Wind Power

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This thesis is presented as part of Degree of
Bachelor of Science in Electrical Engineering

Blekinge Institute of Technology
December 2014

Blekinge Institute of Technology
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Abstract

This Bachelor thesis has been written at the Blekinge Institute of Technology. This thesis concentrates on the wind power and their components, also the large wind farm is studied.

The electrical power is generated by using the power in wind to drive a wind turbine to produce mechanical power. This mechanical power can be converted into electrical power by using electrical induction generators.

There are two types of the wind turbines, the horizontal axis and vertical axis wind turbine, where the horizontal axis wind turbine is mostly used and was studied in this thesis. The rotor can be placed in two directions: an upwind rotor where the blade of turbine faces to the wind, so it operates more smoothly and transmit more power. The other type is a downwind rotor which orients itself with respect for the wind direction. Moreover, the tower shadow makes the blade to flex, consequently resulting in fatigue, noise, and reduces output of the power.

The modern wind turbine has been built with an odd number of blades which is important for the stability of the turbine. The rotor with an odd number of blades can be considered to be similar to a disc when calculating the dynamic properties of the machine.

The main idea of this thesis is to study the wind power in general and large wind parks specifically. The Horns Rev wind park was taken as an example of a wind park in Denmark and the Gotland wind park as an example of a wind park in Sweden too.

Into account, the distance between wind turbine in the wind direction cannot be too small. If the wind turbines are located to close to each other, the wind will be more and more turbulent after it passes through each single wind turbine. This would lead to that wind turbines downstream in the wind park, and it might even have to shut down due to that mechanical loading gets to high during strong conditions.

This is due to the fact that when wind passes through the rotor of the wind turbine it gets very turbulent and the wind speed is decreased. The minimum length of the rotor should be approximately 5-7 rotor diameters to avoid that issue.

Gotland Energy AB (GEAB) considered, that high voltage direct current light would be the only realistic way to solve the technical problems for the high amount of wind power in-feed. One result is that The stability of voltage during transient events, has become much better by using the high voltage direct current light so that the output current stability from the asynchronous generators have been improved, which reduces the stresses on the AC grid and on the mechanical construction of the windmills.

ACKNOWLEDGEMENTS

In the name of Allah, the Most Gracious and the Most Merciful

Thanks to Allah, all praises to Him for the strengths and His blessing in completing this thesis. Several people have been involved in the thesis. Hereby, we kindly acknowledge them.

At first, We would like to thank our supervisor Mr. Erik Loxbo for his supervision, his patience and support and especially for his encouragement and positive attitude during difficult parts of the work. His readiness for consultation at all times, his educative comments, his concern and assistance have been invaluable. We are grateful to Dr. Sven Johansson, Professor and Head, Dept. of Electrical Engineering for providing necessary facilities in the department.

Contents

Abbreviations

PGF…………………………………………………………………………......pressure gradient force

TWh……………………………………………………………….………….. terawatt per hour

Kw/Mw ………………………...…………………………………….………….kilo watt/mega watt

Kwh…………………………………………………………………….….…….……kilo watt per hour

VAWT…………………………………………………………….……….vertical-axis wind turbine

HAWT……………………………………………………………….…horizontal-axis wind turbine

GRP…………………………………………………………………..…….glass reinforced plastic

TSR……………………………………………………...……..……..………...tip speed ratio

Cp_{max}……………………………………………………………....……….……..power coefficient

RPM………………………………………………………………………………...rotation per minute

SWPTC……………………………………………………….Swedish wind power technology center

WTGs…………………………………………………….…………………wind turbine generators

DC/AC…………………………………………..………..…………..direct current/ direct current

PM……………………………………………………………...…………………permanent magnets

IGBT…………………………………….…………………...…..insulated gate bipolar transistor

EESG…………………………………...…..…………………...electrically excited synchronous generators

PMSG……………………………………………….…..permanent magnets synchronous generator

SG…………………………………………………………………………..….synchronous generator

HTS……………………………………………...……………high-temperature superconducting

SWG……………………………………………………….superconducting wind turbine generator

FSIG……………………………..…………………….…………fixed speed induction generator

SQIG……………………………………………………..………squirrel cage induction generator

DFIG……………………………………………….……………doubly fed induction generator

SCIG……………………..………………………..…stator convertor controlled induction generator

PWM…………………………………………………...………………pulse width modulation

RSC……………………………………………………………..…..………………..rotor side convertor

GSC…………………………………………………………..…………………grid side convertor

HVAC…………………………………………………………....…high voltage alternating current

HVDC…………………………..………………………….………high voltage direct current

PCC…………………...……………………………………..……..point common connection

WT……………………………………………………………...…………………wind turbine

Chapter 1

1.0. introduction

The wind is one of the clean renewable energy. It is a flow of gases and it is caused by the differences in the atmospheric pressure. When a difference in the atmospheric pressure happens, the air moves from higher into lower pressure areas. However, all of these caused by sun effects, because the sun heats the wind unequally around the earth and 1 to 2 percent of the solar energy which reaches the earth is stocked in wind.

The human tried to use the wind in his life and get advantages of it. Furthermore, the wind is used in several ways for example; moving sailing boats, rotate windmills to get water from underground, etc.

The wind can be in general divided into two types, global and local. However, the global wind is the large movements around the world and the local is the movements of wind in a specific part on earth. The wind can be described by two main factors speed and direction, and controlled by a combination of three forces which are:

- Pressure-gradient force (PGF).
- Coriolis force.
- Friction.

The wind can be warm or cold because of the earth's surface effects in both friction and pressure of the wind, and the warm wind has less density than the cold. Oceans give a smoother surface more than the land and drastically different certain heat that cause ocean or land breezes through changing of air pressure. In the daytime the heating is increased more over the oceans, so the air over the land goes up and wind speed goes fast from ocean to land and in the opposite direction at night.

1.1. Background

With the use of oil and gas in the production of electricity power which pollute the environment, the researchers started to find sources that can be used in producing electric power without any dangerous impact on the environment.

The air is made of several gas particles and these particles moves quickly during windy days and that produce a movement energy called kinetic force E_k caused duo to the wind motion. The first scientist who figured out this energy is Robert Boyle in 1660, then it has been developed theoretically by Daniel Bernoulli in 1738. After that, the scientists tried to develop it more and more. The Kinetic energy can be obtained by:

$$E_k = \frac{1}{2} m v^2$$

where v is the speed of wind in meter per second (m/s), and m is the mass of wind in kilogram (kg) and known as the body of air with specific characteristics (temperature, humidity and pressure) and given as:

$$m = 3 * \frac{k * T}{v^2}$$

where k is a constant and equal to $1.38 * 10^{-23}$ (J/kg) and T is the air temperature of gas in Kelvin.

Power and Energy:

1-Power is energy per time unit and is expressed in watt (or Kw, Mw, Gw). Power is often notified by the letter P. 1 watt = 1 j/s (joule per second).

2- Energy is power multiplied by the time the power is used. For example: a wind turbine that gives 2000Kw power during two hours has produced 4000KWh.

1.2. Wind Energy

Wind was used by people since 5000 B.C in Egypt to propel boats at Nile River. Wind used earlier in rotating windmills in Middle East, Chine and Persia. New ways of using the wind have spread by the 11^{th} century when people started using the windmills for pumping water from underground. Lately, The scientists has started to get advantages of wind to produce electricity as the wind has a Kinetic energy.

Kinetic energy is the main factor in converting the wind energy into electricity. The wind energy is produced by using a specific type of turbines called wind turbine, where this turbine absorbs the kinetic energy and produces the electricity power P_W. To obtain the power in the wind, we must have the density of the air ρ_A in kilogram per cubic meter (kg/m^3) and we can obtain it by:

$$\rho_A = \frac{0.348444 * P_A - (0.00250 * T - 0.0252582) * H_A}{273.15 + T}$$

where P_A is the air pressure, H_A is the air humidity in percent and T is the absolute temperature in Kelvin.

Then, the wind power is calculated by the formula:

$$P_W = \frac{1}{2} * \rho * A * v^3$$

where A is the projected area which in our case will be the rotor area of a wind turbine and given as:

$$A = \pi r^2$$

where r is the radius of the wind blades.

1.3. History of Wind Energy

The idea of using the wind as an energy started by moving the boats along the Nile River in early time by 5000 B.C, while the first simple windmills were used in china in pumping water 200 B.C, however, Persia and the Middle East used the vertical-axis windmills with woven reed sails for grinding the grain.

Holland was best known for development in windmills design, by 14th century, which preformed many helpful functions in that time, Including timber milling and the most important function was pumping water to drain marshy, low areas and reclaim large lands of Netherlands farming. At the end of 18th century, about 10,000 wind turbines were used in Netherland and Britain as well.

By 1990 in Denmark there were about 2500 windmills for mechanical loads which were producing an estimated combined power approximately to 30MW.

The wind turbine technology is one of the attractive renewable energy. The wind power is developed significantly in 1990, where more than 10,000 megawatt of the wind power capacity used around the world.

The total amount of the Swedish electricity production in 2003 was 143 terawatt hours, the important part comes from hydropower and nuclear power, which participate about 65 terawatt hours each. 11 terawatt hours come from steam power. The total amount of installed wind power was approximately 400MW at the end of 2003.

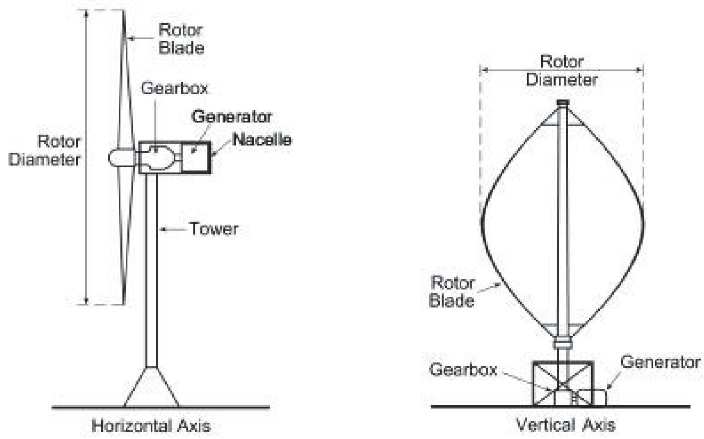
The wind power has been the fastest-growing exporter of the renewable energy around the world in the last years, and ability is also progressively expanding in Sweden.

Since 2000, the Swedish production has grown from 0.5 to 7.1 terawatt hours in 2011, there were approximately 2000 wind turbines in Sweden.

Chapter 2

2.0. Types of Wind Turbines

The wind turbine consist of two types based on the axis in which the turbine rotates. Turbine which rotate around a horizontal axis (HAWT) is more common than other the type of turbine which rotates around a vertical axis(VAWT).



Fuiger1: shows the types of wind turbine. (Ref 1)

The two types are using a rotating motion to produce electricity, and this thesis concentrate on the horizontal axis wind turbine.

2.1. The Vertical-Axis Wind Turbine(VAWT):

There are two main types of VAWTs, the Savonius and the Darrieus. The Darrieus uses blades similar to those used on HAWTS, while the Savonius operates like a water wheel using drag forces.

The blades rotate around a vertical axis, the turbine is in an optimal position to use this wind. The VAWT has an ingrained inefficiency because one blade is working well the wind, the other blades are effectively pulling in the wrong direction.

However, the VAWT resort to be larger than HAWT, also can be not easy to mount them on a tall enough tower to avail of higher and cleaner wind. One of the advantages of VAWT, it does not require a yaw mechanism, since it can harness the wind from any direction.

2.2. The Horizontal –Axis Wind Turbines (HAWT):

The electrical generator and the main rotor shaft are generally placed at the top of a tower for a HAWT. The HAWT has a design which is required that should be faced into the wind to obtain maximum power, this process is called yawing.

In general the turbine is connected to the shaft of the generator through a gearbox which moves the slow rotation of the blades into a faster rotation that is more suitable to drive an electrical generator.

HAWTs can be divided into three types:

1- Dutch windmills.
2- Multi blade Water pumping Windmills.
3- High speed propeller type wind machines.

Dutch windmills:

They were widely used for grinding grains. The blades of Dutch windmills were penchant at an angle to the wind to result in rotation, however, wooden slats or sails were used to industrialize these blades.

Multi blade water pumping windmills:

They have a large number of blades, and wooden or metallic slats were used to manufacture these blades. This is used to rotate the shaft of a water pump. A tail vane is placed on the turbine to orient it to face the wind.

However, the location of the mill does not dependent on the availability of the wind, but by the availability of water. Low cost and sturdiness are the main criteria for the design of these wind mills.

High speed propeller type wind machines:

This type of wind turbine is used most widely for the generation of electricity, this turbine operates on the aerodynamic forces of the wind. It has been found that the wind turbines that work on aerodynamic forces operate at higher efficiency than the ones which operate on thrust forces.

Usually the electrical generator is at the top of the tower, and directed into the wind. The gearbox turns the slow rotation of the blades till a quicker rotation to be suitable to drive an electrical generator.

2.2.1. Horizontal Axis Wind Turbine (HAWT) Parts

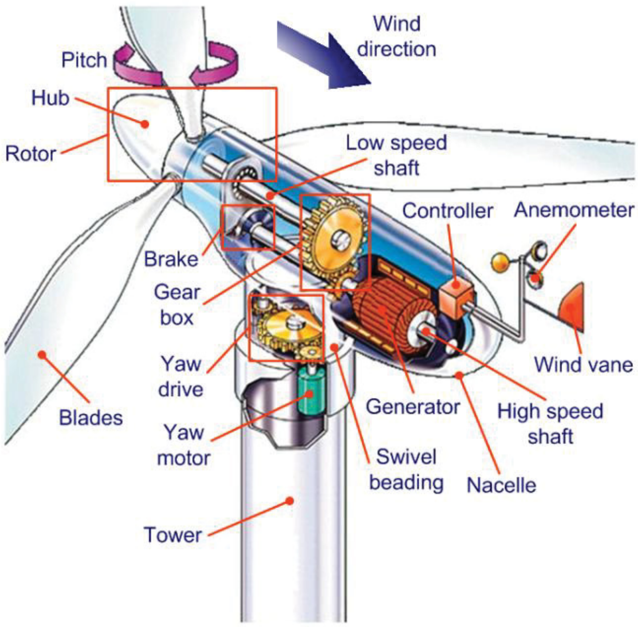


Figure 2: HAWT parts. (Ref 2)

As shown in the above figure 2, the HAWT consist of several mechanical parts. Some of the parts work to generate the electric power and some parts for protecting the turbine. The parts are:

- **The Rotor:**

The rotor works as collecting the energy from the wind, the rotor and its blades convert the wind power to a rotational mechanical power. The rotor consist of two or more wooden, fiberglass, or metal blades. The rotor blade design has advantage from airplanes wind technology, it works by using the Bernoulli aerodynamic lift and drag force, which will be explained later.

The shape of the rotor blade and their angle of attack proportion to the direction of wind and affects on the performance of the rotor blade.

Assembly of the rotor can be placed in two directions (see figure 3 below):

Upwind rotor: this type of turbine has the blade faces to the wind, also for the mega turbines on wind farms, have a motorized drive to force the turbine facing into the direction of the wind, however, it operates more smoothly and transmit more power.

Downwind rotor: the wind controls the yaw(left-right motion), it orients itself with respect for the wind direction. The shadowing of the tower make the blade to flex, consequently resulting in fatigue, noise, and reduces output of the power.

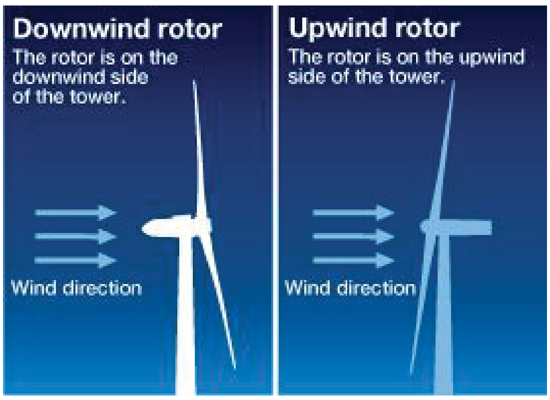


Figure 3: Downwind and upwind rotors. (Ref 3)

The rotors ingrained mechanical properties and its design affect, it is useful service lifetime. The high speed wind machine rotors normally have blades with an airfoil cross section. The blades made of wood soiled or laminated, or fiberglass or metal.

- **The blades:**

It is designed aerodynamically to work on the precept of lift and drag to convert kinetic energy which is produced from the wind into mechanical energy in order to be transferred through the main shaft then converted to electrical energy by using the generator**.** the rotor blades have variables such as materials, number of blades, length and blade pitch.

The following materials have been considered for rotor blades:

1- **Metals**: alloys of aluminum and steel have been used. The mechanical properties of steel has a good fatigue strength. However, it is comparatively dense so that steel can be sort of heavy. The blades Wight would case large oscillatory severity loads on the rotor components. In the upward position of the blades rotor they press the components casing compression on the bearings, and in their downward position they pull on the bearings casing tension. For the same weight aluminum has better properties of tensile than steel.

2- **Wood**: wood has a low density, good strength and good fatigue resistance. An improved use of wood is to shape the blades from bonded stratum of wood sheets using composites technology. A composite wood material can be produced with a good strength as good as flexural and fatigue resistance properties.

3- **Synthetic composites:** it consisted of a polyester or epoxy matrix which is reinforced with glass fibers**.** They have an advantage of low density compared to metals and good tensile properties**.** Glass Reinforced Plastic(GRP) blades are strong, economical with temperate fatigue properties. Long term fatigue test data are not easily available for wind turbine so the definitive fatigue life of such blades is unknown. By developing the filament winding process to make projectile sabots and missile bodies can be used for constructing rotor blades for giving good strength and flexibility.

- **Effect of number of blades:** when the number of blades on a wind turbine increases, the efficiency of aerodynamic increases. However, as we move from two blades to three blades we get an increases in efficiency of 3% but as we move from three blades to four blades the efficiency gain is marginal.

  Moreover, as we increases the number of blades cost of the system increases**.** When we use more number of blades, the blade should be thinner to become aerodynamically efficient. But when the blade is thinner portion at root, may not resist bending stress induced due to, axial wind loads.

  In general the wind turbines with three blades accommodated a thicker root are used**.** Generally, the less number of blades on the wind turbine, the cost of material and manufacturing will be lower.

Figure4: Efficiency gain increases by increases the number of blade. (Ref 4)

The modern wind turbine has been built with an odd number of blades and the important reason of that is the stability of the turbine. The rotor with an odd number of blades can be considered to be similar to a disc when calculating the dynamic properties of the machine.

Moreover, the modern HAWT rotors which are consist of two or three thin blades and have a specification design as low solidity rotors, it is offer a low fraction of the area swept by the rotors being solid.

The wind turbine blades experience mainly two aerodynamic forces Lift and Drag, the lift force is an important factor which make the blade rotate. The shape of cross-section for airfoil is more around on the top and less on the bottom, the advantage of this design basically creates faster airflow over the top of the blade and therefore less pressure.

Since there is less pressure on the top than the bottom of the blade, a force gives that move in the direction of lower pressure which is called lift. The lift is always vertically to the upper surface of the blade and causes the blades to move. However, when the wind blows faster, the more lift that is produced on the blade and more rotation caused.

The drag is a force which is trying to stop the motion of the blade. It is basically the friction of air against the surface of the blade. However, the drag is perpendicular to lift and it is in the same direction as the air flow along the surface of the blade.

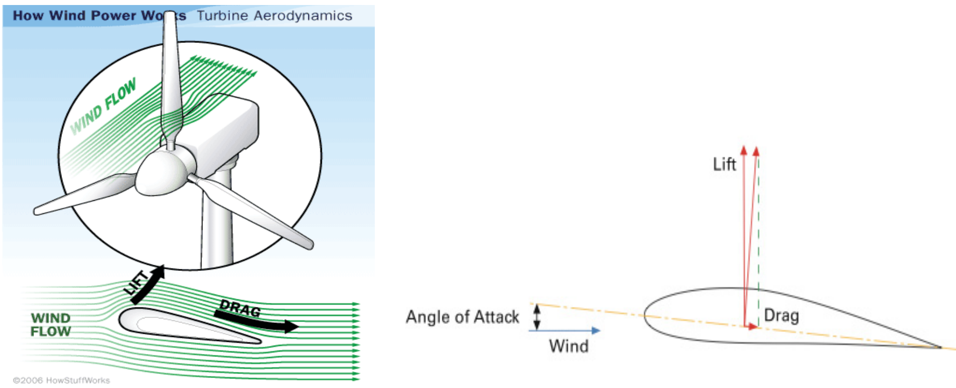


Figure 5: shows the mainly two aerodynamic forces Lift and Drag. (Ref 4)

Generally the lift force increases with angle of attack, Along with that unwanted drag force also increases, during tangential component of the lift force supports rotation of the blade, the drag force opposes it. When lift to drag ratio is maximum the wind turbine can give maximum performance which is called as optimum angle of attack.

The angle of attack: it is between the flight direction and the chord line of the airfoil, by increasing the angle of attack, more lift is created but when the angle of attack becomes larger than 30° the life is decreased which is called *stall* position. When the blades of a wind turbine in a stall position so the flat part would be facing into the direction of wind and the blades are not rotating. On the other hand, *furling* is when the angle of attack becomes smaller, it is also works to reduce rotation of the blades.

One thing that should be considered regarding the rotational speed in combination with the environment issue of noise, the aerodynamic noise is highly affected by the rotational speed, which makes that an important consideration in selecting the rotational speed.

By taking an advantage of Bernoulli effect, the airfoil shape of a blade helps to generate the lift force. The wind turbine blade designers have experimented with many different airfoil shapes over the years in an effort to find the perfect shape that will perform well in a range of wind speeds.

Even minor changes in this blade shape can dramatically affect the power output and noise produced by a wind turbine. In order to optimize the lift and minimize the drag, the shape of blade has to be flatter and narrower toward the tip.

The Tip Speed Ratio (TSR) is an important factor in the wind turbine, the TSR refers to the ratio between the speed of the tips of the wind turbine blades and the wind speed. The TSR is related to efficiency, the higher tip speed gives higher noise levels and require strong blades. The TSR is dimensionless factor and defined by the following equation:

$$\mathrm{TSR}(\lambda) = \frac{\text{Tip speed of blade}}{\text{wind speed}} = \frac{v}{\mathrm{V}} = \frac{\omega \mathrm{R}}{\mathrm{V}}$$

where,

V is the wind speed $[m/sec]$, v is the rotor tip speed $[m/sec]$, R is the distance between the axis of rotation and the tip of the blade $[m]$, $\omega = 2\pi f$ is the angular velocity $[rad/sec]$ and f is the rotational frequency $[Hz]$.

Since the speed of a rotating blade varies from the center to the tip, the angle with which the airflow encounters the airfoil varies along the blade, so the rotor blades should be twisted (see figure 6).

For any tip speed ratio, there is an optimum blade twist can be found out that maximizes the power generated, but when the wind speed changes the twist is no longer optimum. However, there are many ways to deal with that, one of them is the pitch operation which is rotating the whole blade along its axis as the wind speed varies.

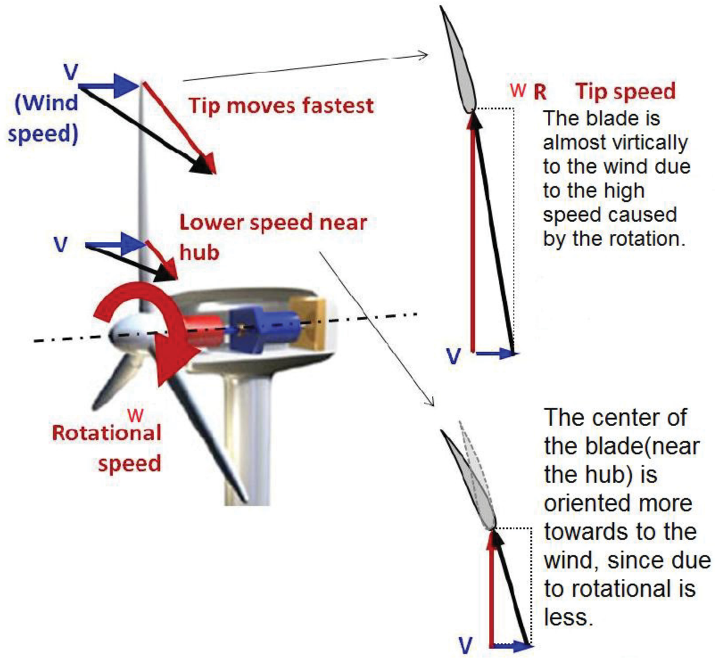


Figure 6 :shows the TSR. (Ref 3)

The optimum tip speed ration depends on the number of blades on the wind turbine. So by having fewer number of blades the faster the wind turbine has to rotate to reproduce maximum power from the wind. The optimum TSR for maximum power output can be obtained by the following equation:

$$\mathrm{TSR}(\lambda)_{\max power} = \frac{4\pi}{n}$$

where n is the number of blades and the time table below shows the optimum TSR with different number of blades by using the mentioned equation.

Number of blades	Optimum TSR
2	Around 6
3	Around 4-5
4	Around 3
6	Around 2

Table1: the optimum TSR with different number of blades.

The Length of Blade:

The blade length is affecting on the performance of the wind turbine, a longer blade will favor the power extraction. However, when the length of the blade increases the deflection of blade tip due to axial wind force also increase as well. So without consider the increase in length of blade may lead to dangerous situation of collision of tower and blade.

The Betz Limit:

Albert Betz, a German physicist, concluded in 1919 that a wind turbine cannot convert more than 59.3% of the kinetic energy of the wind into mechanical energy to turn a rotor and this is called The Betz Limit.

The theoretical maximum power efficiency of any wind turbine designed is 0.59, not more than 59% of the energy carried by the wind can be extracted from a wind turbine which is called "power coefficient" and it is defined as

$$Cp_{max} = 0.59$$

Moreover, the wind turbines cannot be operated at this maximum limit, the Cp value is unique to any type of the wind turbines and is a function of the wind speed that the turbine is operating in. so the real limit is below the Betz limit with values of 0.35-0.45 common even for the best designed wind turbines.

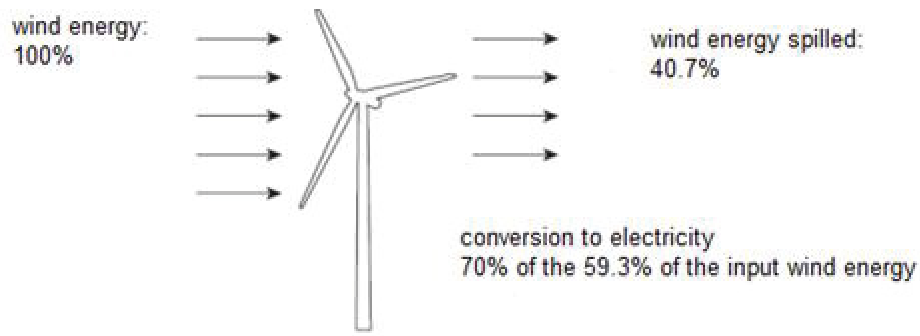


Figure 7: shows the Betz limit (Ref 5).

- **The Hub**:

The hub is the component holds the transmits motion and the rotor together to nacelle and it transmits the loads that which are generated by the blades, most of the hubs are made of steel either cast or welded and there are three main types of them that have been applied in HAWTs.

1- Rigid Hub: it is designed to keep all main parts in a stable position relative to the main shaft, they are the most used design and are roughly universal for machines with three or more blades.

The prime body of a rigid hub is a casting or weld to which the blades are attached and can be connected to the main shaft. However, a rigid hub must have strength enough to withstand all the loads that caused from any aerodynamic loads on the blades. A hub on a pitch controlled turbine should provide for bearings at the roots of blade, a way for securing the blades against all movement except pitching and a pitching mechanism.

The pitching mechanism might use a pitch rod passing through the main shaft to each other with a linkage on the hub. This linkage is connected to the blades roots and rod of the pitch is driven by a motor placed on the main part of the turbine.

Moreover, the hub must be attached to the main shaft in a way that it cannot spin or slip on the shaft, there are two methods used for attaching the hubs. The first method is used to attach the hubs to the wind turbine shafts which is the Ring-feder (Shrink Disc), in a configuration shown, a projection on the slides of the hub over the end of the main shaft and the diameter of the holes inside the hub projection are a little larger than the end of the main shaft.

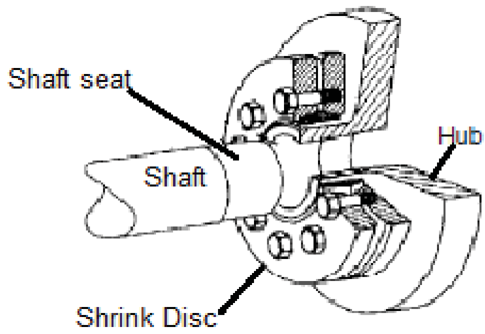


Figure 8: shows a Rigid Hub.(Ref 6)

Moreover, the Shrink Disc consists of two discs and a ring, the interior surface of the ring slides over the outside part of the hub projection and the outside part is sharpened in both axial directions. The two discs are placed on each side of the taper, and pulled to each other with bolts. As they reach each other, the ring is compressed and this, in turn, compresses the hub projection and the compression of the hub projection is clamped it to the hub.
The second method involves the use of a permanent flange in the end of the shaft, the flange might be either added to the shaft or integral and the hub is attached to the flange with bolts.

2- Teetering Hub: this type of hubs are used on roughly all two blades of the wind turbines. The teetering hub can decrease loads due to imbalances of aerodynamic or effects of dynamic from rotation of the rotor or yawing of the wind turbine.

The teetering hub generally more complex than is the rigid hub. Moreover, they consists of at least two prime parts which are the main body of the hub and a pair of trunnion pins as well as dampers and bearings. A typical teetering hub is shown below in figure 9. The main body of the hub is a steel weldment.

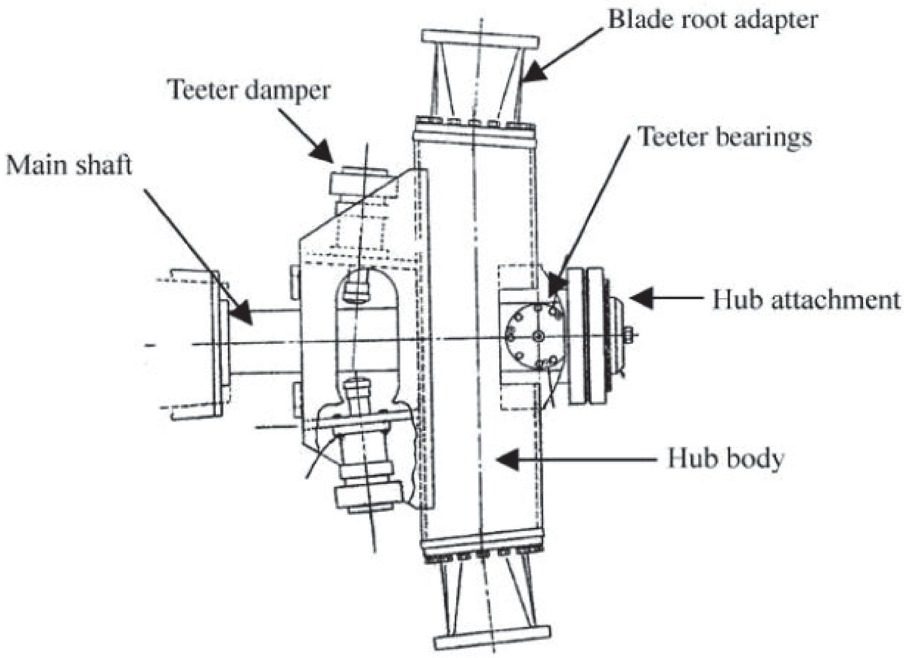


Figure 9: shows the Teetering Hub.(Ref 6)

Most of the teetering hubs have been built for fixed-pitch turbines, but the design of the pitching system is complex since the mechanism of pitching is on the part of the hub which is move proportional to the main shaft.

Moreover, the teetering hubs require two types of bearings, the first one is a cylindrical, radially loaded bearing, the second one is a thrust bearing, there is one bearing of each type on every single pin.

There are two cases for the pin axis, the first one is When the pin axis is horizontal the cylindrical bearings will carry the full load, the second one is when the pin axis is not horizontal, there is an axial component due primarily to the rotor weight. So one of the thrust bearings will carry that part of the load.

A teetering hub moves only a few degrees backwards and forwards during a normal operation, greater teeter excursions can happen by high winds or high yaw rates and to control impact damage of these conditions which that the dampers on the part of the hub opposite the bearings, compliant stops and teeter dampers are provided which has a maximum range allowed of $\pm$ 7 degrees.

3- Hinged Hub:

This type of hubs are basically a rigid hub with hinges for the blades, this hub in some ways a cross between a teetering hub and a rigid hub also the main function of the coupling is to transmit torque between two shafts, but it may have another function too.

However, teetering hub has the advantage that the two blades tend to balance each other, so stiffening of centrifugal lack during low rotation per minute is not a main issue. There is no such counterbalancing on a hinge blade, so some mechanism must be provided to keep the blades from flopping over during low rotational speed.

- **Nacelle**:

It is the housing that protects the components which is attached to it and the prime frame as well, this enclosure is in particular importance for the electric systems of the wind.

However, the nacelle which sits at the top of the tower and is connected to the rotor which consists of the main components of the wind turbine, such as the gearbox, main frame and generator . The nacelle is made of fiberglass and protects the internal components from the environment.

The cover of nacelle is fastened to the main frame, which supports all the other parts inside the nacelle, the main frames are large metal structures that must be able to withstand the large fatigue loads.

- **Yaw Drive**:

It turns the nacelle with the rotor according to the direction of the wind by using a rotary actuator engaging on a gear ring underneath the nacelle. However, it is an important component of the HAWT to ensure that the wind turbine is producing the maximum amount of electric energy all the times.

There are two main types of the yaw drive:

1- The Electric yaw drive, which is commonly used in all of the modern wind turbines.
2- The Hydraulic yaw drive, which is seldom ever used for the modern wind turbines.

- Yaw Mechanism:

HAWT must be oriented to face the wind directions by a process which is called yawing. therefore, the upwind machines with blades upwind of the tower incorporate instead small yaw rotor, a till vane, or fantails to ensure that the machine always faces the upwind.

For the downwind machines blades downwind of the tower have the blades tilted slightly coned or downwind so that they simultaneously act as a tail and this angle ensures proper orientation.

- **Low speed shaft:**

It is the principal – rotating element which is transfer torque from the rotor into the rest of drive train which is transfer power from the rotor to the generator. Moreover, it supports the rotor weight, and it is connected to the gearbox to increase the rotation speed.

- **High speed shaft:**

The high speed shaft transmits the speed and torque from the gearbox and drives the generator to produce electric power.

- **Gearbox**:

The gearbox steps up the speed according to the electric generator requirement. However, gears connected the low speed shaft to the high speed shaft and the rotational speeds increased from about 30 to 60 rotation per minute(rpm) to about 1000 to 1800 rpm, the rotational speed is required by most of generators to produce electricity.

- **Induction Generators:**

The induction generator is the mostly used in wind energy system applications, due to its simplicity and ruggedness, more than 50 years life-time. Moreover, the same machine can be used as a motor or a generator without modification, high power per unit mass of materials and flexibility in the speed range of operation.

The main drawbacks of the induction generator are its lower efficiency and the need for the reactive power to build up the terminal voltage. However, the efficiency can be improved by the modern design and solid-stat converters can be used to supply the reactive power required.

2.3. Safety

Control techniques for the wind turbines:

Since the power is captured from the wind, so it is desired that the power which is captured may be maximized. Also, to ensure that the safety of turbine is not compromised under any circumstances. Thus, control of the power is a most important feature of a wind turbine.

However, to avoid any damage of the wind turbine at very high speeds of wind, the forces of aerodynamic on the rotor can be controlled to limit the power captured.

The giving technique is employed for the same:

Pitch Control:

Through the pitch control, the blades can be turned into or out the wind, and this results in divergence of the force exerted by the wind on the rotor shaft. This type of control has advantages such as a good power control, emergency stop and assisted startup.

Moreover, the pitch control can be used to keep the output of the power close enough to the rated power of the generator. in this case of the drawback is an extra system complexity in the mechanism of the pitch and the higher power fluctuations at high speeds of wind.

Chapter 3

3.0. Statistics

Proposal for New Planning Target for 2020:

The Swedish Energy Agency suggests that the planning target about the wind power for 2020 should be around 30TWh of which 20TWh would be from the wind power ashore and 10Twh would be from offshore (on the water). It means that the wind turbines will increase from less than 900 turbines in 2007 to 3000-6000 units. The goal is to increase the renewable electricity generation by 25Twh compared to the level in 2002, moreover, the electricity from the wind power has increased in 2010 by 3.5Twh to 6.1Twh in 2011, which means that the wind power productions in Sweden has been developed more and more.

However, in 2007 the Swedish wind turbines generated 1.432 terawatts of the electrical energy, that is over 45 percent more than 2006, at that time the generation was less than 1 Terawatt hours.

Swedish Agency financed many wind power research programs as Vindval, Vindforsk III, and the Swedish Wind Power Technology Center(SWPTC), each one of these programs has focused to develop the wind power.

However, the Vindval is a program of a knowledge which is focused on studying the environmental effects of wind power. It runs in period of time from 2009 to 2012 with a budget of 25 million SEK. The Vindforsk III is a technical program which is running between 2009 to 2012 with a budget of 80 million SEK.

The SWPTC in Chalmers institute of technology at Gothenburg city which is running between 2010 to 2014 with a total budget of 100 million SEK, this program focuses on a complete design of an optimal wind turbine, which takes interaction between all components into account.

3.1. Increased Expansion Rate in Sweden:

The expansion rate of the wind power has been grown so fast during 2007. In earlier years, the annual expansion rate was around 50 to 60 megawatts, but it became four times higher in 2007. However, according to the Swedish Wind Energy Association, 129 of the wind turbines with a total output of 217Mw were commissioned during 2007. In the end of 2007 the total installed power was around 788Mw, was distributed onto 958 wind turbines.

3.1.1. Wind Power Development in Sweden:

The wind power has been increased strongly in the recent four years, in general the total effect in Sweden is 3744Mw which is produced by 2403 wind power stations all over Sweden. Moreover, in 2012 the installed effect was 846Mw produced by 366 wind power stations and the production was 7.1Twh which is increased 16% compared to the production in 2011.

Total installed wind generation	2.899 MW
New wind generation installed	755 MW
Total electrical output from wind	6.19 TWh
Wind generation as% of national electric	4.4%
target	30Twh of wind generation by 2020

Table 2: Wind power statistics 2011 in Sweden (Ref 7).

Supply	2010 TWh	2011TWh	Change from 2010
hydropower	66.8	66.0	- 1.2%
Wind power	3.5	6.1	74.3%
Nuclear power	55.6	58.0	4.3%
Other thermal power	19.1	16.8	- 11.9%
Total electrical power output	144.9	146.9	1.4%
Net import/export	2.1	-7.2	-----------
Total domestic electricity usage	147.0	139.7	- 5.0%
Temperature-adjusted electricity usage	144.2	142.5	- 1.2%

Table3 : The energy statistics in Sweden for 2011(Ref 7).

In 2011 Sweden had import and export the electricity from the neighboring countries, which shows that the electricity in Sweden had been grown fast.

TWh	Import / to Sweden	Export / from Sweden
Norway	7.1	7
Finland	4	6.1
Denmark	2.8	5.3
Germany	0.6	2.1
Poland	0.3	1.5
total	14.8	22

Table 4: shows import and export electricity between Sweden and neighboring countries(Ref 7).

In 2011 year, it was the first year when the total amount of plants got installed effect more than 2Mw outnumbered the plants with 1-2MW installed effect.

- Offshore and onshore plants:
  In the end of 2012, the wind power plants in Sweden had 3582 onshore plants with 2605MW installed effect and 164 offshore wind power plants with 163.4MW installed effect.

In 2012 year	MW	Amount of power plants	Produced electricity (T Wh)
onshore	2605	1965	5.59
offshore	163.4	71	0.49

Table 5: the installed effect of onshore and offshore(Ref 7).

3.2. National Incentive Programs:

The promotion of the wind power consist of two main incentive programs, which are electricity certificates and support for technical development in coordination with introduction of market for large-scale plants offshore and in arctic areas.

3.2.1. Electricity Certificates System:

It came into force 2003, and it is created to increase the production of renewable electricity in a cost-efficient way. The increased deployment for the renewable electricity generation will be paid by stipulated quotes that are increased yearly, as well as by a quote of obligation fee.

The precept is that there should be purchasers and sellers of the certificates, and a market to get them together. There are no specify quotes for the wind power, producers of the electricity receive a certificate from the state for each megawatt hour produced from any renewable electricity. This certificate sold to provide additional income above the sale of the electricity, improving the electricity production economics from renewable energy sources and encouraging the new plants construction for the purpose.

The demand for the electricity is created by a requirement under the law that all electricity suppliers and certain users purchase certificates equivalent to a sure proportion of their electricity use or sales, known as their obligation of quote.

The certificate price is determined by demand and supply, and it can be different from one transaction to another.

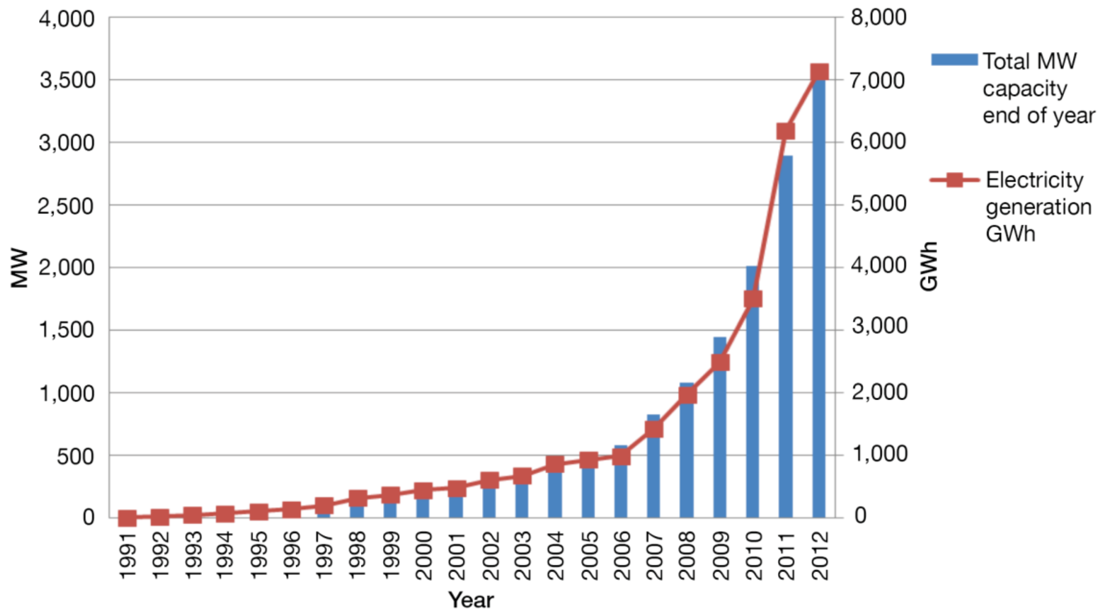


Figure10: shows the installed wind power capacity in Sweden 1991 to 2012(Ref 7).

3.2.2. Support for Technical Development:

The Swedish Energy Agency in 2003, launched a program for supporting the technical development in sort of coordination with introduction of market for large-scale plants offshore and plants in areas of arctic. The goal is to catalyze the market, achievement of the cost reduction, and gain more of knowledge about environmental effects. The budget from 2003 till 2007 was 350 million SEK.

However, the introduction of market program has been prolonged for another five years with an additional 350 million SEK for period 2008 till 2012. These projects were fund up to certain date are shown in the table 6.

Project	Recipient company	Support	location	Estimated production and estimated year of operation
Lillgrund	örestads vindkraftpark AB (owned by Vattenfall)	213 million SEK	Offshore	330GWh; operating since late 2007
Vindpark Vänern	Vindpark Vänern Kraft AB	40 million SEK	Largest Swedish Lake (Offshore)	89GWh; operating in 2009
Uljabouoda	Skellefteå Kraft AB	35 million SEK	Onshore arctic	100GWh in 2008
Kriegers flak	Sweden Offshore Wind AB (VattenfallAB)	9.45 million SEK	Offshore	No production , only development program reported.
Storrun	Storun AB	26.25 million SEK	Onshore	80GWh; 2009
Large scale wind power in northern Sweden	Svevind AB	115 million SEK	Onshore	197GWh; 2009-2011
Large scale wind power in southern Swedish forests	Arise Wind power AB	50 million SEK	Onshore	140GWh; 2009-2010
Large scale wind power in highland areas	O2 Vindkompaiet	72.5 million SEK	Onshore	260GWh; 2011
Havsnäs	NV nordisk Vindkraft AB	20 million SEK		256GWh; 2009-2010
Vindval		35 million SEK		Environment research program

Table 6 : shows the projects with support from the market introduction program (Ref 7).

Chapter 4

4.0. Wind Turbine Generators

The generators is one of the limiting factor in wind turbine, and there is no consensus between industry and academic on the best type of the wind turbine generator technology. In general, there are three main types of wind turbine generators(WTGs) which can be considered as different from one another of the wind turbine systems. The generators are being Direct Current (DC), Alternating Current (AC) synchronous and AC asynchronous generators.

The basic principle, each one of these generators can be run at variable or fixed speed. The fluctuating nature of wind power, cause an advantageous to operate the WTGs at variable speed, which is reducing the physical fatigue on drive train of the turbine and on the blades. By having the variable speed there is improving on the system aerodynamic efficiency and torque transient behaviors. In a power station, several generators are operated in parallel in the power grid to provide the total power needed. They are connected at a common point which is called a *bus.*

4.1. DC Generators Technologies:

In traditional DC machines, the field is on the stator and the armature is on the rotor. The stator consists of a number of poles which are excited either by DC field windings or by permanent magnets (PM). If the machine is eclectically excited, it resort to follow the shunt wound DC generators concept.

An example of the DC wind generators system which is shown in the figure11 .

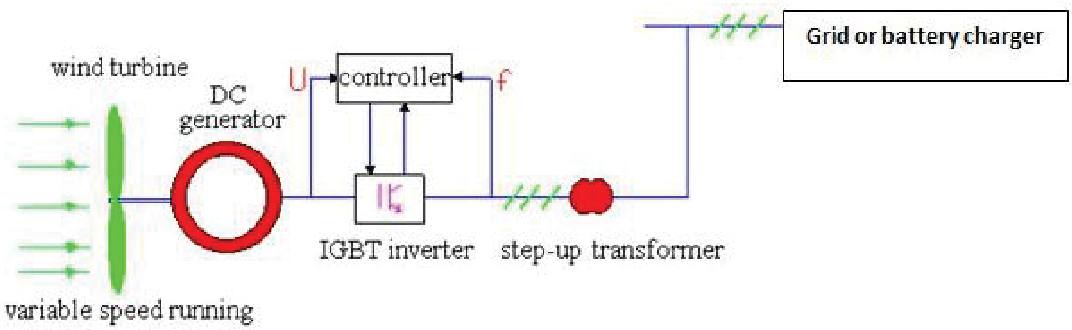


Figure 11: Schematic of a DC generator system(Ref 8).

It consist of a DC generator, a wind turbine, an insulated gate bipolar transistor (IGBT) inverter, a controller, a transformer and a power grid.

To shunt wound the DC generators, the field current and thus magnetic field increases with operational speed whilst the actual speed of the wind turbine determined by the balance between the load torque and the wind turbine drive torque. The rotor includes the wound of conductors on an armature which are connected into a split-slip commentator.

However, the electrical power is extracted out of the brushes connecting the commentator which is used to rectify the generated power (AC) into DC output. In general, they require regular maintenance and it is relatively costly due to the use of brushes and commutators.

4.1. AC synchronous Generator Technologies:

In early time of developing the wind turbine, considerable effects have been made to utilize three-phases synchronous machines. The AC synchronous wind turbine generators can take constant or DC excitations from either electromagnets or permanent magnets and are thus termed Electrically Excited Synchronous Generators (EESGs) and PM synchronous generators (PMSGs) respectively.

Since the rotor is driven by the wind turbine, a three-phase power generated in the stator windings which are connected into the grid through the power converters and transformers. When the speed fixed for the synchronous generators, the speed of rotor must be kept at exactly the same synchronous speed, otherwise the synchronism will be lost.

SGs are a proven machine technology since their performance for the power generation has been studied and widely accepted for a long time. In figure15, it shows that a cutaway diagram for a conventional of synchronous generator. in theory, the reactive characteristics of synchronous WTGs can be easily controlled by the field circuit for the electrical excitation.

However, by using the fixed speed synchronous generators, periodic disturbances and random fluctuation of the wind speed caused by the tower-shading effects and the components natural resonances would be passed onto the power grid.

Moreover, the synchronous WTGs tend to have low damping effect so that they do not allow the transients of drive train to be absorbed electrically. As a consequence, they demand an additional damping element for example; flexible coupling in the drive train, or the gearbox assembly on springs and dampers. While they are integrated to the power grid, synchronizing their frequency to that of the grid calls for a delicate operation.

Moreover, they are generally more costly, complex and more prone to failure than induction generators. In case of using electromagnets in the machines of synchronous, the voltage control is taking place in the synchronous machines while in permanent magnet excited machines, the voltage control is achieving in the convertor circuit.

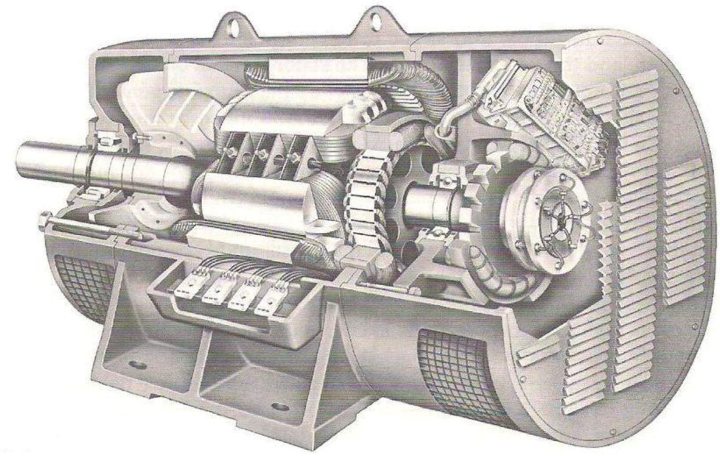


Figure 12: cutaway of a synchronous generator (Ref 8).

In recent decades, PM generators have been progressively used in the applications of the wind turbine due to their low mass and high power density, overwhelmingly these machines are referred to as PMSGs and are considered as the machine of choice in small wind turbine generators. The generator structure is relatively straightforward (figure 16). The rugged PMs are installed on the top of rotor to produce a constant magnetic field and the output electricity is taken from the stator(armature) by the use of the commutators, brushes or slip-rings.

The PMs sometimes can be integrated into a cylindrical cast aluminum rotor which reduces the costs. The principle of PM generator operation is similar to that of synchronous generators except that the PM generators can be operated asynchronous.
The PMGs have many advantages which are the eliminate of commutators, brushes and slip-rings so that the machines are rugged, simple and reliable. The usage of PMs removes the field winding and it is associated the power losses, but it makes the field control impossible.

The PMs can be prohibitively high for large machines, because the actual speeds of wind are variable. Moreover, the PMSGs will not be able to generate electrical power by fixed frequency. As a result of that, they should be connected to the power grid through AC-DC-AC conversion via power converters. Which is the generated AC power with variable magnitude and frequency. It is rectified first into fixed DC then converted back into AC power with fixed magnitude and frequency.

It is also quite attractive to use these permanent magnet machines for a direct drive application. Obviously, in this case they can eliminated troublesome gearbox which causes the majority of the wind turbine failures. The machines should have large numbers of pole and are physically larger than a similarly rated geared machine.

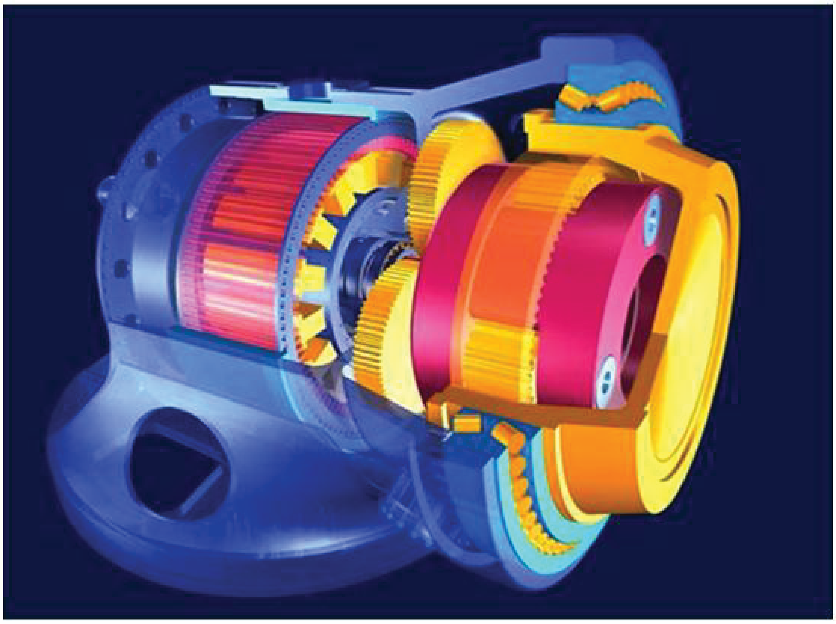


Figure 13: Cutaway of a permanent magnet synchronous generator(Ref 8).

A potential variant of synchronous generators is the High-Temperature Superconducting generator (HTS). See figure17 for a multi-MW low-speed HTS synchronous generator system. The machine consists of the stator copper winding, stator back iron, rotor core, HTS field coils, structure of rotor support, cooling system for the rotor, external and cryostat refrigerator, bearing, housing and shaft and the electromagnetic shield and damper. In the design of this machine, the arrangements of the rotor, stator, gearbox and cooling may compose particular challenges to keep HTS coils in the low temperature operational conditions.

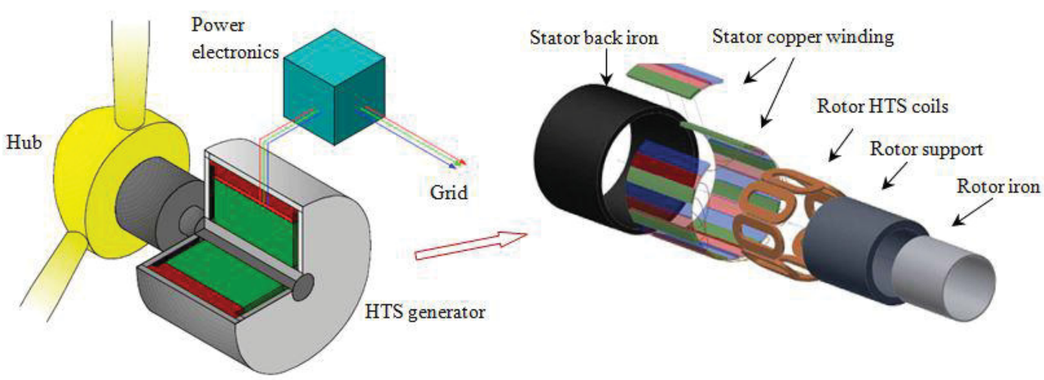


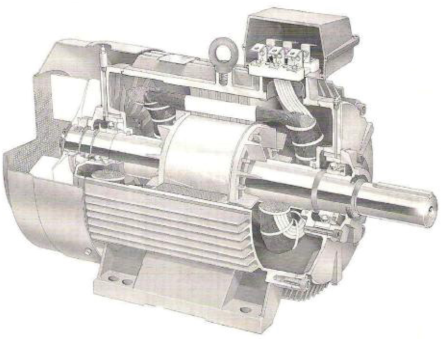
Figure 14: Schematic of a HTS synchronous generator system(Ref 8).

The superconducting coils may carry ten times than conventional of copper wires with conductor losses and negligible resistance. Without a doubt, the usage of superconductors would eliminate all field of circuit power loss and the ability of superconductivity to increase the density of current which allows for high magnetic field, leading to reduction of a significant in size and mass for wind turbine generators. Therefore, the superconducting generators are providing much promise in high capacity and weight reductions, perhaps suited better for wind turbines rated 10 MW or more than that.

In 2005, the world's first superconducting wind turbine generator (SWG) launched by Siemens, this SWG was a 4 MW synchronous generator. In this case, there are many technical challenges to face particularly for the long-life and low-maintenance wind turbine systems. For instance, there is always a need to maintain cryogenic systems so that the time to restore operation and to cool down following a stoppage will be an additional issue.

4.3. AC Asynchronous Generators:

During the conventional power generation utilizes synchronous machines, the modern wind power systems used induction machines widely in the applications of wind turbine. Moreover, these induction generators are divided into two types: induction generators with fixed speed (FSIGs) with a shape as squirrel cage rotors, sometimes it is called squirrel cage induction generators (SQIGs).
The other type is doubly-fed induction generators (DFIGs) with wound rotors. These two types of the induction generators are shown in figure15, 16 and their system topologies are further illustrated in figure 17.



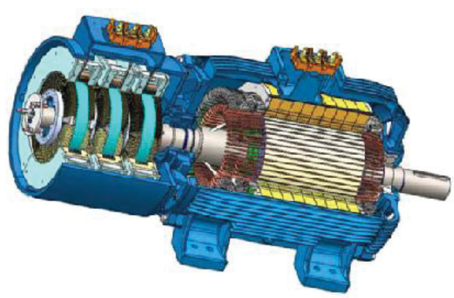


Figure15:Cutaway of a squirrel-cage induction generator, figure16:Cutaway of a doubly-fed induction generator with a rotary transformer(Ref 8).

When the stator supplied with three-phase AC power, a rotating magnetic field is established across the air-gap. If the rotor rotates at speed not the same as the speed of synchronous, a slip is created and the circuit of rotor is energized. In general, the induction machines are reliable, simple, inexpensive and well developed.

They have high degree of damping and drive train transients and are capable of absorbing rotor speed fluctuations.

However, induction machines draw reactive power from the grid and thus some form of reactive power compensation is necessity such as the use of power convertors or capacitors. For FSIGs the stator is connected to the grid by a transformer and the rotor is connected into the wind turbine through a gearbox. The speed of rotor is considered to be fixed. In fact, it is varying within a narrow range.
In 1998, the most wind turbine manufacturers built fixed-speed induction generators of 1.5 MW and below. These generates generally operated at 1500 revolution per minute (rpm) for the 50 Hz utility grid.

SCIGs can be utilized in variable speed wind turbines, as in controlling synchronous machines. As though, the output voltage cannot be controlled and reactive power needs to be supplied externally. Obviously, the induction generators with fixed speed are limited to operate only with a very narrow range of discrete speeds. The other disadvantages of the machines are related to the machines size, low efficiency, noise and reliability. These machines have proven to cause tremendous service failures and consequent maintenance.

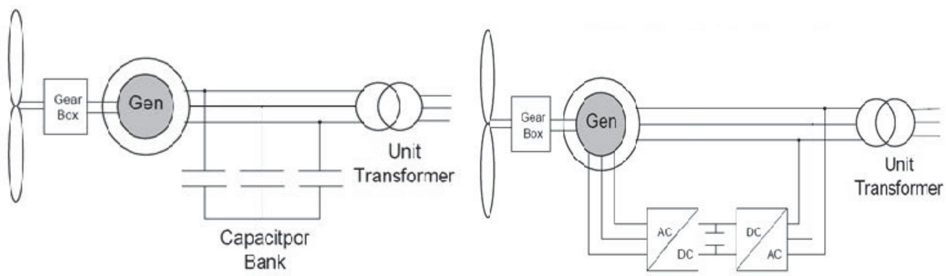


Figure 17 (b): fixed-speed induction generator (Ref 8). (a) with power electronic convertors (Ref 8).

The SCIGs led wind turbine market until the last millennium and overtaken by wide adoption of DFIGs. In present, over 85% of the installed wind turbines utilize DFIGs. The commercial wind turbine product has increased towards 5 MW in industry with DFIG.
In the topology of DFIG, the stator is directly connected into the grid through transformers, on other hand the rotor is connected to the grid through plus-width modulation (PWM) power converters. The converters can control the rotor circuit current, phase angel shifts and frequency. Such induction generators are capable of operating at a wide slip of range, typically -30% or +30 % of the synchronous speed. Moreover, they offer many advantages such as high yield, reduction in mechanical stresses and power fluctuations, and controllability of reactive power.
Moreover, all the reactive power in the induction generators are energizing the magnetic circuit and must be supplied by local capacitors or the grid. These generators are prone to voltage instability. Since the capacitors are used to compensate factor of power, there is a risk by causing of self-excitation. In addition

the damping effect may give rise to power losses in the rotor. There is no direct control over the terminal of voltage for thus reactive power, neither the sustained fault currents.
The reactive power in DFIG is used to evaluate the power output and reactive power is responsible for its electrical behavior in the power network. The DFIG needs some amounts of reactive power in order to establish its magnetic field. In case of grid-connected systems, the generator obtains the reactive power from the grid itself. In condition of isolated system operation, the reactive power requires to be provided by external sources such as batteries or capacitors.

As shown in figure 20(b), the rotor of the DFIG is mechanically connected into the wind turbine through a drive train system, which might contain low and high speed shafts, bearings and a gearbox. The rotor feeds by the bi-directional voltage-source convertors. Thereby, the torque and speed of DFIG can be regulated by controlling the rotor side convertors (RSC). Another feature is that DFIGs can operate both sub-synchronous and super-synchronous conditions.

The stator always transfers power to the grid while the rotor can handle power in both directions. The final is due to the fact that PWM convertors are capable of supplying current and voltage at different phase angels. In the operation of sub-synchronous, the RSC acts as an inverter and the grid-side converter (GSC) as a rectifier. In this case, the active power is flowing from the grid till the rotor. When the super-synchronous under condition the RSC operates as a rectifier and the GSC as an inverter. As a result, the active power is flowing from the stator as well as the rotor till the power grid.

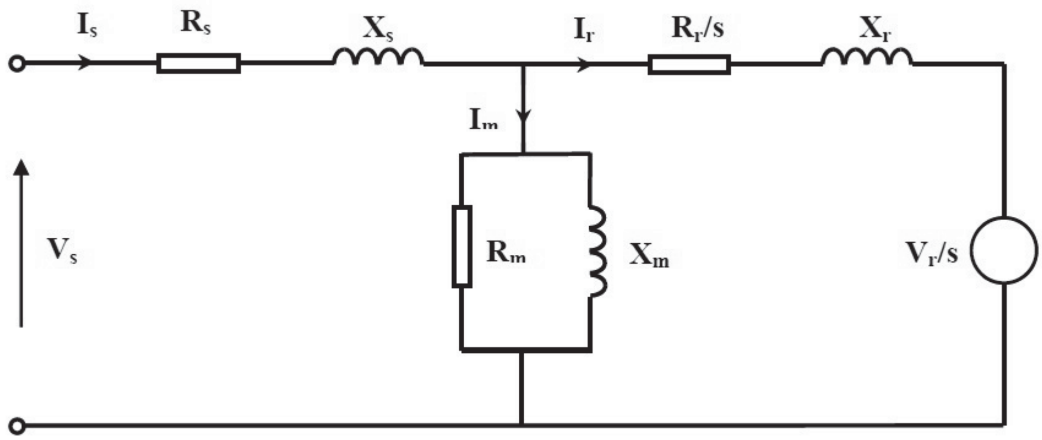


Figure 18: Per-phase equivalent circuit of the DFIG (Ref 8).

To analyze the performance of DFIG, it always needs to adopt its per-phase equivalent circuit, as shown in figure 21. From the figure, it can be seen that the DFIG differs from the conventional induction machine in the rotor circuit which a voltage source is added to inject voltage into the rotor circuit. The actual *d-q* control of the DFIG is similar to the phase and magnitude control of the injected voltage in the circuit.

The matrix form of the equation for this circuit is:

$$\begin{pmatrix} Vs \\ Vr/_{S} \end{pmatrix} = \begin{pmatrix} Rs + j(Xs + Xm) & -jXm \\ -jXm & \frac{Rr}{S} + j(Xr + Xm) \end{pmatrix} * \begin{pmatrix} \mathrm{I}_s \\ \mathrm{I}_r \end{pmatrix}$$

The input power P_{in} can be obtained from the output power P_{out} and the total loss P_{loss}. The latter includes the stator conductor loss P_{cu1}, core loss P_{core}, rotor conductor P_{cu2}, wind age and friction losses P_{wf} and stray load loss P_{stray}. Among all these losses, P_{cu1} is assumed to vary with the square of the stator current I_s while P_{cu2} varies with the square of the rotor current I_r.

However, the stray load loss could be divided into two parts: the fundamental component P_{fun} occurring at the stator side and P_{har} at the rotor side. Thus P_{har} is proportional to $(\mathrm{I}_r)^2$ while P_{fun} is proportional to $(\mathrm{I}_s)^2$. Which P_{har} means harsh or high temperature environment.

The total loss is given by :

$$\boxed{\mathrm{P}_{loss} = 3(\mathrm{I}_s)^2(\mathrm{R}_s + \mathrm{R}_{fun}) + 3\,(\mathrm{I}_r)^2(\mathrm{R}'_r + \mathrm{R}_{har}) + \mathrm{P}_{core} + \mathrm{P}_{wf}}$$

Where we can get the efficiency of the DFIG by:

$$\eta = \frac{\mathrm{P}_{out}}{\mathrm{P}_{in}} = \frac{3\mathrm{V}_{out}\cos\varphi_r}{6\mathrm{I}_s(\mathrm{R}_s + \mathrm{R}_{fun} + \mathrm{R}'_r + \mathrm{R}_{har}) + 3\mathrm{V}_{out}\cos\varphi_r}$$

the efficiency can be expressed as a function of the current load I_s and this function is monotonic and continuous. As a result, the maximum efficiency can be found by:

$$\frac{\partial\eta}{\partial\mathrm{I}_s} = 0$$

Then, the condition of the maximum efficiency for DFIG is:

$$\mathrm{P}_{core} + \mathrm{P}_{wf} = \mathrm{P}_{cu1} + \mathrm{P}_{cu2} + \mathrm{P}_{stray}$$

Chapter 5

5.0. Electric Power Transmission

The electric power transmission is the bulk transfer of electrical energy, from the generated power plants to electrical substations which are located near of demand centers. This is distinct from the local wiring between customers and high-voltage substations which is typically referred to as electric power distribution. When the transmission lines interconnected to each other became transmission networks. The combined distribution networks and transmission is known as the power grid. Figure 23 shows the power system components .

5.1. Power System Components:

1- Transmission system

- 69 KV and above.
- Less than 2% of all outages are due to transmission system outages.

2- Sub-transmission system:
- 35 KV.
- Sometimes 69 KV.

3- Distribution system:

- 25 KV and below.

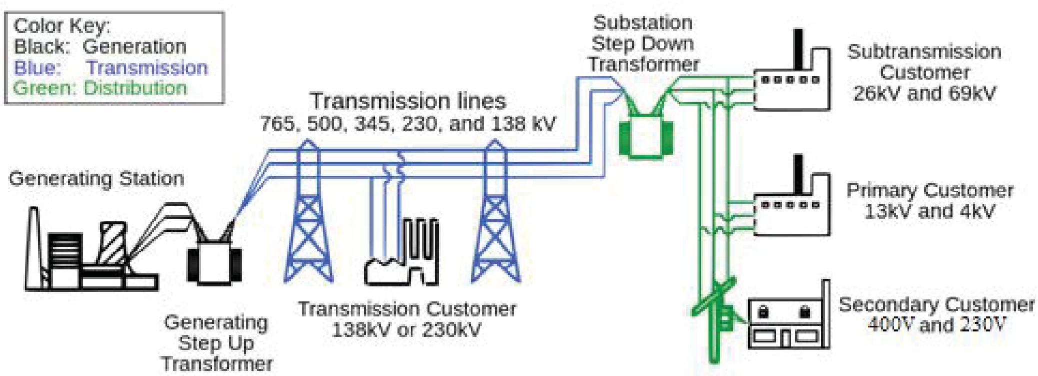


Figure 19: electric power system and the transmission lines (Ref 9).

5.2. Transmission Lines:

Most of the transmission lines are three phases high voltage alternating current (HVAC), also single phase AC which is used in railway electrification system. In other hand, the high voltage direct current (HVDC) technology is mostly used for greater efficiency at very long distance typically hundreds of kilometers.

HVDC links are used also to settle down and control problems in large power distribution networks, where unexpected new loads or blackouts in one part of a network can cause cascading failures and synchronization problems. The electricity is transmitted at high voltage 120 KV or above than that, which means the energy losses will be reduced in long distance transmission.

There are two main types of transmission lines:

5.2.1. Underground Power Transmission:

It can improve the reliability of the electric power system by minimizing damage to the system from

- Ice and snow storm
- Falling trees
- High winds

If a part of the system is impervious to storm caused damage faster restoration of the system is possible.
However, the construction of underground is not immune from all storms damage for example; earthquake damage and rodent and human damage (dig up).

5.2.2. Overhead Power Lines:

The transmission-level voltages are usually considered to be 110 KV and above. For the lower voltages, such as 66 KV and 33 KV are usually considered as sub-transmission voltages, but sometimes are used on long lines with light loads. Since the wires of overhead transmission depend on air for insulation, so the design of these lines requires minimum clearances to be observed to maintain safety.

The amount of power which is generated in the power station (hundreds of MW) is to be transported over a long distance with the help of transmission lines and transmission towers as shown in figure 20:

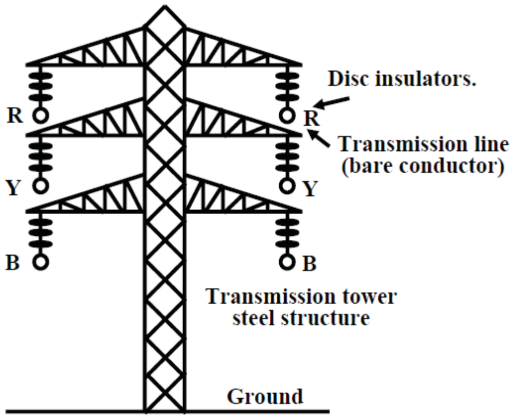


figure 20: transmission tower(Ref 10).

Example: a generating station producing 120 MW power and we want to transmit it over a long distance. The generated voltage is 10 KV, we can easily obtain the current by using power formula circuit for three phases:

$$I = \frac{\mathrm{P}}{\sqrt{3}\ \mathrm{VL}\ \cos\theta}$$

$$I = \frac{120\ \mathrm{MW}}{\sqrt{3} * 10\mathrm{KV} * \ 0.8} = 8660A$$

Where;

P is the power transmitted.

VL is the generated voltage(line to line).

Cosθ is the power factor.

If the transmission voltage is high the current value in the line would be smaller. So the copper conductor will be much smaller, which means that the cost of conductor will be reduced if the power is transmitted in the higher transmission voltage. The advantage by having a higher voltage is reducing voltage drop in the line of reactance and resistance. Also the transmission losses would be reduced.

However, after the generator the step up transformer placed to change the generated voltage to desired the transmission voltage, which is an important step before transmitting it over a long distance with the help of transmission lines supported at regular intervals by transmission towers.

At the load centers voltage level should be brought down at suitable values for supplying different types of consumers by using step down transformer.

The consumers consist of three types:

1- Big industries, such as steel plants.
2- Medium and small industries.
3- Offices and domestic consumers.

5.3. Substations:

Substations are the sites where the level of voltage undergoes change with the help of transformers. Apart from transformers a substation will house switches meters(circuit breakers), relays for protection and other control equipment. In general, a big substation will receive power through incoming lines at some voltage values then the voltage level changed by using a transformer and direct it out wards through outgoing lines.

Typical power system is shown in figure 21. At the lowest voltage level of 400 V, three phases and four wires, the system is adopted for domestic connections. The Fourth wire is called the neutral wire N which is taken out from the common point of the star connected secondary of 10 KV/400 V distribution transformer.

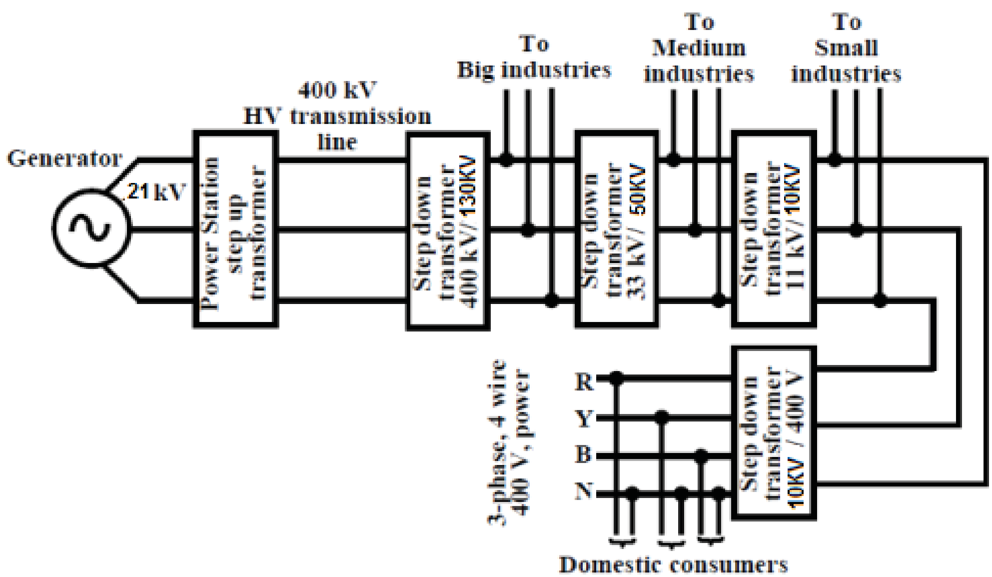


Figure 21: typical voltage level in a power system(Ref 10).

Chapter 6

6.0 General Wind Park Layout

In general, the wind parks can be presented by the flowing figure 22:

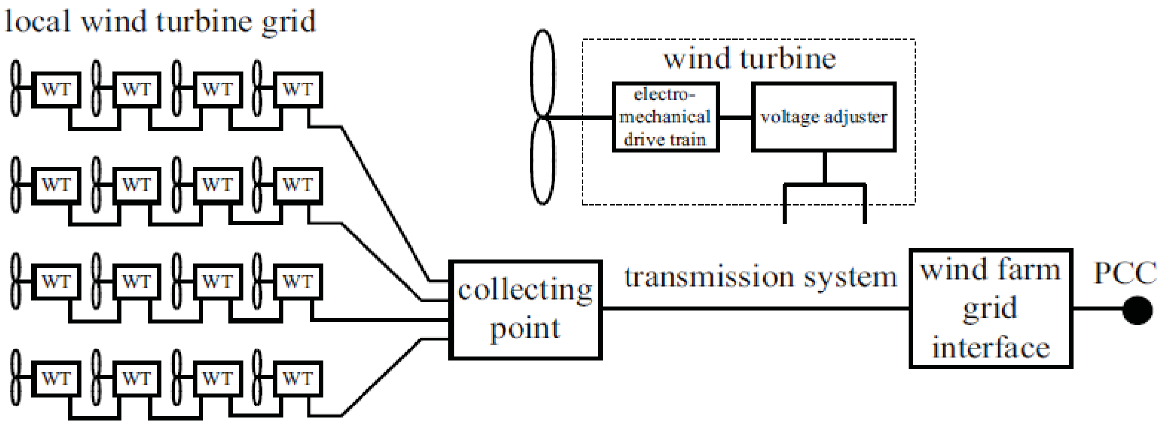


Figure 22: general wind park layout (Ref 11).

As shown in the figure the wind park consist of a number of elements, which are wind turbine, local wind turbine grid, transmission system, collecting point and wind park interface to the point of common connection (PCC). In all wind turbines in the above figure have a voltage adjusting (AC or DC transformer) included in the WT itself. In more details, the local WT grid connects the WT units to the collecting point and the WT units are connected in parallel to radials.

However, the voltage is increased to a level suitable for the transmission system and this operation can be done by the collecting point. The energy is transmitted to the wind park grid interface over the transmission system. The wind park grid interface adapts the frequency, voltage and the reactive power of the transmission system to the frequency, voltage level and reactive power demand of the grid in PCC.

6.1. Rated Power of The Wind Park, Number of Turbines:

The size of the wind turbine has in this thesis been selected to 2 MW, since these turbines are available for all types of wind energy system today. The main results of this thesis would most likely not be very different if another turbine size would have been selected. Most likely, the generator voltage will be increased when the rated power of the generator is increased in order to decrease the losses.

Most commonly wind parks size are:

- 60 MW
- 100 MW
- 160 MW
- 300 MW

The most wind parks today are much smaller than 60 MW, which is used as a small wind park in Sweden. Horns Ref is an example of a 160 MW offshore wind park which is 14 to 20 km out of the west cost of Denmark. In fact there is no larger wind parks than 300 MW have been built, if a larger wind park is going to be build it will be divided into smaller modules. Where a maximum module size of 300 MW seems appropriate.

There are two advantages by using modular building of wind parks, which are the investment cost of the whole wind park is spread out over a longer period of time and that part of the production can be started before the whole park has been totally built. The other advantage of the division is that if cross connection among the modules are made, the park will be more fault tolerate.

6.2. Distance Between the Wind Turbines:

In this thesis will take the Horns Ref wind park as an example since the distance at Horns Ref is 7 rotor diameters. Into account, the distance between WT in the wind direction cannot be too small. This is due to the fact that when wind passes through the rotor of the WT it gets very turbulent and the wind speed is decreased. Which means that if the WTs are located to close to each other, the wind will be more and more turbulent after it passes through each single wind turbine. This would lead to that WTs downstream in the wind park, are subjected to aerodynamically stress, it might even have to shut down due to that mechanical loading gets to high during strong conditions.

Moreover, the energy losses due to the reduced wind speed will be significant when the WTs are placed too close to each other. The minimum length of the rotor to avoid that issue, it should be approximately 5-7 rotor diameters. In fact, if the wind is coming from one direction the WTs can be located in the direction perpendicular to the prevailing winds. But for the Nordic countries the wind directions of wind from northwest to south are quite normal, so the WTs should be placed with an equal distance in all directions

6.3. AC/DC Wind Park

The AC transmission in this system has been replaced with a DC transmission, this wind park known as the AC/DC wind park. This type of system does not exist today, but its frequently proposed when the distance to the PCC is long, or if the AC grid that the wind park is connected to is weak.(see figure23)

In this system we have an independent local AC system in which both the frequency and voltage are fully controllable with the offshore converter station. This can be used for a collective variable speed system of all WTs in the park. The advantages with this are the electric efficiency and the aerodynamic can be increased.

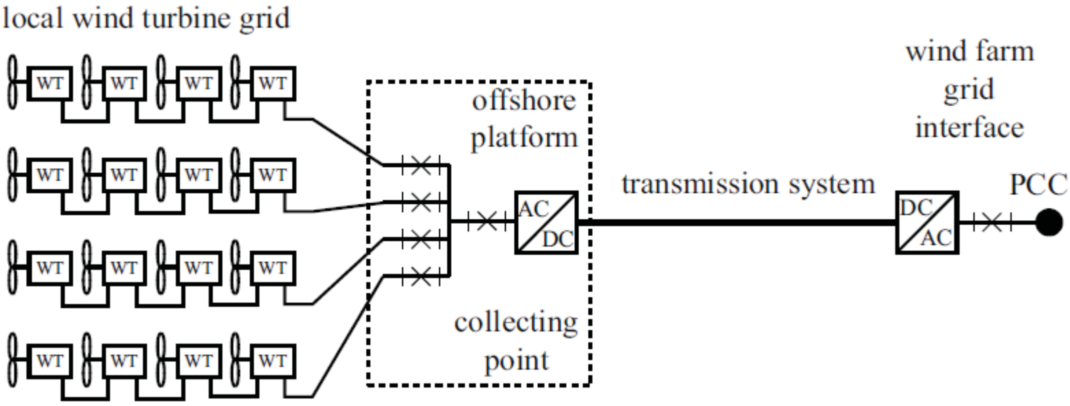


Figure 23: Electrical system of AC/DC wind park(Ref 11).

The two DC transmission cables, one for the negative pole and the other one for positive pole, are assumed to be installed together and therefore there is only one cable installation cost for both of them.

6.3.1.Large AC Wind Park

In this type of system, the WTs are connected to an offshore substation, where the voltage is adjusted to minimize the losses of transmission and reactive power compensation devices are placed.
However, the voltage levels are dependent on the distance to shore and the wind park power rating. The Horns Rev offshore wind farm was built by the Danish utility group Elsam in 2002 and consists of 80 Vestas V80/2Mw wind turbines. The same example was taken before, at Horns Ref the offshore grid voltage is 36 KV while the transmission voltage is 150 KV. The installed power is 160 MW from 80 wind turbines. The wind turbines have been erected 560 meters from each other and they are arranged along 10 lines each with eight turbines as shown in figure 24.

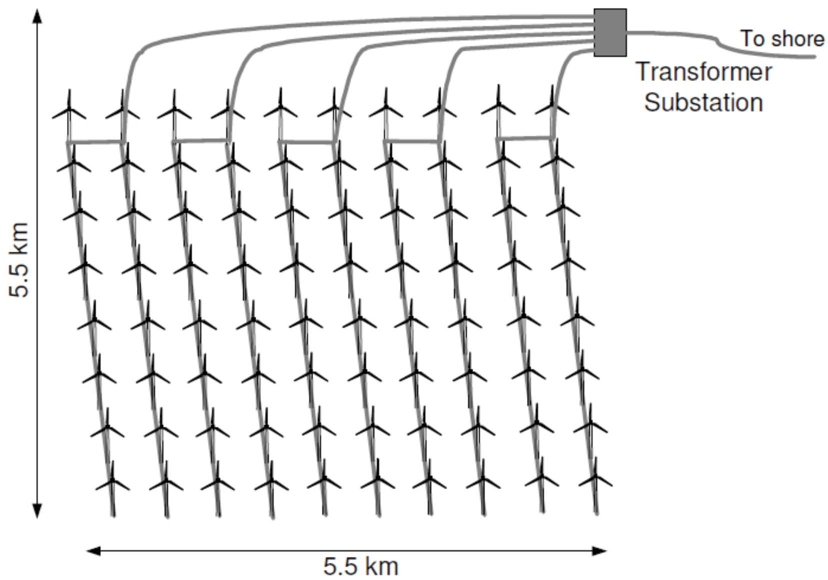


Figure 24: Connection of the turbines to the offshore transformer substation(Ref 11).

Turbine type	Vestas V80/2mw
Rotor type	3 blades
Rotor position	Upwind
Rotor diameter	80 m
Generator type	Doubly –fed induction generator
Generator rated power	2000 kw
Generator number of poles	4 poles
Hub height	70 m

Table 7: the data used in Horns Rev wind farm (Ref 11).

This solution is appropriate for relatively large wind parks that are placed at a long distance from the shore. The limit of transfer for the AC transmission system depends on the distance from shore and is therefore physically limited by this.

A solution to that could be to decrease the offshore frequency and use an offshore with low frequency of AC networks, a suggested by for instance (Schütte, Gustavsson and Ström 2011). The usages of a low frequency system are in electrified railway systems, where the frequency ranges from 16.67 Hz to 25 Hz.

There are two main advantages by using a low frequency of AC network: firstly, the lowered frequency would increase the transfer capability of transmission system, as the capacitive is charging current of the cable is reduced when the frequency drops. The disadvantage of that is the size of transformer would be increased, and hence, the costs of transformer will increased too.

Secondly, the network of a low frequency would allow a simpler design of the offshore WTs. The aerodynamic rotor of a large WT operates at maximum revolutions at 15-20 rpm, and the lower frequency would then allow a smaller gear ratio for turbines with a gearbox, or decrease the poles number for WTs with direct driven generators. This would lead to lighter and cheaper turbines.

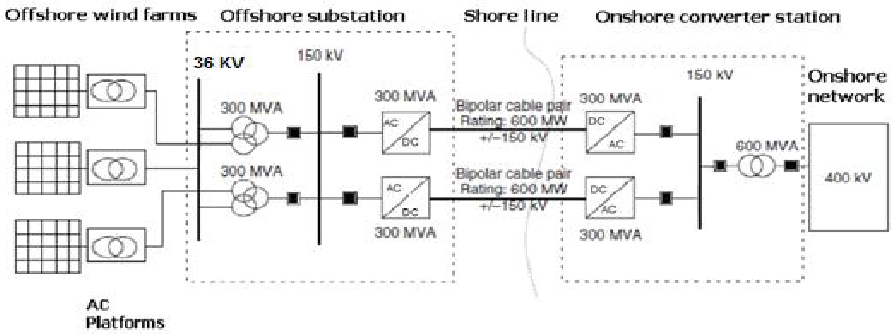


Figure 25: offshore HVDC link connecting 600 MW wind park(Ref 13).

6.3.2. The Frequency Control (or primary control):

Frequency control affects the whole of the Union for the Coordination of the Transmission of Electricity (UCTE) grid. The frequency control is carried out on a proportional basis by the UCTE participants. Fast and large frequency may occur if smaller areas are isolated from the grid, and in that case the wind farms must be able to participate in frequency control. This type of control mode should be implemented in the WTs with adjustable droop and dead-band for both control directions.

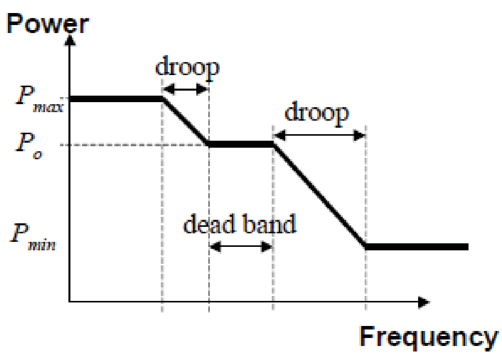


Figure 26: requirement for automatic frequency control with adjustable droop and dead-band (Ref 14).

The frequency control includes dead band and droop as shown in figure 26. In normal operation, the power set-point P_0 will be equal to the maximum available power P_{max}. The power-frequency characteristics in the shown figure will be drooped for over-frequency, because there is no reserve power available for under-frequency.

The main reasons to require the frequency control implemented in the individual wind turbines:

- The frequency control response should be as fast as possible. Implementing the frequency control in the WTs, it would not be slowed down by the communication between the WTs and the wind farm controllers.
- It is an important to not implemented the frequency control and power control in the wind farm controller by shutting down some of the WTs, but that the wind farm is reduced by reducing power on all the WTs and keeping all WTs on-line.
- By requiring control in individual WTs, the requirement for single WT installations would be the same as for WTs in the wind farms.

The requirements to the wind farm regarding operation at frequencies deviating from the rated frequency 50 Hz are as follows:

Under-frequency	Below 47 Hz	Disconnection compulsory after 0.3 second
	Below 47.5 Hz	Disconnection allowed after 10 second
	Between 47.5 and 48 Hz	At least 5 min operating time is required
	Between 49 and 50 Hz	Unlimited operating time is required
Over-frequency	Between 50 and 50.3 Hz	Unlimited operating time is required
	Between 50.3 and 51 Hz	At least 1 min operating time is required
	Above 53 Hz	Disconnection compulsory after 0.3 second

Table 8: controlling the frequency (Ref 14).

6.3.3. Components of an HVDC Link in Offshore Wind Farm:

- A collector platform of AC can collect power from more than one wind farm. In that case there must be more than one offshore AC collection platforms.
- An HVDC converter station comprises of HVDC converters. The AC/DC rectification is accomplished at the converter station which is normally offshore.
- Pair(s) of DC cables which is connected the offshore HVDC converter station AC/DC to an onshore HVDC converter station DC/AC.
- Onshore HVDC converter station which converts the power back to 50Hz.

The main components for the grid connection of the wind turbine are the transformer and the substation with circuit breaker and the electricity meter inside it. Because of the losses in low voltage lines, each turbines has its own transformer from the voltage level of the WT (400 or 690V) to the medium voltage line. The transformers are located directly beside the wind turbine to avoid long low-voltage cables. The small WTGS can be connected directly to the low voltage line of the grid without a transformer.

Moreover, in a farm of small wind turbines, it is possible to connect some of the WT into one transformer, for the large wind farms a separate substation for transformation from the medium voltage system to high voltage system is necessary. At the point of common coupling (PCC) between the single wind turbine or the wind farm and grid a circuit breaker for disconnection of the WT or the whole wind farm must exist.
The circuit breaker is located at the medium voltage system inside a substation, where the electricity meter for the settlement purposes is installed as well.

6.3.4. Description of the Gotland Electrical System:

The turnover of energy in the system is 850GWh, the peak load is 160 MW and the minimum load is 40 MW. It is a meshed 70Kv system with some radial 30Kv lines and there is the distribution grid. Most of all loads are located near of the connection point of the existing HVDC link from the mainland in the north part of the island of Gotland.
In 2003, there were 165 windmills with total installed power of 90MW producing about 200GWh, which is double what it was when the decision was taken to built the HVDC Light in 1997.

The Gotland light project in Sweden, which is operated since 1999. The rating of Gotland HVDC light system is 50 MW and 65 MVA and it is connected in parallel with the existing 70KV/30KV AC grid. The system of Gotland island has a peak load of about 160 MW and today there are a total of 165 windmills with an installed power of 90 MW, which is producing about 200GWh. The short circuit power from the AC grid is less than 60 MVA at connection point in Näs, which the wind power production is connected for the HVDC light system.

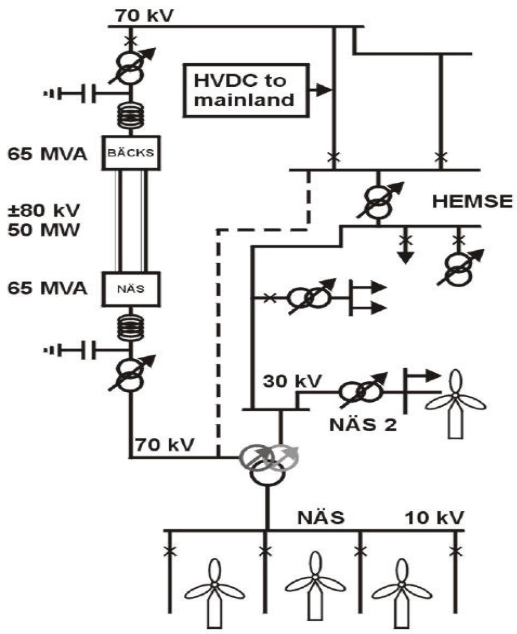


Figure 27: the Gotland network (Ref 12).

The operator of the grid, Gotland Energi AB (GEAB) considered, that HVDC light would be the only realistic way to solve the technical problems for the high amount of wind power in-feed. The experiences have supported expected improvements in the characteristics for example:

- Stability in the system arose.
- Reactive demands, power flows, as well as voltage level in the harmonic and system were reduced.
- Flicker problems were eliminated with the installation of HVDC light and transient phenomena disappeared.

One result is that the stability of voltage during transient events, has become much better by using HVDC light, which improves the output current stability from the asynchronous generators. This reduces the stresses on the AC grid and on the mechanical construction of the windmills. Overall experiences are that the control of power flow from the converters makes the AC grid easier to observe than a conventional AC network and the power variations do not stress the AC grid as much as in normal network. Voltage quality has been better with the increased wind power production.

6.4. The Causes of Blackouts:

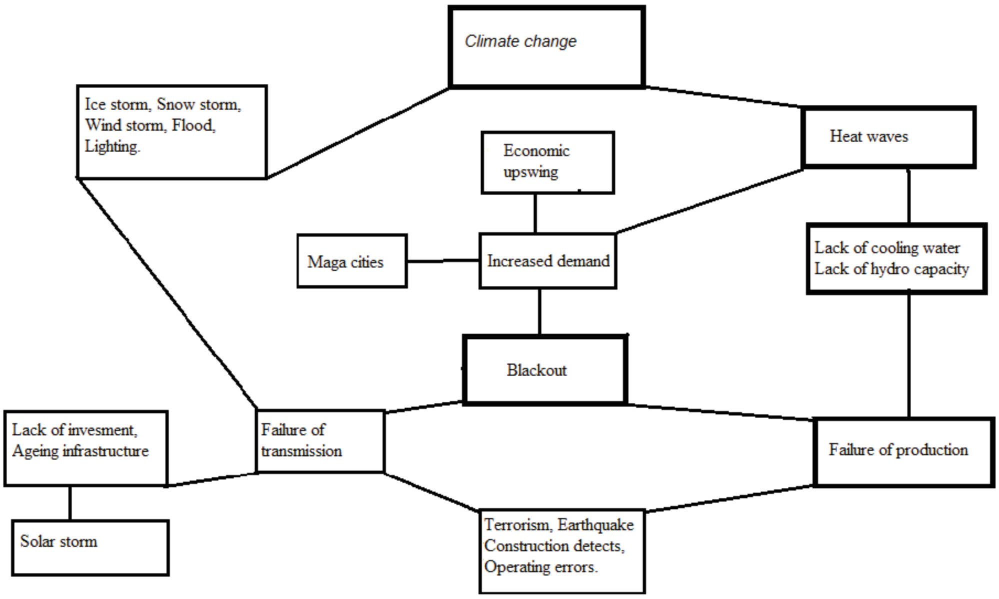


Figure 28 : causes of black outs in general (Ref 15).

Typical power blackouts are not caused by a single event. There is no outage known where a faultless due to a single cause. The following preconditions are the basis for a high power outage risk:

- High grid utilization or high power demand.
- High power plant utilization .
- Defects due to material ageing.

the HVDC transmission is a efficient and safe technology designed to deliver large amounts of electricity over long distance. HVDC was first developed in the 1930s by ASEA, the Swedish electrical conglomerate and one of the founders of ABB.

The ability of HVDC light converters to generate a voltage that can be changed very fast in amplitude and phase, offers the possibility of energizing a network after a blackout. HVDC light can help the restoration in the event of power disruptions, when the frequency and voltage support are much needed. That was proven during August 2003 blackout in the Northeastern U.S by the excellent performance of the Cross Sound cable link that interconnects Connecticut and Long Island.

In a power disruption event, a black start capability can be implemented in HVDC light systems. This can help the operator of an HVDC light to speed up grid restoration, because the lack of energy (typically in the first 6-24 hours) might initiate considerably higher prices for the energy.

However, since the electricity is a basic need in today's world, a blackout carries very large social and economic losses. Thus requiring a way to achieve system restoration as fast as possible. Power system restoration (PSR), after a general blackout is a time consuming task and complex, which is dependent on specific characteristics of the power system in analysis.

In order to reduce the restoration times, plants such as large wind farm that can be quickly connected to the grid through HVDC.

Chapter 7

7.0. conclusion

In general the wind turbines with three blades accommodated a thicker root are used. It is obvious that, the less number of blades on the wind turbine, the cost of material and manufacturing will be lower.

It is worthy to mentioned that, the modern wind turbine has been built with an odd number of blades. When the length of the blade increases the deflection of blade tip due to axial wind force also increase as well. So without consider the increase in length of blade may lead to dangerous situation of collision of tower and blade. Moreover, by increasing the number of blades cost of the system would increased as well.

The limit of transfer for the AC transmission system depends on the distance from shore and is therefore physically limited by this. AC large wind parks that are placed at a long distance from the shore, which means AC long transmission line, and more drop voltage

A solution to AC long transmission line, it could be to decrease the offshore frequency and use a low frequency AC networks. There is a suggestion by for instance (Schütte, Gustavsson and Ström 2011). The usages of a low frequency system are in electrified railway systems, where the frequency ranges from 16.67 Hz to 25 Hz.

However, the network of a low frequency would allow a simpler design of the offshore WTs and The aerodynamic rotor of a large WT operates at maximum revolutions at 15-20 rpm. The lower frequency would then allow a smaller gear ratio for turbines with a gearbox, or decrease the poles number for WTs with direct driven generators. This would lead to lighter and cheaper turbines.

One of the disadvantages by using a low frequency system is the size of transformer would be increased, and hence, the costs of transformer will increased too.

The operator of the grid, Gotland Energy AB (GEAB) considered, that HVDC light would be the only realistic way to solve the technical problems for the high amount of wind power in-feed. The experiences have supported expected improvements in the characteristics for example:

- Stability in the system arose.
- Reactive demands, power flows, as well as voltage level in the harmonic and system were reduced.
- Flicker problems were eliminated with the installation of HVDC light and transient phenomena disappeared.

Moreover, Overall experiences of Gotland Energy AB (GEAB) are that the control of power flow from the converters makes the AC grid easier to observe than a conventional AC network and the power variations do not stress the AC grid as much as in normal network. Voltage quality has been better with the increased wind power production.

A topic to study in the future is the consequences of blackouts in power supply with many wind power farm.

Chapter 8

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