Modeling, Simulation, and Forecasting of Wind Power Plants in Pakistan using Agent-Based Approach

By

MaheMobeen
00000172623

Supervisor

Dr. Imran Mahmood

Department of Computing

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Electrical Engineering

Approval

It is certified that the contents and form of the thesis entitled "Modeling, Simulation, and Forecasting of Wind Power Plants in Pakistan using Agent-Based Approach" submitted by MaheMobeen has been found satisfactory for the requirement of the degree.

.

Advisor: Dr. Imran Mahmood

Signature: ____________________

Date: ____________________

Committee Member 1:

Dr. Asad Waqar Malik

Signature: ____________________

Date: ____________________

Committee Member 2:

Dr. Shahzad Younis

Signature: ____________________

Date: ____________________

Committee Member 3:

Dr. Fahad Javed

Signature: ____________________

Date: ____________________

THESIS ACCEPTANCE CERTIFICATE

Certified that final copy of MS/MPhil thesis written by Ms. MaheMobeen, (Registration No 172623), of School of Electrical Engineering and Computer Science (SEECS) (School/College/Institute) has been vetted by undersigned, found complete in all respects as per NUST Statutes/Regulations, is free of plagiarism, errors and mistakes and is accepted as partial fulfillment for award of MS/M Phil degree. It is further certified that necessary amendments as pointed out by GEC members of the scholar have also been incorporated in the said thesis.

Signature: ________________________

Name of Supervisor: Dr. Imran Mahmood

Date: __________________________

Signature (HOD): ________________

Date: ___________________________

Signature (Dean/Principal): _________

Date: ___________________________

Certificate of Originality

I hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, nor material which to a substantial extent has been accepted for the award of any degree or diploma at NUST SEECS or at any other educational institute, except where due acknowledgement has been made in the thesis. Any contribution made to the research by others, with whom I have worked at NUST SEECS or elsewhere, is explicitly acknowledged in the thesis. I also declare that the intellectual content of this thesis is the product of my own work, except for the assistance from others in the project's design and conception or in style, presentation and linguistics which has been acknowledged.

Author Name: MaheMobeen

Signature: ____________________

Acknowledgment

I thank Allah for giving me the strength to make this little effort reach fruition and for constant reminder that His plans are better than my dreams.

I am greatly obliged to my family for their unconditional love, continuous support, encouragement and prayers in all my endeavors. My deepest gratitude to my parents for bringing the confidence in me to reach for the stars and chase my dreams.

I am grateful to my Supervisor, Dr. Imran Mahmood for his patient guidance, encouragement and advice to complete my thesis and for giving me numerous opportunities to learn and grow.

I am thankful to Dr. Asad Waqar Malik, Dr. Shahzad Younis and Dr. Fahad Javed for being on my thesis guidance and evaluation committee.

I appreciate contribution of Brig. Fareed for providing me with required data of FWEL to validate my simulation results.

I am overwhelmed to acknowledge my depth to all those who have helped me to put these ideas into something concrete, specially my lab members.

Last, but not the least, I thank my all friends for making NUST a home.

Table of Contents

List of Abbreviation

ABM	Agent-Based Modeling
AEDB	Alternate Energy Development Board
Beta (β)	Pitch Angle
Cp	Power Coefficient
DFIM	Doubly Fed Induction Machine
DFIG	Doubly Fed Induction Generator
FWEL	Foundation Wind Energy Limited
HAWT	Horizontal Axis Wind Turbine
IPPs	Individual Power Plants
M&S	Modeling and Simulation
PCRET	Pakistan Council of Renewable Energy Technologies
PITC	Power Information Technology Company
P	Power
P_s	Stator's Power
P_r	Rotor's Power
TSR (λ)	Tip Speed Ratio
u	Voltage
VAWT	Vertical Axis Wind Turbine
WPP	Wind Power Plant
WTS	Wind Turbine System

List of Tables

List of Figures

Abstract

National economy and growth relies heavily on electricity but unfortunately, rapid growth and urbanization with ever-growing inhabitants has caused severe energy crisis in Pakistan. Major portion of electricity generation in Pakistan is carried out using fossil fuels regardless of the fact that it is a country with abundant renewable resources. Electricity generation projects that use renewable energy resources have been established in Pakistan and many are under construction to overcome energy crisis in country. In order to meet long-term targets for a sustainable, efficient, affordable and low carbon energy system, a detailed descriptive study of the dynamics of energy generation and consumption at a country scale is inevitably necessary.

We proposed modeling and simulation of wind power plant in Pakistan to forecast energy generation in a cost effective and productive manner. We develop a dynamic model of wind power plant and simulate short term and long-term energy generation profiles. Agent based approach is used to implement and simulate wind power plant. Agent based modeling focuses on the individual active components of the system. In agent-based simulation, active entities of wind power plant, known as agents, are identified and their behavior is defined. These entities include Turbine's rotor, Drive Train, Generator and Anemometer. Our model is validated on Nordex N100/2500 turbine specification and the historical generation of wind farm at Gharo, Sindh.

A correctly implemented and validated power plant model can be (re)used as a component agent in an integrated Power Generation and Consumption framework and thus aid in realistic analysis of the future dynamics of electricity demand and supply.

Keywords: *Wind Power Plant, Horizontal Axis Wind Turbine, Vertical Axis Wind Turbine, Doubly Fed Induction Generator, Doubly Fed Induction Machine, Tip Speed Ratio, Power Coefficient, Pitch Angle*

Chapter 1

Introduction

This chapter provides the opening and general information of the research to provide a clear understanding about this thesis. It also covers the problem statement along with solution statement.

Pakistan is a country where rapid growth and urbanization have led severe energy crisis in the country since decade. Due to urbanization, load shedding and energy shortage have been a routine in an era where every day activities depend heavily on electricity. Major reason behind energy shortage is that grids are located far away and inefficient power transmission causes line losses and is the most threatening sign of the energy crisis in Pakistan [1][2]. Pakistan focuses on energy generation through fossil fuels whereas reservoirs of fossil fuels are depleting quite quickly and fails to meet electricity demand as well. The extended demand-supply gap and depleting fossil fuels' reservoir with environmental hazards need to change our electricity generation methods.

Renewable energy can play a substantial part in this scenario given the solar irradiance and wind corridors available in Pakistan. This will help Pakistan to face challenges of high-energy demand and will aid to sustain economic growth and development.

For renewable integration, understanding of the existing system is necessary to define new strategies and policies. In order to meet the demand of electrical energy, and to deal with various reservations and incompetence involved in this process, development of sustainable policies through proper planning is becoming highly desirable, yet increasingly challenging. It is necessary to get hands on dynamics of energy generation and consumption at a country scale to meet long-term targets for a sustainable, efficient and affordable systems.

Energy system modeling serves as basis for making strategic decisions where the dynamics of the energy system are evaluated by using empirical datasets and through the simulation of energy generation, transmission and consumption processes. The need for such a system is magnified when considering renewable energy resources with spatio-temporal variations. It is therefore desirable to deploy a dynamic electricity demand and supply model to investigate the structural and behavioral dynamics of the energy inside of the component. Therefore, third party can easily use it without knowing the inner detail of components.

1.1 Challenge

Traditional techniques to generate electricity in Pakistan is by fossil fuels, which is resulting in depletion of fossil fuel reservoirs, also resulting in environmental hazards. Besides this, electricity generation is carried out in an expensive manner, addition to this is the fact that the demand and supply gap is increasing. Therefore, it is necessary to move forward to techniques that are environmental friendly, cheap and can meet demand and supply gap. Renewable energy resources gives the best solution to this problem and produces slight or no global warming emissions. Before switching onto renewable energy resources, great confidence should already be built on them, as this would require change in generation methodologies as well.

1.2 Problem Statement

Pakistan is a country where electricity demand and supply gap is increasing to an extent where black and brown out is a routine. This energy crisis led the need to predict energy potential through Renewable Energy Resources as Pakistan is a country with plenty of solar irradiance and wind corridors. Modeling, simulation and forecasting of energy generation potential in Pakistan through Wind Energy Resources will help energy planners, energy suppliers and strategy makers to take into account electrical energy that can be produced by wind's mechanical energy. This will help to bring a decrease in demand and supply gap, as this has been unresolved and is a challenging task ever since.

1.3 Solution Statement

We propose simulation model of Wind Turbine System for generation of electricity through wind's mechanical energy. It forecasts energy generation at different wind speeds at different instance of time. This forecast of long term and short-term energy generation profile can be used in a productive manner to aid in realistic analysis of the future dynamics of electricity demand and supply.

1.4 Key Contributions

Pakistan being a developing country need to adopt the trends of urbanization as it improves the living standards in terms of health, education, economy and other life activities. Pakistan is a country where renewable energy resources like biomass, wind energy, solar energy, hydro etc. are abundant and can be utilized to overcome the current shortfall of electricity. This will not only eliminate black and brown out from the country but also help to raise economy by providing employability to more people and will be eco-friendly. Older techniques used to generate electricity in Pakistan have so many environmental hazards that can be avoided by the usage of renewable energy resources, as they are associated with no air pollution emissions and has a little or no global warming emissions. Renewable energy can help in providing reasonable electricity prices across the country and can stabilize energy rates in future as well. This has been suggested that wind and solar plants are less prone to failures as these plants are modular and distributed.

1.5 Research Impact

Our proposed framework analyzes the role of Wind Energy for electricity production in Pakistan. This will help Decision Makers to get an estimate of how much total Electrical Energy can be produced using wind potential available at wind corridors of Pakistan. This is component based modeling of wind power plant that will allow the use of different combinations to derive the appropriate combination for futuristic purpose.

1.6 Related Industry

Our proposed framework provides appropriate solution to both private and governmental organizations that involve in energy planning, supplying and policymaking. They include:

- Alternate Energy Development Board (AEDB)
- Pakistan Council of Renewable Energy Technologies (PCRET)

1.7 Model of Study

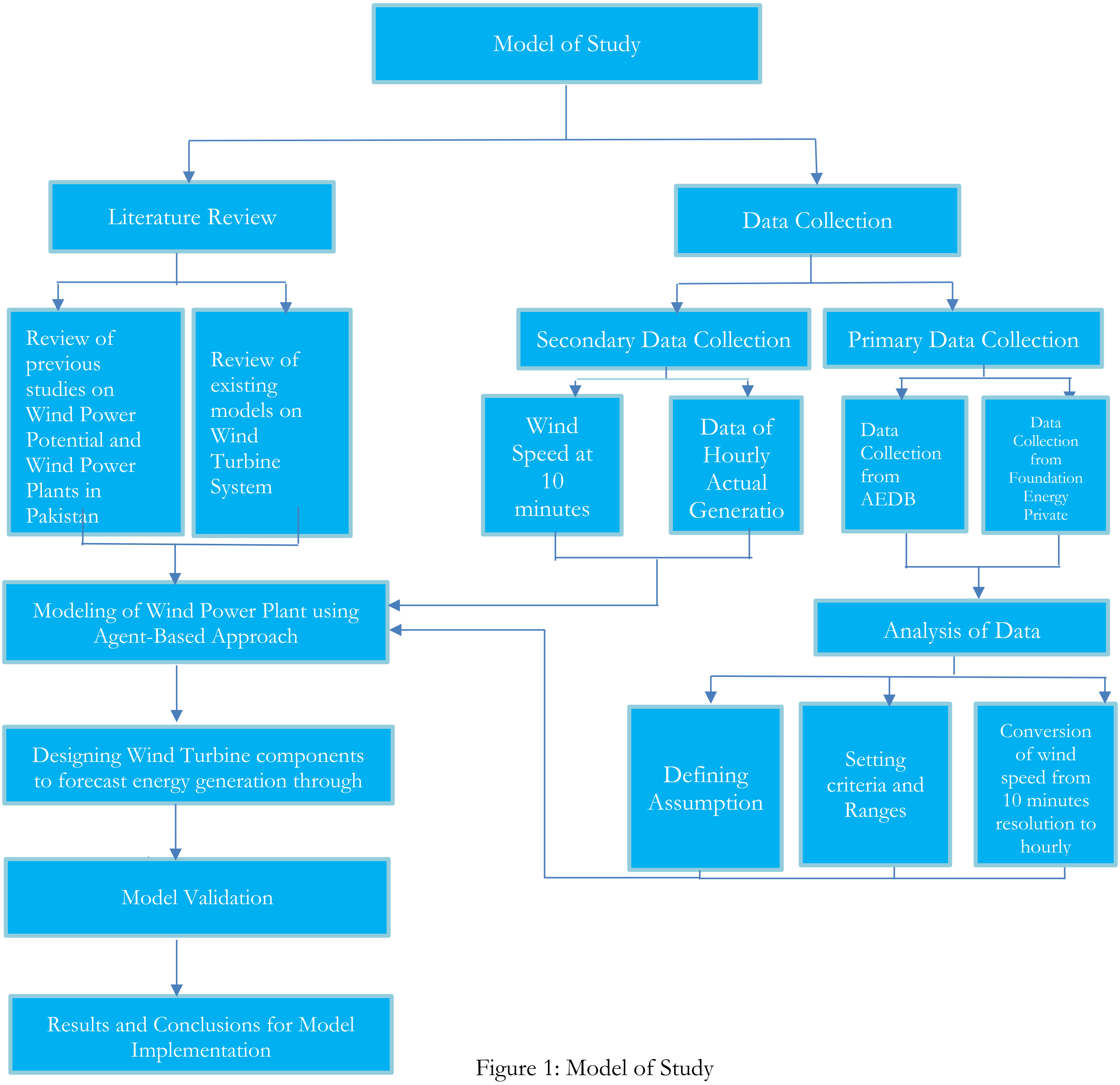

Figure 1: Model of Study

1.8 Thesis Organization

Rest of the thesis is organized in following chapters

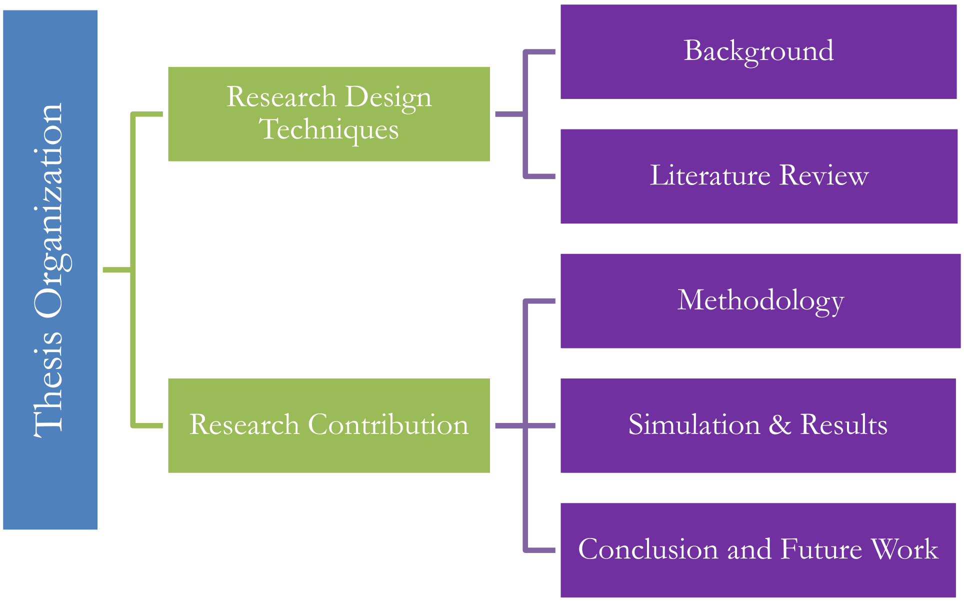

Figure 2: Thesis Organization

1.8.1 Chapter 2: Background

Chapter 2 provides brief overview of Renewable Energy Resources, its types and advantages. This chapter also explains Wind power potential at wind corridors in Pakistan. Moreover, few preliminary concepts, used in methodology chapter are discussed as well.

1.8.2 Chapter 3: Literature

This chapter explains the work done so far related to wind power plants, its component and verification of model. It summarizes the hierarchal approaches of model component and model composability and formulates research directions for this dissertation.

1.8.3 Chapter 4: Methodology

Modeling and simulation of proposed Wind Power Plant is carried out in AnyLogic Software. Brief introduction to the software is provided in this section along with detailed explanation of proposed model and its component. The model is validated on Nordex N100/2500 turbine specification and the historical generation of wind farm at Gharo, Sind.

1.8.4 Chapter 5: Verification of Wind Power Plant

This chapter is dedicated to demonstration of the functionality of our proposed framework taking into account the graphs and energy generation record of wind farm at Jhimpir. The chapter is concluded by results and their detailed discussion.

1.8.5 Chapter 6: Conclusion and Future work

Brief description of my thesis research work is presented in this section provided with tasks that can be carried out later for further research studies.

Chapter 2

Background

This chapter provides a brief overview of Renewable Energy Resources, its types and Wind power potential at wind corridors in Pakistan. It also includes a brief discussion on Wind Turbine System.

2.1 Renewable Energy

Renewable energy resource is a resource that occurs naturally and replenishes over a period to avoid resource extinction. Renewable energy resource is a part of our environment thus replenishes by either biological reproduction or naturally recurrent processes. Renewable energy resource is available in almost every geographical region unlike other resources that are concentrated in some regions. Usage of electricity is our routine now. Our everyday activities rely heavily on electricity and most of the electrical energy is produced through fossil fuels like coal and natural gas that is non-renewable energy resources that do not replenish over a period of time and hence, depleting.

Figure 3: Renewable Energy

2.1.1 Types of Renewable Energy Resources

Our environment contains variety of renewable energy resources and each can contribute vitally in energy generation. Brief overview of different types of renewable resources is listed below.

- **Hydropower**

Water has a potential to generate electricity. Even a small stream of water can help to generate electricity unlike other renewable energy resources.


Figure 4: HydroPower

- **Solar Energy**

Solar energy can be utilized using photovoltaic systems that convert light into electrical energy. This technique is widely used in countries to generate electricity at domestic and industrial level.

Figure 5: Solar Energy

- **Geothermal Energy**

Geothermal energy is extracted from the thermal energy of earth produced by the foundation of planets or radioactive degeneration of minerals. This thermal energy of earth can be converted into electrical energy [3].

Figure 6: Geothermal Energy

- **Bioenergy**

This is the form of renewable energy resource produced by living things. It is either produced by biomass or biofuels. They are used to generate heat and later heat energy is converted into electrical energy.

Figure 7: Bioenergy

- **Wind Energy**

Wind has the potential to produce electrical power. Mechanical energy obtained through wind power plant can be converted into electrical energy.

Figure 8: Wind Energy

2.1.2 Why Renewable Energy Resource

Fossil fuel in not an environmental friendly source to produce electricity, the basic problem with the fossil fuels is that they cause lot of impacts on the environment by consuming primary fuel to convert it into electricity. It may occur mostly due to the toxic emissions that are produced during the operations of plant and causes adverse health effects as well. The major gases produced includes oxides of sulfur and nitrogen as well as carbon dioxide [4]. According to Economic assessment of energy generating systems, it has been revealed that the cost associated with power generation plants includes cost of development, capital cost, operations, initial investment and fuel cost. There is a need to reduce the cost on operations, investments and have less maintenance rate in order to reduce cost of operation for the long run to have minimum environmental consequences [5].

Secondly, to keep up with the pace of growth rates of demand of electric power, the energy supply must be increased to fulfill the demand of population. The high cost of supply of electricity contributes to increased cost of electricity generation and huge investments for transmission and distribution through centralized grid system. This centralized system mainly works with fossil fuel energy systems and extensive distant distribution of electricity to remote areas result in energy loss in long grid. Grid-connected energy system operate on low cost and scales both in presence and absence of grid with more accessibility to remote locations. It is a reliable and environmentally friendly and sustainable approach for distribution of electricity [6].

At the time, Pakistan got its autonomy in 1947; the aggregated power generation was about 60 MW for a population of 31.5 million that makes up 4.5 units/shopper. Even than, this amount of generation was unable to satisfy the prerequisites of the buyers. There were only two electric service organizations in Pakistan before 1998; one was Karachi Electric Supply Company (KESC) in Karachi and another was Water and Power Development Authority (WAPDA) that served whatever remains of the nation.

Thereafter, WAPDA was rebuilt, keeping in mind the end goal to separate business elements, which constitute four generation organizations (GENCOs), eleven conveyance organizations (DISCOS) and one transmission organization National Transmission Dispatch Company (NTDC). Exchange Energy Development Board (AEDB) and Pakistan Council of Renewable Energy Technologies (PCRET) are two fundamental divisions built up in the legislature of Pakistan. The former provides institutional support and creates Renewable Energy strategies and stimulate arrangements of renewable energy ventures in Pakistan while the latter conducts research and development exercises, generate pilot ventures for exhibition purposes and prepare human asset with the goal that they can work and keep up RE based tasks [7].

2.2 Why utilization of Wind Energy in Pakistan

Thermal plants contribute for about 50% of the energy in Pakistan that consist of oil based, coal based and petroleum based power plants. Second, largest source of energy in Pakistan is hydel energy. Tarbela dam has the largest electricity production in Pakistan. Third largest source in Pakistan is nuclear energy. There are two main plants installed in Pakistan. Fourth largest source of energy in Pakistan is wind energy and then comes solar energy [8]. The table below shows the total production of electricity in Pakistan

Resources	Production (MW)
Thermal	14,365
Hydel	6,611
Nuclear	775
Solar	1000
Wind	206.4
Total	22,957.4

Table 1 Production of Electricity in Paksitan [8]

As of early 2008, there were no wind farms located other than small-scale wind turbines (used for community) in Pakistan. In 1980s, very first effort was done to recognize the possible use of wind energy in addition to water pumping and aero-generation in Pakistan [9]. Later in the year 2002, fourteen wind turbines were installed for demonstration, out of which eight were set up in coastal areas of Sind and Baluchistan with installed capacity of 300W and six were of 500 W. So far, 153 small wind turbines each with capacity of 0.5e10 kW and a total capacity of 153kW were installed, which provide electricity to 1500 houses in remote areas of Sindh and Baluchistan [10].

Pakistan Council of Renewable Energy Technologies (PCRET) was inaugurated in 2010 that aim to deliver electricity to 100 coastal villages with net capacity of 2MW using wind turbines of Sindh and Baluchistan. In study, Duragi village of District Sibi of Baluchistan has installed a hybrid electrification system comprising of 7.5kW wind turbine, under empower Consultants of New Zealand.

For the province of Sindh, maximum wind speed reaches 14 m/s that are favorable for wind power generation in southern parts of Pakistan. In wind corridor of Sind province, the range of wind speed reaches about 5-12 m/s. Ample wind source is found in coastal line of Sindh up to 20GW electricity generation potential [11].

2.2.1 Scope and Potential of Wind Energy in Pakistan

Pakistan faces genuine electrical energy deficiencies. Due to increased demand, power is short by around 17,000MW [8].

Pakistan has around 1100 kilometers (km) seaside line for the wind energy potential in which 250 km comes in Sindh territory and 800 km in Baluchistan [12]. According to the report of National Renewable Energy Laboratory (NREL), Pakistan has an enormous potential of about 346 GW to produce electricity from available wind energy.

Wind energy is deemed as dominant and indispensable energy resources, as it is a known renewable resource with benefits of pollution free, cost free and unlimited resource. Both developed and underdeveloped countries have shifted its energy generating sources to more feasible resources such as wind. In Pakistan and Malaysia, utilization of wind energy is studied by researchers to the extent of doing scientific and analytical research, in order to make it work [13].

Energy supply mix for Pakistan, 60% contribution comes from fossil fuels and 30% comes from Biomass fuels. The total consumption was 74.4 MTOE in commercial use for Pakistan in the year 2005-06 corresponding to per capita primary consumption of 0.49 TOE. The shares of gas, oil, hydro, coal and nuclear in 2005-06 were 50.3%, 29.8%, 11%, 7.6% and 1.2% respectively [14].

Wind mapping project was executed to collect data of wind speed and its direction in forty five different sites in the coastal line of Pakistan. Theory states that Sindh has estimated potential of generating 2000e3000FLH (full load hours) and Baluchistan has 1000e1500 FLH. According to [10], along the coastal belts of Sindh and Baluchistan, a 15MV Power plant would be capable of generating 28e40 GWh and 12e20 GWh of electricity per year respectively [15].

The potential of Centralized Grid Connection (CGC) in terms of installed capacity is predicted to be 123 GW (considering wind power density equals to 5.4 MW/Km^2) and to execute CGC, it is considered that 40% local area of Sind and 35% local area of Baluchistan excluding low wind and urban areas are suitable for power generation.

Along the Keti-Bandar-Gharo corridor sites, monthly average wind speed is 7-8 m/s, which can be commercially utilizable wind resource in Southern parts of Punjab especially in coastal regions of Sindh and Baluchistan [16].

2.2.2 Wind Energy in Coastal Regions of Pakistan and Centralized Grid Connection

Wind energy provides so many advantages like electricity generation and water pumping for irrigation purposes. WPPs can be easily deployed in rural and remote areas where main grids are located far away [17].

Due to high infrastructure costs involved, it is very expensive to connect small villages to the national electric grid. In accordance with the experts' opinions, WAPDA (Water and Power Development Authority, Pakistan) does not have enough electricity to supply to them. The only way, coastal areas can be supplied as required, is through the use of wind power, because these areas have the high advantage of year round winds. National Renewable Energy Labs (USA) developed Wind Map of Pakistan and has identified enormous amount of wind potential is available at different regions of the country with a total potential of approximately 340,000 MW [11].

- **Jhimpir(Sindh) Wind Corridor**

Zorlu Energy Pakistan is a local subsidiary of a Turkish company that established first wind farm at Jhimpir, Pakistan with a total investment of $136 million. The project was completed in the year 2002 with total installed capacity of 50 MW [18].

- **Keti Bandar (Sindh) Wind Corridor**

In the southern part of Pakistan exists Keti Bandar wind corridor (Gharo) with an estimated potential of 50,000 MW that seems highly attractive to investors in the field and National Grid [18].

Literature shows that despite of the fact that Pakistan is a country with abundant wind potential, only 1% of wind energy is utilized to produce electrical energy even when power is short by around 17000 MW in the year 2016. However, the use of thermal (coal, fossil fuel) energy is still the highest.

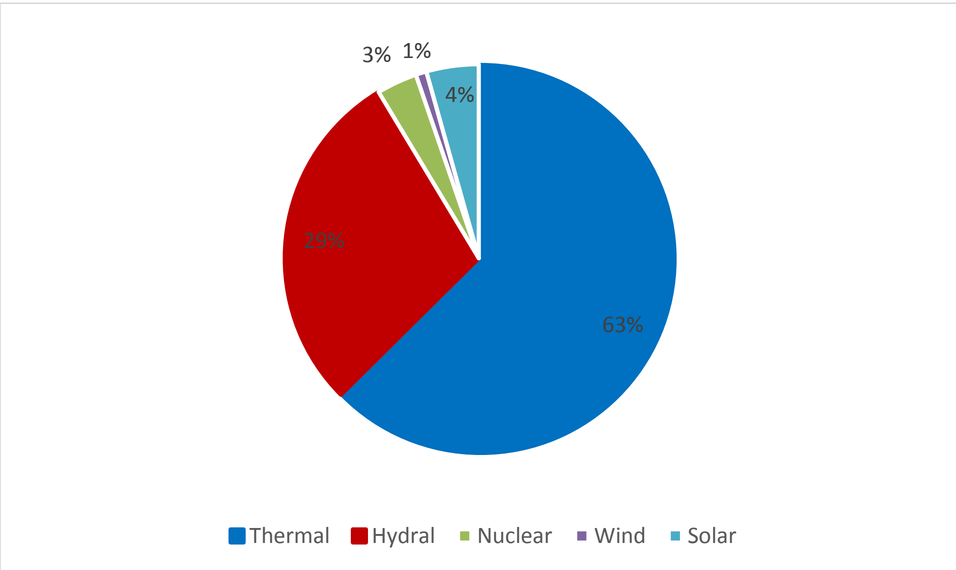

Figure 9 Electricity Generation by Source

2.3 Wind Turbine

Wind turbine is a converter that converts kinetic energy extracted from wind into mechanical energy and later convert mechanical energy into electrical energy. A range of horizontal and vertical axis wind turbines are present where small turbines are used to get electrical energy up to 100KW while large turbines contributes significantly in domestic power supply. Collection of large turbines constitute a wind farm and the trend of generating electricity through renewable energy resources is getting popular because many countries have decided to move onto this approach to decrease their energy generation dependence on fossil fuels.

2.3.1 Mathematical Model of Turbine Rotor

Kinetic energy of a body having a mass 'm' and velocity 'v' is equals to the work done 'WD' in displacing that object from initial (rest) position to a distance 's' under a force 'F' [19].

$$E = WD = Fs \qquad \text{(a)}$$

According to Newton's Law of Motion, we have

$$F = ma \qquad \text{(b)}$$

Substituting the value of force in equation (a), we get

$$E = mas \qquad \text{(c)}$$

Using the third equation of motion

$$v^2 = u^2 + 2as \qquad \text{(d)}$$

Rearranging the above equation as

$$a = \frac{v^2 - u^2}{2s} \qquad \text{(e)}$$

Since initial state of object is rest, so initial velocity is equals to zero

$$a = \frac{v^2}{2s} \qquad \text{(f)}$$

Substituting this in equation (a), the kinetic energy of the blade in motion is obtained

$$E = \frac{1}{2}mv^2 \qquad \text{(g)}$$

Rate of change of energy gives the mechanical power in wind

$$P = \frac{dE}{dt} = \frac{\frac{1}{2}v^2 dm}{dt} \qquad \text{(h)}$$

Mass flow rate is given as

$$\frac{dm}{dt} = \frac{\rho A dx}{dt} \qquad \text{(i)}$$

Rate of change of distance is equals to

$$\frac{dx}{dt} = v \qquad \text{(j)}$$

So, resultant equation is

$$\frac{dm}{dt} = \rho A v \qquad \text{(k)}$$

Hence, the equation for mechanical power is derived as

$$P = \frac{\rho A v^3}{2} \quad (1)$$

2.3.2 Mechanical Power Extraction

Literature has provided a constant solution to extract mechanical power from wind energy by using equation (2). The equation contains product of following parameters divided by 2.

- ϱ = air density
- V= Wind Speed
- A= Swept Area
- Cp= Power Coefficient

In 1919, a German physicist declared that not more than 59.3% of kinetic energy of wind is converted into mechanical power and since then this limit is known as 'Betz Limit' or Betz Law. Therefore, the maximum theoretical power efficiency of any turbine is 0.59. This maximum theoretical power efficiency is known as Power Coefficient and is denoted as Cp. Hence, the power coefficient needs to be factored in equation (1) [19] [20].

$$P = \frac{\rho A V^3 Cp}{2} \quad (2)$$

2.3.3 Power Coefficient

Power coefficient, denoted by Cp, is the measure of turbine's power efficiency. It depends on the wind speed, rotational speed of blade and its parameters such as pitch angle. It is a representative of Tip Speed Ratio (TSR) and Beta, denoted by λ and β respectively [3]. By rearranging equation (1), we get

$$Cp(\lambda, \beta) = \frac{2P}{\rho A v^3} \quad (3)$$

The above equation yields that Cp is a measure of rotor efficiency and can be defined as [21]

$$Cp = \frac{Extracted\ Power}{Power\ in\ Wind} = \frac{Protor}{Pwind} \quad (4)$$

The following figure shows the characteristics of Cp for different pitch angles and TSRs [22].

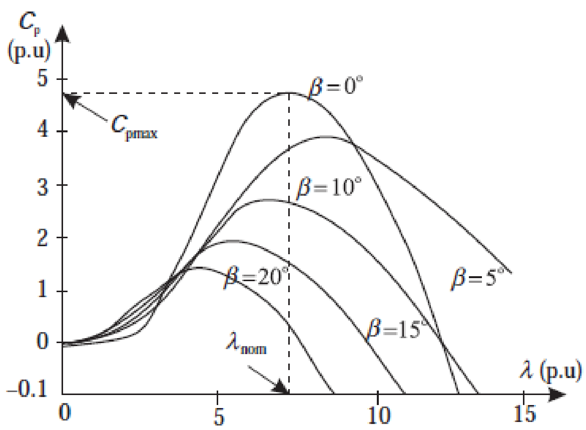

Figure 10: Characteristics of Cp versus β

Figure 10, shows that at a given value of λ, we get the maximum value for Cp and it decreases as the value of λ increases [22].

An optimal value of λ if maintained for all wind speeds can result in an optimal Cp that can help to extract optimal power from wind. Variable wind speed turbines are equipped with pitch mechanism to obtain an optimal Cp [21].

2.3.4 Rotor Axis Orientation

The orientation of the rotor axis is the important decision in designing a wind turbine. There are two types of axis designed for wind turbines and are discussed as follows

2.3.4.1 Vertical Axis Wind Turbine (VAWT)

The rotor blades are vertically oriented and allows wind from every direction eliminating the need for yaw system. This also allows placing drive train or gearbox on a fixed turbine closed to the ground that makes maintenance easier but this turbine does offer only a small production of electrical energy through wind and is not desirable to be used in wind farms [23].

Different control parameters are required to control the movement of blades at the time of high wind season and to control power aerodynamically.

2.3.4.2 Horizontal Axis Wind Turbine (HWAT)

Horizontal axis turbine has rotor parallel to ground or nearly so, making total mass of the blade relative to swept area, costing less on per KW basis. The gearbox and generator are also mounted at the top of the tower with a sensor that records the wind speed at every instance of time. The gearbox turns slow rotation of the blades to fast rotation thus making it possible to deliver maximum of wind energy to generator that can be converted into electrical energy. These turbines are widely used in commercial farms that contribute significant power in national grid. Usually these turbines have a height of 80 meters and are three bladed [24].

2.3.4.2.1 Wind Turbine (HAWT) Components

Wind Turbine is composed of different components that function together to produce electrical power. Brief introduction to these components is provided below.

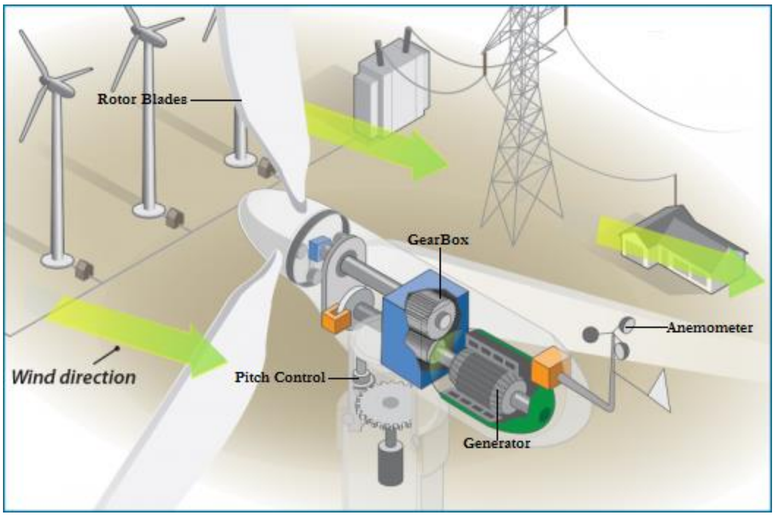

Figure 11: Sketch of Wind Turbine System [25]

- **Anemometer**

Measures the wind speed at every instance of time.

- **Blades**

Blades rotates on capturing the kinetic energy. Mostly there are two three number of blades in a turbine.

- **Brake**

It halts the rotor in emergency and the stop can be mechanical, electrical or hydraulically.

- **Gear box**

It connects slow rotating shaft with a high rotating shaft. It also rises the rotational speed from 30-60 rpm to about 1000-1800 rpm. Since this is the speed required by generators to produce electricity. This part of turbine is the most expensive one and now engineers are working to establish turbines without gearbox.

- **Generator**

Most of the turbines use induction generators, either asynchronous or synchronous. The widely used type of generator is Doubly Fed Induction Generator. It produces AC electricity of 60 Hz frequency.

Mathematical Modeling of DFIG

The designed Doubly Fed Induction Generator makes use of algebraic equations to calculate electrical power and equations used in modeling of generator comprises of dq-reference frame, which calculates stator power and rotor power in d and q frame separately, then combines them to get total simulated electrical power. Stator and rotor voltages are calculated using equation 7, 8, 9, and 10 that use currents and resistances that are provided with default values and are introduced in simulation model as parameters. These set parameters are listed below

- u represents voltage
- R_s denotes stator resistance
- i_{ds} denotes stator's current in d frame
- i_{qs} denotes stator's current in q frame
- i_{dr} denotes rotor's current in d frame
- i_{qr} denotes rotor's current in q frame
- L_s is stator's inductance
- L_r is rotor's inductance
- L_m is mutual inductance
- ω_s is angular velocity
- s denotes slip; slip defines the relative speed of the generator rotor compared with that of stator.

$$uds = -Rs * ids + \omega s(Ls * iqs + Lm * iqr) \quad (5)$$

While stator voltage in q-frame is calculated using following equation

$$uqs = -Rs * iqs - \omega s(Ls * ids + Lm * idr) \quad (6)$$

The equation for calculating rotor voltage is same as stator voltage equations but with a little change as they include product of slip with angular velocity along with rotor resistance and inductance. Rotor voltage in d- frame is calculated using equation stated below.

$$udr = -Rr * idr + s\omega s(Lr * iqr + Lm * iqs) \quad (7)$$

While rotor voltage in q frame is calculated using equation 10.

$$uqr = -Rr * iqr - s\omega s(Lr * idr + Lm * ids) \quad (8)$$

Since, it is common fact that inductance, reactance and resistance has a direct relation with temperature so when temperature increases in generator then values of stator and rotor inductance and resistance do change and this phenomenon is also catered in a function named as 'Temperature Effect' in Agent Generator to make our simulation model smart enough.

After calculating rotor and stator voltage, generator calculates stator power and rotor power using equations 11 and 12 respectively where P_s represents stator power and P_r represents rotor power.

$$Ps = uds * ids + uqs * iqs \quad (9)$$

$$Pr = udr * idr + uqr * iqr \quad (10)$$

The sum of equation 11 and 12 gives total electrical power produced by Agent Generator.

$$Power = Ps + Pr \quad (11)$$

- **High-Speed Shaft**

High Shaft of Gear box drives the generator.

- **Low-Speed Shaft**

It spins the slow rotating shaft to spin at 30-60 rpm.

- **Pitch**

It pitches blades out of the wind to regulate rotor's speed. It helps rotor not to rotate at a speed where turbine cannot generate electricity, means when wind speed is either too slow or too high that it can damage the turbine.

- **Tower**

It is made up of steel and concrete. It basically supports the structure of turbine at a level where turbine can get to experience high wind speed as wind speed rises with height. The more is the height of the wind tower, the more is the wind speed [25].

Chapter 3

Literature Review

This chapter documents the modeling of wind turbine system and its components provided in literature. Moreover, it contributes to understand development in the area of research.

3.1 Area of Research

A detailed literature review has been conducted to identify studies related to Wind Turbine System that includes component based modeling as well. Studies shows that keeping in mind the hazardous issues caused by fossil fuel generation with inclusion of resource depletion and expensive method of electricity generation have urged energy providers to think other way around and proposed the use of renewable energy resources to generate electricity. Study shows that many developed countries have shifted their generation methods to renewable energy resources and to impart this in Pakistan, we have taken in account several literature and studies on wind turbine system. Provided Literature Review is divided into following sub-sections

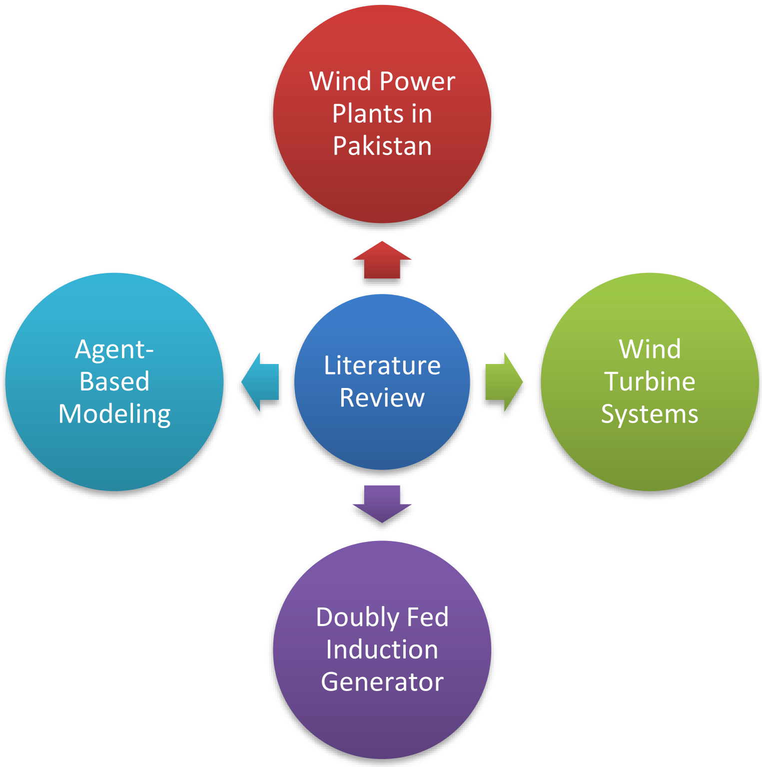

Figure 12: Areas of Research

Table 2; summarizes the literature work in the sequence of division shown in Figure 11 whereas details of these papers are described later.

Wind Power Plants in Pakistan		
Author(s)	**Paper Description**	**Key Features**
Ambreen & Naveed [26]	Provides a review of renewable energy supply and energy efficient technologies and gives details of wind power plants in Pakistan	The authors discuss the scope of alternative energy sources that are more desirable than nuclear power and fossil fuels and help in reducing carbon emissions
Abollhosseini et al [27]	Explains potential of different renewable resources available in Pakistan to produce electricity	The authors identify the technological reasons causing energy shortfall in the country and how renewable energy resources present within the country can contribute significantly to overcome 'load shedding' in the country
Wind Turbine System		
Author(s)	**Paper Description**	**Key Features**
Elsevier [19]	A mathematical model of wind turbine is discussed	This paper derives mathematical equations required to calculate mechanical power extracted from wind's kinetic energy
Manwell et al [28]	Discusses different design procedures for wind turbine	It provides a review of past experiences in designing wind turbines to evaluate design and estimate costs and by keeping these parameters in mind, refinement in wind turbine designing can be made to build and test prototype
Wang & Chiang [20]	A novel dynamic co simulation methodology of complete wind turbine is provided	Provided methodology comprises of aerodynamics, mechanism dynamics, control system dynamics and subsystems dynamics
Linda et al [22]	A complete thorough study of electrical power system dynamics is discussed	Modeling of main components of classical power plants modeling is explained along with a detailed study on synchronous generators and induction motors. It also elaborate the characteristics of wind power generation and related technologies
Mohit [29]	Discusses FAST and MATLAB/SIMULINK interfacing to design type-1, type-2, type-3 and type-4 of Wind Turbine System	Fatigue, Aerodynamics, Structures, and Turbulence (FAST) software is used to model the detailed aerodynamics and mechanical aspects of wind turbine generator and MATLAB to simulate electrical generators.
Asis & Dhiren [30]	This paper provides a detailed analysis of wind turbine's	Power production from wind speed depends upon a number of factors and by improving system liability we can make sufficient electrical energy from

	blade power and efficiency at different tip speed ratios	wind speed. It provides an analysis of tip speed ratio calculation to extract the
Mohit et al [31]	Modeling and simulation environment of MATLAB is used to implement mathematical model and its parameters that affect the electricity generation of wind turbine	Different parameters such as temperature, wind speed, air density and power coefficient are discussed in detail and implementation of wind turbine in MATLAB/SIMULINK is carried out to study the values that maximizes the output power
Philip et al [32]	An open source Modelica Library Wind Power Plant is presented	Either by using statistical or real data of wind speeds, an estimate of power generation can be predict before installing a wind turbine or wind park in a certain region of land
Christina et al [33]	This paper has a detail study on wind turbine systems, starting from its modeling to verification	A rational, integrated framework for the formal modeling, simulation, testing and verification of a simplified wind turbine system is carried out in a sequence of different tools
Thomas et al [34]	This book discusses the theoretical background and technical regularities	It provides historical and current status of wind power, basic integration issues related to wind power, power electronics for wind farm and integration with the power grid
Mohit & Santoso [21]	Modeling of type-1, type-2, type-3, and type-4 wind turbine generators are provided	Type-3 and type-4 wind turbines employ power electronic converters that offer muted response to voltage sag events occurring on grid and this conclusion is drawn by calculating dynamic response of 4 different types of turbines.
Johnson [35]	The paper discuss the dive train mechanism of wind turbine	A model provides an insight of drive train at different wind and grid conditions and to design flexible components of the turbine train
Irving et al [36]	A study to achieve maximum output power from little wind energy in cost effective manner	It discusses aerodynamics and torque calculations to design a drive train
Doubly Fed Induction Machine		
Author(s)	**Paper Description**	**Key Features**
Arantxa et al [37]	This paper shows the simulation results of grid connected wind driven DFIG	Mathematical model of generator is presented to limit the power factor of the energy generated
Gonzalo et al [38]	Topology of electrical system used in wind farm is described	Detailed mathematical modeling of DFIM is presented

Kara et al [39]	Dynamic Modeling of WTS either with DFAG or DFAG with full controller	Fundamentals of DFAG with full power converter is presented
Elazzaoui [40]	Operation of wind turbine, DFIG and its control system is modeled and simulated	Electrical equations of the generator are given in the d-q frame that calculates active power
Khalil et al [41]	Optimal control scheme for the DFIG is proposed	Grid control technologies and advanced control algorithms combined with vector control are proposed to improve DFIG
Agent Based Modeling		
Author(s)	**Paper Description**	**Key Features**
Enrique et al [42]	Agent based simulation model of wind plant at different instance of time	Multi method approach used to fulfil numerous requirements of the model to allow simulations at various time scales to compute best efficiency
Enrique et al [43]	Different modeling paradigms are used to simulate wind power systems on various time scales	Agent based modeling; discrete events and dynamics systems are used at the same time to simulate a wind power system. The model computes the accumulated output power of the wind farm affected by different random factors to reconstruct a representative power unit to be used in integral energy system simulations.
Kremer et al [44]	Agent-Based Approach is used to model decision making in electricity sector by modeling investors as agents	Transition of electricity system is modelled using ABM. The simulation model shows the influence of heterogeneous investors by bringing out key challenges of transition and develops link between fundamental parameters.
Matteo et al [45]	Virtual power plants are proposed to take an account of energy generation through renewable energy resources	To increase the reliability on renewable energy resources Virtual Power Plants are simulated and supply to the grid is shown additionally with energy storage in Electric Vehicles
Gonzalez et al [46]	Generalized energy networks are modeled using ABM.	Model proposes multi-agent algorithm is performed to calculate power flow in electric networks.
Baudry et al [47]	Hybrid Model based on Agent-Based Approach is proposed that allows modelling of systems with dynamic interactions between multiple parts.	Maintenance of wind turbine system includes a series of conditions that are difficult for stakeholders to decide optimal solutions to them. An algorithm is defined to analyze and select different maintenance strategies

Paula et al [48]	Systematic literature review on ABM and socio technical transitions is provided	Study is being carried out to identify and address different components of energy system and results show that 35 of the 62 study directly choose the section of ABM.
Mast et al [49]	Scenario development of offshore wind energy is carried out using ABM	Different scenarios are developed to implement large scale offshore WPP including the uncertainties of future and consequences of decision. Therefore, investigation is done by creating a model using ABM that discusses different scenarios to develop offshore WPP

Table 2: Literature Review

3.2 Wind Power Plants in Pakistan

We all are familiar with the fact that carbon dioxide is the main component of greenhouse gases and is responsible for environmental hazards. Therefore, global concern is shown to reduce carbon dioxide emission and different policies are under consideration to avoid it.

Ambreen & Naveed [26] suggested many encouraging technological innovations including utilization of renewable energy resources in this aspect. The global trend that characterizes the deployment of renewable technologies is that they contributed 1454 GW in 2011 to 2167 GW in 2017, globally. Secondly, they are cost efficient and forecasts that the number of countries producing electricity through renewable energy resource will increase remarkably [26].

According to Ambreen & Naveed [26],Pakistan is a country with significant amount of renewable energy such as wind, solar, hydro and biomass. Significant amount of energy can be produced using renewable energy resources present with in the country [26].

Abollhosseini et al [27], suggested that wind is the most viable resource and the installed capacity of wind is amplified from 4.8 MW to more than 239 GW in 2011. IEA evaluates that the global capacity will rise from 238 GW to nearly 1100 GW by the year 2035. Abollhosseini et al. also proposed that wind energy has contributed a lot in countries like China, America and Germany where the commutative installed capacities are 62, 47, and 29 GW respectively and wind turbine generates as much electricity as a conventional power plant.

Abollhosseini et al [27], discussed that Pakistan has a potential to produce 50000 MW and has got a perfect corridor in Islamabad, Karachi and Thatta region, where wind speed is recorded to be 6 to 7.5 meters/second, good enough to run a turbine that is designed to operate at 3-4 meters/second. Survey report has shown that Pakistan has the potential to produce 300,000 MW electricity from wind and solar resources to meet the demand shortage. Many wind power plant setups have been installed in Sind with installed capacity of 50 MW. Zurlo Energi Engineering installed first wind project in Pakistan and finished installing five turbines out of which one is still uninstalled. Later, Fauji Fertilizer Company energy Limited launched 49.5 MW wind power plant at Gharo Sind. Gradually many companies invested in wind power plants but still we are unable to make use of vast potential of wind available and are facing energy crisis. In inaccessible areas of Sind and Baluchistan, wind turbines can be set up to supply electricity to more than 5000 villages.

3.3 Wind Turbine System

Designing a wind turbine is a big task. It involves the conceptual assembling of so many mechanical and electrical components to extract maximum energy from a varying source of power. This process is dependent on a series of constraints out of which economic viability leads the list. It is quite essential that energy produced by the wind turbine is cheap as compared to other methods of electricity generation. Therefore, it is fundamental to design a turbine that produces energy at a low cost. The price at which energy is produced by a wind turbine depends on various factors. The major ones are turbine's cost, cost of installation, operation and maintenance. The production depends on turbine's design and wind resource. Since, wind resource is not in user control so it is necessary to best design a turbine. To best design a turbine, different techniques have been proposed in literature.

Royal Academy of Engineering derived mathematical model to extract mechanical power from wind's kinetic energy.

Manwell et al [28], states that the design architecture depends on the application of turbine whether it is going to be used for commercial purpose or domestic. Turbines used for utility purposes are smaller and have 10 to 200 kW range while commercial turbines have power ratings in the range of 500 to 1500 kW and are installed in clusters forming wind farms.

Wang et.al [20], proposed novel dynamic co-simulation of wind turbine system in MATLAB/SIMULINK. The design methodology increases the flexibility and controllability of wind turbines.

Mohammed et al [22] has provided a complete thorough study on wind power plants and its components. Detailed discussion is provided on induction generators and motors and different types of generators used in different kinds of wind turbine systems. Best of all is that it has described tip speed ratio as the ratio of peripheral speed, which is, equals to angular velocity times half the diameter over wind speed and suggested that it is very essential to limit the mechanical power produced by wind turbine. The rated power of the turbine should never exceed and this is possible by introducing alternatives as pitch control, active stall control and passive stall control. Pitch control is used in variable speed wind turbine while latter two are used in fixed speed wind turbine. This control enables blades to turn into the wind direction when the wind speed is too low, say below the rated speed and it turns out the blades out of the wind direction when the speed is too high and an emergency stop is required. Pitch control is so far the best control that can contribute a lot at the time of start-up of the machine or when emergency stop is required. Addition to this, it also ensures a constant output power that is close to the rated power unlike other controls where the output power decreases as the wind increases. The pitch angle varies between 0- 25 and sometimes up to 30 by using hydraulic or electrical devices. When the wind gust are too high that generator cannot accept energy then the pitch angle forces the aerodynamic forces acting on the blades to compensate the effects and applies a mechanical brake. When the wind speed reduces to a speed below cut in speed, the power is cancelled by turning the blades at β=90 degrees.

Mohit et al [21] prepared a report where he discussed four types of wind turbine i.e. Type 1, Type 2, Type 3 and Type 4 and discussed modeling of Fixed Turbine (Type-1) wind turbine generators, variable slip (Type-2) wind turbine generators, DFIG (Type- 3) wind turbine generators and full converter (Type-4) wind turbine generators.

Mohit et al [31] presents a report stating work done to develop generator and gearbox models in MATLAB environment and couple it with NREL FAST program. This represents connection of aerodynamic and mechanical models in FAST with excellent electrical generator models found in MATLAB.

Asis et al [30] represents wind turbines place power and efficiency measured at different tip speed ratios and calculated using software tool.

Philip et al [32] presents the new open source library of Modelica for Wind Power Plants. It provides a foreword to predict and estimate energy output either for statistical or real wind data based on time domain simulation.

Johnson et al [35] provides relationship between the power available from wind and power coefficient. In simulations, ϱ and swept area of the wind turbine are kept constant while power coefficient is completely dependent on λ and β. To efficiently utilize the power extracted by wind, drive train plays a vital role. The wind turbine drive train consists of components that convert kinetic energy of the wind into rotational kinetic energy and later into electrical energy as it is coupled to generator through a transmission or gearbox. The basic system is shown below.

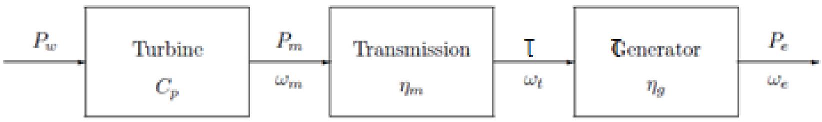

Figure 13: Wind Electric System

Irving et al [36] states system starts with the power in wind Pw and then passes through the turbine producing a mechanical power at turbine angular velocity denoted by ωm, which is then supplied to the transmission. Transmission converts the mechanical power into rotational kinetic energy. The rotational kinetic energy is given the name of torque. The torque produced by the drive train can be extracted out by dividing the transmission power into mechanical power.

3.3.1 Components of Drive Train

A drive train consists of following rotating components

- **Main Bearing:** It is responsible for delivering torque to rest parts of the drive train and is referred as slow rotating shaft or rotor shaft. It also supports the weight of the rotor [28].

- **Gear Box:** It usually increases the speed of the input torque that is fed into the generator. Generators are capable of turning at a speed of 1500 (50 Hz) rpm to 1800 rpm (60 Hz) [28]. The gradual increase in size of wind turbine causes larger forces and torques, which results in failure of gearbox and other components of drivetrain. The expected lifetime of gearboxes is usually 20 years but practice shows that they need to be replaced every 6 to 8 years and 20% of downtime of wind turbine is due to gearbox failure [35].
- **Generator:** Generator is an electrical machine that is responsible for generating electrical power from wind speed. Generators are characterized on the basis turbine's rotational speed (fixed speed or variable speed). Fixed speed wind turbine is simple in design and is connected directly to the grid whereas variable speed wind turbine includes generators that are either synchronous or asynchronous induction generators. DFIG is commonly used generator in variable speed wind turbine [22].
- **Brake:** When wind speed increases to an extent that it can cause damage to turbine than mechanical brakes are applied to halt its operation.

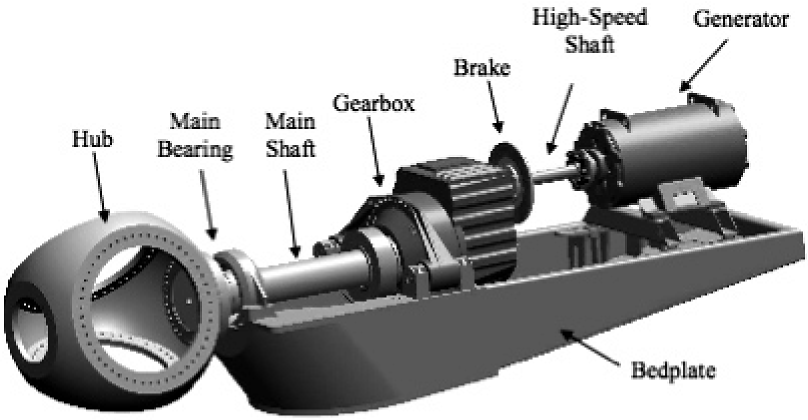

Figure 14: Components of Drive Train [36]

3.4 Induction Generator

Induction generator is widely used in wind turbines because it is good in performance, lightweight and low-priced. The torque produced by wind turbine drives the generator rotor. This generator needs a reactive magnetizing current to excite itself and self-excitation is made possible providing the initial excite from a capacitor bank instead of connecting it to the main grid. Active power created by the generator has a direct relation with slip and slip is defined as the difference between generator rotor speed and generator stator speed. The torque produced by the wind turbine rotates the generator rotor so its angular speed is dependent on it. When the wind speed is too little to produce electrical energy out of it then generator acts as a motor and absorbs energy from the grid, for this purpose, it is usually detached from the grid. The rotor of induction machine is either squirrel cage or wound rotor [22]. A wound rotor induction machine having variable rotor voltage frequency replaces synchronous generators that are interfaced with grids to get a static frequency to produce a constant electrical power whenever a variable speed generation is concerned. As a result, Doubly

Fed Induction Generator is an example of wound rotor machine that is mostly used in industry to produce electrical power from large wind turbines is gaining attention in wind power plants [37].

3.4.1 Doubly Fed Induction Generator

Doubly Fed Induction Generator is gaining popularity now a day due to its frequent use in wind turbine systems and primarily due to great advantages it offers over other types of generators. In variable speed wind turbines, the turbine rotor shows variation in its rotational speed as the wind speed varies. Therefore, a generator is required that offers quasi-constant rotational speed of the generator and DFIG is best example of it as it allows output voltage and frequency of generator to be maintained at constant values regardless of generator rotor speed. A three phase synchronous generator is shown in Figure 7 [50].

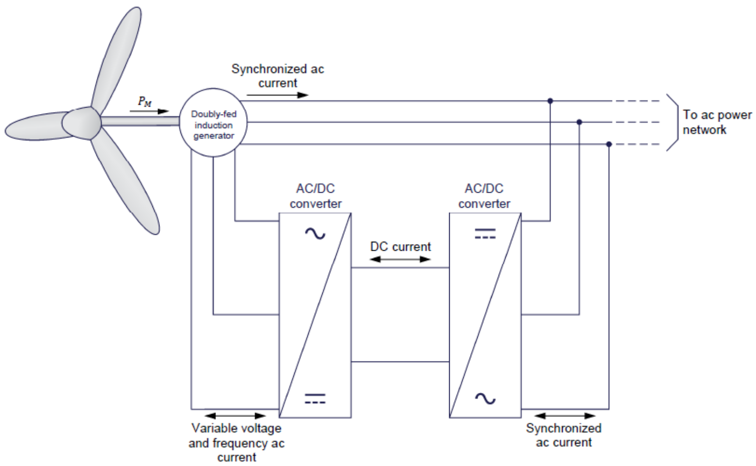

Figure 15: Doubly Fed Induction Generator [50]

The mechanical power captured by the wind turbine is fed into the DFIG that is connected to the grid and has back-to-back converters attached with it. These converters are voltage source converters that converts AC source voltage coming from the rotor side to DC source voltage and then converts DC source voltage to AC source voltage at grid parameters as output. These converters are connected by a dc link capacitor. The rotor side converter controls speed of DFIG and power factor while the stator side converter keeps the dc link voltage constant. Stator is connected directly to the grid whereas rotor needs a step down transformer to get connected with the grid. Energy obtained by wind is fed into the network by both stator and rotor in order to enable a normal generation scheme [41][51].

The algebraic equations are obtained using Park Transformation that converts three-phase generator calculations to two-phase. Park transformation is also known as "dq Transformation" so equations with subscripts as d and q represent these two-phase and are stated in methodology section.

Arantxa et al. presents simulation results of DFIM connected to grid at operating conditions above and below synchronous speed. It also includes the development of mathematical model of wind generator to control power factor.

Gonzalo et al, provides detail of four different types of wind turbines available and then discusses dynamic modeling of doubly fed induction machine along with its steady state analysis. Testing of DFIM and its analysis at voltage dip condition are discussed with vector and direct control strategies of DFIM.

Marouan provides modeling and control of a DFIG based wind turbine system and control vector oriented stator flux strategy is used for controlling purpose.

Shilpi provides a review on doubly fed induction generators as it is most widely used generator in wind turbine systems so its characteristics and properties that make it stand alone from other generator is presented.

3.4.2 Advantages and Disadvantages of DFIG

Table 3; lists down advantages and disadvantages of Doubly Fed Induction Generator.

Advantages of DFIG	Disadvantages of DFIG
It can operate at variable speeds	DFIG requires gearbox maintenance
Contributes to the system stability after fault occurs	Wear and tear, maintenance of slip rings and brushes
No need of power factor correction capacitors because it is bidirectional	Expensive Power Electronic Equipment
Amplitude and frequency of output voltage remains same regardless of wind speed at turbine rotor	It is very sensitive to grid faults

Table 3: Advantages and Disadvantages of DFIG

3.5 Agent-Based Modeling

Enrique et al [42] models the output power of wind warms at different time instances. The modeling includes three different case studies i.e. Low wind speed day, High wind speed day, and simulation over a week. The modeling integrates agent based modeling with discrete events and dynamic systems.

Kramer et al [44] proposed an agent-based modeling technique to model investor's decision making in electricity sector. The model treats investors as agents and predicts solution based on carbon price scenarios and heterogeneous investor behavior.

Matteo et al [45] discussed that the time wind energy gained significance as cleanest renewable energy resource, since then its vital contribution is seen in energy generation sector but unfortunately, due to their inherent uncertainty, wind generators are not as much controllable and predictable as other conventional generators. Therefore, agent-based modeling of VPPs is proposed and integrated with EVs to store energy and avoid irregular nature of the energy supply.

Gozalez et al [46] proposed an approach for modeling generalized energy networks through an agent-based method. It is a modular approach and allows scalability and extension of model by adding new entities. It represents integrated utility structure in which multi-energy agent manages carriers. Application of proposed framework includes small micro grids to large energy systems.

Paula et al [48] et al throw light on the missing area in literature on agent-based modelling and energy transitions. Based on 62 articles authors reviewed the potentials of the agent-base modeling in energy transitions by dividing this study in six areas covering different components of energy system. Articles distribution over different topics shows the continues electricity market related explorations. Four complexity categories were identified on the basis of energy transition complexities indicates the complexity of energy transition and how ABM address these complexities. Choosing ABM to energy transition complexities is shown in the study of 35 out of 62 articles. Rest of the articles shows that ABM should set in context of energy transitions. In model development, more interdisciplinary studies are recommended to report the differences between social practices and modelling of energy transitions.

Baudry et al [47] described that wind turbines maintenance at offshore is complex and is not cost effective keeping in mind the factors such as size of turbines and wind farms and their distance from coastal areas and weather-related conditions, so it is difficult for stakeholders to determine the ideal maintenance strategy. There is a dire need to discover time and cost effective maintenance techniques. Authors proposed a multi-agent based systems based hybrid model for maintenance of wind turbines. They have selected different maintenance strategies and analyzed them on the basis of multi-criteria decision algorithm that is being developed for this purpose. They also presented the cost model that includes cost of installation, monitoring and maintenance cost. NetLogo software has been used to develop simulator to provide experimental results.

Drive Train in on state starts converting mechanical energy into torque to transfer it to the generator. Generator calculates the stator power and rotor power and sums up both powers to extract the active power generated through wind speed.

3.6 Comparison of our proposed framework in State of the Art

Wind turbine designing is as much dynamic as the wind is. Literature offers numerous techniques to design a Wind Turbine System but no model is efficient enough to model microscopic details of it. In order to incorporate wind power plant into a basic energy system simulator, Agent-Based Modeling offers the best solution as it deals with the microscopic details of the system. It allows integration of heterogeneous agents and establish a modular structure that is interoperable with different computer soft wares. Therefore, ABM is best suited to design a wind turbine that can represent same model with different time scales and later on allow different other techniques to combine in model. By adding or removing agents dynamically, efficiency of turbine is enhanced. Our proposed model is depiction of Foundation Wind Energy-II (Private) Limited which, contains Nordex N100/2500 wind Turbines installed at Gharo Sind by Foundation Energy Private Limited with total installed capacity of WPP to be 50 MW. The model contains a turbine with its components as agents and is replicated twenty times to create wind farm and its implementation and validation is carried out in AnyLogic environment, which offers safe way to test different scenarios in modeling and simulation. This is component based modeling of wind power plant that will allow the use of different combinations to derive the appropriate combination for futuristic purpose.

Chapter 4

Methodology

This chapter proposes Agent-Based Approach to develop proposed simulation model of Wind Turbine System.

The proposed framework is the simulation model of Wind Power Plant installed at Gharo, Sind by Foundation Wind Energy Private Limited. The company has installed twenty Nordex N100/2500 turbines in one farm, each with a capacity to produce 2.5 MW, accumulating it to be equal to 50 MW thus contributing the power produced to national grid [52]. Our proposed framework forecasts the energy generation through wind, providing an insight to the energy investor to have an eye on the energy generation at different wind speeds at different instants of time. Keeping in view turbine's characteristics and specifications, an Agent-Based Model is modeled in AnyLogic Environment and its details are discussed below.

4.1 Agent Based Modeling

Agent-Based Modeling (ABM) is used to create workable perceptions of real world and this is the reason it is gaining importance day by day. Agent-Based Modeling builds a model that combines small, reproducible units known as Agents those interact with one another in an environment where they start representing a complex system behavior. Agent-Based Models can possess different qualities and characteristics allowing the appearance of distributed intelligence. For example, if we try to replicate human behavior then Agent-based model of Human will take into account all the characteristics of human such as his/her age, weight, height, physical parts, and nature of job along with other related information. ABM is best suitable for environment where decentralized solutions are required, and a central control solution method is not valid. It focuses on modeling a system at local level through agents and their interactions, agents are planned to be modeled in a simple way, and complexity is the product of their interactions. Following three actions are required to be considered at the time of ABM.

- **Environment Sensing:** Agents acquire information of local environment.
- **Decision Making:** Agents must be intelligent enough to take decisions according to situation to fulfil objectives.
- **Reaction to the Environment:** Feedback loop exists between agents and their environment because agents have a response on environment.

Agent-Based Modeling has been applied to numerous fields successfully and is now paving its path towards power grids and electricity market. It can be combined with different other approaches as well such as System Dynamics and Discrete Event, if needed to best project a model [42].

ABM is playing a vital contribution in energy sector as generalized energy networks are modeled using ABM that proposes multi agent algorithms to calculate power flow in electric networks [45]. It has been used to incorporate Virtual Power Plants to increase reliability on renewable energy resources to generate electric power [45]. The energy thus produced is used to take an account of energy generation through renewable energy resources before installation of complete power plants. Along with this agent based approach is also used to develop different scenarios to implement large scale offshore WPP that includes uncertainties of future and consequences of decision [49].

Agent Based model consists of a number of Agents: (i) Turbine (ii) Anemometer (iii) Rotor (iv) Pitch Drive (vi) Drive-Train and (v) Generator. The turbine agent contains further components of wind power plant as separate agents that function together to predict electricity generation produced against provided wind speed. The model is set on hourly resolution therefore, forecasts energy production accordingly.

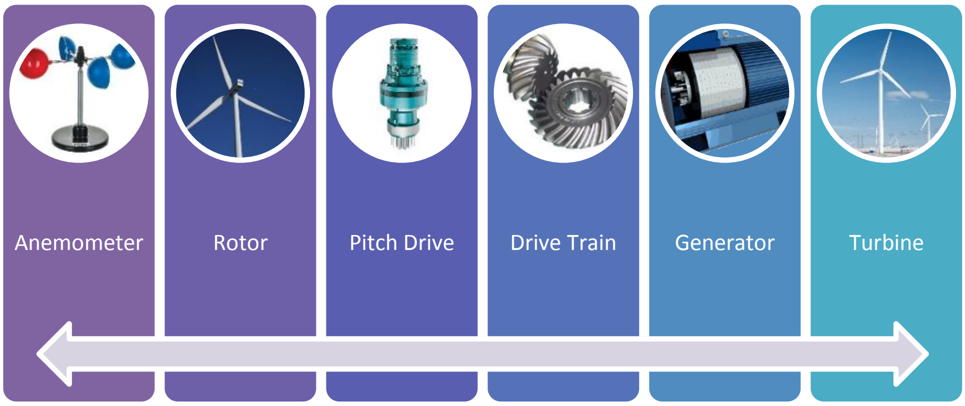

Figure 16: Components of designed Turbine

4.1.1 Agent Turbine

Turbine is the core of wind power plant that captures wind speed, converts it into suitable magnitude to get the required output power. Agent Turbine belongs to the category "population" as it is replicated as twenty turbines to create the wind Farm.The turbine contains its components as Agents and are shown below

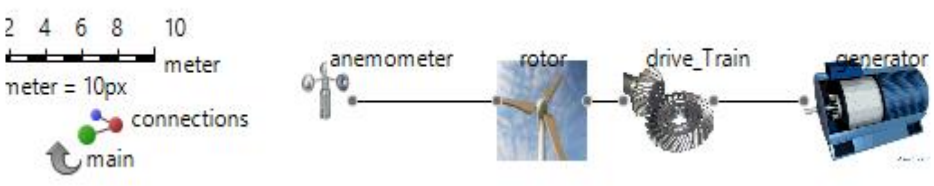

Figure 17: Agents of Turbine

A state machine of wind turbine is constructed that is processed and controlled by set parameters and are triggered as timeouts and conditions, shown in Figure 18. The set parameters are obtained from the Nordex N10/2500 brochure featuring the facts and figures of turbine. The state machine consists of following three states.

- **ON**: The state gets active once turbine is generating output power; no matter the turbine is partially loaded or fully loaded.
- **OFF**: The state gets active once the turbine generates no output power. This state occurs either when wind speed is very high or very low because turbine is designed to switch off under this scenario.
- **Failure**: This state is active when the turbine shuts down either for maintenance purpose or when there is some failure [43].

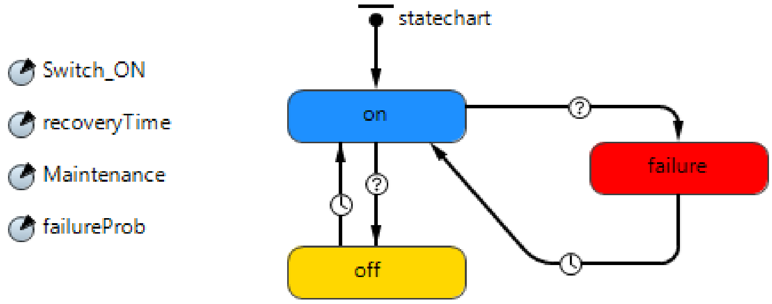

Figure 18: State Machine of Turbine

The state ON is active when the condition of switch on is true. This condition gets true when wind speed is either equals to cut-in speed or below cut-out speed. Turbine gets OFF when condition of switch on is false and condition of maintenance gets true. It goes back to ON state when triggered timeout completes. Since the turbine requires three hours out of twenty-four hours to recover so, the triggered timeout is set to be 3/24. The turbine goes into Failure state when failure probability gets true and states remain in this state until switch does not get on. Failure state goes back to ON state when recovery time is triggered out in timeout.

4.1.2 Agent Anemometer

Anemometer keeps the wind speed record at different instance of time. Our proposed model has a separate agent of anemometer that has two variables named as Wind Speed and Time where the first one contains value of initial wind speed, later contains the initial time whereas the function UpdateWind updates wind speed after every hour, and supplies it to the agent rotor. It reads the wind speed from the database.

Figure 19: Agent Anemometer

Increment one hour in current time,

Time = time(HOUR)+1;

In addition, update wind speed at incremented time from database,

WindSpeed = main.wind_speed(Time);

The wind speed is on hourly resolution and is provided by Foundation Wind Energy Private Limited. The graph plot of wind speed data is shown in Figure 20 with x-axis representing time and y-axis shows wind speed.

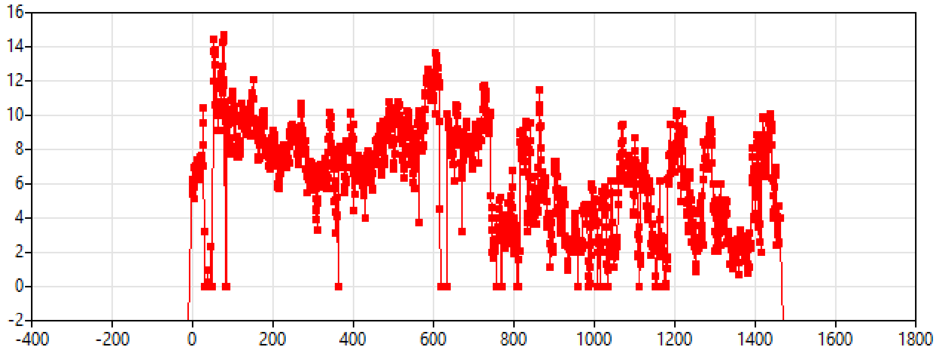

Figure 20: Graph Plot of provided Wind Speed

4.1.3 Agent Rotor

The agent rotor is the main component of wind turbine. Blades of turbine capture kinetic energy of wind and convert it into mechanical power. Nordex N100/2500 Turbine (whose modeling and simulation is proposed) contains three blades with a diameter of 99.8 meters, making its radius to be 49.9 meters and swept area equals to 7823 meters. Swept area is the area in which the rotor sweeps in a circular motion and is the plane of wind by the generator. Rotor rotates when wind speed is between 3 m/s to 25 m/s, rendering 3 m/s as cut-in speed and 25 m/s as cutout speed of wind turbine. Figure 21 shows state machine for rotor in our proposed model. State Machine contains the following three states for turbine rotor.

- **Parked**: When the turbine is in inactive state such that its switch on condition is false then turbine rotor is in parked state.
- **Rotating:** When the turbine's switch gets on, turbine rotor goes into rotating state, converting kinetic energy of the wind into mechanical power using equation 2 on page 13.
- **Braking:** This state gets active when wind speed exceeds the cut out speed and remains in it unless wind speed is equals to or greater than cut in speed. The state checks itself after every one minute to determine which state is to be acquired next. Soon after the wind speed is greater than or equals to cut in speed, it goes back to rotating state.

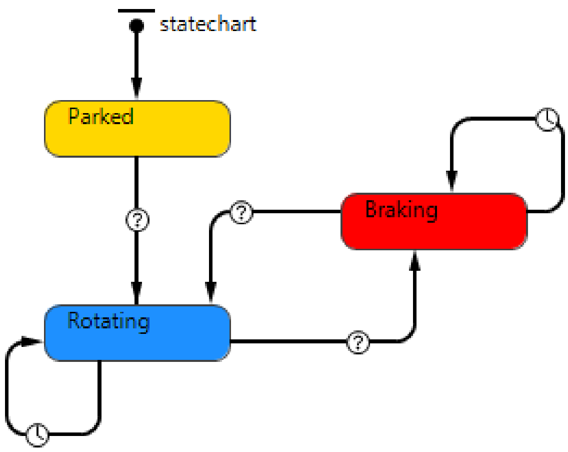

Figure 21: State Machine of Turbine Rotor

Agent Pitch Drive limits the mechanical power by providing optimal β angle to determine optimal value of power coefficient Cp.

4.1.4 Agent Pitch Drive

Pitch Drive is far most the best control strategy in wind turbine systems. It limits the mechanical power by turning the blades into or out of wind gust direction when either wind speed is too low or too high. The angle varies between 0 to 25 degrees. Our proposed simulation model contains an agent Pitch Drive that has six table functions that contains different values of power coefficient across different β angles to get optimal value of Cp against maximum value of Beta and is shown in Figure 22 .

The Java code reads value of λ in table function at zero degrees to obtain β

```
double[] Beta = new double[6];
Beta[0]=TF_0_Degree(Lambda);
```

Then checks value of λ in table function at two degrees to obtain β

```
Beta[1]=TF_2_Degree(Lambda);
```

Then checks value of λ in table function at five degrees to obtain β

```
Beta[2]=TF_5_Degree(Lambda);
```

Then checks value of λ in table function at ten degrees to obtain β

```
Beta[3]=TF_10_Degree(Lambda);
```

Then checks value of λ in table function at fifteen degrees to obtain β

```
Beta[4]=TF_15_Degree(Lambda);
```

Then checks value of λ in table function at twenty five degrees to obtain β

```
Beta[5]=TF_25_Degree(Lambda);
```

And returns maximum β at the end.

```
return MyUtility.getMax(Beta);
```

Maximum β returns optimal value of Cp.

Power coefficient characteristics for different blade pitch angles defined in our simulation model and are shown below.

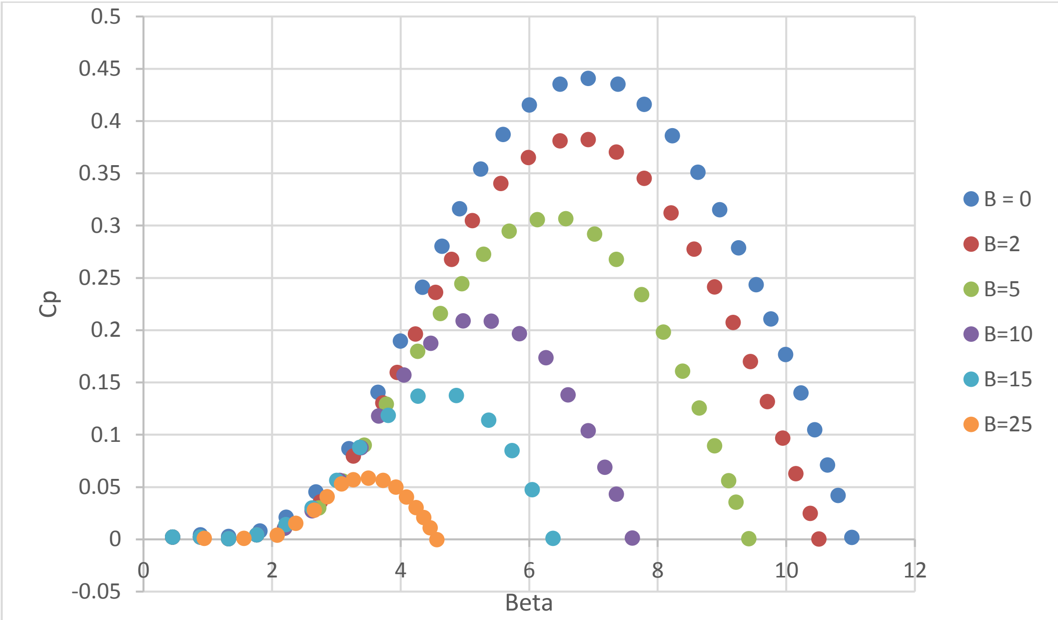

Figure 22: Cp against β

By obtaining maximum β angle against tip speed ratio, we get optimal value of Cp that is used to calculate the mechanical power using equation (2) in rotating state of turbine rotor.

4.1.5 Agent Drive Train

Drive train converts mechanical power into rotating torque that is fed into the generator to produce electrical energy. State machine of Agent Drive Train consists of following two states and shown in Figure 23.

- **OFF:** This state is active when turbine is not active and triggered every minute to check current state.
- **ON:** This state is active when turbine is in active state and turbine rotor is in rotating state.

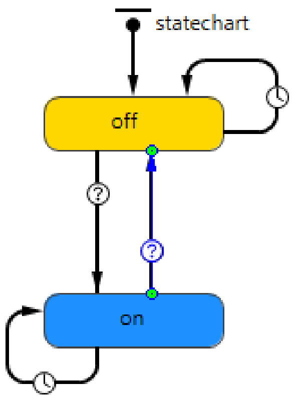

Figure 23: State Machine of Agent Drive Train

When state on is active, drive train calculates torque using following equation.

$$\tau = \frac{Pt}{Pm}$$

This torque is fed into electrical generator designed in our simulation model.

4.1.6 Agent Generator

Agent Generator converts torque calculated in Agent Drive-Train into electrical power. The agent has following two states.

- **OFF:** State remains off when the agent drive train's switch on is false and state is being triggered after every minute
- **ON:** Agent acquires this state when Agent Drive Train is on and torque is being calculated and gained by Agent Generator. The state is triggered every minute.

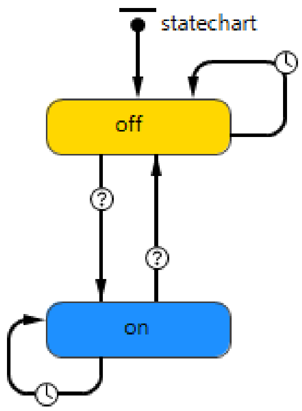

Figure 24: State Machine of Agent Turbine

The agent when gets on calculates stator voltage in d-q frame using equation 5 and 6 respectively on page 15 and 16. At the same instance of time, rotor voltage in d-q frame is calculated using equation 7 and 8 respectively. The voltage equations are then multiplied by rotor and stator currents in d-q frame to obtain rotor and stator power in equation 9 and 10 on page 16. The addition of both powers results in providing us with total electricity generation produced by generator. The temperature has a direct relation with inductance and reactance involved. Therefore, the temperature effect is catered using a function body that variates value of reactance and inductance accordingly.

4.2 Model Composability

Composition of model represents a wind turbine system of Nordex N100/2500 whose capacity is 2.5 MW with set parameters. These set parameters are incorporated in agents to model our proposed framework in accordance with the real time system. Therefore, an agent-based simulation model is represented in which every agent is interlinked with one another. Main supporting agent Turbine contains all sub agents whose working entirely depends on turbine's rotor state. The components are connected through ports in Anylogic environment as shown in Figure 25.

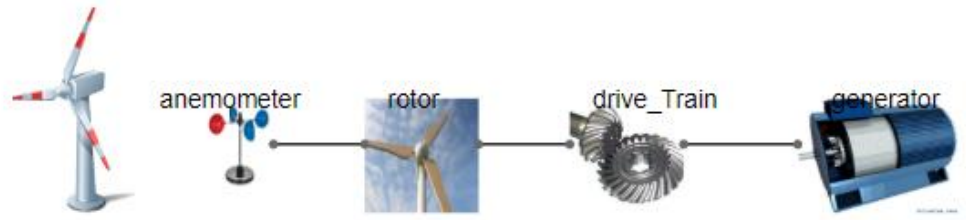

Figure 25: Modular Connection in Main

The moment turbine switch is on; rotor goes into rotating state, captures kinetic energy from wind Rotor in the rotating state, and converts kinetic energy into mechanical power. Soon after the rotor goes into the rotating state pitch-drive starts analyzing the tip speed ratio and Beta angle to provide maximum value of Cp to extract maximum power from wind energy. Turbine drive train gets active when rotor goes into rotating state. Drive Train in on state starts converting mechanical energy into torque to transfer it to the generator. Generator calculates the stator power and rotor power and sums up both powers to extract the active power generated through wind speed. The model halts its operation at the time of turbine failure or maintenance or when wind speed increases above cut out speed that is 25 m/s or decreases below cut in speed that is 3 m/s. Therefore, no electricity is produced until wind speed gets normal and within range of 3 m/s to 25 m/s or maintenance of wind turbine is performed. The recovery time of each turbine is 3 hours and failure probability is 0.025. The model incorporates all parameters to ensure best forecasting results. The simulation results are discussed in detail in next chapter.

Chapter 5

Simulation and Results

This chapter demonstrates the functionality of our proposed framework. We simulate Agent-Based Model of Wind Turbine System that forecasts energy generation and will help regulatory authorities to use wind energy to produce electricity and eliminate blackouts from the country.

5.1 Case Study: Foundation Wind Energy-II (Private) Limited

Fauji Foundation Group comes in the founders who introduced the concept of alternate energy in Pakistan. The plant set up by this group is located at Gharo, Sindh. The total installed capacity of the plant is 50 MW and contains twenty turbines of Nordex N100/2500, each turbine has a capacity to produce 2.5 MW. This plant in ownership with Fauji Foundation, Fauji Fertilizer Bin Qasim Limited, Tapal and IIF Wind One Limited was set up under policy for Development of Renewable Energy for Power Generation, 2006. The policy offers guaranteed internal rate of return, cost indexation and pass-through tariff structure.

Wind farm location on the map, wind farm layout and sitting of wind farm is shown in Figure 26, 27 and 28 respectively [52].

Figure 26: Location of Foundation Wind Farm

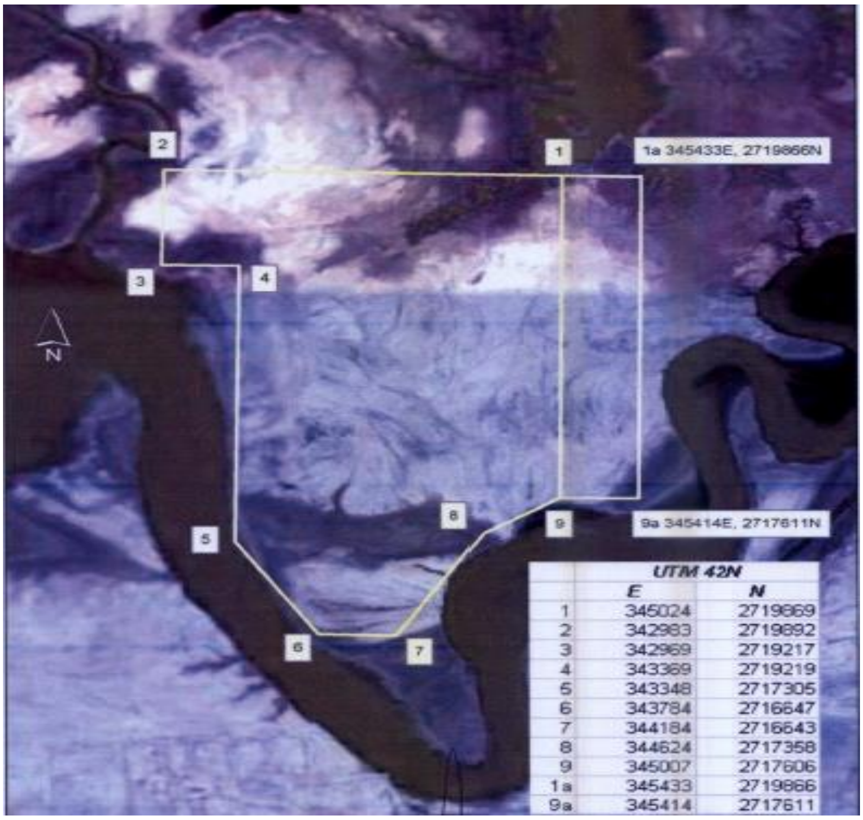

Figure 27: Layout of FWEL

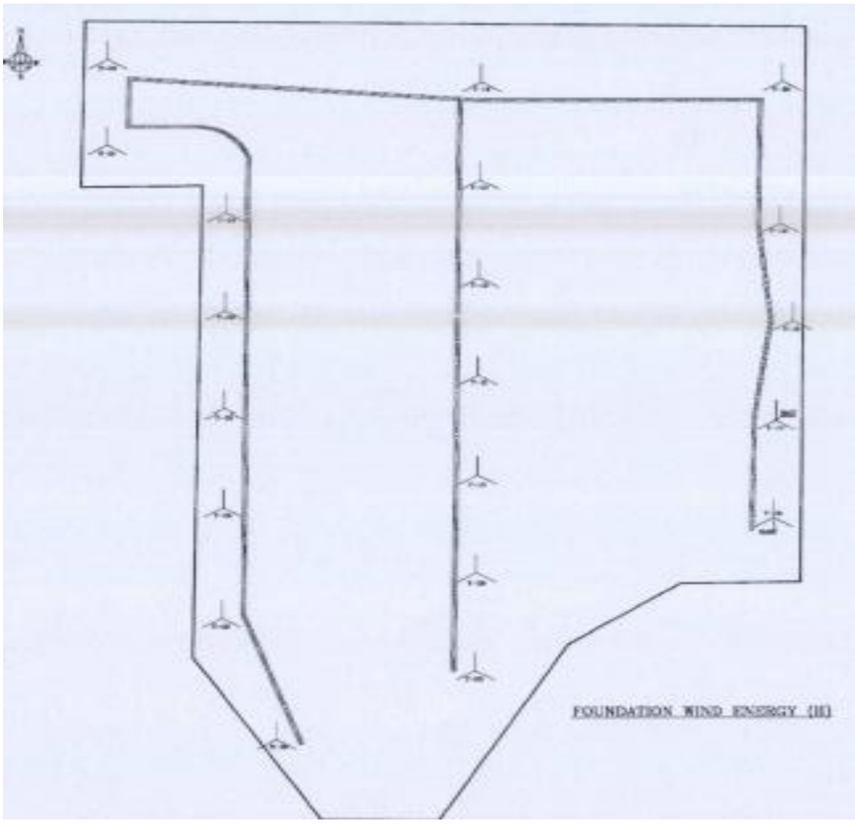

Figure 28: Micro Sitting of Wind Farm

The power curve versus wind speed at air density 1.160 kg/m^3 given in liscence agreement of Foundation is shown in Figure 36 and Table 4 provides output power at different wind speeds.

Wind Speed (m/s)	Output Power (kW)
1	0
2	0
3	1.7
4	95.5
5	241.6
6	446.3
7	722.7
8	1085.50
9	1528.30
10	2018.50
11	2352.10
12	2490.10
13-25	2500

Table 4: Wind speed and Output Power

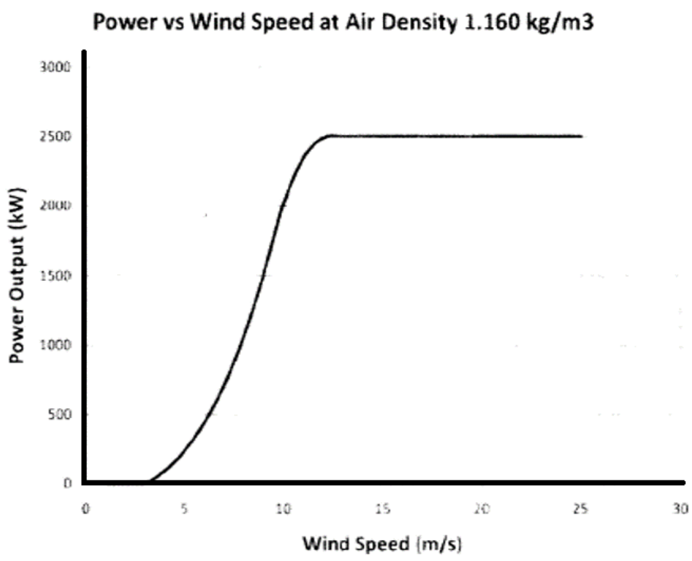

Figure 29: Power vs Wind Speed

5.1.1 Nordex N100/2500 Wind Turbine

Nordex wind turbines are rendered as the most worth investing company in wind turbine sector. It offers a high level of technical availability of more than 98% and it

allows grid operator to directly control the rated power of grid. Nordex N 100/2500 is designed to use for areas with moderate wind conditions with widely different climatic conditions and lies under Gamma Generation. The gamma generation turbines achieve maximum yield at almost every site, maintains voltage, and stabilize frequency of the public grid by outstanding control capabilities.
The facts and figures of Nordex N100/2500 is shown in Figure 30.

N100/2500 IEC 2a	
Operating data	
Rated power	2,500 kW
Cut-in wind speed	3 m/s
Cut-out wind speed	25 m/s
Rotor	
Diameter	99.8 m
Swept area	7,823 m²
Operating range rotational speed	9.6–16.8 rpm
Rated rotatinal speed	14.9 rpm
Tip speed	77 m/s
Speed control	Variable via microprocessor
Overspeed control	Pitch angle
Gearbox	
Type	3-stage gearbox (planetary-planetary-spur gear) or 4-stage gearbox (planetary-planetary-differential-spur gear)
Generator	
Construction	Double fed asynchronous generator
Cooling system	Liquid/air cooling
Voltage	660 V

Figure 30: Facts and Figures of Nordex N100/250

5.2 Simulation

Our proposed framework simulates on data provided by Foundation Wind Energy Private Limited. The data is SCADA data for two months (High Wind and Low Wind) and the trends are same throughout the year for each category. The actual generation against provided wind speed is shown in figure 31 where x- axis represents time and y-axis shows Actual Generation.

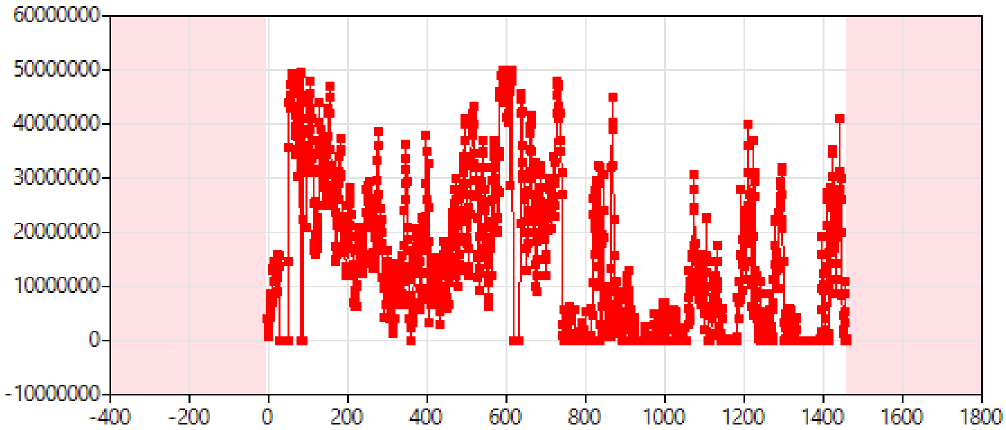

Figure 31: Actual Generation

Simulation runs on the two months data of wind speed and actual generation provided by Foundation Wind Energy Private Limited. Initially, simulation of one turbine was run to visualize simulation trend versus provided actual generation trend. Once the forecasting trend was recognized with actual generation then simulation was run for 20 turbines simultaneously to get total energy generation of Foundation Wind Power Plant for provided two months data. The simulation forecasts energy generation up to 50 MW. The simulation shows high-energy generation pattern for high wind speeds and low generation pattern for low wind speeds whereas there is no energy generation at wind speeds below cut in speed or above cut out speed. The simulation is carried out on hourly resolution thus making the window size equals to 1464 hours. The simulation results are discussed in the following section.

5.3 Results

The simulation model runs in accordance with the provided parameters and generator capacity. The designed generator's output graph versus wind speed is shown in Figure 32. The curve shows a gradual increase in power generation as the wind speed increases. The lowest value of power production is 1700 Watts at 3 m/s and rated power of 2.5 MW is achieved at 13 m/s and continues until speed reaches 25 m/s.

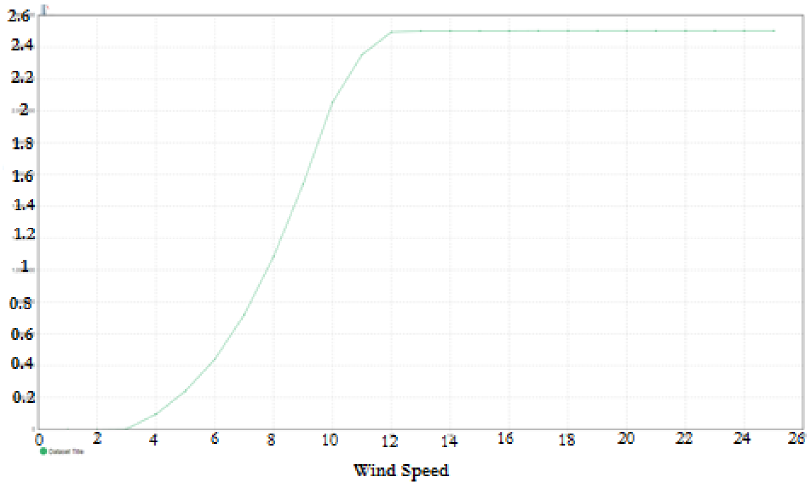

Figure 32: Generator's Power Output vs Wind Speed

The forecasting trend of energy generation of one turbine with a total generation capacity of 2.5 MW is shown in Figure 33

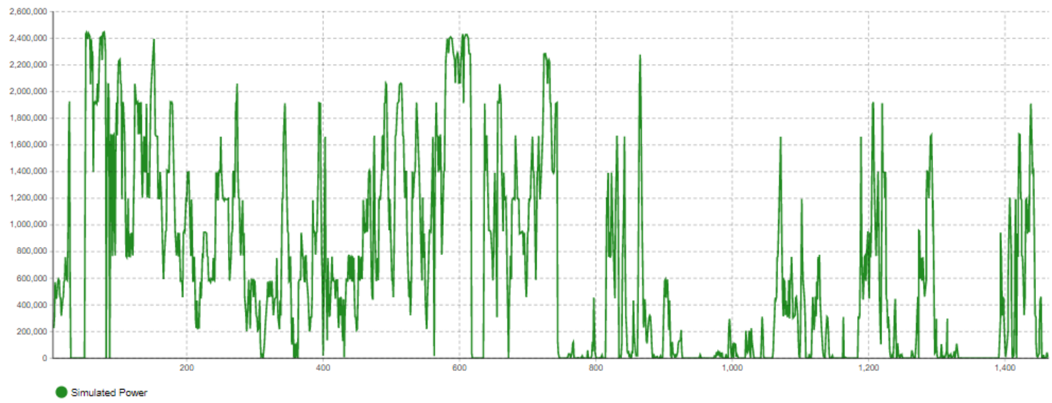

Figure 33: Simulated Generation of Single Turbine

The simulation generation pattern of complete Wind Power Plant is replicated using Agent-Based approach discussed earlier that sums up agent behavior of twenty turbines and shows energy generation trend of simulated power plant. The energy curve shows maximum rise up to 50 MW (equals to installed capacity of Wind Power Plant) and is shown in Figure 34.

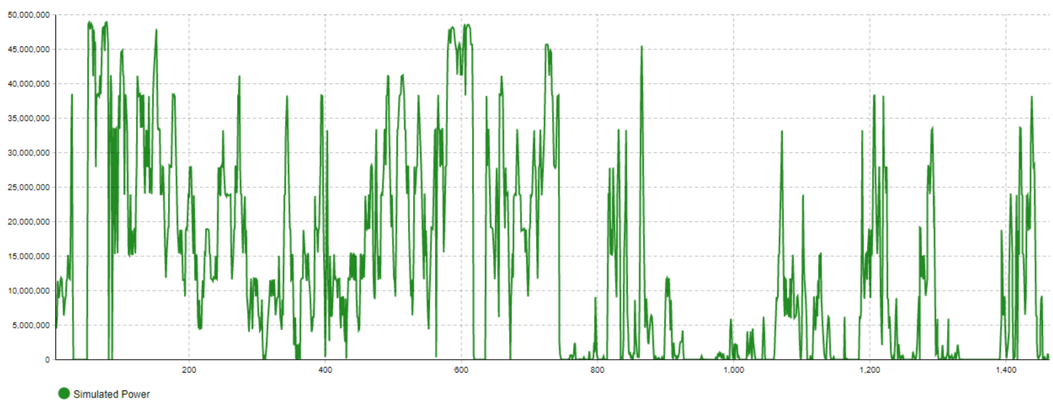

Figure 34: Simulated Generation of WPP

5.4 Model Validation

The model is validated by plotting simulation results parallel with the actual generation trend. Likewise, simulation results, the model is also validated in the same manner by first plotting simulation trend of single turbine versus actual generation trend and is shown in figure 35. The graph plot shows minor difference of simulated generation from actual generation and major difference is that simulated generation is usually more at a given wind speed than actual generation and the fact is simulators cannot model real time parameters. The RMSE value calculated

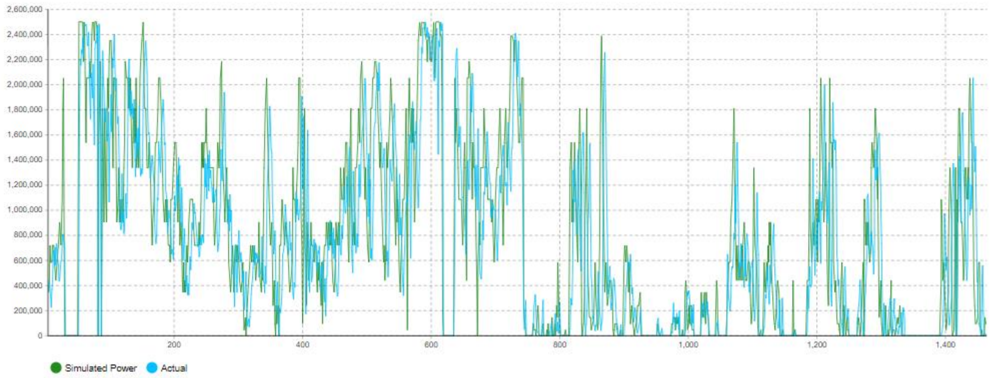

Figure 35: Simulated Generation vs Actual Generation of Single Turbine

The simulator is later run for Wind Power Plant and produces maximum power of 50 MW whereas actual generation is up to 49 MW. The simulated generation trend in comparison with the actual generation trend is shown in Figure 36 and the RMSE value calculated is **9.33**.

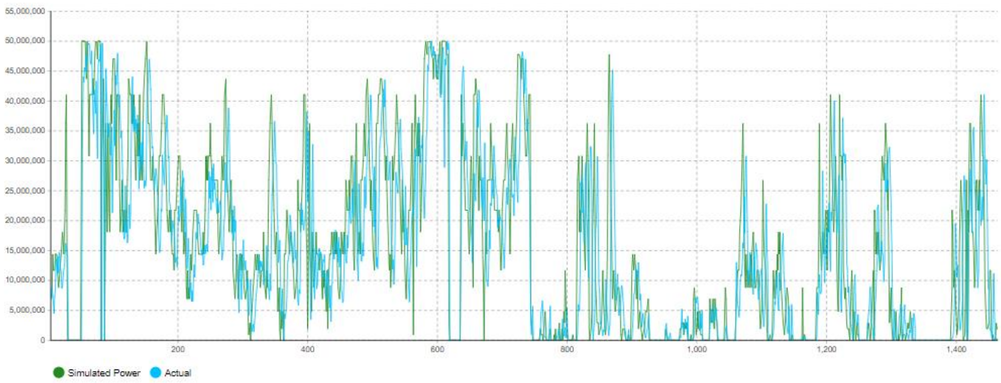

Figure 36: Simulated Generation vs Actual Generation of WPP

The model is also validated in a statistical analysis software Minitab 18 that allows user to focus on analysis of data and interpretation of graphs by automating calculations and creating graphs. The data of simulated generation and actual generation of Foundation Wind Power Plant is streamlined in Minitab 18 to validate actual and simulated generation trend. The graph below shows time series plot of Actual and Simulated Electricity Generation pattern.

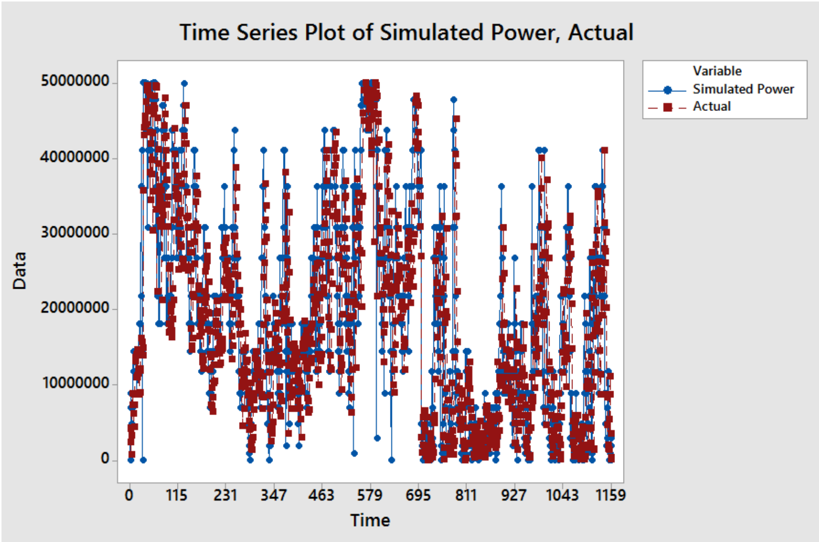

Figure 37: Time Series Plot of Simulated vs Actual Generation

The graph plot shown in Figure 38 represents simulated and actual generation trends with a smoother line, which enables us to explore the potential relationship between actual and simulated generation without fitting in the Wind Turbine model. Smoother lines are calculated using the lowess smoothing method, which is common technique for smoothing line. Lowess stands for locally weighted scatterplot smoother. The default-selected fraction degree of smoothing equals to 0.5 and number of steps equals to '2' are used for all points, using data closest to each x-value on either side of the (x-y) points. Minitab does a weighted linear regression for all data points giving points closest to each x value the most weight in smoothing and limiting the effects of the outliers. Smoother line shows that the curvature of the relationship between Actual Generation and Simulated Generation do not change sharply.

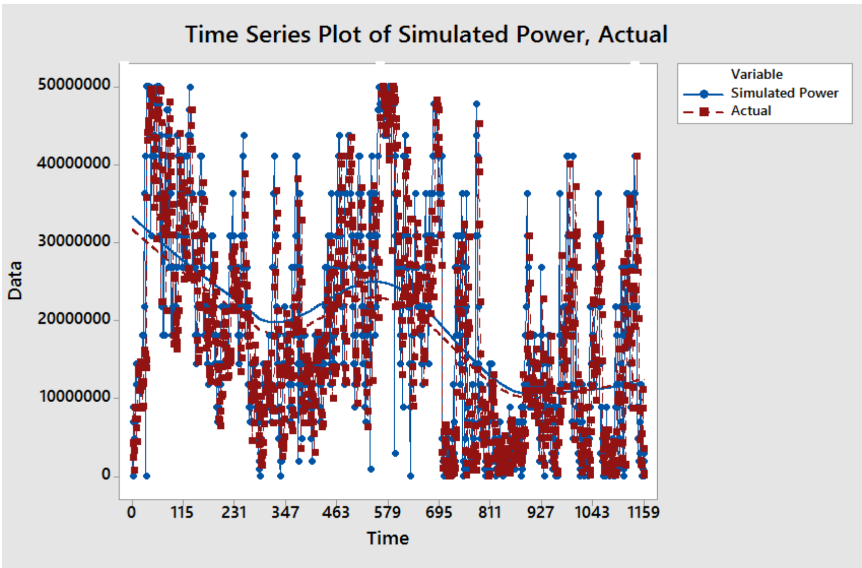

Figure 38: Time Series Plot of Simulated vs Actual Generation with Smoother

The time series analysis is a sequence of discrete time data taken at successive equally spaced intervals and these data points are indexed in time order. Time series are usually plotted using line chart and are widely used in a number of fields that involve temporal measurements. Time series analysis does include Time Series Forecasting that makes use of model to predict future values based on previously observed values. Time series forecasting is implemented on provided dataset of Actual Generation to forecast future values based on previously observed data on Minitab 18. The forecasted fits are produced using HoltWinters Technique and are shown in Figure 39.

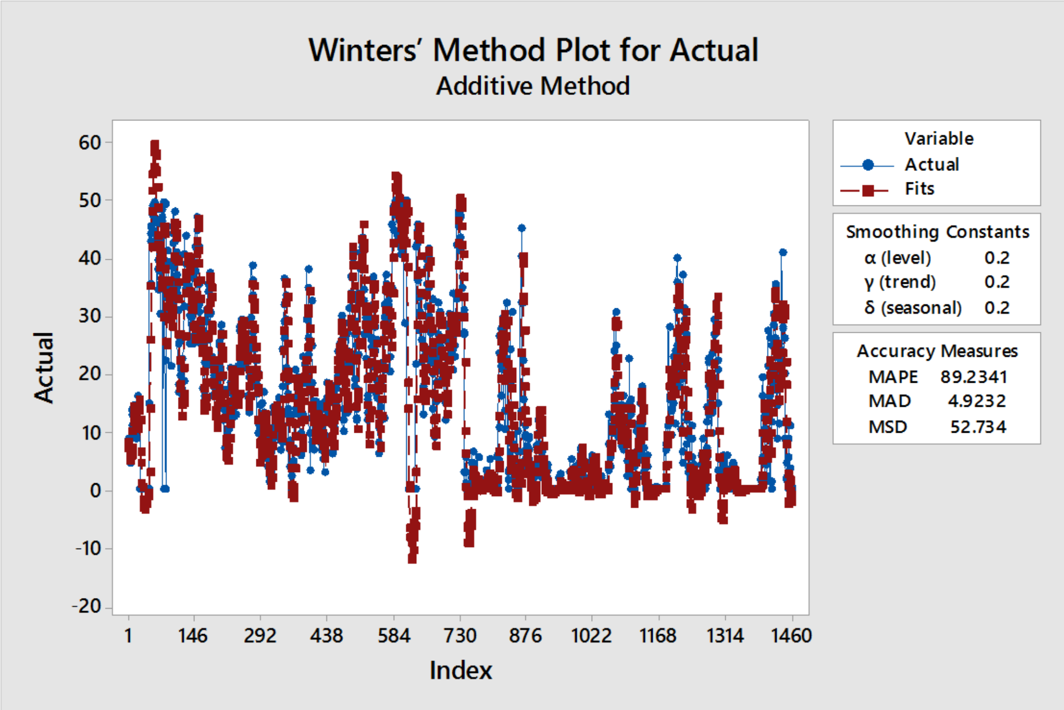

Figure 39: Time Series Analysis using HoltWinter's Technique

The comparison results of simulator's forecast and time series forecast in the form of Mean Absolute Deviation (MAD), Root Mean Square Error (RMSE), Mean Absolute Percentage Error (MAPE) and Mean Signed Difference (MSD) are listed in Table 5.

Analysis	MAD	RMSE	MAPE	MSD
Simulation	4.410	7.407	54.06	54.869
HoltWinter's	4.9232	7.2618	89.2341	52.734

Table 5: Validation Results

Chapter 6

Conclusion and Future Work

This chapter provides the discussion, conclusion and future work of the thesis.

6.1 Conclusion

In this thesis, we discussed advantages of using renewable energy resources to generate electricity in Pakistan where still old typical techniques of generation through fossil fuels is carried out which does not even lack to fulfil energy demand but also result in fossil fuels depletion and cause great environmental hazards. Pakistan is a country with abundant renewable energy resources and coastal regions of the country offers great wind power potential to produce electricity. Many Wind Power Plants have been installed at the coastal areas of Pakistan to make use of wind potential to generate electrical energy but to impart reliability assurance to energy investor to take an account on how much electricity can be produced by the wind potential before implanting turbines is of great importance. Therefore, we propose an Agent-Based Model of Wind Power Plant based on Nordex N100/2500 wind turbine planted by Foundation Energy Private Limited at Gharo, Sind. Our proposed simulation forecasts energy generation pattern of WPP and is validated on SCADA data of wind speed and actual generation provided by the company.

The aim of this study is to help regulatory authorities and energy generation sector to get a better picture of how much wind potential in Pakistan can contribute in electricity generation.

6.2 Future Work

Wind speed acts as a dynamic variable and has vital importance in energy generation forecasting of a Wind Power Plant. Therefore, we intend to modify our proposed framework to predict wind speed dynamically either through calibration or other useful techniques to comprehend energy generation pattern accordingly at a particular instant of time (at present as well as in future). This will not only fill any missing data gaps but will also help in verifying current wind readings.

Addition to this, we plan to run our simulation model for different Wind Power Plants to forecast their energy generation patterns at different instance of time. This will allow Energy Generation sector to get a better insight of their Wind Power Plant's production capacities. Moreover, it will assist decision-making authorities to accommodate any electric shortfalls timely, and will help them cope with current energy deficit.

References

[1] Charles K Ebinger, "Energy and Security in South Asia: Cooperation or Conflict? - Charles K. Ebinger - Google Books," 2011. [Online]. Available: https://books.google.com.pk/books?hl=en&lr=&id=AOtbeFN3b9sC&oi=fnd&pg=PP1&dq=Energy+and+Security+in+South+Asia&ots=GTJ-3t_NZf&sig=DKywTZyUXYmi94nuwv4aoyQ9y1E#v=onepage&q=Energy and Security in South Asia&f=false. [Accessed: 18-Apr-2019].

[2] G. Das Valasai, M. A. Uqaili, H. R. Memon, S. R. Samoo, N. H. Mirjat, and K. Harijan, "Overcoming electricity crisis in Pakistan: A review of sustainable electricity options," *Renew. Sustain. Energy Rev.*, vol. 72, pp. 734–745, May 2017.

[3] S. T. Dye, "Geoneutrinos and the radioactive power of the Earth," *Rev. Geophys*, vol. 50, p. 3007, 2012.

[4] M. Castillo *et al.*, " The alkaloids of L. paniculatum and the structure of paniculatine ," *Can. J. Chem.*, vol. 54, no. 18, pp. 2900–2908, 2006.

[5] S. Chu and A. Majumdar, "Opportunities and challenges for a sustainable energy future," *Nature*, vol. 488, no. 7411, pp. 294–303, Aug. 2012.

[6] M. Amer and T. U. Daim, "Selection of renewable energy technologies for a developing county: A case of Pakistan," *Energy Sustain. Dev.*, vol. 15, no. 4, pp. 420–435, Dec. 2011.

[7] M. H. Baloch, G. S. Kaloi, and Z. A. Memon, "Current scenario of the wind energy in Pakistan challenges and future perspectives: A case study," *Energy Reports*, vol. 2, pp. 201–210, Nov. 2016.

[8] J. B. Faheem, "Energy Crisis in Pakistan," *IRA-International J. Technol. Eng. (ISSN 2455-4480)*, vol. 3, no. 1, pp. 1–16, 2016.

[9] I. A. Raja and R. S. Abro, "Solar and wind energy potential and utilization in Pakistan," *Renew. Energy*, vol. 5, no. 1–4, pp. 583–586, Aug. 1994.

[10] K. Harijan, M. A. Uqaili, M. Memon, and U. K. Mirza, "Forecasting the diffusion of wind power in Pakistan," *Energy*, vol. 36, no. 10, pp. 6068–6073, Oct. 2011.

[11] M. A. Sheikh, "Energy and renewable energy scenario of Pakistan," *Renew. Sustain. Energy Rev.*, vol. 14, no. 1, pp. 354–363, Jan. 2010.

[12] "Wildlife of Pakistan: Introduction to Pakistan." [Online]. Available: http://www.wildlifeofpakistan.com/IntroductiontoPakistan/introductiontoPakistanmain.htm. [Accessed: 18-Apr-2019].

[13] K. Harijan, M. A. Uqaili, M. Memon, and U. K. Mirza, "Assessment of centralized grid connected wind power cost in coastal area of Pakistan," *Renew. Energy*, vol. 34, no. 2, pp. 369–373, Feb. 2009.

[14] "Statistics | World - Total Primary Energy Supply (TPES) by source (chart)." [Online]. Available: https://www.iea.org/statistics/?country=WORLD&year=2016&category=Energy supply&indicator=TPESbySource&mode=chart&dataTable=BALANCES. [Accessed: 18-Apr-2019].

[15] R. P. Butt, I. A. Chaudhry, I. Zahid, and M. Ali Shakir, "Enhancement of Wind

Power Generation in Pakistan," *Sci.Int.(Lahore)*, vol. 27, no. 6, pp. 5053–5058, 2015.

[16] I. Ullah, Q.-Z. Chaudhry, and A. J. Chipperfield, "An evaluation of wind energy potential at Kati Bandar, Pakistan," *Renew. Sustain. Energy Rev.*, vol. 14, no. 2, pp. 856–861, Feb. 2010.

[17] M. A. Türkiye Bilimsel ve Teknik Araştırma Kurumu., F. AHMED, and M. W. AKHTAR, *Turkish journal of physics.*, vol. 30, no. 2. Scientific and Technical Research Council of Turkey, 1994.

[18] "Jhimpir Wind Power: Pakistan's first wind farm gets global recognition | The Express Tribune." [Online]. Available: https://tribune.com.pk/story/368376/jhimpir-wind-power-pakistans-first-wind-farm-gets-global-recognition/. [Accessed: 18-Apr-2019].

[19] RWE npower renewables, "Wind Turbine Power Calculations," *Wind Turbine Power Calc.*, vol. 1, no. 1, pp. 1–5, 2009.

[20] C. S. Wang and M. H. Chiang, "A novel dynamic co-simulation analysis for overall closed loop operation control of a large wind turbine," *Energies*, vol. 9, no. 8, 2016.

[21] M. Singh and S. Santoso, "Dynamic Models for Wind Turbines and Wind Power Plants Dynam,NREL/SR-5500-52780, Golden, Colorado: National Renewable Energy Laboratory," no. October, p. 115, 2011.

[22] I. Press, L. Shafer, G. W. Arnold, and D. Jacobson, *Handbook of Electrical Power System Dynamics*. 2013.

[23] "WIND-WORKS: Quiet Revolution Goes Quiet: Maker of QR5 VAWT Files for Bankruptcy." [Online]. Available: http://www.wind-works.org/cms/index.php?id=64&tx_ttnews%5Btt_news%5D=3103&cHash=be80a2ca690fe1bcec1c0dc0af1e795b. [Accessed: 18-Apr-2019].

[24] "MHI Vestas Launches World's First* 10 Megawatt Wind Turbine | CleanTechnica." [Online]. Available: https://cleantechnica.com/2018/09/26/mhi-vestas-launches-worlds-first-10-megawatt-wind-turbine/. [Accessed: 18-Apr-2019].

[25] "The Inside of a Wind Turbine | Department of Energy." [Online]. Available: https://www.energy.gov/eere/wind/inside-wind-turbine. [Accessed: 18-Apr-2019].

[26] A. Latif and N. Ramzan, "a Review of Renewable Energy Resources in Pakistan," *J. Glob. Innov. Agric. Soc. Sci.*, vol. 2, no. 3, pp. 127–132, 2015.

[27] H. AbolhosSseini, A. Heshmati, and J. Altmann, "A review of renewable energy supply and energy efficiency technologies," *IZA Discuss. Pap. Ser.*, no. 8145, pp. 1–36, 2014.

[28] J. G. M. and A. l. R. J.F. Manwell, *Overview of design chapter*, vol. 2. 2002.

[29] M. Singh, E. Muljadi, J. Jonkman, V. Gevorgian, I. Girsang, and J. Dhupia, "Simulation for Wind Turbine Generators -- With FAST and MATLAB-Simulink Modules," no. April, 2014.

[30] A. Sarkar and D. K. Behera, "Wind Turbine Blade Efficiency and Power Calculation with Electrical Analogy," *Int. J. Sci. Res. Publ.*, vol. 2, no. 1, pp. 2250–3153, 2012.

[31] R. T. Ahmad, "Modeling and Simulation of Wind Turbine Generator Using

Matlab-Simulink Mahdi A . Abdul-Hussain University of Technology," *J. Al Rafidain Univ. Coll.*, no. 40, pp. 282–300, 2017.

[32] P. Eberhart, T. Shan Chung, A. Haumer, and C. Kral, "Open Source Library for the Simulation ofWind Power Plants," *Proc. 11th Int. Model. Conf. Versailles, Fr. Sept. 21-23, 2015*, vol. 118, pp. 929–936, 2015.

[33] C. Seceleanu *et al.*, "Analyzing a wind turbine system: From simulation to formal verification," *Sci. Comput. Program.*, vol. 133, pp. 216–242, 2017.

[34] A. Tuohy and M. O'Malley, *Wind Power in Power Systems*. 2012.

[35] I. P. Girsang, J. S. Dhupia, E. Muljadi, M. Singh, and L. Y. Pao, "Gearbox and drivetrain models to study dynamic effects of modern wind turbines," *IEEE Trans. Ind. Appl.*, vol. 50, no. 6, pp. 3777–3786, 2014.

[36] G. L. Johnson, "Wind Turbine Power , Energy , and Torque," *Wind Energy Syst.*, pp. 1–54, 2001.

[37] A. Tapia, G. Tapia, J. Xabier Ostolaza, and J. R. Sáenz, "Modeling and control of a wind turbine driven doubly fed induction generator," *IEEE Trans. Energy Convers.*, vol. 18, no. 2, pp. 194–204, 2003.

[38] G. Abad, J. López, M. A. Rodríguez, L. Marroyo, and G. Iwanski, *Doubly Fed Induction Machine*. 2011.

[39] N. W. Miller and J. J. Sanchez-gasca, "Modeling of GE Wind Turbine-Generators for Grid Studies Prepared by :," 2008.

[40] M. Elazzaoui, "Modeling and Control of a Wind System Based Doubly Fed Induction Generator: Optimization of the Power Produced," *J. Electr. Electron. Syst.*, vol. 04, no. 01, pp. 1–8, 2015.

[41] K. Valipour, R. Najafi, and M. Bakhshi, "Mathematical modeling and simulation of DFIG wind turbine," *Journal of Engineering and Applied Sciences*, vol. 11, no. 9. pp. 2072–2078, 2016.

[42] E. Kremers, J. M. G. De Durana, O. Barambones, P. Viejo, and N. Lewal, "Agent-Based Simulation of Wind Farm Generation at Multiple Time Scales," *Wind Farm - Impact Power Syst. Altern. to Improv. Integr.*, 2012.

[43] E. Kremers, N. Lewald, O. Barambones, and J. M. G. de Durana, "An Agent-based Multi-Scale Wind Generation Model," *Eur. Power Energy Syst.*, pp. 1–5, 2009.

[44] O. Kraan, G. J. Kramer, and I. Nikolic, "Investment in the future electricity system - An agent-based modelling approach," *Energy*, vol. 151, pp. 569–580, 2018.

[45] M. Vasirani, R. Kota, R. L. G. Cavalcante, S. Ossowski, and N. R. Jennings, "An agent-based approach to virtual power plants of wind power generators and electric vehicles," *IEEE Trans. Smart Grid*, vol. 4, no. 3, pp. 1314–1322, 2013.

[46] J. M. Gonzalez De Durana, O. Barambones, E. Kremers, and L. Varga, "Agent based modeling of energy networks," *Energy Convers. Manag.*, vol. 82, no. June, pp. 308–319, 2014.

[47] M. Sahnoun *et al.*, "Modelling and simulation of operation and maintenance strategy for offshore wind farms based on multi-agent system," *J. Intell. Manuf.*, pp. 1–17, 2015.

[48] P. Hansen, X. Liu, and G. M. Morrison, "Agent-based modelling and socio-

technical energy transitions: A systematic literature review," *Energy Res. Soc. Sci.*, vol. 49, no. November 2018, pp. 41–52, 2019.

[49] E. H. M. Mast, G. A. M. van Kuik, and G. J. W. van Bussel, "Agent-based modelling for scenario development of offshore wind energy," *Proc. 2007 Eur. Wind Energy Conf. Exhib. Milan*, no. January, p. 5, 2007.

[50] Lab-Volt staff, "Principles of Doubly-Fed Induction Generators (DFIG)," p. 39, 2011.

[51] S. Saini, "Review of Doubly Fed Induction Generator Used in Wind Power Generation," vol. 4, no. 2231, pp. 53–56, 2013.

[52] "LPM-of- Foundation -II-dated-December-22-2011.PDF." .