A STUDY OF THE RELIABILITY ENHANCEMENT

OF WIND TURBINES EMPLOYING

DIRECT- DRIVE TECHNOLOGY

By

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Chapter 1

INTRODUCTION

1.1. Current Energy Scenario - Growth of Renewable Energy Technologies

Most of the available energy resources today are from the conversion of incident solar radiation (insolation) to other energy forms. Some of that energy has been preserved over a long period of time as fossil energy; some is directly or indirectly usable. In spite of increasing energy prices, global energy consumption continues to rise at a rapid rate. Research work and discussions are underway, data on energy reserves are available, its prices and apparent alternatives (though moving targets) are known for decades and the world population is much aware of the fundamental steps needed to be taken in order to meet the future energy needs. Hence renewable forms of energy have gained rapid acceptance in the past few years. The world is blessed with fairly evenly distributed renewable energy resources even though many are underdeveloped and unmapped. Renewable energy is a form of energy harnessed from nature and it replenishes by itself within a small duration of time that is they are replaced by nature fast enough before their deployment. In fact, the sun has been, and will be, the primary energy source for most of the renewable forms of energy. Hence these forms of energy can always be replenished as long as solar energy is available. The United States is working towards a more sustainable energy mix, reduced greenhouse gas emissions, lower carbon footprints and less dependency on imported petroleum sources.

Global energy consumption experienced a growth of 5.6% in 2010, the largest increase in terms of percentage since 1973, with China well on its way to being the largest energy consumer in the world. Coal accounted for nearly one half of the increase in global energy use over the past decade with the bulk of the growth coming from the power sector in emerging economies. Renewables supplied around 16% of the total energy supply and contributed 20% to the total global electricity [1]. They continue to grow strongly in many end use sectors such as power, heat and transport. In the United States, renewable energy accounted for approximately 8% of the total energy supply in 2010, with biomass, hydroelectric and wind resources contributing much of it. Figure 1.1 illustrates the global energy consumption of different energy resources from 1985-2010.

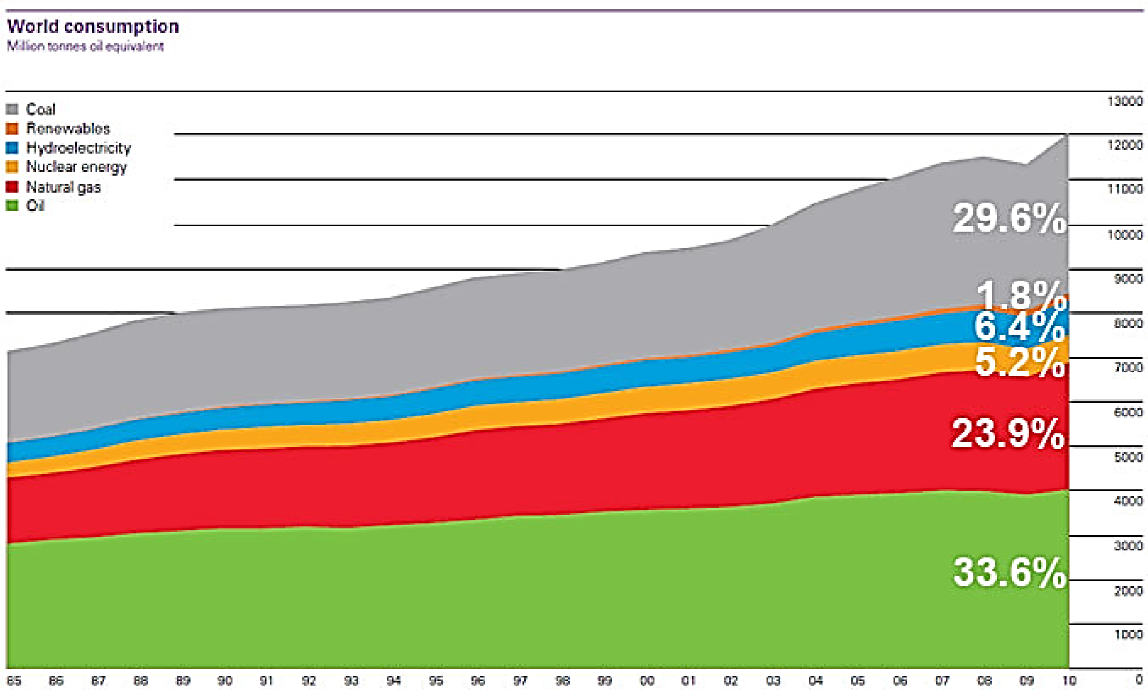

Figure 1.1: World consumption of energy resources 1985-2010[1]

Renewable energy economy must be promoted to ensure national security, mitigate climate change, rural economic regeneration, and resource preservation. Wind energy systems can be a cornerstone of that sustainable energy future because it is affordable and provides substantial and distributed revenue and jobs. Also, wind power systems are almost benign on the environment because they do not pollute the atmosphere, generate hazardous wastes, or deplete natural resources. Embracing wind energy to a high level can lay the foundation for a healthy future to some extent. Wind energy utilization is gaining momentum at a rapid rate among other renewable energy sources with worldwide wind power installed capacity reaching 239 GW at the end of 2011.

1.2 Evolution of Wind Turbine technology

Human beings have been harnessing wind power since ancient times, with the first wind mill recorded as early as in the 6^{th} century A.D. Technology has evolved over the years to utilize them for pumping water, powering sawmills, grinding grains and recently generating electricity. The first commercial multi megawatt wind turbine was constructed in 1978 in Denmark. In 1991, the first commercial wind farm was built in the United Kingdom using 400KW turbines. Figure 1.2 shows the evolution of wind turbines with time, rotor diameters and capacity ratings. Since the late 1970's, there has been a remarkable improvement in the capacity, efficiency and design characteristics of wind turbines. The latest turbine models have long blade lengths which can sweep and capture wind energy from a large area to produce more electricity, thereby bringing the cost per unit of energy generated down. In the last two decades, wind turbines have increased in size by a factor of more than 100 (from 25kW to 2500kW and beyond), the cost of energy has reduced by a factor of more than 5 and wind turbine rotor diameters have been increased by a factor of 8. The largest wind turbine currently in operation has a rotor diameter of 126m and a capacity of 7.58MW (Enercon E126) [2]. Evolution of wind turbine technology is centered on increased reliability and efficiency, noise reduction, compatibility with the grid network and effective aerodynamic blades.

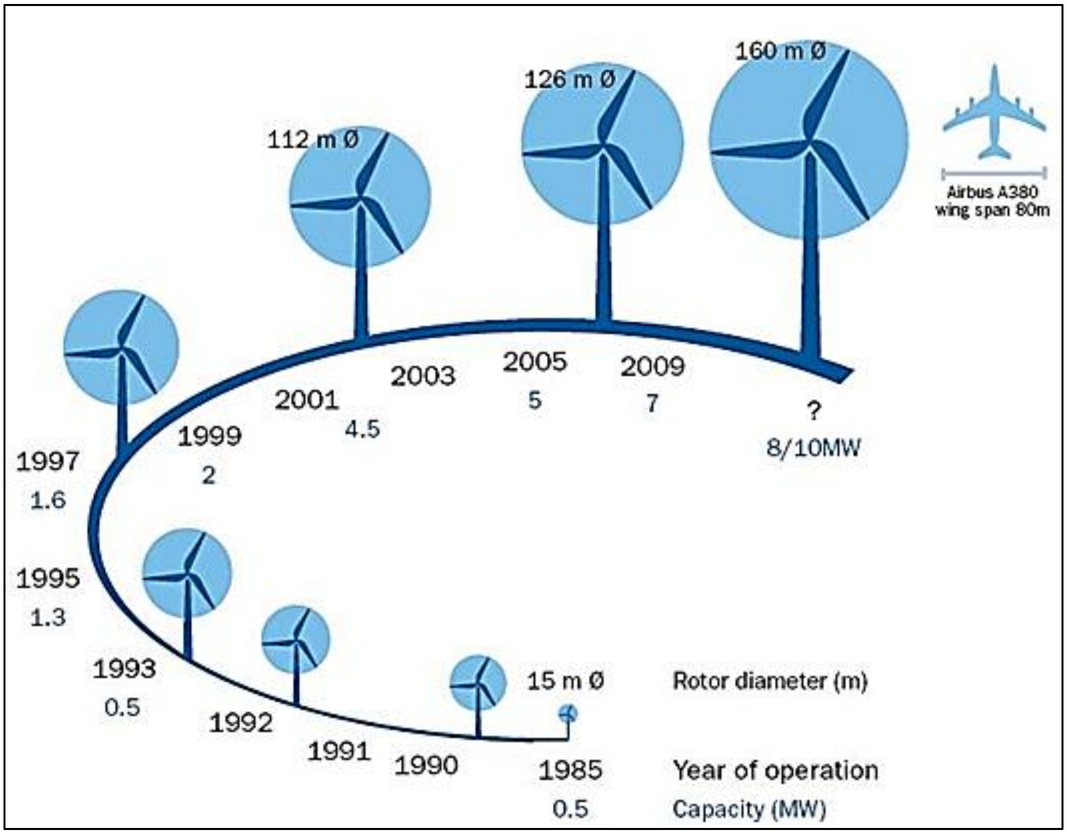

Figure 1.2: Size evolution of wind turbines over time [3]

Wind turbine blades begin to spin typically when wind speed reaches about 3 meters/second (m/s) - 5 m/s (6.71 mph - 11.2 mph). It keeps generating power until around 30 m/s (67.1 mph) at which point wind is considered to be too strong and destructive. The blades are attached to a rotating shaft which transfers the power in the wind to a generator through a gearbox. The power generated is fed to the utility grid through a transformer. Wind turbines have an average life span of 20-25 years, after which the turbines can be replaced with new ones or withdrawn. New developments and innovations in wind turbine designs are continuously being exploited worldwide. The required technological improvements are simple and straight forward: taller towers, lighter weight blades with better aerodynamic features, larger rotors and continuing monitoring process. This would increase the reliability and improve the compatibility when connected to the grid. At present, advanced and the most common wind turbine concept is based on horizontal axis design with 3 blades, variable pitch, upwind operating at variable speed feeding power to the grid through power electronic interfaces.

Offshore wind power refers to wind farms constructed in bodies of water to generate electricity from wind. These are in developmental phase with global offshore wind power capacity expected to reach a total of 75 GW by 2020. They are placed in the sea at depths up to 30m. Stronger and more constant offshore wind speeds help to produce larger amounts of electricity. Currently, offshore wind power capacity is much more expensive than onshore wind power. Wind turbines with ratings up to 5MW have been developed for offshore use until now. Larger wind turbine designs are being developed and are expected to give a boost to offshore wind farms.

Clearly the wind energy industry is in early stages of development and is still evolving. This industry achieved great progress over the past two decades and will play an important role in the production of electricity from renewable energy sources in the future.

1.3 Objective

Because of the increasing need for renewable power, wind turbines and wind energy are gaining importance in the national energy scenario. In traditional wind turbines employing gearboxes, the gearbox which couples the turbine rotor to the generator continues to be the component whose failure results in the most significant cost and downtime. The multiple wheels and bearings in a gearbox are subjected to severe stress because of wind turbulence and any failure in a single component of the gear system can bring the turbine to a halt. This continues to be one of the biggest challenges in the wind industry.

This study explains how a typical generator- gear solution in the wind industry can be replaced by a low speed permanent magnet generator using direct drive technology. The improvement in reliability of direct drive wind turbines as compared to the traditional geared ones is evaluated.

The reliability improvement of the drive train is also studied specifically. Weight and economic comparisons are also made. Due to a lack of availability of failure data for direct drive systems (being a new technology); reasonable estimates are used in the analysis and the discussion that follows.

1.4 Organization of the thesis

This section gives an outline of following chapters in this thesis.

Chapter 2: Literature review: gives an overview of the different renewable energy resources available and presents the global wind energy statistics. The advantages of wind power and a brief description of wind turbine components are also included.

Chapter 3: Reliability of Wind Turbines: summarizes the failure and downtime statistics for geared wind turbines and subsequently introduces the need for the elimination of gearbox. Different issues and challenges with gearbox are presented. This chapter also reviews the basic concepts of reliability.

Chapter 4: Direct drive wind turbines: presents the option to improve reliability using direct drive technology and explains its advantages over its geared counterpart. This chapter explains how a typical generator - gear solution in the wind industry can be replaced by a low speed permanent magnet generator. Some of the operating direct drive turbines across the world are also presented.

Chapter 5: Reliability improvement using direct drive technology: Deals with the mathematical formulation and calculations to evaluate the reliability of wind turbines based on a range of parameters. Swedish data collected over a five year period is considered and used as reference throughout the study. The assumptions used in the calculations are also documented and all the major findings of the study are discussed. Few results from other studies are also presented.

Chapter 6: Summary and Concluding Remarks: summarizes the study and presents some concluding remarks. Scope for further work is also included.

CHAPTER 2

LITERATURE REVIEW

2.1 Renewable energy resources

Renewable energy is the energy that comes from natural sources that are replenished periodically over a short time interval – hours, days, months or a few years. Their flows involve natural phenomena such as sunlight, wind, tides, plant growth, and geothermal heat. They are practically inexhaustible and would not run out when used in contrast to fossil fuels such as coal, oil and natural gas. Use of renewable energy will lead to sustainable development by reducing carbon emissions which, in turn, contributes to increasing energy and climate security.

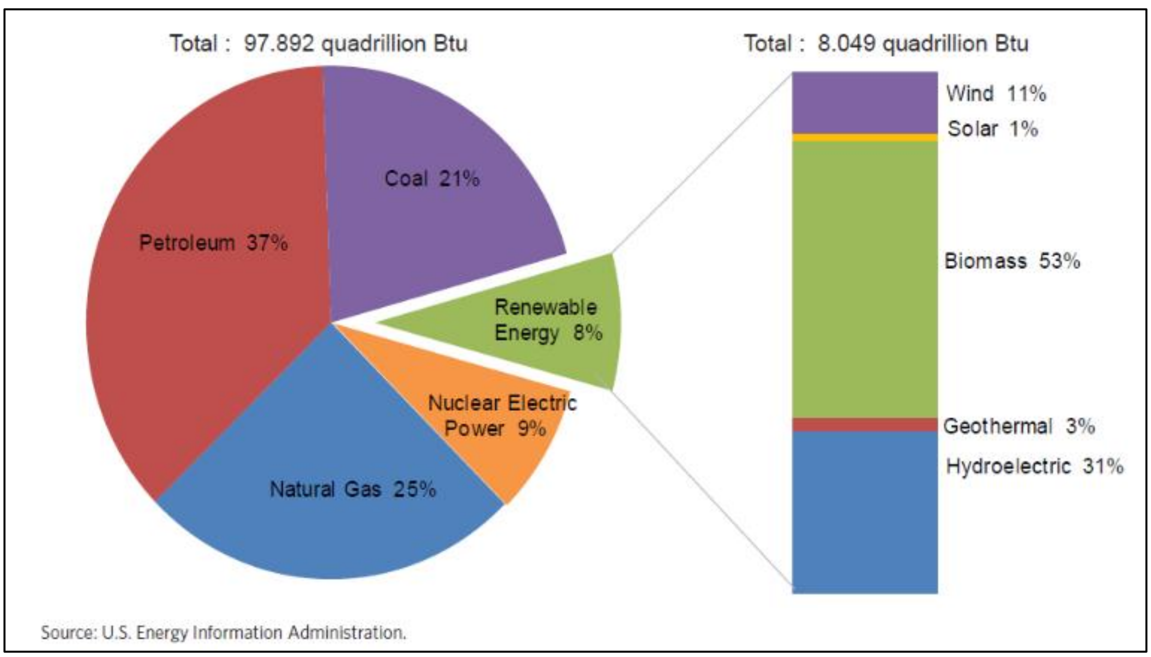

Figure 2.1: Renewable energy consumption in US energy Supply, 2010[4]

The major forms of renewable energy are wind power, hydropower, insolation, biomass, biofuel, geothermal and ocean energy. Each of them is discussed briefly in this section. Figure 2.1 illustrates the role of renewable energy in the nation's energy supply in 2010.

Wind: Wind energy can be harnessed in many ways such as using generators to generate electricity, windmills for mechanical power, wind pumps for water pumping or drainage, and sails to propel ships. A large wind farm may consist of a number of individual wind turbines which are connected to the electric power transmission network. These turbines may be located either onshore or offshore. Offshore wind speeds are usually more consistent so they usually have potential for higher contribution. Europe is the hub of this wind power industry. The total installed global wind power capacity reached 239 GW at the end of 2011.

Biomass: Biomass is the organic material originating from plants and animals. It can be used as a renewable energy resource either directly, or by converting into other energy products such as biofuels. Biomass is carbon, hydrogen and oxygen based. The energy is derived from five distinct sources of energy: garbage, wood, animal waste, landfill gases, and alcohol fuels. Biomass can be converted to other usable forms of energy such as methane gas or transportation fuels such as ethanol and biodiesel. Presently, bio energy is the largest contributor to the renewable energy mix. As of 2011, the installed global biomass capacity has reached 58 GW [5].

Solar power: Solar power is obtained by converting sunlight (insolation) into electricity. This can be done either directly using photovoltaic (PV), or indirectly using concentrated solar power (CSP) systems, when sunlight is converted to dc electric current using photoelectric effect in solar cells. CSP systems use lenses or mirrors and tracking systems to focus a large area of sunlight into a small beam. At the end of 2011, total installed photovoltaic capacity reached over 67.4 GW world-wide, with an annual added capacity of 27.7 GW. The total energy output of the world's

PV capacity run over a calendar year is equal to some 80 billion kWh. This energy volume is sufficient to cover the annual power supply needs of over 20 million households in the world. [6].

Hydroelectricity: In a hydroelectric power plant, water is stored in a reservoir which is often created by damming a river and is converted into energy as it is piped into water turbines. They utilize the use of the gravitational force of falling or flowing water. The turbines are then coupled to generators to produce electricity. China is the largest hydroelectricity producer, with 721 terawatt-hours (TWh) of production in 2010, representing around 17% of domestic electricity use. 30 GW of capacity was added during 2010, with cumulative global capacity reaching 1,010 GW at the end of 2011[1].

Geothermal power: This is the thermal energy generated and stored deep below the surface of the earth. The geothermal energy of the earth originates mainly from the decay of radioactive minerals (80%) and from the original formation of the planet (20%). By the end of 2010, total global geothermal installations aggregated to just over 11 GW and geothermal plants generated about 67.2 TWh of electricity. The United States has the largest geothermal capacity, with over 3.1 GW (28.4% of the world total), followed by the Philippines (2.0 GW), Indonesia (1.2 GW) and Mexico (1.0 GW) [1].

Wave and Tidal: There is a significant amount of energy in the ocean. In many areas of the world wind blows with enough consistency and force to provide continuous waves and tides. Both wave and tidal energy involve harnessing the movement and energy contained in the ocean and converting it into electrical power. Wave energy technology uses the movement of ocean surface waves to generate electricity. This is done with the help of wave machines which are placed either on the shoreline or in deeper waters offshore. Tidal power is based on extracting energy from tidal movements and water currents that accompany the rise and fall in sea level due to the tides. Although existing capacity remained low relative to other renewable technologies, numerous projects were in development or under contract, and at least 25 countries were involved in ocean energy development activities. At the end of 2010, 6 MW of wave (2 MW) and tidal stream (4 MW) capacity had been installed by the 18 member countries of the International Energy Agency (IEA) implementing agreement on ocean energy systems. Although this technology is much underdeveloped, it has potential for future electricity generation and is more predictable than wind and solar energy [1].

2.2 Global Wind Energy Statistics

In 2011, a new record was set in the world market for wind turbines which gained momentum after a comparatively weak year in 2010. A 21% increase was noted over the previous year's capacity. Preliminary data gathered by World Wind Energy Association (WWEA) shows that the total worldwide capacity has come close to 239 GW, which is enough to cover 3% of the world's electricity demand. Globally, 42 GW of new installations were added in 2011, after 37.6 GW in 2010. China confirms its role as global wind locomotive with a share of more than one fourth of the global wind capacity installing 18 GW of new wind turbines in 2011. USA continued to be the second largest market for new wind turbines with 6.8 GW, followed by India (2.7 GW), Germany (2 GW) and then Canada (1.3 GW) of new installed capacity. Spain, France and Italy added around 1 GW each in the year 2011 [7]. The cumulative wind power installation from 2001-2011 is shown in the Figure 2.2.

The cumulative wind power capacity in the United Stated has reached 46.919 GW at the end of 2011. Currently, there are over 8.3 GW of wind power under construction involving over 100 separate projects spanning 31 states along with Puerto Rico. Over the past 4 years, the U.S. wind industry has installed over 35% of all new generating capacity, second only to natural gas. Today, U.S. wind power capacity represents more than 20% of the world's installed wind power. Over 400 manufacturing facilities across the U.S. make components such as towers, blades and assembled nacelles for wind turbines. Table 2.1 contains the data on the growth of global wind power capacity for different countries, as of December, 2011.

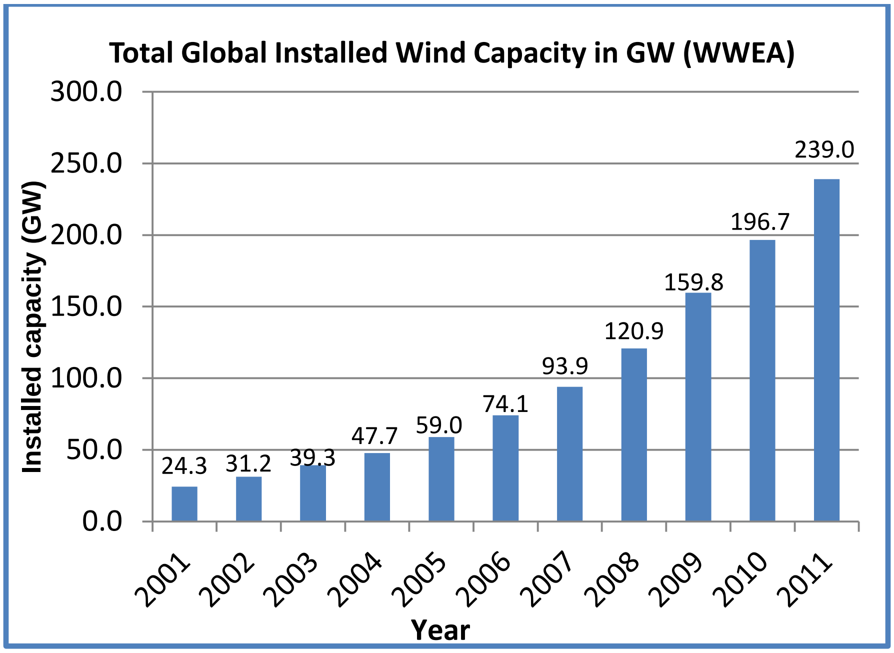

Figure 2.2: Total installed wind capacity from 2001- 2011[7]

Table 2.1: Installed wind power in different countries [7]

Country	Total Capacity end of 2011 [MW]	Added Capacity 2011 [MW]	Total Capacity end 2010 [MW]	Added Capacity 2010 [MW]	Total Capacity end 2009 [MW]
China *	62.733	18.000	44.733	18.928	25.810
USA	46.919	6.810	40.180	5.600	35.159
Germany	29.075	2.007	27.215	1.551	25.777
Spain	21.673	1.050	20.676	1.515	18.865
India *	15.800	2.700	13.065	1.258	11.807
Italy *	6.747	950	5.797	950	4.850
France	6.640	980	5.660	1.086	4.574
United Kingdom	6.018	730	5.203	962	4.245
Canada	5.265	1.267	4.008	690	3.319
Portugal *	4.290	588	3.702	345	3.357
Denmark	3.927	180	3.803	309	3.460
Sweden	2.816	746	2.052	603	1.450
Japan	2.501	167	2.334	251	2.083
Rest of the World*	24.200	6.000	18.201	3.191	15.010
Total*	238.604	42.175	196.629	37.642	159.766
*- Preliminary Data					© WWEA 2012

A number of new wind markets are coming up around the world. Countries like Venezuela, Honduras, and Ethiopia have started using wind energy in 2011. Also, the Dominican Republic installed its first major wind farm and increased its capacity from 0.2 MW to 60.2 MW. Relatively strong growth can be observed in Canada which installed nearly 1.3 GW in 2011. A number of countries introduced new and ambitious legislation for wind power, including Ecuador, Malaysia and Uganda, which adopted systems of feed-in tariffs for the development of renewable energy. Figure 2.3 illustrates the cumulative wind power capacity for the top ten countries around the world.

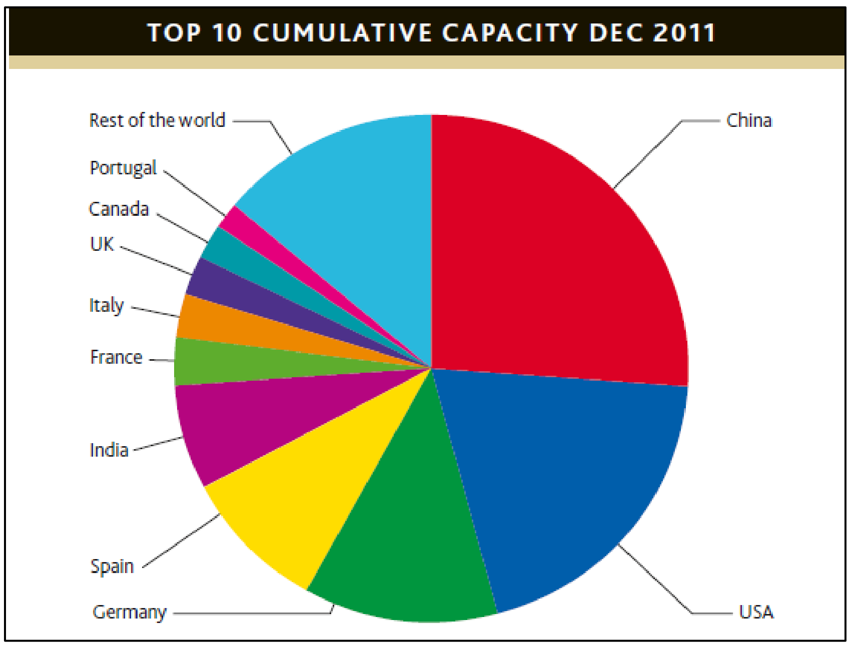

Figure 2.3: Top 10 Cumulative Wind Power Capacity as of Dec 2011[8]

The Enercon E-126, with a rated capacity of 7.58 MW is the largest operating wind turbine at present. It has an overall height of 198 m (650 ft), a rotor diameter of 126 m (413 ft) and has been the world's largest-capacity wind turbine since its introduction in 2007. Many companies are currently working on the development of a 10MW turbine. Many organizations such as the Global Wind Energy Council and National Renewable Energy Laboratory (NREL) have come up with projections on the future of wind energy development. According to the U.S. Department of

Energy, "The U.S. possesses sufficient and affordable wind resources to obtain at least 20% of its electricity from wind by the year 2030." Global Wind Energy Outlook analyzed scenarios on the future potential of wind power and came up with a range of possible outcomes for the global wind energy market.

2.3 Impacts of the Wind power Industry

Wind energy is a free, renewable resource, so no matter how much is harnessed today, there will still be the same supply in the future. Wind energy is also a source of clean, non-polluting, electricity. Wind is a variable resource - i.e. turbines produce electricity only when the wind blows but this variability is monitored and compensated so that there are no changes in power supply for end users. Unlike conventional power plants, wind plants emit no air pollutants or greenhouse gases. Wind power would play an important role in substantially reducing air pollution, water pollution and global climate change that are associated with traditional power generation technologies. Wind power, being a domestic energy resource can also stabilize and diversify national energy supplies. The demand for electricity in US is growing rapidly which indeed leads to search for cleaner power sources and energy-saving practices. The National Renewable Energy Laboratory (NREL) and Lawrence Berkeley National Laboratory have come up with a "20% Wind energy by 2030" collaborative [9]. The report has presented many potential positive impacts such as greenhouse gas reductions, water conservation and energy security.

Greenhouse Gas Reduction: Since traditional energy sources contribute to climate change, increasing attention is being paid to position wind power as a more attractive option for power generation. Increased use of wind energy, therefore, presents an opportunity for reducing emissions today as the nation develops additional clean power options for tomorrow. A 1.5 MW wind turbine will annually displace about 3,000 tons of carbon dioxide generated by nonrenewable energy sources such as coal [9]. From an environmental perspective, the fact that wind turbines do not create any carbon dioxide emissions puts them miles ahead of all nonrenewable energy sources.

According to the U.S. EIA, the United States annually emits approximately 6,000 million metric tons of CO_2. These emissions are expected to increase to nearly 7,900 million metric tons by 2030, with the electric power sector accounting for approximately 40% of the total. Based on the findings by NREL in "20% Wind energy by 2030", generating 20% of U.S. electricity from wind could avoid approximately 825 million metric tons of CO_2 emissions in the electric sector in 2030. As shown in Figure 2.4, this scenario would also reduce cumulative emissions from the electric sector through that same year by more than 7,600 million metric tons of CO_2 (2,100 million metric tons of carbon equivalents) [9].

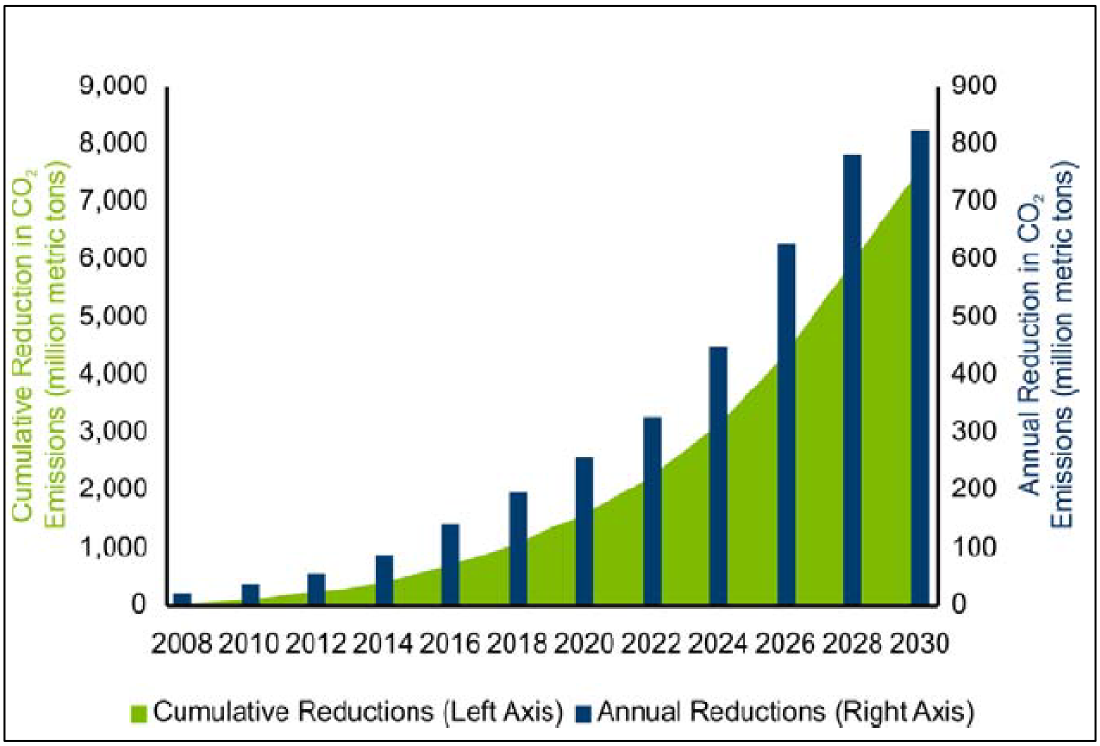

Figure 2.4: Annual CO_2 emissions avoided according to "20% Wind energy by 2030" [9]

Other than greenhouse gas emissions, fossil fuel plants also emit mercury and heavy metals also into the atmosphere. In wind turbines, this is avoided. Also, emissions associated with extracting and transporting of fuels is avoided and there are no solid wastes such as ash or slurry either.

Water Conservation: Electricity generation accounts for almost half of all water withdrawals in the nation with irrigation withdrawals in second place at 34%. A large quantity of water is used in a power plant system for mining and equipment cooling. Although a major portion of it is recycled back through the system, approximately 2 - 3% of the water withdrawn is consumed through evaporative losses. This small fraction can add up to approximately 1.6 to 1.7 trillion gallons of water consumed for power generation each year. In order to produce the same amount of electricity, nuclear plants can take about 600 times more water and coal plants can take about 500 times more water than wind. Considering this negligible water usage by wind power plants, the 20% wind scenario would avoid the consumption of 4 trillion gallons of water through 2030, a cumulative reduction of 8% through 2030. The annual water savings would be approximately 450 billion gallons which would reduce the expected annual water consumption for electricity generation in 2030 by 17% [9].

Energy Security and Stability: Harnessing wind energy improves energy security and stability by diversifying the electricity portfolio in the U. S. Wind energy utilization reduces dependence on foreign energy sources from politically unstable regions, so that a supply disruption will not significantly disrupt the entire economy. As a domestic energy source, wind requires no imported fuel, and the turbine components can be either produced in the nation or imported from any friendly nation with production capabilities. When electric utilities have a power purchase agreement or own wind turbines, the price of energy is expected to remain the same and predictable for the life of the wind project, given that there are no fuel costs and assuming that machines are well maintained. Under the 20% Wind Scenario, wind energy could displace approximately 11% of natural gas consumption in 2030 [9]. This displacement would reduce the nation's energy liability to uncertain natural gas supplies. The price of electricity from fossil fuels and nuclear power can fluctuate greatly due to highly variable mining and transportation costs. Wind can help buffer these costs because the price of fuel is fixed and free.

Disadvantages

Even though the cost of wind power has decreased radically in the last decade, the technology still requires a higher initial investment than fossil-fueled generators. A good amount of the investment is for machinery, with the remaining amount for site preparation and installation. Wind systems can involve the transportation of large and heavy equipment, which can also add to the cost of installation. However, wind costs are much more competitive with other generating technologies, counting fuel and operating expenses over the life of the generator.

Although wind power plants have relatively little impact on the environment compared to fossil fuel power plants, there is some concern over the noise generated by the rotor blades, aesthetic (visual) impacts, and birds having been killed (avian/bat mortality) by flying into the rotors. Most of these problems have been greatly reduced through technological development or by properly siting wind plants. Another negative impact is the shadow flicker which occurs when the blades of the rotor cast a shadow. Studies have shown the worst-case conditions would affect, by way of light alteration, neighboring residents a total of 100 minutes per year, and only 20 minutes per year under normal circumstances. Wind resource development may compete with other uses for the land, and those alternative uses may be more valued than electricity generation. However, wind turbines can be located on land that is also used for grazing or even farming and they would have a very small footprint.

Another major challenge to using wind as a source of power is that it is intermittent and does not always blow when electricity is needed. Wind cannot be stored and not all winds can be harnessed to meet time dependent electricity demands. Further, good wind sites are often located in remote locations far from areas of electric power demand.

2.4 Wind Turbine Technology

Wind turbines convert kinetic energy in the wind to rotary mechanical energy. When mechanical energy is used to produce electricity, the device may be called a wind generator. If mechanical energy is used to drive machinery, such as for grinding grain or pumping water, the device is called a windmill or wind pump. These machines are manufactured in different types and sizes. The smallest turbines are used for applications such as battery charging or auxiliary power on sailing boats; while large grid-connected arrays of wind turbines are becoming an increasingly large source of commercial electric power around the world. Wind turbines are designed to rotate about either a horizontal or a vertical axis, the horizontal one being the older and more common one.

Conventional horizontal axis turbines consist of the following components:

- **Rotor**: It collects energy from the wind and usually consists of 3 blades. Blades are generally 30 to 50 meters (100 to165 feet) long. They are attached to a hub, which in turn is attached to the main shaft.
- **Gearbox:** Gearbox is placed between the main shaft and the generator. Its task is to increase the slow rotational speed of the rotor blades of around 30 rpm to the acceptable generator rotation speeds of 1000 or 1500 rpm. Multiple stages of gearbox are sometimes used to achieve higher ratings. Some turbines use direct drive generators that are capable of producing electricity at a lower rotational speed. These turbines do not require a gearbox. The main focus of this thesis is such turbines.

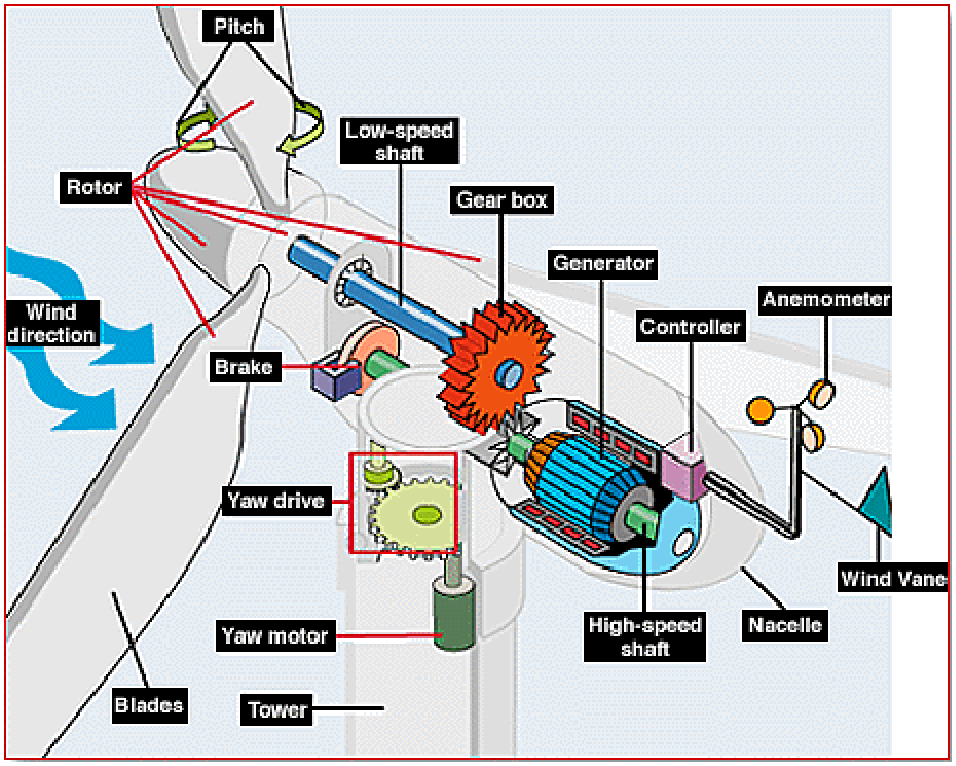

Figure 2.5: Components of a wind turbine [10]

- **Generators:** Wind turbines typically generate electricity through asynchronous machines or induction machines that are directly connected to the electricity grid. Higher efficiencies can be achieved with technologies such as doubly fed induction generators, permanent magnet generators or full-effect converters where the variable frequency current produced is converted to DC and then back to AC, matching the line frequency and voltage.
- **Controller:** There is a controller in the nacelle and one at the base of the turbine. The controller monitors the condition of the turbine and controls the turbine movement. A blade pitch controller regulates the power output and rotor speed in order to prevent overloading of structural components. This is done with the help of wind sensors, along with sensors in generator and drivetrain.

- **Sensors**: They are connected to the control system and are used for sensing wind and its direction, temperature, vibrations, cable twist etc. The number of monitoring sensors can vary; they range from 30-100 typically.
- **Mechanical brake**: This is a disc brake placed on the gearbox high-speed shaft. It prevents the rotational speed of the blades from increasing above the rated rotational speed.
- **Hydraulics**: Pitching, braking and yawing are features within the turbine that rely on hydraulic systems. This system contains bearings, gearwheels, brakes and a yaw motor. Turbine power output is controlled by rotating the blades around their axes. As the blades spin around the rotor hub, the angle of motion of blades with respect to wind changes. This is called controlling the blade pitch.
- **Structural support**: The structural support includes the tower, nacelle and rotor yaw mechanism. Towers are usually tubular steel towers 60 to 80 meters (about 195 to 260 feet) high and consist of three sections of varying heights. The housing for the main components of wind turbine such as the gearbox, generator, shaft etc. is called the nacelle. The yaw system helps the turbine to point itself into the direction of wind by rotating the nacelle around the tower. This is called controlling the yaw.

The concept of the generation of electricity from wind is simple: wind passes over the turbine blades exerting a turning force. The rotating blades turn a shaft inside the nacelle, which goes into a gearbox. The gearbox increases the rotation speed for the generator. The generator uses magnetic fields to convert the rotational energy into electrical energy. The power output goes to a transformer, which converts the electricity from the generator at around 700 Volts (V) to the proper voltage for the distribution system, typically between 11 kV and 132 kV. Regional electricity distribution networks or national grid transmit the electricity around the country, for residential and industrial purposes.

Modern wind turbines, which are currently being deployed around the world, have three-bladed rotors and are typically installed in arrays of 10 to hundreds of turbines perpendicular to the prevailing wind direction. Most utility-scale turbines are upwind machines, which mean that they operate with the blades windward of the tower to avoid the shadowing created by the tower.

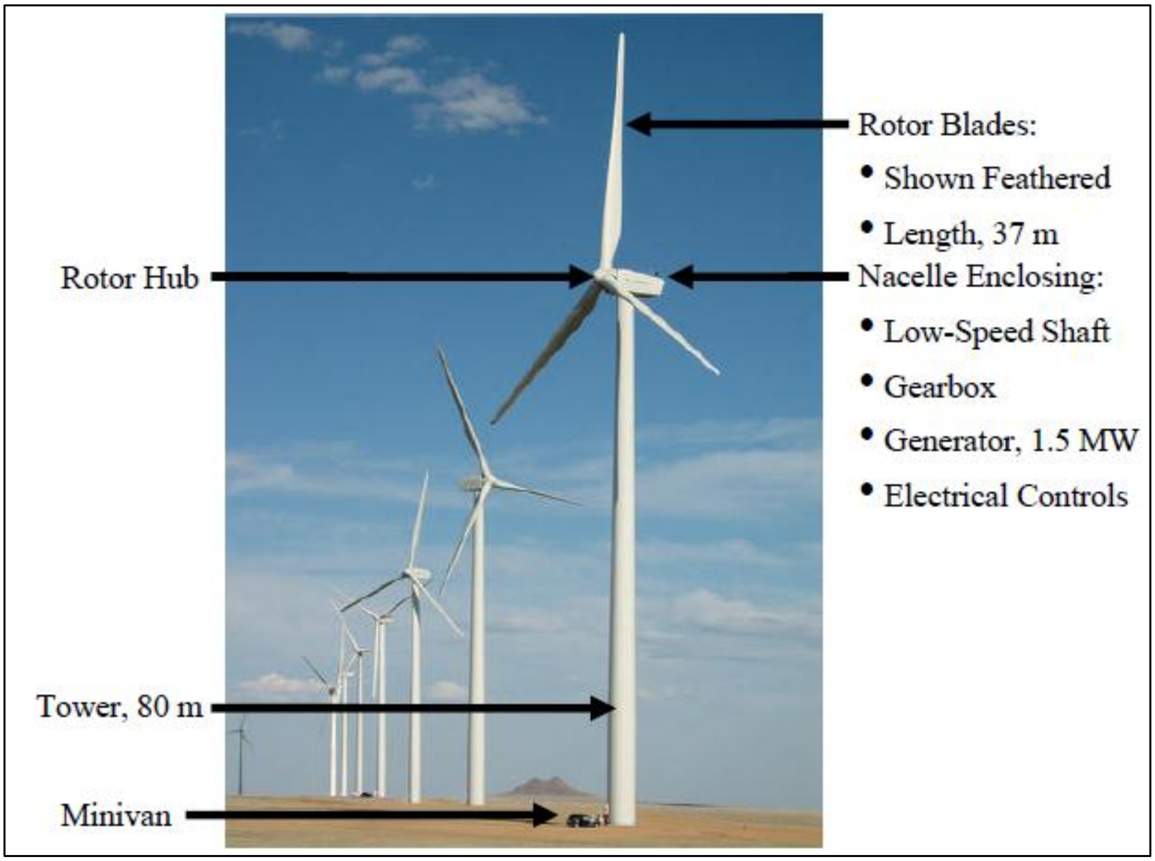

Figure 2.6: Typical parts of a 1.5 MW GE Wind energy system [9]

The parts of a typical 1.5 MW wind turbine of GE are shown in Figure 2.6. The specifications of a classic 1.5 MW wind turbine are as follows [11]:

- Total height of about 328 feet.
- 212-foot tower.
- Three 116-foot blades (with sweeping area about the size of a Boeing 747).
- Concrete and steel rebar platform 30-50 feet across and 6-30 feet deep.
- Total weight of about 328,000 pounds.

- Nacelle weighing about 112,000 pounds (with the size of a school bus).
- An approximate 7 feet by 7 feet gearbox weighing about 35,000 pounds.
- Blade assembly weighing about 72,000 pounds.

The amount of energy that can be harvested from wind is ultimately determined by the size of the rotor blades or "swept area". Frequency and voltage of the electricity that is generated should be compatible with the utility grid. Therefore not all the energy in the wind is available for energy conversion. Energy in the wind available for extraction by the turbine also increases with the cube of wind speed; thus a 10% increase in wind speed results in a 33% increase in available energy. However, only the power for which the electrical system has been designed, called the rated power, is allowed to pass through the rotor. Therefore the turbine can capture only a portion of this cubic increase in energy. According to Betz's law, no turbine can capture more than 59.3% of the kinetic energy in wind.

The power available from the wind can be expressed using the following equation:

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

Where P = Power in Watts

ρ = Air density (1.2kg/m^3 @ sea level and 20° C)

A = Swept area of the turbine blades (m^2 square meters)

V = wind speed (meters per second)

Power curve for a typical wind turbine is shown in Figure 2.7. Generally, a turbine will start generating power at wind speeds of about 5 m/s and will reach maximum power output at about 13 m/s. The turbine will pitch or feather the blades to stop power production at about 30 m/s when the wind speed becomes too strong and destructive. In general, wind speed increases with altitude, so the tower height and the size of wind turbines are maximized while minimizing the costs of materials. But land-based turbine size is not expected to grow as radically in the future as it has been in the past. Larger sizes are physically possible; but the logistical constraints for the transportation of the components via highways and of obtaining cranes large enough to lift the components present a major economic barrier.

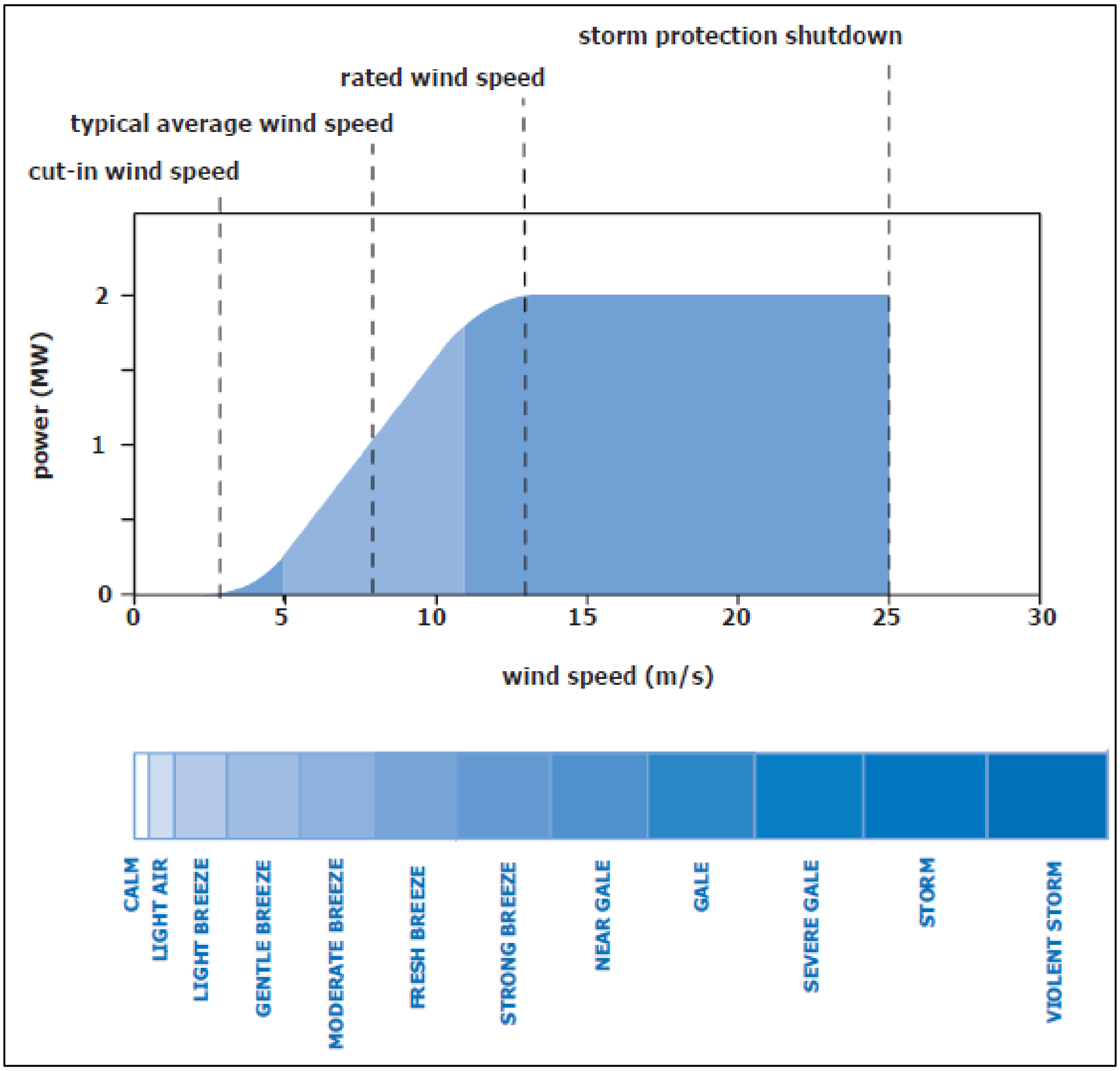

Figure 2.7: Power curve for a typical wind turbine [12]

Weibull distribution is most commonly used to model wind speeds. It is versatile and involves a scale parameter and a shape parameter which can be adjusted to suite the wind regime under study. Using this model, the probability of wind being between any two values can be easily calculated. Typically, wind electric conversion systems (WECS) operate in the variable portion of their characteristics for a significant portion of the time, depending on the wind regime and WECS design parameters [13].

Wind turbines are available in a variety of sizes, and therefore power ratings. The largest of these has blades with lengths more than that of a football field, stands 20 building stories high, and produces enough electricity to power around 1,400 homes. Small home-sized turbines are also built with rotors having 8 - 25 feet diameter and stand about 30 feet high. These have the ability to supply power for an all-electric home or for a small business.

In 2010, nearly 2900 new wind turbines were installed bringing the total USA installation to over 35,600 turbines. The average rating of the turbines installed in the United States in 2010 was 1.77 MW [14]. One MW of wind energy is sufficient to supply electricity to 240-300 homes. Right now, there are enough wind turbines operating in the U.S. to power over five million homes. High-quality products are now delivered by major suppliers of turbines around the world, and complete wind generation plants are being engineered into the grid infrastructure to meet utility needs.

CHAPTER 3

RELIABILITY OF WIND TURBINES

Reliability assessment is an important part in the design of any system and it can even be considered as a design parameter. Quantitative and qualitative terms and measures may be employed in order to obtain high reliability in wind turbines. One of the initial steps to realizing an improvement in reliability would be to understand the components in the systems which are prone to failures. In order to have a good restoration procedure, study of statistical data for wind turbine failures is important. This chapter explains the role that the gearbox plays in different statistics of wind turbine failures. A brief primer on reliability basics and reliability strategies used in wind energy systems is also included.

3.1 Failure statistics of Wind turbines

Even though many surveys have been conducted on wind turbines, it is still evident that the statistical data regarding the failures of its subassemblies is difficult to obtain. This is due to reasons such as the manufacturers refused to reveal their data, no such data was collected for wind farms or the available data was not comparable with respect to time and design details. However, [15] provides a detailed and comparable statistics of these failures and this has been taken as our reference data. A good indicator of the severity of a failure is how often a component fails (failure rate) and for how long the failure lasts, which is the average downtime per failure (repair time). Many surveys have been conducted in order to assess the reliability of different subassemblies in wind turbines. On an average, the wind turbines are shut down twice a year in the first six-ten years of its operation. They are shut down for a week or so for maintenance work or after the malfunctions. After these initial operating years, usually the operating cost remains a constant and only constant monitoring may be needed.

The heavy gearbox in wind turbines has multiple gear wheels and bearings and they are subjected to severe stress because of wind turbulence. Any failure in one of these components can bring the turbine to a halt and thus gearbox becomes one of the highest maintenance parts of the wind turbine. Other critical failure components include planet bearings, intermediate shaft-locating bearings and high-speed locating bearings. The Figure 3.1 shows failure rates and downtimes of the wind turbine subassemblies including over 20000 turbine years as conducted by two European surveys, LWK and WMEP over 13 years [16].

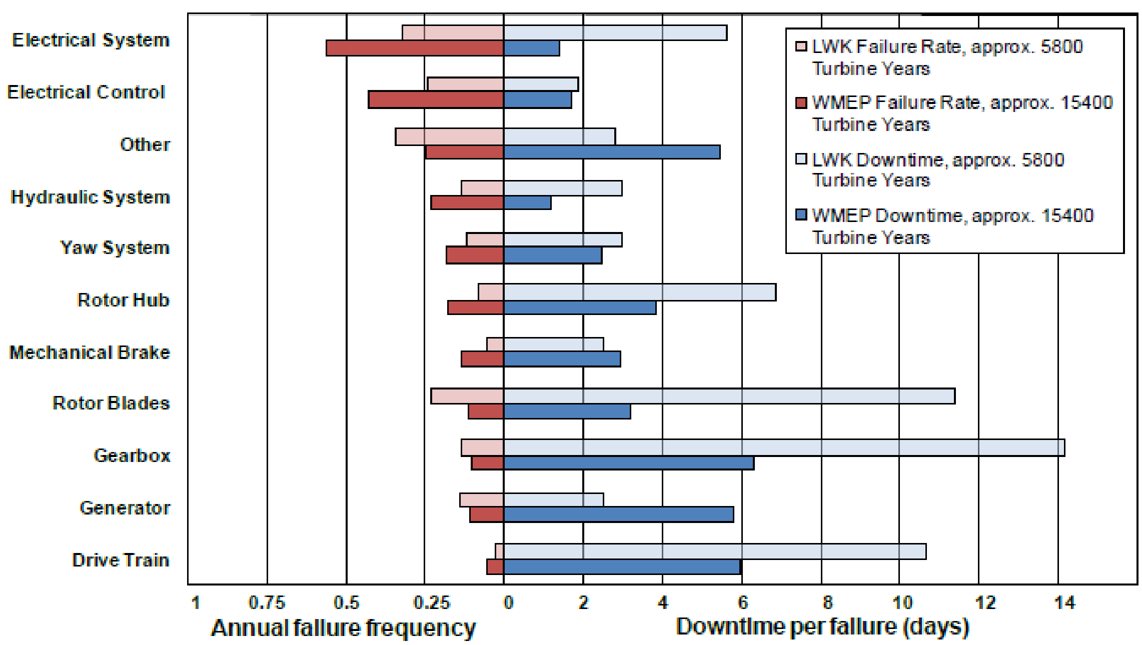

Figure 3.1: Failure data of wind turbines from European surveys over 13 years [16]

Another set of data is also available which contains the failure statistics of Sweden wind power plants as collected by Swedpower AB [15]. This is represented in Figure 3.2. Drive train just refers to the main shaft in the turbine in this survey.

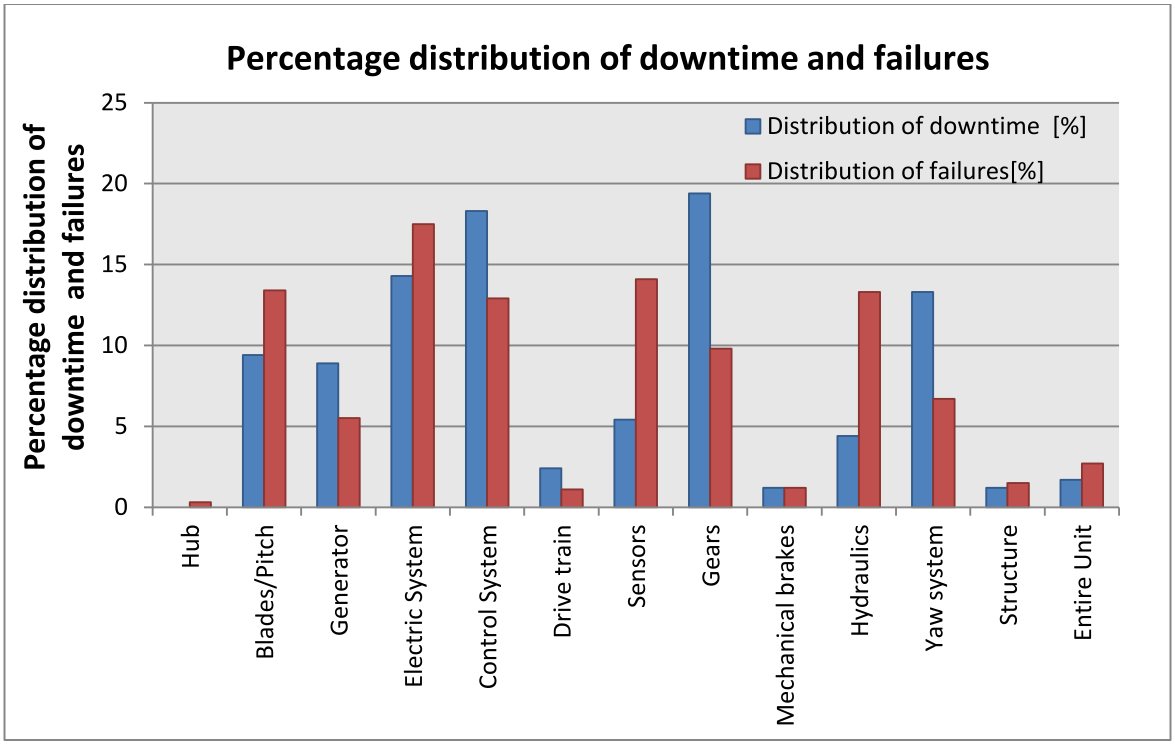

Figure 3.2: Distribution of failures for Swedish wind power plants between 2000-2004 [15]

Surveys conducted on wind reliability data, as shown in Figure 3.1 and Figure 3.2, indicate that gearbox failure rate is not too high comparatively, but the downtime and the resultant costs for the failure are high. This happens due to the fact that the repair procedure for gearbox is complex, especially if turbines are installed offshore. Since we are interested not just to reduce the failure frequency, but also to reduce the time and cost of these repairs, it is important to study the components that contribute the most to repair time and its cost. Downtimes also provide an additional measurement of the lost revenue due to failures. Since many surveys do not provide the cost of repairs, we can take downtimes as an indirect measure of cost and effort to repair.

3.2 Gearbox issues

A gearbox is used to convert the speed of rotation of one shaft into another rotational speed for another rotating shaft. The basic gearbox used in any application consists of a containing case, a lubrication system, and the gears that are held in mesh by axial and radial supporting bearings.

Difference between gearboxes is on the basis of size, type and number of gears and bearings and the designed load range. Most of the industrial gearboxes functions by changing the high speed and low torque to high torque and low speed. But a wind turbine gearbox works the opposite way where it transforms low speed and high torque to low torque and high speed. It transforms the low speed revolutions from the rotor (about 30 rpm) to high speed revolutions (1500 rpm) via a high speed shaft which in is turn connected to the generator. Usually this transformation is not done in a single stage gearbox, instead it gearbox uses several stages to stepwise alter the speed. Each of these stages usually has a ratio about 1:4-1:5. The first stage connects the rotor to the gearbox and is referred to as low speed stage and the last stage is called the high speed stage which is then connected to the generator. There are different configurations of gearbox stages, the most common one being a combination of a planetary gear stage and a parallel gear stage.

Gears operate at constant speed in traditional power plants, whereas in wind turbines, gears have to deal with partial load and variable speed. Also, the gearbox torque is dynamic due to wind speed turbulence. The generator operation is also characterized by high input speeds at relatively low torques. These torque levels cause highly loaded gears and bearings to produce severe stresses inside of the system. The friction between the surfaces result in small particles dropping off, this wear out process is known as micro pitting.

The logistics behind the design, construction and maintenance of wind turbines are a challenge to the renewable energy industry – one of the central issues being the early failure and long downtime of the gearbox. Usually, a wind turbine gearbox is designed to achieve a lifetime of 20 years but studies have shown that many of them are falling far short in the 5-7 year range. One of the main issues with the gearbox is its massive size (up to 50,000 lbs. for the MW turbines) which makes the repair and replacement complex and difficult to handle. Offshore turbine maintenance can be more complex as this involves support ships and cranes and has the additional issue of potentially unfavorable wave and weather conditions. There are only a few numbers of failures that can be rectified on site. Therefore, to repair a failed gearbox will require the removal of the entire unit from the turbine with significant cost and time implications. Gearbox replacement and lubrications account for around 38% of the turbine parts' cost. Taking into account the cost of the gearbox, crane rental, labor and lost revenue, a typical gearbox replacement costs range from $300K-$775K USD [17]. Since gearboxes are one of the most expensive components of a wind turbine, the higher-than-expected failure rates significantly adds to the cost of wind-generated energy.

The surveys conducted on the wind turbine subassemblies by WMEP and LWK [16] have shown that gearboxes exhibit the highest downtime per failure among onshore sub-assemblies. From the Swedish survey represented in Table 3.1, we can see that 14.6% of the annual downtime is caused by gearbox failures on an average. In Finland, the gearbox failures contributed an average of 32% of the total downtime from 1996-2004 as shown in Table 3.2.

Table 3.1: Overview of gearbox failures in Sweden between 1997 and 2004 [15]

Year	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**1997-2004**
No: of failures [n]	21	41	52	26	30	42	13	7	232
Total downtime [hours]	4031	2518	5061	6172	5228	12589	3987	2309	41895
Average downtime per failure [hours/failure]	192	61	97	237	174	300	307	330	181
% of total downtime	9.4	5.3	7.3	15.5	13.6	33.5	14.8	17.4	14.6

Table 3.2: Percentage of downtime for gearbox failures in Finland [15]

Year	**2000**	**2001**	**2002**	**2003**	**2004**	**1996-2004**
Percentage of total downtime	42%	62%	28%	0%	0%	32%

The primary cause of gearbox problems may be due to the gear failure, but the current generation of turbines also most often fails from bearing surface fatigue. The fragments produced by this failure leads to abrasion of other gearbox components. Other critical failure areas include planet bearings, intermediate shaft-locating bearings and high-speed locating bearings. The system needs to adjust to the quick variations in the loads due to wind gusts. In addition, there may be vibrations and oscillations within the entire drivetrain system. Intermediate bearing bodies, such as balls and rollers, vibrate against the outer and inner rings causing the grease to squeeze out of highly loaded contact areas. This produces wear marks and a rippling effect that can severely damage bearings. Sometimes the turbine simultaneously operates under a medium-sized load at low speeds and a low load at high speed, especially during light wind. This leads to the breakdown of the lubricating film, which in turn reduces the bearing life.

Thus the studies conducted over a considerable period of time have concluded the following about gearbox issues: [17]

- Most problems with gearboxes are generic and not due to a specific manufacturer of model.
- Most gearbox failures do not begin as gear failures or gear teeth design deficiencies. The majority of gearbox failures appeared to begin in the bearings.
- No gear box can survive without clean oil. Over 15% of bearings that failed in its first five years and often sooner are due to manufacturing defects in bearing of gearbox, stand-still damage, lubricant starvation or overheating or lubricant contamination

An increase in reliability can result in a huge economic pay off in the wind industry. But one of the main problems in addressing and mitigating gearbox problems is its complexity in design, manufacture and business. There are several different ways of gearbox designs and the business involves many gear and bearing manufacturers as well. Each manufacturer might even rely on several gearbox suppliers. They use their own internally developed design codes that can introduce significant bearing differences.

Many researches are ongoing to solve the gearbox issues, the most notable one being the National Renewable Energy Laboratory's(NREL) Gearbox Reliability Collaborative in Golden, Colorado. It is a cooperative made up of research professionals and key representatives of the supply chain, such as turbine owners, operators, gearbox manufacturers, bearing manufacturers, lubrication companies and wind turbine manufacturers. It aims at giving the participants a venue for addressing and mitigating gearbox issue. There are three aspects to the Collaborative program: Drivetrain software analysis and modeling under simulated field conditions, a full scale dynamometer testing on a 750-KW drivetrain and finally a wind farm field testing conducted on the same drivetrain. ReliaWind, funded by the European Union, is also developing a systematic and consistent process to deal with detailed commercial data collected from operational wind farms. This includes the analysis of 10 minute average SCADA data, automated fault logs and operation and maintenance reports. This research also aims to identify and understand wind turbine gearbox failure mechanisms in greater detail.

It is likely that for turbines with higher power ratings, additional stages of gearbox will be required which may still increase the complication of gearbox issues. In order to compensate for this effect, designs based on a lower generator speed (rpm) may be used. Gearboxes for the offshore turbines will be more complex and the increased complexity may lead to increased possibility of failure. Hence there is a reasonable option that direct drive technologies may prove more attractive compared to its geared counterpart.

3.3 Reliability theory

According to the Sandia laboratories, "Reliability is defined as the probability that a product will perform its intended function under stated conditions for a specified period of time." [18]

For a wind turbine, reliability is a probabilistic theory involving a turbine's planned use, its operating environment and time. Thus, the reliability of a turbine is the percentage of time (probability) that turbine will be functioning at full capacity (intended function) during appropriate wind conditions at a site with specified wind resource characterization (stated conditions) for a fixed period(time).

Reliability assessments interface with all aspects of design, O&M requirements and limitations, and life cycle costs. Figure 3.3 shows a conception of distinguishing between different aspects in lifetime of a system or component. It is a complete failure intensity curve whose three regions is described using different values for the shape parameter β. Failure rate, also referred to as hazard rate, is often a function of time and it follows a bathtub curve.

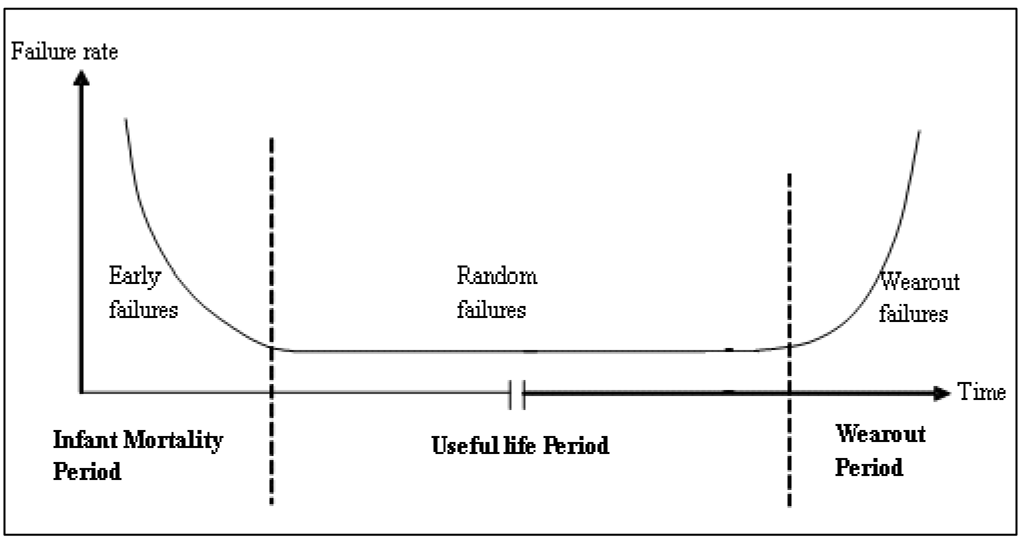

Figure 3.3: Bathtub Curve Showing product life cycle [19]

Three regions can be identified in the curve.

- An infant mortality period with a decreasing failure rate: The failure rate is high in a turbine's early life due to wear-in-failures or failures due to poor quality assurance. The better the quality assurance of design assembly and construction, the lower this part of the curve starts and sooner this period ends. Reliability of a wind turbine may not be quantitatively measured during this period, but using a qualitative analysis, reliability and safety during this period can be improved.

- Normal life period (also known as "useful life") with a low, relatively constant failure rate: This stage represents random failures.
- Wear-out period with an increasing failure rate: The failure rate of this period again increases due to ageing and deterioration of components. By using preventive maintenance and regular monitoring, starting point of this period van be regulated.

Reliability parameters

Often, reliability metrics are used in combination with each other. Occasionally, these parameters are stated together for the performance of a “RAMS Analysis”, where Reliability, Availability, Maintainability, and Safety are all addressed together. “Maintainability” is associated with access, clearances, and provisions for repair and replacement items, such as lifting or transporting devices and it is a non-numeric definition. “Safety”, along with the same aspects, also includes training for these operations in the greater environmental safety and health aspects. Reliability analyses can have an immense impact on safety if the number of hazardous actions can be reduced through decreased failure rates and enhanced reliability.

Availability: Availability is most closely related to energy production and revenues and is a key measure of system performance. All power plants must be taken down for maintenance; both scheduled and, at times, unscheduled maintenance. The percentage of time that a wind power plant is not down for maintenance and is able to operate satisfactorily is called its availability. Because the wind does not always blow, the percentage of time that the machine is actually producing electricity will be lower than the availability. Unexpected loss of load resulting from the stochastic nature of wind resource and mechanical failures as a result of severe weather conditions are some of the serious causes of reduced availability of WECS output [20].

Maintainability: Maintainability is a design objective which provides for easy, accurate, safe, and economical performance of maintenance functions. It is the probability that the product will conform to specified conditions within a given period of time when maintenance action is performed with prescribed procedures and resources.

Safety: Safety is the probability that the product will operate satisfactorily and without any occurrence of accidents, when under stated conditions.

Mean Time between failures (MTBF): A principle measure of the system performance is the mean time between failures. MTBF, as the name suggests, is the average time between failures of a component.

MTBF=Operational Time/ Number of failures

Mean Time to Repair (MTTR) or Downtime: It is defined as the average time taken to repair or replace a failed module.

MTTR=Total repair time/ Number of failures

Repair rate, $\mu = 1/MTTR$

Mean Time to Failure (MTTF): This value is very similar to MTBF and is used when evaluating nonrepairable systems. MTBF assumes that a device is to experience multiple failures in a lifetime, and after each failure a repair occurs. For non-repairable systems, there is no repair. Therefore, in the lifetime of a non-repairable device, the device fails once and MTTF represents the average time until this failure occurrence.

Exponential distribution

For the majority of systems, and particularly for electrical and digital systems, the failure distribution is exponential during its useful life. Such a rate implies that the occurrence of failures is purely random and there is no deterioration of the strength or soundness of the component with time. In addition, using some simple transformations, a distribution such as Weibull can be expressed as an exponential distribution. Furthermore, according to the method of stages, any distribution can be expressed as a combination of exponential distributions. Although this analysis is not realistic for all lifetime, it is a good approximation during the useful life time (the horizontal portion of the bathtub curve) of the component. A constant hazard rate leads to a simple model which requires only one parameter to be defined.

$\lambda(t) = \lambda$, a constant

The reciprocal of the failure rate is referred to as the mean time to failure (MTTF)

MTTF = $1/\lambda$.

In the case of repairable components, MTBF is used to represent the mean time between failures.

MTBF = mean time to failure + mean time to repair

= MTTF + MTTR

If MTTR << MTTF, then MTBF approximately = MTTF

For constant failure rate systems, reliability is calculated as

$R = \exp(-\lambda t)$ where t is the mission time and λ is the failure rate.

Wind turbine manufacturers usually guarantee turbine availability (95- 98%), useful life of (10-14 years) and power curve (100%) during the warranty period (usually 2 to 10+ years).

Components in series: Consider the case of n components logically in series. Let λ_i and r_i be the failure rate and repair time of each of these components respectively. We would want them to be replaced by an equivalent component with a failure rate of λ_s and a repair time of r_s [20]

$\lambda_s = \lambda_1 + \lambda_2 + \ldots\ldots + \lambda_n$

$r_s = (\lambda_1 r_1 + \lambda_2 r_2 + \ldots\ldots \lambda_n r_n) / \lambda_s$

Equivalent reliability $R_s(t) = \exp(-\lambda_s t)$

System unavailability $U_s = \lambda_1 r_1 + \lambda_2 r_2 + \ldots\ldots \lambda_n r_n$

Availability $A_s = 1 - U_s$

CHAPTER 4

DIRECT DRIVE WIND TURBINES

For wind turbines with ratings of more than 3 MW, it is likely that more stages will be required in the gearbox and thus the complexity of the gearbox issues will increase. There are only a limited number of failures that can be rectified in the wind- farm site. Most of the failures would require the removal of the entire unit from the turbine with significant cost, effort and time implications. Hence new approaches such as direct drive technologies, condition monitoring (CM) of gearboxes, etc. are introduced. A good CM system can detect significant health condition changes of the wind turbine subassemblies such as the gearbox at an early stage.

An effective way to increase wind turbine reliability is by completely eliminating the gearbox using direct drive wind turbine technology. By coupling a low-speed generator directly to the wind turbine, a compact and more reliable drive system is achieved due to the elimination of the mechanical gearbox. Wind turbines can be made to have either constant-speed or variable-speed mechanical output. In the last couple of decades, technology has evolved much in the development of innovative variable-speed wind turbines. There are several advantages associated with variable-speed wind turbines such as higher energy extraction from wind, lower noise at low wind speeds and cleaner power transfer to the grid. Two configurations of variable-speed electromechanical converters are being focused nowadays: doubly-fed induction generator with gearbox and direct-drive alternator with power electronic converter. Doubly-fed induction generator with gearbox uses an induction generator with a wound rotor and slip rings. The rotor circuit (excitation winding) is connected to an AC/AC power converter, which exchanges electrical energy between the rotor and the AC grid. The induction generator is rotating at a conventional speed (around 1500 rpm) and a gearbox is needed to adapt the low-speed rotating shaft (around 25 rpm) to the generator.

4.1 Concept of direct drive technology

In direct-drive configuration, the generator is directly connected to the mechanical shaft carrying the rotor blades. The generator electrical output is connected to a power electronic converter, which, in turn, is connected to the electrical network (the grid). The one with a permanent magnet alternator (PMA) is the most commonly used direct drive system now and is characterized by its simple, robust design, requiring no excitation power. A typical configuration of a direct drive wind turbine based on PMA and full-power converter is illustrated in Figure 4.1. It consists of:

- Gearless drive train and aerodynamics
- Pitch angle control
- Multi-pole PMA
- Full-scale frequency converter and its control

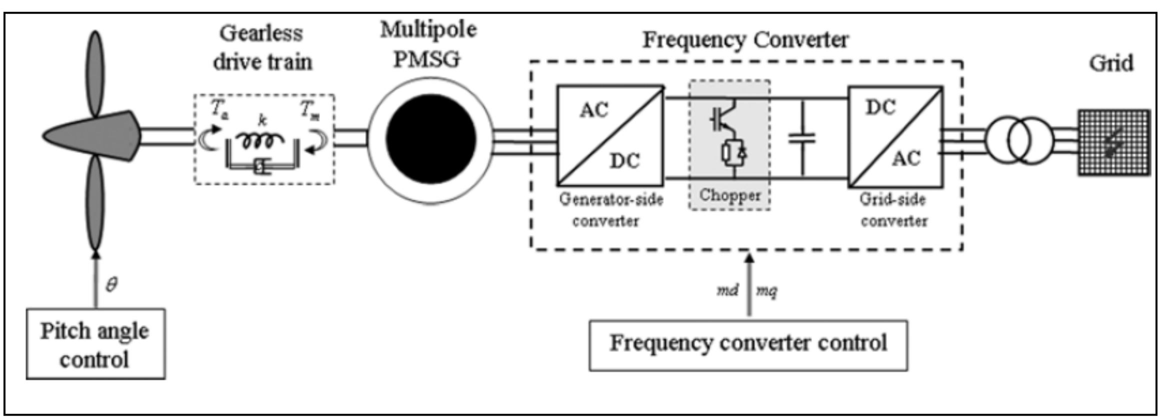

Figure 4.1: Multi-pole PMA wind turbine configuration [22]

As shown in Figure 4.1, the aerodynamic rotor of the wind turbine configuration is directly coupled to the generator through a gearless drive train. The alternator is connected to the grid through a full-power frequency converter system, which controls the speed of the alternator and power flow to the grid. The permanent magnets are mounted on the rotor, providing a fixed excitation to the generator. The power output is fed via the stator windings into the full-power frequency converter, which converts the varying alternator output frequency to the constant grid frequency. The full-power frequency converter system consists of two back-to-back voltage source converters controlled by IGBT switches [22].

The components of a direct drive wind turbine are shown is Figure 4.2. In this system, rotating permanent magnets provide the rotating magnetic field and the windings in which emf is induced is stationary. They are optimized for efficient energy capture with a higher power curve. They transform the rotor movement directly into electrical power with no inertial and mechanical friction losses associated with gearboxes. The magnets spin around a set of windings to generate electrical output. The faster the magnets spin, the more current is induced in the coil. To make up for a direct drive generator's slower spinning rate, the radius of rotation is increased, effectively increasing the speed with which the magnets sweep past the stator windings.

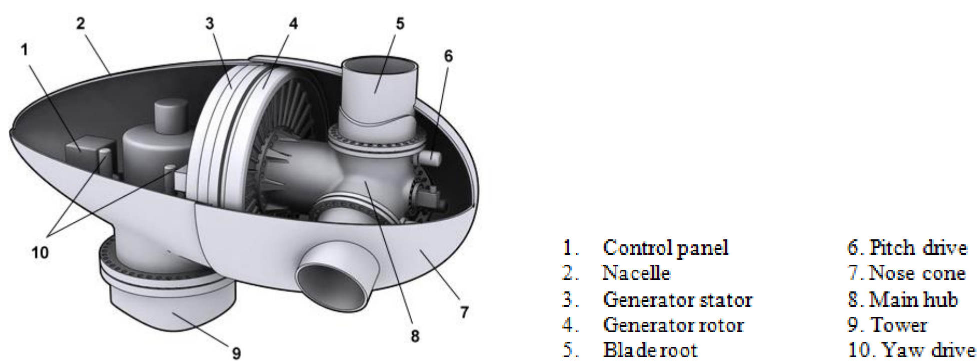

Figure 4.2: Schematic of direct drive wind turbine [23]

The generators of the gearless wind turbines are some of the largest permanent magnet machines ever to be built. They have rotational torques in the range of 2,500 kNm. By comparison; a strong electric drive for a vehicle has much less than 1 kNm torque. The proprietary full power converter, in combination with the PM generator, optimizes the overall power train performance. This optimized system results in more power delivered to the grid. Full power converter and main transformer are located up-tower. Electricity is converted to medium voltage closer to the point of generation, minimizing long power cable losses between components. This layout eliminates field excitation losses, and results in significant rotor loss reduction and higher efficiency, yielding more revenue-generating power.

4.2 Permanent magnet generators

Permanent magnet (PM) (alternators) generators can be designed in many ways. It can be surface-magnet or buried-magnet radial-flux PM machines, axial-flux PM machines, transverse-flux PM machines, switched reluctance machines and a linear induction machine. The stator core can be slotted or slotless [24]. The rare earth element required in the manufacture of high performance permanent magnets is “Neodymium” (Nd). Most of the PM generators in direct drive turbines use the compound neodymium iron boron (NdFeB). Two of the most common types of these generators are described in the following section.

4.2.1 Radial-Flux Permanent-Magnet Generators

The most common type of PM machine used in industry is radial-flux PM machines (RFPM) where the magnetic flux is along the radius of generator. These are well known to have higher torque capability than the more common induction machine [25], [26]. Radial flux permanent magnet generators may be of two types - surface-magnet or buried magnet machines. A surface magnet generator rotor is constructed by mounting the magnets onto the surface of rotor having a number of poles. In order to provide a high flux density in the air gap, it is necessary to use high-energy magnets such as NdFeB magnets. In a buried magnet machine, cheaper ferrite magnet material may be used. The machines are excited by surface-mounted NdFeB magnets or by buried ferrite magnets. The RFPMs can also be classified based on the existence of slots and the type of polyphase winding. In non –slotted version, stator structure is slotless and consists of a stack of laminated steel. Back-to-back connected polyphase windings are wrapped around the stator in a toroidal fashion and termed airgap windings since the windings are not placed into slots. The places in between the windings are filled with epoxy resin to increase robustness and provide better conduction heat transfer. The rotor structure consists of surface mounted NdFeB magnets, rotor core and shaft. For torque production, only the windings facing the rotor PMs are used. The portion of winding on the outer surface of stator is considered to be end windings and will not contribute to torque production. These long end windings can result in high copper loss. Additionally, the large airgap will result in reduced flux density. However, an important advantage is that the structure transfers heat from the stator frame very easily. Therefore, machine electrical loading can be relatively high.

The design of the radial-flux machine is simple and is widely used in wind power applications. These machines have higher torque capability and efficiency due to the lack of rotor windings than induction machines. However, magnet maintenance must be carefully implemented so that the rotor does not fly apart and this stands as a disadvantage of the RF machines [26].

4.2.2 Axial Flux Permanent Magnet Generators

A simple axial flux permanent magnet machine is formed by a rotor disc carrying permanent magnets that produce an axial flux and a stator disc containing phase windings. Different variations in this basic design are possible such as single-sided, double-sided, torus, and multi-disc designs [27], [28], [29], [30].

Figure 4.3 shows a two-rotor, one stator design, where a single stator is placed between two permanent magnet (PM) rotor discs. The axially magnetized NdFeB magnets are placed on two rotor discs on both states of the stator i.e. the disc shaped rotors carry the surface mounted permanent magnets on their inner surfaces. The rotor structure is formed by arch-shaped surface mounted NdFeB magnets, rotor core and shaft. The stator of the machine is realized by tape wound core with polyphase AC airgap windings which are wrapped around the stator core with a back-to-back connection.

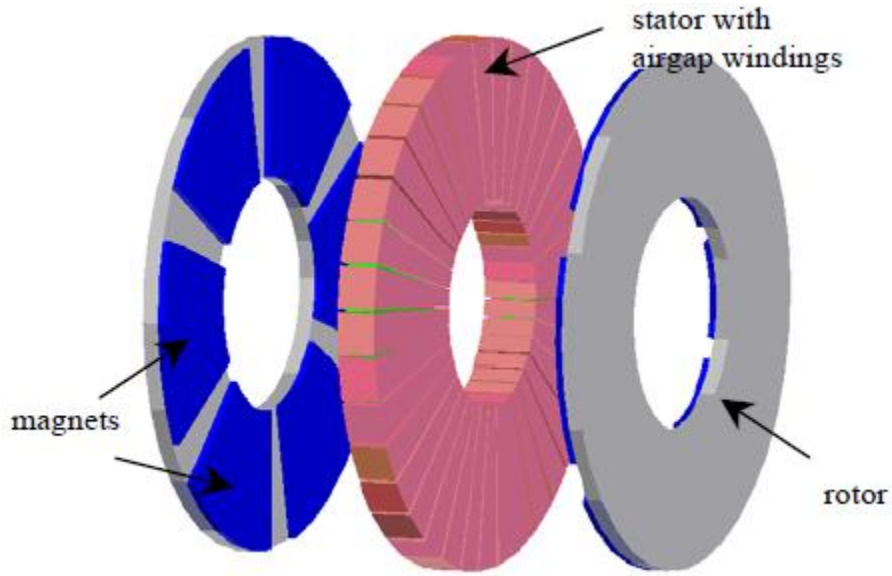

Figure 4.3: Axial flux torus type non-slotted surface mounted PM generator [26].

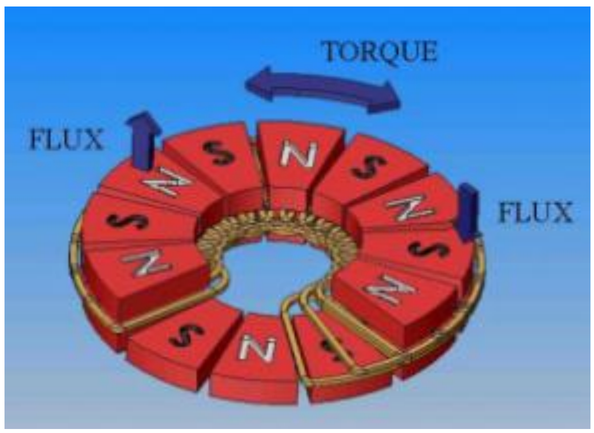

Figure 4.4: Permanent magnet axial flux configuration [31]

Flux directions of axial flux non slotted PM generator are shown in Figure 4.4. Figure 4.5 illustrates the detailed views of the stator and rotor structures of slotless AFPM generators with airgap windings. The active conductor portions are the radial portions of toroidal windings facing the rotor structures [26].

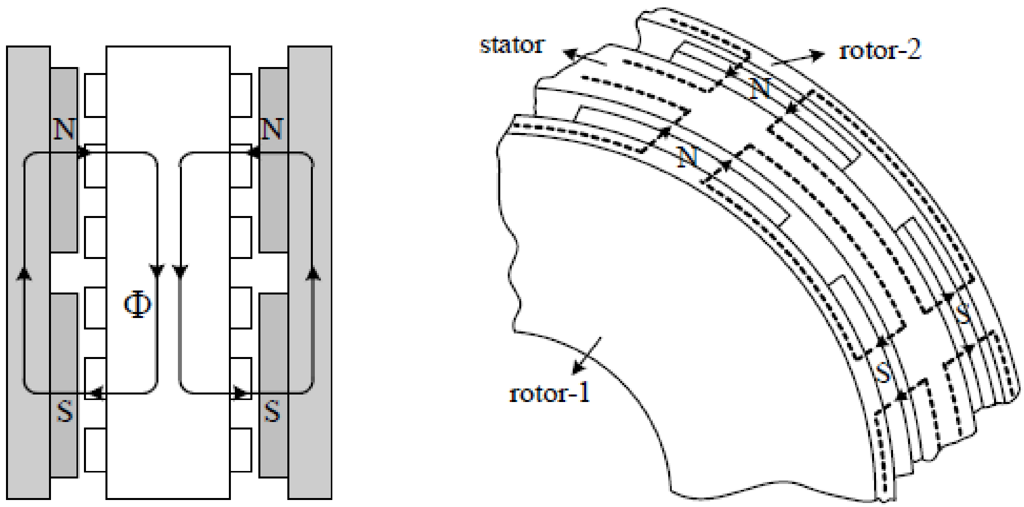

Figure 4.5: Flux directions of axial flux non slotted PM generator: 2D (left) and 3D (right) [26].

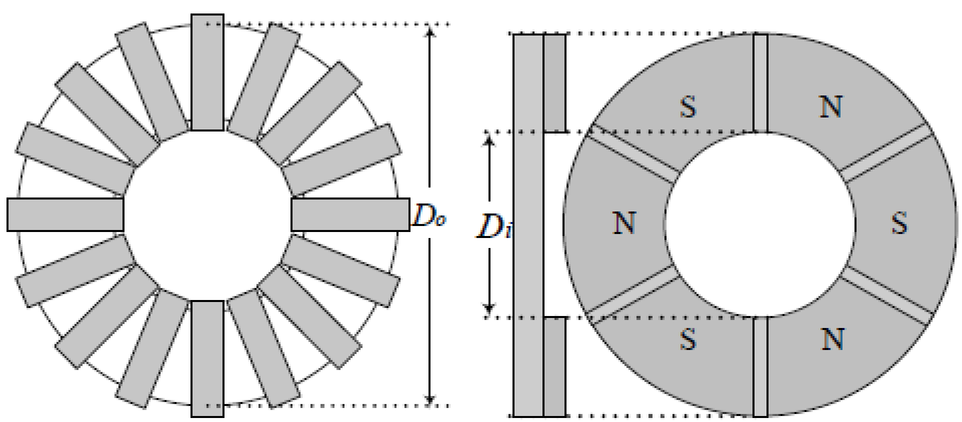

Figure 4.6: Stator (left) and rotor (right) structure of slotless AFPM generators [26].

The disc shaped AFPM generator is an attractive alternative to cylindrical RFPM generators in wind turbine applications due to some reasons. Firstly, AFPMs can be designed to obtain a larger power-weight ratio resulting in less core material and higher efficiency. This construction of

AFPM is simple with more flexible winding design and many machines can be mechanically connected with each other. Additionally, this construction also has a relatively high moment of inertia, which allows the rotating machine to store energy, thereby helping to obtain smooth power output during transients [32]. The axial flux configuration is amenable to the low-speed, high-torque operation of a direct drive wind energy system. The portions between the airgap windings are assumed to be filled with epoxy resin as in all non-slotted structures in order to increase the robustness and provide better conductor heat dissipation. Moreover, the windings in the airgap are used for torque production and thus the torque-per-unit-volume and torque-per-unit-weight are both considerably better than RFPMs. The end windings are quite short which results in making the copper loss of these generators smaller. Effects resulting from the slots such as flux ripple, cogging torque, high frequency rotor loss, and saturation on stator tooth are eliminated and this feature leads to a low noise machine.

The main disadvantage is due to the large axial force exerted on the stator by the rotor magnets. This magnet force could even twist the structure very easily. This axial force will be less severe if the stator teeth are removed since this force is exerted on the iron, not on the copper windings. Also, special attention must be paid to the choice of structural materials. The leakage flux will induce eddy currents causing extra losses and heating if the casing is too close to the rotating magnets. Another concern with the AFPM generator is its large outer diameter will require larger amount of magnet material.

4.3 Advantages of direct drive technology

We can identify a few drawbacks of the variable speed doubly-fed wind turbine configuration as mentioned in [32]:

- Heat dissipation caused by friction between gears
- Long-term wear due to friction between gears

- Oil is required, which must be replaced at regular intervals
- Audible noise from the gears' rotational motion
- Limited capability of supplying reactive power to compensate the grid power factor
- High torque peaks in the machine and large stator peak currents under grid fault conditions
- External synchronization circuit required between the stator and grid to limit the start-up current.

All of the above-listed disadvantages favor the direct-drive configuration. However, one important drawback of direct-drive is the high torque rating. Mass of electrical machines depends on their torque rating. For example, a 750-kW generator rotating at 25 rpm will be many times heavier and many times more expensive than a 750-kW generator rotating at 1500 rpm.

In section 3.2, it was mentioned that the gearbox is one of the major components that contribute to the downtime of wind turbines. Gearbox appears logically in series with other subassemblies in a wind turbine; hence its elimination will also result in elimination of failure rate and downtime contributed by the same. When a gearbox fails due to any defect or failure in its individual parts, the entire turbine comes to a standstill. Thus the failure rate is significantly increased and therefore reliability of direct drive wind turbines is much higher than its geared counterpart.

The reduction of downtime in direct drive technology is an especially important consideration for offshore wind farms. This is because performing maintenance at sea is far more complex and expensive than on land. The reduction of mechanical maintenance due to gearbox elimination will ultimately result in financial savings.

Having fewer moving parts than its geared counterpart implies having fewer parts prone to failure, which, in turn, indicates longer lifetime. Failures in other systems are usually caused by aging of the component such as a stretched belt or a worn out gear.
In addition to high reliability, maintenance and replacement requirements will be less compared with an asynchronous slip ring type generator because no abrasion parts or equipment which requires oil lubrication such as brushes are required.

High torque and low inertia also allow faster positioning times in permanent magnet synchronous servo drives. The full power converter totally decouples the generator from the grid. Hence grid disturbances have no direct effect on the generator which leads to higher power quality supplied.

Gearbox is a major source of noise in a wind farm. In a direct drive mechanism, there is no gearbox vibration, which results in less noise and stress on the turbine tower and foundation. This reduces the overall noise emission from a wind farm.

Due to the elimination of high energy loss gearbox, the permanent magnet direct drive design is about 3-5% more efficient than the traditional geared DFIG. It also has an advantage in low wind conditions because no current is required for generator excitation. The power saver is made fully available to the grid. Direct drive systems also offer increased efficiency as the power is not wasted in friction from the belt, chain, gearboxes etc. More efficient operation will lead to more annual output power [34].

4.4 Operating Direct Drive Wind Turbines

The wind industry is all about scaling up, cutting costs, and improving reliability. Wind turbine manufacturers such as Enercon, Siemens, Vestas, Northern Power Systems, Japan Steel Works (JSW), General Electric (GE) etc. have come up with their own new technology direct drive turbines within the last few years.

Enercon

Enercon GmbH, based in Aurich, Germany, is the fourth-largest wind turbine manufacturer in the world and has been the market leader in Germany since the mid-nineties. As of July 2011, Enercon has installed more than 17,000 wind turbines, with a power generating capacity exceeding 24 GW. One of its key innovations is the use of a gearless, direct drive mechanism, used in combination with an annular generator. Other than utilizing gearless drives, Enercon's wind turbines have distinctive drop-shaped generator housings and their towers are painted with green rings at the base to blend in with their surroundings. With numerous steel and precast concrete tower versions, it is designed to ensure maximum yield in the upper power range [34]. The Enercon E-126 (rated 7.5 MW) is the largest wind turbine model built to date. The first turbine of this model was installed in Emden, Germany in 2007. A total of 35 turbines of this model are installed (or in construction) as of September 2011[35]. The E-126 does not have permanent magnets though. Enercon turbines are usually suitable for sites with high wind speeds. The drive system for ENERCON wind energy converters are based on a simple principle: fewer rotating components reduce mechanical stresses while at the same time increasing the equipment's technical service life.

Northern Power Systems

Northern Power Systems is a fully integrated company that designs, manufactures, and sells wind turbines to the global marketplace from its headquarters in Vermont. It has over 30 years of experience in developing advanced, innovative wind turbines. The company's next generation wind turbine technology is based on a vastly simplified architecture that utilizes a unique combination of a permanent magnet generator and direct-drive design. Even at modest speeds, the Northern Power 100 can produce enough electricity to represent significant savings in utility costs. The wind turbine incorporates technology that is often only found on much larger turbines. The Northern Power 100 is optimized for low winds and the turbines can begin generating power at wind speeds as low as 3 meters per second (6 mph) and can provide clear economic benefits in all kinds of wind regimes [36].

The Northern Power Systems Inc. has also announced the strong commercial momentum for 2.3 MW permanent magnet direct drive (PM/DD) wind turbine, the “NPS 2.3” recently. The NPS 2.3 is the largest PM/DD wind turbine in commercial operation in North America today. It incorporates advanced PM/DD technology that is the result of more than 10 years of research and development at Northern Power Systems. The initial NPS 2.3 prototype turbine has been in commercial operation in Michigan since January 2011[36].

Siemens

Siemens has started selling its 3 MW direct drive system since 2010 and replaces the conventional high speed generator with low speed one. These generators are as large as over four meters in diameter. Still Siemens claims that the nacelle weight is just 73 metric tons, which is 12 tons less than that of its geared 2.3 MW turbines. Much of the weight reduction comes from use of permanent magnet in the rotor. Henk Polinder, an expert in permanent-magnet generators at Holland's Delft University of Technology, says that a 15-millimeter-thick segment of permanent magnets can generate the same magnetic field as a 10- to 15-centimeter section of copper coils. Siemens's rotor is a steel cylinder with permanent magnets on the inside, and this rotor spins around a column-like stator in contrast to GE’s direct drive turbines where a steel rotor covered with permanent magnets spins inside a stationary doughnut-shaped stator.

Siemens Energy has installed the first prototype of its next generation offshore wind turbine in Denmark. The new SWT-6.0-120 wind turbine with a power rating of 6 megawatts (MW) and a rotor diameter of 120 meters uses the innovative Siemens direct drive and proven rotor technology. Nacelle and rotor of the SWT-6.0-120 weigh together less than 350 tons, setting a new low-weight standard for large offshore machines [37]

CHAPTER 5

RELIABILITY IMPROVEMENT USING DIRECT DRIVE TECHNOLOGY

This chapter deals with the comparison of geared and gearless wind turbine concepts based on reliability, efficiency, weight and cost. Failure statistics are often difficult to collect because most of the wind turbine manufacturers seldom reveal their failure data. In this chapter, we will use values based on educated guesses to evaluate the improvement in the reliability of direct drive wind turbines. The Swedish data for wind turbine failures as collected by Swedpower AB [15] has been taken as the primary reference source. All the calculations, graphs and results have been performed and assembled using Microsoft Excel 2007. This chapter also shows results of comparison studies between direct drive and geared turbines made by other studies.

According to statistical data collected from Sweden, the number of turbines that were under survey is mentioned in Table 5.1. Each year, new turbines were installed and were added to the survey. An average of nearly 625 turbines was surveyed in Sweden by Swedpower AB for the years 2000-2004[15]

Table 5.1: Number of installed turbines used in survey in Sweden [15]

Year	2000	2001	2002	2003	2004	Average during 2000-2004
Number of turbines in survey	527	570	620	682	723	624.5

5.1 Assumptions used in the study

- Failure rates of individual components are assumed to be constant (constant hazard model).
- All the components are considered to be repairable.
- Component reliability calculations are made for a period of one year (by setting t=1). For longer periods, t values are changed accordingly.
- Main shaft is represented as the "drive train" component in the analysis
- By the component "entire unit" mentioned in Table 5.2, all other components which have contributed to failure or downtime are considered.
- For direct drive turbines, failure data for permanent magnet generator was difficult to obtain. Hence the failure rate and repair times were assumed to be comparatively small, namely 0.001 failures per year and 100 hours per failure respectively. Since these are hypothetical values, we also assume a range of different values and evaluate corresponding reliabilities.

There are a number of large and small components in a wind turbine. All the major components have been included in the analysis as shown in Figure 5.1.

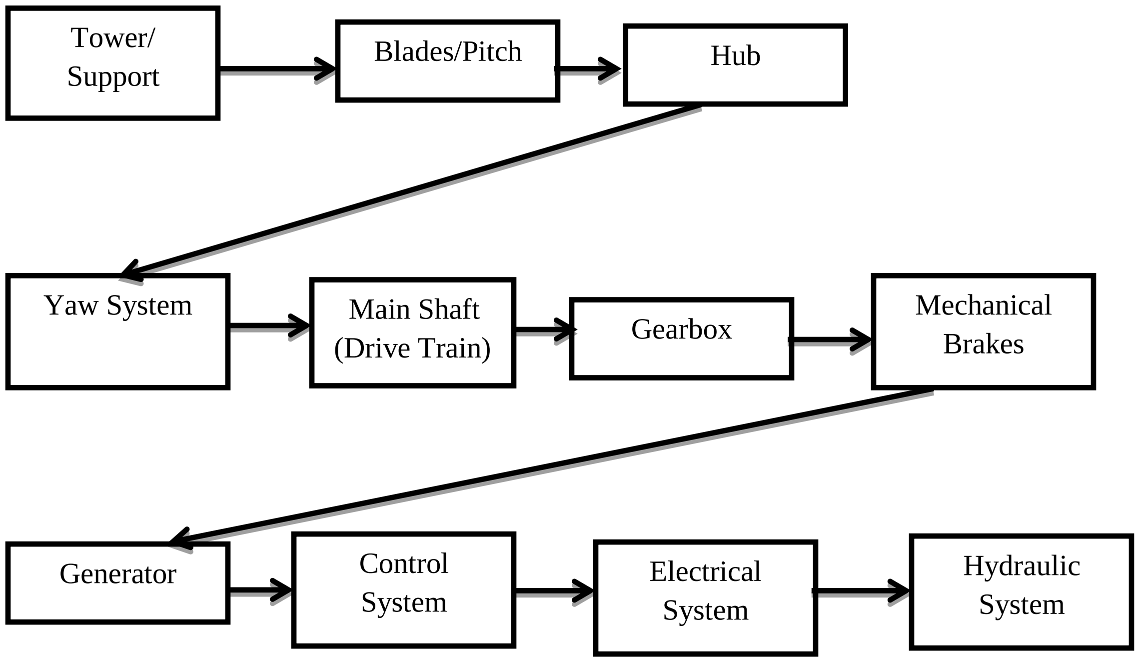

Figure 5.1: Wind turbine system description in block diagram form

Table 5.2: Downtime and failure frequency Statistics for Swedish wind power plants 2000-2004[15]

Component	Total downtime per component [h]	Average downtime per year [h/yr]	average downtime per year per turbine [h/yr/turbine]	Distribution of downtime [%]	Total number of failures per component[n]	Average number of failures per year [n/yr]	Average number of failures per year per turbine [n/yr/turbine]	Distribution of failures[%]	Average downtime per failure [h/failure]
Hub	50	10	0	0	4	0.8	0.001	0.3	12.5
Blades/Pitch	14743	2949	4.7	9.4	161	32.2	0.052	13.4	91.6
Generator	13906	2781	4.5	8.9	66	13.2	0.021	5.5	210.7
Electric System	22395	4479	7.2	14.3	210	42	0.067	17.5	106.6
Control System	28620	5724	9.2	18.3	155	31	0.05	12.9	184.6
Drive train	3788	758	1.2	2.4	13	2.6	0.004	1.1	291.4
Sensors	8357	1671	2.7	5.4	169	33.8	0.054	14.1	49.4
Gears	30286	6057	11.6	19.4	118	23.6	0.045	9.8	256.7
Mechanical brakes	1881	376	0.6	1.2	15	3	0.005	1.2	125.4
Hydraulics	6918	1384	2.6	4.4	160	32	0.061	13.3	43.2
Yaw system	20754	4151	6.6	13.3	80	16	0.026	6.7	259.4
Structure	1874	375	0.6	1.2	18	3.6	0.006	1.5	104.1
Entire Unit	2631	526	0.8	1.7	33	6.6	0.011	2.7	79.7
Total	**156202**	**31240**	**52.3**	**100**	**1202**	**240.4**	**0.403**	**100**	**130**

5.2 Calculations

From the reliability theory discussed in Section 3.3, it can be concluded that

- Average downtime per failure [h/failure] = Repair time, r = MTTR; and
- Average number of failures per year per turbine [n/yr/turbine] = Failure rate (λ)

Hence, all the other values can be found using the mathematical expressions given below:

- Repair rate μ [#/yr/turbine] = 1/ repair time =1/r
- Mean time to failure, MTTF [h/yr/turbine] = $1/\lambda$
- Mean time between failures, MTBF [h/yr/turbine] = MTTR + MTTF
- Reliability of each component, $R(t)= \exp(-\lambda t)$

System parameters

- Failure rate of the system, λ_s [#/yr/turbine] = $\lambda_1+ \lambda_2+ \ldots\ldots+\lambda_n$
- Repair time of the system, r_s [hours] = $(\lambda_1 r_1+ \lambda_2 r_2+ \ldots\ldots \lambda_n r_n) / \lambda_s$
- Repair rate of the system, μ_s [#/yr/turbine] = $1/ r_s$
- Failure Distribution function $F(t) = 1 - \exp(-\lambda_s t)$
- Failure Density function $f(t) = \lambda_s \exp(-\lambda_s t)$
- System reliability function, $R_s(t) = \exp(-\lambda_s t)$
- System unavailability, $U_s = \lambda_s r_s = \lambda_1 r_1+ \lambda_2 r_2+ \ldots\ldots \lambda_n r_n$
- System Availability, $A_s = 1 - U_s$

5.3 Results

5.3.1 Geared Wind Turbines

From Table 5.3, it can be seen that MTTR (repair time) and failure rate per turbine are directly read from the survey. Repair rate, MTTF and reliability values are calculated for each component.

The last row indicates aggregate values for the system. Clearly, gearbox contributes to 22.4% of the total downtime and 11.2% of the total failures during the survey period.

Table 5.3: Calculated values of repair rate, MTTF and reliability for geared wind turbines

	Repair time r(MTTR)	λ	λr	μ = 1/r	R(t)= exp(-λt)	1/ λ
Component	**Average downtime per failure [h/failure]**	**Average number of failures per year per turbine [#/yr/turbine]**	**average downtime per year per turbine [h/yr/turbine]**	**Repair rate [#/h/turbine]**	**Mean time between failures (MTTF) [h/yr/turbine]**	**Reliability for t=1yr**
Hub	12.5	0.001	0.0125	0.08000	1000.00000	0.99900
Blades/Pitch	91.6	0.052	4.7632	0.01092	19.23077	0.94933
Generator	210.7	0.021	4.4247	0.00475	47.61905	0.97922
Electric System	106.6	0.067	7.1422	0.00938	14.92537	0.93520
Control System	184.6	0.05	9.23	0.00542	20.00000	0.95123
Drive train	291.4	0.004	1.1656	0.00343	250.00000	0.99601
Sensors	49.4	0.054	2.6676	0.02024	18.51852	0.94743
Gearbox	256.7	0.045	11.5515	0.00390	22.22222	0.95600
Mechanical brakes	125.4	0.005	0.627	0.00797	200.00000	0.99501
Hydraulics	43.2	0.061	2.6352	0.02315	16.39344	0.94082
Yaw system	259.4	0.026	6.7444	0.00386	38.46154	0.97434
Structure	104.1	0.006	0.6246	0.00961	166.66667	0.99402
Entire Unit	79.7	0.011	0.8767	0.01255	90.90909	0.98906
Total	**130**	**0.403**	**52.4652**			**0.66831**

Figure 5.2 and Figure 5.3 illustrate the average downtime and number of failures per year per turbine respectively for traditional geared turbines. Figure 5.4 and Figure 5.5 illustrate the overall reliability and failure distribution of the system as a function of time for a period of 20 years. Figure 5.6 shows reliability of each of the wind turbine component for a year. The overall system reliability is found by multiplying the individual reliabilities.

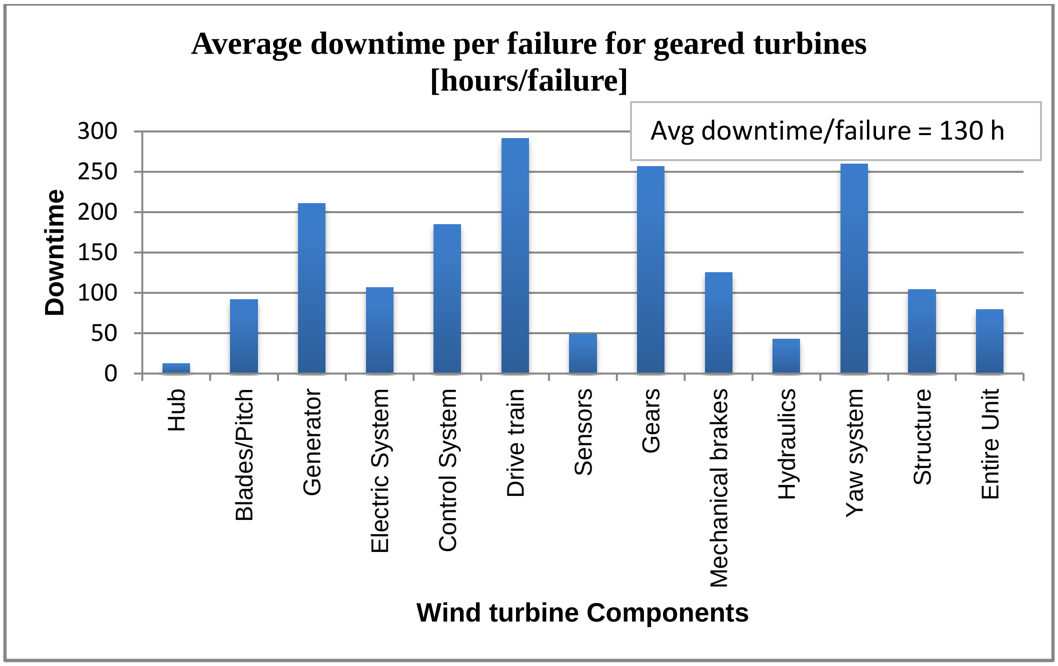

Figure 5.2: Average downtime per year per turbine for geared turbines

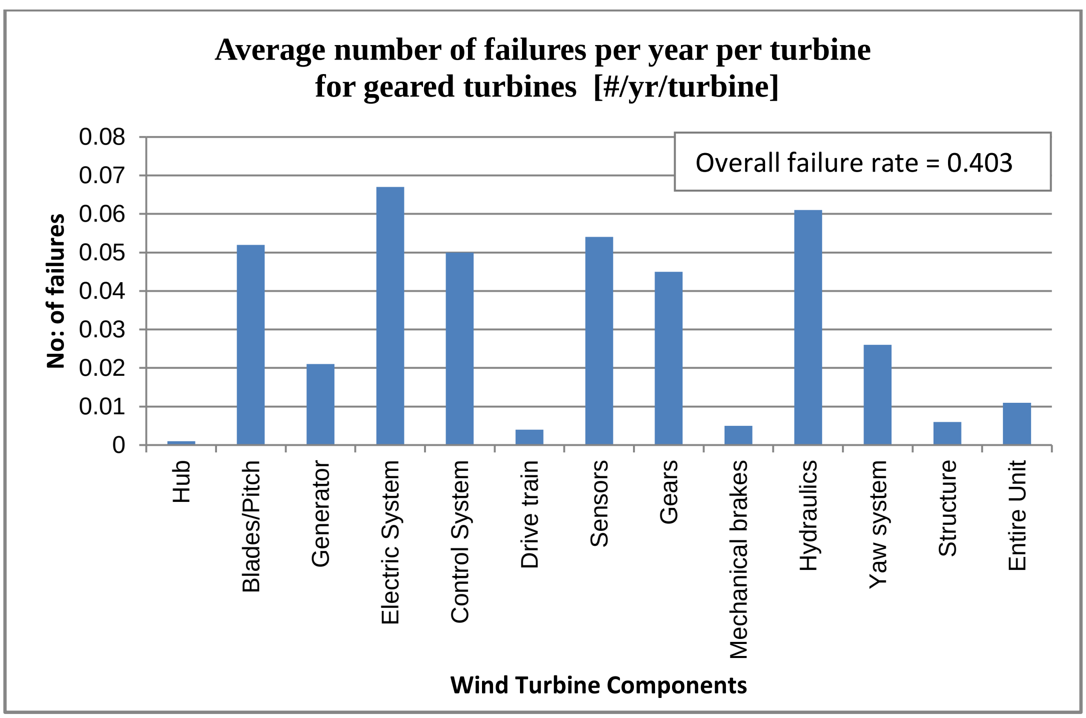

Figure 5.3: Average number of failures per year per turbine for geared turbines

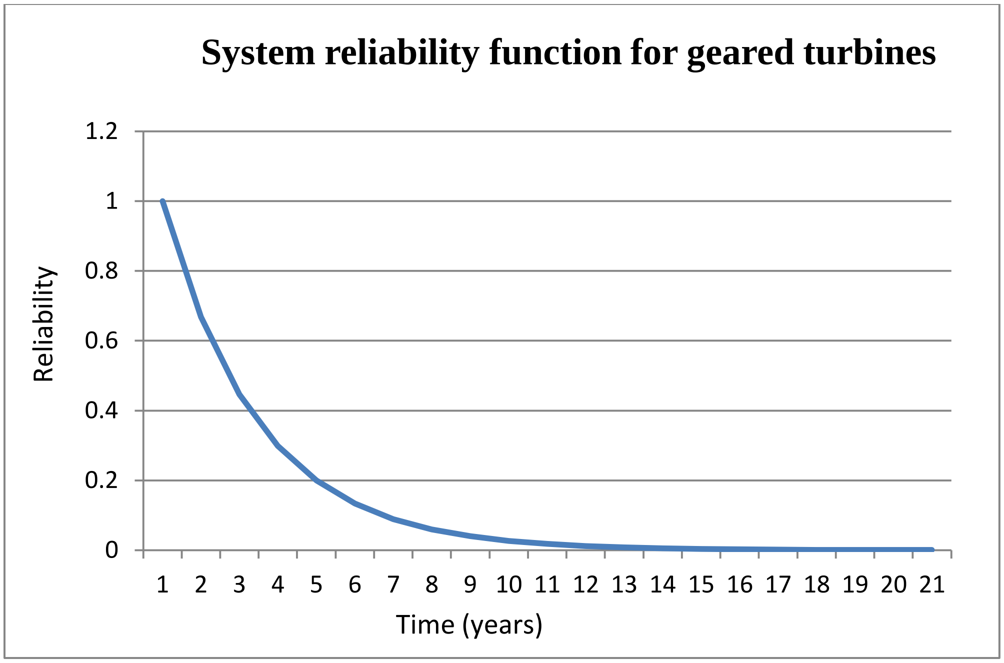

Figure 5.4: System reliability verses time for geared turbines

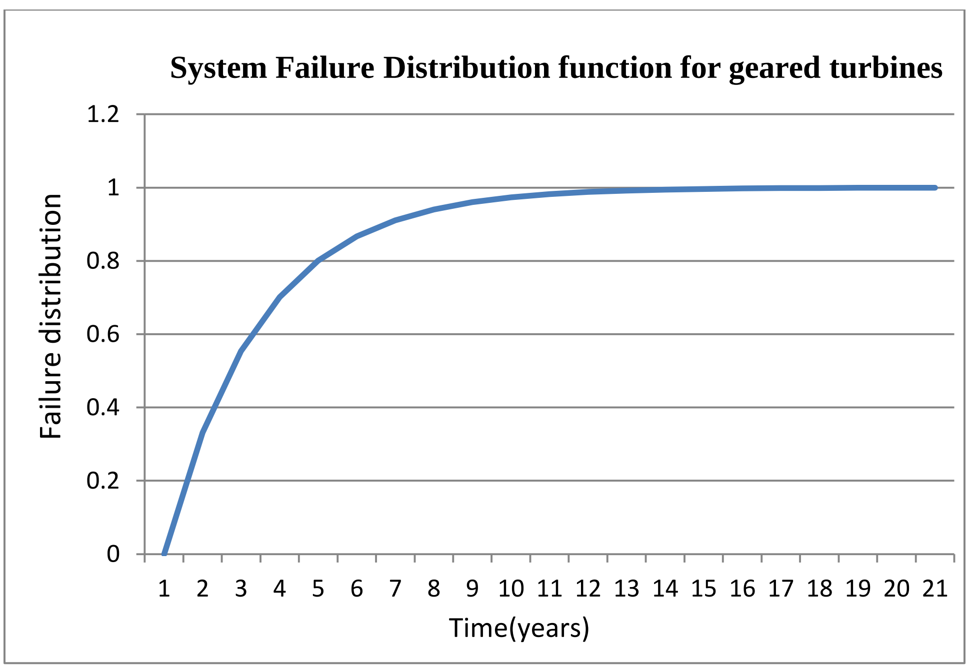

Figure 5.5: System Failure Distribution function for geared turbines

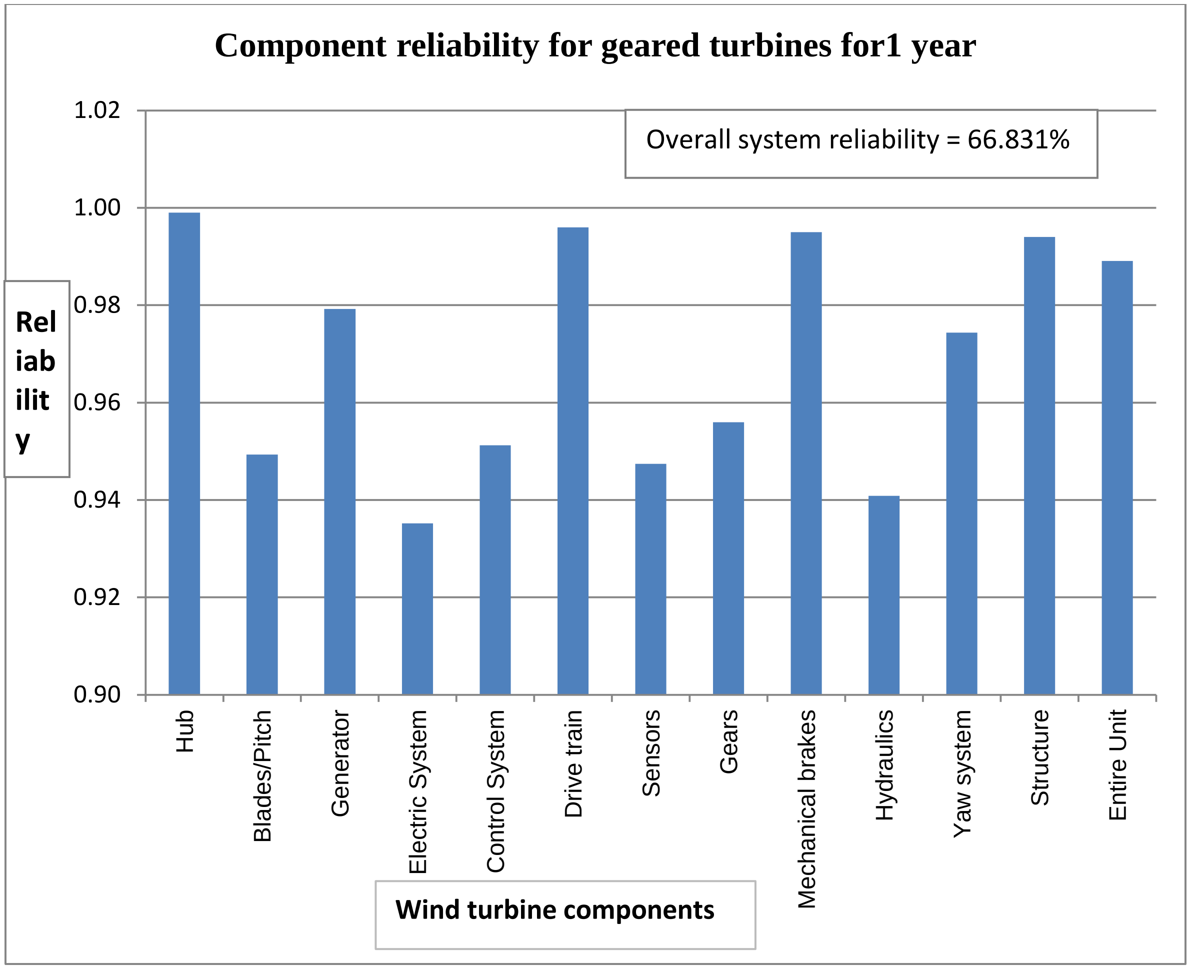

Figure 5.6: Component reliability for geared turbines

Hence, for geared wind turbines, we can summarize the calculated values as follows:

- Overall failure rate = 0.403 per year per turbine
- Average downtime per failure = 130 hours
- Overall system reliability = 66.831%
- System unavailability = 52.46552 hours per year/8760 hours = 0.00599
- System availability = 1- 0.00599 = 99. 401 %

5.3.2 Direct Drive Wind Turbine

In Table 5.4 also, it can be seen that MTTR (repair time) and failure rate per turbine are directly read from the survey. Repair rate, MTTF and reliability values are calculated for each component. The last row indicates aggregate values for the system. The absence of gearbox and introduction of PM generator with lower failure rates will lead to increased reliability as calculated in Table 5.4. The overall system reliability is found by multiplying the individual reliabilities. Figure 5.7 and Figure 5.8 illustrate the average downtime and number of failures per year per turbine respectively for direct drive turbines. Figure 5.9 and Figure 5.10 illustrate the overall reliability and failure distribution of the system as a function of time for a period of 20 years.

Table 5.4: Calculated values of repair rate, MTTF and reliability for direct drive wind turbines

	Repair time, r (MTTR)	**λ**	**λr**	**μ = 1/r**	**1/ λ**	**R(t)= exp(-λt)**
Component	**Average downtime per failure [h/failure]**	**Average number of failures per year per turbine [#/yr/turbine]**	**Average downtime per year per turbine [h/year/turbine]**	**Repair rate [#/yr/turbine]**	**Mean time between failures (MTTF) [h/yr/turbine]**	**Reliability for t=1yr**
Hub	12.5	0.001	0.0125	0.08000	1000.00000	0.99900
Blades/Pitch	91.6	0.052	4.7632	0.01092	19.23077	0.94933
PM Generator	100	0.001	0.1	0.01000	1000.00000	0.99900
Electric System	106.6	0.067	7.1422	0.00938	14.92537	0.93520
Control System	184.6	0.05	9.23	0.00542	20.00000	0.95123
Drive train	291.4	0.004	1.1656	0.00343	250.00000	0.99601
Sensors	49.4	0.054	2.6676	0.02024	18.51852	0.94743
NO GEARBOX						
Mechanical brakes	125.4	0.005	0.627	0.00797	200.00000	0.99501
Hydraulics	43.2	0.061	2.6352	0.02315	16.39344	0.94082
Yaw system	259.4	0.026	6.7444	0.00386	38.46154	0.97434
Structure	104.1	0.006	0.6246	0.00961	166.66667	0.99402
Entire Unit	79.7	0.011	0.8767	0.01255	90.90909	0.98906
Total	**120.7**	**0.338**	**36.589**			**0.71320**

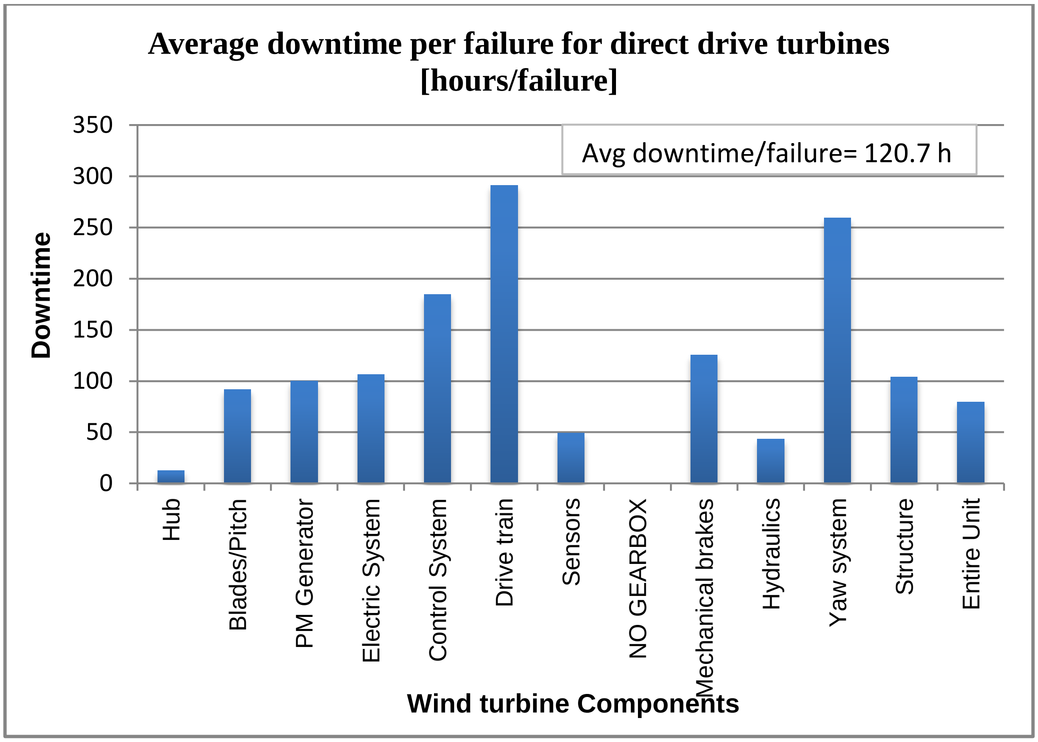

Figure 5.7: Average downtime per year per turbine for direct drive turbines

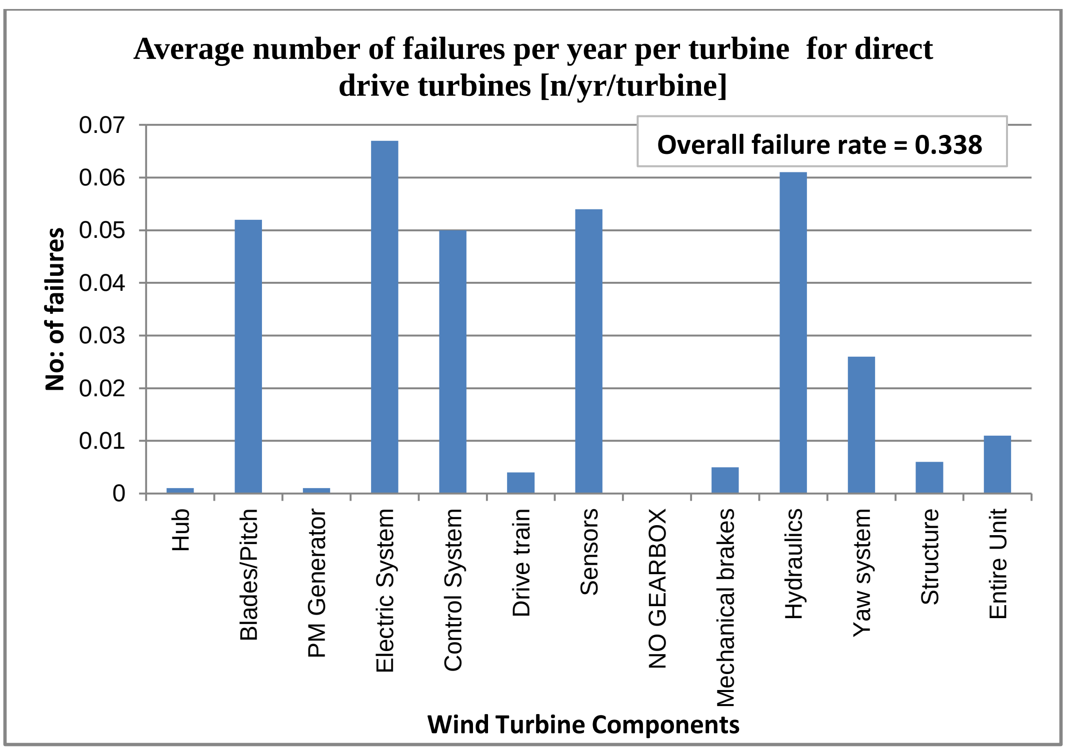

Figure 5.8: Average number of failures per year per turbine for direct drive turbines

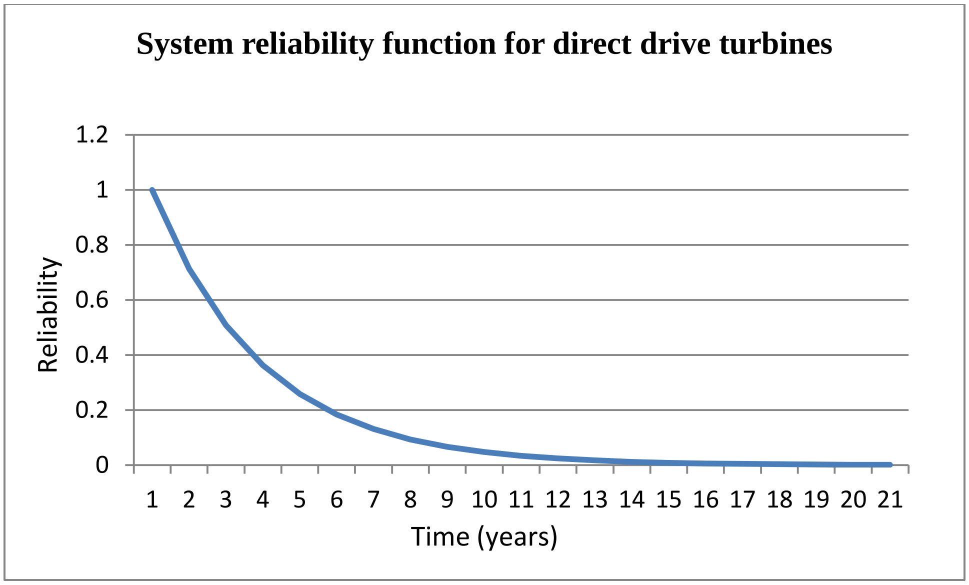

Figure 5.9: System reliability function for direct drive turbines

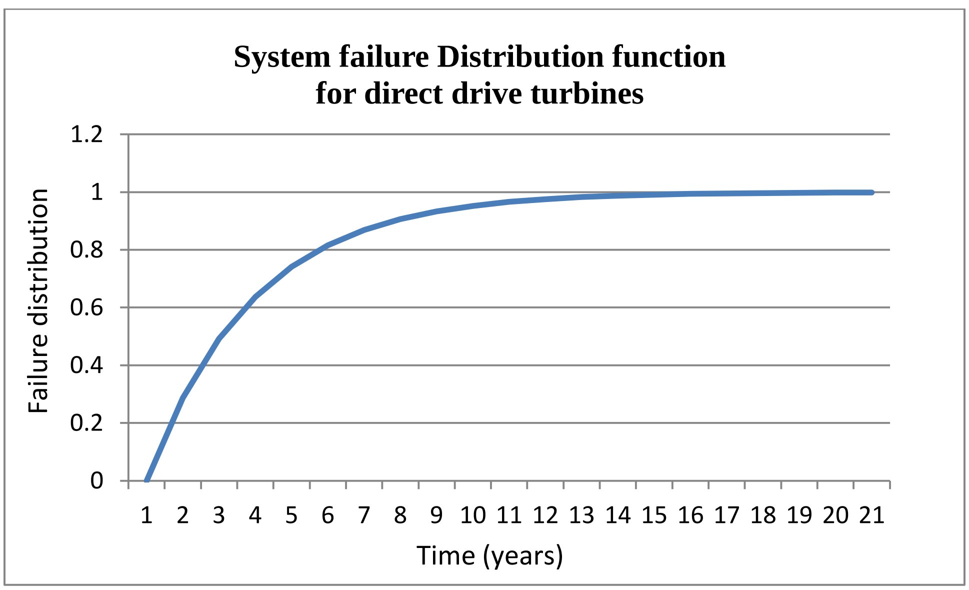

Figure 5.10: System failure distribution function for direct drive turbines

Figure 5.11 shows reliability of each of the wind turbine component for a year. The overall system reliability is found by multiplying the individual reliabilities.

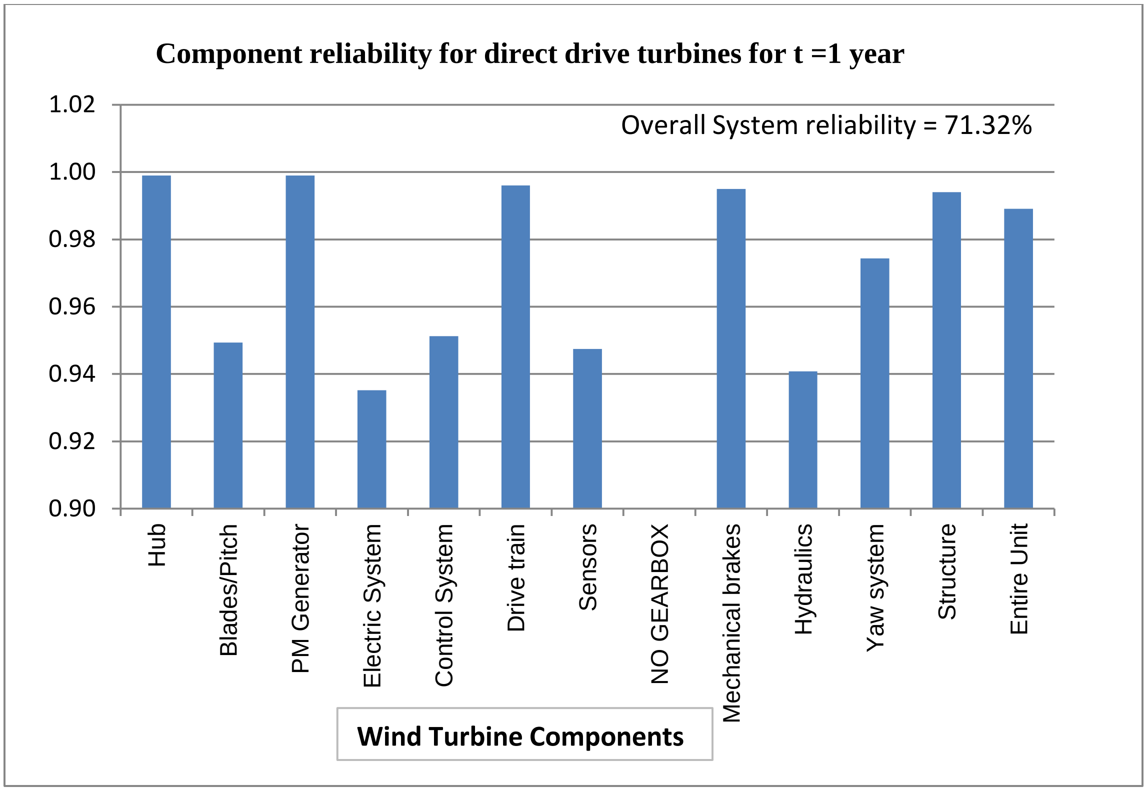

Figure 5.11: Component reliability for direct drive turbines

Hence, for direct drive wind turbines, we can summarize the calculated values as follows:

- Overall failure rate = 0.338 per year per turbine
- Average repair time = 120.7 hours per failure
- Overall system reliability = 71.32%
- System unavailability = 36.589 hours per year/8760 hours = 0.0041768
- System availability = 1- 0.0041768 = 99. 582%

In the initial calculation of improvement in reliability and failure rates of direct drive turbines, assumed values have been used for permanent magnets. Table 5.5 shows the improvement in corresponding values for different values of failure rates and repair times of permanent magnets. The last row indicates the values when the failure rate and repair times are assumed to be same as that of the generator in a geared turbine.

Table 5.5: System reliability for different failure and repair rates of permanent magnet

Average downtime per failure [h/failure] r	**Average number of failures per year per turbine [#/yr/turbine] λ**	**Reliability of PM generator**	**Total failure rate λs**	**System Reliability Rs(t) %**	**Total λr**	**Availability As %**
0	0	1	0.337	71.391	36.489	99.584%
20	0.001	0.999	0.338	71.32	36.509	99.583%
40	0.002	0.998	0.339	71.248	36.569	99.582%
60	0.003	0.997	0.34	71.177	36.669	99.581%
100	0.01	0.99	0.347	70.68	37.489	99.572%
120	0.02	0.9802	0.357	69.977	38.889	99.556%
210	0.021	0.97922	0.358	69.907	40.899	99.533%

Table 5.5 also indicate that even if the permanent magnet generator fails as much as that of any other generator used in geared wind turbines, overall system reliability and failure rates are still improved in direct drive turbines.

On considering drive train alone, which usually consists of generator, parking brakes, main shaft and the gearbox, we can see that drive train reliability is much greater in direct drive turbines than in geared turbines. This is tabulated in Table 5.6 for different values of failure rates of permanent magnet generator. Figure 5.12 illustrates the comparison of drive train reliability as a function of time for a period of 50 years.

Clearly, for direct drive systems, following remarks can be noted when compared with geared turbines:

- Increase in reliability
- Decrease in system failure rate
- Decrease in system repair time
- Slight increase in availability

Table 5.6: Drive train reliability for different failure and repair rates of Permanent magnet

Average downtime per failure [h/failure] r	Average number of failures per year per turbine [#/yr/turbine] λ	Drive train reliability with gearbox	Drive train reliability without gearbox
0	0	0.94743	0.99104
20	0.001	0.94648	0.99004
40	0.002	0.94554	0.98906
60	0.003	0.94459	0.98807
100	0.01	0.938	0.98118
120	0.02	0.92867	0.9714
210	0.021	0.92774	0.97044

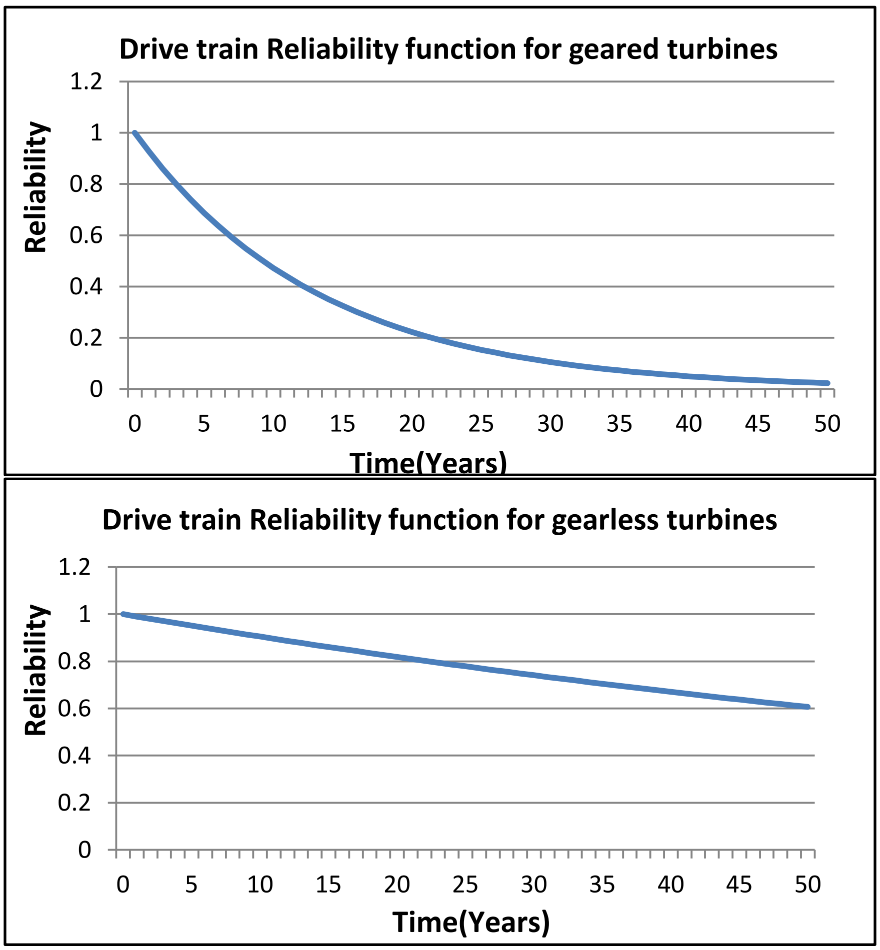

Figure 5.12: Comparison of Drive train reliability as a function of time

Hence for a period of 1 year and a failure rate of 0.001 failures per year per turbine for a permanent magnet generator, we can compare and tabulate the results as shown in Table 5.7

Table 5.7: Direct drive verses Geared turbines

	Direct Drive Wind Turbines	**Geared Wind Turbines**
Overall failure rate (# /year/turbine)	0.3380	0.4030
Average repair time (hours/failure)	120.7 hours	130 hours
Overall system reliability(%)	71.320%	66.831%
Drive train reliability(%)	99.004%	94.648%
Average downtime (hours/year)	36.589 hours	52.465 hours
System unavailability(%)	0.418%	0.599%
System availability(%)	99.582%	99.401%

5.3.3 Results from other studies

Availability comparison: Another study on reliability comparison was by Tavner et all [38] and is summarized in Table 5.8 and Table 5.9. In that study, geared turbines (Vestas V39/500KW and Tackle TW/1.5MW) and direct drive turbines (Enercon E40/500KW and Enercon E66/1.5MW) were compared for failure rates, repair rates and availability. The net failure rate proved higher for geared turbines rated 1.5 MW. On the other hand, for 500KW turbines, the direct drive turbines showed higher net failure rates.

Table 5.8: Geared wind turbine reliability data [38]

	Vestas V39/500		Tacke TW 1.5s	
	λ (f/year)	μ (rep./y)	λ (f/year)	μ (rep./y)
Blade	0.162	265.3	0.214	523.0
Gearbox	0.168	269.2	0.554	60.2
Generator	0.085	170.7	0.268	89.9
Converter	0.254	508.1	0.357	415.2
Pitch	0.095	559.9	0.500	226.3
Yaw	0.097	436.7	0.161	433.2
Turbine years considered	804		96	

Table 5.9: Direct drive wind turbine reliability data [38]

	Enercon E40		Enercon E66/15.66	
	λ (f/year)	μ (rep./y)	λ (f/year)	μ (rep./y)
Blade	0.240	133.0	0.167	620.8
Generator	0.354	143.7	0.120	270.5
Converter	0.317	430.7	0.287	291.7
Pitch	0.292	512.0	0.417	533.4
Yaw	0.116	348.3	0.139	428.0
Turbine years considered	900		154	

Table 5.10 shows the availability results for geared and direct drive wind turbines. This study clearly shows that direct drive turbines prove to be more available at larger ratings and geared turbines still have higher availabilities for lower rating turbines.

Table 5.10: Availability values for geared and direct drive turbines [38]

Turbine Concept	Turbine Type	Up	Down	Availability
Geared Generator	Vestas V39/500 500KW)	0.9974	0.0026	0.9974
	Tackle TW 1.5s (1.5 MW)	0.984	0.016	0.984
Direct Drive	Enercon E40 (500KW)	0.994	0.006	0.994
	Enercon E66 (1.5 MW)	0.9972	0.0028	0.9972

Weight comparison: Table 5.11 shows a comparison based on the headmass weight (nacelle and rotor together) for the gear driven and direct drive generators from different wind manufacturers. It can be seen that there is not much savings in the weight in a direct drive approach even though the heavy gearbox is removed. This is due to the large size (diameter) of the permanent magnet direct drive generator.

Table 5.11: Weight comparison for geared and direct drive wind turbines [39]

Turbine	Turbine generator type	Nameplate capacity	Top headmass (Nascelle+Rotor)	Rotor diameter
Northern power 100	Direct Drive PM	100W	7.2 tons	21m
JSW J82 -2.0	Direct Drive PM	2 MW	140 tons	83.3m
Acciona AW 3000	geared	3 MW	180 tons	
Vestas V112	4 stage gearbox - PM	3 MW	175 tons	112 m
GE 3.6s	3 stage gearbox - DFIG	3.6 MW	280 tons	104m
Siemens 3.6-107	Direct Drive ASG	3.6 MW	210 tons	107 m
Enercon E-112	Direct Drive SG	5 MW	500 tons	114m
Repower 5M	3 stage gearbox - DFIG	5 MW	410 tons	126m
Multibrid M5000	1 stage gearbox- PM SG	5MW	310 tons	116m
Siemens	Direct Drive PM	6 MW	350 tons	120m
Enercon E-126	Direct Drive	6 MW	600 tons	126m

PM: Permanent magnet SG: Synchronous generator
DFIG: Doubly fed Induction generator ASG: Asynchronous generator

Rebuild cost comparison: Figure 5.12 illustrates the comparison of estimated costs for a gearbox and generator repair as of 2006, with the cost for removal, shipping, taxes and reinstallation excluded. As turbine sizes get larger, crane lease costs increase significantly for gearbox replacement. The actual replacement costs would also include taxes and reinstallation charges and the personnel time to repair or replace the failed subassemblies.

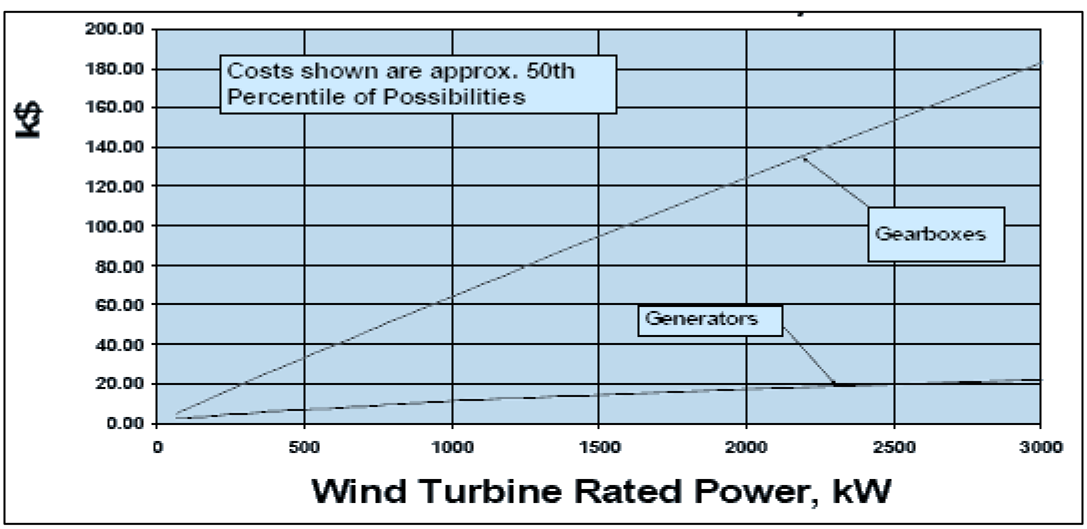

Figure 5.13: Estimated rebuild costs for gearboxes and generators – 2006 costs [39]

Drive train efficiency comparison: Efficiency curves were established for alternative drive train designs to represent the differences in annual energy production between drivetrain design choices. Constant, linear, and quadratic style losses were modeled from the WindPACT Alternative Drive Train Study for standard, single stage, multi drive (6 generators), and direct drive turbines [31].

Except for the standard geared drivetrain, all generators were assumed to be a permanent magnet design. PMG provides an overall increase in efficiency since it produces more power at part load operation than achieved by a conventional generator, which reaches peak efficiency at full load. High efficiency at part load increases the energy output of wind turbines, which operate at full capacity only during periods when the wind is blowing strong enough for the machine to be operating at full load capacity. Drivetrain efficiencies for all four drivetrain configurations are shown in Figure 5.13 from 6% of rated power to 100% of rated power.

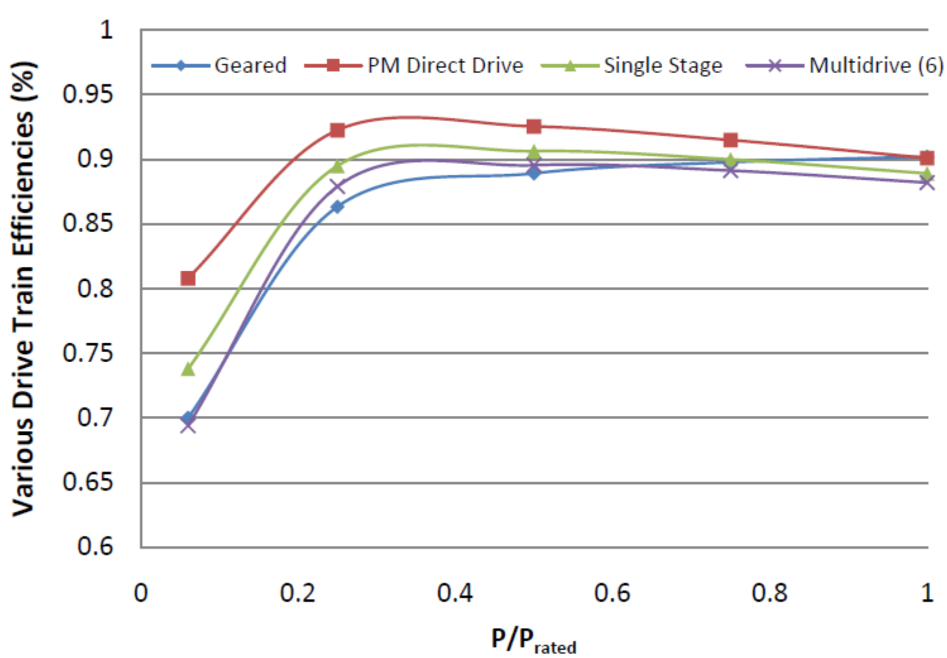

Figure 5.14 : Drivetrain efficiencies for various drivetrain designs from 6% to 100% of rated power [31]

5.4 Discussion of Results

- Failure rates of direct drive turbines are much lower than those for geared units.
- Time spent for repair of wind turbines is also lower in direct drive turbines due to the elimination of gearbox
- Reliability of wind turbines increase by nearly 5% by the elimination of gearbox
- Drive train reliability reaches 98-99% for a year for direct drive turbines
- The amount of time and money spent on the removal, repair and replacement of gearbox increases with increase in power rating and this is absent in direct drive technology.
- There is not much savings in the head mass weight in a direct drive wind turbine even though gearbox is removed. This is due to the large size of permanent magnet generator.
- According to the results collected from study [38] as mentioned in Section 5.3.3, direct drive turbines proved better for larger rated turbines in terms of availability and reliability.
- The energy yield and drive train efficiency proved better for direct drive permanent magnet wind turbines as compared to the ones employing gearboxes.

CHAPTER 6

SUMMARY AND CONCLUDING REMARKS

In this study, it was shown that gearbox is one of the components that contribute to most of the downtime in wind turbines. As the gearbox appears logically in series with other components in a turbine, its elimination can increase the overall reliability and it is evaluated in this thesis. These directly coupled turbines employ a new generation of permanent magnet generators. The adoption of large permanent magnets in a direct drive machine can lead to more efficient turbines, which is beneficial particularly in low wind speed conditions. The market has started showing interest in direct drive systems with full-scale power converters in recent years.

Weight, size and initial cost are higher in direct drive systems. The high cost and weight of permanent magnet material and large outer diameters (high number of poles), however, is balanced by a lower specific mass (kg/kW) and elimination of the massive gearbox. Additionally, there is a concern that there may not be adequate supply of crucial raw material for permanent magnets, Neodymium (Nd). Nd is the best choice for permanent magnet material and there is hardly any substitute for it. Currently, China owns 95% of the global rare earth production and 80% of global permanent magnet production. Even though there are several reserves available in other countries such as US, Brazil, India and Australia, new mining capacity would take several years to become operational. As a result, direct drive may be growing but will remain as a niche technology for the next few years. Hence the current geared players (especially non-Chinese manufacturers) may retain focus on geared solution and view direct drive as complimentary rather than substitute [34].

Even though direct drive technology is evolving, gearbox technology will not disappear. The multiple stage geared drive DFIG systems are still dominating the current market. Testing by the Reliability Collaborative at NREL is providing insights into how to design and operate gearboxes that can have longer lifetime. So while the current geared systems can do the job reliably, direct drive mechanisms that use about half as many parts should be even more reliable and reduce operating costs over the long-term, making electricity from wind farms even more competitive.

Further, there is scope to analyze how much reduction in cost must be made on the direct drive turbines in order to make it competitive with geared doubly-fed system. The cost of a direct-drive generator depends not only on the cost of its subassemblies, but also on the production services used, the number of machines sold, the profits made by the manufacturer and other variables which are beyond the scope of studies in electrical engineering. A complete picture would require market models and production models, which researchers in industrial engineering and marketing might be able to do. Future research can also be done by collecting real-life permanent magnet failure data from wind farms.

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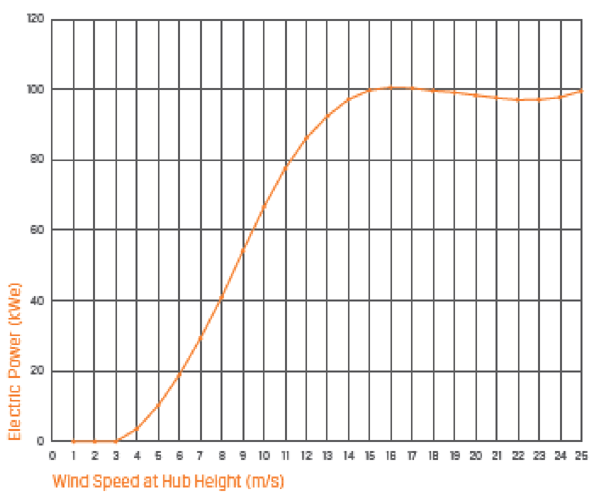
APPENDICES

Appendix A: Northern Power 100 specifications (Direct Drive - 100KW)

(http://www.industrycortex.com/datasheets/profile/502733750/northern-power-100-kw-specifications)

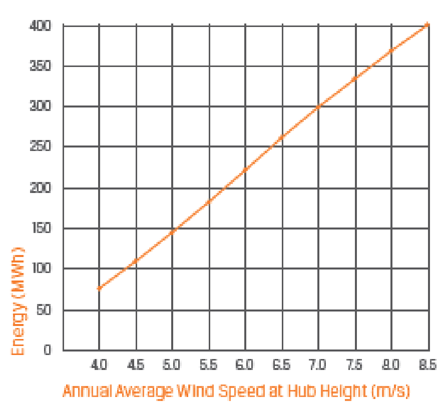
Power Curve: 21-Meter Rotor Standard Air Density (1.225 kg/m³)



Wind Speed (m/s)	Power (kWe)	Wind Speed (m/s)	Power (kWe)
1	0	14	97.3
2	0	15	100.0
3	0	16	100.8
4	3.7	17	100.6
5	10.5	18	99.8
6	19.0	19	99.4
7	29.4	20	98.6
8	41.0	21	97.8
9	54.3	22	97.3
10	66.8	23	97.3
11	77.7	24	98.0
12	86.4	25	99.7
13	92.8		

1 m/s = 2.24 mph

Annual Energy Production*: 21-Meter Rotor Standard Air Density, Rayleigh Wind Speed Distribution



Average Annual Wind Speed (mph)	Average Annual Wind Speed (m/s)	Annual Energy Output (MWh/yr)
8.9	4.0	77
10	4.5	110
11	5.0	145
12	5.5	183
13	6.0	222
15	6.5	260
16	7.0	298
17	7.5	334
18	8.0	368
19	8.5	400

*Annual energy production estimates assume standard conditions, 100% availability and no losses.

Appendix B: JSW Direct Drive Turbine (2 MW) technical data
(http://www.jsw.co.jp/en/product/ecology/wind/pdf/JSWJ82_E.pdf)

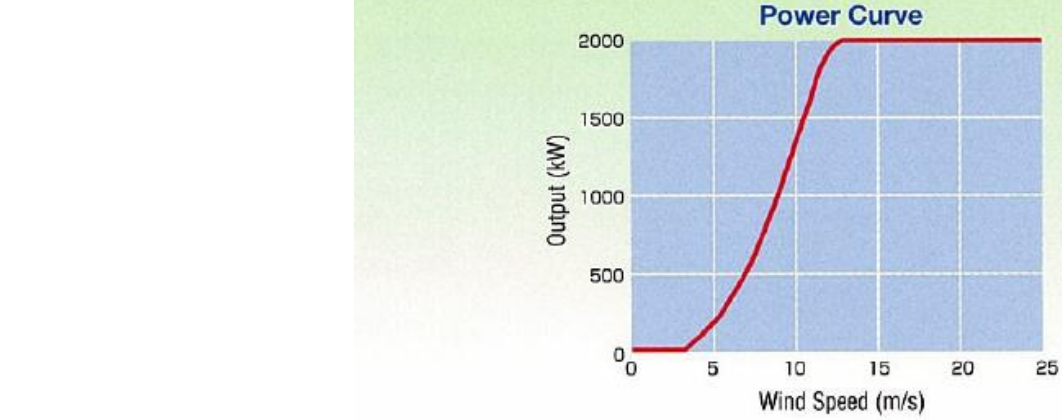
JSW J82-2.0

JSW Wind Turbine System/2MW Permanent Magnet Synchronous Gearless Wind Turbine Generator

Technical Data

Main Specification	J82-2.0/Ⅱ
Rated Power	2000kW
Cut-in Wind Speed	3.5m/s
Rated Wind Speed	13m/s
Cut-out Wind Speed	25m/s
IEC Class	S
Extreme Wind Speed according to IEC61400 class Ⅰ	70m/s
Average Wind Speed	8.5m/s (Ⅱ)
Turbulence Intensity	0.18
Rotor	
Diameter	83.3m
Rated Rotational Speed	19rpm
Length of Blade	40m
Material	GFRE
Tower	
Hub Height	70m
Electrical Specifications	
Generator Type	Direct-Drive-Gearless Permanent Magnet Synchronous Generator
Nominal Voltage	660V
Transformer Output Voltage	6.6kV, 22kV or 33kV
Voltage Frequency	50/60Hz
Control	
Output Control	Pitch control, variable speed control
Yaw Control	Active yaw control
Weight	
Rotor	42 tons
Nacelle + Sub Frame	34 tons
Generator	60 tons
Tower	145 tons (Hub Height 70m)

Power Curve



JSW THE JAPAN STEEL WORKS, LTD.

Appendix C: Direct Drive Wind Turbine Manufacturers from Morgan Stanley research

(http://wenku.baidu.com/view/92cbbc7fa26925c52cc5bf72.html)

Morgan Stanley

MORGAN STANLEY RESEARCH

June 8, 2010
Clean Tech

Exhibit 6

Wind Turbine Manufacturers: Direct Drive Products

Manufacturer	Country	Turbine model	Power(kW)	Generator type	Status
Emerrgya Wind Technology	Netherlands	DirectWind DW 54	750/900	Wound rotor	In production
		DirectWind DW 90	2000	PM Synchronous	Prototype
Enercon	Germany	E-33	330	Wound rotor	In production
		E-44/48/53	900/800	Wound rotor	In production
		E-70/82	2000/2300	Wound rotor	In production
		E-112	4,500	Wound rotor	In production
		E-126	6000/7000	Wound rotor	In production
Fuji Heavy	Japan	Subaru 22/100	100	PM Synchronous	
Vensys	Germany	VENSYS 62/64	1,200	PM Synchronous	In production
		VENSYS 70/77	1,500	PM Synchronous	In production
		VENSYS 90/100	2,500	PM Synchronous	In development
Lagerwey	Netherlands	L82	2,000	PM Synchronous	
		L90	2,500	PM Synchronous	
		N/A	3,500	N/A	N/A
Leitwind (Leitner)	Italy	LTW 61	1,200	PM Synchronous	In production
		LTW 77	1,350	PM Synchronous	In production
		LTW 80	1,500	PM Synchronous	Certification in 2010
		LWT 106	2,500	PM Synchronous	Development
		LWT 70	2,000	PM Synchronous	Prototype in 2010
		LWT 93	3,000	PM Synchronous	Prototype in mid 11
Mitsubishi	Japan		2,000	PM Synchronous	
MTorres	Spain	MTorres TWT 1650	1,650	Wound rotor	
Northern Power System (NPS)	US	Northwind 100	100	PM Synchronous	In production
		Northwind 2.2	2,200	PM Synchronous	
Scanwind (GE wind)	Norway	SW 3500 DL	3,500	PM Synchronous	Prototype/Production
Siemens	Germany	SWT-3.0-101	3,600	PM Synchronous	Launch
XEMC (Harakosan/Zephyros)	China (Japan)	Z72	2,000	PM Synchronous	In production
XEMC (Darwind)	China (Netherlands)		5,000	PM Synchronous	
Unison	Korea	U50/54/57	750	PM Synchronous	
		U88/U93	2,000	PM Synchronous	

Source: Company data, Morgan Stanley Research PM= Permanent Magnet N/A = Not available

Exhibit 7

Wind Turbine Manufacturers: Hybrid

Manufacturer	Country	Turbine model	Power (kW)	Generator type	Status
Clipper Wind	US	Liberty	2500	PM	
Multibrid	France	M5000	5000	PM Synchronous	Prototype
Vensys			3000	PM Synchronous	In development
			5000	PM Synchronous	
WinWinD	Finland	WWD-1	1000	PM Synchronous	
		WWD-3	3000	PM Synchronous	
Gamesa	Spain	G40x	4500	PM	
Dewind(Daewoo)	Germany(Korea)	D8.2	2000	Synchronous	

Source: Company data, Morgan Stanley Research PM= Permanent Magnet

VITA

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Candidate for the Degree of

Master of Science

Thesis: A STUDY OF THE RELIABILITY ENHANCEMENT OF WIND TURBINES EMPLOYING DIRECT- DRIVE TECHNOLOGY

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Name: Reeba Sara George | Date of Degree: May, 2012

Institution: Oklahoma State University | Location: Stillwater, Oklahoma

Title of Study: A STUDY OF THE RELIABILITY ENHANCEMENT OF WIND TURBINES EMPLOYING DIRECT- DRIVE TECHNOLOGY

Pages in Study: 76 | Candidate for the Degree of Master of Science

Major Field: Electrical Engineering

Scope and Method of Study:

In traditional wind turbines employing gearboxes, the blades spin a shaft that is connected through a gearbox to the generator. The multiple wheels and bearings in a gearbox are subjected to severe stresses because of wind turbulence and any defect/failure in a single component of the gear system can bring the wind turbine to a halt. The main hypothesis in this work is that the typical generator- gear solution in the wind industry can be replaced by a low speed permanent magnet generator using direct drive wind turbines. In this thesis, development of direct-drive wind energy systems is reviewed where the gearbox is completely eliminated. This work discusses the failure rates and downtimes of the subassemblies in a wind turbine and evaluates the contribution of the gearbox towards the same. Analysis in terms of estimated parameters is performed to assess the improvement in reliability obtained with direct drive turbines. Weight and economic comparisons are also discussed briefly for the direct drive and geared turbines.

Findings and Conclusions:

Failure data of wind turbines from different surveys are collected and studied. It has been found that gearbox failure is a major contributor to the failure rate and downtime of wind turbines. Directly coupled wind turbines which make use of permanent magnet generators are studied and the overall improvement in terms of failure rate, reliability and availability is assessed. Results show that there is an overall enhancement in the performance of direct drive wind turbines. There is considerable reduction in failure rate and significant improvement in reliability of the wind turbine with the elimination of gearbox. There is a noticeable improvement in reliability even when the drive train of the turbine is considered by itself. Though gearbox technology dominates the wind industry, direct drive wind turbines are evolving and will lead to more reliable and efficient wind electric conversion systems.

ADVISER’S APPROVAL: Dr. R. Ramakumar