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windEXT

Advanced maintenance, lifetime extension and repowering of wind farms supported by advanced digital tools

Project nº 612424-EPP-1-2019-1-ES-EPPKA2-KA

MODULE B: General description and critical components

WP4

Written by

TU Delft

Project consortium

SUB-MODULE A

Components description

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Summary

This part of the training material will allow students to gain a basic understanding of how a wind turbine is designed and operated, including a description of the basic components. The students will should an appreciation of how the components function as a system and how wind turbines are connected to the grid in the form of a wind farm including aspects of layout optimisation, e.g. minimisation of wake losses. Students will be taught about the common faults that are experienced by a wind turbine, their root causes and consequences. Through the use of simulation software, students will be able to see how common problems such as yaw and pitch misalignment give rise to reduction in power output and adverse loads.

Learning Outcomes:

- To understand the purpose of function of the major components of a wind turbine
- To understand how a wind turbine generator works as a system including the loads experienced and the power generated
- To understand how a wind turbine is controlled
- To understand how wind turbines are operated together efficiently as a wind farm including the role of other balance of plant, e.g. the network
- To be able to describe the common faults experienced by a wind turbine, including their frequency and severity
- To understand the underlying causes and consequences of common faults
- To experience how common problems such as pitch and yaw misalignment affect power output (and loads)

Training Materials

- Online lectures
- Written material
- Visualisation software
- Interactive simulation software
- Online assessment (e.g. multiple-choice questions)

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Section 1

Course structure

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Section 1 Course structure

1.1. Introduction to the course

This module introduces the basic subassemblies of a wind turbine. A description is given of what they look like, what they do and some underlying theoretical principles. The information will be given in the form of written text, diagrams and videos. By the end of module, the student should have a good appreciation of the basic operating principles of a wind turbine and how the various subassemblies fit together as a system.

1.2. Course structure

The information in this module is divided up into subsections which describe the major subassemblies or basic 'building blocks' of a wind turbine. Videos and 3D visualisation tools are provided to give you a better understanding of what each subassembly looks like 'in real life'. At the end of each section a series of questions will be asked to see if you have understood the basic principles of each subassembly

1.3. Course objectives

1.4. Course organization(e.g. Discussion forums, Hangout sessions, Evaluation procedures, etc.)

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Section 2

Introduction to wind turbine components

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Section 2 Introduction to wind turbine components

2.1. Operational principles of a wind turbine generator

A wind turbine generator is designed to extract power from the wind by converting aerodynamic forces developed by a rotor into mechanical torque and eventually electrical energy. The design of most modern wind turbines has been refined from what is known as the 'Danish Design' whereby two or more commonly three blades are mounted on a hub which is connected via a main horizontal shaft connected either directly to a generator or via a gearbox to the generator which is controlled appropriately to feed electrical power into a local grid.

2.2. Components of a wind turbine generator

2.2.1. Blades

What Does the Subassembly Look Like?

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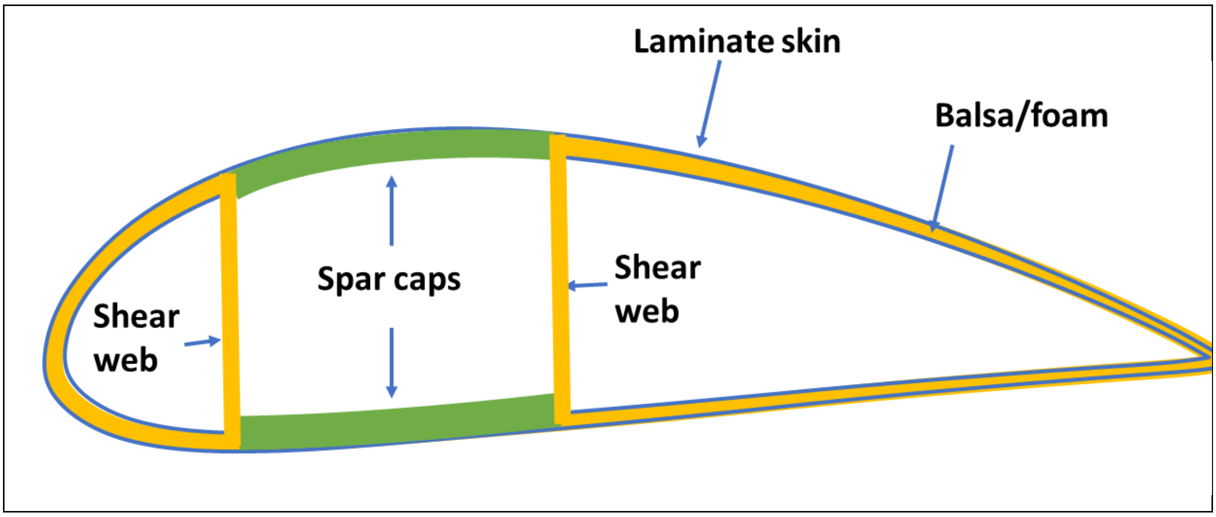

Figure 1: Top: a blade in a bending test; Bottom: cross-section through a blade showing how it is constructed.

A blade is made primarily of composite material but also contains wood, foam and sometimes carbon fibre. It is designed to be flexible and fatigue resistant. The construction consists of a load-bearing spar sandwiched between two aerodynamic skin shells which are bonded into one piece. Each blade is connected to hub using T-bolts or bushings at the root

What Does the Subassembly Do and What are its Underlying Physical Principles?

The primary objective of the blade is act like a wing to produce an aerodynamic lifting force. However, unlike the wing of a plane which produces a force to keep the aircraft in the air, in this case, the lift force is used to produce a torque. The torque causes a rotation of a horizontal shaft which when connected to a generator (directly or through a gearbox) produces useful electricity. A modern wind turbine can produce several megawatts of power and do so requires blades of a length ~100m. These structures are subject to enormous forces which are static, cyclic and stochastic. A blade is subject to millions of fatigue cycles during its lifetime and is by nature highly exposed to the elements. For this reason, it needs to be robust and well-maintained.

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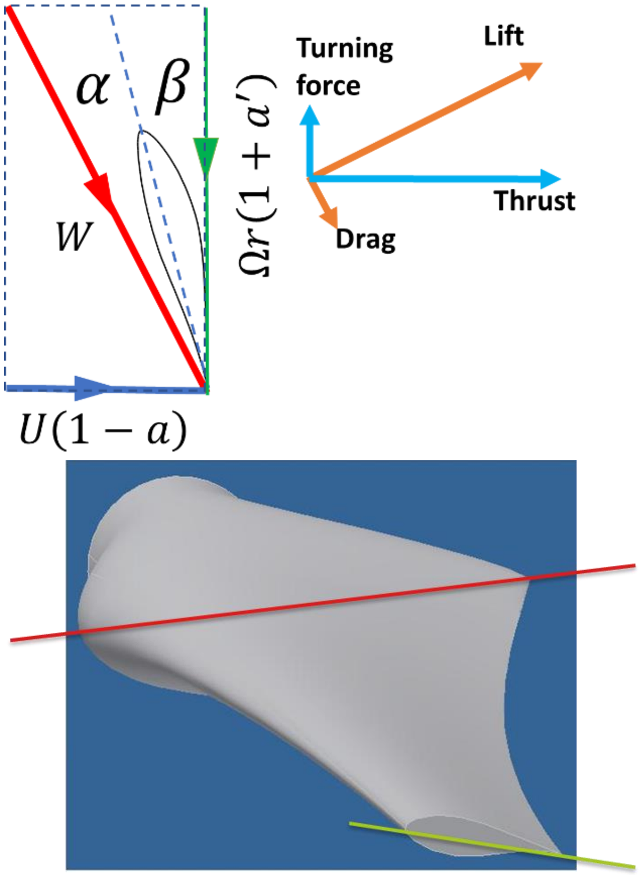

Figure 2: Left: A vector diagram to show how a moving blade develops aerodynamic forces in its axis of rotation; Right: illustration of how a blade incorporates twist between root and tip.

The outer skin of a wind turbine blade has an aerodynamic profile much like a wing which develops both lift and drag. An illustration of those forces at a particular cross section along a blade is shown in Figure 2 (left). The blade is rotating in a plane which projects out of the page. At a particular radius r from the wind turbine hub to the tip of the blade, this cross-section of blade will have a tangential speed of $\Omega r(1+a')$ where Ω is the rotational speed (in radians per second) of the rotor and a'(a so-called tangential flow induction factor) represents the reaction motion of the air in the wake of the rotor which rotates slowly downstream in the opposite direction to the rotor's direction of rotation. This values is typically very small ($\ll 1$). At the same time, the wind approaches the rotor with an upstream value of U. As the wind flow gets close to the rotor (the spinning blades), the rotor acts as a blockage to the wind and slows the wind down to a value of $U(1-a)$ at the rotor where a is known as the axial flow induction factor and is a function of the aerodynamic design of the blades and the rotational speed of the rotor. Typically,a has a value of around 0.3 when the wind turbine is operating at optimum efficiency. These two perpendicular components (speed of the blade relative to the air and effective wind speed at the rotor) dictate the angle that the effective wind speed Wmakes with the blade section. The chord of the blade (marked as a dotted line cutting through the blade in Figure 2 (left)) makes an angle with W of α. This angle is known as the 'angle of attack'. This angle is critical to determine how much lift and drag the blade produces. Typically the lift increases as α increases until α gets so high that the blade section 'stalls' whereby the lift starts to do down and the drag force increases. There is another important angle which controls the value of α and that is β. This angle is the 'pitch angle' and a blade can be actuated using an electrical motor or a hydraulic mechanism at its root to change this angle and thus adjust α. This is very important in the control of a turbine. The amount of power extracted by the wind by the blades thus depends on the wind speed, the speed of rotation of the rotor and the blade pitch angle. An important fact to note is that as r increases, so the angle of attack will reduce (if all other variables stay the same). To keep α the same along the blade and thus maximise the blades aerodynamic efficiency, then β must reduce from hub to tip. This means that blades are designed with a twist as shown in Figure 2 (right).

The forces in Figure 2 (left) are also shown. The lift and drag have also been mentioned, but what is of most importance is the force in the direction of blade rotation which creates the torque and produces useful power. At the same time, there is another less useful, but no less important force in the direction of the rotor shaft which is the thrust. This is a significant force acting on the blades which creates a large moment at the blade root. The force is not steady as the wind speed is also varying (is 'turbulent') and when the blade passes the tower this affects the wind speed creating a cyclic force. What is more, as the blade rotates from the top of the rotor plane to the bottom, it experiences a cyclic gravity load on top of a centrifugal loading force. These forces together create the main fatigue loads experienced by blade and dictate its overall lifetime. Normally, a blade is designed to survive these fatigue loads and extreme loads that may come about from very high gusts, but sometimes they do fail in service due to unforeseen problems or poor maintenance.

What About the Maintenance of the Subassembly?

From the description above, it can be seen that blades experience significant fatigue loads during service. Blades need to be periodically inspected (or monitored) to ensure the loads do not cause cracks in the structure. For example, particularly in the root section where the bending moment is greatest, cracks can occur due to delamination of the two skin sections bonded to the spar cap, particular at the trailing edge (downwind end of the blade). Impacts on a blade may also cause damage, e.g. lightning strikes or physical contact such as a bird strike. Another significant problem is leading edge erosion. The tip of a blade is moving at high speed (>80m/s for large blades) and so even small particles can create damaging erosion. Frequently, leading edges have some type of protection, e.g. sacrificial tape, which can be replaces periodically. Blade inspection is carried out visually, or using a drone. In situ monitoring systems are also available though not widely used due to the difficulties associated with detecting damage in a large composite structure. Sometimes, strain gauges are placed at the root of the blade to detect loading on the drive train but these are rarely used to detect accumulated fatigue damage.

Self-Test

- What is a blade made of?
- How does a blade convert power in the wind to electrical power?
- What are the main sources of blade fatigue?
- What damage is typically seen on a blade and how is it detected?

2.2.2. Hub

What Does the Subassembly Look Like?

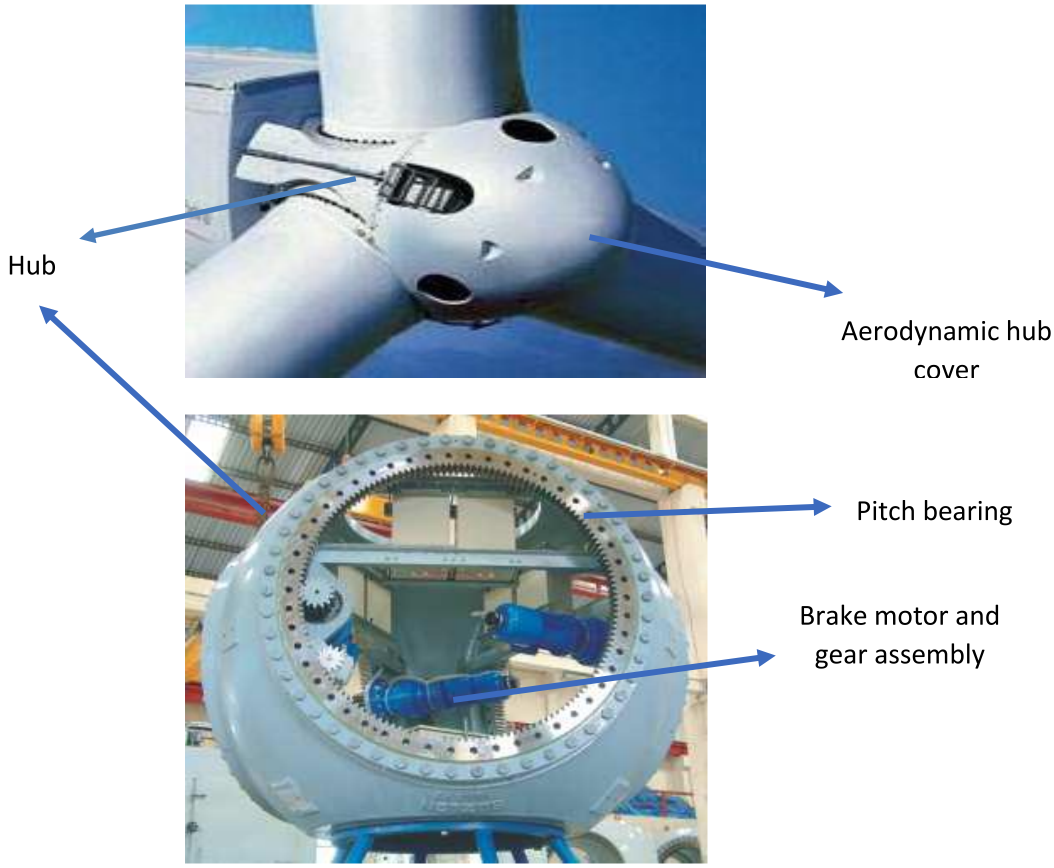

Figure 3: Top: Aerodynamic hub assembly including the hub cover; Bottom: hub assembly including, pitch bearing, brake motor and gear assembly.

The hub assembly consists of hub, hub cover and pitch bearing as shown in Figure 3. The hub is made of cast iron and is covered by a hub cover which is a composite aerodynamic cover and it is installed on the front part of the hub (the nose of the hub)and gives an appropriate aerodynamic shape to the hub in order to prevent the formation of turbulent flow in the front of the blades. The hub cover is constructed separately and installed later after the hub has been installed. The pitch bearings are an important part of the hub structure.

What Does the Subassembly Do and What are its Underlying Physical Principles?

The primary objective of the hub is to hold the blades and to adjust the pitch angle of each blade by means of a pitch bearing and a pitch assembly. The pitch system controls the power of the wind turbine, particularly it maintains the power of the wind turbine at rated power for incoming wind velocities above the rated wind speed.
The pitch system of the wind turbine blade consists of a pitch bearing, an electronic control box, a motor brake, a planetary drive and gear drive. The pitch bearing consists of two parts, an inner ring(gear ring) and outer ring as shown in Figure 4.

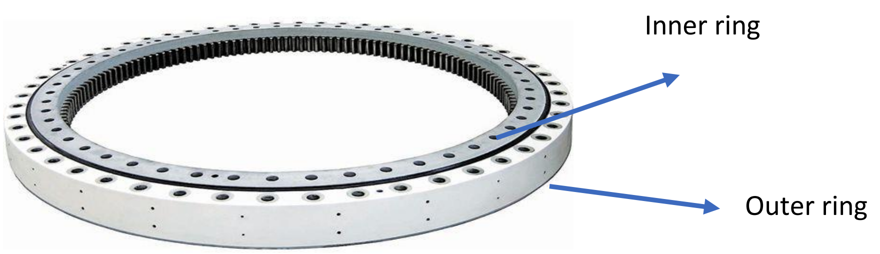

Figure 4: A view of a pitch bearing.

The inner ring is connected to the flange of the blade and is rotated by the means of an electric brake motor and planetary drives. Brake motors are a type of AC motor which come to a rapid stop in a defined time frame which is important for such as precision alignment of the blades for a given wind speed. The brake motor is connected to a planetary drive which provides the required torque for rotating the gear drive and eventually the pitch bearing and the blade. A planetary drive is a multi-stage slewing planetary gear (see Figure 5) which by means of its structure can withstand very high torque values but is efficient, compact, and relatively light. It transfers high torque to the gear drives which rotate the pitch bearing.

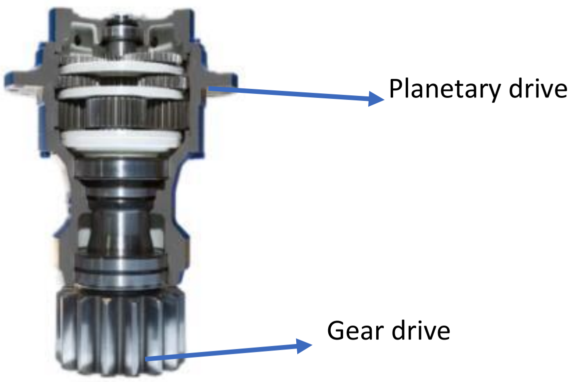

Figure 5: Multi-stage slewing planetary gear and gear drive.

Self-Test

- What are the main parts of the hub?
- What are the main parts of the pitch system?
- How is the pitch angle of the blade adjusted?

2.2.3. Nacelle

What Does the Subassembly Look Like?

Figure 6: Top: Nacelle assembly for a wind turbine, Bottom: Close-up view of a nacelle assembly.

The wind turbine nacelle is one of the main supporting structures of a wind turbine which hosts most of the wind turbine subassemblies. The weight of a new modern offshore wind turbine nacelle is on the scale of >300 tonnes. The nacelle is essentially a covered frame made of two main parts (see Figure 7). The front or main frame of the nacelle is generally made of cast steel and holds the yaw system, gearbox, and main shaft. The generator, transformer, and electrical cabinets are secured to a rear frame constructed of formed and welded steel. The two halves of the frame are joined by heavy bolts and spring pins. The entire assembly is attached by brackets to the bottom half of the nacelle’s fiberglass cover.

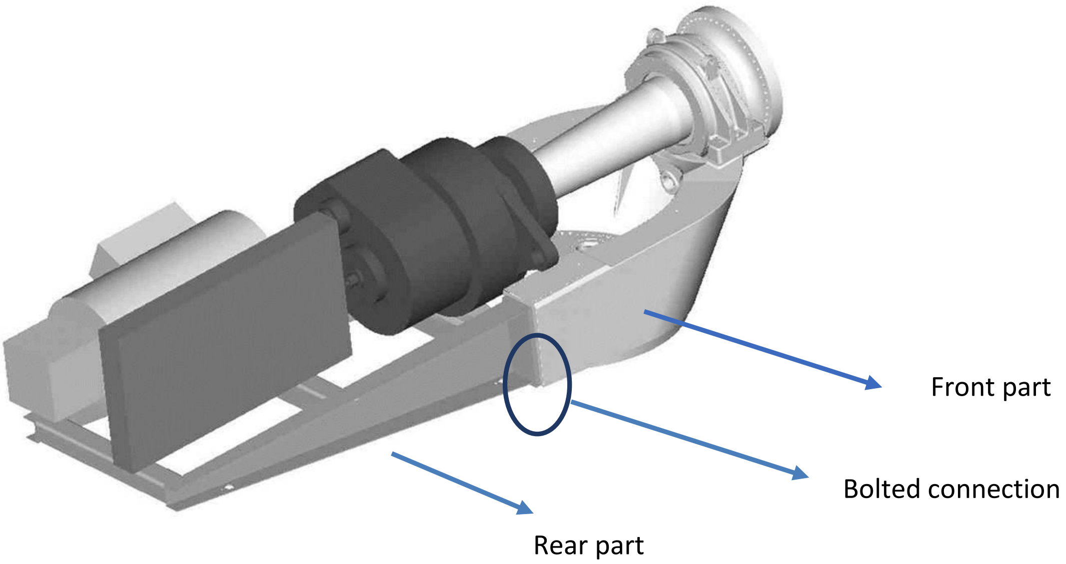

Figure 7: Front and rear part of nacelle.

What Does the Subassembly Do and What are its Underlying Physical Principles?

The primary objective of the nacelle is to host the sub-assemblies including the rotor, gearbox, generator, inverters, hydraulic system and yaw bearing. The nacelle at one side is connected to the hub through the nacelle flange and at the other side is conceded to the tower through the yaw assembly as shown schematically in Figure 8 with an example of a real system in Figure 9. The yaw bearing consists of two parts: an inner ring and an outer ring or ring gear. The nacelle is connected to the inner ring and the tower is connected to the outer ring by means of a tower flange. With a similar working principle to the pitch system, the electric motor rotates the planetary drive and the planetary drive provide the required torque for rotation of the gear drive which in turn rotates the inner part of yaw bearing and eventually the whole nacelle assembly. A hydraulic brake system is used to hold the nacelle assembly in a fixed aligned position. The braking assembly consists of brake pistons and brake pads. Brake pads are connected to the flange of the tower while the brake piston is mounted onto the bed plate of the nacelle. The hydraulic pressure applies the force to the piston which pushes the inner ring of the pitch bearing against the brake pads.

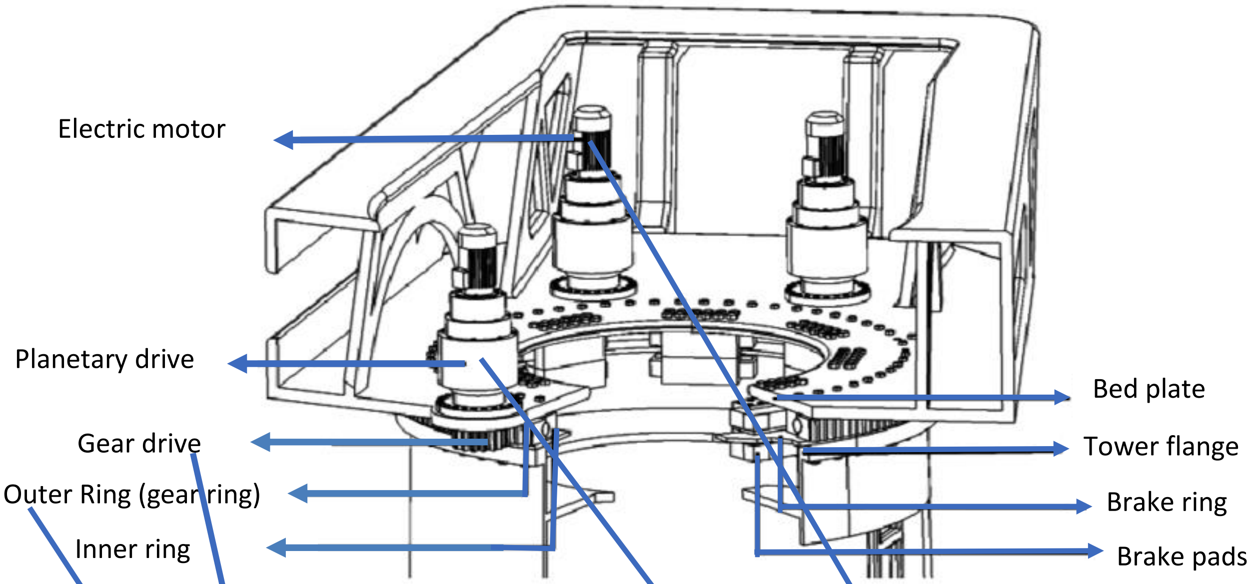

Figure 8: Schematic illustration of a yaw assembly.

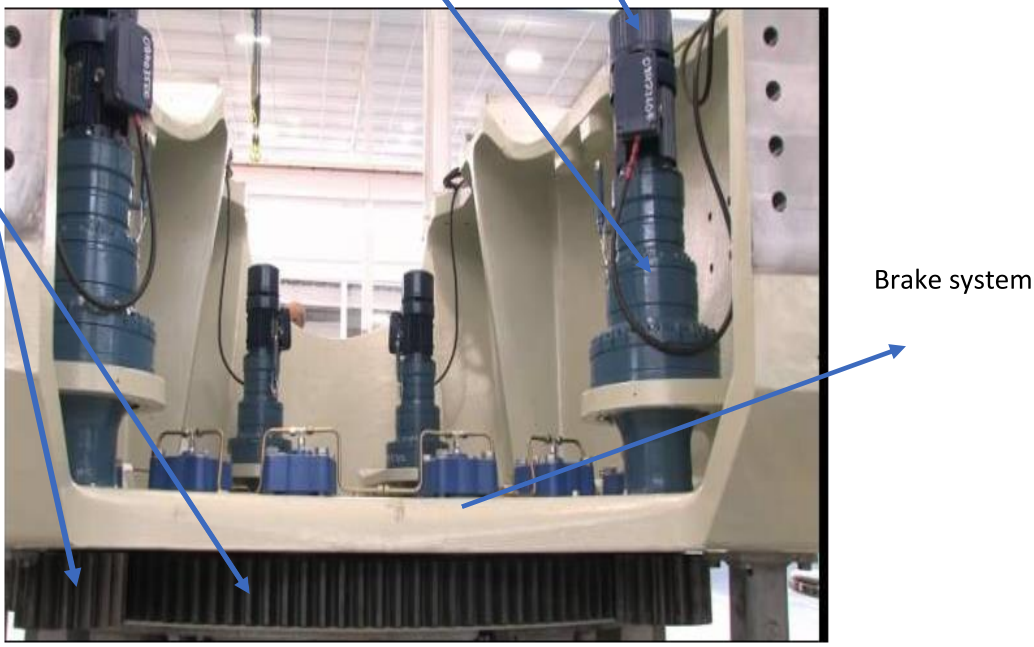

Figure 9: Top: Schematic illustration of a yaw assembly of a wind turbine, Bottom: view of an actual yaw assembly.

Self-Test

- What are the main parts of the nacelle?
- What are the main components of the yaw system?
- How does theyaw system of a wind turbine work?

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2.2.4. Drive train assembly

The drive train assembly includes the main shaft, gearbox (in some cases), high speed shaft and generator. Some turbines do not have a gearbox and the main shaft is coupled directly to the generator. Each of these subassemblies is explained in the following sections.

2.2.4.1. Main shaft (turbines with a gearbox)

What Does the Subassembly Look Like?

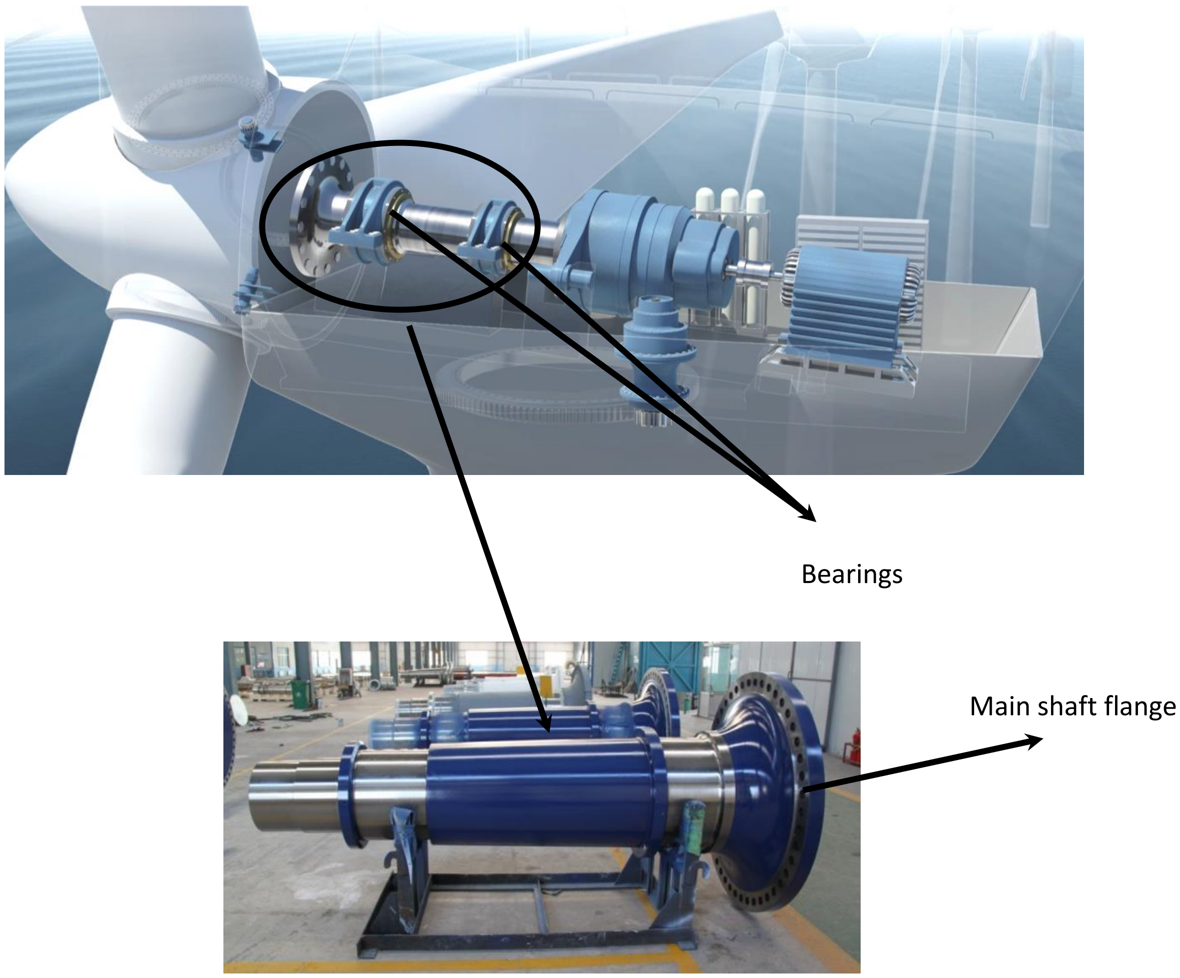

Figure 10: Top: Schematic illustration of the main shaft including its two bearings, Bottom: view of an actual main shaft without bearings.

The main shaft is an important component of the wind turbine located in the nacelle. Its job is to transmit the torque generated from the blades via the hub to the drive train. It is usually a hollow shaft manufactured by a casting or forging process. The shaft is mounted on two bearings as shown in Figure 10.

What Does the Subassembly Do and What are its Underlying Physical Principles?

On one side, the main shaft is connected to the hub through a flange and on the other side is connected to a gear box (where one is present) through a planet carrier. It transfers the torque from the rotor to the gear box. During this process, a torsional moment is applied to the shaft and it experiences a shear stress. In addition, radial and axial loads are imposed on the main shaft. The radial load is mostly due to the weight of the rotor and hub and the axial load is mainly due to the axial force imposed by the wind on the rotor. To support these loads and allow for rotation, the main shaft is mounted on two bearings: one close to the hub and the other close to the gearbox. Clearly, the bearings must be designed and installed correctly to support the axial and radial loads. Due to the turbulent characteristics of the wind, these loads varying time causing the bearings to experience fatigue loads. Usually, two single or double row tapered-roller bearings which can withstand both the radial and axial loads are used in the main shaft of a wind turbine. An schematic of a double row tapered roller bearing is shown in Figure 11.

Figure 11: Double row tapered roller bearing.

2.2.4.2. Gearbox

What Does the Subassembly Look Like?

The gearbox (when present) is located between the main shaft and low speed shaft of the wind turbine.

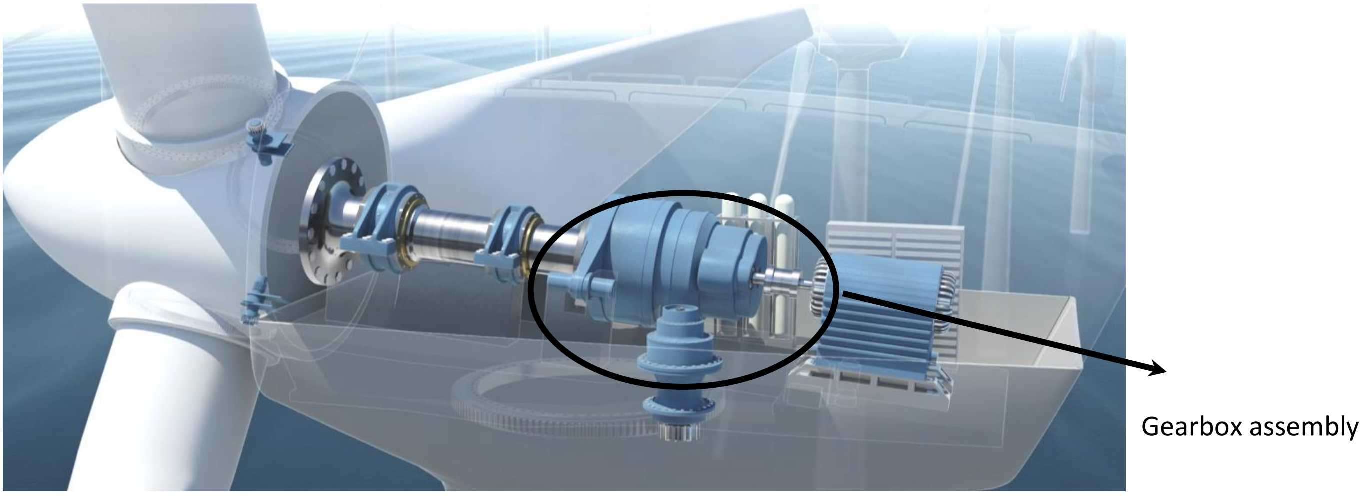

Figure 12: Schematic illustration of a gearbox assembly.

Depending on the gear ratio which varies for different types and sizes of generator, various configurations of gear box are used. For a doubly-fed induction generator, usually a three-stage gearbox, including two planetary and one parallel stage is used as shown in Figure 13. The three stages are generally known as the Low-Speed Shaft (LSS) stage, Intermediate-Speed Shaft (ISS) stage and High-Speed Shaft (HSS) stage reflecting their respective relative speeds.

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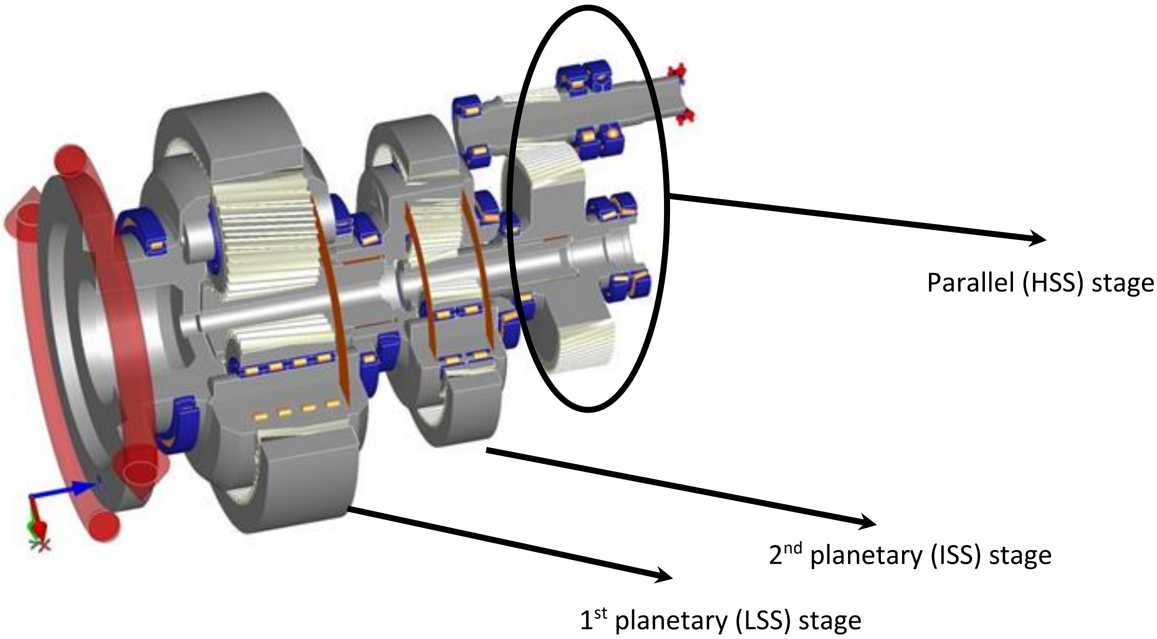

Figure 13: Typical gearbox configuration used in a wind turbine with a doubly fed induction generator. High torque is applied at low rotational speed from the main shaft as shown by the large red arrows on the left-hand side of the figure. On the right-hand side of the figure, the small red arrows show the low torque output at high speed which is applied to the generator. LSS=Low-Speed Shaft, ISS=Intermediate-Speed Shaft, HSS=High-Speed Shaft.

What Does the Subassembly Do and What are its Underlying Physical Principles?

The gearbox converts the high torque/low speed rotation of the rotor to low torque/high speed rotation required by the generator. A typical large wind turbine rotor rotates at around 10 rotations per minute (rpm) at its rated wind speed. A typical generator has a synchronous speed of 1500rpm (assuming a 50Hz AC network) meaning that a typical gearbox ratio would be around 1:150. Two common types of gear stages are used in a wind turbine gearbox: a parallel shaft and a planetary gear. In a parallel shaft, two gears are mounted (as the name suggests) on parallel shafts where the smaller (the output) is known as the pinion, as shown in Figure 14.The gears can be either a spur or helical type. For smooth rotation and to reduce noise, helical gears are preferred.

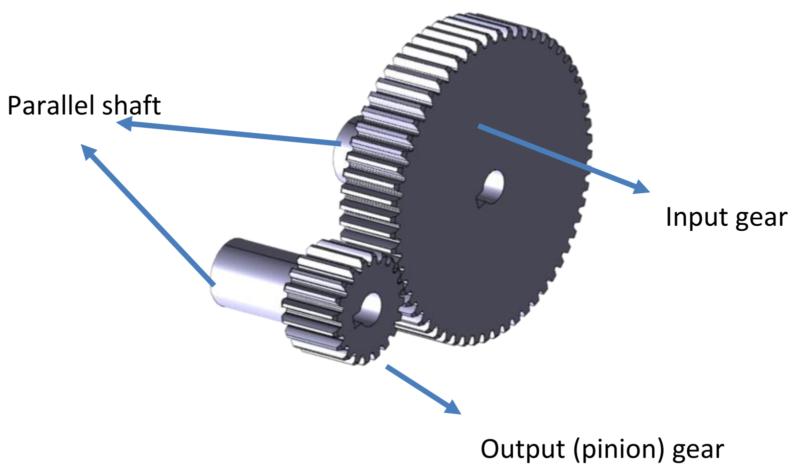

Figure 14: Schematic illustration of a parallel gear stage using spur-type gears.

The gear ratio (GR) for this type of gear is given by:

$$GR = \frac{-N_i}{N_o} \quad (2.1)$$

where N_i and N_o are the number of gear teeth of the input and output gears, respectively. Note that the negative sign implies that the input and output gears rotate in the opposite sense.

A planetary gear is shown in schematic form in Figure 15. It comprises a ring gear and planetary gears (commonly three) which are connected to a sun gear through a carrier.

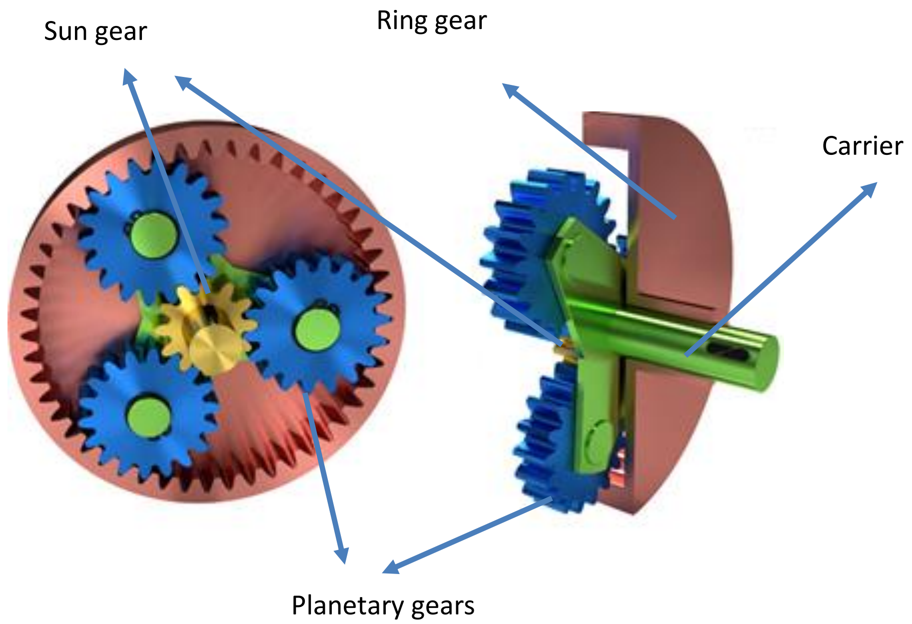

Figure 15: Schematic illustration of a planetary gear type.

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The gear ratio of a planetary gear is dependent on which part of the gear assembly is used as the input, output and fixed gear. If the highest gear ratio is required then the carrier is used as input, the sun gear as output and the ring gear is fixed. This configuration, known as planetary epicyclic, is usually used in a wind turbine generator. The gear ratio of a *planetary epicyclic stage*s:

$$GR = \frac{N_s+N_r}{N_s} \qquad (2.2)$$

whereN_s and N_r are the number of gear teeth of the ring and sun gears, respectively.

An alternative configuration used is when the ring gear is used as input, the carrier gear is fixed and the sun gear is used as output. This configuration is called *star gear epicyclic*. For this configuration, the gear ratio is:

$$GR = \frac{-N_r}{N_s} \qquad (2.3)$$

You can watch this video to understand the working principle of a planetary gear: https://youtu.be/ARd-Om2VyiE.

Based on the size of generator and the space available in the nacelle, different combinations of parallel and planetary gears are used to provide the appropriate gear ratio. According to the American gear manufacturing association (AGMA) [1], the range of gear ratios shown in Table 1 can be used for different types of stage to maximize the load bearing capacity while minimizing the weight and cost of the gearbox.

Table 1:Typical gear ratios for different types of gear stage.

Gear type	**Gear ratio**
Parallel shaft	1-4
star gear epicyclic	3-6
planetary epicyclic	4-7

The gearbox experiences a significant fatigue load during the lifetime of the wind turbine. This fatigue load is associated with the loads on the contact area of the gear teeth. As for the bearings, these loads are variable due to the turbulent characteristics of the wind. These loads lead to two different types of fatigue, namely contact fatigue and bending fatigue which are important considerations for the correct selection of gears at the design stage.

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2.2.4.3. High speed shaft

What Does the Subassembly Look Like?

The pinion gear shaft of the last stage of parallel gear in a gear box is connected to the generator shaft through the coupling. This coupling is a hollow shaft including two flanges in both ends which is connected to the flanges of pinion gear shaft and the generator shaft. Usually the pinion gear shaft including the coupling is called high speed shaft, figure 15.

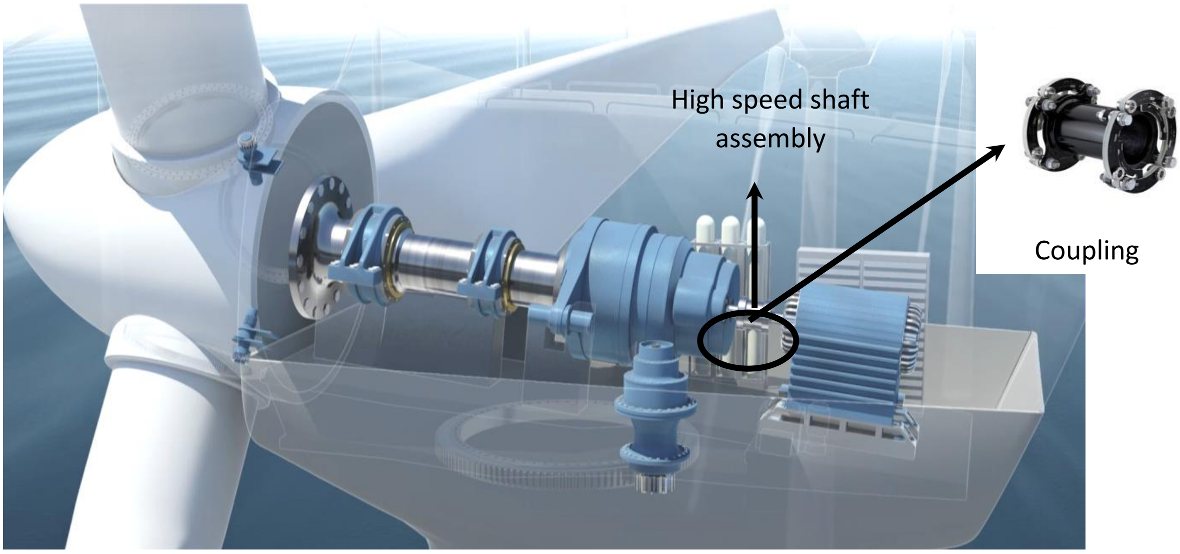

Figure 16: Schematic illustration of the high speed shaft.

What Does the Subassembly Do and What are its Underlying Physical Principles?

Main element of the high speed shaft assembly is coupling. Flexible coupling is used on the high-speed (output) shaft of the gearbox to drive the generator and accommodate the misalignment between the two. In contrast with the main shaft, high speed shaft experience lower torque and less stress therefore its diameter and thickness is smaller than main shaft.

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2.2.4.4 Generator

What Does the Subassembly Look Like?

Generator is connected to a high speed shaft in a non-direct drive train or connected directly to the main shaft in a direct drive train, figure 17 shows schematic illustration of generator in a non-direct drive train.

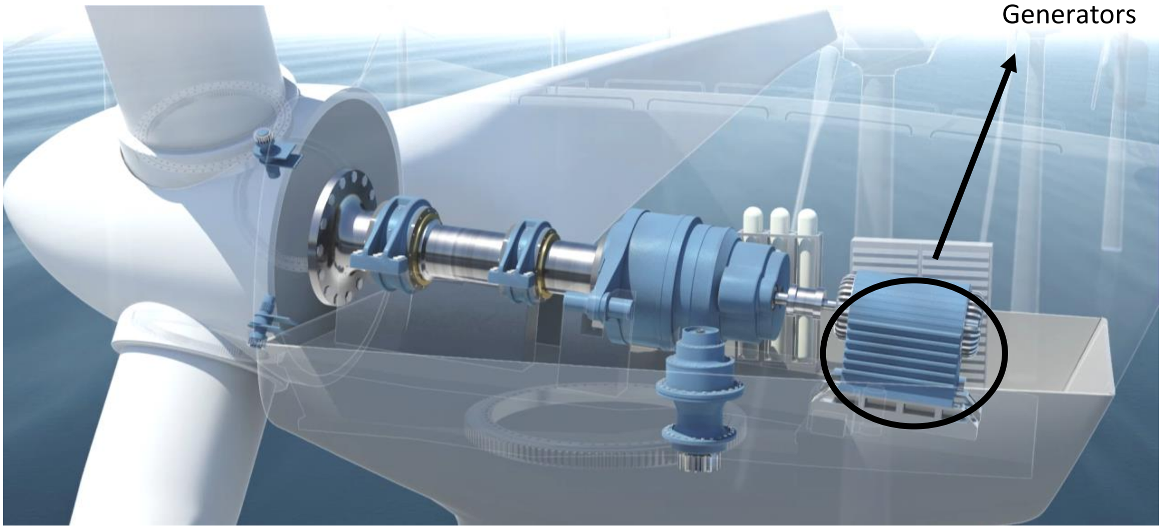

Figure 167: Schematic illustration of a generator in a non-direct drive train.

Generally, all types of generators made of three main parts, rotor, stator and winding. The stator is the stationary part of a generator and it carries three phase AC winding. Rotor is the rotating part of a generator and depending on the generator type it may or may not carry the winding. Two major types of AC generators are used in the wind industry, synchronous and asynchronous or induction generators.

Synchronous generator

A conventional synchronized generator is consisted of a stator, rotor, winding, slip ring assembly and brushes. Stator of synchronize generator has three main parts, frame, core and winding. The frame is outer body of whole generator assembly and it is made of cast iron and protects the core, figure 18, left image. The stator core is made of a number of silicon steel material stamps that are insulated from each other. Slots are cut on the inner periphery of the stator core to place the winding, figure 18 right image. Winding is made of enamelled copper and is placed usually as 3-phase AC in the core slots.

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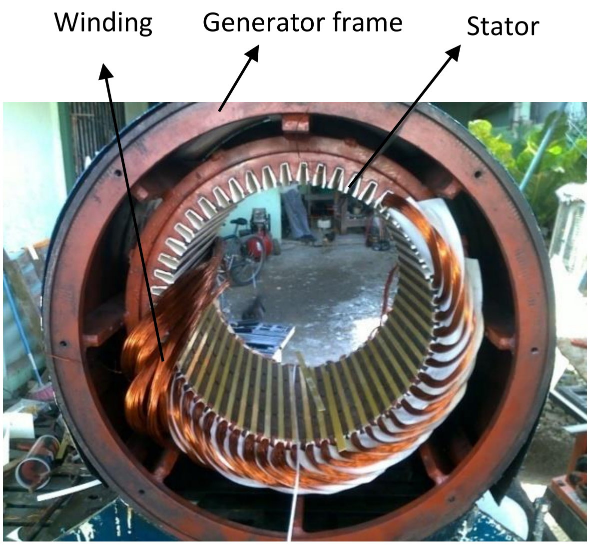
A rotor of synchronized generator is usually available in two types, the salient pole and the cylindrical type. A salient pole rotor is consisted of poles projecting out from the surface of the rotor core to place the winding, figure 19, right. Non-salient pole rotors has a cylindrical shape with parallel slots on their surface to place the winding, figure 19 , left. Rotor is made of steel lamination to reduce the eddy current losses.



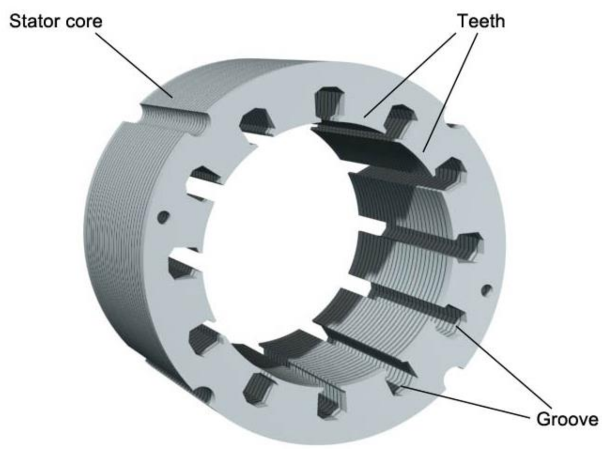


Figure 17: Left: Actual view of stator including the winding. Right: Schematic view of the core of a stator

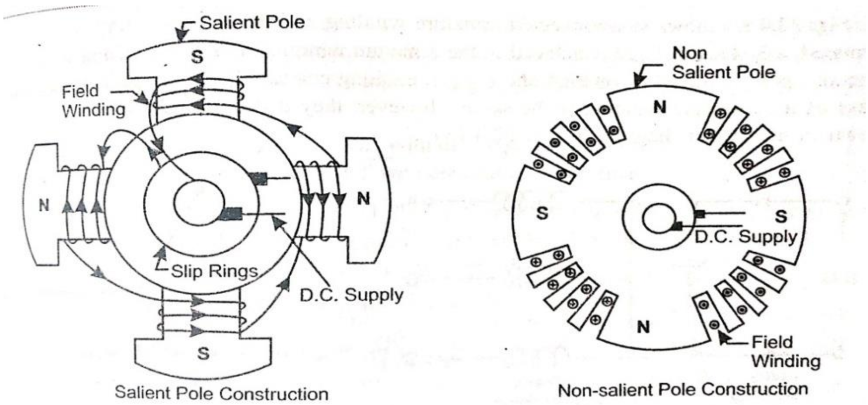


Figure 19: Top, Left: Schematic illustration of salient pole rotor. Top, right: Schematic illustration of cylindrical type rotor. Down, Left: actual view of salient pole rotor. Down, Left: actual view of cylindrical type rotor.

Slip ring assembly is consisted of rings of metal conductors which are mounted on the shaft and rotates with the shaft. They are made of copper or copper alloys insulated from the shaft.
Rotor winding are connected to slip ring through the studs attached to the rings, figure 20. The outer part of the slip ring is in continuous sliding contact with stationary brushes which is connected to DC exiting supply source.

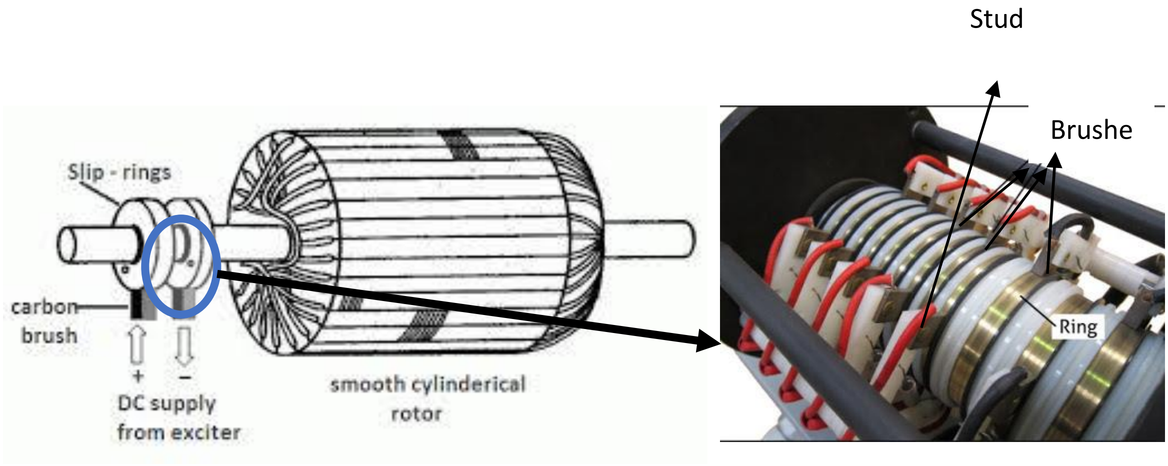


Figure 20: Right: Schematic illustration of synchronous generator including the slip ring assembly. Left: actual view of a slip ring assembly.

In synchronous generator the frequency of output power is equal to the rotational speed of rotor so if the rotational speed of rotor changes, then the convertor should be used to adjust the frequency of output power of the stator with the grid frequency i.e. to 50 or 60 Hz. Recently in the wind turbine industry, permanent magnet(PM) synchronized generator is used. In this type generator, rotor winding is replaced with permanent magnet, figure 21.

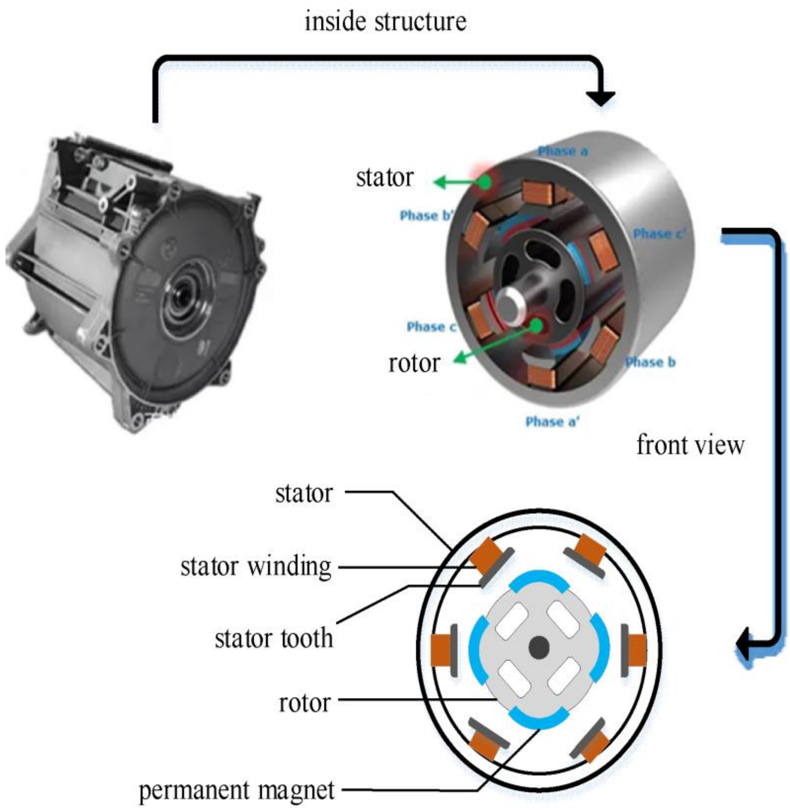


Figure 21:Shematic view of permanent, magnet Synchronized generator including different components.

Asynchronous generator

Another type of generator is asynchronous or induction generator which the rotor rotates a bit above the synchronous speed .For this reason, it is called an asynchronous generator. The rotor of induction (asynchronous) generators may or may not have a winding. Squirrel cage rotor is a type of rotor which doesn't have a winding. It is composed of bars with highly conductive metal (typically aluminium or copper) which are connected at the ends by a metal rings, figure 22. Actually these bars are embedded in the slots of laminated cylindrical which is called iron core, figure 23. The purpose of iron core is to reduce the loss of magnetic flux from stator to rotor because of the air gap between the bars.

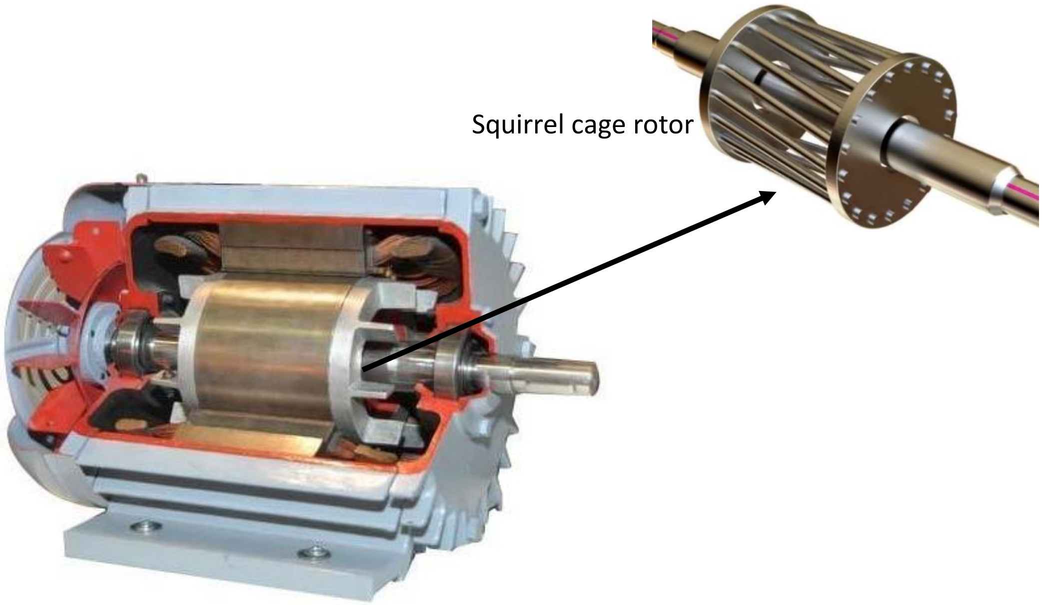


Figure 22: Schematic view of induction generator with Squirrel cage rotor.

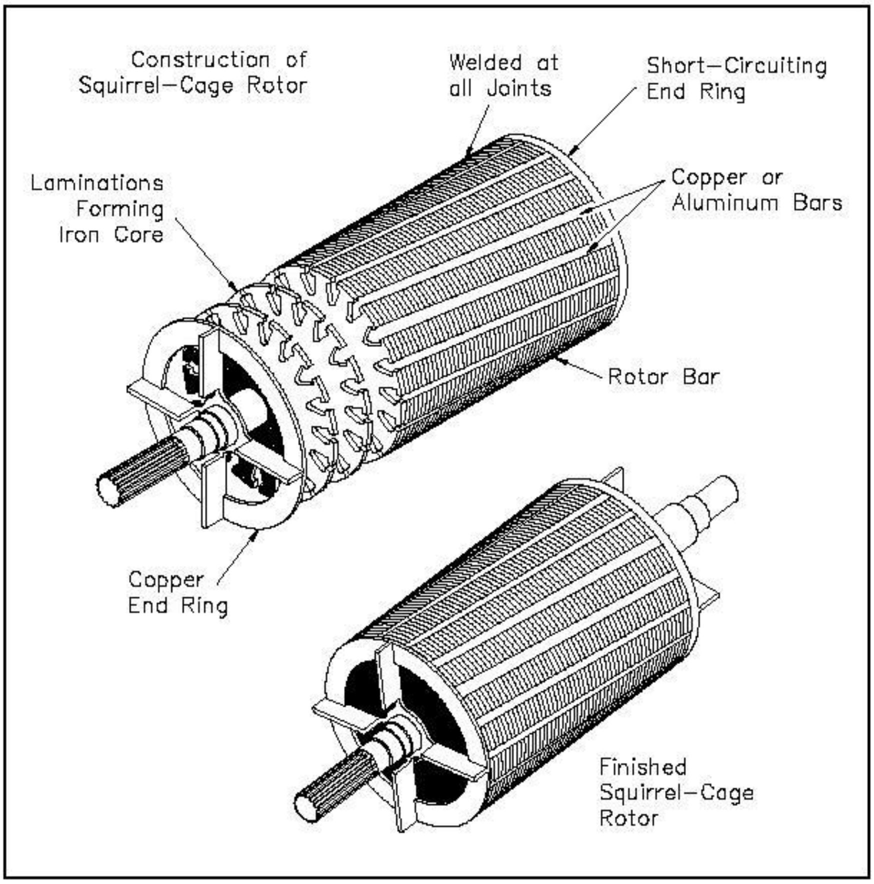


Figure 23: Schematic view of core of Squirrel cage rotor.

In an early wind turbine with low rated power(less than 1.5-2 MW) this type of generator was used. It was easy to control and to connect it to the grid. But it cannot follow the maximum torque-speed scheme of a wind turbine. This lead to decrease the overall efficiency of wind turbine especially when the rated power of wind turbine is high. To solve this deficiency a specific type of induction generator was developed. This type of generator is called doubly feed induction generator and its rotor carries the winding so it can feed or can be fed by the grid by the means of slip ring assembly and use of convertors. Recently brushless doubly fed induction generator has been designed which doesn't need the slip ring assembly and its stator is connected directly to the convertor, figure 24.

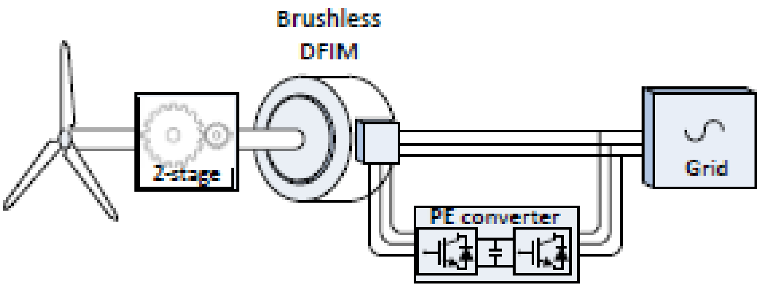


Figure 24: A brushless doubly feed induction drive-train topology.

Overall, in wind turbine industry three main generator topologies are used, permanent magnet, conventional doubly feed induction generator and brushless doubly feed induction generator, figure 25.

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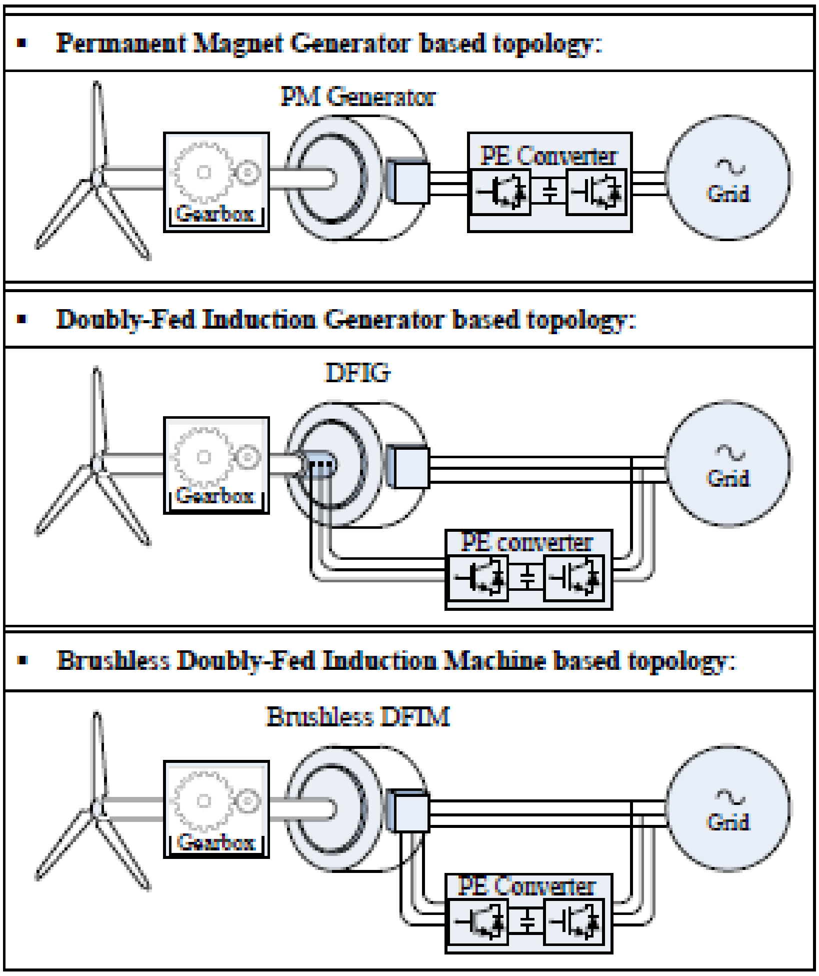

Figure 25: Wind Turbine Drive-Train topologies.

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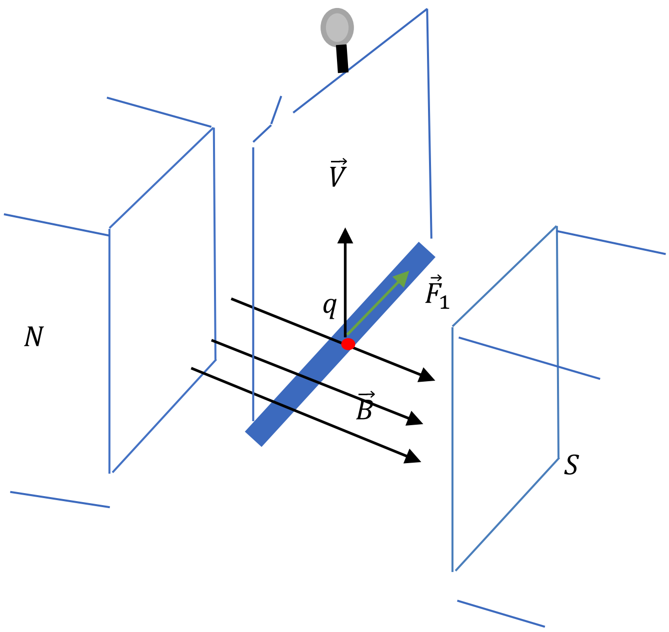
What Does the Subassembly Do and What are its Underlying Physical Principles?

Generator is a device which converts mechanical energy of blade extracted from the wind to the electrical energy. All type of generators work on the principal of two basic laws of electromagnetism expressed by the Lorenz.

I. When charges move in a magnetic field, they are subjected to the force. This force pushes the charges and creates a voltage in the conductor. If conductor with charges q is moving with the velocity of $\vec{V}$ respect to the magnetic field($\vec{B}$), the force and its direction which is imposed on the charge can be calculated by Lorentz's law , figure 26:



$$\vec{F}_1 = q\vec{V} \times \vec{B} \qquad (2.4)$$

Figure 26: Movements of conductors in constant magnetic field and the force which is imposed on its charges.

II. When the conductor of figure 26 is connected to a close loop including a load, then current flows in the circuit and it produce a magnetic field $\vec{B}_L$.Interaction of this magnetic field with original magnetic field $\vec{B}$ induce a force on the conductor which is in opposite direction to the upward motion of conductor, figure 27.This force can be expressed as;

$$\vec{F}_2 = I\vec{L} \times \vec{B} \qquad (2.5)$$

Where, I is current in the conductor and $\vec{L}$ is a vector of length L pointing along I direction.

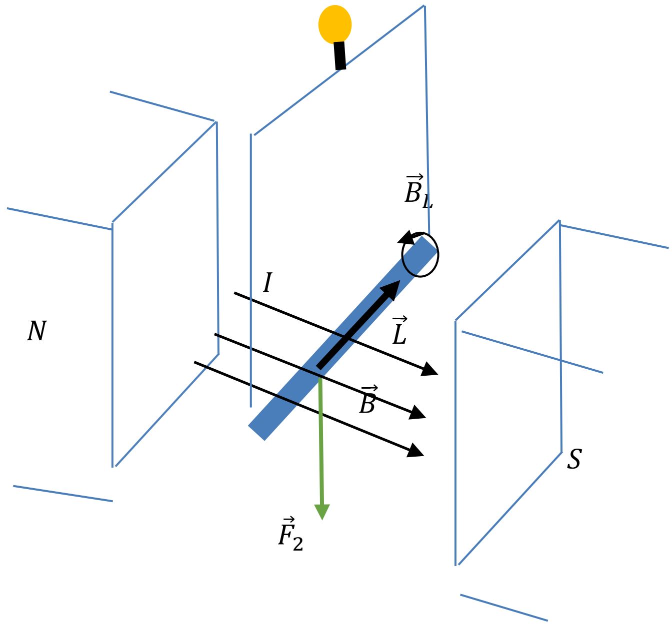


Figure 27: Force on conductor carrying current in the constant magnetic field and.

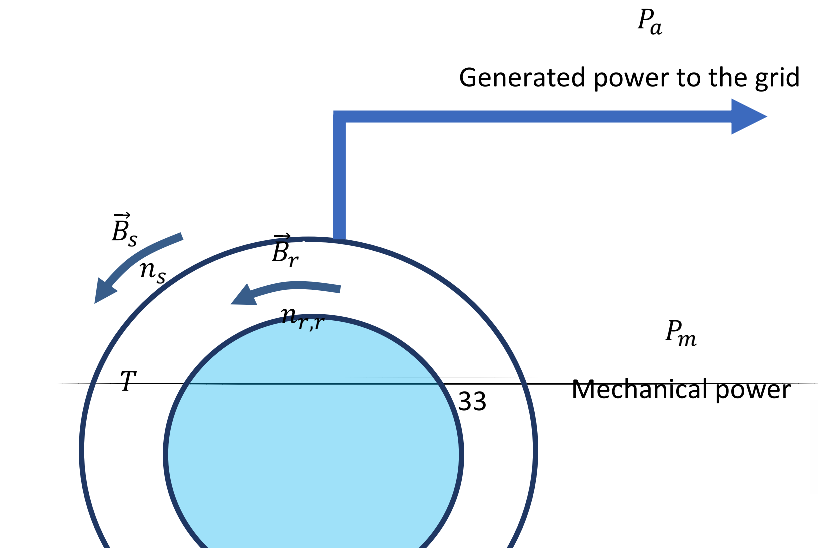
These two laws are the fundamental laws for development of an AC machine. How to use these laws to produce the electrical power? If we move the conductor in upward direction then potential electricity is produced in the conductor. If we connect this voltage source to a load then a current is flowed in the conductor (first law). This current produces a magnetic field which interacts with main magnetic field. As a result of this interaction the force $\vec{F}_2$ is applied on the conductor(Second law).In order to keep producing of electrical power we need to apply a force equal o $\vec{F}_2$ but in opposite direction on the conductor. Therefore our mechanical power which is equal to $P_m = \vec{F}_2 V$ is converted to electrical power which is, $P_E = VI$.
To maintain the voltage in the conductor, it should keep its movements or to move the conductor in upwards and downwards direction and produce a cyclic voltage. If the conductor is constructed as a coil then this upward and downward motion can be made by rotating the coil. It is the basic idea behind the AC generator machine. With this basic knowledge the working principal of two major type of generator which are used in a wind turbine generator; permanent magnet synchronize generator and doubly feed induction generator can be explained.

Permanent magnet synchronize generator.

In this device the rotor windings have been replaced with permanent magnets. Permanent magnets on the rotor rotates and produce a constant rotating magnetic field. This rotating magnetic field produce electric voltage in the stator winding (first law).Generated electricity in the stator produce a magnetic field which interact with the original magnetic field (rotor magnetic field) and this interaction induce a torque on the rotor. In order to keep producing the electricity this torque should be compensated by the wind turbine blade and allow the rotor to rotate. The advantage of PMG generator includes the elimination of slip ring assembly and brushes. Another advantage is that the use of permanent magnet in the rotor eliminates the loss of power in the rotor which arises due to winding.

Induction generator.

In a conventional induction generator, the stator is connected to the AC grid. It establish three phase AC current in the stator winding. It leads to a resultant magnetic flux which is constant and rotates at frequency of AC network (50 or 60 Hz) in the stator.
Rotor of this type generator is squirrel cage and is consisted of metal bars which are short circuited at the end rings, figure 22. Rotating magnetic field of stator $\vec{B}_s$,rotates with grid frequency n_s and induce AC voltage and current in the motor (first law).Induced AC current in the motor generate a resultant magnetic field in the rotor. Interaction of stator and rotor magnetic field produces a force/torque on the rotor bars (second law) and it rotates the shaft with rotational speed of n_m.When rotor rotates with the rotational speed n_m then stator magnet field rotates with rotational speed of $n_s - n_m$ relative to rotor. This rotating magnetic field create a current with frequency of $n_s - n_m$ in the rotor. This current in the rotor bars produces a constant resultant magnetic field which rotates at same frequency as current, $n_{r,r} = n_s - n_m$ relative to rotor, figure 28.



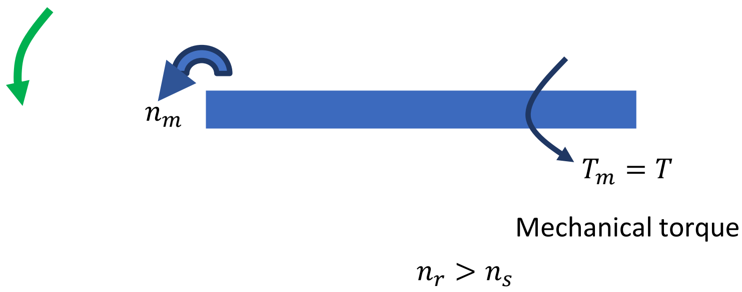


Figure28: Working principal of an induction machine as motor.

Rotational speed of rotor relative to earth observer n_r can be calculated as;

$$n_r = n_{r,r} + n_m = n_s \qquad (2.6)$$

Torque produces by interaction of these two rotating magnetic field which rotates at the same rotational speed, figure 29.

$$T = K\vec{B}_r \times \vec{B}_s = K|\vec{B}_r|\,|\vec{B}_s| \sin\delta \qquad (2.7)$$

Where K is constant coefficient and δ is angle between two magnetic field vector.

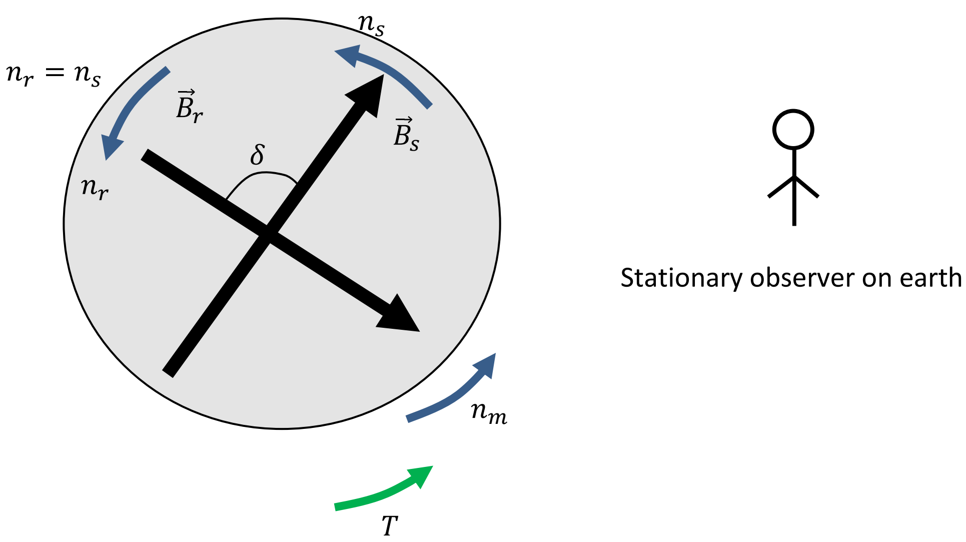


Figure 29: Interaction of stator and rotor magnetic field and production of torque when AC machine works as motor, $n_s > n_m$.All rotational speed shown in the figure are relative to earth observer.

As far as the rotational speed of rotor is different from the rotational speed of stator magnetic field this force/torque is applied on the rotor. The direction of force and polarity of electrical current of stator is depended on the rotational speed of rotor. If the rotor rotates with rotational speed (n_m) less than rotational speed of stator magnetic field (n_s) then the power is taken from the AC network and torque is applied in a same direction as the rotor rotates, figure 29. In this case the AC machine works in motor mode. If the rotational speed of rotor (n_m) exceed the rotational speed of stator magnetic field (n_s), the polarity of current changes and the power is given to AC network and torque is applied on the rotor in the opposite direction to its rotation, in this case the AC machine works in generator mode, figure 30.

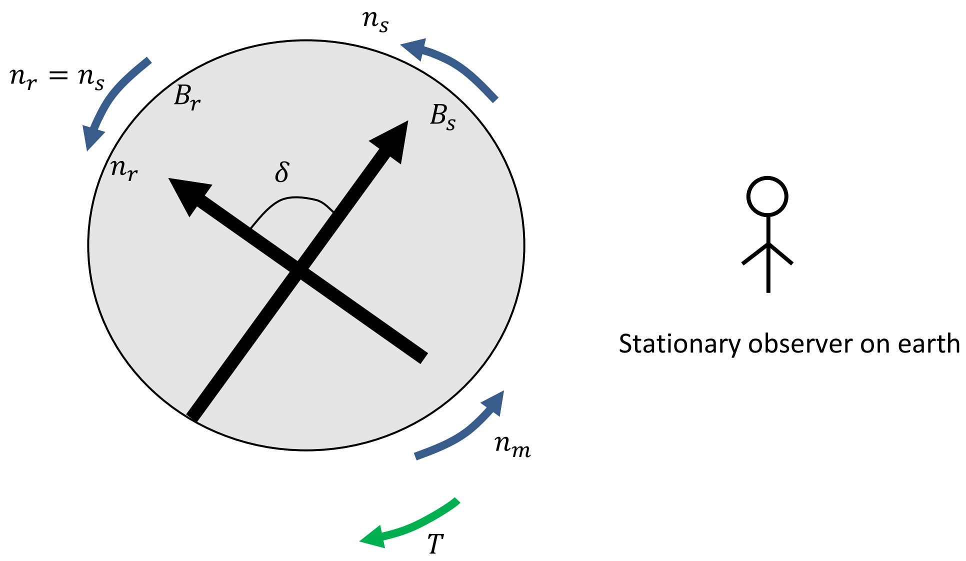


Figure 30: Interaction of stator and rotor magnetic field and production of torque when AC machine works as generator. n_s is rotational speed of rotor and stator magnetic field and rn_m is rotational speed of mechanical shaft, $n_s < n_m$. All rotational speed shown in the figure are relative to earth observer.

In case of generator ,the rotor should maintain its rotation to keep producing the power. This can be achieved by applying a mechanical torque on the rotor in opposite direction to the produced torque by the generator. This mechanical torque/power is taken from the blades extracted from the kinetic energy of wind.

The applied torque on the rotor is depended on the difference between the rotational speed of rotor (n_m) and rotational speed of stator magnetic field (n_s).Slip ratio for this machine is defined as,

$$S = \frac{n_m - n_s}{n_s} \qquad (2.8)$$

When slip ratio is small then, $\vec{B}_r$ is mostly concerned with the winding resistance and the angle δ is close to 90 degree. When slip ratio increases then the induce voltage and the current on the rotor increases. It increases $\vec{B}_r$ but because the inductance of motor increases it leads to increase $\delta > 90$. Usually the maximum torque occurs when slip ratio is between 2-5 percent.

Doubly feed induction generator.

In a doubly feed induction generator the rotor is equipped with three phase AC current. So it can feed the grid or it can be fed by the grid. When rotor shaft rotates at a rotational speed greater than stator magnetic field, $n_m > n_s$ then induced rotor magnetic field rotates with the $n_{r,r} = n_m - n_s$ in counter clock wise direction relative to rotor. It produces voltage with frequency of $n_m - n_s$ in rotor. In conventional induction generator (squirrel cage) this voltage has not been concocted to the load and it has short circuited at end rings. If this voltage is connected to a resistive load then $\vec{B}_r$ increases without increase in δ and it leads to increase the torque. Produced power has the frequency of $n_m - n_s$ which is not same as grid frequency. In order to convert this frequency to the grid frequency, convertor is used, figure 31.

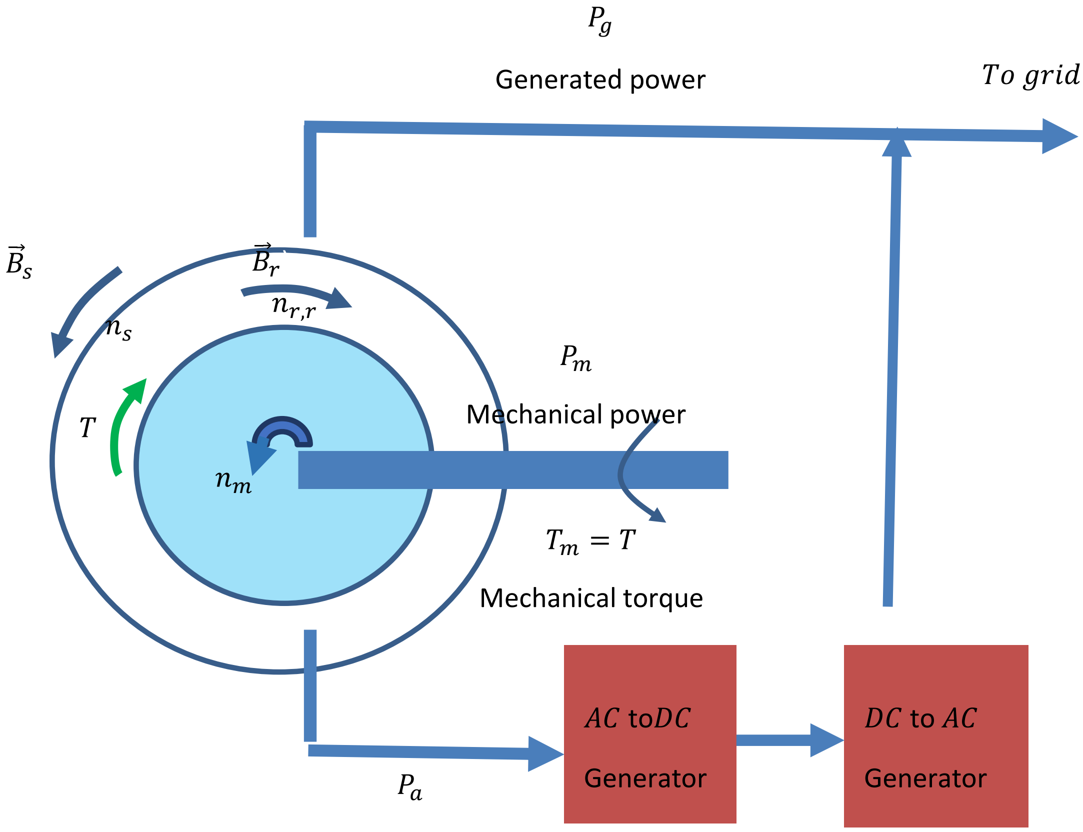


Figure31: Working principal of doubly feed induction generator when, $n_m > n_s$

When rotor shaft rotates at a rotational speed less than stator magnetic field frequency, $n_m < n_s$ then induced rotor magnetic field rotates with the $n_{r,r} = n_s - n_m$ in a clock wise direction relative to rotor. It produces voltage with frequency of $n_s - n_m$ in rotor. In conventional induction generator (squirrel cage) this voltage has not been concocted to the load and it has been short circuited at the end rings and it acts as a motor, figure32. If the rotor winding is connected to source voltage with a frequency of $n_s - n_m$, this voltage can feed the rotor and produce a current in reverse polarity in compare with squirrel cage induction moor.

This causes the machine works as a generator and torque is applied on the rotor in opposite direction to its rotation. To provide a voltage source with frequency of $n_s - n_m$ converter should be used, figure 32.

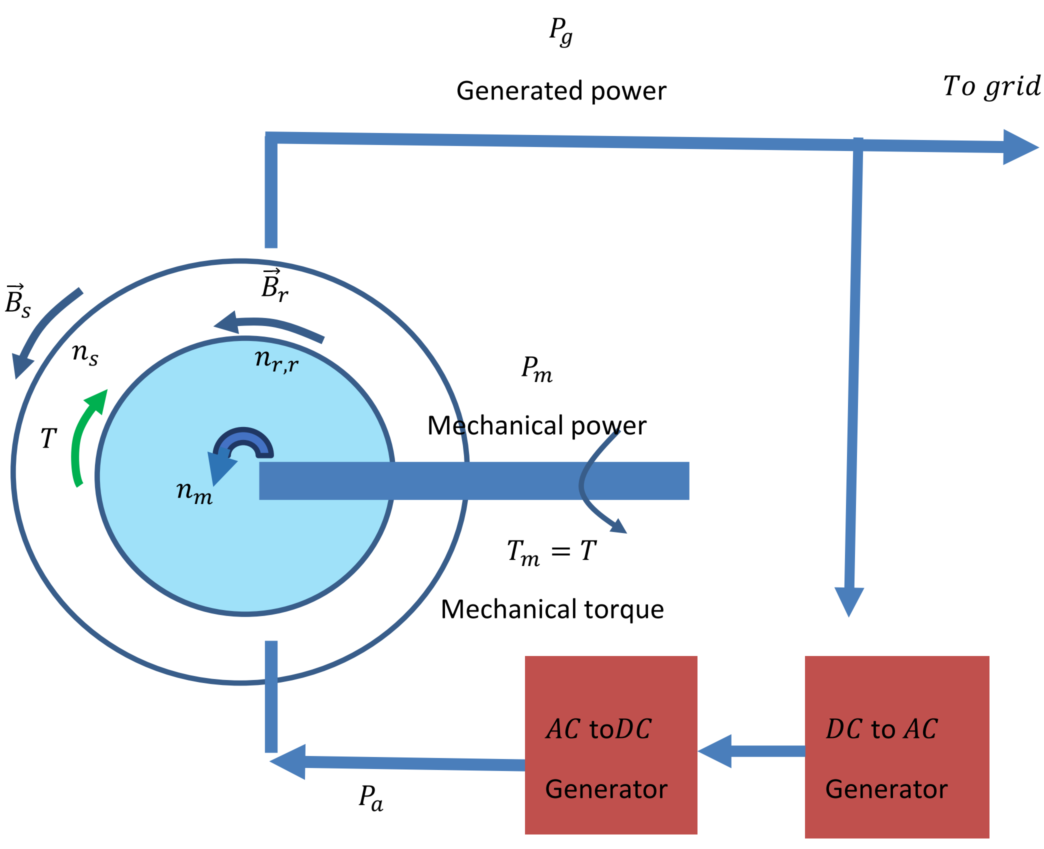


Figure32: Working principal of doubly feed induction generator when ,$n_m < n_s$

Self-Test

- What are main components in a drive train assembly?
- What is the main objecives of main shaft?

- What are the main components of a gear box?
- What is the role of coupling in high speed shaft?
- How do the synchoronous and asynchronous generator work?
- What is the slip ratio and why it is important factor in induction machine?
- What are the three main drive train topolgies which are used in the wind turbine?

2.2.5. Electrical components

2.2.5.1. Control cabinet

What Does the Subassembly Look Like?

Control cabinet is a control centre of a wind turbine. It hosts data handling equipment and program logic controllers (PLC), figure 33. It can be located either in the nacelle or in the tower.

Figure 33: Actual view of a control cabinet of a wind turbine.

What Does the Subassembly Do and What are its Underlying Physical Principles?

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Control cabinet receive signals from the sensors. These input signals are processed by the programmable logic controller and based on its logic, output signals are sent back to the actuators. The actuator then change the state of devices, figure 34.

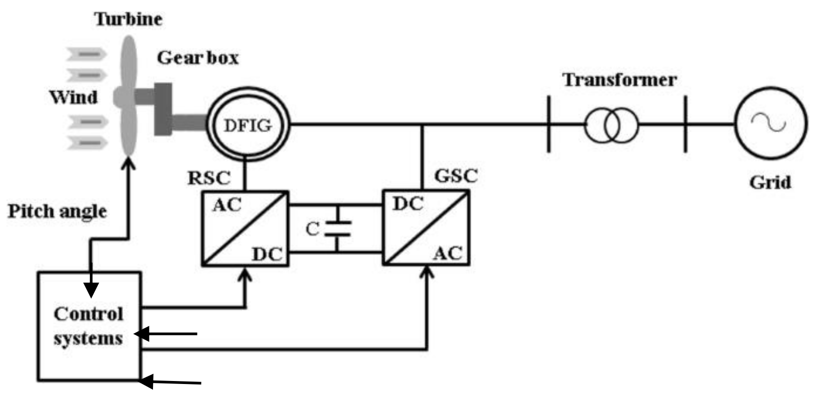

Figure 34: Interaction of control system with other components of non-direct drive wind turbine.

2.2.5.2. Converter

What Does the Subassembly Look Like?

Convertor is located in the nacelle. In a wind turbine a back to back convertor is used. One is connected to the grid through the transformer and it is called grid side convertor. The other is connected to the rotor of doubly feed induction generator or to the stator of permanent magnet generator and it is called generator side convertor. The actual view of a convertor has been shown in figure 35.

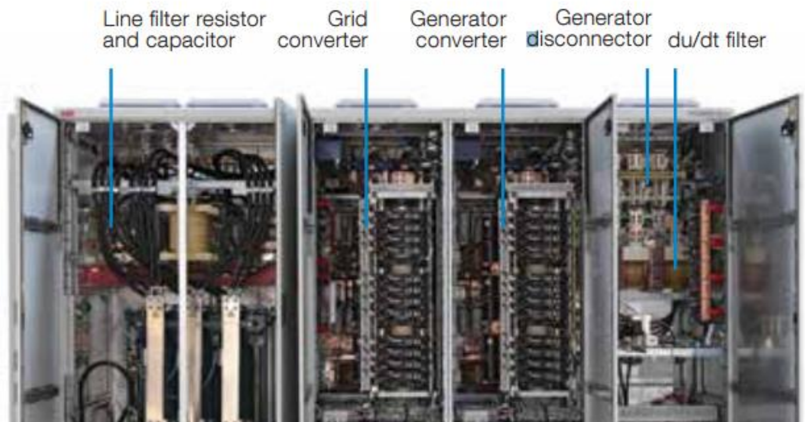

Figure 35: Actual view of a convertor in the wind turbine.

What Does the Subassembly Do and What are its Underlying Physical Principles?

The purpose of convertor in a wind turbine is to convert AC power with predefined frequency to a DC power and then from DC power to AC power with desired frequency. The convertor has four main parts, rectifier, DC link, investors and filter. Rectifier changes an AC power to the DC power by means diodes. Inverter change a DC power to the AC power by means of switches. To smooth the current and voltage filters are used. A ‘DC-link’ capacitor is fitted to provide a low impedance path for high frequency switching currents and to provide energy storage.

Self-Test

- What are the main electronic equipments in a wind turbine generator?
- What is the objective of power cabinet in a wind turbine generator?
- What is the objective of convertor in wind urbine generator and why a back to back convertor is needed?

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2.2.6. Power transmission equipment

2.2.6.1. Power cabinet

What Does the Subassembly Look Like?

Power distribution cabinet which can also be called a switch gear, is connected to the transformers. It is consisted of four compartments, Circuit breaker (CB) compartment, cable compartment, bus bar compartment and low voltage compartment, figure 36.

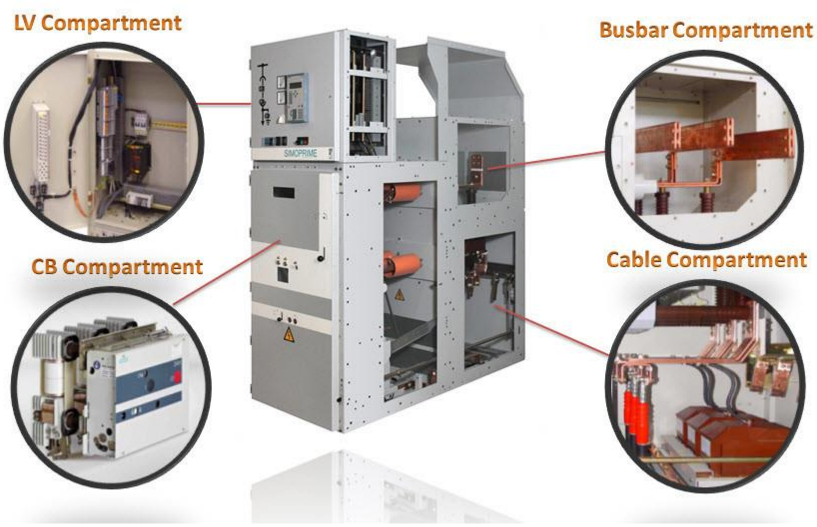

Figure 36: Schematic view of a switch gear with different compartments.

What Does the Subassembly Do and What are its Underlying Physical Principles?

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In a wind turbine a generated terminal voltage is less than 1KV (usually 575 V or 690 Volt).This terminal voltage is stepped up by a transformer to a medium voltage 20-30KV.Switch gear receives this voltage by means of bas bar and a circuit breaker .It he send this power to the next terminal or substation in a safe manner . In term of any faulty condition, a control signal from low voltage compartment is sent out to the circuit breaker .It is opened and disconnects the bas bar from the cabinet.

2.2.6.2. Transformer

Transformer is connected to the switch gear through a three phase medium voltage cables. Transformer is located in the nacelle If there is enough space otherwise it is located in the tower, figure 37.

Figure37 : Schematic view of a transformer in the nacelle.

Transformers is comprised of three main parts, primary winding, secondary winding, and the steel laminate core. The primary and secondary winding are mounted on the steel core, figure 38.

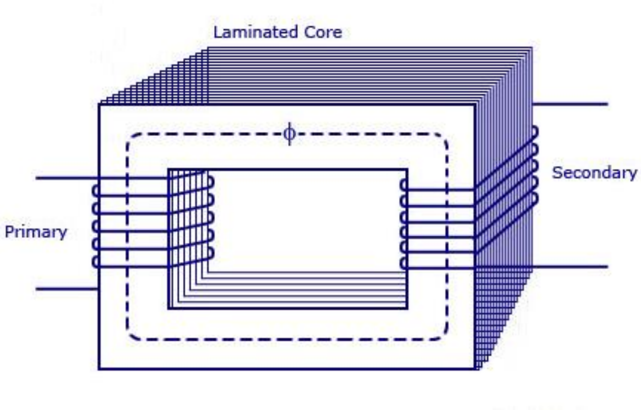


Figure 38: Schematic view of primary and secondary winding mounted on the steel laminated core.

Due to passage of current in the windings, transformers generate significant heat so they need to be cooled. Depending on the methods which are used to cool the transformers, they are classified as liquid filled and dry type transformers. In **liquid type transforms**, windings and core are immersed in the oil tank, figure 39. Heat is transformed from windings and core to the oil tank. Oil tank is equipped with radiator. Oil is heated up and passes through the radiators. The heat from the radiators surfaces is removed by natural or force air blown by a fan. Water can also be used to remove the heat from radiators surfaces.

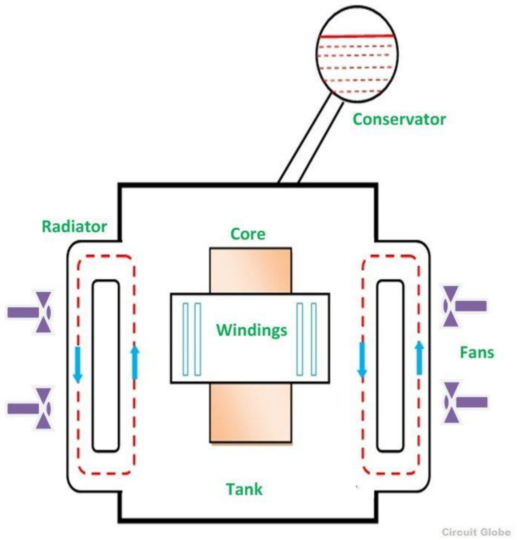


Figure 39: Left: Schematic view a transformer with oil tank cooling system. Right: Actual view a transformer with oil tank cooling system.

In a **dry type transformer** the windings and core are immerged in an insulated material such as resin. Dry transformers are classified in various types. These types are dependent on the type of insulated materials and the methods which are used to immerse the winding and cores in insulated material. Four most common types of dry transformers are open wound, cast coil transformer, vacuum pressure encapsulation and vacuum pressure impregnated, figure 40.

Figure 40: Different types of dry transformers

What Does the Subassembly Do and What are its Underlying Physical Principles?

Transformers step up or step down the voltage level of an AC line. AC power generated by a wind turbine generator should be transmitted to a substation (distribution centre) through a transmission line. In order to reduce the power loss in a transmission line, the current should be decreased. It can be accomplished by increasing the voltage level of AC line because the transmitted power through the line ($P = VI$) is constant. In a modern wind turbine usually a generated terminal voltage is less than 1KV (usually 575 V or 690 Volt).This terminal voltage is stepped up by a transformer to a medium voltage 20-30KV and then it is transmitted to the substation. Transformers works on the following principal; they convert electrical energy to magnetic energy and then magnetic energy to electrical energy, figure 41.

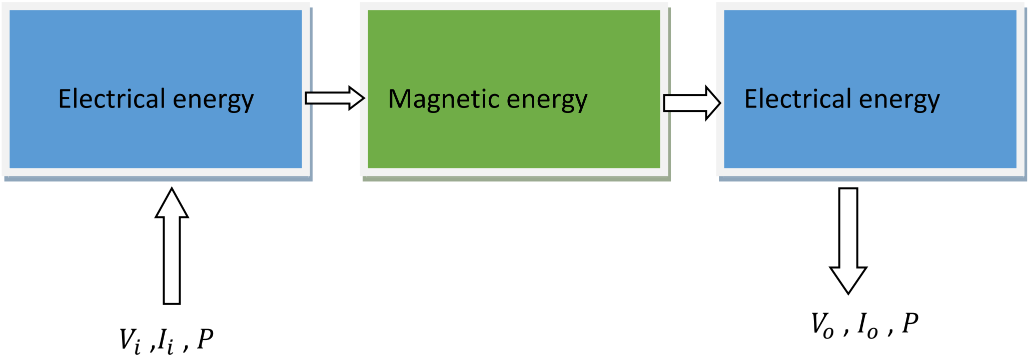


Figure 41: Energy conversion in a transformer(V_i ,I_i , P are input voltage , current and power respectively. V_o , I_o are out put voltage and current respectively).

In a transformer primary voltage set an AC current in the primary winding. The AC current then establishes a time varying magnetic flux in the primary winding (change of electrical energy to magnetic energy), 42. This initial magnetic flux before to be affected by the induced current in the secondary winding is called mutual flux, figure 42. Actually this flux is equal to the flux when secondary winding has not been connected to the load(circuit is open).

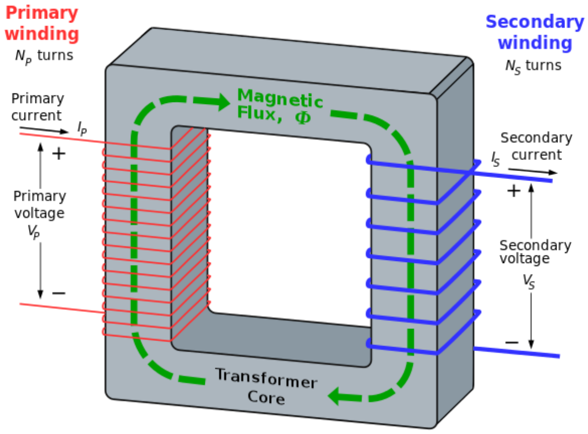
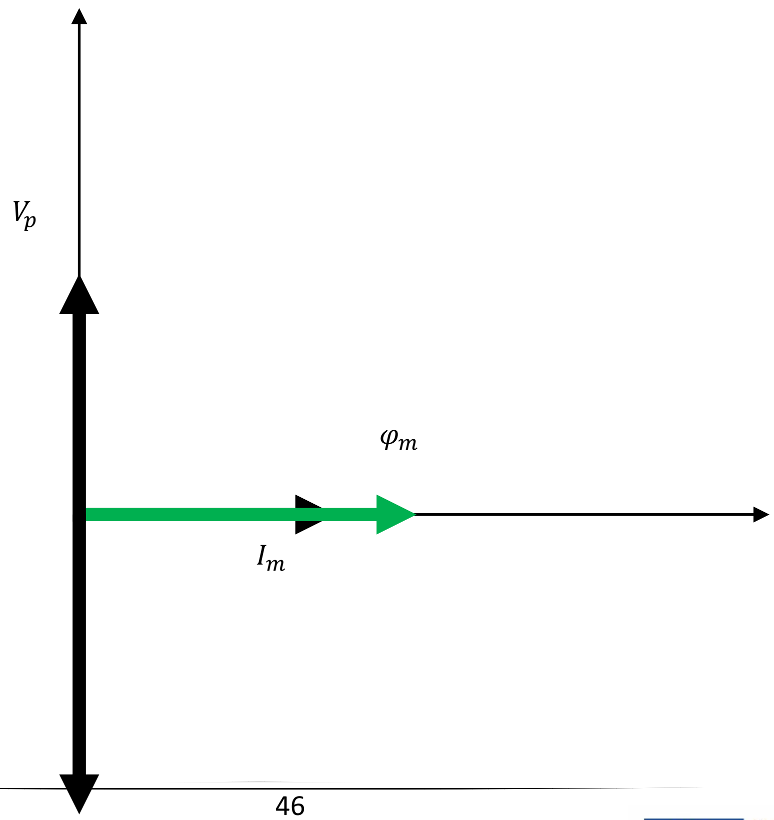


Figure 42: Schematic view of Mutual flux production in a transformer.

The flux generated in primary winding is passed through the secondary winding by means of the core. From the Faraday's law, time varying flux in secondary winding builds up a voltage. If the secondary winding is connected to a load then current is established in the secondary winding (change from magnetic energy to electrical energy). This current generated a counter flux which push the mutual flux back. In order to keep producing the current in secondary winding the mutual flux should be preserved so the primary winding extracts the current from power source (the source which has built up a primary winding voltage) to diminish the counter flux. Interaction of secondary and primary flux for an ideal transformer (neglecting all the losses) can be shown by a phasor diagram.

When the secondary circuit is open and the primary winding is connected to the source. The only load in the primary circuit is primary winding which is inductor therefore the current and voltage are 90 degree out of phase. It is obvious that in the secondary circuit only voltage is induced and there is no current and no generated flux, figure, figure 43. When the secondary winding is connected to a load then current passes through the circuit. Depending on the type of loads in the circuit, current can make a phase lag or phase lead with the voltage. Assume the current has a θ phase lag with the voltage. This current generates a flux with magnitude of φ_s and in phase with current. In order to preserve the mutual flux, the primary winding extract the current from the power source to produce the flux φ_p which is equal in magnitude but in reverse direction respect to the φ_s.This flux (φ_p) diminish the φ_s and maintain the mutual flux φ_m , figure 44.



V_s

Figure 43: Phasor diagram of an ideal transformer in no load condition.

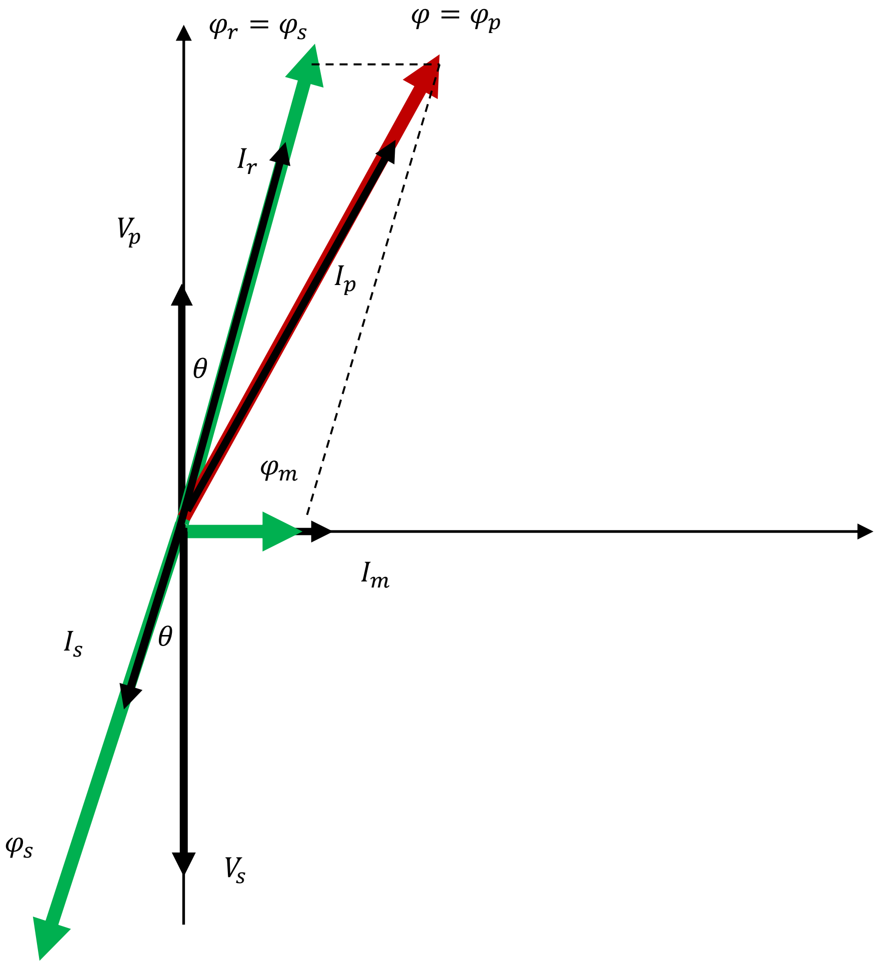


Figure 44 : Phasor diagram of an ideal transformer in inductive load condition.

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The number of coils in primary and secondary winding is proportional to voltage levels,

Because the mutual flux is preserved in the core, then according to Faraday's law,

$$V_p = \frac{N_p d\varphi_m}{dt} \qquad (2.9)$$

$$V_s = \frac{N_s d\varphi_m}{dt} \qquad (2.10)$$

From equations (2.9) and (2.10) then

$$\frac{V_p}{V_s} = \frac{N_p}{N_s} \qquad (2.11)$$

Because the input and output power are same then,

$$P = V_p I_p = V_s I_s \qquad (2.12)$$

And then from equations (2.11) and (2.12),

$$\frac{V_p}{V_s} = \frac{N_p}{N_s} = \frac{I_s}{I_p} \qquad (2.13)$$

Self-Test

- What is the objective of the switch gear in a wind turbine generator?
- What is the objective of the transormer in a wind urbine generator?
- How do usually the transfermores are calssified? What are the two major types of transormers and what are their differences?

2.2.7. Tower and foundation

What Does the Subassembly Look Like?

The nacelle of wind turbine is connected to the tower. Tower of wind turbine is made of tabular hollow steel manufactured in different sections. Sections are between 20-30 meter which are connected together by means of flanges in both ends. The tower has a conical shape which its diameter increases toward the base, figure 45.

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Figure 45: Actual view of wind turbine tower.

The tower is mounted on the foundation. In offshore industry depending on the depth of water different type of foundation can be used. Mono-pile, Gravity-based, Jacket, tripods, Tripiles and the floating platform are the types of the foundations used in offshore wind industry, figure 46. The contributions of these foundations in the offshore industry have been shown in figure 47.

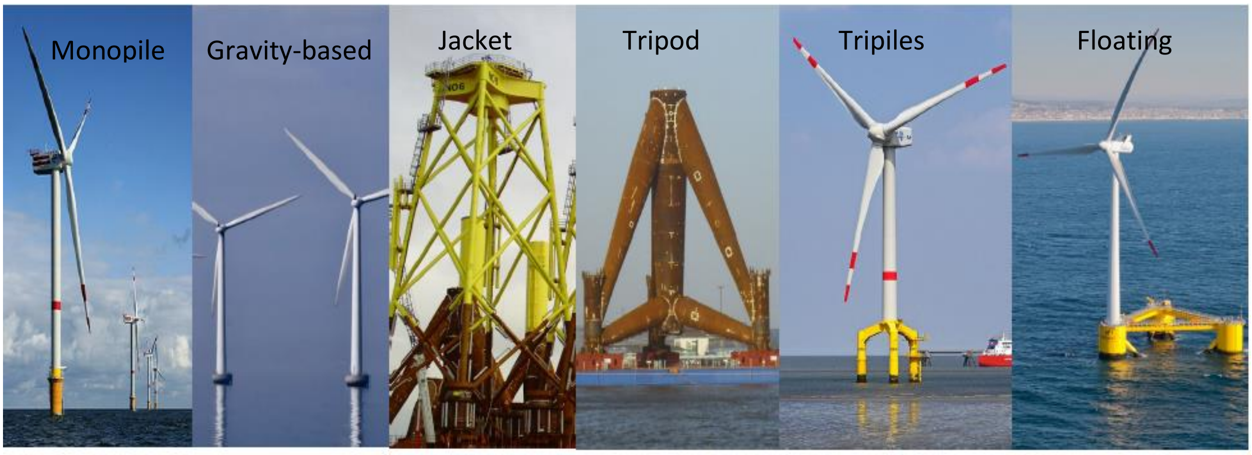

Figure 46: Various types of foundation used in wind offshore industry.

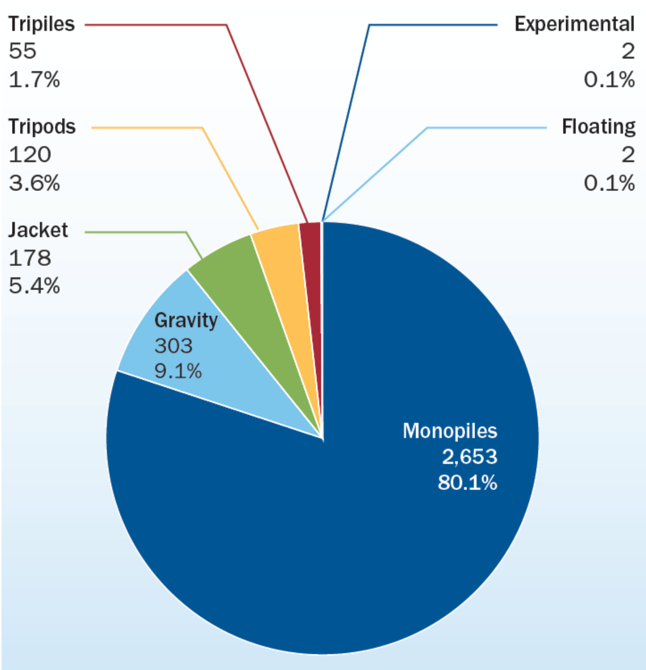

Figure 47: contributions of different foundation types in the wind offshore industry.

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Mono-pile and the Gravity-based are the two major type foundations which constitutes 90 percent of all installed foundation. The mono pile foundation has a simple construction. The foundation consists of a steel pile with a diameter of between 3.5 and 4.5 metres, figure 48. The pile is driven some 10 to 20 metres into the seabed depending on the type of underground.

Figure 48: Actual view of Mono-pile foundation.

Gravity Based Foundation (GBF) is a concrete foundation that is constructed on the land, in a dry dock, figure 49. From the dry dock where it has been produced, the self-floating GBF is floated to its

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destination and then immersed by ballasting it with water and sand. The GBF rests firmly on the hard sea bed and the wind turbine is then installed on this foundation.

Figure 49: Actual view of gravity based foundation.

What Does the Subassembly Do and What are its Underlying Physical Principles?

The tower supports the whole weight of wind turbine including the blades, hub and nacelle. Because the wind speed increases with the height so the tower enables the wind turbine to capture more wind and produce more power. The purpose of foundation is to support the tower and to withstand the entire loads exerted on the blades from the winds and the current .

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Self-Test

- What are the main types of offshore foundation?
- What is the different bteween gravity based and pile foundation?

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