Modelling of Wind Farms in the Load Flow Analysis

A DISSERTATION Report
Submitted by

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Under the guidance of

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CANDIDATE'S DECLARATION

I hereby declare that this dissertation entitled MODELLING OF WIND FARMS IN THE LOAD FLOW ANALYSIS which is being submitted to the Department of Electrical Engineering, Indian Institute of Technology, Roorkee in fulfillment of the requirements for the award of the Degree of Master of Technology in Electrical Engineering with specialization in Power System Engineering is a bonafide work carried out by me during the period May 2017 to May 2019 under the supervision of Dr. Dheeraj Kumar Khatod, Associate Professor, Department of Electrical Engineering, IIT Roorkee. The material contained in this dissertation has not been submitted by me for the award of any other degree of this institute or any other institute.

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This is to certify that the above statement made by the candidate is true to the best of my knowledge and belief.

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ABSTRACT

The purpose of this project is to Model of Wind Farms in the Load Flow Analysis. Two methods are proposed, for the simulation of wind farms with asynchronous generators in the load flow analysis. Both methods are based on the steady-state model of the induction machine. The first involves improving the conventional PQ bus, and the second involves modeling the generators in steady-state in the bus where the wind farm is located.

When the conventional PQ bus model is used, the real and reactive powers have constant values, although some authors propose methods for modifying these values in order to represent loads depending either on the voltage or on the frequency. When the PX bus model is used, the real power is known and the reactive power is calculated as a function of the magnetizing reactance of the generators.

Both methods suppose prior knowledge of the WT features. The turbine's power curve is generally supplied by the manufacturer. When the induction generator parameters are not known, they must be estimated. One of the problems that wind energy will create in electrical power systems is the dependence of the injected power on the wind speed. The wind speed cannot be predicted, but the probability of a particular wind speed occurring can be estimated. This can be done if the probability distribution is known by assuming it to be a Wei-bull distribution in which Rayleigh probability density function is used.

Probabilistic distribution model is used for wind turbine integration to 33 Bus System. For the system, 3 years of historical data were taken regarding the hourly load and the hourly wind speed profile. Load flow is run hour by hour for the entire year. During each hour, wind based DG penetration is changed based on the wind speed profile. Finally, the power loss calculated for each hour are aggregated to obtain the annual energy loss.

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CHAPTER 1

WIND ENERGY- AN OVERVIEW

1.1 INTRODUCTION

The conventional energy sources are limited and pollute the environment. So more attention and Interest have been paid to the utilization of renewable energy source such as Wind Energy, Fuel-cell, Solar Energy etc., Wind Energy is the fastest growing and most promising renewable Energy source among them as it is economically viable.

1.2 ECONOMY OF WIND ENERGY IN INDIA

In the early 1980's, the Department of Non-conventional Energy Sources (DNES) came into existence with the aim to reduce the dependence of primary energy sources like coal, oil etc. in view of the country's energy security. The DNES became Ministry of Non-conventional Energy sources (MNES) in the year 1992 and now from 2006, the ministry was renamed as Ministry of New & Renewable Energy (MNRE).

The growth of Renewable Energy in India is enormous and wind energy proves to be the most effective solution to the problem of depleting fossil fuels, importing of coal, greenhouse gas emission, environment pollution etc. Wind energy as a renewable, non-polluting and affordable source directly avoids dependency of fuel and transport, can lead to green and clean electricity.

With an installed capacity of 32790 MW (September 2017) of wind energy, Renewable Energy sources (excluding large Hydro) currently accounts for 17.65% of India's overall installed power capacity of 329298 MW. Wind energy holds the major portion of 55.75% of total RE capacity (58303 GW) among renewable and continued as the largest supplier of clean energy.

The Government of India has announced a laudable Renewable Energy target of 175 GW by 2022 out of which 60 GW will be coming from wind power. The wind potential in India was first estimated by National Institute of Wind Energy (NIWE) at 50m hub-height i.e. 79 GW but according to the survey at 80m hub height, the potential grows as much as 102 GW. Further a new study by NIWE at 100m height has estimated a potential 302 GW.

One of the major advantages of wind energy is its inherent strength to support rural employment and uplift of rural economy. Further, unlike all other sources of power, wind energy does not consume any water-which in itself will become a scarce commodity.

Overall the future of wind energy in India is bright as energy security and self-sufficiency is identified as the major driver. The biggest advantage with wind energy is that the fuel is free, and also it does not produce CO2 emission. Wind farm can be built reasonably fast, the wind farm land can be used for farming as well thus serving dual purpose, and it is cost effective as compare to other forms of renewable energy. (Numerical Data Sources: CEA, NIWE, MNRE)

1.3 WIND POTENTIAL

The potential for wind power generation for grid interaction has been estimated at about 1,02,788 MW taking sites having wind power density greater than 200 W/sq. m at 80 m hub-height with 2% land availability in potential areas for setting up wind farms @ 9 MW/sq. km.

1.4 TURBINE TECHNOLOGY

Two types of wind turbines namely stall regulated and pitch regulated are being deployed in the country and abroad for grid-interactive power. The stall regulated wind turbine have fixed rotor blades whereas pitch regulated wind turbines have adjustable rotor blades that change the angle of attach depending upon wind speed. Both technologies have their own advantages and disadvantages. Wind turbines are also available with lattice, steel tubular and concrete tubular tower.

1.5 MANUFACTURING BASE OF WIND ELECTRIC GENERATORS

Wind Electric Generators are being manufactured in the country by a dozen manufacturers, through (i) joint ventures under licensed production (ii) subsidiaries of foreign companies, under licensed production and (iii) Indian companies with their own technology. An indigenization level up to 70% has been achieved in machines of unit sizes up to 500 kW. The important content is somewhat higher in higher capacity machines. The current annual production capacity of domestic wind turbines is about 9500 MW.

1.6 WIND FARMS IN INDIA

Tamil Nadu

Tamil Nadu's wind power capacity is around 29% of India's total. The Government of Tamil Nadu realized the importance and need for renewable energy, and set up a separate Agency, as registered society, called the Tamil Nadu Energy Development Agency (TEDA) as early as 1985. Now Tamil Nadu has become a leader in Wind Power in India. In Muppandal windfarm the total capacity is 1500 MW, the largest wind power plant in India. The total wind installed capacity in Tamil Nadu is 7633 MW.During the fiscal year 2014-15, the electricity generation is 9.521 GWh, with about a 15% capacity utilization factor.

Maharashtra

Maharashtra is one of the prominent states that installed wind power projects second to Tamil Nadu in India. As of end of March 2016, installed wind power capacity is 4655.25 MW. As of nowthere are 50 developers registered with state nodal agency "Maharashtra energy Development Agency" for development of wind power projects. All the major manufacturers of wind turbines including Suzlon, Vestas, Gamesa, Regen, Leitner Shriram have presence in Maharashtra.

Gujarat

Gujarat government's focus on tapping renewable energy has led to sharp rise in the wind power capacity in the last few years. According to official data, wind power generations capacity in the state has increased a staggering ten times in just six years. ONGC Ltd. has installed a 51MW wind energy farm at Bhuj in Gujarat. Renewable energy projects worth a massive Rs 1 lakh crore of memorandums of understanding (MoUs) in the Vibrant Gujarat Summit in 2017.

Rajasthan

4031.99 MW wind power installed as per 31.03.2016.

Madhya Pradesh

In consideration of unique concept, Govt. of Madhya Pradesh has sanctioned another 15 MW project to Madhya Pradesh Windfarms Ltd. MPWL, Bhopal at Nagda Hills near Dewas underconsultation from Consolidated Energy Consultants Ltd. CECL Bhopal. All the 25 WEGs have been commissioned on 31.03.2008 and under successful operation.

Kerala

55 MW production of wind power is installed in Kerala. The first wind farm of the state was set up 1997 at Kanjikode in Palakkad district.

The agency has identified 16 sites for setting up wind farms through private developers.

Odisha

Odisha a coastal state has higher potential for wind energy. Current installation capacity stands at 2.0 MW. Odisha has a windpower potential of 1700MW. The Govt of Odisha is actively pursuing to boost Wind power generation in the state. However it has not progressed like other states primarily because Odisha having a huge coal reserve and number of existing and upcoming thermal power plants, is a power surplus state.

West Bengal

The total installation in West Bengal is 2.10 MW till Dec 2009 at Fraserganj, Distt- South 24 Paraganas. More 0.5 MW (approx) at Ganga Sagar, Kakdwip, Distt - South 24 Paraganas. Both the project owned by West Bengal Renewable Energy Development Agency (WBREDA), Govt. of WB and project was executed on turnkey basis by Utility Powertech Limited (UPL).

Jammu and Kashmir

The Kargil, Ladakh occupied Gilgit and China occupied Aksai Chin regions of Jammu and Kashmir state are potential wind energy areas, which are yet to be exploited. Wind Speeds are higher during the winter months in the state, which is complimentary to the hydro power available during the summer months from the snow melt water. Being a Himalayan state located at higher altitude, the heating energy requirements are high which can be met by the renewable energy resources such as wind, solar and hydro power. The state is yet to open its account in grid connected wind power installations.

CHAPTER 2

FUNDAMENTALS OF WIND TURBINES

2.1 Power contained in the wind

Wind energy isnot a constant source of energy. It varies continuously and gives energy in sudden bursts. About 50% of the entire energy is given out in just 15% of the operating time. Wind strengths vary and thus cannot guarantee continuous power. It is best used in the context of a system that has significant reserve capacity such as hydro, or reserve load, such as a desalination plant, to mitigate the economic effects of resource variability. The total capacity of wind power on this earth that can be harnessed is about 72 TW. There are now many thousands of wind turbines operating in various parts of the world, with utility companies having a total capacity of 59,322 MW. The power generation by wind energy was about 94.1GW in 2007 which makes up nearly 1% of the total power generated in the world. Globally, the long-term technical potential of wind energy is believed to be 5 times current global energy consumption or 40 times current electricity demand. This would require covering 12.7% of all land area with wind turbines. This land would have to be covered with 6 large wind turbines per square kilometer. The power extracted from the wind can be calculated by the given formula:

$$P = 0.5 \times \rho \times A \times V^3 \times C_P \qquad (1)$$

P= extracted power from the wind,

ρ = air density, (approximately 1.225 kg/m^{3}at 20^{o}C at sea level)

V= wind velocity (m/s) (velocity can be controlled between 3 to 30 m/s)

C_P =the power coefficient which is a function of both tip speed ratio, and blade pitch angle, Power coefficient (C_P) is defined as the ratio of the output power produced to the power available in the wind.

Betz Limit:

No wind turbine could convert more than 59.3% of the kinetic energy of the wind into Mechanical energy turning a rotor. This is known as the Betz Limit, and is the theoretical Maximum coefficient of power for any wind turbine. The maximum value of C_P according to Betz limit is 59.3%. For good turbines it is in the range of 35-45%.

2.2. Types of Wind energy Conversion Devices.

A wind turbine is a rotating machine which converts the kinetic energy in wind into mechanical energy. If the mechanical energy is then converted to electricity, the machine is called a wind generator, wind turbine, wind power unit (WPU), wind energy converter (WEC), or aero generator. Wind turbines can be separated into two types based by the axis in which the turbine rotates. Turbines that rotate around a horizontal axis are more common. Vertical-axis turbines are less frequently used.

1. Horizontal axis wind turbine
    a) “Dutch-type” grain grinding windmills.
    b) Multi-blade water-pumping windmills.
    c) High speed propeller type windmills
2. Vertical axis wind turbine
    a) The Savonius rotor.
    b) The Darrieus rotor.

2.3 Power speed characteristics:

The wind turbine power curves shown in figure illustrate how the mechanical power that can be extracted from the wind depends on the rotor speed. For each wind speed there is an optimum turbine speed at which the extracted wind power at the shaft reaches its maximum. Such families of Wind turbine power curves can be represented by a single dimensionless characteristic curve namely the C_P - curve, as in the figure, where the power coefficient is plotted against the TSR. For a given turbine, the power coefficient depends not only on the TSR but also on the blade pitch angle. Figure shows the typical variation of the power coefficient with respect to the TSR **λ** with the blade pitch control. The mechanical power transmitted to the shaft is—

$$P = 0.5 \times \rho \times A \times V^3 \times C_P \tag{2}$$

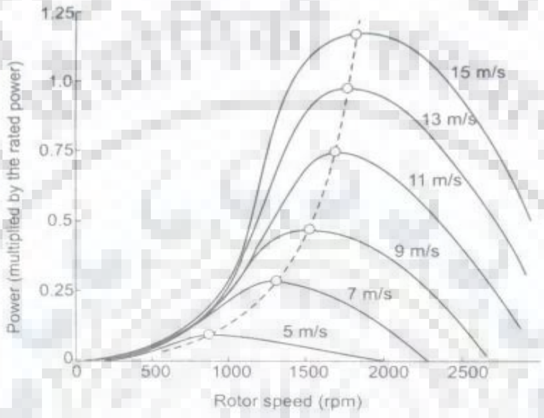


Figure 2.6 Power Speed Characteristics of Wind Turbine

Where is the function of TSR **λ** and the pitch angle α. For a wind turbine with radius R, it can be expressed

$$\lambda = \frac{\omega \times R}{V} \tag{3}$$

The maximum value of the shaft mechanical power for any wind speed can be expressed as

$$P = 0.5 \times C_P \times \pi \times (R^5 / \lambda^3) \times \omega^3 \tag{4}$$

Thus the maximum mechanical power that can be extracted from the wind is proportional to the cube of the rotor speed.

2.4 Wei-bull Distribution-

Wind speed keeps changing hence to define constant power there is a need of probability speed distribution.It is done by Wei-bull or Rayleigh Distribution.

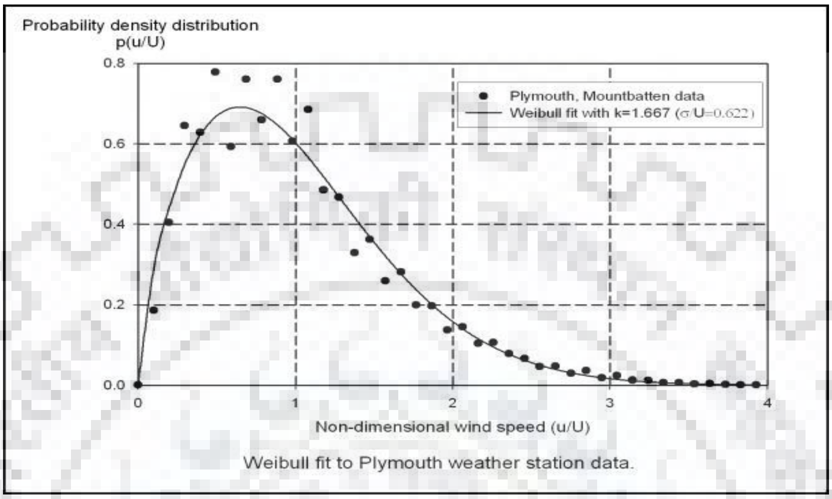


Fig- Probability density function variation with wind speed

Due to the non-linear variation of power with steady wind speed, the mean power obtained over time in a variable wind with a mean velocity U_m is not the same as the power obtained in a steady wind of the same speed.

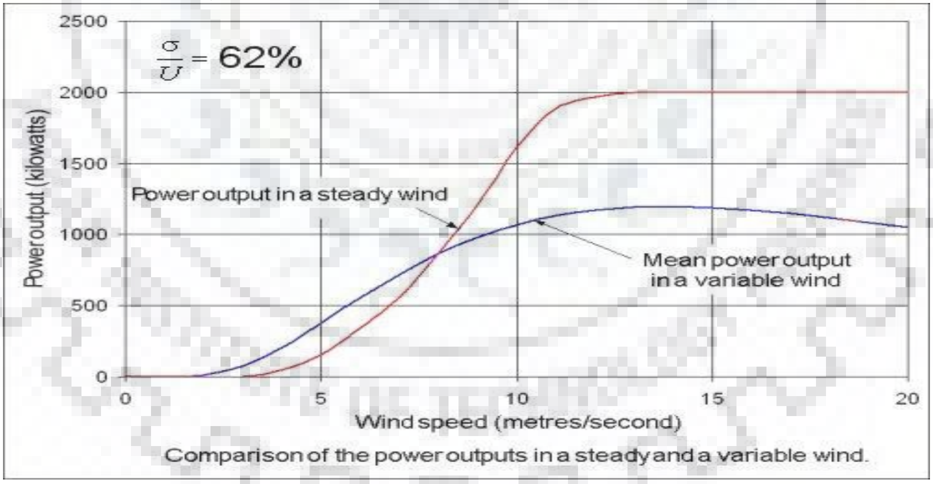


Fig- Power output variation in steady and variable wind

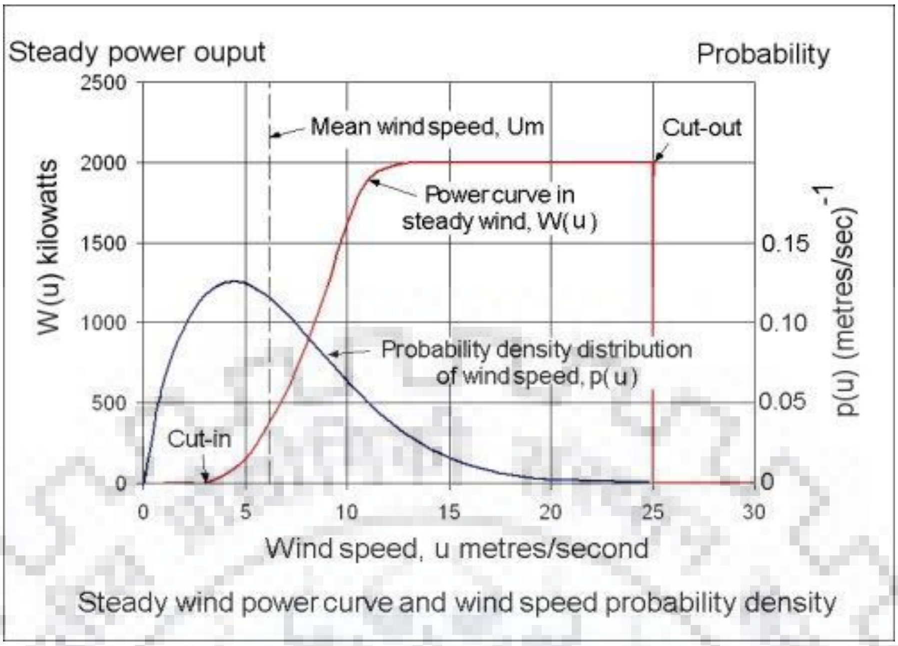


Fig- Steady wind power curve and wind speed probability density.

The final mean power at a mean wind speed Um is the steady power W(u) multiplied by the probability density distribution P(u) and summed (i.e. integrated) over all the range of wind speeds. Thus, the mean power P_m at a mean speed U is given by:

$$P_m = \int_0^\infty P(u).W(u).du$$

CHAPTER 3

Wind Turbine Control Systems

Wind turbines require certain control systems. Horizontal-axis turbines have to be oriented to face the wind. In high winds, it is desirable to reduce the drive train loads and protect the generator and the power electronic equipment for overloading, by limiting the turbine power to the rated value up to the furling speed. At gust speeds, the machine has to be stalled. At low and moderate wind speeds, the aim should be to capture power as efficiently as possible. Along with many operating characteristics, the technical data sheet of a turbine mentions its output at a particular wind speed. This is the minimum wind speed at which the turbine produces its designated output power. For most turbines, this speed is normally between 9 and 16 m/s. The choice of the rated wind speed depends on the factors related to the wind characteristics of a given site. The generator rating is best chosen so as to best utilize the mechanical output of the turbine at the rated wind speed. Wind turbines can have four different types of control mechanisms, as discussed below:

3.1 Pitch Angle Control:

The system changes the pitch angle of the blades according to the variation of wind speed. As discussed earlier, with pitch control, it is possible to achieve a high efficiency by continuously aligning the blade in the direction of the relative wind. On a pitch controlled machine, as the wind speed exceeds its rated speed, the blades are gradually turned about the longitudinal axis and out of the wind to increase the pitch angle. This reduces the aerodynamic efficiency of the rotor, and the rotor output power decreases. When the wind speed exceeds the safe limit for the system, the pitch angle is so changed that the power output reduces to zero and the machine shifts to the stall mode. After the gust passes, the pitch angle is reset to the normal position and the turbine is restarted. At normal wind speeds, the blade pitch angle should ideally settle to a value at which the output power equals the rated power. The input variable to the pitch controller is the error signal arising from the difference between the output electrical power and the reference power. The pitch controller operates the blade actuator to alter the pitch angle. During operation below the rated speed, the control system endeavors to the pitch the blade at an angle that maximizes the rotor efficiency. The generator must be able to absorb the mechanical power output and deliver to the load. Hence, the generator output power needs to be simultaneously adjusted.

3.2 Stall Control:

(a) Passive stall control:

This stall control to limit the power output at high winds is applied to constant-pitch turbines driving induction generators connected to the network. The rotor speed is fixed by the network, allowing only 1-4% variation. As the wind speed increases, the angle of attack also increases for a blade running at a near constant speed. Beyond a particular angle of attack, the lift force decreases, causing the rotor efficiency to drop. This lift force can be further reduced to restrict the power output at high winds by properly shaping the rotor blade profile to create turbulence on the rotor blade side not facing the wind.

(b) Active stall control:

In this method of control, at high wind speeds, the blade is rotated by a few degrees in the direction opposite to that in a pitch controlled machine. This increases the angle of attack, which can be controlled to keep the output power at its rated value at all high wind speeds below the furling speed.

A passive controlled machine shows a drop in power at high winds. The action of active stall control is sometimes called deep stall. Owing to economic reasons, active pitch control is generally used only with high capacity machines.

3.3 Power Electronic Control:

In a system incorporating a power electronic interface between the generator and load (or the grid), the electrical power delivered by the generated to the load can be dynamically controlled. The instantaneous difference between mechanical power and electrical power changes the rotor speed following the equation

$$J.\frac{d\omega}{dt}=\frac{P_m-P_e}{\omega} \tag{6}$$

Where J is the polar moment of inertia of the rotor, ω is the angular speed of the rotor, is the mechanical power produced by the turbine, and is the electrical power delivered to the load. Integrating, we the above equation, we get:

$$0.5\times J\times(\omega_2^{\,2}-\omega_1^{\,2})=\int_{t_1}^{t_2}(P_m-P_e).dt \tag{7}$$

3.4 Yaw Control:

Turbine is continuously oriented along the direction of the wind flow. This is achieved with a tail-vane in small turbines, using motorized control systems activated either by fan-tail, in case of wind farms, by a centralized instrument for the detection of the wind direction. It is also possible to achieve yaw control without any additional mechanism, simply by mounting the turbine downwind so that the thrust force automatically pushes the turbine in the direction of the wind.

Speed of the rotor can also be controlled using the yaw control mechanism. The rotor is made to face away from the wind direction at high wind speeds, thereby reducing the mechanical power. Yawing often produces loud noise, and it is restriction of the yawing rate in large machines to reduce noise is required.

3.5 Control Strategy:

Different speed control strategies are required for the five different ranges of wind speed.

a) Power is not generated by the machine below a cut-in speed. Rotation of the machine may start in this speed range if there is sufficient starting torque. But no power is generated and rotor rotates freely.
b) Maximum power is extracted from the wind at normal wind speeds. This is achieved at a particular TSR value. Hence, for tracking maximum power point, rotational speed is changed continuously proportional to the wind speed.
c) At high wind speeds, rotor speed is limited to a maximum value which depends on the design of the mechanical components. Here Cp is lower than the maximum value. Power output is not proportional to the cube of the wind speed.
d) At even higher wind speeds, output power is kept constant at the maximum value allowed by the electrical components.

CHAPTER 4

GRID CONNECTED AND ASYNCHRONOUS GENERATOR FOR WIND TURBINES

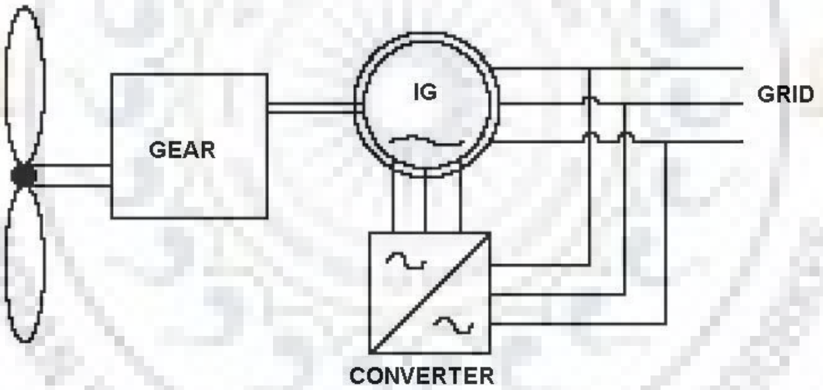
In terms of the generators for wind-power application, there are different concepts in use today. The major distinction among them is made between fixed speed and variable speed wind turbine generator concepts. In the early stage of wind power development, fixed-speed wind turbines and induction generators were often used in wind farms. But the limitations of such generators, e.g. low efficiency and poor power quality, adversely influence their further application. With large-scale exploration and integration of wind sources, variable speed wind turbine generators, such as doubly fed induction generators (DFIGs) and permanent magnetic synchronous generators (PMSGs) are emerging as the preferred technology. In contrast to their fixed-speed counterparts, the variable speed generators allow operating wind turbines at the optimum tip-speed ratio and hence at the optimum power efficient for a wide wind speed range. As the penetration of wind power increases, integrating large wind farms to power grids and the relevant influences on the host grids needs to be carefully investigated. So, accurate and reliable model of variable speed wind turbine generators are urgently needed for power system simulation analysis. The paper is dedicated to analyzing the complete model of a variable speed wind turbine with permanent magnet synchronous generator and developing control schemes for the wind turbine generator. The modeled system consists of a PMSG model, a pitch-angled controlled wind turbine model and a drive train model.

4.1 Aerodynamic Model

The wind turbine extracts power from wind and then converters it into mechanical power. The amount of aerodynamic torque is related to the wind speed. The drive train of PMSG consists of five parts, namely, rotor, low speed shaft, gearbox, high-speed shaft and generator. In the analysis, other parts of wind turbines, e.g. tower and flap bending modes can be reasonably neglected. When the interest of study varies the complexity of the drive train differs. For example, when the problems such as torsional fatigue are studied, dynamics from both sides of gearbox have to be considered. So, two-lumped mass or more sophisticated models are required. But when the study focuses on the interaction between wind farms and AC grids the drive train can be treated as one-lumped mass model for the sake of timeefficiency and acceptable precision. So, the drive train takes the form of the latter one in the paper and is displayed in figure in which the parameters have been referred to the generator side.

4.2 Generator Model

Doubly fed electric machines are electric motors or electric generators that have windings on both stationary and rotating parts, where both windings transfer significant power between shaft and electrical system. Usually the stator winding is directly connected to the three-phase grid and the three-phase rotor winding is fed from the grid through a rotating or static frequency converter.



PRINCIPLE OF DFIG CONNECTED TO A WIND TURBINE

Although the multiphase slip ring assembly reduces reliability and requires regular maintenance, it allows easy control of the rotor (moving) winding set so both multiphase winding sets actively participate in the energy conversion process with the electronic controller controlling half (or less) of the power capacity of the electric machine for full control of the machine.

This is especially important when operating at synchronous speed, because then the rotor current will be DC current. Without slip rings the production of DC current in the rotor winding is only possible when the frequency converter is at least partly located in the rotor and rotating with it. This kind of rotor converter naturally requires its own winding system (preferably using high frequency in the 10 kHz range for compact size) for power transfer out of or into the rotor. Furthermore, there are thermal and mechanical constraints (for example centrifugal forces) of the power electronic assembly in the rotor. However, high speed alternators have had electronics incorporated on the rotor for many years. Furthermore, high frequency wireless power transfer is used in many applications because of improvements in efficiency and cost over low frequency alternatives.

4.3 Requirement of the load flow analysis for the power system

DC power flow is a simplification, and linearization of a full AC power flow. DC power flow looks only at active power flows, neglecting voltage support, reactive power management and transmission losses. Thanks to its simplicity and linearity it is very often used for contingency analysis [5] and techno economic studies of power systems for assessing the influence of commercial energy exchanges on active power flows in the transmission network. The method as such is well-known and its fundamentals have been discussed extensively.

The classic power flow problem consists of active and reactive power flow and can be formulated using four variables per node – voltage angle, voltage magnitude, active and reactive power injections. Active power losses are not known in advance as they depend on the active power injection pattern and voltage profile. Other variables are also interdependent, making the problem non-linear. This is why it is often linearized and the solution is obtained using successively linearized stepsiteratively. The losses are re-estimated at each iteration based on all other variables. Modern power system analysis tools use as a basis the Newton-Raphson algorithm. Assumptions of DC power flow:

- Voltage angle differences are small

- Flat voltage profile
- Line resistance is negligible

4.4 Load flow model considered

- **BACKWARD/ FORWARD SWEEPMETHOD**

Let us consider a radial network, the backward/forward sweep method for the load-flow computation is an iterative method in which, at each iteration two computational stages are performed: The load flow of a single source network can be solved iteratively from two sets of recursive equations. The first set of equations for calculation of the power flow through the branches starting from the last branch and proceeding in the backward direction towards the root node. The other set of equations are for calculating the voltage magnitude and angle of each node starting from the root node and proceeding in the forward direction towards the lastnode.

- **ForwardSweep**

The forward sweep is basically a voltage drop calculation with possible cur-rent or power flow updates. Nodal voltages are updated in a forward sweep starting from branches in the firstlayertowardthoseinthelast.Thepurposeoftheforward propagation is to calculate the voltages at each node starting from the feeder source node. The feeder substation voltage is setatitsactualvalue.Duringtheforwardpropagationthe effective power in each branch is held constant to the value obtained in backward walk.

- **BackwardSweep**

The backward sweep is basically a current or power flow solution with possible voltage updates. It starting from the branches in the last layer and moving towards the branches connected to the root node .The updated effective power flows in each branch are obtained in the backward propagation computation by considering the node voltages of previous iteration. It means the voltage values obtained in the forward path are held constant during the backward propagation and updated power flows in each branch are transmitted backward alongthefeederusingbackwardpath.Thisindicatesthatthe backward propagation starts at the extreme end node and proceeds towards source node.

It is well known that there exist three main variants of the forward/backward sweep method that differ from each other based on the type of electric quantities that at each iteration, starting from the terminal nodes and going up to the source node (backward sweep), arecalculated.

1. The current summation method, in which the branch currents areevaluated;
2. The power summation method, in which the power flows in the branches areevaluated;

The admittance summation method, in which, node by node, the driving point admittances are evaluated. In other terms, the three variants of the B/F method simulatethe loads within each iteration, with a constant current, a constant power and a constant admittance model. In the forward phase, the three variants are identical since, based on quantities calculated in the backward phase, the bus voltages are calculated starting from the source node and going towards the ending nodes. Voltages are then used to update, based on the dependency of loads on the voltage, the quantities used in the backward sweep in order to proceed to iteration. The process stops when a convergence criterion isverified.By comparing the calculated voltages in previous and present iterations, the successive iteration is obtained. The convergence can be achieved if the voltage mismatch is less than the specified tolerance i.e., 0.0001. Otherwise new effective power flows in each branch are calculated through backward walk with the present computed voltages and then the procedure is repeated until the solution isconverged.

The backward/forward sweep method is now reformulated in a way suitable for the analysis of the convergence of the iterative process. Consider Fig. 2, a branch is connected between the nodes ‘k’ and ‘k+1’.The effective active (P_k) and reactive (Q_k) powers that of flowing through branch from node ‘k' to node ‘k+1’ can be calculated backwards from the last node and is givenas,

$$P_k = P'_{k+1} + r_k \frac{({P'_{k+1}}^2 + {Q'_{k+1}}^2)}{{V_{k+1}}^2}$$

$$Q_k = Q'_{k+1} + X_k \frac{({P'_{k+1}}^2 + {Q'_{k+1}}^2)}{{V_{k+1}}^2}$$

Where,

$$P'_{k+1} = P_{k+1} + P_{LK+1}$$

$$Q'_{k+1} = Q_{k+1} + Q_{LK+1}$$

$P_{Lk+1}$and Q_{Lk+1} are loads that are connected at node ‘k+1’,$P_{k+1}$and Q_{k+1} are the effective real and reactive power flows from node‘k+1’.

The voltage magnitude and angle at each node are calculated in forward direction. Consider a voltage V_k&$\delta_k$at node ‘k’ and V_{k+1}€ δ_{k+1} at node ‘k+1’, then the current flowing through the branch having an impedance, z_k= r_k+ $x_k$connectedbetween‘k’and‘k+1’isgivenas,

The magnitude and the phase angle equations can be used recursively in a forward direction to find the voltage and angle respectively of all nodes of radial distribution system.Initially,aflatvoltageprofileisassumedatallnodesi.e. 1.0pu.Thebranchpowersarecomputediterativelywiththeupdated voltages at each node. In the proposed load flow method, power summation is done in the backward walk and voltages are calculated in the forward walk.

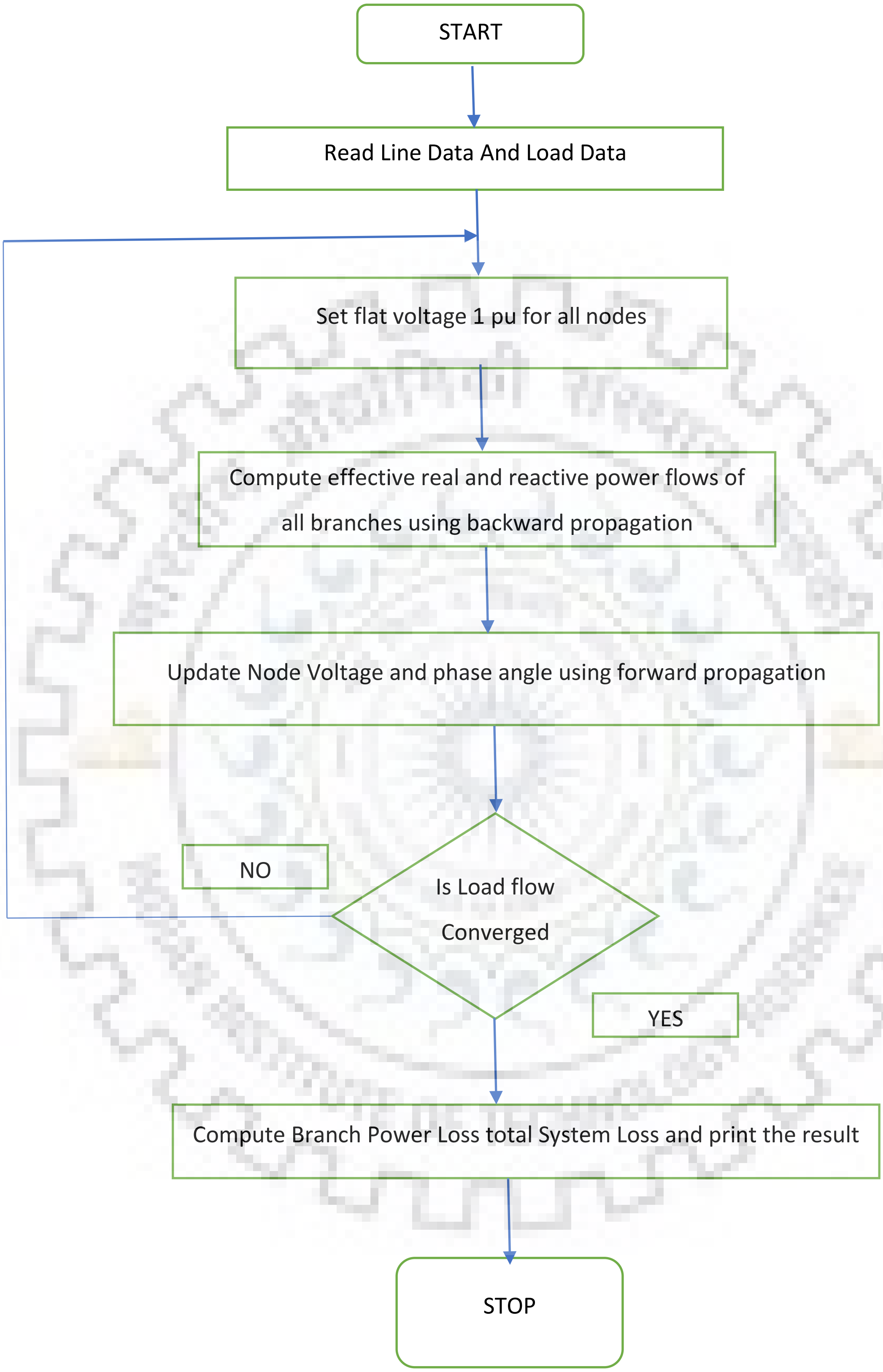


Fig: Flow Chart For Backward Forward Sweep Algorithm

CHAPTER 5

MODELS OF ASYNCHRONOUS WIND TURBINES

5.1 INTRODUCTION

Wind energy is one of the important renewable energy sources. As opposed to the currently existing carbon-based energy sources such as coal, petroleum, and natural gas, wind energy has the advantages that it is clean, unpolluted, inexhaustible, and free in term of its natural existence . Current trend shows that wind energy is getting popular to replace the traditional energy sources due to the expectable depletion of traditional energy resource and the humankind's effort in reduction of carbon dioxide emission but not affecting the usable energy production for the continuous developments. Wind energy, although with the advantages mentioned, is still developed at preliminary stage of power generation. Generally, wind energy is converted into kinetic energy before the Conversion to the usable electrical energy. Wind energy is converted to low speed rotational energy via blades and through the gear box, the rotational energy is used to drive the generator for electric power generation. Wind energy is an abundant resource with free cost but it is important to study the way to maximize the power generation by wind energy. Several control methods of wind energy conversion system has been proposed by researchers to maximize the wind energy harvest. However, most of the proposed methods have rather low efficiency to extract power. Besides, the extracted energy is the very unstable since the nature of wind flow is spontaneous which this situation will lower the power extraction and subsequently reduce the efficiency of power generation.

Wind Turbine with Variable Speed Generator The wind turbine model is used to generate mechanical torque. The negative value of output torque means the wind turbine is providing torque. Result shows the output torque is positive for wind speed smaller than 7 m/s, which represent that the wind turbine is not providing power, but consuming power from the load. Hence, the value of wind speed at 7 m/s could be possibly as the cut-in speed of the wind turbine model and the result of output mechanical torque. For a range of wind speed is shown in Figure, the effect of both varying generator speed and wind speed on the output torque is investigated in simulation and the results are shown in Figure. It can be noticed that higher wind speed can provide larger torque and hence larger power to the load. For instance, at Ω 1.5 m/s, the turbine output torque by wind speed 12 m/s is about -0.38 W, but the turbine output torque by wind speed 18 m/s is about -1.35 W. wind turbine at higher output torque can provide larger output power, hence improving the power efficiency of the power generation.

5.2 PQ MODEL OF AN ASYNCHRONOUS WIND TURBINE

A way to model a wind farm as a PQ bus is to assume a generated real power and a given power factor, with which the consumed reactive power is calculated. Some improvements can be achieved if the steady-state model of the induction machine is taken into account. The model shown in Fig is assumed. In this model, applying the conservation of complex power theorem (Boucherot's theorem) allows the following expression to be written for the reactive power consumed by the machine:

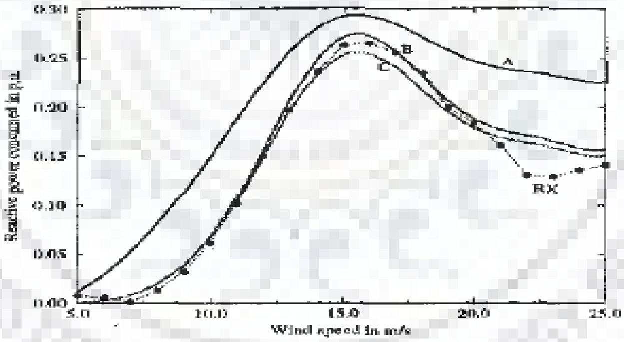


Fig. Reactive Power consumed variation with wind speed

The reactive power curve as a function of wind speed can be seen in Fig.

$$Q = -Q_0 - Q_1 P - Q_2 P^2 \tag{8}$$

Where above mentioned constants are experimentally obtained. If the wind speed is desired to be the input datum for the problem, the real power can be obtained as a function of it:

$$P = 0.5 \times \rho \times A \times V^3 \times C_P \tag{9}$$

All parameters have been mentioned already.

5.3 RX MODEL OF AN ASYNCHRONOUS WIND TURBINE

The other method proposed here consists of modeling the machine as an RX bus, following the next three steps-

(a) Calculate the power that each WT can extract from the wind for a given wind speed and a given rotor speed, according to its power coefficient curve.

(b) Calculate the power that each WT can generate, according to the results of the load flow analysis, and to the rotor speed given in step (a).

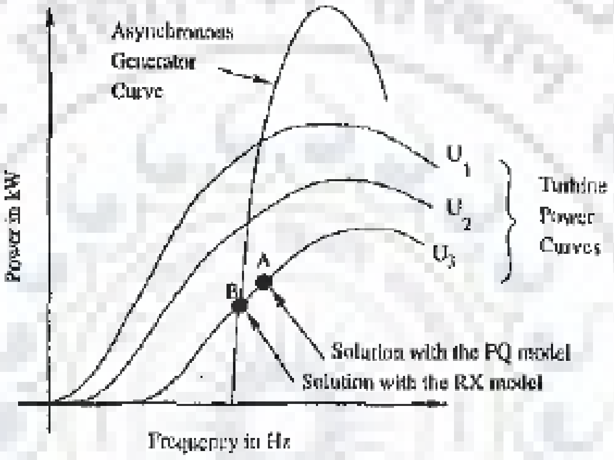


Fig- Curves for the generator and turbine

(a) Compare both powers and look for the value of the slip,for which the electrical and the mechanical powers coincide,for the wind speed given.

CHAPTER 6

WIND MODELLING

6.1 WIND SPEED MODELLING

A very good expression often used to model the behavior of wind speed is the Rayleigh probability density function (pdf). Rayleigh pdf is a special case of Weibull pdf in which the shape index is equal to:

$$f(v) = \left(\frac{2v}{c^2}\right)\exp\left[-\left(\frac{v}{c}\right)^2\right] \qquad (10)$$

Where c is called the scale index.

If the mean value of the wind speed for a site is known, then the scaling index c can be calculated as in (11) and (12):

$$v_m = \int_0^\infty v\, f(v)\, dv = \int_0^\infty \left(\frac{2v}{c^2}\right) \exp\left[-\left(\frac{v}{c}\right)^2\right] dv = \frac{\sqrt{\pi}}{2}\, c \qquad (11)$$

$$C=1.128\, v_m \qquad (12)$$

In order to incorporate the output power of the wind-based DG units as a multi-state variable in the planning formulation, the continuous pdf has been divided into states, in each of which the wind speed is within specific limits. The number of states is carefully selected for the Rayleigh distribution because a small number of states affects the accuracy, whereas a large number increases the problem complexity. In this work, the step is adjusted to be 1 m/s as shown in Table 1:

Table 1 Selected wind speed states:

Wind speed state (w)	Wind speed limits, m/s
1	0 – 1
2	1 – 2
.	.
.	.
.	.
Last state	$v_{max} - 1 \; to \; v_{max}$

The probability of each state P(G_w) is calculated using (13) as shown:

$$P(G_w) = \int_{v_{w1}}^{v_{w2}} f(v)\, dv \tag{13}$$

Where v_{w1} and v_{w2} are the speed limits of state w.

The output power of the wind turbine corresponding to each state is calculated using the wind turbine power curve parameters as in equation (14). For the sake of simplicity, the average value of each state (v_{aw}) is utilised to calculate the output power of that state (e.g. if the second state has limits of 1 m/s and 2 m/s, the average value for this state is(v_{a2}) = 1.5 m/s)

$$P_{o/pw}(v) = \begin{cases} 0, & 0 \le v_{aw} \le v_{ci} \\ P_{rated} \times \frac{(v_{aw}-v_{ci})}{(v_r-v_{ci})} & v_{ci} \le v_{aw} \le v_r \\ P_{rated}, & v_r \le v_{aw} \le v_{co} \\ 0, & v_{co} \le v_{aw} \end{cases} \tag{14}$$

Where v_{ci}, v_r and v_{co} are the cut-in speed, rated speed and cut-off speed of the wind turbine. The annual average power and capacity factor (CF) of anywind turbine can be calculated using (15) and (16).

$$P_{ave} = \sum_w P_{o/pw} \times P(G_w) \tag{15}$$

$$\mathrm{CF} = \frac{P_{ave}}{P_{rated}} \tag{16}$$

6.2 LOAD MODELLING

In order to proceed with an accurate planning decision, the system peak load will be assumed to follow the hourly load shape. Based on this assumption, the load will be divided into ten levels using a cluste ring technique, utilising the central centroid sorting process, which verifies that choosing ten equivalent load levels (states), with different probabilities(P(L_y)), provides a reasonable trade of between accuracy and fast numerical evaluation.

6.3 COMBINED GENERATION LOAD MODEL

The aforementioned modelling of the wind-based DG outputpower and the load is utilised to generate the combined wind-load model. In this work, the wind speed states andthe load states are assumed to be independent (uncorrelated).

In other words, the diurnal and seasonal components of the wind speed, as well as the load are neglected. This assumption will not affect the results if aweak correlation exists Steven the wind speed and the load. However, if a strong correlation exists between both of them, the accuracy of the results will be affected based on the nature of the correlation (either it is positive ornegative). The rationale behind this is that the main reason of the constraints violation is the reverse power flow which occurs if the output power of the DG units is higher than the load. If there is a positive correlation between the wind Speed and the load, it is expected that the amount of the reverse power flow will decrease; hence, the optimal penetration of the DG units is expected to be higher than the value calculated based on the aforementioned assumption. On the other hand, if a negative correlation exists, the optimal penetration of the DG units is expected to be lower than the value calculated based on the same assumption. Based on this assumption, the probability of any combination of load and wind-based DG output (P(C)) can be

obtained by convolving the two probabilities as given in the following equation:

$$P\left(C_g\right) = P_w(G) \times P_y(L) \qquad (17)$$

Based on this concept a generation-load model, for m wind turbines, is obtained by listing all possible combinations of the wind-based DG output power and the load. The complete generator-load model is given as (9):

$$R = \left[\left\{C_g, P(C_g)\right\}: g = 1: N\right] \qquad (18)$$

Where m is set of all available turbines in the market, where each turbine has its own power performance curve; R is the complete annual generation load model of m turbines; C is a matrix of m+1 columns that includes all possible combinations of the wind output power states Corresponding to the available turbines, and the load states (i.e. columns from 1 to m represent the output power of the available m turbines as a fraction of the rated power of each turbine, where as column m +1 represents the different load levels); P(C_g) is a one-column matrix that represents the probability corresponding to matrix C; and N is total number of states in model R, which is equal to the product of the wind speed states and the load states.

Table: 2 Wind speed probabilities

Wind speed limits, m/s	Hours/year	Probability
0-4	1804	0.205936
4-5	579	0.066096
5-6	984	0.112329
6-7	908	0.103653
7-8	983	0.112215
8-9	799	0.091210
9-10	677	0.077283
10-11	439	0.050114
11-12	395	0.045091
12-13	286	0.032648
13-14	219	0.025
14-25	687	0.078425
Greater than 25	0	0

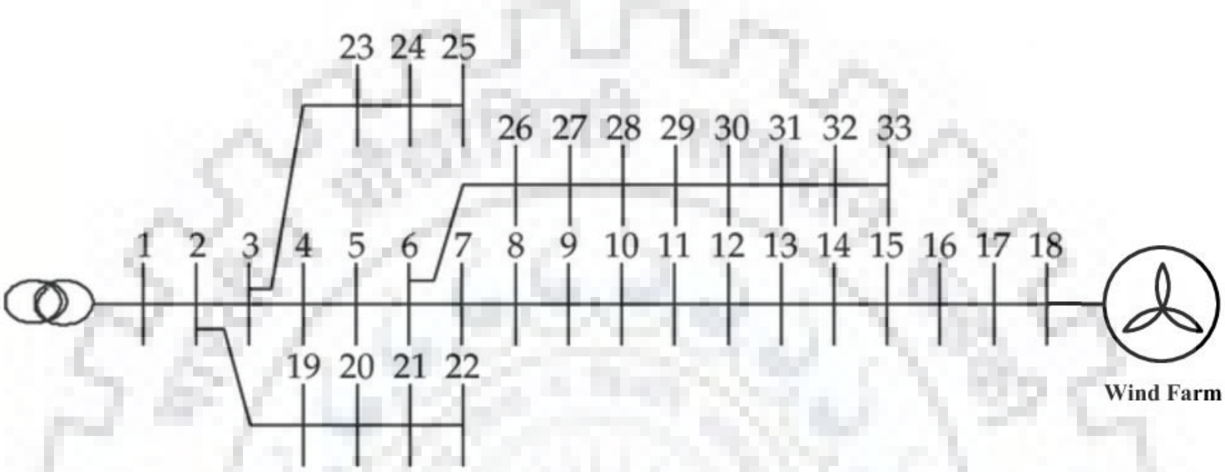
Based on the power curve parameters of the available turbine, some states are aggregated together to reduce the total number of states (e.g. states for wind speed up to 4 m/s are aggregated in one state since all corresponds to speeds below the cut-in speed). In this study, the effective wind speed states are reduced to be 12 as in Table 3, where state 13 represents speed greater than the cut-out speed.

Table: 3 Wind Power probabilities

State No.	.% rated Power	Probability
1	100	0.078425
2	94.9696	0.025
3	84.9728	0.032648
4	74.976	0.045091
5	64.9792	0.050114
6	54.9824	0.077283
7	44.9856	0.09121
8	34.9888	0.112215
9	19.9936	0.103653
10	14.9952	0.112329
11	4.9984	0.066096
12	0	0.205936

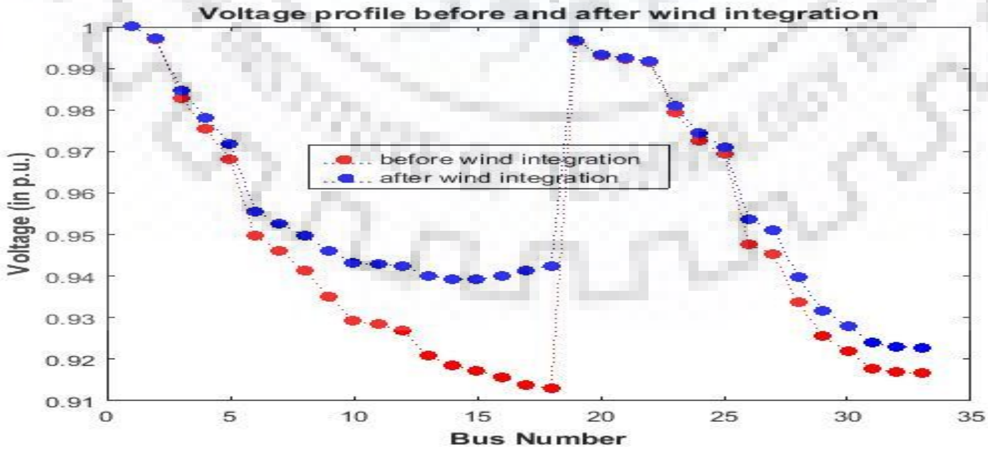
CHAPTER 7
LOAD FLOW AND RESULTS

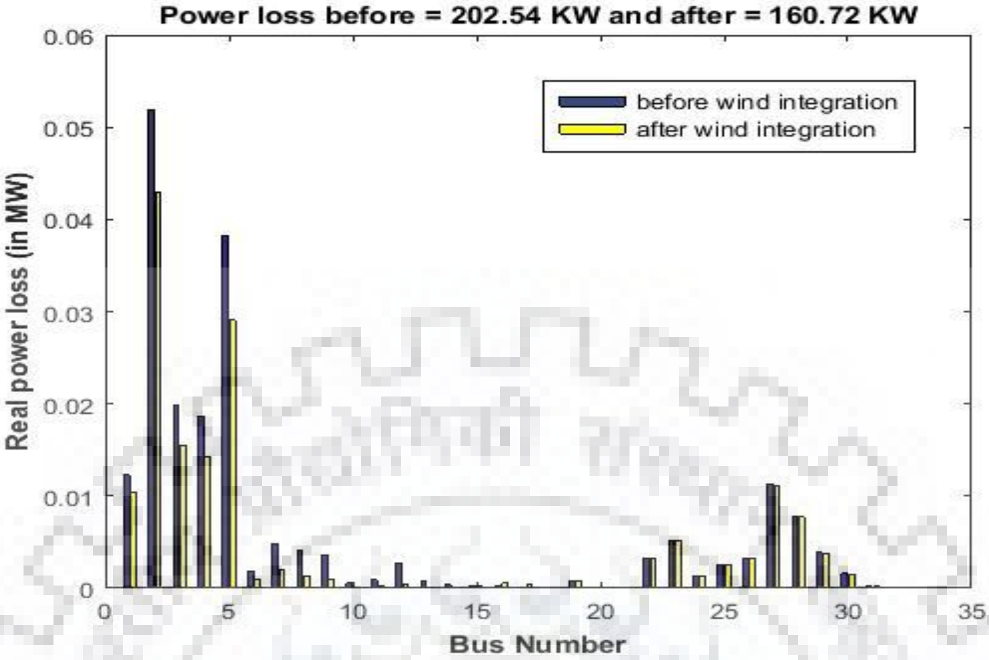
33 Bus System With Wind Turbine Connected At Node 18:



Load Flow Results for probabilistic distribution of Wind Power :

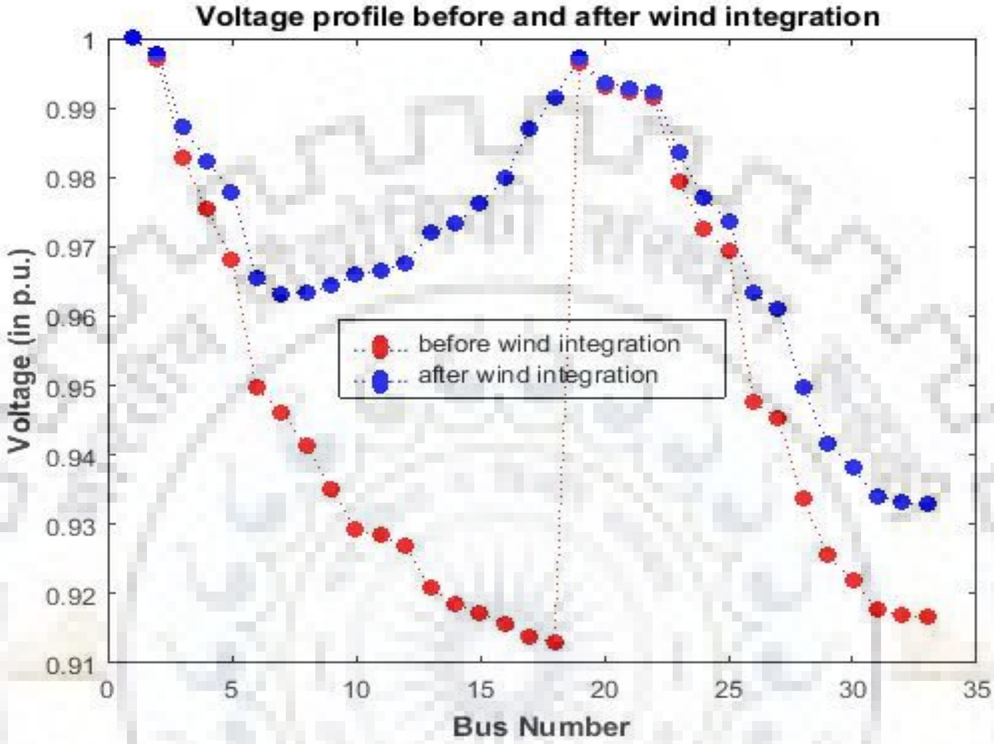
Results of 1st Run of Load Flow solutions for Wind turbine connected at 18th Bus:

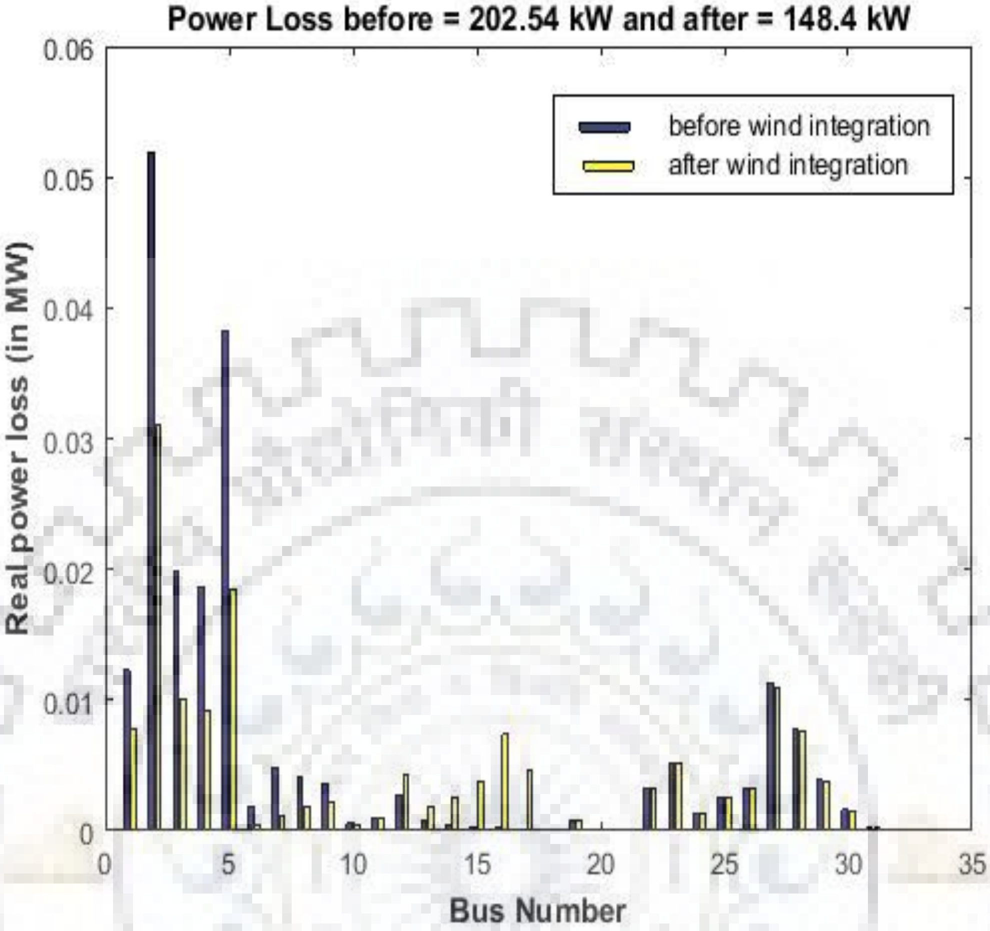




Bus	Wind Probability	Wind speed (m/s)	Wind Power (MW)	Power loss before wind integration (MW)	Power loss after wind integration (MW)
Bus 18	0.54688	7.5	0.385	0.20254	0.16072

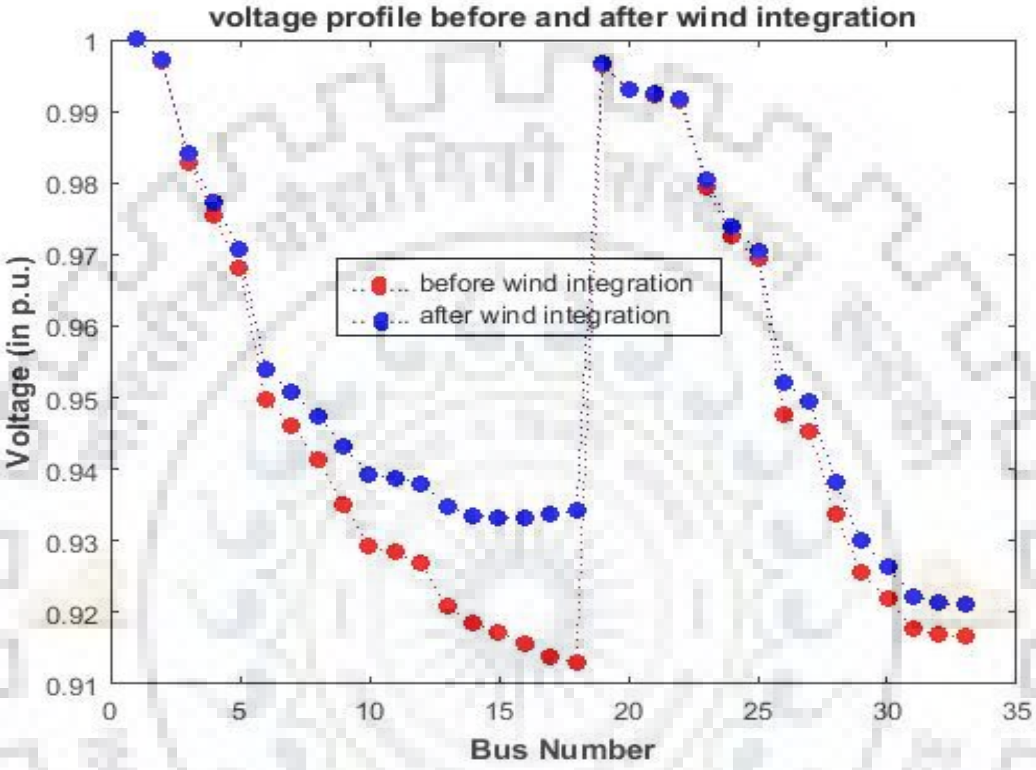
Results of 2nd Run of Load Flow solutions for Wind turbine connected at 18th Bus:

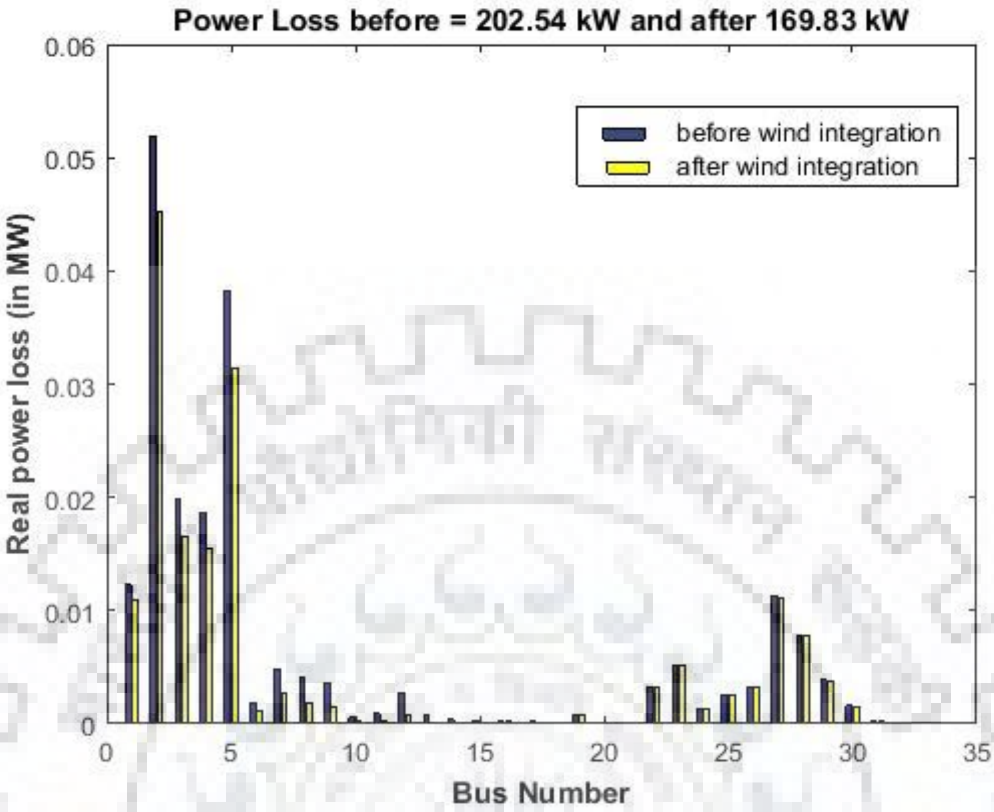




Bus	Wind Probability	Wind speed (m/s)	Wind Power (MW)	Power loss before wind integration (MW)	Power loss after wind integration (MW)
Bus 18	0.97059	19.5	1.1	0.20254	0.1484

Results of 3rd Run of Load Flow solutions for Wind turbine connected at 18th Bus:





Bus	Wind Probability	Wind speed (m/s)	Wind Power (MW)	Power loss before wind integration (MW)	Power loss after wind integration (MW)
Bus 18	0.42176	6.5	0.275	0.20254	0.16983

Discussion And Conclusion

1. With its abundant, inexhaustible potential, its increasingly competitive cost, and environmental advantage, wind energy is one the best technologies available today to provide a sustainable supply to the world development. In depth understanding and investigation of wind power generators, wind farm integration, grid core and etc. is very meaningful.

2. In terms of generators for wind power application, there are different concepts in use today. The major distinction among them is made between fixed speed and variable speed wind turbine generator concepts. In the early stage of the power development, fixed speed wind turbines and induction generators were often used in wind farms. But the limitations of such generators like low efficiency and poor power quality adversely influences their further application. With large scale exploration and integration of wind sources, variable speed wind turbines generators, such as doubly fed induction generator (DFIG) and permanent magnet synchronous generators are emerging as preferred technology. In contrast to their fixed speed counterparts, the variable speed induction generators allow operating wind turbines at the optimum speed tip speed ratio and hence at the optimum power efficient for a wide wind speed range.

3. As the penetration of wind power increases, integrating large wind farms to power grids and the relevant influences on the host grids needs to be carefully investigated. So, accurate and reliable model of the variable speed wind turbine generators and urgently needed for power simulation analysis. Two models were propose namely PQ and RX model. It was found that RX model was better as it obtained a single working point for each wind speed. However the conventional PQ model has its advantage of being simpler and easy to implement.

4. One of the greatest problem facing wind farms is that the electrical power generated depends on variable characteristics of the wind. To become competitive in liberalized market, the reliability of wind energy must be guaranteed. Good local wind forecast are therefore essential for accurate prediction of generation levels for each moment of the day.

5. Probabilistic distribution model is used for wind turbine integration to 33 Bus System. For the system, 3 years of historical data were taken regarding the hourly load and the hourly wind speed profile.

6. For each scenario, load flow is run hour by hour for the entire year. During each hour, wind based DG penetration is changed based on the wind speed profile. Finally, the power loss calculated for each hour are aggregated to obtain the annual energy loss.

7. From load flow analysis of different wind turbines models it was concluded that Backward Forward sweep method was best for performing load flow analysis as it is more accurate for 33 Bus distribution System due to High R/X Ratio.

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