A STUDY OF SENSORLESS CONTROLLER

FOR DIRECT DRIVE WIND

ELECTRIC CONVERSION SYSTEMS

By

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Title of Study: A STUDY OF SENSORLESS CONTROLLER FOR DIRECT DRIVE WIND ELECTRIC CONVERSION SYSTEMS

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Abstract: The direct drive machine used in wind turbine systems (WECS) is efficient due to absence of losses rotor losses and lower no load current. The goal of this study is to propose and develop a neuron-based controller to optimize wind turbine output power by considering two objectives; maximize power extraction by wind turbine and predict and analyze pitch angle to gain maximum power. The proposed controller is designed to take the following inputs: wind velocity, pitch angle and wind turbine electrical output. The controller then finds the optimal pitch to predict the maximum power that can be extracted. The controller has a neural network model that is a feed forward, three-layered perceptron. This model explains the integration of controller providing wind speed estimation and robust control of maximum power extraction with no rapid drift on the power coefficient curve.

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List of symbols used:

v - wind speed in m/s

$v_{\circ}$ - average wind speed in m/s

C_n - magnitude of Eigen swing n (constant)

ω_n - Eigen frequency of the Eigen swing n in rad/s

P - power generated in W

ρ - air density in kg/m^3

A - area in m^2

P_{opt} - optimal power extracted from the wind in W

K_{opt} is the optimal constant in power in wind equation

$\sigma(\varepsilon)$ – threshold function

ε – transfer function at an instant'‘t’

E - error between desired output and output

$\Delta_i(n)$ – gradient at node ‘i’

D – difference in rank in Spearman’s rank correlation

β – pitch angel in degree

λ – tip speed ratio (constant)

R – position

ω – generator speed in rad/s

C – power coefficient (constant)

T_m or T_{turb} – mechanical torque in N-m

T_e – electrical torque in N-m

K_s – machine rotor constant

J_m – torsion in drive train in Nm

J_g – generator torsion acting in Nm

i_{im} - stator current in motor for ‘i’ phase in A

v_i back emf induced in phase ’i’ in V

L_{ij} stator winding inductance between ‘i’ and ‘j’ phases in H

φ – flux linkage in Wb/m^2

R_m – internal resistance in generator in ohms

L_s – internal inductance of generator in H

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CHAPTER 1

INTRODUCTION

1.1 Current Energy Scenario

Stability of global economy and its growth require a secure, reliable and affordable energy supply. This energy supply comes from many resources such as coal, oil, natural gas, nuclear and renewable energy. Use of nonrenewable resources emit harmful pollutants such as sulfur dioxide, nitrogen oxide, ozone, particulate matter, mercury and carbon dioxide and this has accelerated the shift to utilization of renewable resources. The growing public awareness of environmental changes, limited energy supplies and uncertain energy prices have resulted in global shift towards "green" technologies.

Almost all the available energy resources are direct or indirect products of incident solar radiation (insolation). This energy is used for lighting homes, for generating electricity, hot water heating, cooking and many other diverse uses in commercial and industrial sectors. Renewable resources replenish themselves within a certain span of time and hence they have gained wider acceptance in the past few decades. Therefore, these replenishable resources can be used as long as we have solar energy incident on the earth's surface. Renewable energy benefits the nation by providing energy security, conserving natural resources, lowering the risk of oil spills in addition to reducing the need for imported fuels. However, these resources are dilute and require high capital costs to harness them. Global electricity consumption is increasing rapidly along with growing energy prices. This is accelerated by population growth with increasing expectations. Coal consumption is expected to be doubled by 2030 and to make matters worse; renewable energy (excluding Hydro and biomass) use is growing only at 6% annually and aggregates to only 2% of primary share at present [1]. To meet the global need, research and development of new techniques are required in the case of all resources available such as data on energy resources, prices and alternatives that can help improve their use to meet the future needs. Global electricity consumption experienced a growth of 5.91% in 2012 [2]. The global consumption of energy resources is shown in figure 1.1. Liquid fuel include petroleum, liquefied petroleum gas, bio diesel and alcohols. Coal consumption is growing at a higher rate as compared to other fuel types.

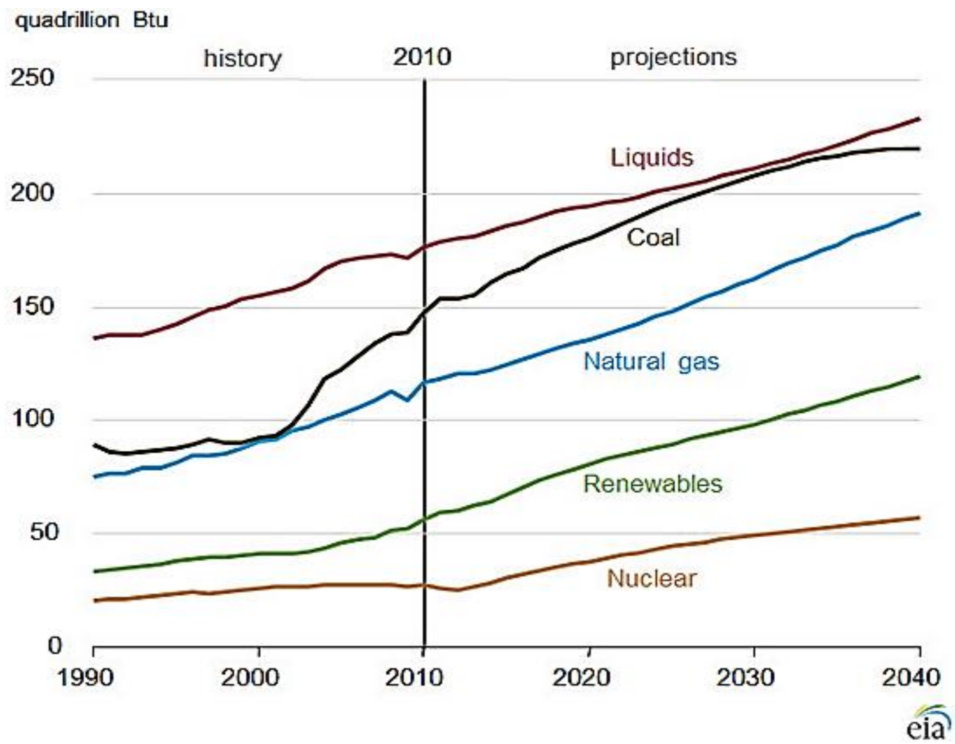


Figure 1.1: Global consumption of electricity by fuel type [7]

Wind energy, recognized as one of the significant forms of renewable energy, has enjoyed rapid expansion of investments. Moreover, the power derived from wind is a driving force for a sustainable future since it is cost-effective and generates revenue and job opportunities. The U.S. Energy Information Administration reported an increase in contribution of wind energy to electricity supply by 2.6 percent per year since 2010 [3].

However, challenging concerns, such as higher operation, maintenance and market costs as compared to other conventional energy sources in many areas across the country, pose a great challenge. To address this issue, several questions related to wind energy need to be answered, including providing control strategies to increase wind energy extraction with the given design limitation.

1.2 Evolution of Wind Energy Conversion Systems

The history of wind turbines shows a broad evolution from the use of basic lightweight devices driven by aerodynamic lift, heavy material drag devices all the way to light material (fiberglass) efficient drag devices for the modern age. The technique used in wind turbines is not new as it is one of the earliest known means used in sailboats, which had important impact on transportation. Earliest sailors intuitively knew lift and used it every day although they lacked the knowledge

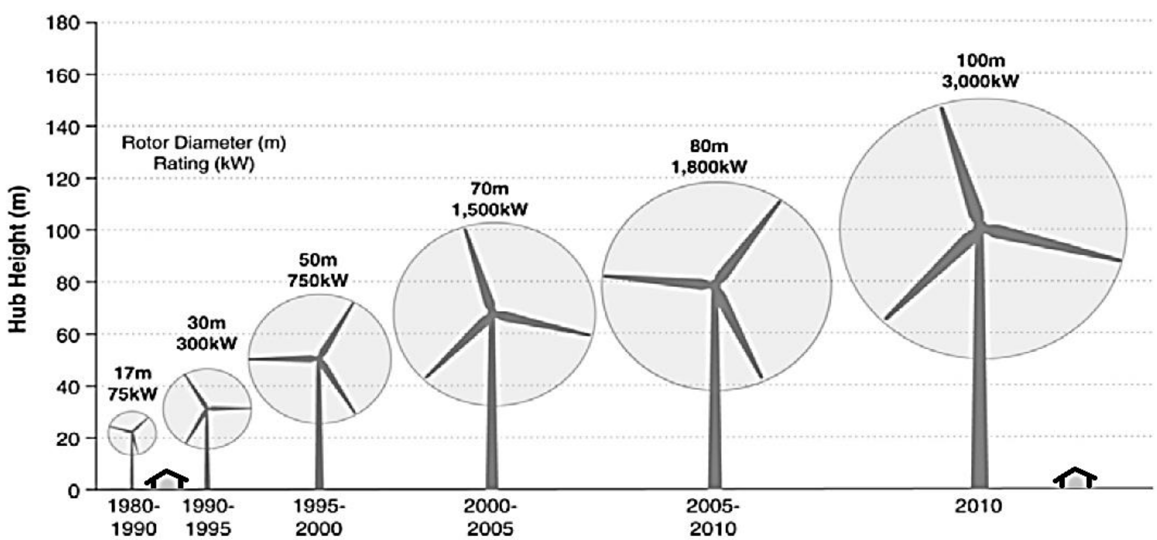


Figure 1.2: Wind turbine size evolution since 1980 [8]

how or why it worked. The first working windmill was for of grain grinding, water pumping, etc. dating back to 500-900 A.D. However, not until the 19^{th} century the technology was used for electricity generation as developed by Charles F. Brush (1888) [3]. The evolution of the wind turbine size has increased exponentially as shown in figure 1.2.

After its economic advantages were known, involvement of federal interest in wind turbines rose to be the conventional electricity generation with current market share of 60% [4]. During the past two decades, wind turbine ratings have grown steadily with an average power rating of 1.5 MW in the case of large units, simultaneously reducing the life cycle cost of energy. The size of these machines is increased and the rotor is installed at a suitable height to capture maximum wind, thus avoiding the wind turbulence generated by the terrain surrounding the wind turbines. This approach increases the capacity factor of the turbines (as illustrated in above fig.1.2). This often leads to land transportation restrictions, crane specifications and lift to move the rotor to the required tower height. With advancements in design and research, better design models can help overcome the limit to size [5].

The rotor blade lengths have increased from 8m to 50m since 1980 to the present. Blades are designed to be weight tolerant, lighter and stronger and are less prone to fatigue. During the past two decades, the aerodynamic performance of wind turbines has improved radically with rotor blade system capturing as much as 30% of the wind energy, optimizing low speed efficiency and regulating aerodynamic loads in high winds. At present, controllers are integrated with sensors to control power generated, torque, blade pitch angle and rotor speed of the wind turbine to maximize its efficiency. Wind turbines have evolved in their application to offshore with ratings up to five mega-watts each. Offshore wind turbines, constructed on oceans, lakes, etc. have the advantage of low turbulent wind flowing through them giving smooth power output and less environmental limitations. As of 2012, globally 4,620 MW of wind system capacity was derived from offshore wind turbines, amounting to 2% of total installed wind power capacity [6].

Evidently, the designs of such machines are undergoing rapid evolution, including the design of direct drive systems. In the recent past, wind turbines served the utility sector well and will continue to play a significant role of electricity generation and a hope for a renewable energy future.

1.3 Objective

The goal of this thesis is to propose and develop a neuron-based controller to optimize wind turbine output power by considering two objectives; maximize power extraction by wind turbine and predict and analyze pitch angle to gain maximum power. Engineers introduced models to predict wind power and describe variations. The majority of published research deals theoretical data and PID controllers whereas the data in this thesis contains real time data of Elk City, Oklahoma. It is widely recognized such models involve assumptions and therefore may not represent reality. Variability in the wind speed-power output characteristic between cut-in wind speed and rated wind speed of a wind electric conversion system is considered. The wind data collected in real-time for Elk City, Oklahoma is used in this study.

The proposed controller is designed to take the following inputs: wind velocity, pitch angle and wind turbine electrical output. The controller then finds the optimal pitch to predict the maximum power that can be extracted. The controller has a neural network model that is a feed forward, three-layered perceptron. This model explains the integration of controller providing wind speed estimation and robust control of maximum power extraction with no rapid drift on the power coefficient curve.

1.4 Thesis Outline-

Figure 1.3 shows the block diagram of the thesis structure

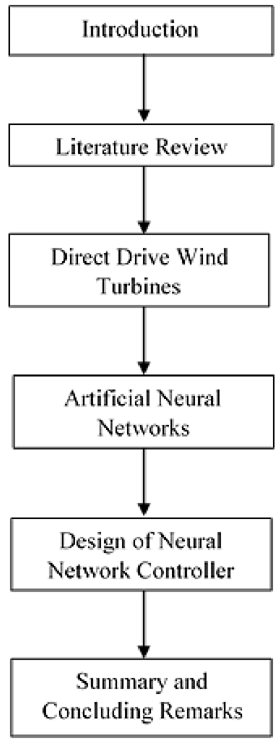


Figure1.3: Thesis structure

Introduction discusses present trends in renewable energy systems. It outlines the evolution of wind turbines and presents the objective of the thesis.

Chapter 2: Literature Review: Gives a synopsis of all types of renewable energy sources with their statistics and their respective global impact. It concludes with a discussion of wind turbine technology and its components.

Chapter 3: Direct Drive Wind Turbine: This chapter explains the low speed direct drive permanent magnet alternator technology and compares it with the geared doubly-fed induction generator. It also cites currently operational permanent magnet alternator wind turbine and answers the challenges and issues of gearbox in wind turbine.

Chapter 4: Artificial Neural networks: This chapter includes a synopsis of Neural Network history, biological model, structure & mathematical model of Artificial Neural Network, architectures, learning process, its benefits in wind turbine technology and concludes with Feed-Forward algorithm. This also contains the model for direct drive permanent magnet wind turbine developed in MATLAB's Simulink platform.

Chapter 5: Design of Feed Forward Neural Network Controller: This chapter discusses the simulation of controller using the Simulink Model to evaluate the performance based on the parameters the neural network is given. Data of wind velocity for Elk City, Oklahoma for the month of August 2000 is used to formulate real time input for the controller. Assumptions made for this study are documented with findings, which are discussed later. This is also compared with studies conducted on similar intelligent systems.

Chapter 6: Summary and Concluding remarks: This chapter summarizes the results achieved from the model with concluding remarks. This also includes the assumptions in the model and scope of further research.

CHAPTER 2

LITERATURE REVIEW

2.1 Renewable Energy Resources

Energy resources are constantly replenished by nature. Insolation, water, plants, earth's heat and the wind are defined as renewable energy resources. Technologies are being developed to tap this energy, turning them into practical forms such as mechanical, heat, electrical or chemical energies. Unlike non-renewable resources, which are limited, these renewable resources in their various forms ensure a sustainable future by decreasing carbon emissions, which in turn increases climate security [11]. The renewable energy resources currently being harnessed are geothermal,

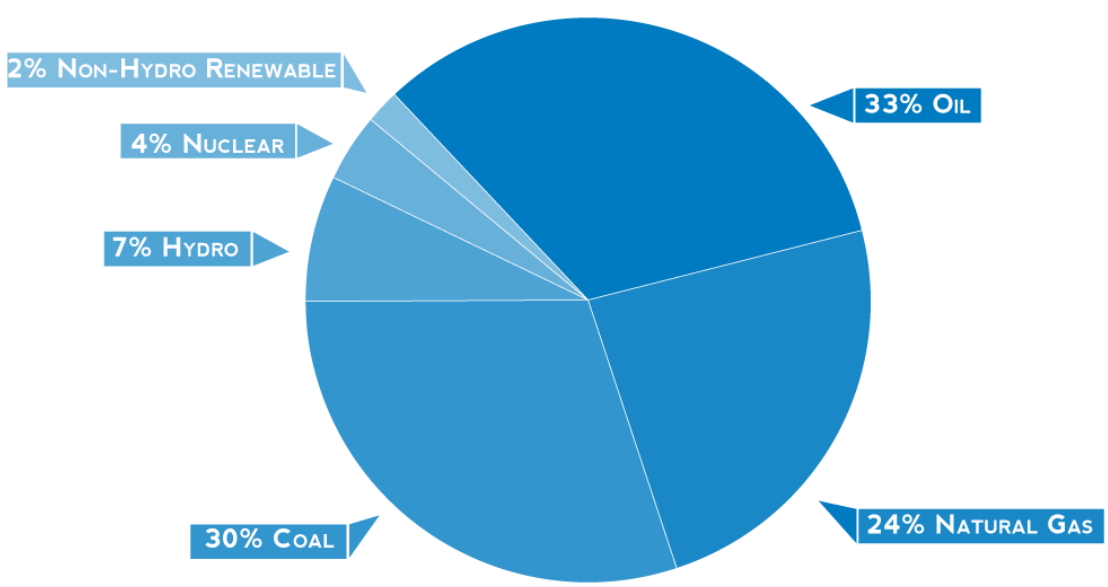


Figure 2.1: World Energy Consumption by the end of 2012 [7]

wind power, hydropower, tidal energy, biomass, biofuel, and solar radiation. Each of these types are explained in the following section. Figure 2.1 shows the global energy consumption distribution in 2012.

Geothermal Energy: The heat from within the Earth's core is recovered and used for electricity generation or heat pumping. This heat is continuously generated inside the earth, hence it is renewable in nature. Temperature equal to surface temperature of the sun is produced inside the earth due to the gradual decay of radioactive elements (80%) which is common in rocks and other minerals (20%) [10]. By May 2012 globally, 11,224 MW installed capacity of geothermal power was operational, with the US producing 3,187 MW, making it the largest user of geothermal power. The US is followed by the Philippines that produce 1,972 MW; Africa produces 217 MW & China produces 24 MW [11].

Wind Energy: Wind is air flow due to the difference between the temperatures of two locations due to uneven heating. The energy in winds is sufficient to drive sailboats, water pumping, grinding and generate electricity. A wind turbine converts wind energy into rotary mechanical energy which can be converted to electrical form. It may operate as a single turbine or as a combination of several inter-connected wind turbines in a "wind farm". They are located either on land or offshore. The topographic nature determines the nature of the wind, which in turn affects the output of the wind farm. Therefore, offshore wind farms are preferred over inland wind farms, as the flow of wind over seas (or oceans) is smooth, whereas on-shore the wind's flow is not as even due to the terrain. The global wind-electric generation capacity reached 254,000 MW by the end of the second quarter of 2012 with an annual growth of 16.5%. The top wind markets are China, US, Spain and India representing 74% of the overall wind capacity with China producing 75,324 MW and US producing 59,882 MW [12].

Hydropower: Streams, lakes and rivers are parts of the hydrological cycle that carry water back to the ocean for the cycle to begin again. Water at an elevation contains stored potential energy and can be utilized from the sources directly. This energy from flowing water is harnessed for irrigation, watermills, sawmills, cranes and electricity production. This running water drives the blades of turbines its kinetic energy and using gravitational force, which is coupled to a generator that produces electricity. Worldwide hydropower production by the end of 2012 was 1,127 GW with an annual generation of 3,524 TWh. China has the largest installed capacity (51%) in the world accounting to 240.7 GW [13].

Ocean Power: Energy from oceans is extracted in three forms namely *wave energy*, *tidal energy* and *ocean thermal energy*. The movement of the waves generates *Wave energy*. Waves are generated by the wind flowing over the ocean or sea bodies. The energy capacity of wave energy is small compared to tidal energy or ocean thermal energy. Tides are caused by the rise of fall of the sea level, occurring each lunar day for a given location due to attraction between moon and the earth. T*idal energy system* captures this kinetic energy from the ebbing and surging of the tides thus providing significant potential for electricity generation due to huge size of oceans. It requires at least 16 feet difference between high tide and low tide and is observed only in a few locations. *Ocean thermal energy* uses the temperature difference between top and deep layers of ocean bodies that is at least 38°F. Power plants use this difference in thermodynamics cycles to drive turbine blades to generate electricity [14]. Viable tidal power generated by the end of 2013 was 529 MW with small projects in the US. This energy resource is still in its nascent stage with a steady growth [15].

Biomass: Bioenergy or biomass is the energy derived that is stored in plants or plant based products. The earliest use of this resource was burning of wood that made wood the largest energy resource while other forms such as agricultural residues, food crops, municipal and industrial wastes and other organic wastes follow in the list of bioenergy resources. Additionally, gases such as methane and other complex hydrocarbons from landfills are also forms of bioenergy [16]. The methods used to extract useful power from bio-energy resources are *direct* *combustion, co-firing, repowering, combined heat and power, biomass gasification* and *anaerobic digestion.* Direct combustion in the presence of air is a common method for converting bioenergy to thermal energy and then into electricity. Co-firing is combustion of the mixture of coal and biomass to produce energy. Repowering involves converting a coal fired (or natural gas) power plant to run on biomass. Combined heat and power is the use of wasted heat during ventilation of buildings or industrial practices to generate electricity. Biomass gasification is the conversion of biomass in controlled environment to cleaner fuel that run turbines to produce electricity. Anaerobic digestion is the use of microorganisms to break biomass into simpler hydrocarbons releasing methane, which is later used to produce electricity [17]. From [15], the bioenergy supply globally is 10% of net energy generation. It is the fourth major source of energy globally with respect to other energy resources. US is the top bioenergy generating nation (62 TWh annually).

Solar Power: The use of solar energy dates back to human existence on this planet. The source of this energy is the sun, without which life would not exist on this planet. The peak power incident on one m^2 of land in 1kW, given the day is clear. This power can be harnessed in three methods: Solar water heater, solar thermal electricity, central tower power plant and photovoltaics. Solar water heater extracts incident solar heat from panels located on rooftops by heating the cold water running through them. Solar thermal electricity utilizes parabolic dish or through reflectors that generate steam from the fluid flowing through the central point of the reflector, which is used is turbine to generate electricity. Central tower power plant consists of mirrors (called heliostats) that are capable of orienting towards the sun and concentrate the incident solar energy onto a tower through which a fluid flows. Solar heat is absorbed by the fluid, which is converted into steam that drives a turbine to generate electricity. *Solar cell* or photovoltaics is another technology of extracting solar energy. A wafer of silicon is a constituent of the solar cell that absorbs the solar energy converting it into electricity. This single wafer is called a cell. Cells linked together form a module. Collection of such modules is called arrays that are designed to get the required power [18]. The global share of solar power capacity is 26% or 255 GW by 2012. US accounts for 35% share of this power [15].

2.2 Global Wind Energy Scenario

By the end of 2013, 14 MW of additional operational wind power was integrated in to the power systems increasing the global wind capacity to 296 MW. Additionally, 2012 was a promising year for wind power as it added more capacity than any other renewable energy technology with a large market demand. The cumulative growth during the period 2007 to 2012 for wind power was 25% [19].

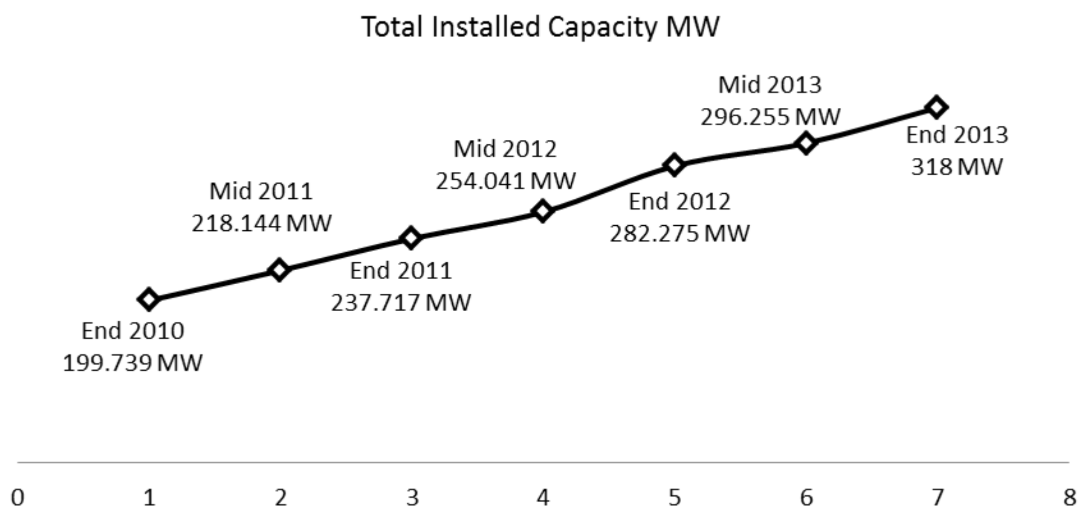


Figure 2.2: Total installed capacity MW [19]

As per the figure 2.2 USA's wind power capacity was 45% of the total power capacity as compared to its other significant resources like natural gas, which powered 15.2 million homes. By 2013, US had 318MW operational wind power with prominent contribution from Texas, California, Kansas and other states that contributed more than 1MW.

China by the end of 2012 had 75.3 GW of wind capacity with 13 GW installed in 2012 alone. However, China experienced a major drop in the installation and market share as compared to the period 2009-2011. The reason for the decline was the stricter approval procedures for their quality, safety and grid access. The wind capacity accounted for 100.4 billion kWh with 37% increase, exceeding power generated from nuclear power station for the very first time. Wind power's share was 25% by the Inner Mongolia Autonomous Region, 10.6% by Heibei, 8.6% by Gansu, 8.1% by Liaoning provinces and other provinces with more than 3 GW and 14 more expected. China installed more than 1 GW in the first quarter of 2013 summing to 5.5 GW. Europe achieved a groundbreaking wind capacity of 100 GW, with 11.9 GW added in 2012 summing to total of 106 GW at the year's end. Wind energy is not the major electricity resource for Europe since solar energy supplies a significant fraction of electricity (37%). Integration of wind energy to Europe's grid is a major challenge affecting its growth. Other concerns like land area needed have been reported in spite of larger shore area. Europe's foremost wind power producing country was Germany with the maximum number of wind power plant installations totaling to 31 GW followed by UK adding 1.9 GW, Italy 1.3 GW, Spain 1.1 GW, Romania 0.9 GW and Poland 0.9 GW. Both Romania and Poland had major landmarks in wind power; Romania doubled its wind capacity and Poland increased 55% of wind capacity compared to the previous year. By 2013, Europe had 9.6 GW wind capacity with 1.3 GW installed in the first quarter of 2013. Germany remained a leader for wind market with a cumulative operating capacity of 32.4 GW [19].

India added 2.3 GW in 2012, with 18.5 GW total wind capacity. Wind power incentives were cut back even though the country had strong policies in 2013, therefore faced slow market growth. Countries like India and China had slow growth but Asia at large stayed the largest market for wind power for four consecutive years with 15.5 GW added in 2012 compared to North America (14.2 GW) and Europe (12.1 GW). Other countries like, Brazil 1.1 GW, Mexico 0.8 GW, making significant growths summing 2.5 GW 1.4 GW respectively also Argentina, Costa Rica, Nicaragua, Uruguay and Venezuela had their first commercial wind farm rated 30 MW [19].

By the end of 2013, China, USA, Germany, Spain and India shared 73% of the global wind capacity. Countries that installed more than 1 GW by first quarter of 2013 were China (5 GW), India (1.2 GW), UK (1.3 GW) and Germany (1.1 GW) [19].

2.3 Impacts of Wind Power Generation

Wind is the fuel for wind power generation. It is renewable and clean in nature making it the fastest growing energy technology. Its power can be harnessed today, with same amount of power still extractable in the future. However, wind has a nature of intermittency i.e. it flows only during certain periods of the day. Therefore, it is difficult to predict the stochastic output from a wind power plant.

Wind plants emit no greenhouse gases or any pollutants that affect air, water or the climate as

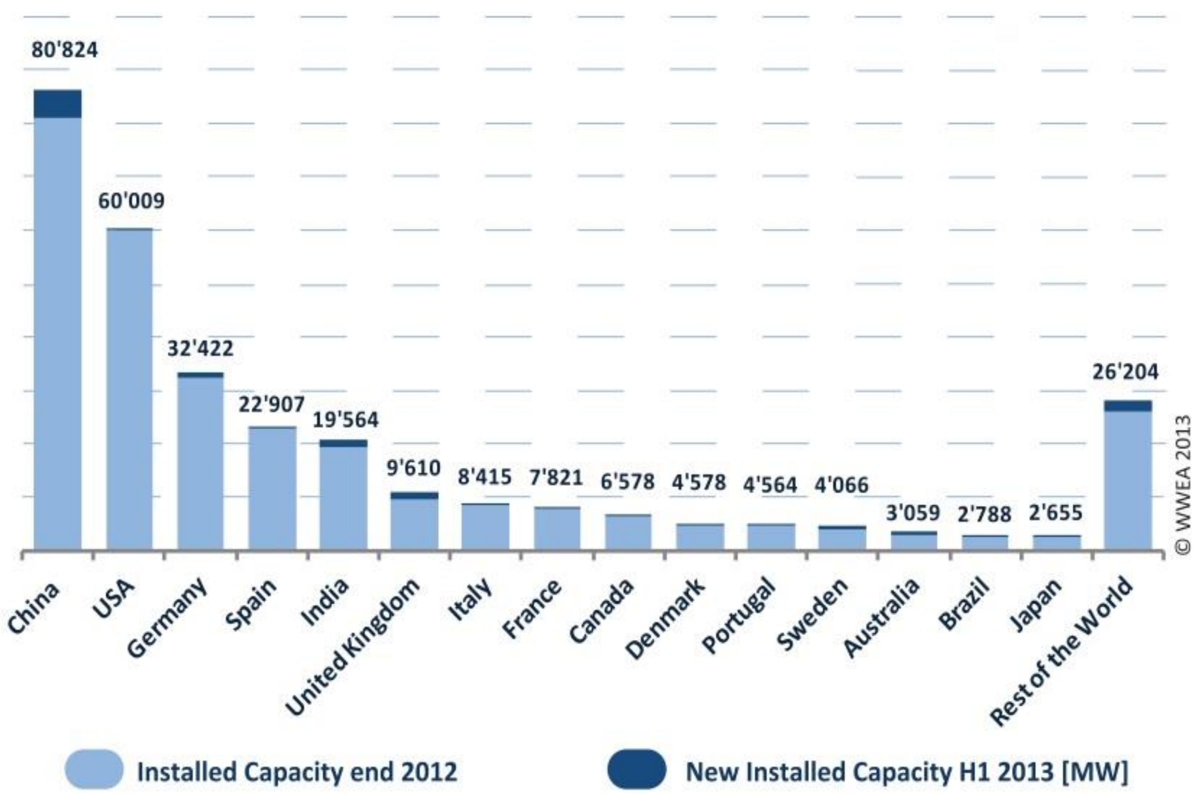


Figure 2.3: Total Installed capacity by 2013 MW [19]

compared to the conventional power plants. Compared to other energy resources, wind energy is having a stabilizing impact on USA's ever-growing energy demand leading to shift of energy dependency on cleaner energy generation as well as a good energy saving practice. According to Independent Statistics and Analysis department of the U.S Energy Information Administration, globally, "Renewable energy, excluding hydropower, accounts for 28% of the overall growth in electricity generation from 2012 to 2040" [21]. This report gives the predictions of renewable energy for the year 2040 showing concerns of increasing coal price and the promising effects of renewable energy on the global scale [19].

Economic Stability and Energy Security: Wind energy resources are subsidized by the government, but is low compared to other energy resources. According to a Harvard study published in 2011 [22], stated that true cost of coal for electricity is about 18 cents per kWh (best estimate) which is considerably more compared to wind power, conclusively proving that taxpayers are paying the price which does not show up in electric bills. These indirect subsidies totaled from $175 to $500 billion per year. The price of electricity generated from fossil fuels varies due to highly fluctuating mining transportation and mining costs. As wind is free and price of a wind turbine is fixed, electricity generated from wind farms can safeguard these costs. The cost of wind-generated electricity has plummeted since 1980's (40₵) to present 2013 (5-8₵) depending on the location of the wind farm (off shore or on shore) and the project size. Adding to it, diversification of the economy of rural areas is another advantage like generating tax revenue. Wind farms produce short and long-term jobs, which attract the attention of the levels of employment. Comparing to the jobs created from nuclear and coal power plant's per unit of energy generated with respect to the wind energy, wind energy creates 66% and 30% more respectively. Distributed wind farms provide defense against potential terrorist attacks to power plants as compared to a nuclear power plant that have to be centrally located. Furthermore, power generated from wind farm can control spikes in fuel costs caused by non-renewable energy. The energy mix of wind farms and other resources can help small businesses and developing local resources that are operated by local owners, meaning lesser fuel imports thereby generating revenue [22].

Pollution Reduction: Particulate emissions such as mercury cause contamination in water bodies observed in fossil fuel fired power plants that contribute to water pollution but not observed in wind turbines. Power plants use water as coolant or as a working fluid to rotate a generator. According to U.S. Geological Survey's study (USGS), power plant cooling accounts for 40% freshwater consumption as shown in fig. 2.4. Options for existing plants to decrease emissions are limited, as the filtering methods require major upgrades causing an increase in the overall cost

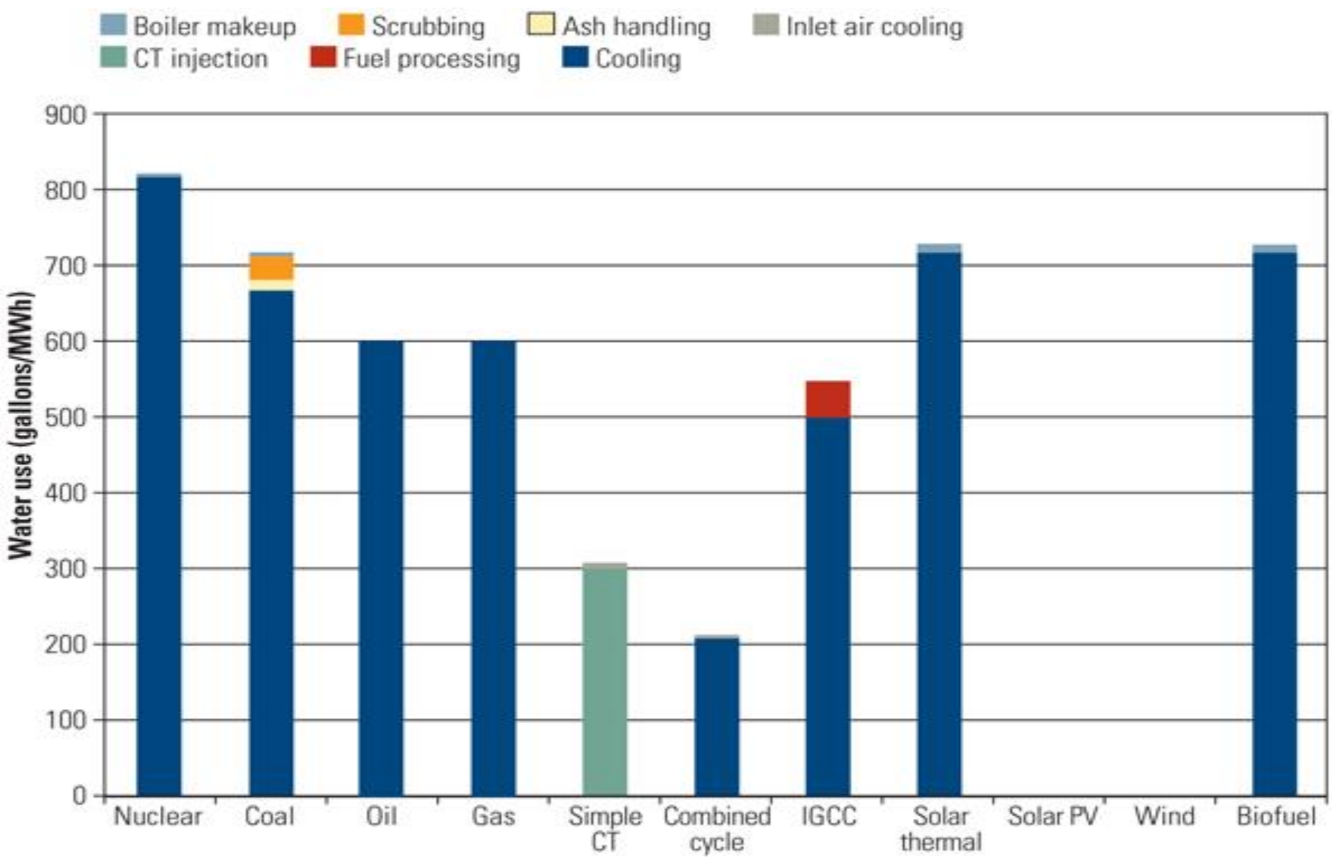


Figure 2.4: Water use by power plant type [23]

and limitation to the capability of the plant [23]. Electricity generated from thermal power plants emit carbon di-oxide that contribute to greenhouse effect. Annually U.S. releases 5.4 billion metric tons of carbon di-oxide with the power sector discharging 38% of the total. Wind farms release zero carbon dioxide and other greenhouse emissions therefore it can be accepted that the electricity generated from greenhouse gas emitting power plants can be moderated by generating some of power from wind turbines. The year 2013 was not a promising year for net carbon emissions globally as it reached a new level of 40 billion tons, representing a 2.1% increase since the last year and 61% as compared to 1990 [19].

Drawbacks of Wind Energy Conversion Systems: As the investments on wind farms have rapidly increased globally, generated electricity price from wind farms have decreased significantly but faced issues during initial investments on wind farms. Governments are making these costs manageable by allocating subsidies, tax breaks and the return of investment costs. Costs include transportation (generally the largest as the equipment involved is heavy and large), site preparation and installation. According to Betz's law, maximum power that can be extracted from the wind, independent of the design of the wind turbine cannot exceed more than 59.3% of the wind's kinetic energy. It is major weakness for wind energy systems making them insufficient to fulfill the load demand.

Wind, the driving force of wind turbine blades is an intermittent source hence when converted to electric power is discontinuous in nature. In addition, wind farms on exposure to high winds tend to breakdown creating unsafe vicinity around the wind farms. A specific wind speed should flow on the wind blades in order to operate the wind turbine economically and safely else mandatorily shut down to remove the concerns of safety. Since the movement of wind is on a wide-ranging area, the power density in the wind decreases as the area increases requiring huge number of wind turbines to extract that power. Therefore, as the number of wind turbines increase, the cost of investment increases. The location selected for wind turbine installation should meet the wind speed requirements, which are rare to find. Therefore, many wind farms are located on or near coastal areas and hilly areas. The electricity generated from wind cannot be stored for later use, without an energy storage and reconversions system.

People find wind farms noisy, visually unappealing and have found them interfering with the reception of television and telephones. The machinery used in wind turbines are noisy based on the nearness to the operating turbine, though it emits zero pollutants that affect those who live or work nearby. This restricts the number of locations for wind farm installation. The visual deterioration of land with a wind farm on it has resulted in petitions filed to prohibit installation of wind farms surrounding societies. Therefore, sites where wind farms are accepted are function limited. Land used per Megawatt of wind power is about 60 acres, which is larger than nuclear power plants (1.6 acres/MW) making it another disadvantage. Larger area requirement for safe operation adds to its limitation. Since these turbines are located in large areas with great heights, the rotor blades rotate continuously often killing migratory or local birds and bats flying near them. To prevent it rotor blades of the wind turbine are painted for distinction, cautioning the nearby flying birds.

2.4 Wind Turbine Technology

Energy from wind for electricity generation is extracted by two technologies namely; horizontal axis and vertical axis wind turbines. Their primary function is conversion of kinetic energy in wind to rotary mechanical energy. The wind turbine’s generator performs the conversion of rotary mechanical to electric energy. The turbine size and the site determine the capacity of the wind turbine. The ratings of wind turbines range from 10 kW to 7.5 MW. The types of application decides the turbine size; small sized machines in battery charging operation, pumping water, irrigation, grinding, etc., medium sized machines are used to power a house or a row of houses where as large machines or array of inter-connected machines are used in industries or commercial buildings. Vertical axis wind turbines are less efficient since its blades are rarely at optimal angle that is required to extract maximum kinetic energy from the wind, therefore horizontal axis wind turbine are preferred for electric generation. The following section describes the anatomy of a standard horizontal axis wind turbine [24].

- **Nacelle:** It forms the external hub that covers the internal assembly of electrical and mechanical systems. It is designed to provide weather protection, and it is made from fiberglass around a steel framework. Internal parts include hatches, wiring, lightening rod and ducting.
- **Blades:** They provide the lifting force and torque to generate power and shares 7% of total wind turbine weight. It is usually 30-55 meters in length. Internally it consists of lightening protection, de-icing systems with protective coating.
- **Tower:** This vertical structure supports the wind turbine by attaching the rotor to the concrete base and foundation. In addition, it also maximizes the height to capture good

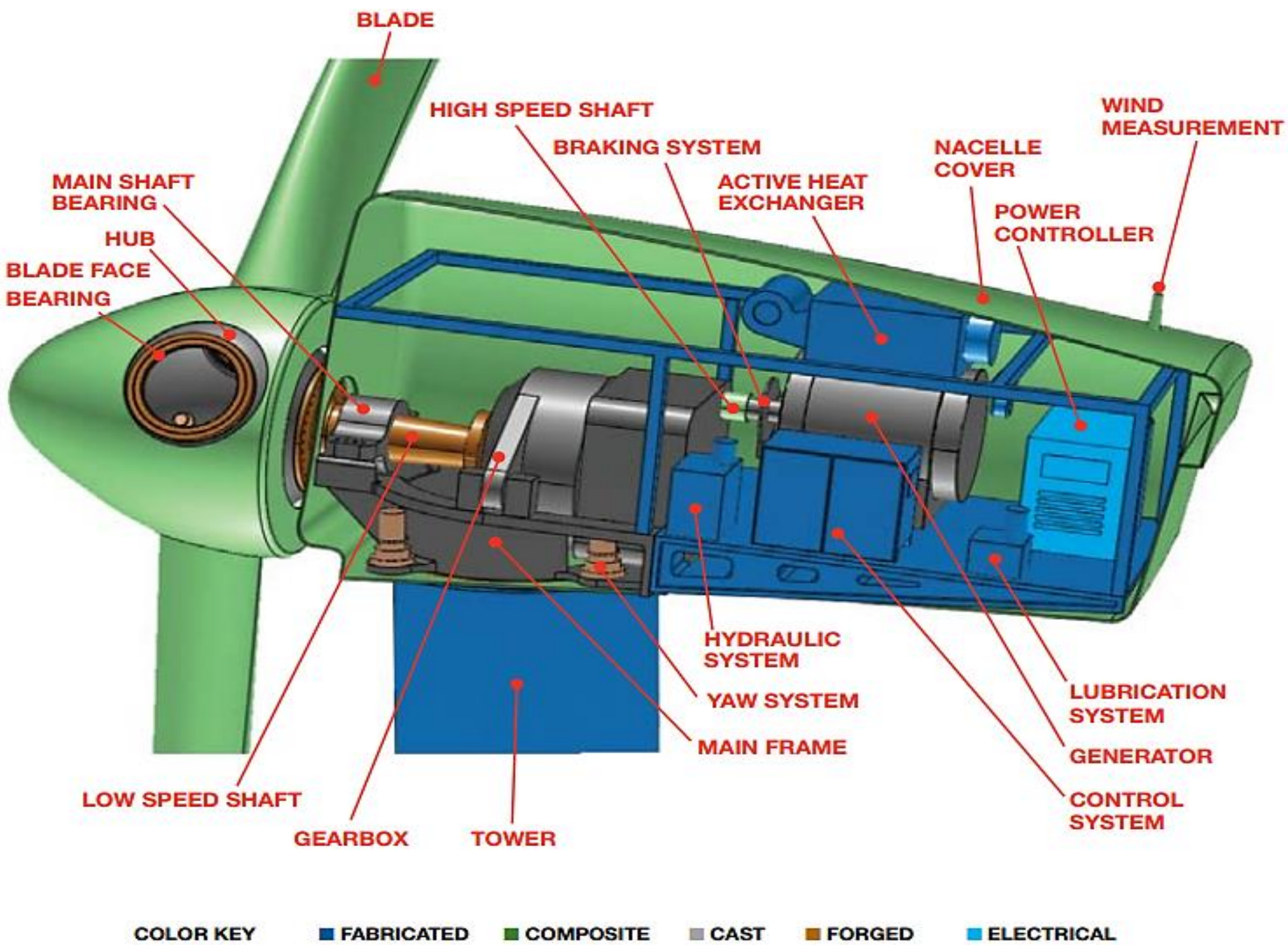


Figure 2.5: Components of Wind turbine [25]

wind. Of the total wind turbine weight, tower shares 66%.

- **Rotor, Rotor Hub and Pitch System:** The rotor extracts the rotary power from the wind absorbed from the blades, mounted on the main shaft via the rotor hub. This is the largest components weighing nearly 7 to 20 tons. The pitch control determines how much power is extracted from the flowing wind. Pitch control system is used to stall the rotor to stop or slow the rotation of blades with each blade controlled separately. Hub connects the rotor blades to the generator. It encloses the connection between blades and the shaft.
- **Drive Train Assembly:** Consists of rotary components like rotor, driving shaft, coupling, gearbox, brakes and the generator. It amplifies the low speed 10-20 rpm to 1200-2000 rpm. A disc brake used to control the rotation of the blades giving a control over the machine.
- **Generator:** It converts the high-speed rotary energy to electric power. There are three types of generators used in wind turbines; synchronous, asynchronous and doubly fed induction generator (DFIG). DFIG is the most common type of generator; however, permanent magnet generators are gaining a pace in wind turbines with direct-drive units(no gear box)
- **Gearbox:** One of the heaviest and most costly part of a wind turbine and has two design forms namely, planetary and parallel-shaft gearboxes. An integral part of drive train assembly that transforms shaft speed from 10-20 rpm to 1500-1800 rpm. This mechanism is absent in direct-drive wind turbines.
- **Electrical Assembly:** It houses the power converters DC-to-AC converter (DAC) inverter system and AC-to DC converter (ADC) rectification system, transformers that step up or down to required voltage level, switchgear to safeguard the grid from faults or wind turbine. It also consists of sensors, grounding system, power factor correcting circuit, harmonic filters, soft starters and motor contractor.
- **Yaw and Control System:** Yaw control system orientates the wind turbine into the wind

direction with the help of 3-4 motors with a braking system. The control system consisting of sensors, controllers, microprocessors, power amplifiers, actuators that stabilize and optimize turbine operation and power production which also is the human-machine interface of the wind turbine.

Wind turbines act as reverse fans, i.e. utilize wind energy to generate electricity as opposed to generating wind from electricity but on a larger scale. High strength magnetic field in the generator air gap is cut by conductors to induce voltages , which are collected to form the electrical output. Certain machines have multiple gears in the gearbox enabling multiple speed operation. This speed generates electricity that is variable in nature and is stabilized by a transformer (700 V typically). It is later stepped down to distribution voltage for

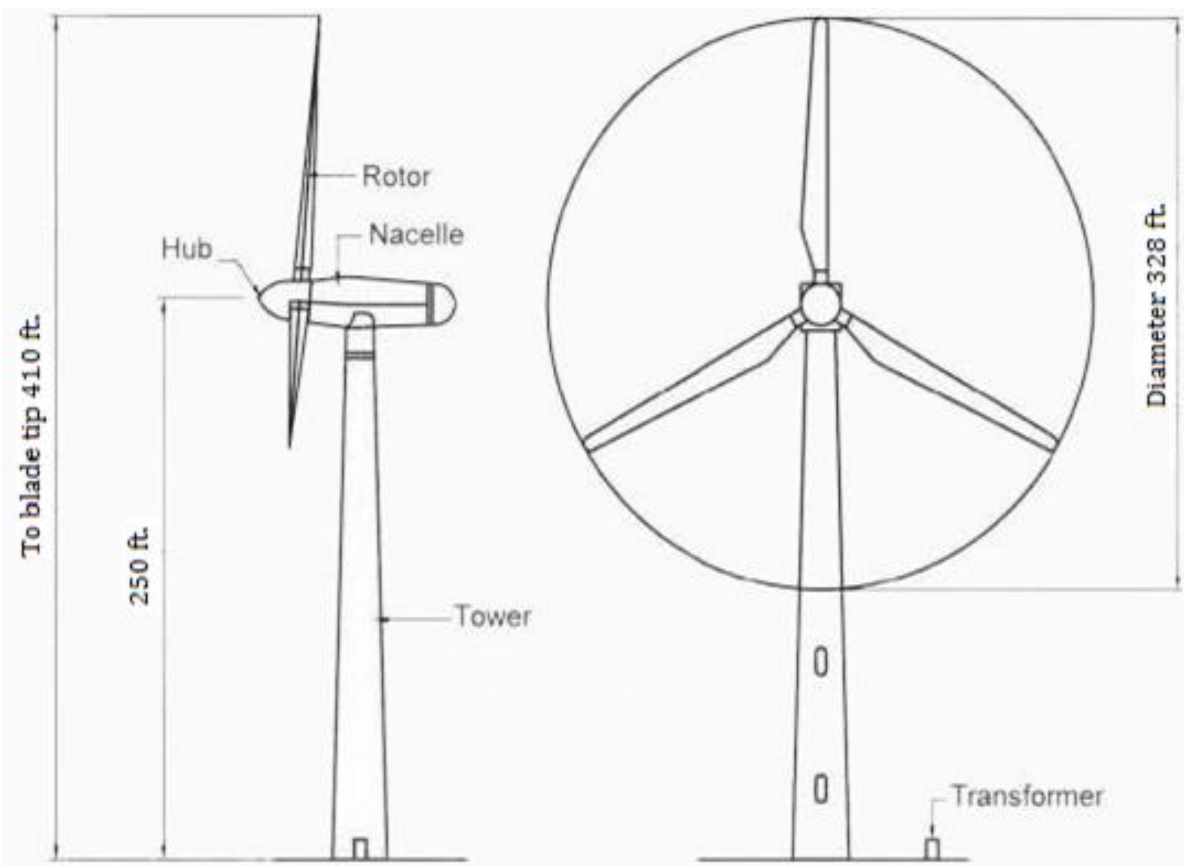


Figure 2.6: Front and Side Elevation of Wind Turbine [25]

distribution(11kV to 500kV typically).

This power generated is transmitted to the national distribution grid reaching residential, commercial or industrial consumers. Current wind turbines use 3-blade design rotor model and spread over an area forming an array.

These turbines are located in upwind direction meaning, the blades capture wind in the windward direction with respect to the tower, which eliminates shadowing effects. Parts and specification of a typical wind turbine rated 2.75 MW from General Electric are as follows [25],

- Blade: 110ft. long and weighing 80,000lb (average).
- Output rated voltage: 700 V
- Tower: 250ft. (may vary based on location), tubular steel monopole with average weight of 32,000lb.
- Rotor Speed Range: 4.7-14.1 rpm
- Nacelle: 140,000 lb.
- Rotor: 82,000 lb.
- Gearbox: 37,500 lb., three operating gears.

The blades size determines the power generated by a wind turbine. Area swept is the circular area that the blades occupy during operation. Larger the swept area, larger the power generated. However, there are other factors affecting a turbine such as location and wind regime of the site. Based on the characterization of the wind variable from Xing et al, 2006 monthly wind velocity is represented by,

$$v=v_{\circ}[1+\sum_n C_n \sin(\omega_n t)] \quad (1)$$

where,

v is the wind speed,

$v_{\circ}$ is average wind speed,

C_n the magnitude of Eigen swing *n*,

ω_n is the Eigen frequency of the Eigen swing *n*.

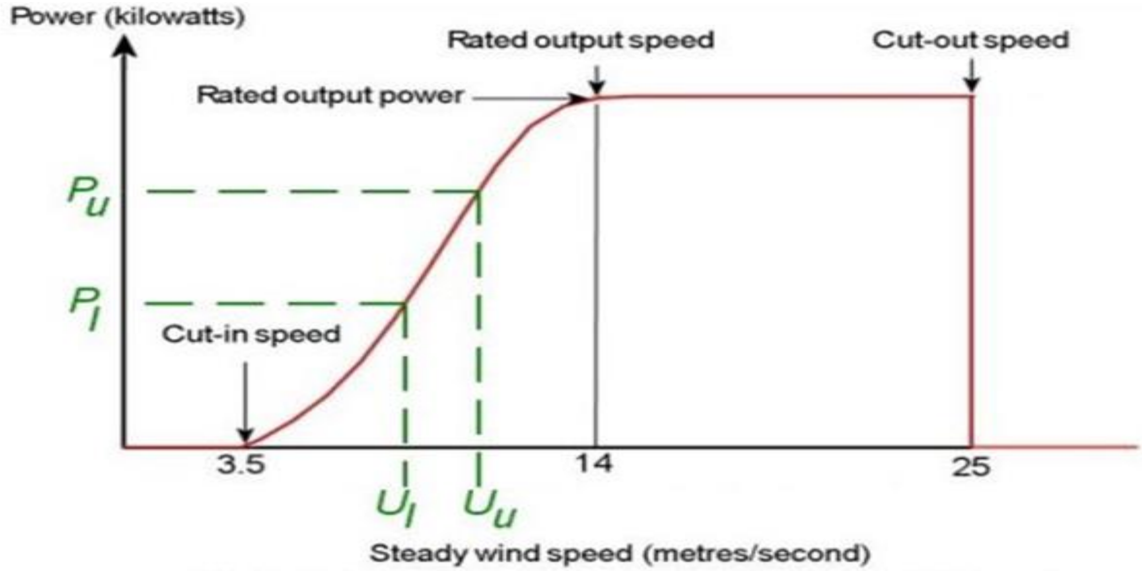


Figure 2.7: Typical wind turbine output with steady wind speed

Weibull distribution is used to model wind speeds for a given location. Consider the

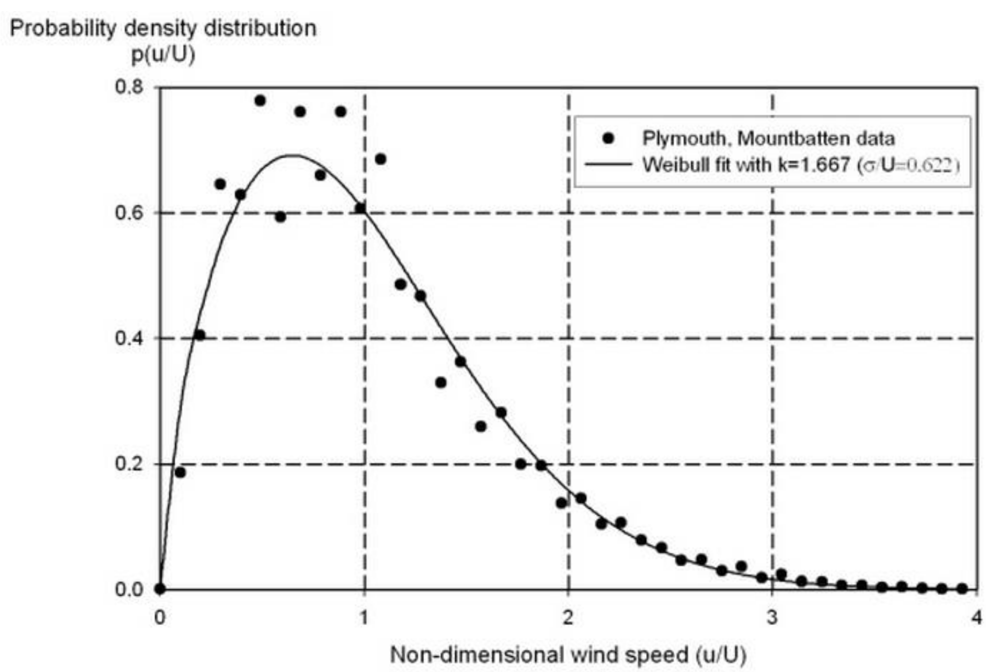


Figure 2.8: Weibull fit to Plymouth weather station data [37]

example of Plymouth Mountbatten, UK weather station as an example. The wind data is modelled by Weibull fit shown in the following figure.

Where, u is the unsteady wind speed component, U is the mean wind speed and σ is the standard wind speed deviation. Wind speed behavior is affected by several factors; therefore, it is modeled by its intermittent nature represented by a random variable that is dependent on direction and magnitude (Chen &Spooner 2001). This random variable is a deterministic sum of harmonics with frequency range of 0.1 to 10Hz. Mechanical power from the wind turbine is computed by the equation,

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

where,

P is power generated in Watts,

ρ is air density in kg/m,

A is the area swept in m^2,

v is the wind velocity in m/s

Based on swept area and wind velocity at the site, the plot of power with respect to wind velocity called "power curve" of a wind turbine. It is unique for every turbine with respect to the site. Fig. 2.7 shows a typical wind turbine output with respect to the wind velocity characteristic. Until the velocity is 3.5 m/s, there is no output from the turbine. This wind velocity is termed cut-in speed. Once the velocity exceeds 3.5 m/s and reaches 14 m/s rated output power is generated. Wind velocity greater than or equal to 25 m/s is dangerous for the machine's operation. To stop the operation, pitch control mechanism changes the pitch angle of the blades slowing the machine and later bringing it to complete halt. Wind velocity increases as the altitude increases; therefore, wind turbines need great height to capture maximum wind speed.

By the end of the third quarter of 2013, 69 MW of wind power capacity was installed in US with 2,300 MW wind capacity under construction, which was lowest since 2008[26]. Utility companies also responded positively to utility ownership that will build 1,870 MW wind turbines, totaling the U.S. wind capacity to 60 GW. With technology improvements and price reductions, wind farms are growing at a faster pace to meet the global need.

CHAPTER 3

DIRECT DRIVE WIND TURBINE

Wind turbines have evolved to extract maximum power from the incident wind regime. It is achieved by increasing the range of operation by integrating suitable gearboxes. The complexity and reliability issues of wind turbines increase as the operating speed range increases. Gearboxes are prone to failures that cannot be repaired on site. During the repair period, the entire gearbox is isolated from the turbine rendering the turbine non-functional for power generation. This is linked to substantial cost, man-hours and down-time based on the severity of the repair. Under these circumstances, wind turbine engineers have developed a conditioning monitor for the gearbox that monitors the performance of the gearbox and health that help detect problems at early stages. Another approach that is considered is the direct drive technology. Direct drive wind technology eliminates the use of gearbox resulting in improvement in the reliability of wind turbines. It consists of low speed and heavy large diameter permanent magnet alternator. Direct drive wind turbines are promising as they have many advantages such as greater power extraction capability, low noise level during operation and efficient power conversion and transmission to the grid.

Further developments have made wind turbines to operate under variable speed or constant speed. At present, variable speed wind turbines have two primary designs to extract power-doubly fed induction generator and direct drive permanent magnet alternator. DFIG are induction generators with wound rotor, slip rings, gearbox and power electronic converters. Due to the high power density of the turbine generated from large flux linkages, the cost per kW is lowered, thus improving the economics of wind turbines. At high wind speed (25mph), higher shaft speed is achieved with the gearbox that drives the generator. However, direct drive wind turbines lack the gearbox with a larger power density as compared to doubly fed induction wind turbine eliminating the need of gearbox maintenance, replacements and less moving parts leading to less wear and tear.

3.1 Direct Drive Wind Turbine Concept:

Direct drive wind turbines use direct drive mechanism that involves the rotor shaft directly attached to the generator spinning at the blade speed. Electric power generated is fed to a power converter before transmitting it to the grid. The most common practice in direct drive wind turbine is the use of permanent magnet alternator or a magneto as the generator rather than separately excited generator. This avoids the need of magnetizing current in the rotor making it simple and compact in shape. They require no external excitation power and are robust in design. The electro-mechanical layout of a direct drive wind turbine is as shown in the figure 3.1. The layout consists of:

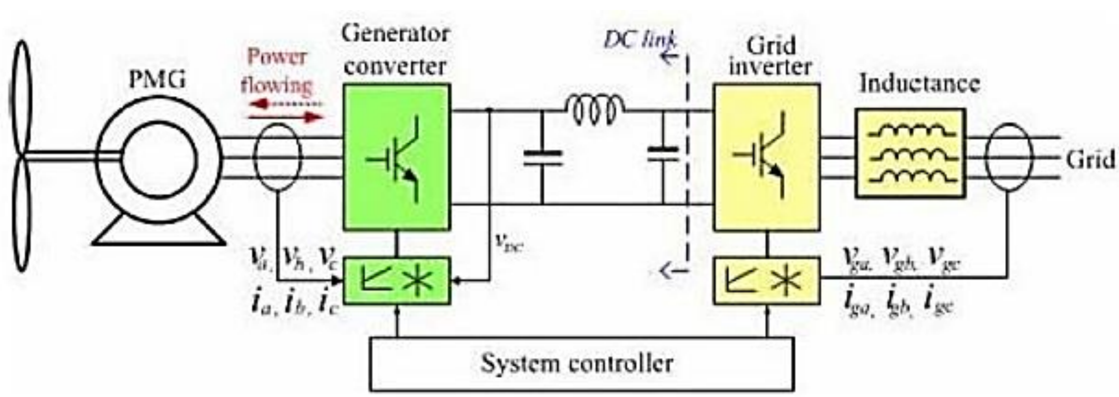


Figure 3.1: Typical direct drive electro-mechanical layout [38]

- Permanent magnet generator or permanent magnet alternator
- Generator and Frequency Controller

- DC Link with condenser
- Pitch control mechanism
- Voltage and current (D and Q) sensors
- Grid Inverter

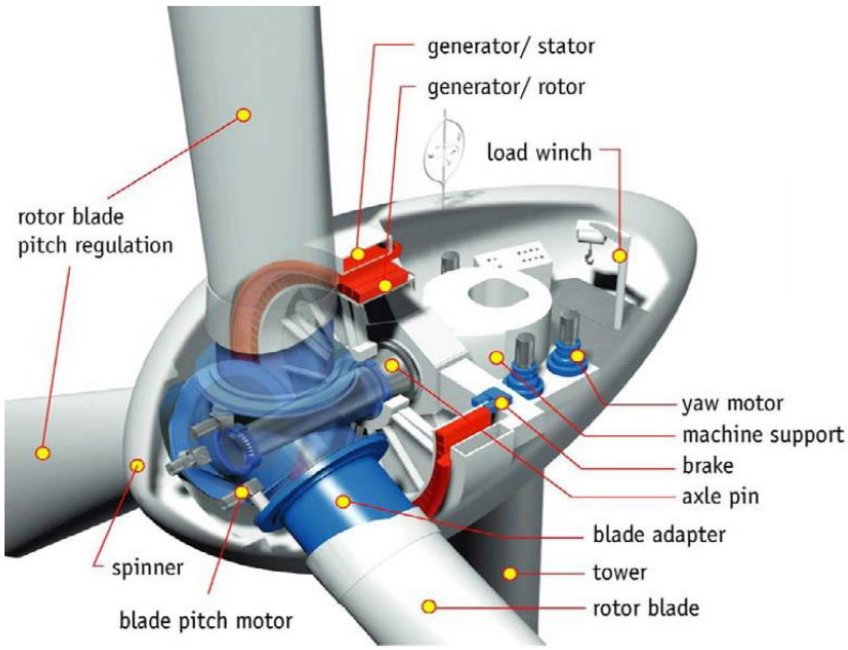


Figure 3.2: Direct-drive wind turbine schematic [27]

From the figure, it is inferred that the generator is directly coupled with a gearless shaft that is moving on the hub but not connected with a gearbox. Rotor of the generator comprises permanent magnet pole pairs that act as excitation system for generating mechanism. To eliminate the frequency harmonics and other related harmonics, power electronic converters in the generator converter system are used which typically consists of IGBT switches operating at a fixed duty cycle.

The generator and the hub rotate typically between 8 to 15 rpm. A representation of the direct drive wind turbine is shown in fig.3.2. During operation, magnetic field lines from the permanent magnets are cut by stator windings; generate alternating electric power at variable frequency. To enhance power capture of wind turbines, pitch control mechanism is used to change the angle of attack of the blades operating at optimum location of the power curve (fig 2.7). During the operation, permanent magnets revolve around the windings to generate electric power. Faster the revolution of the magnets, larger flux linkages leading to larger current induction in the windings. Direct drive machines function at low rotational speeds, for a fixed axial length. The machine's diameter is increased to gain higher torque and higher peripheral speed of the permanent magnets. This need of large diameter demands use of excess permanent magnet material making it expensive. Furthermore, it increases the difficulty of handling the machine during transportation and installation. On the other hand, the design eliminates field excitation losses improving overall efficiency that helps yielding profit in terms of revenue.

3.2 Permanent Magnet Directly Driven Wind Turbine Topologies

Permanent magnet direct drive generators have a good potential for off-shore and on-shore investments and developments as compared to separately excited wind turbines and switched reluctance generators. However, the key issue for integration of these wind turbines is its large size and heavy structure. The primary component of turbine is the high performance permanent magnet, manufactured with Neodymium in its compound form called Neodymium Iron Boron, a rare earth metal. Different topologies are proposed in the literature, common type of categorization is the orientation of magnetic flux with respect to the shaft of the machine namely; Radial flux, axial flux and transverse flux permanent magnet wind turbines. Another categorization of the generators is in terms of the presence of iron in stator's core namely; Iron cored or air cored [27].

There are three types of direct drive wind turbine topologies:

- Radial Flux Permanent Magnet Alternators
- Axial Flux Permanent Magnet Alternators
- Transverse Field Permanent Magnet Alternators

3.2.1 Radial Flux permanent Magnet Alternators

The radial flux generators (shown in fig. 3.3) are the most common type of permanent magnet

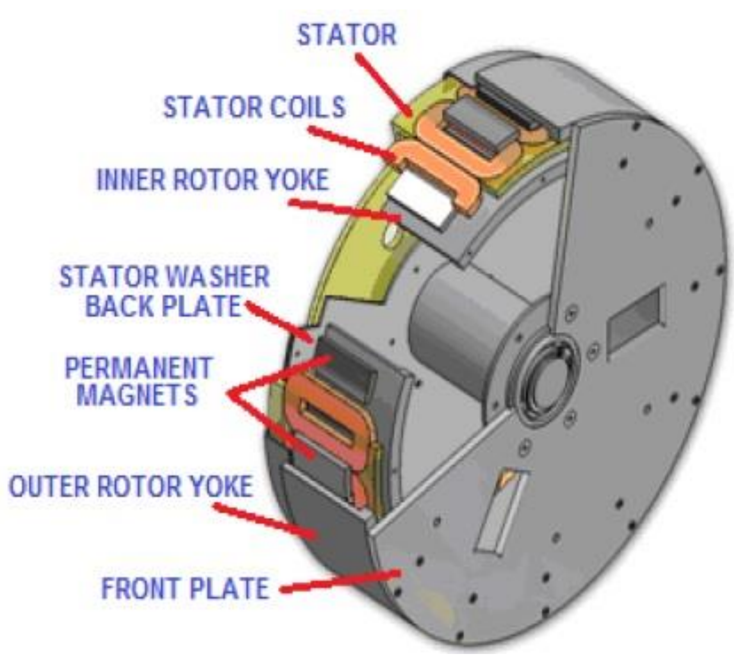


Figure 3.3: Radial Flux Permanent Magnet Generator [29]

machines used as they have higher torque to weight ratio as compared to other designs. The flow of magnetic flux is radially across the air gap. Radial flux permanent magnet generators have two topologies-

- Surface mounted radial flux permanent magnet alternator
- Buried magnet radial flux permanent magnet alternator
- Torodial type radial flux permanent magnet alternator

Surface mounted permanent magnet generator is usually iron cored (iron in stator's core) with surface mounted permanent magnet poles rotating by stator armature windings as shown in fig. 3.3. In buried type stator, the stator is slot less consisting stacks of laminated steel that reduce the total weight and cost of the machine.

3.2.1.1 Torodial Type Radial Flux Permanent Magnet Alternator:

The other type of connection of windings is torodial in nature called air gap winding as they are placed in a flat pocket. This further reduces the cost as less number of windings used. The lack of teeth lessens the iron core losses and hence increases the overall efficiency.

The rotor consists of rotor core, permanent magnets and shaft. Rotor and stator are distinguished by the large air gap between them that improves the machine's efficiency and allow large number of poles. This causes increase in the overall weight and complexity of the machine. Additionally, cooling mechanism such as liquid or gas cooling systems are required. This adds to reliability issues, maintenance issues and costs. Another approach to reduce overall cost of the machine is the use of fractional pitch winding in stator (shown in fig. 3.4). This also makes the design simple. To eliminate this flux concentrators are used. Flux concentrators are structures that concentrate flux into the air gap, filtering the lower flux density.

Radial flux generator with surface mounted magnets are simple in design that produce high torque density, high energy and improved reliability making it widely applicable in wind power conversion systems. Although, permanent magnet's life is short and require constant attention [27].

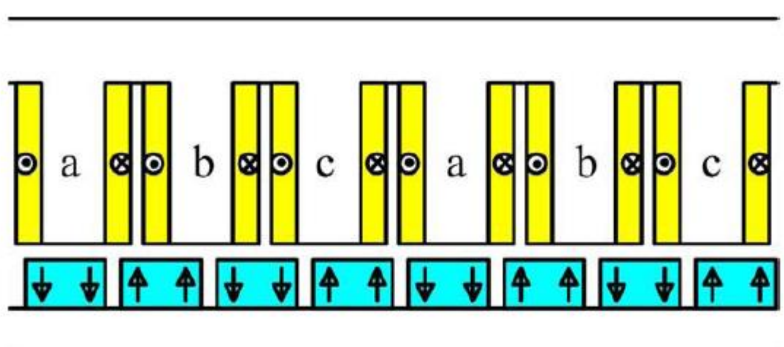


Figure 3.4: Cross section of eight-pole permanent magnet alternator with fractional pitch winding [29]

3.2.2 Axial Flux Permanent Magnet Alternators

In axial flux generator (fig. 3.5), the magnetic flux flows in the axial direction across the air gap. The most common structure consists of rotor disc carrying permanent magnets and the stator disc

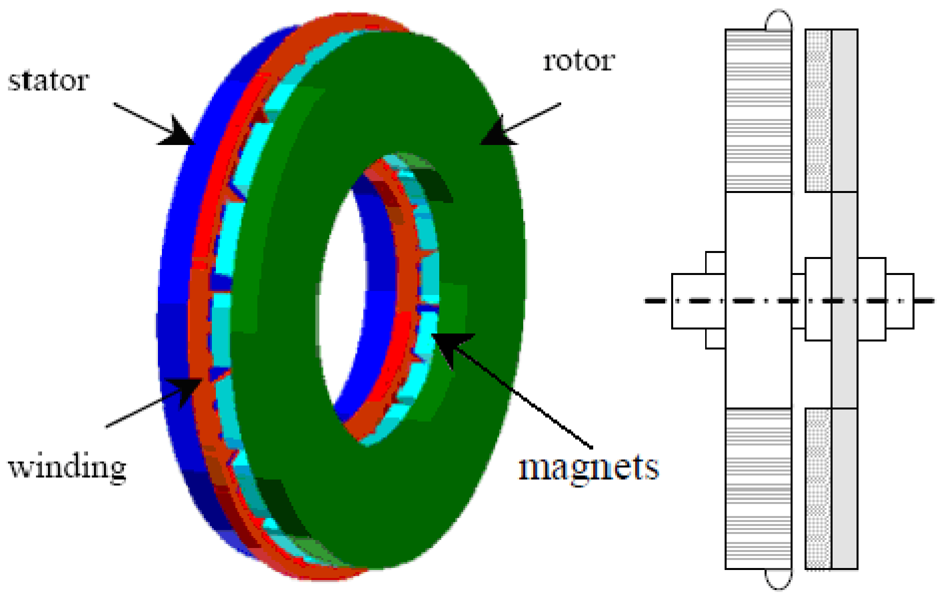


Figure 3.5: Single-sided slotted axial flux permanent magnet alternator [29]

containing windings. Axial flux generator with slots are known for their low noise, compact design, short axial length and high torque density. In [28], Dubois concludes axial flux machines have lower cost per torque ratio as compared radial flux generators.

The drawback of this design is the magnetic interaction between the permanent magnet and iron stator that obstruct free movement of the rotor. Additional rotor or stator is used to form double-sided machine that neutralize the magnetic interactions between the stator and the rotor. This makes the machine bulky as compared to the rest of the topologies. Another approach is the use of double stator or double rotor. From [28], double stator design with permanent magnet mounted is lighter compared to single sided or double rotor design. This design is complex to manufacture. The flux leakage creates additional magnetic field. It is in the same direction of the main flux and is radial and axial in nature that results in complex three-dimensional electromagnetic design. The calculation and modelling of this design is complex and makes it hard to predict the behavior and performance of the machine. Structural difficulties such as maintenance of air gap for large diameter, cooling systems, etc. also cause problem while designing. Large numbers of stator teeth are used to eliminate these design disadvantages.

3.2.2.1 TORUS Axial Flux Permanent Magnet Alternator:

Another design proposed by Spooner et al., called "TORUS machine" which consisted of torodial windings in the slot less axial flux generator. The stator of torus machine is a stack of laminated steel with windings wound around the core in torodial design. It is a doubly sided machine with single stator sandwiched between the two rotors that have permanent magnets embedded in them (shown in fig. 3.6).

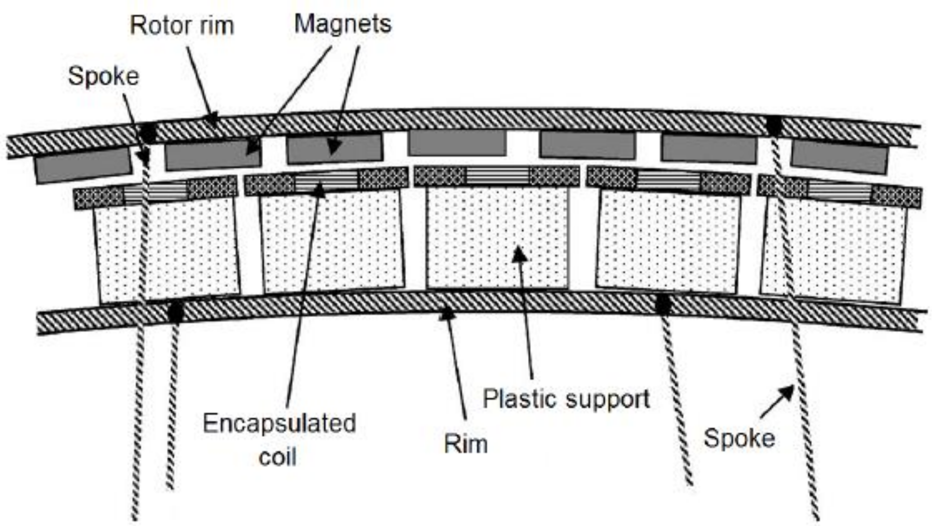


Figure 3.6: Spooner's design of ironless radial flux permanent magnet alternator [29]

Slot-less stator design contributes short end windings that reduce copper losses, leading to improved efficiency and making the entire assembly compact with short axial length resulting in cheaper and simpler manufacturing process. Structural changes lead to eradication of rotor loss linked to high frequency, cogging torque and flux ripple. The cost per torque ratio is twice as compared to other topologies for any diameter making it expensive for high power wind turbine.

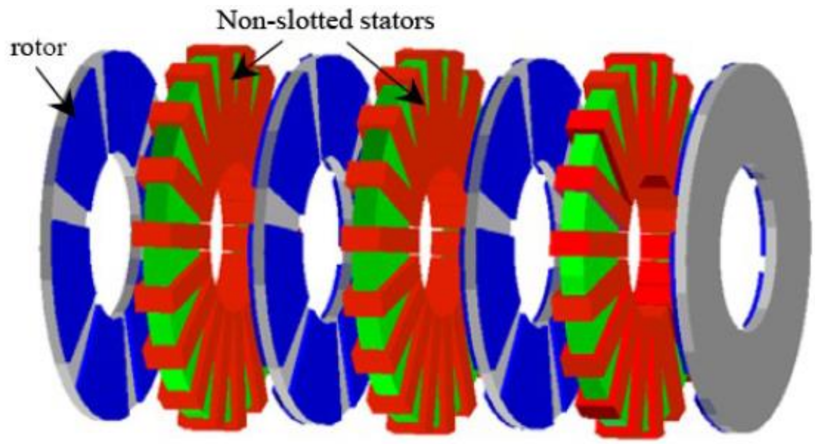


Figure 3.7: TORUS generator 3 stages [29]

Air cored permanent magnet wind turbine (absence of iron in the stator) with double sides (two rotors and a stator) is the most common type of axial flux permanent magnet generator. The stator section is removed in this design and the conductive windings are placed in a non-magnetic recess made of glass fiber reinforced epoxy. Rotor however comprises of permanent magnets

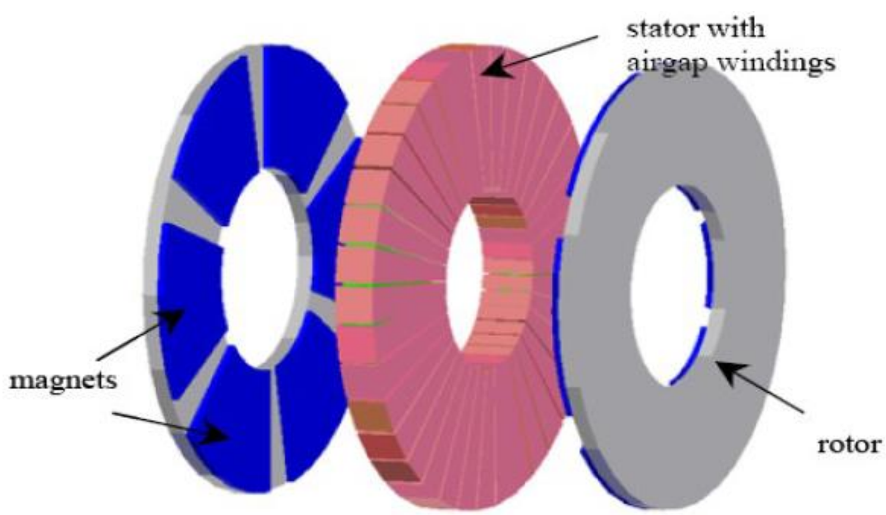


Figure 3.8: Double side axial flux permanent magnet TORUS generator cross section [29]

placed on the disc. The air-gap between the stator and rotor is the least compared to other designs, making the machine compact, lightweight and easier to manufacture. Furthermore, cogging torque and iron losses are zero with low machine inductance leading to insignificant armature reaction compared to TORUS design. The shortcomings of the design are the need of large volumes of permanent magnets in rotor as the iron core for magnetic flux propagation is absent to get the necessary amount of flux across the air gaps [28].

A hybrid design was also proposed; TORUS and air cored generator integrated into multiple stages with small diameter but meet the high torque demand (shown in fig. 3.7). The operation of multi-stage TORUS machine has a shortcoming such as force imbalance between outer rotor and stator and the flux density between the rotor and stator is uneven making it inapplicable to large power application. The entire structure is designed to balance the load between the stages else the stages operate asymmetrically and might break open from the entire structure. Another design variation proposed called the C-core design that consists of a core fixed on the rotor, while the stator windings are held freely among them, which could be radially or axially orientated. The axial flux orientation is preferred as it is simple in structure and extendable to multi-stages.

The disadvantage of axial flux permanent magnet generator is the large axial force applied on the stator by the rotor windings that could twist the structure easily. This can be avoided by removing stator teeth as it is made of laminated iron core that cause magnetic linkages. The leakage flux induces eddy currents causing heating and other losses that can be avoided if the air gap is very small. Another weakness of the axial flux machine is the large amount of permanent magnet material needed since the machine's diameter is large [28].

3.2.3 Transverse Flux Permanent Magnet Generators

In this design, the flux flow in the core is perpendicular to the axis of rotor's rotation as show in fig.3.9. The design uses minor pole pitches permitting high force and high current loading density compared to other permanent magnet generators. It also increases the winding space without hindering the main flux flow thereby reducing the amount of copper used. Losses linked with the windings and the overall weight of the machine reduces the ratio of weight to torque thus improving the torque density of the machine. According to [27], transverse flux permanent magnet generators offer significant potential in terms of power density and cost to torque ratio.

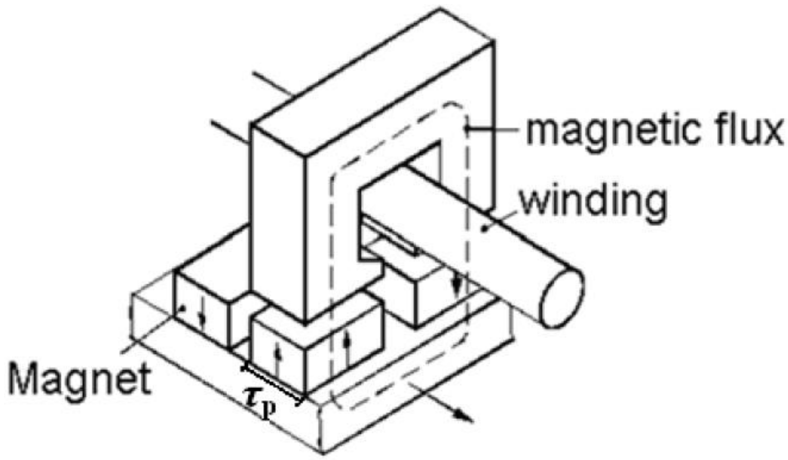


Figure 3.9: Single-sided surface-mounted TFPM machine [29]

Drawback of this design is that it offers low power factor (0.35 for surface mounted and 0.55 for buried magnets) as the field leakage from the armature is large. This can be corrected by using a suitably selected power converter and active control or the use of digital signal processing controller at each phase to optimize the power factor. Other techniques are magneto-static and three dimensional transient finite element analyses that finds the magnetic circuit with least amount of leakage path. The structure however is complex with complicated core design making it difficult to manufacture and assemble as compared to radial and axial flux designs. Air-cored transverse flux machines (absence of iron in stator) that could reduce the manufacturing procedure are not conceivable. Since, the core design is complicated as it produces a flux perpendicular to the rotor axis with a requirement of small air gap.

The air gap along with the designed core produces instability on the average force acting during operation causing vibrations and noise. These topologies are suggested to make the design simpler and easy to manufacture. Two basic categories of the design are concentrating (fig. 3.10) and non-concentrating flux permanent magnet (fig 3.11) poles on the rotor disc. Other topologies are the placement of rotor i.e. inner or outer rotor. Outer rotor is expensive and heavier hence inner rotor design is used with concentrating and non-concentrating poles. Another topology is the use of windings: one sided, double sided windings and U-core.

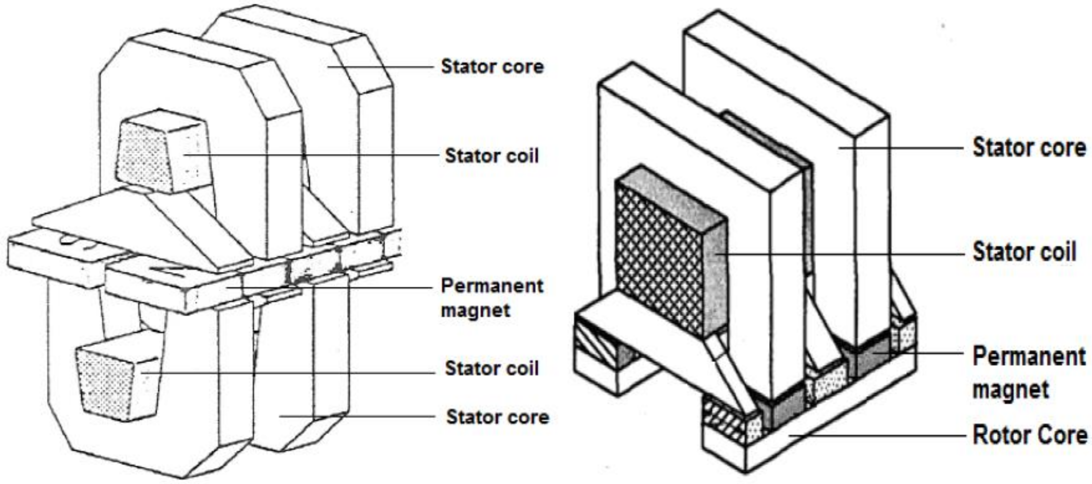


Figure 3.10: Transverse flux permanent magnet generator without concentrator [29]

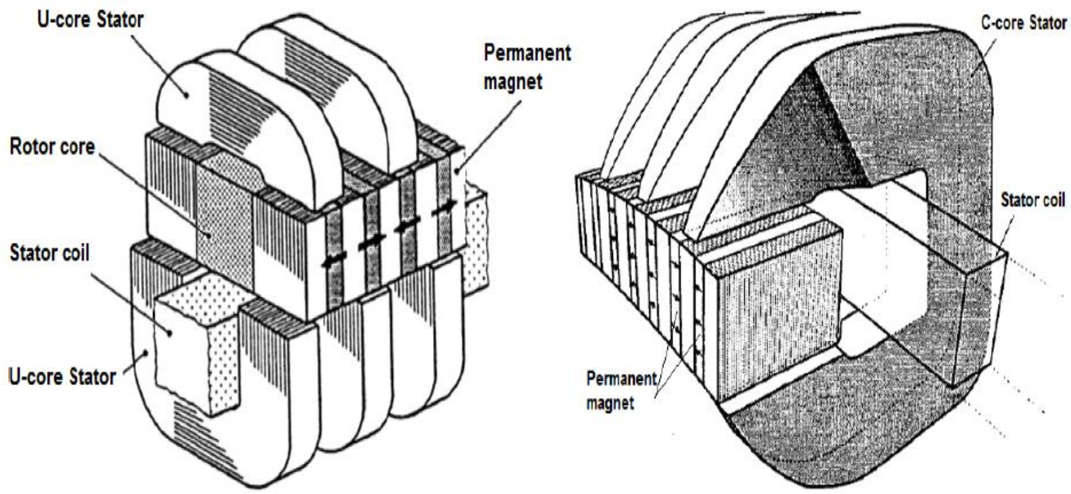


Figure 3.11: Transverse flux permanent magnet generator with concentrator [29]

A flux concentrating design was proposed by Dubois, which was simple in design with same features as conventional radial axis flux permanent magnet generator in terms of its mass per torque and cost per torque ratio. The ratio increases rapidly if the diameter exceeds by one meter or if the torque rating exceeds 10 kNm making it inapplicable in large power applications.

According to [29], C-core flux concentrating design has the highest torque density for least weight compared to the other design consideration.

3.4 Maximum Power Tracking in Direct Drive Technology

As power in wind changes with respect to time of day, power generated from wind turbine varies accordingly. Hence, it is necessary to extract maximum power from available wind. To increase the wind energy output, peak power points of operation are tracked by a maximum power point tracking controller, which is irrespective of generator used. There are three control algorithms namely;

- Control and hill climb search,
- Tip speed ratio and
- Power feedback control

Hill climb search algorithm: The hill climb and search algorithm continuously seeks the peak

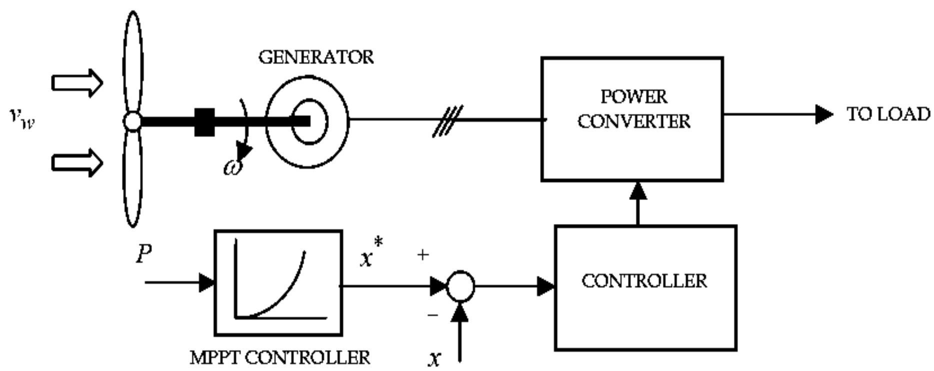


Figure 3.12: Hill-Climb and Search Controller in Wind Turbines [30]

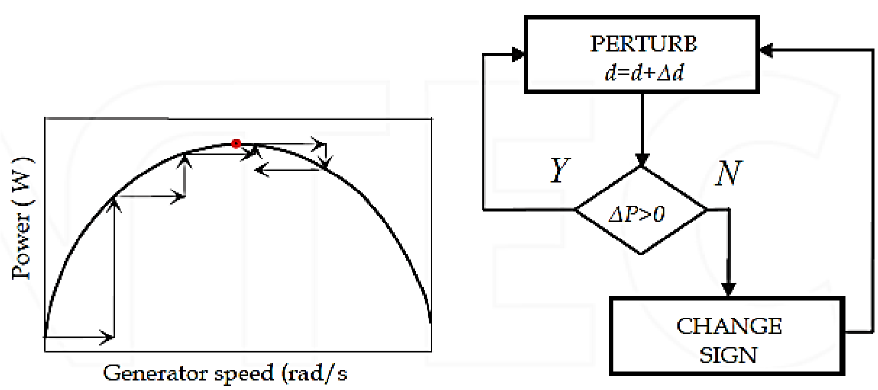


Figure 3.13: Hill-Climb Search Control Principle [30]

power of the wind by computing the optimal signal based on the location of the operating point on the power curve and relation between power and speed. The control principle and algorithm are shown in fig. 3.12, 3.13. Where'd' represents change in generator speed.

In direct drive technology, the control algorithm additionally uses search-remember-reuse technique that uses memory for storing peak power points as training data as well as reference data. At start, controller has zero memory and poor performance. After required iterations, training is carried from the previous data collected by advanced hill climb search technique while recording the training experience.

Tip Speed Ratio Controller: Tip speed ratio is the ratio of rotational speed at tip to the wind velocity flowing through the turbine blades**.** Controller is designed to regulate the rotational

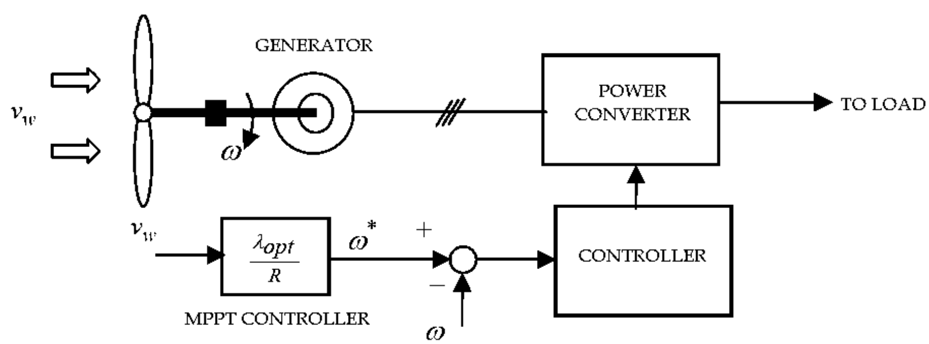


Figure 3.14: Tip speed ratio control in wind turbines [30]

speed of the generator to maintain the tip speed ratio to value at which maximum power is extracted. Therefore, the algorithm requires wind speed and turbine speed (ω) to be measured to calculate the optimal tip speed ratio (λ_{opt}) to extract maximum power. In direct drive wind turbines, intelligent systems are used to estimate wind velocity and tip speed ratio, which is later used to find the optimal speed to extract maximum power. A proportional-integral controller is integrated to sense actual rotor speed by varying the switching ratio of PWM inverter to meet the load demand.

Power Signal Feedback Control: This controller uses information of the wind turbine's power curve and tracks it by control mechanism that is obtained from simulations or experiments conducted on individual turbine. Based on the power curve obtained or from the mechanical

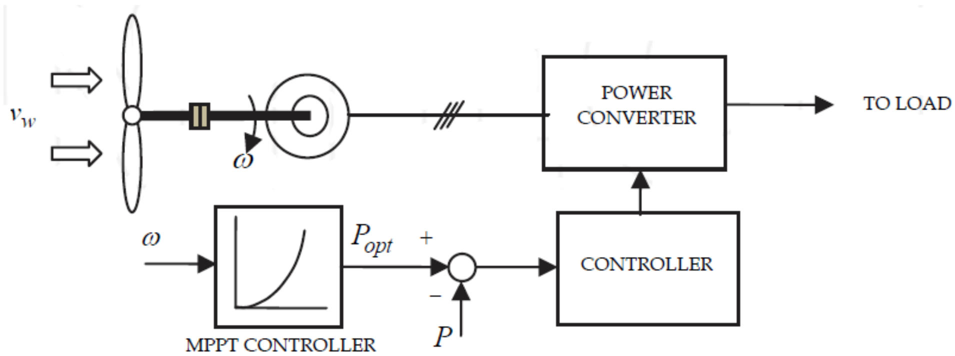


Figure 3.15: Power signal feedback control in wind turbines [30]

power equation with rotor speed as input, reference power is set.

In direct drive machines, optimal power is calculated by the following equation;

$$P_{opt} = K_{opt}\omega_r^3 \qquad [2]$$

P_{opt} is the optimal power extracted from the wind, K_{opt} is the optimal constant of the equation from the power equation and ω_r is the rotational speed of the shaft. Following block diagram

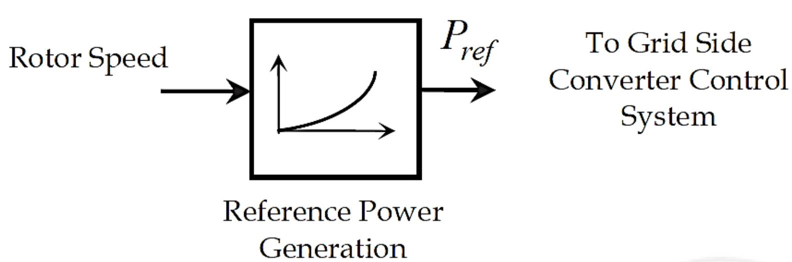


Figure 3.16: Reference Power generation in direct drive machines [30]

explains power feedback signal operation in direct drive permanent magnet synchronous wind turbine;

3.5 Advantages of Direct Drive Wind Turbines

Direct drive wind turbines have several advantages, which makes them superior in terms of performance and reliability. The DFIG and switched reluctance generators face the following drawbacks:

- Heat losses linked to friction caused due to gearbox operation.
- Noise level generated at the vicinity of an operating wind turbine.
- Early aging of the machine due to wear and tear during gear operation
- Lower reactive power compensation contribute to poor grid power factor.
- Coolants such as oils and liquids must be replaced and need constant attention.
- Use of an external circuit to stop wind turbine from with drawing power back from the grid.
- Large fault currents and high torque production during a fault at grid level.

These disadvantages lead to the use of direct drive wind turbine in electricity generation. In addition, improvements in power electronic technology and cost of the permanent magnets are favoring the integration. The advantages of direct drive wind turbine are:

- High energy yield as compared to DFIG and switched reluctance turbines especially off-shore operation
- Improved reliability as the gear box in the drive system and slip rings are eliminated
- Efficiency improvement as the losses are reduced
- High power to weight ratio
- No additional power supply needed

The only disadvantage of direct drive technology is the high torque rating of the machine that is directly proportional to the mass of the electrical machine. For a given power rating of the turbine, lower the torque rating of the machine, greater is the price of the machine.

With the constraints given, it becomes necessary to extract maximum power from the turbine for a given rated torque. A controller with suitable control algorithm that controls the wind turbine's blade to capture power is carefully selected to optimize the performance of the machine. Apart from this, gearbox adds to deterioration of wind turbine's reliability and efficiency. During repair of gearbox, the wind turbine does not function making it useless for electricity production. Therefore, the absence of gearbox in operation of the direct drive wind turbines, improves the reliability of the machine as compared to conventional wind turbines.

Drives are designed to ensure faster and precise position timings to track the maximum power and maximum aerodynamic performance while operating at flexible frequency modes in order to do so. Sensors are located to adjust generator speed to obtain required shaft speed and sense the wind speed acting on the wind turbine.

The controller design with maximum point tracking is an important aspect in turbine design to achieve optimal performance of the turbine that are located specifically offshore.

3.6 Direct Drive Wind turbines in Service

As the direct drive turbine proved it has improved their capability, it caught the attention of major wind turbine industries. Within the last decade, manufacturers such as General Electric (GE), Alstom, Dongfang Japan Steel works, Enercon, Goldwind, Siemens, Repower, Vestas, Sinovel, STX Group, etc. are designing their own technology and designs for direct drive wind turbines.

General Electric

General electric is the largest wind turbine manufacturing industry in the US since 2008. The company has 10 different wind turbine designs for onshore use with ratings ranging from 1.5 MW to 3.2 MW and 4.1 MW direct drive offshore capability. The 4.1 MW wind turbine was designed and came into operation by the end 2005 tested in a harsh near shore environment. The energy production has improved by 5% and 50%, with reduction of installation time with the use of direct drive turbine. The turbine has once a year maintenance cycle with 7 days for installation and commissioning for energy production. The first 4.1 MW direct drive turbine was tested in Sweden in December 2011 that lasted 200 hours [30].

Alstom

Alstom shares the second major global wind turbine capacity of 2,500 operational wind turbines and with 150 on the way that will deliver approximately 4 GW. The onshore designs variants are asynchronous doubly fed induction generator are ECO 100, ECO 110 and ECO 122. ECO 100 and ECO 110 are rated at 3 MW, whereas ECO 122 is designed to generate 2.7 MW. They include 3 staged gearbox. The off shore variant Haliade is rated for 6 MW is direct drive with modular rotor design operating at variable speed and independent pitch control by blade. This is the sixth largest off shore wind turbine with efficiency improvement of 15% and feeding 5,000 residential sectors [31].

Siemens

Siemens manufactures wind turbines with power rating varying from 2.3 MW to 4 MW onshore turbines and 3 to 6 MW offshore wind turbines. These machines are pitch regulated. Siemens was the first company to serve offshore project. Its largest offshore project was rated 165 MW, with 500 MW offshore projects underway. The first offshore wind turbine was in 1991 rated 450 kW installed at Vindeby, Denmark. It is one if the four largest direct drive wind turbine manufacturer. The company has 1,000 offshore operational wind turbines, generating 3 GW. Another major project by Siemens is the London array project which is the largest off shore wind power plant [32].

Goldwind

Goldwind made its way into the market in 1980s from China. They have two variants to the direct-drive wind turbine design; 1.5 MW and 2 MW. In US alone, Goldwind has 17 projects with 271 MW under contract. The 1.5 MW rated wind turbines contribute to 198 MW of the total global capacity and the rest by the 2.5 MW rated turbine. Major products to the direct wind turbine is the pitch system that consists of toothed belt rather than gears making turbine's cost low, improving stability and reducing vibrations during operation are the advantages of this technology. Another improvement is the use of ultra-capacitors for energy storage, which is efficient as compared to lead acid batteries. It also is has a better charge-discharge cycle, lighter in weight and larger power density for same mass of lead cell to store this wind power.

Vestas

Vestas designs turbines rated from 2 MW to 8 MW. The global total number of Vesta's wind turbine by 2012 was 47,335 with generating capacity of 51,747 MW. Among their achievements, one of them is the installation of 100 wind turbines in less than 100 days. The permanent magnet wind turbine by Vestas is rated 7 MW. However, the design incorporates a gearbox while other manufactures of direct drive turbines use gearless turbines.

CHAPTER 4

ARTIFICIAL NEURAL NETWORKS

The human brain is a complex parallel operating machine capable of solving real world problems. Even though we have understanding of its basic operations, we still have a lot to explore its other capabilities. The fundamental unit of a brain called a “Neuron” (fig.4.1). A neural network consists of well-connected neurons. The center of the neuron is called the nucleus to which other nuclei are connected with the help of dendrites and axons. This inter-connection is called synaptic connection.

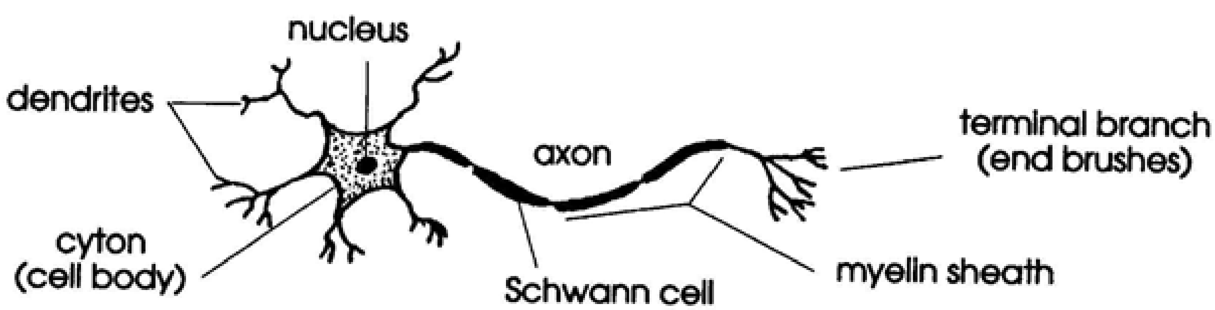


Figure 4.1: Generalized neuron model [29]

A neuron, when triggered, fires electric pulses through the synaptic connections that are received by the dendrites of the other neurons. On receiving these pulses, it triggers another pulse through the axon that is sent to other neurons. This process propagates the information through the network. Synaptic interconnections change all through the neuron lifetime, so does the amplitude of the pulse received to activate the neuron. This process helps the neuron network to learn while training. Brain consists of roughly 10^{11} neurons with 10^{15} inter-connections. It is connected to the nervous system through which it can perceive the external environment with the help of sensory organs. Modeling this operation for real time applications is possible but complex to program and train. The closest modeling approach is the mathematical modeling of a simple neuron called artificial neural network.

Artificial neural network mimics the brain functioning but not as large or complex as the brain. However, simple networks are trained and are being used in applications such as pattern recognition, business analysis, predictive modeling, etc. The training of artificial neural network is simple and flexible giving the user to experiment while widening its scope in artificial intelligence research. Additionally, neural networks are very efficient in generalizing from the training data, making them good learners. For instance consider an example of classification of colored pencils; the network will be able to predict whether a given pencil will be outside the original collection of pencils from the entire group knowing the features of the pencil by finding it out by itself.

4.1 Mathematical Modeling of a Neuron

McCulloch and Pitts designed the first neuron model in 1949 (fig. 4.2). The model is defined as a

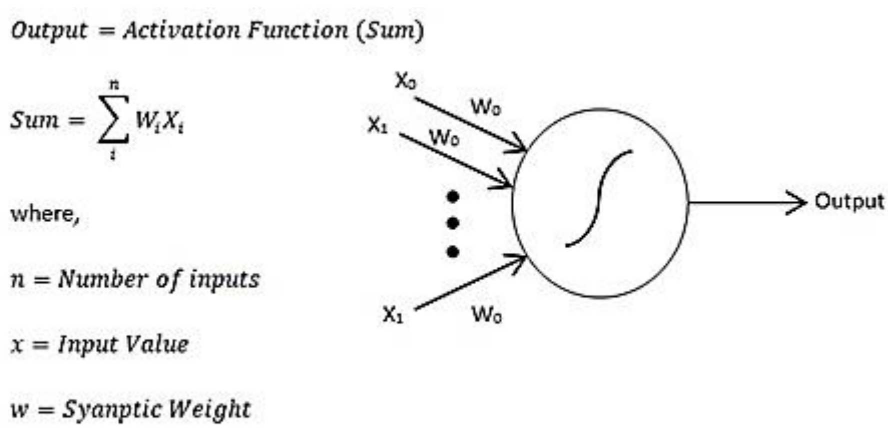


Figure 4.2: Mathematical Model of a Neuron [29]

binary processing unit i.e., a neuron when fired or not the output signal is controlled by threshold logic or an activation function. It consists of multiple inputs and an output. Each input linked with weight acting as a synaptic resister. The output is a function of sum of the multiplications of each input and their respective weights. The activation is the sum value from the first iteration.

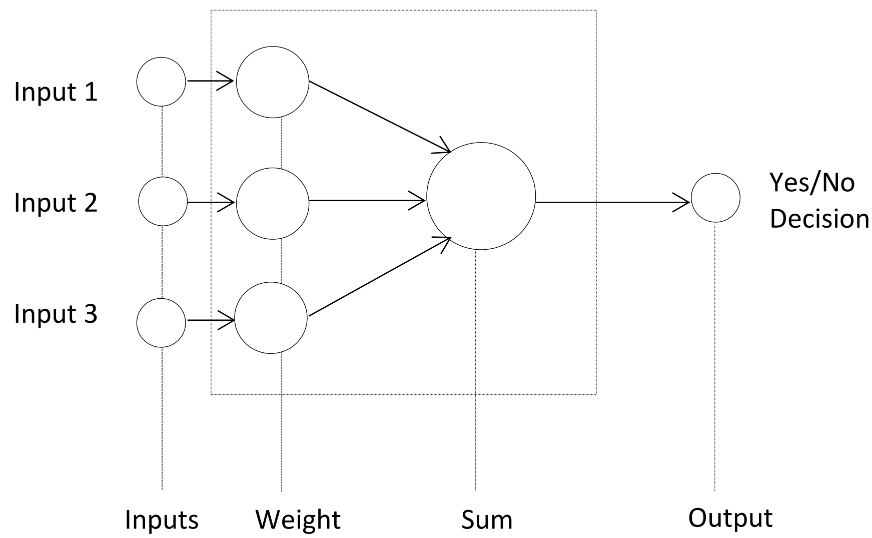


Figure 4.3: Single layered perceptron [29]

Minsky, Marvin and Seymour proposed another model in 1988. It was called perceptron which is an extension to the previous model. It consisted of multiple neurons forming a layer with learning capability. Single layered perceptron could be trained to solve simple problems such as simple digital gates like AND and OR. However, this model could solve only linearly separable problems. Linearly separable is the classification of each class with respect to the problem. For example, XOR gate in the digital logic gate is not linearly separable. Therefore, this model cannot be used to model an XOR gate.

4.2 Dynamics in Neural Networks

Dynamics in neural network are classified as architectural dynamics, computational dynamics and adaptive dynamics.

4.2.1 Architectural Dynamics

Architectural dynamics is the network topology and the possible changes in the topology. These changes are within the structure of the network like addition of neurons and connections when needed. Typically, these changes are avoided to reduce the complexity of the network for debugging. Two types of interconnections exist based on the interconnection of the neurons.

Recurrent Network: A cyclic network is which a group of neurons is inter-connected into a ring cycle. Meaning that in the group of neurons, output of the first neuron is fed as input to the next neuron and so forth till the last neuron's output is fed back to the first neuron as its input. The

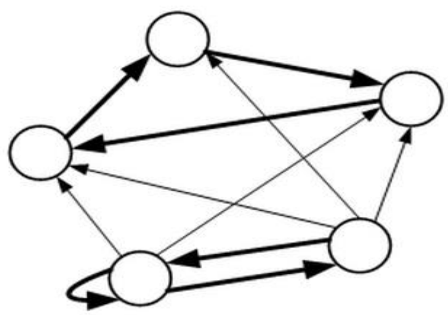


Figure 4.4: Recurrent architecture [29]

dark lines in figure 4.4 represent the neural path. The simplest recurrent network is a neuron with its output as is its input whereas a complete recurrent network is the one where each neuron's output is the input of the next neuron.

Feed-forward Network: This network topology does not contain any cycle but, all the neural

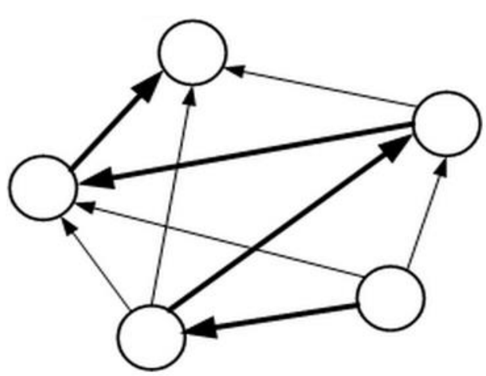


Figure 4.5: Feed-forward neural network [29]

paths lead in one direction. In fig 4.5 neurons are divided in layers that are ordered so that the logic flow is from lower layer to upper layer. The model's neural flow gets much more complicated in multilayered neural network with the lower layer as the input layer, upper layer being the output layer and the remaining neurons as the hidden layers.

4.2.2 Computational Dynamics of Neural Networks

Computational dynamics requires the network's initial state and a rule that updates with respect to time given the network topology is fixed. For the first computation, the input's state is

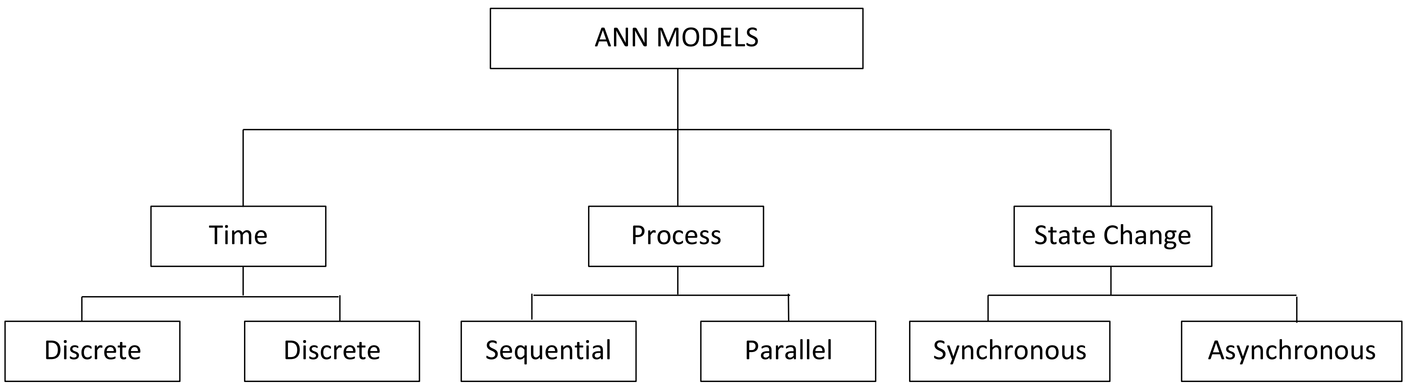


Figure 4.6: Neural network model classification based on computational dynamics [29]

assigned to the network's input and the remaining neurons in itself set their initial state. These inputs and states form the input and state space of the network respectively after which proper computations are performed. Based on the dynamic operation of the network, networks are classified as Continuous-time dynamic systems and Discrete-time dynamic systems. Continuous time dynamic systems are generally described as differential set of equations. These networks operate with signals that are time dependent represented by a continuous variable. Spatial variables can also be used as well. Discrete-time dynamic system operate with signals that are a functions of discrete variables, however discrete spatial variables could be used. At start, the time step is zero. Later the network is updated at time steps 1, 2...etc. At a time step, a neuron or set of neurons (series or parallel) are selected based on a rule for computation. Inputs are selected by neurons, that update the state based on the outputs of incident neuron.

Another distinction is the functioning of neurons either centrally or independently called synchronous or asynchronous models respectively. The states that represent the output neurons that varies with respect to time are output of the neural network that is resulted from previous computations. Computational dynamics is considered to ensure constant output after a period of time. Due to this operation, a function is implemented in the input space such that each network's input computes one output. This function is identified by computational dynamics whose equations are framed by the topology and configurations that are set during the computation mode.

Neurons that contain the same formal form are called homogenous neural network that can have their function determined by computational dynamics, which is usually the same for all the neurons. Excitation levels are the weighted sum of inputs values for a given neuron. It depends on the distance between input and the respective weight corresponding to the neuron approximated by continuous activation function or by other functions. The activation function are hard limiter, piecewise linear, standard sigmoid (also called logistic function) and the hyperbolic function.

Hard limiter:

$$\sigma(\varepsilon) = \begin{cases} 1 \ if \ \varepsilon \geq 0 \\ 0 \ if \ \varepsilon < 0 \end{cases}$$

represented by,

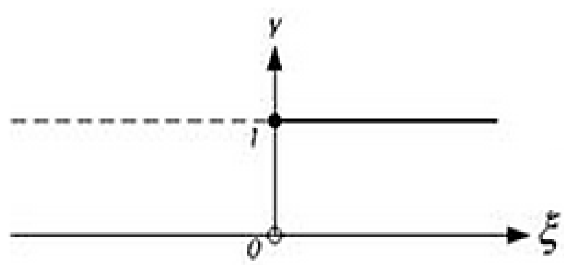


Figure 4.7: Hard limiter transfer function [29]

Piecewise Linear:

$$\sigma(\varepsilon) = \begin{cases} 1, & x < 0 \\ \varepsilon, 0 \leq \varepsilon \leq 1 \\ 0, & \varepsilon \geq 0 \end{cases}$$

represented by;

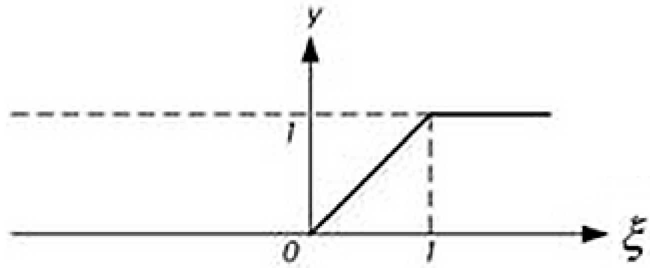


Figure 4.8: Piecewise linear transfer function [29]

Standard sigmoid:

$$\sigma(\varepsilon) = \frac{1}{1 + e^{-\varepsilon}}$$

represented by,

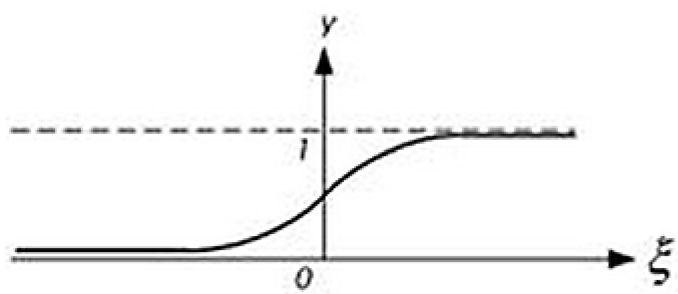


Figure 4.9: Standard (logistic) sigmoid transfer function [29]

Hyperbolic Tangent:

$$\sigma(\varepsilon) = tanh\left(\frac{1}{2}\varepsilon\right) = \frac{1 - e^{-\varepsilon}}{1 + e^{-\varepsilon}}$$

represented by,

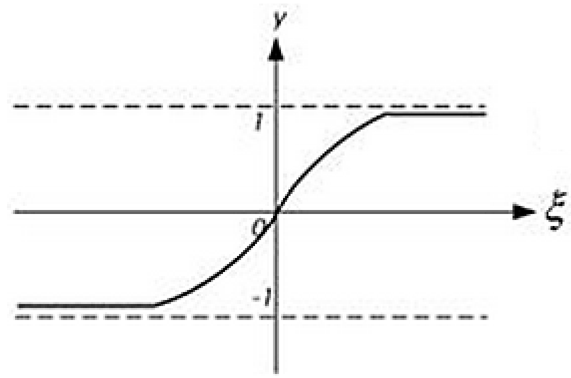


Figure 4.10: Hyperbolic tangent transfer function [29]

4.2.2 Adaptive Dynamics in Neural Networks

It deals with the network's initial configuration and the neural flow in the network and weights with respect to time. Network configuration forms the weight space of a neural network, which at start is set to initial configuration. With respect to the computational dynamics and with continuous time evolution, weights are adjusted based on the differential equation on which the model was set.

Based on the configuration of the model, the network function is set during the computational mode. The weight adjustment in computational mode is such that it the aim of adaptation is satisfied without violation of the desired function. In computational mode the network configuration's as computations are exploited, whereas in adaptive mode learning of the desired function is considered. There are various successful learning algorithms for all types of neural networks. Among them, the most common type is the back-propagation algorithm used in multilayered perceptron. The learning (programming) algorithm is a complex optimization problem that is non-linear in nature and is time consuming even for small tasks.

Neural networks are programmed for a set of inputs that give a desired set of outputs based on the application. Several methods exist to vary the strengths and connections between them. Primary among them is set the weights explicitly with prior knowledge or by teaching patterns to the neural network due to which weights are adjusted based on set of rules.

Usually network functions are specified by the training set of inputs and the corresponding training set of outputs which are called training patterns. The training function behaves as a teacher who imports the correct network inputs for a given output pattern to the adaptive mechanism. This is called supervised or associative learning. Associated learning needs a teacher that provides the input-output pairs or can be provided by the network itself. In some scenarios, the teacher calculates the quality of outputs by mark rather than giving the desired output associated with the sample input. This is termed as "Reinforcement Learning".

Another method of programming or training a network called unsupervised learning or self-organization wherein the teacher is absent. Due to this, the training set contains restricted sample inputs to which the neural network itself organizes the pattern and discovers its functioning. This leads to outputs that are framed within the set of inputs but the network on itself discovers patterns within the input population. Since the patterns are unknown, unsupervised learning does not categorize the patterns; rather it builds up on the set of inputs given to it.

Examples of supervised feed forward networks include least mean squared error networks, radial basis network and backpropagation networks. They are typically used for function approximation application. Unsupervised feed forward networks are used to extract significant properties from the input data and map it on the demonstration domain. This is further categorized as "Hebbian network" and "Competitive network". Hebbian networks perform principal component analysis whereas competitive network perform learning vector quantization on the input data. Feedback networks learn and process the input data evolving the internal state of the network with respect to time. Examples of such networks are recurrent back-propagation networks, adaptive resonance network and associative memories.

4.3 Modeling the Back-propagation Algorithm:

To explain the process, consider a three layer neural network with two inputs and one output as shown,

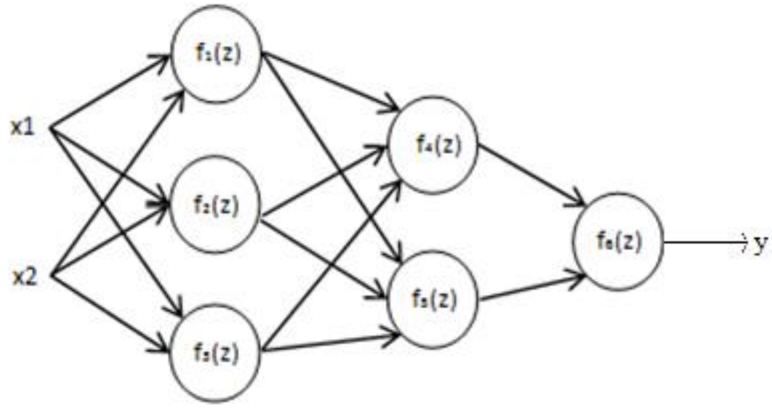


Figure 4.12: Three layered neural network [29]

The back-propagation algorithm is based on the error-correction learning rule which uses the least mean squared technique. Back-propagation algorithm uses two passes at different layers of the neural network. They are called forward pass and the backward pass [33]. During the first pass, inputs are applied to the first layer of neurons and are propagated through the network's layers. The responses are stored for the final pass with fixation of the weights. At the start of backward pass, the weights are then corrected by following the error correction rule. Difference between recorded outputs and desired outputs are treated as an error signal. This signal is further propagated back into the network opposite to the synaptic connections, hence called backward phase. This brings the net output closer to the desired output by setting the weights.

The network uses non-linear activation function typically the sigmoid function or hyperbolic tangent function. The non-linarites of these functions are vital for the logical operation of the network else, the network would reduce into single layer neural network. Hidden layers enable the network to learn complex tasks although they are not part of the input or output layers. The network once trained consists of higher degree of connectivity. Changing the connectivity is done by changing the number of weights.

Learning rule: With the working explained, the learning process is as follows,

$$y_1 = f_1(w_{11}.x_1 + w_{21}.x_2) \tag{4}$$

$$y_2 = f_2(w_{12}.x_1 + w_{22}.x_2) \tag{5}$$

$$y_3 = f_3(w_{13}.x_1 + w_{23}.x_2) \tag{6}$$

$$y_4 = f_4(w_{14}.y_1 + w_{24}.y_2 + w_{34}.y_3) \tag{7}$$

$$y_5 = f_5(w_{15}.y_1 + w_{25}.y_2 + w_{35}.y_3) \tag{8}$$

$$y_6 = f_3(w_{13}.x_1 + w_{23}.x_2) \tag{9}$$

Error is the difference between outputs of the network and the desired outputs that are computed as;

$$\Delta = y' - y \tag{10}$$

$$\Delta_4 = w_{46}.\Delta \tag{11}$$

$$\Delta_5 = w_{56}.\Delta \tag{12}$$

$$\Delta_3 = w_{34}\Delta_4 + w_{35}\Delta_5 \tag{13}$$

$$\Delta_2 = w_{24}\Delta_4 + w_{25}\Delta_5 \tag{14}$$

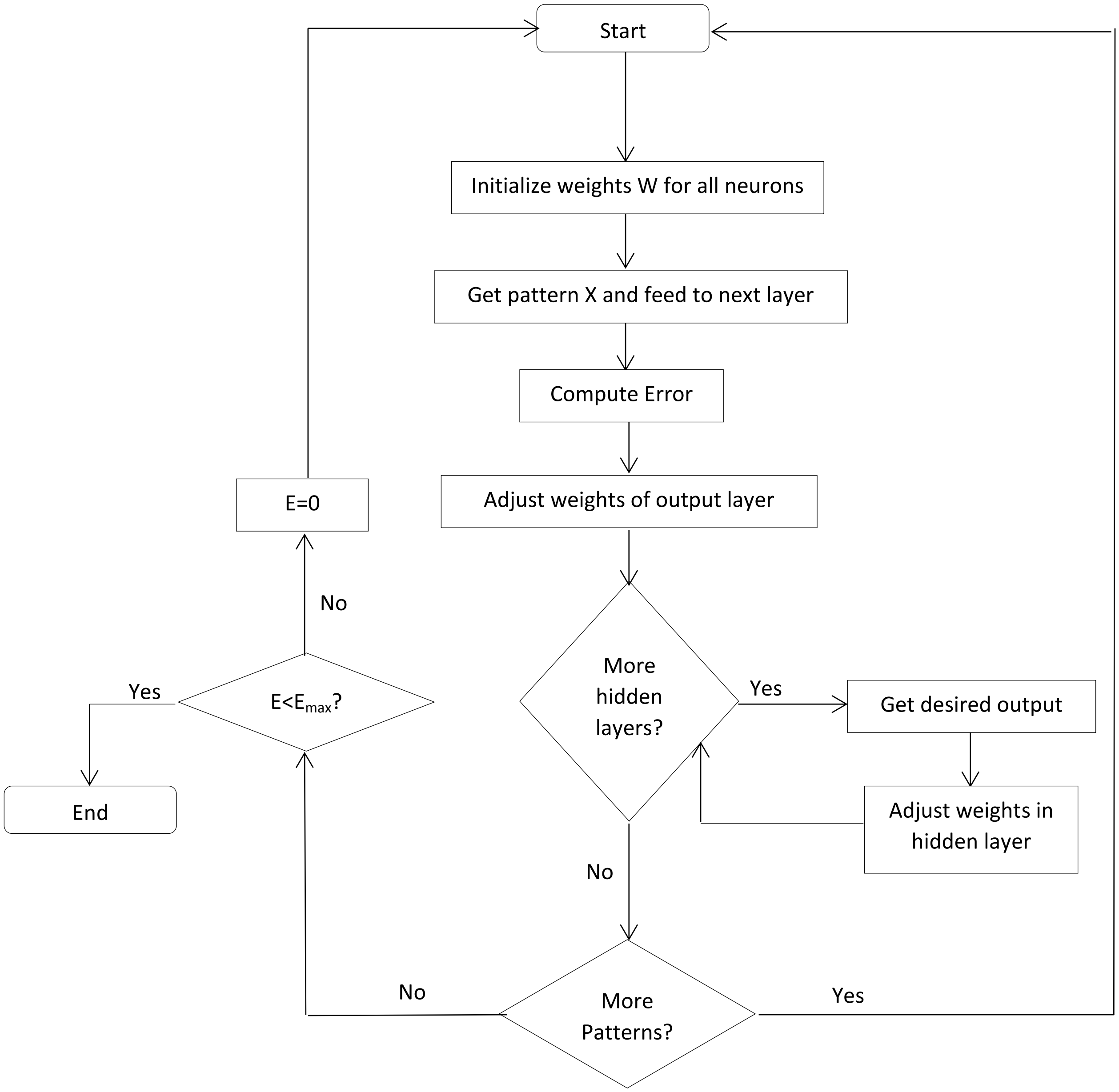


Figure 4.13: Flowchart of backpropagation algorithm[29]

$$\Delta_1 = w_{14}\Delta_4 + w_{15}\Delta_5 \tag{15}$$

The weight correction equation is,

$$\delta w_{ij} = \alpha\Delta_i(n).\, y_j(n) \tag{16}$$

Where E is the error between desired output and output resulted from computation, i and j are the weights connecting neuron j to neuron i accordance with the delta rule. Gradient $\Delta_i(n)$ depends on the connection between neurons existing between neurons or hidden node. For an output node 'i', $\Delta_i(n)$ equal to the product of derivative and error signal. For a hidden node 'j', $\Delta_j(n)$ is equal to the product of the derivative and the weighted sum of errors computed for the next hidden or output layer neurons that connected to neuron j.

4.4 Application of Neural Networks in Wind Energy Conversion Systems

There are many examples where neural networks are used to link two or more variables to model real-time wind energy conversion systems. A few of them are described in the following subsection.

Wind Power Prediction: Z. Liu et al. [38] describe the use of neural networks for wind farm's power prediction. The authors use short-term power forecast of a wind farm by training a neural network with historical data. Raw data is first collected to train the network, after which filtering and other data sorting processes are conducted to ensure effective operation of the network with removal of redundant data. The neural network used to model predicted wind is the probabilistic neural network for wind velocity prediction. Complex valued recurrent neural network is used to predict the wind turbine's power generation. The data consists of wind power plant distribution, wind direction, site of wind turbine, wind speed classification based on period of flow and power generated at the respective time-period. The network, once trained, predicted the next ten minutes values of wind velocity with error.

Generator Monitoring: Jianping X. et al. [39] monitor the condition of wind turbine's generator. Temperatures of the bearings are modelled as a function of the generator's speed during operation. To model, the authors have used a higher order differential equation to gain higher accuracy to fit the measured data and the modelling data. Patterns of measured temperatures and real time temperatures are recognized with a neural network. The generator speed difference is set as the input to the feed forward network and the temperature difference as the training data. The error is calculated later and is compared with the real time data.

Wind Energy Forecast: Piers R.J. C. et al. [40], use neural networks with back propagation algorithm to forecast wind energy yield. It consists of four layers; input layer with three input nodes activated by linear activation function, two hidden layers with two nodes and sigmoid and gaussian activation functions respectively and an output layer with single node activated by sigmoid activation function. It predicts the hourly wind speed data with an error of 0.8 m/s that is later fed to a simulated wind turbine. This can help the wind turbine engineers to locate and asses different wind turbine sites for high power yield.

CHAPTER 5

DESIGN OF NEURAL NETWORK CONTROLLER

This chapter discusses the proposed neural network prediction controller with the following steps;

- Data acquisition and pre-processing
- Data normalization
- Statistical analysis
- Design of single module direct drive wind turbine in Simulink
- Design of controller
- Training and Results

5.1 Data acquisition and preprocessing

The data selected is for Elk City, Oklahoma. It is wind speed, direction, temperature, wind chill, dew point, humidity, pressure, wind direction and precipitation (shown fig 5.1). Unfortunately, the data is absent from 1973 till 1997 and restricted to a height of 1923 ft. This leads to work on data normalization and assumptions of wind data for the required height.

5.2 Data Normalization

Time (CST)	Temp.	Windchill	Dew Point	Humidity	Pressure	Visibility	Wind Dir	Wind Speed	Gust Speed	Precip	Events	Conditions
12:53 AM	37.0 °F	28.1 °F	28.9 °F	73%	30.07 in	-	NNW	15.0 mph	-	N/A		Clear
METAR KCSM 310653Z AUTO 33013KT CLR 03/M02 A3007 RMK AO2 SLP183 T00281017												
1:53 AM	37.0 °F	28.5 °F	30.0 °F	76%	30.07 in	-	NNW	13.8 mph	-	N/A		Clear
METAR KCSM 310753Z AUTO 33012KT CLR 03/M01 A3007 RMK AO2 SLP183 T00281011												
2:53 AM	37.0 °F	28.1 °F	30.0 °F	76%	30.09 in	-	NW	15.0 mph	-	N/A		Scattered Clouds
METAR KCSM 310853Z AUTO 32013KT SCT070 03/M01 A3008 RMK AO2 SLP188 T00281011 51012												
3:53 AM	36.0 °F	26.3 °F	28.9 °F	76%	30.09 in	-	NNW	16.1 mph	-	N/A		Scattered Clouds
METAR KCSM 310953Z AUTO 34014KT SCT075 02/M02 A3008 RMK AO2 SLP189 T00221017												
4:53 AM	35.1 °F	25.9 °F	27.0 °F	72%	30.10 in	-	North	13.8 mph	-	N/A		Clear
METAR KCSM 311053Z AUTO 36012KT CLR 02/M03 A3009 RMK AO2 SLP192 T00171028												
5:53 AM	35.1 °F	26.4 °F	25.0 °F	67%	30.13 in	-	North	12.7 mph	-	N/A		Clear
METAR KCSM 311153Z AUTO 35011KT CLR 02/M04 A3012 RMK AO2 SLP203 T00171039 10033 20017 53011												
6:53 AM	33.1 °F	24.4 °F	24.1 °F	70%	30.19 in	-	WNW	11.5 mph	-	N/A		Clear
METAR KCSM 311253Z AUTO 30010KT CLR 01/M04 A3017 RMK AO2 SLP224 T00061044												
7:53 AM	34.0 °F	25.0 °F	24.1 °F	67%	30.22 in	-	WNW	12.7 mph	-	N/A		Clear
METAR KCSM 311353Z AUTO 30011KT CLR 01/M04 A3020 RMK AO2 SLP234 T00111044												
8:53 AM	36.0 °F	26.3 °F	25.0 °F	64%	30.25 in	-	NW	16.1 mph	-	N/A		Clear
METAR KCSM 311453Z 32014KT CLR 02/M04 A3023 RMK AO2 SLP242 T00221039 51035												
9:53 AM	39.0 °F	30.6 °F	24.1 °F	55%	30.27 in	-	NNW	15.0 mph	-	N/A		Clear

Figure 5.1: Screenshot of wunderground database of Elk City,OK

A copy of the data measured has been created in Microsoft's excel sheet and is normalized by dividing each value with the maximum value of the data set. In addition, data is restricted in Excel sheet because the neural network will not be able to take the complete number of wind readings as it consumes a large memory of MATLAB thereby reducing its operational speed. With large memory consumed, the processing of data will take a lot of time and making the neural network unstable. For a complete year, the total number of readings is (every hour of the day) 8760. This is calculated as; a day with 24 hours, 365 days in a year leads to 8760 hours in total. The year for which the neural network was trained correspond to, 5th of August 2012 to 5th of August 2013. This data consists of redundancies such as missing data or zero values because of sensor malfunctions, etc. Missing data is replaced with the average of the data before and after the hour. Zero values are dealt is the same way.

$$Normalized\ data = \frac{Actual\ data}{Maximum\ of\ the\ data} \tag{17}$$

5.3 Statistical Analysis:

Correlation is one approach to find the variation of variables with respect to one another. It is usually denoted by ‘r’. Correlation of wind data is calculated with respect to temperature, humidity and pressure at the site. Properties of correlation are;

- Measures the closeness of the fit.
- Varies between -1 and 1.
- Correlation, if perfect and positive then it represented by positive ‘1’, perfect neagative is represented by ‘-1’
- Zero correlation means the variables are independent of each other.
- Coefficient off correlation is independent of changes to origin and scale of magnitude and is a pure number.

Method to study the correlation used is Spearman’s rank correlation method. The equation used is,

$$R = 1 - \frac{6 \times \sum D^2}{n(n^2 - 1)} \tag{18}$$

Where, D represents the difference between the ranks of each observation. Correlation between temperature and wind velocity is found to be 0.58 and between humidity and wind velocity is calculated as 0.10 and wind velocity and atmospheric pressure is 0.39. From the calculations, it is clear that the parameters are positive.

5.4 Design of single module direct drive wind turbine in Simulink

The design of the direct drive wind turbine is carried out on Simulink of MATLAB 2011. The model consists of;

- Pitch Angle controller
- Wind turbine model

- 2 Mass drive train
- Permanent magnet alternator

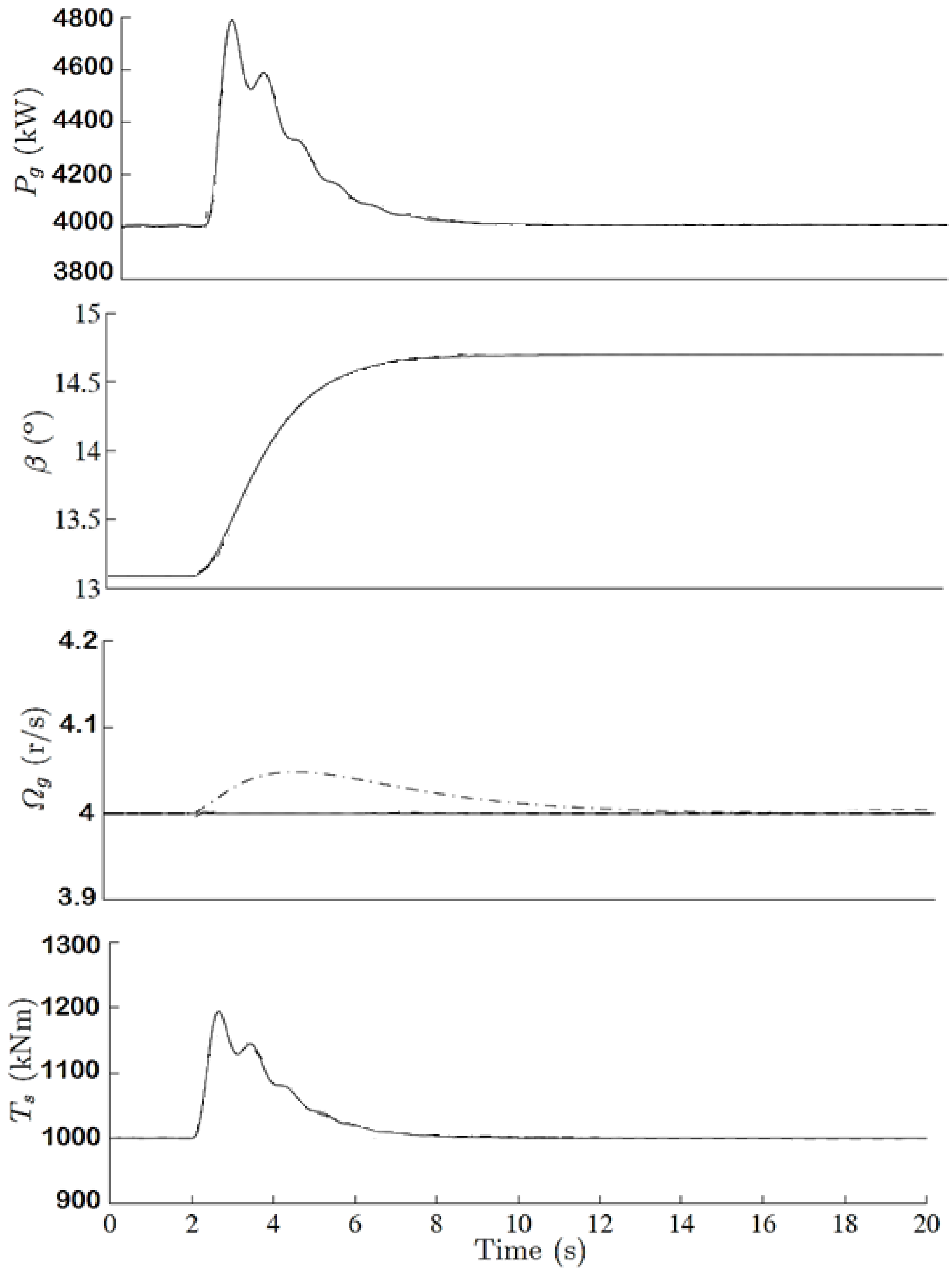


Figure 5.2: Controller behavior for multi-speed and variable pitch

- 3 phase RLC Load

5.4.1 Pitch Controller:

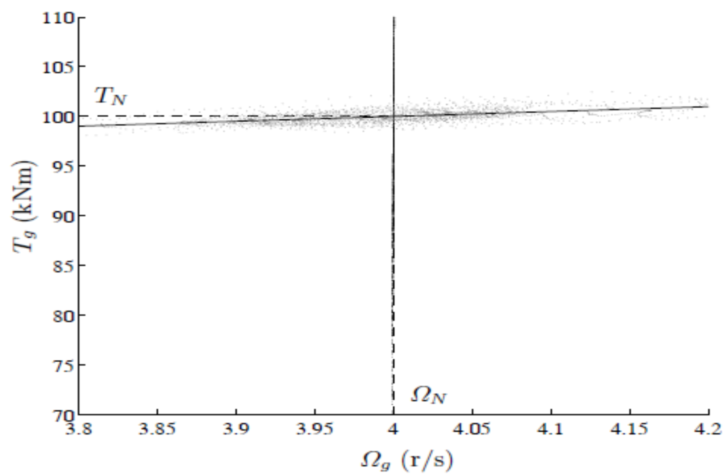


Figure 5.3: Generator speed vs. Torque generated at 18 m/s

The controller designed is variable pitch variable speed. It is represented in fig.5.4. For this simulation realistic wind speed profile with a mean speed of 5 m/s is considered, the behavior is shown in fig. 5.3. In fig 5.2, the first plot is the power generation with respect to time, second plot is the generator speed and the third plot is the pitch angle, and the last plot is the torque generated. The solid line depicts the multi speed and variable pitch. The advantage of this controller is mechanical loads on drive train are lower. At low wind speeds, zero torque speed and pitch angle is set to 4 rad/s that optimizes the output to increase the energy capture. Linear parametric control is used in this type of controller, however the input to the controller is from a non-linear controller i.e. neural network controller.

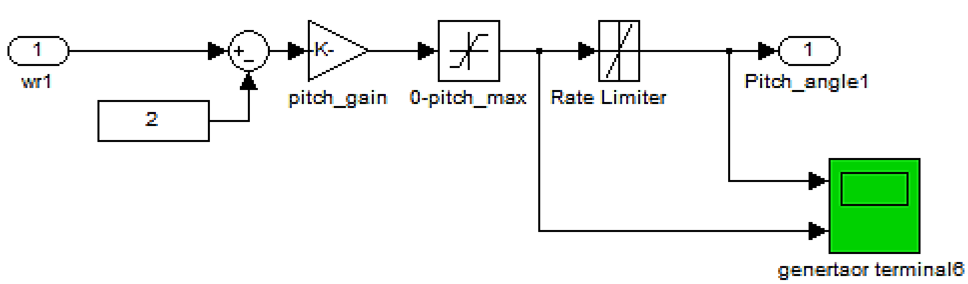


Figure 5.4: Pitch Controller in SIMULINK

At full speed operation, non-linarites are introduced because of the system dynamics due to its varying operating range. A single controller is the simplest approach instead of the use of multiple controllers that use complicated algorithms operating for different wind speeds.

5.4.2 Wind turbine model

From the studies conducted, the variable speed permanent magnet is used for the turbine model. The associated block diagram is shown in fig. 5.5. The generator is based on Park transformation with 6 rectifiers in bridge layout. Inverter and a current controller follow this layout that signals the inverter switches.

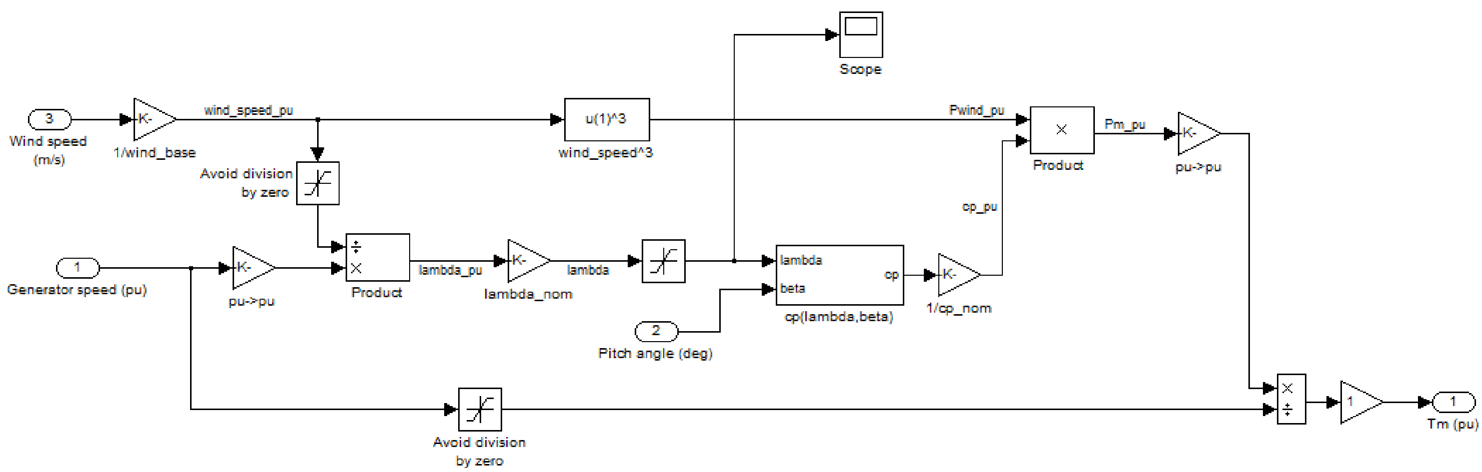


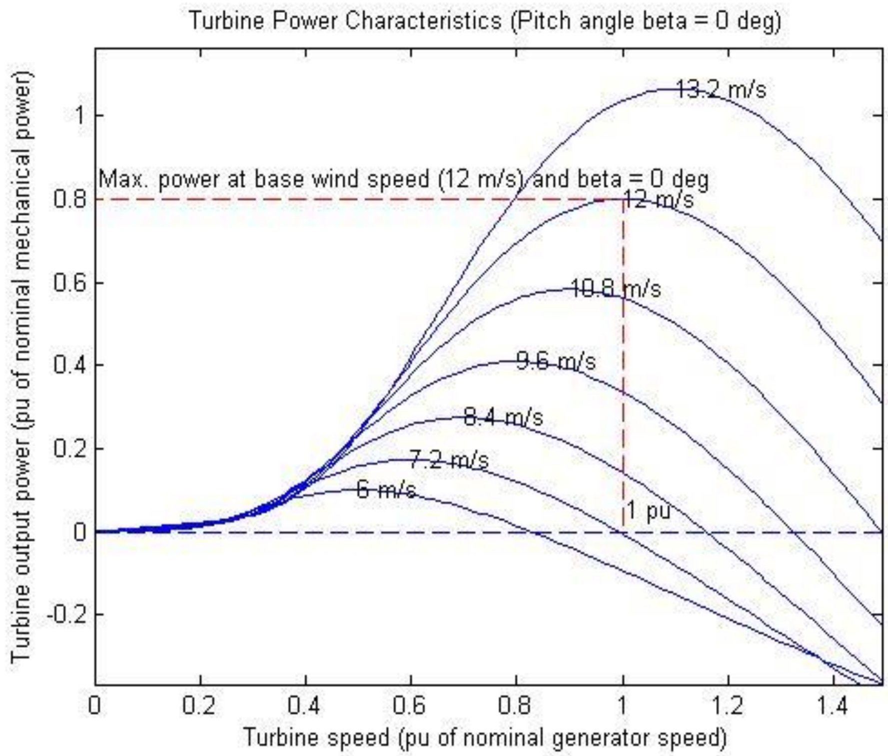
Figure 5.5: Wind turbine SIMULINK Model

The subsystem follows;

$$\lambda = \frac{R\omega}{v} \tag{19}$$

Where λ is tip speed ratio, R is the position, ω is the angular velocity and v is the wind speed velocity. This leads to selection of the coefficient of power from the formula;

$$C_P(\lambda, \vartheta) = C_1\left(C_2\frac{1}{\beta} - C_3\vartheta - C_4\vartheta^x - C_5\right)e^{-C_6\frac{1}{\beta}} \tag{20}$$



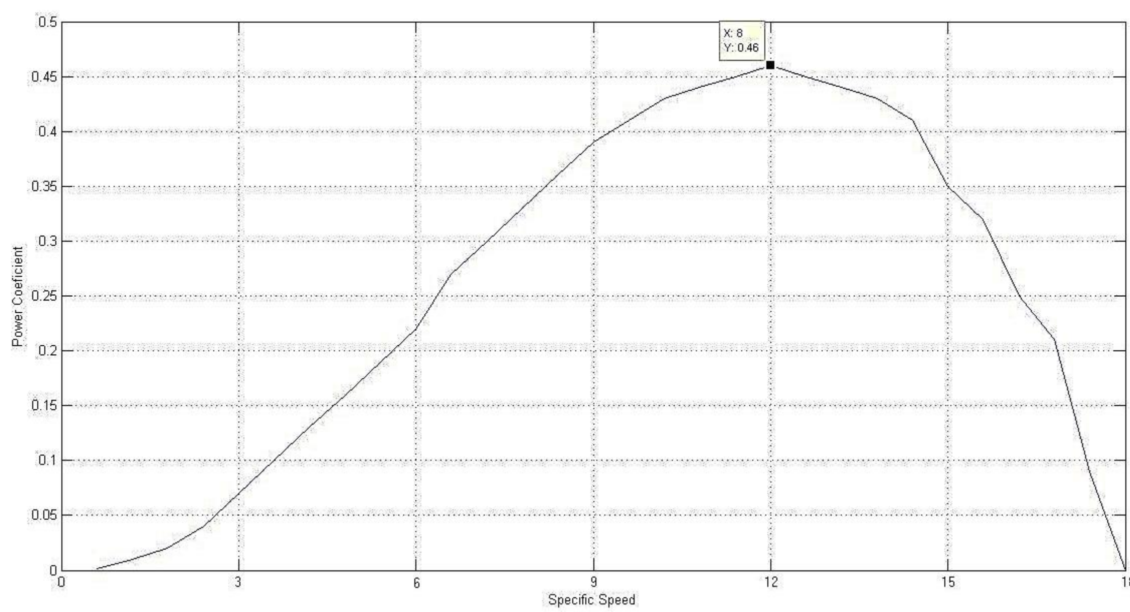


Figure 5.6: (a) Wind turbine characteristics at zero pitch (b) Specific speed vs. Power coefficient for 1.5 MW Wind turbine

C is the power coefficient constant, β is the pitch angle and v is the wind speed in m/s. The fig. 5.6 depicts the wind turbine characteristics for simulation. Firstly, the wind velocity is converted to per unit value. This is the dividend for the generator speed resulting to tip speed ratio λ. Upon multiplication with the pitch angle, power coefficient and wind velocity cubed results in power generated from the wind turbine.

5.4.3 Two Mass Drive train

On impact of the wind on the turbine blades, it is sufficient to consider simple mass model to represent the dynamic operation of the wind turbine. The two masses are; inertial mass of the generator and inertial mass due to the turbine. Fig 5.7 shows the Simulink equivalent of the two mass drive train during disturbances, two mass models described by the following equations represent the shaft's dynamic response;

$$\frac{d\omega_m}{dt} = \frac{T_m - T_e}{J_m} \quad (21)$$

$$\frac{d\omega_{turb}}{dt} = \frac{T_{turb} - K_s\gamma}{J_{turb}} \quad (22)$$

$$\frac{d\gamma}{dt} = (\omega_{turb} - \omega_m) \quad (23)$$

$$T_m = K_s\gamma - D_{turb}(\omega_{turb} - \omega_m) \quad (24)$$

$$\frac{d\omega_r}{dt} = \frac{1}{J_g}(T_m - F\omega_r - T_e) \quad (25)$$

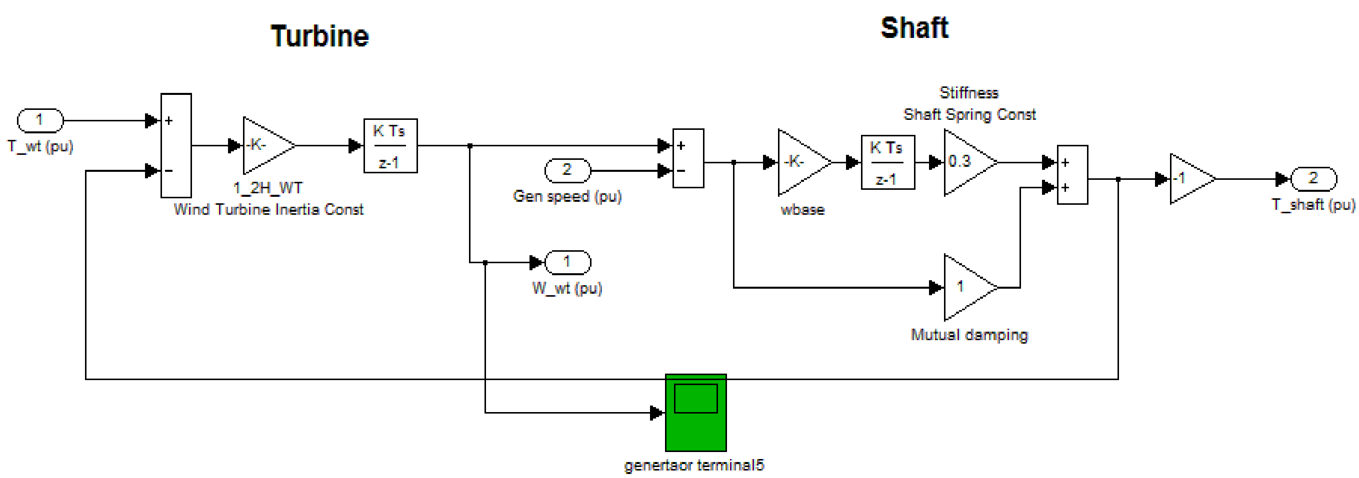


Figure 5.7: SIMULINK model of the two masses drive train

5.4.4 Permanent magnet alternator

To describe the machine at steady state electrically, it can be represented by a simple electrical circuit and equations that include back electromotive forces. Assumptions made to from this model are;

- Saturation due to magnetic and electrical fields are neglected.
- Eddy current and hysteresis losses are neglected.
- No field dynamics are included in the calculations.
- The electromagnetic forces generated are sinusoidal.

$$\begin{bmatrix} v_{am} \\ v_{bm} \\ v_{cm} \end{bmatrix} - \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = (R_m + sL) \begin{bmatrix} i_{am} \\ i_{bm} \\ i_{cm} \end{bmatrix} \tag{26}$$

Where,

$$R_m = \begin{bmatrix} R_m & 0 & 0 \\ 0 & R_m & 0 \\ 0 & 0 & R_m \end{bmatrix} \text{ and } L = \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ab} & L_{bb} & L_{bc} \\ L_{ac} & L_{bc} & L_{cc} \end{bmatrix} \tag{22, 23}$$

With v_{im} stator phase voltages with abc coordinates, i_{im} stator currents, v_i back emfs and L_{ij} stator winding inductances which includes self and mutual inductances for the abc co-ordinates.

Applying Park's transform to the above machine model yields q-axis to be coincident with instantaneous stator's magneto motive force appearing to move in phase synchronously. This is helpful as any AC signals spinning at synchronous speed are converted to dc in rotor's dq frame leading to neglecting of zero sequence components.

$$\begin{bmatrix} v_{dm} \\ v_{qm} \end{bmatrix} - \begin{bmatrix} v_d \\ v_q \end{bmatrix} = (R_m + sL_s) \begin{bmatrix} i_{dm} \\ i_{qm} \end{bmatrix} + \begin{bmatrix} -\omega_s & 0 \\ 0 & \omega_s \end{bmatrix} L_s \begin{bmatrix} i_{qm} \\ i_{dm} \end{bmatrix} \tag{24}$$

Where,

$$R_m = \begin{bmatrix} R_m & 0 \\ 0 & R_m \end{bmatrix}, L_s = \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix}, v_d = \omega_s \varphi_{qm} \text{ and } v_q = \omega_s \varphi_{dm} \tag{25}$$

Flux linkages φ's with respect to the dq frame as shown from the above set of equations is modified in terms of flux linkages due to rotor and the stator.

$$s\begin{bmatrix} i_{dm} \\ i_{qm} \end{bmatrix} = \begin{bmatrix} \frac{-R_m}{L_d} & \omega_s \\ -\omega_s & \frac{-R_m}{L_q} \end{bmatrix} \begin{bmatrix} i_{dm} \\ i_{qm} \end{bmatrix} + \begin{bmatrix} \frac{v_{dm}}{L_d} \\ \frac{v_{qm} - \omega_s \varphi_m}{L_q} \end{bmatrix} \tag{26}$$

The active and reactive power are calculated as,

$$p = \frac{3}{2}(v_{dm} i_{dm} + v_{qm} i_{qm}) \tag{27}$$

$$q = \frac{3}{2}(v_{dm} i_{qm} + v_{qm} i_{dm}) \tag{28}$$

Torque developed is represented by the equation;

$$T_e = \frac{3}{2} P_p \left[\varphi_m i_{qm} + (L_d - L_q) i_{dm} i_{qm}\right] \tag{29}$$

This is represented in SIMULINK shown in the following figure.

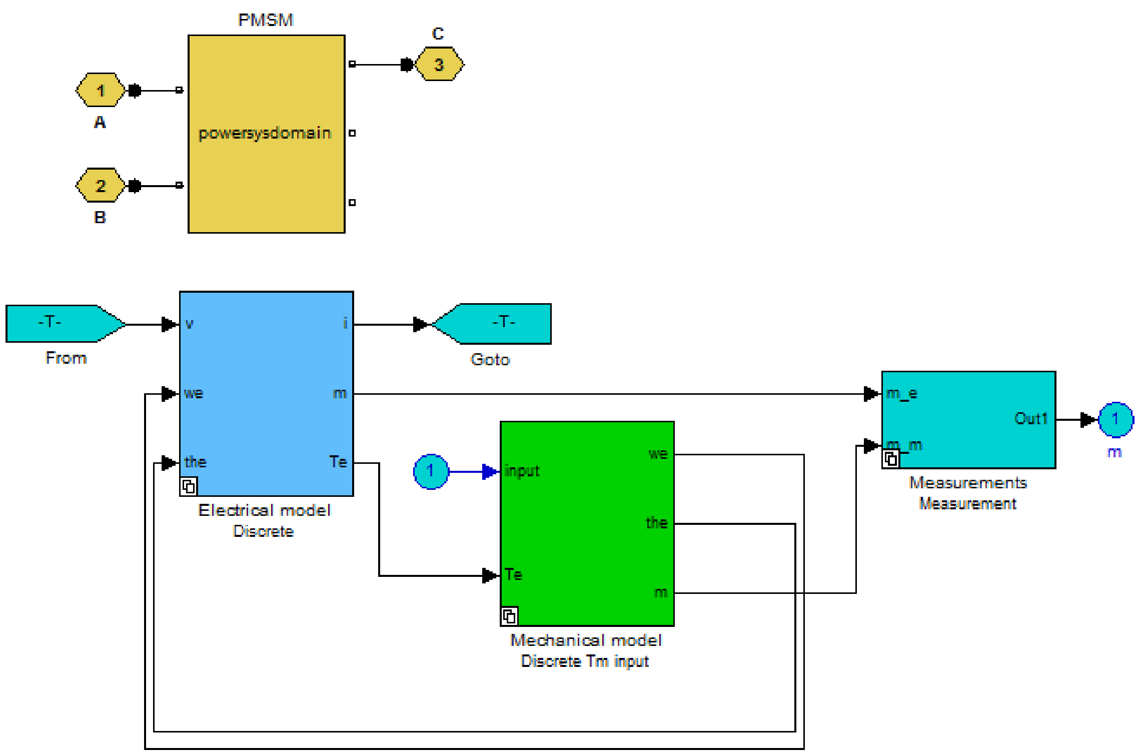


Figure 5.8: SIMULINK model of permanent magnet alternator

5.4.5 Three Phase RLC Load

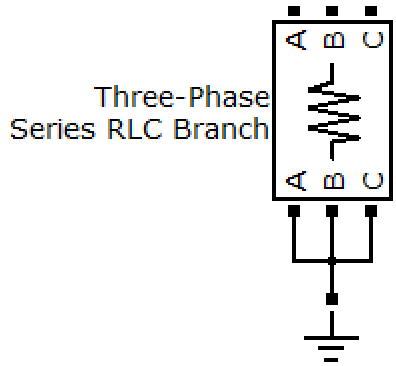


Figure 5.9: SIMULINK Model for a RLC Load

This is a simple RLC load represented in the SIMULINK Environment. In this model, we select resistance of 25 ohms, Inductance of 1μH and capacitance of 1nF.

5.5 Design of Neural Network Controller

In this controller, mechanical power is produced from the simulation of the wind turbine with rotor speed and wind velocities at Elk City, Oklahoma. The rotor speed and power samples each 1200 in number, after normalization are fed as inputs to neural network. The wind velocity is treated as outputs under which the neural network is trained. It consists of four neurons that are in the hidden layer, two input neurons and an output neuron.

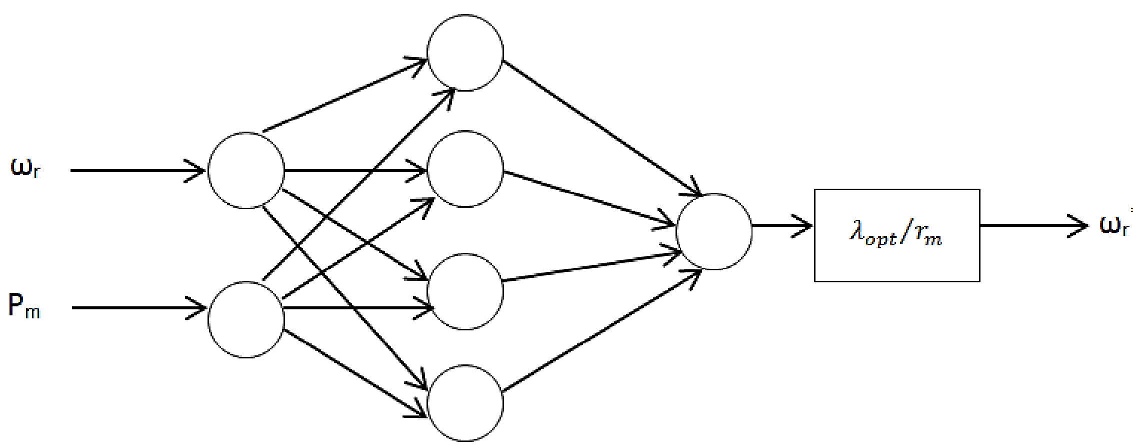


Figure 5.10: Neural network designed

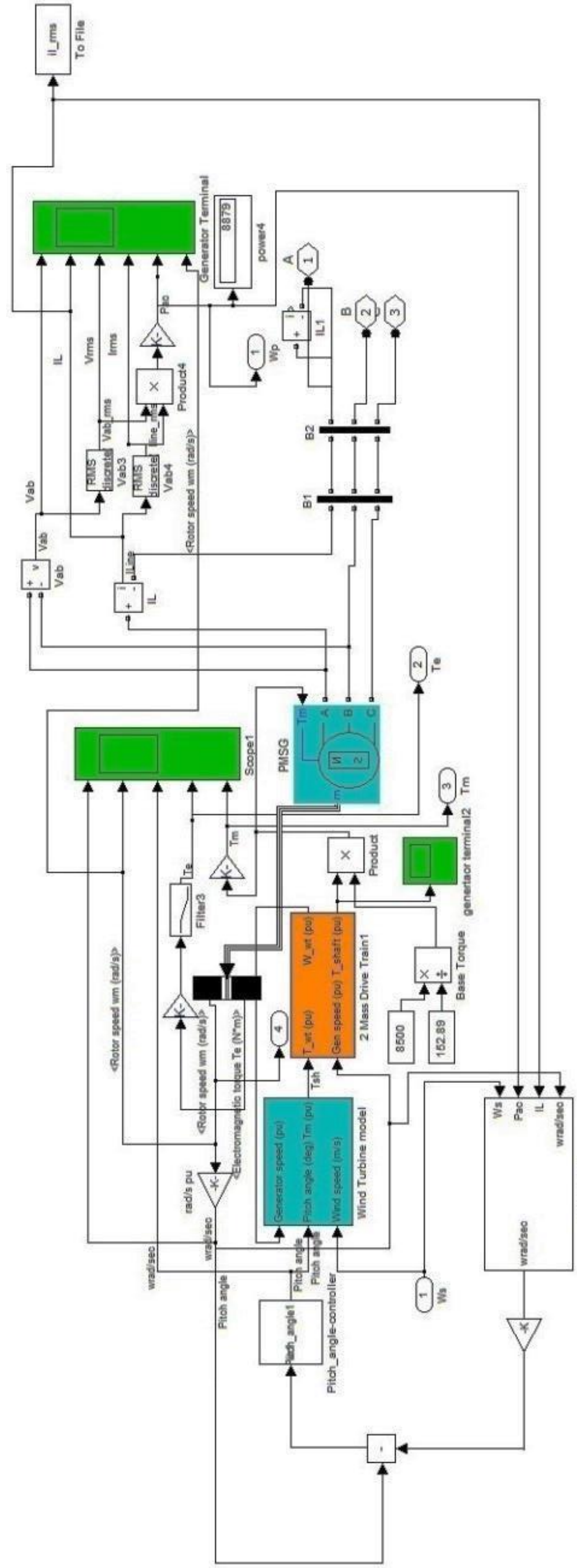
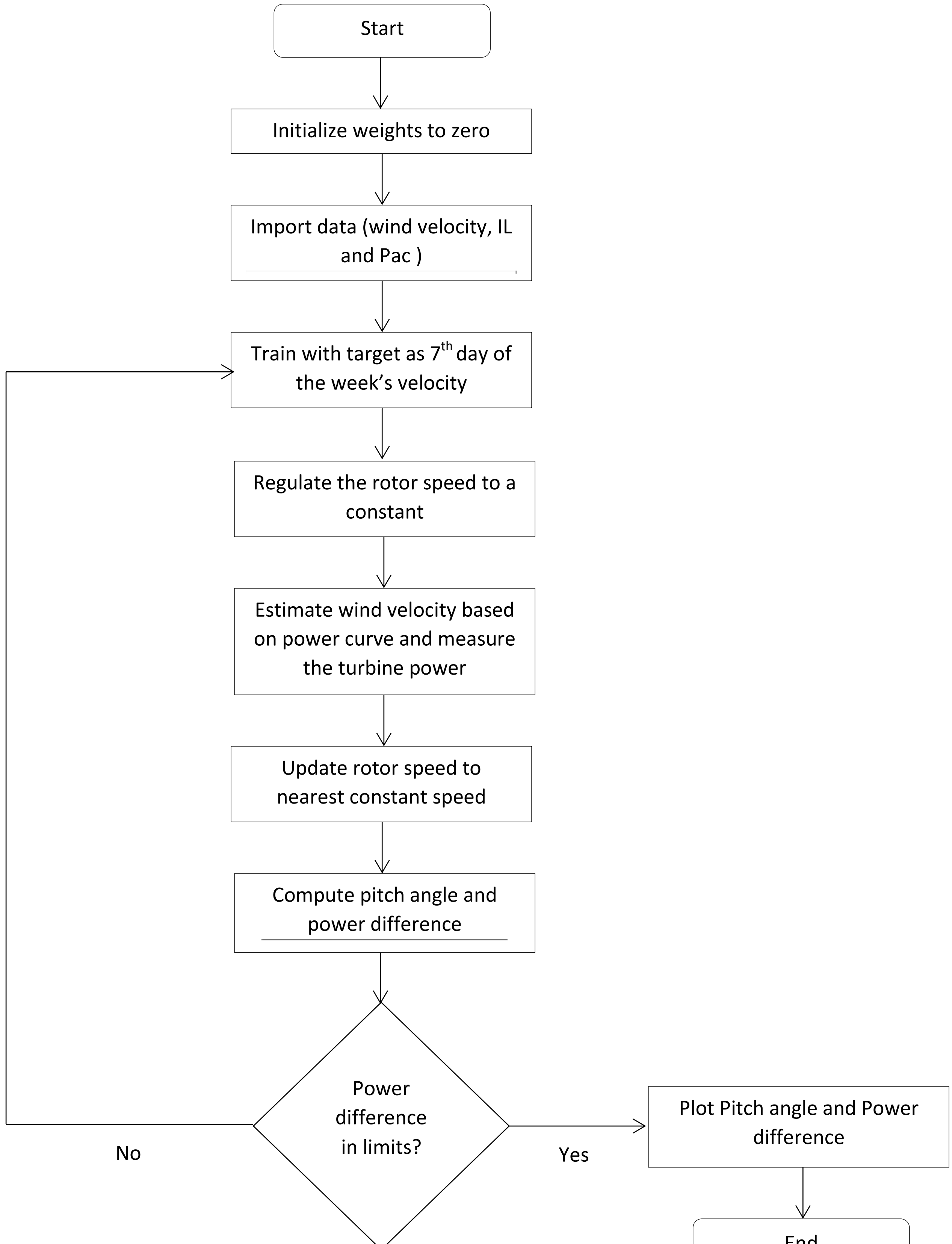


Figure 5.11: SIMULINK model of Neural Network Controller integrated in direct drive machine


Start
Initialize weights to zero
Import data (wind velocity, IL and Pac)
Train with target as 7th day of the week's velocity
Regulate the rotor speed to a constant
Estimate wind velocity based on power curve and measure the turbine power
Update rotor speed to nearest constant speed
Compute pitch angle and power difference
Power difference in limits?
No
Yes
Plot Pitch angle and Power difference
End

5.6 Results

During the training process, the layout of each neuron layer is as follows,

Layer	Number of Neurons	Training Function	Adaptation learning Function	Performance Function
Input Layer	2	Trainlm	LearnGDM	MSE
Hidden Layer	4	Trainlm	LearnGD	MSE
Output Layer	1	Trainlm	LearnGD	MSE

The plot of pitch from controller with respect to pitch on fifth day is as follows;

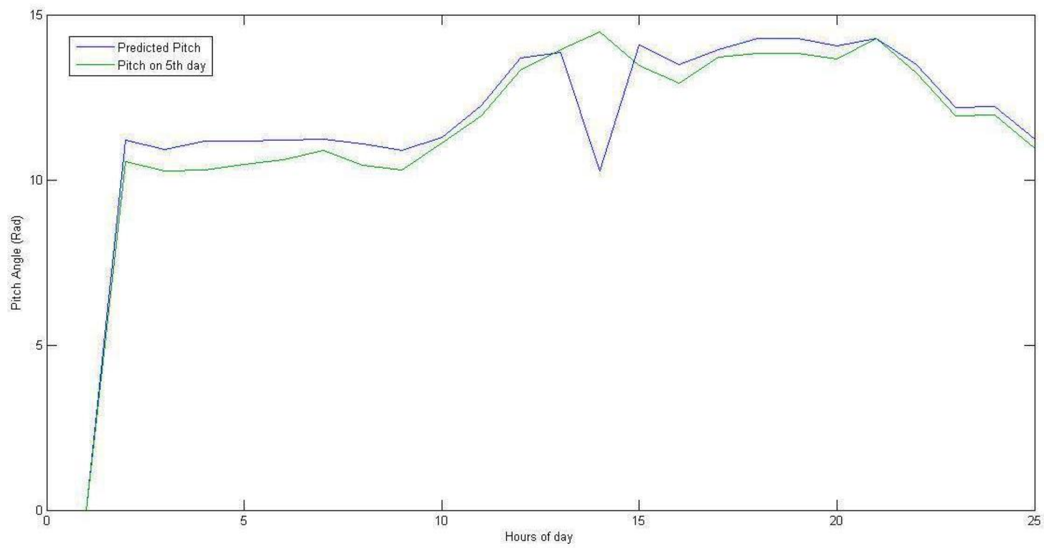


Figure 5.12: Pitch prediction from the controller

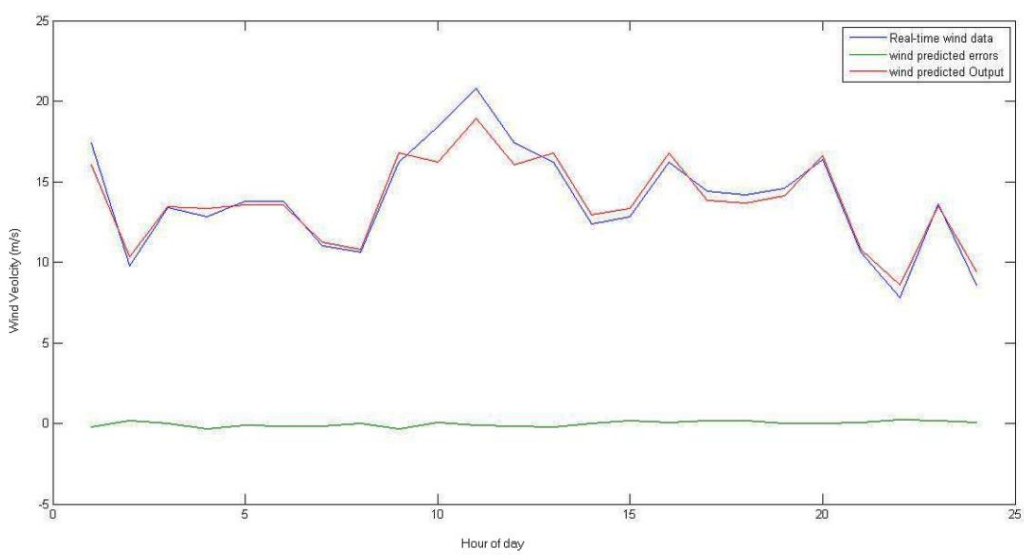


Figure 5.13: Wind Speed prediction from the controller

The controller output after integrated with the neural network logic resulted in the following plot;

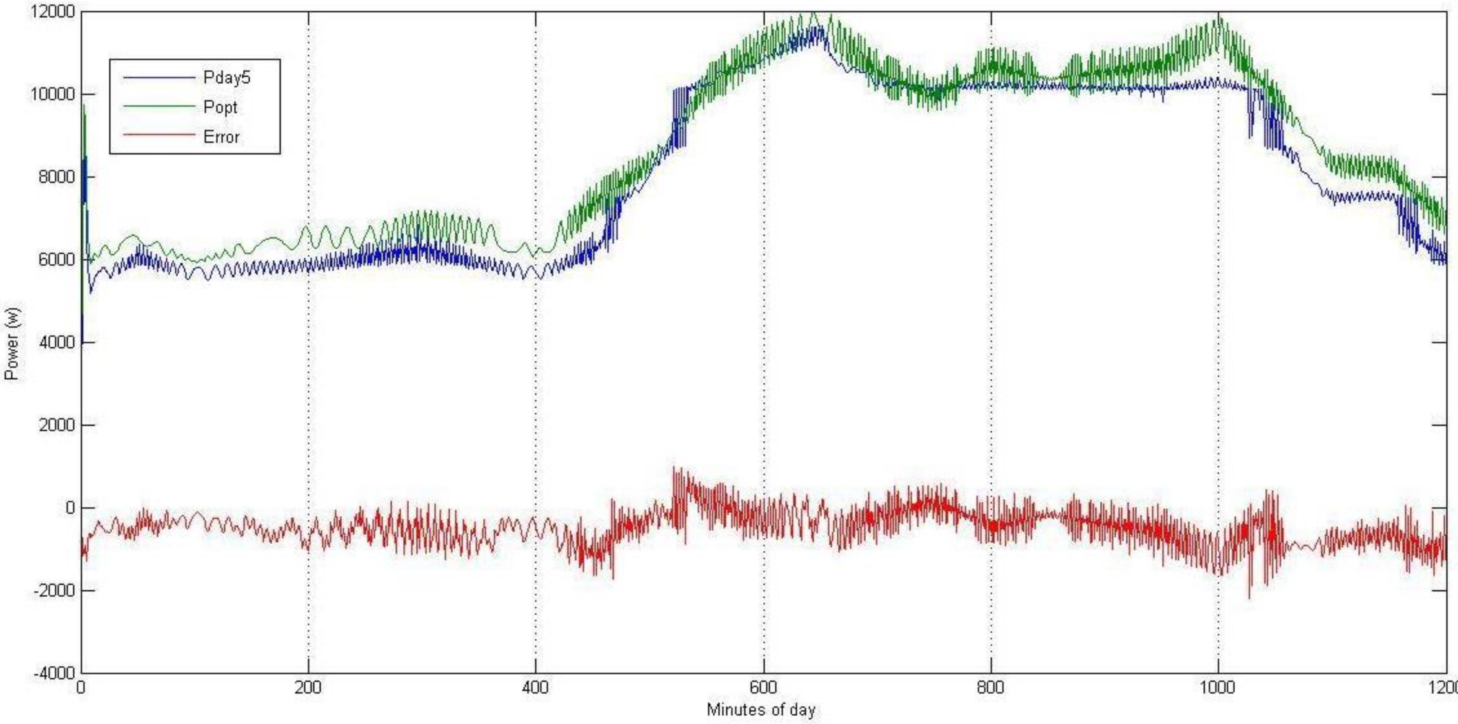


Figure 5.14: Power from the turbine before and after Neural Network controller integration

The energy efficiency of the wind turbine is found out as 30% with the controller, however without the controller the efficiency is 32%. The increased efficiency is advantage to the use of direct drive machines as compared to other machines in wind turbines.

CHAPTER 6

SUMMARY AND CONCLUDING REMARKS

Wind electric conversion systems employing direct drive technology with no gear boxes are gaining acceptance world-wide. Such systems enable some unique control strategies to be incorporated for improved performance. In this simulation study, a neural network control strategy is proposed to track maximum power from directly driven permanent magnet wind turbines without gearboxes. Neural network controller is selected to handle the non-linearity introduced by wind velocity and wind direction. This method tracks the maximum mechanical power in dynamic state and hence has the potential to improve the machine's aerodynamic efficiency to 32%. Wind velocity prediction is used to ensure fast and accurate wind velocity and direction information without the use of anemometers. The proposed concept is verified by comparing simulation results for the year 2014 that include wind velocity, wind direction and pitch angle.

Employment of this controller will enable the system to maximize capture of wind energy by keeping track of the historical wind velocity data. Programmable logical controller and micro-controller are used in wind turbines to control the pitch and yaw, making it easy to integrate this controller with micro-controller on a real time basis. Use of direct drive technology in wind turbines however has its downsides such as increased weight and higher initial cost. This excess weight is due to massive permanent magnets needed to produce the required magnetic flux. Also, with low operating speeds, large diameter stators will be needed. It is somewhat compensated by lower specific mass (kg/kW) with the elimination of the gearbox. Gear boxes need extra maintenance for efficient operation and avoid heating losses and down-times due to its malfunction. On the other hand, permanent magnets, which are an important part of direct drive wind turbines are facing supply shortages. Alternate material options are under consideration to replace Neodymium that is being used at present. 2012 and 2013 have seen rapid growth in both research deployment technological developments in direct drive systems.

This thesis contributes to the study of neural network controllers for the wind turbines optimal tip speed ratio is calculated to help in predicting the wind speed of a direct drive wind turbine for a given wind regime. Maximum operating point is tracked on the power curve to predict the maximum power that can be generated.

Integration of intelligent control systems in machines has been growing to gain maximum operational capability. One among them is the use of neural networks, as discussed in this work. These systems require large memories to store data and often require time for computations. Furthermore, the availability of electrical engineers with intelligent systems experience is still lagging. Apart from this challenge, cost issue is another concern. The costs and its reduction have to be worked upon to make the direct drive competitive with the geared doubly fed induction generator. Further work can be conducted on use of genetic algorithm on the controller. Apart from that, other parameters such as line current and generator speed can be selected to determine the optimal tip speed ratio from the neural network controller. In real time, if two or more modules have to use this controller based on terrain same controller can be used if the wind velocity variation is minimum else different controller have to be used.

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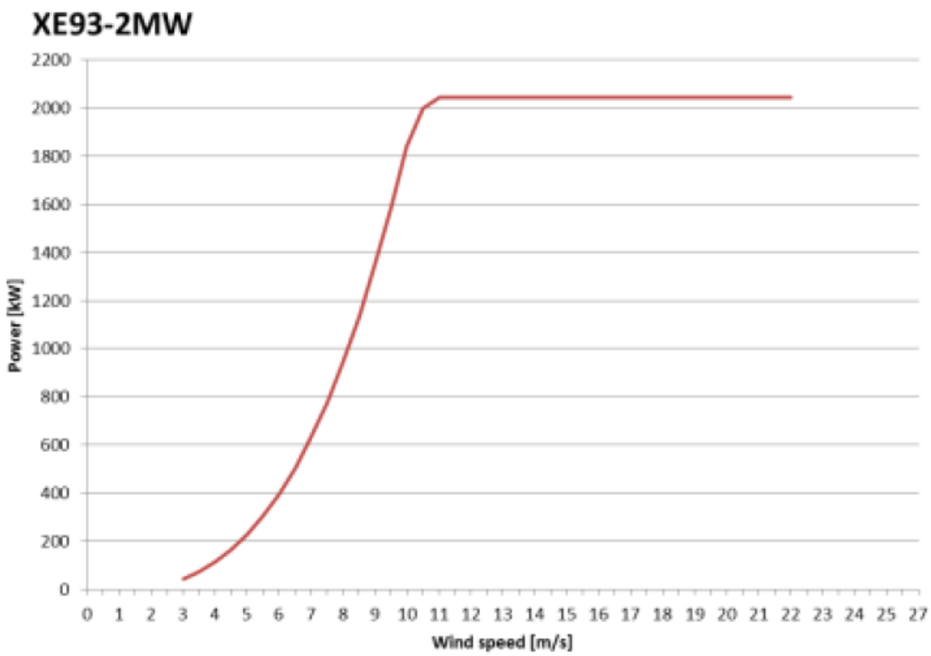
Appendix

Wind turbine characteristics:

Darwnid 2 MW on-shore wind turbine
(Source: http://www.darwind.nl/Wind-turbines/XE93-2MW)



Technical datasheet

	Onshore
Turbine type	XE93
Rated power [MW]	2
Operational data	
Cut in wind speed [m/s]	3
Cut out wind speed [m/s]	22
Rated wind speed [m/s]	11
Designed for wind class (According to IEC 61400-1)	3A – 2B
Rotor	
Diameter [m]	93,4
Speed [rpm]	Variable 7,5-17 Nominal 17
Power regulation	Pitch control
Tilt angle [°]	6
Blade material	Glass fiber reinforced epoxy
Generator	
Type	Synchronous Permanent magnet Direct drive
Cooling	Air
Main bearing	Single main bearing. Multiple row, cylindrical roller bearing
Converter	
Type	Voltage source inverter
Voltage [V]	690
Grid coupling	AC-DC-AC
Tower	
Material	Steel / hybrid
Hub heights [m]	80-140
Foundation / support structure	Concrete - anchor tube
Masses [ton]	
Rotor (hub + blades)	47,5
Generator	66
Nacelle	18,5
Total top mass	**132**

Date	Hour	Velocity (mph)	Normalized Wind
5-Aug-13	1:00 AM	**17.3**	0.87
	2:00 AM	**18.4**	0.92
	3:00 AM	**18.4**	0.92
	4:00 AM	**12.7**	0.64
	5:00 AM	**13.8**	0.69
	6:00 AM	**13.8**	0.69
	7:00 AM	**12.7**	0.64
	8:00 AM	**15**	0.75
	9:00 AM	**16.1**	0.81
	10:00 AM	**18.4**	0.92
	11:00 AM	**20.7**	1.04
	12:00 PM	**17.3**	0.87
	1:00 PM	**16.1**	0.81
	2:00 PM	**9.2**	0.46
	3:00 PM	**12.7**	0.64
	4:00 PM	**16.1**	0.81
	5:00 PM	**10.4**	0.52
	6:00 PM	**17.3**	0.87
	7:00 PM	**17.3**	0.87
	8:00 PM	**15**	0.75
	9:00 PM	**13.8**	0.69
	10:00 PM	**13.8**	0.69
	11:00 PM	**11.5**	0.58
	12:00 AM	**18.4**	0.92

Wunderground Wind data sample for August 2013

Hour	Power_day_1	Normalized
12:00 AM	2209.17	0.17
1:00:00 AM	7025.17	0.55
2:00 AM	9643.50	0.76
3:00:00 AM	9196.49	0.72
4:00 AM	7605.23	0.60
5:00:00 AM	6761.79	0.53
6:00 AM	6217.22	0.49
7:00:00 AM	5914.64	0.47
8:00 AM	5879.11	0.46
9:00:00 AM	5941.31	0.47
10:00 AM	6075.08	0.48
11:00:00 AM	6216.39	0.49
12:00 PM	6320.82	0.50
1:00:00 PM	6387.99	0.50
2:00 PM	6432.08	0.51
3:00:00 PM	6465.11	0.51
4:00 PM	6493.62	0.51
5:00:00 PM	6519.32	0.51
6:00 PM	6540.30	0.52
7:00:00 PM	6551.79	0.52
8:00 PM	6547.00	0.52
9:00:00 PM	6518.68	0.51
10:00 PM	6462.46	0.51
11:00:00 PM	6382.006	0.502672
12:00 AM	6294.927	0.495813
1:00:00 AM	6235.562	0.491137
2:00 AM	6248.962	0.492193
3:00:00 AM	6370.811	0.50179
4:00 AM	6593.916	0.519363
5:00:00 AM	6837.399	0.53854
6:00 AM	6959.097	0.548126
7:00:00 AM	6849.303	0.539478
8:00 AM	6565.811	0.517149
9:00:00 AM	6360.86	0.501006
10:00 AM	6485.838	0.51085
11:00:00 AM	6891.742	0.542821
12:00 PM	7145.837	0.562834

1:00:00 PM	6899.362	0.543421
2:00 PM	6490.91	0.51125
3:00:00 PM	6591.982	0.51921
4:00 PM	7135.573	0.562026
5:00:00 PM	7206.593	0.567619
6:00 PM	6664.138	0.524894
7:00:00 PM	6642.533	0.523192
8:00 PM	7285.383	0.573825
9:00:00 PM	7195.314	0.566731
10:00 PM	6610.75	0.520689
11:00:00 PM	7064.617	0.556437
12:00 AM	7456.782	0.587325
1:00:00 AM	6759.369	0.532394
2:00 AM	7024.517	0.553278
3:00:00 AM	7525.786	0.59276
4:00 AM	6777.588	0.533829
5:00:00 AM	6968.65	0.548878
6:00 AM	7485.728	0.589605
7:00:00 AM	6824.696	0.53754
8:00 AM	6745.969	0.531339
9:00:00 AM	7390.303	0.582089
10:00 AM	7071.408	0.556972
11:00:00 AM	6563.269	0.516949
12:00 PM	7027.589	0.55352
1:00:00 PM	7340.973	0.578204
2:00 PM	6781.616	0.534147
3:00:00 PM	6547.378	0.515697
4:00 PM	7063.347	0.556337
5:00:00 PM	7254.952	0.571428
6:00 PM	6746.048	0.531345
7:00:00 PM	6474.133	0.509928
8:00 PM	6860.681	0.540374
9:00:00 PM	7208.356	0.567758
10:00 PM	6942.039	0.546782
11:00:00 PM	6489.559	0.511143
12:00 AM	6485.265	0.510805
1:00:00 AM	6879.67	0.54187
2:00 AM	7119.129	0.56073
3:00:00 AM	6902.893	0.543699
4:00 AM	6508.352	0.512623
5:00:00 AM	6361.943	0.501092

6:00 AM	6569.168	0.517413
7:00:00 AM	6888.26	0.542546
8:00 AM	7009.429	0.55209
9:00:00 AM	6839.419	0.538699
10:00 AM	6535.733	0.51478
11:00:00 AM	6323.44	0.498059
12:00 PM	6319.286	0.497732
1:00:00 PM	6489.993	0.511177
2:00 PM	6710.441	0.528541
3:00:00 PM	6852.851	0.539757
4:00 PM	6854.098	0.539856
5:00:00 PM	6729.94	0.530076
6:00 PM	6544.898	0.515502
7:00:00 PM	6369.776	0.501709
8:00 PM	6252.544	0.492475
9:00:00 PM	6209.98	0.489122
10:00 PM	6233.815	0.491
11:00:00 PM	6302.072	0.496376
12:00 AM	6389.555	0.503266
1:00:00 AM	6475.011	0.509997
2:00 AM	6544.508	0.515471
3:00:00 AM	6591.693	0.519188
4:00 AM	6619.268	0.521359
5:00:00 AM	6640.245	0.523012
6:00 AM	6654.206	0.524111
7:00:00 AM	6654.166	0.524108
8:00 AM	6633.261	0.522462
9:00:00 AM	6588.054	0.518901
10:00 AM	6520.085	0.513547
11:00:00 AM	6436.03	0.506927
12:00 PM	6346.928	0.499909
1:00:00 PM	6266.823	0.4936
2:00 PM	6210.84	0.48919
3:00:00 PM	6192.667	0.487759
4:00 PM	6221.527	0.490032
5:00:00 PM	6299.002	0.496134
6:00 PM	6416.393	0.50538
7:00:00 PM	6553.746	0.516199
8:00 PM	6681.878	0.526291
9:00:00 PM	6768.273	0.533096
10:00 PM	6786.304	0.534516

11:00:00 PM	6725.382	0.529717
12:00 AM	6598.157	0.519697
1:00:00 AM	6440.81	0.507303
2:00 AM	6304.405	0.49656
3:00:00 AM	6239.015	0.491409
4:00 AM	6275.689	0.494298
5:00:00 AM	6411.865	0.505024
6:00 AM	6605.382	0.520266
7:00:00 AM	6783.196	0.534271
8:00 AM	6868.179	0.540965
9:00:00 AM	6816.363	0.536883
10:00 AM	6645.471	0.523423
11:00:00 AM	6434.888	0.506837
12:00 PM	6291.223	0.495521
1:00:00 PM	6295.433	0.495853
2:00 PM	6458.141	0.508668
3:00:00 PM	6703.17	0.527968
4:00 PM	6895.366	0.543106
5:00:00 PM	6915.583	0.544698
6:00 PM	6743.911	0.531177
7:00:00 PM	6486.658	0.510915
8:00 PM	6314.829	0.497381
9:00:00 PM	6352.261	0.500329
10:00 PM	6588.633	0.518947
11:00:00 PM	6868.527	0.540992
12:00 AM	6984.736	0.550145
1:00:00 AM	6840.281	0.538767
2:00 AM	6545.052	0.515514
3:00:00 AM	6339.767	0.499345
4:00 AM	6402.08	0.504253
5:00:00 AM	6697.006	0.527482
6:00 AM	6980.449	0.549808
7:00:00 AM	6992.794	0.55078
8:00 AM	6718.18	0.52915
9:00:00 AM	6414.171	0.505205
10:00 AM	6363.754	0.501234
11:00:00 AM	6617.834	0.521247
12:00 PM	6945.751	0.547075
1:00:00 PM	7033.027	0.553949
2:00 PM	6791.277	0.534908
3:00:00 PM	6458.108	0.508666

4:00 PM	6359.532	0.500902
5:00:00 PM	6595.623	0.519497
6:00 PM	6942.417	0.546812
7:00:00 PM	7050.938	0.55536
8:00 PM	6806.386	0.536098
9:00:00 PM	6461.886	0.508963
10:00 PM	6371.9	0.501876
11:00:00 PM	6632.793	0.522425
12:00 AM	6982.845	0.549996
1:00:00 AM	7050.801	0.555349
2:00 AM	6760.382	0.532474
3:00:00 AM	6426.892	0.506207
4:00 AM	6409.181	0.504812
5:00:00 AM	6732.099	0.530246
6:00 AM	7051.494	0.555403
7:00:00 AM	7009.413	0.552089
8:00 AM	6651.641	0.523909
9:00:00 AM	6383.196	0.502766
10:00 AM	6505.566	0.512404
11:00:00 AM	6889.693	0.542659
12:00 PM	7099.758	0.559205
1:00:00 PM	6886.72	0.542425
2:00 PM	6501.907	0.512116
3:00:00 PM	6396.324	0.5038
4:00 PM	6696.842	0.527469
5:00:00 PM	7058.321	0.555941
6:00 PM	7044.3	0.554837
7:00:00 PM	6670.038	0.525358
8:00 PM	6393.64	0.503588
9:00:00 PM	6550.267	0.515925
10:00 PM	6958.634	0.548089
11:00:00 PM	7116.201	0.5605
12:00 AM	6820.943	0.537244
1:00:00 AM	6448.167	0.507883
2:00 AM	6466.207	0.509304
3:00:00 AM	6858.992	0.540241
4:00 AM	7133.012	0.561824
5:00:00 AM	6928.949	0.545751
6:00 AM	6514.709	0.513124
7:00:00 AM	6429.709	0.506429
8:00 AM	6789.136	0.534739

9:00:00 AM	7134.594	0.561949
10:00 AM	6997.386	0.551142
11:00:00 AM	6562.05	0.516853
12:00 PM	6447.586	0.507837
1:00:00 PM	6843.196	0.538997
2:00 PM	7192.829	0.566535
3:00:00 PM	6959.003	0.548118
4:00 PM	6507.128	0.512527
5:00:00 PM	6565.601	0.517132
6:00 PM	7069.452	0.556818
7:00:00 PM	7197.572	0.566909
8:00 PM	6725.751	0.529746
9:00:00 PM	6481.479	0.510507
10:00 PM	6915.203	0.544669
11:00:00 PM	7275.221	0.573025
12:00 AM	6893.631	0.542969
1:00:00 AM	6495.391	0.511602
2:00 AM	6855.714	0.539983
3:00:00 AM	7306.715	0.575505
4:00 AM	6952.727	0.547624
5:00:00 AM	6517.687	0.513359
6:00 AM	6908.942	0.544175
7:00:00 AM	7342.312	0.578309
8:00 AM	6896.707	0.543212
9:00:00 AM	6546.317	0.515614
10:00 AM	7076.916	0.557406
11:00:00 AM	7335.038	0.577736
12:00 PM	6737.169	0.530646
1:00:00 PM	6670.617	0.525404
2:00 PM	7315.606	0.576206
3:00:00 PM	7163.158	0.564198
4:00 PM	6587.784	0.51888
5:00:00 PM	7003.339	0.55161
6:00 PM	7415.421	0.584068
7:00:00 PM	6800.137	0.535605
8:00 PM	6730.087	0.530088
9:00:00 PM	7408.873	0.583552
10:00 PM	7090.469	0.558473
11:00:00 PM	6625.108	0.521819
12:00 AM	7268.216	0.572473
1:00:00 AM	7313.49	0.576039

2:00 AM	6649.301	0.523725
3:00:00 AM	7120.58	0.560845
4:00 AM	7441.053	0.586086
5:00:00 AM	6722.005	0.529451
6:00 AM	7024.831	0.553303
7:00:00 AM	7503.365	0.590994
8:00 AM	6784.518	0.534375
9:00:00 AM	6992.476	0.550755
10:00 AM	7533.937	0.593402
11:00:00 AM	6809.259	0.536324
12:00 PM	7021.432	0.553035
1:00:00 PM	7545.57	0.594319
2:00 PM	6792.534	0.535007
3:00:00 PM	7112.861	0.560237
4:00 PM	7525.215	0.592715
5:00:00 PM	6752.715	0.53187
6:00 PM	7267.896	0.572448
7:00:00 PM	7439.326	0.58595
8:00 PM	6736.605	0.530601
9:00:00 PM	7465.035	0.587975
10:00 PM	7256.933	0.571584
11:00:00 PM	6819.44	0.537126
12:00 AM	7626.899	0.600724
1:00:00 AM	7000.946	0.551422
2:00 AM	7068.01	0.556704
3:00:00 AM	7616.946	0.59994
4:00 AM	6803.746	0.53589
5:00:00 AM	7441.387	0.586113
6:00 AM	7340.648	0.578178
7:00:00 AM	6876.246	0.5416
8:00 AM	7692.418	0.605885
9:00:00 AM	6945.571	0.54706
10:00 AM	7294.863	0.574572
11:00:00 AM	7510.402	0.591549
12:00 PM	6852.818	0.539755
1:00:00 PM	7705.651	0.606927
2:00 PM	7013.475	0.552409
3:00:00 PM	7305.841	0.575437
4:00 PM	7528.138	0.592946
5:00:00 PM	6899.173	0.543406
6:00 PM	7752.65	0.610629

7:00:00 PM	6963.112	0.548442
8:00 PM	7477.64	0.588968
9:00:00 PM	7390.058	0.58207
10:00 PM	7056.734	0.555816
11:00:00 PM	7744.989	0.610026
12:00 AM	6897.918	0.543307
1:00:00 AM	7737.428	0.60943
2:00 AM	7097.312	0.559012
3:00:00 AM	7434.099	0.585539
4:00 AM	7471.201	0.588461
5:00:00 AM	7098.947	0.559141
6:00 AM	7762.49	0.611404
7:00:00 AM	6942.415	0.546812
8:00 AM	7825.242	0.616347
9:00:00 AM	7016.068	0.552613
10:00 AM	7675.892	0.604583
11:00:00 AM	7248.412	0.570913
12:00 PM	7423.781	0.584726
1:00:00 PM	7519.742	0.592284
2:00 PM	7141.874	0.562522
3:00:00 PM	7745.405	0.610058
4:00 PM	6935.101	0.546236
5:00:00 PM	7796.06	0.614048
6:00 PM	6985.657	0.550218
7:00:00 PM	7525.749	0.592757
8:00 PM	7343.658	0.578415
9:00:00 PM	7060.962	0.556149
10:00 PM	7708.765	0.607173
11:00:00 PM	6851.007	0.539612
12:00 AM	7594.1	0.598141
1:00:00 AM	7200.504	0.56714
2:00 AM	7032.879	0.553937
3:00:00 AM	7665.274	0.603747
4:00 AM	6822.853	0.537395
5:00:00 AM	7417.381	0.584222
6:00 AM	7353.34	0.579178
7:00:00 AM	6806.204	0.536083
8:00 AM	7605.374	0.599029
9:00:00 AM	7035.903	0.554175
10:00 AM	6944.195	0.546952
11:00:00 AM	7601.079	0.598691

12:00 PM	6849.655	0.539506
1:00:00 PM	7055.48	0.555717
2:00 PM	7537.194	0.593659
3:00:00 PM	6766.953	0.532992
4:00 PM	7076.804	0.557397
5:00:00 PM	7496.691	0.590469
6:00 PM	6748.139	0.53151
7:00:00 PM	7001.044	0.55143
8:00 PM	7490.938	0.590016
9:00:00 PM	6797.962	0.535434
10:00 PM	6840.358	0.538773
11:00:00 PM	7466.447	0.588087
12:00 AM	6954.353	0.547752
1:00:00 AM	6653.656	0.524068
2:00 AM	7313.782	0.576062
3:00:00 AM	7212.088	0.568052
4:00 AM	6594.725	0.519426
5:00:00 AM	6960.093	0.548204
6:00 AM	7390.731	0.582123
7:00:00 AM	6841.59	0.53887
8:00 AM	6588.685	0.518951
9:00:00 AM	7171.222	0.564834
10:00 AM	7260.307	0.57185
11:00:00 AM	6653.78	0.524078
12:00 PM	6639.159	0.522926
1:00:00 PM	7210.198	0.567903
2:00 PM	7173.114	0.564983
3:00:00 PM	6602.722	0.520056
4:00 PM	6596.49	0.519565
5:00:00 PM	7122.84	0.561023
6:00 PM	7186.804	0.566061
7:00:00 PM	6675.819	0.525814
8:00 PM	6469.045	0.509527
9:00:00 PM	6866.383	0.540823
10:00 PM	7197.638	0.566914
11:00:00 PM	6935.565	0.546272
12:00 AM	6489.969	0.511175
1:00:00 AM	6486.229	0.510881
2:00 AM	6889.238	0.542623
3:00:00 AM	7133.078	0.561829
4:00 AM	6898.768	0.543374

5:00:00 AM	6495.1	0.511579
6:00 AM	6390.982	0.503379
7:00:00 AM	6667.86	0.525187
8:00 AM	6996.941	0.551107
9:00:00 AM	7022.559	0.553124
10:00 AM	6731.037	0.530163
11:00:00 AM	6414.22	0.505209
12:00 PM	6344.153	0.49969
1:00:00 PM	6549.783	0.515887
2:00 PM	6838.639	0.538638
3:00:00 PM	6973.992	0.549299
4:00 PM	6861.301	0.540423
5:00:00 PM	6595.63	0.519498
6:00 PM	6359.012	0.500861
7:00:00 PM	6284.818	0.495017
8:00 PM	6392.368	0.503488
9:00:00 PM	6601.764	0.519981
10:00 PM	6792.422	0.534998
11:00:00 PM	6870.048	0.541112
12:00 AM	6807.674	0.536199
1:00:00 AM	6644.129	0.523318
2:00 AM	6451.943	0.50818
3:00:00 AM	6299.726	0.496191
4:00 AM	6228.171	0.490555
5:00:00 AM	6244.498	0.491841
6:00 AM	6329.582	0.498543
7:00:00 AM	6450.144	0.508039
8:00 AM	6571.003	0.517558
9:00:00 AM	6664.396	0.524914
10:00 AM	6714.721	0.528878
11:00:00 AM	6718.736	0.529194
12:00 PM	6682.645	0.526351
1:00:00 PM	6617.949	0.521256
2:00 PM	6537.564	0.514924
3:00:00 PM	6453.045	0.508267
4:00 PM	6375.302	0.502144
5:00:00 PM	6312.221	0.497175
6:00 PM	6257.525	0.492867
7:00:00 PM	6214.574	0.489484
8:00 PM	6201.209	0.488431
9:00:00 PM	6243.093	0.49173

10:00 PM	6359.132	0.50087
11:00:00 PM	6542.513	0.515314
12:00 AM	6745.591	0.531309
1:00:00 AM	6883.493	0.542171
2:00 AM	6871.748	0.541246
3:00:00 AM	6692.842	0.527154
4:00 AM	6446.794	0.507775
5:00:00 AM	6319.714	0.497765
6:00 AM	6454.27	0.508364
7:00:00 AM	6796.697	0.535335
8:00 AM	7060.524	0.556115
9:00:00 AM	6961.55	0.548319
10:00 AM	6589.059	0.51898
11:00:00 AM	6403.978	0.504402
12:00 PM	6702.72	0.527932
1:00:00 PM	7144.849	0.562756
2:00 PM	7084.875	0.558032
3:00:00 PM	6604.682	0.520211
4:00 PM	6535.432	0.514756
5:00:00 PM	7074.648	0.557227
6:00 PM	7268.457	0.572492
7:00:00 PM	6731.811	0.530224
8:00 PM	6605.086	0.520242
9:00:00 PM	7236.744	0.569994
10:00 PM	7248.05	0.570885
11:00:00 PM	6628.552	0.522091
12:00 AM	6952.765	0.547627
1:00:00 AM	7467.848	0.588197
2:00 AM	6842.469	0.53894
3:00:00 AM	6840.185	0.53876
4:00 AM	7536.626	0.593614
5:00:00 AM	6948.798	0.547315
6:00 AM	6900.879	0.54354
7:00:00 AM	7603.99	0.59892
8:00 AM	6890.841	0.54275
9:00:00 AM	7145.232	0.562786
10:00 AM	7574.672	0.596611
11:00:00 AM	6800.705	0.53565
12:00 PM	7574.147	0.596569
1:00:00 PM	7218.901	0.568589
2:00 PM	7097.915	0.55906

3:00:00 PM	7699.997	0.606482
4:00 PM	6895.121	0.543087
5:00:00 PM	7772.039	0.612156
6:00 PM	7067.816	0.556689
7:00:00 PM	7588.062	0.597665
8:00 PM	7364.928	0.580091
9:00:00 PM	7440.128	0.586014
10:00 PM	7571.048	0.596325
11:00:00 PM	7428.616	0.585107
12:00 AM	7639.863	0.601746
1:00:00 AM	7548.686	0.594564
2:00 AM	7578.073	0.596879
3:00:00 AM	7792.332	0.613755
4:00 AM	7417.717	0.584248
5:00:00 AM	8076.986	0.636175
6:00 AM	7336.141	0.577823
7:00:00 AM	8116.219	0.639265
8:00 AM	7651.28	0.602645
9:00:00 AM	7713.548	0.607549
10:00 AM	8204.84	0.646245
11:00:00 AM	7551.528	0.594788
12:00 PM	8019.633	0.631658
1:00:00 PM	8201.663	0.645995
2:00 PM	7655.876	0.603007
3:00:00 PM	8071.182	0.635718
4:00 PM	8343.549	0.657171
5:00:00 PM	7867.393	0.619667
6:00 PM	7932.75	0.624814
7:00:00 PM	8404.87	0.662
8:00 PM	8312.74	0.654744
9:00:00 PM	7973.646	0.628036
10:00 PM	8083.663	0.636701
11:00:00 PM	8441.775	0.664907
12:00 AM	8518.565	0.670956
1:00:00 AM	8308.012	0.654372
2:00 AM	8164.912	0.6431
3:00:00 AM	8259.359	0.650539
4:00 AM	8472.739	0.667346
5:00:00 AM	8622.311	0.679127
6:00 AM	8641.306	0.680623
7:00:00 AM	8579.876	0.675785

8:00 AM	8516.547	0.670797
9:00:00 AM	8496.014	0.669179
10:00 AM	8521.73	0.671205
11:00:00 AM	8575.732	0.675458
12:00 PM	8638.054	0.680367
1:00:00 PM	8695.893	0.684923
2:00 PM	8744.406	0.688744
3:00:00 PM	8783.957	0.691859
4:00 PM	8817.255	0.694481
5:00:00 PM	8847.638	0.696875
6:00 PM	8878.493	0.699305
7:00:00 PM	8913.233	0.702041
8:00 PM	8956.822	0.705474
9:00:00 PM	9018.363	0.710322
10:00 PM	9098.361	0.716623
11:00:00 PM	9184.265	0.723389
12:00 AM	9244.883	0.728163
1:00:00 AM	9239.365	0.727729
2:00 AM	9158.048	0.721324
3:00:00 AM	9077.235	0.714959
4:00 AM	9144.898	0.720288
5:00:00 AM	9416.155	0.741653
6:00 AM	9657.026	0.760625
7:00:00 AM	9530.489	0.750659
8:00 AM	9228.041	0.726837
9:00:00 AM	9403.712	0.740673
10:00 AM	9897.387	0.779557
11:00:00 AM	9694.713	0.763594
12:00 PM	9321.445	0.734194
1:00:00 PM	9921.782	0.781478
2:00 PM	9976.048	0.785753
3:00:00 PM	9416.343	0.741668
4:00 PM	10182.68	0.802028
5:00:00 PM	9882.912	0.778417
6:00 PM	9731.173	0.766465
7:00:00 PM	10423.14	0.820967
8:00 PM	9593.736	0.75564
9:00:00 PM	10584.27	0.833659
10:00 PM	9713.982	0.765111
11:00:00 PM	10642.43	0.83824
12:00 AM	9815.8	0.773131

1:00:00 AM	10781.19	0.849169
2:00 AM	9845.157	0.775443
3:00:00 AM	10919.12	0.860033
4:00 AM	10023.14	0.789462
5:00:00 AM	10708.18	0.843418
6:00 AM	10677.37	0.840992
7:00:00 AM	10152.32	0.799636
8:00 AM	11149.76	0.878199
9:00:00 AM	10550.97	0.831036
10:00 AM	10370.57	0.816827
11:00:00 AM	11265.61	0.887324
12:00 PM	10923.9	0.860409
1:00:00 PM	10392.94	0.818588
2:00 PM	10971.89	0.864189
3:00:00 PM	11482.37	0.904397
4:00 PM	11112.15	0.875237
5:00:00 PM	10666.34	0.840122
6:00 PM	10820.63	0.852275
7:00:00 PM	11324.95	0.891997
8:00 PM	11655.88	0.918063
9:00:00 PM	11634.33	0.916366
10:00 PM	11414.43	0.899045
11:00:00 PM	11184.83	0.880961
12:00 AM	11048.82	0.870248
1:00:00 AM	11040.04	0.869557
2:00 AM	11144.46	0.877782
3:00:00 AM	11317.6	0.891419
4:00 AM	11506.27	0.906279
5:00:00 AM	11668.72	0.919074
6:00 AM	11783.99	0.928153
7:00:00 AM	11850.05	0.933357
8:00 AM	11876.36	0.935428
9:00:00 AM	11876.51	0.935441
10:00 AM	11863.45	0.934412
11:00:00 AM	11847.26	0.933136
12:00 PM	11834.68	0.932146
1:00:00 PM	11829.63	0.931748
2:00 PM	11833.88	0.932082
3:00:00 PM	11847.72	0.933172
4:00 PM	11870.41	0.93496
5:00:00 PM	11900.35	0.937318

6:00 PM	11935.06	0.940052
7:00:00 PM	11971.01	0.942883
8:00 PM	12003.52	0.945445
9:00:00 PM	12026.96	0.947291
10:00 PM	12035.31	0.947948
11:00:00 PM	12023.49	0.947017
12:00 AM	11989.33	0.944326
1:00:00 AM	11935.85	0.940115
2:00 AM	11873	0.935164
3:00:00 AM	11817.45	0.930789
4:00 AM	11789.43	0.928582
5:00:00 AM	11805.93	0.929881
6:00 AM	11871.92	0.935079
7:00:00 AM	11973.42	0.943074
8:00 AM	12077.73	0.951289
9:00:00 AM	12145.23	0.956606
10:00 AM	12150.65	0.957033
11:00:00 AM	12102.29	0.953224
12:00 PM	12042.8	0.948538
1:00:00 PM	12024.03	0.94706
2:00 PM	12068.87	0.950592
3:00:00 PM	12150.37	0.95701
4:00 PM	12212.11	0.961874
5:00:00 PM	12219.7	0.962471
6:00 PM	12194.17	0.960461
7:00:00 PM	12186.27	0.959838
8:00 PM	12216.43	0.962214
9:00:00 PM	12255.3	0.965276
10:00 PM	12273.06	0.966674
11:00:00 PM	12284.57	0.967581
12:00 AM	12311.93	0.969736
1:00:00 AM	12325.89	0.970836
2:00 AM	12310.03	0.969586
3:00:00 AM	12302.28	0.968976
4:00 AM	12329.63	0.97113
5:00:00 AM	12359.84	0.973509
6:00 AM	12348.46	0.972613
7:00:00 AM	12316.06	0.970061
8:00 AM	12327.03	0.970925
9:00:00 AM	12380.49	0.975136
10:00 AM	12396.08	0.976363

11:00:00 AM	12348.93	0.97265
12:00 PM	12328.49	0.971041
1:00:00 PM	12388.14	0.975739
2:00 PM	12435.92	0.979501
3:00:00 PM	12389	0.975806
4:00 PM	12337.79	0.971773
5:00:00 PM	12392.96	0.976118
6:00 PM	12468.13	0.982039
7:00:00 PM	12426.13	0.978731
8:00 PM	12351.03	0.972815
9:00:00 PM	12403.54	0.976951
10:00 PM	12498.77	0.984452
11:00:00 PM	12453.96	0.980923
12:00 AM	12362.51	0.973719
1:00:00 AM	12425.17	0.978655
2:00 AM	12531.85	0.987057
3:00:00 AM	12467.31	0.981974
4:00 AM	12371.05	0.974393
5:00:00 AM	12463.4	0.981666
6:00 AM	12564.54	0.989632
7:00:00 AM	12460.54	0.981441
8:00 AM	12384.63	0.975462
9:00:00 AM	12522.7	0.986337
10:00 AM	12582.88	0.991077
11:00:00 AM	12433.13	0.979282
12:00 PM	12422.97	0.978482
1:00:00 PM	12595.84	0.992098
2:00 PM	12563.37	0.98954
3:00:00 PM	12404.75	0.977047
4:00 PM	12507.93	0.985174
5:00:00 PM	12647.34	0.996154
6:00 PM	12495.13	0.984165
7:00:00 PM	12425.97	0.978718
8:00 PM	12627.66	0.994604
9:00:00 PM	12618.98	0.99392
10:00 PM	12425.22	0.978659
11:00:00 PM	12543.67	0.987989
12:00 AM	12696.17	1
1:00:00 AM	12502.67	0.98476
2:00 AM	12462.7	0.981611
3:00:00 AM	12666.03	0.997626

4:00 AM	12564.39	0.989621
5:00:00 AM	12389.85	0.975873
6:00 AM	12458.86	0.981309
7:00:00 AM	12508.75	0.985238
8:00 AM	12405.71	0.977122
9:00:00 AM	12328.49	0.97104
10:00 AM	12341.62	0.972075
11:00:00 AM	12344.23	0.97228
12:00 PM	12303.43	0.969067
1:00:00 PM	12272.92	0.966663
2:00 PM	12260.81	0.965709
3:00:00 PM	12224.26	0.962831
4:00 PM	12159.66	0.957742
5:00:00 PM	12116.97	0.95438
6:00 PM	12129.78	0.955389
7:00:00 PM	12170.77	0.958617
8:00 PM	12180.95	0.959419
9:00:00 PM	12126.28	0.955114
10:00 PM	12022.53	0.946941
11:00:00 PM	11916.24	0.938569
12:00 AM	11849.92	0.933346
1:00:00 AM	11840.27	0.932586
2:00 AM	11877.43	0.935513
3:00:00 AM	11937.14	0.940216
4:00 AM	11994.48	0.944732
5:00:00 AM	12032.55	0.947731
6:00 AM	12044.84	0.948698
7:00:00 AM	12033.12	0.947776
8:00 AM	12003.86	0.945471
9:00:00 AM	11964.91	0.942403
10:00 AM	11923.48	0.93914
11:00:00 AM	11885.27	0.93613
12:00 PM	11854.35	0.933695
1:00:00 PM	11833.41	0.932046
2:00 PM	11823.9	0.931297
3:00:00 PM	11825.93	0.931457
4:00 PM	11837.82	0.932393
5:00:00 PM	11855.15	0.933758
6:00 PM	11869.82	0.934914
7:00:00 PM	11869.43	0.934882
8:00 PM	11838	0.932407

9:00:00 PM	11759.35	0.926213
10:00 PM	11623.83	0.915538
11:00:00 PM	11437.73	0.90088
12:00 AM	11231.87	0.884666
1:00:00 AM	11062.63	0.871336
2:00 AM	10998.04	0.866249
3:00:00 AM	11086.27	0.873198
4:00 AM	11314.13	0.891145
5:00:00 AM	11578.22	0.911946
6:00 AM	11710.67	0.922378
7:00:00 AM	11585.06	0.912485
8:00 AM	11237.67	0.885123
9:00:00 AM	10891.71	0.857874
10:00 AM	10817.25	0.852009
11:00:00 AM	11100.36	0.874308
12:00 PM	11502.12	0.905952
1:00:00 PM	11602.77	0.913879
2:00 PM	11235.65	0.884964
3:00:00 PM	10762.2	0.847673
4:00 PM	10728.25	0.844999
5:00:00 PM	11196.53	0.881882
6:00 PM	11550.29	0.909746
7:00:00 PM	11237.11	0.885078
8:00 PM	10658.21	0.839482
9:00:00 PM	10679.75	0.841179
10:00 PM	11280.89	0.888527
11:00:00 PM	11431.76	0.90041
12:00 AM	10798.11	0.850501
1:00:00 AM	10494.83	0.826614
2:00 AM	11090.83	0.873557
3:00:00 AM	11401.64	0.898038
4:00 AM	10724.05	0.844668
5:00:00 AM	10446.6	0.822815
6:00 AM	11161.94	0.879158
7:00:00 AM	11228.6	0.884408
8:00 AM	10427.1	0.821279
9:00:00 AM	10639.59	0.838015
10:00 AM	11325.14	0.892012
11:00:00 AM	10691.45	0.8421
12:00 PM	10337.56	0.814227
1:00:00 PM	11175.68	0.88024

2:00 PM	10872.85	0.856389
3:00:00 PM	10223.29	0.805226
4:00 PM	11043.06	0.869795
5:00:00 PM	10894.38	0.858084
6:00 PM	10170.26	0.80105
7:00:00 PM	11025.6	0.868419
8:00 PM	10762.77	0.847718
9:00:00 PM	10163.45	0.800513
10:00 PM	11098.51	0.874162
11:00:00 PM	10470.57	0.824703
12:00 AM	10311.32	0.81216
1:00:00 AM	11095.22	0.873903
2:00 AM	10111.68	0.796436
3:00:00 AM	10706.15	0.843258
4:00 AM	10730.21	0.845154
5:00:00 AM	10064.11	0.792689
6:00 AM	11033.44	0.869037
7:00:00 AM	10114.02	0.79662
8:00 AM	10630	0.83726
9:00:00 AM	10762.66	0.847709
10:00 AM	10072.66	0.793362
11:00:00 AM	11071.72	0.872052
12:00 PM	10327.91	0.813467
1:00:00 PM	10438.75	0.822197
2:00 PM	11082.55	0.872905
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4:00 PM	10783.51	0.849352
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9:00:00 PM	10184.51	0.802172
10:00 PM	11061.52	0.871249
11:00:00 PM	10881.38	0.85706
12:00 AM	10218.28	0.804832
1:00:00 AM	11039.82	0.869539
2:00 AM	11020.9	0.86805
3:00:00 AM	10256.5	0.807842
4:00 AM	10896	0.858212
5:00:00 AM	11225.39	0.884156
6:00 AM	10402.66	0.819354

7:00:00 AM	10622.28	0.836653
8:00 AM	11338.2	0.893041
9:00:00 AM	10773.72	0.848581
10:00 AM	10372.99	0.817017
11:00:00 AM	11119.27	0.875798
12:00 PM	11263.91	0.88719
1:00:00 PM	10512.96	0.828042
2:00 PM	10604.35	0.83524
3:00:00 PM	11342.18	0.893355
4:00 PM	11146.83	0.877968
5:00:00 PM	10482.43	0.825637
6:00 PM	10741.75	0.846062
7:00:00 PM	11406.04	0.898385
8:00 PM	11187.18	0.881146
9:00:00 PM	10556.11	0.83144
10:00 PM	10709.51	0.843523
11:00:00 PM	11366.54	0.895273
12:00 AM	11377.54	0.89614
1:00:00 AM	10767.93	0.848125
2:00 AM	10590.69	0.834164
3:00:00 AM	11125.41	0.876281
4:00 AM	11532.55	0.908349
5:00:00 AM	11212.37	0.88313
6:00 AM	10689.59	0.841954
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8:00 AM	11260.38	0.886911
9:00:00 AM	11567.49	0.911101
10:00 AM	11238.41	0.885181
11:00:00 AM	10714.36	0.843905
12:00 PM	10706.2	0.843263
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2:00 PM	11544.46	0.909287
3:00:00 PM	11164.74	0.879379
4:00 PM	10641.67	0.838179
5:00:00 PM	10745.65	0.846369
6:00 PM	11326.47	0.892117
7:00:00 PM	11492.16	0.905168
8:00 PM	10965.54	0.863689
9:00:00 PM	10564.26	0.832082
10:00 PM	10916.79	0.859849
11:00:00 PM	11466.8	0.90317

12:00 AM	11304.47	0.890384
1:00:00 AM	10682.43	0.84139
2:00 AM	10625.48	0.836905
3:00:00 AM	11230.64	0.884569
4:00 AM	11468.55	0.903308
5:00:00 AM	10908.56	0.859201
6:00 AM	10516.88	0.828351
7:00:00 AM	10973.38	0.864306
8:00 AM	11475.16	0.903829
9:00:00 AM	11101.45	0.874394
10:00 AM	10520.48	0.828634
11:00:00 AM	10785.14	0.84948
12:00 PM	11412.65	0.898905
1:00:00 PM	11215.77	0.883398
2:00 PM	10553.18	0.83121
3:00:00 PM	10676.26	0.840904
4:00 PM	11351.92	0.894122
5:00:00 PM	11258.01	0.886725
6:00 PM	10563.79	0.832046
7:00:00 PM	10631.55	0.837383
8:00 PM	11327.79	0.892221
9:00:00 PM	11241.62	0.885434
10:00 PM	10533.4	0.829652
11:00:00 PM	10643.1	0.838292
12:00 AM	11345.94	0.89365
1:00:00 AM	11166.27	0.879499
2:00 AM	10468.95	0.824575
3:00:00 AM	10719.21	0.844287
4:00 AM	11386.11	0.896814
5:00:00 AM	11018.67	0.867874
6:00 AM	10404.67	0.819512
7:00:00 AM	10874.27	0.8565
8:00 AM	11396.91	0.897665
9:00:00 AM	10793.24	0.850118
10:00 AM	10405.94	0.819613
11:00:00 AM	11097.9	0.874114
12:00 PM	11294.3	0.889583
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2:00 PM	10557.05	0.831515
3:00:00 PM	11313.77	0.891117
4:00 PM	10985.35	0.865249

5:00:00 PM	10340.05	0.814423
6:00 PM	10919.37	0.860052
7:00:00 PM	11311.05	0.890903
8:00 PM	10529.87	0.829373
9:00:00 PM	10498.95	0.826938
10:00 PM	11288.72	0.889144
11:00:00 PM	10891.09	0.857825
12:00 AM	10302.79	0.811488
1:00:00 AM	11019.24	0.867918
2:00 AM	11180.25	0.8806
3:00:00 AM	10345.89	0.814883
4:00 AM	10695.69	0.842435
5:00:00 AM	11296.44	0.889752
6:00 AM	10523.69	0.828887
7:00:00 AM	10444.01	0.822611
8:00 AM	11263.52	0.887159
9:00:00 AM	10727.34	0.844928
10:00 AM	10296.99	0.811031
11:00:00 AM	11152.53	0.878417
12:00 PM	10893.03	0.857978
1:00:00 PM	10232.49	0.805951
2:00 PM	11026.65	0.868502
3:00:00 PM	11001.08	0.866488
4:00 PM	10213.05	0.80442
5:00:00 PM	10923.86	0.860406
6:00 PM	11056.25	0.870833
7:00:00 PM	10207.23	0.803962
8:00 PM	10861.22	0.855472
9:00:00 PM	11069.38	0.871867
10:00 PM	10196.56	0.803121
11:00:00 PM	10844.15	0.854128
12:00 AM	11046.81	0.87009
1:00:00 AM	10175.9	0.801494
2:00 AM	10872.6	0.856368
3:00:00 AM	10986.69	0.865355
4:00 AM	10152.76	0.799671
5:00:00 AM	10941.61	0.861804
6:00 AM	10880.46	0.856988
7:00:00 AM	10147.1	0.799226
8:00 AM	11036.78	0.8693
9:00:00 AM	10719.75	0.84433

10:00 AM	10189.52	0.802567
11:00:00 AM	11126.77	0.876388
12:00 PM	10509.64	0.827781
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2:00 PM	11164.27	0.879342
3:00:00 PM	10302.39	0.811456
4:00 PM	10520.73	0.828654
5:00:00 PM	11106.5	0.874792
6:00 PM	10156.47	0.799964
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8:00 PM	10946.33	0.862176
9:00:00 PM	10105.99	0.795987
10:00 PM	10977.87	0.86466
11:00:00 PM	10708.48	0.843442
12:00 AM	10174.12	0.801354
1:00:00 AM	11122.84	0.876078
2:00 AM	10443.38	0.822562
3:00:00 AM	10358.27	0.815858
4:00 AM	11143.72	0.877723
5:00:00 AM	10218.39	0.804841
6:00 AM	10621.79	0.836614
7:00:00 AM	11019.44	0.867934
8:00 AM	10100.4	0.795547
9:00:00 AM	10895.48	0.858171
10:00 AM	10772.29	0.848468
11:00:00 AM	10134.57	0.798238
12:00 PM	11092.25	0.873669
1:00:00 PM	10470.01	0.824659
2:00 PM	10324.58	0.813204
3:00:00 PM	11135.86	0.877104
4:00 PM	10209.61	0.804149
5:00:00 PM	10620.42	0.836506
6:00 PM	10995	0.866009
7:00:00 PM	10085.9	0.794405
8:00 PM	10922.7	0.860315
9:00:00 PM	10706.91	0.843318
10:00 PM	10155.05	0.799851
11:00:00 PM	11111.56	0.87519
12:00 AM	10374.41	0.817129
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2:00 AM	11096.79	0.874027

3:00:00 AM	10130.94	0.797952
4:00 AM	10746.99	0.846475
5:00:00 AM	10867.96	0.856003
6:00 AM	10085.74	0.794392
7:00:00 AM	11033.21	0.869019
8:00 AM	10514.45	0.828159
9:00:00 AM	10272.12	0.809072
10:00 AM	11122.1	0.87602
11:00:00 AM	10195.26	0.803019
12:00 PM	10618.63	0.836365
1:00:00 PM	10953.81	0.862765
2:00 PM	10068.58	0.79304
3:00:00 PM	10966.95	0.8638
4:00 PM	10651.33	0.83894
5:00:00 PM	10205.01	0.803787
6:00 PM	11154.35	0.87856
7:00:00 PM	10480.33	0.825472
8:00 PM	10370.69	0.816836
9:00:00 PM	11216.91	0.883488
10:00 PM	10465.13	0.824274
11:00:00 PM	10427.85	0.821338
12:00 AM	11253.11	0.886339
1:00:00 AM	10579.79	0.833306
2:00 AM	10377.77	0.817394
3:00:00 AM	11242.62	0.885512
4:00 AM	10837.04	0.853568
5:00:00 AM	10302.98	0.811503
6:00 AM	11070.22	0.871934
7:00:00 AM	11193.24	0.881623
8:00 AM	10411.03	0.820013
9:00:00 AM	10681.38	0.841307
10:00 AM	11371.66	0.895677
11:00:00 AM	10897.36	0.858319
12:00 PM	10398.75	0.819046
1:00:00 PM	10996.52	0.866129
2:00 PM	11411.57	0.89882
3:00:00 PM	10806.8	0.851186
4:00 PM	10475.33	0.825078
5:00:00 PM	11078.49	0.872585
6:00 PM	11461.06	0.902718
7:00:00 PM	10941.11	0.861764

8:00 PM	10520.17	0.82861
9:00:00 PM	10940.46	0.861714
10:00 PM	11486.28	0.904704
11:00:00 PM	11278.61	0.888347
12:00 AM	10705.71	0.843224
1:00:00 AM	10672.76	0.840628
2:00 AM	11216.87	0.883485
3:00:00 AM	11561.85	0.910657
4:00 AM	11261.35	0.886988
5:00:00 AM	10768.14	0.848141
6:00 AM	10725.86	0.844811
7:00:00 AM	11170.99	0.879871
8:00 AM	11577.28	0.911872
9:00:00 AM	11505.82	0.906243
10:00 AM	11079.91	0.872697
11:00:00 AM	10771.91	0.848438
12:00 PM	10878.24	0.856813
1:00:00 PM	11283.03	0.888696
2:00 PM	11620.94	0.915311
3:00:00 PM	11621.14	0.915326
4:00 PM	11314.19	0.89115
5:00:00 PM	10934.85	0.861272
6:00 PM	10776.42	0.848793
7:00:00 PM	11017.47	0.867779
8:00 PM	11454.78	0.902223
9:00:00 PM	11524.51	0.907716
10:00 PM	11003.66	0.866691
11:00:00 PM	10555.61	0.831401
12:00 AM	10878.14	0.856805
1:00:00 AM	11434.85	0.900654
2:00 AM	11112.2	0.875241
3:00:00 AM	10433.55	0.821787
4:00 AM	10774.87	0.848671
5:00:00 AM	11359.32	0.894704
6:00 AM	10704.87	0.843157
7:00:00 AM	10341.87	0.814567
8:00 AM	11164.57	0.879366
9:00:00 AM	10845.32	0.85422
10:00 AM	10195.46	0.803035
11:00:00 AM	11059.72	0.871107
12:00 PM	10687.84	0.841816

1:00:00 PM	10175.18	0.801437
2:00 PM	11098.14	0.874133
3:00:00 PM	10247.01	0.807095
4:00 PM	10483.51	0.825722
5:00:00 PM	10828.77	0.852916
6:00 PM	9968.837	0.785185
7:00:00 PM	10955.24	0.862877
8:00 PM	9979.639	0.786035
9:00:00 PM	10671.65	0.840541
10:00 PM	10204.01	0.803708
11:00:00 PM	10343.08	0.814661
12:00 AM	10369.25	0.816722
1:00:00 AM	10131.6	0.798004
2:00 AM	10405.87	0.819607
3:00:00 AM	10047.09	0.791348
4:00 AM	10322.96	0.813077
5:00:00 AM	10078.7	0.793838
6:00 AM	10124.27	0.797428
7:00:00 AM	10225.03	0.805363
8:00 AM	9830.583	0.774295
9:00:00 AM	10424.07	0.82104
10:00 AM	9578.073	0.754407
11:00:00 AM	10450.37	0.823112
12:00 PM	9644.234	0.759618
1:00:00 PM	10048.03	0.791422
2:00 PM	10100.98	0.795593
3:00:00 PM	9507.656	0.74886
4:00 PM	10276.38	0.809408
5:00:00 PM	9670.358	0.761675
6:00 PM	9640.962	0.75936
7:00:00 PM	10183.21	0.80207
8:00 PM	9493.462	0.747742
9:00:00 PM	9581.575	0.754682
10:00 PM	10046.59	0.791309
11:00:00 PM	9528.882	0.750532
12:00 AM	9324.016	0.734396
1:00:00 AM	9788.262	0.770962
2:00 AM	9761.825	0.76888
3:00:00 AM	9296.616	0.732238
4:00 AM	9253.012	0.728803
5:00:00 AM	9575.28	0.754187

6:00 AM	9651.04	0.760154
7:00:00 AM	9376.232	0.738509
8:00 AM	9128.785	0.719019
9:00:00 AM	9137.35	0.719693
10:00 AM	9295.722	0.732167
11:00:00 AM	9398.717	0.74028
12:00 PM	9360.398	0.737262
1:00:00 PM	9229.771	0.726973
2:00 PM	9093.713	0.716256
3:00:00 PM	9003.594	0.709158
4:00 PM	8964.395	0.706071
5:00:00 PM	8956.464	0.705446
6:00 PM	8957.604	0.705536
7:00:00 PM	8953.611	0.705222
8:00 PM	8939.199	0.704086
9:00:00 PM	8914.839	0.702168
10:00 PM	8883.471	0.699697
11:00:00 PM	8848.546	0.696946
12:00 AM	8813.36	0.694175
1:00:00 AM	8781.125	0.691636
2:00 AM	8755.112	0.689587
3:00:00 AM	8738.265	0.68826
4:00 AM	8731.747	0.687747
5:00:00 AM	8732.228	0.687785
6:00 AM	8728.833	0.687517
7:00:00 AM	8702.679	0.685457
8:00 AM	8633.769	0.680029
9:00:00 AM	8518.062	0.670916
10:00 AM	8387.685	0.660647
11:00:00 AM	8312.146	0.654697
12:00 PM	8355.675	0.658126
1:00:00 PM	8497.966	0.669333
2:00 PM	8592.474	0.676777
3:00:00 PM	8475.495	0.667563
4:00 PM	8198.122	0.645716
5:00:00 PM	8068.342	0.635494
6:00 PM	8275.622	0.65182
7:00:00 PM	8501.472	0.669609
8:00 PM	8290.663	0.653005
9:00:00 PM	7945.008	0.62578
10:00 PM	8089.537	0.637164

11:00:00 PM	8451.5	0.665673
12:00 AM	8356.893	0.658222
1:00:00 AM	7998.239	0.629973
2:00 AM	8035.45	0.632903
3:00:00 AM	8401.268	0.661717
4:00 AM	8441.214	0.664863
5:00:00 AM	8088.814	0.637107
6:00 AM	7977.674	0.628353
7:00:00 AM	8303.612	0.654025
8:00 AM	8491.819	0.668849
9:00:00 AM	8211.357	0.646759
10:00 AM	7963.575	0.627242
11:00:00 AM	8180.662	0.644341
12:00 PM	8486.291	0.668413
1:00:00 PM	8349.236	0.657619
2:00 PM	8014.557	0.631258
3:00:00 PM	8060.909	0.634909
4:00 PM	8408.861	0.662315
5:00:00 PM	8463.765	0.666639
6:00 PM	8135.886	0.640814
7:00:00 PM	7988.483	0.629204
8:00 PM	8269.029	0.651301
9:00:00 PM	8506.916	0.670038
10:00 PM	8302.766	0.653958
11:00:00 PM	8006.354	0.630612
12:00 AM	8111.583	0.6389
1:00:00 AM	8444.677	0.665136
2:00 AM	8454.77	0.665931
3:00:00 AM	8129.856	0.640339
4:00 AM	8008.811	0.630805
5:00:00 AM	8287.81	0.65278
6:00 AM	8514.27	0.670617
7:00:00 AM	8320.577	0.655361
8:00 AM	8027.9	0.632309
9:00:00 AM	8107.978	0.638616
10:00 AM	8432.81	0.664201
11:00:00 AM	8483.169	0.668168
12:00 PM	8182.279	0.644468
1:00:00 PM	8014.058	0.631219
2:00 PM	8242.618	0.649221
3:00:00 PM	8509.781	0.670264

4:00 PM	8395.59	0.66127
5:00:00 PM	8085.374	0.636836
6:00 PM	8064.809	0.635216
7:00:00 PM	8364.963	0.658857
8:00 PM	8522.82	0.671291
9:00:00 PM	8295.998	0.653425
10:00 PM	8035.615	0.632917
11:00:00 PM	8129.357	0.6403
12:00 AM	8439.077	0.664695
1:00:00 AM	8402.33	0.6618
2:00 AM	7980.709	0.628592
3:00:00 AM	7937.047	0.625153
4:00 AM	8358.361	0.658337
5:00:00 AM	8246.029	0.64949
6:00 AM	7756.477	0.61093
7:00:00 AM	8047.404	0.633845
8:00 AM	8332.528	0.656303
9:00:00 AM	7742.322	0.609816
10:00 AM	7861.237	0.619182
11:00:00 AM	8291.544	0.653074
12:00 PM	7638.26	0.601619
1:00:00 PM	7866.096	0.619565
2:00 PM	8164.425	0.643062
3:00:00 PM	7457.105	0.587351
4:00 PM	8074.616	0.635988
5:00:00 PM	7765.285	0.611624
6:00 PM	7554.976	0.595059
7:00:00 PM	8104.408	0.638335
8:00 PM	7306.695	0.575504
9:00:00 PM	8070.966	0.635701
10:00 PM	7377.7	0.581097
11:00:00 PM	7829.685	0.616697
12:00 AM	7532.703	0.593305
1:00:00 AM	7599.722	0.598584
2:00 AM	7625.091	0.600582
3:00:00 AM	7461.368	0.587687
4:00 AM	7619.997	0.600181
5:00:00 AM	7422.5	0.584625
6:00 AM	7515.169	0.591924
7:00:00 AM	7485.851	0.589615
8:00 AM	7309.53	0.575727

9:00:00 AM	7642.278	0.601936
10:00 AM	7047.789	0.555111
11:00:00 AM	7791.926	0.613723
12:00 PM	6902.154	0.543641
1:00:00 PM	7688.496	0.605576
2:00 PM	7117.989	0.560641
3:00:00 PM	7190.367	0.566341
4:00 PM	7589.396	0.597771
5:00:00 PM	6790.957	0.534882
6:00 PM	7531.619	0.59322
7:00:00 PM	7193.77	0.566609
8:00 PM	6825.133	0.537574
9:00:00 PM	7571.726	0.596379
10:00 PM	6982.699	0.549985
11:00:00 PM	6819.036	0.537094

Three Month Power data sample from August to October 2013

VITA

Kshitiz Shivanand Byahatti

Candidate for the degree of

Master of Science

Thesis: A STUDY OF SENSORLESS CONTROLLER FOR DIRECT DRIVE WIND ELECTRIC CONVERSION SYSTEMS

Major Field: Electrical Engineering

Biographical:

Education:

Completed the requirements for the Master of Science in Electrical Engineering, Oklahoma State University, Stillwater, Oklahoma in May, 2014.

Completed the requirements for the Bachelor of Engineering in Electrical and Electronics , B.V.Bhoomraddi College of Engineering, India in 2011.

Experience:

Research Assistant in the Engineering Energy Laboratory, School of Electrical and Computer Engineering, Oklahoma State University (January 2012 to May 2014).

Project Trainee, Innovative Process Equipment Private Limited, Hubli, India, (Aug 2011 to Nov 2011