CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Wind energy is one of the vital inputs for the social and economic development of any nation. It supplies affordable, inexhaustible energy to the economy. It is an alternative clean energy source and has been the world’s fastest growing renewable energy source with a growth rate of 28% in the last decade (Joselin Herbert et al 2010). Technological improvements over the last 5 years have placed wind energy in a stable position to compete with conventional power generation technologies. Due to the impending exhaustion of fossil fuels, it is crucial to develop clean wind energy as an alternative source of energy. Issues such as energy security, sustainable development and environmental protection have been a major topic of international discussions in recent years. Wind energy is eco-friendly and does not pollute the atmosphere like thermal power plants.

Mejia Juan et al (2006) analyzed the performance of a Wind Turbine Generator (WTG) by studying its capacity factor. It is to be noted that a 225 kW wind turbine installed in a moderately high wind area, generates about 600 MWh per year. The same amount of energy, when generated in a thermal power plant, consumes about 250 tonnes of coal and emits 800 tonnes of CO\textsubscript{2} and other poisonous gases into the atmosphere. To address the problems of global warming and environmental degradation, steps need to be taken to slash down the amount of CO\textsubscript{2} that various power plants emit. The
replacement of traditional fossil fuel-based energy with wind energy offers
great opportunities for the reduction of CO$_2$ emission (Sen Zekai 1997). Repair and replacement cost of the major and precious components such as gearbox, bearing, generator and other drive train components in wind industries are very high and time consuming. The combination of premature failure of wind turbine gearboxes and the downtime caused by those failures leads to an increase in the cost of electricity produced by the wind. There is a need for guidance to asset managers regarding how to maximize the longevity of their gearboxes in order to help and keep the cost of wind energy as low as possible. Researchers from relevant disciplines have worked together to establish gearbox standards, but the gearbox failure rate is still high. In general, gearbox replacement and lubrication account for 38% of the turbines spares cost. Servicing and replacement cost due to the breakdown of gearbox for a 1.5 mW capacity wind turbine may come around $250,000 or even more which include crane rent, labour, lubricant cost etc (Tribology & Lubrication Technology 2010).

According to the recent survey reported by Mani Entezami (2010), frequent failure of the wind turbine happened because of the defects in gearbox and structural in stability problems. These are significant issues since from the inception of wind turbines and have always need to be dealt with by the wind turbine manufacturers. Wind turbine producers have focused to resolve these reoccurring problems over the past thirty years to enhance the reliability and safety of contemporary wind turbines. Lack of sophisticated technology for reliable monitoring of the structural and operational conditions of wind turbines have forced the European Union Commissions to look for searching techniques to reduce the failure rates (Mani Entezami 2010). Further, it is an essential task to increase the availability of the WTG in wind industries by more than 95% to satisfy and win over the customer for repeated order and to compete in the global market. This can be achieved by
reducing the frequency of breakdowns and keeping the turbine in operational mode as quickly as possible immediately after the stoppage. Whenever the WTG went on break down mode, it is obligatory to analyze the cause for failure so that re-occurrences of such failures shall be prevented in future. Hence, the “Root Cause for Failure and Analysis” plays a significant role in the wind industry.

1.2 PROBLEMS ASSOCIATED WITH WIND TURBINE MAINTENANCE

Since from 1980, progress in aerodynamics, fundamental dynamics and micrometeorology (Study of weather conditions on a small scale) have been making a 5% annual enhancement in the wind energy industry. Researchers and scientist have made attempts to evolve design and develop lighter and more efficient wind turbine components especially outsized tower and blades. The annual turbine energy output have yielded tremendous growth while the weights of the wind turbines and its noise produced is decreased within the span of ten years. Though the recent wind turbines are built with high technical standards, there are still some scope for research avenue in the wind industry for enhancing the operational efficiency, particularly for megawatt-size turbines and its maintenance methods.

Mani Entezami (2010) projected in his analysis that in a wind farm maintenance costs nearly 40% of the cost related to unexpected failures of wind turbine components, which may lead to unscheduled corrective maintenance actions. Sudden stoppage of wind turbine due to mechanism failure and also non-corrective maintenance is always aspired to go for analyzing the reason for such failures. The consequence due to intermediate pinion failure in gearbox called catastrophic failure is shown in Figure 1.1. If the pinion fails in an intermediate stage of the gearbox, then either replacement of that pinion or overhauling of the gearbox is difficult task due
to complication in the gearbox assembly, size and weight of the gearbox at an elevated height. Sometimes, the damaged intermediate pinion may injure smooth functioning of its mating gear, bearings and other stage gear trains.

Figure 1.1 Catastrophic failure of a wind turbine gearbox due to IMS pinion failure
Courtesy: Suzlon Wind Energy–Nicaragua

Further, the de-erection of the gearbox or nacelle located at the top of the tower demands a huge crane (400 Tonne to 800 Tonne capacity) at the wind turbine site to swap the gearbox. Figure 1.2 shows swapping of the gearbox at the tower top without de-erecting the rotor (blade with hub). Also, it requires heavy fixture (Figure 1.3) to hold the rotor shaft while exchanging the gearbox. Wind turbine gearboxes are made to serve for minimum life of 20 years; whereas most of the turbines require significant repairs and even complete overhauls in every 5-7 year period, well before that benchmark life time (Rasmussen et al 2004, Windpower monthly 2005, Tavner and Xiang 2006). High repair rates of the expensive gearboxes are one of the major portions of the wind turbine operating cost as it escalates the wind energy cost (Walt Musial et al 2007).
Figure 1.2 Gearbox exchange at tower top  
Courtesy: Suzlon Wind Enerji-Turkey

Figure 1.3 Rotor shaft is being clamped after removal of the gearbox at tower top  
Courtesy: Suzlon Wind Energy-Nicaragua
1.3 MOTIVATION FOR THE RESEARCH WORK

Increased gearbox failure is a major concern for the operation and maintenance team, service and commissioning team since from the installation when there is no design flaw. Adequate studies have not been taken up to address the issues related with gearbox functionality in wind turbine generator. Hence it is thought of worthwhile to take up research in identifying the root cause for the problem and provide solutions to avoid the mechanism failure. In this connection, many field surveys were carried out in Indian wind site for about 8 years starting from 2004 to find out the most critical failure of mechanical components in wind turbine generator gearbox to formulate the research problem. It is observed from the survey that bearing failure followed by the gear damage and shear pin failure were the major critical area to be enlightened.

It is noticed that the critical failures were found in the intermediate pinion and its locating bearings, high speed pinion and its locating bearings and also in the planet gears and bearings. In some cases the slow speed bearing too have failed. Gear failure can occur independently of the bearing failure for reasons such as wear from poor lubrication, abrasion and surface fatigue initiated by bearing debris. The debris produced in the gearbox and the bearing failure leads to abrasion of other components in the gearbox assembly. Shear pins are coming under the coupling assembly of WTG to transmit the drive from the gearbox to the electric generator. Shear pin is a mechanical sacrificial component like an electric fuse designed to break itself as and when the mechanical overload occurs to prevent the severe damage of the expensive components in the gearbox assembly and electric generator.
Most of the problems with the current fleet of wind turbine gearboxes are generic, not specific to a single manufacturer or model. The majority of wind turbine gearbox failures not begin as gear failure, rather, failures tend to stem from several specific bearing locations under certain application which may be due to debris that migrate into the gear teeth. However, field engineers have noted lower failure rates of bearing in certain gearbox designs with tapered roller bearings over spherical roller bearings for large direct-drive systems and integrated flex systems for planetary gear sets over conventional planetary designs. Despite the fact that most gearboxes are designed and developed using the best practices available, the majority of wind turbine gearbox failures appear to initiate from the bearings. Some of the failures encountered during the period of research study since from 2004 to 2012 are given in Figures 1.4 to 1.11.

Figure 1.4(a) Failure in intermediate pinion - Case I
Courtesy: Suzlon Windfarm Services Pvt Ltd
Figure 1.4(b) Failure in intermediate pinion - Case II
Courtesy: Suzlon Energia Eolica Do Brasil

Figure 1.5(a) Failure in intermediate pinion - Case III
Courtesy: Suzlon Wind Energy – Nicaragua
Figure 1.5(b)  Failure in intermediate pinion - Case IV  
Courtesy: Suzlon Wind Energy – Nicaragua

Figure 1.6(a)  Failure in intermediate pinion–Case V  
Courtesy: Suzlon Windfarm Services Pvt Ltd
Figure 1.6(b)  Failure in intermediate pinion–Case VI
Courtesy: Suzlon Energy Pty Ltd - Australia

Figure 1.7(a)  Gear tooth failure
Courtesy: Suzlon Wind Enerji Tic Ve San Ltd Sti – Turkey
Figure 1.7(b) Failure in gear tooth
Courtesy: Suzlon Windfarm Services Pvt Ltd

Figure 1.8(a) Failure in high speed pinion- Case I
Courtesy: Suzlon Windfarm Services Pvt Ltd
Figure 1.8(b)  Failure in high speed pinion- Case II  
Courtesy: Suzlon Windfarm Services Pvt Ltd

Figure  1.9  Failure in low speed non-drive end bearing  
Courtesy: Courtesy: Suzlon Windfarm Services Pvt Ltd
Figure 1.10 Failure in intermediate non-drive end bearing
Courtesy: Suzlon Windfarm Services Pvt Ltd

Figure 1.11(a) Failure in shear pins
Courtesy: Suzlon Windfarm Services Pvt Ltd
This background stimulated me to finalise my motto as to undertake research study to identify the thrust area that could solve the problem in the wind turbine generator. Further, no one has made an attempt to analyze the reason for the failure of gears, shear pins and the bearing employed in any particular model of the wind turbine generator gearbox and found the remedial action to avoid such failure to the best knowledge of the investigator. Therefore, it is imperative to him to investigate the problem of failure of gears, shear pins and the bearing in WTGs.

1.4 WIND

Wind is the movement of air mass from a high pressure area to a low pressure area and is mainly caused by the differences in temperature within the atmosphere. A high difference of pressure exists due to an increased wind velocity, climate changes, location, region and altitude etc which will have a significant effect on the wind speed and direction.
1.4.1 Importance of Wind Energy

Increasing world population and growing global economy with high human living standards leads to huge demand for electricity. Consumption of electricity is highly correlated with the economic growth. In the recent past, economic growth has been an important factor in tripling the electricity consumption worldwide. The ongoing economic growth in India warranted huge demand for electricity, whereas developed nations such as United States, Japan and Europe still need more electricity production to meet out its higher consumption and to fulfill the growing number of applications. Many countries are still dependent on fossil fuels like coal, natural gas, hydro or nuclear fission to meet out their energy demand. These generation technologies are generally affordable, reliable and have been used in the power systems over decades.

However, one of the major concern related with these non-renewable energy resources are their finiteness and the transmission losses associate with uneven distribution to different regions creating fuel dependencies. Coal, oil and natural gas that are used for power generation have posed threats to the environment due to the emission of CO$_2$ while burning. Nuclear fission also brings concern like accumulation of nuclear waste, radiation hazards both to the surroundings and to the human livings in the installation zone and hence it is a major problem in many countries. Therefore the authorities have started to give much importance for utilizing new renewable energy sources. Renewable energy technologies such as biomass, geothermal, wind power, solar photovoltaic, tidal and wave power make use of the natural energy resources for producing electricity.
1.4.2 Advantages of Wind Energy

In this context, wind energy seems to be proven for renewable energy resource since it is available in plenty across the world. Thus, the wind energy has emerged as a major source for generating electricity to cater to the needs of world’s energy demand. Wind power has number of benefits that makes it unique among the other renewable energy sources. First and foremost is its global availability in abundance both on land and sea. The wind power investment cost is relatively low when compared to other renewable energy sources for example, solar photovoltaics. In addition to, there are no environmental issues because of wind turbines. The concept of capturing the wind power and converting it to an usable energy had been in use since the time of early Egyptians. But, the effective utilization of wind energy has emerged only after 1980’s.

1.4.3 Wind Power Installation and Consumption in Global Scenario

Worldwide there are thousands of wind turbines operating, with a total nameplate capacity of 238,351 MW as on December 2011 (Global Wind Energy Council-2012). The European Union alone acquired nearly 100,000 MW nameplate capacity by September 2012, whereas US surpassed 50,000 MW and State Grid of China is having 50,000 MW till August 2012. By the end of 2011, worldwide nameplate capacity of wind-powered generator was 238.351 Giga Watts (GW) which is higher by 40.5 GW over the preceding year 2010. The World Wind Energy Association (2012), an industrial organization projected that wind power has yielded the capacity to generate 430 TWh annually, which amount 2.5% of worldwide’s electricity usage. Wind power market penetration is expected to reach 3.35% by 2013 and 8% by 2018. Many countries have already achieved fairly high levels of penetration i.e.
28% of the stationary (grid) electricity production in Denmark (2011), 19% in Portugal (2011), 16% in Spain (2011), 8% in Germany (2011) and 4% in Ireland (2010). Statistics by World Wind Energy Association (2012) shows as on 2011, 83 countries around the world were using wind power on a commercial basis. The top 10 countries in the wind power electricity production by 2010 and in the wind power capacity until 2011 are projected in Table 1.1.

Table 1.1  Top 10 countries worldwide wind power production and capacity

<table>
<thead>
<tr>
<th>Country</th>
<th>Wind power production (TWh)</th>
<th>% world total</th>
<th>Country</th>
<th>Wind power capacity (MW)</th>
<th>% world total</th>
</tr>
</thead>
<tbody>
<tr>
<td>United States</td>
<td>95.2</td>
<td>27.6</td>
<td>China</td>
<td>62,733</td>
<td>26.3</td>
</tr>
<tr>
<td>China</td>
<td>55.5</td>
<td>15.9</td>
<td>United States</td>
<td>46,919</td>
<td>19.7</td>
</tr>
<tr>
<td>Spain</td>
<td>43.7</td>
<td>12.7</td>
<td>Germany</td>
<td>29,060</td>
<td>12.2</td>
</tr>
<tr>
<td>Germany</td>
<td>36.5</td>
<td>10.6</td>
<td>Spain</td>
<td>21,674</td>
<td>9.1</td>
</tr>
<tr>
<td>India</td>
<td>20.6</td>
<td>6.0</td>
<td>India</td>
<td>16,084</td>
<td>6.7</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>10.2</td>
<td>3.0</td>
<td>France</td>
<td>6,800</td>
<td>2.8</td>
</tr>
<tr>
<td>France</td>
<td>9.7</td>
<td>2.8</td>
<td>Italy</td>
<td>6,747</td>
<td>2.8</td>
</tr>
<tr>
<td>Portugal</td>
<td>9.1</td>
<td>2.6</td>
<td>United Kingdom</td>
<td>6,540</td>
<td>2.7</td>
</tr>
<tr>
<td>Italy</td>
<td>8.4</td>
<td>2.5</td>
<td>Canada</td>
<td>5,265</td>
<td>2.2</td>
</tr>
<tr>
<td>Canada</td>
<td>8.0</td>
<td>2.3</td>
<td>Portugal</td>
<td>4,083</td>
<td>1.7</td>
</tr>
<tr>
<td>Rest of the world</td>
<td>48.5</td>
<td>14.1</td>
<td>Rest of the world</td>
<td>32,446</td>
<td>13.8</td>
</tr>
<tr>
<td>World total</td>
<td>344.8 TWh</td>
<td>100%</td>
<td>World total</td>
<td>238,351 MW</td>
<td>100%</td>
</tr>
</tbody>
</table>
It is estimated that nearly 72 terrawatt (TW) of the Earth’s wind power is commercially viable. As of now, the energy consumption at the global level is expected around 25 TW (Tribology & Lubrication Technology 2010). Presently wind turbine is being used to generate power between 0.25 megawatts (MW) and 4.0 MW of electricity. It is a known fact that one MW of wind energy is enough to supply electricity to nearly 250 homes.

1.5  **WIND TURBINE AN OVERVIEW**

A wind turbine is a rotating mechanical device that converts the wind kinetic energy into practical mechanical energy which is used for production of electricity. Depending on the location of rotary part, turbine can be of either vertical axis (Figure 1.12) or horizontal axis (Figure 1.13).

![Vertical axis wind turbine](Figure 1.12)

*Figure 1.12  Vertical axis wind turbine*

*Courtesy: Darrieus Wind Energy*
In the vertical-axis wind turbines the gearbox and transmission systems are placed at ground level which is an added advantage to capture the wind irrespective of wind direction. But, difficulty may arise while removing the rotor as is often required during overhauling period. Major drawback with this vertical axis wind turbine is that the captured wind is insufficient and also larger area is required in the wind turbine site as guide wire is necessary for supporting the structure.
In the horizontal axis wind turbine, the rotor (hub with the blades) is positioned on the top of the tower. The nacelle which contains gearbox, generator, coupling assembly and the cover is included in the system and it operates more efficiently even though the wind force is very low. A yaw system is turning the nacelle and the rotor to face the wind direction and enables the turbine to capture the majority of the wind force. Extraction of a significant amount of energy requires a large rotor diameter for megawatt series thus the turbine speeds are low and the rotational speed must be increased to match the higher generator speed.

The modern wind turbine drive trains consist of an integrated serial approach where rotor shaft, main bearing, gearbox and the generator are as close as together for possible compactness and mass reduction. Field study reveals that the construction approach of horizontal axis wind turbine leads to mechanism failure of drive train components, in spite of robust components being used in nacelle assembly. The modern drive train consist of a three-blade that operates at low speed, usually between 10 and 20 rpm of rotor speed, shrink disc which connects the rotor shaft with the gearbox, brake disc, axial dampers and the coupling assembly. Recent wind turbines above 1.5mW capacity both ON shore and OFF shore are coming with “Doubly Fed Induction Generator (DFIG)” concept with more than 88 meters rotor diameter for maximum power generation (Muller et al 2002). This turbine drives a generator through a speed increasing gearbox comprises of a planetary first stage and one or two additional parallel shaft helical stages. The generator produces 1.5mW at rated speed of 1500 rpm and more depending upon the frequency (50 Hz or 60 Hz) of the turbine. Many of the wind turbines are variable speed machines and the speed depends on the wind
conditions and can vary over a wide range. Modern wind turbines are designed to work most efficiently even up to 25 m/s wind speed.

Some model of wind turbine blades have movable blade tips (stall control) to act as air brakes and in some advanced model wind turbines blade have pitch regulating system. Figure 1.14 depicts a three bladed horizontal-axis wind turbine with its components. The wind turbine is designed and developed in order to suit a specific orientation or topology according to the following six basic criteria; i) Hub height ii) Rotor diameter or Swept area iii) Blade solidity iv) Tip speed ratio v) Rated power and vi) Rated wind speed (Jesse Agwandas Andrawaus 2008, Walker and Jenkins 1997). A common design topology of the wind turbine according to Manwell et al (2002) is presented in Table 1.2.

![Figure 1.14 Components of the wind turbine generator](www.freebreezeuk.com)
Table 1.2  Common design topology of wind turbines

<table>
<thead>
<tr>
<th>S.No</th>
<th>Sub-system</th>
<th>Design options</th>
</tr>
</thead>
</table>
| 1.   | Rotor axis orientation      | a. Horizontal Axis Wind Turbine (HAWT)  
                                        b. Vertical Axis Wind Turbine (VAWT)     |
| 2.   | Rotor power control         | a. Stall control  
                                        b. Variable pitch control  
                                        c. Aerodynamic control  
                                        d. Yaw control                  |
| 3.   | Rotor position              | a. Down wind rotor  
                                        b. Up wind rotor              |
| 4.   | Yaw control                 | a. Free control  
                                        b. Active control               |
| 5.   | Rotational speed            | a. Constant speed  
                                        b. Variable speed              |
| 6.   | Tip speed ratios            | a. High speed  
                                        b. Low speed                     |
| 7.   | Hub                         | a. Rigid  
                                        b. Teetering  
                                        c. Hinged or gimbaled            |
| 8.   | Rigidity                    | a. Stiff  
                                        b. Flexible                         |
| 9.   | Number of blades            | a. Three blades  
                                        b. Two blades                        |
| 10.  | Tower structure             | a. Tubular  
                                        b. Pipe-type  
                                        c. Trusses                           |
| 11.  | Foundations                 | a. Concrete caissons foundation  
                                        b. Steel gravitational foundation  
                                        c. Tripod foundation  
                                        d. Mono piles foundation             |
1.5.1 Principal Parts in Wind Turbine Generator

**Blades:** are used to capture the wind energy. It is made out of an advanced composite material like Glass Fiber Reinforced Plastic (GFRP). Nowadays, prepreg carbon fiber is also used for manufacturing the wind turbine blades as it is lighter in weight, stronger and stiffer than the infused glass fiber. The wind turbine blade is designed accordingly with aerodynamic requirements. Blade should be thicker than the aerodynamic norms and optimum at the root since the stresses due to bending are greater. The blade length is arrived based on the turbine model and capacity, Normally, it ranges from 15 meter to 45 meter and weight of the individual blade would be more than 4 tonne for megawatt series wind turbines, say 2.1 MW to 7.0 MW. Presently some of the wind turbine manufacturers have started to introduce “vortex” generator on the blades to avoid escaping of the wind from the blade and thus increasing the production by 3% to 4 % (Peder Bay Enevoldsen and Soeren Hjort 2008).

**Rotor:** Constitutes blades and hub to collect energy from the wind. Blades are attached to the hub which in turn is attached to the main shaft.

**Pitching Mechanism:** It turns the angle of attack of the blades into or out of the wind to control the production or absorption of power. The modern wind turbines are coming with micro pitching mechanism, which is used to pitch the blades in to 0.1 degree accuracy through Lust drive, Encoder and the Resolver, allowing the control system to “feather” the blades to accommodate varying wind conditions.

**Rotor Shaft:** It is the critical part in the wind turbine power generation because it is one of the key elements which converts wind kinetic energy into rotary motion. In turn, delivering that rotary energy to the generator coupled
with the wind turbine. Generally, the rotor shaft is a tapered (4° to 5°) hollow circular section connected to the gearbox through shrink disc.

**Gearbox:** Most of industrial gearboxes are used for either high speed low torque or high torque and low speed. A gearbox in the wind turbine is used for converting low speed and high torque to low torque and high speed (speed increasing gearbox).

**Brake:** It is a mechanical caliper disc brake operated by hydraulic system and is used in the wind turbines to hold the turbine at rest during maintenance. Brakes are usually applied only after blade furling and gradually bringing down the turbine speed. Mechanical brakes would often wear quickly if it is used to stop the turbine at full speed. The gradual braking (soft braking) period is normally 90 to 120 seconds. Hard braking period is around 60 to 90 sec and normally is used during emergency time. Frequent hard braking is not recommended since it is danger to gearbox life and safety.

**Asynchronous Generator:** It is a device that converts the mechanical energy in to an electrical energy. The output power of a wind turbine generator is fluctuating according to the wind speed. In wind turbine, initially the generator will act as a motor when slip is started to generate at 1501 rpm then it will act as a generator. Further, the generated power will not be of the same frequency in order to maintain it with uniform supply this will be passed through number of capacitors (capacitor bank) before connected to the grid.

### 1.6 WIND TURBINE CONDITION MONITORING SYSTEMS

The operational costs of the wind turbines are very high to make the wind projects economically practical. The cost for operation and maintenance are likely to be around 30 to 35% of the cost of electricity.
Condition Monitoring System (CMS) is one of the approaches for early fault detection that reduces the costs of corrective maintenance of wind turbines. If faults are detected and identified at an early stage, the consequences in breakdown and damages will be less so that the repair costs will be less. The early failure detection of wind turbines enables not only to rectify the repairs but also leads to shorter downtimes thereby minimize revenue losses.

A condition monitoring system for wind turbines that predicts or detects incipient critical failures is the-state-of-the-art in the system safety, which remains as one of the most important attribute of the wind energy industry. “Condition monitoring can either be used to enhance safety or to make the current level of safety more affordable”. The purpose of wind turbine condition monitoring systems has considerably developed in the last decade. Because of the financial limits in the wind turbine industry, the relatively little production wounded and the negligible effects on the electricity network, the applications remain limited to some trial projects. Over the last few years, wind turbine manufacturers and operators have been trying to develop an advanced condition monitoring system in order to evaluate the structural condition of wind turbines as well as the operational state that achieve a significant enhancement in preventing the failures and reducing maintenance time.

1.6.1 Condition Monitoring Techniques

The following techniques have been used to monitor the working condition of the wind turbine and to diagnose the mechanism failures.

i) Oil analysis

ii) Temperature measurements

iii) Visual inspection
iv) Vibration analysis  
v) Physical condition of materials  
vi) Strain measurement  
vii) Acoustic measurements  
viii) Electrical effects  
ix) Process parameters  
x) Performance monitoring  
xi) Self diagnostic sensors

Among these techniques some of the techniques frequently used in wind turbine operation and maintenance are discussed below;

**Oil analysis**

i) Oil analysis is normally conducted to ensure the safe operation of sliding and moving parts inside the gearbox to avoid wear and tear of components.

ii) Safeguarding the oil quality (contamination by parts, moist). As per ISO 81400-4 for the wind turbine gearbox, the cleanliness level code for the new oil is -/17/14 that is 80 to 160 parts per milliliter (ppm) of greater than 6 micron and 640 to 1300 parts per milliliter (ppm) of greater than 14 microns are allowed.

iii) Safeguarding the components involved (characterization of parts).

iv) Oil analysis is mostly executed off line, by taking samples for every 5 months or based on the gearbox supplier’s
recommended oil hours. However for safeguarding the oil quality, application of on-line sensors is increasing. Sensors are nowadays available at an acceptable price level for part counting and moist. Besides this, safeguarding the state of the oil filter (pressure loss over the filter) is mostly applied nowadays for hydraulic as well as for lubrication oil.

**Temperature measurements**

Temperature measurements is one of the condition monitoring technique available in WTG to monitor various bearing temperature such as high speed, intermediate stage bearings in the gearbox and main bearing. As most of the failures in the WTG are attributed to the bearing failure due to lack of lubrication to the bearing, contamination in the lubricant and etc, different types of PT 100 sensors are available in the market to monitor the bearing temperature in the wind turbine generator gearboxes.

**Strain measurement**

Strain measurement by strain gauges is a common technique, however not often applied for condition monitoring. Strain gauges are not robust on a long term. Especially for wind turbines strain measurement can be very useful for life time prediction and safeguarding of the stress level especially for the blades, rotor shaft and the gearbox.

**1.7 RESEARCH SIGNIFICANCE AND BENEFITS**

This research study was executed by keeping in mind to analyse the root cause for frequent failure of the wind turbine generator. Gearbox, bearing and shear pin have been analyzed to investigate the reasons for its failure. Though numerical methods have been in practical use for failure analysis,
very few general studies in the past have discussed the failure of gears, bearings and shear pins in the wind industry. This failure analysis will have great utility during designing and developing the wind turbine components such as gears, shear pin and also to diagnose the bearing fault during preventive maintenance so that mechanism for failure can be reduced. In short, the wind turbine availability can be improved by means of reducing the rate of failure frequency.

1.8 THESIS ORGANIZATION

This research study is focused on failure analysis of WTG and its associated components. The study dealt with the basic concepts of the wind turbine and case study on the gear failure, shear pin failure and bearing failure in some model of WTG’s. Solution to improve the spur gear tooth strength and prevent the helical gear tooth damage through profile modification, failure analysis and design optimization of shear pin neck diameter and failure analysis of bearing are discussed in this thesis. This thesis work is divided into eight chapters. Chapter 1 enumerates the background and motivation that excited the author to take up this research study along with detailed description of the basic concepts of the wind energy and the WTG. A detailed literature review on challenging approaches to tackle the failure of wind turbine gearbox components are presented in Chapter 2. Chapter 3 summarizes the research methodology and the related model development adopted in this doctoral work. Chapter 4 discuss the method of improving the spur gear tooth strength and Chapter 5 deals with prevention of tooth damage in the helical gear by profile modification. Chapter 6 and Chapter 7 enumerate the case studies undertaken for failure analysis of shear pins and bearing. Chapter 8 presents the conclusion of the doctoral work and the scope for future research. Flow chart in Figure 1.15 outlines the organization of the research program.
Figure 1.15  Organization of the thesis