NTNU
Norwegian University of
Science and Technology

Use of Hywind in Oil and Gas Platforms to Reduce CO2 and NOx Gas Emissions

Nikhila Gopal

Master of Science in Electric Power Engineering
Submission date: July 2016
Supervisor: Elisabetta Tedeschi, ELKRAFT
Co-supervisor: Wei He, Statoil

Norwegian University of Science and Technology
Department of Electric Power Engineering

NTNU – Trondheim
Norwegian University of
Science and Technology

Use of Hywind in Oil and Gas Platforms to Reduce CO_2 and NO_x Gas Emission

Nikhila Gopal

Master of Science in Electric Power Engineering
Submission Date: July 2016
Supervisor: Elisabetta Tedeschi, ELKRAFT, NTNU
Co-supervisor: Wei He, Principal Engineer, Statoil

Norwegian University of Science and Technology
Department of Electric Power Engineering

Use of Hywind in Oil and Gas Platforms to Reduce CO_2 and NO_x Gas Emissions

Nikhila Gopal
July, 2016

MASTER OF SCIENCE THESIS

DEPARTMENT OF ELECTRIC POWER ENGINEERING
NORWEGIAN UNIVERSITY OF SCIENCE AND TECHNOLOGY

NTNU – Trondheim
Norwegian University of
Science and Technology

Abstract

In oil and gas industry, need of the renewable energy like wind energy is growing. In Norway, oil and gas industry is the main reason for the emission of the greenhouse gases. The greenhouse gases in oil and gas industry can be reduced by integrating wind energy. This thesis report mainly focus on the possibilities of integrating the offshore wind power with oil and gas platforms using Hywind technology at North Sea platforms to reduce CO_2 and NO_x gas emission and save the fuel consumption. The main goal of the project was to analyze the role of different operational strategy of the gas turbines in reducing the emission of greenhouse gases.

Oil and gas platforms are huge structures which is run using gas turbines and is connected to the onshore grid. The gas turbines release the greenhouse gases which create climatic problems. The wind farm technology has helped to save the fuel consumption and reduce the emission of greenhouse gases from the gas turbine. Hywind technology is used as a good alternative to generate the available power in Deep Sea.

In the report, initially wind assessment was done based on the real power curve of the wind turbine for both 2.3 MW and 6 MW Hywind turbine. The software used in this thesis work was Matlab. In the project work the analysis of different operational strategies to save the fuel and emission of CO_2 and NO_x gas was a big challenge as both the gas turbines cannot work together when wind energy is integrated. The main aim was to meet the load requirement at the platform hence the main challenge was to identify the better operational strategy for the simulation.

Two operational strategy was considered where one refers to the load sharing operation and the other with start/stop operation of the gas turbine. Here one gas turbine is allowed to run while the other one is shut down. The simulation was run for both 2.3 MW and 6 MW wind turbines with and without wind power integration and the results were compared to identify the better operational strategies. The results showed that there is a significant reduction in the greenhouse gases and better results are found with conventional operation than that of start/stop operational strategy of gas turbines. The results are much better with 6 MW wind turbine than with the 2.3 MW. The simulations were run for one year.

From the project work it can be concluded that wind energy is the best renewable energy resource that can be used in oil and gas industry to save the fuel consumption and reduce greenhouse gas effects. Further work can be carried out in the storage system of the platform, electrical grid stability simulations also can be carried out further and in identifying the number of wind turbines to be used for integration.

Keywords: Wind power Integration; CO_2 and NO_x gas reduction; oil and gas offshore platform.

Acknowledgment

I would like to express my deepest gratitude to my supervisor Professor Elisabetta Tedeschi, NTNU, Trondheim and Co-supervisor, Wei He, principal engineer at Statoil. I am very thankful to Prof. Elisebetta for giving guidance and efforts in correcting my thesis work. Mrs. Wei He was always there to help me in giving research data and keeping regular meetings in her busy schedule. I am happy to have them as my supervisors and I really appreciate the effort they have taken for helping me to continue with my thesis work.

I am thankful to Mr Olve, Sintef Energy, NTNU for giving appropriate suggestions in many meetings during the progress of the work.

I also express my gratitude to Abel Assegid Taffese, PhD Scholar, NTNU who helped me a lot especially whenever I stuck with my simulations in Matlab. He was very helpful and gave direction for the progress of my work.

Contents

List of Figures

List of Tables

Chapter 1

1. Introduction

1.1. Background Study

Renewable energy is inexhaustible, clean, domestic and free hence solar energy, wind energy are being developed very recently. The main advantage of using these renewable energy is that they are they are infinitely available and is free from many harmful gases. Oil and gas industry use wind energy, wave energy as a source of energy. In recent few years, oil and gas industry gets much focus of the whole world in power generation. It is found that there are around 9,600 offshore fields worldwide. Offshore platform have many applications in oil extraction, navigation, etc. Offshore oil extraction accounts 28 percent of the global production and is increasing [1]. They should function very safely even during harsh wind periods.

Recent several studies reports that wind installation in the offshore industry is being developed. Wind power led to the dramatic changes in the configuration of wind turbine both in Europe, United States and other parts of the world. Many statistics shows that their demand is getting increased recently. The European offshore wind industry key trends and statistics 2013 shows the increase in the wind installations in Europe. Here it shows that the demand started to dramatically increase by 2009 and still is growing.

By 2013 total installed capacity has become 6,562 MW. A total in 69 offshore wind farms in 11 countries across Europe, 2,080 wind turbines are installed and connected to the electricity grid now. In Europe, UK is the largest country to install the offshore wind turbines. Second largest country of installations is by Denmark which is followed by Belgium and Germany. Around 6,562 MW of offshore wind capacity are installed in the North Sea [2]. Figure 1.1 shows the statistic of installation capacity in Europe by the report of European Wind Energy Association, 2013 [2].

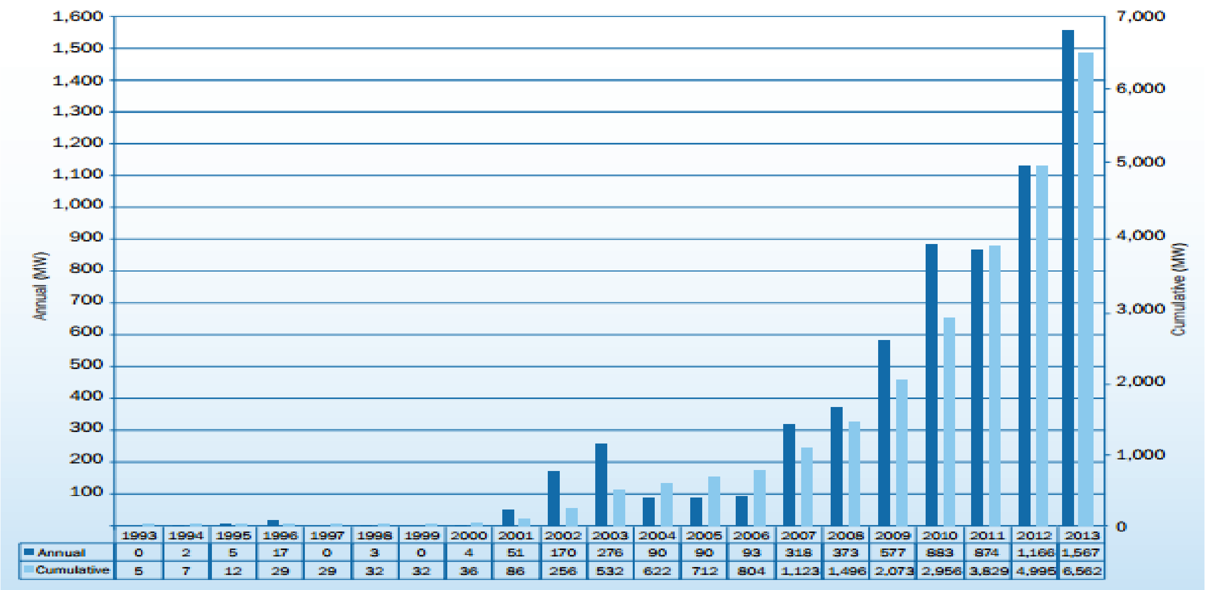

Figure 1.1. Cumulative and annual offshore wind installations (MW) [2]

Offshore oil and gas platforms are very huge in structure and are designed by huge steel or concrete structures. Which helps to drill well, extract oil and helps in power generation. Different types of platforms are fixed platforms, complaint platforms, floating platforms etc. Oil and gas platforms are equipped with their own energy sources and becomes housing for electricity generation and delivers it to onshore by pipeline or by tankers or to a floating platform. These platforms use gas turbines to generate electric power for their functioning. Gas turbines emit large amount of CO_2 and NO_x gas to the atmosphere which create climatic problems. Because of the impact of these gases on the climatic changes, around the world, the focus on CO_2/NO_x gas emission is being increasing. Many of the countries started to impose tax and measures were taken to reduce its impact. A typical oil and gas platform is shown in the figure. Depending on their use and water depths they are categorized as [1],

- Moveable offshore drilling platforms/rigs
- Offshore oil rig and platform types
- Drilling barges
- Submersible platforms/rigs
- Semi-submersible platforms/rigs
- Jackup platforms/rigs

Figure 1.2. Oil and gas platform [3]

1.2. Objective of the report

The work focuses on the wind power integration in the oil and gas platforms. The main objectives of the thesis work is,

- Estimation of available wind power from the wind turbine based on the ideal power curve of the real turbine
- Estimation of electrical load data at the platform
- Analysis of different operational strategy of the gas turbines at the platform
- Estimate the CO_2 and NO_x gas emission and save fuel consumption based on the two operational strategy
- Matlab Simulations for both 2.3 MW and 6 MW Hywind turbine

1.3. Limitations

Limitations of the work can be explained as follows,

- The analysis done in project work is focused only for 2.3 and 6 MW wind turbines.
- The research data like wind speed data, load data at the platform, fuel and CO_2 and NO_x gas emission of gas turbine of the project was given by the manufacturer which contained

certain missing inputs. The reliability of the data is not verified. More accurate data is required.

- Data provided from the site was not having the same dates compared with the data of the load at the platform over one year. Hence for estimating the load, the values had to recirculate to make them in correct order for the whole year to match with the wind data date.
- Operational strategy is based on the margin added to load, P_{margin} is assumed for 50 percent of the rated power. For more accurate results much more simulations is to be done with various values.

1.4. Thesis Structure

Chapters are organized as

- **Chapter 2** gives a study on the literature review on various papers related to the work of the project.
- **Chapter 3** gives the general description of the system model implemented and theoretical background on the gas turbine. It also presents the significance of its applications.
- **Chapter 4** indicates a general overview of the wind energy and its application in wind industry. It also discuss the applications of different wind turbines and their usage in the oil and gas industry.
- **Chapter 5** gives the study on method and the tools used during the entire work of the project. The simulations are done in Matlab.
- **Chapter 6** represents the results of the simulation study.
- **Chapter 7** gives the conclusion and future work

Chapter 2

2. Literature Review

Pedersen (1997), performed a study on the both energy conservation and CO_2 gas separation from the gas turbine exhaust as the government has imposed tax on the emission of CO_2 gas. The studies showed that major constraints in the offshore installation is the weight and the volume occupied [4].

Mathew et al. (2011) has done a method for assessing the wind energy at a particular wind farm site. The method used is useful for the initial assessment of the wind power project. They found that two turbines with different rating, first turbine is found to generate more power. Here they have done detailed analysis on the energy density of the wind turbine and production of wind energy output based on the power curve of the wind turbine. Wind speed response of the wind turbine is well described in the paper [5].

Korpås, et al. (2012) in their paper, reached in the conclusion that offshore wind energy is the best option for supplying power to the oil and gas platforms. The paper presented the possibility of assuming the wind farm which is being operated in parallel with the gas turbines. They conducted a numerical simulations for fuel saving and emission reductions. It is being stated that operational strategy should be carefully selected for getting stable and economic operation. The work is similar to the present project where they presented the possibility of four 5 MW wind farm running in parallel with gas turbines with 40% wind energy penetration. They have done two operational strategy of gas turbines of load sharing and the start/stop strategy where one turbine is shut down [6]

In [7] , authors investigated a large scale of 95MW per day wind power system as grid power generation system. Here wind data analysis and load data over one year assessment is done in HOMER software tool. They have also investigated cost and payback period. And the results showed that there is 19% reduction in the emission of greenhouse gases.

Doherty (2004) presented a test system to show the effect during different modes of system operation during the wind power integration. The system was run for no wind and fuel saver cases. The impact on emission of various gases were also studied [8]

In [9], the work done is on reducing the CO_2 gas emission of wind power with various methods. They have shown the results from different countries. The results showed that the wind power reduced about 0.3-0.4 $MtCO_2/MWh$ when it is replaced with the gas.

In this thesis report many ideas were taken from the paper, He, et al. (2010) where they had done a research study which is a related work to the present report. In the paper, a 20 MW wind power integration was assessed in terms of savings in fuel consumption and CO_2/NO_x emission reduction. They have also done a case study of nine dynamic simulations, the electrical grid stability after wind power integration and then simulations has been compared to identify the maximum amount of wind power output for integration [10].

A case study on interconnected system with five oil and gas platforms and 100 MW wind farm was conducted in the paper by Aardal, et al. (2012). They have done a case study of wind power integration and without wind power integration to compare the results. The result obtained was 21-30% reduction in fuel consumption depending on the operational strategy of gas turbines. Simulations was also done for reduction in CO_2/NO_x emissions also [11].

In [12], a similar work is done where wind energy is integrated to reduce greenhouse gas emission. Here wind farm technology was employed with different platforms. Here system model consists of five oil and gas platforms connected to 100 MW offshore wind farm. Every platform contains two gas turbines running in parallel. Here two operational strategies was involved for the gas turbines. The results obtained was 21 to 33% reduction.

Chapter 3

3. System Model

3.1. Theoretical background

In the present world, oil and gas platforms connected to wind farms are gaining its priority. An offshore wind farm with floating turbines has become one of the realistic approach for offshore, deep water power production. There can be one or more platforms connected to each other and with the offshore wind farms. Each platforms consists of one or more gas turbines which can be or cannot be in operation. The grids are connected to theses energy generating system with the submerged cables. The electricity from the wind farm is collected together and sent through a transformer which is supplied to the distribution grid. The system of the project is shown in a schematic representation in the Figure 3.1.

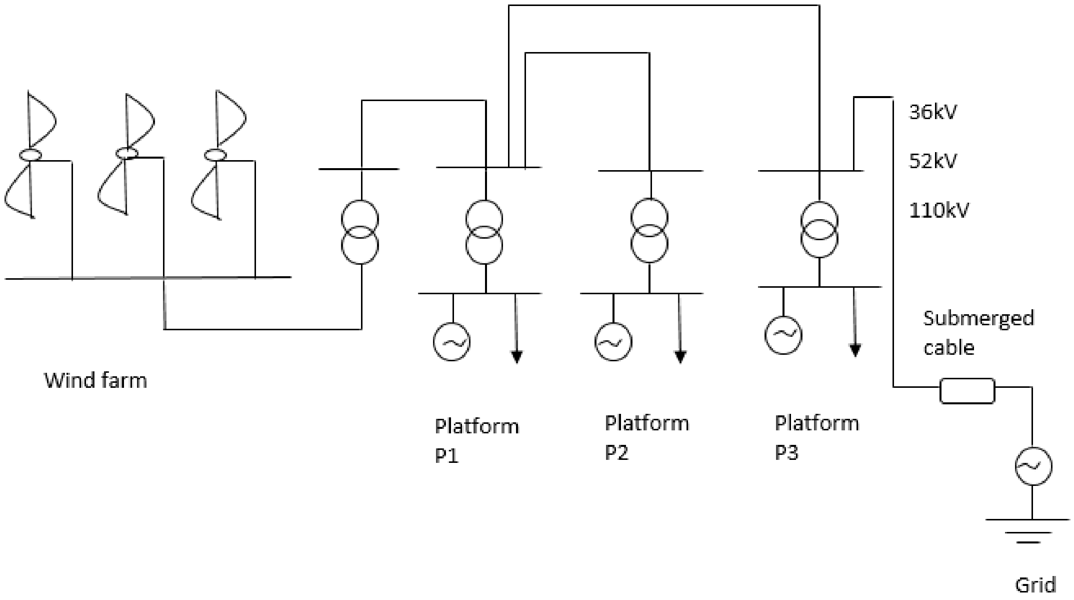

*Figure 3.1.*Single-line diagram of windfarm connected to oil and gas platform

3.2. Gas turbine

In offshore industries, petrochemical and in power generation, use of gas turbines is getting its shining period. They are also used in aerospace and in many industrial applications. A gas turbine is a combustion engine which converts the fuel fed into the engine into mechanical energy and further into electrical energy by a generator. Reliability, high efficiency, operating flexibility at low emissions make the gas turbines very attractive. Its low weight, compactness, multiple fuel application etc. makes it accepted stand for offshore platforms. Today gas turbines run on diesel fuel, methane, crude, natural gas, biomass gases etc. In the past 20 years there came an advanced growth in the gas turbine technology. It was in 1990's [13] that the electricity production using natural gas in power plants began to emerge. New technologies arrived as the growth started in new cooling systems, new coating, in material technology etc. Among all the plants, nuclear plant is the most expensive.

There are mainly two types of turbines [13] used in the gas turbine and they are radial-inflow type and axial-flow type. Gas turbines are much better than steam turbines as it can be easily installed and has less cost. The size of a typical gas turbine ranges from 0.25 to 500 MW. Gas turbines use the thermodynamic process known as Brayton cycle. For the electricity generation, turbines are connected to the generators. They usually run at very high rotational speed as 1200r.p.m or more. Major part of the power is used to run the compressor, auxiliary equipment and do other useful work. The power left is used as mechanical output. The figure shows the type of plants with their overall efficiency.

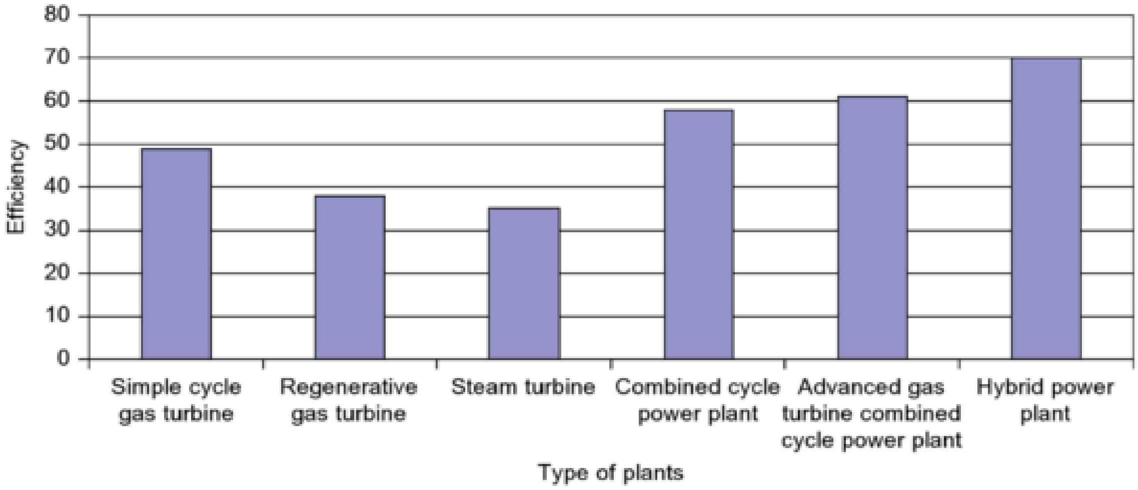

Figure 3.2. Efficiency of typical power plants [13]

3.3. Gas turbine performance.

Compressor, regenerators, combustors an turbine are the major part of a gas turbine which are connected together as shown in the Figure 3.3.

Engine sections

Different parts of a gas turbine are [14],

- **Compressor**
  It provides the air needed. For the turbine in an efficient manner. It has fourteen stages of rotor blades and stator vanes. To prevent the air leakage, seals are incorporated at the base of each row of vanes. Blades and vanes are placed at optimum angles so as to provide efficient air flow at rated speed.

- **Diffuser**
  Air passes through the exit guide vanes from the compressor and converts the radial air flow into straight-line flow. Next comes the diffuser section of the turbine whose function is aerodynamic. Apart from that, it provides structural support for the engine. It forms mounting for the fuel nozzles. It also provides support for the compressor bearings and seals.

- **Combustor**
  From the diffuser, the air reaches the combustor. It has to play the major role of controlling the burning of large amounts of fuel and air. It also has to position and control the fire so that the flame contact on the metal parts can be avoided. For the combustion process, primary air is used and the left air which is referred as secondary air is led to the liners in controlled manner. It releases the gas stream and controls the static pressure.

- **Turbine**
  Turbine converts the gaseous energy into mechanical energy by expanding the high pressure hot gas into low temperature and pressure which drives the compressor [15].

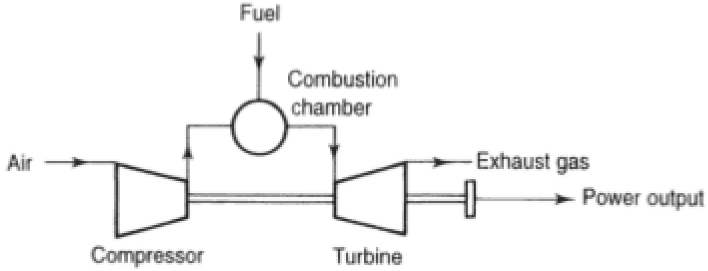

Figure 3.3. Simple gas turbine [15]

The key factors enhancing the performance of a gas turbine are

- Turbine inlet temperature
- Component efficiencies
- Compressor pressure ratio
- The performance of a gas turbine can be also be predicted from the specific heat (C_P) which depends on the fuel composition and the relative humidity of air.

The efficient conversion of fuel to energy is given by the efficiency and the heat rate. Efficiency is the ratio of the output power to the intake power in the plant. The overall plant efficiency includes the generators, transformer losses other parasitic losses and the gas turbine. In turbomachinery there are many efficiencies used such as adiabatic thermal efficiency, polytropic efficiency etc. Thermal efficiency can be defined as a comparison between the amounts of power in the fuel given in the system to the power yielded. Thermal efficiency is important as it effects the cost and the fuel consumption. It is theoretically represented as [13]

$$\eta_{th} = \frac{P}{W_f\, E_f} \tag{1}$$

Where,

η_{th} is the efficiency of the turbine

P is the power

E_f is the lower heating value

W_f is the mass flow rate

Heat rate is given as [13],

$$HP = \frac{1}{\eta_{th}} \tag{2}$$

Combination of plant cycles resulted in increases in their efficiency. The efficiency [13] of a combined-cycle power plant is around 55% whereas in steam turbine plants, the efficiency is around 35%. But in new technologies this efficiency range is made around 60-65%.

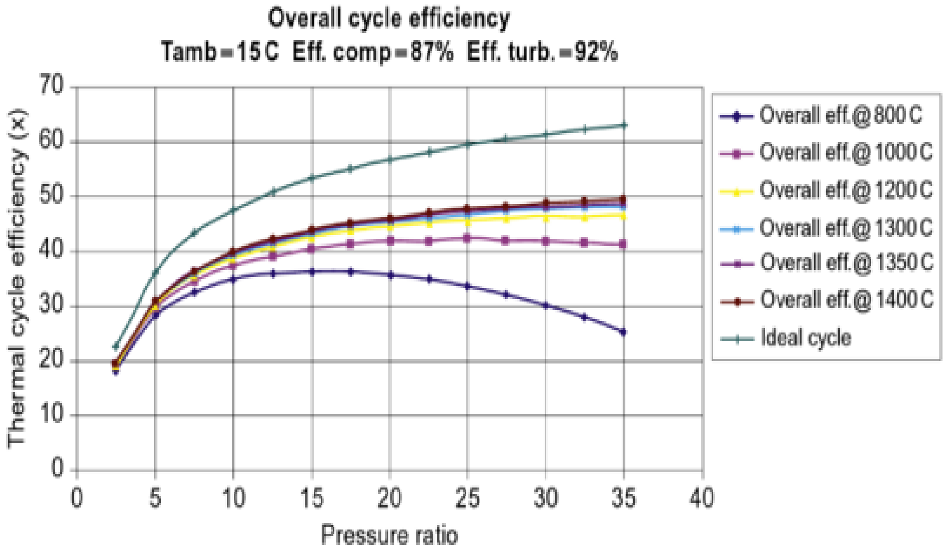

Figure 3.4. Overall cycle efficiency [13]

The major factors which effect the efficiency of the turbine is firing temperatures and pressure ratios. Pressure ratio is the ratio of the pressure measured at the front and rear of the compressor of the gas turbine. At a given temperature, the increase in pressure ratio increases the overall efficiency of the turbine. But at high pressure ratio, the operation range of the compressor tends to reduce which results in the drop in turbine performance and efficiency.

Better cooling technology and metallurgy of the blades of the turbine made the temperature to be high. In the design of the new turbines, steam is used as the better cooling agent. The most important parameters in the design of a gas turbine is high availability and reliability. Where availability is the percentage of available time of the plant to generate the power at a given period. Reliability is the percentage of time between the planned repairs. Reliability depends on the type of fuel, operating mode, temperatures and the maintenance process. Continuous start-ups and shut downs can create life threat to the unit.

There will be an increase in NO_x emission when the temperature is high. Hence the development of new dry NO_x combustors played a crucial role in reducing the NO_x emission [13]. The advanced gas turbines are digitally controlled and are online monitored. Now multiple fuel applications are in great demand. There are several types of gas turbines like industrial gas turbines, microturbines, small gas turbines, vehicular gas turbines etc.

3.4. Fuel consumption

Because of the affordable price and clean burning, natural gas makes it good choice of fuel in gas turbine. Preference of natural gas has increased its demand throughout the world. In Europe it is around 71% [13]. One of the most important characteristics is the heating value of the fuel. It is the amount of heat produced for a unit quantity of fuel during combustion. Fuel can have both higher and lower heating value. In new technology, diffusion combustors are replaced by dry low NO_x (DLN) combustors which help to reduce NO_x gas emissions. They create many environmental problems because during the combustion of various gases in the combustion, causes different pollutants to be expelled such as smoke, CO_2, oxides of Nitrogen, Carbon monoxide (CO) etc.

The amount of fuel given to the combustor controls the gas generator of the turbine. The speed of the gas generator only depends on the load applied. It has two operating constraints which are the maximum generator speed and the firing temperature. If the speed is lower, it causes the efficiency of the turbine to get reduced. As the fuel flow gets increased, either the temperature or the maximum speed is reached. Hence the gas turbine will be at its maximum power which enhances the maximum power production. Turbine speed mainly depends on the generator load and the ambient temperature. So at lower loads, the turbine speed is reduced which in turn reduces the efficiency of the gas turbine. Theoretically it is said that every engines has its highest exhaust temperature at full load. Modern gas turbines use variable stator and inlet vanes which can control the fuel flow without affecting the turbine speed

Chapter 4

4. Wind Energy

As fossil fuels create harmful gases in the atmosphere and nuclear power which generates radioactive waste, wind energy is different from them as it is clean an environment friendly. It is available in plenty and will remain in the future too which makes it suitable in energy technology. Wind energy is converted into electrical energy using several power converting machines. The project mainly focus on the utilization of wind power as the ultimate source of energy.

The main application of wind energy is in wind turbines. As the wind pass through the wind turbine, the blades start to rotate. But only a small portion of the wind power is converted into electrical power. A small change in the wind speed can cause a big change in the wind power output as it is proportional to the cubic power of the mean wind speed. Wind speed, wind direction, air density, swept area, height above the sea level, wind power density are the important parameters which helps to conduct wind resource assessment at a particular site.

4.1. Wind data analysis

Wind speed is proportional to the strength of the sunlight. It is higher during day time. Sinden [16] in his research study, done an analysis on the wind speed during many years and concluded that wind speed is higher in the winter and lower in summer as monthly average wind speed is inversely proportional to monthly average temperature. Wind speed varies with the wind height. The wind speed varies significantly with height because of the frictional resistance offered by the earth's surface. It is clearly illustrated in the Figure 4.1.

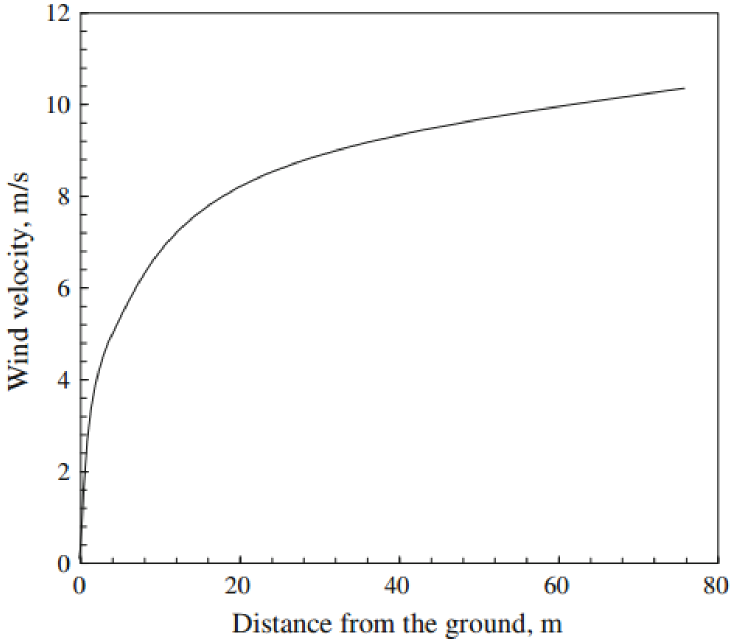

Figure 4.1. Variation of wind speed with height [5]

Wind speed frequency can be described by two important probability functions like Weibull and Rayleigh functions. Weibull distribution function, helps to describe the variation in the wind speed at a particular site. It is an illustration of the probability of mean wind speed appearing at a particular period of time. Many research studies are done based on Weibull distribution function however it is not much focused in the present project work. It is said that the wind speed at a given period t has two components, mean wind speed u and the instantaneous speed fluctuations u' (t) and it is expressed as [17],

$$u(t) = u + u'(t) \tag{3}$$

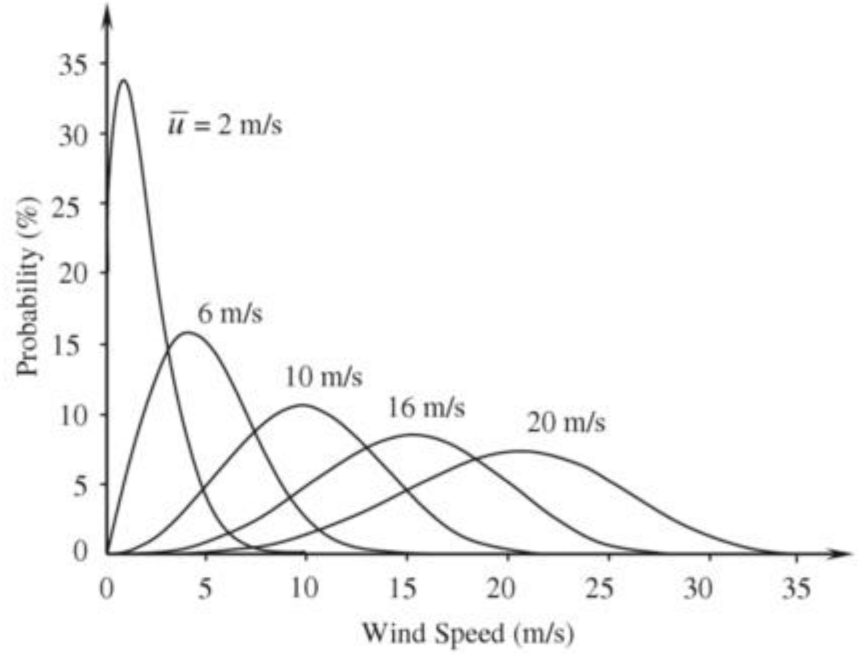

Figure 4.2. Weibull distributions for various mean wind speeds [17]

At a given site, wind speed usually varies its speed and direction. It can be seasonally variation and changes with the topography of earth surface. Wind data gives the observation of wind speed and its direction which can be taken for 10 minutes interval for one whole year and is expressed in time series and frequency based statistics. If the wind data is for a prolonged period then the wind power potential results will be even more reliable. Even though the accuracy cannot be more reliable. Usually the wind speed and its direction will be recorded by anemometer which will be mounted on the poles at a certain height around 15, 30 meters respectively.

4.2. Wind speed variation with height

As the height increases there is a considerable change in the wind speed too. At higher distance above the ground level, wind speed is higher because of the effect of surface features and as the height increases, the turbulence gets diminished. Usually only a fraction of the energy gets extracted. Theoretically [17] total wind energy extraction from the wind turbine can be expressed by the given equation,

$$E_a = 0.5\rho\, v^3 A \qquad (4)$$

Where, E_a is the total wind energy, ρ is the air density kg/m^3, A is the area where the wind speed is reduced. The equation gives us the idea that the wind power output increase with the cube of the wind speed and linearly with density and area. Before a project is being initiated first we have to measure the wind speed over a given period at the particular site.

4.3. Energy density

The available wind power output from the wind turbine for a velocity V, per unit rotor area is shown in the equation,

$$P_v = {}^1\!/_2\, \rho_a v^3 \qquad (5)$$

Where,

P_v is the power output
ρ_a is the density of air
v is the velocity of wind [5]

4.4. Power curve

Performance of a wind turbine can be evaluated by the power curve. Power curve shows the power output of the turbine as a function of mean wind speed. At low wind speed called cut-in speed, wind output will be less. The wind power gradually increases as the wind speed increases and reaches at a particular saturation level where the wind power output is at its maximum value. It is known as the rated power. . Due to the activation of power control, further increase in the wind speed will not alter the power output.

Cut-out speed is the maximum speed above which can cause damage to the turbine and hence it will have to shut down at this speed. So cut-in and cut-out speeds are the two operating point of the wind turbine

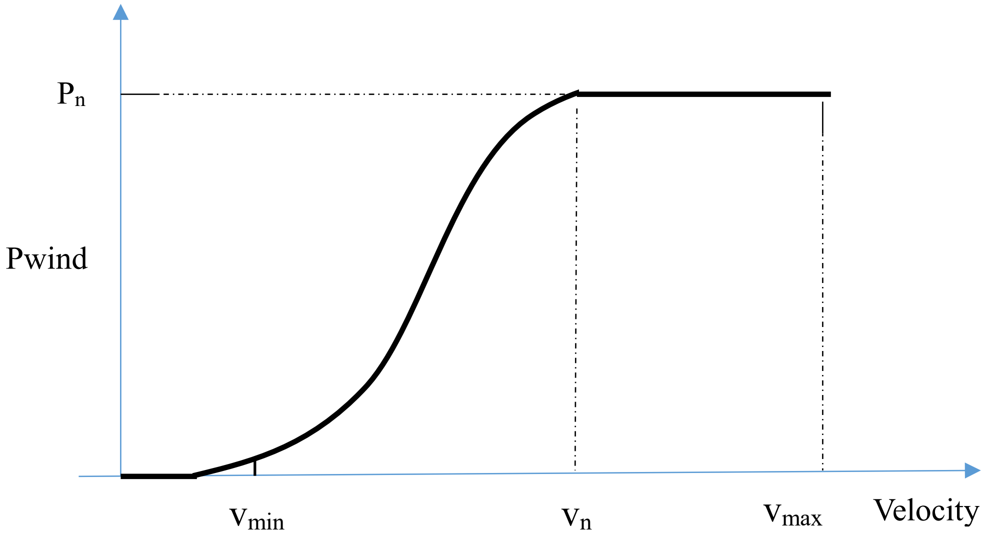

Figure 4.3. Power curve of a typical wind turbine

4.5. Capacity Factor

Capacity factor is an important parameter of a wind turbine as it gives the measure of actual wind power output at a given period of time divided by its power output for the turbine operated during the entire period of time. It mainly depends on the blade pitch angle and specific wind conditions at a particular site. The figure shows the relation between the C_p and tip speed ratio. Usually capacity factor will be around 0.25 to 0.30. In modern wind turbines, C_p wil be around 0.5. It is found that offshore wind turbines have higher capacity factors than the same used in the on shore sites. Theoretically, maximum C_p is given by the Betz limit [13],

$$C_{pmax} = \frac{16}{27} = 0.593 \qquad (6)$$

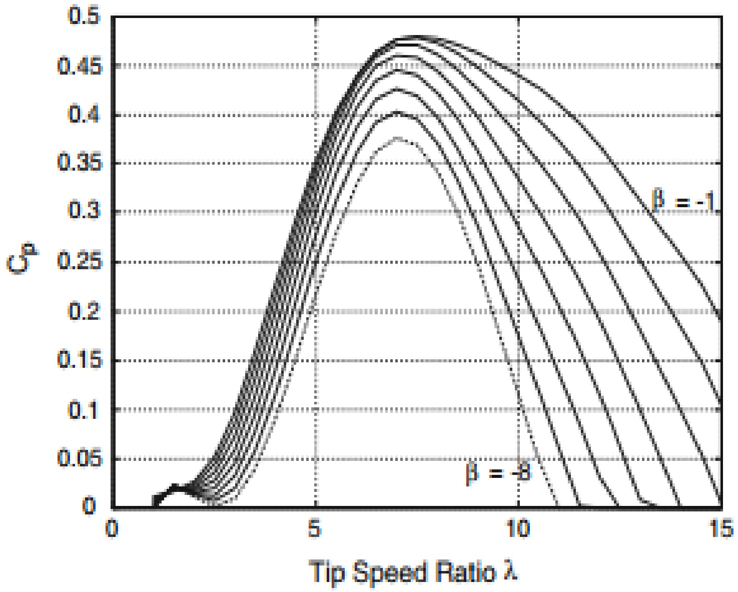

Figure 4.4.C_p as a function of tip speed ratio [13]

4.6. Wind turbine

One of the most prominent renewable energy in the world is wind energy. In 1888 [17], Charles Brush designed and built the first automatically operating wind turbine in the world. A wind turbine captures the wind energy at its fullest form and then converts the kinetic energy into electrical energy. When the wind resource is good, then the electricity generation also becomes good. The wind power integration from the wind farm helps to save the fuel gas and CO_2/NO_x gas emissions. In recent centuries many remarkable advance has been done in wind turbine technology which include minimizing the cost, improving the output and increasing the efficiency and reliability. Wind turbines have their applications either in off grid or on grid applications.

By 20th century many small wind farms were developed which were used in farms, household, and even connected to distribution grids. Many researches and studies led to the new technology which created several megawatts wind turbine in the present world. Today there are two types of wind turbines in use. They are horizontal-axis design and vertical-axis design. Advantage of vertical axis wind turbine is that they need no yaw control. Horizontal-axis wind turbines are used commonly today which have two or three blades with these blades facing into the wind. High turbine efficiency, low cut-in speeds, low cost and high power density makes these turbines even more efficient in the markets.

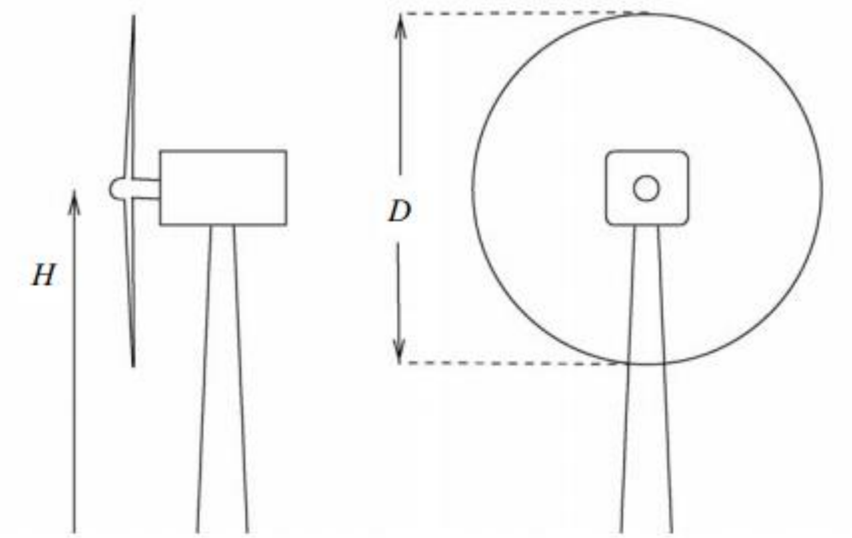

Figure 4.5. Horizontal-axis Wind Turbine [18]

There are micro, small, large and ultra large wind turbines available. Small wind turbines are those of 100 kilowatts which are used in home, farm, other small scale business purpose etc. Wind turbines have their size ranging from 100 kilowatts to several megawatts. They form together a wind farm which produce bulk power to the grid. Especially in offshore wind farms, they use megawatts wind turbines. They provide electricity to utility grids which again supply them to the consumers. In order to develop a particular wind turbine supported electricity distribution system we have to initially check and do an analysis study on the wind resource at the particular site, permitting and sitting and the transmission study for several years. Mostly the wind projects are designed for about 20 to 30 years life time [20].

4.7. Layout of Wind Turbine

Offshore wind turbine is similar to the onshore wind turbine in the structural design only with some adjustments in their design in order to cope with strong sea conditions. The main part of a wind turbine is tower, hub, nacelle and the blades. The nacelle is supported at a certain height by the cylindrical shaped tower which is made up of steel for offshore wind turbines. The nacelle is the heart of the turbine as it forms a big box consisting of all power producing systems. Power capacity is proportional to the blade dimension. Today the length of the turbines differ from 40 to 60 meters. In case of strong winds, wind turbines are provided with brake which protect the blades from running too fast and getting damaged. For better performance of the turbine the wind speed should be at a speed of 12 to 15 miles per second. Now many of the manufactures produce wind turbines of 4 to 8 MW ranging [21].

Wind turbines have mostly two or three of rotating blades, which look like propeller blades. Rotational speed of a wind turbine rotor will be around 20 to 50 rpm. Since the speed of the generator shaft is 1000 to 3000 rpm, a gear box is to be fixed between them. But some turbines are provided with multipole generators which can rotate slowly and so no gear box is needed. Height and the rotor diameter is very important as the wind speed increases with the height and rotor diameter gives the area for getting the available wind power as shown in the equation. A wind vane will be mounted on the turbine so as to measure the direction of the wind.

Power electronics is being developed in the wind turbines. The signal is then coupled with the nacelle. Power electronic converters are also used in the variable speed wind turbines. Control systems is to be involved in the turbines for extracting maximum wind power and protecting it from high wind and stress. Control system in the turbine helps to avoid the damage as it controls the output power at allowable wind fluctuations. Today modern wind turbines involve hydraulic control and electric control system. Four main control techniques are [21],

- Stall control
- Pitch control
- Turbine yawning
- Speed variation

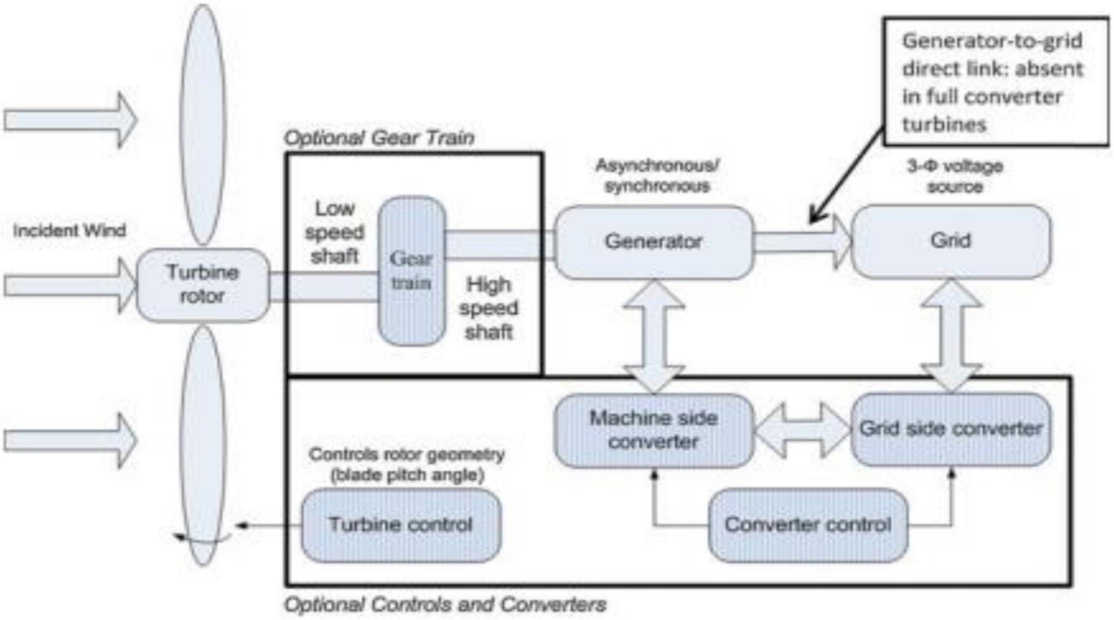

Figure 4.6. Block diagram of a typical wind turbine [21]

Based on different generator technologies, wind turbines are classified as,

- Fixed-speed wind turbines
- Variable-slip wind turbines
- Doubly fed induction generator wind turbines(DFIG)
- Full converter wind turbines

4.8. Doubly fed induction generator wind turbines (DFIG)

They employ a back-to-back AC/DC/AC converter in the rotor circuit to recover the slip power so as to solve the power loss problem in the rotor circuit. Flux-vector control of rotor currents helps in maximum wind power extraction. Major problem of these turbine are that of its high cost and complexity.

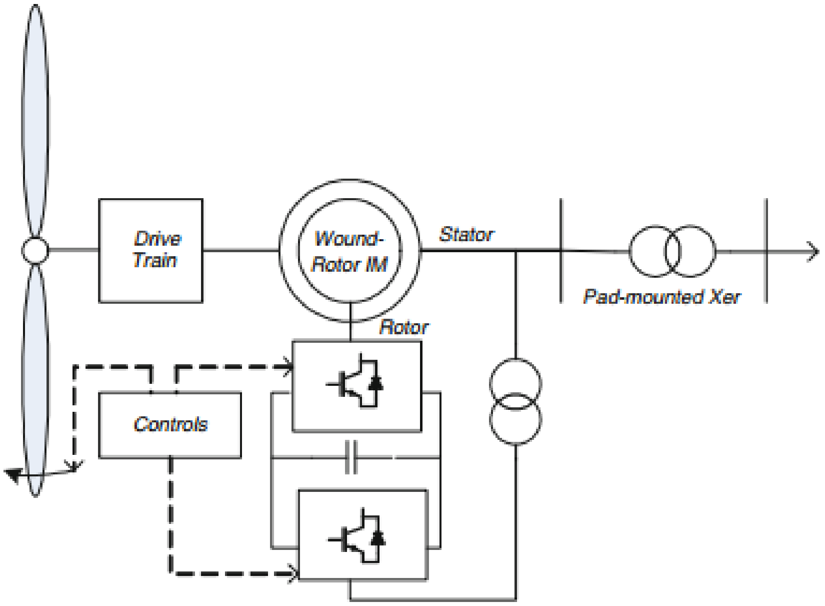

Figure 4.7. Doubly fed induction generator wind turbines (DFIG) [21]

4.9. Full converter wind turbines

They employ a back-to-back AC/DC/AC converter for the power to flow from the wind turbine to the grid. There is no direct connection to the grid is not directly connected. These turbines use high pole count permanent magnet synchronous generators so that they allow the elimination of the gearbox and increase reliability. These turbines are also expensive. The schematic diagram is shown in the figure.

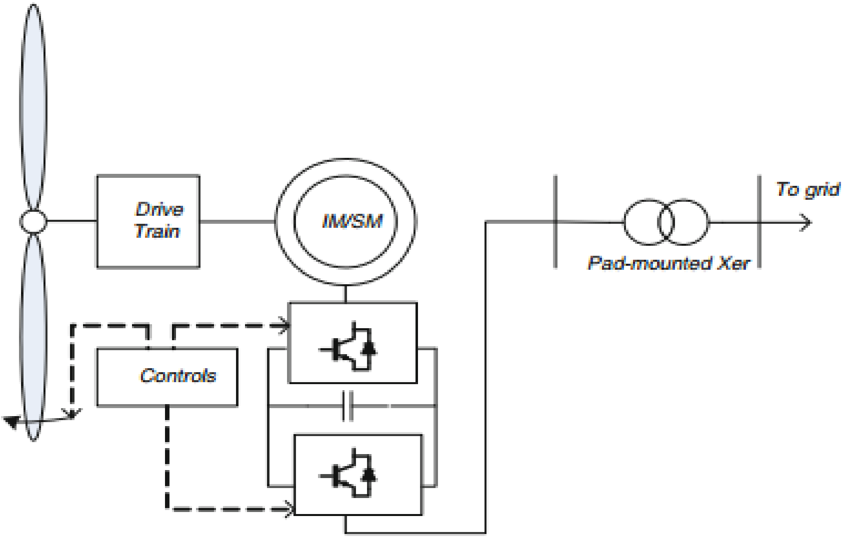

Figure 4.8. Full converter wind turbines [21]

4.10. Fixed-speed wind turbines

They employ squirrel-cage induction machines directly connected to the grid. They can get torque spikes which may damage the mechanical subsystems within the turbine and may cause electrical transients. These turbines employ blade pitch regulation in order to control the power at high wind speeds. They are relatively robust and reliable and reactive power compensation is required.

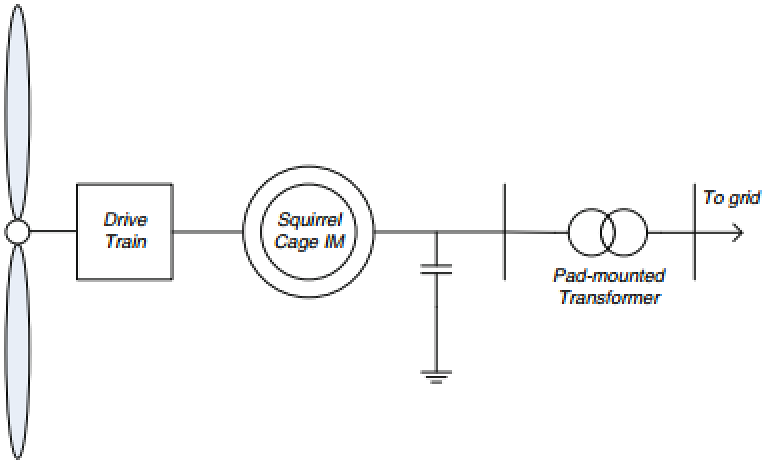

Figure 4.9. Fixed-speed wind turbines [21]

4.11. Variable-slip wind turbines

These wind turbines operate at a wide range of rotor speeds and employ blade-pitching for power regulation. Power and Speed controls helps to extract more energy. Variable-slip turbines use wound rotor induction machines. The rotor is connected to an AC–DC converter and a fixed resistance. Here, in the external rotor circuit resistance power is lost as heat and hence a controller may be employed.

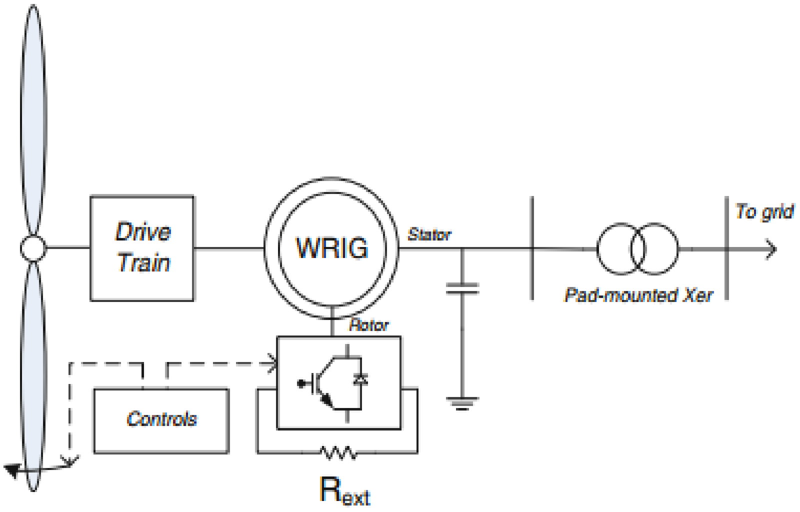

Figure 4.10. Variable-slip wind turbines [21]

At present in the world, Denmark is the highest wind energy consuming country based on the per capita. In 2014 [2], around 860kW was installed whereas other EU-28 countries installed only 250kW. As there came an increase in the capacity of the wind turbine, correspondingly the height, weight and volume of the machine increased consequently. Increase in the hub height and weight caused difficulties in installation industry as it requires bigger lifting capacities to install them carefully. Usually the installation of the wind turbine is done after the construction of the foundation base.

By The European offshore wind industry key trends and statistics 2014 [2], the report shows the dramatic increase in the usage of wind turbine in the Europe. UK is found to be the largest in the market to install the wind turbines followed by Denmark, Netherlands, and Germany. Full scale floating turbine was owned by Portugal and Norway as per the report.

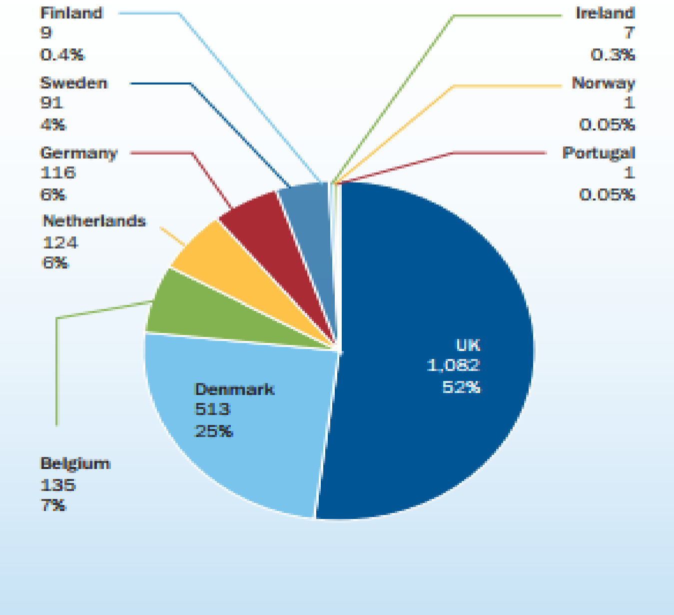

Figure 4.11. Installed turbines by different European country [2]

4.12. Hywind turbine

It was Heronemus [22] in 1972 who proposed the design of offshore wind turbine. The idea of floating concept was done by him which was used to produce hydrogen to deliver to a pipeline at the shore. Hywind [23] technology is the emerging technology in the deep water sites. Hywind turbine is an offshore floating wind turbine which is being attached on a floating surface in water depths in order to produce electricity. It is constructed in such a way that it can withstand strong waves and winds to produce electricity effectively.

Hywind turbine is designed for being installed at water depth of 120-700m. It captures the wind energy in the deep water sites and convert it into electricity using the generators. In 2009, the first Hywind turbine of 2.3 MW was being installed at North Sea near Norway by Statoil. The design of this Hywind turbine include the floating spar which consists of heavy ballasts hung on a long cylindrical tank which provide the buoyancy. They are used at water depth of 100 meters deep and the rotor diameter is about 150meters. It is still continuing in work and producing electricity for the Norwegian Grid. The major challenge is the coordination needed for the development of transmission lines.

4.13. Challenges

Even though wind turbines have many advantages in the power generation but there are some challenges and problems which cannot be ignored. One major challenge is its installation. In order to improve the installation process, there is a big challenge of identifying the factors that leads to difficulties in installation performance. The wind and sea behavior also limits the safe installation. While selecting the site, it is said that the site should have good wind speeds and significantly wave heights too. Another major impact is on environment as poorly site wind energy facilities can affect the migration of birds. It can also create noise problems. Storage technology still has its problems which can limit the application of wind energy.

Chapter 5

5. Methodology

At the platform, the energy demand is met by running two gas turbines by keeping one gas turbine as back-up. The gas turbines are having 13 MW capacity each and the fuel details are same for all gas turbines. Methodologies for integration of wind turbine to reduce greenhouse gases and fuel savings are described here.

Wind data analysis

Usually the oil and gas platforms are at the water depth of hundred meters. Wind fluctuates seasonally and it is usually good near offshore platforms because of greater average wind speed and reduced turbulence intensity [10]. Average wind speed is found be often around 10-14 m/s near the platforms and the wind turbines work for the wind speed of 4- 26 m/s. When the wind speed goes beyond the maximum speed, wind converters are to be shut off because it can cause damages. In the present work, the oil and gas platform is situated in the North Sea and the wind data provided by the manufacturer is taken from the site at the North Sea.

Measured wind speed data obtained is in time series format where each point represents the wind speed corresponding to that particular period of time. Usually wind speed data is available both in time series format and in frequency distribution format. In the wind data used in the report has the wind speed measured for one whole year for each one hour time period. The *Table 1* shows the sample of wind speed measured for a particular period of time.

Table 1. Wind speed series taken near a platform

Time (Hour)	Speed (m/s)
1	23.83
2	24.84
3	26.06
4	25.86
5	24.73
6	23.63
7	23.51

8	23.11
9	22.75
10	22.73
11	23.02
12	23.49

Wind power is generated based on the wind speed data. An example of wind power production from 2.3 MW Hywind turbine is shown in Figure 5.1. Here, the wind speed taken is for ten minutes interval for three days.

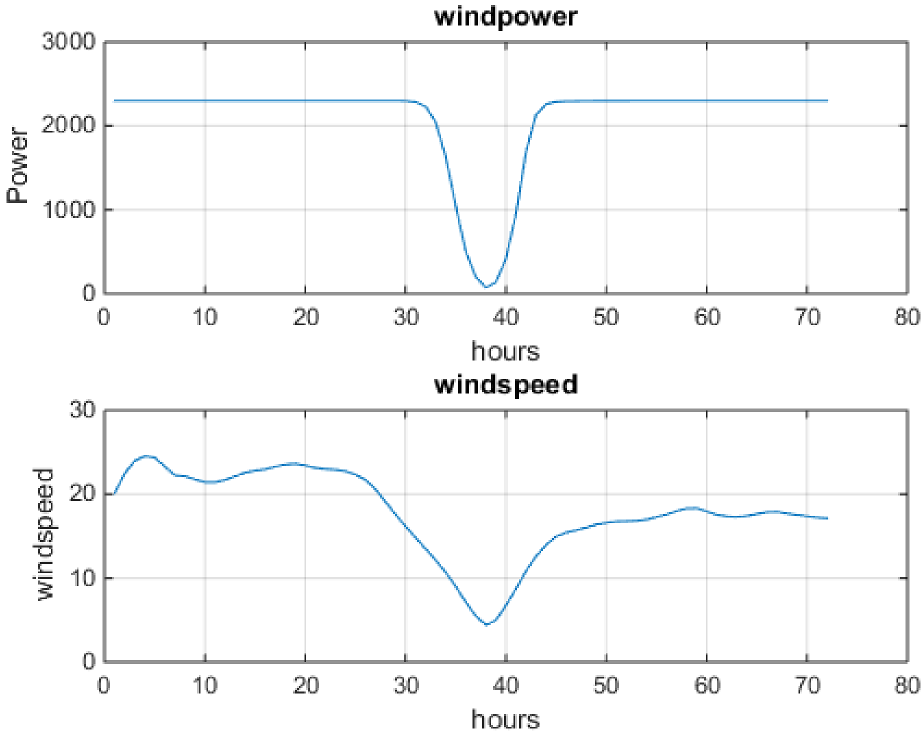

Figure 5.1. Wind power and wind speed as a function of hours

Wind tower height plays a major role in the wind power generation. In the case study analysis, a reference height of 100m of hub height is used for 2.3 MW Hywind turbine and 150m is assumed for 6 MW Hywind turbine [24]. For 2.3 MW wind turbine, since the turbine height is at 66m, the wind speed was re-calculated for the actual turbine height. This is done using the wind profile power law. Two forms of wind power profile is used [25]. They are

- Power law

$$u = ut \times \left(z/_{zt}\right)^{\alpha} \tag{7}$$

- Logarithmic wind profile

$$\alpha = \frac{\ln(u/ut)}{\ln(z/zt)} \tag{8}$$

In the present report, power law is used to calculate the wind turbine height,

Where,
u is the wind velocity recalculated for 66 meter turbine height,
ut is the wind velocity at reference height of 100m,
z is the actual height at 66m,
zt is the reference height of 100m,
α is the empirically derived coefficient with the value of 0.143

For 6 MW wind turbine, in the data provided by the manufacturer, the data contained the dimension of rotor diameter with 154 meter. Hence the wind turbine height was assumed as 150 meters height [24]. Using the wind profile law, wind speed was re-calculated for 150 meters height.

Qualitative estimation of wind power from the wind speed

The power output is calculated using the power curve (Figure 5.2) for the wind turbine given by manufacturer. The input is a series of wind speed which was taken in a platform at North Sea. The simulations are carried out for two cases for both 2.3MW and 6 MW wind turbine.

Initially case study was run for 2.3 MW (Siemens) and then for 6 MW (Senvion) Hywind turbines. Simulation were run based on the data provided by the manufacturer. The methodology used was

- Power curve estimation
  The power output from the wind turbine depends on the wind speed. The simulation can be done in Matlab [26] simulation. A code was generated to analysis the wind speed which was measured near the platform. In the data provided, wind speed was measured hourly and was taken for one whole year. The wind turbine starts rotating with a minimum wind speed of 13m/s.

  Power curve well describes the wind turbine performance which shows that how much power output from the wind turbine depends on the wind speed [27]. Code was generated for the power curve simulation so that it is possible to get the available wind power for any wind speeds. The real wind power curve was given by the manufacturer for a particular number of wind speeds. The real power curve is shown in Figure 5.2.

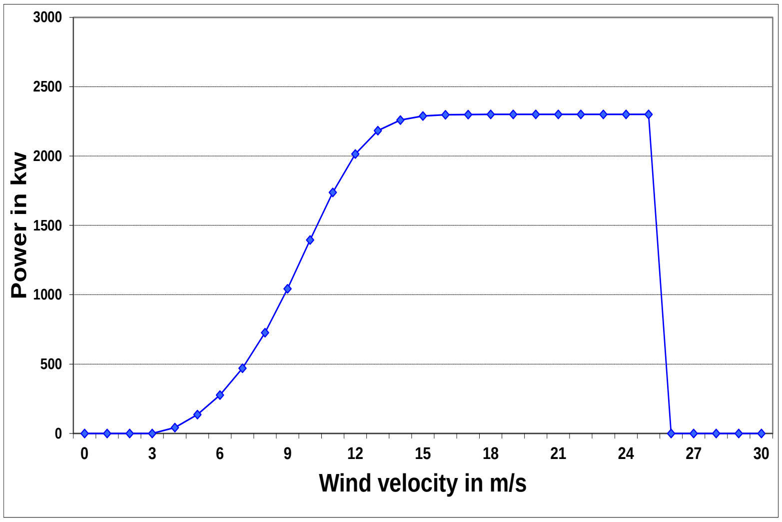

Figure 5.2. Real power curve for 2.3 MW [28]

At 66 meter turbine height, a power curve is generated for a series of wind speed data for one whole year for a platform in North Sea. Corresponding to the real power curve, simulated power curve in Matlab was interpolated since the generated power curve is not similar to the real power curve provided by the manufacturer. A cubic polynomial function was derived as an analytical expression which is given in equation (9)

$$P_{wind} = 0 \qquad for\ v < v_{min}$$

$$P_{wind} = P_n\left(-6.23\left({}^{v}/_{v_n}\right)^3 + 11.62\left({}^{v}/_{v_n}\right)^2 - 5.07\left({}^{v}/_{v_n}\right) + 0.68\right) \qquad for\ v_{min} \le v \le v_n$$

$$P_{wind} = P_n \qquad for\ v_n \le v \le v_{max}$$

$$P_{wind} = 0 \qquad for\ v > v_{max} \tag{9}$$

Where,

v_n is the nominal wind speed
v_{min} is cut-in wind speed
v_{max} is the maximum wind speed
P_n is the rated power

Interpolated curve for both 2.3 MW and 6 MW Hywind turbine is given in the Figure 5.3 and Figure 5.4. In the figures, real curve given by the manufacturer is indicated by green circled line and the interpolated curve is indicated by red line. In 2.3 MW interpolated curve, there is a small inclination before the power output falls to zero. But in the case of 6 MW, it is a straight line.

For 6 MW wind turbine, wind power for cubic region when vmin $\le$ v $\le$ v_n the given formula is given by,

$$P_{wind} = P_n\left(-2.76\left({}^{v}/_{v_n}\right)^3 + 6.29\left({}^{v}/_{v_n}\right)^2 - 2.87\left({}^{v}/_{v_n}\right) + 0.383\right) \qquad for\ v_{min} \le v \le v_n (10)$$

Based on the real power curve maximum, minimum and rated wind speed is assumed as for 2.3 MW,

v_{min}=4m/s,
v_{max}=25m/s,
v_n=15m/s,
P_n=2.3 MW

For 6 MW,

v_{min}=4m/s,
v_{max}=25m/s,
v_n=12m/s,
P_n=6 MW

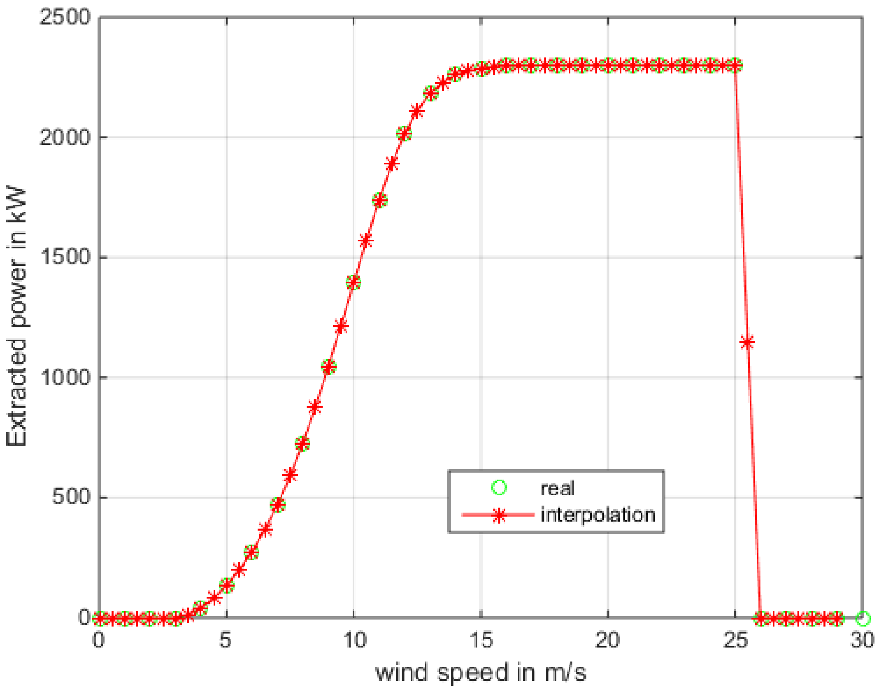

Figure 5.3. Interpolated curve for 2.3 MW wind turbine [28]

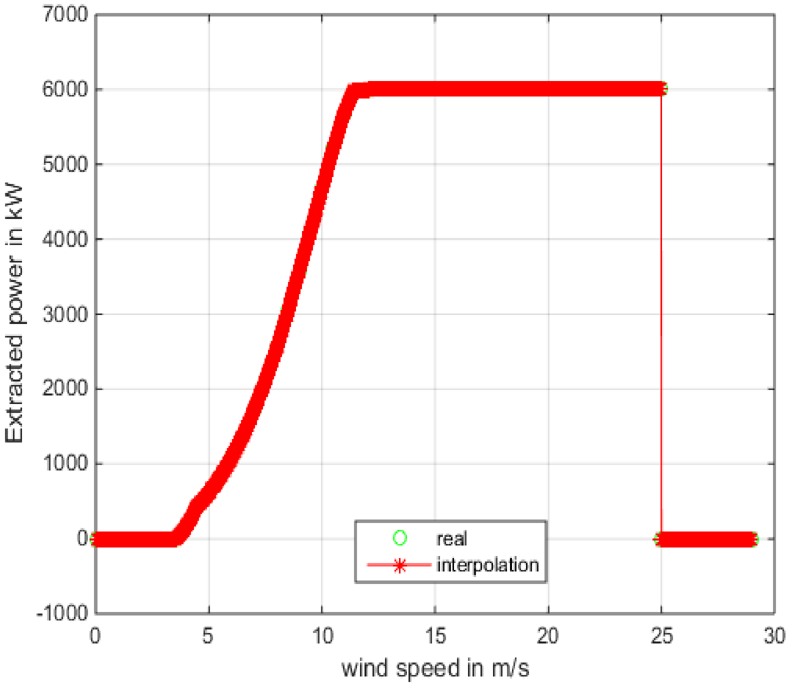

Figure 5.4. Interpolated curve for 6 MW wind turbine [28]

Based on this interpolated curve, extractable wind power from the wind turbine is generated. The wind power extracted for both 2.3 MW and 6MW Hywind turbine is given in Figure 5.5 and Figure 5.6. From the graph, when the wind velocity is below the minimum wind speed (v_{min}), the power from the wind turbine is zero. When the wind velocity is between the cut-in wind speed ($\mathrm{v_{min}}$) and rated speed (v_n), wind power is given by the equation (2). A third order polynomial function is used here. When the wind speed is between rated speeds (v_n) and cut-out wind speed (v_{max}), the wind power becomes equal to rated power. Here the power remains stable irrespective of the changes in the wind speed. The wind speed falls to zero when the wind speed is beyond maximum wind speed (v_{max}).

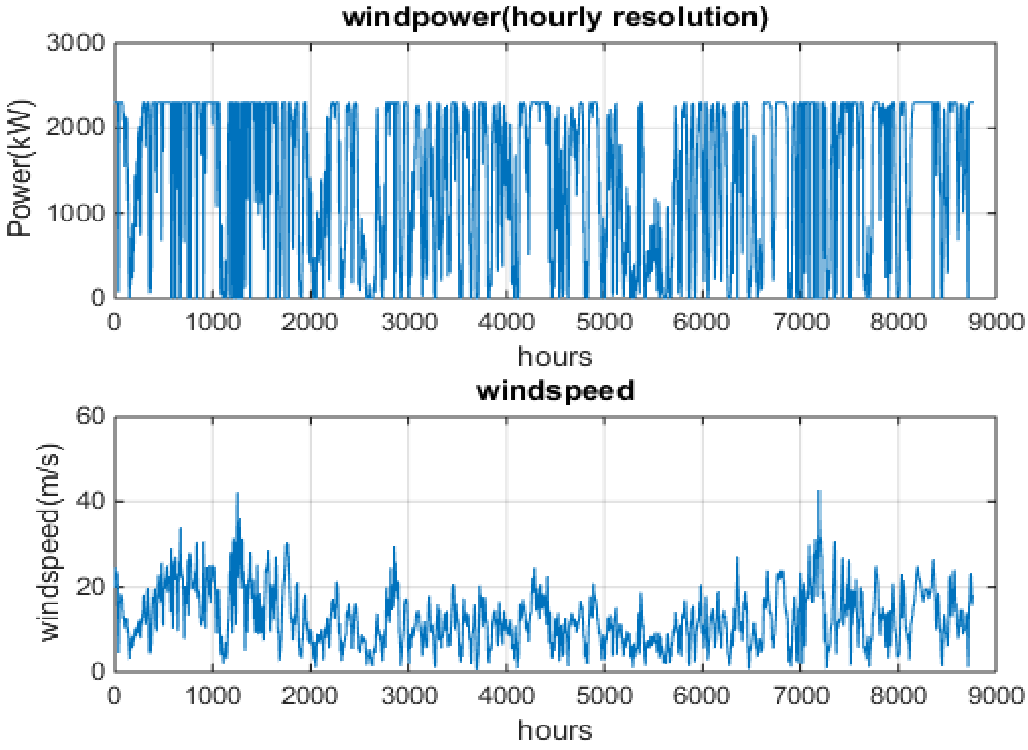

Figure 5.5. Extractable wind power for 2.3 MW [28]

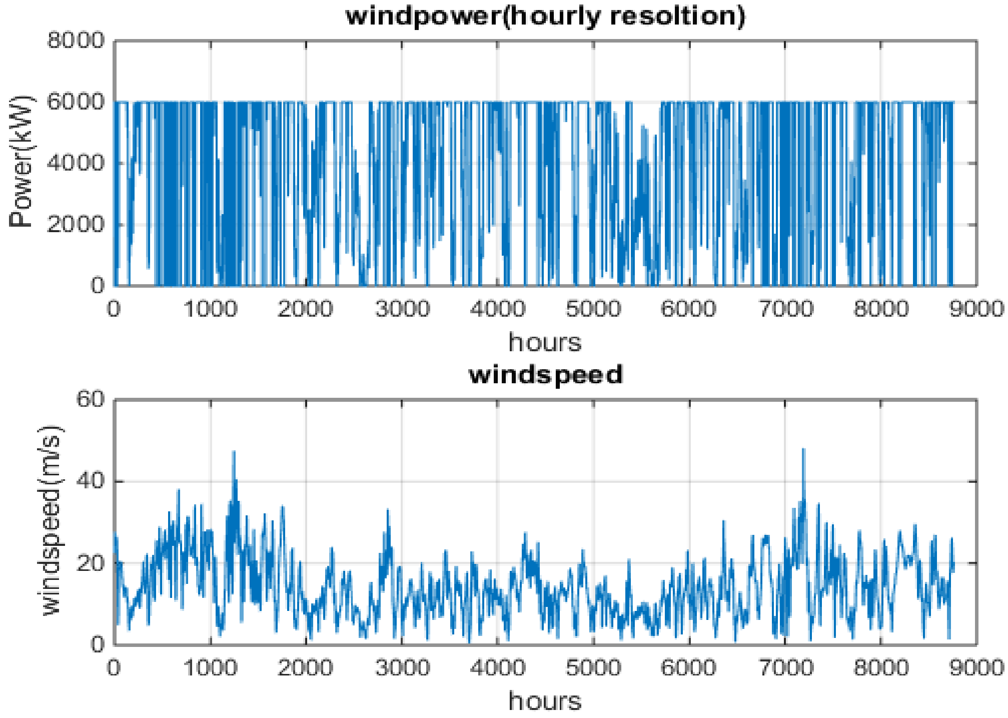

Figure 5.6. Extractable wind power for 6 MW [28]

Using a distribution function for 10 minutes variation, intermediate wind velocity for this 10 minutes interval for one year is generated for the wind speed series obtained from the platform at North Sea. The histogram of the wind velocity time series is shown in Figure 5.7. It shows that maximum frequency is between 10-15 m/s. This statistical distribution gives the calculation of variation in wind energy. Histogram of the wind speed series is done using 1 m/s bins.

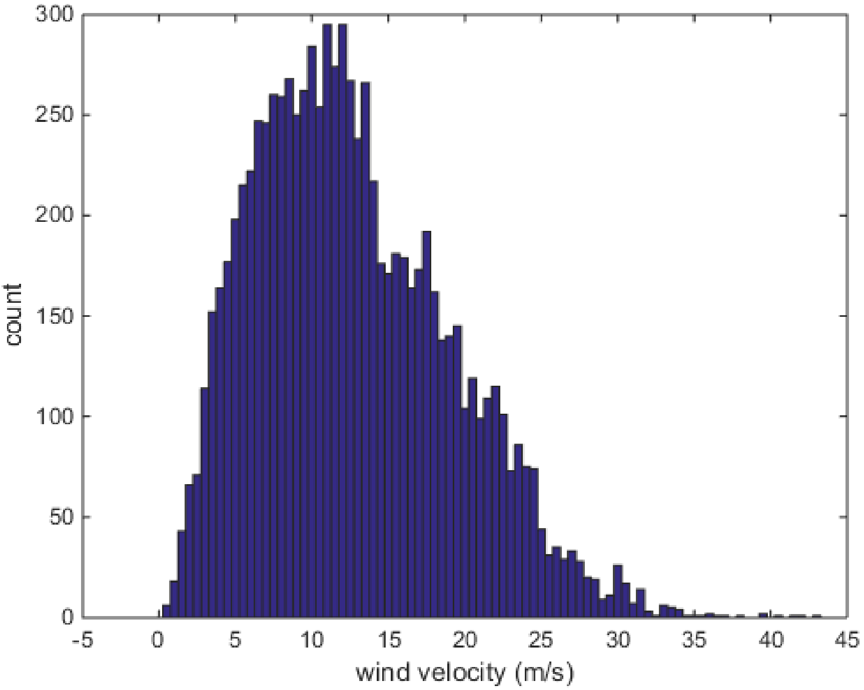

Figure 5.7. Histogram of wind speed series for 2.3 MW wind turbine

In Matlab, capacity factor is calculated based on one year data and is calculated by dividing the average power by the rated power. It is shown in the equation

$$\text{Capacity factor} = \text{average power}/\ \text{rated power} \tag{11}$$

Table 2. Capacity factor and average power of both the wind turbines

	2.3 MW	6MW
Average power	1.24MW	3.98MW
Capacity Factor	54.10%	66.49%

Chapter 6

6. Results

The wind farm technology helps in saving the fuel and helps in reducing the emissions. Various results of the Matlab simulations such as amount of wind power generated, zero and maximum power production, electrical load consumption, fuel savings and CO_2/NO_x reduction for 2.3 MW and 6 MW wind turbines and operational strategies are discussed.

The simulation were done for effectiveness of integration of Hywind turbines runs parallel with gas turbines present at platform. The operational strategies of the gas turbines and saving the fuel is measured by doing a case study on the oil and gas platform at North Sea. Logistic simulations shows that considerable amount of greenhouse gas emission is reduced mainly for start/stop operational strategy of the gas turbines.

6.1. Wind power production

From the interpolated power curve, wind power output was estimated over one year. From the simulation, total power production, zero power production and maximum power production was calculated. The power produced from 2.3 MW and 6 MW Hywind turbines is tabulated are shown in *Table 3* after the simulation run for one year.

Table 3. Wind power production for 2.3 MW and 6 MW wind turbines [28]

	2.3 MW	**6 MW**
Total hours for zero power production	528(6%)	1056(12%)
Total hours for maximum power production	1489(17%)	3999(45.64%)
Total wind energy along the year	12.62GWh	36.005GWh

It is found that there is 6 percent greater in the zero power production than that of 2.3 MW wind turbine. Maximum power generation for 6 MW wind turbine is 28.64 percent greater than that of 2.3 MW. The total wind energy produced for 6 MW is greater than that of 2.3 MW wind turbine over one year.

From the data provided, the fuel consumption at the platform varies between 10 to 20 MW over one whole year. It is run in natural gas. In the data some load is considered to be bad inputs in which some data are missing. Hence these missing data are estimated by linear interpolation. As per Korpås [6] it is said that with no special criterion in operational strategy of the gas turbines, the high wind power can cause reduced operational efficiency.

For simulation a Matlab code was generated based on the time step series. Time step is taken as 1 hour for one whole year.

6.2. Electrical load consumption

Electrical load at the platform is simulated from the data provided by the manufacturer for one whole year. The data contained details of the actual load capacity and the power from the two generators running at the platform. The values are linearly interpolated as at certain situations there were bad inputs in the data. In the graph shown in Figure 6.1, blue and green lines represent the power from the gas turbines G1 and G2. Red color represents the total added load from both the 13 MW gas turbines. G1 represents the power from gas turbine 1 and G2 from gas turbine 2.

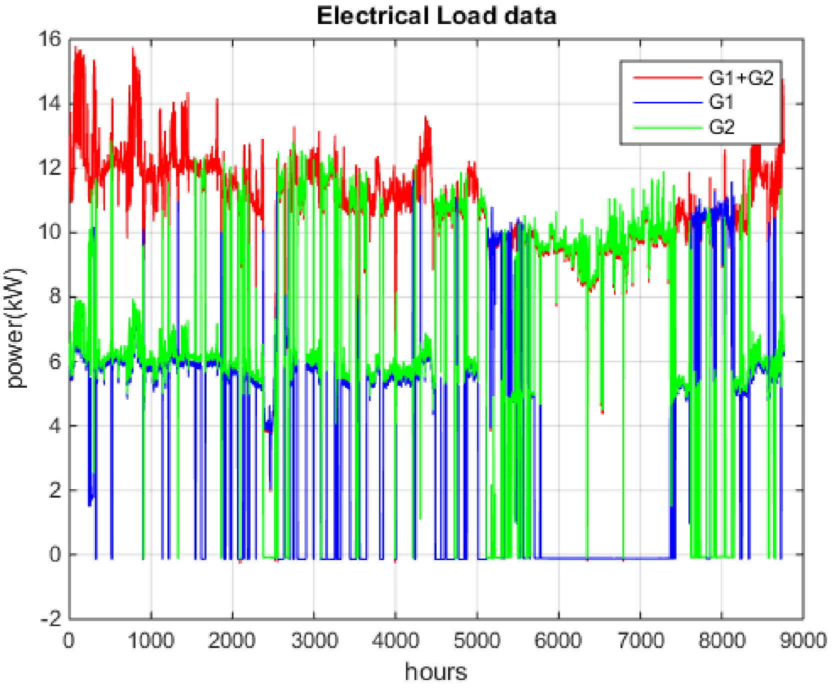

Figure 6.1. Electrical load as a function of hours over one year

For the estimation of CO_2 and NO_X gas emission and saving in fuel consumption, Matlab code was run to generate the extractable wind power depending on the wind speed. Fuel, CO_2 and NO_X gas emission details for gas turbine was provided by the manufacturer. This details are similar for both the gas turbines. This value was imported in Matlab and was interpolated correspondingly to the power at the platform. To get the savings in emission and fuel consumption, simulation was run with wind power integration. The actual load will be the available load after subtracting the wind power from the total load at the platform. Correspondingly greenhouse gas emission and fuel consumption was estimated and the results are compared with results of without wind power integration. The graph is shown in Figure 6.3 and Figure 6.5 for both the wind turbines.

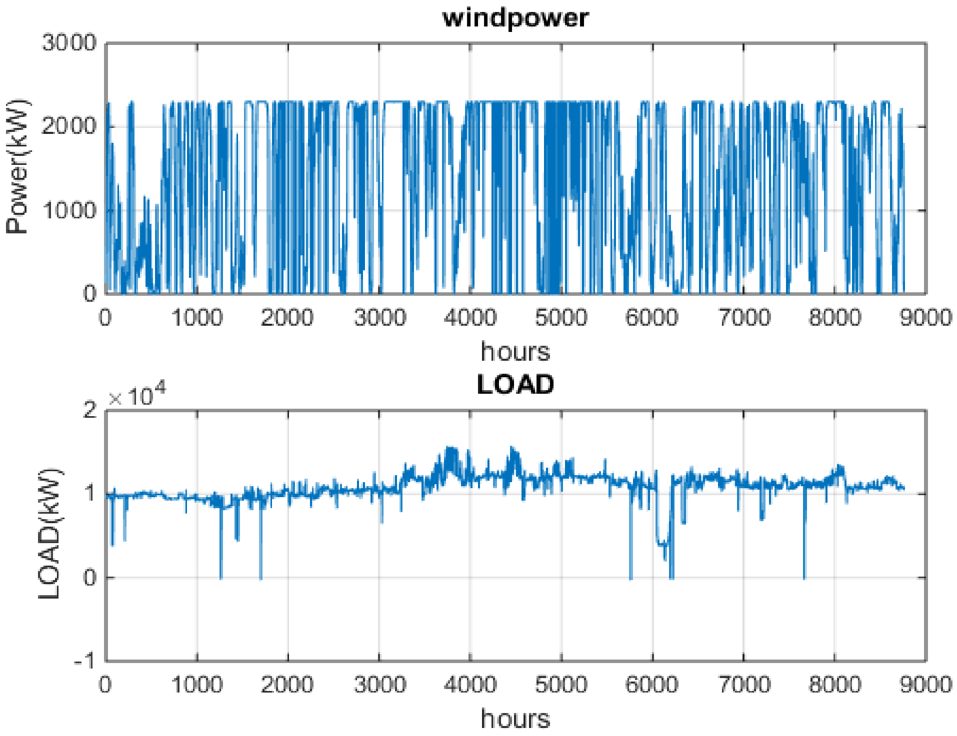

Figure 6.2. Time -series of wind power and load for 2.3 MW wind turbine [28]

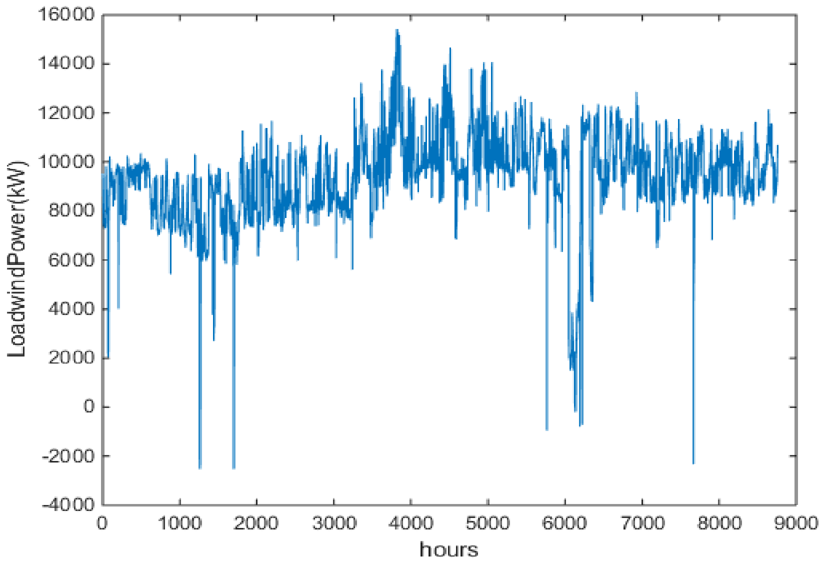

Figure 6.3. Load minus wind power for 2.3 MW wind turbine[28]

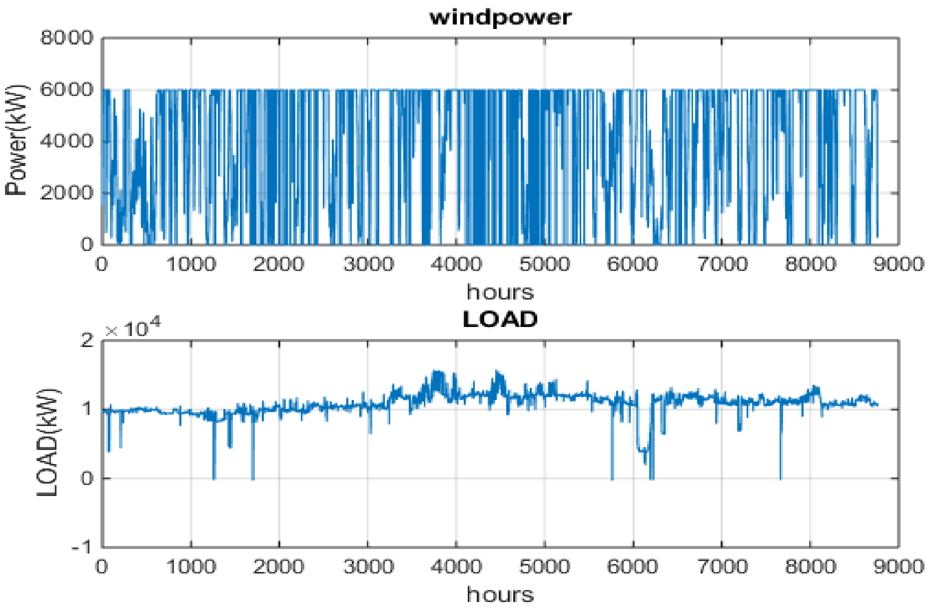

Figure 6.4. Time -series of wind power and load for 2.3 MW wind turbine [28]

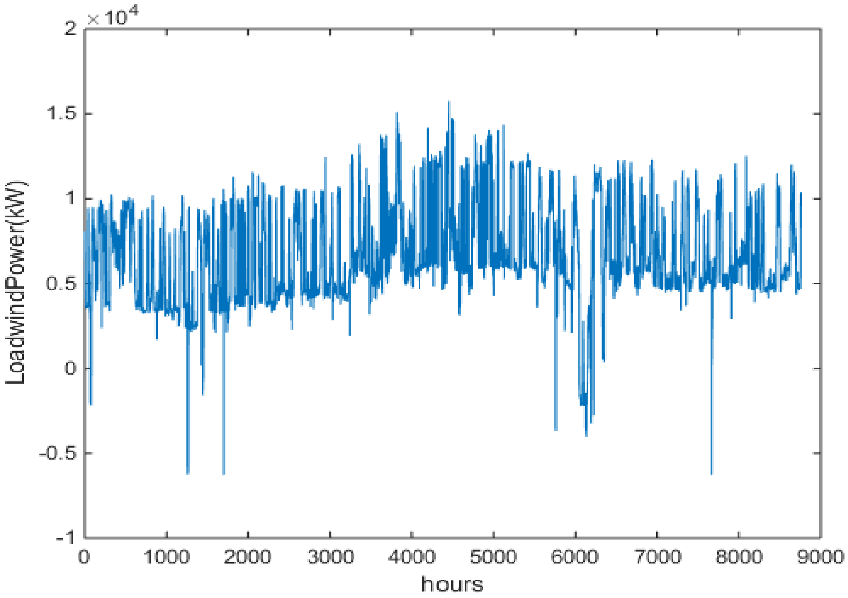

Figure 6.5. Load minus wind power for 6 MW wind turbine [28]

6.3. Operation strategy for gas turbines

The simulation for the operational strategy of the combined wind power gas system are done in Matlab simulation. The platforms are run by the gas turbines. The wind power system is always intended to cover the load. Mainly the platforms use the whole available wind power to cover the load. When the load demand exceeds then the gas turbines are run along with the wind turbines.

This helps to save the fuel consumption and reduce CO_2 and NO_x gas emissions. So there can be two operational strategy to run the gas turbines at the platforms [10],

1. To share the remaining load equally, it is called conventional operation. Here both the gas turbines are run parallel and in the following results, equally load sharing strategy is adopted where difference between the load and the wind power is simulated to get the savings.
2. In second strategy, any one of the gas turbine is shut down when it is not desired to cover the load and the other gas turbine runs with greater efficiency. It is also called fuel saving strategy. It is based on the time step so that the condition is satisfied,

$$P_{wind}(t) + P_{rated\ gas} > \max\left[P_{load}\left(t, t + t_{gas,start}\right)\right] + \Delta P_{margin\ wind} \times t_{gas,start} \quad (12)$$

Where,

$P_{wind}(t)$ is the wind power output
t is the time step (1 hour time interval is taken)
$P_{rated\ gas}$ is the rated power output of gas turbine
$t_{gas,start}$ is the startup time of gas turbine (15 minutes is taken)
$\Delta P_{margin\ wind}$ is the margin added to the load

During conventional operation, gas turbines run at low load which in turn cause the efficiency to decrease. Since both the gas turbines are running, when the wind power is integrated, capacity margin gets increased. But when only one gas turbine works, then it is more expected to have faults and when any damage is caused to the running turbine, wind power alone will have to be supplied to meet the load until the second turbine starts running. The main goal for start/stop operational strategy is that when the wind power and the load from one of the gas turbine meets the needed load at the platform, the other gas turbine is to be shut down. This can be done by considering the equation (12) by taking the start-up time of the second gas turbine.

$P_{margin\ wind}$ is the margin added to the load so that there can be a reduction in wind power. When the wind power usage is less, a lower margin is added which increase the shutdown period of second gas turbine for a longer time in order to reduce the fuel consumption. Larger margin is added when the wind power is fully in need while the load from gas turbine is not considered. Here P_{margin} with 50%, and with zero values are simulated and the results are compared for both the 2.3 MW and 6 MW Hywind turbines. It is said that before the second turbine gets started there should be sufficient amount of power being supplied because starting time for the turbine takes a few seconds. This is possible as the minimum wind power does not drop zero and hence a minimum power will be supplied. In this case study this operating time period is set as 15 minutes and if this operating period is taken as large period, then it can cause wear and tear. This operational strategy refers to the start/stop operation.

For load sharing strategy, the load will be shared between the two gas turbines. When start/stop strategy is implemented, low loading is reduced significantly. According to the need of load most of cases, one gas turbine runs around 5 to 10 MW in most of the cases whereas, the second turbine will be shut down most of the cases. From the simulation. During initial days most of the time, the load is reduced very much around 6 MW and between 1500 and 8500 hours (Figure 6.6), the load is always stable at 12.8 MW.

For the estimation of CO_2 and NO_x gas emission and the fuel consumption, simulation is run in Matlab. Initially for both the wind turbines, estimation of greenhouse gas reduction is done without wind power integration and the Matlab code is again simulated with wind power penetration to compare the results. This is done in both the operational strategy for load sharing and for start/stop operational strategy. The available wind power and the estimated load for start/stop operation is shown in Figure 6.6.

For the emission estimation, the actual power needed to find the emission estimation at the platform is simulated based on the equation (12). From the equation, $t+t_{gasstart}$ is taken as 15 minutes and $P_{load}(t+t_{gasstart})$ is obtained by linearly interpolating the P_{load}. P_{margin} was taken 50 percent of the rated power. If the condition as per the equation is satisfied one gas turbine will be shut down or else both will be running. The emission of CO_2 and NO_x gas is estimated initially without wind power integration and then with wind power integration. Figure 6.7 shows the power required to get the total emission and is obtained by subtracting the load from the platform satisfying the equation condition minus the wind power. The results are shown in the *Table 4* and *Table 5*

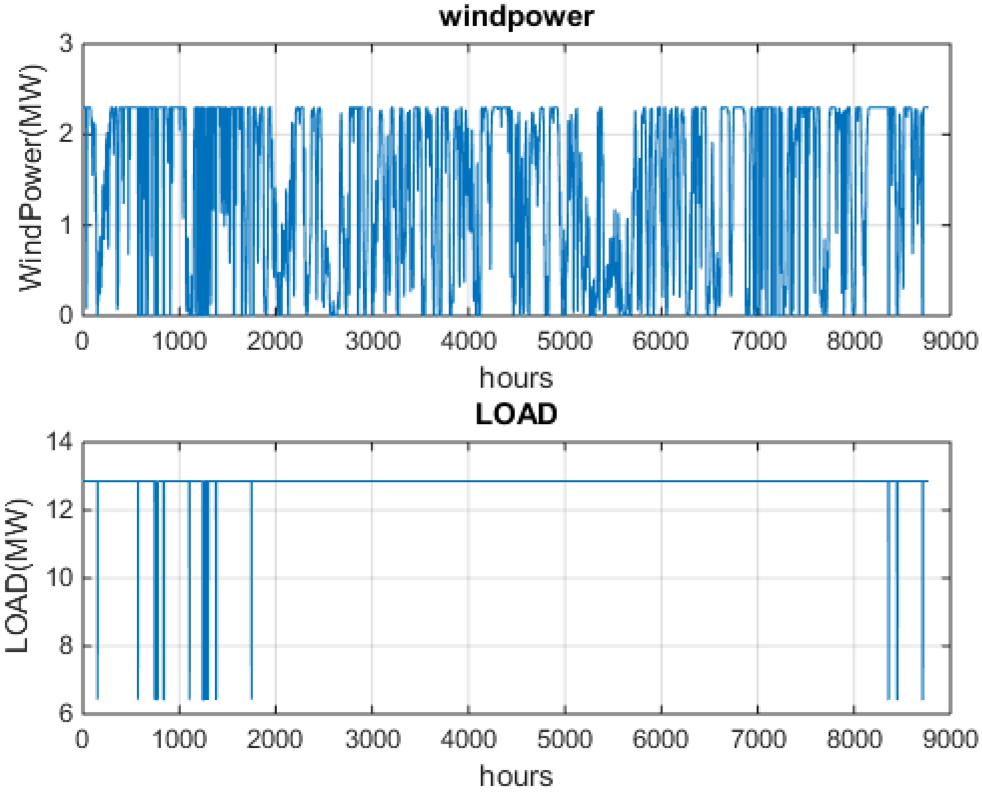

Figure 6.6. Time -series of wind power output and load for 2.3 MW wind turbine

From the results it is found that while wind power integration is done by subtracting the wind power from the load power at the platform, the load drops to 6 MW during some hours and then the power remains stable at 12 MW and again drops at certain hours.

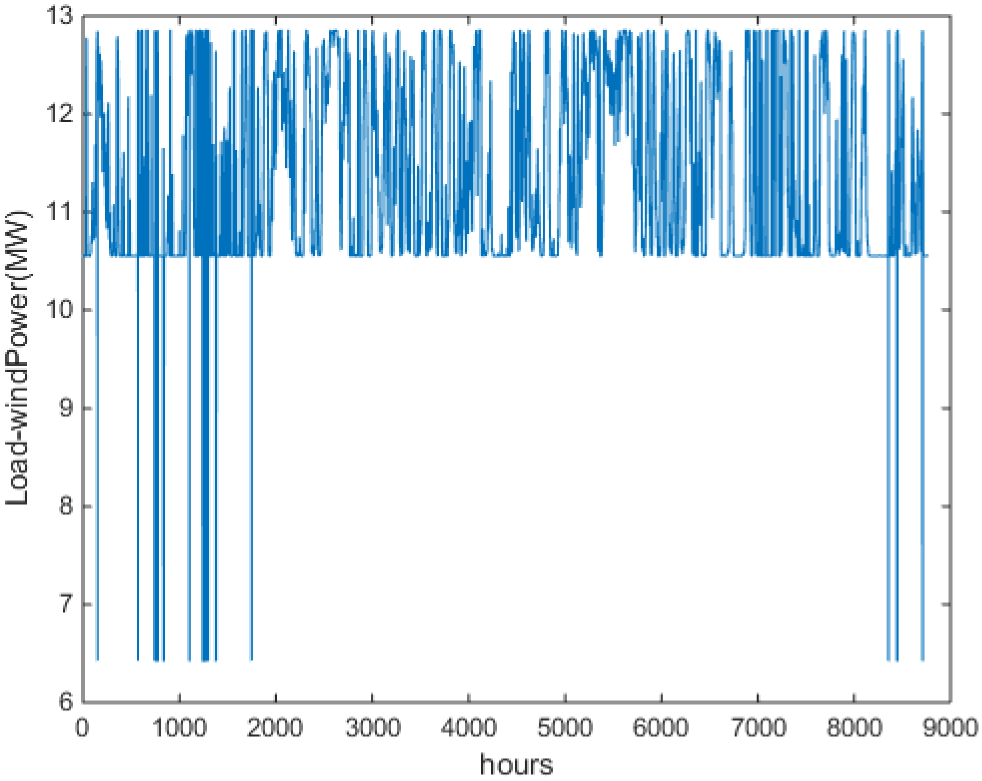

Figure 6.7. Load minus wind power output for 2.3 MW wind turbine

Table 4. Results without wind power integration for 2.3 MW wind turbine

Operation strategy	Fuel (Tones)	CO_2 (Tones)	NO_x (Tones)
Load sharing	22629.5	57420.1	182.69
Start/stop	55417.18	138919.96	116.81

.

Table 5. Results with wind power integration for 2.3 MW wind turbine

Operation strategy	Fuel (Tones)	CO_2 (Tones)	NO_x (Tones)
Load sharing	20470.21	51959.83	149.05
Start/stop	45284.42	112703.59	84.27

Table 6. Percentage in savings of fuel, CO_2 and NO_x gas

Operational strategy	**Fuel savings**	**CO_2 Reduction**	**NO_x Reduction**	Wind
Between operational strategies themselves	32787.68 (59%)	81499.86 (58%)	65.88 (36%)	0MW
Load sharing	2159.35 (9.5%)	5460.29 (9.5%)	33.64 (18.4%)	2.3 MW
Start/stop	10132.76 (18.2%)	26216.37 (18.8%)	32.54 (27.8%)	2.3 MW

In load sharing operation (conventional operation), simulation is run by sharing the available load at the platform between both the gas turbine. In start/stop operational strategy, one gas turbine is shut down while other one is running. When the operational strategies are compared within themselves, the reduction of gases is about 60 percent between fuel and CO_2 gas. Results of the comparison between the two operational strategies within themselves with no wind power and with power integration is shown in *Table 6*.

Based on the results, when comparing the operational strategies themselves, fuel consumption is seen to be used less in conventional operation than in start/stop operation. So it can be said that conventional operation will be suitable as operational strategy.

Case study for 6 MW Hywind turbine

Similar simulations are carried for 6 MW Hywind turbine like 2.3 MW wind turbine. Simulation results for emission of greenhouse gases and fuel consumption saving is shown in *Table 9*.

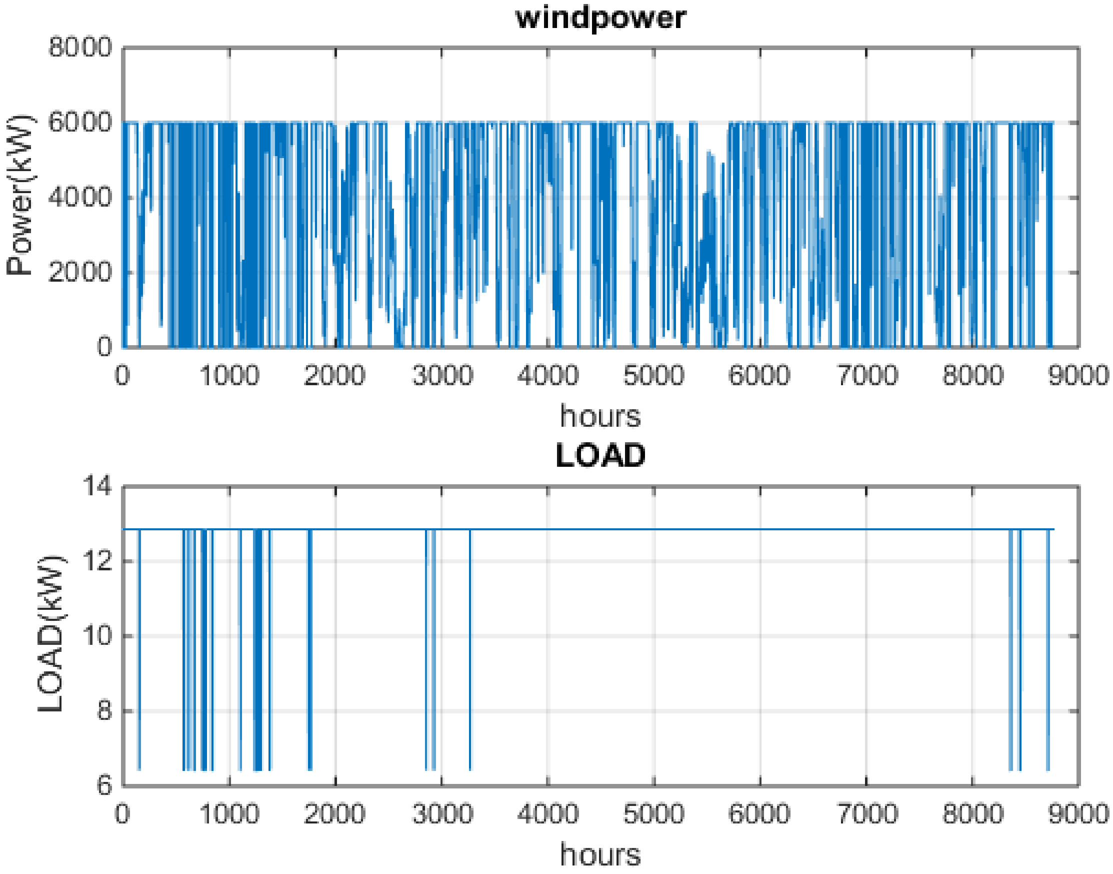

Figure 6.8. Wind power and load estimation as a function of hours for 6 MW wind turbine

During wind power integration, for 6 MW wind turbine, the load drops to 6 MW and remains stable at 7 MW and again drops at certain hours.

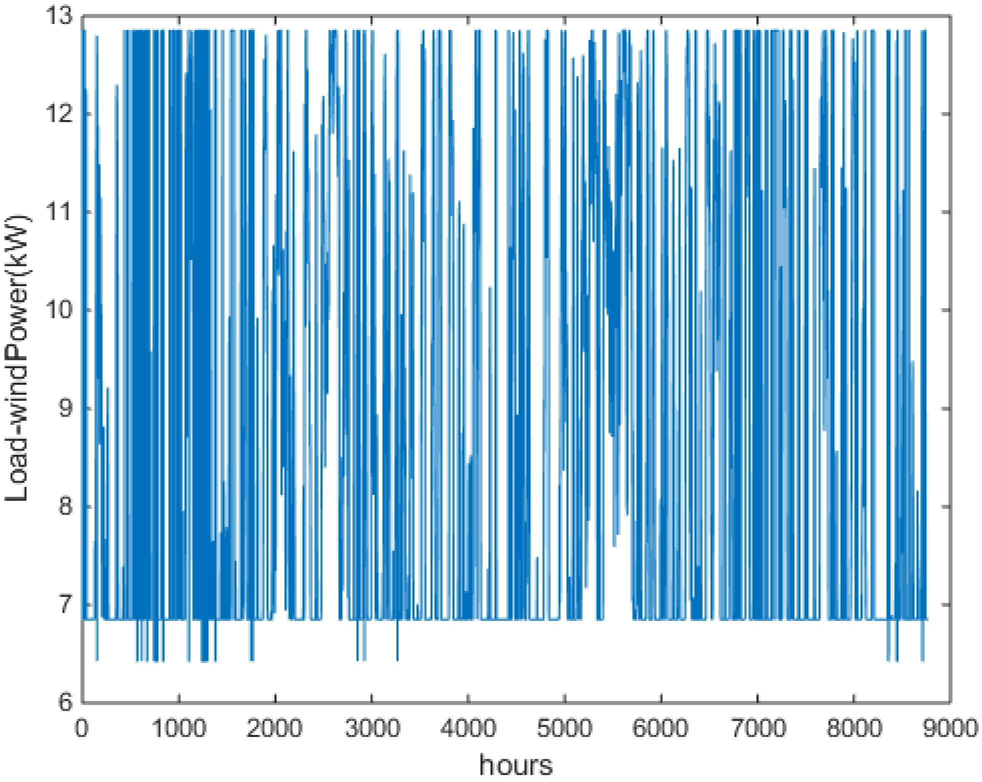

Figure 6.9. Load minus wind power output for 6 MW wind turbine

Table 7. Results without wind power integration for 6 MW wind turbine

Operation strategy	Fuel (Tones)	CO_2 (Tones)	NO_x (Tones)
Load sharing	22629.5	57420.1	182.69
Start/stop	55417.18	138919.96	116.81

Table 8. Results with wind power integration for 6 MW wind turbine

Operation strategy	Fuel (Tones)	CO_2 (Tones)	NO_x (Tones)
Load sharing	16484.02	41849.4	100.44
Start/stop	26480.56	63903.44	62.91

Table 9. Percentage in savings of fuel, CO2 and NOx gas for 6 MW wind turbine

Operational strategy	**Fuel savings**	**CO_2 Reduction**	**NO_x Reduction**
Load sharing	6145.48 (27.15%)	15570.7 (27.1%)	82.25 (45.02%)
Start/stop	28936.62 (52.2%)	75016.52 (54%)	53.9 (46.1%)

From the results, it can be concluded that between the operational strategies, load sharing (conventional operation) is much more suitable than start/stop as fuel consumption is reduced. When the results are compared with and without wind power based on percentage reduction, 6 MW Hywind turbine is more suitable to use than 2.3 MW wind turbine.

Chapter 7

7. Conclusion and Future Work

This thesis work investigated the possibilities of integrating the wind energy with the oil and gas platforms. Research says that wind energy penetration method will be developing in the near future. The studies involve the Hywind technology which is also increasing its demand in the recent few years. The huge platforms in the Deep Sea always need to cover load to meet their need like drilling, power supply etc. This increases its necessity to involve gas turbines to meet this need. Since the greenhouse gas gets tax impose hence measures are needed to control the emission. This demands several operational strategies which mainly this thesis work covers.

Usually there are several software's involved in the analysis like HOMER but here the entire work is done in Matlab itself. Here mainly two operational strategies of the gas turbine was involved. Initially load sharing operation was done ad then start/stop operational strategy where one gas turbine s allowed to shutdown and other running. The simulation was done for one whole year. It can be concluded that wind energy is the better option of renewable energy source to be used.

The simulation was run for both 2.3 MW and 6 MW Hywind turbines and the results showed that for 2.3 MW for load sharing strategy, the fuel and CO_2 emission reduction is 9.5% and for NO_X gas reduction is 18.4%. But for start/stop operational strategy, the savings for fuel and CO_2 is 18% whereas for NO_x gas reduction the savings is 27%. For 6 MW the result was obtained as 27% for both fuel and CO_2 gas savings and NO_x gas reduction is 45% for load sharing operational strategy. For start/stop operation, savings in fuel and CO_2 gas is 52 and 54% whereas for NO_x gas is 46% saved for 6 MW wind turbine.

The start/stop operation was done based on the equation (12) with 15 minute $t_{gasstart}$. Pmargin was selected as 50 percent of the rated gas for both the turbines. The results showed that fuel saving and the greenhouse gas emission reduction has better results in load sharing (conventional operation) than in savings for the start/stop operational strategy. However, much more research work can be done with various P_{margin} values. But in this thesis work only with one value is simulated.

Further work

- Since the weight and space is main concern in the oil and gas platforms, further work can be carried with the internal storage capacity on the oil and gas platforms.
- Research work can also be carried with HVDC cable connecting the oil and gas platforms with the grids which is not considered in this thesis work
- Further work can also be done on the switch on/off of the performance of the gas turbines and its lifetime

- Further work can also be carried on with various values of P_{margin} and continue with the start/stop operational strategy of the gas turbine
- Cost estimation part can also be done in future work
- Electrical grid stability simulations including different dynamic cases can be done as further work
- Number of wind turbines to be included can also be studied in future

References

[1] Sadeghi, K. 2007. An Overview of Design, Analysis, Construction and Installation of Offshore Petroleum Platforms Suitable for Cyprus Oil/Gas Fields. *GAU Journal of Social & Applied Sciences*, 2 (4), pp.1-16.

[2] Report by European Wind Energy Association. 2014. *The European Offshore Wind Industry: Key Trends and Statistics 2013*, January 2014, EWEA, Belgium.

[3] Oil Rig Photos-Njord Alpha, http://www.oilrig-photos.com/picture/number2744.asp

[4] Pedersen, O.F. and H. Dannstrom. 1997. Separation of Carbon dioxide from Offshore Gas Turbine Exhaust, *Energy Conversion Management*, Vol. 38, Suppl., pp. S81-S86.

[5] Mathew, S., G.S. Philip and C.M. Lim. 2011. *Advances in Wind Energy Conversion Technology*, Springer publications, pp. 71-83.

[6] Korpås, M., L. Warland, W. He and J. O. Tande. 2012. A Case-Study on Offshore Wind Power Supply to Oil and Gas Rigs, *Energy Procedia,* Vol.24, pp. 18-26.

[7] Koussa, D. S. and M. Koussa. 2014. Homer Analysis for Integrating Wind Energy into the Grid in Southern of Algeria, Proceedings of International Renewable and Sustainable Energy Conference, IEEE, Morocco, 17-19 October 2014, pp. 360-365.

[8] Doherty, R., E. Denny and M. O'Malley. 2004. System Operation with a Significant Wind Power Penetration*, Proceedings of Power Engineering Society General Meeting, IEEE*, 6-10 June 2004, Denver,Vol.1, pp. 1002-1007.

[9] Holttinen, H., etal. 2015. Reduction of CO_2 Emissions Due to Wind Energy: Methods and Issues in Estimating Operational Emission Reductions, *Proceedings of the Power & Energy Society General Meeting*, IEEE, Denver, 26-30 July 2015, pp.1-5.

[10] He, W., G. Jacobsen, T. Anderson, F. Olsen, T. Hanson, M. Korpås, T. Toftevaag, J. Eek, K. Uhlen and E. Johansson. 2010. The Potential of Integrating Wind Power with Offshore Oil and Gas Platforms, *Wind Engineering*, Vol.34 (2), pp. 125-138.

[11] Aardal, A. R., J. I. Marvik, H. Svendsen and J. O. Giaever Tande. 2012. Study of Offshore Wind as Power Supply to Oil and Gas Platforms, *Proceedings of Offshore Technology Conference*, Article no. OTC23245-MS, Texas, 30 April 2012.

[12] Jorun, I. M. and G. S. Harald. 2011. Integration of Wind Power with Multiple Oil and Gas Platforms in an Isolated Offshore System, *EWEA Offshore*, SINTEF Publication.

[13] Boyce, M.P. 2012. *Gas Turbine Engineering Hand Book*, Butterworth-Heinemenn Publications, 4th Edition.

[14] Fundamentals of Gas Turbine Engines, http://www.skybrary.aero/bookshelf/books/1621.

[15] Saravanamuttoo, H.I.H. 2009. *Gas Turbine Theory*, Henry Ling Ltd, Great Britain, 6th Edition.

[16] Sinden, G. 2007. Characteristics of the UK Wind Resource: Long Term Patterns and Relationship to Electricity Demand. *Energy policy,* Vol. 35(1), pp.112-127.

[17] Tong, W. 2010. *Wind Power Generation and Wind Turbine Design*. WIT Press, 1st Edition.

[18] Singh, M. and E. Muljadi. 2013. *Power Electronics for Renewable and Distributed Energy Systems-Wind Power Generation*, Springer Publications, pp. 111-149.

[19] Hansen. M.O.L. 2008. *Aerodynamics of Wind Turbines*, Earthscan UK, 2nd edition.

[20] Wind 101: the basics of wind energy, http://www.awea.org/Resources/Content.aspx?ItemNumber=900.

[21] Chakraborty, S., M.G. Simoes and W.E. Kramer. 2013. *Power Electronics for Renewable and Distributed Energy Systems- A Sourcebook of Topologies, Control and Integration*, Springer Publications.

[22] Heronemus, W. E. 1972. Pollution-Free Energy from Offshore Winds, *Proceedings of the 8th Annual Conference and Exposition Marine Technology Society*, Washington D.C., September 1972, pp. 11-13.

[23] StatoilHydro, Hywind by StatoilHydro, *The World's First Full Scale Floating Wind Turbine*, June 2009.

[24] Ottmar E. (ed.), 2012. *A Report of Working Group III of the IPCC, Special Report on Renewable Energy Sources and Climate Change Mitigation*, Potsdam Institute for Climate Impact Research, Switzerland.

[25] Manwell. J. F., J. G. McGowan and A. L. Rogers. 2009. *Wind Energy Explained Theory, Design and Application*, Wiley Publications, 2nd Edition. pp. 45-47.

[26] Matlab,The MathWorks Inc, Massachusetts,USA.

[27] Tedeschi, E., E. Robles, M. Santos, O. Duperray and F. Salcedo. 2012. Effect of Energy Storage on a Combined Wind and Wave Energy Farm, *Proceedings of Energy Conversion Congress and Exposition (ECCE)*, IEEE, Raleigh,15-20 September 2012, pp. 2798-2804.

[28] Gopal, N. 2015, *Use of Hywind in Oil and Gas Platforms to Reduce* CO_2 *and* NO_x *Gas Emissions*, Specialization Project, NTNU, Department of Electric Power Engineering, Elkraft.

8. APPENDIX A

Matlab code for 2.3 MW Hywind turbine

```
clear all
close all
WTcurve=xlsread('Siemens_SWT_82_2_3_MW.xls');                  % Actual power
curve of the WT Siemens 2.3

%%wind velocity calculation from 100m to 66m
alpha=0.143;
ut=xlsread('load_new.xlsx','WIND');                          %ut is wind speed
at reference height for one whole year
zt=100;                                                       %zt is reference
height(100m)
z=66;                                                       %z is WT height(66m)
n=length(ut);
for i=1:n
v=ut*((z/zt)^0.143);                                          %v is wind speed
for corresponding WT height(66m)
n=length(v);
end

%%Wind Power calculation with approximated formula
Pn=2.3;      %nominal power of wind turbine
vmin=4;      %cut-in speed
vmax=25;     %maximum wind speed
 vn=15;       %rated wind speed (assumed 15 based on the trend)

 Pwind=zeros(1,n);
for i=1:n
if (v(i)<vmin);
    Pwind(1,i)=0;
elseif(v(i)>=vmin)&&(v(i)<=vn);
    %curve fitting based on the third order polynomial function
   Pwind(1,i)=Pn*(11.62*((v(i)/vn)^2)-6.226*((v(i)/vn)^3)-
5.07*(v(i)/vn)+0.68);

end
if(v(i)>=vn)&&(v(i)<=vmax);
   Pwind(1,i)=Pn;
elseif(v(i)>vmax)&&(v(i)<26);
  Pwind(1,i)=-2.3*v(i)+59.8;
elseif (v(i)>=26)
  Pwind(1,i)=0;
end
% Limit the power output to 2.3 MW
if (Pwind(i)>2.3)
   Pwind(i)=2.3;
end
```

```
   if(Pwind(i)<0)
       Pwind(i)=0;
   end
end

%%Graph of actual and approximated(analytical) power versus wind velocity inthe
platform
figure(1)
plot(v',Pwind*1000,'r*')                    %Approximated power extraction from
analytical approximation
hold on
grid on
plot(WTcurve(:,1),WTcurve(:,2))       %Real power capture from WT Siemens 2.3
xlabel('wind speed in m/s')
ylabel('Extracted power in kW')

%%interpolation for getting exact curve
xdata = WTcurve(2:length(WTcurve),1);
ydata = WTcurve(2:length(WTcurve),2);
yadd(1)=0;

% A small quantity must be added to the output vector ydata to make it
% monotonically increasing before interpolation
for k=2:length(xdata)
    yadd(k)=yadd(k-1)+1e-9;
end
x = 0:0.5:29;    % Vector where we want to interpolate
% Interpolate output values for x
y = interp1(xdata,ydata+yadd',x','cubic');
y2 = interp1(xdata,ydata+yadd',v,'cubic');

%% Graph of interpolated curve and real curve
figure(2)
plot(WTcurve(:,1),WTcurve(:,2),'go')      %Real power capture from WT Siemens
2.3
hold on
grid on
plot(x,y,'r-*')                                  % power extraction from Matlab
interpolation
xlabel('wind speed in m/s')
ylabel('Extracted power in kW')
legend('real','interpolation')

%% Graph for wind power generated at every hour in a year
figure(3)
  D=(1:8760);                   %Number of hours
  ax1=subplot(2,1,1);           %ax1 is windpower graph
  ax2=subplot(2,1,2);           %ax2 is windspeed graph
  plot(ax1,D,y2)
  title(ax1,'windpower(hourly resolution)')
  ylabel(ax1,'Power(kW)')
  xlabel(ax1,'hours')
  grid(ax1,'on')
  plot(ax2,D,v,'-')
  title(ax2,'windspeed')
  ylabel(ax2,'windspeed(m/s)')
```

```
  xlabel(ax2,'hours')
  grid on

   %%calculating the total wind energy along the year
E=trapz(D,y2)/1000; % in MWh with Matlab approximation  (preferred one)

% %%Calculation of Number of zero MW and Maximum rated power
a=nnz(y2<=0.001);   %% No. of zero power
b=nnz(y2>=Pn*1000);  %% No. of maximum power


% Plotting a histogram of wind speeds
dv = 0.5;
vbins = 0:dv:ceil(max(v));

% Plotting a histogram of wind speeds
figure(4); hist(v', vbins);
xlabel('wind velocity (m/s)'); ylabel('count');

% Calculating power curve
powervbins = Pn*(vbins.^2 - vmin^2)/(vn^2 - vmin^2);
powervbins(vbins <= vmin) = 0;
powervbins(vbins > vmax) = 0;
powervbins(vbins >= vn & vbins <= vmax) = Pn;

% Plotting power curve
figure(5); plot(vbins, powervbins, '*')
xlabel('velocity (m/s)');
ylabel('turbine power (W)');
title('Turbine Power Curve')

% Calculate probability of wind speed range
nelements = hist(v', vbins);
probvbins = nelements/sum(nelements);        % Probability of a given velocity
range

% Calculate average power by summing the products of vel probability and power
avgPower = sum(probvbins .* powervbins);    %  (W)

% Calculating capacity factor (average power / rated power)
cf = avgPower / Pn;
%%Estimation of load at platform
L=xlsread('load_new.xlsx','actualload');  %reading the load at the platform
D=(1:8760);                               %number of hours in one year
TL=L(1:8760,2)+L(1:8760,3);                                %%Total summed load
of G1 and G2
TLn=TL/2;
figure(6)
plot(D,TL,'r');                            %represents total power from G1 and
G2
hold on;
plot(D,L(1:8760,2),'b');                  %represents power from G1
hold on;
plot(D,L(1:8760,3),'g');                  %represents power from G2
hold off;
```

```
title('Electrical Load data');
ylabel('power(kW)');
xlabel('hours');
grid on;

%%interpolation of CO2of the turbine corresponding to power
effcurve=xlsread('CO2gas.xlsx');   %CO2 of turbine wrt to power
Adata = effcurve(1:length(effcurve),2); %reading power in kw
Bdata = effcurve(1:length(effcurve),1);  % reading CO2
Badd(1)=0;

% A small quantity must be added to the output vector ydata to make it
% monotonically increasing before interpolation
for K=2:length(Adata)
    Badd(K)=Badd(K-1)+1e-9;
end
CO2 = interp1(Adata,Bdata+Badd',GL,'cubic');
CO2sum=sum(CO2)*0.453/1000; %in Tonnes
CO21=CO2*2;
CO2sum1=sum(CO21)*0.453/1000;               %total emission of CO2

%%NOX by interpolation
Pdata = effcurve(1:length(effcurve),2);     %reading power in kw
Ndata = effcurve(1:length(effcurve),4);     % reading NOx
Nadd(1)=0;
for H=2:length(Pdata)
    Nadd(H)=Nadd(H-1)+1e-9;
end
NOx = interp1(Pdata,Ndata+Nadd',GL,'cubic');           %in pounds(LB)
NOxsum=sum(NOx)*0.453/1000;                            %in Tonnes
NOx1=NOx*2;
NOxsum1=sum(NOx1)*0.453/1000;                      %total emission of NOx

%%interpolation of fuel
Fdata = effcurve(1:length(effcurve),2);            %reading power in kw
Hdata = effcurve(1:length(effcurve),5);            % FUEL reading
Hadd(1)=0;
for J=2:length(Fdata)
    Hadd(J)=Hadd(J-1)+1e-9;
end
FUEL = interp1(Fdata,Hdata+Hadd',GL,'cubic');%in pounds(LB)
Fsum=sum(FUEL)*0.453/1000;
FUEL1=FUEL*2;
Fsum1=sum(FUEL1)*0.453/1000;                 %total fuel consumption

%%Wind power integration and estimation of CO2,NOx and FUEL to
%%corresponding load
WL=xlsread('load_new.xlsx','2.3P');         %Wind power for 2.3MW turbine from
january to august

figure(7)
  D=(1:8760);                   %Number of hours
  ax1=subplot(2,1,1);           %ax1 is windpower graph
  ax2=subplot(2,1,2);           %ax2 is electrical load graph
  plot(ax1,D,WL)
  title(ax1,'windpower')
```

```
  ylabel(ax1,'Power(kW)')
  xlabel(ax1,'hours')
  grid(ax1,'on')
  plot(ax2,D,GL)
  title(ax2,'LOAD')
  ylabel(ax2,'LOAD(kW)')
  xlabel(ax2,'hours')
  grid on

figure(8)            %load minus wind power at the platform during wind power
integration
GL1=xlsread('load_new.xlsx','totalload');  %reading total load at the platform
GL1=GL1*1000;
plot(D,GL1-WL);
INT=GL1-WL;
INT1=INT/2;
ylabel('LoadwindPower(kW)');
xlabel('hours');

%%CO2 emission after wind power integration
IAdata = effcurve(1:length(effcurve),2);         %reading power in kw
IBdata = effcurve(1:length(effcurve),1);         % reading CO2
IBadd(1)=0;
for IK=2:length(IAdata)
    IBadd(IK)=IBadd(IK-1)+1e-9;
end
ICO2 = interp1(IAdata,IBdata+IBadd',INT1,'cubic');
ICO2sum=sum(ICO2)*0.453/1000;                    %in Tonnes
ICO21=ICO2*2;
ICO2sum1=sum(ICO21)*0.453/1000;

%%NOX by interpolation
IPdata = effcurve(1:length(effcurve),2);         %reading power in kw
INdata = effcurve(1:length(effcurve),4);         % reading NOx
INadd(1)=0;
for IH=2:length(IPdata)
    INadd(IH)=INadd(IH-1)+1e-9;
end
INOx = interp1(IPdata,INdata+INadd',INT1,'cubic');        %in pounds(LB)
INOxsum=sum(INOx)*0.453/1000;                            %in Tonnes
INOx1=INOx*2;
INOxsum1=sum(INOx1)*0.453/1000;                      %total emission of NOx

%%interpolation of fuel
IFdata = effcurve(1:length(effcurve),2);             %reading power in kw
IHdata = effcurve(1:length(effcurve),5);             % FUEL reading
IHadd(1)=0;
for IJ=2:length(IFdata)
    IHadd(IJ)=IHadd(IJ-1)+1e-9;
end
IFUEL = interp1(IFdata,IHdata+IHadd',INT1,'cubic');     %in pounds(LB)
IFsum=sum(IFUEL)*0.453/1000;
IFUEL1=IFUEL*2;
IFsum1=sum(IFUEL1)*0.453/1000;

%% FOR START/STOP operational strategy of gas turbine
```

```
pwind=xlsread('Pwind.xlsx','Pwind');  %reading output power from wind turbine
Prated=13;
t=xlsread('Pwind.xlsx','t');          %time interval of hourly period
Pn=2.3;
Pmargin=0.5*Pn;                      %50 percentage of 2.3MW

%%calculation of pload(t+tgas)

Pload=xlsread('Pwind.xlsx','Pload');     %reading load from both tha gasturbine
G1 and G2 at the platform
m=length(Pload);
Ploadtgas=zeros(1,m);
tgas=zeros(1,m);
for  i=1:(m-1)                                      %interpolating Pload to get
Pload(t+tgas)
    tgas(i)=t(i)+0.25;
    Ploadtgas(i)=Pload(i)+(Pload(i+1)-Pload(i))/(t(i+1)-t(i))*(tgas(i)-t(i));
end
n=length(Pload);
numGen=zeros(1,n); % This variable stores the number of generators running at
time i
for i=1:n
    if              pwind(i)+Prated>max(Pload(i),Ploadtgas(i))+(Pmargin*0.25);
%tgas=0.25hr
        numGen(i) = 1; % This implies one Gen is shutdown
    else
        numGen(i) = 2; % This implies both Gens are running
    end
end

% the power that is used to calculate the emissions as shown below

P_emission = Pload(i)./numGen; % Pload has to be the total load


%%interpolation of CO2of the turbine corresponding to power
effcurve=xlsread('CO2gas.xlsx');   %CO2 of turbine wrt to power
Adata = effcurve(1:length(effcurve),2); %reading power in kw
Bdata = effcurve(1:length(effcurve),1);  % reading CO2
Badd(1)=0;

% A small quantity must be added to the output vector ydata to make it
% monotonically increasing before interpolation
for K=2:length(Adata)
    Badd(K)=Badd(K-1)+1e-9;
end
sCO2 = interp1(Adata,Bdata+Badd',P_emission,'cubic');
sCO2sum=sum(CO2)*0.453/1000;                          %in Tonnes
semiCO2_total = CO2sum.*numGen;                       %total emission of CO2
sECO2=trapz(t,emiCO2_total)/1000;

%%NOX by interpolation
Pdata = effcurve(1:length(effcurve),2);     %reading power in kw
Ndata = effcurve(1:length(effcurve),4);     % reading NOx
Nadd(1)=0;
```

```
for H=2:length(Pdata)
    Nadd(H)=Nadd(H-1)+1e-9;
end
sNOx = interp1(Pdata,Ndata+Nadd',P_emission,'cubic');            %in pounds(LB)
sNOxsum=sum(NOx)*0.453/1000;                             %in Tonnes
semiNOx_total = NOxsum.*numGen;                          %total emission
sENOx=trapz(t,emiNOx_total)/1000;

%%interpolation of fuel
Fdata = effcurve(1:length(effcurve),2);           %reading power in kw
Hdata = effcurve(1:length(effcurve),5);           % FUEL reading
Hadd(1)=0;
for J=2:length(Fdata)
    Hadd(J)=Hadd(J-1)+1e-9;
end
sFUEL = interp1(Fdata,Hdata+Hadd',P_emission,'cubic');%in pounds(LB)
sFsum=sum(FUEL)*0.453/1000;
semiFUEL_total = Fsum.*numGen;
sEFUEL=trapz(t,emiFUEL_total)/1000;
% where emi is the one calculated by interpolating P_emission

%%Wind power integration and estimation of CO2,NOx and FUEL to
%%corresponding load
WL=xlsread('load_new.xlsx','2.3P');          %Wind power for 2.3MW turbine from
january to august

figure(9)
  D=(1:8760);                 %Number of hours
  ax1=subplot(2,1,1);         %ax1 is windpower graph
  ax2=subplot(2,1,2);         %ax2 is electrical load graph
  plot(ax1,D,WL)
  title(ax1,'windpower')
  ylabel(ax1,'Power(kW)')
  xlabel(ax1,'hours')
  grid(ax1,'on')
  plot(ax2,D,P_emission)
  title(ax2,'LOAD')
  ylabel(ax2,'LOAD(kW)')
  xlabel(ax2,'hours')
  grid on

figure(10)           %load minus wind power at the platform during wind power
integration
plot(t,P_emission'-WL);
INT=P_emission'-WL;
INT1=INT/2;
ylabel('LoadwindPower(kW)');
xlabel('hours');

%%CO2 emission after wind power integration
IAdata = effcurve(1:length(effcurve),2);         %reading power in kw
IBdata = effcurve(1:length(effcurve),1);         % reading CO2
IBadd(1)=0;
for IK=2:length(IAdata)
    IBadd(IK)=IBadd(IK-1)+1e-9;
end
```

```
sICO2 = interp1(IAdata,IBdata+IBadd',INT1,'cubic');
sICO2sum=sum(ICO2)*0.453/1000;                    %in Tonnes
semiICO2sum_total = ICO2sum.*numGen;
sEICO2=trapz(t,emiICO2sum_total)/1000;

%%NOX by interpolation
IPdata = effcurve(1:length(effcurve),2);         %reading power in kw
INdata = effcurve(1:length(effcurve),4);         % reading NOx
INadd(1)=0;
for IH=2:length(IPdata)
    INadd(IH)=INadd(IH-1)+1e-9;
end
sINOx = interp1(IPdata,INdata+INadd',INT1,'cubic');        %in pounds(LB)
sINOxsum=sum(INOx)*0.453/1000;                            %in Tonnes
semiINOx_total = INOxsum.*numGen;                         %total emission of
NOx
sEINOx=trapz(t,emiINOx_total)/1000;

%%interpolation of fuel
IFdata = effcurve(1:length(effcurve),2);             %reading power in kw
IHdata = effcurve(1:length(effcurve),5);             % FUEL reading
IHadd(1)=0;
for IJ=2:length(IFdata)
    IHadd(IJ)=IHadd(IJ-1)+1e-9;
end
sIFUEL = interp1(IFdata,IHdata+IHadd',INT1,'cubic');     %in pounds(LB)
sIFsum=sum(IFUEL)*0.453/1000;
semiIFUEL_total = IFsum.*numGen;
sEIFUEL=trapz(t,emiIFUEL_total)/1000;
```