WIND AS A RENEWABLE SOURCE OF ENERGY

A project report submitted

in partial fulfillment of the requirements

for the degree of

Bachelor of Technology

In

Electrical Engineering

By

Ishan Patnaik
(10502038)

National Institute of Technology Rourkela

Rourkela-769008, Orissa

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Under the guidance of

PROF. S. RAUTA

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ACKNOWLEDGEMENT

I would like to express my gratitude towards all the people who have contributed their precious time and effort to help me. Without whom it would not have been possible for me to understand and complete the project.

I would like to thank Prof S.Rauta and Prof. S.Ghosh, Department of Electrical Engineering, my Project Supervisor for his guidance, support, motivation and encouragement through out the period this work was carried out. His readiness for consultation at all times, his educative comments, his concern and assistance even with practical things have been invaluable.

We are grateful to Dr. B.D.Subudhi, *Professor and Head*, Dept. of Electrical Engineering for providing necessary facilities in the department.

Date: 11/05/09 ISHAN PATNAIK (10502038)

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CERTIFICATE

This is to certify that the Project entitled **“WIND AS A RENEWABLE SOURCE OF ENERGY”** submitted by **Ishan Patnaik** has in partial fulfillment of the requirements for the award of **Bachelor of Technology Degree** in **Electrical Engineering** at **National Institute of Technology, Rourkela** (Deemed University) is an authentic work carried out by him under my supervision and guidance.

Place: NIT Rourkela
Date:

(Prof. S.Rauta)
Department of Electrical Engineering
NIT Rourkela

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INTRODUCTION

Renewable Energy Sources are those energy sources which are not destroyed when their energy is harnessed. Human use of renewable energy requires technologies that harness natural phenomena, such as sunlight, wind, waves, water flow, and biological processes such as anaerobic digestion, biological hydrogen production and geothermal heat. Amongst the above mentioned sources of energy there has been a lot of development in the technology for harnessing energy from the wind.

Wind is the motion of air masses produced by the irregular heating of the earth's surface by sun. These differences consequently create forces that push air masses around for balancing the global temperature or, on a much smaller scale, the temperature between land and sea or between mountains.

Wind energy is not 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 power extracted from the wind can be calculated by the given formula:

$$P_W = 0.5\rho\pi R^3 Vw^3 C_P(\lambda,\beta)$$

P_w = extracted power from the wind,

ρ= air density, (approximately 1.2 kg/m^3 at 20° C at sea level)

R = blade radius (in m), (it varies between 40-60 m)

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

Cp = the power coefficient which is a function of both tip speed ratio (λ), and blade pitch angle, (β)(deg.)

Power coefficient (Cp) is defined as the ratio of the output power produced to the power available in the wind.

Betz Limit:

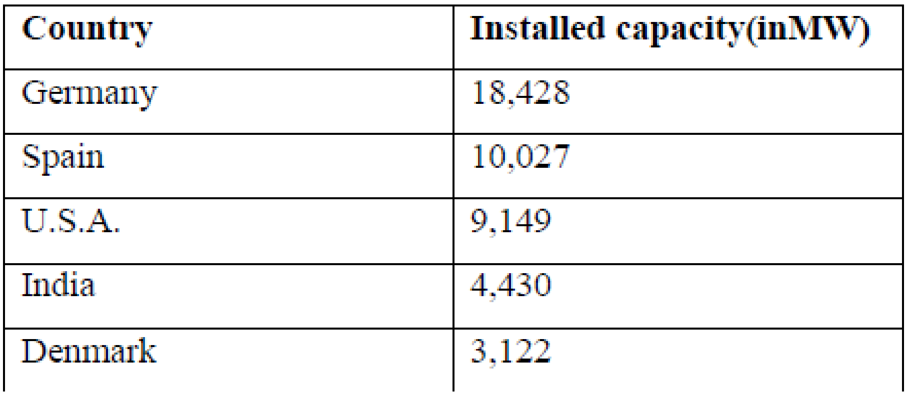
No wind turbine could convert more than **59.3%** of the kinetic energy of the wind into mechanical energy turning a rotor. This is known as the Betz Limit, and is the theoretical maximum coefficient of power for any wind turbine.

The maximum value of $\mathbf{C_P}$ according to Betz limit is 59.3%. For good turbines it is in the range of 35-45%.

The **tip speed ratio** (λ) for wind turbines is the ratio between the rotational speed of the tip of a blade and the actual velocity of the wind. High efficiency 3-blade-turbines have tip speed ratios of 6–7.

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.

Some 80 percent of the global wind power market is now centered in just four countries—which reflects the failure of most other nations to adopt supportive renewable energy policies. Future market growth will depend in large measure on whether additional countries make way for renewable energy sources as they reform their electricity industries.



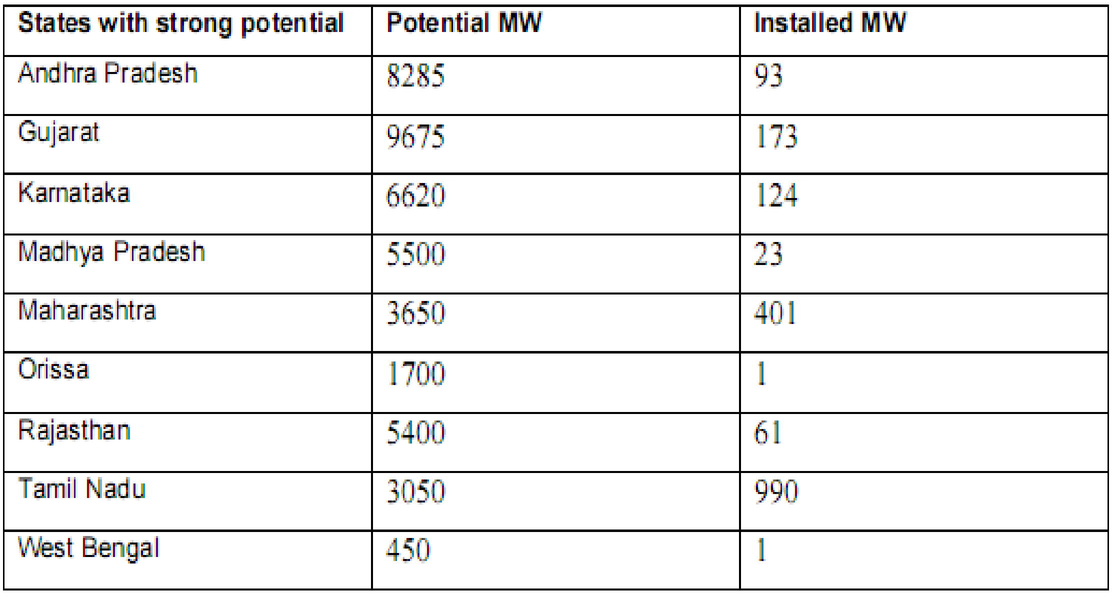
Country	Installed capacity(inMW)
Germany	18,428
Spain	10,027
U.S.A.	9,149
India	4,430
Denmark	3,122

Table 1.Countries with installed capacity

India’s Market Overview of Wind Energy

Overview

India has a vast supply of renewable energy resources. India has one of the world’s largest programs for deployment of renewable energy products and systems 3,700 MW from renewable energy sources installed.



States with strong potential	Potential MW	Installed MW
Andhra Pradesh	8285	93
Gujarat	9675	173
Karnataka	6620	124
Madhya Pradesh	5500	23
Maharashtra	3650	401
Orissa	1700	1
Rajasthan	5400	61
Tamil Nadu	3050	990
West Bengal	450	1

Table 2 States with strong potential: (potential MW /installed MW)

The Project

The projects are to install two 0.8 MW wind turbine in Karnataka, India. These will generate renewable electricity, to displace fossil fuel powered electricity from the grid. Each turbine will generate enough electricity each year to power the equivalent of 550 homes in the UK – saving 1,500 tonnes of CO2 each per year.

ABSTRACT

This report describes about he wind power and its potential that can be harnessed in the future to meet the current energy demand. With detailed description of the wind turbine and the wind generator focus has been given on the interconnection of the generators with the grid and the problems associated with it. The use of power electronics inn the circuitry and their applications have also been emphasized. In the end a voltage stability analysis has been done with respect to various models of the wind turbines to find the best way to clear faults and have optimum output.

CHAPTER 1

WIND TURBINES

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.

HORIZONTAL AXIS WIND TURBINES

Fig.1.1 Horizontal axis wind turbine

Horizontal-axis wind turbines (HAWT) have the main rotor shaft and electrical generator at the top of a tower, and must be pointed into the wind. Most have a gearbox, which turns the slow rotation of the blades into a quicker rotation that is more suitable to drive an electrical generator.

Since a tower produces turbulence behind it, the turbine is usually pointed upwind of the tower. Turbine blades are made stiff to prevent the blades from being pushed into the tower by high winds. Additionally, the blades are placed a considerable distance in front of the tower and are sometimes tilted up a small amount.

Downwind machines have been built, despite the problem of turbulence, because they don't need an additional mechanism for keeping them in line with the wind, and because in high winds the blades can be allowed to bend which reduces their swept area and thus their wind resistance. Since cyclic (that is repetitive) turbulence may lead to fatigue failures most HAWTs are upwind machines.

HAWT advantages

- Variable blade pitch, which gives the turbine blades the optimum angle of attack. Allowing the angle of attack to be remotely adjusted gives greater control, so the turbine collects the maximum amount of wind energy for the time of day and season.
- The tall tower base allows access to stronger wind in sites with wind shear. In some wind shear sites, every ten meters up, the wind speed can increase by 20% and the power output by 34%.
- High efficiency, since the blades always move perpendicularly to the wind, receiving power through the whole rotation. In contrast, all vertical axis wind turbines, and most proposed airborne wind turbine designs, involve various types of reciprocating actions, requiring airfoil surfaces to backtrack against the wind for part of the cycle. Backtracking against the wind leads to inherently lower efficiency.

HAWT disadvantages

- The tall towers and blades up to 90 meters long are difficult to transport. Transportation can now cost 20% of equipment costs.
- Tall HAWTs are difficult to install, needing very tall and expensive cranes and skilled operators.
- Massive tower construction is required to support the heavy blades, gearbox, and generator.
- Reflections from tall HAWTs may affect side lobes of radar installations creating signal clutter, although filtering can suppress it.
- Downwind variants suffer from fatigue and structural failure caused by turbulence when a blade passes through the tower's wind shadow (for this reason, the majority of HAWTs use an upwind design, with the rotor facing the wind in front of the tower).
- HAWTs require an additional yaw control mechanism to turn the blades toward the wind.

Vertical axis Wind Turbines

Fig.1.2 Vertical axis wind turbine

Vertical-axis wind turbines (or VAWTs) have the main rotor shaft arranged vertically. Key advantages of this arrangement are that the turbine does not need to be pointed into the wind to be effective. This is an advantage on sites where the wind direction is highly variable. VAWTs can utilize winds from varying directions.

With a vertical axis, the generator and gearbox can be placed near the ground, so the tower doesn't need to support it, and it is more accessible for maintenance. Drawbacks are that some designs produce pulsating torque. Drag may be created when the blade rotates into the wind.

VAWT advantages

- A massive tower structure is less frequently used, as VAWTs are more frequently mounted with the lower bearing mounted near the ground.
- Designs without yaw mechanisms are possible with fixed pitch rotor designs.
- A VAWT can be located nearer the ground, making it easier to maintain the moving parts.
- VAWTs have lower wind startup speeds than HAWTs. Typically, they start creating electricity at 6 M.P.H. (10 km/h).
- VAWTs may have a lower noise signature.

VAWT disadvantages

- Most VAWTs produce energy at only 50% of the efficiency of HAWTs in large part because of the additional drag that they have as their blades rotate into the wind.
- While VAWTs' parts are located on the ground, they are also located under the weight of the structure above it, which can make changing out parts nearly impossible without dismantling the structure if not designed properly.
- Having rotors located close to the ground where wind speeds are lower due to wind shear, VAWTs may not produce as much energy at a given site as a HAWT with the same footprint or height.
- Because VAWTs are not commonly deployed due mainly to the serious disadvantages mentioned above, they appear novel to those not familiar with the wind industry. This has often made them the subject of wild claims and investment scams over the last 50 years.

Wind Turbine Glossary

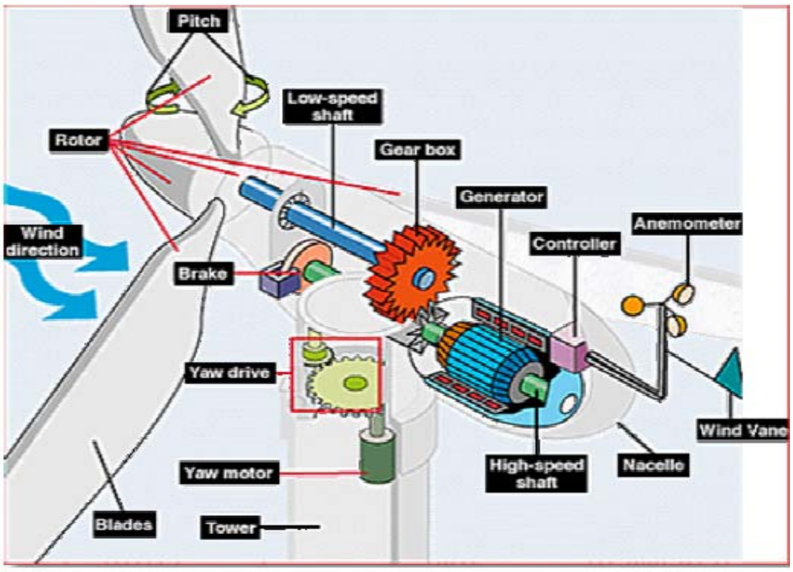


Fig.1.3 Parts of a wind turbine

Anemometer: Measures the wind speed and transmits wind speed data to the controller.

Blades: Most turbines have either two or three blades. Wind blowing over the blades causes the blades to "lift" and rotate.

Brake: A disc brake which can be applied mechanically, electrically, or hydraulically to stop the rotor in emergencies.

Controller: The controller starts up the machine at wind speeds of about 8 to 16 miles per hour (mph) and shuts off the machine at about 65 mph. Turbines cannot operate at wind speeds above about 65 mph because their generators could overheat.

Gear box: Gears connect the low-speed shaft to the high-speed shaft and increase the rotational speeds from about 30 to 60 rotations per minute (rpm) to about 1200 to 1500 rpm, the rotational speed required by most generators to produce electricity. The gear box is a costly (and heavy) part of the wind turbine and engineers are exploring "direct-drive" generators that operate at lower rotational speeds and don't need gear boxes.

Generator: Usually an off-the-shelf induction generator that produces 60-cycle AC electricity.

High-speed shaft: Drives the generator. Low-speed shaft: The rotor turns the low-speed shaft at about 30 to 60 rotations per minute.

Nacelle: The rotor attaches to the nacelle, which sits atop the tower and includes the gear box, low- and high-speed shafts, generator, controller, and brake. A cover protects the components inside the nacelle. Some nacelles are large enough for a technician to stand inside while working.

Pitch: Blades are turned, or pitched, out of the wind to keep the rotor from turning in winds that are too high or too low to produce electricity.

Rotor: The blades and the hub together are called the rotor.

Tower: Towers are made from tubular steel (shown here) or steel lattice. Because wind speed increases with height, taller towers enable turbines to capture more energy and generate more electricity.

Wind direction: This is an "upwind" turbine, so-called because it operates facing into the wind. Other turbines are designed to run "downwind", facing away from the wind.

Wind vane: Measures wind direction and communicates with the yaw drive to orient the turbine properly with respect to the wind.

Yaw drive: Upwind turbines face into the wind; the yaw drive is used to keep the rotor facing into the wind as the wind direction changes. Downwind turbines don't require a yaw drive, the wind blows the rotor downwind.

Yaw motor: Powers the yaw drive.

The following is a graph between Power Coefficient (C_P) vs Tip Speed Ratio (λ)

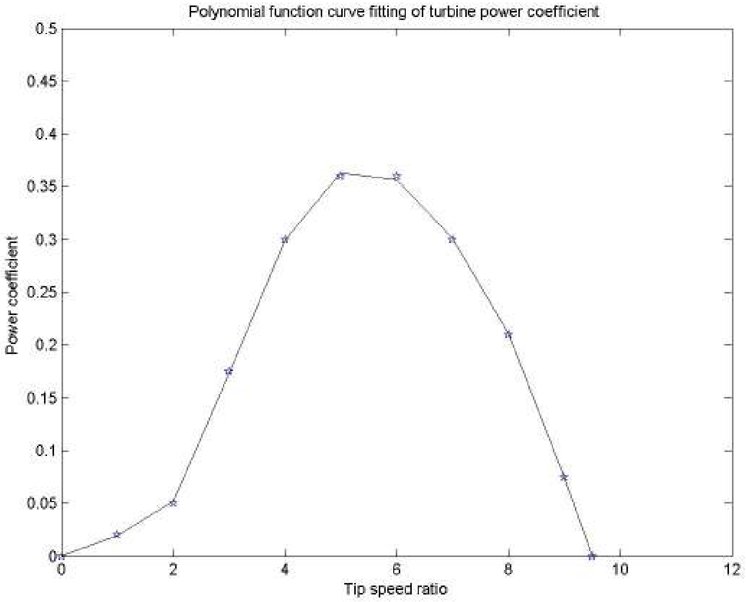


Fig.1.4 Power coefficient vs tip speed ratio

Wind turbines typically have two degrees of freedom to optimize power generation.

1. ***The ability to change their yaw or compass orientation*** by turning (using motors) the entire nacelle unit so the rotor is pointed directly into the wind. This process is controlled by wind direction information from nearby wind vanes which are located to minimize the effect due to wake turbulence from the wind turbines.
2. ***The pitch of the blades*** which can be changed to keep a near-constant rotation rate under varying wind speeds, where the rotation rate is chosen to optimize the power-generation efficiency of the turbine. Another purpose of both the blade pitch control and yaw Mechanisms is to act as a brake under extremely strong wind condition.

   Cut- in speed: The lowest wind speed at which a wind turbine begins producing usable power is called cut-in speed. It is about **3m/s**.

   Cut-out speed: The highest wind speed at which a wind turbine stops producing power is called cut-out speed. It is about **30m/s**.

CHAPTER 2

CONTROLLERS

Power control

A wind turbine is designed to produce a maximum of power at wide spectrum of wind speeds. The wind turbines have three modes of operation:

- Below rated wind speed operation
- Around rated wind speed operation
- Above rated wind speed operation

If the rated wind speed is exceeded the power has to be limited. There are various ways to achieve this.

Stall

Stalling works by increasing the angle at which the relative wind strikes the blades (angle of attack), and it reduces the induced drag (drag associated with lift). Stalling is simple because it can be made to happen passively (it increases automatically when the winds speed up), but it increases the cross-section of the blade face-on to the wind, and thus the ordinary drag. A fully stalled turbine blade, when stopped, has the flat side of the blade facing directly into the wind.

A fixed-speed HAWT inherently increases its angle of attack at higher wind speed as the blades speed up. A natural strategy, then, is to allow the blade to stall when the wind speed increases. This technique was successfully used on many early HAWTs. However, on some of these blade sets, it was observed that the degree of blade pitch tended to increase audible noise levels.

Pitch control

Furling works by decreasing the angle of attack, which reduces the induced drag from the lift of the rotor, as well as the cross-section. One major problem in designing wind turbines is getting the blades to stall or furl quickly enough should a gust of wind cause sudden acceleration. A fully furled turbine blade, when stopped, has the edge of the blade facing into the wind.

Standard modern turbines all pitch the blades in high winds. Since pitching requires acting against the torque on the blade, it requires some form of pitch angle control. Many turbines use hydraulic systems. These systems are usually spring loaded, so that if hydraulic power fails, the blades automatically furl. Other turbines use an electric servomotor for every rotor blade. They have a small battery-reserve in case of an electric-grid breakdown. Small wind turbines (under 50 kW) with variable-pitching generally use systems operated by centrifugal force, either by flyweights or geometric design, and employ no electric or hydraulic controls.

Other controls

Yawing

Modern large wind turbines are typically actively controlled to face the wind direction measured by a wind vane situated on the back of the nacelle. By minimizing the yaw angle (the misalignment between wind and turbine pointing direction), the power output is maximized and non-symmetrical loads minimized. However, since the wind direction varies quickly the turbine will not strictly follow the direction and will have a small yaw angle on average. The power output losses can simplified be approximated to fall with $\cos^3$(yaw angle).

Electrical braking

Braking of a small wind turbine can also be done by dumping energy from the generator into a resistor bank, converting the kinetic energy of the turbine rotation into heat. This method is useful if the kinetic load on the generator is suddenly reduced or is too small to keep the turbine speed within its allowed limit.

Cyclically braking causes the blades to slow down, which increases the stalling effect, reducing the efficiency of the blades. This way, the turbine's rotation can be kept at a safe speed in faster winds while maintaining (nominal) power output. This method is usually not applied on large grid-connected wind turbines.

Mechanical braking

A mechanical drum brake or disk brake is used to hold the turbine at rest for maintenance. Such brakes are usually applied only after blade furling and electromagnetic braking have reduced the turbine speed, as the mechanical brakes would wear quickly if used to stop the turbine from full speed. There can also be a stick brake.

CHAPTER 3

GENERATOR

A generator is a device which converts mechanical energy into electrical energy. Wind generators have traditionally been wind turbines, i.e. a propeller attached to an electric generator attached to appropriate electronics to attach it to the electrical grid.

Generators can be classified broadly into two categories:

a) Synchronous Generators
b) Asynchronous Generators

The basis of this categorization is the speed at which the generators are run. Synchronous generators are run at synchronous speed (1500 rpm for a 4 pole machine at 50Hz frequency) while asynchronous generators run at a speed more than the synchronous speed.

SYNCHRONOUS GENERATOR

Synchronous generators are doubly fed machines which generate electricity by the principle when the magnetic field around a conductor changes, a current is induced in the conductor. Typically, a rotating magnet called the rotor turns within a stationary set of conductors wound in coils on an iron core, called the stator. The field cuts across the conductors, generating an electrical current, as the mechanical input causes the rotor to turn.

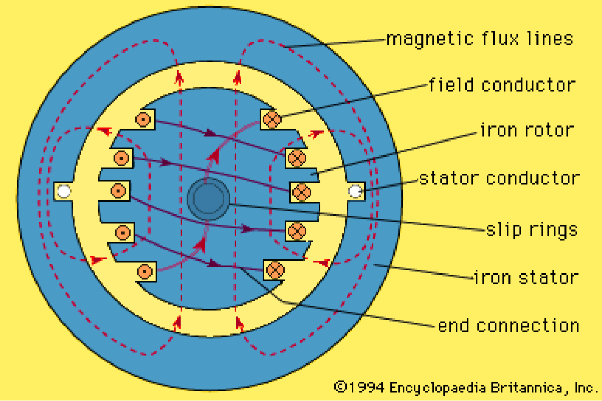


Fig.3.1 Synchronous Generator

The rotating magnetic field induces an AC voltage in the stator windings. Often there are three sets of stator windings, physically offset so that the rotating magnetic field produces three phase currents, displaced by one-third of a period with respect to each other.

The rotor magnetic field may be produced by induction by permanent magnets (in very small machines), or by a rotor winding energized with direct current through slip rings and brushes. The rotor magnetic field may even be provided by stationary field winding, with moving poles in the rotor. Automotive alternators invariably use a rotor winding, which allows control of the alternator generated voltage by varying the current in the rotor field winding. Permanent magnet machines avoid the loss due to magnetizing current in the rotor, but are restricted in size, owing to the cost of the magnet material. Since the permanent magnet field is constant, the terminal voltage varies directly with the speed of the generator.

ASYNCHRONOUS GENERATOR

Asynchronous generators or Induction generators are singly excited a.c. machine. Its stator winding is directly connected to the ac source whereas its rotor winding receives its energy from stator by means of induction. Balanced currents produce constant amplitude rotating mmf wave. The stator produced mmf and rotor produced mmf wave, both rotate in the air gap in the same direction at synchronous speed. These two mmf s combine to give the resultant air-gap flux density wave of constant amplitude and rotating at synchronous speed. This flux induces currents in the rotor and an electromagnetic torque is produced which rotates the rotor.

Asynchronous generators are mostly used as wind turbines as they can be operated at variable speed unlike synchronous generator. Two kinds of asynchronous generators are used namely

a) Squirrel cage induction generator (SCIG)
b) Doubly fed induction generator (DFIG)

SQUIRREL CAGE INDUCTION GENERATOR

A **squirrel cage rotor** is the rotating part. In overall shape it is a cylinder mounted on a shaft. Internally it contains longitudinal conductive bars (usually made of aluminum or copper) set into grooves and connected together at both ends by shorting rings forming a cage-like shape. The core of the rotor is built of a stack of iron laminations.

Fig.3.2 Cage Rotor

The field windings in the stator of an induction motor set up a rotating magnetic field around the rotor. The relative motion between this field and the rotation of the rotor induces electric current in the conductive bars. In turn these currents lengthwise in the conductors react with the magnetic field of the motor to produce force acting at a tangent to the rotor, resulting in torque to turn the shaft. In effect the rotor is carried around with the magnetic field but at a slightly slower rate of rotation. The difference in speed is called *slip* and increases with load.

DOUBLY FED INDUCTION GENERATOR

DFIG is Double Fed Induction Generator, a generating principle widely used in wind turbines. It is based on an induction generator with a multiphase wound rotor and a multiphase slipring assembly with brushes for access to the rotor windings.

Principle of a Double Fed Induction Generator connected to a wind turbine

The principle of the DFIG is that rotor windings are connected to the grid via sliprings and back-to-back voltage source converter that controls both the rotor and the grid currents. Thus rotor frequency can freely differ from the grid frequency (50 or 60 Hz). By controlling the rotor currents by the converter it is possible to adjust the active and reactive power fed to the grid from the stator independently of the generators turning speed. The control principle used is either the two-axis current vector control or direct torque control (DTC). DTC has turned out to have better stability than current vector control especially when high reactive currents are required from the generator

The doubly-fed generator rotors are typically wound with from 2 to 3 times the number of turns of the stator. This means that the rotor voltages will be higher and currents respectively lower. Thus in the typical ± 30 % operational speed range around the synchronous speed the rated current of the converter is accordingly lower leading to a low cost of the converter. The drawback is that controlled operation outside the operational speed range is impossible because of the higher than rated rotor voltage. Further, the voltage transients due to the grid disturbances (three- and two-phase voltage dips, especially) will also be magnified. In order to prevent high rotor voltages - and high currents resulting from these voltages - from destroying the IGBTs and diodes of the converter a protection circuit (called crowbar) is used.

The crowbar will short-circuit the rotor windings through a small resistance when excessive currents or voltages are detected. In order to be able to continue the operation as quickly as possible an active crowbar has to be used. The active crowbar can remove the rotor short in a controlled way and thus the rotor side converter can be started only after 20-60 ms from the start of the grid disturbance. Thus it is possible to generate reactive current to the grid during the rest of the voltage dip and in this way help the grid to recover from the fault.

As a summary, a doubly fed induction machine is a wound-rotor doubly-fed electric machine and has several advantages over a conventional induction machine in wind power applications. Firstly, as the rotor circuit is controlled by a power electronics converter, the induction generator is able to both import and export reactive power. This has important consequences for power system stability and allows the machine to support the grid during severe voltage disturbances (low voltage ride through, LVRT). Secondly, the control of the rotor voltages and currents enables the induction machine to remain synchronized with the grid while the wind turbine speed varies. A variable speed wind turbine utilises the available wind resource more efficiently than a fixed speed wind turbine, especially during light wind conditions. Thirdly, the cost of the converter is low when compared with other variable speed solutions because only fraction of the mechanical power, typically 25-30 %, is fed to the grid through the converter, the rest being fed to grid directly from the stator. The efficiency of the DFIG is very good for the same reason.

CHAPTER 4

POWER ELECTRONICS APPLICATIONS IN WIND ENERGY CONVERSION SYSTEM

Soft Starting with Thyristors

If you switched a large wind turbine on to the grid with a normal switch, the neighbours would see a brownout (because of the current required to magnetize the generator) followed by a power peak due to the generator current surging into the grid.

Another unpleasant side effect of using a "hard" switch would be to put a lot of extra wear on the gearbox, since the cut-in of the generator would work as if you all of a sudden slammed on the mechanical brake of the turbine. To prevent this situation, modern wind turbines are **soft starting**, i.e. they connect and disconnect gradually to the grid using thyristors, a type of semiconductor continuous switches which may be controlled electronically. Thyristors waste about 1 to 2 per cent of the energy running through them. Modern wind turbines are therefore normally equipped with a so called **bypass switch**, i.e. a mechanical switch which is activated after the turbine has been soft started. In this way the amount of energy wasted will be minimized.

PWM IGBT RECTIFIER AND INVERTER

A device that converts dc power into ac power at desired output voltage and frequency is called an Inverter.

Voltage Source Inverter is one in which the dc source has small or negligible impedance. In other words, a voltage source inverter has a stiff voltage source at its input terminals.

AC loads may require constant or adjustable voltage at their input terminals. When such loads are fed by inverters, it is essential that output voltage of the inverters is so controlled as to fulfill the requirements of the ac loads.

PWM control is a method to control the output voltage that is widely in application. In this method, a fixed dc input voltage is given to the inverter and a controlled ac output voltage is obtained by adjusting the on and off periods of the inverter components.

The advantages possessed by PWM technique are as under:

i. The output voltage control with this method can be obtained without any additional components.
ii. With this method, lower order harmonics can be eliminated or minimized along with its output voltage control. As the higher order harmonics can be filtered easily, the filtering requirements are minimized.

The **insulated gate bipolar transistor** or **IGBT** is a three-terminal power semiconductor device, noted for high efficiency and fast switching. Since it is designed to rapidly turn on and off, amplifiers that use it often synthesize complex waveforms with pulse width modulation and low-pass filters.

WIND GENERATION SYSTEM DESCRIPTION USING PWM IGBT CONVERTERS

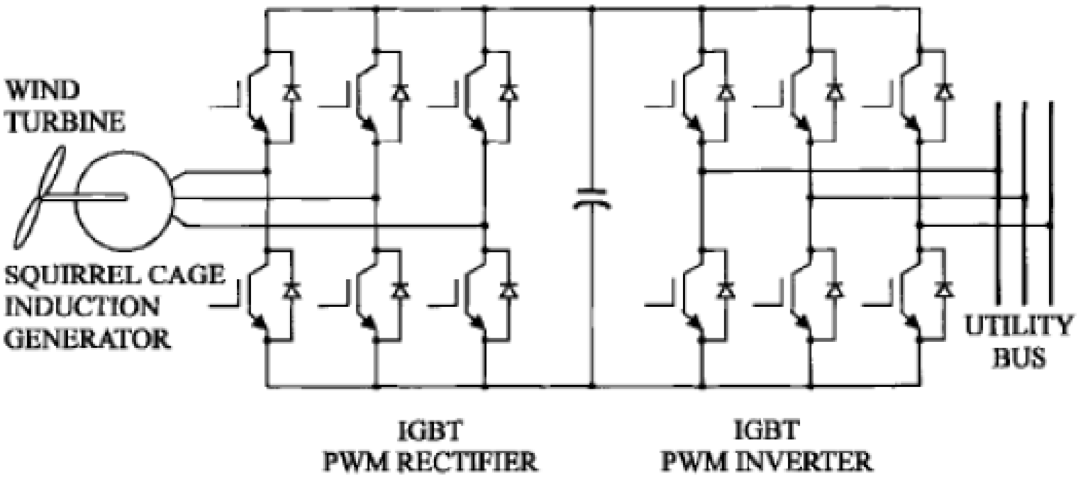


Fig.4.1 A voltage fed double PWM converter wind generation system

Converter System

The voltage-fed converter scheme used in this system is shown. A vertical (or horizontal) wind turbine is coupled to the shaft of a squirrel cage induction generator through a speedup gear ratio (not shown). The variable frequency variable voltage power from the generator is rectified by a PWM IGBT (insulated gate bipolar transistor) rectifier. The rectifier also supplies the excitation need of the machine. The inverter topology is identical to that of the rectifier, and it supplies the generated power at 60 Hz to the utility grid.

STATCOM

A **STATCOM** or Static Synchronous Compensator is a regulating device used on alternating current electricity transmission networks. It is based on a power electronics voltage-source converter and can act as either a source or sink of reactive AC power to an electricity network. If connected to a source of power it can also provide active AC power.

A **STATCOM** works by rebuilding the incoming voltage waveform by switching back and forth from reactive to capacitive load. If it is reactive, it will supply reactive AC power. If it is capacitive, it will absorb reactive AC power. This is how it acts as a source/sink.

Uses

Usually a STATCOM is installed to support electricity networks that have a poor power factor and often poor voltage regulation. There are a number of other uses for STATCOM devices including, wind energy voltage stabilisation, and harmonic filtering. However, the most common use is for voltage stability.

Back-to-back voltage source convertor is used in doubly fed induction generator which controls the grid and rotor currents. By controlling the rotor currents by the converter it is possible to adjust the active and reactive power fed to the grid from the stator independently of the generators turning speed. Rotor circuit is controlled by a power electronics converter, the induction generator is able to both import and export reactive power

Salient advantages of the converter system include the following:

- Line side power factor is unity with no harmonic current injection (satisfies IEEE 519).

- The cage type induction machine is extremely rugged, reliable, economical, and universally popular.
- Machine current is sinusoidal—no harmonic copper loss.
- Rectifier can generate programmable excitation for the machine.
- Continuous power generation from zero to highest turbine speed is possible.
- Power can flow in either direction permitting the generator to run as a motor for start-up (required for vertical turbine). Similarly, regenerative braking can quickly stop the turbine.
- Autonomous operation of the system is possible with either a start-up capacitor or with a battery on the dc link.
- Extremely fast transient response is possible.
- Multiple generators or multiple systems can be operated in parallel.
- The inverter can be operated as a VAR/harmonic compensator when spare capacity is available.

Considering all the above advantages, and with the present trend of decreasing converter and control cost, this type of conversion system has the potential to be universally accepted in the future. Of course, in recent years, soft-switched resonant link and resonant pole topologies have been proposed, but additional research and development are needed to bring them to the marketplace.

CHAPTER 5

GRID CONNECTION REQUIREMENTS

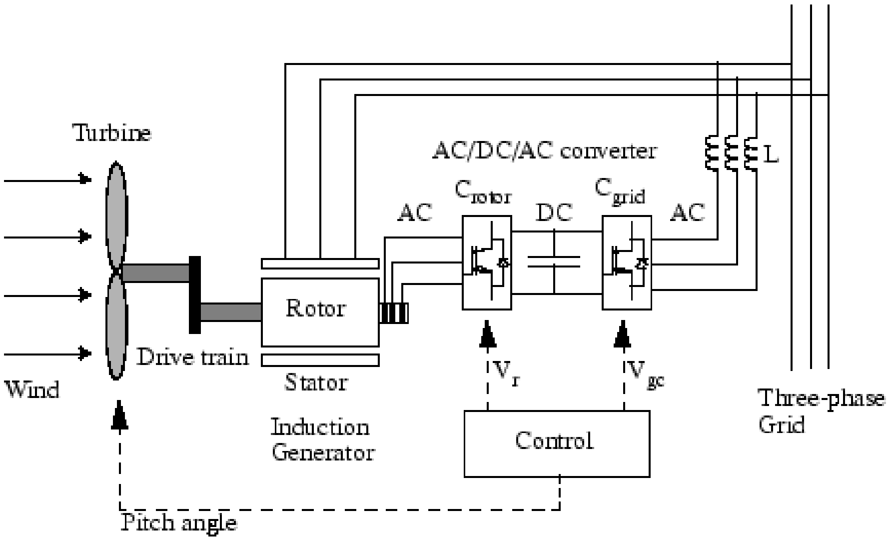


Fig.5.1 Interconnection of the Doubly fed induction generator to the grid

Requirements Wind Farm Connections to the Grid

If wind farms would be installed solely to maximize energy output, they would have major limitations in terms of:

1. Power Control and Frequency Range.
2. Power Factor and Voltage Control
3. Transient Fault Behavior, Voltage Operating Range

These are the three main issues that new grid codes must address for wind farm connection. The most worrying problem that wind farms must face is a voltage dip in the grid. The effects of transient faults may propagate over very large geographical areas and the disconnection of wind farms under fault conditions could pose a serious threat to network security and security of supply because a great amount of wind power could be disconnected simultaneously.

Reactive Power Control

Voltage and current are typically measured 128 times per alternating current cycle, (i.e. 50 x 128 times per second or 60 x 128 times per second, depending on the electrical grid frequency). On this basis, a so called DSP processor calculates the stability of the grid frequency and the active and reactive power of the turbine. (The reactive power component is basically a question of whether the voltage and the current are in phase or not).

The term "power quality" refers to the voltage stability, frequency stability, and the absence of various forms of electrical noise (e.g. flicker or harmonic distortion) on the electrical grid. More broadly speaking, power companies (and their customers) prefer an alternating current with a nice sinusoidal shape.

Power Control and Frequency Range

It must be possible to limit the active power output from every operating point as a percentage of the nominal power. For power reduction a ramp rate of at least 10% of nominal power per minute must be possible. If power is ramped down, this must not imply disconnection of single turbines from the grid. In the wake of loss of grid voltage, power has to be ramped up with a gradient of not more than 10% of nominal power per minute. This ramp can be realized in steps (reconnection of single wind turbines), if the step size does not exceed 10% of nominal power per minute. The frequency range wind turbines have to tolerate is about 47.5-51.5 Hz. According to the requirements of German transmission grid operators, large wind farms have to be treated in the future like conventional power plants.

Power Factor and Voltage Control

It has to be possible to operate wind farms with nominal power of less than 100 MW with power factor between 0.95 lagging and 0.95 leading. The required power factor values are always applied at the grid connection point. Wind farms rated 100 MW or more have to be able to operate at power factor between 0.925 lagging and 0.95 leading. The power factor range is however limited depending on the grid voltage to avoid leading power

Indirect Grid Connection of Wind Turbines

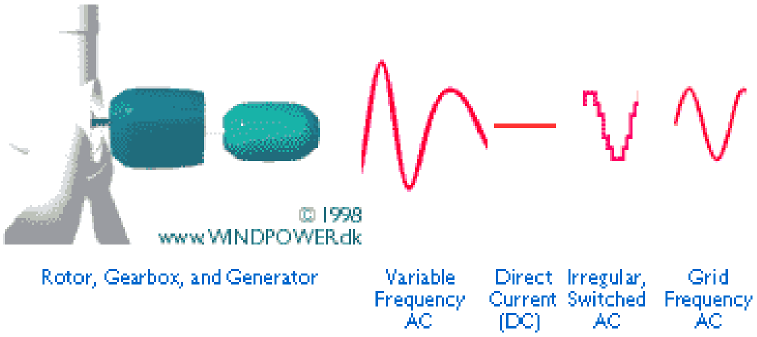


Fig. 5.2 Indirect Grid connection of wind turbines and the production of fixed frequency AC

Generating Alternating Current (AC) at Variable Frequency

Most wind turbines run at almost constant speed with direct grid connection. With indirect grid connection, however, the wind turbine generator runs in its own, separate mini AC-grid, as illustrated in the graphic. This grid is controlled electronically (using an inverter), so that the frequency of the alternating current in the stator of the generator may be varied. In this way it is possible to run the turbine at variable rotational speed. Thus the turbine will generate alternating current at exactly the variable frequency applied to the stator.

The generator may be either a synchronous generator or an asynchronous generator, and the turbine may have a gearbox, as in the image above, or run without a gearbox if the generator has many poles.

Conversion to Direct Current (DC)

AC current with a variable frequency cannot be handled by the public electrical grid. We therefore start by rectifying it. The conversion from variable frequency AC to DC can be done using thyristors or large power transistors.

Conversion to Fixed Frequency AC

We then convert the (fluctuating) direct current to an alternating current (using an inverter) with exactly the same frequency as the public electrical grid. This conversion to AC in the inverter can also be done using either thyristors or transistors.

Filtering the AC

The rectangular shaped waves can be smoothed out, however, using appropriate inductances and capacitors, in a so-called AC filter mechanism. The somewhat jagged appearance of the voltage does not disappear completely.

Advantages of Indirect Grid Connection: Variable Speed

The advantage of indirect grid connection is that it is possible to run the wind turbine at variable speed. The primary advantage is that gusts of wind can be allowed to make the rotor turn faster, thus storing part of the excess energy as rotational energy until the gust is over. Obviously, this requires an intelligent control strategy, since we have to be able to differentiate between gusts and higher wind speed in general. Thus it is possible to reduce the peak torque (reducing wear on the gearbox and generator), and we may also reduce the fatigue loads on the tower and rotor blades.

The secondary advantage is that with power electronics one may control reactive power (i.e. the phase shifting of current relative to voltage in the AC grid), so as to improve the power quality in the electrical grid. This may be useful, particularly if a turbine is running on a weak electrical grid.

Theoretically, variable speed may also give a slight advantage in terms of annual production, since it is possible to run the machine at an optimal rotational speed, depending on the wind speed. From an economic point of view that advantage is so small, however, that it is hardly worth mentioning.

Disadvantages of Indirect Grid Connection

The basic disadvantage of indirect grid connection is cost. As we just learned, the turbine will need a rectifier and two inverters, one to control the stator current, and another to generate the output current. Presently, it seems that the cost of power electronics exceeds the gains to be made in building lighter turbines, but that may change as the cost of power electronics decreases. Looking at operating statistics from wind turbines using power electronics, it also seems that availability rates for these machines tend to be somewhat lower than conventional machines, due to failures in the power electronics.

Other disadvantages are the energy lost in the AC-DC-AC conversion process, and the fact that power electronics may introduce harmonic distortion of the alternating current in the electrical grid, thus reducing power quality.

Although the size and direction of the wind is stochastic and the output power of the wind turbine varies with the starting and ceasing of the system, the induction generator has many merits, such as low cost, high credibility and easy servicing. The modes of induction generator connected to grid are adopted in large wind farms. There're two types of wind turbine connected to grid. One is the direct grid-connection mode; the other is connected to grid though a power electronics.

- Doubly fed induction generator with cascaded converter slip power recovery;
- Doubly fed induction generator with cycloconverter slip power recovery
- Synchronous generator with line-commutated and load commutated thyristor Converters

In addition to the above schemes, squirrel cage generators with shunt passive or active VAR (volt ampere reactive) generators have been proposed which generate constant voltage constant frequency power through a diode rectifier and line-commutated thyristor inverter. Recently, a variable reluctance machine and doubly stator-fed induction machine have also been proposed in wind generation systems. Very recently, a double sided pulse width modulated (PWM) converter system has been proposed to overcome some of the above problems. This describes a VSWT system with a squirrel cage induction generator and a double-sided PWM converter where fuzzy logic control has been used extensively to maximize the power output and enhance system performance. All the control algorithms have been validated by simulation study and system performance has been evaluated in detail. An experimental study with a 3.5-kW-laboratory drive system is in progress. It will eventually be transitioned into a 200-kW prototype generation system.

CHAPTER 6

STABILITY ANALYSIS

Wind power penetration will increase rapidly because of the abundant wind resources in various areas and the government policy impetus. However, the power system security and stability may be affected due to the higher wind power penetration. Because majority of the wind farms with higher installed capacity intends to be connected into the transmission network of 220kV voltage level, their impacts are becoming more widespread. In the grid impact studies of wind power integration, voltage stability is the mostly concerned problem that will affect the operation and security of wind farms and power grid.

In the grid impact studies of wind power integration, the voltage stability issue is a key problem because a large proportion of wind farms are based on fixed speed wind turbines equipped with simple **induction generator (IG).** Induction generators consume reactive power and behave similar to induction motors in the duration of system contingency, which will deteriorate the local grid voltage stability. Also variable speed wind turbines equipped with **doubly fed induction generator (DFIG)** are becoming more widely used for its advanced reactive power and voltage control capability. DFIG make use of power electronic converters and are thus able to regulate their own reactive power, so as to operate at a given power factor, or to control grid voltage; But because of the limited capacity of the PWM converter, the voltage control capability of DFIG can't catch up with that of the synchronous generator. When the voltage control requirement is beyond the capability of the DFIG, the voltage stability of the grid is also affected.

MODELS OF WIND TURBINES

Wind turbines model based on different generator technologies such as simple induction generator or doubly fed induction generator with identical rated power (1.5MW) are presented. As in Figure 1, a simple configuration of different types of wind turbines concept is shown.

Doubly fed induction generator model

The DFIG is a wound-rotor induction generator whose stator is directly connected to the grid, but the three phase rotor windings are connected through slip rings to the grid via a partially rated power electronics converter. A typical configuration of a DFIG is shown

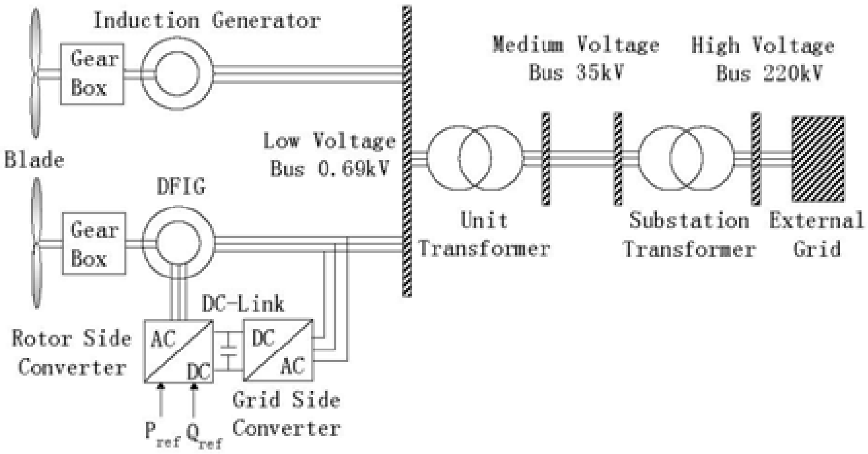


Fig. 6.1 Configuration of IG based wind turbines and DFIG based wind turbines and interconnection of grid

The DFIG can be regarded as a traditional induction generator with a nonzero rotor voltage.

For representation of DFIG models in power system stability studies, the stator flux transients are neglected in the voltage relations.

The power converter in such wind turbines only deals with slip power, therefore the converter rating can be kept fairly low, approximately 20% of the total generator power. The PWM converter inserted in the rotor circuit allows for a flexible and fast control of the generator by modifying magnitude and phase angle of the rotor voltage. The controllability of reactive power help DFIG equipped wind turbines play a similar role to that of synchronous generators. Under steady-state conditions, the flux transient's items disappear.

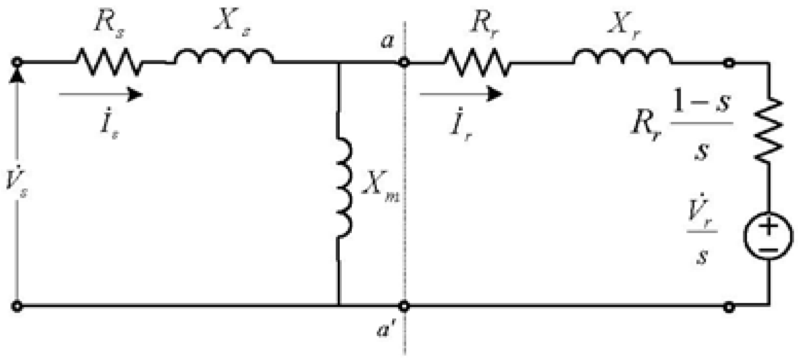


Fig. 6.2 Steady-state equivalent circuit of doubly fed induction generator

During normal steady-state operation the wind turbines or the wind farm can be considered as a PQ node or a PV node depending on the control strategy that the wind farm adopted .

B. Induction generator model

The rotor of induction generator is a wound-rotor or a squirrel-cage rotor with a short circuit winding not connecting to an external voltage source. The steady-state equivalent circuit of the induction generator is given in Figure 3.

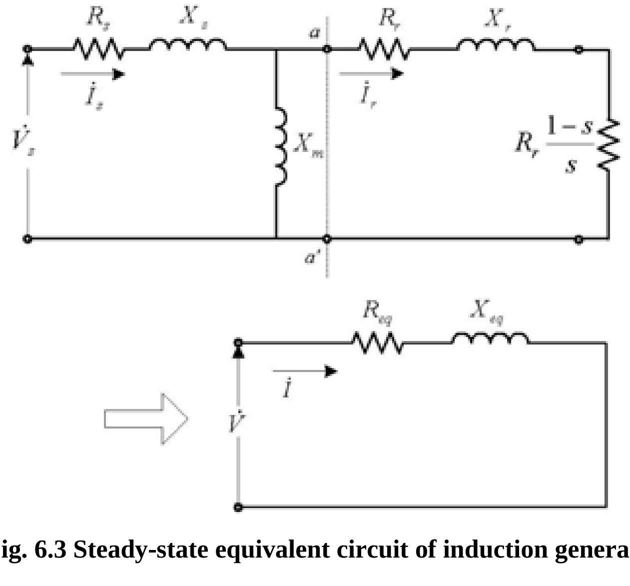


Fig. 6.3 Steady-state equivalent circuit of induction generator

From the equivalent circuit of induction generator in Figure 3, the active power and reactive power expression are easily derived.

$$P_e = \frac{V^2 R_{eq}}{\sqrt{R_{eq}{}^2 + X_{eq}{}^2}} \qquad Q_e = \frac{V^2 X_{eq}}{\sqrt{R_{eq}{}^2 + X_{eq}{}^2}}$$

C. Converter model

The converter consists of two voltage source converters connected back-to-back and enables variable speed operation of the wind turbines by decoupling control that controls the active power and reactive power of the generator separately. The rotor-side and grid-side converters are usually set-up by six-pulse bridges illustrated in figure 4.

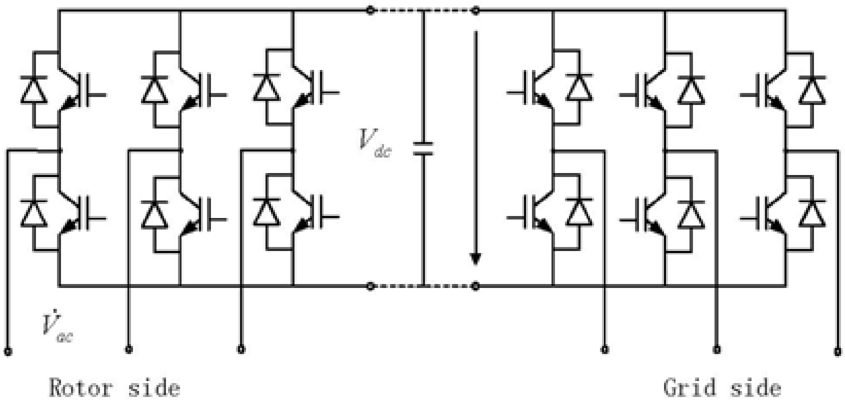


Fig. 6.4 VSC-PWM converter configuration

Control strategy of DFIG based wind turbines

DFIG make use of power electronic converters and are thus able to regulate their own reactive power, so as to operate at a given power factor, or to control grid voltage. The rotor-side converter is controlled by a two stage controller. The first stage consists of fast current controllers regulating the generator rotor currents to reference values that are specified by a slower power-controller which is the second stage controller. There are two independent PI controllers, one for the d-axis component, and one for the q-axis component. The output of the current controller defines the pulse-width modulation factor Pm in stator voltage orientation.

Voltage control can also be realized by replacing the reactive power controller by a voltage controller defining the d-axis current reference. Up to now, this feature of the DFIG based wind turbine is mainly used to keep the generator reactive power neutral. However, as wind power penetration in power systems is increasing, it will probably be desirable for wind turbines to provide voltage control. The controller can regulate either the voltage or the power factor, but the maximum possible reactive power production is defined by the converter ratings.

STEADY-STATE VOLTAGE STABILITY ANALYSIS

In this section, the steady-state voltage stability limit of wind farms based on different wind turbine technologies is assessed. Three cases are conducted: case (1) wind turbines equipped with no-load compensated induction generator; case (2) wind turbines equipped with full-load compensated induction generator; case (3) wind turbines equipped with DFIG controlling the POI as a PQ node with Q = OMVar.

A. P-V curve analysis of wind-farm with different generator

Wind farms based on different types of wind turbines are interconnected into the transmission grid. When the active power output of wind farm is low, the POI voltage does not affected significantly but when wind power injects into the POI increasing largely then the voltage decreases fast. The P-V curves of the wind farms as wind farm active power output increasing are plotted in Figure 7.

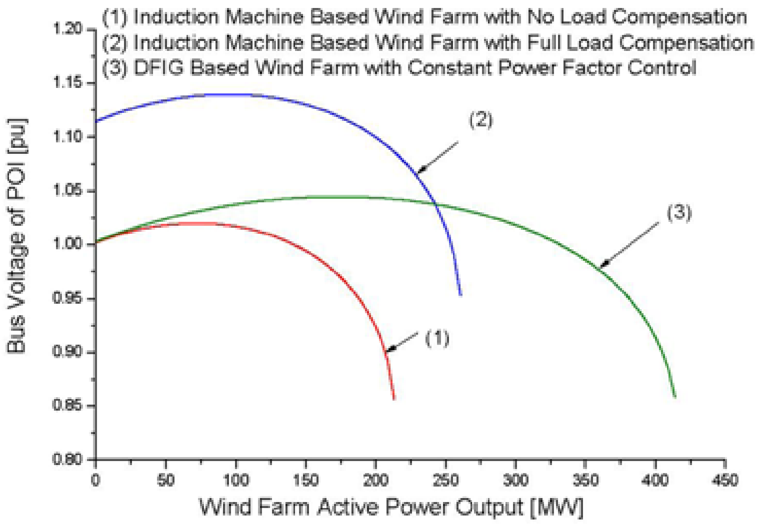


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Fig. 6.5 P-V curves of wind farms based on different wind turbine technology

It can be that the steady-state voltage stability limits of induction generator based wind farm with no-load compensation is only 213MW. When more real wind power injects into the POI than 213MW, the voltage will collapse. When the DFIG based wind farm with constant power factor control that control the POI as a PQ bus with Q= 0 MW, the steady-state voltage stability limits are increased largely to 424MW. When 350MW real wind power injects into the grid, the voltage stability margin can be acceptable. It must be noted that induction generator based wind farm with full-load compensation can enhance the voltage stability limit, but not very obviously; the full-load shunt capacitor compensation should not be put into use in low wind power output totally or else that will arise bus voltage higher than acceptable voltage level such as the curve (2). In actual operation of wind farm with full-load compensation, the shunt capacitor should be switched on gradually along with the active power output increasing. Due to the shunt capacitors compensation, the voltage collapse value in case (2) equal to 0.95 pu is higher than that in case (1) or case (3) equal to 0.85 pu. Because the reactive power output of shunt capacitors is proportional to V2 as the grid voltage decreasing, the

capacitors cannot provide the rating reactive power. The shunt capacitor's reactive power capability is limited in case of lower voltage and cannot improve the voltage stability of the

local grid fundamentally.

B. V-Q curve analysis of wind-farm with different generator

V-Q curve is a powerful tool to analysis the steady-state voltage stability limits and reactive power margins of the grid by describing the relationship between the bus voltage and the injected reactive power into the same node. It illustrates the reactive power distance from the normal operation point to the voltage collapse point. In this studies, the VWQ curves of different active power output of wind farms based on different types of wind turbines are shown in figure 8 to figure 10. In the case of induction generator based wind farm with no-load compensation, there is a 13MVar reactive power margin when the wind farm active power output is 200MW; in the case of DFIG based wind farm, there is a 12MVar reactive power margin when the wind farm active power output is 400MW. The acceptable injected real wind power in case (3) double than that in case (1) because the DFIG based wind turbines can provide the reactive power to keep a constant power factor of the whole wind farm and reactive power exchange zero in the POI. This characteristic of DFIG based wind farms would enhance the voltage stability of the local grid integrating wind power. High demand of reactive power is the major characteristic of large wind farms that causes voltage problems to power networks. The larger the wind farm, the more severe this effect could be. If the network is not able to meet the wind farm reactive power requirement, the wind power penetration into the power system should be limited.

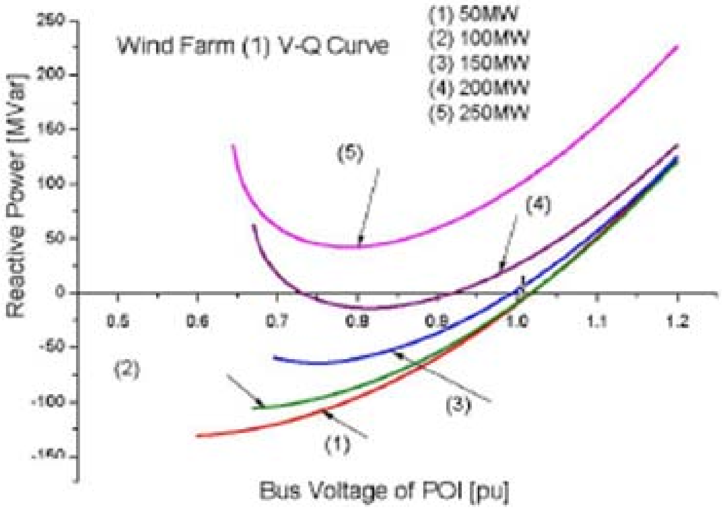


Fig. 6.6 V-Q curve of wind farm based on IG with no-load compensation

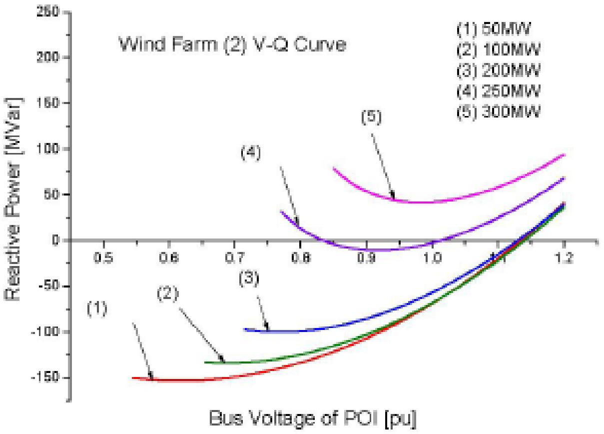


Fig. 6.7 V-Q curve of wind farm based on IG with full-load compensation

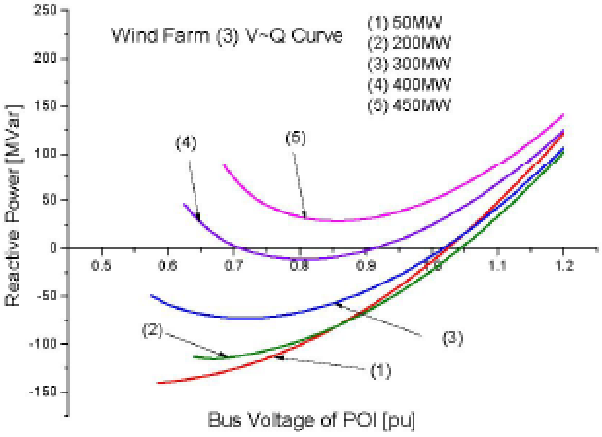


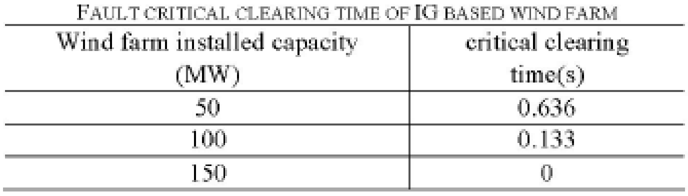
Fig. 6.8 V-Q curve of DFIG based wind farm

TRANSIENT VOLTAGE STABILITY ANALYSIS

In the transient voltage stability analysis of wind power integration, the voltage recovery issue of grid-connected wind turbines after the clearance of an external short-circuit fault is a basic topic. If the terminal voltage of the grid-connected wind turbines can be restored, the wind turbines can still be connected into the grid and keep in service. If the voltage cannot be restored, the wind turbines need to be tripped or it will collapse the local grid voltage. For transient voltage stability study in this paper, the three phase short-circuit fault on the line from bus 3 to bus 6 is simulated at the simulation time t = Is. After the fault clearance, the transmission line will be tripped simultaneously.

A. Transient voltage stability of IG based wind-farm

In the case of wind farm with induction generator, the fault critical clearing time is calculated with the wind farm installed capacity increasing. The simulation results are shown in table 1.



FAULT CRITICAL CLEARING TIME OF IG BASED WIND FARM

Wind farm installed capacity (MW)	critical clearing time(s)
50	0.636
100	0.133
150	0

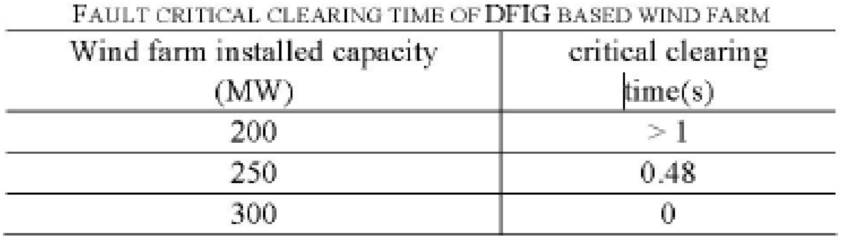
Table 6.1 Fault Critical Clearing time of IG based wind farm

Along with the wind farm installed capacity increasing, the fault critical clearing time is reduced significantly. When the wind farm installed capacity is above 150MW, the fault critical clearing time is reduced to 0 s. Which means even if the fault clearing time is infinite small, the induction generator terminal voltage cannot be restored because the network is weakened due to the tripped line. The transmission network should not meet the reactive power demand of the wind farm with high output and the local loads so that the voltage collapse is occurred. When the power system relay protection is considered, the line with 3 phase short-circuit fault will be tripped in 0. Is.

It can be seen that when the wind farm installed capacity exceed 150 MW, the wind farm's voltage cannot be restored after the fault clearance; the wind turbine generator speed is accelerated up to over-speeding. Because wind turbines based on induction generator still need reactive power consumptions during the voltage recovery period and the tripped line weakens the network configuration, the local network transient voltage stability will be destroyed.

B. Transient voltage stability of DFIG based wind-farm

In the case of wind farm with doubly fed induction generator, the fault critical clearing time is calculated with the wind farm installed capacity increasing. The simulation results are shown in table 2.



FAULT CRITICAL CLEARING TIME OF DFIG BASED WIND FARM

Wind farm installed capacity (MW)	critical clearing time(s)
200	> 1
250	0.48
300	0

Table 6.2 Fault Critical Clearing time of DFIG based wind farm

When the wind farm installed capacity is lower than 200MW, the fault critical clearing time is larger than 1 s; the transient voltage stability of local grid is greatly larger than in the case of induction generator. More wind power installed capacity increasing; the fault critical clearing time is also reduced demonstrating that the transient voltage stability is deteriorated. When the wind farm installed capacity reaches 300MW, the fault critical clearing time is reduced to 0 s. When the power system relay protection is considered, the line with 3 phase short-circuit fault will be tripped in 0. Is. The wind turbines generator terminal voltage profile. The wind turbines protection system doesn't be taken into account.

In all the study cases, the DFIG based wind turbines have a **better voltage recovery performance** than the same rating IG based wind turbines. Due to the control capability to regulate reactive power and voltage, the DFIG wind turbines will mitigate the adverse affect on voltage stability of the local transmission grid. Even if the wind farm installed capacity reaches 300MW, the control system of the DFIG also can prevent the generator speed from over-speeding after the fault clearance; but there is an imbalance between the wind turbines mechanical power and electric power because the low voltage following the fault that limits the wind farm active power output, which results in the oscillation of the speed, power and voltage of the wind farm. In actual operation, it can be resolved by tripping some wind turbines or by adopting pitch control to reduce the mechanical power of the wind turbines.

The following things can be concluded from the studies done above:

a. Wind turbines equipped with simple induction generator are not provided with reactive power regulation capability. Voltage stability deterioration is mainly due to the large amount of reactive power absorbed by the wind turbine generators during the continuous operation and system contingencies.

b. Wind turbines equipped with doubly fed induction generator (DFIG) controlled by the PWM converters are provided with reactive power regulation capability; can absorb or supply reactive power during normal operation. The adverse affect on local network voltage stability is mitigated so that more wind power installed capacity can be incorporated into the grid.

c. The transient voltage stability characteristics of wind turbines with DFIG are better than wind turbines with induction generator because of the voltage control capability of the DFIG based wind turbines; The DFIG based wind turbines have a better voltage recovery performance than the IG based wind turbines with same rating.

CHAPTER 7

CONCLUSIONS

CONCLUSIONS

From the report we studied that wind has a lot of potential in it and if properly harnessed then it can help solve the energy crises in the world. The study of wind turbine and its characteristics showed that how it can be properly designed and used to get the maximum output. The power electronic circuitries have helped the concept of wind power a lot. Without them this concept would have been too expensive and far fetched. With the thyristors and converters being used not only the operations have been smoothened but also the efficiency has been increased to a great extent. From the voltage stability analysis it was showed that how a doubly fed induction generator has superior characteristics than a simple induction generator. This report also showed the integration of wind farms with the transmission grid and the problems associated with it and the probable solutions that can be applied to solve them and have a better performance.

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