POLITECNICO DI MILANO

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DESIGN ASPECTS OF DIRECT DRIVE PERMANENT MAGNET MACHINES FOR WIND POWER GENERATION

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Abstract

In the recent years the renewable energy sources are becoming more and more popular. This phenomenon is mostly driven by the environmental issues arisen as a result of usage of conventional energy sources. Wind energy being one of the most widely used renewable energy source is more and more crucial role in the energy industry. That fact pushes the wind turbine generator manufacturers to produce more efficient wind turbine generator topologies with less cost in order to be competitive in a market. As a result, in recent years, direct drive technology is becoming more and more popular in the wind energy generation industry due to its advantages over conventional drive systems with gearbox. In this work, we have discussed all the possible generator topology solutions that can be used in wind turbine. After that a detailed design aspects of direct driven permanent magnet machine were discussed. Finally, an example of real life PMDD generator was described with all its features. Although, DDPM machine topology seem good solution for wind turbine, there are still a lot of improvements that can be done in this sector.

Acknowledgements

First of all I would like to thank my supervisor, Professor Antonino Di Gerlando, for his tremendous support in my thesis study and research.

I am very thankful to Politecnico di Milano for this amazing experience and for all the knowledge gained here from all the professors and stuff.

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Introduction

Wind power generation

It is a well-known fact that human activity, especially after industrialization era, has led to global ecological problems on our planet. As we need more and more energy, our impact on ecology would respectively increase and this of course will lead to even more pollution of our environment. On the contrary, most of the renewable energy sources contribute very small or even no emissions. That is the main reason pushing all the scientists and research and development sectors off all the huge industrial companies towards finding solutions for making renewable energy usage more accessable and advantageous than conventional energy sources. Wind energy, in its turn, nowadays is one of the most reliable and important sources of renewable energy. However, imlementation of wind power is not a new idea. As the first examples of wind power usage we can mention vertical-axis windmills (sails connected to a vertical shaft which is in turn, connected to a grinding stone) found in ancinet Persia. The horizontal-axis windmills, where sails were connected to a horizontal shaft, the axles were used to translate horizontal motion to a rotational. In 19th century wind-rose horizontal axis windmills for water pumping were found throughout America. The first large size wind electricity generation turbine was built by Charles Brush in 1888, which was a 17 m diameter wind-rose configuration with the capacity of 12 kW (Kalmikov). Wind turbines then were standartized to have three upwind blades, horizotlal axis and to stand on a monopole tower. We can list the most important factors than influenced acceleration of the wind power generation development as follows:

1. High-strength fiber composites for construction of large low-cost blades
2. Recent fall in prices of power electronic converters

3. Variable-speed mode operation of electrical generators to reproduce maximum energy
4. İmproved plant operation leadin the availability up to 95 %
5. Economy of scale, as both, plants and turbines are getting larger in size.
6. İncrease in the accumulated field experience (which is also called learning curve effect) improves the capacity factor

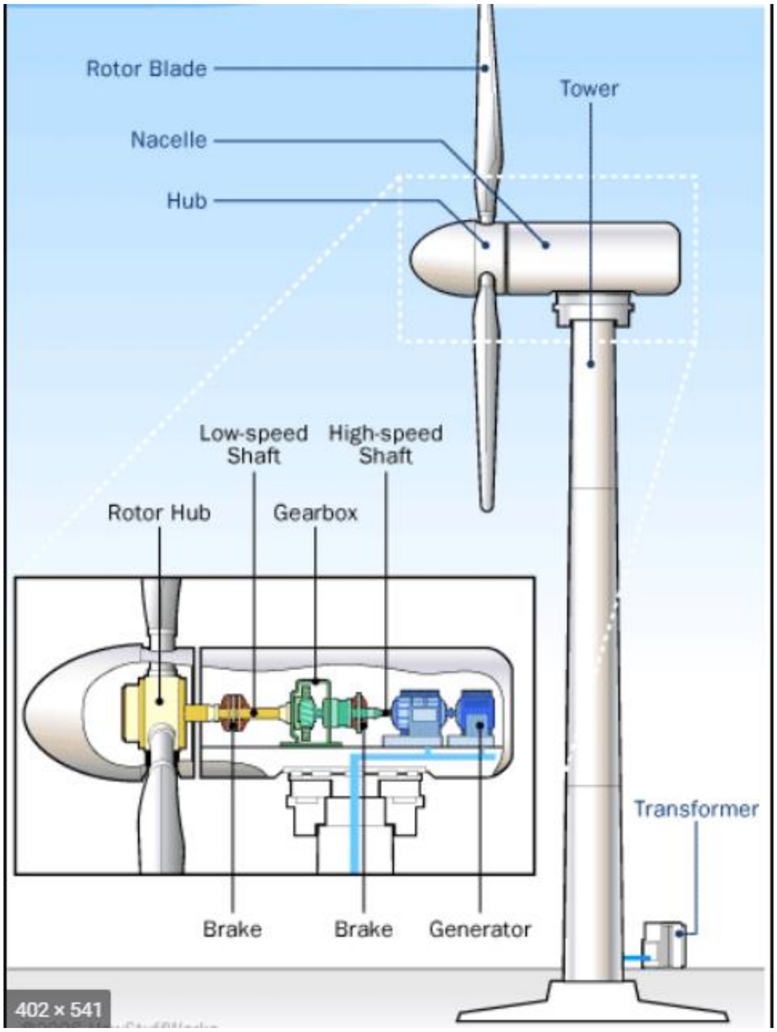


Figure1: Wind turbine main individual components

The main benefits of wind power are:

1. Endless and clean fuel- wind power does not produce emissions and is not extinguished with time.

2. A 1MW wind turbine operating for one year can reduce emission of over 1500 tons of carbon dioxide, 6 tons of Sulphur dioxide, 3 tons of nitrogen oxide and 60 pounds of mercury (Tripathy).

3. Scale-able and modular technology

4. Stable energy price- by decreasing dependence on conventional types of fuel, it takes off the extra burden from them and plays role in regulating their price, indirectly.

How do wind turbines work

In this section, we will review all the main wind turbine components and describe their role in the electricity generation process by wind turbine (Figure 1). Broadly speaking, there are two main types of Wind Turbines:

1. Horizontal Axis Wind Turbines (HAWTs) –they are of an ‘axial’ flow type meaning that wind flowing parallel to the axis is can be harnessed. These wind turbines are mostly used in a modern day electricity generation systems. Their major drawback is that they can harness wind speed only in a one particular direction. As the wind direction can fluctuate quite often and routinely, this becomes a major disadvantage.

2. Vertical Axis Wind Turbines (VAWTs) - they are of the ‘cross” flow type meaning that wind flowing in perpendicular direction to the axis is harnessed. Theoretically, these kind of wind turbines should have better efficiency and be more effective compared to their horizontal rivals. In reality, they usually

have very complex and sophisticated shapes and hence are very difficult and economically disadvantageous to manufacture.

The functions and aims of the wind turbine individual parts are explained below:

The Nacelle

The Nacelle is one of the most important wind turbine components. It houses the components which convert the kinetic energy of wind into mechanical energy to turn a generator producing electricity. The Nacelle sits on top of the tower and holds the shafts, the gearbox, the brake and the engine, both low and high speed. It also houses a sensor receiving data from an anemometer measuring wind speed, a vane measuring wind direction, a pitch control mechanism controlling blade angle, and the Yaw drive controlling the turbine's orientation relative to the wind.

The effect of rotor orientation on turbine

The wind direction influences the turbine design-whether it should be upwind or downwind. The upwind turbines have the rotor facing the wind in front of the nacelle while downwind turbines have the rotor behind the nacelle and faced away from the wind. The rotor orientation effect, i.e. upwind or downwind, has a dominant impact on the wind turbine system's instable loads.

The wind vane on top of the Nacelle informs the controller from whence the wind comes. The nacelle and the rotor changes direction respectively while the wind is shifting direction. In order to catch the wind properly the rotor should always be facing the wind. The wind turbine controller must also ensure the rotor is turned towards the wind. Near to all wind turbines are built upwind.

The Rotor

Together, the turbine blades and the core form a wind turbine rotor. Many turbines have two or three bladed propellers (generally accepted standard are three blades). The hub is the part which links the blades to the main shaft and respectively to the rest of the drive train that transfers mechanical rotational power of the rotor hub to the electric power of generator. The rotor is attached to the Turbine's main shaft. The wind energy spins the turbine blades around the rotor, rotating the power generator and turning the mechanical energy at the turbine shaft into electrical energy via electromagnetic field. Therefore, the function of the turbine rotor explains in practice how a wind turbine produces electricity.

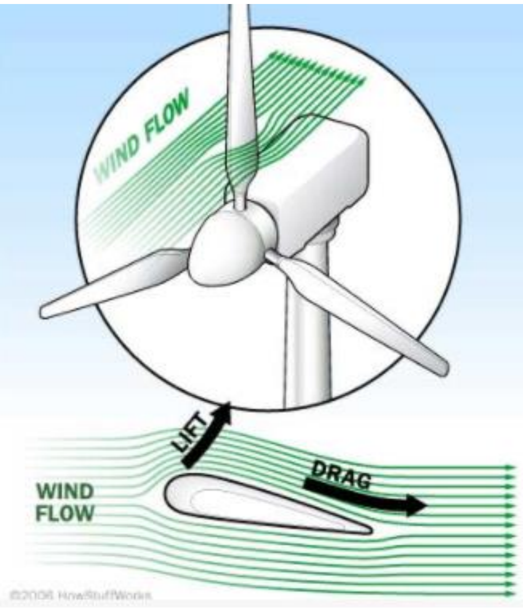


Figure 2: Wind turbine blades operation

The blades of wind turbine are the origin of conversion of wind kinetic energy to rotary-mechanical energy. Due of their varying shapes, the blades operate by creating lift and drag as the wind blows over them, like an aircraft.

The two key aerodynamic forces that operate in the rotor of wind-turbine are lift, which acts perpendicular to the wind flow direction and drag, which acts parallel to the flow direction. The blades of a wind turbine are manufactured more curved on one side (rear) than on the other side (front), this design technique creates pressure differential when the air moves through the blades. On the downwind side of the blade forms the low-pressure air pocket which pulls the blade towards it, respectively, causing the rotor to turn, and this phenomenon is called lift. Alternatively, the drag phenomenon is caused by wind’s force acting against the front side of the blade. The wind’s lifting force is generally much stronger than the dragging force which results in a net lifting force perpendicular to the flow direction of the air over the turbines blades which in turn, creates torque in the wind turbine rotor causing it to spin like a propeller.

Main shaft

The low speed shaft, which is the turbine's main shaft, has essential functions. It supports the rotor (blades and hub), and drives via the Gear Box the high-speed shaft connected to it. The low-speed shaft transmits the rotor's rotary motion and torque momentum via the Gear Box to the high-speed shaft to drive the generator.

Gear Box

The power extracted from the wind turbine rotor rotation is transmitted through the power train to the generator, i.e. through the low-speed shaft (main shaft), gearbox, and high-speed shaft. The Wind turbine rotor is rotating at a fairly slow rate. Via gearbox this slowly rotating, high torque power of the rotor is converted into low torque power with high speed, which is necessary for the generator connected to the high speed shaft. The Gear Box usually increases the generator's rotational speed from about 15 to 20 rotations per minute (rpm) for a massive, one-megawatt turbine to around 1,800 revolutions per minute required by most generators to produce electricity.

Controller

A control system is employed to maximize the functionality of a wind turbine. The controller raises power output and reduces the loads on the structural components. The control system consists of a variety of computers that continuously monitor the wind turbine condition and collect operating statistics from the sensors. The controller continuously optimizes energy output based on a continuous measurement of mainly wind and its direction. At wind speeds of about 8 to 16 miles per hour (mph) it starts the machine and at about 55 mph controller shuts off the machine. Turbines should not operate at wind speeds above about 55 mph, as high winds can damage the turbines.

The breaking system

The breaking system automatically stops the rotor when the rotational speed exceeds its cut-out point in order to prevent any electrical or mechanical damage. The aerodynamic braking system is primary and most widely used braking system for modern wind turbines which stops the turbine in a couple of rotations. Moreover, the aerodynamic braking system provides a very gentle and smooth way of breaking the turbine, without any major tear, stress and wear on the machinery and on the tower.

Generator

The wind turbine generator transforms the mechanical rotational power produced by the rotor blades into electric power. The wind pushes directly against the turbine blades, which transforms the wind's linear motion into the rotary motion required to spin the generator rotor to generate electricity with the use of an electromagnetic field.

All the wind turbines have special characteristics associated with wind speed. The generator, for example, will not generate output power until its rotational speed is above the so-called cut-in wind speed, at which the force of the wind on the rotor blades is high enough to overcome friction forces and the rotor blades are able accelerate enough for the generator to start producing electricity.

The power output from the generator will rise above this cut-in speed as a cube of wind speed (if the wind speed doubles, the power output would rise eight times) before it reaches its maximum rated power output. If the wind speed continues to rise, the wind turbine generator automatically would stop at its so-called cut-out point to prevent any electrical or mechanical damage.

Pitch system

The Pitch mechanism in a wind turbine is a closed loop drive system which controls the angle of the turbine blades by spinning them in such a way that the blades use the correct amount of available wind energy to produce the most power output, while ensuring that the turbine does not surpass its maximum rotation speed. This ensures the safety of the turbine in the event of high winds, electrical load failure or other harmful occurrences.

Wind Turbine Tower

Wind turbines are mounted onto a tower to harness wind energy. The turbine's main body lies on the top of tower, behind the blades. A wind turbine tower supports both the Nacelle and the Rotor (the hub with three blades attached). The taller towers allow wind turbines to absorb more energy and produce more electricity as the wind speed rises further away from the ground and at a higher atmosphere the wind blows more steadily.

Summary of wind turbine system overview

Now, when the key wind turbine components have been clarified to provide an overview of how wind turbines operate, let's summarize how electricity is produced in this system:

1. When the wind blows on the turbine's angled blades that are attached to a rotor, this causes the rotor to spin, hence, converting the wind's kinetic energy into mechanical energy;

2. The rotor is attached to the Turbine's main shaft. By means of a gearbox the rotor shaft is connected to a generator. The gearbox transfers the drive shaft's low-speed rotation into high-speed rotation fast enough to drive the generator

and transmit the mechanical energy at the turbine shaft to electrical energy via electromagnetic field;

3. The electrical current initiated by the generator flows through a cable which is running down the turbine tower's interior;
4. Finally, a step-up transformer is used to convert the electricity to a higher voltage in order to transmit it to the power grid;

Wind Energy Generation Systems

As it was mentioned earlier, wind turbines generate electricity by using wind power to drive an electric generator. Wind produces lift and exerts a turning force when passing over the blades. Within a nacelle, the rotating blades turn a shaft that connected to the gearbox. The gearbox, in its turn, sets the rotational velocity to that optimal for the generator. The generator, respectively, converts the rotational energy of blades and rotor into electric power. The power output itself goes to a grid-connected converter, which normally converts the electricity from generator (around 700 V) to the suitable voltage fir the power transmission and collection system (around 33kV). The wind power is generally given by the kinetic energy of the passing air mass per unit time. Which is:

$$P_{air} = \frac{m * V_\infty^2}{2} = \frac{\rho * A * h * V_\infty^2}{2}$$

Where:

P_{air} is stands for the power held in the wind (Watts)

ρ is the density of air (1.225kg/m^3 at the temp. 15° C)

A is the area swept (m^2)

V_∞ is the wind velocity (speed) at infinite distance from the blades of the turbine, which means wind speed without any rotor interference.

Of course, we have to take into account the losses during the harvesting of wind energy by wind turbine and introduce the power coefficient $C_p$which is given by:

$$C_p = \frac{P_{Wind\ Turbine}}{P_{P\ air}}$$

Hence:

$$P_{Wind\ Turbine} = \frac{C_p * \rho * A * V_\infty^3}{2}$$

The Betz limit is defined for the maximum value of C_p, which states that a turbine can never extract more than 59.3% power from an air stream. Moreover, in reality, wind turbine rotors have a maximum $C_p$values ranging between 25-45%.

Another important feature in the design process of the wind turbine is the so-called tip speed. Tip speed is in fact the tangential velocity of the rotor at the edge (tip) of the blades, which is like any other speed measured in m/s.

$$V_{tip} = \omega * R$$

Where:

$V_{tip}$is the tip speed

ω is angular velocity

R is the tip radius

The tip speed ration then defined as:

$$\lambda = \frac{\omega * R}{V_\infty}$$

Solidity describes the fraction of the area swept that is solid, to be more clear, wind turbines with large number of blades are called high-solidity wind turbines and with less blades are called low-solidity wind turbines. As it was already mentioned, modern electricity-producing wind turbines use low-solidity rotors (most of them have 3 blades as a standard).

WIND TURBINE APPLICATIONS

Wind Turbines are used in a different applications like harnessing offshore wind resources, onshore wind resources, generating electricity for a single home and for a whole plant or a small city and etc:

- Mostly used by utilities to provide power to a grid, large wind turbines of a range from hundred kilowatts to several megawatts. These type of turbines (called utility scale) are commonly installed together in wind farms in order to produce large electricity amounts. These kind of wind farms usually consist of a hundreds of turbines, which can produce enough power to provide thousands of homes with electricity.
- On the contrary, small wind turbines, which are about up to 100 kilowatts, are usually installed in the locations close to the areas where the produced electricity will be used, for example, near telecommunications dishes, near homes or water pumping stations. Small turbines are occasionally connected to diesel generators, photovoltaic systems and batteries. These connected systems are called hybrid wind systems.
- In order to harness the energy of consistent, strong winds taking place at the coastlines and in the sea, many countries are using offshore wind turbines.

Types of Generators Used in Wind Turbines

Broadly speaking, there are two types of generators:

1. Induction Generators
2. Synchronous Generators

Essentially, induction generators are those in which the primary mover and consequently the rotor spin at super-synchronous speeds (in generating mode), thus transmitting energy from the generator to the load. In the case of standalone loads, the magnetizing current is provided by a capacitor bank and the magnetizing flux is thereby established.

In the case, if it is connected to the electrical grid, then the grid will provide magnetizing current. To this category of generators, we can refer the Squirrel Cage, Doubly Fed and Wound Rotor type of generators.

Synchronous generators are the ones in which the rotor precisely rotates at the synchronous speed. The synchronous machine acts as a generator when the air-gap electromotive force lags the excitation electromotive force by an angle δ (0<δ<180). In such a case the grid or the connected load will be supplied with energy. Also, in this case, the generator rotor is either electrically excited, or by a permanent magnet. To this category of generators we can refer Permanent Magnet and Wound Rotor. In this chapter we will discuss all these generator types and explore them more in detail.

INDUCTION GENERATORS

It is a form of AC electrical generator with operating principle similar to an Induction motor, only distinction being that it runs at super-synchronous speed, thus converting the mechanical energy input from the prime mover into electric energy at the output. Like all the other generators, it has two main components:

rotor and stator. The stator itself is stationary while the flux created by the three phase windings rotates at a velocity called synchronous speed Ns. The rotor is the machine's moving part and the speed at which it spins is defined as Nm – the mechanical speed. The ratio of difference between mechanical and synchronous speed divided by synchronous speed is denoted by letter “s” slip.

$$s = \frac{N_s - N_m}{N_s}$$

The slip “s” has to be negative ($N_m > N_s$) for the generating mode.

$$N_s = \frac{120 * f_s}{P}$$

Where:

f_s is the stator current frequency

P is the number of poles per phase in the stator

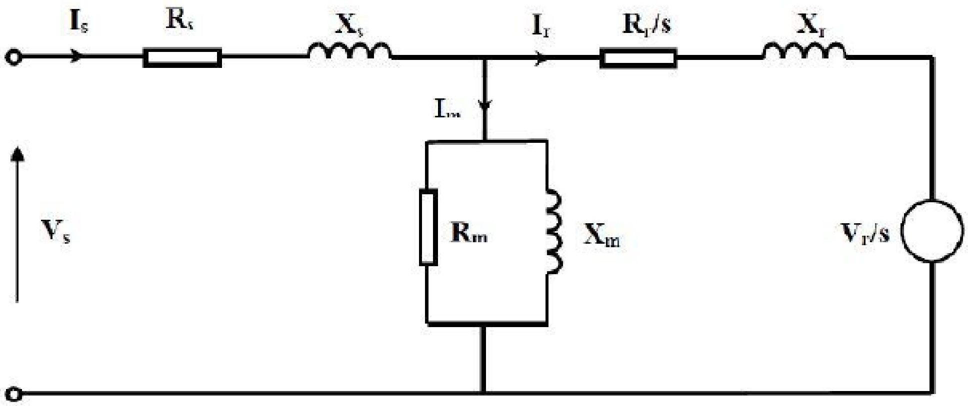


Figure 3: Equivalent Circuit of an Induction Generator

Where: I_s is the stator current, I_r is the rotor current, R_s is the stator resistance, X_s is the stator reactance, X_r is the rotor reactance, R_r/s is the rotor resistance, $I_m$is the no load current, $R_m$is the working component, $X_m$is the magnetizing component,

V_r/s is the voltage across rotor, $V_s$is the grid terminal voltage or in other words stator voltage.

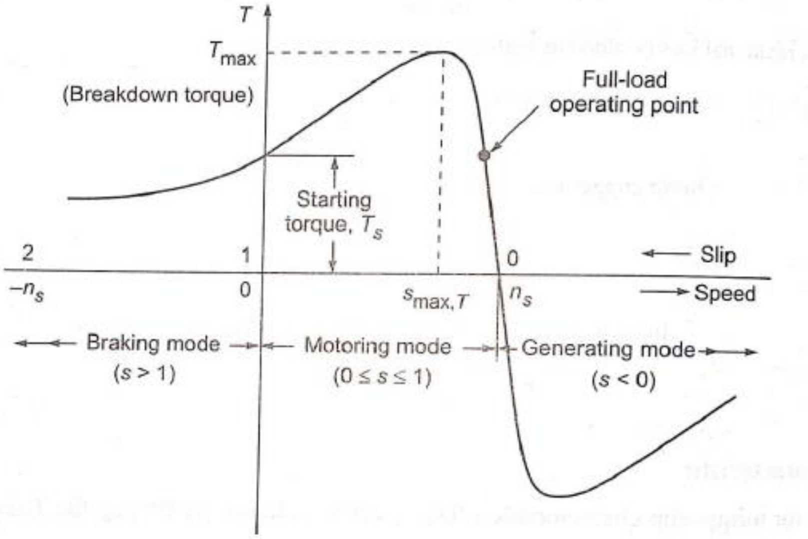


Figure 4: Slip-Torque Characteristics. (H.Li, January 2007)

The graph above describes the torque-slip characteristics of an induction generator, from which it is obvious that for the generating mode the slip has to be negative. The motoring and generating curves are actually very similar, they are in fact inverted versions of each other. For the breaking mode the slip has to be more than one, for motoring mode it ranges between zero and one (both included in the region).

In wind power generation three types of Induction generators are generally used:

1. Squirrel Cage Induction Generator (SCIG)
2. Doubly Fed Induction Generator (DFIG)
3. Wound Rotor Induction Generator (WRIG)

Although, all these generators are referred to the same category, they operate with different types of power converters, which define their speed concepts (variable, limited variable or fixed).

Being asynchronous generators, induction generators may have variable speeds, hence because of the broad range of wind speeds involved, they are said to be best suited for wind power generation. The most popular type of induction generator used in wind power generation is DFIG, this and other generators types will be reviewed in this chapter along with their advantages and disadvantages.

Types of Induction Generators used in Wind Turbines

Squirrel cage induction generator (SCIG)

CONSTRUCTION

It has a unique structure, with the rotor having solid bars of conductive material mounted in rotor slots and shorted by the end rings. Copper bars alloyed in large machines are driven in the slots and brazed onto the copper end rings, while smaller ones use die cast bars of aluminum. The rotor circuit can't be matched with, so the starting torque of the system is low, although it has excellent running efficiency. Another significant aspect of design is that the number of stator slots must be a non-integral multiple of the number of rotor slots to prevent the rotor and stator teeth from being magnetically locked during the startup. The rotor teeth are skewed slightly for tor the same reason. For the same purpose the rotor teeth are skewed slightly. The design is quite similar to that of a traditional squirrel cage, widely used in the past and therefore this name is given to the Induction Generator.

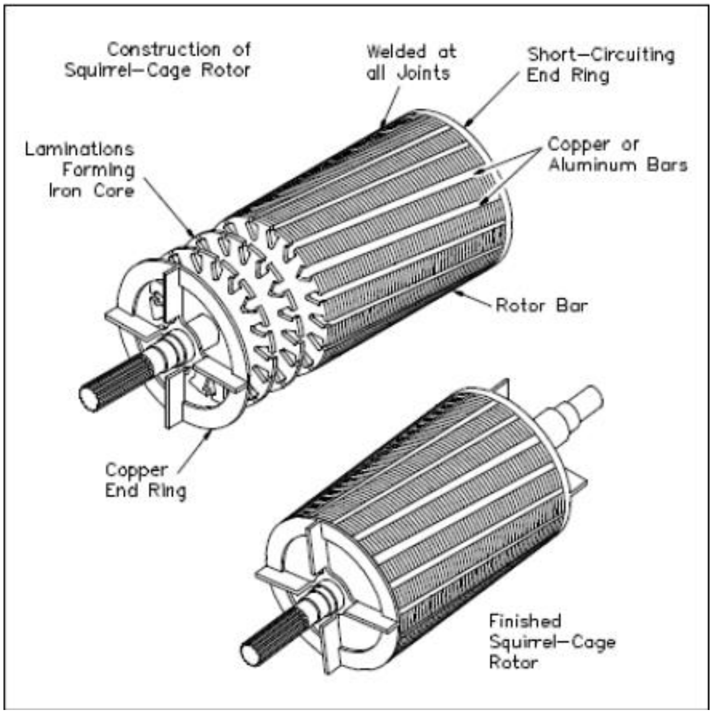


Figure 5: Components of Squirrel Cage induction generator

The SCIG includes a power converter and a capacitor bank to sustain the magnetizing current. A multi-stage gearbox is used, and as shown, the SCIG is connected directly to the Grid through a transformer. Since the SCIG only works at a limited range near the synchronous speed, the wind turbines fitted with this form of generator are sometimes referred to as the fixed speed wind generator. This is the traditional design introduced in the 1980s and 1990s by some Danish wind turbine manufacturers which is an upwind, stall controlled, three-bladed wind turbine using a SCIG, so it is also called the Danish concept.

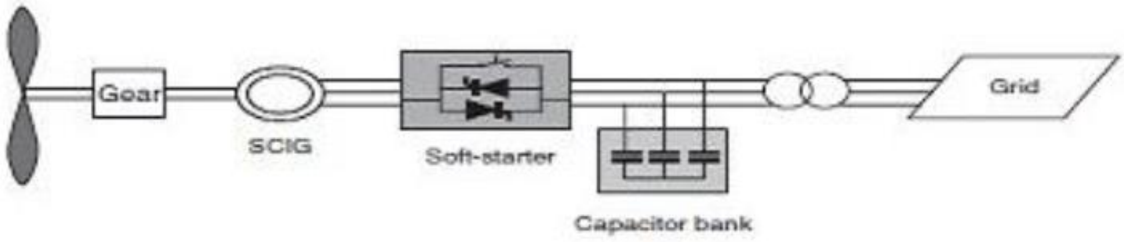


Figure 6: Schematic diagram

ADVANTAGES

1. It is robust and simple.
2. Cheap and easy for mass production.
3. It enables machines to operate at a relatively constant speed when it is connected to a grid, thus providing a stable control frequency.
4. Absence of current harmonics since no frequency conversion occurs.

DISADVANTAGES

1. Uncontrollable speed and variable only over a very small range, in which only speeds a bit higher than the synchronous speed are feasible for generator operation.
2. Efficiency is low.
3. Wind speed and the turbine speed cannot be adjusted to obtain aerodynamic efficiency, because wind speeds can vary to a large extent.
4. Big issues in gear box maintenance.
5. Highly noisy.

Another popular configuration is when SCIG is directly connected to the wind turbine via multi-stage gearbox. Stator is connected to the main grid via force commutated PWM inverter and an uncontrolled rectifier. The aim is to contain power flow over DC link. Here, a full-scale back to back power converter is used instead of capacitor bank and soft starter. It is a very widely used machine due to its mechanical simplicity, design and construction.

ADVANTAGES

1. Energy is captured better, than in fixed speed SCIG concept.
2. No need in capacitor bank.
3. Variable speed concept Reduction of the mechanical stress on the turbine due to variable speed concept.
4. Electrically isolated from the grid.

DISADVANTAGES

1. Gearbox maintenance problem still remains.
2. Issue with obtaining excitation current from the stator terminal is not solved.
3. High converter rating leads to increase in the converter cost.

Wound rotor induction generator (WRIG)

CONSTRUCTION

The only difference from the SCIG here is in the construction of the rotor. The winding of the wound-rotor is poly-phase with coils installed in the slots of the rotor core. It is similar to that of stator concept except that the number of slots is less and fewer turns per phase are used due to heavier conductor. Due to the flexible rotor circuit, WRIG is used effectively in wind turbine applications for dynamic speed control.

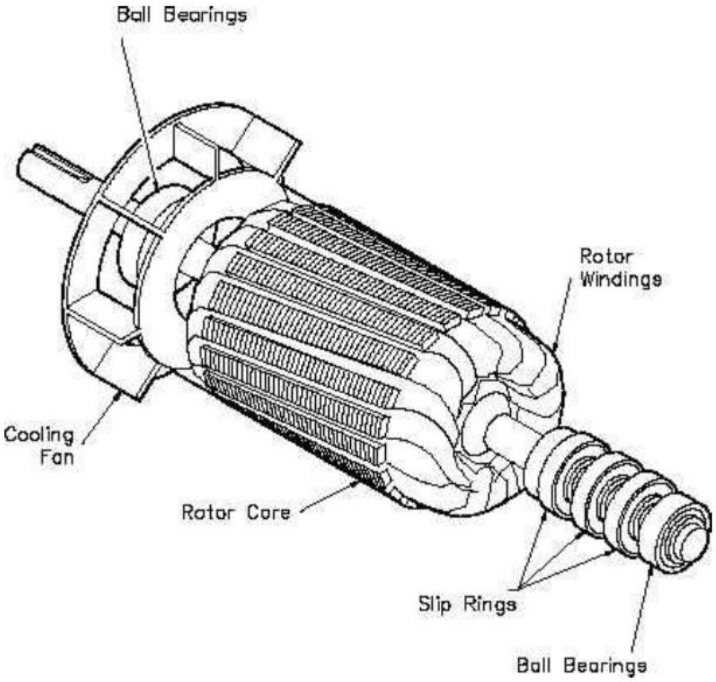


Figure 7: Wound rotor (air cooled)

The rotor core is laminated, with slots suitably punched in to accommodate rotor winding / bars. In the case of small machines, the punched laminations are stacked and mounted directly onto a shaft, while in the case of large machines a stack of annular punching of an appropriate cross-sectional area is placed onto a spider-web structure on the shaft.

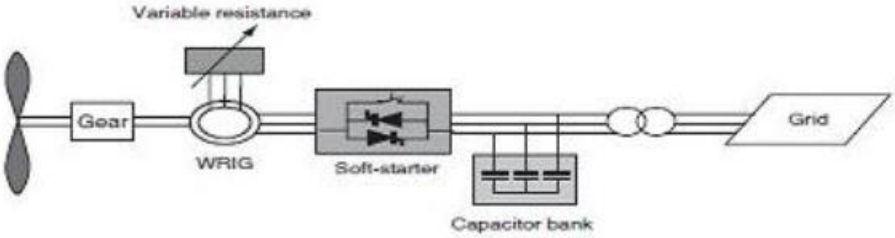


Figure 8: WRIG SCHEMATIC DIAGRAM

In the figure 8 the schematic of WRIG used wind turbine system is given, where variable resistance and a power electronic converter are used. The stator of the IG is connected to the grid through a power converter and a transformer, while the rotor winding is connected with a controlled resistor in series. By controlling the energy extracted from a WRIG rotor the variable speed operation can be achieved; however this extracted power must be dissipated in the external resistor. The increase in variable speed range leads to a higher slip which in turn means a higher power extracted by the rotor and subsequently lower generator efficiency. That means the rating of the used resistor must also be higher. The dynamic speed control range depends on the rating and size of the variable rotor resistance. A typical value for limited variable speed range is usually less than 10 percent above the synchronous speed. (H.Li, January 2007).

ADVANTAGE

1. In comparison with the SCIG, this configuration is more suitable due to wider range of operating speeds above synchronous speed

DISADVANTAGES

1. Huge amount of the essential rotor energy is released through the external rotor resistance.
2. A separate arrangement of capacitor bank for reactive power compensation is still required
3. Lower efficiency, subsequently less profitable concept.
4. Although the speed range is wider as compared to SCIG, it is still not enough as wind speed applications require even larger ranges of speeds.
5. The usage of multiple-stage gearbox means that this system is prone to mechanical defects and inefficiency.

DOUBLY FED INDUCTION GENERATOR (DFIG)

Double fed induction generator is very similar in design and construction to WRIG, the difference is that the rotor here is fed from the grid via rotating or static frequency converter. Stator is connected directly to the grid while a rotor is connected to grid via slip rings through four-quadrant ac-ac converter equipped with Insulated Gate Bipolar Transistors (IGBTs). This system presents the following advantages:

1. Decreased inverter cost, as inverter rating accounts for almost 30 percent of the total system power.

2. Advanced system efficiency.

3. Power-factor control can be achieved at a lower expense without using of capacitor bank.

4. Full control of active power and reactive power.

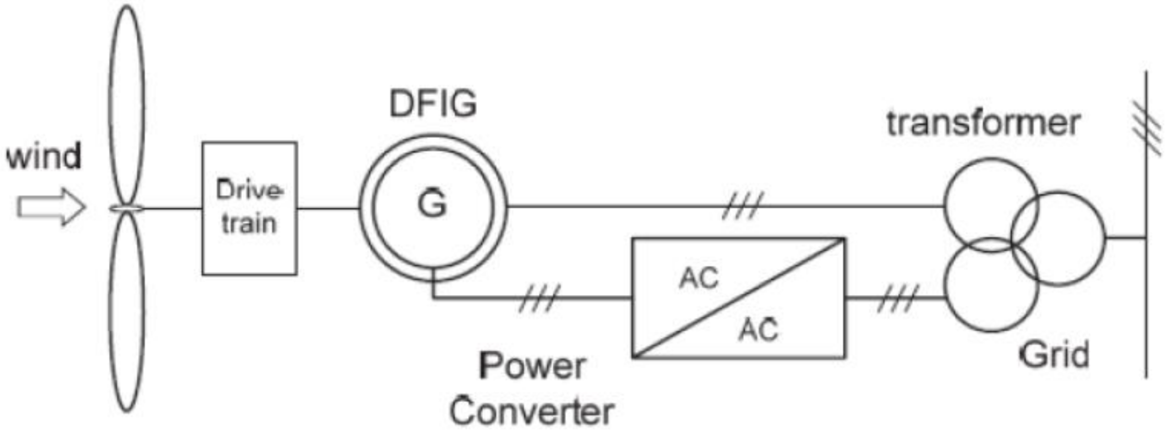


Figure 9: Schematic Diagram of DFIG

The DFIG with a power controller like the one shown in the figure 9, is a highly controllable and at the same time simple way to convert the energy from the variable speed rotor to electric utility grid with a constant frequency. The major argument for the popularity of DFIG used in the national networks is their ability to supply power at constant frequency and voltage while the rotor speed varies.

1. Capability to produce more output compared to its rated power avoiding overheating.

2. Capability to transfer maximum power in sub synchronous and super synchronous modes.

3. Converter connected to a rotor, so that its power rating is reduced hence the whole power passes through the stator.

All these benefits make DFIG a preferable choice for WECS if we are choosing among induction motor models.

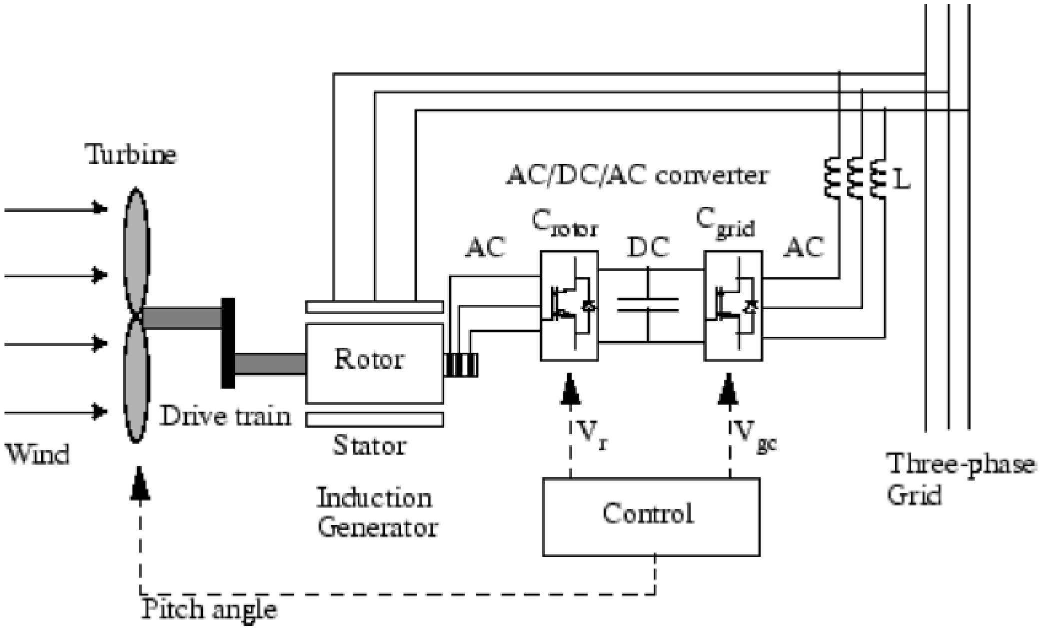


Figure 10: DFIG operation

SYNCHRONOUS GENERATORS

These generators as it is quite obvious from the name are electric machines where the rotor runs exactly at the synchronous speed and the speed of the rotor and stator flux is the same. The excitation field produced by permanent magnet or electrically produced, magnetizes the rotor. Here the rotor is the rotating assembly placed in the center of the generator while the stator is the stationary armature which is electrically connected to the grid or load. In standard utility equipment, a set of three conductors form the armature winding, wired to the transmission lines. The excitation magnetomotive force in the rotor produces the *excitation electromotive force*, also the excitation mmf together with the vector combination of armature reaction produces the resultant mmf. Hence this resultant mmf produces *air-gap emf*. The mechanical energy from the primary mover is transmitted to the rotor in magnetic domain which in its turn transmits the energy across stator in the electrical form, all these happens when the excitation electromotive force vectorically leads the air gap electromotive force by an angle δ.

CONSTRUCTION

Generally there are two construction types of the rotor in SG.

1. Salient pole type

This type of rotor is usually used for the small speed machines which have large diameters and relatively small axial lengths.

The features associated with the field pole construction are

1. They have a large horizontal diameter compared to a shorter axial length.
2. The pole shoes cover only 2/3rd of the pole pitch.
3. Poles are laminated to reduce eddy current losses.

2. Cylindrical rotor type

This type of rotor is generally used for high speed operation and is usually employed in turbo generators. It has uniform length in all directions giving a cylindrical shape to the rotor thus providing uniform flux cutting in all directions.

1. It gives better balance.
2. Lesser windage losses.
3. It also has a quieter operation.

Basically, Synchronous generators are of two major types

i. Permanent Magnet Synchronous Generator (PMSG)

ii. Wound Rotor Synchronous Generator (WRSG)

Synchronous Generators types used in Wind Turbines

WOUND ROTOR SYNCHRONOUS GENERATOR (WRSG)

This type of synchronous generator is also called electrically excited synchronous generator (EESG)

CONSTRUCTION

The WRSG is usually built with the rotor carrying a field system provided with a DC excitation. The stator carries a 3-phase winding similar to that of an induction machine. The rotor may be of cylindrical type or may have salient poles . In low-speed machines salient poles are more usual and that is why may be the most useful and common version for direct-drive wind turbines applications. The diagram for WRSG is given below:

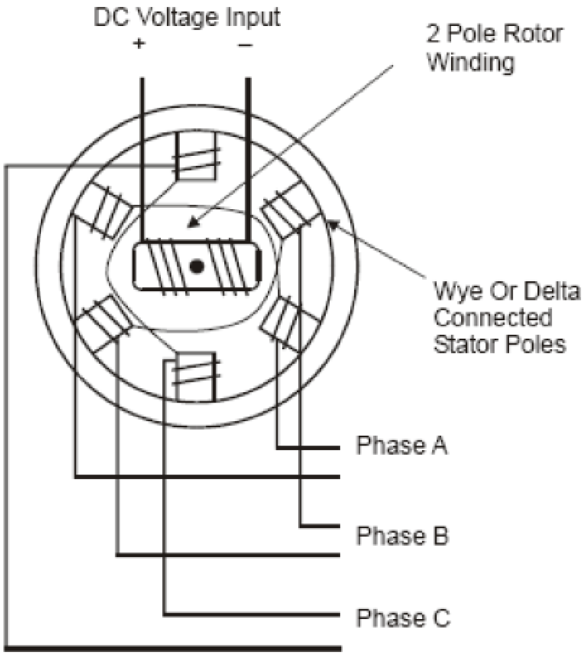


Figure 11: Diagram of WRSG

The frequency and the amplitude of the voltage can be totally controlled by the power electronic converter placed at the generator side, meaning that the generator is totally controllable over a very wide range of speeds.

ADVANTAGES

1. Suitable for the generation of high power.
2. Independent control of active and real power.
3. As it is self-excited generator it has improved power factor.
4. No need of gearbox.
5. Less sensitive to grid fault connection because the generator is electrically isolated from grid.

DISADVANTAGES

1. Heavy and expensive solution due to the large number of windings and parts. Because the pole pitch must be large enough in order to supply space for pole shoes and excitation winding.
2. Field losses are inevitable as it is compulsory to excite the rotor with DC, with brushes or brushless exciter and with slip rings
3. Additional converter is needed to excite the rotor winding.
4. Higher maintenance cost compared to induction generator.

PERMANENT MAGNET SYNCHRONOUS GENERATOR (PMSG)

CONSTRUCTION

Here the excitation field is provided not by the coil but by the permanent magnet instead. Stator is the stationary armature as always that is electrically connected to a load while the rotor contains permanent magnets mounted on it. The armature winding is made up from a set of 3 conductors placed 120° apart in space, this topology provides a uniform torque or force on the generator rotor. The uniformity of the torque arises because the magnetic field resulting from the currents in the three conductors of the armature winding combine spatially in such a way as to resemble the magnetic field of a single rotating magnet. The stator magnetic field appears as a steady rotating field and spins at the same frequency as the rotor when the rotor contains a single dipole magnetic field. The two fields, (stator and rotor magnetic fields) move synchronously and maintain a fixed position with respect to each other while rotating. The combination of armature mmf vectorically with the permanent magnets persistent flux, leads to a higher air gap flux density and subsequently to core saturation. The output voltage is proportional to the speed in the PMSG.

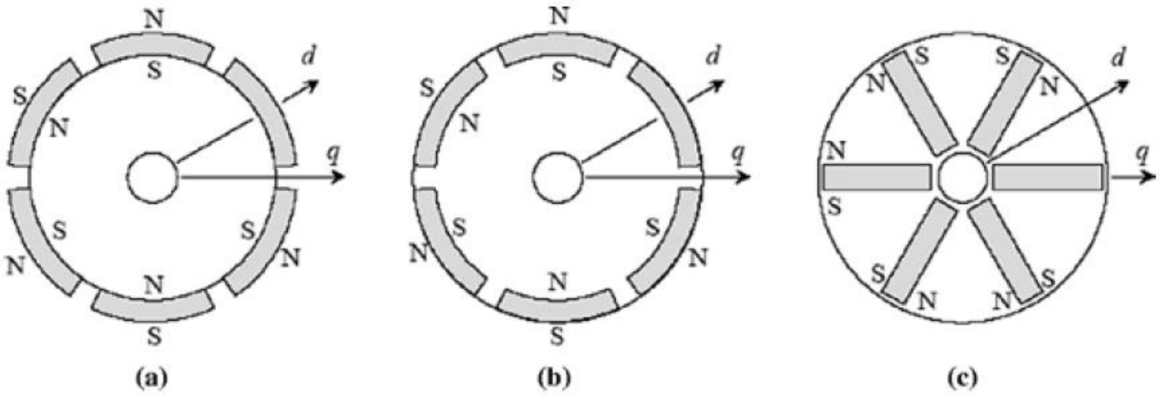


Figure 12: Permanent magnet SG

ADVANTAGES

1. Relatively small size and light weight.
2. High efficiency and low losses.
3. External excitation current is not needed.
4. Gearless (no gearbox).

DISADVANTAGES

1. Very useful for small wind turbines, nevertheless, for large wind turbines the magnet size and quantity has to be increased.
2. Demagnetization of permanent magnet as a result of different malfunctions aggressive atmospheric conditions.

However, because of the advantages listed above, especially for high efficiency direct-drive applications make PMSG based WECS very promising. Therefore in the recent years this area is attracting a lot of research.

Direct drive or conventional gearbox comparison

Here we will focus on different direct drive generator topologies for wind turbines and give an overview on the various permanent magnet generator technologies. The advanced characteristics of PM direct drive generators have recently attracted a number of manufacturers, as a result these generators now represent nearly 20 percent of the wind turbine generators sold worldwide. In order to obtain high torque level these generators require increased air gap diameter. As it is shown in the figure 13, in a direct drive system there is no gearbox, hence the generator is directly connected to the hub of the wind turbine. As a result they rotate at the same speed which is generally around 8 to 15 rpm depending on the power rating. There are several advantages of elimination of the gearbox:

1. Reduced noise
2. Drive train simplification
3. Increased reliability
4. Reduction of losses as a result of fewer energy conversion steps
5. Low maintenance cost

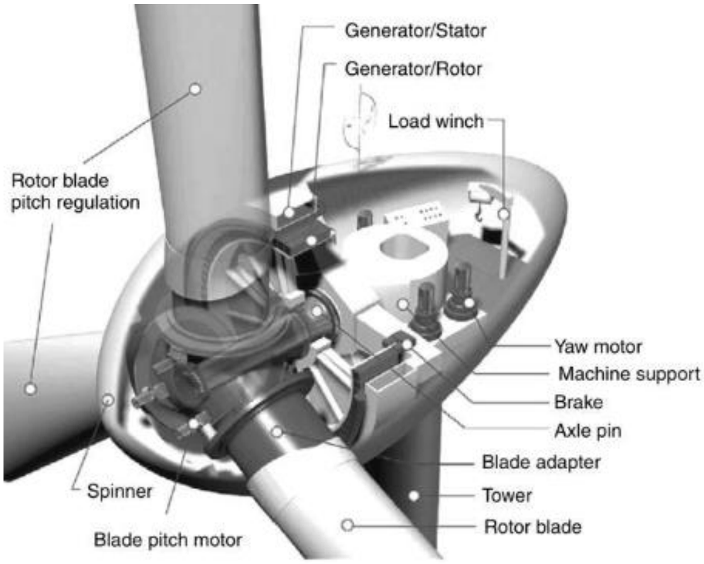


Figure 13: Direct Drive System components

For direct drive generators to compete with high speed conventional geared generators, they have to reach high torque values. This statement is clear from the equation of power output of the rotating machine:

$$P = \omega * T$$

Where:

P is the power output (W), ω is the angular velocity (rad/s) and T is the torque. Hence, if angular velocity is low (like in the case with direct drive PM machines), torque needs to be high in order produce the same power output. The torque of the rotating machine can be obtained from the equation (2), well known from the design and construction of electrical machines background:

$$T = 2 * \pi * R^2 * l * F_d$$

Where:

R is the radius of the machine, l is the axial length and F_d is the shear stress applied to the machine's structure.

Based on the two equations given above we can state that for a fixed axial length and shear stress, in order to obtain the required torque levels, it is necessary to increase the diameter of the machine. Larger diameter means larger size machines. Which, in turn, leads to large amount of expensive material needed for the construction of the machine. Also, it is not very easy to build, transport and install large size generators. So, one of the most important aspects in the design of direct drive PM generators for wind turbine is the production of a highly efficient machine with reduction in the structural mass. In other words, production of large power output, with the least possible weight.

Excitation techniques.

Synchronous machine can be excited electrically or with the use of permanent magnet. As an example of electrically excited generator we can mention Switched reluctance generator (SRG), which has a single electrical excitation located on the stator, and excitation on the rotor. The magnetization of rotor poles is provided by DC source in the electrically excited direct drive machines (EEDD). This type of excitation (DC source) is usually provided by brushes and slip rings in the wind turbine generator design. EEDD machine can have salient or cylindrical rotor poles (salient is more commonly used). However, in every case, the rotor poles have to be large enough in order to provide sufficient space for excitation windings. In order to process the power generated and connect the generator (EEDD) to the grid a power converter is used. As a result, the frequency and amplitude of the voltage, active and reactive power of machine are fully controlled. Moreover, the speed of the generator is also controlled for a very wide range of wind speed. EEDD have robust and simple construction, they also have a better efficiency and power factor in comparison with the induction machines. The drawback is the constant need of direct current supply, which leads to reducing overall efficiency due to additional losses of the generated heat. Nevertheless, EEDD generator technology is nowadays the dominant technology for the low speed applications of the direct drive in the wind turbine industry.

Permanent magnet direct drive generators

Here, the synchronous machine is excited using permanent magnet. This electrical excitation of the rotor poles in the direct drive machine can cause resistive heat losses in system. As a result, the overall efficiency of the system reduces and some maintenance issues can arise. In order to avoid these heat losses, complicated cooling techniques are implemented.

No external power supply is needed in PMDD machine as the rotor poles here are made of permanent magnet material. Hence, there is no excitation losses in the generator like in EEDD. As a result, the overall efficiency and energy yield are increased, also the reliability of the system is increased due to absence of the slip rings. The drawback of PM machine, as it was mentioned earlier, is the size and large amount of expensive material needed in the construction. The stator in PMDD is usually similar to that in EEDD, although some alternative topologies exist, they require a full scale power converters in order to connect to the grid. Recent advances in power electronic converter design have led to their significant cost reduction allowing the production of a clean power output in PMDD.

The material used in the rotor poles of PMDD are made of rare earth materials like samarium cobalt (SmCo), neodymium iron boron (NdFeB) which proclaim high density of magnetic energy in a small geometry and volume. Although SmCo magnets are the primary choose for high temperature applications, NdFeB magnets can produce greater flux density (1.2 T compared to 1.0 T of SmCo) and hence decrease the overall prize and mass of the PMDD generator. As the rare earth materials implemented in PMDD are now being found at increased number of sites, the future of PMDD generators seems promising from this point of view. To conclude, the reduction of price in PM materials and advances in power electronics sector (hence the price of converters) has led to recent big interest in the development and implementation of PMDD generators making them a primary candidate for applications in direct drive wind turbines.

PMDD generator topologies

The main constraint in the design of PMDD machine is to achieve high torque/mass and power/cost ratio. We can divide the PMDD generators to three categories based on the orientation of the magnetic flux crossing the air gap within the machine:

1. Radial Flux (RF PMDD)
2. Axial Flux (AF PMDD)
3. Transverse Flux (TF PMDD)

Also, the machine can be slotted or slot less depending on the core design of the stator. An alternative way to categorize these generators is the fact of presence or absence in the stator core of iron, which results in air cored or iron cored machine topologies accordingly.

Radial Flux RF PMDD machine

Here, the magnetic flux passes radially across the air gap. Due to its robust design and structural stability, the iron cored RF machine (Fig 14) is the most prevailing topology used in PMDD generators. The most common one is the slotted RF PMDD generator because in includes structural characteristics of EEDD generator and also includes advanced magnetic characteristics of the PMDD generators. Moreover, RF machines due to their reduced weight and high torque levels are considered as the most suitable option for industrial PMDD machines, for very large wind applications (MW scale).

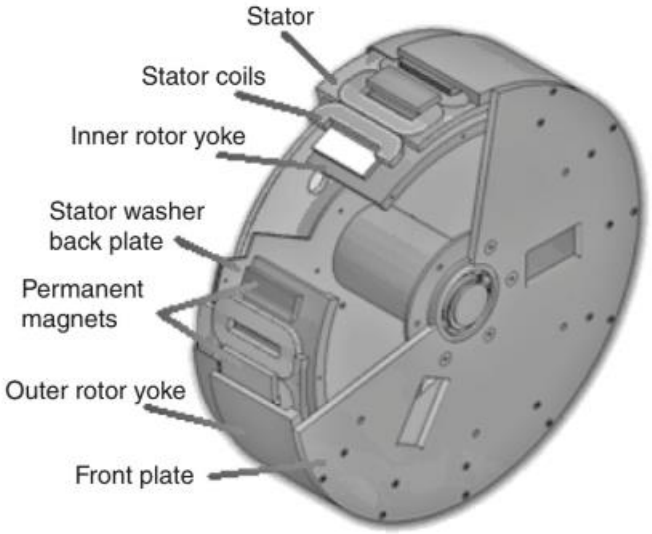


Figure 14: Radial flux PMDD machine

To reduce the active material requirement, flux concentration techniques can be applied, which allow higher flux density in comparison with remanent flux density from permanent magnets. However, fitting magnets along with the flux concentrators is quite complicated task and implies manufacturing issues in a complex structure.

The rotor of the RF PMDD machine can be positioned outside of the machine. This structure will allow a larger air gap diameter, subsequently improving the machine efficiency (greater number of magnetic poles are used). But the disadvantage is that stiffer structure will increase the complexity and the total mass of the machine, moreover complex cooling techniques for he stator will be required (as a result of absence of the natural cooling). These cooling systems will add reliability issues extra maintenance cost. Some other research and development institutes propose using fractional pitch winding (to reduce the cost of RF PMDD due to lower number of simple coils on the stator teeth). But here, due to increased subharmonics, more eddy current losses occur in the magnets.

Despite all the possible alternative options, researchers conclude that conventional RF PMDD machine with permanent magnets based on the rotor surface are still the optimal choice due to its structural simplicity, reliability, torque density, high energy yield and relatively small manufacture and maintenance costs.

Axial Flux PMDD

In this type of machines the magnetic flux passes across the air gap in the axial direction. Most commonly used structures are disc structures. The basic structural design for AF PMDD is the slotted machine with PM material based on the rotor and the stator is facing the rotor.

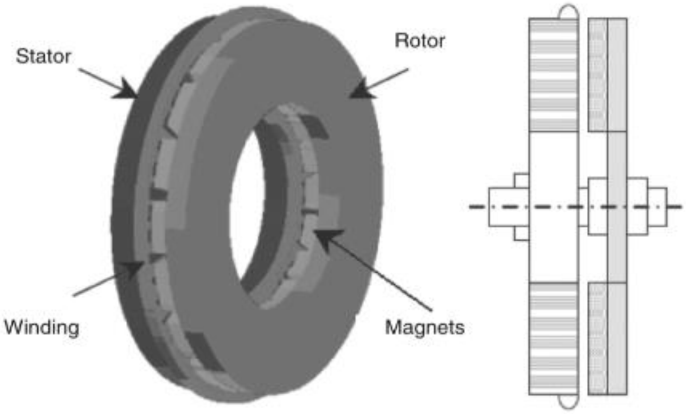


Figure 15: Single sided slotted AF PMDD machine

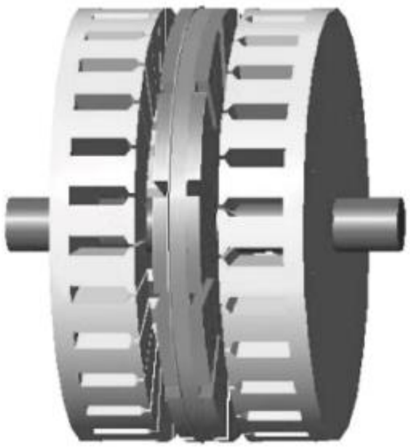


Figure 16: Double sided slotted AF PMDD machine with stator balance

Slotted AF PMDD machines generally have compact design structure, relatively low noise and cogging torque, high torque density and short axial length. The basic issue with the single sided axial flux machine is the strong magnetic attraction force between the iron stator and the PM disc, which enhances the stiffness requirements of the machine. The problem can be solved by using extra rotor or stator thus forming double sided machine where the forces are balanced. However, adding extra stator or rotor increases the mass of the machine making it heavier than his RF prototype. Complicated core design of slotted AF generator is more difficult to manufacture than the RF PMDD generator. The efficient way of the reduction of complexity is the removal of stator teeth. This slot less stator design with short end windings reduces copper losses, creates more compact design (easier and cheaper to design) with higher overall efficiency. But this design technique has a low power density, thus necessary to use large outer diameter and thicker magnets in order to compensate. Hence, for high power rated wind turbines this configuration is not cost effective.

Transverse flux TF PMDD machine

In this topology of PMDD machine, the magnetic flux in the core crosses perpendicularly the rotor rotation. The transverse flux topology have very small pole pitches (τ), which leads to the high force density and current loading than in other PMDD machines. Without decreasing the available space for the main flux, TF machine allow an increase in the space of windings. The research held by Dubois (Ref), concluded that the iron cored TF PMDD machines have the greatest potential regarding the cost/torque ration and in terms of the power density.

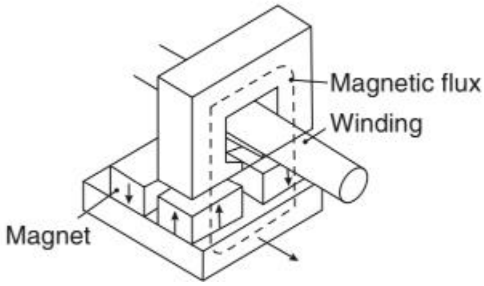


Figure 17: Single sided, surface mounted TFPM machine

The basic drawback of transverse axial machines is that due to the large amount of armature leakage fields their power factor is significantly low (0.35-0.55 87). This low power factor even with using flux concentrators (0.7) initiates a high reactive power demand and relatively small real power output, making these generators less attractive for large wind turbine applications. The power factor can be increased by an active current control of the converter linked to the each phase of the TF generator. Magnetostatic and transient finite element analysis (FEA) are other optimization methods used for realization of the best magnetic circuit for the machine to reduce minimize the leakage paths.

Although, TF PMDD machines have a number of advantages, due to their complex core design and complicated structures, they are more difficult to manufacture in comparison with RF and AF PMDD machines. Air cooled or slot less design techniques which in theory can simplify the manufacturing process, but as the complex core design is needed for creation of a flux path perpendicular to the movement of the rotor, are not possible in the TF PMDD machines. Hence, different topologies of TF PMDD machines were proposed to ease their manufacturing and decrease the complexity.

The inner position of rotor in the TF machine is the optimal choice, because the outer rotor topologies lead to a heavier and subsequently more expensive machine. Among the proposed topologies for TF machine without flux concentrators we can mention single or double sided winding, various core design methods like U-core or claw pole (Fig 18).

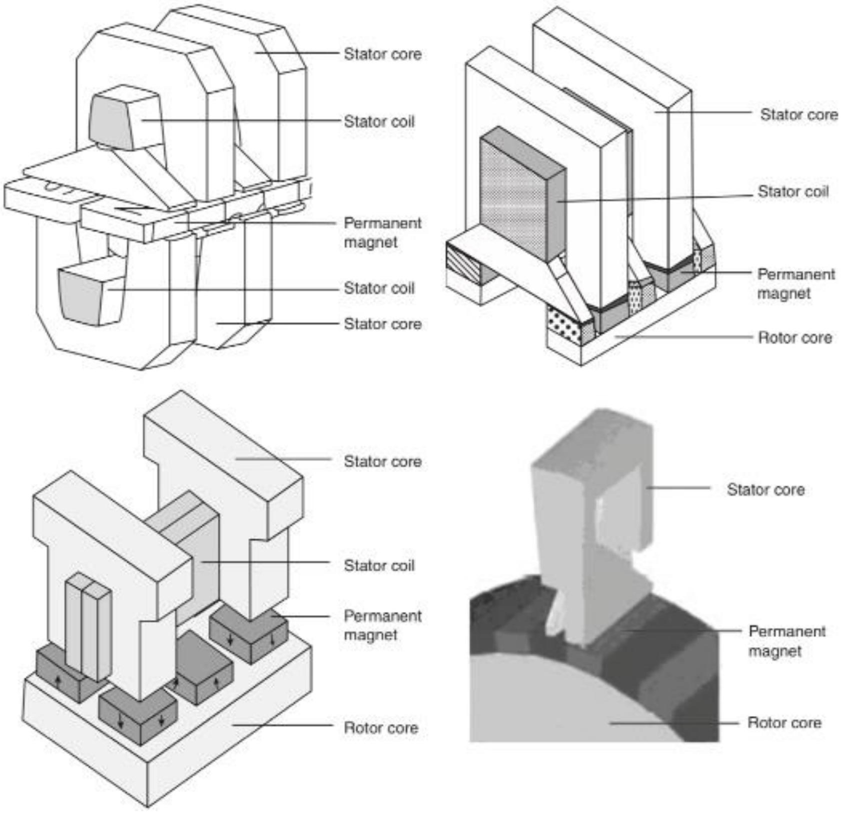


Figure 18: TFPM topologies without flux concentrators

Clearly, the TF machines with flux concentration are superior than surface mounted ones in terms of power factor and force density. In the figure 19 all the core design methods with flux concentration are illustrated. If we compare the single and double winding stator core topologies, then the single winding would be a better choice due to its efficiency and lightweight, because second winding would increase the diameter and structural complexity of the machine leading to larger air gaps and reduction in torque density. Depending on the stator core shape we can differentiate U-core, E-core, C-core and claw pole designs. The C-core stator with flux concentration arrangement is the one with highest torque density and lightest mass.

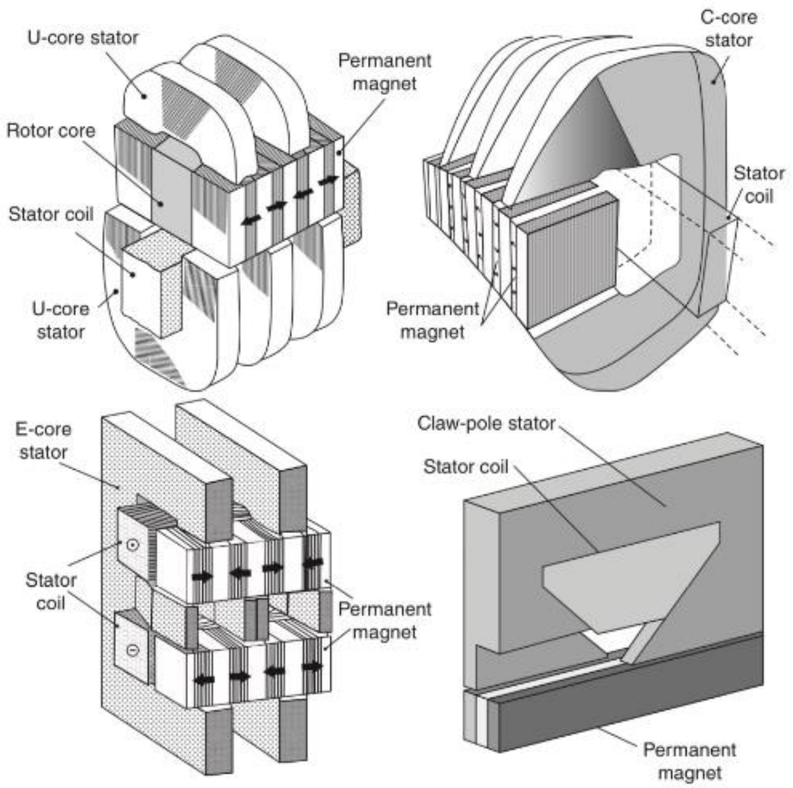


Figure 19: TFPM topologies with flux concentration

Conclusion

Compared to EEDD and SRG machines, PMDD machines are more reliable and have higher energy yield making them superior. Moreover, as it was mentioned already, the expected further reduction in the prize of PM materials and improvement of performance of power electronic converters makes PMDD machines more attractive for on and offshore wind turbine applications.

Among the different topologies of PMDD machines described in this chapter, the slotted RF PMDD machine with the inner rotor and surface mounted permanent magnets is considered to be the lightest and the most reliable. The topology with C-core stator core AF PMDD machine is attractive choice due to its structural simplicity, increased efficiency and zero cogging torque. This machine has less active and structural mass requirement compared to other AF PMDD and RF designs. The C-core TF PMDD machine with an inner rotor and flux concentrators combines all the beneficial features of a TF machine like high current loadings, high force density, reduced copper losses and highest torque/mass ratio in comparison with RF, AF and other TF PMDD machine designs.

Design Aspects of PMDD generators

In this chapter we will focus on the electromagnetic design of direct driven machines for wind energy generation, their requirements, main topologies and material choices, along with their advantages and disadvantages. An engineer needs to make a number of decisions regarding design choices and methods in order to design an optimal direct drive generator for a given purpose.

Design requirements

Let’s start with the statement of the supreme purpose of the direct drive generator which is the conversion of an input torque or force and speed into electrical power in absence of a gearbox. There are also a number of major requirements in terms of the manufacture, transportation and installation of the generator. These generators impose a number of practical limitations due to their large size and heavy weight. It would be very wise to consider all these aspects at the early stages of the design process. Another important aspect, which has to be mentioned is the location where the generator will be installed and utilized. The weather conditions can affect the quality and life spin of the generator. For example, humidity and salt (offshore) can damage the insulation materials and permanent magnets of the generator if they are not well protected. The main requirements can be listed as follows:

1. Up and foremost requirements are the force or torque and the speed of the generator

2. Cogging torque has to be small enough to enable startup (at low power ratings), to obtain tolerable audible noise levels
3. High efficiency
4. Cost criterion: the cheapest generator which is able to do the job is the best one

The cost itself includes: material cost, manufacturing, transportation, maintenance and operation and finally decommissioning costs.

Design Options

Material Preferences

Main materials used in the design of the PM machine are laminated electrical steel, permanent magnets and copper. The primary goal of the laminations is to provide a low reluctance pathway for the magnetic flux especially in regions where the flux density is mot constant. The two main characteristics of the used electrical steel type are the iron losses and the saturation flux density. The highest possible force density can be achieved at the highest saturation flux density. But, high saturation level laminations have o low percentage of silicon and subsequently have high iron losses. So, there is a so-called trade-off between losses and the saturation flux density. However, due to the fact that in the direct drive machines the frequencies at rated load are generally so low that the iron losses are small in comparison with copper losses. Although, they can be significant at partial load.

The primary purpose of copper windings is to enable the extraction of electrical power from generator. There are a number of alternatives available in the design of the copper winding: concentrated, single-layered, double-layered, strip wound coils, round wire coils and preformed coils. The main aspect in the selection of the winding arrangement is the application of the generator.

Magnets: the most frequently used type of the permanent magnet is the so-called rare earth magnet neodymium iron boron (NdFeB). The two main advantages of using this magnet type are its high magnetic field and relatively low price. Main issues that have to be considered when using PMs are listed below.

1. The presence of eddy current losses in the generator (particularly when concentrated fractional pitch type windings are used) as the resistivity of PMs is not infinite. The cooling must be sufficient to extract these heat losses.
2. When the temperature increases the magnetization decreases reversibly. That means, in the design procedure of the machine we have to use the magnetization at the maximum operating temperature.
3. The generator becomes useless when PMs lose their magnetization, hence the permanent demagnetization has to be prevented.

Generally speaking, there could be three main causes of demagnetization

1. Magnets can be demagnetized by a high temperature. Necessary measures should be taken in order to avoid these high temperatures.
2. High currents which produce a magnetic field in the opposite direction of the magnetization. Usually, these currents occur at short circuit of the generator. For this reason, generators are commonly designed so that unexpected short circuits can't affect the magnetization of the magnets even if the generator is operating at the maximum allowable operating temperature.
3. The NdFeB magnets are prone to corrosion. Therefore, these magnets have to be protected quite well especially operating in the salty and humid environments.

Machine topology preferences (advantages and disadvantages of different topologies)

In this chapter we will review the benefits and drawbacks of different DD machine topologies. Generally, all the manufacturers of direct driven wind turbines, are using a stator with a winding in slots. In order to get light constructions, by avoiding the large attraction forces between stator and the rotor, some investigations have proposed to use air gap windings and air cored machines (no iron in the stator). Nevertheless, due to the robustness, efficiency and considered low cost, the manufacturers are still sticking to the well-known and tested technology of DD machines with windings in slots. To prevent the windings from coming out of the slots when the machine is operating, the slot wedges are used. The slot openings itself should be small in order to have minimum reluctance for the major flux due to the magnets. This feature also helps to reduce noise and cogging. However, the minimum necessary size of the slot opening should be considered for insertion of the windings. This slot opening can be quite small for round copper, but for diamond coils, the slot openings have to be as wide as the slot itself.

In the previous chapter radial flux, axial flux and transverse flux machine topologies were described. Although, most direct drive wind turbines are equipped with radial flux generators, in recent years several investigations were held on axial flux generator topologies (Lampola 2001, Dubois 2004 and etc). The investigations showed that despite having smaller size than radial flux machines, axial flux machines have some significant disadvantages:

1. Not optimal force density at all radii. As the slots have constant width, the narrow teeth at the inner radius are most likely heavily saturated, on the other hand, wide teeth at the outer radius are most likely not yet saturated.
2. The bearing loads increase due to the attractive forces between rotor and the stator.
3. The laminations are different at different radii making the production more difficult.

Electrical or PM excitation

Figure 20 and 21 show a few pole pitches of a machine with PM excitation and a machine with electrical excitation. Most companies (Siemens, General Electric and etc.) in the sector are using PM excitation due to its important advantages summarized in the list below:

1. No excitation losses, subsequently a better energy yield.
2. Significant reduction in the weight of the active materials. PMs are much smaller than the poles with electrical excitation.
3. PM machines can be cheaper than EE machines (Polinder 2006).

Nevertheless, EE machines also have benefits:

1. No risk of demagnetization.
2. No problems with the availability of expensive rare earth materials (NdFeB).
3. Increased feasibility of controlling the field current. It can be reduced to reduce the losses.

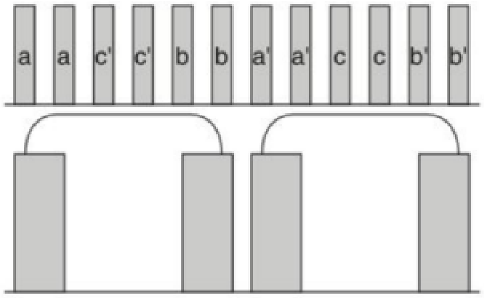


Figure 20: Two pole pitch cross section of EE generator

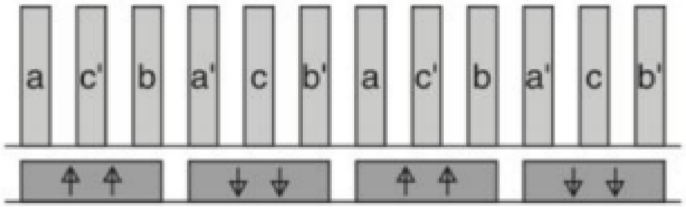


Figure 21 Four pole pitch cross section of a PM excited generator

Concentrated fractional pitch windings or distributed windings

Generally the majority of classic AC machines are equipped with the distributed windings where the number of slots per pole per phase is one, in some cases more than one. Nevertheless, in PM machines, fractional pitch concentrated windings (Fig 2.4) are increasingly used. Here, the number of stator teeth is usually very similar to the rotor poles number. The advantages of this topology are listed below:

1. The machine with the fractional pitch windings is more compact du e to the very short end winding
2. As the pole pitches are smaller, the stator yokes also can be thinner
3. The demagnetizing risk is smaller
4. Significantly lower manufacturing cost

Among the disadvantages we can mention the unbalanced magnetic forces in fractional pitch winding (REF WU et al 2010). Also, these machines have noteworthy space harmonics, which may lead to the eddy current losses in the back iron and magnets (REF Polinder et al 2007).

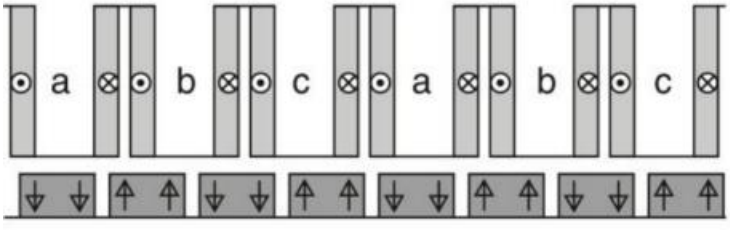


Figure22: Cross section of a machine with a concentrated fractional pitch winding

Skewing

Skewing is the technique used for reducing cogging and the audible noise. Cogging itself means the existence of preferred rotor positions. Rotor and stator can be skewed with respect to each other. The stator slots also can be skewed or the magnets on the rotor may be skewed.

Surface mounted magnets or buried magnets with flux concentration.

Surface mounted magnets are used in the majority of the machines. Here, the magnets are screwed or glued to the back iron with perpendicular magnetization to the rotor surface. On the other hand, buried magnets can also be used in the machine design, where the magnets are buried in the rotor iron structure. The advantage of burying the magnets is that it is possible to implement flux concentration here: as a result the flux density in the air gap is larger in comparison with the flux density in the magnet.

Power factor

The equivalent circuit of a synchronous machine and its phasor diagram are shown in the figure (Fig 23). Here the angle between the current and the terminal voltage or the angle between the current and the electromotive force can be chosen. In the case when the current is in phase with electromotive force, we get the minimum copper losses, but the flux density level will be increased in the machine resulting in saturation. Then the converter has to be overrated considering the low converter power factor. In the case when the current is in phase with the terminal voltage, the power level of the converter is the minimum. This will limit the power taken from the generator in the case of large synchronous inductance. As a result we can conclude that the phase of the current must be set in a point somewhere between the phase of terminal voltage and the electromotive force like in the figure (23).

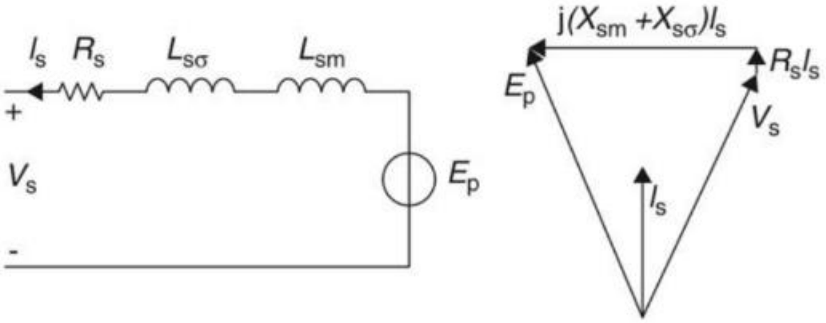


Figure 23: Phasor diagram: current phasor is in between the electromotive force and terminal voltage and equivalent circuit of a PM machine

Design example

As an example we will consider the PM direct drive generator for 3 MW wind turbine with the rated speed 15 rpm. Based on the information and facts described in the previous chapters some design choices were made:

1. A radial flux PM machine with surface mounted magnets is chosen
2. Three phase distributed winding is chosen with one slot per pole per phase
3. Diamond coils, two layer winding
4. With respect to each other, magnets and stator slots are skewed over one slot pitch
5. Active rectifier is used to keep the phase of the stator current at point between the terminal voltage and the electromotive force

These design choices are most common in the PM direct drive generators (Polinder et al 2004). Here we will focus on the determination of the main parameters of the machine and the main losses. By main parameters, the parameters of the equivalent circuit are considered. The parameters of the machine are calculated in common way described by the Richter (1967). Assumptions made:

1. Negligible space harmonics of magnetic flux density distribution at the air gap. The fundamental harmonic is the only one considered
2. Magnetic flux density crosses perpendicularly the air gap

First of all the so called effective air gap of the machine should be determined. This parameter is critical factor for calculation of the inductances and the flux densities.

$$g_{eff} = k_c(g + \frac{l_m}{\mu_{rm}})$$

Where:

g - is the mechanical air gap

k_c- is the Carter factor

l_m- is the length of magnet in the magnetization direction

μ_{rm} – is the magnet relative recoil permeability

The carter factor (described by Richter, 1967) can be found through:

$$k_c = \frac{\tau_s}{\tau_s - g_1 * \gamma}$$

$$g_1 = g + \frac{l_m}{\mu_{rm}}$$

$$\gamma = \frac{4}{\pi}(\frac{b_{so}}{g_1 * 2}\arctan\left(\frac{b_{so}}{g_1 * 2}\right) - log\sqrt{1 + (\frac{b_{so}}{2 * g_1})\hat{}2)}$$

Where:

b_{so} is the width of slot opening

τ_s is the slot pitch

The fundamental space harmonic of magnetic flux density in air gap can be found using this effective air gap:

$$B_g = \frac{l_m}{g_{eff} * \mu_{rm}} * B_{rm} * \frac{4}{\pi} * \sin(\frac{\pi * b_p}{2 * \tau_p})$$

Where:

τ_p is the pole pitch

b_p is the magnet width

B_{rm} is the magnets remanent flux density

The no load voltage in a stator winding induced by this flux density is then:

$$E_p = \sqrt{2} * k_w * N_s * \omega_m * r_s * l_s * B_g$$

Where:

k_w is the winding factor

N_s is the phase winding number of turns

Finally, the AC machine main inductance can be calculated:

$$L_{sm} = \frac{6 * \mu_0 * r_s * l_s * (k_w * N_s)\hat{}2}{\pi * g_{eff} * p^2}$$

P is the number of pole pairs.

Basic design principles for machine sizing

The force density F_d, is considered as a good starting point for sizing the machines. It represents the force acting per unit surface area of the air gap and can be calculated using:

$$F_d = \frac{B_g * A_s}{2} * \cos(\gamma)$$

Where:

B_g is the amplitude of air gap flux density caused by magnets

A_s is the amplitude of the stator surface current density (A/m)

γ is the angle between the linear current density and the flux density

The air gap flux density is limited by the saturation of the stator teeth. The linear current density is in turn, limited by allowed maximum heat dissipation. Knowing these two factors we can state that the force density is rather a constant value for various machines. For example, for air –cooled DD machines the force density is in the range of 30-60 kN/m^2, depending on the chosen cooling method.

Then the power for the machine can be written as:

$$P = \omega_m * T = \omega_m * r_s * F = 2 * \omega_m * \pi * r_s^2 * l_s * F_d = 2 * \omega_m * V_r * F_d$$

Design Equations

1 General Definitions

In this Section we will review some basic equations used in the design of permanent magnet machine described in the work. (Graucers)

The number of pole pairs can be determined using the diameter and the pole pitch:

$$p = \frac{\pi * d}{2 * \tau_p}$$

Where:

$d = diameter$

$\tau_p = pole\ pitch$

$p = pole\ pairs$

The total number of slots of the stator can be found through:

$$Q = 2 * p * m * q$$

Where:

$q = the\ number\ of\ slots\ per\ phase\ and\ pole\ (which\ is\ set\ to\ one)$

$m = number\ of\ phases$

Then the slot pitch is calculated:

$$\tau = \frac{\tau_p}{m * q}$$

Usually the slot is defined by its depth-$h_s$and its width-b_s. Where the width of the slot can be obtained using slot pitch and the tooth width-b_d.

$$b_s = \tau - b_d$$

In order to get a better understanding of the configuration of the slot and the two layer winding, the Figure 24 is provided below:

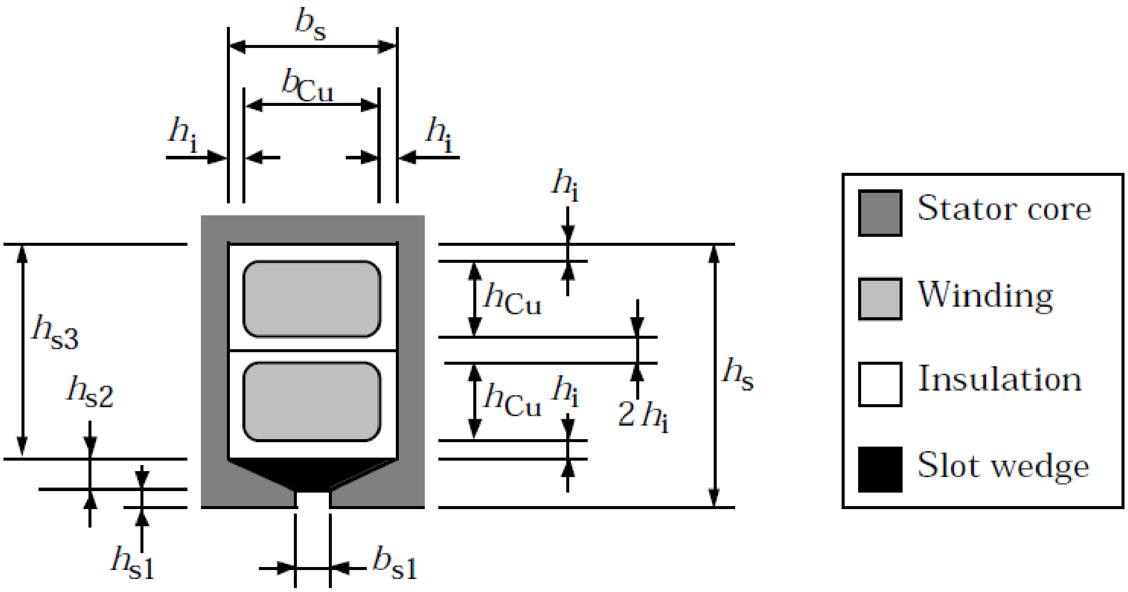


Figure 24: Two layer winding and the slot pitch

From which it is clear that we can determine the winding height using:

$$h_{s3} = h_s - h_{s1} - h_{s2} \tag{5}$$

After calculating the winding height we can obtain the conductor height-h_{Cu} and width-b_{Cu} using the coil insulation thickness and the slot width:

$$h_{Cu} = \frac{h_{s3} - 4\,h_i}{2}$$

Where:

$h_i = coil\ insulation\ thickness$

$h_{s3} = the\ winding\ height$

$$b_{Cu} = b_s - 2h_i$$

If we assume that the winding is a full-pitch winding, then the winding pitch would be equal to the pole pitch:

$$W = \tau_p$$

The length if useful iron can be calculated using:

$$l_u = k_{Fes} * l$$

Where:

$k_{Fes} = stator\ iron\ fill\ factor$

The magnet width is usually varies between 0.6-0.8 times the pole pitch. The frequency then at rated speed would be:

$$f = p * n_N$$

Where:

$n_N = rated\ speed\ of\ the\ generator$

$l = stator\ length$

Finally, the stator outer diameter and the approximate total length were calculated:

$$d_{se} = d + 2 * h_s + 2 * h_{ys}$$

$$l_{total} = l + 2 * W$$

Losses

The major losses in the machine are the losses in the stator windings and the iron losses which occur in the stator laminations. Copper losses can be calculated using currents and resistances:

$$P_{Cu} = 3 * R_s * I_s^2$$

The phase resistance used in the equation above can be found through:

$$R_s = \frac{\rho_{Cu} * l_{Cus}}{A_{Cus}}$$

Where:

ρ_{Cu} is the copper resistivity

A_{Cus} is the conductor cross section area

l_{Cus} is the length of the conductor of the phase winding

Let's now make clear the parameters used in the previous equation. The length of the conductor itself is equals to the number of turns multiplied the turn length. Where turn length is four times the pole pitch plus twice stack length:

$$l_{Cus} = N_s * (2 * l_s + 4 * \tau_p)$$

The conductor cross section area:

$$A_{Cus} = \frac{p * q * k_{sfil} * b_{sav} * h_s}{N_s}$$

Where:

k_{sfil} is the slot fill factor

b_{sav} is the average slot width

h_s is the slot height

q is the number of slots per pole per phase

The specific iron losses, on the other hand, are the sum of the eddy current losses and hysteresis losses (Ref. Fitzgerald 2003).

$$P_{Fe} = 2 * P_{Fe0h} * \left(\frac{f_e}{f_0}\right) * \left(\frac{B_{Fe}}{B_0}\right)^2 + 2 * P_{Fe0e} * \left(\frac{f_e}{f_0}\right) * \left(\frac{B_{Fe}}{B_0}\right)^2$$

Where:

f_e is the field frequency in the iron

P_{Fe0h} and P_{Fe0e} are the hysteresis and eddy current loss per unit mass respectively (at a flux density B_0 given by the manufacturer of the material and the given angular frequency f_0).

Then, in order to obtain total iron losses, we have to multiply the specific iron losses in the teeth and yokes by the weight of these parts.

Optimization criterion

The two most important aspects in the machine design optimization are maximization of the annual energy yield and the minimization of the generator cost. (Polinder, Slootweg 2001).

$$C = C_{Fe} * M_{Fe} + C_{Cu} * M_{Cu} + C_{pm} * M_{pm} - P * C_E * E_y$$

Where:

C_{Fe}, C_{Cu}, C_{pm} are the cost of the iron, copper and permanent magnets respectively (currency/kg)

M_{Fe}, M_{Cu}, M_{pm} are masses of the iron, copper and the permanent magnets respectively

P is the period

E_y is the annual energy yield

C_E is the price of a kWh energy

From the given equation it is obvious that the machine dimensions are the variables to be varied to optimize the design of the machine.

Efficiency

As it was mentioned earlier the efficiency of the direct drive machines is limited as a result of the low speed. In a PM generator, the induced voltage per unit length of the conductor in a slot can be derived from:

$$E = B * v$$

Where:

v is the relative speed between the translator and the stator

B is the air gap flux density

Although the equation given above is not valid for the transverse flux machines, nevertheless, it can be used most of the conventional machine types. There is also a resistive voltage drop in the same conductor where this voltage was induced.

$$E = \rho_{Cu} * J$$

Where:

J is the current density in conductor

ρ_{Cu} is the resistivity of the conductor (copper in for example)

Generally, in the machines with a winding in a slots, the air gap flux density has a values about 1 T. If we assume the speed of the magnetic flux density in the air gap to be around 4 m/s we will get the induced voltage in the conductor of about 4 V/m using the first equation. In the case where the current density amplitude is in the order of 5 A/mm^2, we will get a resistive voltage drop in the conductor of about 0.125 V/m using the resistivity of the copper and the second equation. 0.125 V/m makes 3 percent of 4 V/m of the induced voltage, resulting that the efficiency of the machine will be physically limited to around 97 percent. Taking into account that this resistive voltage drop is also present in the cable connections and in the end windings, we can conclude that actual efficiency of the machine will be lower. In the direct drive machines this effect leads to a serious limitation in the efficiency.

Structural, Electrical and Thermal aspects of the generator design

Size of the DD machines

In order to produce large power, the DD electrical machine has to produce a very large torque because the power of the generator is the multiplication of the torque (T) of the electrical machine and its angular velocity (Ω):

$$P = T * \Omega$$

If we model conventional electrical machine by a cylinder (Fig. 25) and consider the shear stress on the surface of this cylinder then the torque produced would be:

$$T = 2 * \pi * \sigma * R^2 * l$$

Where:

σ is the shear stress

R is the air gap radius

l is the generator axial length

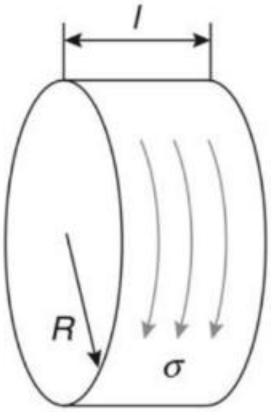


Figure25: Cylinder model of torque developed by the generator

Knowing that there is an upper limit of the developed shear stress due to the practical limits of electrical and magnetic loading in the electrical machine, we can conclude that, in order to get the high torque DD generator has to have large radius and length compared to conventional high speed machines with gearbox. Direct drive mechanism leads to bulky generators relative to their electrical power output.

Forces in DD electrical machine

Large machine have large forces as a result of the large surface areas which act a larger distances from the mounting point of the nacelle.

1. Shear stress or torque transmission: this is a major force in DD EM giving rise to torque. The goal of the designers is to maximize the shear stress in order to get maximum torque. The mechanical energy is converted into electrical energy in the area near the air gap. The rotor transmits mechanical torque to air gap and the stator has to be able to resist this same torque. Shear stress can be calculated through:
$$\sigma = \frac{1}{2} * B * K * cos\delta$$
Where:
δ is the displacement of the distribution of the flux density and electric loading
B is the peak value of the distribution of flux density
K is the peak value of the loading
2. Normal stress (normal component of Maxwell stress): large forces of attraction between the stationary parts of the machine and the rotating parts as a result of magnets on the rotor. It is a function of the square of air gap flux density:
$$q = \frac{B^2}{2 * \mu_0}$$
Where μ_0 is the permeability of free space
3. Gravity: the weight of the generator is an important load to consider during assembly, transportation and installation. As the gravity acts on generator along two axes, there are two components: major and minor. The major components is of magnitude of g*cosØ (Ø is the tilt angle, usually 5^o in an conventional wind turbine). This component deflects the stator and rotor back iron and structural members. The minor component of gravity is g*sinØ. It is axially directed and leads to misalignment of the stator and rotor in the axial direction. This minor components becomes more significant in a vertical axis wind turbine.
4. Thermal strain: temperature rises in the machine parts as a result of a significant amount of the heat generated. These different temperature rates, rises and falls lead to differential thermal contraction and expansion. The expansion is given by:

$$\Delta L = L_0 * \alpha * \Delta T$$

Where:

ΔL is the change in the dimension

L_0 is the original dimension

ΔT is the temperature rise

α is the thermal coefficient of expansion of material

5. Centripetal forces: they are relatively small at low speeds
6. Wind turbine loading: loading from the rotor blades, horizontal and vertical wind shear, weight of the rotor blades, yaw error and the inertial effects.

Interaction between different design aspects

A successful generator design must include perfect understanding of the connections between thermal, electromagnetic and structural design elements. In the figure below, some example relationships between these elements of the design are brought

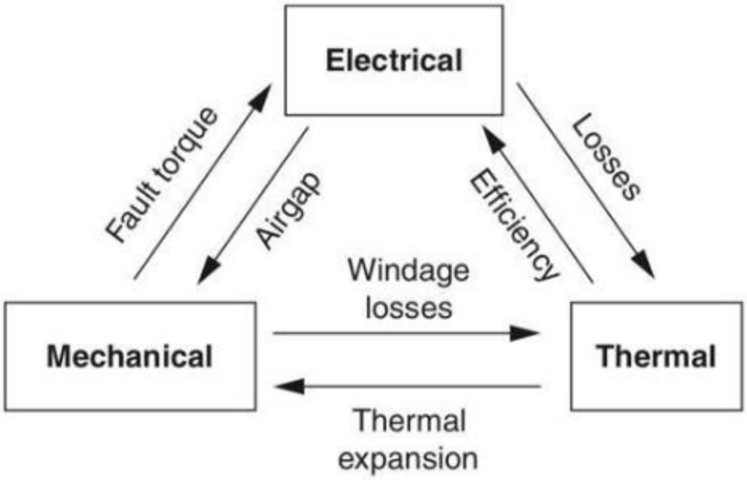


Figure 26: Interaction between thermal, electromagnetic and structural elements

Electrical design perspective

From the electrical design of view the most important is to get the maximum performance which means maximum power output and efficiency, using the smallest feasible amount of the material like copper and permanent magnet. Another important aspect is the electrical insulation. Electrical design account around for 50 percent of the cost of a direct drive PM generator. Figure below provides the electrical design perspective of the DD PM machine.

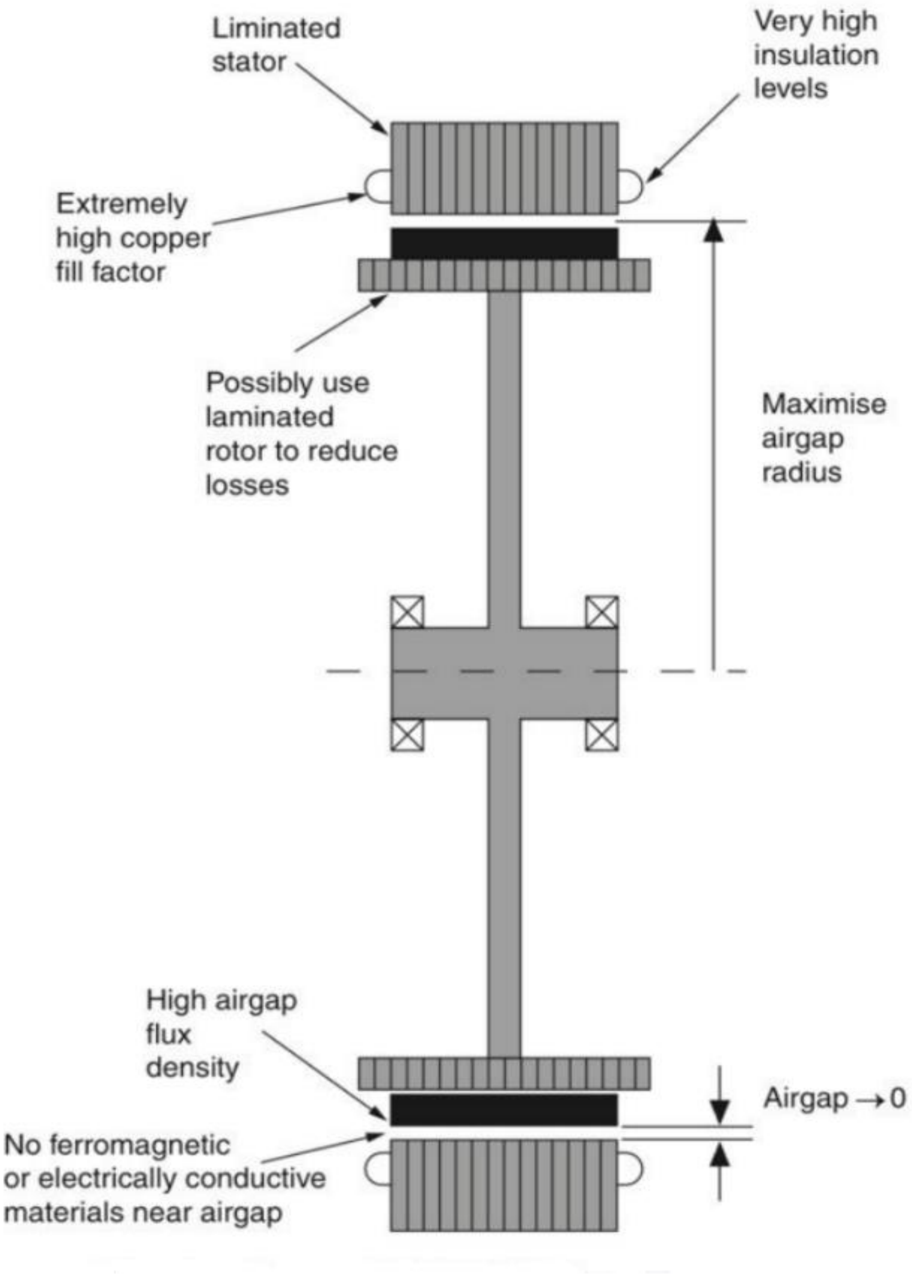


Figure 27: Electrical design perspective

Mechanical design perspective

Mechanical design includes the terms like strain, stress, fatigue, strength and physical robustness of the generator. Producing safe electrical machine using low cost and lightweight assemblies is the primary goal of a mechanical engineer. The mechanical design parts account for almost 55 percent of the overall DD machine mass. Figure below shows the mechanical design perspective of the DD PM machine.

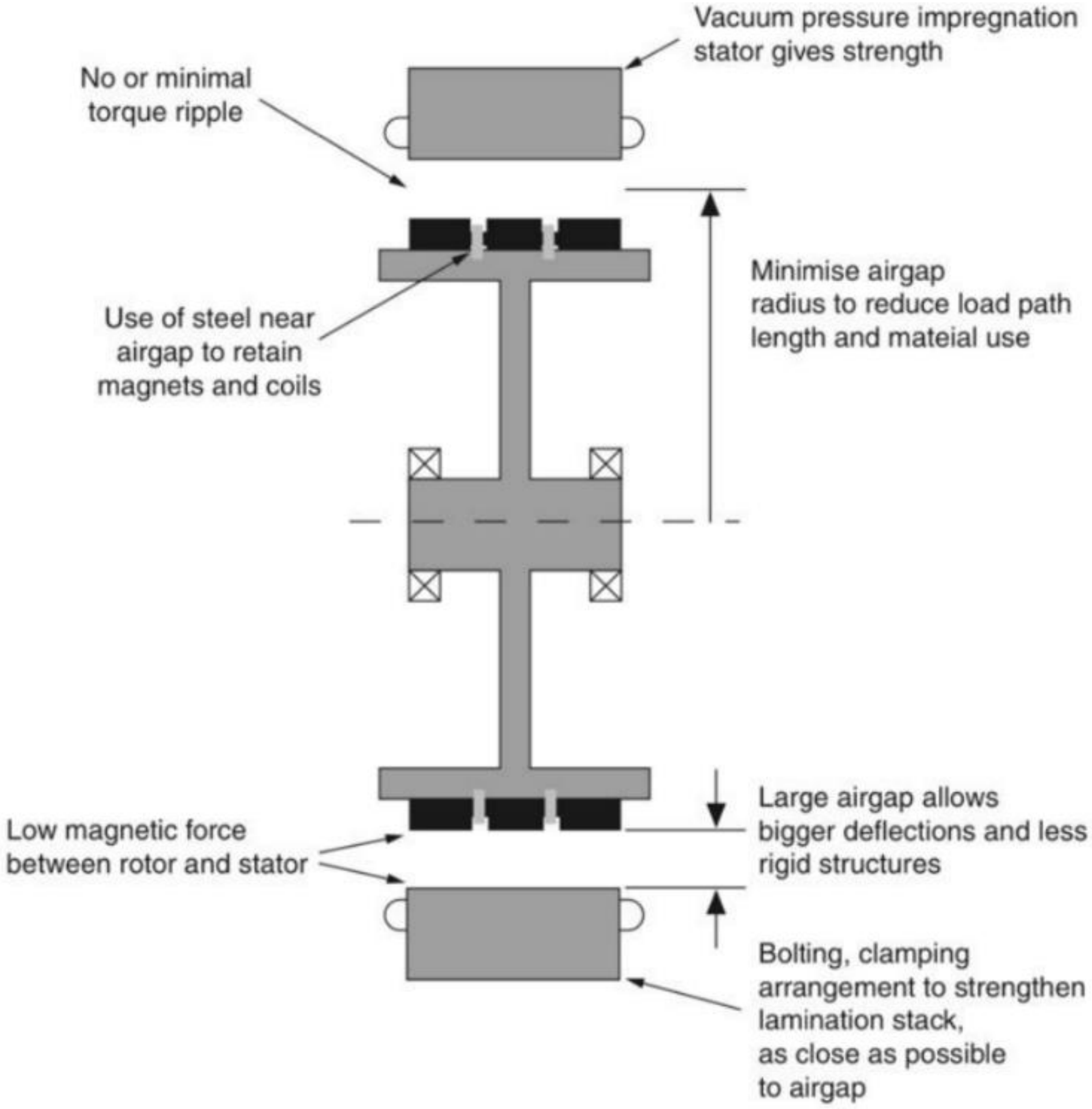


Figure 28: Mechanical design perspective

Thermal design aspects

Electrical machines produce losses in the form of heat. The peak temperatures, at which the electrical machine can operate are limited by the material properties of the insulation and magnets (in the case of permanent magnet machine). In order to maintain the allowable temperature limit in the machine, cooling systems are used. There are some significant differences in thermal management of low speed and high speed generators used in the operation of the wind turbine. As it was mentioned earlier, the size of the low speed direct drive permanent magnet generator is much larger than the size of the high speed conventional generator with gearbox for a given power rating. Subsequently, the available surface area for the heat dissipation is much bigger in DDPM machines, leading to a better passive heat transfer. There is also less radial space in the DDPM machines for water jackets and for other alternative auxiliaries if they needed, due to the size of these machines. In a high speed wind turbine, where the generator is located within a nacelle, the heat exchanger is usually linked to a radiator placed on the top or at the back of the nacelle. On the contrary, in the DDPM machine, the outer skin of the DD generator is commonly in direct contact with moving outside air.

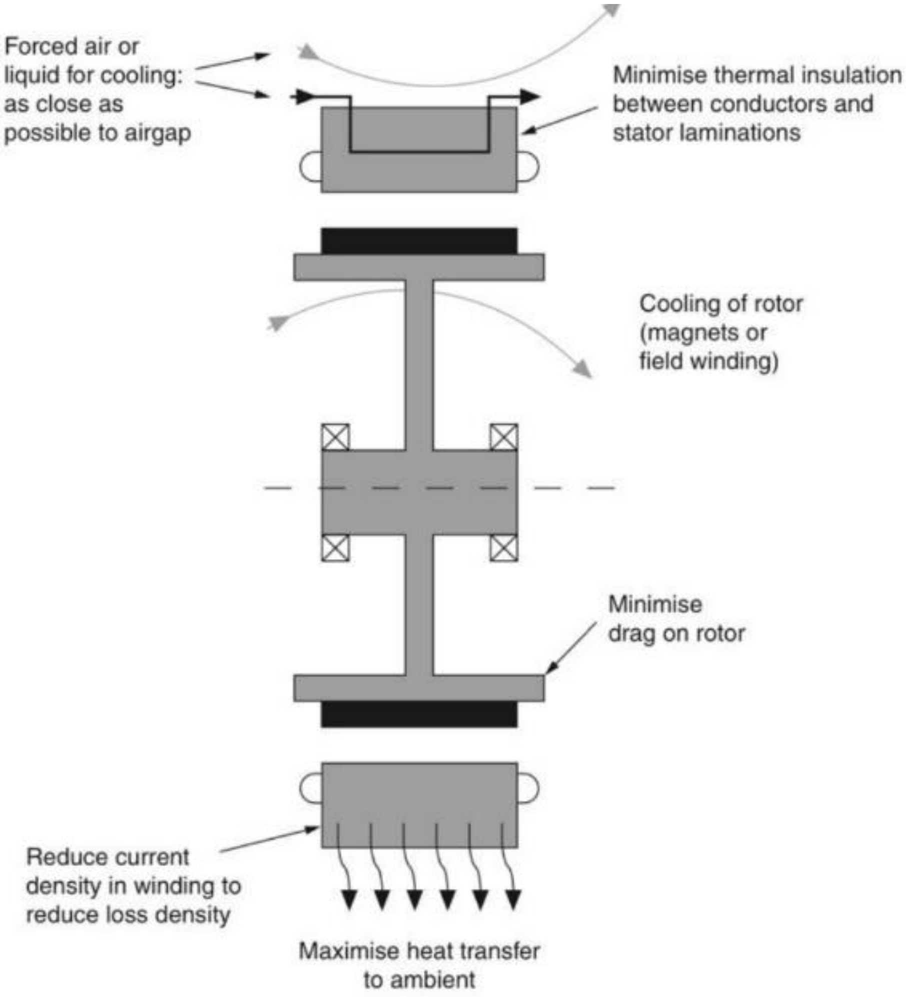


Figure29: Thermal design perspective

Cooling techniques of the generator

There are generally three major cooling approaches of a generator.

1. Passive cooling: In this case the heat produced in the generator is conducted, convected and/or radiated from the generator to outside. The convected or radiated outside the machine is then transferred to the air flow. This approach does not require any auxiliary systems, like pumps and fans which require maintenance and servicing periodically. An example of the passive cooling approach is given in the Figure 30:

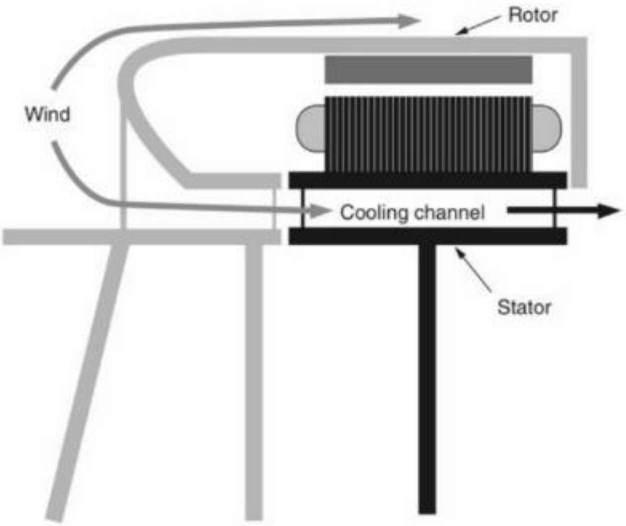


Figure 30: The wind is used to cool the rotor and stator back sides through internal ducts

2. Forced air cooling: Here, in order to circulate the air within the generator, fans are used. Due to the higher air velocities, in this approach, convection heat transfer coefficients are greater than in the passive cooling. Although this technique requires extra energy consumption and extra cost (running the fans), the resulting efficiency, improved power density and reduction in the winding temperature are usually worth it. An example of this approach is provided in the Figure 31.

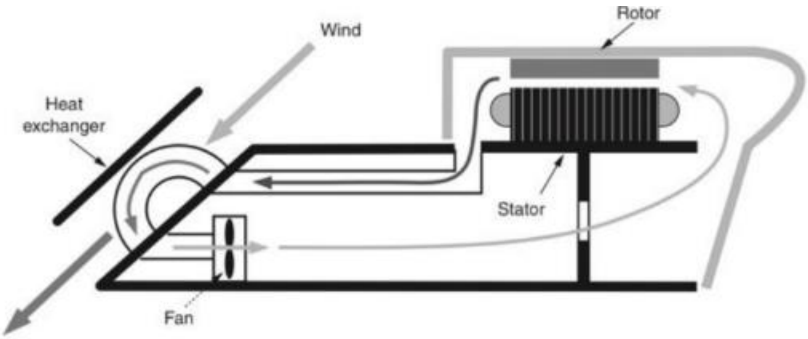


Figure 31: Fan is used to cool the generator through heat exchanger

3. Liquid cooling: Due to the fan energy consumption and ducting cross sectional area, there is always a limited amount of heat that can be transferred using forced air cooling. So, the liquid cooling has to be implemented to

transfer the heat from generator to a radiator. Liquid cooling technique results in reduction of the size of the generator and even leads to an increase in the power rating.

Reliability comparison of geared and direct drive machines

Generally, geared wind turbines are considered unreliable compared to the direct drive systems due to the trouble prone gearbox mechanism. In fact, there has been a number of issues with the machine gearbox operation and a number of failures were registered. Nevertheless, in the recent time as a result of latest improvements in the machine design, the progress in gearbox lifetime has been achieved. According to the recent investigations, today there is no such a big difference in the reliability of the direct drive and geared wind turbines (they are comparable). In majority of cases, relatively inexpensive components of the generator like broken fuses, defects in print boards, faulty electrical connections and etc. cause the faults in the generator operation. Another noteworthy fact is that power converter in the wind turbines cause more failures than the generator due to its far more number of components compared to the generators.

Case study

In this chapter we will review the design example of the permanent magnet direct drive generator named Zephyros (**Ref**) implemented in the wind turbine. A multi-pole synchronous PM generator was chosen (Fig. 32). The turbine is equipped with three glass fibre reinforced plastic blades and with tubular steel tower.

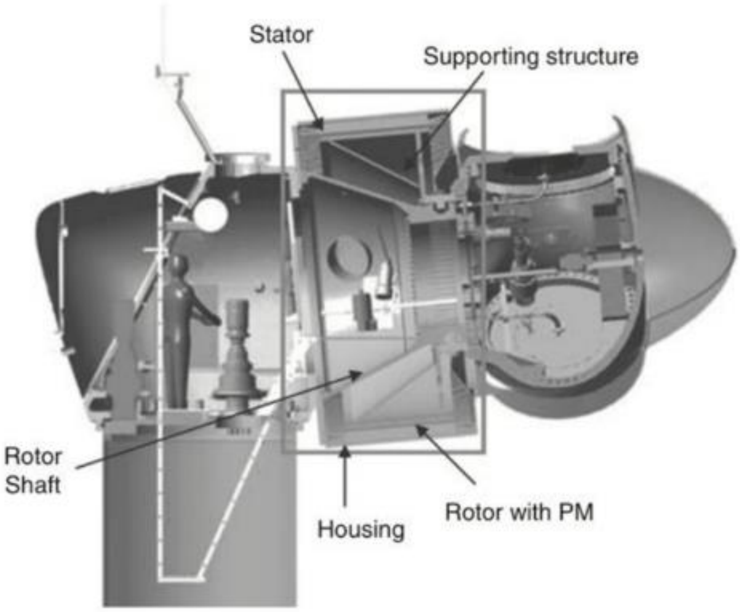


Figure 32: Zephyros wind turbine example

First of all, in the design procedure of the generator, the site conditions, where the wind turbine will be installed should be considered. The primary requirement for wind turbine is obviously the amount of available wind at a particular site. This is referred as first design constraint. Average available amount of wind at a particular site defines the amount of possible speed and developed torque of the machine. In our case we will consider the following site conditions:

1. Ambient temperature is 20-40 C°
2. Environment is clean with low salt content
3. Average wind speed is about 7.5-8.5 m/s at the height of the wind turbine hub

As the location of the generator within a turbine, the front side of the tower was chosen due to the following benefits:

1. Better integration with the wind turbine hub
2. Better cooling
3. Weight reduction

Bearing configuration

The bearing configuration generally can be single bearing or double bearing. In our case, the generator with single bearing configuration was chosen, which is directly coupled with the rotor structure. This arrangement is described in the Figure 33 below.

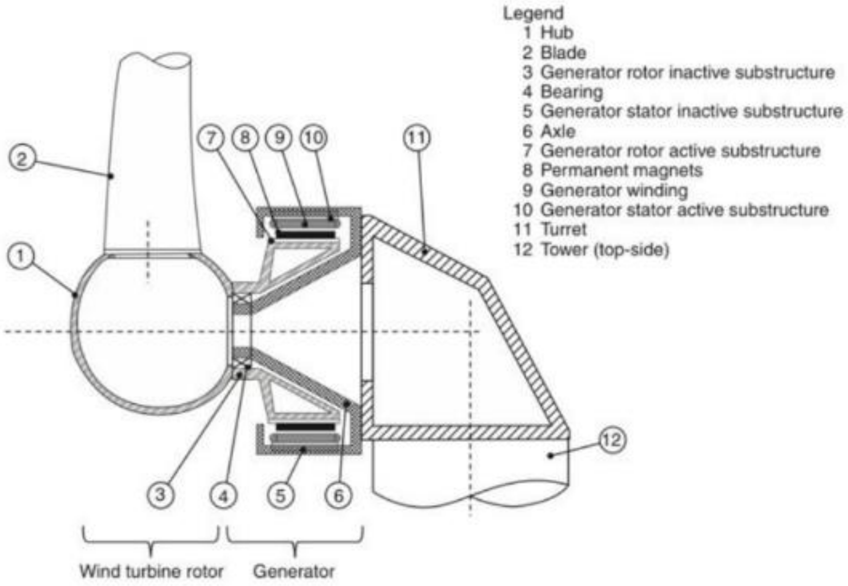


Figure 33: Single bearing design used in Zephyros

The selection of size and topology of the machine is based on the following factors:

1. Transportation limits
2. Tip speed for an allowable noise level
3. Required heat dissipation per unit surface area
4. Required force density

For the Zephyros generator, the primary design features were:

1. Nominal power of 1500 kW
2. Nominal rotational speed of 18 rpm
3. Nominal outer diameter of generator: 4 m

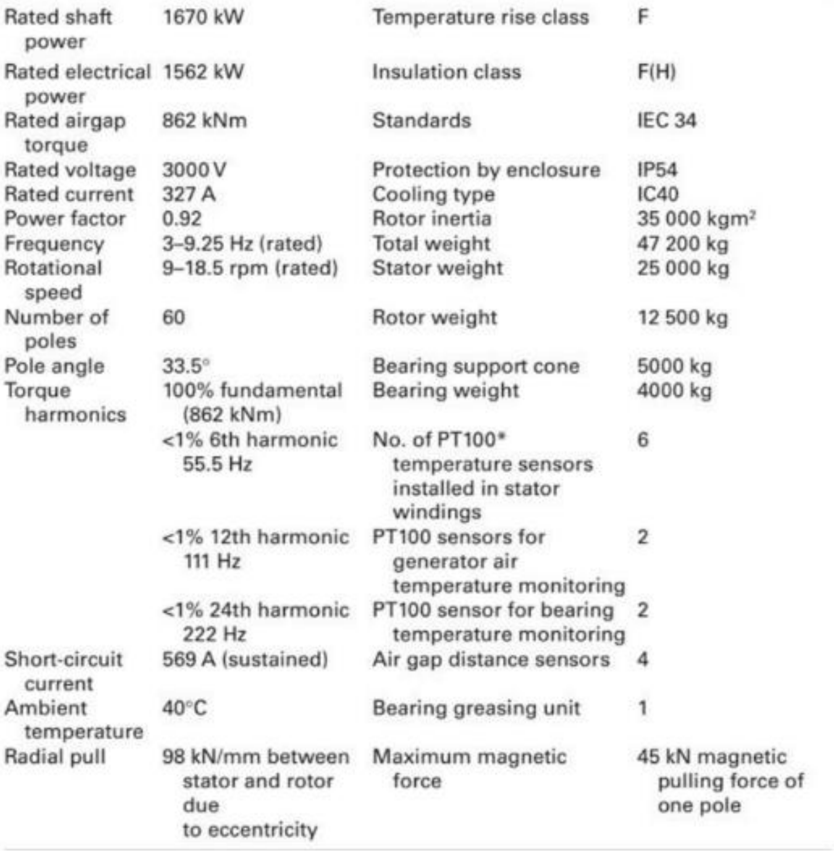
Voltage level and converter

For the Zephyros generator, nominal voltage was established to be 3 kV and with insulation level of 7.5 kV. High insulation level makes possible an increase in the voltage level rather than in the current level, in the case of an increase in the power output.

A medium voltage converter system containing fewer components was chosen, in order to obtain better efficiency. The AC-DC-AC converter used in this wind turbine is installed in the tower base and allows the operation of the generator with a variable speed, although the power fed into the grid is at constant frequency of 50 Hz.

Dimensions and Efficiency

Based on the electromagnetic design equations provided in the previous chapters and based on the experience the dimensions of the teeth, stator and rotor back iron, slots and magnets are calculated. The results of these calculations for the Zephyros generators are summarized in the Figure 34:



Rated shaft power	1670 kW	Temperature rise class	F
Rated electrical power	1562 kW	Insulation class	F(H)
Rated airgap torque	862 kNm	Standards	IEC 34
Rated voltage	3000 V	Protection by enclosure	IP54
Rated current	327 A	Cooling type	IC40
Power factor	0.92	Rotor inertia	35 000 kgm^2
Frequency	3–9.25 Hz (rated)	Total weight	47 200 kg
Rotational speed	9–18.5 rpm (rated)	Stator weight	25 000 kg
Number of poles	60	Rotor weight	12 500 kg
Pole angle	33.5°	Bearing support cone	5000 kg
Torque harmonics	100% fundamental (862 kNm)	Bearing weight	4000 kg
	<1% 6th harmonic 55.5 Hz	No. of PT100* temperature sensors installed in stator windings	6
	<1% 12th harmonic 111 Hz	PT100 sensors for generator air temperature monitoring	2
	<1% 24th harmonic 222 Hz	PT100 sensor for bearing temperature monitoring	2
Short-circuit current	569 A (sustained)	Air gap distance sensors	4
Ambient temperature	40°C	Bearing greasing unit	1
Radial pull	98 kN/mm between stator and rotor due to eccentricity	Maximum magnetic force	45 kN magnetic pulling force of one pole

Figure 34: Design features of Zephyros

Winding design

The choice of winding is based on the type and size of the machine. On the other hand, the turn number of the winding depends on the voltage level which hac to be generated in the machine. The choice includes: distributed or concentrated type winding and single layer or double layer winding. A full pitch distributed double layer winding was chosen in the Zephyros generator design due to the following benefits:

1. Sinusoidal voltage output, low harmonic content
2. One type of coil is required as the coils and end connections are symmetrical

Zephyros generator was design also for offshore application in mind. Moreover, at offshore conditions, due to the higher rotational speed, higher noise (no noise restriction in offshore) and higher voltage the same generator is capable to deliver far more power to the grid compared to onshore conditions. But here also some challenges arise:

1. The access to the offshore wind turbines is limited, hence the maintenance of the generator should be minimum and the reliability even higher.
2. High commissioning costs
3. Highly corrosive environment demanding high protection and insulation level

Future trends

Although direct drive generators are seem like a nice solution for wind energy generation they have some disadvantages. The major drawback is the large size and subsequently the heaviness and high prize of these generators when they used for large power levels. The main reason of that is low speed and limited force density. A second major drawback is that it is not easy task to protect these completely closes large generators from aggressive environment conditions (like offshore). The efficiency of these machines is also physically limited as it was described in the previous chapters. In order to find solutions for these disadvantages a number of research works and investigations are being held.

One of the solutions to reduce the size of the direct drive generators is the increasing the force density. That is why machines with higher force densities are being investigated. Among them are the machines like transverse flux PM DD machine or variable reluctance machine.

Optimizing the support structure is very important aspect also, as it accounts for a significant part of the machine weight. The main reason why the support structure is so heavy is that it has to keep rotor and stator separated by a small air gap in the presence of the large attractive forces. These forces can be reduced or even neglected in a machine where an air gap winding is used or in a machine where the iron behind the stator coil is absent. Direct drive machines can also be made modular, this will make their transportation and repair cheaper and easier. For example, large generators of Enercon nowadays can be transported in parts, when other manufacturers even propose to make modules with coils and magnets for improving the reliability.

In regards of the cost reduction, the fractional pitch concentrated winding can be used. That is the reason why their implementation in the PM machine is increasing. The drawback of using this technique is that it leads to eddy current losses in the back iron and in the magnets.

Wind turbines are large structures and from the recent trends it is clear that in the near future even larger turbines will be necessary in order to produce more torque. With the increase in the size of the turbine their commissioning and erection will be even more challenging. Another important aspect to consider is the cost of the wind turbine (its capital cost and operating costs) because this aspect defines the price of the produced electricity. As an example, the cost breakdown of the Zephyros generator described in the previous chapter is provided below.

Fig.

From the figure it is quite obvious that the main cost affecting parts of the wind turbine are the generator, rotor and the converter system. Leading research companies in this area are investigating mainly the more expensive parts in order to find solutions for cost/weight reduction.

Being the leading source of renewable energy, and as the demand in the renewable energy increases, the demand in the wind energy also exponentially increases. As a result of this the primary trend in the wind energy generation in the recent years is to moving offshore. The major reasons pushing the wind energy generation to offshore are listed below:

1. Higher energy yield as a result of higher wind availability at the offshore conditions
2. No visual impact

3. No noise restrictions

Another trend is that in recent years manufacturers are pushing towards the small number of large wind turbines rather than to the big number of small wind turbines. This trend applies for both onshore and offshore applications.

Conclusion

In this work we have discussed all the different generator topologies that may be used in the wind energy generation. Then the focus was made on the direct drive permanent magnet machines. All the design aspects of DDPM machines were discussed with mentioning their advantages and disadvantages over other generator topologies. We can conclude that DDPM machine seem quite good solution for wind energy generation, however there are still some aspects (mentioned in previous chapters) where further investigation and research is necessary to make these machines even more efficient and common.

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