Bearing Fault Detection, Analysis and Protection for PMSG based Wind Turbine - Generator system

A thesis is submitted to fulfil the requirement of the degree

Master in Electrical Engineering

Submitted by

Arnab Chatterjee

Examination Roll No. - M4ELE22032

Registration No. - 154022 of 2020-2021

Year - 2nd , Semester - 2nd

Under the guidance of

Prof. Suparna Kar Chowdhury ,

Prof. Arindam Kumar Sil ,

Prof. Dipten Maiti

Department of Electrical Engineering

Jadavpur University

Kolkata-700032

August 2022

JADAVPUR UNIVERSITY

FACULTY OF ENGINEERING AND TECHNOLOGY

Certificate

This is to certify that the thesis titled " Bearing Fault Detection, Analysis and Protection for PMSG based Wind Turbine - Generator system " carried out by ***Mr. Arnab Chatterjee*** *under our supervision during session 2021-2022 in the department of Electrical Engineering, Jadavpur University is an authentic work and can be accepted in the partial fulfilment of the requirement of the degree of* ***Master in Electrical Engineering****.*

Prof. Arindam Kumar Sil
Supervisor
Electrical Engineering Department
Jadavpur University
Kolkata-700032

Prof. Suparna Kar Chowdhury
Supervisor
Electrical Engineering Department
Jadavpur University
Kolkata-700032

Prof. Dipten Maity
Supervisor
Electrical Engineering Department
Jadavpur University
Kolkata-700032

Prof. Saswati Majumdar
Head
Electrical Engineering Department
Jadavpur University
Kolkata-700032

Prof. Chandan Mazumdar
Dean of Faculty of Engineering & Technology
Jadavpur University
Kolkata-700032

JADAVPUR UNIVERSITY
FACULTY OF ENGINEERING AND TECHNOLOGY

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The forgoing thesis titled " Bearing Fault Detection, Analysis and Protection for PMSG based Wind Turbine - Generator system " is hereby approved as a creditable study of an Engineering subject carried out and presented in a manner that fulfil its acceptance as a prerequisite to the degree for which it is submitted. It is understood that by this approval, the undersigned doesn't necessarily endorse or approve any statement made, opinion expressed or conclusion drawn therein but approves the thesis only for the purpose for which it is submitted.

Signature by the Examiner

Prof. Arindam Kumar Sil
Supervisor
Electrical Engineering Department
Jadavpur University
Kolkata-700032

Prof. Suparna Kar Chowdhury
Supervisor
Electrical Engineering Department
Jadavpur University
Kolkata-700032

Prof. Dipten Maity
Supervisor
Electrical Engineering Department
Jadavpur University
Kolkata-700032

ACKNOWLEDGEMENT

With the submission of my thesis work I would like to extend my deep gratitude and sincere thanks to my guide Prof. Arindam Kumar Sil, Electrical Engineering department, Jadavpur University, without whose proper guidance and support this work could not been possible. His continuous encouragement, support, suggestions and technical expertise helped me a lot to overcome the difficulties during the course of work.

I am also very much thankful to Prof. Suparna Kar Chowdhury, Electrical Engineering Department, Jadavpur University and Prof. Dipten Maiti, Electrical Engineering Department, Jadavpur University who helped me a lot by providing valuable advices to modify and upgrade my simulations for better performance.

I am thankful to all my classmates and the department research scholars for their co-operation and unfailing help during the Thesis work.

ABSTRACT

Wind energy is one of the important and dominating renewable energy sources that are commercially available. It is clean, mostly free from producing harmful bi-products. It also has economic and social benefits. But, the efficiency of the wind power system is greatly affected by many factors, which ultimately decides the amount of wind energy converting into electrical energy. The utilization of wind energy is going to increase in the future. That means, more number of wind turbines will be installed around the world. As a result, condition monitoring will become a very important aspect to take care of various faults.

Among all the faults that are found in Wind Turbine Generator system , a very common case is the Bearing fault, which also happens in a large number. This makes it a very important fault to be considered to be detected and treated as soon as possible. If we can detect this fault at early stage and if we can replace the faulty bearings at proper time, we can prevent the fault to grow more and can prevent possible catastrophic damages. This reduces downtime of the whole system, possible large recovery cost and increase reliability of the whole system.

MATLAB/SIMULINK tool is used to simulate the model consisting of basic structure of wind turbine-generator, which is made according to our requirements in this thesis. We have also used Permanent Magnet Synchronous Generator as the generator of Wind Turbine Generator system. The output of Generator is observed to find out the difference due to faulty condition. According to that, we have made a detection and protection mechanism to save the whole system from large value of fault. By that, we can avoid system breakdown, recovery time from breakdown, huge replacement cost for valuable components in the whole system.

ABBREVIATION AND ACRONYMS

AC	Alternating Current
DC	Direct Current
PMSG	Permanent Magnetic Synchronous Generator
PMSM	Permanent Magnetic Synchronous Motor
DFIG	Doubly Fed Induction Generation
WTG	Wind Turbine-Generator
PM	Permanent Magnet
RMS	Root Mean Square
BPFO	Ball Passing Frequency of Outer Race
BPFI	Ball Passing Frequency of Inner Race
FTF	Fundemental Train Frequency
BSF	Ball Sping Frequency
1X	Machine Running Speed
FL	Fuzzy Logic
NN	Neural Network
ELM	Extreme Learning Machines
SVM	Support Vector Machine
ICA	Independent Component Analysis
FDA	Fisher Discriminant Analysis
SAP	Subspace Aided Approach
SNR	Signal-to-noise ratio
EMD	Empirical Mode Decomposition
TSA	Time Synchronous Average
HHT	Hilbert–Huang transforms
FFT	Fast Fourier Transformation
DFT	Discrete Fourier Transformation
STFT	Shorttime Fourier Transform
WVD	Wigner–Ville distribution
SPWVD	Smoothed Pseudo Wigner–Ville distribution
ANFIS	Adaptive Neuro-Fuzzy Inference System

LIST OF SYMBOLS USED

T_L	Load Torque
T_e	Electromagnetic Torque
P_w	Wind power
V	Wind speed in m/s
P_m	Mechanical power in watts
P_e	Electrical output power
P_L	Power losses in wind turbine
ρ	Air density in kg/m3
A	Swept area in m^2
C_p	Power coefficient of wind turbine
N_B	Number of balls in a ball bearing.
R	Wind turbine rotor radius
D_b	Ball diameter of a ball bearing.
D_c	Pitch diameter of a ball bearing.
θ	Ball contact angle of a ball bearing.
r_{cage}	Radius of cage centerline
r_{or}	Inner radius of outer ring.
r_{re}	Radius of rolling element.
r_{ir}	Outer radius of inner ring
θ_{ir}	The angular widths of the rolling element fault sensed by the outer and the inner ring.
θ_{ir}	The angular widths of the rolling element fault sensed by the inner ring.

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Organization of the Thesis

This section presents an outline of the work carried by the author.

Chapter-1 Contains the motivation behind the work along with the review of different literature available on the above-mentioned topic and their limitations. Various type of fault detection schemes along with the information is also presented.

Chapter-2 Contains the information about wind energy utilization and the brief history of the same. This chapter also includes the description of various parts of Wind Turbine Generator system with their structural descriptions in brief. The next segment is about the Permanent Magnet Synchronous Generator, which is used as the generator of the Wind Turbine Generator system.

Chapter-3 Contains the description of Condition Monitoring and faults of Wind Turbine-Generator System. Various condition monitoring approaches have been discussed here. Different kinds of Fault diagnosis techniques have been discussed with brief description and respective modelling. In the next section Common cases of Wind Turbine failure are described. At last, a brief discussion about Bearing Faults is done with suitable diagrams.

Chapter-4 Contains Mathematical Modelling of Wind Turbine-Generator. Here all the mathematical equations, input and output parameters, values of different parameters are discussed. MATLAB Simulink model of Wind Turbine-Generator is described with detailed descriptions and associated diagrams.

Chapter-5 Contains Results of the simulation and the associated discussions. All the output parameters under healthy and fault condition are compared and discussed here. Various graphs of different parameters under Healthy and Fault conditions are also included in this section. At last, different approaches of Fault Detection is shown to detect the Bearing Fault.

Chapter-6 Contains the conclusion and future scope of the thesis.

Chapter 1

Introduction

1.1 Motivation of the Work

Wind energy is one of the important renewable energy sources that we have for many years. Though, In the past few decades importance has been given on the expansion of the scale of production of wind power. It also has economic benefits similar to solar power. So most of the developed countries are planning to establish wind power generation in a large scale to cope-up with the non-renewable energy crisis in the future. On the other hand, developing countries are trying to find out economic ways to achieve efficient wind energy converting systems.

Both the cases require establishment of large number of wind turbines. To maintain those turbine, we also need to focus on various condition monitoring and fault diagnosis techniques from now. An efficient system must have less operating cost as well as less maintenance cost. Fault detection at right time helps to achieve that.

Bearing faults are the large portion of all faults that can be seen in wind turbine generators. Here in this thesis, we are trying to detect the bearing fault as early as possible, so that we can replace the faulty bearing at proper time and prevent the fault to grow more and subsequently prevent the damage of valuable components of the whole system. This reduces downtime of the whole system, large recovery cost and increase reliability of the whole system.

1.2 Literature review

Utilization of wind energy started a long time ago. The forms of utilization were very different from now, but at those times wind energy was used in many day to day works as per the technological capabilities. In Persia in the 10th century and in China in the 13th century, the Windmills were used for grinding grain.[1] Previously, wind energy was very much used for transportation (sailboats), pumping water, drainage water, grinding grain, sawing wood and many other day to day works. During Europeans colonization , windmills were built in a large number. Farm windmills were very famous among Americans in the United States [3]. From 1850 on, large number of water pumping windmills were manufactured. Later, Windmills were made of metal.

Many attempts were made over the years to construct large wind turbines. Different designs were approached to capture wind energy more efficiently. Today the best designs are available for commercial wind turbines. There are also options available for different sizes . Compact, efficient, low maintenance wind turbines are available for domestic installation.

The global wind industry has grown much more in the past decade compared to the past years. In 2021, globally almost 94 GW of Wind Power capacity has been added, which is 1.8% more than the capacity of the year 2020. In 2021 the commissioned offshore wind capacity was 21.1 GW, which is thrice compared to 2020. Total global wind power capacity is 837 GW as of now. Also, it is expected to add 557 GW additional capacity in the next 5 years [2].

With the increase in renewable energy market, the wind energy came forward to contribute a huge part of renewable energy . As the demand is continuously growing, the establishment of more wind turbines is happening every year. Along with that the requirement of condition monitoring of those wind turbines is also increasing . Previously the condition monitoring used to happen almost completely manually. But after the boost of techniques like AI and Machine Learning, the condition monitoring system is trying to evolve into partially or almost automatic system. Though the proposed system is not yet widely established into the industry, but planning and researches are going on this topic.

Wind turbines are generally exposed to the environment for all the time. So the climatic conditions effect the internal and external failure of the wind turbines.

The External Failure of Wind turbine may be the damage to the blades due to some reasons i.e. Bird strikes, delamination, blade cracks, corrosion of the blades, rainfall.

The Internal failure of the Wind Turbine can be due to the failure of the internal electrical components or due to the failure of the internal mechanical components or due to both. Both Internal and External Failures effect the performance of the wind turbine. They also have an effect on the reliability of the WTGs. More failure also results in downtime of the whole system, recovery cost.

Salih Mohammed Salih, Mohammed Qasim Taha, Mohammed K. Alawsaj have done some works on the performance analysis of wind turbine systems under the effect of different parameters [8]. They used simulation models to study the performance of small wind turbine generator systems based on different parameters. They have extracted the results using MATLAB for analyzing the performance of two wind turbines: Whisper-500 3.2KW and NY-WSR1204 600W. The considered parameters are : wind speed, air density, air pressure, temperature and the length of blades for wind generators. The results are analyzed to determine the sensitivity of input power on the output of wind generators.

Yaoyu Li, Xin Wu and Zhongzhou Yang have done some important review on the recent advances in wind turbine condition monitoring and fault diagnosis [13] , with the primary focus is on rotor and blades, gearbox and bearing, generator and power electronics, system-wise turbine diagnosis. The important points in this work includes Acoustic emission to detect incipient failures, development of model based reasoning algorithms for fault detection and isolation as cost-effective approach, the effect of unsteady aerodynamic load on the robustness of diagnostic signatures.

Bearing fault is one of the most common and important faults that happens in the WTGs [5]. We must try to detect the bearing fault as early as possible, so that we can replace the faulty bearing at proper time and prevent the fault to grow more and subsequently prevent the damage of valuable components of the whole system. There are several methods available for condition monitoring of bearings in electrical machines. We can classify them as : Vibrational Monitoring, Temperature monitoring, Chemical analysis, monitoring with acoustic emission, monitoring with sound pressure , monitoring with laser monitoring, current monitoring [6] .

In the year of 2007, Wei Zhou, Bin Lu, Thomas G. Habetler, Ronald G. Harley have done Bearing Fault detection with Noise Cancellation of the Stator Current Using Wiener Filter [14]. They detected the bearing fault signature by estimating and removing non-bearing fault components with a specific noise cancellation method. In this method, they considered all the stator current components, that are not related to bearing fault, as noise. The noise components are ultimately removed and the remaining components helped to detect the Bearing Faults.

Another important approach was taken by Lucia Frosini, Ezio Bassi in 2010. They used Stator Current and Motor Efficiency to detect different types of Bearing Faults in Induction Motors. They used the experimental results of different types of bearing defects: crack in the outer race, hole in the outer race, deformation of the seal, and corrosion. They analysed and pointed out the decrease in efficiency of the motor with incipient faults and the extent of energy waste as a result of the fault condition before the breakdown of the machine.

The current based bearing fault diagnosis method has got attention due to some advantages i.e. Less costly, easy to implement, more reliable . This technique uses the measurement of generator current which is already used by the control system of the Wind Turbine Generator. So, there is no requirement of extra sensors or data acquisition devices. Current signals are also reliable and easy to access from ground without intruding the WTGs [7] . So it is widely used. But there are some problems present with using this technique. Firstly, the useful information present in the current signal in case of bearing fault generally has a low signal to noise ration. Secondly, due to operating with variable shaft rotating frequency of the WTG it is difficult to detect bearing fault.

Some important works related to the Bearing Fault have been done by Jaroslav Cibulka, Morten K. Ebbesen and Kjell G. Robbersmyr in 2012 [12] , where they did the analysis of different types of Bearing Fault and the change in the output parameters due to those different types of Bearing faults. The main contribution of their work was to investigate the capability of fault detection of a motor current signature analysis where the fault can even occur in the gearbox part. The process of detecting the different types of bearing faults through the analysis of the stator current is an interesting alternative to traditional vibration analysis. Bearing faults effects and changes the stator current spectrum which can be analyzed with proper methods and the fault can be diagnosed. Three different types of bearing faults i.e. outer raceway defect, the inner raceway defect, and the rolling element defect have different stator current spectrum. The bearing fault can be detected as the stator current phase modulation at the calculated bearing defect frequency.

In the year 2017, Xiang Gong and Wei Qiao have done another work on this topic. They have suggested an approach to diagnose Bearing Fault for Direct-Drive Wind Turbines with the help of Spectrum Analysis and Impulse Detection. They presented an algorithm based on power spectral density (PSD) analysis for extraction of the signature of Bearing fault by only using stator current. Then they have used an impulse detection method to screen out the excitations in the PSD spectrum, where the excitations at the characteristic frequencies of the bearing fault are extracted and are considered as the fault signature. Then the evaluation of the wind turbine is done with a median filter-based method to determine whether maintenance is required. This is a effective method for bearing faults diagnosis of a direct-drive wind turbine operating at variable-speed conditions.

There is another approach to detect the Bearing fault of WTGs, which is analysis of the Vibration signal. Xin Weidong, Liu Yibing, He Ying and Su Boxian worked with this method in 2012. They used vibration signals of main shaft, measured from a healthy direct-driven wind turbine and a faulty direct-driven wind turbine. They analyzed and studied the vibration characteristics of main shaft bearing. Signals from both the units were compared and studied from time domain, frequency domain and cepstrum domain. After that, narrowband envelope analysis had been done. This process can effectively identify the bearing fault state [16].

Here in this thesis, we will try to detect the Bearing fault with some different approach, that is Analysis of mechanical torque waveform, analysis of electromagnetic torque waveform and thermal analysis. All these analysis together can lead to the detection of Bearing Fault.

We will also use the AI based system to properly identify the bearing fault and at last we will be using a system to isolate the system when bearing fault is detected, to effectively stop the fault from reaching towards a large value and from causing more damage subsequently.

Chapter 2

Wind Energy and Wind Turbine-Generator System

2.1. Introduction

Utilization of Wind has a long history. From ancient times, wind energy has been used in many ways. As the education and technological development progressed over years, the way of utilization changed. It became more efficient, more effective, less of a manual process. The wind turbine generator system is the most modern system that we have which can utilize wind energy to produce electrical energy as much as it can based on the available technology. So here we will briefly discuss the journey and the current status of wind energy globally.

2.2. Wind Energy Utilization

The use of wind energy started in antiquity. In Persia in the 10th century and in China in the 13th century, the Windmills were used for grinding grain.[1] Previously, wind energy was very much used for transportation (sailboats), pumping water, drainage water, grinding grain, sawing wood and many other day to day works. During Europeans colonization , windmills were built in a large number. Netherlands used to have over 9,000 windmills actively operated at that time. The mills had sophisticated aerodynamics structure of the blades.

The amount of sail on the blades ultimately controlled the rotational speed and power of the mills. Farm windmills were very famous among Americans in the United States [3].

From 1850 on, large number of water pumping windmills were manufactured. Later, Windmills were made of metal. The farm windmills increased wind energy utilization in a large scale. In United States around 30,000 farm windmills used to produce an approximated output of 6MW , though their individual power output was 0.2–0.5 kW. Though the problem was that, the maintenance cost was very high. So it was difficult to replace old parts with the new ones.Charles Brush built a windmill in 1888, to generate electricity. It could produce 12kW of energy in a good wind condition.

Many attempts were made over the years to construct large wind turbines. Different designs were approached to capture wind energy more efficiently. Shape of blades was given prime important in this phase to develop a better wind turbine generator model. The other important factors were Magnus effect, Rotor axes, Rotor orientation system etc.

Today the best designs are available for commercial wind turbines. There are also options available for different sizes. Compact, efficient, low maintenance wind turbines are available for domestic installation.The global wind industry has grown much more in the past decade compared to the past years. In 2021, globally almost 94 GW of Wind Power capacity has been added, which is 1.8% more than the capacity of the year 2020. In 2021 the commissioned offshore wind capacity was 21.1 GW, which is thrice compared to 2020. Total global wind power capacity is 837 GW as of now. Also, it is expected to add 557 GW additional capacity in the next 5 years [2]

2.3. Wind Turbine-Generator System

The wind turbine-generator system has following major parts :

1. Tower

2. Hub

3. Rotor blade

4. Turbine

5. Gearbox

6. Generator

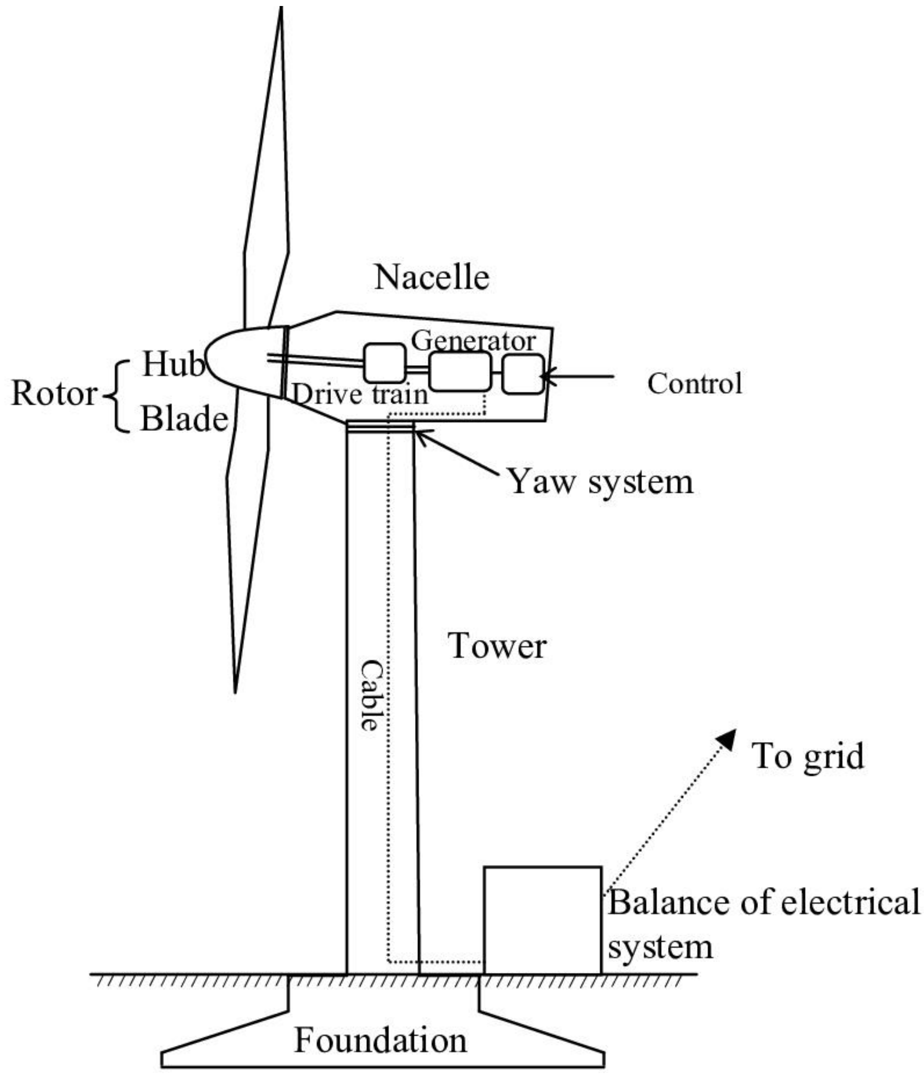

Figure 2.1 Main components of a horizontal axis wind turbine

1. <u>Tower</u>

Tower is the main structure that holds the whole wind turbine-generator system at a particular height from the ground. It also absorbs the static loads produced by the varying power of the wind. Generally a concrete or steel construction is used as a tower. Sometimes the lattice tower form is also used. They are prepared to withstand high load that can be caused by the nacelle part. The weight can even be as high as several hundred tonnes. The force due to variation in wind flow and stress from rotor blades also vary the effective weight.

The Tower costs about 12-20% of the total cost. The greater height causes more cost of the tower. But again, more height also effectively increases the output of the system. The height of the tower is decided by many factors depending on the location and climate.

The following types of towers are available:

- Steel towers
- Concrete towers with climbing formwork
- Pre-cast concrete towers.
- Steel lattice towers
- Hybrid towers
- Guyed poles

2. <u>Hub</u>

Hub is the frontal part of the WTGs where the blades are attached. The Hub is made up of cast iron or cast steel. The rotor blades are normally attached to the hub in a fixed position. Sometimes, the blades are also attached as a pendulum arrangement in case of two-blade rotor. Though the fixed hub is more common, sturdy, less prone to failure, more reliable, easy to construct.

Hub transfer the mechanical energy generated with rotor blades to the generator part. The process can be in two ways.

1. If there is a gearbox present before the generator part, then the hub is connected to the gearbox, which eventually increase the rotational speed to the generator side.

2. If the system is a direct drive system, then the hub transfer the rotational energy to the shaft of the generator directly.

3. Rotor Blade

Rotor blades are very important part of the WTGs. The shape and size of the rotor blades are given prime importance. It can greatly affect the efficiency and performance of the WTGs. The blades are generally made of fiberglass. Turbine blades can be of different sizes. Generally in a typical wind turbine, the blades are 351 feet long. When wind flows across the blades, an air pressure difference is created between both the sides of the blades. This creates both Lift Force and Drag Force. The Lift force is more than Drag Force, that causes the rotor blades to spin.

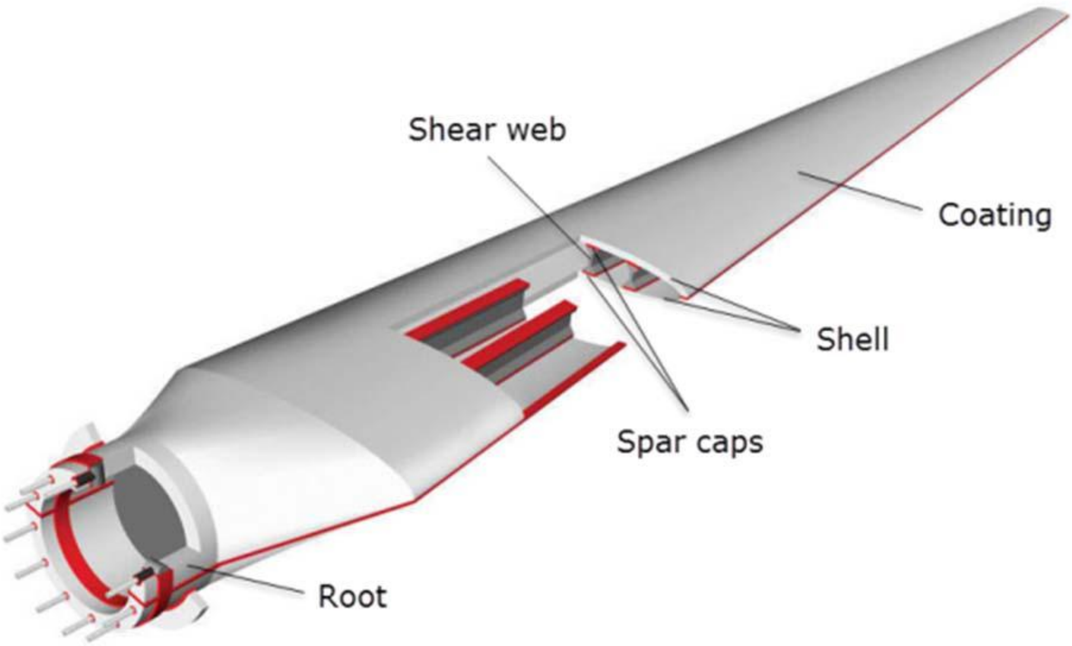

Figure 2.2 Wind turbine blade structure.

In the following figure, the structure of the Wiind Turbine blade is shown. The root is for connecting with wind turbine hub. The shell is to provide the aerodynamic shape and a structural role in stiffness and strength. The shear web and spar caps form the spar enhancing structure strength of a blade. The coating is for protecting the blade from environmental threats such as UV radiation and impacts from foreign bodies. Reproduced from.

Rotor Blades can be of different numbers :

1. Wind Turbine with 2 Blades :

If the chord length is same as three blades of WTG, then the performance is less compared to 3 blades WTG. If chord lengh is increased, then performance can be increased, But, the manufacturing cost also increases. As a result, the Model is not cost effective according to experts. Also if we increase the rotational speed, we can increase the performance, but that will cause more noise and more apparent weight. As a result the cost of foundation and tower is needed to be increased, which will cost more. So this model is not preferred.

2. Wind Turbine with 3 Blades :

Most common case. It has the proper balance of efficiency and economy. So this model is preferred by most experts.

3. Wind Turbine with 4 Blades :

It may seems to have greater performance with more number of blades, but in practical case the cost of manufacturing exceeds the revenue over the years. So this model is less preferred compared to 3 Blades model.

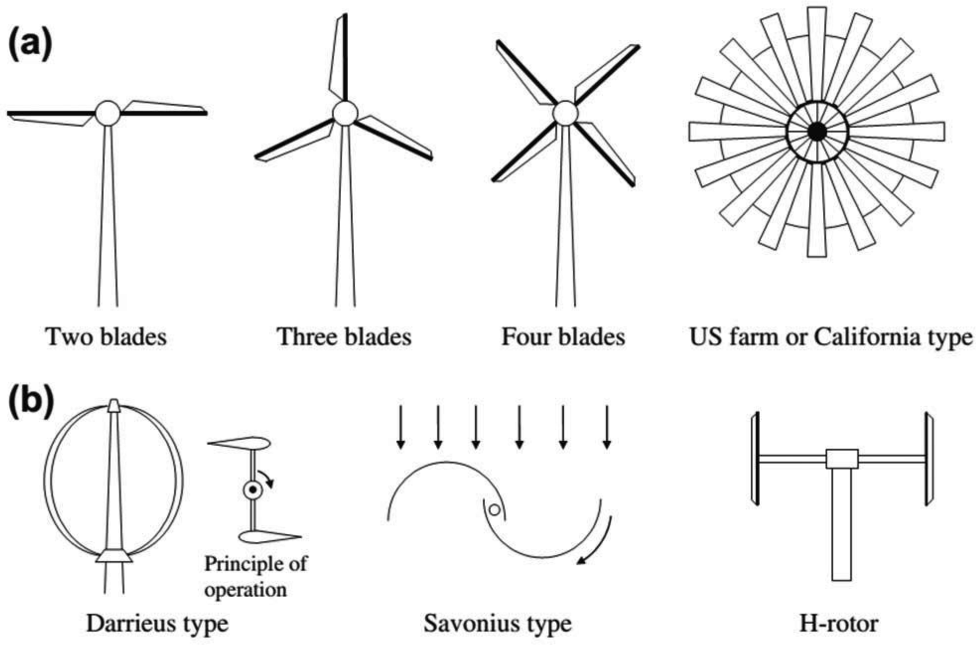

Figure 2.3 Wind turbine configurations.

(a) Horizontal axis wind turbines. (b) Vertical axis wind turbines.

4. Turbine :

Turbine is the part of the system which takes the force applied by air on the blades and transforms it into mechanical energy. The mechanical energy is then transferred to the generator part. The blades and hub together forms the rotor part of the turbine. The front part of the turbine is connected to the Hub and the backside of the turbine is attached to the shaft of the generator or to the gearbox.

5. Gearbox :

The gearbox helps to convert the low rotational speed of rotor to high speed which is required by the generator. Gearbox generally have oil based cooling system. It actually do the task of matching the rotational speed of slow moving rotor and the fast moving generator and also adjusts the effect due to various wind speeds. The Planetary Gearbox is used in Wind Turbine for several reasons, i.e. High reduction ratio, compact, Lightweight, Less installation space, high efficiency.

6. Generator :

The main work of the Generator is to convert the mechanical energy into electrical energy. There are several options available for Generator to be used in WTGs, though there is no fixed choice of generator in WTGs which is best. Mainly there can be 3 main types of Generator which can be used in WTGs.

A) DC Generator B) AC Synchronous Generator C) AC Asynchronous Generator

All of them can run with fixed or variable speed. But operating the generator in variable speed mode is more advantageous for a wind turbine as the speed of the wind is variable, practically.

Mostly the following Generator are used in WTGs by manufacturers for practical advantages and various other reasons :

A) Induction Generator
B) Doubly Fed Induction Generator
C) Permanent Magnet Synchronous Generator
D) Synchronous Generator

Here in the thesis we have considered PMSG as the generator for some reasons. We will discuss about PMSG in the next section .

2.4 Permanent Magnet Synchronous Generator :

In recent times, Permanent Magnet Synchronous Generators have got more importance as a generator to be used in WTGs due to their high value of power density as well as low mass. This option is mostly preferred for small wind turbine generator.

If we discuss the basic structure of PMSG, there is a PM installed in the rotor part of the machine to produce constant magnetic field. This rotor shaft is connected to either gearbox or directly to the shaft of Turbine. Stator of the machine has armature winding. So, when the rotor is rotated by the turbine due to the air flow, then the PM also rotates and the magnetic field lines cut the armature wire . This incident results in the production of induced emf in the armature windings and ultimately electricity is taken from the armature.

PMSG can also operate in asynchronous mode, which is a big advantage for WTGs. The advantage of PMSG is that it is free from commutator, slip rings and brushes. The machines are simple, reliable and rugged. In some cases the PM is integrated into a cylindrical cast aluminum rotor which reduce costs.

PMSG generate electrical power with variable frequency as the speed of the wind is variable with time. So there is a AC-DC-AC conversion system present before connecting it to the power grid. By this process, the AC power with variable frequency and variable voltage level is converted into DC power and then the DC power is either stored in the battery or converted back into the AC power with fixed frequency and fixed voltage level. There is also direct-drive PMSG system present where the gearbox is not present.

Advantage of using PMSG as generator of WTG system :

1) PMSG is lightweight. So it is good for Yaw part of Wind Turbine

2) PMSG has permanent magnet on rotor. So it does not require an extra power source for powering the magnet in the rotor, unlike the other machines. The advantage can be found useful in application with WTG systems. Wind Turbines are generally located at remote places, where it is difficult to get extra power supply and providing the same at a particular interval. PMSG solves the problem in this case.

3) PMSG operate silently, so they can be preferred for operation in locality.

4) They are Brushless, So no extra maintenance cost is required.

5) The overall Maintenance cost is low compared to other machines. It is also easy to install.

6) PMSG has smooth torque and dynamic performance.

7) PMSG can maintain full value torque even at low speed. So it is very much advantageous for WTGs.

8) PMSG is available in small sizes also which can be fitted perfectly in compact size low rating wind turbines. So very much useful for domestic wind turbine installation.

9) It can maintain high efficiency at high speed also.

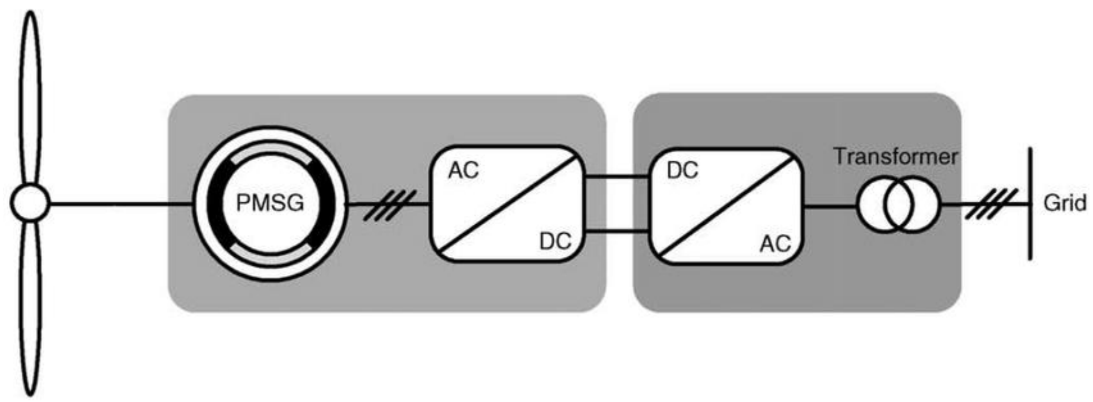

Figure 2.4 Schematic diagram of a typical PMSG wind turbine

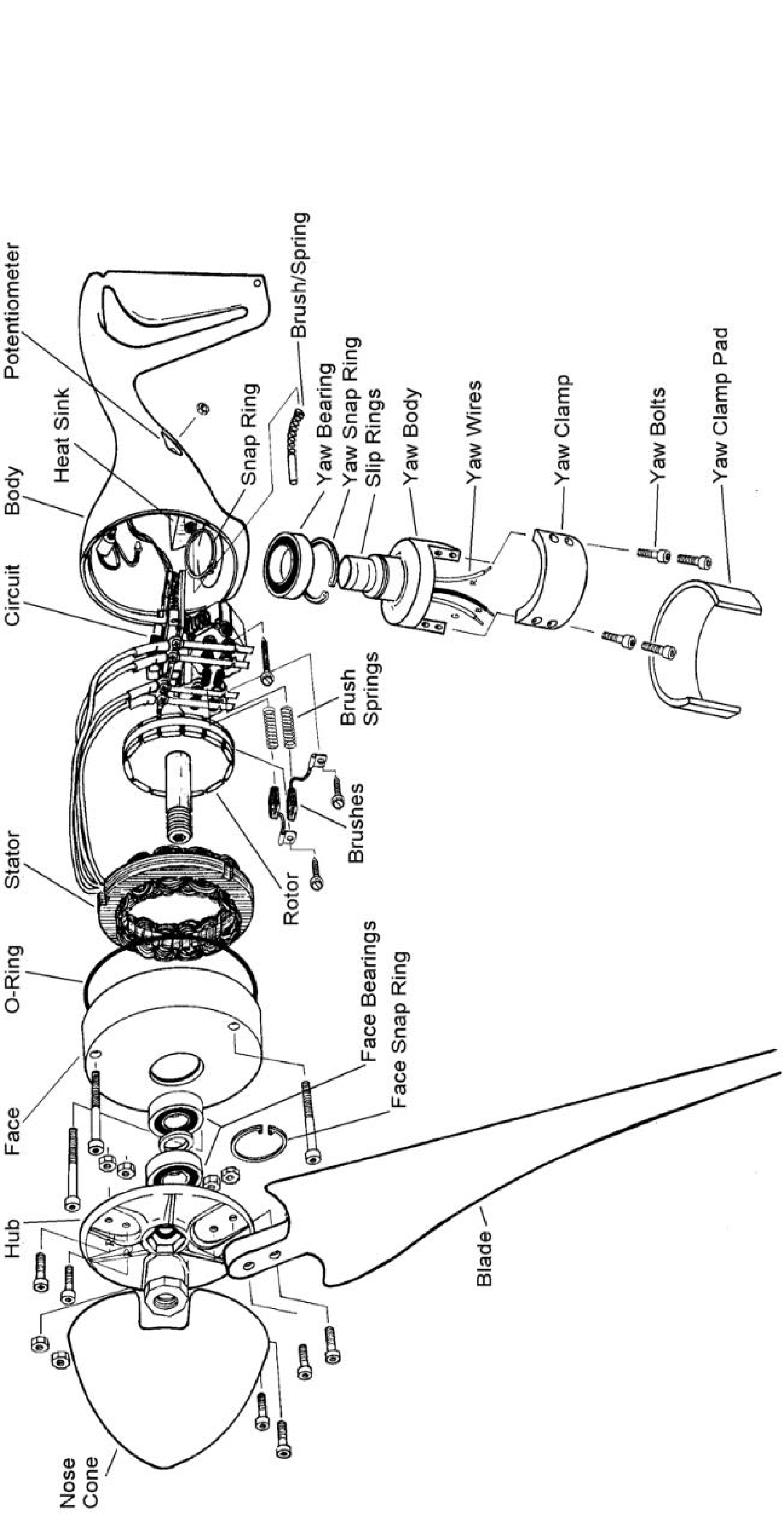

Figure 2.5 Structural view of AIR-X 400 Watt Wind Turbine

Chapter 3

Condition Monitoring and Faults of Wind Turbine-Generator System

3.1 A brief overview of Condition Monitoring and Faults of WTG system

Over the years, wind energy is contributing to more and more portions in the world energy market. However, considerable failure rate of turbines is one of the many reasons that is preventing from getting greater investment. Large wind turbines are expensive, less tolerant for degradation of system performance. So there is more chance of unscheduled system shut downs and system damages caused by various faults or malfunctions occurring in system components such as rotor blades, generator, hydraulic systems, electronic control units, sensors, electric systems, and so forth. So, it is a high priority to improve the operation reliability, productivity and availability of WTGs. It is very important to detect any kinds of abnormalities and identify them as early as possible. The next step is to predict potential faults in the remaining useful life of the components, design and implement proper control and management system to minimize degradation in the performance. Another important aspect is to monitor the economic cost, and avoiding dangerous situations. Intensive research results were reported on fault diagnosis, prognosis, and resilient control techniques for wind turbine systems during the last 20 years.

To increase the capability of harvesting wind energy, wind turbines have become larger, but it has also become more complex and expensive. Wind turbine systems are subjected to a variety of anomalies and faults due to working under harsh environments and varying load conditions. The operation and maintenance cost for a wind turbine is relatively high, especially for offshore wind turbines. The operation and maintenance costs is almost 10–15% and 20–35% of the total life costs for onshore and offshore wind turbines respectively. Therefore, there is a high demand of improvement in the reliability, safety, productiveness and availability of the wind turbine systems. Condition monitoring and fault diagnosis is one of the important techniques.

It requires to monitor whether a system is healthy, detect any faults or malfunctions in their early stages, determine the location if the faults occur, and analyse the severity of the faults so that we can take appropriate actions in order to avoid further damages in wind turbine systems. Prognosis is the technique which helps to predict potential faults, and estimate the remaining useful life of WTG so that maintenances and repairing can be scheduled at particular interval. Resilient control is a technique to minimize the effects from the faulty components or sudden disruptions so that the WTG can work up to an extent under some abnormal conditions. Essential studies were carried out in the area of monitoring, fault diagnosis, prognosis, and resilient control for wind energy systems during the past two decades. Non-destructive testing methods of ETGs at manufacture and in-service were observed and analyzed to inspect potential flaws in WTGs.

A WTG is a complex electromechanical system that helps to convert wind energy to electrical energy. A WTG has various components and subsystems such as blades, rotor, yaw, gearbox, generator, controller, anemometer, tower, break and many other components. In the following figure, a typical structural view of a WTG is shown. Wind flow applies force on the blades and rotor to run, which then rotates the main shaft. The speed is increased with the help of the gearbox to drive the generator. The Generator converts wind energy into mechanical energy, and then finally to the electrical energy. Practically, the wind speed is not constant due to the changing weather conditions. So there is the system to adjust the pitch angle to adapt the change of wind speed. The anemometer identifies the direction of the wind flow and according to that, the yaw system can align turbine with the direction of the wind. The controller is present to generate desired electricity. The housing or nacelle is mounted at the top of a tower. It covers most of these components.

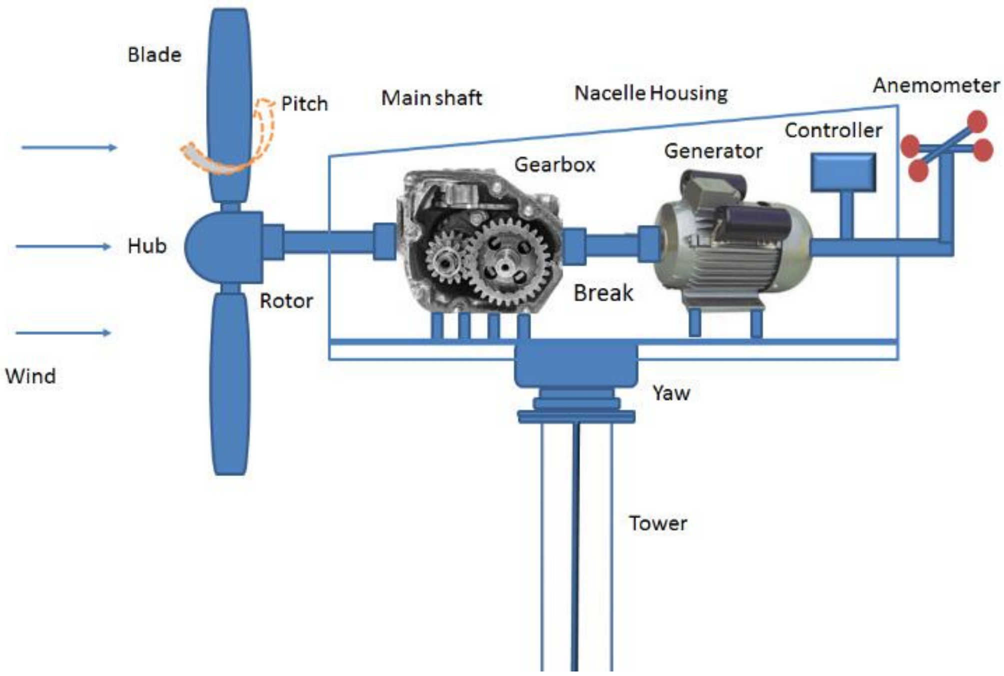

Figure 3.1 Different components of Wind Turbine - Generator System

The WTG components are prone to malfunctions or faults due to various reasons, leading to system interruptions and revenue losses. Unexpected behaviors of wind turbines can also be identified as faults and failures. A fault is defined as an unacceptable deviation of the system structure or the system parameters from the nominal situation. A failure is defined as inability of a system or a component to fulfil its function [18,19].

The common faults in wind turbines are shown with their respective percentage with a pie chart, and the main causes of the typical faults are summarized in a table. If an sudden fault is not detected in the early stage and proper action can not be taken, failures can occur as a consequence.

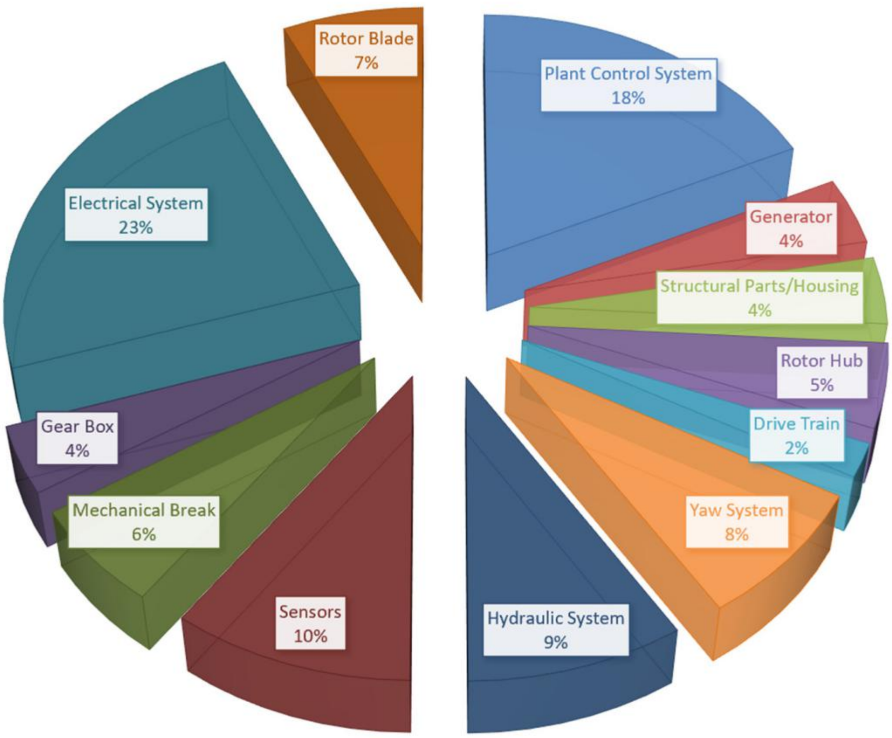

Figure 3.2 Percentages of typical faults in wind turbines [20].

Typical faults in wind turbines are summarized below [21,22,23] :

Types of Faults	Causes of Faults
Faults on blades and rotors	Corrosion of blades and hub; crack; reduced stiffness; increased surface roughness; deformation of the blades; errors of pitch angle; and imbalance of rotors, etc.
Faults on gearbox	Imbalance and misalignment of shaft; damage of shaft, bearing and gear; broken shaft; high oil temperature; leaking oil; poor lubrication, etc.
Faults on generator	Excessive vibrations of generator; overheating of generator and bearing; abnormal noises; insulation damage, etc.
Faults on bearing	Overheating; and premature wear caused by unpredictable stress, etc.
Faults on main shaft	Misalignment; crack; corrosion; and coupling failure, etc.
Hydraulic faults	Sliding valve blockage; oil leakage, etc.
Faults on mechanical braking system	Hydraulic failures; and wind speed exceeding the limit, etc.
Faults on tower	Poor quality control during the manufacturing process; improper installation and loading; harsh environment, etc.
Faults on electrical systems/devices	Broken buried metal lines; corrosion or crack of traces; board delamination; component misalignment; electrical leaks; and cold-solder joints, etc.
Faults on sensors	Malfunction or physical failure of a sensor; malfunction of hardware or the communication link; and error of data processing or communication software etc.

Wind turbine generators can be classified into :

A) Gear-box coupled wind turbine generators (e.g., doubly-fed induction generators)

B) Direct-drive wind turbine generators (e.g., permanent-magnet synchronous generators).

The purpose of Condition monitoring is to monitor operation parameters of machinery in order to identify significant changes as an indication of a developing fault. Fault diagnosis is the process to detect the fault occurrence, locate the components with fault, and identify the types, patterns, and magnitudes of the faults at an early stage, and the three tasks respectively are named as fault detection, fault isolation, and fault identification.

The purpose of Prognosis is to predicting remaining operation time before faults leads to the failures. Resilient control is to design control laws such that the adverse effects from faults can be eliminated or reduced, so that the system can work normally even under faulty conditions, which may avoid the need of an immediate component replacement or repairing for non-vital faults.

These issues are shown with the following schematic diagram.
Fa denotes actuator faults, fc denotes process or component faults, and fs denotes sensor faults. V denotes reference inputs, u denotes control inputs, and y denotes measurement. The faulty components can be detected and located by fault diagnosis based on the recorded input and output data. The recorded data can be also used for fault prognosis and prediction of remaining useful life. Resilient controls and decisions can be taken to mitigate the adverse influences from the faults based on fault diagnosis and prognosis information. If we implement appropriate fault diagnosis, prognosis, and resilient control strategies, the safety and reliability of wind turbine systems can be increased, and we can reduce the maintenance cost and downtime which are of significant importance to achieve increase productivity and economic consistency.

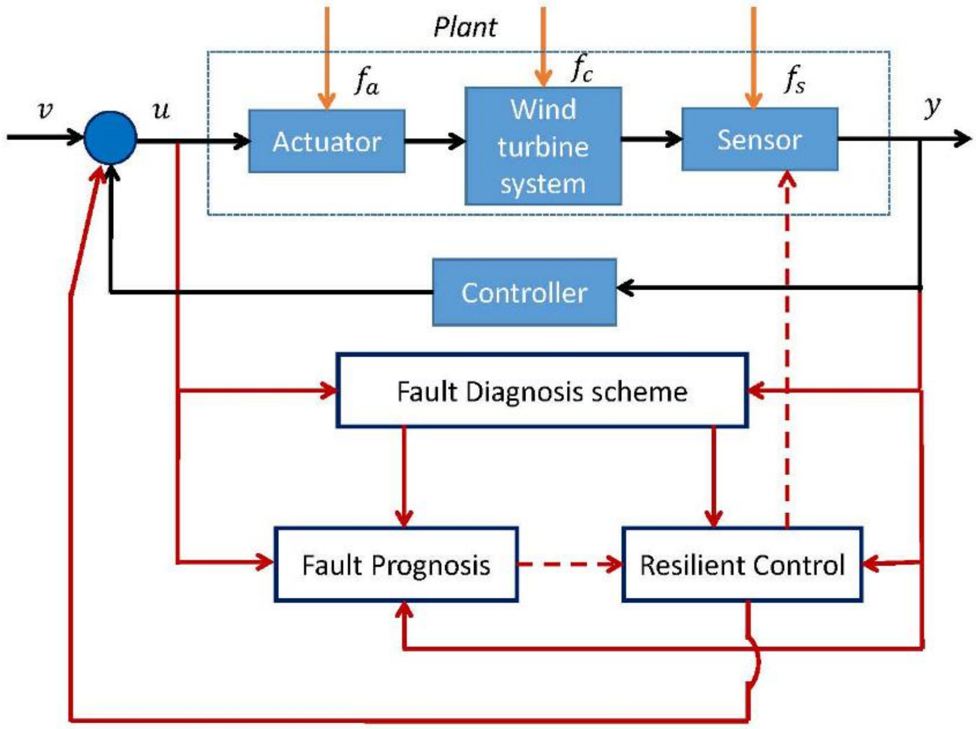

Figure 3.3 Schematic diagram of fault diagnosis, prognosis and resilient control

3.1.1 Fault Diagnosis of Wind Turbines

The purpose of Condition monitoring is to monitor operation parameters of machinery in order to identify significant changes as an indication of a developing fault, and fault diagnosis is done to detect, locate, and identify different types of faults, which gives us the scope to plan repair strategies of the system before the complete failures. Condition monitoring is actually a way of fault detection, therefore we will discuss this process in details. Fault diagnosis can be broadly categorized into 4 types of methods.

1. Mode-based methods 2. Signal-based methods 3. Knowledge-based methods, 4. Hybrid methods

3.1.2 Model-Based Fault Diagnosis for Wind Turbine Systems

Model-based fault diagnosis is followed in case of non-stationary operation for wind turbines. For this method, the models of WTG system is established by using either physical principles or systems identification techniques. A versatile wind velocity model was established In [24], which can deliver a capability of simulation of a wide range of wind-variations and disturbances. To simulate a doubly fed induction generation (DFIG) wind turbine with a single-cage and double-cage description of the generator rotor, and a characterization of its control and protection circuits, a dynamic model was derived in [25].

In [26], a dynamic modeling and simulation of a grid connected variable speed wind turbine was addressed by using an industrial standard simulation tool, namely PSCAD/ EMTDC.
In [30], a generic three-blade horizontal variable speed wind turbine with a full converter coupling was addressed with a 4.8 MW wind turbine benchmark model, and the model was described with more detail in [27].
In [32], a 5MW enhanced wind turbine benchmark model was built by considering nonlinear behavior of aerodynamics and more realistic wind inputs which is based on wind turbine modeling software FAST.

The development and applications of model-based fault diagnosis for wind turbine systems is supported by the WTG models. In the following figure, a schematic diagram of model-based fault diagnosis is shown. Model-based fault diagnosis method aims to provide the same inputs to the real-time WTG and wind turbine model. It also helps to monitor the differences between the outputs of both real-time wind turbine and the model. If the difference is Zero or the difference is within the permissible limit, it is detected that the wind turbine is under healthy state. But if inconsistency is seen between the output of real-time wind turbine and the model, then it is concluded that a fault has occurred in wind turbine systems. One of the important consideration is that, WTG models usually have modeling errors. On the other side, real-time turbine systems are also subjected to external disturbances and varying loads. So, there is a obvious chance of considerable false alarm. In order to decrease the false alarm and improve the diagnosis performance and fault detection, effective diagnosis algorithms are needed to be developed, so that, the models become robust against modeling errors and external disturbances but also sensitive to faults.

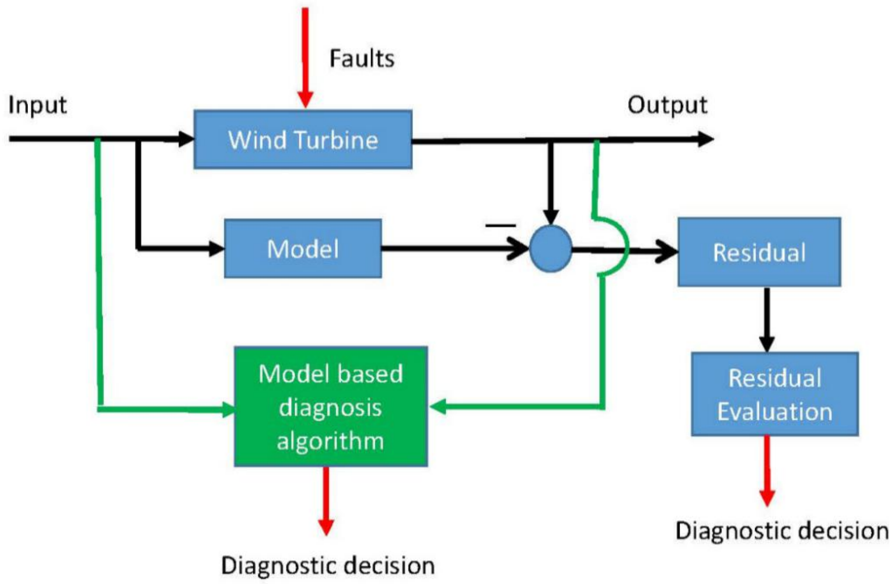

Figure 3.4 Schematic diagram of model-based fault diagnosis

Observer based fault detection approach is a popular approach. In this approach, an observer is designed to estimate the model output, and also to observe the residuals between the wind turbine outputs and the calculated model outputs. To improve the process, Optimization approaches are used.
In [28], actuator and sensor faults for a linearized 3MW wind turbine system is detected using a Lu-enberger observer based fault detection algorithm. Here, searching of an optimal observer gain is done with both parameter eigenvalue assignment approach and evolutionary algorithm so that the residual was sensitive to faults but robust against noises and perturbations.
In [29], back-to-back converters of a permanent magnet synchronous generator (PMSG) drive for wind turbine systems is considered as a subject for fault diagnosis. Also, to ensure a reliable diagnosis which is independent of drive operation conditions, a Luenberger observer and adaptive threshold were used.
Nonlinearities and partially known properties are very difficult and challenging for mathematical modeling of wind turbines. So, Takagi-Sugeno (T-S) fuzzy models have drawn more attention. Here the nonlinear dynamics is approximated by using weighted aggression of a set of linear models valid around selected operating points. As a result complexity of the nonlinear problems can be reduced to the linear range.

In [30], for a 4.8 MW wind turbine, a T-S fuzzy model was established. Based on developed fuzzy representation, a corresponding residual based fault diagnosis methodology was developed.
In [31], for a 4.8 MW wind turbine system, a T-S fuzzy model was built. Also for estimation of actuator and sensor faults, a fault estimator was addressed. Here a robust fault estimation is developed for fault related to both generator torque actuator and rotor speed sensor against modeling errors and noises by using an augmented system approach, robust observer technique, and linear matrix inequality optimization method together.
One of the very powerful alternative to describe WTG dynamics is Time-varying model. In [32], for a 4.8 MW WTG system, a time-varying model was created, where the scheduling parameters were blade pitch angle, tip-speed ratio, and rotor speed and they had to be updated real-time.
In [33], wind turbine dynamics were described with the internal model. In this case, uncertainties were located in the parameters bounding their values by intervals. A 5 MW wind turbine system was considered for testing with the designed internal observers. It was checked if the real-time measurements fall inside the estimated output interval and the fault detection was achieved by this way.
For the Fault detection of WTG system where it is considered that the process and measurement noises are random, as WTG dynamics are more or less associated with random noises in either wind speed or measurements, Kalman filter also plays an important role in parallel with the observer. Kalman filter is associated with various statistic tools like generalized likelihood ratio test. From [34], we can see by testing on whiteness, mean, and covariance of the residuals, the nature of the faults can be extracted.

In [35], a system identification algorithm was used for a three-blade horizontal axis wind turbine. The purpose of the algorithm was to establish a state-space linearized model. Then a diagnosis algorithm based on Kalman filter was used to detect additive and multiplicative sensor faults.

In [36], Cascaded Kalman filters were shown to detect WTG faults. Generally this can achieve fast detection but this also may fail under the scenario of low fault-to-noise signal ratio.

In [37], unscented Kalman filter was used to achieve more accurate means and covariance of faults. This was used to identify three fault modes : gearbox faults, lubrication oil leakage, and pitch damages. It was assumed here that the faults were reflected in the physical parameters, such as electrical voltages and oil temperatures of the systems. Here the residuals are considered as the parameter estimation errors. They were used to check estimated parameters' consistency with real process parameters.

In [38], a fault diagnosis method based on adaptive parameter estimation was used to detect and isolate faults in wind turbine hydraulic pitching systems.

In [39], a WTG was treated with a nonlinear parameter estimation approach by monitoring temperature trend. If the model parameters have an explicit mapping with the physical coefficients, then this method is straightforward. Though the accuracy of the measured parameters is a very important factor for the diagnostic performance.

3.1.3 Signal-Based Fault Diagnosis for Wind Turbine Systems

Signal-based approach basically is related to sensor data analysis of WTG. So, appropriate sensors are required to be installed in the WTG to gather the required signals like electrical signals, vibration, and sound signals. By this method, symptoms corresponding to faults are extracted with various signal processing techniques. Healthy signals is considered from prior knowledge and experiences, so that it can be compared with real-time signals. This comparison between both types of signals helps in the diagnosis process and decision making. The given schematic diagram shows signal-based fault diagnosis approach.

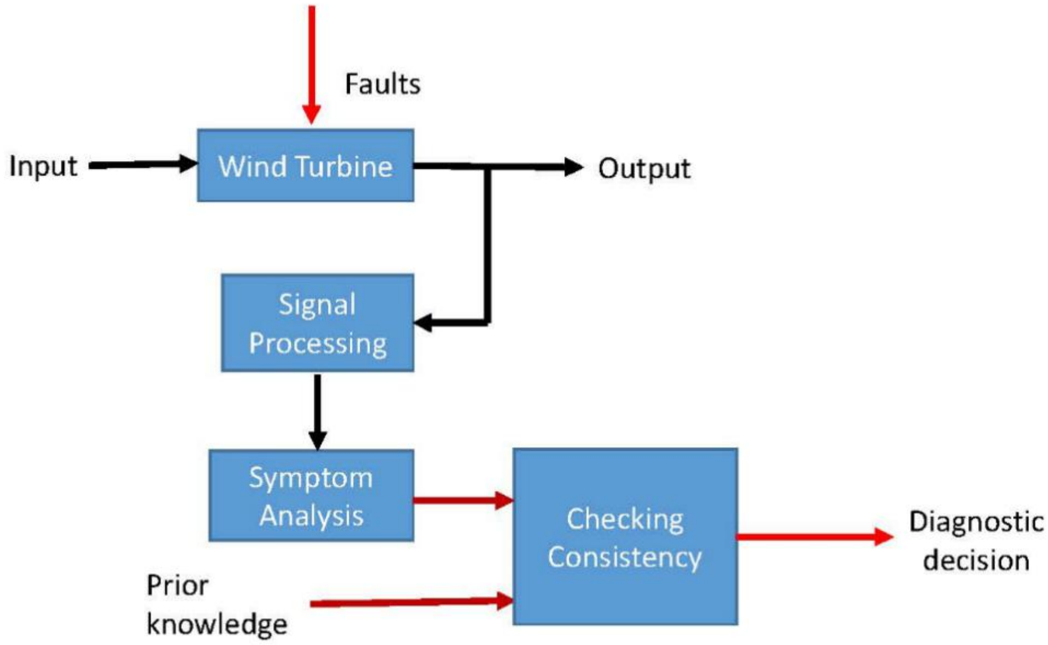

Figure 3.5 Schematic diagram of signal-based fault diagnosis.

Signal-based fault diagnosis can be classified into the following :

1. Time-domain method .
2. Frequency-domain approach.
3. Time-frequency technique.

Time-domain signal-based fault diagnosis uses time-domain parameters which are associated with the defects or failures of WTG. These parameters are : Peak Value, RMS value etc.

In [40], multiple open-circuit faults in two converters of PMSG drives for wind turbine application was used for fault diagnosis. Here the use of the absolute value of the derivative of the Park's vector phase angle is done as a fault indicator.

Frequency-domain signal-based fault diagnosis approaches use various techniques of spectrum analysis. In [41,42], we see the use of discrete Fourier transformation (DFT), which can be calculated by using fast Fourier transformation (FFT). It is used to transform a time-domain waveform into its frequency-domain equivalence to perform monitor and fault diagnosis of the system. In [41], we can see the application of a two-stage fault diagnosis algorithm, where raw time-domain vibration signals are converted into frequency spectrum with FFT technique, and severity factors and levels were computed with the help of kurtosis values by comparing with desired frequencies of the non-fault conditions. In [42] gear vibration spectra is used to detect gear tooth damages. Another approach is time-frequency analysis, which is achieved by combining both time-domain waveform and corresponding frequency spectrum. It has received much attention due to the advantages of this approach.

It includes wavelet transforms [43–45], Hilbert transform [46,47], Wigner–Ville distribution (WVD) [48], and shorttime Fourier transform (STFT) [49]. For enhancing signal-to-noise ratio (SNR) of non stationary signals, Wavelet transform is used. For faulty symptom extraction, Continuous wavelet transform is used. But, for achieving noise cancellation, discrete wavelet transform is used [43,45]. For reducing the influences from noises and uncertainties, Hilbert transform is combined with other tools, like time synchronous average (TSA) and Empirical Mode Decomposition (EMD).

Hilbert–Huang transforms (HHT) is another important technique, developed by Hilbert transform and EMD. In [46], it is used to detect gear-pitting faults.

In [47], extraction of periodic waveform from noisy signals in vibration signals is done with a time synchronous average (TSA) when faults were detected by Hilbert transform.

In [49], detecting of tooth crack faults are done with spectral kurtosis . Here combination of STFT and TSA were used. Practically to achieve better diagnosis performances, sometimes these methods are often jointly used. For example, in [48], the handling of extra noises and Smoothed Pseudo Wigner–Ville distribution (SPWVD) spectrum is handled by Morlet continuous wavelet transforms to cope with cross terms.

For generator bearing fault diagnosis, empirical wavelet transform (EWT) was adopted in [50], considering advantages of both wavelet transform and EMD. There is no need to establish an explicit of mathematical model for wind turbine system in case of Signal-based monitoring methods. This is suitable for monitoring and diagnosing of WTG rotating components, like bearings of generator and main bearing, wheels and bearings of gearbox etc.

3.1.4 Knowledge-Based Fault Diagnosis for Wind Turbine Systems

The previous methods reply on either prior mathematical model or known signal pattern, but Knowledge-Based Fault Diagnosis is different from them. It relies on a large volume of historical data available. It also tries to to extract knowledge base, representing dependency of system variables. with symbolic and computational intelligence techniques. After checking the consistency between the knowledge base and the real-time operation, diagnostic decision is taken. The given schematic diagram shows knowledge-based fault diagnosis model.

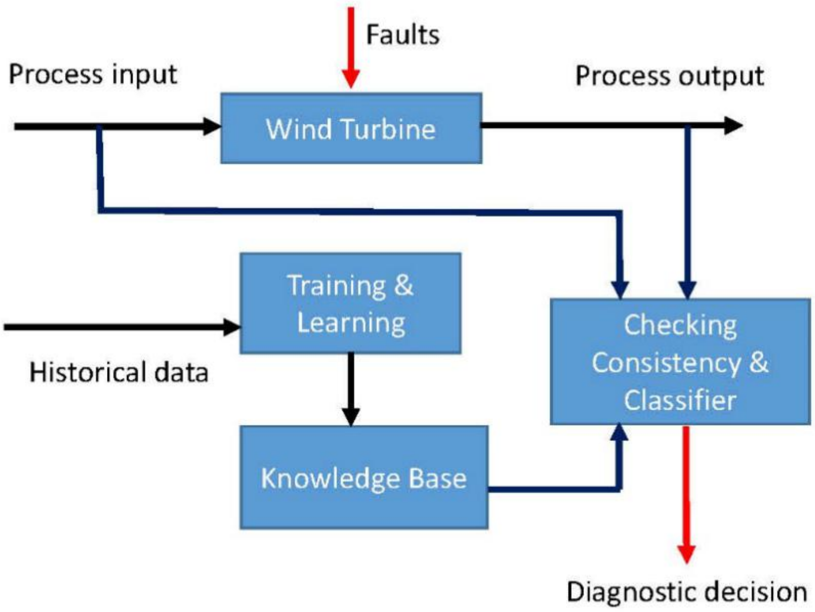

Figure 3.6 Schematic diagram of knowledge-based fault diagnosis.

knowledge-based fault diagnosis methods can be classified into the following :
1. Qualitative approach :
(a) Statistical-analysis-based (b) Non-statistical-analysis-based

2. Quantitative approach.

Qualitative knowledge approaches for condition monitoring and fault diagnosis is generally referred as a Root cause and fault tree analysis approach and expert system-based method [51, 52]. For example, n [53-56] it has been applied. In [53], evaluation of the severity of faults has been done with fault tree analysis by considering a set of potential system failures, and cost-priority-number. In [54], risk and failure mode analysis in offshore wind turbine systems have been done with fuzzy fault tree analysis approach. Here grey theory analysis is also used for determining the risk priority of the failure modes.
In [56], determining of the levels of faults of wind turbine gear box is done with a fuzzy expert system. These aapproaches are also often called data-driven approaches due to the use of historical data, knowledge based approaches in greater amount. Some Statistical-analysis-based approaches are : independent component analysis (ICA) [58], principal component analysis (PCA) [57], fisher discriminant analysis (FDA) [60], subspace aided approach (SAP) [59], and support vector machine (SVM) [61,62]. They help to achieve better results in fault extraction by preserving significant trends of original data set with the use of a variety of dimensionality reduction approaches.

The SVM is an example of nonparametric statistical method. It is used to detect faulty response of WTG due to the excellence capability for classification. In [61], function of weather and turbine response variables were trained using least squares SVM to identify faulty conditions.

Statistical-analysis-based approaches can attain more accurate identifications with proper nonlinear kernels tested on dataset. In [62], advantages of a SVM diagnosis approach based on kernel in wind turbines were demonstrated in comparison with traditional methods.

Along with statistical data-driven diagnostic techniques, non-statistical approaches, like fuzzy logic (FL) [65], neural network (NN) [63, 64] are vary much used for condition monitoring and fault diagnosis of WTG. In case of Fuzzy Logic approach, we do partitioning a feature space into fuzzy sets and we utilize fuzzy rules for reasoning. In [65], estimation of wind turbine power curve is done with Cluster center fuzzy logic approach. Neural Network can take intelligent decisions in presence of disturbances like corrupted data, faulty system, noises. In [66], fault detection of a direct-drive wind turbine systems is done with a deep neural network based fault detection process. In [67], multiple extreme learning machines (ELM) layers were used to develop a fault diagnosis algorithm for achieving feature learning and fault classification.

There are advantages and disadvantages in both statistic and non-statistic data-driven fault diagnosis techniques . So, sometimes, both are used together. Fuzzy Logic is a difficult approach as it requires extensive expert knowledge of the whole system. But, NN is preferred in those situations, where the information about the system is available and stored in a large quantity. But here also the back tracking of output is comparatively difficult due to some reasons. So there is a recent approach which is called adaptive Neuro-Fuzzy Inference System (ANFIS). It helps to combine the good qualities of both the previous methods and helps to achieve better fault diagnosis performances. In [68], this method is shown to be faster than NN in monitoring abnormal behaviors in wind turbines. Some other algorithms are also used together to monitor operation of a WTG [69] to develop more efficient system.

3.1.5 Hybrid Fault Diagnosis for Wind Turbine Systems

As we have discussed earlier, each of the previously described methods has their own advantages as well as disadvantages. Let us look into the brief overview of these methods.

Model-based fault diagnosis method :

- Very good fault detection capability.
- Good capability in and fault identification and fault isolation.
- Works when the System model is available.
- It has the advantage of off-line design and on-line implementation.
- Excellent real-time performance.

Signal-Based Fault Diagnosis method :

- Independent of mathematical models.
- Less knowledge is required about input signals.
- Installation of more sensors is costly, which is a disadvantage.

Knowledge-based Fault Diagnosis method :

- Depends on historical data, symbolic and computational intelligence.
- Performs efficiently with SCADA data.
- Can be equipped with smart sensors.
- The training and learning process is time consuming, which is a disadvantage.

Hybrid Fault Diagnosis method is an approach, where we combine more than one of the approaches. It can enhance fault diagnosis performance for WTG systems by compensating the weak points of each individual method to some extent.

In [70], main frequency of disturbances was detected with FFT analysis. After that, evolutionary algorithm was used to decrease the effects in the estimation error from dominant disturbances and faults with low-frequency. So ultimately for a 5 MW WTG system, a fault estimation algorithm was developed. In [71], signal-based methods and model-based methods were combined for the work. In [71], for the WTG model, a artificial neural network was used. Also, linear matrix inequality optimization was used to find an optimal observer gain. In [72], a mixed Bayesian/Set-membership was used for fault detection and isolation of WTG system. In [71,72], we can see the application of a hybrid of model-based and data driven approaches.

The rotational parts of wind turbines produces non-stationary Vibration signals. It also has limited fault samples. This problem is solved in [73], by a fault diagnosis algorithm based on SVM and diagonal spectrum. Here fault features can be extracted from the vibration signals, and SVM and can easily classify faults. In [74], we see the achievement of an effective 3D space visualization which is effective in fault diagnosis and classification. In [73, 74], a hybrid of signal-based and data-driven based approach was used for WTG system.

3.2. Summary of typical condition monitoring techniques

Sensing Scheme	Monitored Components	Advantages & Disadvantages
Vibration	• Gearbox • Bearing • Shaft	**Advantages** • Reliable • Standardized (ISO10816) **Disadvantages** • Expensive • Intrusive • Subject to sensor failures • Limited performance for low speed rotation
Torque	• Rotor • Gear	**Advantages** • Direct measurement of rotor load

		Disadvantages • Expensive • Intrusive
Oil/Debris Analysis	• Bearing	**Advantages** • Direct characterization of bearing condition **Disadvantages** • Limited to bearings with closed-loop oil supply system • Expensive for online operation.
Temperature	• Bearing	**Advantages** • Standardized (IEEE 841) **Disadvantages** • Embedded temperature detector required. • Other factors may cause same temperature rise.
Acoustic Emission	• Bearing • Gear	**Advantages** • Able to detect early-stage fault • Good for low-speed operation • High signal-to-

		noise ratio • Frequency range far from load perturbation **Disadvantages** • Expensive • Very high sampling rate required
Stator Current/Power	• Bearing • Gear	**Advantages** • No additional sensor needed • Inexpensive • Non-intrusive • Easy to implement **Disadvantages** • Displacement based rather than force based • Difficult to detect incipient faults • Sometimes low signal-to-noise ratio.

3.3 Common cases of Wind Turbine failure

Some of the most common types of failure in wind turbines happens in the following parts : turbine blades , generators, and gearboxes.

Challenges can be found in regular maintenance and inspections of wind turbines due to the following reasons:

- Remote locations of the wind farms.
- The size and height of the turbines.
- Rotor blades are massive and difficult to access.

So, it can be understood that it is very difficult to evaluate the blade materials and the complex surface areas. In recent times, new technologies are used to inspect the blades, like the use of drones. Only with proper monitoring and maintenance, we can prevent component failure.

1. Blade Failure

The demand for renewable energy is growing every year. So it is an important factor for the wind industry to find ways to boost the output energy of the wind turbines. One way can be increment in the size of the rotor blades.

Larger blades can produce greater power. So, rotor blade arcs are now made up to 80 meters. But with increasing blade size, additional pressure can be put on the structure and other components in the turbine.

It is found that 3,800 incidents of blade failure happen each year. Common flaws can be debonding, splitting along fibers, joint failure, gel coat cracks, and erosion.

Other than that, some contributing factors for blade failure are : lighting strikes, damage from foreign objects, material or power regulator failure and poor design. The most common failure in wind turbines is Blade failure. It can lead to costly repairs and loosing of revenue from shut down condition.

2. Generator Failure

The generator in a wind turbine creates the electricity by converting mechanical energy into electrical energy. When the generator fails, power production is stopped, resulting the wind farm operator to loose valuable revenue. There are various reasons for the failure of generator, including wind loading, thermal cycling and weather extremes. There are some other reasons also. Mechanical failure of the bearings, electrical failure of the bearings, voltage irregularities, excessive vibration and failure of cooling system can lead to excessive heat. Lastly, manufacturing or design faults, problem in the lubricant , improper installation and issue with electrical insulation can also cause the failure of the generator. To improve the reliability, a comprehensive maintenance and repair program is preferred. This will also increase the longevity of the generator, decrease costly shutdowns and frequent repairs.

3. Gearbox Failure

The Gearboxes are designed to meet the harsh operational conditions. Though they are designed for 20-year lifespan but, most of them do not make it past ten years. Each year there are reports of approximately 1,200 gearbox failures. Within the gearbox, the bearings and gears make up almost 96 percent of the failing components. Some contributing factors of failure are : contaminated lubrication, considerable temperature fluctuations, improper maintenance, improper bearing settings and transient loads leading to sudden accelerations and reversal of load-zone. When a gearbox fails, it needs a costly recovery. It is found that, the gearbox is 13 % of the overall cost of the turbine. So, it is an expensive component to replace. Also, during replacement, the turbine will be in shut down condition for a few days. If the work is complex, it can take a couple of months based on different factors. Any time the turbine is not running, we are loosing generating revenue.

Preventing Wind Turbine Failures :

Preventive maintenance can reduce the chance of failures in a wind turbine and that can lead to the extension of their lifetimes. Constant monitoring of Current signals, temperatures, vibration signals, and structural integrity of components help to detect the possible failures and can give chances to prevent them. If we can understand the root cause of the different types of failure, we can ultimately improve the design and increase the the component reliability. Again, creating reliability models of the various components helps in reducing risk and improving planning and maintenance. Turbine components failure leads to unscheduled repairs and downtime, resulting in lost revenue. By minimizing the risk of failure of wind turbine components, we can avoid costly shutdowns.

3.4 A brief discussion about Bearing Faults :

Bearings are one of the important components of the wind turbine generator system. The bearings of wind turbines sometimes fail due to various reasons. Wear and tear of bearings is a common reason that leads to the failure of the bearings. The vibration is another reason that causes the bearings to become damaged and that ultimately leads to the failure. So the nature of the bearing failure is very important to know and the monitoring of bearing failure is also equally important to take care of the problems in proper time.

Wind turbine bearings can be mainly divided into 4 categories:

1. Pitch bearings

2. Yaw bearings

3. Transmission system bearings (main shaft and gearbox bearings)

4. Generator bearings.

The pitch system helps to change the aerodynamic torque obtained by the WTG by adjusting the pitch of the blade and changing the angle of attack of the blades when there is extreme wind conditions i.e. The wind speed is too high or too low. So it helps to keep a stable output power level.

There are two main functions of the yaw system : First one, helping the wind wheel to track the wind direction; the second one, other is that due to yaw, to make the cables automatically unwound, when the cables drawn out of the cabin.

Spindle bearings helps to hold the hub and blades, which helps to transmit the obtained torque to the gearbox.

The gearbox is the component which is situated behind the hub and before the Generator. It helps to connects the main shaft and the generator. The main function of the Gearbox is to convert the low-speed operation input of the main shaft into the medium-speed or high-speed output required by generator [17].

If we consider the fault development process, can be we can categorize bearing faults into two types [11]:

1) Single-point fault :

It is a single and localized fault. Generally at the initial stage, this type of bearing fault occurs. In this case, bearing surface is relatively undamaged. So overall the amount of fault is very small and hard to be detected. Single-point fault can be catagorised into the following types of faults :

1. Defects in the outer raceway
2. Defects in the inner raceway
3. Defects in the rolling element

2) Generalized roughness :

In this type of bearing fault, the bearing surface has been degraded, damaged, became rough over a large surface area. This type of fault generally occurs at the later stage of the fault.

The faults ultimately results in the vibration of the shaft torque of the machine [10]. The characteristic frequency of vibration in case of a single point fault depends on the rotating frequency and bearing geometry.

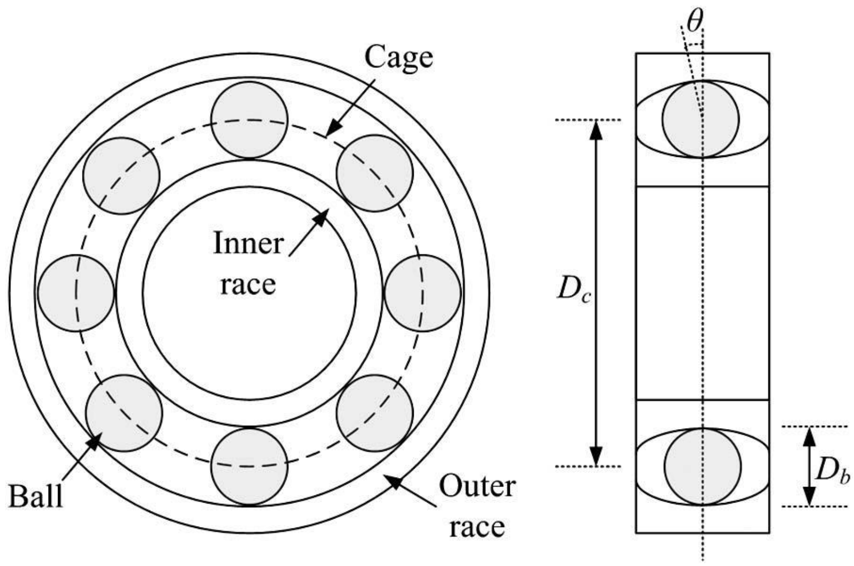

Figure 3.7 Configuration of a ball bearing.

The WTG system can have the Bearings in different places. In case of Direct Drive system, the bearings are present on the shaft. If the gearbox is present in the WTG, then the Bearings can be present both in the Gearbox and on the Shaft. The below figure is representing the Multiple bearing configuration of a direct-drive PMSG wind turbine [7].

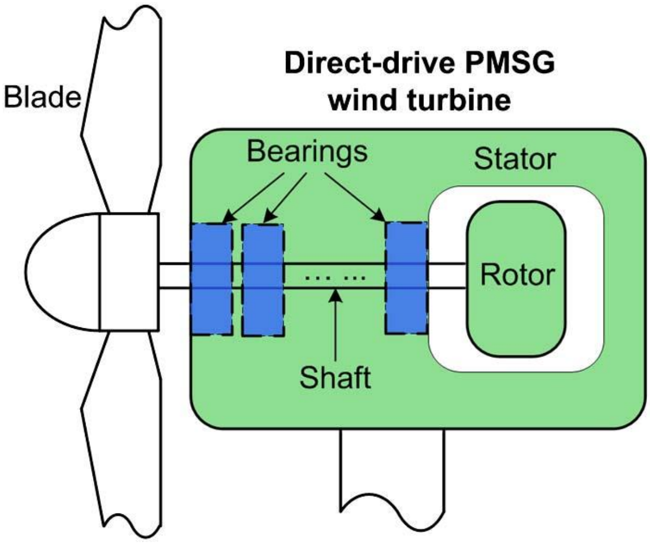

Figure 3.8 Configuration of a direct-drive PMSG wind turbine equipped with multiple bearings .

For each part of the bearing, there are corresponding characteristic frequencies, which are determined by its size and dimensions. The calculation formulas are :

Inner circle characteristic frequency:

$$BPFI = (n / 2)[1 + (d / D) \cos \theta] \quad (1)$$

Outer circle characteristic frequency:

$$BPFO \quad (n / 2)[1 - (d / D)\cos \theta] \quad (2)$$

Rolling element characteristic frequency:

$$BSF = (D/2d) \{1 - [(d/D)\cos \theta]^2\} \quad (3)$$

Cage characteristic frequency:

$$FTF = [1 - (d / D)\cos \theta]/ 2 \quad (4)$$

Where:
d is the diameter of rolling element
D is the average diameter of rolling bearing (diameter at the center of rolling element)
θ is the contact angle in radial direction
n is the number of rolling elements.

When fault occurs in different parts of the bearing, the waveform characteristics and frequency spectrum is found different, the degree of fault is also found different, its waveform amplitude is found different. The most common types of bearing faults of wind turbine are: wear fault, fatigue fault, notch or dent fault and corrosion fault. The characteristic of fatigue failure can be describes as the shedding or damage of the rolling element or the surface of the raceway. The main reason behind this case is that the manufacturing process of the supporting devices, like shafts and cages, is not up to the mark, that results in the problem of their accuracy. Notch or dent failure of the bearing can be caused by Overload, improper installation and foreign particles. Certain elements like Water, moisture, or corrosive substances can cause the bearing to rust, create gray-black stripes between the raceways. The rust spots can also be found on the raceway and the bearing surface. The dark brown or gray-black grooves on the raceways and rollers can be found due to electro-chemical corrosion. When the current passes through the rotating bearings, these types of corrosion happens.

Forces and Torque Variations related to Bearing Fault :

When the bearing fault comes into contact with another bearing element, Torque variation can be seen. When the rolling element rolls into the fault, it produces a torque on the inner ring in the direction of rotation of the inner ring. This incident reduces the external load. When the rolling element rolls out of the fault, another torque is also produced on the inner ring in the direction opposite to the rotation. This incident increases the external load [12].

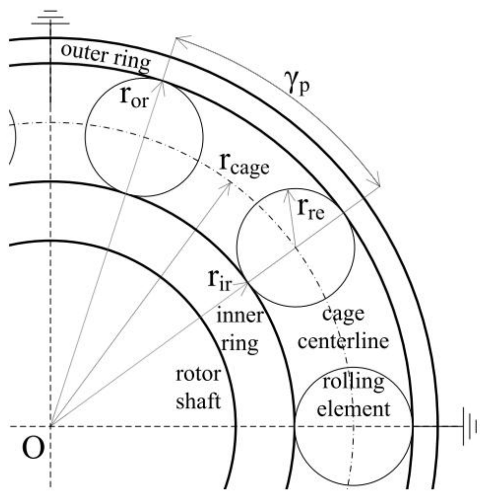

Figure 3.9 Structure and Components of a part of bearing

Rolling Element Fault

In the following bearing fault diagram, we can see the kinematic interaction between rolling element fault and rings , which is presented as point contact related to origin, similarly as in fault-free case. It is assumed that while passing the fault, the bearing elements remain in contact. For each complete rotation of the loaded rolling element the loss/gain of contact occurs twice : the contact with inner ring and the contact with outer ring. Depending on if the fault on the rolling element is in contact with the outer ring or inner ring respectively and if the ring is rolling into or out of the fault, different expressions are set up for the contact.

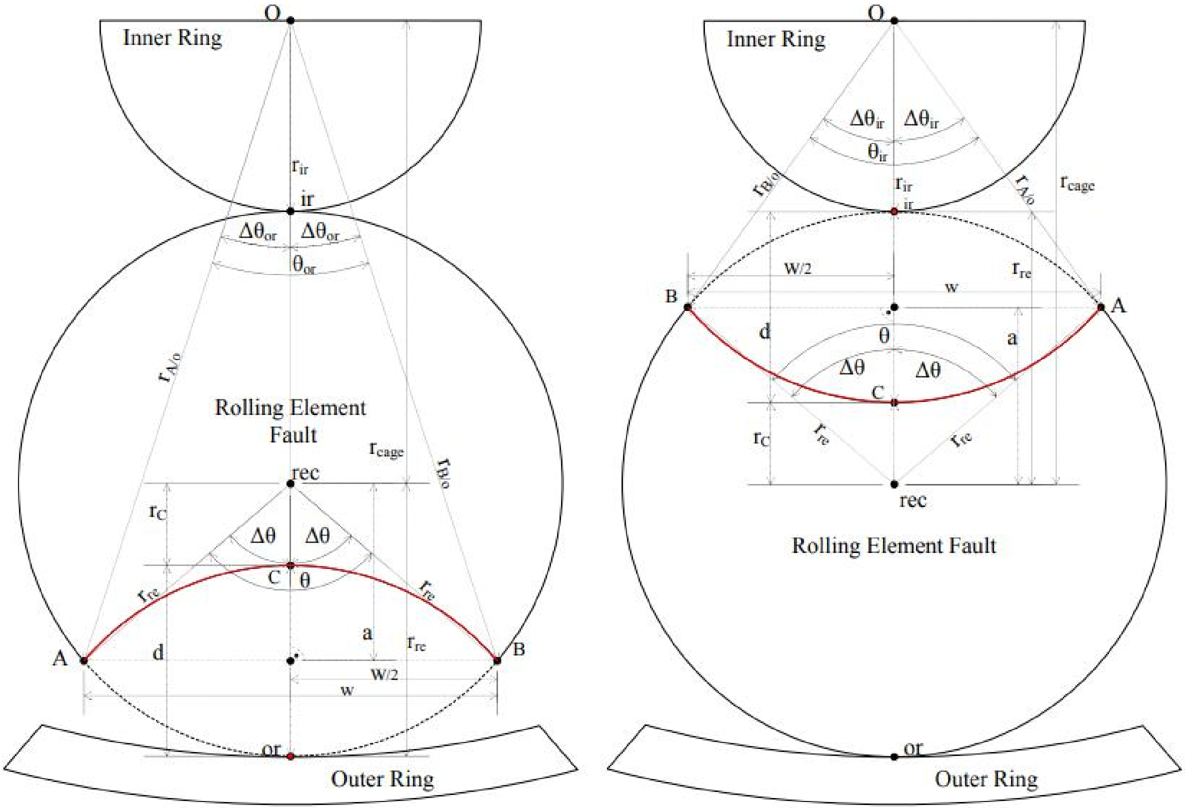

Figure 3.10 Rolling element fault as sensed by the outer ring and the inner ring.

The torque variations related to rolling element fault appear in a periodic pattern with respect to the spin frequency of the rolling element, ωre, over rings in the load zone.

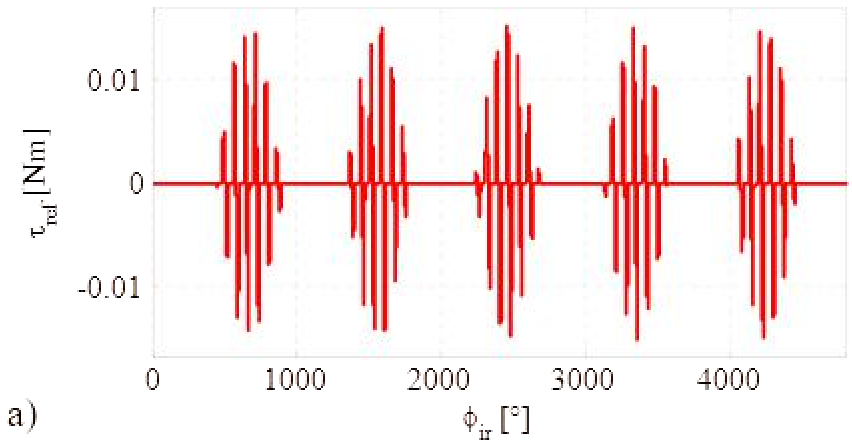

Figure 3.11 The rolling element fault-related torque variations, τ_{ref} , applied on the inner ring

Outer Ring Fault

The Figure shows the the characteristic resultant torque variation applied on the inner ring: by consecutive rolling elements in the outer ring fault zone, relative to the inner ring position ϕ_{ir}. The outer ring fault-related torque variations, τ_{orf} , appear in a periodic pattern with respect to the passing frequency of the rolling elements, i.e. cage speed, $\omega_{cage.}$ It is a kinematical function of the rotor shaft speed, ω_{ir}. As the outer ring fault is located at the maximum of the distributed load, i.e. where the probability of occuring the defect is highest, the outer ring torque variations related to fault , τ_{orf} , have constant amplitudes.

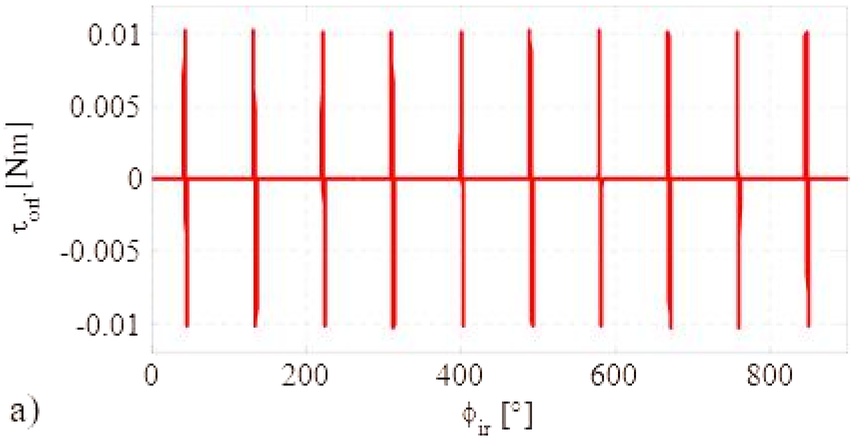

Figure 3.12 The outer ring fault-related torque variations, τ_{orf} , applied on the inner ring by consecutive rolling elements

Inner Ring Fault

The torque variations of resultant inner ring fault, τ_{irf} , appears in a periodic pattern with respect to the passing frequency of the inner ring fault over rolling elements in the load zone, i.e. the inner ring speed, ω_{ir}. Figure shows the variation of torque applied on the inner ring by consecutive rolling elements in the inner ring fault zone according to inner ring position, ϕ_{ir}.

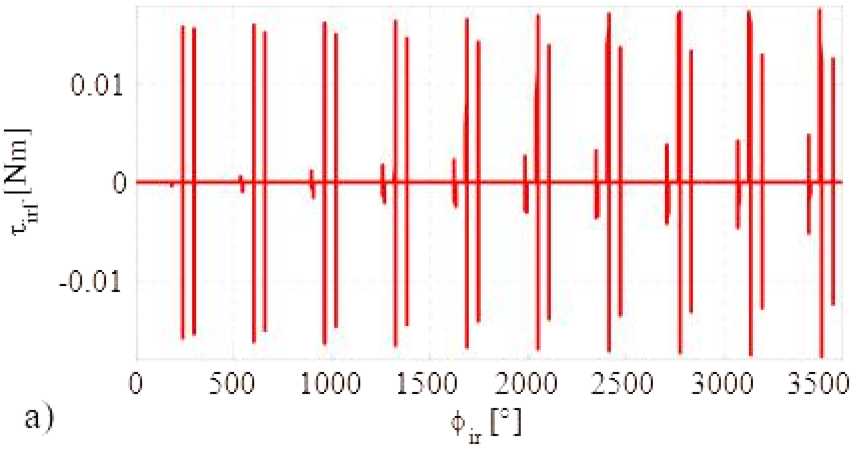

Figure 3.13 The inner ring fault-related torque variations, τ_{irf} , applied on the inner ring by consecutive rolling elements

The inner ring fault is constantly moving in and out of the load zone as the ring rotates with the rotor shaft. The radial load distribution effect in the bearing is considered here. Therefore the torque related to the inner ring fault varies in amplitude, depending to the position of the inner ring fault and rolling element, within the load zone. When the rolling element hits the inner ring fault in the middle of the load zone, the torque appears to be maximum.

Chapter 4

Mathematical Modelling of Wind Turbine-Generator

The Wind Turbine Generator is a system, which converts the wind energy into the required electrical energy. It primarily consists of a turbine and a generator which are coupled together or connected through the gearbox.

There are many components present which effect the performance of the WTG. The parameters can be External, i.e. wind speed, location, and height of wind tower, weather parameters. Or the Internal parameters, i.e. electrical connection, efficiency of wind generator, copper and iron losses, rotor size, and blade shape [8].

Equation (1) is describing the expression for Wind Power P_w .
Equation (3) is describing the expression for mechanical power P_m .
Equation (4) is describing the expression for electrical output power P_e.

$P_w=(1/2)\rho\times A\times V^3$ (1)

but

$P_m=C_p\times P_w$ (2)

therefore

$P_m=(1/2)\rho\times A\times C_p\times V^3$ (3)

and

$P_e=P_m-P_L$ (4)

Tip speed ratio (λ)
$\lambda = \omega t \times r/V$ (5)

where: P_w = wind power, P_m = mechanical power in watts,
P_e = electrical output power, P_L= power losses in wind turbine,
ρ = air density in kg/m3 , A = swept area in m^2 ,
C_p =power coefficient of wind turbine, V = wind speed in m/s.
r = wind turbine rotor radius, V = wind speed,
ωt = mechanical angular rotor speed of the wind turbines.

Albert Betz, a German Physicist, found out that we can only harvest, maximum 59.3 % of the power from the wind. This 59.3 % is called the Betz coefficient. It is theoretically the maximum efficiency at which a wind turbine can work to harvest power from wind [9]. The power conversion from mechanical to electrical is dependent on power losses (mechanical, electrical and iron losses) . Generally, wind turbine can do power conversion of (90-70) %. So, the WTG would convert (59-41) % of the available wind energy into electrical power .

Effect of Blade Length can be seen from the following data in a practical WTG system , with constant air density equal to 1.225 kg/m3 :

Scale	**Swept Area Diameter**	**Power rating**
Micro	Less than 3 m	50 W to 2 KW
Small	3 m to 12 m	2 KW to 40KW
Medium	12 m to 45 m	40 KW to 999 KW
Large	46 m and larger	More than 1 MW

From the data, it can be observed that, as the blade length increased from 0.8m to 1.8m, the mechanical power grew from 700W to 3550W at constant wind speed of 12m/s.

In this model we have used the following parameters as input parameters of WTG :

1. Rotor Radius (Rm)
2. Wind Speed (Vw)
3. Pitch Angle (β)
4. Rotor Speed (w)
5. Air Density (ρ)

And the output of the wind turbine are :

1. Mechanical Power (P_m)
2. Mechanical Torque (T_m)

After getting the output from the turbine part, we use the Mechanical Torque (T_m) as the input of the Generator part.

Here we have used PMSG as the generator of the system.

It is to be noted that, MATLAB Simulink Library has Permanent Magnet Synchronous Machine block. But we needed the PMSG to be placed in the Simulation Model. For that purpose, we have purposefully reversed the sign of the Mechanical Torque (Tm) value before we use that value as the input of Permanent Magnet Synchronous Machine block. The reason is that, For a Positive torque value Permanent Magnet Synchronous Machine block act as a Motor by default. But, when we give negative torque value as the input of the Permanent Magnet Synchronous Machine block, it act as a Generator. So ultimately we can use Permanent Magnet Synchronous Machine as a PMSG. That fulfills our requirement here.

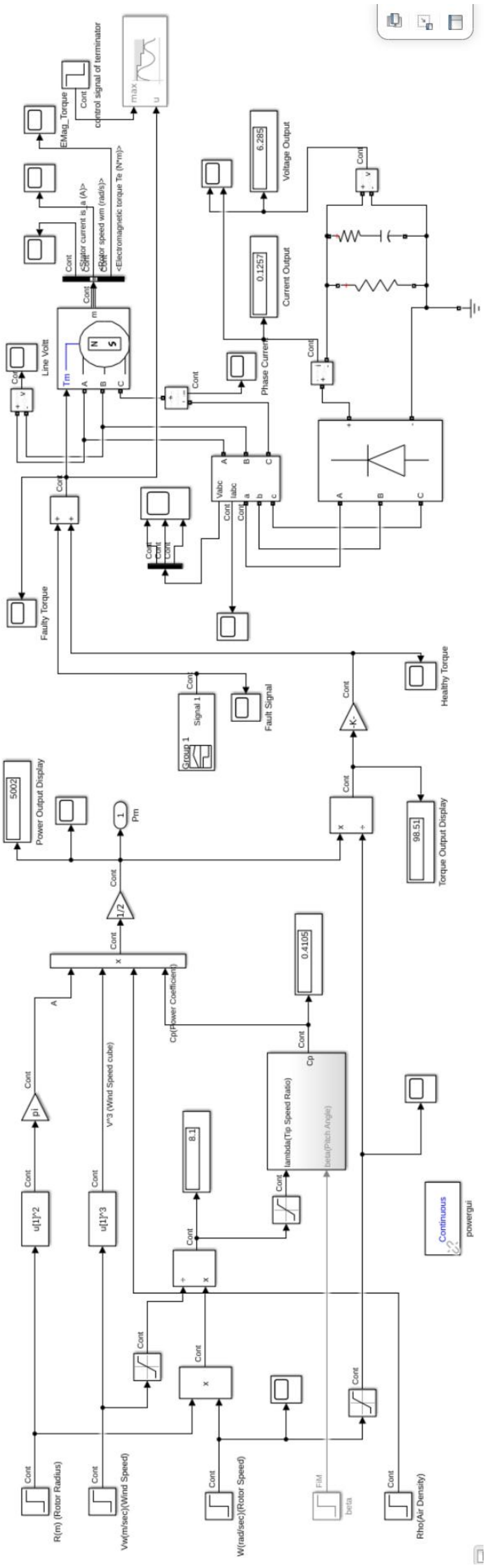

Figure 4.1 MATLAB Simulink Model of Wind Turbine - Generator System

Now, after a brief overview of the WTG model, we will see the detailed explanation of each part of the simulation model. For convenience, we can consider the whole model to be divided into 3 segments : Turbine , Generator , Output Circuit.

4.1 Segment 1 : Turbine

Turbine part is the first part of the model. All the input parameters are present in this part. The described mathematical equations of the Wind Turbine are utilized in this segment in the form of different Simulink functions and operations. The output of this part is the Mechanical Torque and Mechanical Power. The value of the Mechanical Torque depends on the input parameters of the model. This Mechanical Torque is ultimately given as the input to the next part, that is Generator.

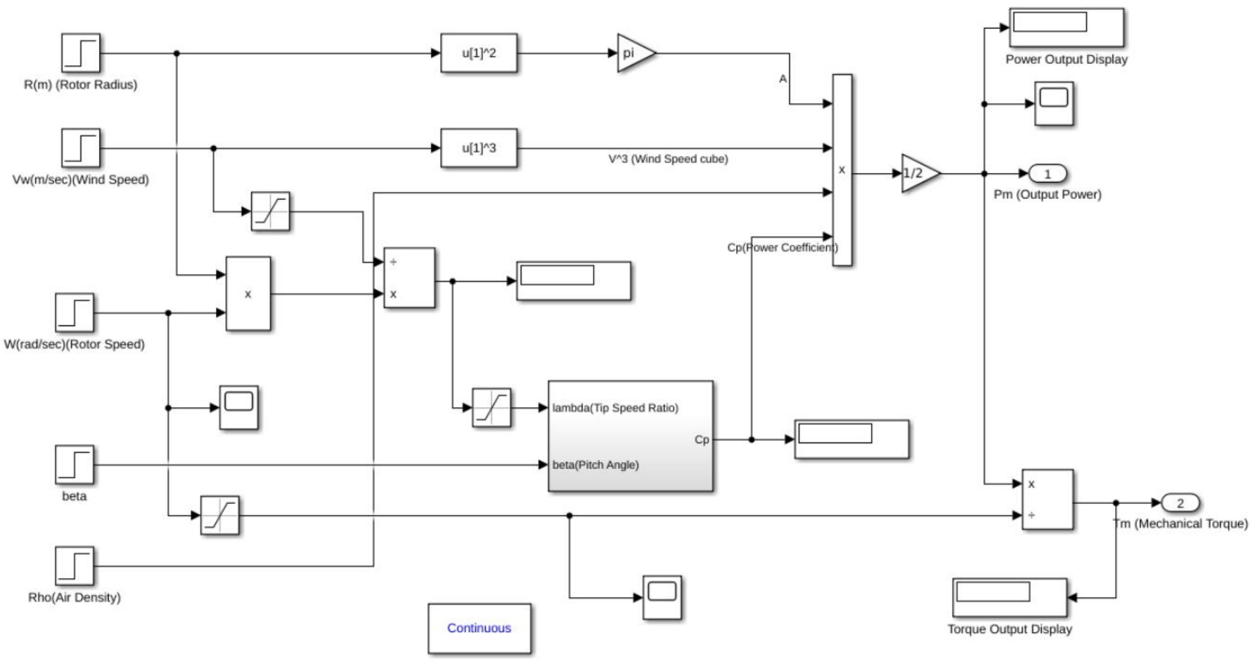

Figure 4.2 MATLAB Simulink Model of Turbine

In the First Segment, there are 5 inputs used for the Wind Turbine modelling. They are :

- Rotor Radius (R_m)
- Wind Speed (V_w)
- Pitch Angle (β)
- Rotor Speed (w)
- Air Density (ρ)

For all these parameters, Step Functions are used as input in the Simulink model. The values which are taken for these step functions are given below :

	Initial Value	**Final Value**	**Step Time**	**Sample Time**
Rotor Radius (R_m)	0	1.91431	0.1	0
Wind Speed (V_w)	0	12	0.1	0
Pitch Angle (β)	0	0	0.1	0
Rotor Speed (w)	0	50.775	0.1	0
Air Density (ρ)	0	1.225	0.1	0

The equation (3) and (5) which are used in modelling of Wind Turbine are :

$Pm=(1/2)\rho\times A\times Cp\times V^3$ (3)

where: Pw = wind power, Pm = mechanical power in watts,
ρ = air density in kg/m3 , A = swept area in m2 ,
Cp =power coefficient of wind turbine, V = wind speed in m/s.

Tip speed ratio (λ)
$\lambda = \omega t \times r/V$ (5)

where: r = wind turbine rotor radius, V = wind speed,
ωt = mechanical angular rotor speed of the wind turbines.

Another set of important equations, which are used at intermediate steps, are :

$Cp= C_1* [(C_2/\lambda_i) - (C_3*\beta) - (C_4 * \beta^x) - C_5] * \exp(-C_6/\lambda_i)$ (6)

$(1 / \lambda_i) = [1 / (\lambda + (0.08 * \beta))] - [0.035 / (1 + \beta^3)]$ (7)

These equations are utilized with the help of various function blocks in this segment.

A subsystem is developed in this segment for calculation of C_p. We have used the equation (6) and (7) for that purpose.

$Cp= C_1* [(C_2/\lambda_i) - (C_3*\beta) - (C_4 * \beta^x) - C_5] * \exp(-C_6/\lambda_i)$ (6)

$(1 / \lambda_i) = [1 / (\lambda + (0.08 * \beta))] - [0.035 / (1 + \beta^3)]$ (7)

The values of parameters, as we have considered :

- Wind Speed (Vw) =12 m/s
- Pitch Angle (β) = 0
- Rotor Speed (w) = 50.775 rpm
- Air Density (ρ) = 1.225 kg/m^3

Some additional parameters are : $C_1 = 0.5$, $C_2 = 116$, $C_3 = 0.4$, $C_4 = 0$, $C_5 = 5$, $C_6 = 21$

These values have been used in the equations to calculate the following results :

From equation (5), have found : $\lambda = 8.1$,
From equation (6), have found : Cp = 0.041034
From equation (7), have found : $\lambda_i = 11.304$

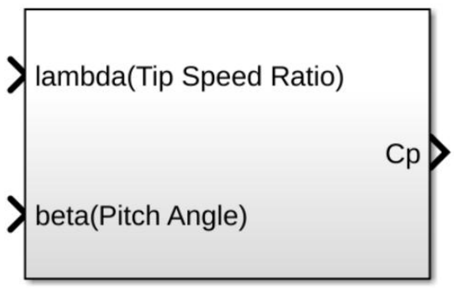

Figure 4.3 MATLAB Simulink Model of Subsystem for calculation of Cp (External View)

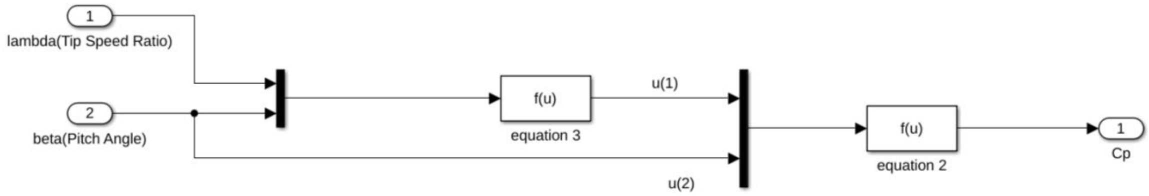

Figure 4.4 MATLAB Simulink Model of Subsystem for calculation of Cp (Internal View)

In the following model, equation 3 is the function block, made with Equation (6) and equation 2 is the function block, made with Equation (7) . Ultimately we are getting the Final output value of Cp at the output of the subsystem.

Saturation Blocks are used in appropriate places within the model to eliminate the possibility of getting some parameters value as 0 at any point of time. Zero value of those parameters can lead to undefined or infinite value of some other parameter, which is practically not possible. So we have given a very small value 1e-6 as the lower value of the saturation blocks and the uppar values are set as infinite. This setup solves the problem of Zero value as well as do not interfere with the maximum value of their own.

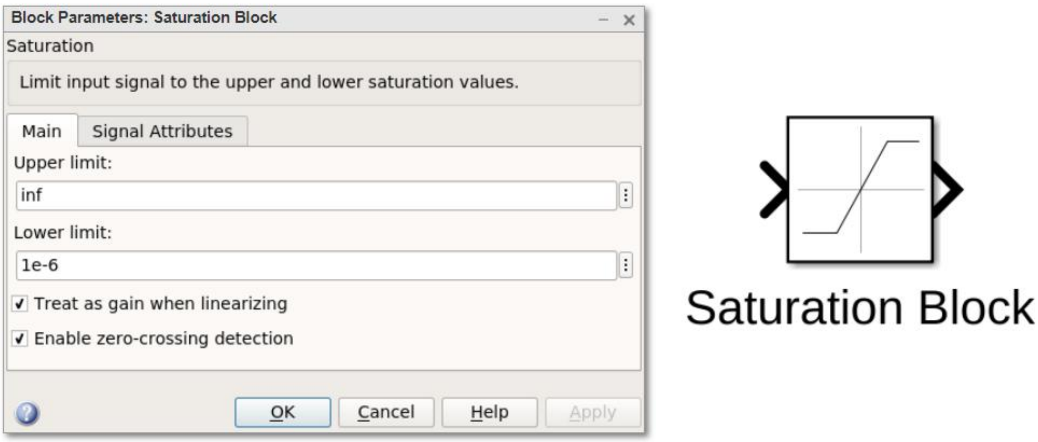

Figure 4.5 Saturation Block and the block parameters

There are a few components present in the simulation model inbetween the Segment 1 and Segment 2 . We will discuss that first before entering into Segment 2.

Mechanical Torque Gain for Generator :

This Gain block is present just after the Output mechanical torque from Segment 1, as described before. It helps to process the value of Mechanical Torque (Tm) for the next segment, where we use Generator block.
From the simulation of Segment 1, that is Wind Turbine, we get the output mechanical torque value (Tm) = 98.51 N*m . Practically, during the simulation we have found that this large value of Torque is very time consuming to work with. The simulation model takes a large amount of time to complete the simulation and get results. Instead, we can just reduce the actual torque value to a low value torque and solve the issue. For that purpose, we use the gain block of (-1/985.1).

Here the negative sign is used as we want the input torque of the Permanent Magnet Synchronous Machine to be negative, as we want to operate the MATLAB Simulink Library's Permanent Magnet Synchronous Machine block as PMSG block. The negative torque value of the Permanent Magnet Synchronous Machine results the block to work as PMSG. This is a very important requirement for our simulation.

So the final torque value is -0.1 N*m. This torque value is given as the input of the PMSG block which is present at the next step.

Fault Signal of Bearing Fault :

Another important component in this simulation is the Fault Signal of Bearing Fault. When the Bearing Fault is considered, this fault signal is included in the mechanical torque (Tm) waveform at the input of the Generator. So, when we consider there is no fault, we get a constant value of torque at the input of the PMSG. When we consider there is fault, the torque waveform has disturbances due to presence of the Fault Signal of Bearing Fault. We have generated the Fault Signal with the Signal Builder block, as shown in the model. There is a Add block present before the PMSG, which overlap the Fault Signal to the Steady Torque Signal. Ultimately we get a faulty torque waveform at the output of the Add block. This Faulty Torque is given as the input of the PMSG to see the change in output parameters of the PMSG.

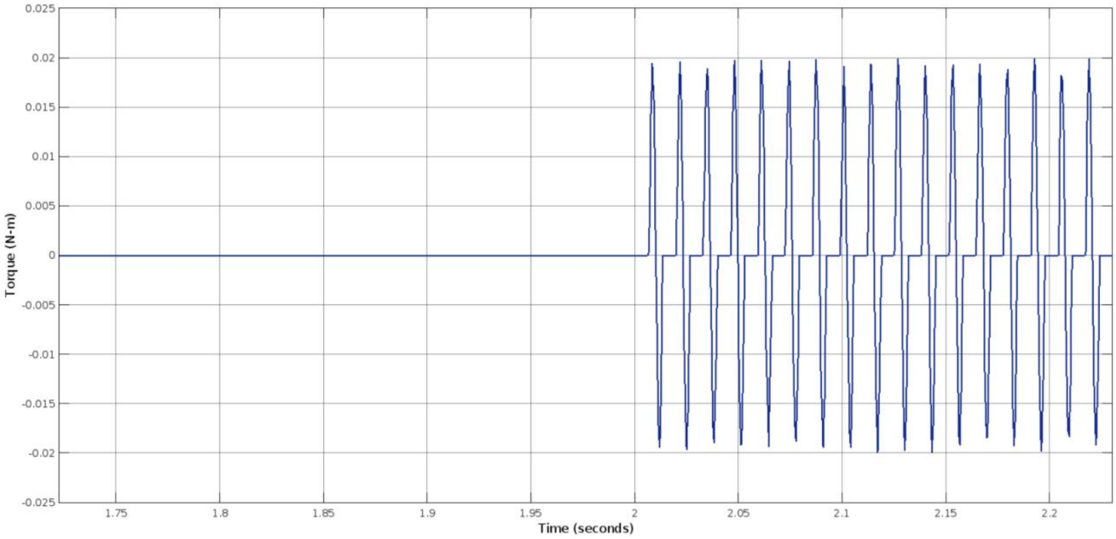

Figure 4.6 Fault Signal of Bearing Fault

4.2 Segment 2 : Generator

The Generator part is present after the Wind Turbine segment and the additional few components as described earlier. Here in this Simulation Model, we have used Permanent Magnet Synchronous Generator as the Generator of the WTG system.

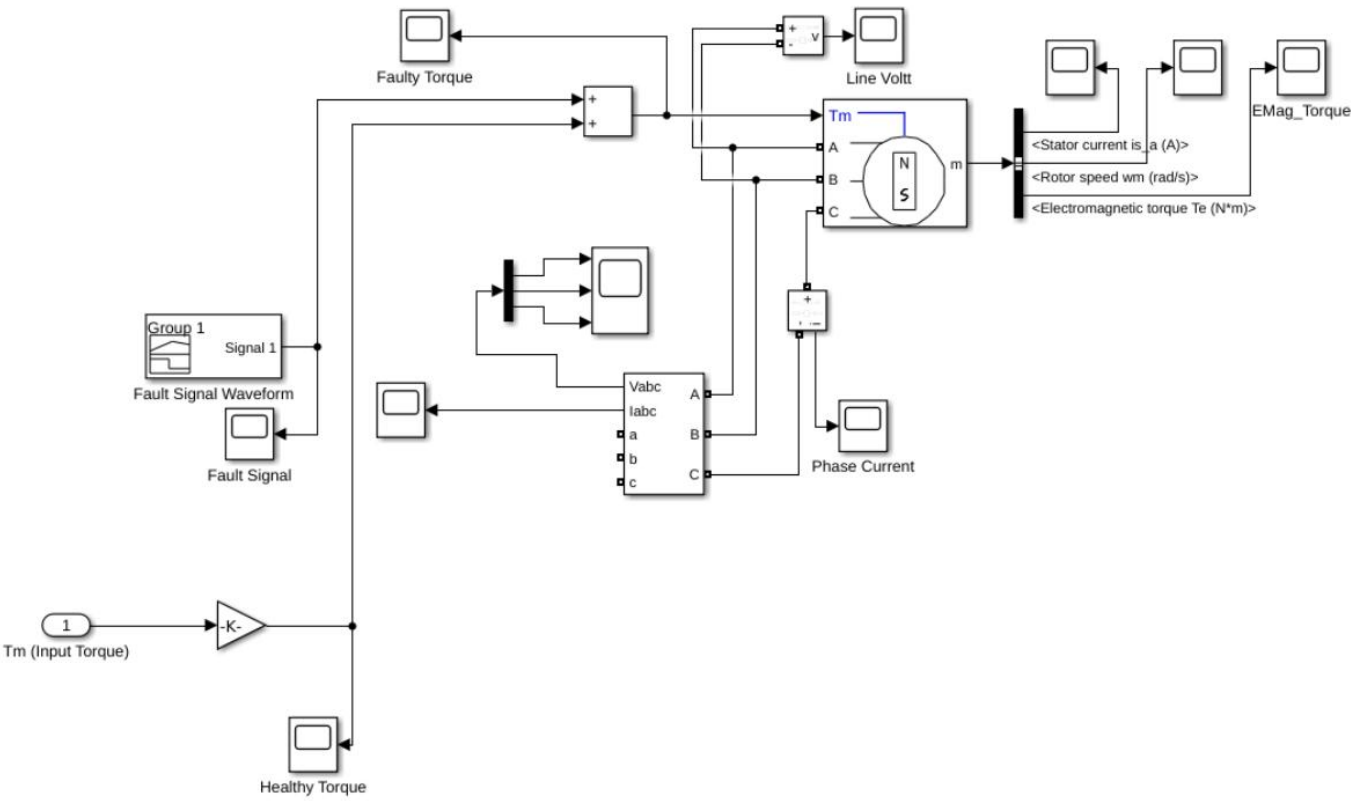

Figure 4.7 MATLAB Simulink Model of Generator

The configurations and Parameters of the Permanent Magnet Synchronous Machine, that is used in our Simulation Model are :

Number of phases = 3 Back EMF waveform = Sinusoidal
Rotor Type = Round Mechanical Input = Torque Tm
Preset Model = No

Stator phase resistance Rs (Ohm) = 0.00485
Armature inductance (H) = 0.011395
Flux Linkage (V.s) = 0.1194 Inertia (kg.m^2) = 0.0027
Viscous Damping (N.m.s) = 0.0004924 Pole Pairs = 4
Static Friction(N.m) = 0

There are various outputs available from the Permanent Magnet Synchronous Machine, among which we have selected 3 outputs : Stator Current, Rotor Speed, Electromagnetic Torque. In the Results and Discussions section, we will see the outputs of these parameters and will analysis with some special techniques for Fault Detection and analysis. Also, we have connected a Three Phase V-I Measurement block at the output of the PMSG to measure the Output Voltage and Output Current.

4.3 Segment 3 : Output Circuit

We can see a circuit is connected to the output of the PMSG which consists of various blocks and components. This whole segment is denoted here as Output Circuit of the WTG system. Let us describe each components in this segment.
Starting from the Output Stator Windings of the PMSG, we can see, a Three phase V-I measurement block is first connected to measure the Voltage and Current of the Stator windings.

The three phase windings are then carried to a Universal Bridge block, which basically implements a universal three-phase power converter. It consists of up to six power switches, which are connected in a bridge configuration. This block can be used to convert AC components to DC components or vice-versa according to the arrangement. Here the block is acting as a AC-DC Converter to get the DC components at the output circuit.

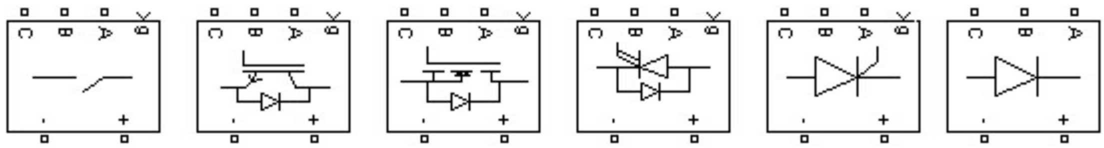

Figure 4.8 Universal Bridge working with different switches.
(i.e. Ideal Switch, IGBT, MOSFET, GTO, Thyristor, Diode)

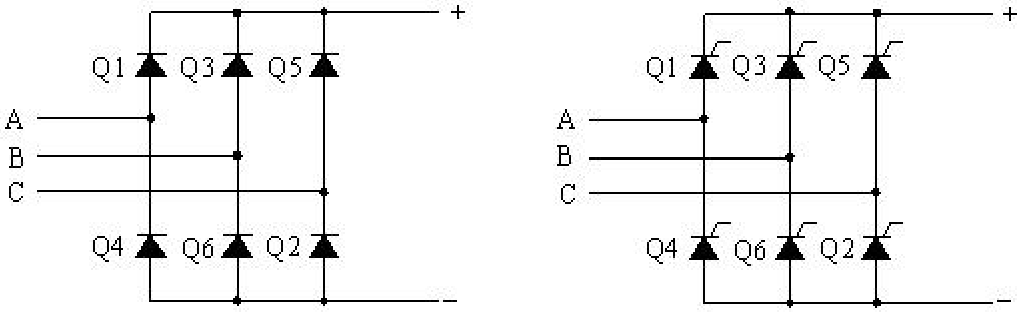

Figure 4.9 Universal Bridge working as a AC-DC converter with different switches.

The output of the Converter is connected to a DC circuit. The DC circuit consists of a series R-C branch in parallel with a Resistance.
For series R-C branch : R = 0.1 ohm, C = 0.5 micro Farad
For R branch : R = 50 ohm

A current measurement block is placed in series with the DC circuit to measure the current value. A Voltage measurement block is placed across the R-C branch to measure the Voltage across it. A Scope is present to view the graphical nature of the Current and Voltage waveform.

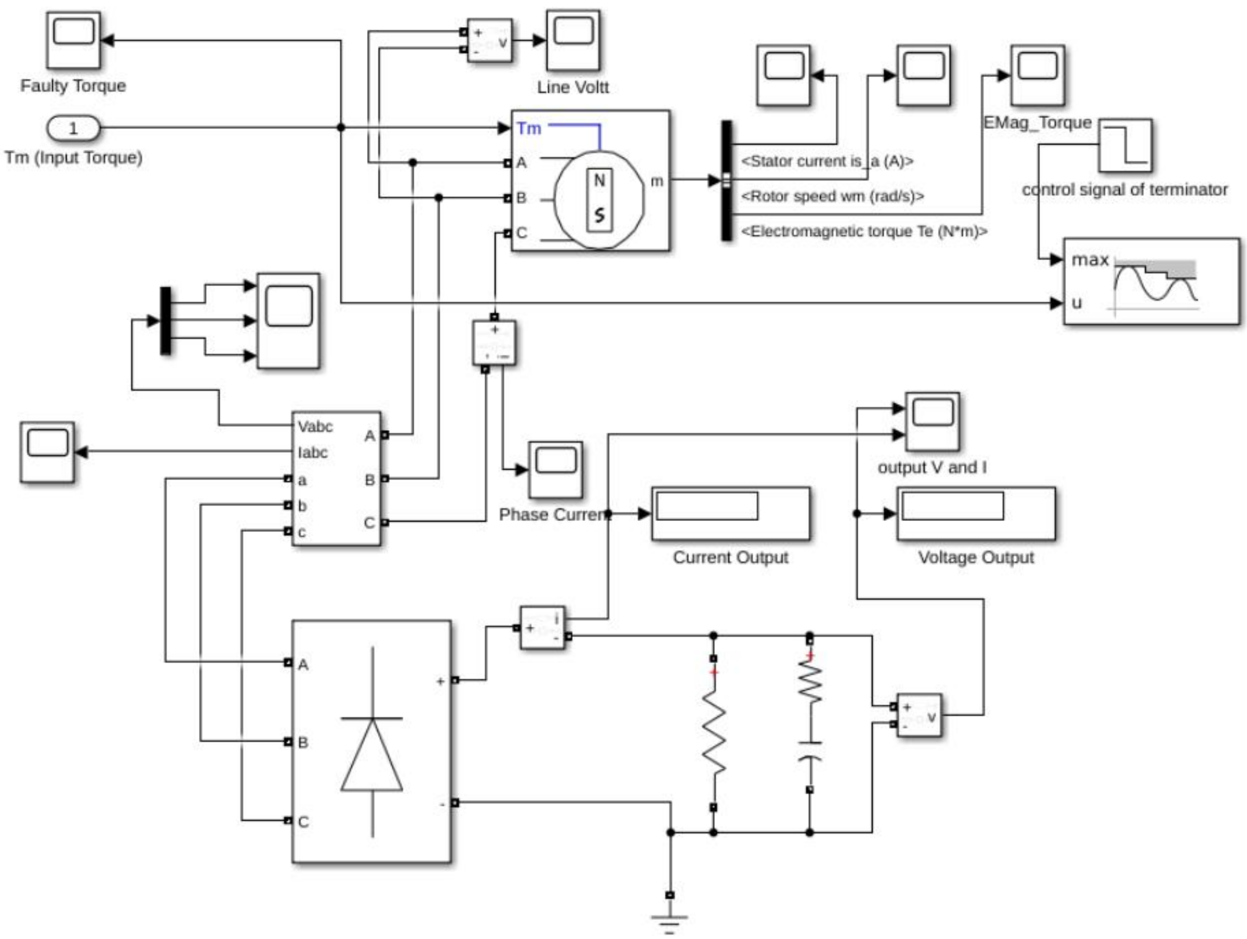

Figure 4.10 MATLAB Simulink Model of Output Circuit.

Protection System for Bearing Fault:

When the fault is detected, the system is also needed to be protected from that condition and we need to stop the fault from growing more and becoming a larger fault in future. In this simulation, we have designed a system to detect the fault and isolate the fault as soon as possible.

We have used a MATLAB Simulink block " Check Dynamic Upper Bound ", which checks if the reference signal, max, is greater than the input signal, at each point of time and disconnects the system at the moment it finds that the reference signal is smaller than the input signal . We have given the Faulty Torque as the input signal to the block and also have set the reference signal as the maximum permissible upper limit of Torque value. The system detects the first moment when the Faulty Torque exceeds the permissible upper limit of torque. At this moment the system gives a warning of the fault and disconnects the system. This prevents the fault to grow more and prevents from larger damage in the whole system.

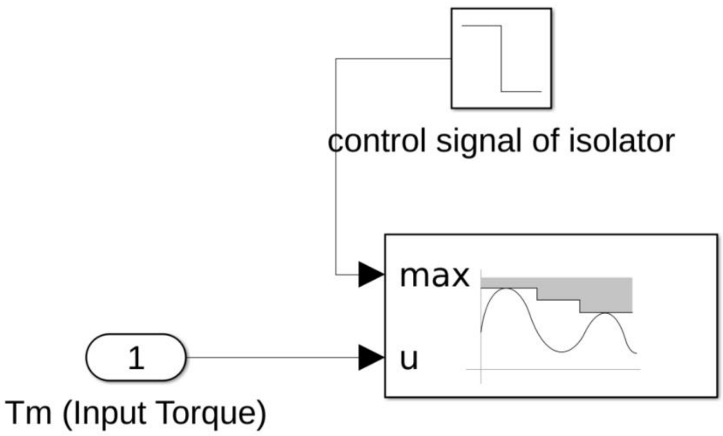

Figure 4.11 Components for Fault Detection and Isolation system.

Chapter 5

Results and Discussions

5.1 Simulation Model Results

The selected parameters are present at the input side of the simulation model. These parameters are the part of the equation for the mathematical model of Wind Turbine which have been already discussed in the previous section. For each parameter at the input side, practical values are taken for the simulation. The output from the wind turbine part is the mechanical power P_m and the Torque value T_m . This torque is given as input to the Generator part which gives the output as three phase voltage. The output of the Generator is connected to an converter block and the output of the converter is finally connected to the load.

We have taken the values for the following parameters for this simulation :

- Wind Speed (Vw) =12 m/s
- Pitch Angle (β) = 0
- Rotor Speed (w) = 50.775 rpm
- Air Density (ρ) = 1.225 kg/m^3

Some additional parameters are : C1 = 0.5, C2 = 116, C3 = 0.4, C4 = 0, C5 = 5, C6 = 21

Previously, we have found the following results :

λ = 8.1 , Cp = 0.041034, λ_i = 11.304

And the outputs of the wind turbine are :

Mechanical Power (P_m) = 5002 W
Mechanical Torque (T_m)= 98.51 N-m

In the next step we decrease the actual torque value for our convenience of simulation and to reduce the large simulation time taken due to the original large value of torque. For that purpose, we use the gain block of (-1/985.1).

So the final torque value is -0.1 N-m. This torque value is given as the input of the Permanent Magnet Synchronous Machine block which is present at the next step.

Before Fault (Healthy Condition) :

When the system is healthy (without fault), the input mechanical Torque (T_m) is constant, steady and without any fault related disturbances. We can see the waveform of the Healthy Torque in the following graph :

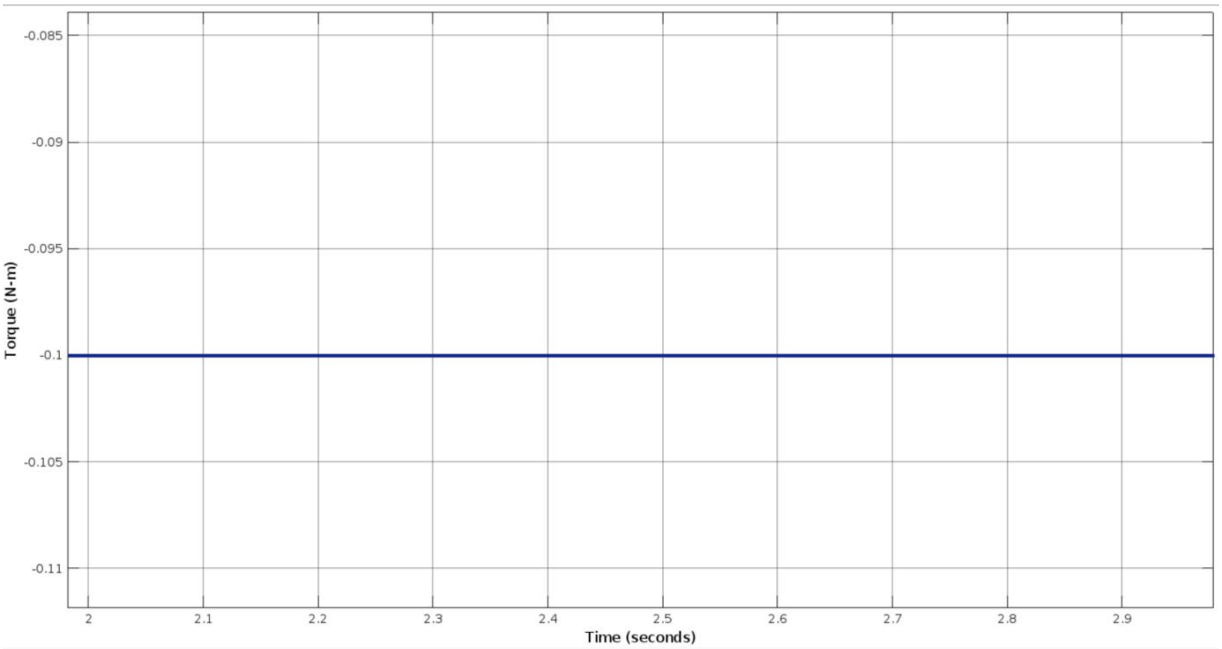

Figure 5.1 Mechanical Torque waveform before fault (Healthy Condition)

The nature of Line Voltage that is found from the Stator winding of the PMSG is shown below :

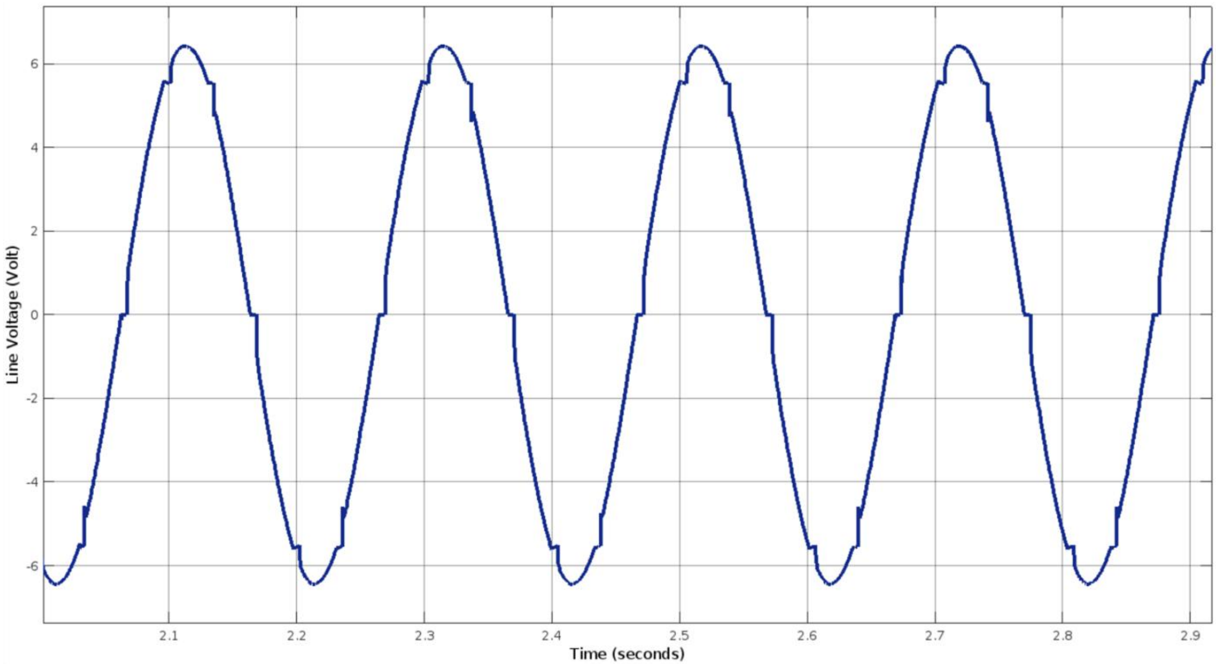

Figure 5.2 Line Voltage at the output of PMSG (Healthy Condition)

The nature of Phase Current that is found from the Stator winding of the PMSG is shown below :

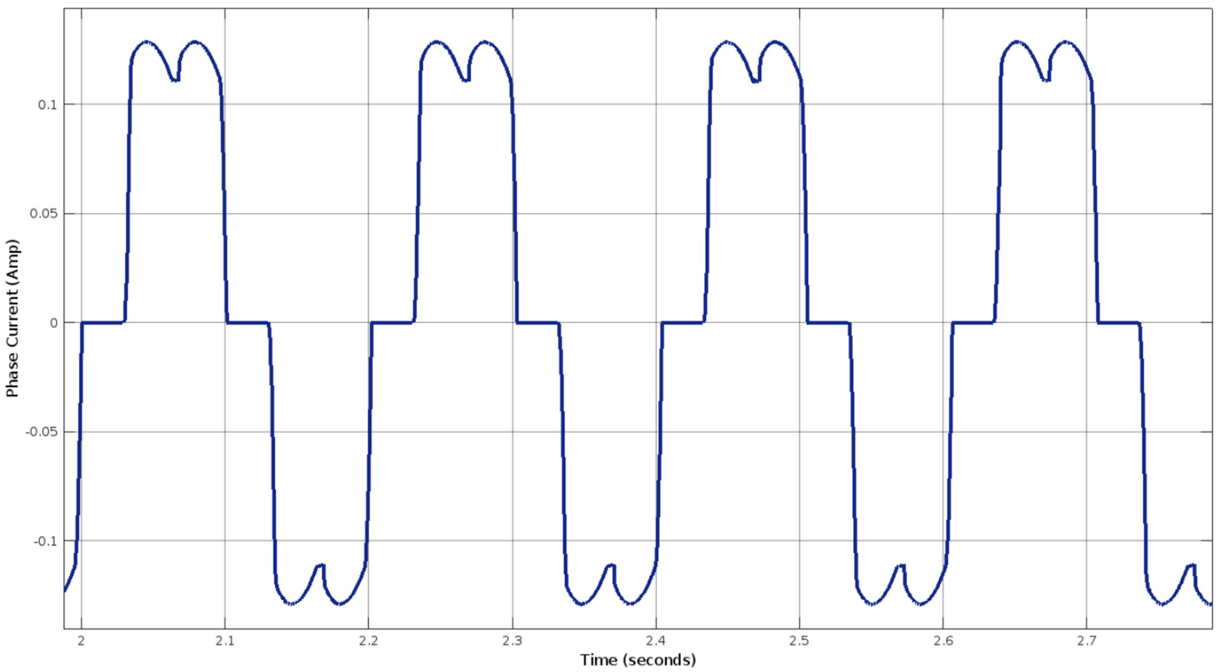

Figure 5.3   Phase Current at the output of PMSG (Healthy Condition)

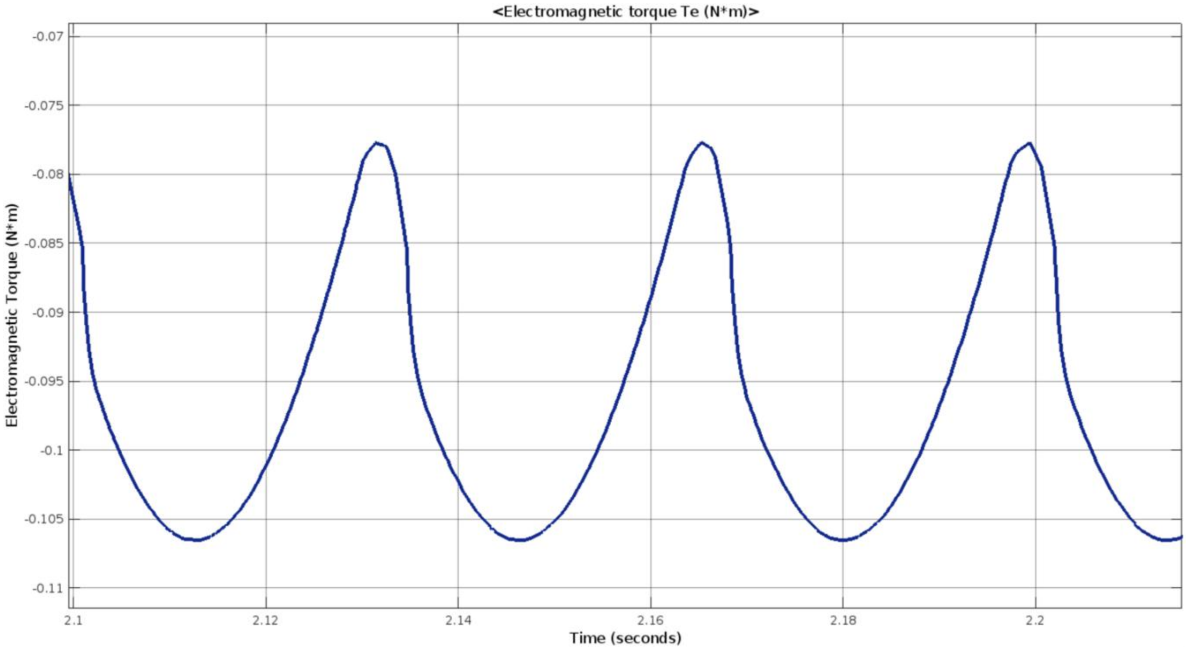

Figure 5.4 Electromagnetic Torque at the output of PMSG (Healthy Condition)

During Fault (Faulty Condition) :

When we consider the Bearing Fault, the Torque has now become Faulty Torque. If we closely observe the Faulty Torque waveform, we can see the torque waveform is not constant and steady anymore. In this simulation, we have considered fault signal starting after t = 2 sec. So, as a result, we can see that the resultant Faulty Torque has fault signatures starting from t = 2 sec. There are ripples present on the torque waveform starting from t = 2 sec.

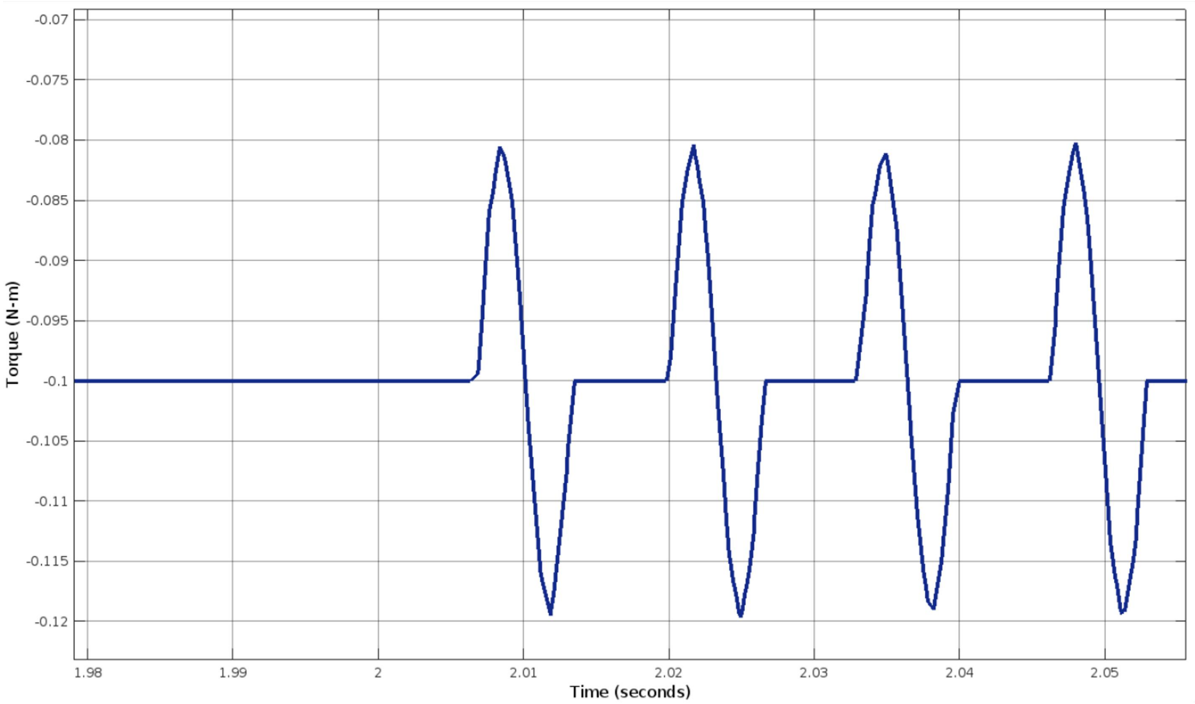

Figure 5.5 Mechanical Torque waveform during fault (Faulty Condition)

This faulty torque is used as the input of the PMSG. The output parameters from PMSG due to the fault are shown below. There are differences present between the Parameters for healthy condition and faulty condition, which will be discussed with detailed analysis in the next section.

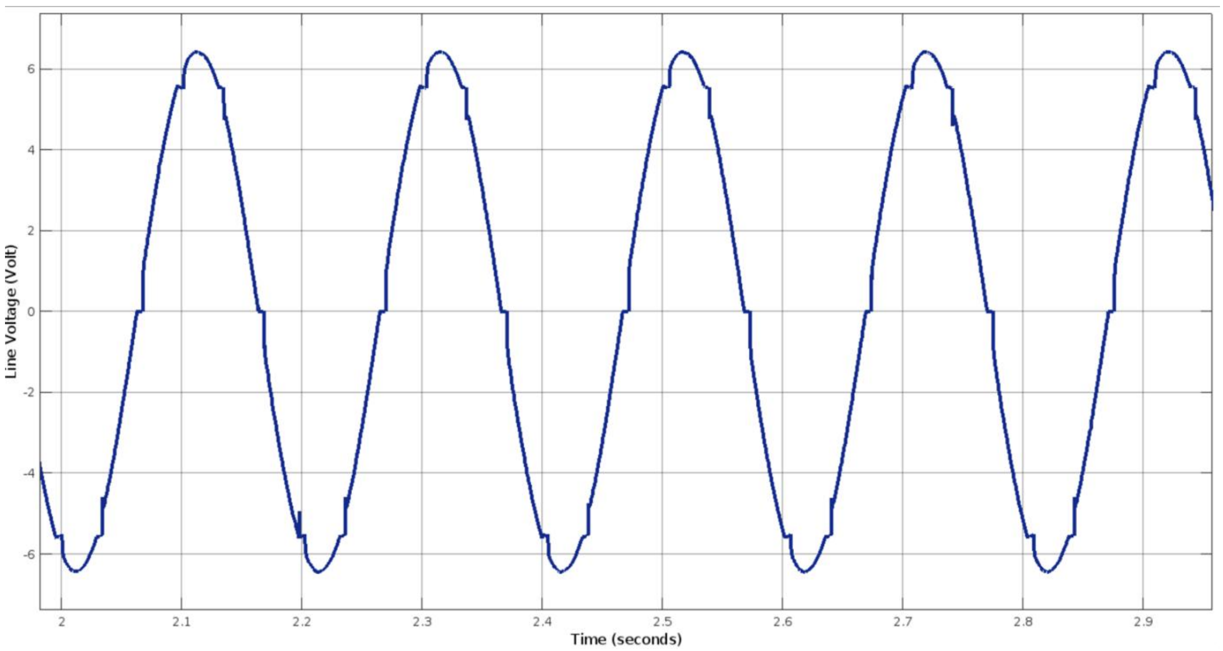

Figure 5.6 Line Voltage at the output of PMSG (Faulty Condition)

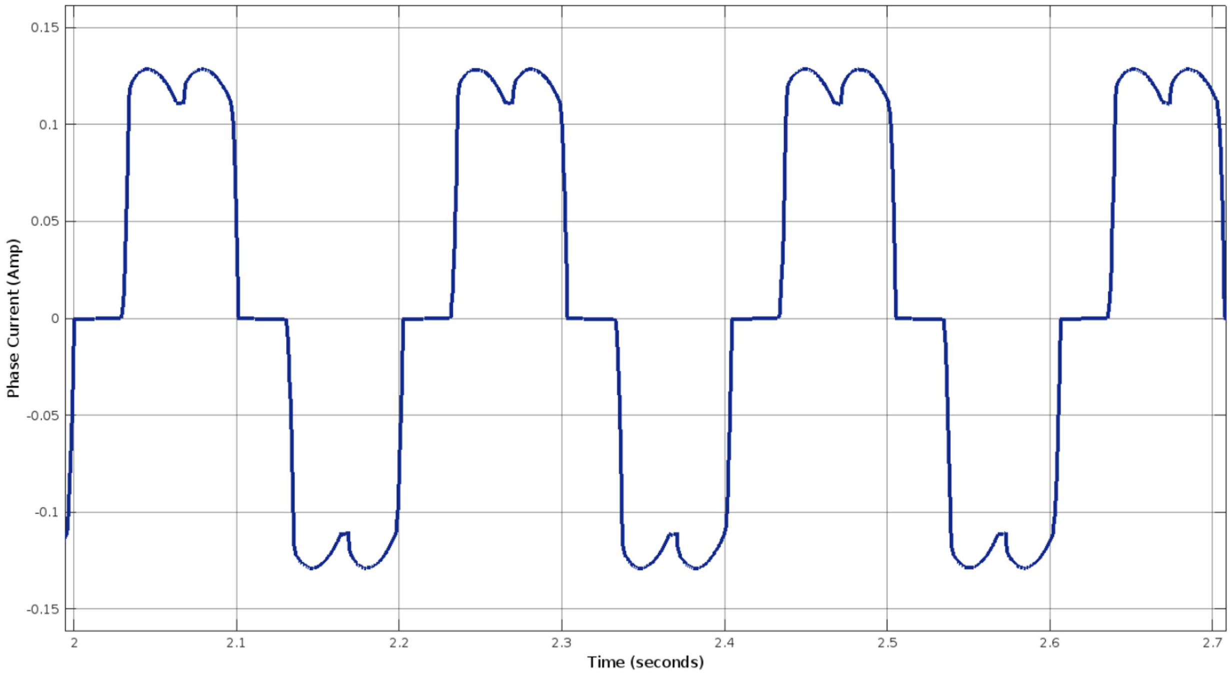

Figure 5.7 Phase Current at the output of PMSG (Faulty Condition)

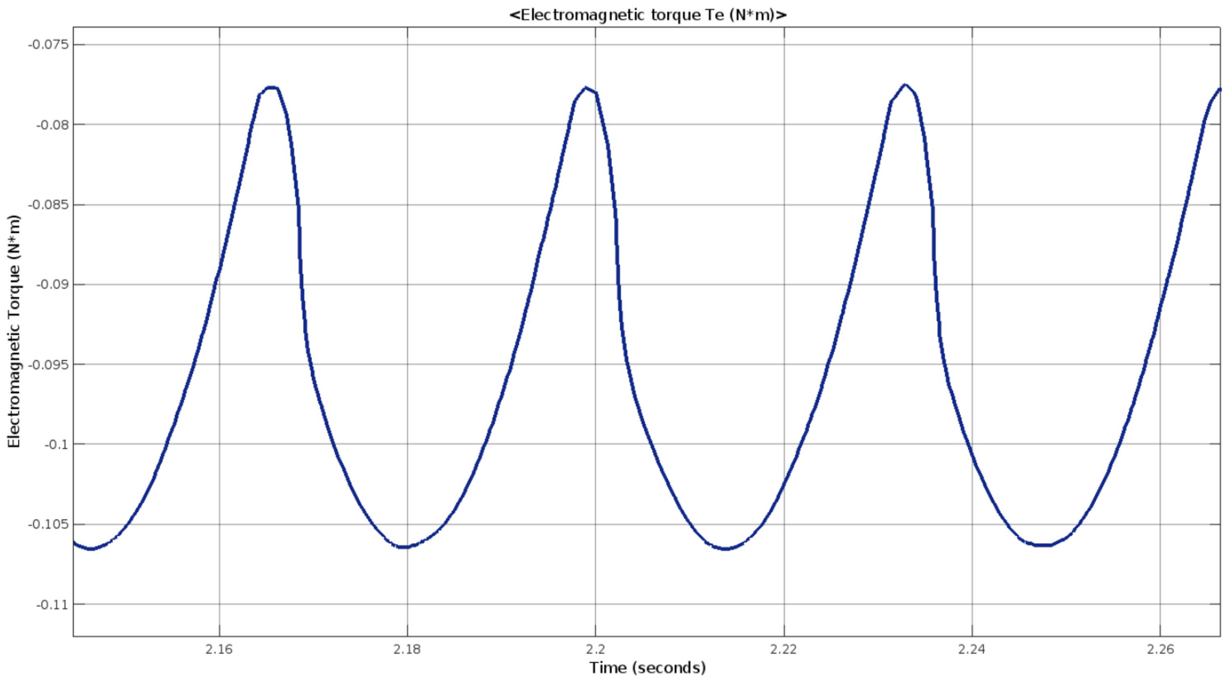

Figure 5.8 Electromagnetic Torque at the output of PMSG (Faulty Condition)

5.2 Detection of Fault

5.2.1 Detection of Fault with Mechanical torque analysis

From [12], we see the variation in torque due to the Bearing Fault follows a particular pattern. If we find that pattern in the Faulty Torque waveform, we can say that the Fault is possibly bearing fault in that case. We can analyze the Torque waveform with a special technique, Fast Fourier Transform (FFT) analysis. The FFT gives the frequency information about the signal by converting a signal into individual spectral components. So, it provides frequency information about the signal.

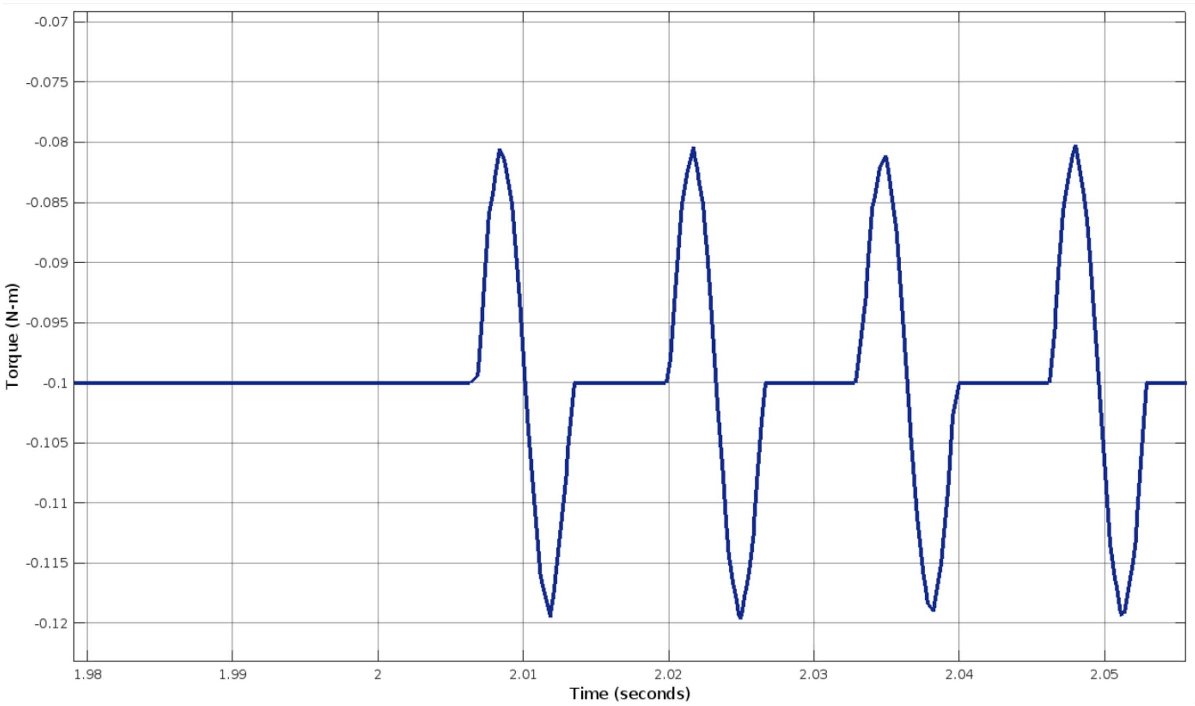

Figure 5.5 Mechanical Torque waveform during fault (Faulty Condition)

When we do the FFT analysis of the Faulty Torque waveform starting from t = 2 sec, it gives the frequency components of the Torque waveform and their respective amplitudes. If we observe the peaks and their respective frequency values, we find that the highest amplitude is present for the DC component (0 Hz). But here we look for only the AC components. We find here that the first peak has a frequency of 76 Hz. The next peak is at 152 Hz . The third frequency is 228 Hz. So the second and third frequencies (152 Hz and 228 Hz) are multiple of the first frequency (76 Hz). From this analysis, we take the 76 Hz frequency of the fist peak for further analysis.

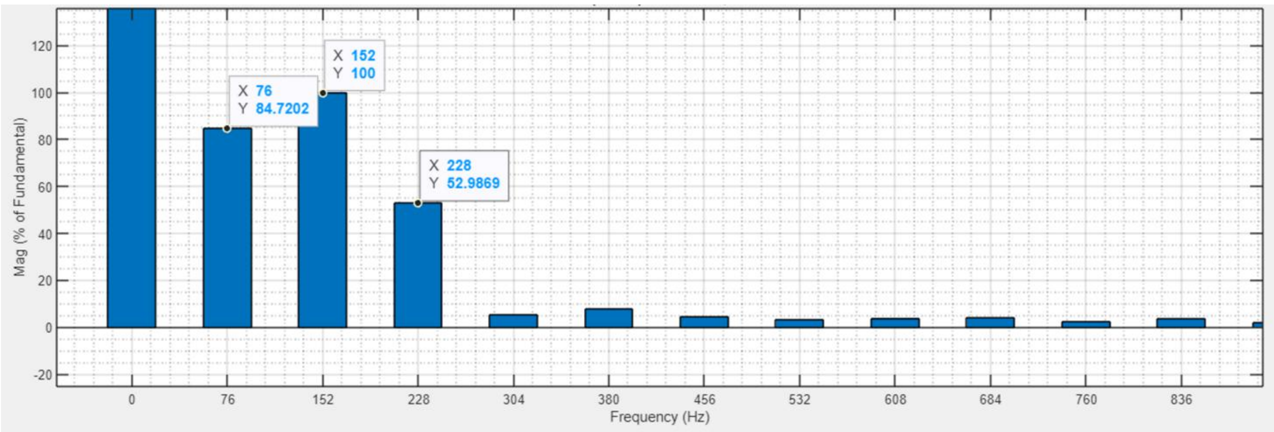

Figure 5.9 FFT of Torque waveform due to Bearing Fault

At the next step we use the frequency at the input of the Fuzzy System to analyze if the fault is Bearing fault.

As discussed earlier, we have taken a Bearing Fault signal at the input side of the PMSG. For the same bearing, we have also taken the data of all the possible frequency ranges of different types of faults related to that particular bearing. These values have been collected from the Bearing Manufacturer company [75].

Rolling Element Bearing Fault Frequencies (Hz)

1X - Machine Running Speed	25.000 Hz
BPFO - Ball Passing Frequency of Outer Race	76.750 Hz
BPFI - Ball Passing Frequency of Inner Race	123.250 Hz
FTF - Fundemental Train Frequency	9.500 Hz
BSF - Ball Sping Frequency	51.000 Hz

We have used these information to make the Fuzzy system. So, when the Fuzzy system takes the input as the frequency of faulty torque, found in the FFT analysis, it checks if that particular frequency is matching with any of the frequency ranges present in the database and based on this it takes the decision about the nature of the fault.

So here for this fault, we give 76 Hz as the input of the Fuzzy Logic system. The output indicates the fault is a Bearing Fault.

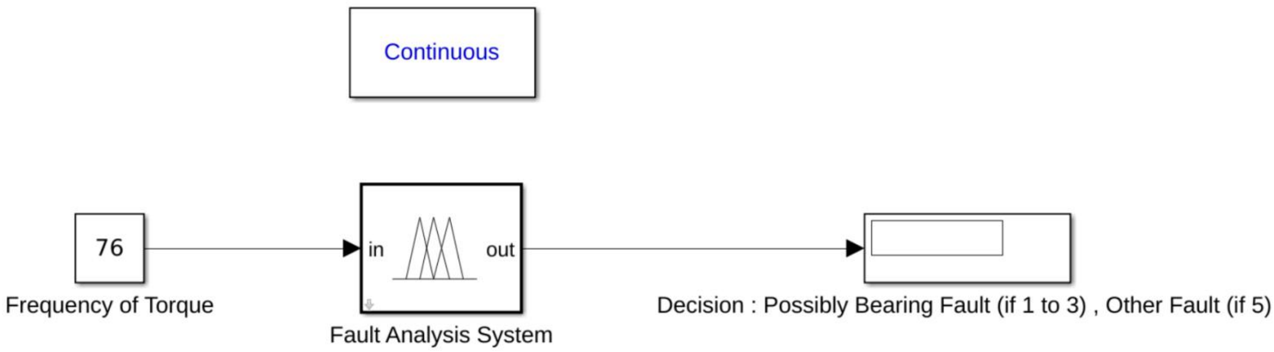

Figure 5.10 Fuzzy Logic System to detect Bearing Fault

5.2.2 Detection of Fault with Electromagnetic torque analysis

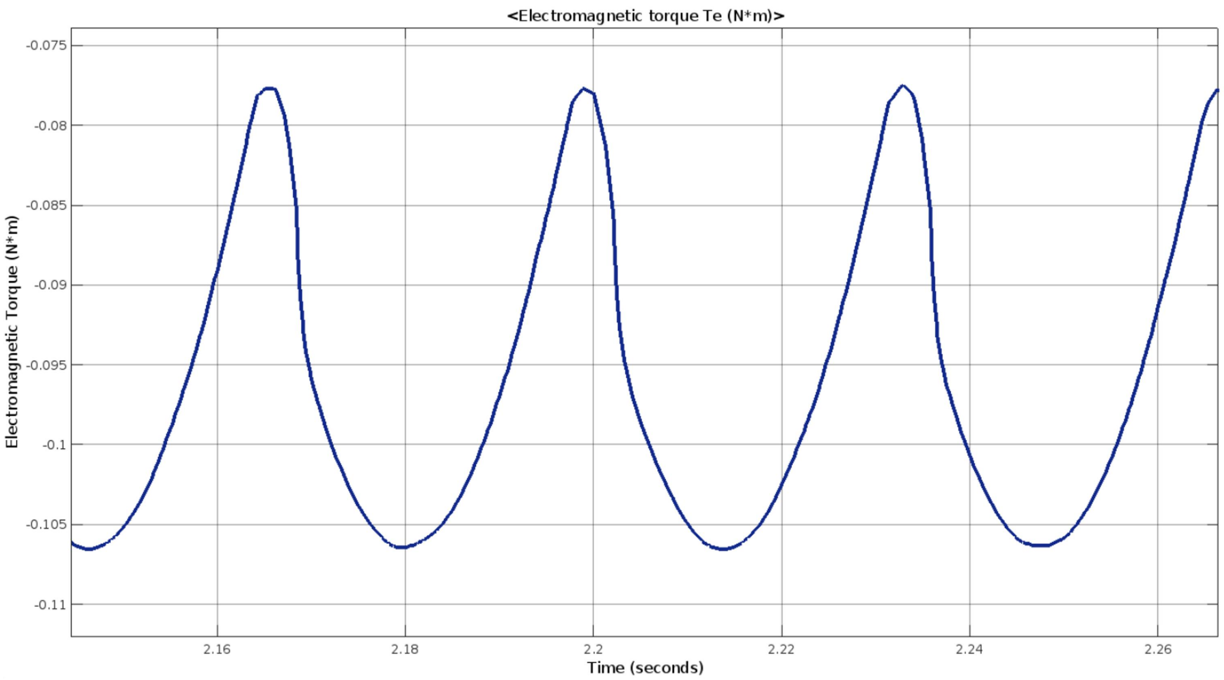

Figure 5.8 Electromagnetic Torque at the output of PMSG (Faulty Condition)

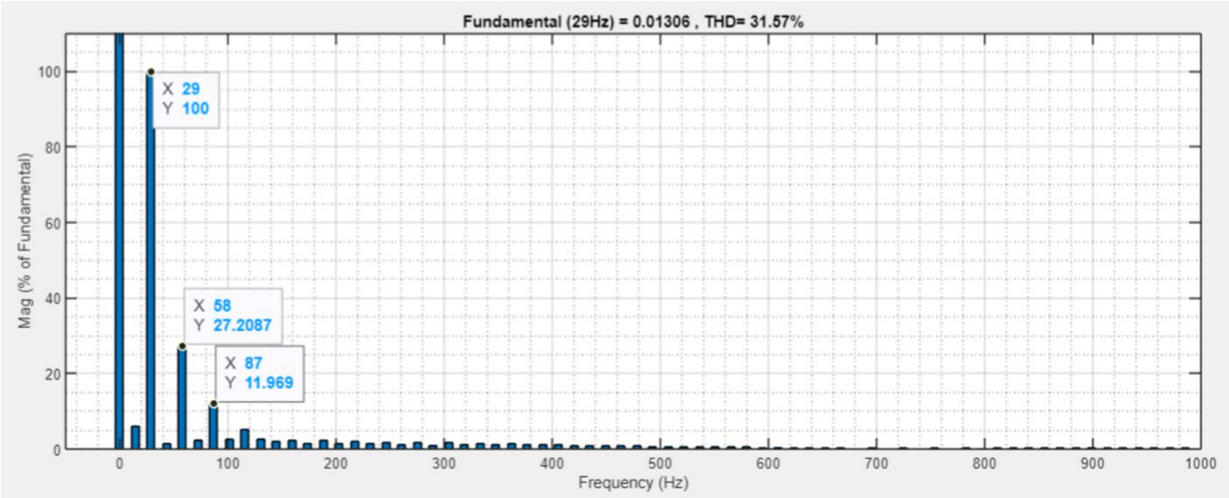

Figure 5.11 FFT analysis of Electromagnetic Torque at the output of PMSG (Faulty Condition)

When we do the FFT analysis of the Electromagnetic Torque waveform starting from t = 2 sec, it gives the frequency components of the Electromagnetic Torque waveform and their respective amplitudes. If we observe the peaks and their respective frequency values, we find that the highest amplitude is present for the DC component (0 Hz). But here we look for only the AC components. We find here that the first peak has a frequency of 29 Hz. The next peak is at 58 Hz . The third frequency is 87 Hz. So the second and third frequencies (58 Hz and 87 Hz) are multiple of the first frequency (29 Hz). It is one of the characteristics of Bearing Fault.

5.2.3 Detection of Fault with Thermal analysis

From the previous section, we can see the Phase Current at the output of PMSG for two different conditions : Healthy Condition and Faulty Condition. As we have already seen, the Mechanical torque is not constant and steady for Faulty Condition, rather it has ripples present on the steady waveform for the time duration of Bearing Fault. As a result, it also effects the thermal loss due to the Phase Current at the output of PMSG. We have analysed the thermal loss in both the cases with the help of FFT analysis of Phase Current at the output of PMSG.

Before Fault :

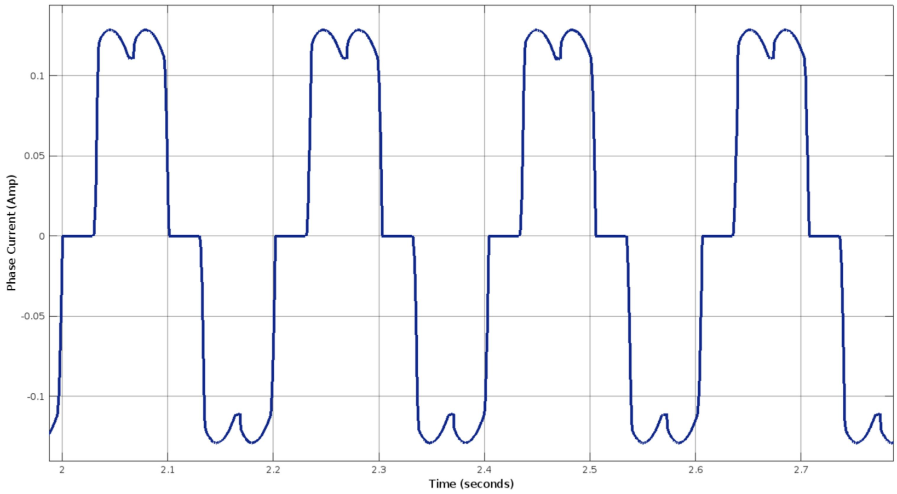

Figure 5.3 Phase Current at the output of PMSG (Healthy Condition)

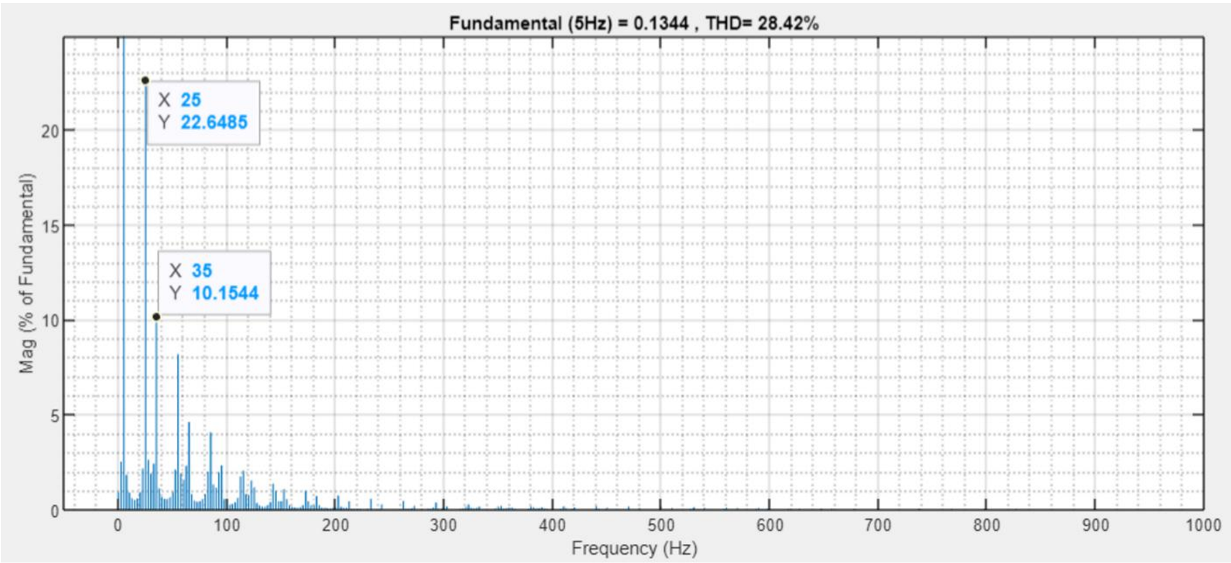

Figure 5.12 FFT of Phase Current at the output of PMSG (Healthy Condition)

From the following FFT analysis, we have observed all the frequency components and we have only considered the dominating components for heat loss calculation in the Thermal Analysis process.

Frequency components	Amplitude (% of Fundamental)	Amplitude (RMS)
5 Hz (Fundamental)	100 %	0.09506 A
25 Hz (5^{th} Harmonics)	22.65%	0.02153 A
35 Hz (7^{th} Harmonics)	10.15%	0.00964 A

Power Loss = $I^2 * R$ = (0.09506^2 + 0.02153^2 + 0.00964^2) * 0.00485 = 0.00004652 W

After Fault :

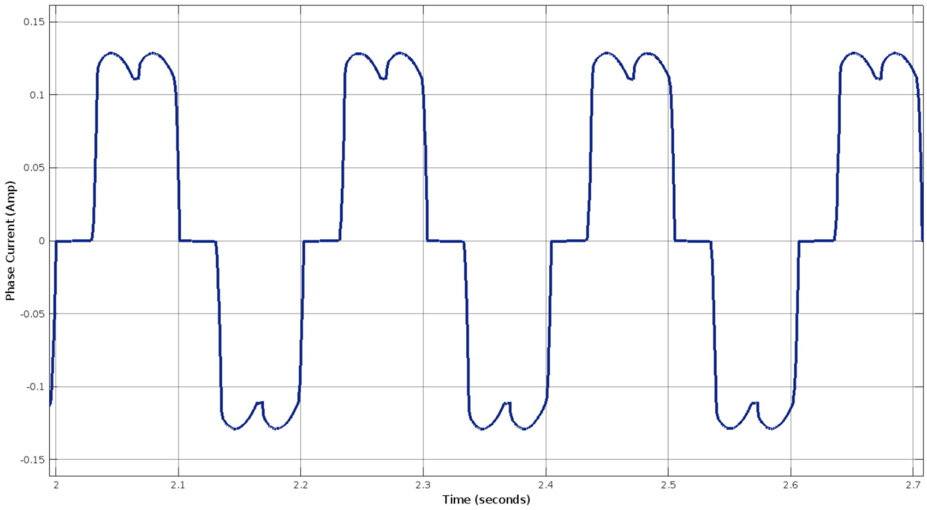

Figure 5.7 Phase Current at the output of PMSG (Faulty Condition)

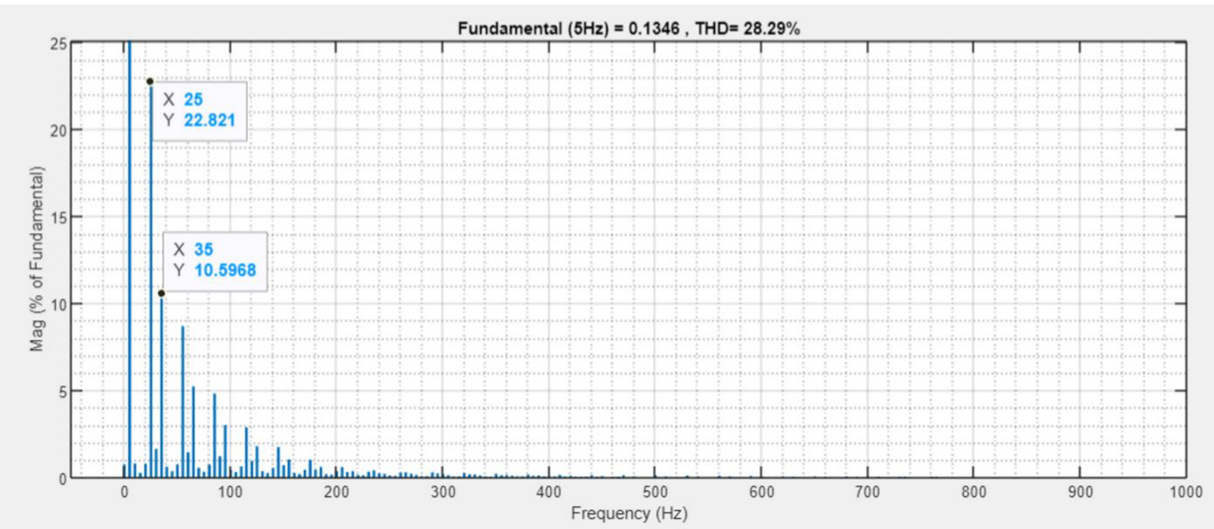

Figure 5.13 FFT of Phase Current at the output of PMSG (Faulty Condition)

From the following FFT analysis, we have observed all the frequency components and we have only considered the dominating components for heat loss calculation in the Thermal Analysis process.

Frequency components	**Amplitude (% of Fundamental)**	**Amplitude (RMS)**
5 Hz (Fundamental)	100 %	0.09519 A
25 Hz (5^{th} Harmonics)	22.82 %	0.02172 A
35 Hz (7^{th} Harmonics)	10.60 %	0.01009 A

Power Loss = I^2 * R = (0.09519^2 + 0.02172^2 + 0.01009^2) * 0.00485
= 0.00004672 W

Comparison and discussion :

The extra amount of Power loss after Bearing Fault = (0.00004672 - 0.00004652) W
= 0.0000002 W

The increment in Power loss = (0.0000002 / 0.00004652) * 100 = 0.42 %

In this simulation, we have worked with only about 0.09 Amp (RMS), which is very small value, but convenient for the simulation model. Practically, the phase current value can be hundred times or even thousand times of the present value. The power loss also increase with the square of the multiplication factor. That means if we just increase the value of current to 10 times (0.9 Amp), the Power loss increases 100 times (42 %), which is a high value and can be easily detected and analyzed further. So, per second Power loss, which implies the heat loss in this method, can be an approach to detect the Bearing Fault. The detection of heat can be done with various methods in practical scenario. Infrared Thermography is one of the very popular and widely used methods, where the thermographs can be acquired by a fixed thermographic camera to detect the increment in temperature in the Bearings .

5.3. Protection From Bearing Fault :

Previously we have discussed the nature of the bearing fault and the process of detecting the fault with the described analytical methods. After the fault is detected, the system is also needed to be protected from that condition and we need to stop the fault from growing more and becoming a larger fault in future. In this simulation, we have designed a system to detect the fault and isolate the fault as soon as possible.

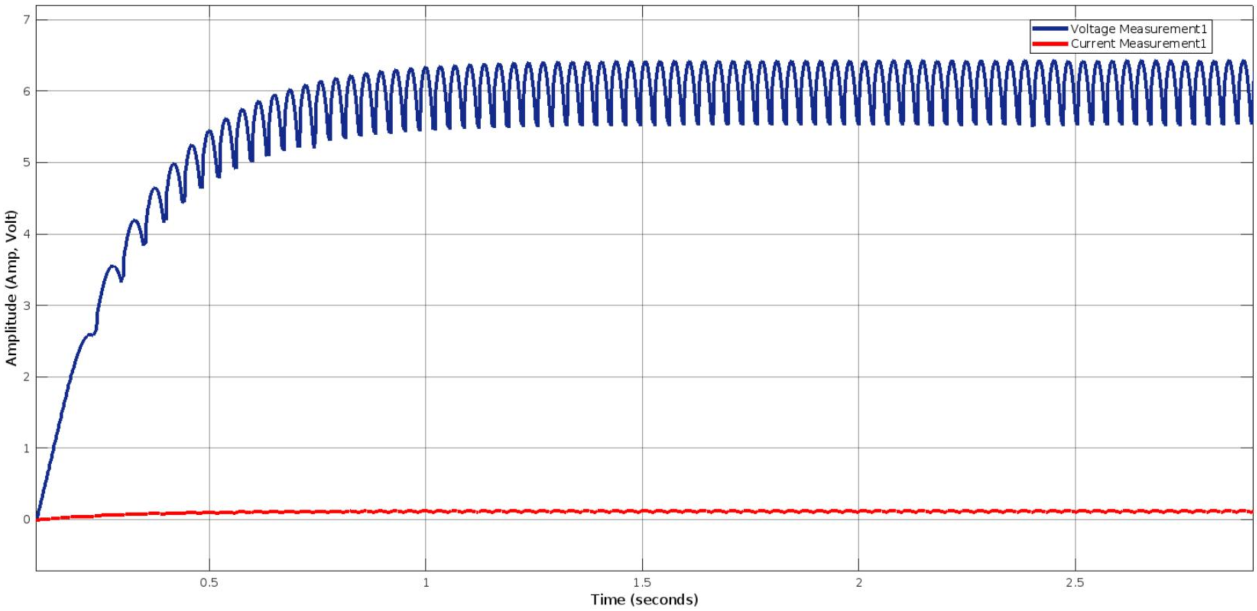

Figure 5.14 Output Voltage and Output Current before fault isolation

We have used a MATLAB Simulink block " Check Dynamic Upper Bound ", which checks if the reference signal, max, is greater than the input signal, at each step of time and disconnects the system after comparison. We have given the Faulty Torque as the input signal to the block and also set the reference signal as the maximum upper limit of Torque value, that is permissible according to our need. The system detects the first moment when the Faulty Torque exceeds the permissible upper limit of torque. At this moment the system gives a warning of the fault and disconnects the system. This prevents the fault to grow more and prevents from larger damage in the whole system.

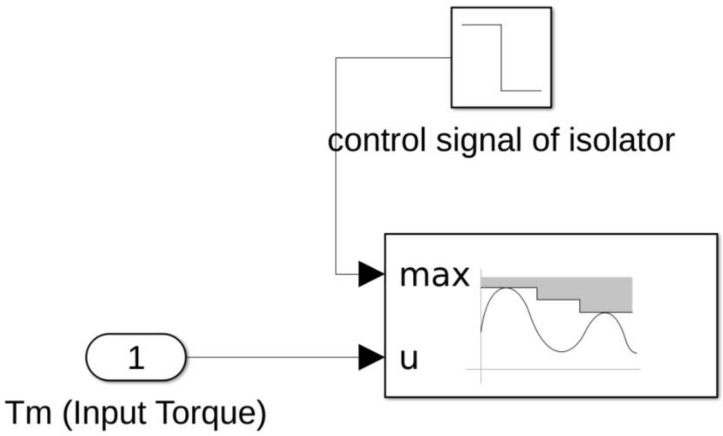

Figure 4.11 Components for Fault Detection and Isolation system.

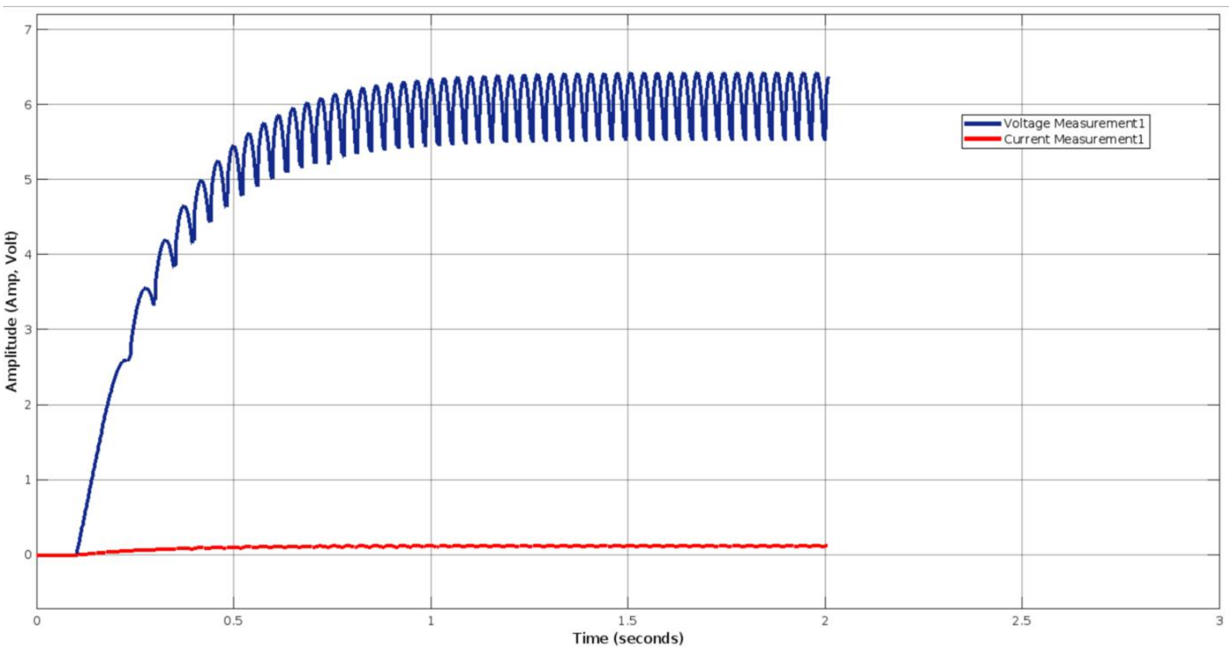

Figure 5.15 Output Voltage and Output Current after fault isolation

Chapter 6

Conclusion and Future Scope

6.1 Conclusion :

As we have discussed earlier, there are several methods available for analysis of Bearing Fault in the system. The most recent widely used methods are analysis of stator current in fault condition and Vibration Signal analysis method. But, there are some disadvantages and limitations in thiese methods :

- Current-frequency and current-amplitude-demodulated signals have been proposed to be used for bearing fault diagnosis of PMSG wind turbines. However, during the operation of WTG with a variable 1P frequency (shaft rotating frequency of a wind turbine the bearing fault) characteristic frequencies of the current demodulated signals are not found as constant. Therefore, the signatures of bearing faults due to the characteristic frequencies may be interfered by the components which are created by variable Wind Turbine Generator rotating speed in the current-demodulated signals. It becomes nearly impossible to extract that directly with PSD analysis which is traditionally used.
- In the traditional method, various steps are involved for the analysis, like Frequency Demodulation, Amplitude Demodulation, 1P frequency estimation, Interpolation, Variable-Rate Down Sampling, PSD analysis etc. So, it is clear that the process is very complex and time taking in the computational aspect.
- Another important approach is Vibration Signal analysis. Though the structure of the main shaft of a wind turbine is comparatively simple, but practically in operation, the vibration signal contains complex frequency components. So it becomes very difficult to accurately identify the fault only with time-domain and frequency-domain analysis.

In this thesis, we have focused on detection of the Bearing Fault based on the Mechanical Torque analysis, Electromagnetic Torque analysis and Thermal analysis. When the bearing fault is not present, the Healthy Torque waveform can be found. But, when there is a Bearing Fault present in the system, the torque waveform becomes Faulty Torque Waveform, which is different from the former waveform. The faulty torque waveform generally has additional ripples compared to healthy steady torque waveform, which can be seen. When the Bearing Fault is in its very early stage, the ripples are very small and hard to detect with any detection mechanism. The greater the Bearing Fault, the more the amplitude of the ripples can be found. At the output side of the Generator, voltage waveform and current waveform can be found with more harmonics as the Bearing Fault increases. If we properly analyze the Faulty Torque due to the bearing fault, we can say at a very early stage, the variation in torque waveform is within the range of 1% to 5% . At this stage the detection of faults is very difficult. The pattern of the ripples present in the Faulty torque waveform can be analyzed properly to identify if the Fault is a Bearing Fault. Certainly, in case of Bearing Fault, the ripples have a repetitive pattern and that also in a particular frequency. A standard Bearing model also has a certain range of frequencies for different types of Bearing Fault, which can be found either directly from the manufacturer or can be calculated with the Bearing specifications, which helps to detect the Bearing Fault. The next approach is Electromagnetic Torque analysis. We have already seen that the Electromagnetic Torque changes with the change in Mechanical Torque waveform. So, the occurrence of fault changes the Mechanical Torque as well as the Electromagnetic Torque. We have already seen that the analysis of Electromagnetic Torque can be observed to find a particular repetitive pattern which indicates the occurrence of Bearing Fault. The Thermal analysis additionally helps to identify the extra temperature increment in the system due to Bearing Fault and reinforce the decision making process in this case.

There are certain advantages in this method compared to the previously mentioned traditional methods :

- The Torque analysis method is a comparatively simple process and also less time consuming approach.
- The computational aspect such as Algorithmic complexity, number of intermediate steps are less compared to other methods, which saves time and reduce error.
- At the input stage, the variation in Torque can be easily detected with less complex analysis as compared to Current Signal analysis at the output terminal.
- Torque waveform analysis is comparatively a new approach in case of PMSG based Wind Turbine System. There is a possibility to make this approach more advantageous with the application of AI, Machine Learning and the Neuro-Fuzzy system with this method in future.

6.2 Future Scope :

- The Fuzzy Logic System can be improved with more input parameters with their respective information. Greater information improve the design of Fuzzy Logic. As a result, better outcomes can be found.
- We can incorporate Machine Learning Techniques in the Fault Detection and Classification process for better result.
- We can also consider the other analytical methods, like Output Current waveform analysis, Vibrational analysis, in parallel with the methods used in this thesis for improved result.
- Infrared Thermography can be included to get better result, where the thermographs can be acquired by a fixed thermographic camera to detect the increment in temperature in the Bearings .
- Adaptive Neuro-Fuzzy Inference System (ANFIS) is a modern approach, which helps to combine the good qualities of both the constituting individual methods and helps to achieve better fault diagnosis performances.

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