MODELING AND ASSESSMENT OF ENERGY MANAGEMENT CHALLENGES FOR DISTRIBUTED WIND FARMS

By

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ABSTRACT OF THE THESIS

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The advent of deregulation of electricity to meet the increasing load demands and the call for more efficient sustainable energy practices, have dominantly amplified the need for incorporation of renewable energy systems in today's power networks. Wind energy systems can be a leading source of renewable energy with adequate exploration into the uncertainty surrounding its dependency on climatic changes.

The aim of the thesis is to analyze the potential of energy savings through the inclusion of wind energy in the already existing network. Wind, in conjunction with the conventional power generators, needs to meet the continuously varying load demand while considering the technical real-time constraints imposed by the system. The output from conventional generators is deterministic while in the case of wind, due to its

stochastic nature, the output is intermittent. This is modeled by Weibull probability distribution function due to its discontinuous behavior.

The first step involved in planning and operating the power system with a wind farm, is providing a load flow solution. Among various techniques, Newton-Raphson is one of the most widely used methods to calculate the total generation and line losses involved in transmission. The next step is to use the load flow solution to optimize the economic dispatch of the real power in the system. The optimal allocation of the generated power among conventional and wind units are based on the operating cost of the units and the cost of wind power. The cost of wind units accounts for various scenarios such as the penalty cost due to overestimation and underestimation of wind power and the direct cost pertaining to the issue of ownership of the wind generators.

The research involved in this thesis provides a novel model for power system operation combining conventional and renewable energy along with remote energy storage systems, which are validated effectively for the proposed system. Furthermore, with the help of the Newton-Raphson load flow technique followed by economic dispatch, an efficient and economical solution is provided to determine the optimal output at the lowest cost while keeping the transmission and other operational constraints in check.

Acknowledgement

First and foremost, I would like to express my sincerest and deepest gratitude to my advisor, Professor Hana Godrich, who has supported and guided me throughout my thesis with utmost patience. Her keen perspective, acute engineering insights, wide knowledge and constructive comments has been of been great value for my thesis.

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CHAPTER 1:

Introduction

1.1. The Need for Electricity and the Growing Importance of Renewable Energy

One of the most important factor for development of social and economic growth today's modern world is the availability of electricity [3] While Graph 1 depicts the relationship between energy consumption and prosperity for various countries around the world, Graph 2 depicts the relation between the 2 factors from 1960 to 2010 in the US. [4] Thus it is clear that over the past 50 years, the Gross Domestic Product (GDP) per capita has increased with an increase in the electricity consumption per capita. Should we continue this upward trend, it can be expected that this consumption will only continue to increase. The main cause behind this assumption is the constant pressure on power generation utilities to meet the demands of a growing world population and growth in industrial development to meet their electrical demands.

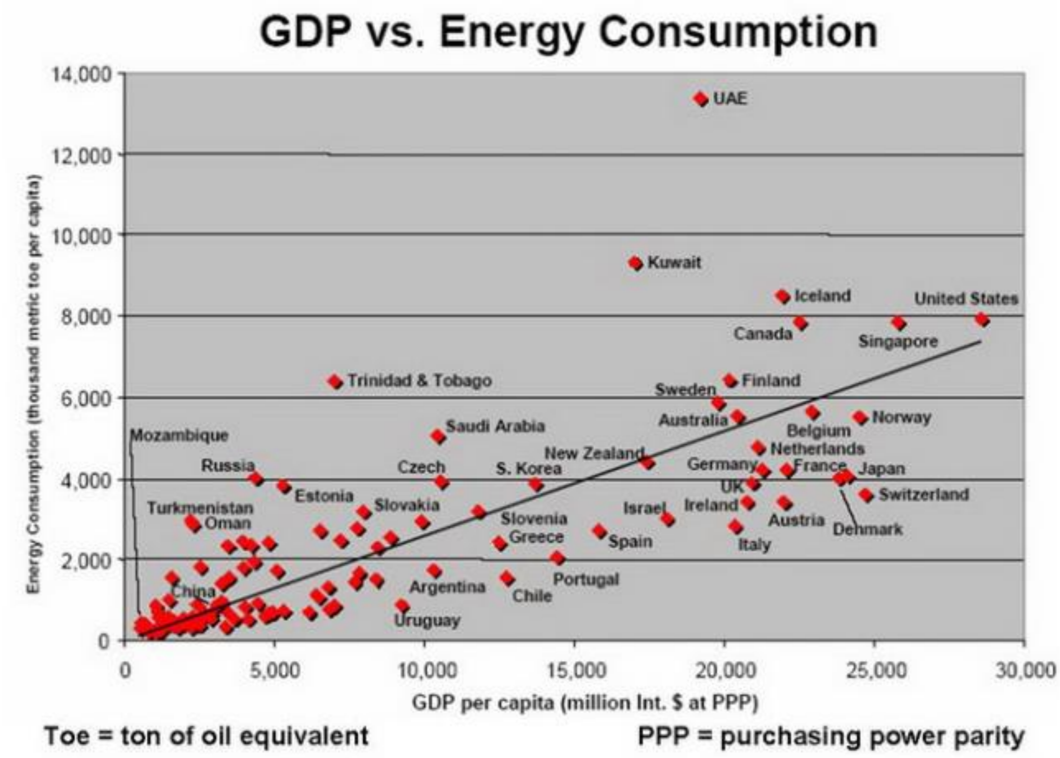


Figure 1 Movement of GDP with change in Energy Consumption in the World

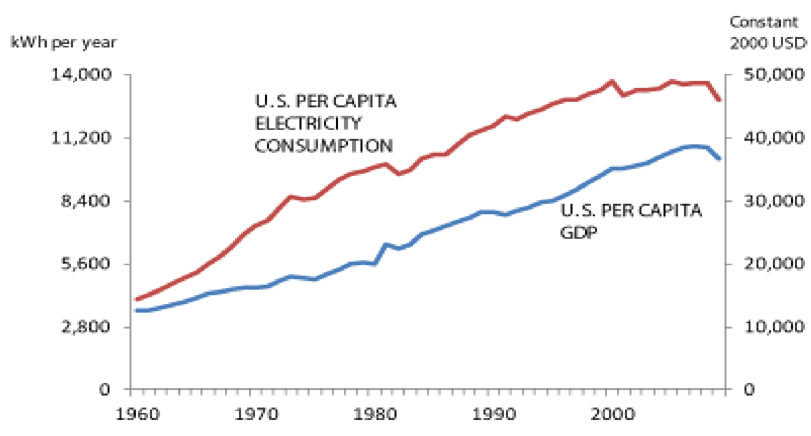


Figure 2 US Electricity Consumption and Per Capita GDP Growth

The above graph provides us with important data from the EIA which represents the consumption of electricity. Although the numbers constantly keep varying and follow a stochastic pattern, nevertheless they provide an annually estimated arrangement. Thus, we notice that the annual consumption of energy resources in the United States has been at an all-time high and is projected to increase through 2040, in all the three sectors (commercial, residential and industrial). In 2015, US consumed almost 3.7 trillion kilowatt-hours (kWh) of energy and it's projected that the total sales would rise 0.7% annually through 2040. [5]

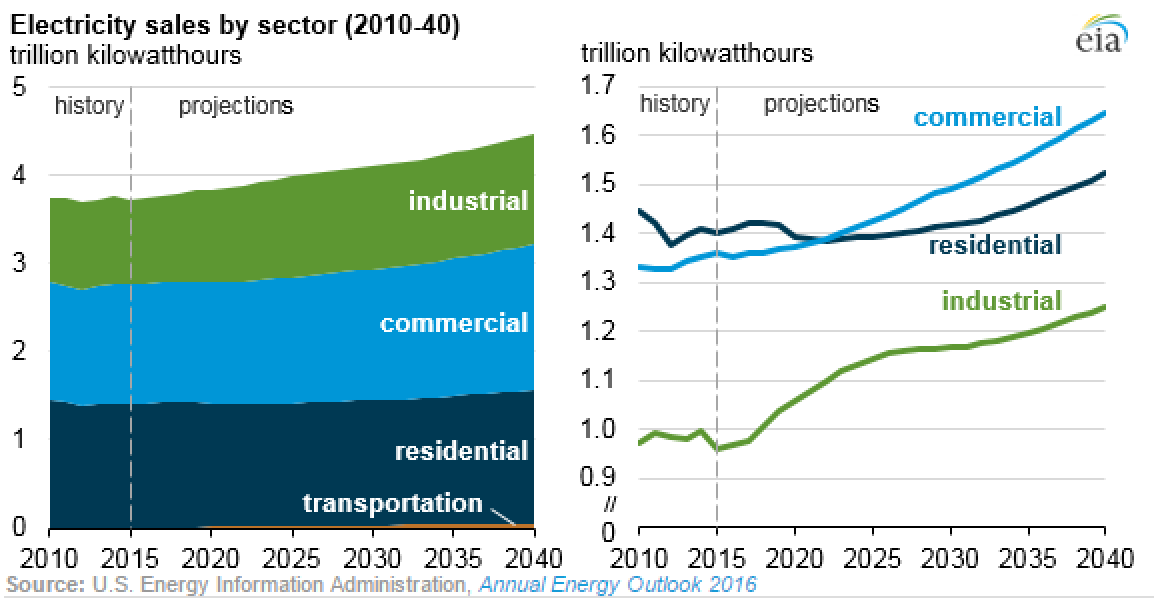


Figure 3 Electricity Sales by Sector

1.2. Urbanization and Mega-cities

Over the past decades, cities around the world have experienced enormously unprecedented economic development. This in turn has contributed to a population increase through rapid and uncontrolled growth. The result has been the enhanced environmental pollution and increase consumption of energy resources.

These issues were described by Thomas L. Friedman in "*Hot, Flat and Crowded*", 2008. He discussed the improper use of energy leading to Global warming due to the increase of greenhouse gasses. As shown in Graph 4, the unequal distribution of available energy is a major contributing factor. While countries such as United States, Canada and other industrialized nations have high energy resources available at their disposal, developing nations such as Bangladesh and countries in Africa depend on developing countries for energy.

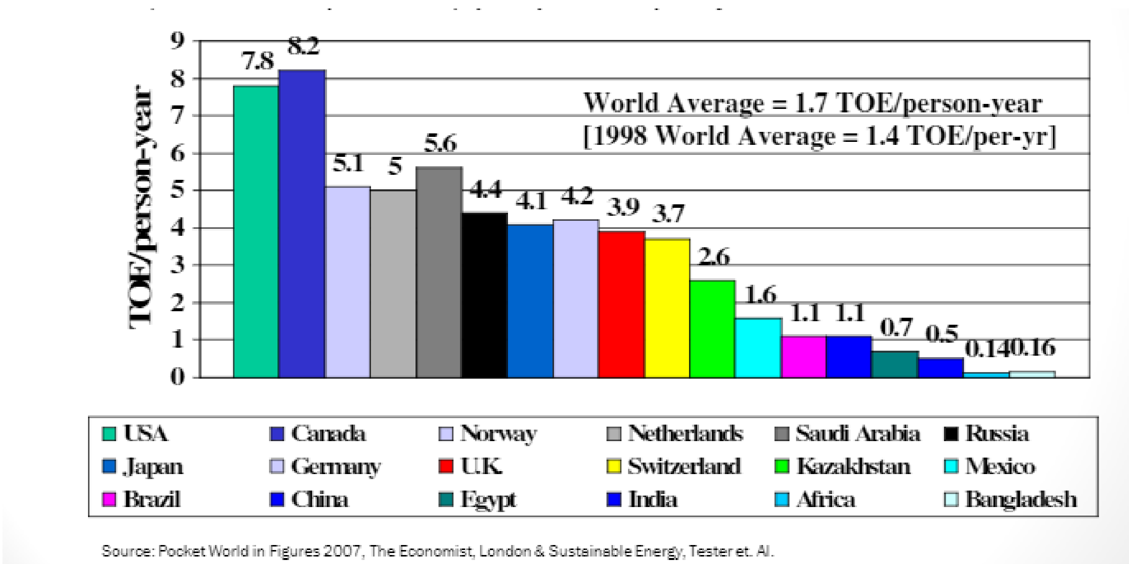


Figure 4 Distribution of Energy Across the World

1.2.1. Energy consumption

Comprehending the flow of materials and the drivers of energy in cities is vital for addressing the environmental challenges at a global scale. Accessing, sharing, and managing energy and material resources is particularly critical for megacities, which face enormous social stresses because of their sheer size and complexity.

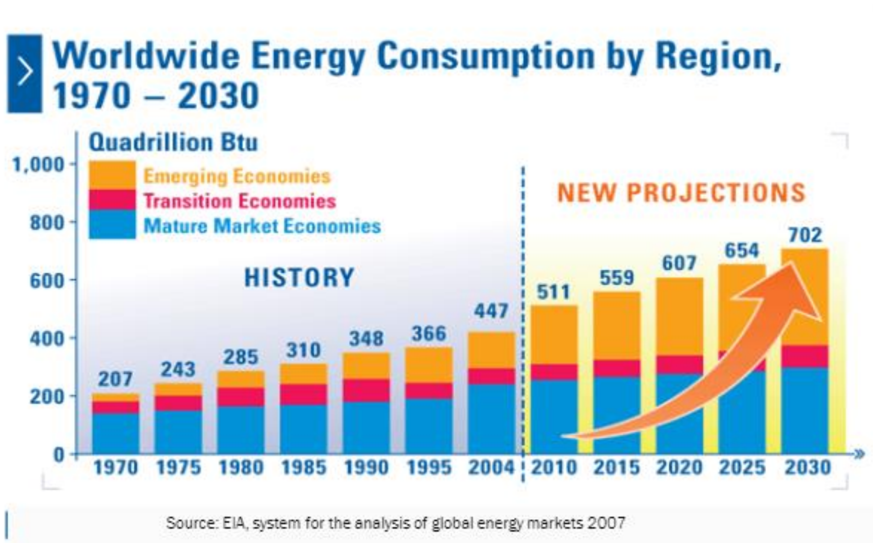


Figure 5 Energy Consumption Across the World

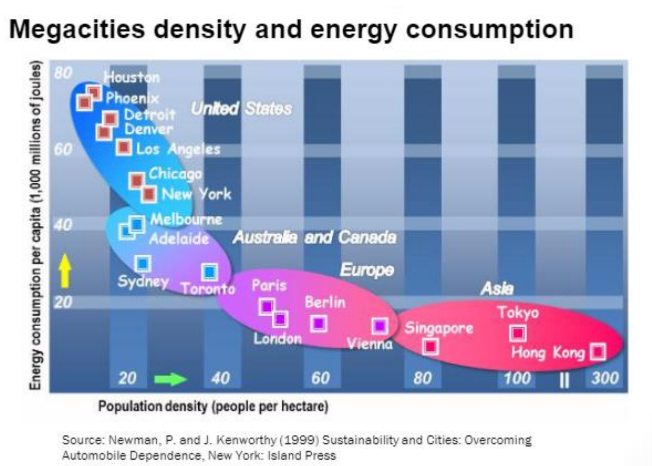


Figure 6 Energy Consumption Per Capita

1.2.2. Population explosion

In the 19th century the world population crossed the 1 billion mark. Post this, the rate of increase in population was exponential. Currently the world population stands at 7 billion. Before the 19th century the deaths were caused by critical reasons like epidemic, famine or both together. With the advancement in science and technology the health conditions improved, elimination of deadly diseases like small pox, better transportation, well connected canals for irrigation. These advancements have led to decrease in mortality rate.

As the population is rising, so is the energy demand increasing. The per capita energy needs have also increased with improvement in living conditions, increase in standard of living etc. The growth in world population has also put a tremendous strain on the energy industry so that they can meet these demand supply gap.

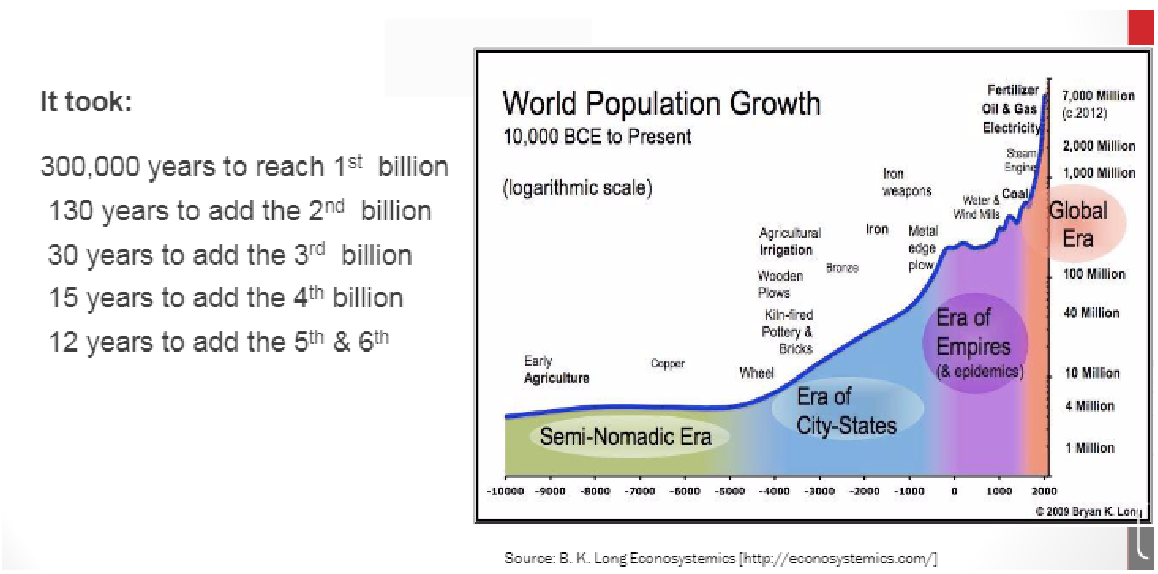
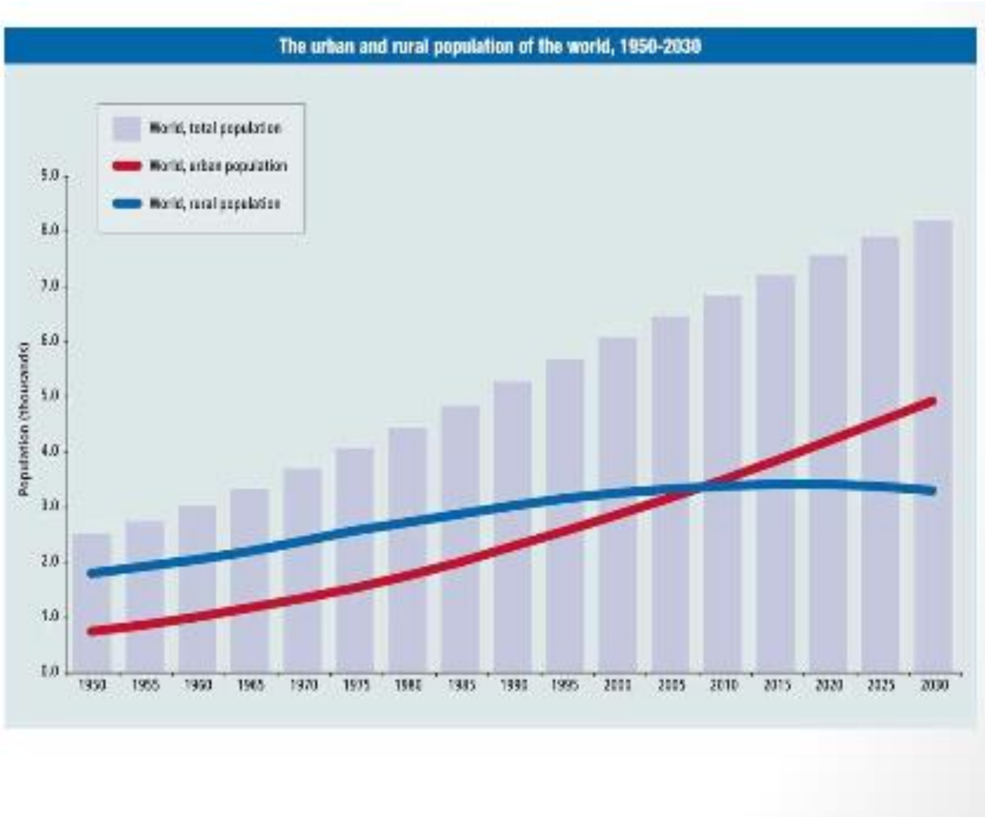


Figure 7 World Population Growth

1.2.3. Megacity trends



Source: the UN population division & International Federation of Surveyors

According to the OECD and the World Economic Forum, the contribution from the energy industries to the GDP of the United States has grown from 4% in 2009 to 5.9% in 2016. [6]Out of this, the EIA estimated that 65% was generated from fossil fuels, about 20% of nuclear energy and only 15% from the renewable resource. [7]This rising demand is a potential cause for the deterioration of the environment because of the combustion of fossil fuels to meet the energy requirements. So, in order to keep meeting the generation capacity while ensuring minimum carbon dioxide emissions, more emphasis needs to be put on renewable energy resources. Among the various renewable energy resources, wind energy has been considered by far the most promising resource. [8]

In the past two decades, wind energy has proven to be one of the fastest growing technologies. Moreover, with the increasing technological advancements, harvesting wind energy has proven to be highly reliable, profitable and efficient. As per the American Wind Energy Association (AWEA) press release, US lead the world in wind energy production, which has tremendously increased from 4.7% in 2015 to 5.6% in 2016 and is forecasted to increase to 20% by 2030. [9]

1.3. Eco-city

Socio and economic modernization throughout the world have brought about booms as nations attempt to strengthen their economic growth. These societal changes are accompanied by two major issues that nations need to address, a population growth explosion and a shortage of energy for the masses. As counties reach this point in their growth, a balance needs to be reached between nature, energy, food, water and necessities, and the economic growth of the nation. [1] The aim is to building self-sustaining cities and neighborhoods, one would be able to reduce the ecological footprint and make for a more environment friendly place. This point is coined with the term Eco-City or Sustainable City, a term coined by urban theorist and author Richard Register. He theorizes that by creating this type of environment nations would reduce water and air pollution, caused by methane, CO2, etc., while supplying its own energy, food, water and necessities.

In creating a sustainable city, the interaction between technology and human behavior is vital. Large stakeholders need to be involved in creating and running of such an infrastructure. A current example of this type of Eco-City is Sino-Singapore Tianjin

Eco City in China. It is considered a landmark project, using smart grid construction that uses wind and photovoltaic power, integrated into the micro grid. The Eco-City grid helped in reducing the fuel consumption by 1,074 tons per year and saved 5,930 tons of coal. Other new technologies such as auto-distribution, equipment on-line monitoring, intelligent scheduling and substations were adopted that improved power quality and power supply reliability. [2]

These types of ideas combined with the promotion of renewable energy are here today. Combining these technologies, along with a sustainable energy philosophy, and an increase of technological innovations that target building a viable, affordable and highly reliable renewable source are the future and will help us in creating a smart and efficient energy infrastructure.

1.4. Smart Grid

With the increasing demand for power and electricity, more power plants and transmission and distribution facilities are built to meet the needs. However, these modifications are very expensive and are hard to achieve while keeping the environmental regulations in check. So, alternatively, it’s imperative to revise the current power distribution network and harness the renewable energy such as the wind and solar power in a more efficient way. This approach can be effectively implemented through smart grid technology as a productive and profitable solution.

A smart grid, although based on the physical grid, is an electrical infrastructure that integrates renewable energy with advanced computer technology, sensor measurement, communication and control technology. [10] The primary target is to manage and monitor the energy usage by providing a sense of energy independence, which would provide the liberty to choose when and how to use the electricity. With the help of smart meters, the users would have a better knowledge about the real time pricing information of electricity during normal and peak hours which would in-turn optimize the demand and supply chain use of it.

1.4.1. Smart Grid – Motivation and Objectives

The electrical power grid that still exists today was designed almost fifty years ago. With the increasing power needs, a lot of pressure is put on these systems, which results in occasional blackouts causing interruption of services which inadvertently pose significant safety and economic threats. In such a scenario, smart grids offer a sound system that allows automatic monitoring and evaluation of the grid conditions. The various devices on the network have the capability to communicate with each other and detect and repair faults and automate rerouting if required, at the time of power line faults. This helps reduce the power outages.

Communication is also possible between the user and the power suppliers through the help of smart meters. These meters provide a means of accumulating and transmitting accurate power consumption reports with respect to the quantity of the power used at specific times of the day, which further provide information such as the real time pricing and emergency requests to lower consumption when needed.

Newer technologies have been integrated into the smart grid system that is meant to encourage consumers to invest in distributed generation system, or locally generated sources like solar panels on the rooftop of a home, to supplement the needs. [11] For example, the Pecan Street project near Austin, Texas, integrates a variety of DER (Distributed Energy Resources) technologies and the residents have not experienced a power outage in over four years. [12] Moreover, houses could install solar panels and can power their homes by its solar energy during the day, and sell any extra energy produced back to the grid.

The smart electric infrastructure presents an unprecedented opportunity to provide an efficient and reliable structure that will help in our economic and environmental growth. It is much more than just utilities and technologies, it is about providing the information and the tools to use energy judiciously.

1.5. Impact on Economy

The increase of dependence on high-quality and reliable energy delivery system has persuaded out economic security for growth to become more reliant on replenishable forms of energy. The complete deployment and integration of Smart Grid technologies in the system will most certainly assuage the pressure put on American businesses as a result of congestions, power fluctuations, failures of the present electric grid. The vital step towards improving the American economy at a global level is to increase the energy efficiency and the reliability of the system.

Several studies suggest that the optimization capacity provided by the smart grid system will proportionally improve the consistency in energy delivery, reduce waste and lower the business costs. [13]Although, the impact of power blackouts and power inconsistency may affect residential areas on a minor level, at an industrial scale they could be devastating. One such overwhelming power outage occurred in southern California in 2003 when the blackout created a loss of approximately $75 billion dollars and resulted in the collapse of one of the largest energy company in the state, Enron Corporation [14]. In such a scenario, Smart Grid system will provide the energy security required to sustain an energy dependent economy by optimizing the system and ensuring the electrical normalcy is returned within a short frame of time or avoiding the disruption completely.

Moreover, Smart Grid is helping in the creation of a new market which is gaining popularity and momentum. This involves developing energy efficient and intelligent appliances, smart meters and passenger vehicles. Tis would in turn pave a path to new and enhanced communication procedures and capabilities. According to Department of Energy, shift to Smart Grid system will create a market for $100 billion in smart technologies [15]. Consecutively, an additional GDP of $2 trillion dollars will be created. Therefore, adoption of the Smart Grid has made the market competitive, secure and given birth to numerous new market opportunities.

CHAPTER 2:

Wind Energy

2.1. Historical Background and Development of Wind Turbines

Wind energy is considered to be one of the most abundant renewable resources and for centuries man has tried to harvest it. It has been predicted that humans have tried to harness wind energy for about 4000 years in different aspects of their daily work such as powering sailing ships. The Windwheel of Heron of Alexandria which used the energy of the passing gusts of wind was one of the first known instances of wind-powered machinery. [16] As early as the 17th century BC, the emperor of Babylonian, King Hammurabi used wind-powered scoops for the irrigation of the plains in Mesopotamia. [17] However, the Panemone windmills were the first practical wind-powered machinery that was built in Sistan, a region between Afghanistan and Iran, around the 7th century. [18] They were vertical axle windmills with braided mats utilized to generate drag to rate the device around a central axis. These windmills were used to pump water and grind grain and corn. The first wind turbine to generate electricity was built by James Blyth in

July 1887. He used the electricity to charge accumulators which were then used to power the lights in his cottage. [19]

So, though wind energy was used for electricity generation in early times, the low cost of fossil fuels, such as coal and oil, made the harvesting of the wind economically unappealing. But, with the oil energy crises of 1973 and the growing environmental concerns about the effect of fossil fuel usage, a new interest was inspired by alternative energy resources and the research on Wind Electric Systems (WES) or WECS (Wind Energy Conversion Systems) was invigorating. Thus, over the last few decades, the WECS technology has given birth to several configurations of wind turbines, which utilize various types of electric generators.

2.2. Current Status of Wind Energy

The sixth edition of the Global Wind Energy Outlook released on November 14, stated about 3.7% of the global electricity demand was met by wind power in 2015 and it was predicted that with the increasing growth of renewable sources the share could reach up to 12% by the year 2020. The Renewable 2017 Global Status Report states that in 2016, almost 55GW of wind power capacity was added which brought the total global installed capacity to 487GW. By the end of the year, more than 90 countries had some kind of commercial power activity.

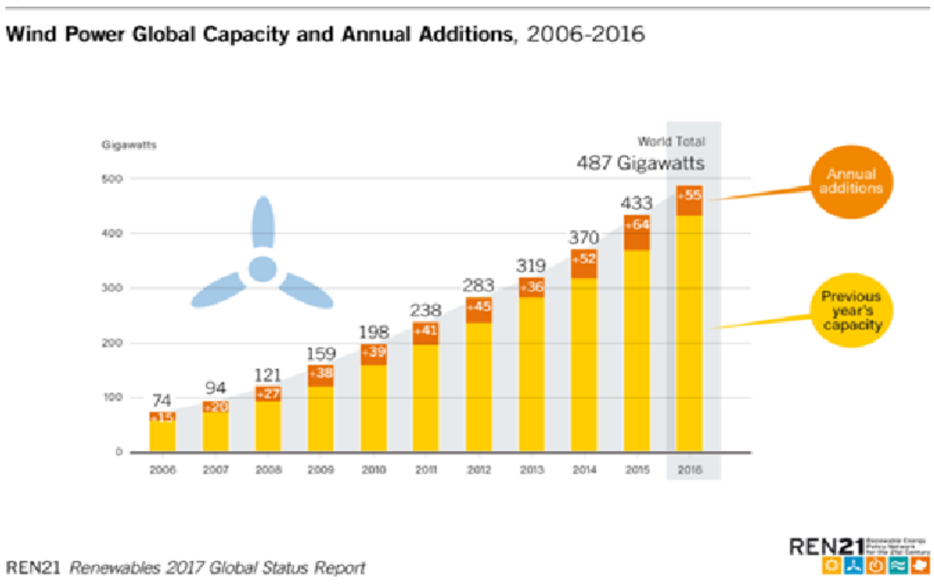


Figure 8 Global Cumulative Installed Wind Power Capacity- 2006 to 2016

The above graph depicts a steady growth of installations, happening at a rapid pace until 2010. From the period of 2009 to 2013, there was an unprecedented decline in new installations which went as below as 21%. This further affected the industry wherein the sales and the profit declined incredibly. Although from 2014 onwards, the industry quickly recovered and then in 2015 the 63.5GW of new capacity was installed which brought the total to 432.9 GW. In 2016, the new installations went up by 55GW and it's predicted to be followed by 68GW in 2017 which is equivalent to an increase of 6.3%.

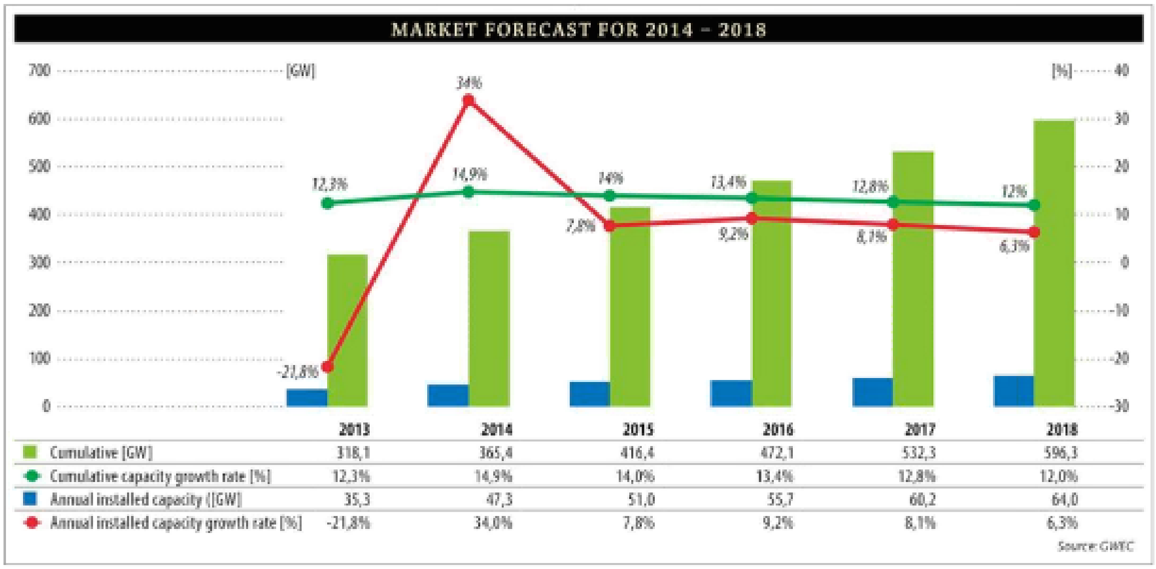
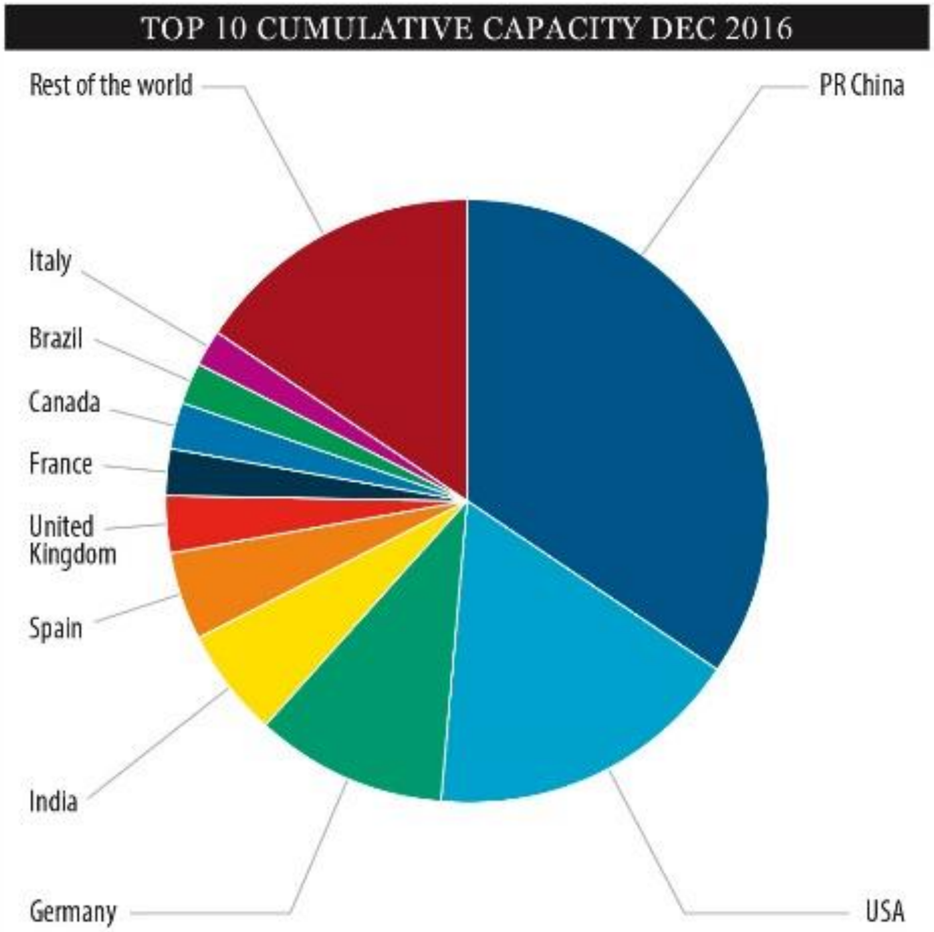


Figure 9 Cumulative Wind Power and Installation Capacity Around the World

The data indicates that from the year 2014 to 2018, even though the cumulative wind power capacity in 2013 illustrated a low growth rate of 12.3%, it increased tremendously in 2014. [20] [21]



Country	MW	% Share
PR China*	168,690	34.7
USA	82,184	16.9
Germany	50,018	10.3
India	28,700	5.9
Spain	23,074	4.7
United Kingdom	14,543	3.0
France	12,066	2.5
Canada	11,900	2.4
Brazil**	10,740	2.2
Italy	9,257	1.9
Rest of the world	75,577	15.5
Total TOP 10	**411,172**	**84**
World Total	**486,749**	**100**

Source: GWEC

Figure 10 Cumulative Capacity of Wind Energy across the World

It is also very interesting to note that 84% of the cumulative capacity (411,172 MW) was contributed by the top 10 countries i.e. China, USA, Germany, Spain, India, UK, France, Brazil, and Italy. [22]China has been experiencing a boom in wind energy and currently accounts for 34.7% share of the world's total installed capacity.

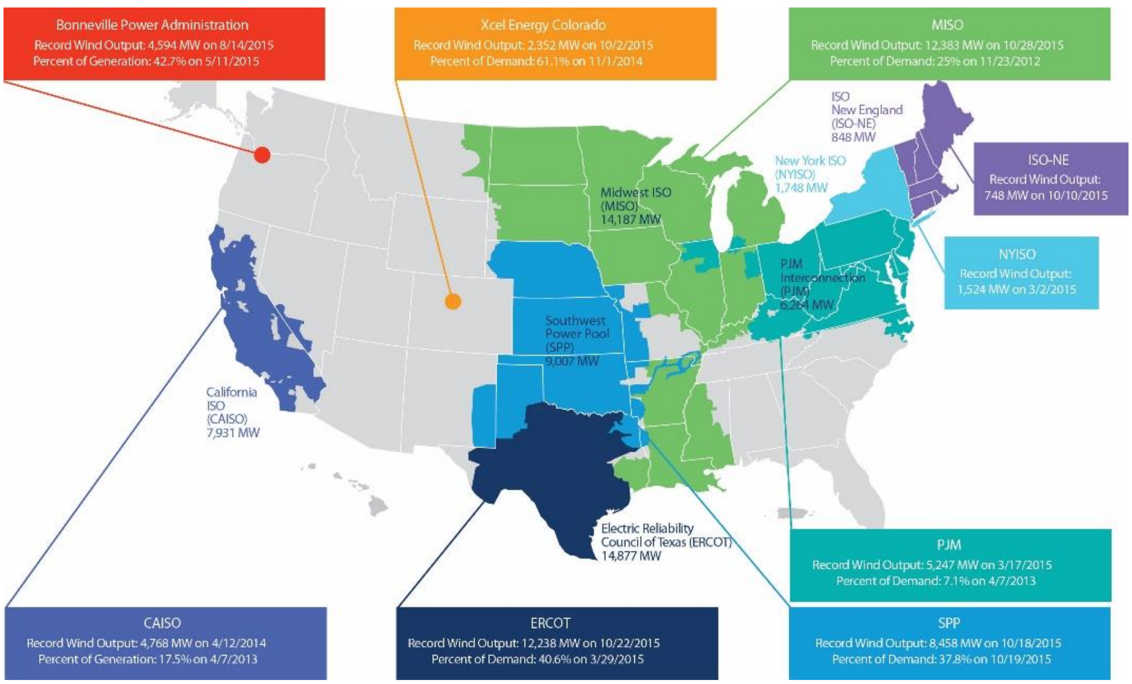


Figure 11 Consumption and Generation of WInd Energy across North America

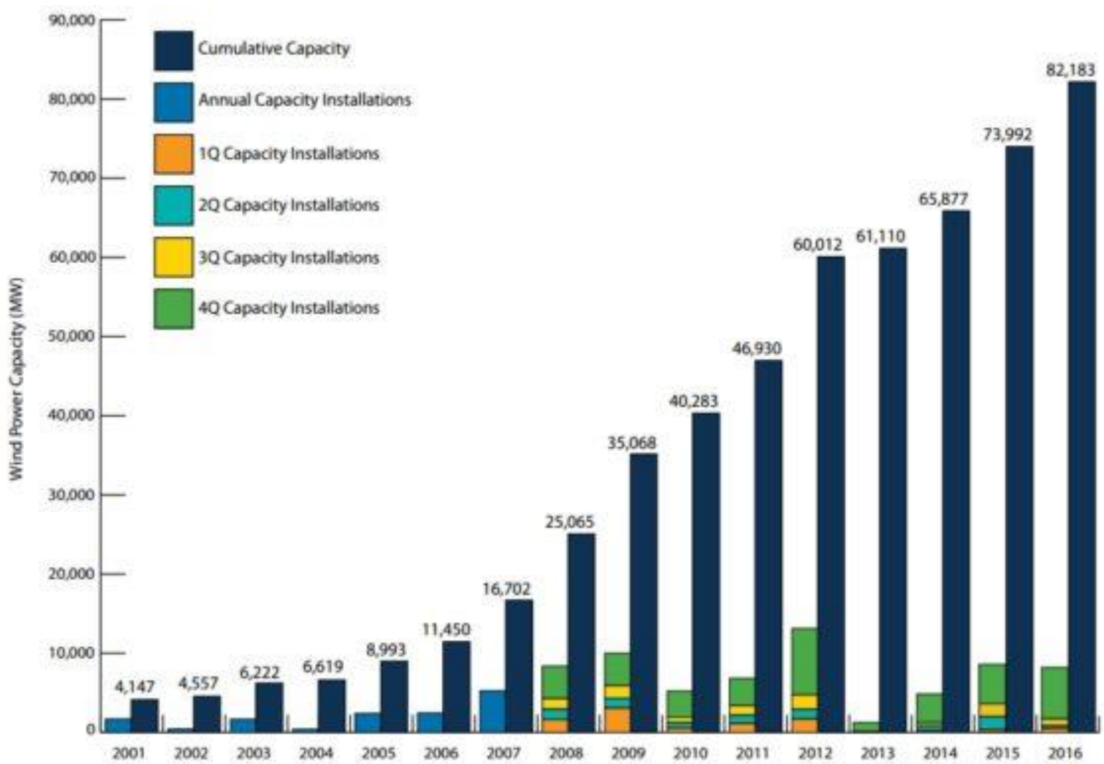


Figure 12 Wind Power Capacity in North America

The United States is also gaining momentum and has supplied around 5.55% of the total electricity generated in the country in 2015. The installed wind power capacity has doubled from 40,283 MW (2011) to 82,183 MW (2016) over a span of 5 years. According to the "Electric Power Monthly" Report by U.S. Department of Energy, Energy Information Administration, the electricity currently produced from wind power in the USA amounts to about 226.5 terawatt-hours.

A lot of initiatives have been undertaken by the US. Department of Energy through various lucrative programs. Programs such as the ‘Wind and Water Power Program’ and the federal production tax credit (PTC) sought to support and accelerate wind power deployment. Ample opportunities are provided to promote the development of small scale wind power generation industries. The federal government has issued numerous tax- based policies as incentives in order to encourage various companies to increase production and installations while ensuring that the reliability and efficiency of the turbines are constantly increasing. These incentives could be structured as tax credits, renewable electricity standards and grants at the local, state and federal levels. Apart from this, the Department of Energy also offers short and long-term loans and financial assistance to help the industries and small scale private wind farm owners to deploy clean and innovate technologies that reduce the production of harmful gases. According to the report Wind Vision: A New Era for Wind Power in the United States released by DOE, the intention is to supply 10% of the country's electricity from wind power by 2020, 20% by 2030 and 35% by the year 2050. [23]

Generally, wind turbines capture 20% to 40% of the energy of the wind. So at a site with average wind speeds of 7 m/s, a typical turbine will produce about 1,100 kWh per square meter of area per year. If the turbine's blades are 35 meters long, for a total swept area of 1,000 square meters, the power output will be about 1.1 million kWh for the year.

The power output from a wind turbine is a function of the cube of the average wind speed. In other words, if wind speed doubles, the power output increases eight times. Also, wind speed increases as the height from the ground increases. For example, if the average wind speed at 10 meters above ground is 6 meters/second (m/s), it will typically be about 7.5 m/s (25% greater) at a height of 50 meters. Finally, the power in the wind varies with temperature and altitude, both of which affect the air density. Chilly winter winds in Minnesota will carry more power, due to greater air density, than warm summer winds of the same speed high in the passes of southern California.

On the other hand, wind turbines operate over a limited range of wind speeds. If the wind is too slow, they won't be able to turn, and if too fast, they shut down to avoid being damaged. Ideally, a wind turbine should be matched to the speed and frequency of the resource to maximize power production.

Another factor in the cost of wind power is the turbines' distance from transmission lines. It is not unusual for remote areas (for example, northern Canada or Siberia) to have high average wind speeds, but be too far from major electricity demand centers (cities) for the wind power to be used economically. Considerable wind energy development has taken place in recent years in U.S. states like Indiana and Illinois, which are not as windy as North Dakota or Montana but have substantial transmission capacity.

For offshore wind projects, the economics depend on the distance from shore because turbine foundation costs increase rapidly with increasing water depth. Offshore wind turbines are generally much larger than land-based turbines. Larger rotors can be incorporated more easily because large rotor blades can easily be transported by ship.

2.3. Wind Resources

Wind energy is originated by the Sun. The uneven heating caused by the rays of the Sun heats up the surface of the Earth in an uneven manner which consequently produces the wind. Only a small fraction of the wind produced near selected locations, close enough to the surface has sufficient strength to run the wind turbines in order to generate electricity. Places such as the Great Plains regions in the mid-west, like the

North and South Dakota, if fully exploited, have the capability to generate 50% of current US electricity consumption.

2.4. Advantages and Disadvantages

With increasing environmental concerns and exponentially escalating fuel prices, the research behind the integration of wind power generation with the conventional power system is also rising. The main target is to reduce the dependency on non-renewable resources while curtailing the greenhouse gas emissions in order to ensure the protection of the environment. In addition, after the initial land and capital costs, there is no other cost involved in the generation of electricity as the cost of the fuel is zero.

However, the intermittent and unpredictable nature of the wind speed which varies during the day and according to the season makes wind power generation unreliable and rather difficult to control in terms of frequency and scheduling of generation. Also, the inability to find a cheap means of storage makes it an undesirable renewable energy that can be harnessed. Moreover, most of the fields, which have a high potential such as the Dakotas and other off-shore wind farms are not in a reasonable proximity to large population areas which in turn require the construction of expensive high-voltage transmission systems that result in large line losses.

2.5. Wind Energy and Quality / Extracting Energy from the Wind

Wind turbine power generation is based on the principle that the kinetic energy of air can be converted into rotating mechanical power of the turbine blades to generate electricity. It is therefore essential to know the amount of kinetic energy available and the amount of extractable energy from the wind.

The power, W, due to the wind velocity relative to the ground is given by the following equation:

$$W = \frac{1}{2} mV^2$$

Where:

V: wind speed

m: mass flow rate of wind through column of area A

The mass flow rate through an area A is given by:

$$m = \rho A V$$

Where:

ρ: air density

A: cross-sectional area of column

On combining the above two equations, we get:

$$W \qquad = \frac{1}{2}(\rho\, A\, V) * \; V^2$$

$$= \frac{1}{2}\rho\, A\, V^3$$

This result is highly imperative because we can deduce that the power available in a cross-sectional area of wind is proportional to the cube of the value of the wind speed. Thus, if the wind speed is doubled, there will be an eightfold increase in the wind power relative to the ground.

Mostly, the wind farms experience high wind speeds only for a few hours in a day. So, with the varying wind velocity, the spectrum-average power plays a crucial role.

$$P''(v) \;=\; \int_{0}^{\infty} \; P'(v)\, f(v)\; dv$$

Where:

$$\int_0^{\infty} f(v)\, d(v) \;=\; 1$$

Where:

f (v): frequency spectrum which is defined as the fraction of the time over a year when the wind blows at velocity v

2.6. Wind Turbine Efficiency

According to the first law of thermodynamics, Conservation of mass, the energy that comes out of the wind turbine over a period of time should equal the energy that fed into the turbine over the same amount of time. It is not possible to convert all of the kinetic energy of the wind into mechanical; some of the energy is lost in the atmosphere. Thus, the output energy is equal to the mechanical energy converted to electricity and the energy left in the air.

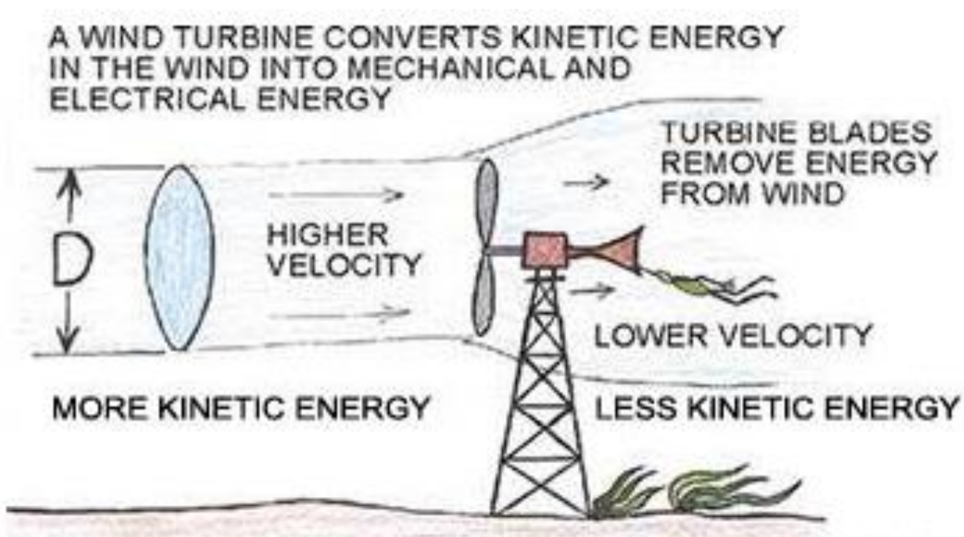


Figure 13 Conversion from Wind Energy to Electrical Energy

The above figure, [24], depicts the similar scenario. The wind enters the turbine at very high speed. The turbine with a diameter of “D” sweeps a circular area represented by the blue oval, which is the area available for production of power. The energy is affected by the velocity of the wind and the density of the air.

2.7. Factors Affecting Wind Energy:

2.7.1. Velocity of the wind

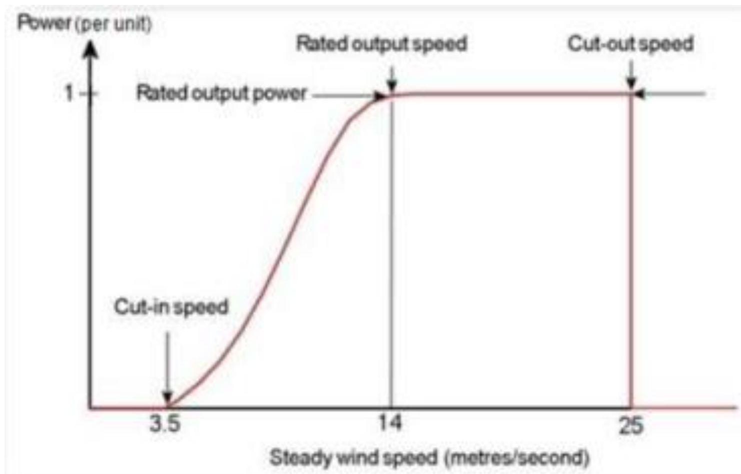


Figure 14 Steady State Wind Speed - Power Curve

Figure 7, depicts that at very low wind speeds, around 3-4m/s, the cut-in speed, the power that can be generated is too low to be utilized [25]. The wind turbine is started at cut-in speed and the power is increased till the moment, the rated speed is reached. This usually ranges from 12 m/s to 25 m/s. The amount of power produced is limited at the rated power of the turbine with stall-regulators or pitch-control systems. As soon as the wind speed exceeds 20-25 m/s, also termed as the cut-out speed, the turbines are brought to a standstill to avoid the high mechanical loads on the turbine elements.

2.7.2. Air Density

$$\boldsymbol{P'}(v) = \frac{P(v)}{A} = \frac{\rho\, v^3}{2}$$

So, when the temperature is 1°C and 1 atmosphere, the dry air has a density equal to 1.226 kg/m^3. Now, when the turbine is placed above sea level, for example, in case of Denver, which is 1.6km above sea level, the air density reduces to 0.84 kg/m^3. Moreover, factors such as water vapor in the air, also decreases the density.

2.7.3. Betz Ratio

The Betz law is analogous to the Carnot cycle efficiency in thermodynamics. It states that the maximum theoretical power that can be extracted from the wind by a wind turbine is 16/27 (59.3%) of the total kinetic energy of air flowing through the effective disk area of the turbine. This ratio, limits the upper bound on the annual energy that can be extracted at a site. Moreover, as the wind speed varies according to various factors, the annual capacity of a site is around 25% to 60% of the energy that would be generated with constant wind.

2.8 Wind Machinery and Generating Systems

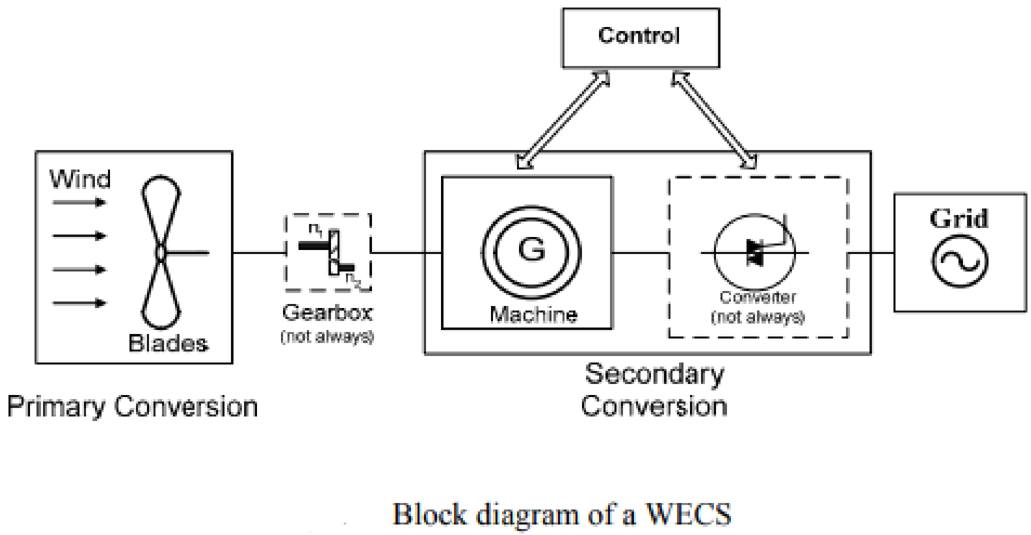
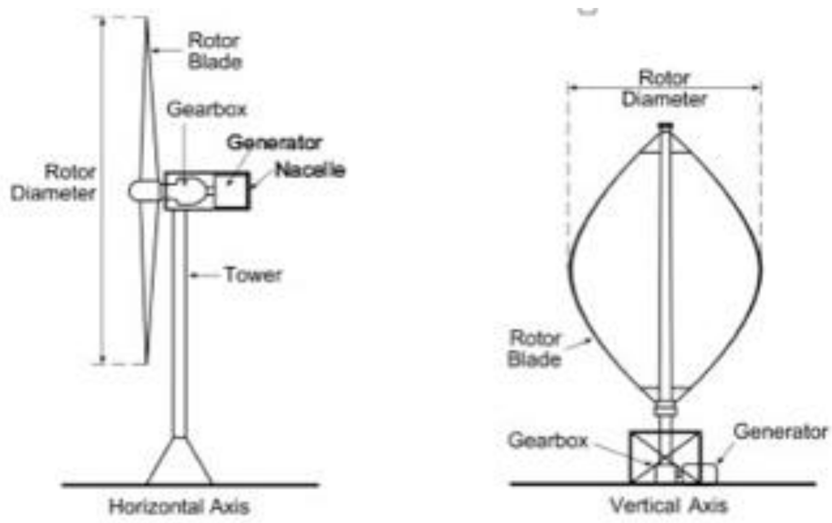


Figure 15 Wind Energy Conversion System

Figure 8, [26] shows how the energy from wind can be harnessed through a Wind Energy Conversion System (WECS). The system comprises of the wind turbine blades, a power electronic converter, an electric generator, and a required control system. Although the functional objective is to convert the kinetic energy into electric power and in turn inject this power into a utility grid, there are different WECS configurations. These are based on if they use synchronous or asynchronous machines, and stall-regulated or pitch regulated systems.

Wind turbines can be further classified according to the orientation of the axis of rotation with respect to the direction of the wind, which is vertical-axis and horizontal axis.

The figure below depicts the two type configurations. [27]



Horizontal-axis and vertical-axis wind turbines configurations

Figure 16 Wind Turbine Configurations

2.8.1 Vertical - Axis Wind Turbine

Initially, the first windmills, in small-scale installations, were of vertical structure. Some of the typical ones include Darrius rotor. They have numerous advantages and disadvantages as mentioned below.

2.8.1.1 Advantages:

- They provide easy maintenance for ground mounted generators
- No yaw control is required so they can receive wind from any direction
- The simplicity of the blade design promoted low cost of fabrication

2.8.1.2 Disadvantages:

- They need a generator to start the motor, so they don't self-start
- The efficiency is lower and the blades lose energy as they out of the

2.8.2 Horizontal- Axis Wind Turbine

These comprise the most common design of the modern turbines. They are mounted on towers, which raise the turbine above the ground to intercept stronger winds in order to harness more energy.

2.8.2.1 Advantages:

- The efficiency is high
- The cost to power ratio is low
- The blades are turned with more ease, thereby reducing the wear and tear over the years.

2.8.2.2 Disadvantages:

- The need to mount the generator and gearbox on the tower, restricts the service
- The design is more complex as a yaw or tail drive has to be incorporated

2.9 Major Components of the Turbine

One of the most common configurations is a 3-blade horizontal-axis turbine for large grid-connected turbines. The turbine comprises of four major components: Foundations, Tower, Nacelle, Blades, Hub and Transformer (step up 690V to MV) [28].

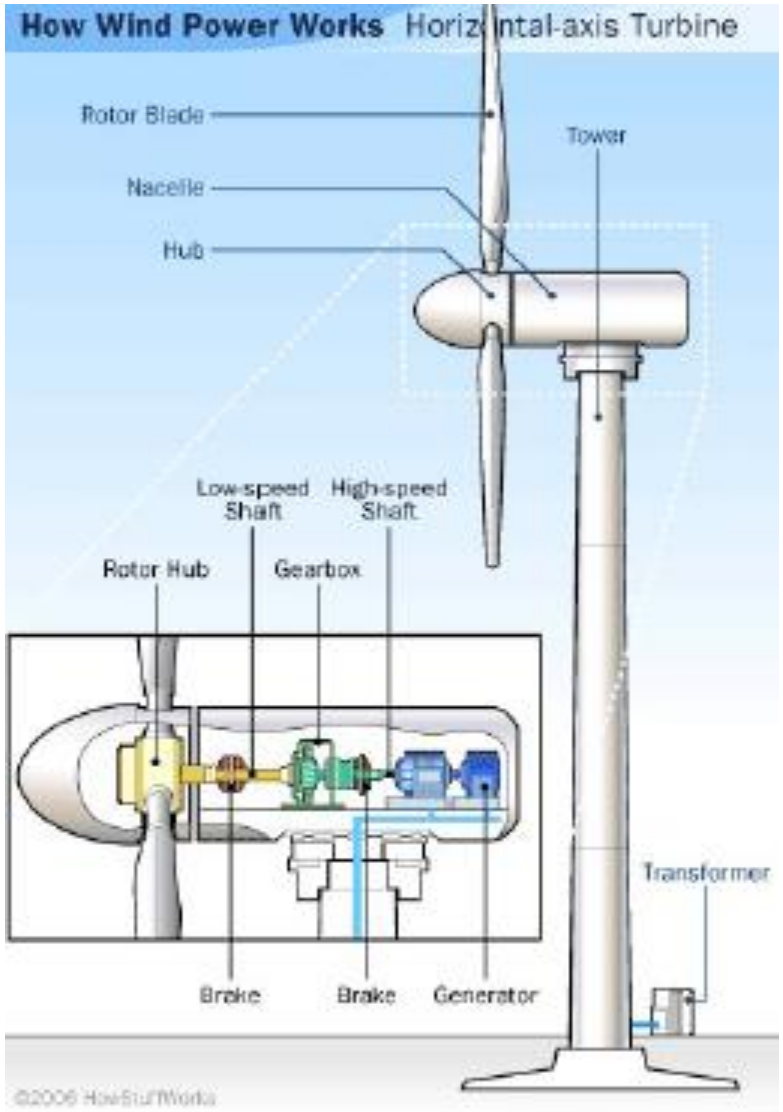


Figure 17 Horizontal-Axis Turbine Parts

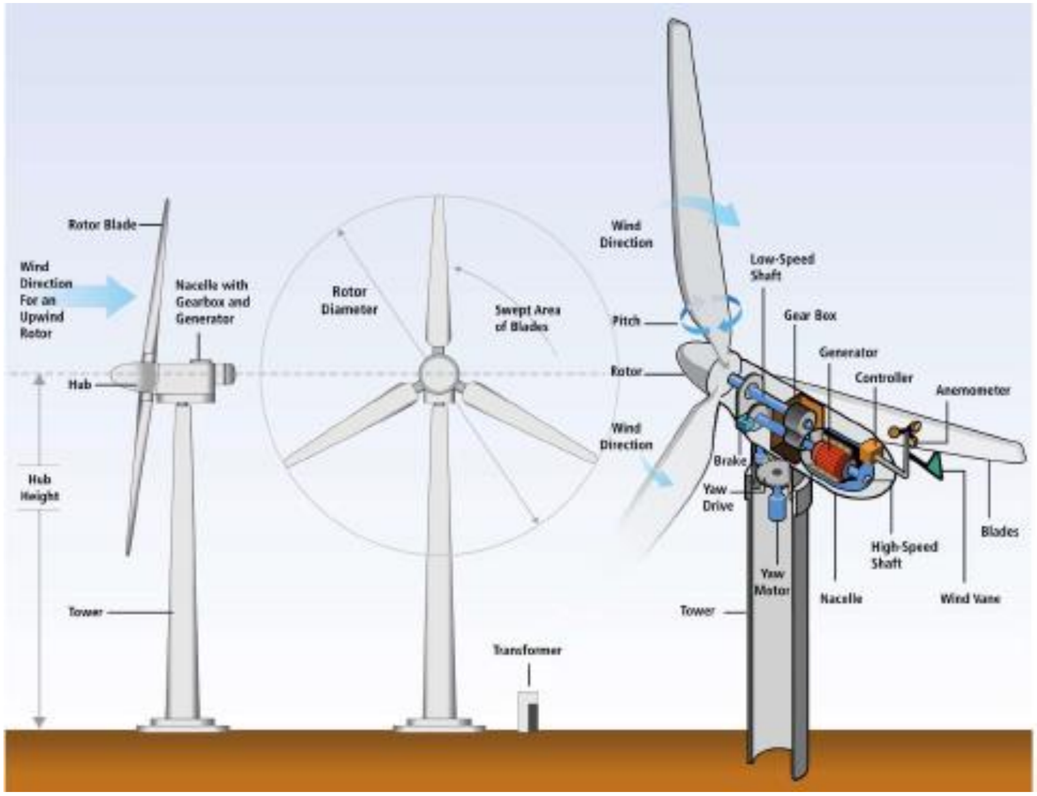


Figure 18 Turbine Components

2.9.1. **Rotor:** It is also called the hub. It connects the blades to the gear box and the power generation train within the nacelle.

2.9.2. **Nacelle:** It is an enclosure mounted on top of the tower. It contains the electrical and mechanical components, namely the gear box, controller, the brake, the generator, the high speed shaft and the yaw mechanism. It comprises of

2.9.2.1. Gearbox: The gearbox is used to connect the low-speed shaft to high-speed shaft to increase the rotational speed of the shaft to match the required rotation speed of the generator, to produce electricity optimally.

2.9.2.2. Generator: An induction generator, doubly-fed induction generator or asynchronous generator converts the mechanical energy into electrical energy. The synchronous generators require lesser rotational speed and can be operated without the gearbox.

2.9.3. **Tower**: They are tubular steel structures made from concrete or steel lattice that support the rotor and the nacelle. Towers enable the rotor to be raised high in the air where the blades would be exposed to stronger winds. They are made up of several sections of varying heights

2.9.4. **Blades**: Most turbines are comprised of two or three blades, of 30-50 meters length. These rotor blades need to be light and durable and so are made of composite material such as fiberglass and vacuum resin infusion.

2.9.5. **Controller**: The controller is used to start the turbine when the wind reaches the cut-in speed and shuts it off when the cut-off speed is reached.

2.9.6. **Transformer:** The electric power generated by the turbines need to be delivered to the grid. The voltage need to be stepped up in order to transfer. The system consists of a large transformer for this operation.

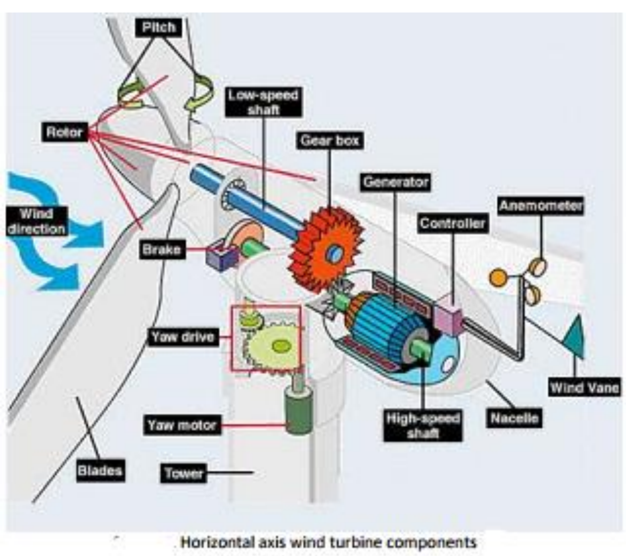


Figure 19 Components of a WInd Turbine

2.10 Integration into the Wind

Each unit of electric power generated by wind, prevents the emission of greenhouse gases, waste products and various pollutants. They are connected to an already existing grid and replace the plant whenever they are able to do so. The replace the other conventional generators which are used to back up to follow the fluctuations in power demand within the system.

One of the major economic benefits includes fuel savings that indirectly arise from the reduced need to run other generating conventional plants. In turn, lower amount of fuel is used while reducing the staff and other variable costs including plant maintenance.

The vital factors that must be taken into account while introducing wind systems into already existing electrical network include, operation and maintenance cost savings, fuel savings within the plant and the expenses from the enforced operation of the additional conventional generators at no full load conditions.

The capacity of a grid is dictated by the magnitude of demand at peak conditions. Therefore, it is vital that the WECS is able to contribute at that demand. Since wind is a very unstable power source, it sometimes doesn’t have a capacity credit. At increasing wind energy penetration levels, the relative capacity credit reduces drastically. This suggests that another wind plant needs to be added to the system with higher penetration levels to substitute the existing system.

2.11 Economics of Wind Power

Wind is a free source, so the fuel cost is zero for electricity generation. 80% of the costs are mainly based on the capital. Typically, the cost for an onshore wind farm has reached a value of $1,000/kW of installed rated capacity and in case of offshore wind farms it is about $1,600/kW. [29]The corresponding costs vary due to the variations in wind speed and locations.

The main factors regulating the wind power economics are as follows

- Investment costs like the cost required in providing the grid connection etc.
- Operation and maintenance costs
- Average wind speed
- Life of the turbine
- Discount rate provided by various entities.

Out of all the above parameters, the investment costs and the electricity produced by the turbine are vital as they are dependent on wind conditions which in turn require most apt site selection. The predicted lifetime- levelized cost of wind energy is around 4-16 c/kWe hr onshore and 15-23 c/kWe hr offshore.

The cost of wind energy is a direct function of 3 basic features, the speed of the wind, the time intervals in which the resource is available, specifically the hour, day, month or season when its effects would be most readily available.

As compared to conventional fossil fuels that are non-renewable, many economists consider wind energy as a massive indigenous power source that is safe, clean and available in abundance around the world. In contrast, resources such as, nuclear, coal, etc., are considered to have high volatile market prices, the energy provided by through wind turbines has the price volatility of zero through its lifetime.

In addition to the various wind and power forecasting techniques, the Government and the private entities can determine an estimated of the expected production for both short (48-72 hours) and long terms (5-7 days). This methodology enables them to maintain and improve system operation and reliability by reducing the operating costs and wind curtailment. [30]

The cost of wind power generation has dropped by more than 80% over the past 20 years, which has immensely helped in the growth of wind energy investments. In the early 1980's, when the first large scale wind farms were set up, wind power was sold at 30 cents per kilowatt-hour (¢/kWhr). While presently, due to the latest technological advancements and better forecasting and techniques, electricity is produced for less than 5 ¢/kWhr. Apart from this, the higher prices of fossil fuels such as coal and natural gas which are priced at $5-15 per million British Thermal Units (BTUs) are making wind power ever more competitive. [31]

The National Renewable Energy Laboratory and the U.S. Department of Energy's office of Energy Efficiency and Renewable Energy established the Database for State Incentives for Renewable and Efficiency (DSIRE) project in 1995. The project provides incentives through the Production Tax Credit (PTC) and the Investment Tax Credit (ITC). While the ITC grants invests for specific ventures such as wind projects, the PTC provides tax credits for the wholesale electricity producers from the wind energy facilities, based on the amount of generated. [32]

CHAPTER 3:

Newton Raphson Load flow and Economic Dispatch

3.1 Power Flow Analysis

Power flow analysis or load-flow study is a vital tool involving numerical analysis to determine the operating conditions of a power system in a steady state. It provides a sinusoidal steady state of the system which includes real and reactive power absorbed and generated, the voltages and the line losses. This method of analysis is widely used during the operation and planning of power distribution while designing the system. The steady state as well as the reactive power supplied by the bus is expressed through non-linear algebraic equations which involve an iterative solution methodology. The load or power flow analysis, unlike the traditional circuit analysis, uses simple notation such as one-line diagrams. This allows expansion of the system in the future as well.

3.2 Classification of Buses

A bus is a node wherein one or more loads and generators are connected. Each node or bus in the system has four variables: voltage angle, voltage magnitude, real and reactive power. Each bus, at the point of operation has two known and two unknown variables. The objective of the power flow analysis is to deduce the voltage magnitude of each bus and the angle when the loads and powers generated are pre-specified. The buses are classified as generation and load buses. The generation buses inject active and reactive power to meet the network demand and to regulate the bus voltage. The load buses consume power from the network.

The different buses are classified in order to facilitate the classification of the buses in the system.

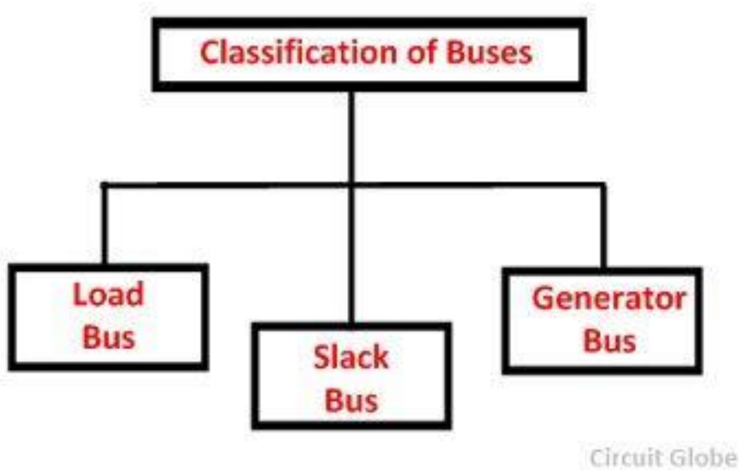


Figure 20 Classification of Buses

3.2.1 Slack Bus or Swing Bus or Reference Bus

The slack bus is a generation bus which is also called as the reference bus. It's usually the first bus in the system. It is connected to a generator of high rating relative to other generators. It is one of the important buses as it sets the reference for the angles for the rest of the bus voltages. At the time of operation, the voltage of the bus is specified and remains constant in magnitude and the angle is chosen as 0°.

3.2.2 Generator Buses or Voltage Controlled Buses

These generation buses are PV buses which determine the active power injection. Thus, the generation is manipulated with the help of a prime mover while controlling the terminal voltage through the excitation of the generator. The automatic voltage regulator keeps the voltage, $|V_i|$ of the bus constant, while the input power, P_{Gi}, is kept constant through a turbine controller. The reactive power, Q_{Gi}, supplied by the generator varies according to the configuration of the system.

3.2.3 Load Buses

In these PQ buses, there is a fixed injected active power and reactive power. But, the load will vary the powers at the bus in a random manner. During operation, complex real and reactive power values have to be assumed at the bus. Thus, the real and reactive powers, P_{Gi} and Q_{Gi} from the generators are taken as 0. The load drawn are called real and reactive power depicted as $-P_{Li}$ and $-Q_{Li}$, where the negative sign indicated that the power is flowing out of the bus. The objective is to find the bus voltage magnitude $|Vi|$ and its angle δ_i.

Bus Type	Given Variables	Unknown Variables
PQ	P_i , Q_i	V_i , δ_i
PV	P_i , V_i	Q_i , δ_i
Slack	V_i , δ_i	P_i , Q_i

Table 1 Bus Variable Values

3.3 Load Flow/ Power Flow Techniques

The electric power generated needs to be balanced to meet the load demand as it is not possible to store the AC power in a device. Moreover, with the changing load, the power system should meet the peak load and the base load demand for economic and reliable use of power. This is where power flow analysis comes to the rescue [33]. There are various solutions for performing the analysis, the three most common methods are: Gauss - Siedel method, Newton- Raphson method and Fast decoupled method. The Gauss Seidel method is based on rearranging the power flow equation in order to estimate the bus voltages. It is considered to be simpler than the Newton Raphson method. But the Newton Raphson method has been proven to have better convergence and is faster than the primary method. The third method, fast-decoupled method is an approximation of the Newton Raphson method and provides the same results for most of the power flow systems. But the Newton power flow technique is widely used due to its robustness and for the ability to process large amounts of data comprising of longer branches and buses. It is used for solving non-linear equations.

3.3.1 Load Flow Objectives

The preeminent objectives of the power flow study are as follows:

a. This analysis is essential during the addition of new networks to an already existing grid network or while building new systems in orders to meet the increased demand or introduction of renewable energy.

b. The study is very helpful in determining the optimal sites and the generation capacity.

c. The ability to calculate the voltages at the buses allows the monitoring of voltage within particular tolerance levels

d. The solution provides voltages and angles at every node and hence the power injected and power flow can be calculated at each bus and through various interconnecting power channels respectively.

e. The performance of the transformer, generator and transmission lines can be studied at the steady state condition and the transmission losses can be minimized.

f. The line flow can be determined which would in turn ensure that the line is not overloaded

3.4 Newton Raphson Load Flow Analysis

The method is used in finding roots for nonlinear equations with the help of linear approximations. Newton Raphson performs quadratic convergences in the less than 10 iterations, even for larger cases. It is less sensitive to the start point but there is a possibility that it may not converge in some cases. [34]

3.4.1 The Formulation of Admittance Matrix, Real and Reactive Power

Electric networks consist of linear elements connected by transmission lines. Initially, they are modeled as equivalent circuits based on impedance matrix (Z) or admittance matrix (Y). This impedance matrix is a crucial element for performing the fault analysis of power systems. The admittance matrix, Y, is the inverse of the impedance matrix. It is commonly used to model the electric network for solving the power flow. Y_{ii} is called self-admittance and is the sum of all admittances connected to the bus. The off-diagonal elements Y_{ij}, are called mutual admittance and include negative value of admittance between the buses (i) and (j).

Thus, the self-admittance at bus I is defined as,

$$Y_{ii} = |Y_{ii}| \angle\theta_{ii} = |Y_{ii}| \, (cos\theta_{ii} + jsin\theta_{ii}) \; = \; G_{ii} \; + \; B_{ii}$$

Similarly, the mutual admittance between buses i and j can be formulated as,

$$Y_{ij} = |Y_{ij}| \angle\theta_{ij} = |Y_{ij}| \, (cos\theta_{ij} + jsin\theta_{ij} \,) = G_{ij} + jB_{ij}$$

In order to calculate the real and reactive power entering a bus, following quantities are defined.

Let the voltage at the i_{th} bus be denoted as,

$$V_i = V_i \angle\delta_i = |V_i|(cos \; \delta_i + j \; sin\delta_i)$$

Assuming, that the power system contains n total number of buses, the current injected at bus *I* is given as,

$$I_i \; = \; Y_{i1} \, V_1 \; + \; Y_{i2} \, V_2 \; + \; \dots \dots \dots \; + \; Y_{in} \, V_n \; = \sum_{k=1}^{n} Y_{ik} \, V_k$$

The most common assumption is that the current entering the bus is considered positive and that leaving the bus is negative. So, the active power and reactive power entering the bus is positive.

The complex power at bus I will be,

$$P_i - jQ_i = V_i * I_i$$

$$= V_i * \sum_{k=1}^{n} Y_{ik} V_k$$

$$= |V_i|e^{-j\delta i} \sum_{k=1}^{n} |Y_{ik}|e^{j\theta_k} |V_k|e^{-j\delta_k}$$

$$= \sum_{k=1}^{n} |Y_{ik} V_{ik} V_k| e^{j(\theta_k + \delta_k + \delta_i)}$$

$$= \sum_{k=1}^{n} |Y_{ik} V_{ik} V_k| \cos(\theta_{ik} + \delta_k - \delta_i) + j \sum_{k=1}^{n} |Y_{ik} V_{ik} V_k| \sin(\theta_{ik} + \delta_k - \delta_i)$$

Therefore, the real and reactive powers are,

$$Pi = \sum_{k=1}^{n} |Y_{ik} V_{ik} V_k| \cos(\theta_{ik} + \delta_k - \delta_i)$$

$$Qi = \sum_{k=1}^{n} |Y_{ik} V_{ik} V_k| \sin(\theta_{ik} + \delta_k - \delta_i)$$

3.4.2 Data for the Power Flow

The real and reactive power generated at bus i can be denoted as P_{Gi} and $Q_{Gi.}$ The real and reactive power consumed at the i^{th} bus be by P_{Li} and Q_{Li}

Then the net real power injected in bus i will be denoted as

$$P_{i,inj} = P_{G_i} - P_{L_i}$$

Let the injected power that was calculated by the power flow program be $P_{i,\, calc}$. The mismatch between the calculated and the injected real values will be given by

$$\Delta P_i = P_{i,inj} - P_{i,calc} = P_{G_i} - P_{L_i} - P_{i,calc}$$

Similarly, in case of reactive power, it is

$$\Delta Q_i = Q_{i,inj} - Q_{i,calc} = Q_{G_i} - Q_{L_i} - Q_{i,calc}$$

The load flow aims at minimizing the mismatch for both real and reactive powers. Using equations (3.6) and (3.7), the real and reactive powers in equations (3.9) and (3.10) are calculated. Yet, since the magnitude and angle of the voltages isn't knows beforehand, an iterative process estimates the bus voltages and angles to calculate the mismatch. According to the method, the mismatch P_i and Q_i reduce with each iteration and the target is to help the system converge when the difference values of the buses become lesser than a known value.

3.4.3 Power Flow Method

Assuming an n-bus power system containing a total n_p number of P-Q (Load) buses and n_g number of P-V (Generator) buses such that,

$$n = n_p + n_g + 1$$

There is one slack bus in the system which is Bus 1. The relationship between the change in active and reactive power and the change in voltage magnitude and angle is provided by the following equation:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix}$$

At each iteration, a Jacobian matrix is formed and solved for the corrections. The size of the Jacobian matrix is (n + n_p -1) x (n + n_p -1). The formation of the Jacobian matrix sub-matrices is as follows:

1. Formation of J_{11}

The sub-matrix is used to represent the changes in the active power relative to the change in voltage angle. The bus voltage angle for a slack bus is fixed, so J_{11} now becomes:

$$J_{11} = \begin{pmatrix} \frac{\partial P_2}{\partial \delta_2} & \cdots\cdots & \frac{\partial P_2}{\partial \delta_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial P_n}{\partial \delta_2} & \cdots\cdots & \frac{\partial P_n}{\partial \delta_n} \end{pmatrix}$$

The matrix J_{11} is a matrix of dimension (n-1) x (n-1). The elements are derived by differentiating equation (3.6) with respect to δ.

The diagonal and off-diagonal elements can be found in the following manner:

$$\frac{\partial P_i}{\partial \delta i} = -V_i \sum_{k=1,k\neq i}^{n} |Y_{ik}V_k| \sin(\delta_i - \delta_k - \theta_{ik})$$

$$\frac{\partial P_i}{\partial \delta i} = |V_i\, Y_{ik}V_k| \sin(\delta_i - \delta_k - \theta_{ik}) \quad i \neq k$$

2. Formation of J_{12}

This submatrix has a dimension of (n-1) x n_p. It is formed by differentiating the active power with respect to the magnitude value of the voltage. Here, the magnitudes values of the voltages are fixed and the derivate terms for the same are neglected.

$$J_{12} = \begin{pmatrix} \frac{\partial P_2}{\partial |V|_2} & \cdots & \frac{\partial P_2}{\partial |V|_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial P_n}{\partial |V|_2} & \cdots & \frac{\partial P_n}{\partial |V|_n} \end{pmatrix}$$

The diagonal and off-diagonal elements can be found in the following manner:

$$\frac{\partial P_i}{\partial |V_i|} = 2V_i\, Y_{ii} \cos\theta_{ii} + \sum_{k=1,k\neq i}^{n} |Y_{ik}V_k| \cos(\delta_i - \delta_k - \theta_{ik})$$

$$\frac{\partial P_i}{\partial |V_k|} = |Y_{ik} V_k| \cos(\delta_i - \delta_k - \theta_{ik}) \quad i \neq k$$

3. Formation of J_{21}

This (n_p) x (n-1) dimension submatrix is generated by finding the partial derivate of the reactive power with respect to the voltage angle.

$$J_{21} = \begin{pmatrix} \frac{\partial Q_2}{\partial \delta_2} & \cdots & \frac{\partial Q_2}{\partial \delta_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial Q_n}{\partial \delta_n} & \cdots & \frac{\partial Q_n}{\partial \delta_n} \end{pmatrix}$$

The diagonal and off-diagonal elements can be found in the following manner:

$$\frac{\partial Q_i}{\partial \delta_i} = V_i \sum_{k=1, k\neq i}^{n} |Y_{ik} V_k| \cos(\delta_i - \delta_k - \theta_{ik})$$

$$\frac{\partial Q_i}{\partial \delta_i} = -|V_i Y_{ik} V_k| \cos(\delta_i - \delta_k - \theta_{ik}) \quad i \neq k$$

4. Formation of J_{22}

The matrix J_{22} is a (n_p) x (n_p) formed by the derivative values of the reactive power with respect to the magnitude of the voltage value. It is given by:

$$J_{12} = \begin{pmatrix} \frac{\partial Q_2}{\partial |V_2|} & \cdots & \frac{\partial Q_2}{\partial |V_n|} \\ \vdots & \ddots & \vdots \\ \frac{\partial Q_n}{\partial |V_2|} & \cdots & \frac{\partial Q_n}{\partial |V_n|} \end{pmatrix}$$

The diagonal and off-diagonal elements can be found in the following manner:

$$\frac{\partial Q_i}{\partial |V_i|} = 2V_i\, Y_{ii}\, \sin\theta_{ii} + \sum_{k=1,k\neq i}^{n} |Y_{ik}V_k| \sin\left(\delta_i - \delta_k - \theta_{ik}\right)$$

$$\frac{\partial Q_i}{\partial |V_k|} = |Y_{ik}V_k| \sin\left(\delta_i - \delta_k - \theta_{ik}\right) \quad i \neq k$$

3.5 Modified Newton Raphson Power Flow

3.5.1 Wake Effect

Wind turbines generate electricity by using wind as the fuel. So the wind leaving the turbine has lower energy content than the wind entering at the front of the turbine. Thus, there is a wake behind the turbine where the wind is turbulent and at a lower speed. [35] The wake effect is the cumulative influence on the production of energy from the wind farm.

Figure 21 Wake Effect

In case of the model generated here, in order to calculate the wind speed for the turbines in the second row, the following equation is used:

$$U_2 \;=\; U_1 K$$

$$= \; U_1 \left(1 - \left(1 - \sqrt{1 - c_t}\right) \left[\frac{D}{D + 2kX}\right]^2\right)$$

Where:

U_1: Wind speed for the first turbine,

U_2: Wind speed for the second turbine,

c_t : turbine thrust coefficient,

D: Rotor diameter,

X: Axial distance between both wind turbines,

k: wake decay constant, calculated as,

$$k = \left({}^{A}\!/_{\ln({}^{h}\!/_{z_0}}\right)$$

Wherein:

A = 0.5

h: hub height

z_0: roughness length

3.5.2 RX Bus Model with Wind Farm

The primary step involved in calculating the power flow for such an electrical network is modeling of the farm. WT is considered to operate as a RX load with equivalent impedance Z= R+jX, where R and X are Resistance and Reactance respectively of the wind turbine. The inclusion of the wind turbine while excluding the stator impedances modifies the NR power flow in the following manner:

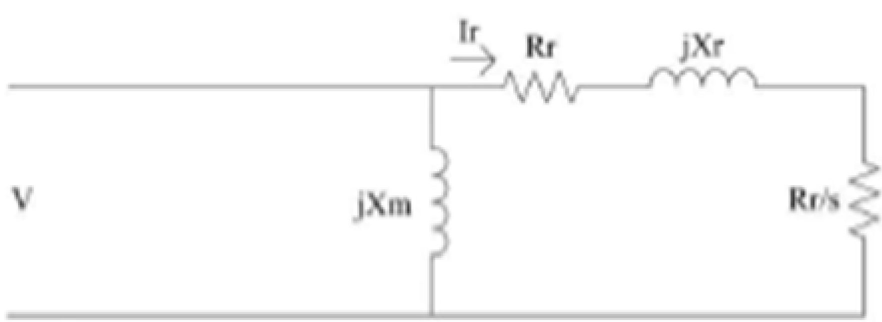


Figure 22 Generator's Equivalent Circuit Discounting Stator Impedance

R_s and X_s are disregarded and it is assumed that

$$\left(\frac{1-s}{s}\right) = \frac{1}{s}$$

Where, s is the slip of the wind turbine

$$|I_r|^2 = \frac{|V|^2}{\left(R_r \frac{s+1}{s}\right)^2 + X_r^2}$$

Mechanical power is computed by the formula:

$$P_{mech} = -|I_r|^2 \frac{R_r}{s}$$

$$= -\frac{|V|^2 R_r s}{(s+1)^2 R_r^2 + s^2 X_r^2}$$

Organizing the above equation, the slip is derived as:

$$s = -\frac{(2P_{mech}R_r + |V|^2 R_r) \pm \sqrt{\Delta}}{2\left(P_{mech}{R_r}^2 + P_{mech}{X_r}^2\right)}$$

Where,

$$\Delta = \left(2P_{mech}{R_r}^2 + |V|^2 R_r\right)^2 - 4P_{mech}{R_r}^2\left(P_{mech}{R_r}^2 + P_{mech}{X_r}^2\right)$$

The RX model is based on the steady state model with impedance Z_{wt}.

$$Z_{wt} = \frac{jX_m\left(R_r\ \frac{s+1}{s} + jX_c\right)}{R_r\ \frac{s+1}{s} + j(X_m +\ X_r)}$$

$$= \ R_1\ +\ jX_1$$

Where, R_1 and X_1 are

$$R_1 = \ \frac{{X_m}^2 R_r\ \frac{s+1}{s}}{\left(R_r \frac{s+1}{s}\right)^2 + (X_m +\ X_r)^2}$$

$$X_1 = \ \frac{X_m X_r\,(X_m + X_r) +\ X_m\left(R_r \frac{s+1}{s}\right)^2}{\left(R_r \frac{s+1}{s}\right)^2 + (X_m +\ X_r)^2}$$

The active power generated by the rotor windings and the input mechanical power can be expressed as:

$$P_{gen}\ =\ {I_r}^2 R_1$$

$$= \frac{\left(\frac{S}{|V|}\right)^2 R_r \frac{s+1}{s}\ {X_m}^2}{\left(R_r \frac{s+1}{s}\right)^2 + (X_m +\ X_r)^2}$$

$$P_{mech} = \ \frac{\left(\frac{S}{|V|}\right)^2 (1-s)\ R_r\ \frac{s+1}{s}\ \ {X_m}^2}{R_r \frac{s+1}{s}\ {X_m}^2}$$

The Jacobi matrix is then computed by the below equation

$$[J] = \frac{\partial P_{mech}}{\partial s}$$

$$\frac{\partial P_{mech}}{\partial s} = \frac{\partial}{\partial x}\left\{\frac{\left(\frac{S}{|V|}\right)^2 X_m(1-s)\, R_r\, \frac{s+1}{s}}{\left(R_r \frac{s+1}{s}\right)^2 + (X_m + X_r)^2}\right\}$$

$$= A\left\{\frac{{R_r}^2(1-4s^2 - 4s^3 - s^4) - (s^2 + s^4)(X_m + X_r)^2}{\left[{R_r}^2 + s^2(X_m + X_r)^2\right]^2}\right\}$$

Where:

$$A = \left(\frac{S}{|V|}\right)^2 {X_m}^2 R_r$$

$$S = \sqrt{P_g^2 + Q_c^2}$$

$$P_g = -\frac{|V|^2}{|Z_{wt}|} Re(Z_{wt})$$

$$Q_c = \frac{|V|^2}{|Z_{wt}|} Im(Z_{wt})$$

With all the known values, now the active power extracted from the wind can be determined in the following manner:

$$P_{wind} = ½ \rho A\, v_{wind}^{3}\, C_p$$

Where:

P: Air density,

A: Swept area of blades,

$v_{wind:}$ Wind speed

$C_{p:}$ Power coefficient, defined as

$$C_p = ½ (\lambda - 5.6)\, e^{-0.17\lambda}$$

Where:

λ: Tip speed ratio (TSR) of the wind turbine

R: length of the blade of the turbine

ω_r: Rotor speed

$$\lambda = \frac{\omega_r\, R}{v_{wind}}$$

$$= \frac{\omega_s\,(1 - s)\, R}{v_{wind}}$$

In general, due to the initially assumed slip value, the mechanical power and the wind power are not equal to each other. After the first set of iterations of the power flow calculations, if the difference between them is not zero, the new slip value is updated continuously. The process stops when $\Delta P_m \leq \varepsilon$.

$$\Delta P_m = P_{wind} - P_{mech}$$

When the two powers are not equal, the next iteration begins. The result is updated in the following manner:

$$s_{k+1} = s_k + \Delta s$$

Where:

$$\Delta s = J^{-1} \Delta P_m$$

3.5.3 Algorithm

With the inclusion of Wind farm in the system, the Newton Raphson power flow algorithm will be solved in the following manner:

1. A value of slip is assumed for the wind turbine which is equal to the rated slip. The equivalent impedance, $Z_{wt,}$ is calculated using the proposed slip value.
2. Using the corresponding Z_{wt} value, the admittance matrix is modified such that it includes the admittance of the Wind turbines.
3. After the first iteration of the original power flow with the obtained voltages, the input mechanical power is computed.
4. The wind power is calculated with the values of slip, TSR and power coefficient.
5. The difference between the two powers is found and the difference is checked against the tolerance level. If the difference is not satisfied, the slip value is updated and all the steps from Step 2 are solved. Otherwise, the iteration is stopped and the solution is printed.

3.5.4. Flow Chart:

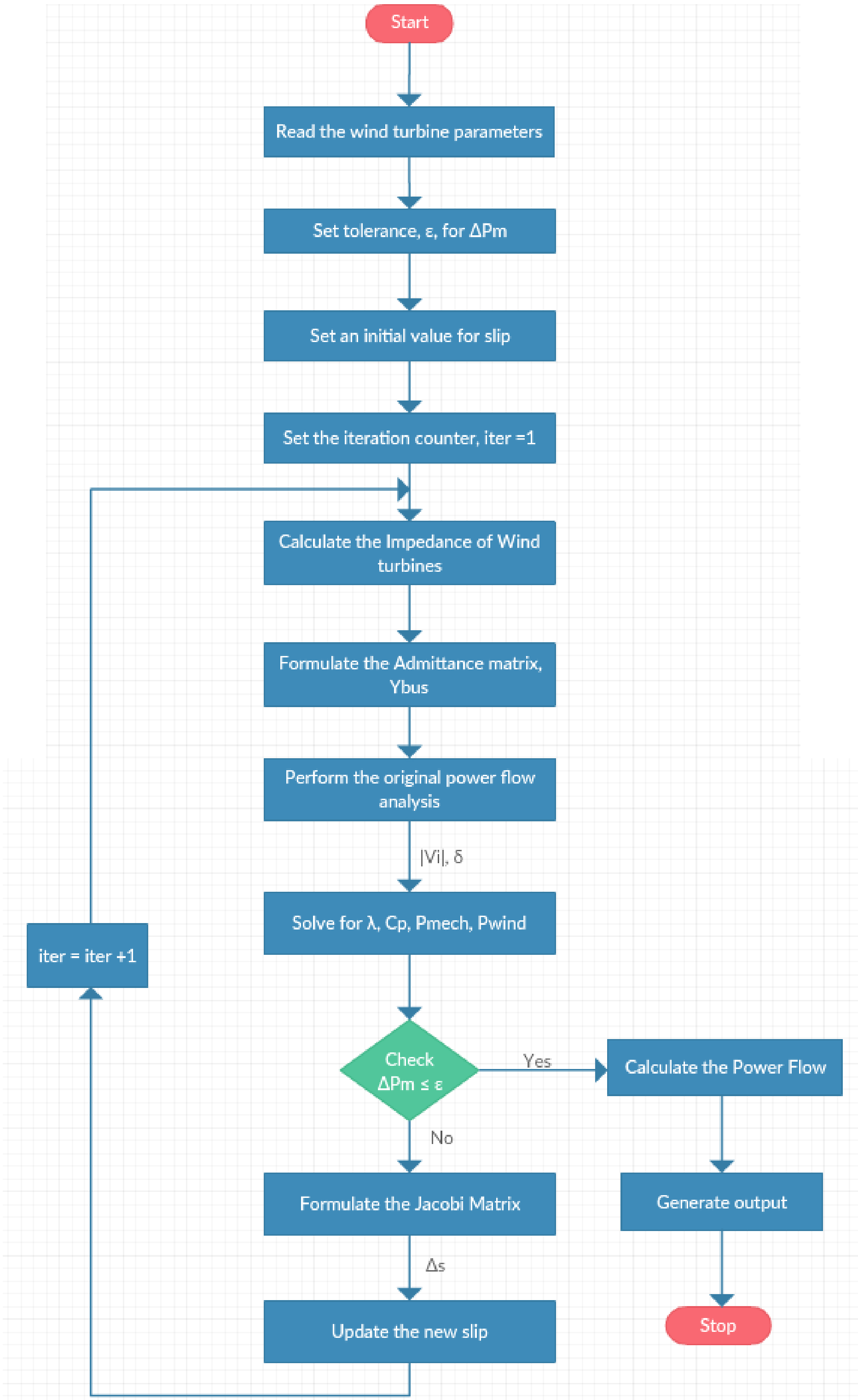


Figure 23 Flow Chart for NR Power Flow with Wind

3.6 Economic Dispatch

Any interconnected power system generally consists of three stages. The first stage is production wherein the generators produce electrical energy. This is followed by transmission of the power through transmission lines to meet the demand. The final stage is the consumption of electricity by various loads. During each of these phases, some amount of energy is lost to the environment. Thus, the main objective of a power system is to supply power to the load continuously and as economically as possible. The process of planning the power distribution and generation for each unit is done by optimizing the power flow and the economic load dispatch.

The optimal power flow problem aims at optimizing the cost function, subject to certain objectives, under provided capacity and network constraints. While, the network constraints may include variables such as real and reactive power outputs, voltages magnitudes, and phase angles at a number of buses, the objective may be the minimization of generation cost and power losses while maximization of the lifetime of the wind farm.

The economic load dispatch problem, on the other hand, allocates the generation limit among the various generators, such that, the overall cost of generation is minimized while meeting the constraints. Unlike optimal power flow, economic dispatch does not consider power loss through the transmission lines, so the total power generated is real and equal to the total load. The total cost of generation is analyzed as a quadratic equation and includes the cost of labor, fuel cost, the maintenance and the supplies.

Economic dispatch allows the allocation of output power in the power system among all the available generators with the given constraints. This process of allocation depends on various factors such as the security of the system, the operating cost and the CO_2 emissions which together are called as the cost factors.

3.6.1. Objective of Economic Dispatch Problem

The main objective of an economic dispatch problem is to minimize the operating cost of real power generation. Both the constraints as well the objective function is non-linear. The optimal combination of the power generators is detected such that the total cost of generation is minimized while satisfying equality and inequality constraints. The operating cost for conventional generators is a quadratic cost function which is represented by

$$C_i\ (p_i) = \frac{a_i}{2}\, p_i^2 + b_i p_i + c_i$$

Where:

p_i: power from the i^{th} conventional generator

a, b, c: cost coefficients of the i^{th} generator

The variables a, b, and c values are dependent on the particular type of fuel used and the input-output curve generated.

In case of wind power generators, there is a linear cost function involved. The generation cost may not exist if the wind farms are owned by the power operators as the power requires no fuel. But it may be considered as a maintenance cost, renewal cost or a payback cost. However, in a non-utility owned system, the generation through wind has a price associated to it that may be based on special agreements.

This cost is represented as

$$C_{w,I}\ (w_i) = d_i w_i$$

Where:

w_i: the scheduled wind power from the i^{th} wind-powered generator

d_i: direct cost coefficient for the i^{th} wind generator

As we are aware, the wind speed is highly uncertain and unpredictable in nature, so the power generated from wind is also highly ambiguous. From the figure below, the variation of availability of wind energy over a certain period of time is observed. [36]

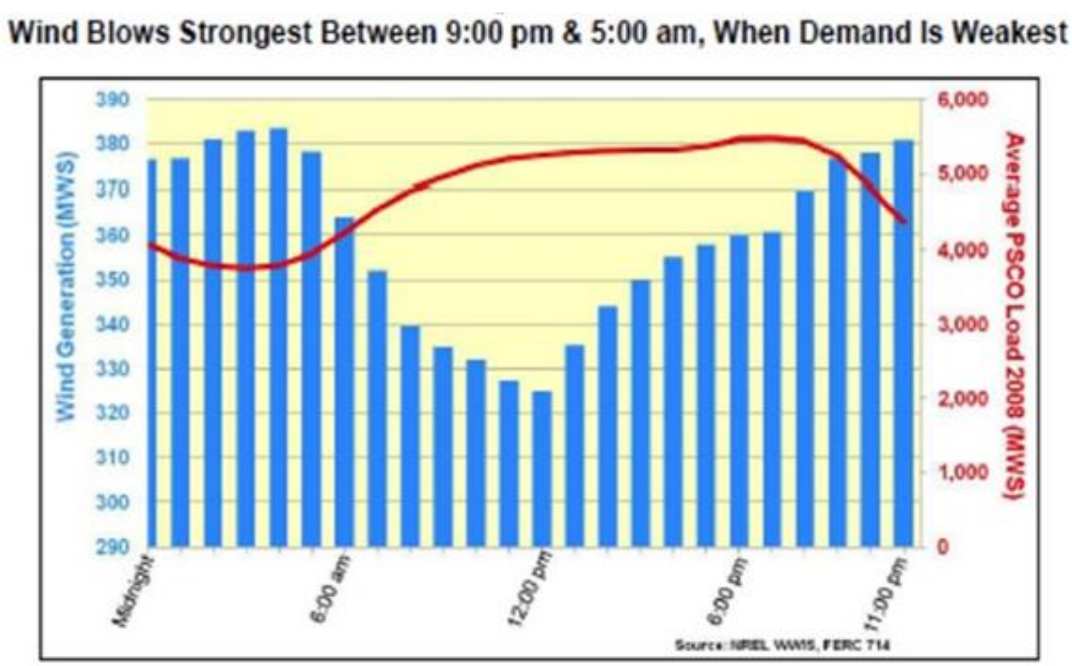


Figure 24 Wind Energy Availability over a Day

There is surplus of wind wherein the wind power produced is more than the scheduled wind power, w_i, has a cost associated to it when the turbines are not owned by the utility. So, if there is a surplus of unused wind power, the operator who owns the turbine is paid a certain amount.

While, if there is a deficit of power, which occurs when available wind power is less than scheduled, the difference in power has to be supplied or compensated by a reserve power source such as standby generators, batteries or any such energy storing systems.

Thus, the penalty cost applied for not utilizing all the available wind power at that period of time is linearly related to the difference between the available wind power and the actual wind power used. It is defined as:

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

$$= k_{p,i} \int_{w_i}^{w_{r,i}} (w - w_i)\, f_W(w)\, dw$$

Where:

f_W : Weibull distribution for wind speed after its conversion to wind power

$k_{p,i}$: Penalty cost coefficient for the i^{th} wind generator due to the underestimation of available wind

Similarly, the reserve cost requirement is represented by the reserve power wherein the scheduled wind power is not sufficient. So, the difference between the scheduled and available wind power is integrated over the pdf value of the wind power. It can be written as:

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

$$= k_{r,i} \int_0^{w_i} (wi - w)\, fW(w)\, dw$$

Where:

$k_{r,i}$: Penalty cost coefficient for the i^{th} wind generator due to the overestimation of available wind power

In order to simplify the model, the difference between the available and scheduled wind power multiplied by the probability density function of the wind power output is assumed to be linearly related to the reserve cost.

3.6.2. Constraints of the Economic Dispatch Problem

Each system operation should satisfy certain constraints to find a feasible solution because of the operational limits in case of a practical system. These constraints include:

- Constraints on generation capacity

The real power output in case of each generator is bound by upper and lower limits.

$$p_i^{min} \le p_i \le p_i^{max}$$

$$0 \leq w_i \leq w_{r,i}$$

Where:

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

- Constraints on balancing the power values:

The total demand must be met by the total power from conventional and wind generators. So,

$$\sum_{i=1}^{M} p_i + \sum_{i=1}^{N} w_i = L$$

Where:

M: Number of conventional power generators

N: Number of wind-powered generators

L: System load and losses

- Constraints on operating the system:

$$V_i^{min} \leq V_i \leq V_i^{max}$$

$$S_{line_i} \leq S_{line_i}^{max}$$

Where:

V_i: Magnitude of voltage at the *i*th bus

$S_{line,I}$: Rating of the *i*th transmission line

In summation, the main objective of economic dispatch is to minimize the operating cost from the conventional and wind- powered generators while including the penalty cost from underestimation and overestimation of the wind power, while subject to specific constraints.

The model for economic dispatch is defined in the following manner:

$$\sum_{i=1}^{M} C_i\,(p_i) + \sum_{i=1}^{N} C_{w,i}\,(w_i) + \sum_{i=1}^{N} C_{p,i}\,(w_i) + \sum_{i=1}^{N} C_{r,i}\,(w_i)$$

Subject to:

$$p_i^{min} \leq p_i \leq p_i^{max}$$

$$0 \leq w_i \leq w_{r,i}$$

$$\sum_{i=1}^{M} p_i + \sum_{i=1}^{N} w_i = L$$

$$V_i^{min} \leq V_i \leq V_i^{max}$$

$$S_{line_i} \leq S_{line_i}^{max}$$

3.7 Probability Analysis of Wind Power

In order to approach the economic dispatch with wind-powered generation system, it is necessary to identify the wind speed characterization of the uncertainty nature of wind through the principles of probability and the subsequent transformation to wind power.

3.7.1 Wind Speed Characterization

The wind speeds, according to prior research [37], in a particular location, closely follow and take the form of a Weibull distribution over time. The probability density function (pdf) of the Weibull distribution is defined by the following equation:

$$F_W(w) = \left(\frac{k}{c}\right)\left(\frac{w}{c}\right)^{k-1} e^{-(vc)^k} \qquad 0 < w < \infty$$

Where:

W: wind speed random variable

w: wind speed

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

k: shape factor at a given location (dimensionless)

The PDF value of Weibull distribution is:

$$F_w(w) = \int_0^w f(\tau)\, d\tau$$

$$= 1 - e^{-(W/c)^k}$$

CHAPTER 4:

IMPLEMENTATION AND RESULTS

4.1 Test Case: IEEE 14-Bus Test System

A standard IEEE 14 bus system is considered as a basic model for analysis. It consists of 2 synchronous condensers at Buses 6, and 8 providing both active and reactive powers. There are three synchronous condensers at Buses 3, 6 and 8. Automatic voltage regulators (AVR) of type II are incorporated in each machine. The base generation of the system is 392.0304MW and 204.2345MVar. Apart from that, there are 11 loads at Buses 2, 3, 4, 5, 6, 9, 10, 11, 12, 13, and 14. The general case is modeled in the following way

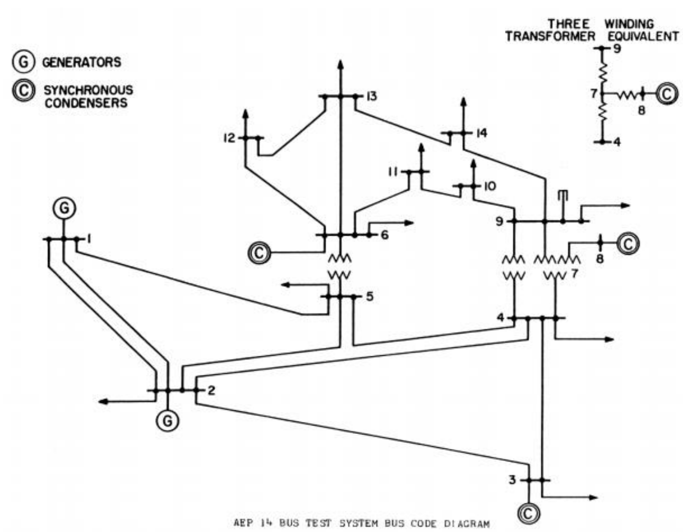


Figure 25 IEEE 14 Bus Single Line Diagram

4.2 Wind Generator Placement

Consequently, the power grid model is modified into the smart grid which incorporates wind energy into the bus. The model is represented as a single line diagram. The simulation is generated using the Power System Analysis Toolbox (PSAT) in MATLAB and is depicted in figure 19. Bus 6 is found to be the most suitable bus for addition of the wind turbine due to its maximum strength stability and proven increased penetration. [38] For simulation, GE's 1.6MW wind turbines are used to construct the wind farm. This wind farm is added at bus 6 in place of the synchronous condenser. It has the following Parameters:

Parameters	Value
Rated power, P (MW)	1.6
Rated voltage, V (kV)	.69
Rated frequency, f (Hz)	50
Number of pole pairs, p	4
Rotor diameter, d (m)	100
Stator resistance, Rs (pu)	0.00706
Rotor resistance, Rr (pu)	0.005
Stator leakage inductance, Xs (pu)	0.171
Rotor leakage inductance, Xr (pu)	0.310
Magnetizing inductance, Xm (pu)	2.0
Gear ratio	1:91

Table 2 Wind Turbine Parameter

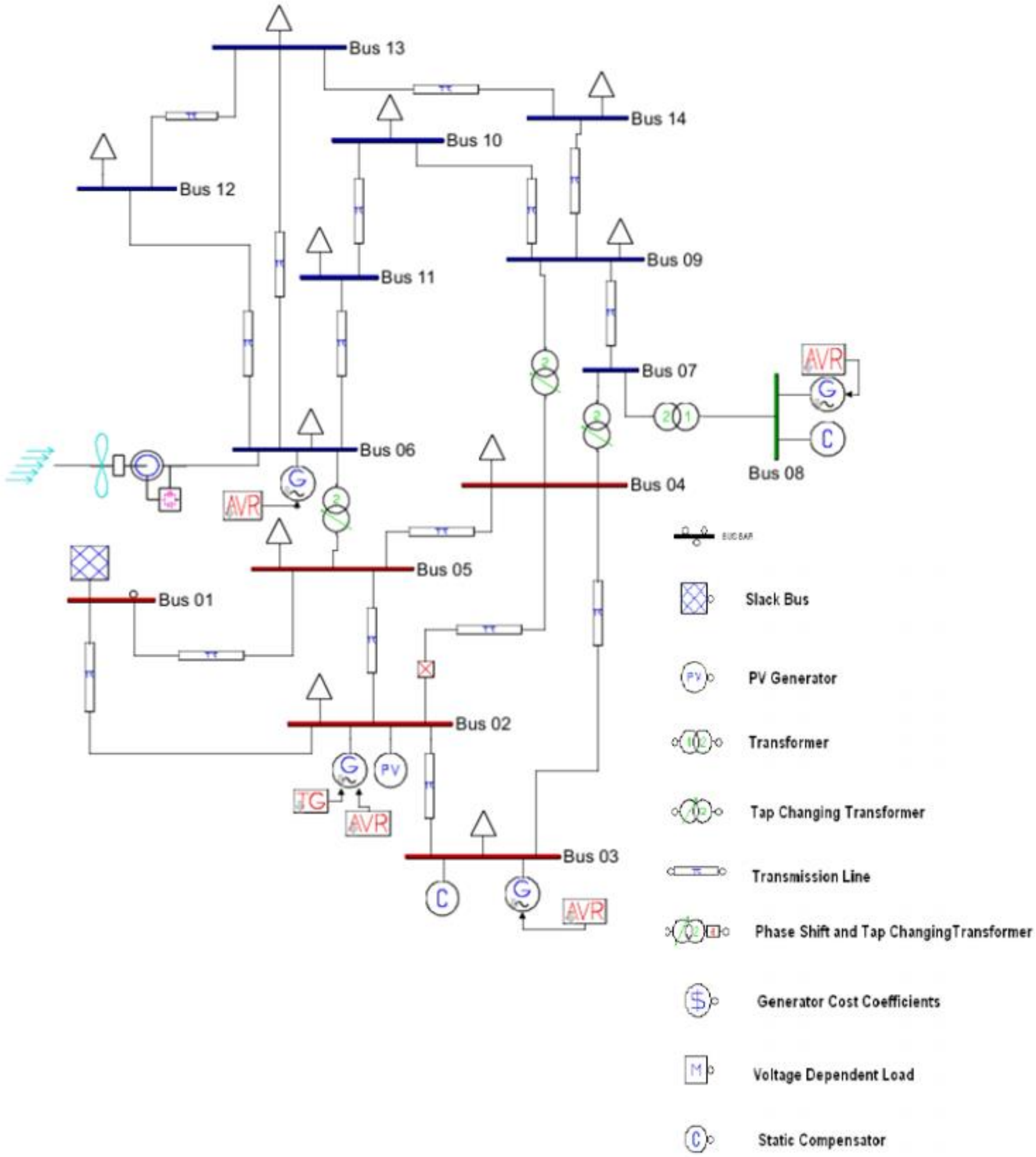


Figure 26 Modified IEEE 14 bus with Wind Turbine [PSAT Model]

The wind farm is composed of two rows of wind turbines. It is ensured that they are separated by a distance large enough to ensure that there is no interaction between the two rows when the wind blows in a direction perpendicular to them. At the same time, it is made sure that they wind turbines are close enough to make the interaction among the turbines important due to the presence of wake effect. The total wind power obtained from the two rows of wind turbines is calculated by taking the wake effect into consideration.

Furthermore, the line and bus data for the simulation are given in the tables below.

LINE DATA:

From Bus	To Bus	R pu	X pu	B/2 pu	X'mer TAP (a)
1	2	0.01938	0.05917	0.0264	1
1	5	0.05403	0.22304	0.0246	1
2	3	0.04699	0.19797	0.0219	1
2	4	0.05811	0.17632	0.0170	1
2	5	0.05695	0.17388	0.0173	1
3	4	0.06701	0.17103	0.0064	1
4	5	0.01335	0.04211	0.0	1
4	7	0.0	0.20912	0.0	0.978
4	9	0.0	0.55618	0.0	0.969
5	6	0.0	0.25202	0.0	0.932
6	11	0.09498	0.19890	0.0	1
6	12	0.12291	0.25581	0.0	1
6	13	0.06615	0.13027	0.0	1
7	8	0.0	0.17615	0.0	1
7	9	0.0	0.11001	0.0	1
9	10	0.03181	0.08450	0.0	1
9	14	0.12711	0.27038	0.0	1
10	11	0.08205	0.19207	0.0	1
12	13	0.22092	0.19988	0.0	1
13	14	0.17093	0.34802	0.0	1

Table 3 Line Data for Modified IEEE 14 Bus with Wind Farm

BUS DATA:

Bus	Type	Vsp	theta	PGi	QGi	PLi	QLi	Qmin	Qmax	Qsh
1	1	1.060	0	0	0	0	0	0	0	0
2	2	1.045	0	40	42.4	21.7	12.7	-40	50	0
3	2	1.010	0	40	23.4	94.2	19.0	0	40	0
4	3	1.0	0	0	0	47.8	-3.9	0	0	0
5	3	1.0	0	0	0	7.6	1.6	0	0	0
6	2	1.070	0	8	0	11.2	7.5	0	0	0
7	3	1.0	0	0	0	0.0	0.0	0	0	0
8	2	1.090	0	40	17.4	0.0	0.0	-6	24	0
9	3	1.0	0	0	0	29.5	16.6	0	0	0
10	3	1.0	0	0	0	9.0	5.8	0	0	0
11	3	1.0	0	0	0	3.5	1.8	0	0	0
12	3	1.0	0	0	0	6.1	1.6	0	0	0
13	3	1.0	0	0	0	13.5	5.8	0	0	0
14	3	1.0	0	0	0	14.9	5.0	0	0	0

Table 4 Bus Data for Modified IEEE 14 Bus with Wind Farm

4.3 Results of the Modified Newton Raphson Power Flow Algorithm

The results obtained in table 5, depict that the algorithm for the load flow analysis converged after 4 iterations for a primary wind speed of 9m/s. The calculated value of the slip for the turbine is -2.1321×10^{-10}.

Solutions	Value
No. of iterations	4
Tolerance, ε	1×10^{-4}
Wind Turbine slip, s	-2.1321×10^{-10}
Total active power generation (MW)	289.902
Total reactive power generation (MVar)	19.315
Total active load (MW)	259.000
Total reactive load (MVar)	73.500
Total active line loss (MW)	4.632
Total reactive line loss (MVar)	19.333

Table 5 Convergence characteristics and power system values

When compared to the values from actual power flow without wind, a remarkable influence can be noticed on the bus voltage at bus 6, where the wind turbines are connected.

It is ensured that the calculated voltages across all buses, including bus 6 to which the wind farm is connected, are within permitted limits. However, during exceptional cases or faults, such as a short circuit occurring at the bus connected to the turbines, the voltage values would be modified significantly. Apart from that, the rapid and dynamic changes in wind speed would make the injected power in the network highly variable. The rate of change and the intensity would in turn make the regulation of voltage challenging which would directly impact the quality level of the electrical energy.

After the iterations for the electrical network are performed and the solution converges, the load flow in each branch is found and represented in the model as shown below. The sent and received active and reactive powers in each branch vary by a small value. Every step of the iteration has been modeled below to represent the data at each bus and the line losses. It is noticed that as the slip is varied, the solution converges and the generation is increased while reducing the losses.

ITERATION: 1

Newton Raphson Loadflow Analysis

Bus No	V pu	Angle Degree	Injection MW	Injection MVar	Generation MW	Generation MVar	Load MW	Load MVar
1	1.0600	0.0000	156.238	-11.065	156.238	-11.065	0.000	0.000
2	1.0450	-3.1077	23.074	-7.203	44.774	5.497	21.700	12.700
3	1.0100	-7.7254	-53.912	-20.612	40.288	-1.612	94.200	19.000
4	1.0369	-7.2656	-49.152	7.612	0.000	0.000	47.800	-3.900
5	1.0427	-6.5259	-5.063	8.388	0.000	0.000	7.600	1.600
6	1.0700	-12.4251	-4.659	35.575	33.571	43.075	11.200	7.500
7	1.0554	-7.7731	1.745	5.562	0.000	0.000	0.000	0.000
8	1.0900	-4.0694	42.188	22.752	42.188	22.752	0.000	0.000
9	1.0407	-10.5673	-32.724	-15.781	0.000	0.000	29.500	16.600
10	1.0391	-11.2025	-9.482	-5.868	0.000	0.000	9.000	5.800
11	1.0529	-11.9436	-3.133	-0.143	0.000	0.000	3.500	1.800
12	1.0566	-13.1648	-5.817	-0.302	0.000	0.000	6.100	1.600
13	1.0510	-13.0440	-13.010	-3.776	0.000	0.000	13.500	5.800
14	1.0269	-12.7329	-15.600	-4.708	0.000	0.000	14.900	5.000
Total			30.694	10.431	289.694	83.931	259.000	73.500

Table 6 Load Flow for Iteration1

Line Flow and Losses

From Bus	To Bus	P MW	Q MVar	From Bus	To Bus	P MW	Q MVar	Line Loss MW	Line Loss MVar
1	2	100.422	-3.266	2	1	-98.681	8.583	1.741	5.316
1	5	55.816	-2.068	5	1	-54.316	8.261	1.500	6.193
2	3	45.172	9.484	3	2	-44.255	-5.621	0.917	3.862
2	4	42.095	-7.476	4	2	-41.122	10.428	0.973	2.951
2	5	34.488	-8.772	5	2	-33.827	10.789	0.660	2.016
3	4	-9.657	-12.104	4	3	9.814	12.505	0.157	0.402
4	5	-34.116	-3.057	5	4	34.262	3.516	0.146	0.459
4	7	4.740	-9.359	7	4	-4.740	9.568	0.000	0.209
4	9	11.532	-0.389	9	4	-11.532	1.057	0.000	0.667
5	6	48.818	-9.622	6	5	-48.818	14.972	0.000	5.349
6	11	-0.283	9.375	11	6	0.356	-9.222	0.073	0.153
6	12	6.832	2.345	12	6	-6.776	-2.229	0.056	0.117
6	13	13.739	8.694	13	6	-13.586	-8.393	0.153	0.301
7	8	-42.188	-19.345	8	7	42.188	22.752	0.000	3.406
7	9	48.673	15.339	9	7	-48.673	-12.767	0.000	2.572
9	10	13.094	-2.906	10	9	-13.041	3.046	0.053	0.140
9	14	14.388	-1.165	14	9	-14.143	1.685	0.245	0.520
10	11	3.559	-8.914	11	10	-3.489	9.078	0.070	0.164
12	13	0.959	1.927	13	12	-0.950	-1.919	0.009	0.008
13	14	1.526	6.536	14	13	-1.457	-6.394	0.070	0.142
Total Loss								6.822	34.949

Table 7 Line Flow and Losses for Iteration1

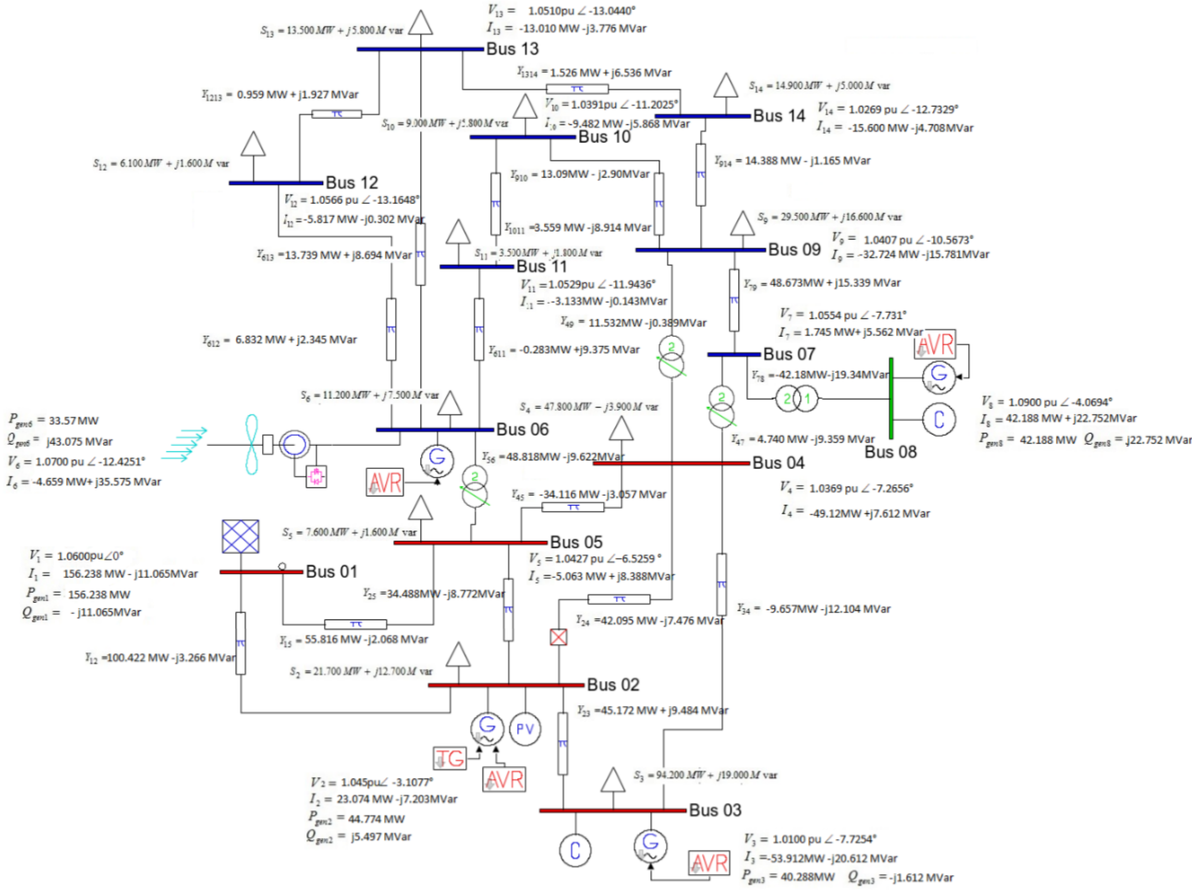


Figure 27 Power Flow Model for Iteration1

ITERATION: 2

Newton Raphson Loadflow Analysis

Bus No	V pu	Angle Degree	Injection MW	Injection MVar	Generation MW	Generation MVar	Load MW	Load MVar
1	1.0600	0.0000	157.232	10.515	157.232	10.515	0.000	0.000
2	1.0450	-1.4447	18.983	-32.648	40.683	-19.948	21.700	12.700
3	1.0100	-3.4280	-53.802	-64.592	40.398	-45.592	94.200	19.000
4	1.0424	-3.5349	-47.230	4.865	0.000	0.000	47.800	-3.900
5	1.0471	-3.2058	-7.132	1.818	0.000	0.000	7.600	1.600
6	1.0700	-6.0852	-2.923	47.897	35.307	55.397	11.200	7.500
7	1.0613	-3.8275	-0.649	1.420	0.000	0.000	0.000	0.000
8	1.0900	-2.0951	39.708	36.068	39.708	36.068	0.000	0.000
9	1.0535	-5.0842	-29.010	-15.159	0.000	0.000	29.500	16.600
10	1.0530	-5.3920	-8.722	-5.709	0.000	0.000	9.000	5.800
11	1.0598	-5.7865	-3.394	-1.822	0.000	0.000	3.500	1.800
12	1.0618	-6.4154	-6.060	-1.590	0.000	0.000	6.100	1.600
13	1.0593	-6.3456	-13.375	-5.762	0.000	0.000	13.500	5.800
14	1.0475	-6.1070	-14.340	-4.856	0.000	0.000	14.900	5.000
Total			29.286	-29.555	288.286	43.945	259.000	73.500

Table 8 Load Flow for Iteration 2

Line Flow and Losses

From Bus	To Bus	P MW	Q MVar	From Bus	To Bus	P MW	Q MVar	Line Loss MW	Line Loss MVar
1	2	101.502	21.689	2	1	-100.573	-18.852	0.929	2.837
1	5	55.730	0.287	5	1	-54.983	2.796	0.747	3.083
2	3	43.380	27.292	3	2	-42.814	-24.911	0.565	2.381
2	4	41.825	-9.827	4	2	-41.334	11.317	0.491	1.490
2	5	34.351	-13.221	5	2	-33.997	14.299	0.353	1.079
3	4	-10.988	-33.907	4	3	11.405	34.972	0.417	1.065
4	5	-33.844	-12.841	5	4	33.925	13.095	0.081	0.254
4	7	5.525	-19.339	7	4	-5.525	19.720	0.000	0.381
4	9	11.018	-4.159	9	4	-11.018	4.503	0.000	0.344
5	6	47.924	-19.184	6	5	-47.924	22.038	0.000	2.854
6	11	-0.574	11.246	11	6	0.627	-11.136	0.053	0.110
6	12	6.834	3.569	12	6	-6.802	-3.502	0.032	0.066
6	13	13.422	10.854	13	6	-13.335	-10.684	0.086	0.170
7	8	-39.708	-33.935	8	7	39.708	36.068	0.000	2.133
7	9	44.584	15.635	9	7	-44.584	-14.545	0.000	1.090
9	10	12.805	-3.450	10	9	-12.780	3.517	0.025	0.067
9	14	13.787	-1.666	14	9	-13.676	1.901	0.110	0.235
10	11	4.058	-9.226	11	10	-4.020	9.314	0.038	0.088
12	13	0.743	1.912	13	12	-0.739	-1.908	0.004	0.004
13	14	0.699	6.830	14	13	-0.663	-6.757	0.036	0.073
Total Loss								3.967	19.803

Table 9 Line Flow and Losses for Iteration 2

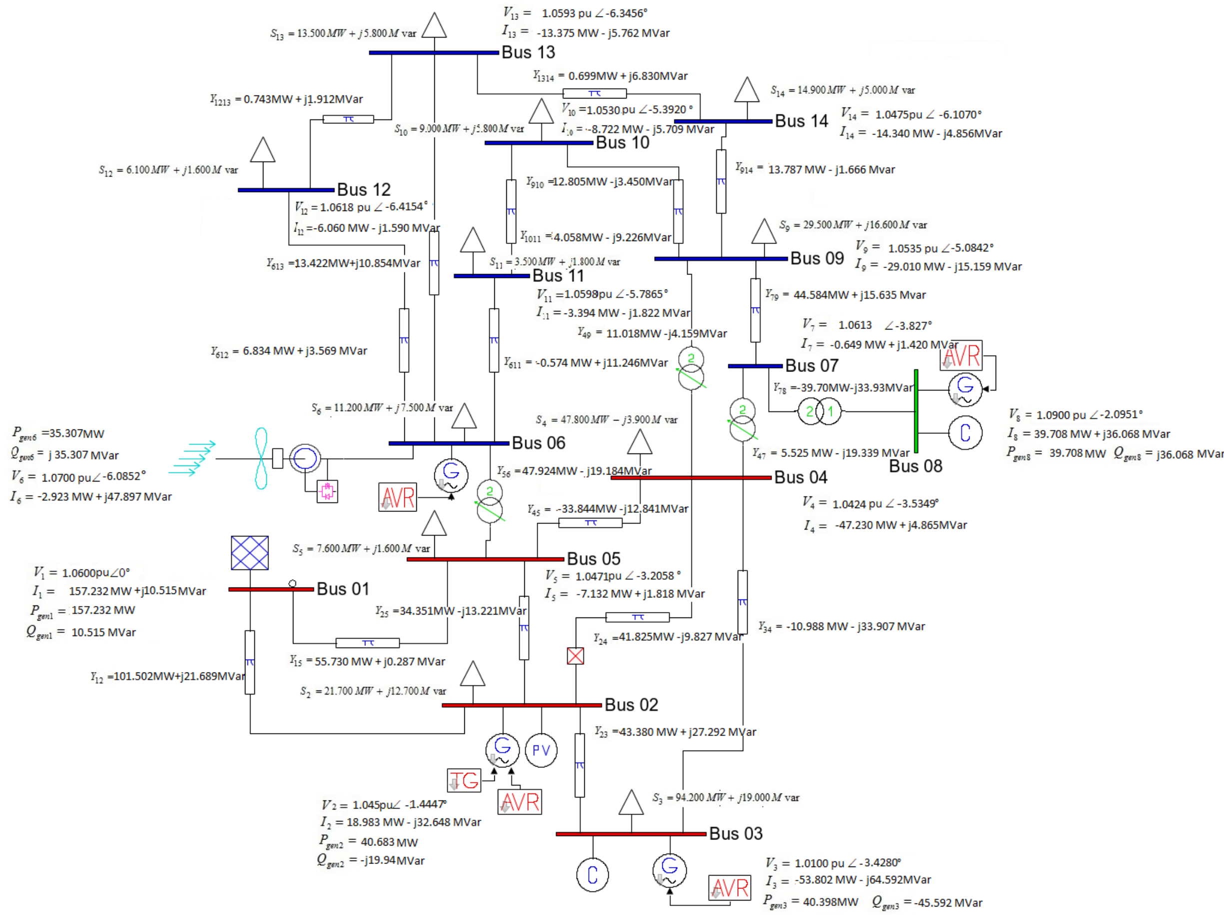


Figure 28 Power Flow Model for Iteration2

ITERATION: 3

Bus No	V pu	Angle Degree	Injection MW	Injection MVar	Generation MW	Generation MVar	Load MW	Load MVar
1	1.0600	0.0000	175.703	82.303	175.703	82.303	0.000	0.000
2	1.0350	-0.8992	-8.420	-135.066	13.280	-122.366	21.700	12.700
3	1.0000	-2.0341	-58.807	-122.069	35.393	-103.069	94.200	19.000
4	1.0442	-2.3509	-35.620	35.674	0.000	0.000	47.800	-3.900
5	1.0487	-2.1507	-2.361	28.400	0.000	0.000	7.600	1.600
6	1.0600	-4.1298	-24.193	1.308	14.037	8.808	11.200	7.500
7	1.0634	-2.5524	0.476	18.239	0.000	0.000	0.000	0.000
8	1.0800	-1.3978	39.413	30.928	39.413	30.928	0.000	0.000
9	1.0573	-3.4049	-29.442	-16.437	0.000	0.000	29.500	16.600
10	1.0572	-3.6217	-8.967	-5.786	0.000	0.000	9.000	5.800
11	1.0625	-3.9077	2.665	11.250	0.000	0.000	3.500	1.800
12	1.0644	-4.3477	-1.172	8.492	0.000	0.000	6.100	1.600
13	1.0625	-4.2965	-3.538	13.558	0.000	0.000	13.500	5.800
14	1.0538	-4.1168	-14.835	-4.979	0.000	0.000	14.900	5.000
Total			30.902	-54.185	289.902	19.315	259.000	73.500

Table 10 Load Flow for Iteration 3

Line Flow and Losses

From Bus	To Bus	P MW	Q MVar	From Bus	To Bus	P MW	Q MVar	Line Loss MW	Line Loss MVar
1	2	118.779	96.140	2	1	-117.436	-92.041	1.343	4.099
1	5	56.924	3.354	5	1	-56.403	-1.202	0.521	2.152
2	3	41.812	45.278	3	2	-41.256	-42.938	0.555	2.340
2	4	37.376	-27.944	4	2	-36.982	29.139	0.394	1.195
2	5	29.828	-33.813	5	2	-29.468	34.913	0.360	1.100
3	4	-17.550	-70.641	4	3	18.734	73.662	1.183	3.021
4	5	-34.407	-22.564	5	4	34.477	22.782	0.069	0.218
4	7	5.730	-29.387	7	4	-5.730	29.948	0.000	0.560
4	9	11.306	-7.521	9	4	-11.306	7.824	-0.000	0.304
5	6	49.033	-14.269	6	5	-49.033	16.126	0.000	1.857
6	11	-6.904	-0.671	11	6	6.917	0.699	0.014	0.028
6	12	1.969	-6.377	12	6	-1.953	6.411	0.016	0.034
6	13	3.506	-7.956	13	6	-3.491	7.985	0.015	0.029
7	8	-39.413	-29.664	8	7	39.413	30.928	0.000	1.263
7	9	45.619	17.956	9	7	-45.619	-17.177	0.000	0.779
9	10	13.270	-4.641	10	9	-13.251	4.691	0.019	0.050
9	14	14.212	-2.443	14	9	-14.133	2.611	0.079	0.168
10	11	4.283	-10.478	11	10	-4.252	10.551	0.031	0.073
12	13	0.781	2.081	13	12	-0.778	-2.078	0.003	0.003
13	14	0.731	7.651	14	13	-0.701	-7.590	0.030	0.061
Total Loss								4.632	19.333

Table 11 Line Flow and Losses for Iteration3

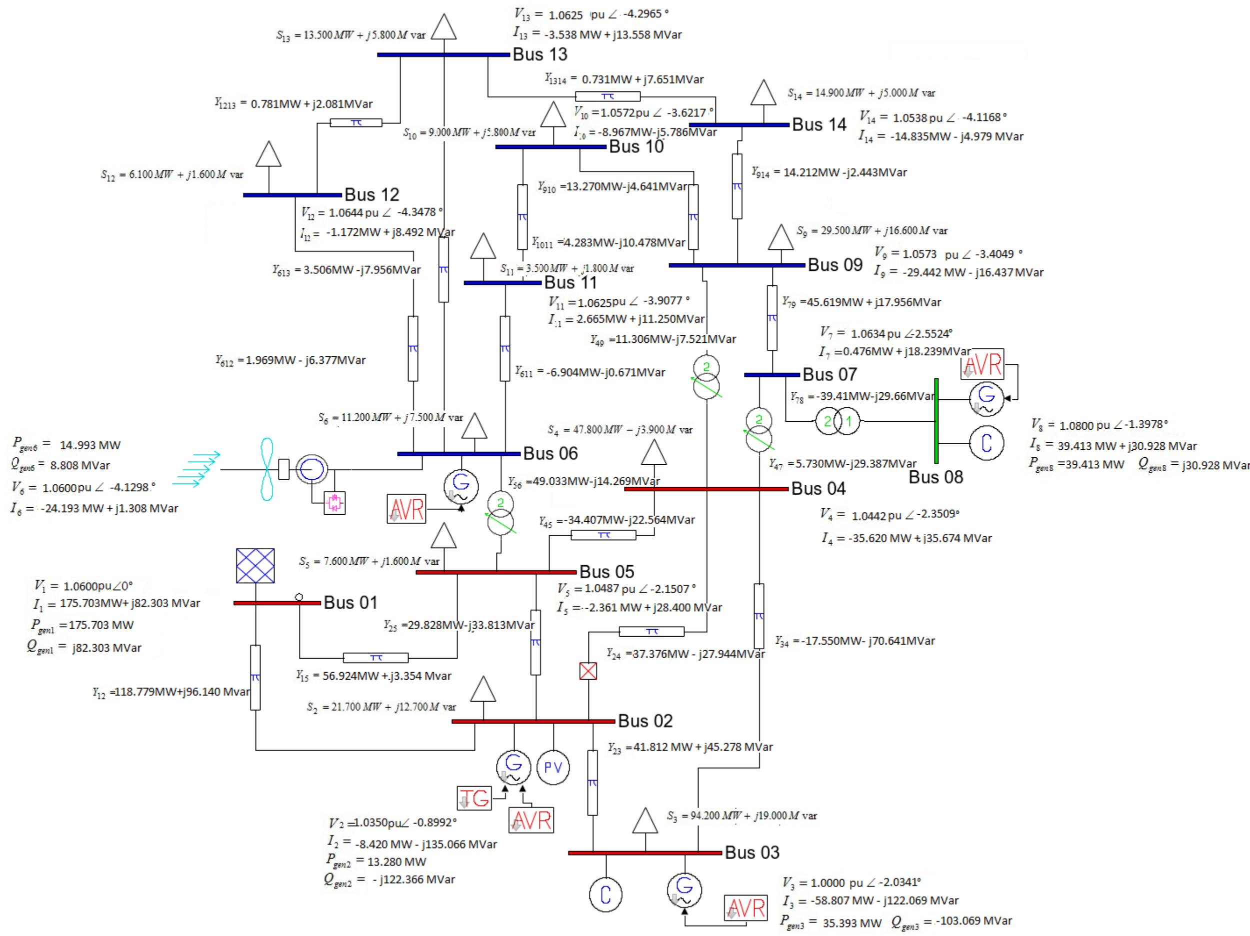


Figure 29 Power Flow Model for Iteration 3

From the above results, we can draw conclusions that the total active and reactive powers generated are 289.902 MW and 19.315 MVar. Out of this, the slack bus (bus 1) was the major contributor towards the active power generation, providing 175.703MW. The positive and negative signs in front of the power values designate if the power was consumed by the bus or generated at that point.

4.4 Economic Load Dispatch Model for the Modified Test Case

In the preceding sections, the base IEEE 14 bus model was described and the modified bus model incorporating the wind farm was developed. Weibull probability distribution was used to model the wind speed and with the help of linear power equations, from Chapter 3, the wind speed distributions were converted into wind power distributions.

MATLAB was used to develop a program based on the economic dispatch model with the modified case system to generate a tool to examine the effect of variations in wind speeds and cost coefficients on the optimum solution of the ED problem. The assumed wind farm parameters and generator data is specified below.

P_{min}(MW)	P_{max}(MW)	V_i(m/s)	V_r(m/s)	V_o(m/s)	K_d	K_p	K_r
0	35	5	15	45	1.12	1	1

Table 13 Parameters of Wind Power Plant

BUS	a_i	b_i	c_i	P_i^{min}	P_i^{max}
1	0.007	7	240	50	500
2	0.0095	10	200	20	200
3	0.009	8.5	220	20	300
6	0.009	11	200	20	150
8	0.008	10.5	220	20	200

Table 12 Generator Data for Modified IEEE 14 Bus Test System

The economic dispatch is modeled to minimize the operating cost of the real power generation in an electrical network. In order to achieve that various scenarios have been taken into considerations such as, varying the shape and size parameters in Weibull pdf, modifying the wind speed profile, etc. The best case is found with the least operating cost that would satisfy the model. The different cases are as follows.

4.4.1. Effects of Wind Power Coefficients

The primary case would be the investigation of the effects of change in wind speed profile on the output of the generators in the model. Initially, the penalty cost coefficient would be zero for the prototype. This is the case where the wind farms are owned by the power system operator. So, accessing a cost for overuse or no use is not required.

The constants a, b, and c for the generators are taken from table 13. For the wind-powered generator, the direct cost coefficient d =1.12 is assumed. Initially, no penalty cost coefficient is assumed, a reserve cost coefficient of 1 is taken. This is followed by cases wherein the wind farms are owned by the private entities, such that there is an over estimation and under estimation cost involved. These situations are not always ideal in terms of threats caused to the stability and security of the system.

The critical wind speed parameters for the turbines are provided in table 12. The scale factor for the Weibull pdf is varied from 5 to 25. While the shape factor is kept constant at k=2.

Based on the Weibull distribution, the scale factor, c has a proportional impact on the wind speeds. As the c factor increases, the probability of obtaining a greater proportion of wind speed also increases.

4.4.1.1. Effect of Reserve Cost Coefficient

Firstly, assuming that the wind farms are owned by utility so the penalty cost of the additionally available wind power over the scheduled wind power, $k_p = 0$. As the scale factor of the Weibull pdf grows, the reserve cost decreases.

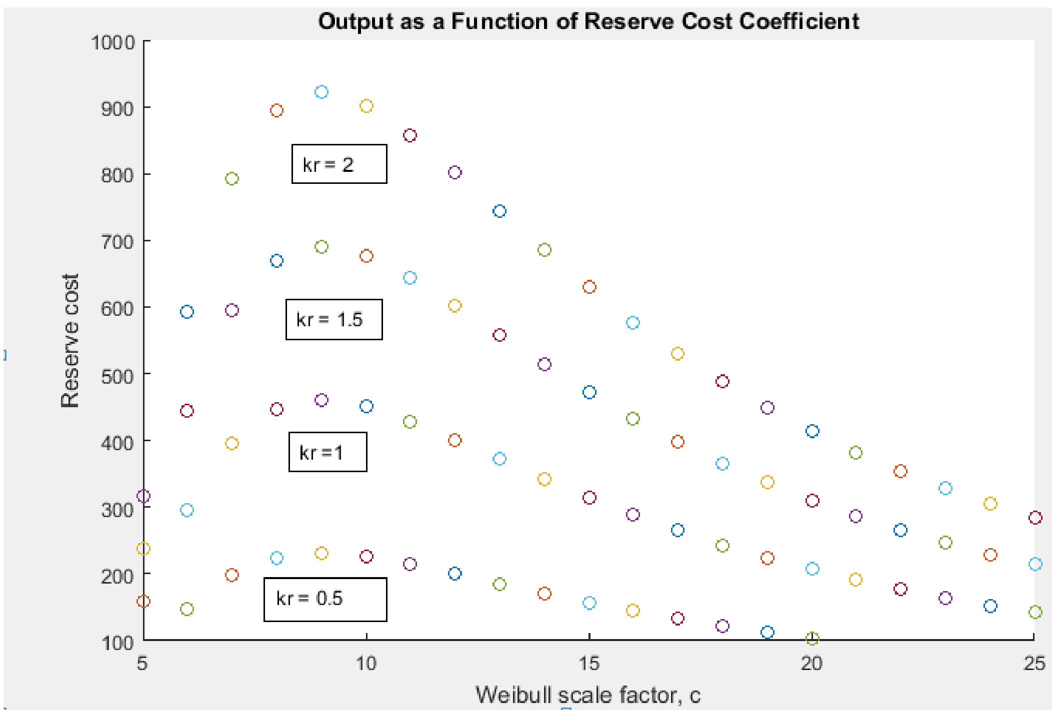


Figure 30 Effect of Reserve Cost Coefficient on the Output

Figure 23 verifies the above statement. The graph is plotted by taking the various values of reserve cost coefficients. When the value of c which is the scale factor increases, there is a greater amount of wind energy, which means there is more available wind power from the generators. However, at a higher reserve cost, the wind at a higher speed becomes less attractive and the output of the turbine falls to a lower rate. So, the reduction in reserve cost, in turn increases the output of wind powered generators. Hence, increasing the reserve cost coefficient requires the operator to be more conservative with the scheduling of energy as a greater price would have to be paid for overestimating the amount of scheduled wind power in a given time frame under certain restrictions.

4.4.1.2. Effect of Penalty Cost Coefficient

The effect of the penalty cost coefficient for underestimation is modeled next. In this scenario, the reserve cost coefficient is set to 0 in order to isolate the changes of the penalty cost coefficients.

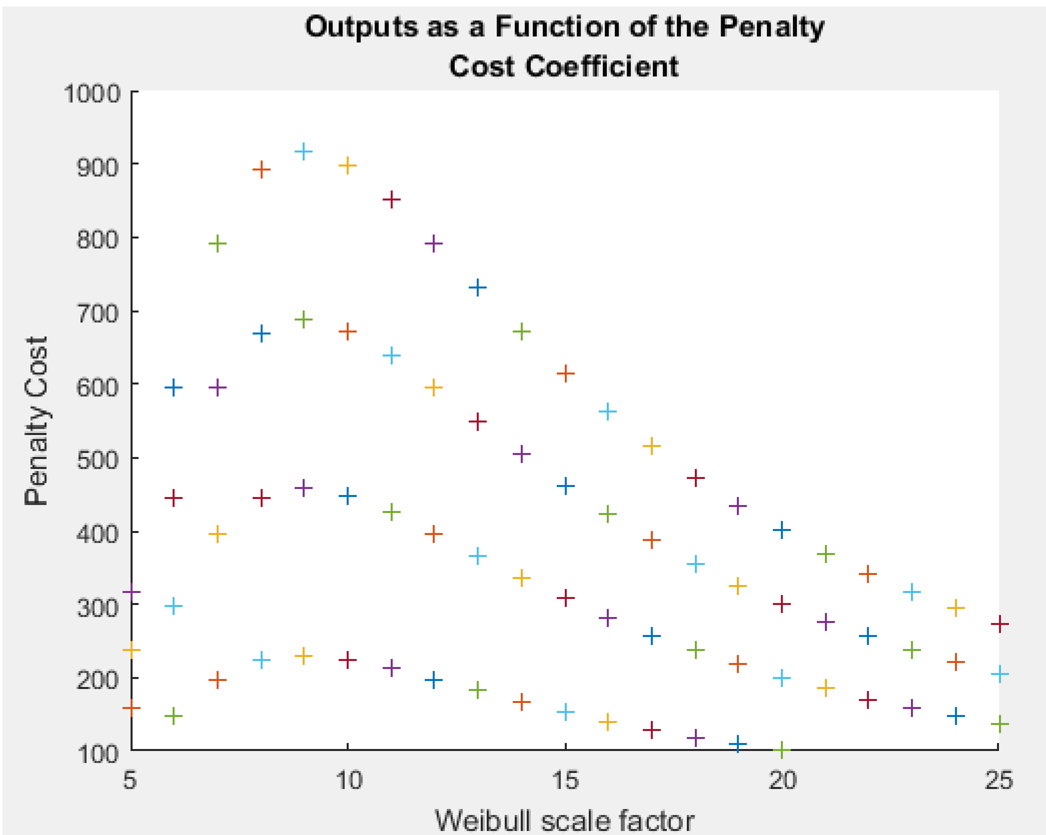


Figure 31 Effect of Penalty Cost Coefficient

The effect of penalty cost on the scheduled output is explained in figure 24. With the increase in the penalty cost coefficient, k_p more wind power would have to be used for the model. This is because with increase in k_p, the operator is encouraged to take more risk, thereby increasing the scheduled wind power limit. This in turn means that as the wind farm has the ability to meet the load demand under no reserve cost, the other conventional generators would be kept at their minimal levels.

Therefore, the previous two sections provide a stronger understanding of the trends involved with the inclusion of wind energy into the electrical network. So, an increase in the reserve cost coefficient would decrease the scheduled amount of wind power, while an increase in the penalty cost coefficient would increase the scheduled amount of wind power.

CHAPTER 5:

Conclusion and Future Scope

5.1. Conclusion

The tremendous potential of wind energy, along with its environment-friendly distinction and its increasing competitiveness in the energy market, has made it one of the most popular fuels for power generation in the modern era. It is quickly becoming one the preeminent technologies to provide a viable and sustainable source to the world's development, but is still shrouded in misunderstandings due to lack of research. This makes it imperative to conduct in-depth studies and research in order to understand and comprehend the wind power generation and develop modern ways to integrate the wind farms into existing electrical networks.

With the increase of penetration of wind power, the process of integration of wind farms to power grids is getting trickier as it involves understanding the significant influences on the already existent host system. Moreover, in order to become competitive in the liberalized market, precise prediction of the generation levels for each moment of the day is essential. Thus, there is a need for more reliable and accurate models for performing the power simulation analysis that could account for the variability and inconsistency of wind availability.

The preliminary step of the research has been focused on modeling a load flow system. Proper analysis is required for finding a method for distributing the power within an electrical grid when a Wind Energy Conversion System has been included. For this purpose, the wind farm has been modeled as an RX load bus and the already existing Newton-Raphson Power Flow method has been modified to incorporate the new bus system such that it would reflect the real, accurate, and steady output of the generators. In this paper, we consider a wind farm with 10 turbines used to replace a synchronous condenser at bus 6 in the IEEE 14 bus system. The changes in the power generation are observed and vetted against an existing model consisting of conventional generators. The simulation results validate that the model is effective for practical use and has the capability to converge in lesser time. The proposed model and the technique involved in computing the system can be further utilized for more complex distributions.

Apart from analyzing the power distribution, it is essential to further comprehend the irregular nature of wind speed to generate an algorithm to modulate the power allocation. The uncertainty of wind is modeled by the Weibull probability density function. To the already existing economic dispatch model, two more factors accounting for the over- and under-estimations of available wind power is added. The reserve and the penalty cost factors play a vital role while scheduling the amount of wind power. So, if the reserve cost coefficient is increased, the scheduled amount of power from the wind farms will be reduced as over-estimation of the wind power, while it increases the load on other generators. This increases the need for other conventional generators to produce more energy to satisfy the load requirements. Conversely, if the penalty cost coefficient is increased, it means that the wind farms are not being utilized to their full potential. This provides the operator an incentive to take more risk and increase the scheduled amount of wind power. In both cases, the efficiency of the system is reduced. Thus, these incremental costs, when compared to quadratic costs of the conventional units, could provide a simplified economic model that would incorporate both thermal and wind power.

Analytical arguments have been presented to demonstrate that the proposed algorithm is capable of achieving the minimum cost allocation under certain constraints over time. This developed model can be further used as a fundamental design in the future for building more cost-efficient environmental-friendly systems.

5.2. Future Scope

5.2.1. Algorithm Optimization

The basic algorithm for economic dispatch with wind farm integration described in this research can be refined and extended in numerous ways. Using the provided model and constraints, the optimum minimal solution can be found. There are several optimization techniques available which can be applied to the economic dispatch problem. Such improvements can use basic calculus or can include modern stochastic searching solutions, such as the direct search method, particle swarm optimization, Lagrangian relaxation, genetic algorithm and simulated annealing. These optimization techniques provide a precise oversimplified model of the system with the help of contemporary mathematical properties. Using optimization tools, we can generate a system such that the load allocation is more accurate and none of the generators are loaded above the safe point.

5.2.2. Incorporation into Smart Grids

The research has been motivated by the needs to satisfy the future grid networks by providing a system wherein the generators and the load respond intelligently. This would enable a real-time system and maximize the efficiency for better energy utilization. It is imperative to extend the load flow and the cost optimization problem into a distributed approach.

5.2.3. Storage System

The economic dispatch model with wind energy has two more factors which account for the over-estimation or under-estimation of wind power. At the time of under-estimation, such as during the nighttime or when more wind is generated, the excess of energy can be stored for future use. The inclusion of a storage system can be an effective option as it would allow for a larger penetration of such renewable energy resources. This would warrant that the efficiency is not reduced and the excess energy can be stored in a battery or in some other form. One such example could be the running of the Robert Moses Niagara Power Plant at night by using the excess energy generated by the wind farms rather than depending on generators.

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