest is denoted as Gbest. The best cost value in the population is denoted as Gbest and remaining individuals are assigned as Pbest.

Step 6: Modify the member velocity V of each individual P_{gi} according to equation shown below

$$V_{id}^{k+1} = wv_i^k + c_1 rand_1 * \left(Pbest_i^k - X_i^k\right) + c_2 rand_2 * \left(Gbest_i^k - X_i^k\right)$$

If $V_{id}^{(k+1)} > V_d^{max}$,then $V_{id}^{(k+1)} = V_d^{max}$.

If $V_{id}^{(k+1)} < V_d^{min}$, then $V_{id}^{(k+1)} = V_d^{min}$

Step 7: Modify the member position of each P_{gi} according to the equation shown below;

$$Pg_{id}^{(k+1)} = Pg_{id}^{(k)} + V_{id}^{(k+1)}$$

Step 8: If the evaluation value of each individual is better than the previous $Pbest$, the current value is set to be $Pbest$. If the best $Pbest$ is better than $Gbest$, the value is set to be best.

Step 9: If the number of iterations reaches maximum, then go to step 10. Otherwise, check if ΔP is less than ϵ, if true calculate cost of generation with these values of powers then go to step 10, otherwise go to step 5.

Step 10: The individual that generates the latest $Gbest$ is the optimal generation power of each unit with the minimum total generation cost.

3.7 Flow Chart

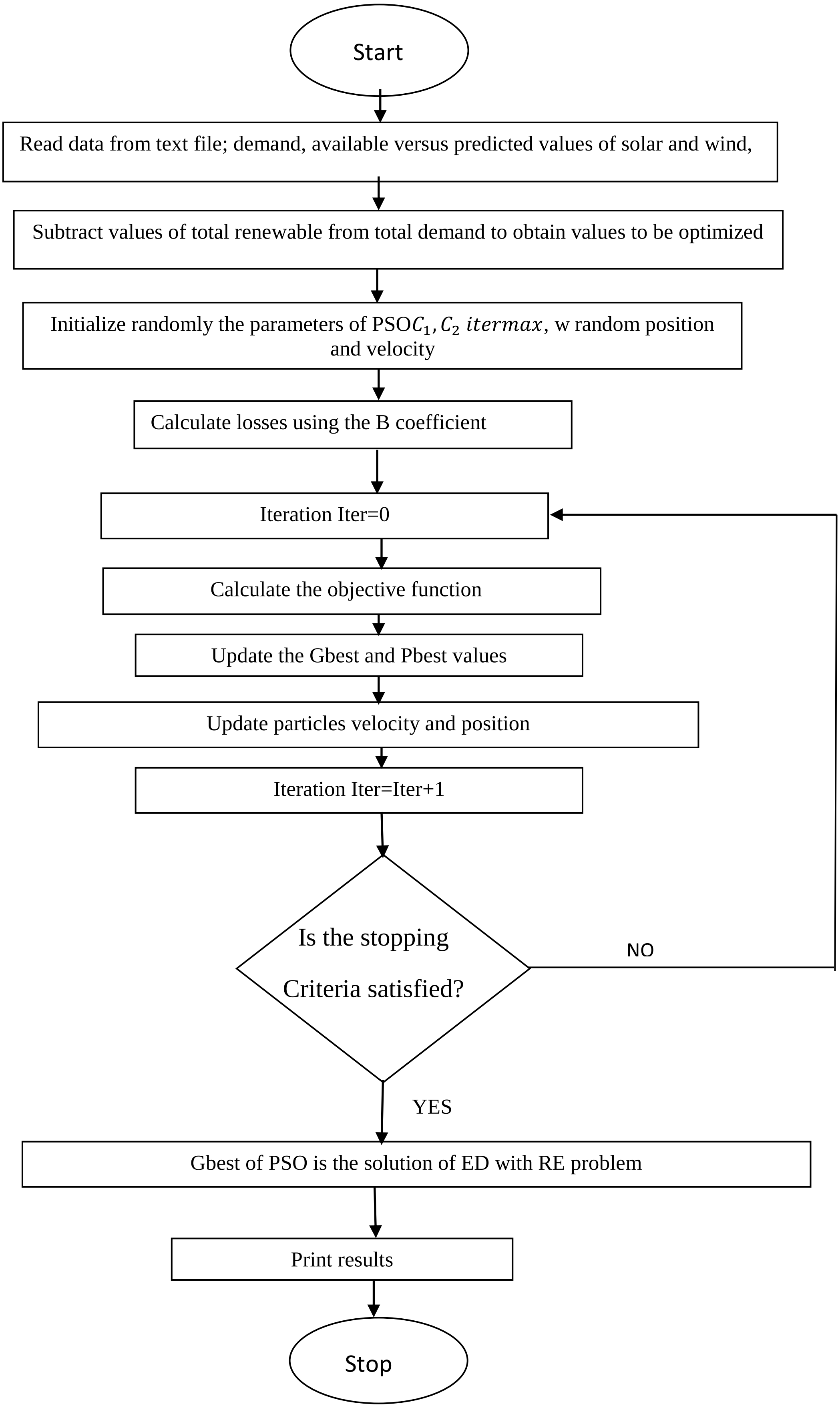

Figure 3.1

CHAPTER 4: RESULTS, ANALYSIS AND DISCUSSION

The proposed algorithm was tested on IEEE-30 bus system shown below

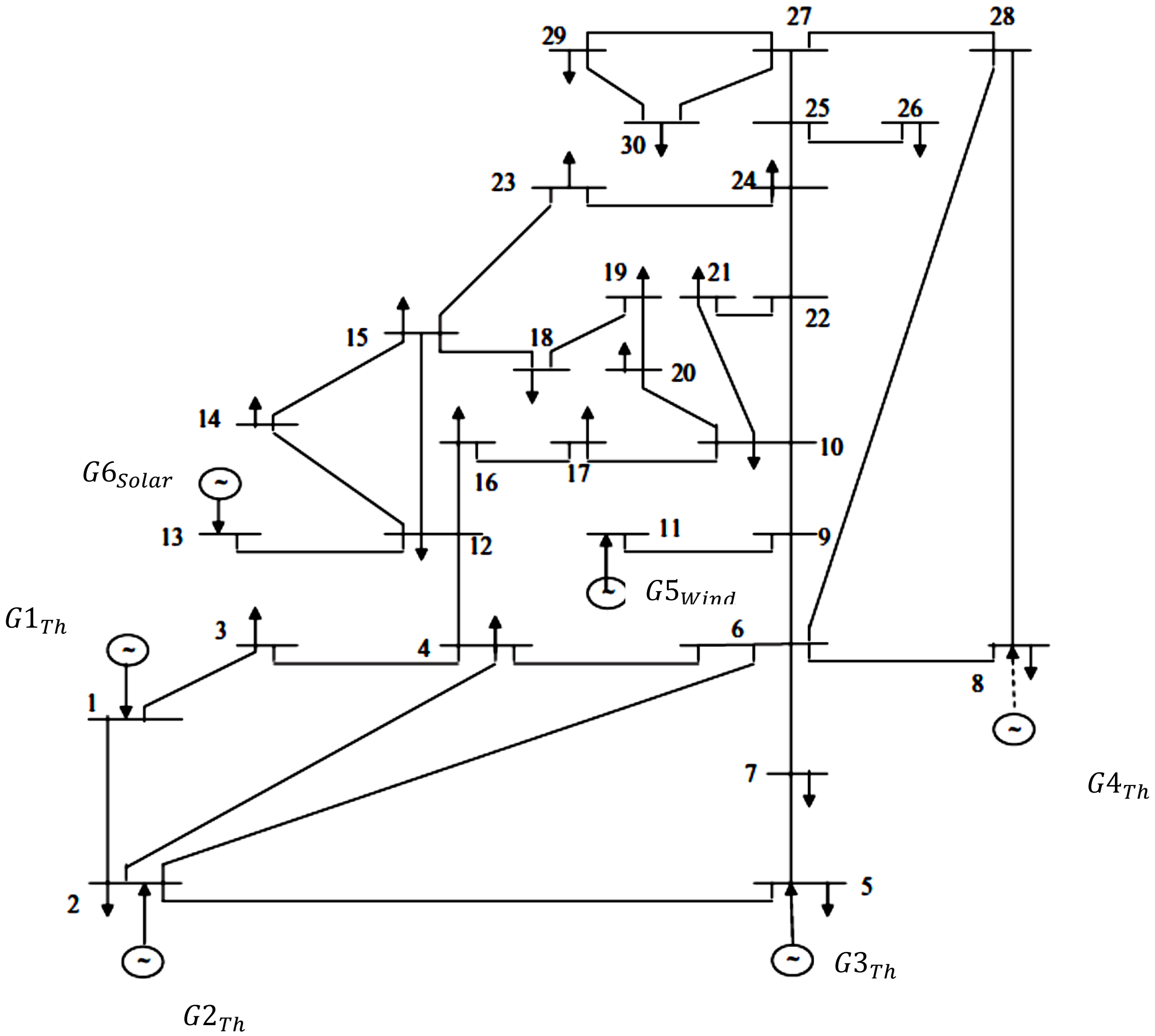

Fig 4.1: One line diagram of IEEE 30-bus system [1]

4.1 Simulation Results

At a penetration level of RE of 30%

P_D=400 MW; **W_{av}=39** MW; **W_p= 39** MW;

S_{av}=28 MW; **S_p=28** MW;

Table 4.1 Optimal generation for 0MW discrepancy

Generator type	Power Generated in (MW)	Cost ($/Hr)
Thermal generator 1	200	550
Thermal generator 2	80	252
Thermal generator 3	31.488	93.4562
Thermal generator 4	35	123.967
Solar generator	28	70
Wind generator	39	68.25
Iterations taken to converge	90	
Power loses	13.4793	
Total	413.488	1157.67

P_D=400 MW; **W_{av}=39** MW; **W_p= 34** MW;

S_{av}=28 MW; **S_p=23** MW;

Table 4.2 Optimal generation for 5MW discrepancy

Generator type	Power Generated in (MW)	Cost ($/Hr)
Thermal generator 1	200	550
Thermal generator 2	80	252
Thermal generator 3	31.4847	93.4402
Thermal generator 4	35	123.967
Solar generator	28	140
Wind generator	39	123.25
Iterations taken to converge	81	
Power loses	13.4793	
Total	413.485	1282.66

$\mathbf{P_D=400}$ MW; $\mathbf{W_{av}=39}$ MW; $\mathbf{W_p= 28}$ MW;

$\mathbf{S_{av}=28}$ MW; $\mathbf{S_p=17}$ MW

Table 4.3 Optimal generation for 10MW discrepancy

Generator type	Power Generated in (MW)	Cost ($/Hr)
Thermal generator 1	200	550
Thermal generator 2	80	252
Thermal generator 3	31.4821	93.4273
Thermal generator 4	35	123.967
Solar generator	28	224
Wind generator	39	189.25
Iterations taken to converge	156	
Power loses	13.4792	
Total	413.482	1432.64

$\mathbf{P_D=400}$ MW; $\mathbf{W_{av}=39}$ MW; $\mathbf{W_p= 24}$ MW;

$\mathbf{S_{av}=28}$ MW; $\mathbf{S_p=13}$ MW

Table 4.4 Optimal generation for 15MW discrepancy

Generator type	Power Generated in (MW)	Cost ($/Hr)
Thermal generator 1	200	550
Thermal generator 2	80	252
Thermal generator 3	31.4774	93.4039
Thermal generator 4	35	123.967
Solar generator	28	280
Wind generator	39	233.25
Iterations taken to converge	172	
Power loses	13.4791	
Total	413.477	1532.62

$\mathbf{P_D=400}$ MW; $\mathbf{W_{av}=39}$MW; $\mathbf{W_p= 18}$ MW;

$\mathbf{S_{av}=28}$ MW; $\mathbf{S_p=7}$ MW

Table 4.5 Optimal generation for 20MW discrepancy

Generator type	Power Generated in (MW)	Cost ($/Hr)
Thermal generator 1	200	550
Thermal generator 2	80	252
Thermal generator 3	31.4737	93.3856
Thermal generator 4	35	123.967
Solar generator	28	416.5
Wind generator	39	393.75
Iterations taken to converge	74	
Power loses	13.479	
Total	413.474	1829.6

At a constant demand of; $\mathbf{P_D=350}$ MW; **Apha=0;** where alpha = (available – predicted RE power)

Table 4.6 Total cost of Generation against amount of RE available

Total value of RE (MW)	70	60	50	40	30	20	10	0
Total cost of power generation ($/Hr)	943.245	959.886	977.073	995.878	1018.09	1043.62	1075.52	1124.81

Plot of Cost of Power Generation against alpha; where alpha is the absolute difference between available value and the predicted value of RE is shown below in figure 4.2

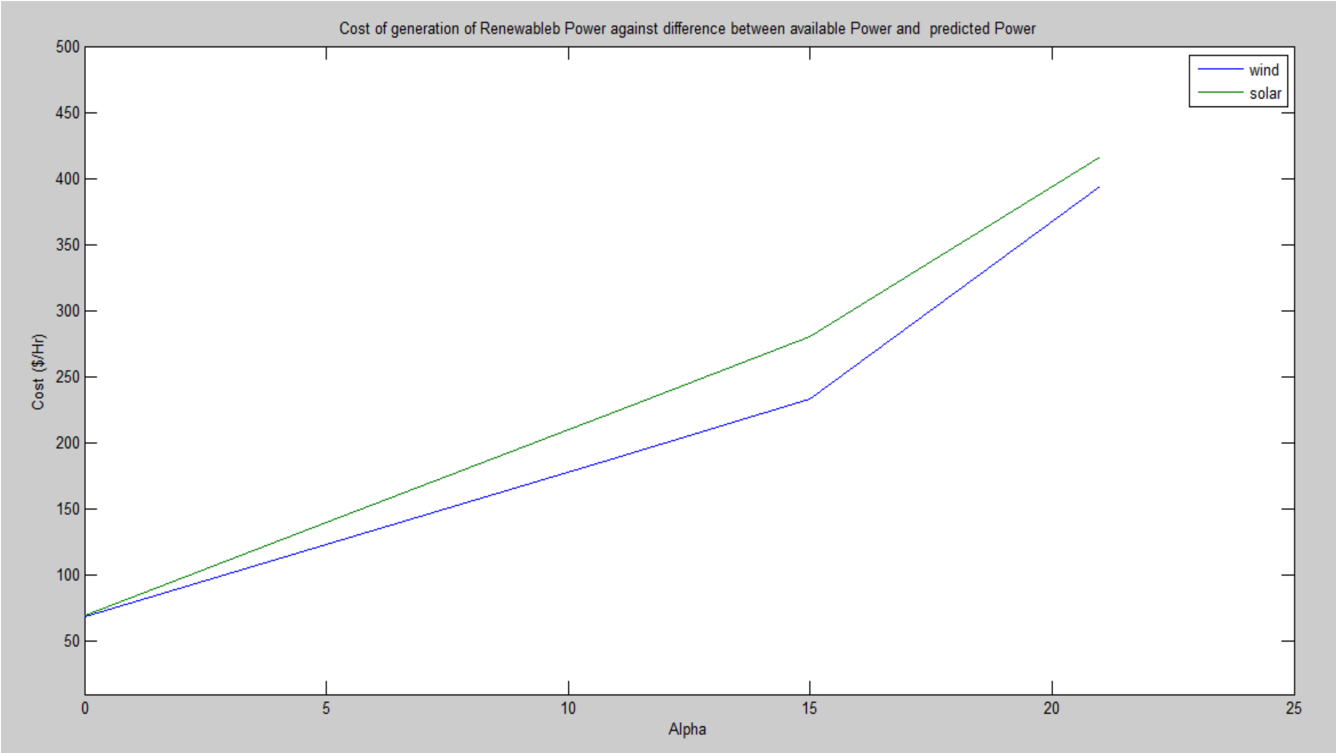

Figure 4.2: A graph of Total Cost of power generation against level of discrepancy

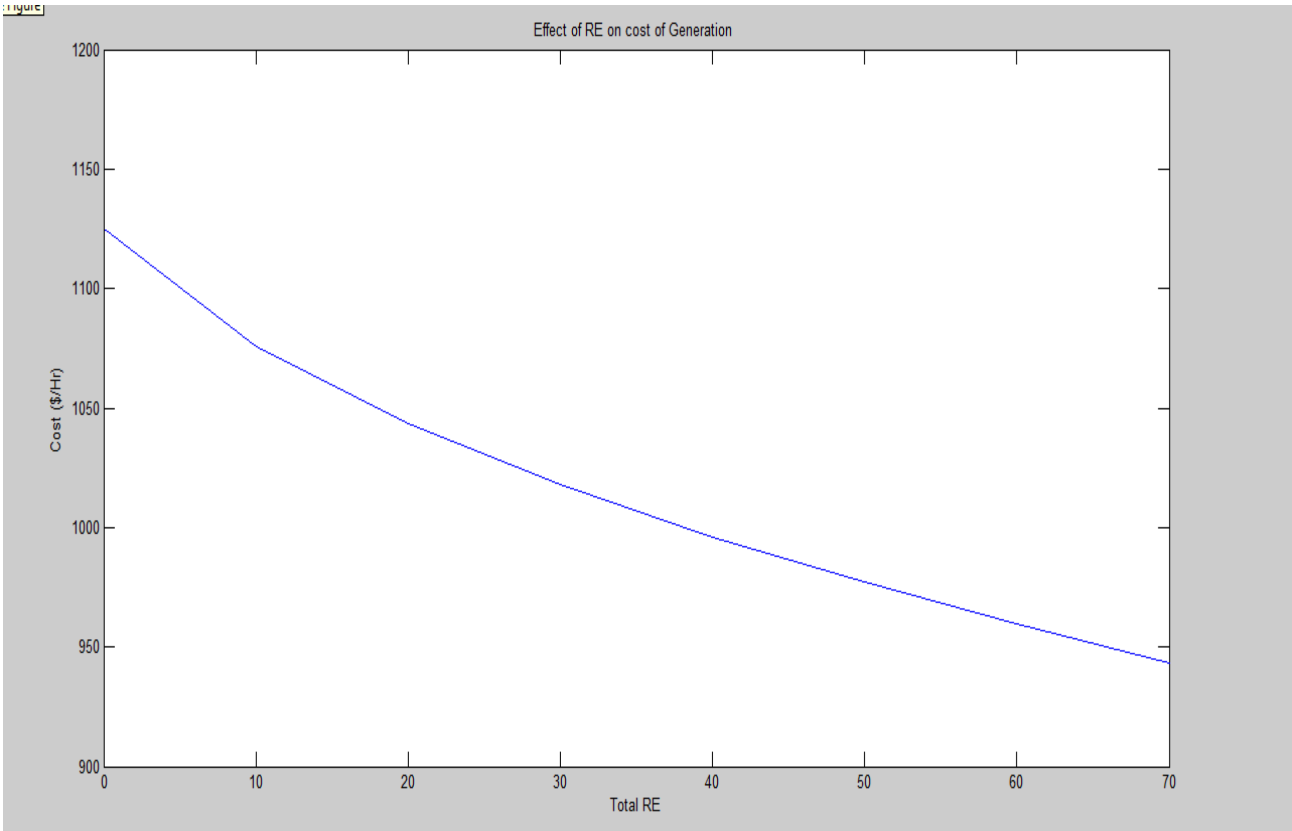

Figure 4.3: A graph of available RE against the Total Cost of power generation

At a penetration level of 50%

P_D=**300** MW**;** W_{av1}=**39**MW; W_{p1}= **39** MW; W_{av2}=**19**MW; W_{p2}= **19** MW;

S_{av}=**28** MW**;** S_p=**28** MW

Table 4.7 Optimal generation for 30% and 50% penetration level of RE

Alpha(Available RE-predicted RE)	**0**	**5**	**10**	**15**	**20**
30% RE penetration cost of generation($/Hr)	**766.243**	**891.257**	**1016.25**	**1141.21**	**1316.2**
50% RE penetration cost of generation($/Hr)	**735.15**	**915.108**	**1095.12**	**1275.15**	**1433.16**

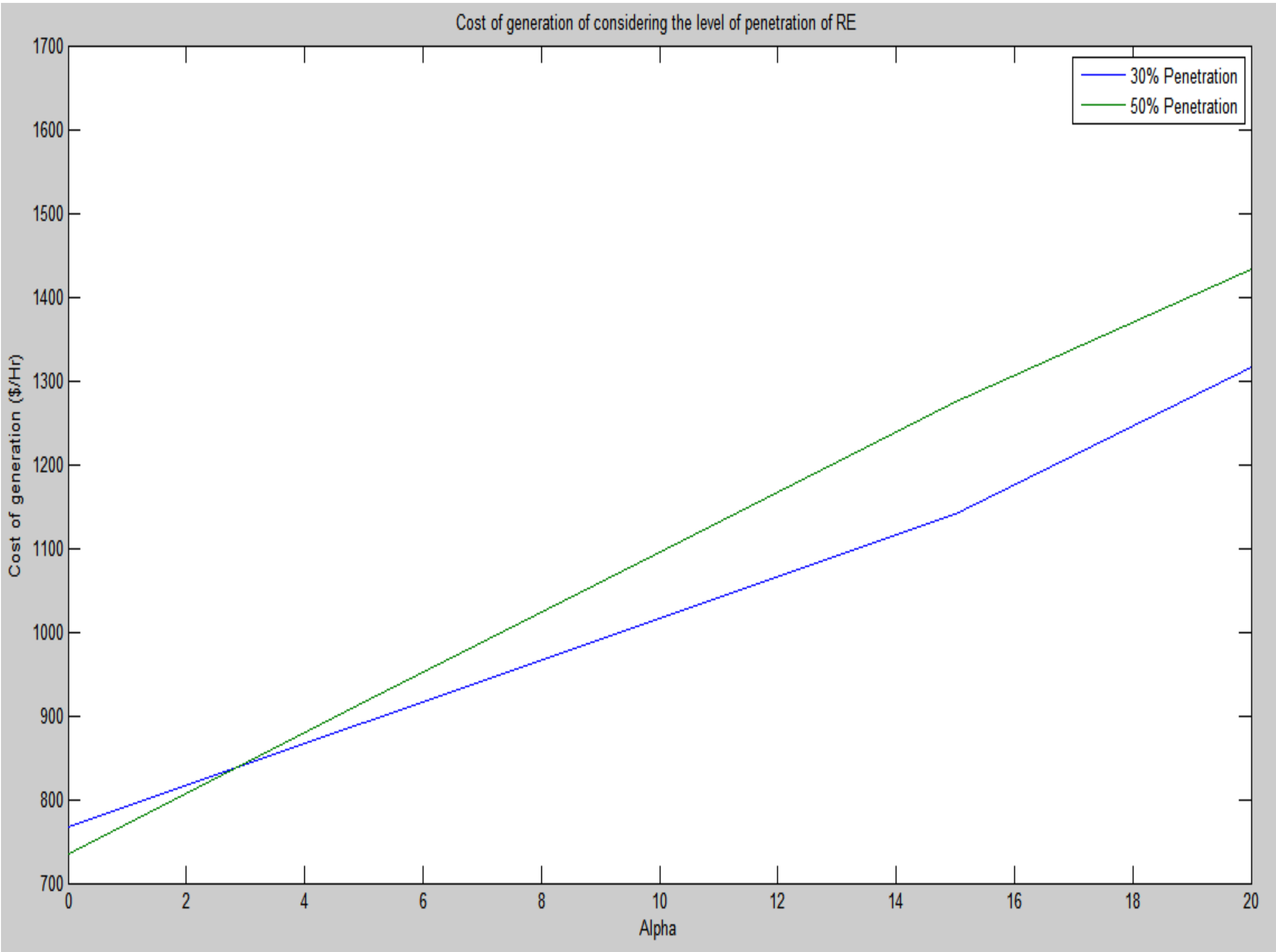

Figure 4.4: A graph of cost of generation for 30% and 50% penetration level of RE against discrepancy

4.2 Analysis & Discussion

Comparing the total costs of generation, it is seen that the cost is minimum when the difference between the predicted power and the available power is minimum. As the discrepancy between the predicted and the available power increases the cost also increases. This is therefore calls for precise prediction of RE power for efficient planning of operations of the power system. As shown by figure 4.2, with increasing uncertainty of RE, more costs are incurred in terms of energy reserves due to overestimation and the penalty cost for not using all available power from the renewable sources due to underestimation. These results shows that to be able to generate power using RE sources at an economical cost and be an alternative to the thermal generation, wind speed profile for wind generators and solar irradiance for PV generators need to be forecasted accurately so as to minimize the cost of reserves which has direct influence on the total cost of generation.

From the graph plotted of figure 4.3, showing the variation of cost with the total amount of RE, it is seen that the cost of generation reduces with increase in the amount of RE power. This shows that the cost of generation of RE under minimum uncertainty, is lower than that of thermal generators. This can be explained by the fact that thermal generators are fuel dependant, so the total cost incurred is the cost of fuel, operating costs and maintenances costs while for RE there is no cost of fuel, the resource is available in nature for free. The only costs incurred are maintenance and operating costs.

At a penetration level of 50% of RE, and low uncertainty levels the cost of generation is lower than that at 30% level of RE penetration. However, as uncertainty of RE increases the cost of generation with high penetration level increases more than that of 30% penetration of RE as shown by figure 4.4 above. This therefore shows that higher levels of RE penetration in the power system can only be economical if uncertainty in the prediction of wind speed profile and solar irradiance can be done accurately. Accurate forecasting of RE, helps in planning operations of the power system. It also minimizes costs of reserves and penalties incurred when all the energy from RE sources is not utilized.

High penetration of renewable energy comes with merits and also demerits. Prior studies have shown that with 10 - 15% intermitted renewable energy penetration levels, traditional planning and operational practices will be sufficient. However, once it exceeds the 30% penetration levels of renewable resources, it requires a change in planning and operational practices.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

Renewable sources of energy are encouraged to be integrated into the power system due to their benefits over fossil fuel driven power plants. This project develops a model to include wind and solar generators in the economic dispatch problem. The biggest challenge in the integration of RE into the conventional thermal system is the uncertain nature of these renewable resources. Availability and quantity of the RE depended on the prevailing weather conditions. The speed of wind and solar irradiance, which directly affect their availability, is shown to be varying at every instant.

The Matlab code was written in such a way that it accommodates the uncertainty of solar and wind, and also treating the uncertainty by charging the overestimation and overestimation of RE at different levels depending on the discrepancy between the available and the predicted value of renewable energy. The optimization problem was then solved numerically for two cases in which the level of penetration of RE is 30% and 50%respectively.

The overall cost of generation of power was found to decrease with increase in integration of renewable sources with minimum or no uncertainty, at 30% penetration with a demand of 300MW, the cost is 766.243$, while at 50% penetration of RE cost is 735.15$. However, the cost of generation increased with increasing uncertainty of RE. When difference between predicted and available power was more than 20, the cost of generation to meet the same demand of 300MW at 30% penetration was 1316.2$ while at 50% penetration the cost was 1433.16$. This can be explained by costs incurred due to reserves and failure to utilize all the available green energy. Since the availability of wind and solar resources are stochastic in nature, it can deviate from the scheduled value therefore adequate reserve capacity has to be maintained for reliable and stable operation of power system.

Accurate forecast of wind speed and solar irradiance by use of both modelled and onsite monitoring reduces the generation costs. Moreover, it enables planning of operations in the power system, ensuring smooth integration of the renewable resources while maintaining security of power systems.

5.2 Recommendations

This project considered uncertainty on generation availability; in future it could be extended to consider uncertainties on load requirements, fuel prices, regulatory uncertainties and uncertainties due to nature such as extreme weather conditions.

More studies should be done to determine the amount of penetration of renewable energy that can be integrated into the power system while still maintaining reliability and stability in operation of power system.

REFERENCES

[1] Jizhong Zhu. Optimization of Power System Operation. John Wiley & Sons, Inc., Hoboken, New Jersey. 2009

[2] C. Opathella, B. Venkatesh. Managing Uncertainty of Wind Energy with Wind Generators Cooperative. IEEE Transactions on Power Systems, Vol. 28, No. 3, August 2013

[3] Naoto Yorino, Yutaka Sasaki, Emil Popov Hristov, Yoshifumi Zoka. Dynamic Load Dispatch for Power System Robust Security against Uncertainties. 2013 IREP Symposium-Bulk Power System Dynamics and Control –IX (IREP), August 25-30, 2013, Rethymnon, Greece

[4] Soroudi, Alireza; Amraee, Turaj. Decision making under uncertainty in energy systems: State of the art. Elsevier, 2013-12

[5] Dr. L.V.Narasimha Rao. PSO Technique for Solving the Economic Dispatch Problem Considering the Generator Constraints. International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering (IJAREEIE). Vol. 3, Issue 7, July 2014

[6] Azza A. ElDesouky. Security and Stochastic Economic Dispatch of Power System Including Wind and Solar Resources with Environmental Consideration. International Journal of Renewable Energy Research Azza A. ElDesouky, Vol.3, No.4, 2013

[7] Soroudi, Alireza; Aien, Morteza; Ehsan, Mehdi. A Probabilistic Modeling of Photo Voltaic Modules and Wind Power Generation Impact on Distribution Networks. IEEE Systems Journal, 6 (2): 254-259; 2011-01

[8] M. Milligan, P. Donohoo, M. O'Malley. Stochastic Methods for Planning and Operating Power System with Large Amounts of Wind and Solar Power. National Renewable Energy Laboratory (NREL) Conference Paper, NREL/CP-5500-56208, presented in Lisbon, Portugal November 13–15, 2012

[9] Paul Komor. Wind and Solar Electricity: Challenges and Opportunities. Pew Center on Global Climate Change. June 2009

[10] Behnam Tamimi, Claudio Ca˜nizares, Kankar Bhattacharya. System Stability Impact of Large-scale and Distributed Solar Photovoltaic Generation: The Case of Ontario, Canada. IEEE Transactions on Sustainable Energy, November 2012

[11] Rohit Kumar Pancholi, K.S.Swarup. Particle Swarm Optimization for Economic Dispatch with line flow and voltage constraints. 0-7803-765l-xI01/$l7.Q00 2 003 IEEE

[12] T.R. Ayodele, A.A. Jimoh, J.L Munda, J.T Agee. Challenges of Grid Integration of Wind Power on Power System Grid Integrity: A Review. International Journal of Renewable Energy Research. T.R. Ayodele Et Al., Vol.2, No.4, 2012

[13] Mimoun Younes, Riad Lakhdar Kherfane, Fouad Khodja. A hybrid Approach for Economic power Dispatch. WSEAS Transactions on Power Systems. E-ISSN: 2224-350X. Issue 3, Volume 8, July 2013

[14] Dr.K.Balaraman. Wind Forecasting. Power Research and Development Consultants Pvt. Ltd. West of chord road, Bangalore - 560 086. Karnataka.

[15] Selvaraj Durai, Srikrishna Subramanian, Sivarajan Ganesan. Preferred Economic Dispatch of Thermal Power Units. Journal of Power and Energy Engineering, 2015, 3, 47-69. http://www.scirp.org/journal/jpee

[16] Jong-Bae Park, Ki-Song Lee, Joong-Rin Shin, and Kwang Y. Lee. A Particle Swarm Optimization for Economic Dispatch with Nonsmooth Cost Functions. IEEE Transactions on Power Systems, Vol. 20, No. 1, February 2005

[17] S.S. Baghsorkhi and I.A. Hiskens, “Impact of wind power variability on sub-transmission networks”, Proceedings of the IEEE Power and Energy Society General Meeting, San Diego, CA, July 2012.

[18] David J. King, Cuneyt S Ozveren. Economic Load Dispatch Optimization of Renewable Energy in Power System Using Genetic Algorithm. Conference Paper August 2007. DOI: 10.1109/PCT.2007.4538655. IEEE

[19] Giovanni Petrone, Carlo de Nicola, Domenico Quagliarella, Jeroen Witteveen and Gianluca Iaccarino. Wind Turbine Performance Analysis under Uncertainty. 49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition. 4 - 7 January 2011, Orlando, Florida.AIAA 2011-544

[20] Brandon Keith Mauch. Managing Wind Power Forecast Uncertainty in Electric Grids. Carnegie Mellon University Pittsburgh, PA. December 2012

[21] George Kariniotakis. The Uncertainty of wind Output- declines during the day. Conference ‘The role of market design for the achievement of 20% Renewables Target’ Brussels, 10.06.2010

[22] Hannele Holttinen, Jari Miettinen, Samuli Sillanpää. Wind power forecasting accuracy and uncertainty in Finland. Julkaisija – Utgivare – Publisher. ISBN 978-951-38-7985-3 (URL: http://www.vtt.fi/publications/index.jsp)

[23] Naoto Yorino, Muhammad Abdillah, Yoshifumi Zoka. A New Method of Evaluating Robust Power System Security against Uncertainties. IEEJ Transactions on Electrical and Electronic Engineering. 2015 Wiley Online Library (wileyonlinelibrary.com). DOI:10.1002/tee.22130

[24] Mohamed Abuella, Constantine J. Hatziadoniu. The Economic Dispatch for Integrated Wind Power Systems Using Particle Swarm Optimization. arxiv: 1509.01693vi[cs CE] 5 Sep 2015

[25] Marie Schnitzer, Christopher Thuman, Peter Johnson. Reducing Uncertainty in Solar Energy Estimates. Albany, New York, Barcelona, Bangalore. 2011

[26] Javad Ansari, Siamak Bandari, Mehdi Ghazavi Dozein, Mohsen Kalantar. The Effect of Wind Power Plants on the Total Cost of Production in Economic Dispatch Problems. Research Journal of Applied Sciences, Engineering and Technology 6(8): 1335-1340, 2013. ISSN: 2040-7459; e-ISSN: 2040-7467

[27] N.M.Ramya, M.Ramesh Babu, T.D.Sudhakar. Solution of Stochastic Economic Dispatch Problem using Modified PSO Algorithm. International Journal of Computer Applications. (2013).

[28] S. Mishra, Y. Mishra, S. Vignesh. Security Constrained Economic Dispatch Considering Wind Energy Conversion Systems. Department of Electrical Engineering Indian Institute of Technology Delhi (2013).

[29] Revathy K, Nithiyanandham C. Economic Dispatch Using Particle Swarm Optimization. International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering. Vol. 3, Special Issue 4, May 2014

[30] Hyundai Heavy Industries Co., Ltd Electro Electric Systems. General Specification for HQ1650. 3 Dec 2010. http://www.hyundai-elec.co.kr

[31] Global Wind Energy Council (GWEC), “Global wind statistics 2011,” 2014. http://www.gwec.net/wp-content/uploads/2014/04/6_21-2_global-cumulative-installed-wind-capacity-1996-2013.jpg

[32] Franck Bourry. Management of Uncertainties Related to Renewable Generation Participating in Electricity Markets.

[33] Duong Quoc Hung, Mithulananthan Nadarajah. Technical Challenges, Security and Risk in Grid Integration of Renewable Energy. Reasearch Gate March 2016. https://www.researchgate.net/publication/29409137

[34] http://pveducation.org/pvcdrom/p (Nov 27, 2014)

[35] Dr. Johan Enslin, Quanta Technology. Grid Impacts and Solutions of Renewables at High Penetration Levels.

[36] Prema V, K. Uma Rao. Predictive Models for Power Management of a Hybrid Micro grid.

[37] Saoussen Brini, Hsan Hdj.A, Abderrrazak Ouali. Economic Dispatch for Power System included Wind and Solar Thermal energy, Leonardo journal of Sciences ISSN 1583-0233 2009

[38] Rania Hassan, Babak Cohanim, Olivier de Weck. A Comparison of Particles Swarm Optimization and Genetic Algorithm. Vander Plaats Research and Development, Inc. Colorado Springs, CO, 8096.

[39] Kwang Y.Lee, Jong-Bae Park. Application of Particle Swarm Optimization to Economic Dispatch problem: Advantages and Disadvantages. 2006

[40] Tetsuyuki Takahama, Setsuka Sakai. Constrained Optimization by Combining α Constrained method with Particle Swarm Optimization.

[41] Manjeet Singh, Divesh Thareja. A Thermal Economic Dispatch Problem Solving by Particle Optimization. International Journal of Electrical Engineering (IIEE). Volume 1, 6th December 2013

[42] Chaoyi Peng, Shunbo Lei, Yunhe Hou, Felix Wu. Uncertainty Management in Power System Operation. CSEE Journal of Power and Energy System. Vol. 1 NO. 1 March 2015.

APPENDICES

The test system consists of four thermal units, one wind farm and one solar farm. The parameters of the generators in the system; cost coefficients, minimum and maximum limits of the thermal units and the renewable units (wind and solar), are given in are given below in Table 5.1 and table 5.2 respectively.

The cost coefficients of IEEE-30 bus system are slightly modified to incorporate Renewable sources (wind, solar). The cost coefficient of solar and wind generators are of three forms; one based on solar irradiance for solar or based on wind profile for wind generators, penalty reserve requirement cost and penalty for not using all the available Renewable Energy.

Table 5.1: Generator data for IEEE 30-bus system

Type of Generator	Minimum power from each generator(MW)	Maximum power from each generator(MW)	**a_i**	**b_i**	**c_i**
Thermal gen1	50	200	0.00375	2.0000	0
Thermal gen 2	20	80	0.01750	1.7500	0
Thermal gen 3	15	50	0.06250	1.0000	0
Thermal gen 4	10	35	0.00830	3.2500	0
Solar gen	00	30			
Wind gen	00	40			

The cost coefficients, of Renewable Energy generators used were as listed below; [26, 27]

Table 5.2: Renewable Generators data

Type of generator	Direct cost (C_{wi})	Overestimation (C_{pwi})	Underestimation $(C_{r,wi})$
Wind generator	1.75	1.5	3.0
Solar generator	2.50	1.5	3.0

C =5 m/s, K=2 (Weibull PDF parameters)
Cut-in wind speed $v_i = 5m/s$, rated wind speed $v_r = 15m/s$, cut-out wind speed $v_o = 45m/$s

Penalty reserve requirement cost and also the penalty for not using all the available RE power increased with increasing discrepancy between the actually available RE power and the predicted value as shown below in table 5.3

Table 5.3: Uncertainty treatment of Renewable Generation availability

Type of generator	<= 5		<= 10		<= 15		<= 20		>20	
Wind generator	Crwj	Cpwj	Crwj	Cpwj	Crwj	Cpwj	Crwj	Cpwj	Crwj	Cpwj
	1.5	3.0	2.0	4.0	3.0	6.0	4.5	6.5	7.0	8.5
Solar generator	Crpvi	Cppvi	Crpvi	Cppvi	Crpvi	Cppvi	Crpvi	Cppvi	Crpvi	Cppvi
	1.5	3.0	2.5	4.0	5.5	6.0	6.5	7.5	8.0	8.5

B- Coefficients [28]

$$
\begin{matrix}
0.000170 & 0.001200 & 0.000700 & -0.00010 & -0.00050 & -0.00020 \\
0.001200 & 0.001400 & 0.00090 & 0.000100 & -0.00060 & -0.00010 \\
0.000700 & 0.000900 & 0.00310 & 0.00000 & -0.00100 & -0.00060 \\
-0.00010 & 0.000100 & 0.00000 & 0.00240 & -0.00060 & -0.00080 \\
-0.00050 & -0.00060 & -0.00100 & -0.00060 & 0.012900 & -0.00020 \\
-0.00020 & -0.00010 & -0.00060 & -0.00080 & -0.00020 & 0.01500
\end{matrix}
$$

Table 5.4: The parameters of PSO used in simulation

Population size	100
Maximum iterations	500
Acceleration constants	$C_1 = C_2 = 2$
Number of total units	6
Number of thermal units	4
Number of wind units	1
Number of solar units	1

PROGRAM LISTING

```
% Particle swarm optimization
clear all;% to clear the workspace
clc;% to clear all previous command
no_units=4; %Number of thermal units
pd=input ('Enter the value of demand in MW = ');
wind_a=input('Enter the value of available wind Power in MW=');
while(wind_a > 40)
 fprintf('The value exceeds the gnerator capacity;it should be less th40');
   wind_a = input ('\nEnter the value of available wind Power in MW= ');
end
wind_p=input('Enter the value of wind predicted Power in MW=');
while(wind_p > 40)
fprintf('it exceeds the generator capacity;it should be less than 40');
   wind_p = input ('\nEnter the value of available wind Power in MW= ');
end
solar_a=input('Enter the value of available solar Power in MW=');
while(solar_a > 30)
   fprintf('it exceeds the gnerator capacity;it should be less than 30');
```

```
   solar_a = input ('\nEnter the value of available solar Power in MW= ');
end
solar_p=input('Enter the value of solar predicted Power in MW=');
while(solar_p > 30)
   fprintf('it exceeds the gnerator capacity;it should be less than 30');
   solar_p = input ('\nEnter the value of available solar Power in MW= ');
end
PD=(pd-wind_a-solar_a);
pmax=[200 80 50 35 30 40]; %maximum generation
pmin=[50 20 15 10 00 00]; %minimum generation

%cost coefficients
a=[0.00375 0.01750 0.06250 0.00834 0.02500 0.02500];
b=[2.00 1.75 1.00 3.25 3.00 3.00]; %accounts for generation changes
c=[0 0 0 0 0 0]; %accounts for plant operation

B=[ 0.000218 0.000103 0.000009 -0.000010 0.000002 0.000027
0.000103 0.000181 0.000004 -0.000015 0.000002 0.000030
0.000009 0.000004 0.000417 -0.000131 -0.000153 -0.000107
-0.000010 -0.000015 -0.000131 0.000221 0.000094 0.000050
0.000002 0.000002 -0.000153 0.000094 0.000243 -0.000000
0.000027 0.000030 -0.000107 0.000050 -0.000000 0.000358];
no_part=30; %Population size
itermax=1000;%Maximum number of iterations.
%increasing cost
beta=2*a;% differentianting cost function with respect to Pi
alpha=b;% differentianting cost function with respect to Pi
for i=1:no_units
Lambda_min(i)=alpha(i)+beta(i)*pmin(i);%
Lambda_max(i)=alpha(i)+beta(i)*pmax(i);%
end
lambda_min=min(Lambda_min);
lambda_max=max(Lambda_max);
lambda_min=lambda_min';
lambda_max=lambda_max';
for i=1:no_part
part(i)= unifrnd(lambda_min,lambda_max);%Generate random numbers wthn rnge
end
%initializing pso
Pbest=zeros(1,no_part);
vel_max=(lambda_max-lambda_min)/10;
for i=1:no_part
vel(i)= unifrnd(-vel_max,vel_max);%generate random values within range given
end
c1=2;% cognitive behaviour factor(pBest)
c2=2;% social behaviour factor(gBest)
psi=c1+c2;
K=2/abs(2-psi-sqrt(psi*psi-4*psi));
Gbest=0.0;
P=zeros(no_part,no_units);
for iter=1:itermax
for i=1:no_part
for k=1:no_units
temp=0;
for j=1:no_units
if j~=k
temp=temp+B(k,j)*P(i,j);
end
end
end
```

```
%inequality
temp=2*temp;
for j=1:no_units
Nr(j)=1-(alpha(j)/part(i))-temp;
Dr(j)=(beta(j)/part(i))+(2*B(j,j));
if P(i,j)>pmax(j)
P(i,j)=pmax(j);
end
if P(i,j)<pmin(j)
P(i,j)=pmin(j);
 end
end
%determining of losses
P_loss=0;
for k=1:no_units
for j=1:no_units
P_loss=P_loss+(P(i,k)*B(k,j)*P(i,j));
end
end
%generations
Pgen(i)=0.0;
for j=1:no_units
Pgen(i)=Pgen(i)+P(i,j);
end
%error evaluation
error(i)=abs(Pgen(i)-PD-P_loss);
fit(i)= 1.0/(100.0+abs(error(i))/PD);
if Pbest(i)<fit(i)
Pbest(i)=fit(i);
Pbest_part(i)=part(i);
end
%pbest and gbest positions
if Gbest<Pbest(i)
Gbest=Pbest(i);
Gbest_part=Pbest_part(i);
end
%weighting factor
Wmin=0.4;
Wmax=0.9;
W=Wmax-((Wmax-Wmin)*iter/itermax);
%new velocity
vel(i)=K*(W*vel(i)+c1*rand()*(Pbest_part(i)-part(i))+c2*rand()*(Gbest_part-part(i)));
if abs(vel(i))>vel_max
if vel(i)<0.0
vel(i)=-vel_max;
end
if vel(i)>0.0
vel(i)=vel_max;
end
end
%position update
tpart=part(i)+vel(i);
for k=1:no_units
ttemp=0;
for j=1:no_units
if j~=k
ttemp=ttemp+B(k,j)*P(i,j);
end
end
end
```

```
%optimization
ttemp=2*ttemp;
for j=1:no_units
Nr(j)=1-(alpha(j)/tpart)-ttemp;
Dr(j)=(beta(j)/tpart)+2*B(j,j);
tp(j)=Nr(j)/Dr(j);
if tp(j)>pmax(j)
tp(j)=pmax(j);
end
if tp(j)<pmin(j)
tp(j)=pmin(j);
end
end
tP_loss=0;
for k=1:no_units
for j=1:no_units
tP_loss=tP_loss+(tp(k)*B(k,j)*tp(j));
end
end
tpgen=0.0;
for j=1:no_units, tpgen=tpgen+tp(j);
end
terror=tpgen-PD-tP_loss;
Error(iter)=terror;
tfit= 1.0/(1.0+abs(terror)/PD);
if tfit>fit(i)
part(i)=tpart;
Pbest(i)=tfit;
Pbest_part(i)=part(i);
end
if Gbest<Pbest(i)
Gbest=Pbest(i);
Gbest_part=Pbest_part(i);
end
end
if abs(terror)<0.01
break;
end
end
fprintf('\nUNCERTAINTY TREATMENT IN ECONOMIC DISPATCH WITH RENEWABLES \n');
fprintf('\n Problem converged in %d iterations\n',iter);
for j=1:no_units
fprintf('\n Thermal generator(%d)= %g MW',j,tp(j));
end
fprintf('\n Solar generator=%g MW', solar_a);
fprintf('\n Wind generator= %g MW', wind_a);
fprintf('\n Total Power Generation = %g MW\n',sum(tp)+wind_a+solar_a);
fprintf('\n Total Power Demand = %g MW',pd);
fprintf('\n Total Power Loss = %g MW\n',tP_loss);
%RENEWABLE ENERGY
 Cwj = 1.75;      %initializing Wind Cost coefficient
dw = abs(solar_a-solar_p);
if dw <= 5
   Crwj = 1.5;
   Cpwj = 3;
end
if dw <= 10
   Crwj = 2;
   Cpwj = 4;
end
```

```
if dw <= 15
   Crwj = 3;
   Cpwj = 6;
end
if dw <= 20
   Crwj = 4.5;
   Cpwj = 6.5;
end
if dw >20
   Crwj = 7;
   Cpwj = 8.5;
end

%Wind_Fuel_Cost = (Cwj*(wind_a))+ abs(Crwj * (wind_a-wind_p))+ abs(Cpwj *(wind_p-wind_a));
Wind_Fuel_Cost = (Cwj*(wind_a))+ Crwj * dw+ Cpwj *dw;

% COST OF SOLAR GENERATION
Cpvi = 2.5;        %initializing Solar Cost coefficient

ds = abs(solar_a-solar_p);
if ds <= 5
   Cppvi = 1.5;
   Crpvi = 3;
end
if ds <= 10
   Cppvi = 2.5;
   Crpvi = 4;
end
if ds <= 15
   Cppvi = 5.5;
   Crpvi = 6;
end
if ds <= 20
   Cppvi = 6.5;
   Crpvi = 7.5;
end
if ds >= 20
   Cppvi = 8;
   Crpvi = 8.5;
end;

%Solar_Fuel_Cost = (Cpvi *(solar_a))+ abs(Cppvi * (solar_a-solar_p))+ abs(Crpvi *(solar_a-solar_p));

 Solar_Fuel_Cost = (Cpvi *(solar_a))+ Cppvi * ds+ Crpvi *ds;

total_cost=0.0;
for j=1
Thermal_Fuel_cost(1)=c(j)+b(j)*tp(j)+a(j)*tp(j)*tp(j);
end
for j=1
fprintf('\n Thermal Fuel cost of Gen.(%d)= %g $/Hr',j,Thermal_Fuel_cost(1));
end
for j=2
Thermal_Fuel_cost(2)=c(j)+b(j)*tp(j)+a(j)*tp(j)*tp(j);
end
for j=2
fprintf('\n Thermal Fuel cost of Gen.(%d)= %g $/Hr',j,Thermal_Fuel_cost(2));
end
for j=3
Thermal_Fuel_cost(3)=c(j)+b(j)*tp(j)+a(j)*tp(j)*tp(j);
```

```
end
for j=3
   fprintf('\n Thermal Fuel cost of Gen.(%d)= %g $/Hr',j,Thermal_Fuel_cost(3));
end
for j=4
Thermal_Fuel_cost(4)=c(j)+b(j)*tp(j)+a(j)*tp(j)*tp(j);
end
for j=4
   fprintf('\n Thermal Fuel cost of Gen.(%d)= %g $/Hr',j,Thermal_Fuel_cost(4));
end
for j=5
  fprintf('\n Solar Cost of Gen.(%d)= %g $/Hr',j,Solar_Fuel_Cost);
end
for j=6
  fprintf('\n Wind Cost of Gen.(%d)= %g $/Hr',j,Wind_Fuel_Cost);
end

Total_Thermal_Fuel_Cost=Thermal_Fuel_cost(1)+Thermal_Fuel_cost(2)+Thermal_Fuel_cost(3)+Thermal_Fue
l_cost(4);
  total_cost=total_cost+Total_Thermal_Fuel_Cost+Wind_Fuel_Cost+Solar_Fuel_Cost;

fprintf('\n Total fuel cost= %g $/Hr\n',total_cost);
fclose('all');
```

At 50% penetration level of RE the code was the same the only part that was changed is shown below

```
no_units=3; %Number of thermal units
pd=input ('Enter the value of demand  in MW = ');
wind_a1=input('Enter the value of available wind Power from gen 1 in MW=');
while(wind_a1 > 40)
   fprintf('The value exceeds the gnerator capacity;it should be less than 40');
   wind_a1 = input('\nEnter the available wind Power from gen 1 in MW=');
end
wind_p1=input('Enter the wind predicted Power from gen 1 in MW=');
while(wind_p1 > 40)
   fprintf('The exceeds the gnerator capacity;it should be less than 40');
   wind_p1 = input('\nEnter the available wind Power from gen 1 in MW= ');
end
wind_a2=input('Enter the value of available wind Power from gen 2 in MW=');

while(wind_a2 > 20)
   fprintf('The value exceeds the gnerator capacity;it should be less than 20');
   wind_a2 = input ('\nEnter the value of available wind Power from gen 2 in MW= ');
end
wind_p2=input('Enter the value of wind predicted Power from gen 2 in MW=');
while(wind_p2> 20)
   fprintf('The value exceeds the gnerator capacity;it should be less than 40');
   wind_p2 = input ('\nEnter the value of available wind Power in MW= ');
end
solar_a=input('Enter the value of available solar Power in MW=');
while(solar_a > 30)
   fprintf('The value exceeds the gnerator capacity;it should be less than 30');
   solar_a = input ('\nEnter the value of available solar Power in MW= ');
end
PD=(pd-wind_a1- wind_a2-solar_a);
pmax=[200 200 50 20 40 30]; %maximum generation
pmin=[80 20 10 0 00 00]; %minimum generation
```