University of Sallahadin
College of Engineering
Electrical Engineering Dept.

Distributed Generation

Chapter Seven

Wind Energy II

By:
Sarkar Jawhar
MSc in Electrical Engineering

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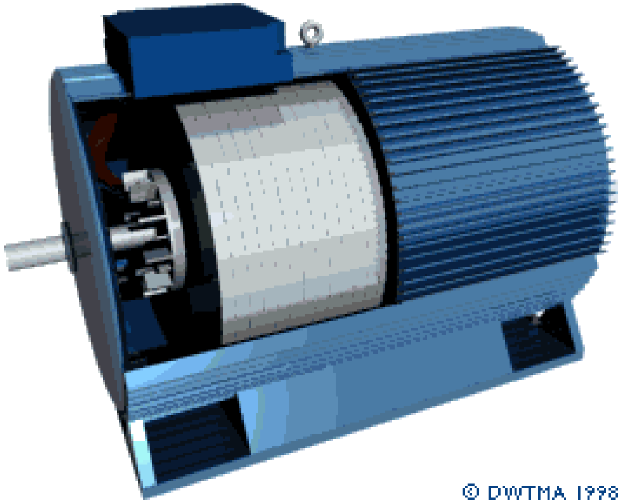
Introduction

- *The electrical system identify as the second essential system in wind turbine.*
- *The wind turbine generator converts mechanical energy to electrical energy.*
- *Wind turbine generators are a bit unusual, compared to other generating units attached to the electrical grid.*
- *The generator has to work with a power source (the wind turbine rotor) which supplies very fluctuating mechanical power (torque).*

Wind Turbine Generators

- Due to the fluctuating nature of wind power, it is advantageous to operate the wind turbine generators at variable speed which reduces the physical stress on the turbine blades and drive train, and improves system aerodynamic efficiency and torque transient behaviors.



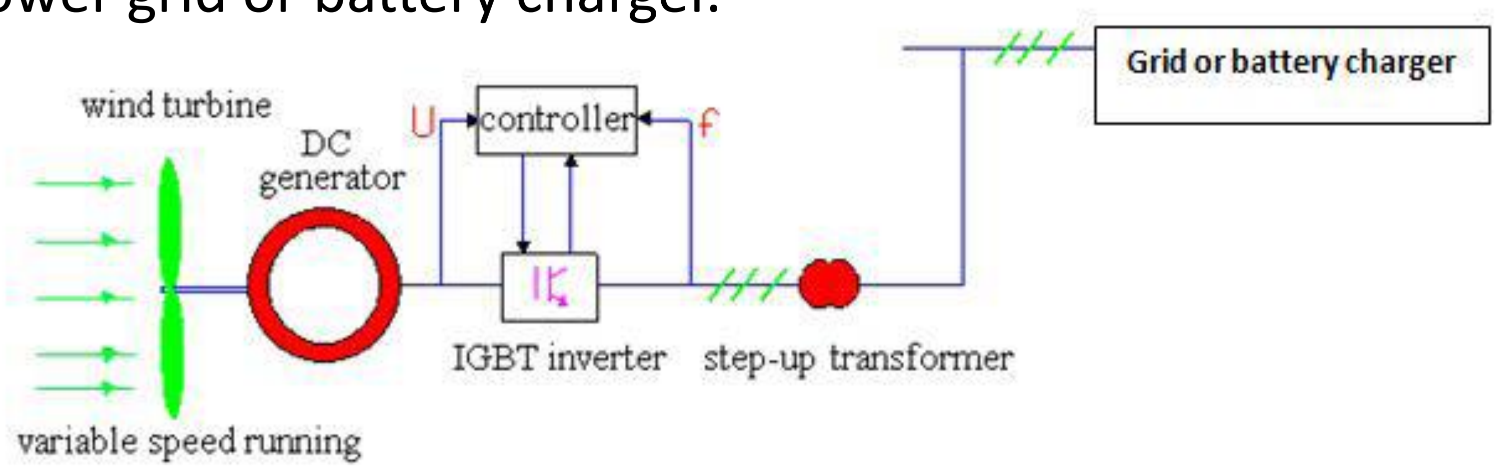
Wind Turbine Generators

1. DC generators
2. Synchronous generators
3. Asynchronous generators.

DC Wind Generator

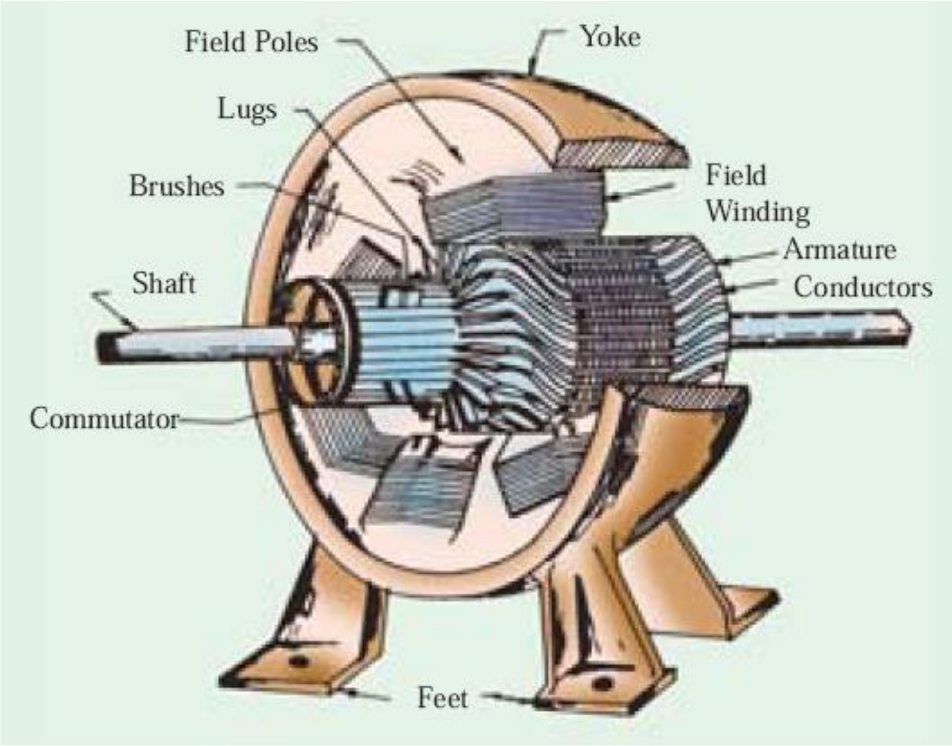
DC wind generator system is consists of:

1. Wind turbine
2. DC generator
3. Insulated gate bipolar transistor (IGBT) inverter
4. Controller
5. Transformer
6. Power grid or battery charger.



DC Wind Generator

- In conventional DC generators, the field is on the stator and the armature is on the rotor.
- The stator comprises a number of poles which are excited either by permanent magnets or by DC field windings.



DC Wind Generator

- For shunt wound DC generators, the field current (and thus magnetic field) increases with operational speed whilst the actual speed of the wind turbine is determined by the balance between the wind turbine drive torque and the load torque.

- The rotor includes conductors wound on an armature which are connected to a split-slip ring commentator.

- Electrical power is extracted through brushes connecting the commutator which is used to rectify the generated AC power into DC output.

DC Wind Generator

Disadvantages:

1. They require regular maintenance
2. Are relatively costly due to the use of commutators and brushes.

- DC wind generators are unusual in wind turbine applications except in low power demand situations where the load is physically close to the wind turbine, in heating applications or in battery charging.

Synchronous Wind Generator

Synchronous wind generators can be:

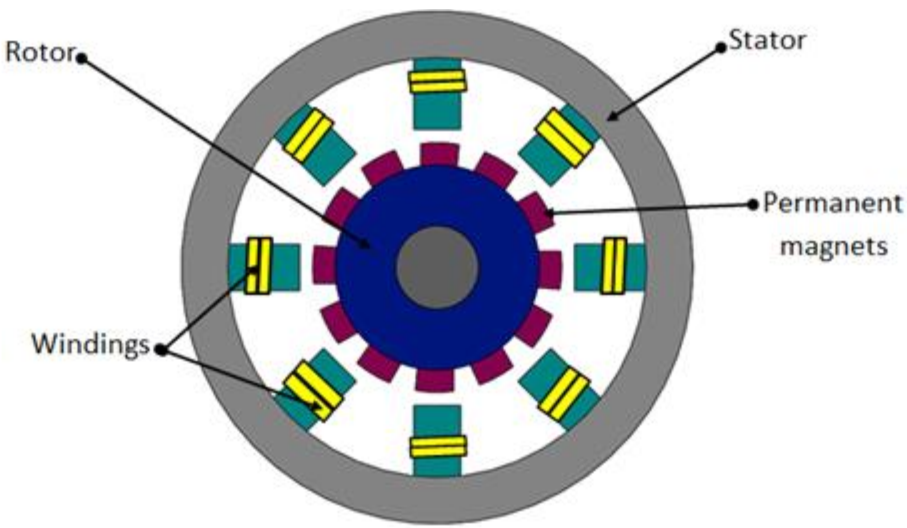
- Permanent magnet synchronous generators (PMSGs).
- Electrically excited synchronous generators (EESGs).

Synchronous Wind Generator

Synchronous wind generators can be:

- **Permanent magnet synchronous generators (PMSGs):**

  Constant excitations from either permanent magnets made of metals, like **Neodynium**.

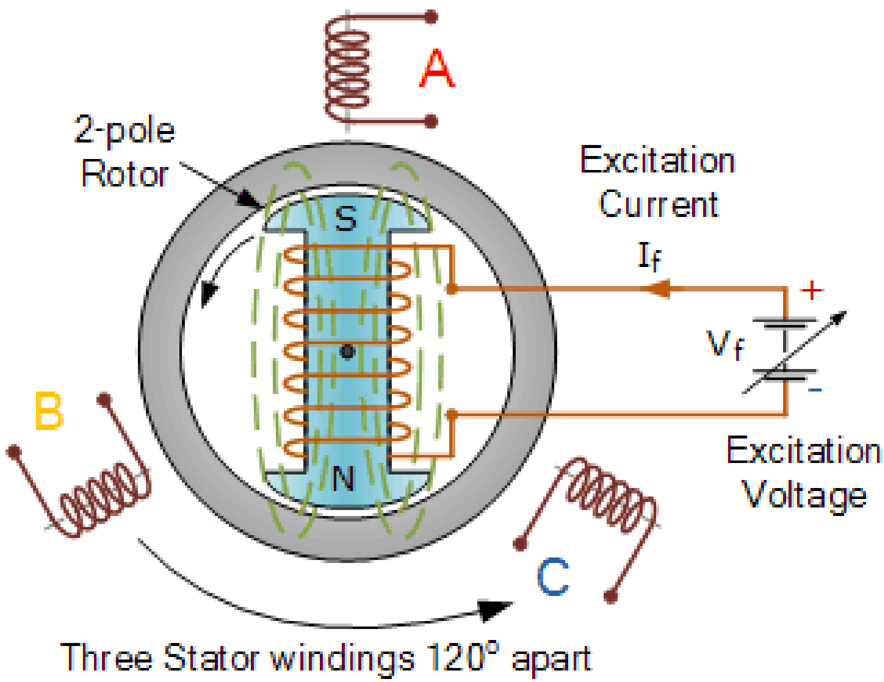


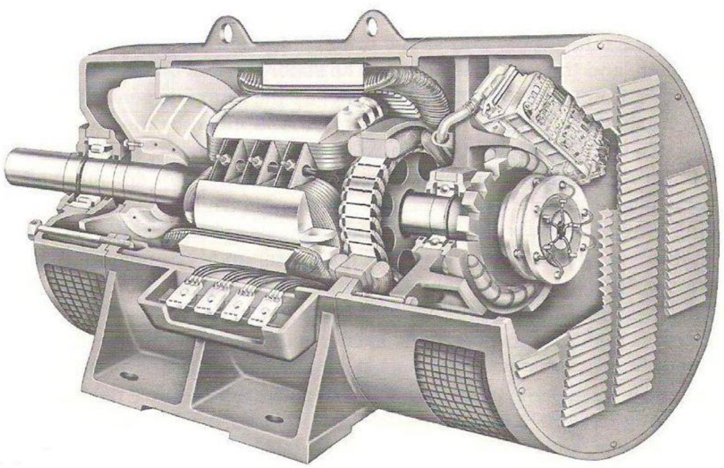
Synchronous Wind Generator

Synchronous wind generators can be:

- **Electrically excited synchronous generators (EESGs):**

  DC excitation from electromagnets.





Synchronous Wind Generator

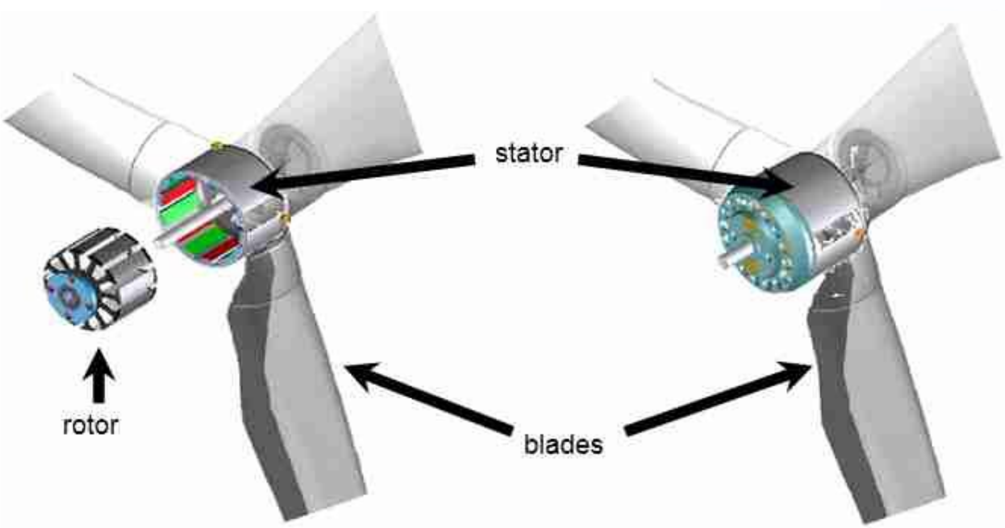
In practice, permanent magnet synchronous generators are not used very much. That's due to:

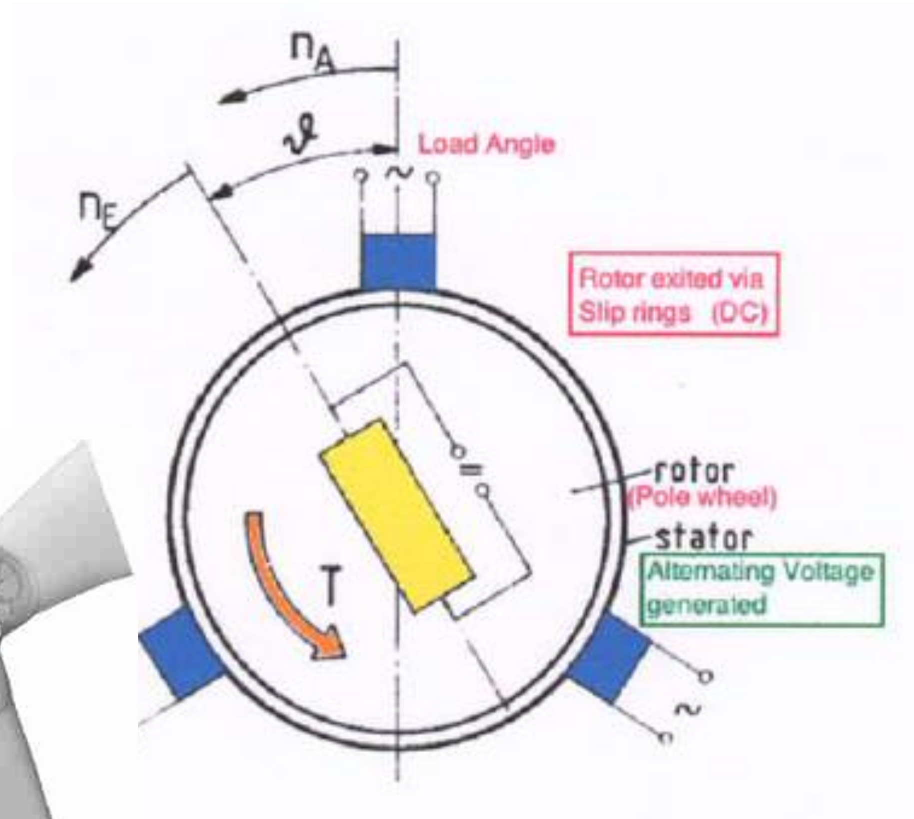
1. Permanent magnets tend to become demagnetized by working in the powerful magnetic fields inside a generator.
2. Powerful magnets are quite expensive, even if prices have dropped lately.

Synchronous Wind Generator

Synchronous wind generators consist of:

- Armature field (Stator)
- Exciter field (Rotor)





Synchronous Wind Generator

Synchronous generators features:

- It runs at synchronous speed or not at all i.e. while running it maintains a constant speed. The only way to change speed is to vary the supply frequency.

$$N_s = 120\, f/P$$

N_s: Synchronous speed, f: Field Frequency, P: No. of pole pairs (rotor)

- It is not self starting. It has to be run upto synchronous speed before it can be synchronized to the supply.

- It is capable of operating under a wide range of power factors.

Synchronous Wind Generator

- Wind turbines which use synchronous generators normally use electromagnets in the rotor which are fed by direct current from the electrical grid.

- Since the grid supplies alternating current, they first have to convert alternating current to direct current before sending it into the coil windings around the electromagnets in the rotor.

- The rotor electromagnets are connected to the current by using brushes and slip rings on the axle (shaft) of the generator.

Synchronous Wind Generator

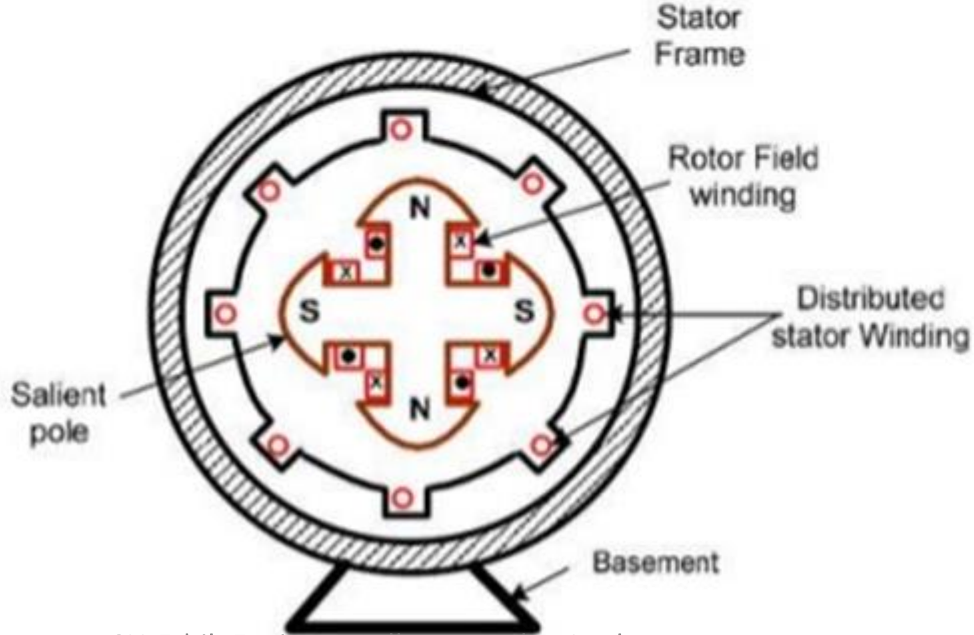
Changing Generator Rotational Speed

- The speed of a generator which is directly connected to a three-phase grid is constant, and dictated by the frequency of the grid.
- If the number of magnets in the stator doubled the magnetic field rotates at half the speed.
- When we double the number of poles in the stator of a synchronous generator we will have to double the number of magnets in the rotor. Otherwise the poles will not match.

Types of Synchronous Generator

Salient-pole

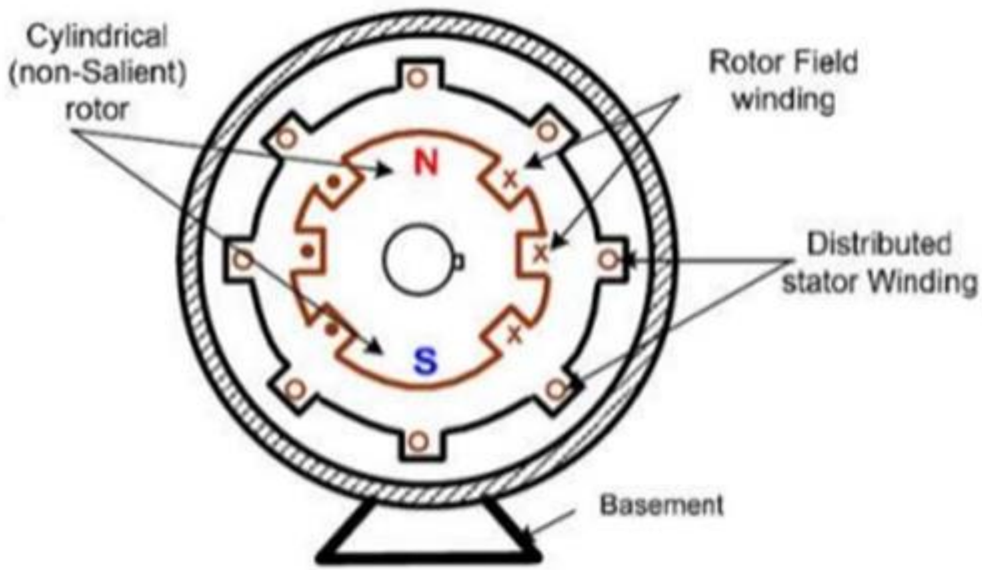
- Large number of pole pairs
- Large rotor diameter and short in axial length.
- Low rotational speeds
- Specific for hydro turbines and Horizontal-axis win turbines



Types of Synchronous Generator

Cylindrical Rotor

- Few pole pairs.
- Small rotor diameter.
- High rotational speeds.
- Specific for steam turbines.



Asynchronous (Induction) Generator

- Most wind turbines in the world use asynchronous (induction) generator to generate alternating current.
- This type of generator is not widely used outside the wind turbine industry, and in small hydropower units.

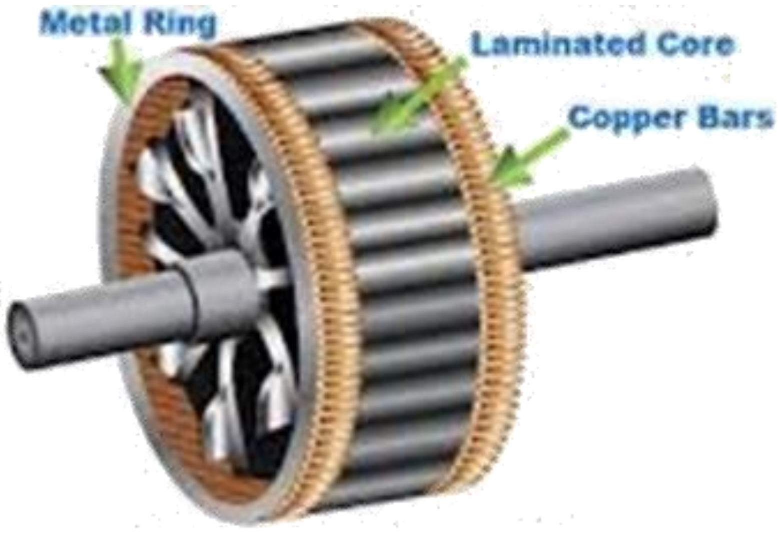
Advantages:

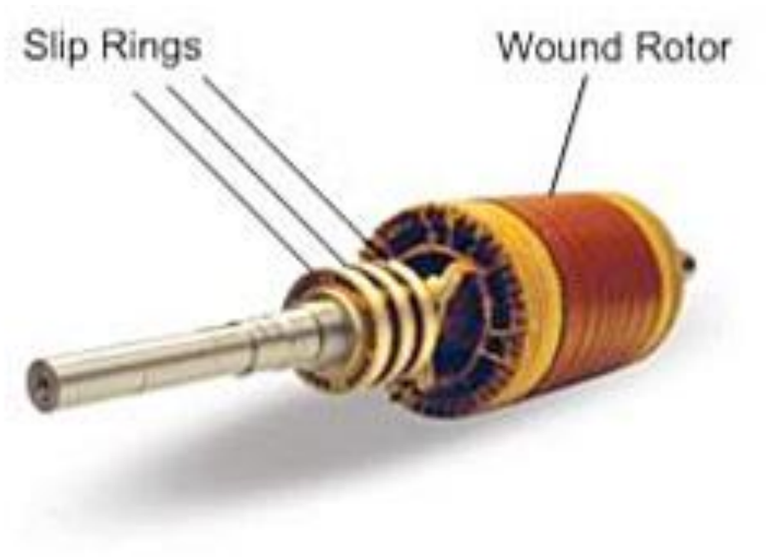
1. It is very reliable.
2. Comparatively inexpensive.
3. Generator slip
4. Overload capability.

A major **drawback** is the reactive power that it consumes for its excitation field and the large starting current. To ameliorate these effects the turbine typically employs a soft starter and discrete steps of capacitor banks within the turbine.

Asynchronous (Induction) Generator

- Rotor design:
  - Squirrel-cage rotor
  - Slip-ring wound rotor





Asynchronous (Induction) Generator

The Squirrel-cage Rotor

- It is the rotor that makes the asynchronous generator different from the synchronous generator. The rotor consists of a number of copper or aluminum bars which are connected electrically by aluminum end rings.

Asynchronous (Induction) Generator

The Squirrel-cage Rotor

- The rotor is provided with an "iron" core, using a stack of thin insulated steel laminations, with holes punched for the conducting aluminum bars.
- The rotor is placed in the middle of the stator which is directly connected to the three phases of the electrical grid.

Asynchronous (Induction) Generator

Generator Slip

- The speed of the asynchronous generator will vary with the turning force (moment, or torque) applied to it.

- In practice, the difference between the rotational speed at peak power and at idle is very small, about 1 per cent.

- This difference in per cent of the synchronous speed , is called the generator's slip.

- Thus a 4-pole generator will run idle at 1500 rpm if it is attached to a grid with a 50 Hz current. If the generator is producing at its maximum power, it will be running at 1515 rpm.

Asynchronous (Induction) Generator

Generator Slip

- It is a very useful mechanical property that the generator will increase or decrease its speed slightly if the torque varies.
- This means that there will be less tear and wear on the gearbox. (Lower peak torque).
- This is one of the most important reasons for using an asynchronous generator rather than a synchronous generator on a wind turbine which is directly connected to the electrical grid.

Asynchronous (Induction) Generator

Automatic Pole Adjustment of the Rotor

- The clever thing about the **Squirrel-cage rotor** is that it adapts itself to the number of poles in the stator automatically.
- The rotor can therefore be used with a wide variety of pole numbers.

Speed Control

- Increasing terminal voltage.
- Connecting external resistors in slip-ring rotor.
- Pole reconnection in squirrel-cage rotor.

Synchronous Arrangements

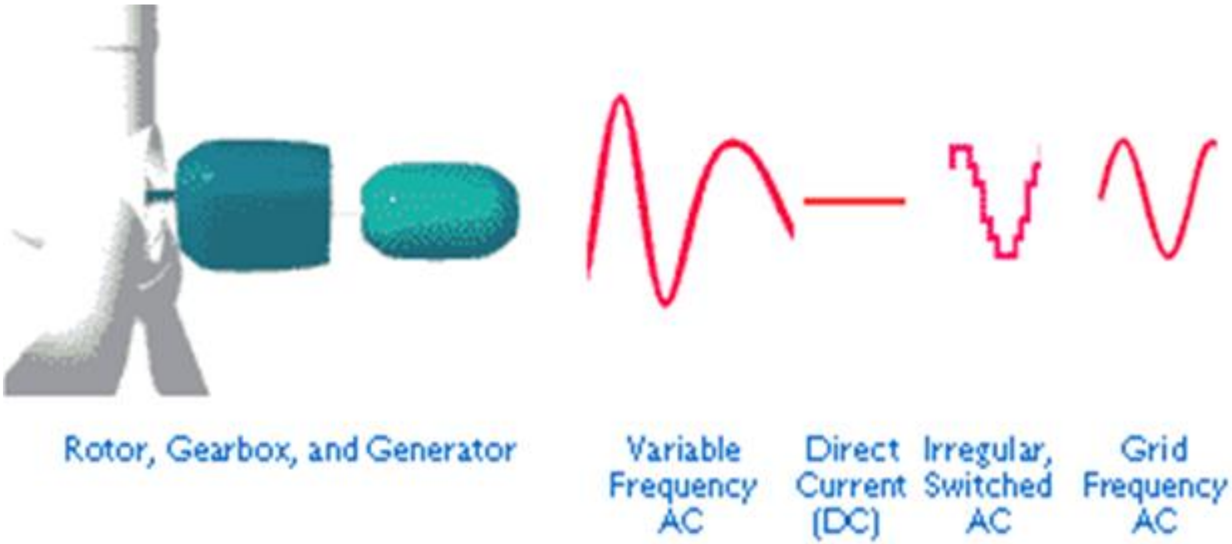
- Generator.
- Invertor. AC-DC-AC
- Rectifier.
- Control and support system.
- Power supply for control system. (DC)
- Medium-voltage distribution for auxiliaries.
- Power transmission cable.
- Step-up Transformers.
- Reactive power compensation.
- Electricity safety devices and lightning protection.

Wind Turbine Generators

Forms of Wind turbines generators connection to grid:

1. **Direct grid connection**: the generator is connected directly to the (usually 3-phase) alternating current grid.
2. **Indirect grid connection**: the current from the turbine passes through a series of electric devices which adjust the current to match that of the grid. With an asynchronous generator this occurs automatically.

Indirect Grid Connection of Wind Turbines



Indirect Grid Connection of Wind Turbines

Generating Alternating Current (AC) at Variable Frequency

- Most wind turbines run at almost constant speed with direct grid connection.
- With indirect grid connection, however, the wind turbine generator runs in its own, separate mini AC-grid.
- This grid is controlled electronically (using an inverter), so that the frequency of the alternating current in the stator of the generator may be varied.

Indirect Grid Connection of Wind Turbines

Generating Alternating Current (AC) at Variable Frequency

- In this way it is possible to run the turbine at variable rotational speed. Thus the turbine will generate alternating current at exactly the variable frequency applied to the stator.
- The generator may be either a synchronous generator or an asynchronous generator , and the turbine may have a gearbox or run without a gearbox if the generator has many poles.

Indirect Grid Connection of Wind Turbines

Conversion to Direct Current (DC)

- AC current with a variable frequency cannot be handled by the public electrical grid.
- It rectified, i.e. convert it into direct current, DC.
- The conversion from variable frequency AC to DC can be done using thyristors or large power transistors.

Indirect Grid Connection of Wind Turbines

Conversion to Fixed Frequency AC

- The DC current converts to an alternating current (using an inverter) with exactly the same frequency as the public electrical grid.
- This conversion to AC in the inverter can also be done using either thyristors or transistors.
- The alternating current gets out of an inverter not looks likes the smooth sinusoidal curve alternating current. Instead, we get a series of sudden jumps in the voltage and current.

Indirect Grid Connection of Wind Turbines

Filtering the AC

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

Characteristics of Wind Turbine Generators

Wind Turbine Generator types as a speed control can be divided into:

Type 1 : Fixed speed.

Type 2 : Limited variable speed.

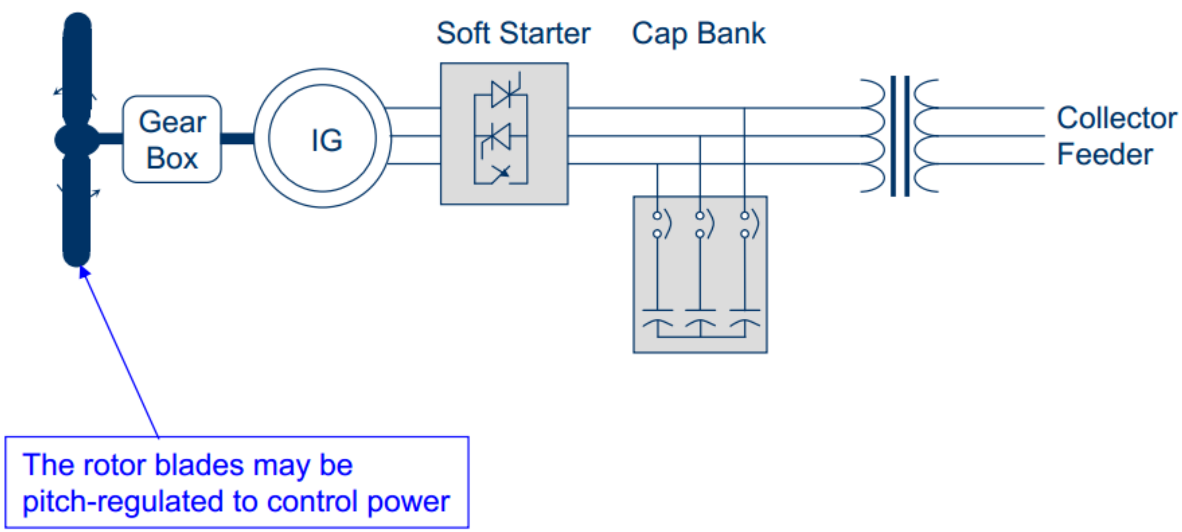
Type 3 : Variable speed with partial power electronic conversion.

Type 4 : Variable speed with full power electronic conversion.

Type 5 : Generator speed control via mechanical torque converter in gearbox.

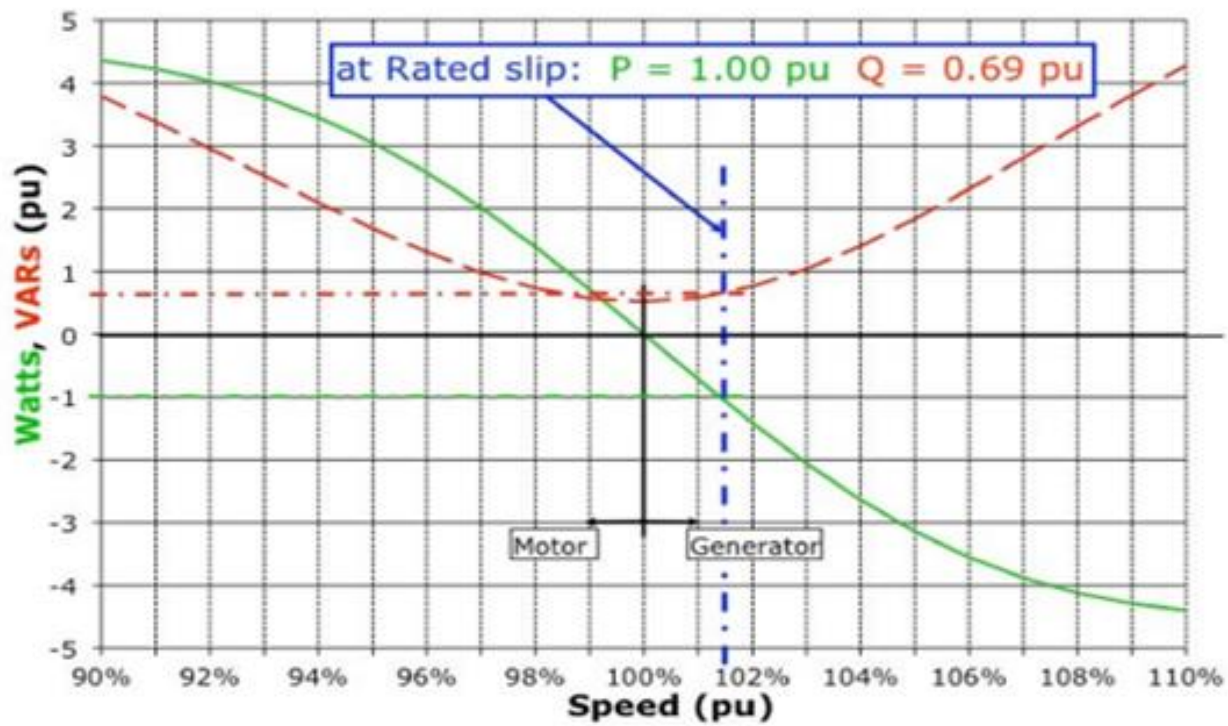
Type 1 : Fixed speed

- Implemented with a squirrel-cage induction generator (SCIG) and is connected to the step-up transformer directly.
- The turbine speed is fixed to the electrical grid's frequency, and generates real power (P) when the turbine shaft rotates faster than the electrical grid frequency creating a negative slip.



Type 1 : Fixed speed

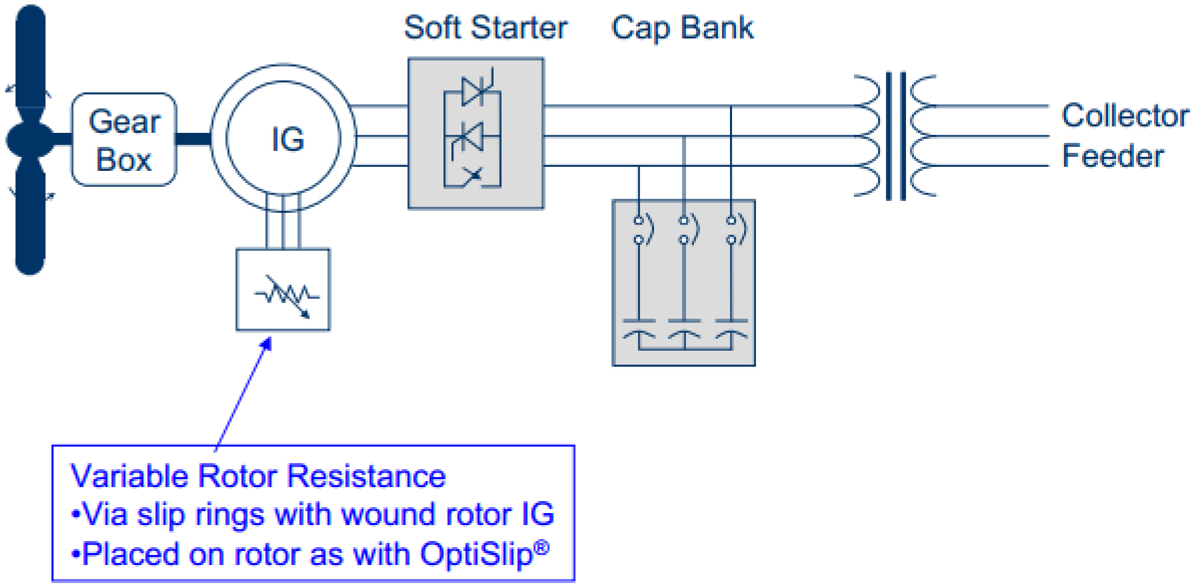
- While there is a bit of variability in output with the slip of the machine, Fixed speed turbines typically operate at a rated speed.



Variation of Real and Reactive Power for SCIG

Type 2 : Limited variable speed

- In Type 2 turbines, wound rotor induction generators are connected directly to the wind turbine step-up transformer in a fashion similar to Type 1 with regards to the soft stator circuit, but also include a **variable resistor** in the rotor circuit.

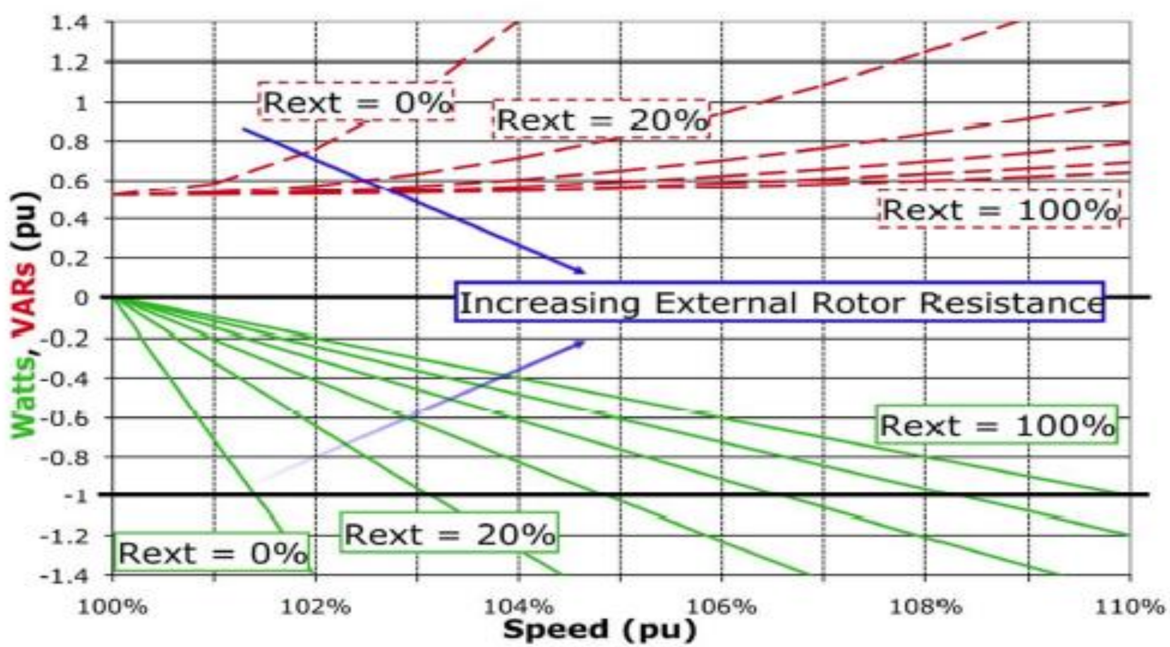


Type 2 : Limited variable speed

- This can be accomplished with a set of resistors and power electronics external to the rotor with currents flowing between the resistors and rotor via slip rings.
- Alternately, the resistors and electronics can be mounted on the rotor, eliminating the slip rings—this is the **Weier design**.
- The variable resistors are connected into the rotor circuit softly and can control the rotor currents quite rapidly so as to keep constant power even during gusting conditions, and can influence the machine's dynamic response during grid disturbances.

Type 2 : Limited variable speed

- By adding resistance to the rotor circuit, the real power curve can be moved to the higher slip and higher speed ranges.
- That is to say that the turbine would have to spin faster to create the same output power, for an added rotor resistance.

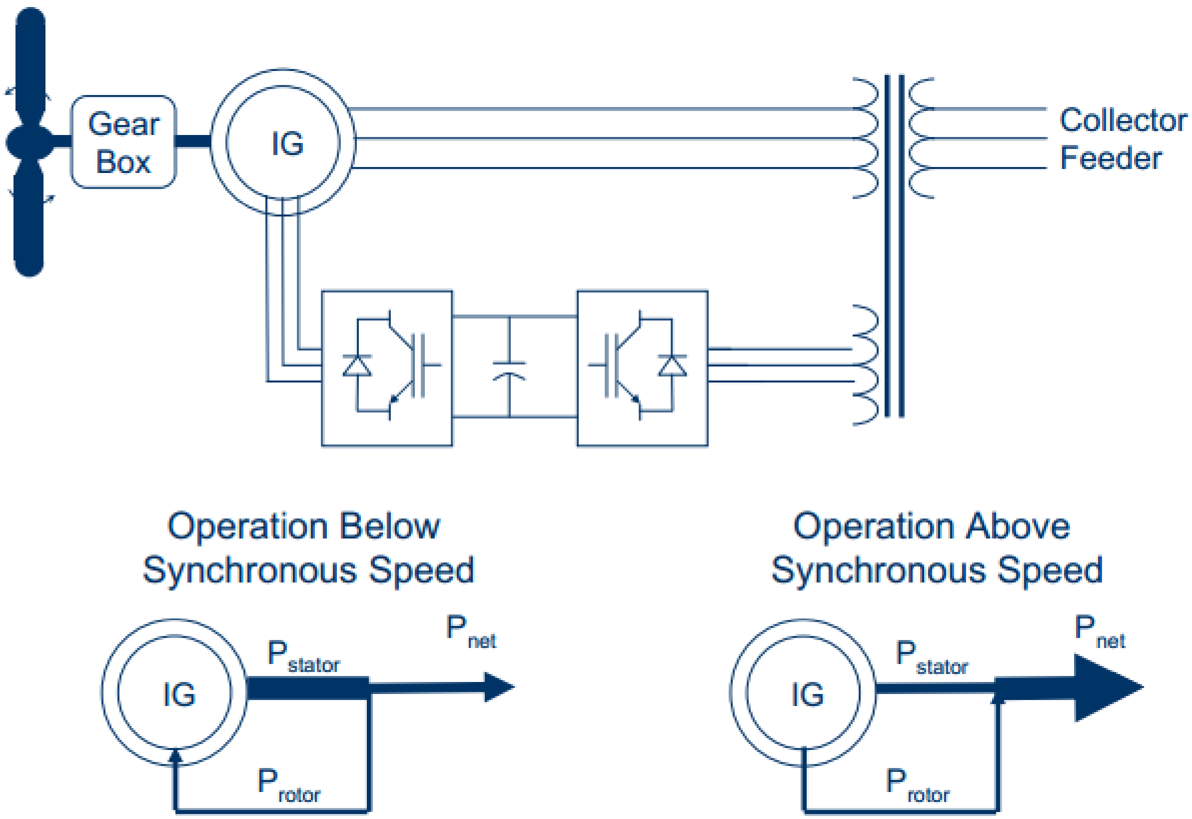


Type 2 : Limited variable speed

- This allows some ability to control the speed, with the blades' pitching mechanisms and move the turbines operation to a tip speed ratio to achieve the best energy capture.
- It is typical that speed variations of up to 10% are possible, allowing for some degree of freedom in energy capture and self-protective torque control.

Type 3 : Variable speed with partial power electronic conversion

- The Doubly Fed Asynchronous (Induction) Generator used in type 3 turbine, by adding variable frequency ac excitation instead of simply resistance to the rotor circuit.



Type 3 : Variable speed with partial power electronic conversion

- The additional rotor excitation is supplied via slip rings by a current regulated, voltage-source converter, which can adjust the rotor currents' magnitude and phase nearly instantaneously.
- This rotor-side converter is connected back-to-back with a grid side converter, which exchanges power directly with the grid.
- A small amount power injected into the rotor circuit can affect a large control of power in the stator circuit. This is a major advantage of the Doubly Fed Asynchronous (Induction) Generator.

Type 3 : Variable speed with partial power electronic conversion

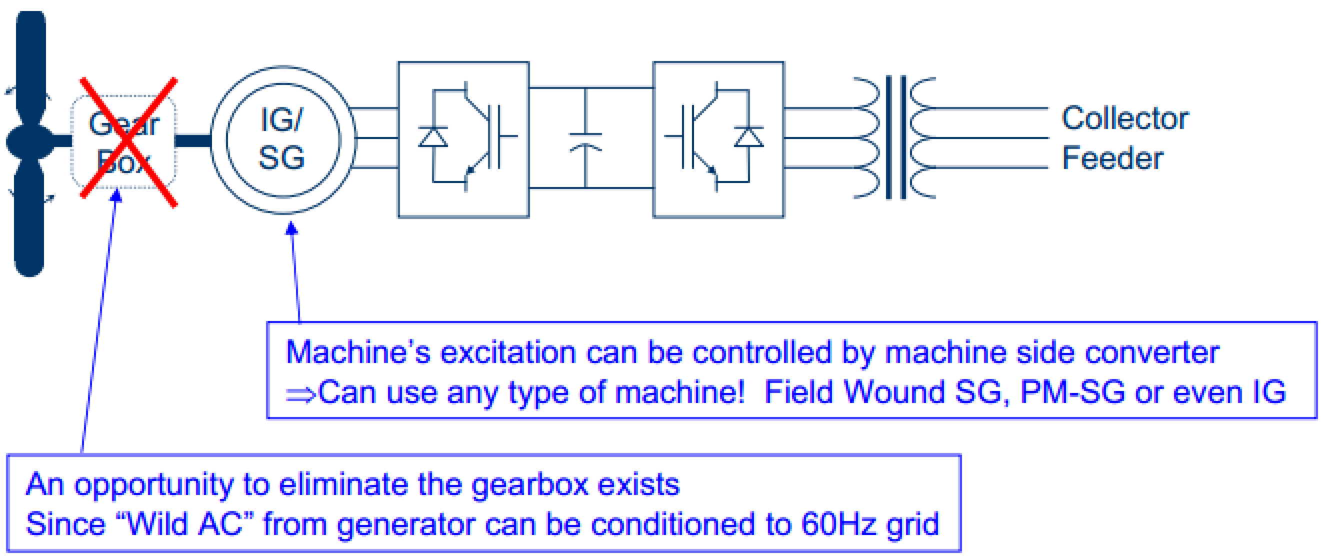
- In addition to the real power that is delivered to the grid from the generator's stator circuit, power is delivered to the grid through the grid-connected inverter when the generator is moving faster than synchronous speed.
- When the generator is moving slower than synchronous speed, real power flows from the grid, through both converters, and from rotor to stator.
- These two modes, made possible by the four-quadrant nature of the two converters, allows a much wider speed range, both above and below synchronous speed by up to 50%, although narrower ranges are more common.

Type 3 : Variable speed with partial power electronic conversion

- The greatest advantage of the DFIG, is that it offers the benefits of separate real and reactive power control, much like a traditional synchronous generator, while being able to run asynchronously.
- Indeed, while more expensive than the Type 1 or 2 machines, the Type 3 is becoming popular due to its advantages.

Type 4 : Variable speed with full power electronic conversion

- The Type 4 turbine offers a great deal of flexibility in design and operation as the output of the rotating machine is sent to the grid through a full-scale back to back frequency converter.
- The turbine is allowed to rotate at its optimal aerodynamic speed, resulting in a "wild" AC output from the machine.



Type 4 : Variable speed with full power electronic conversion

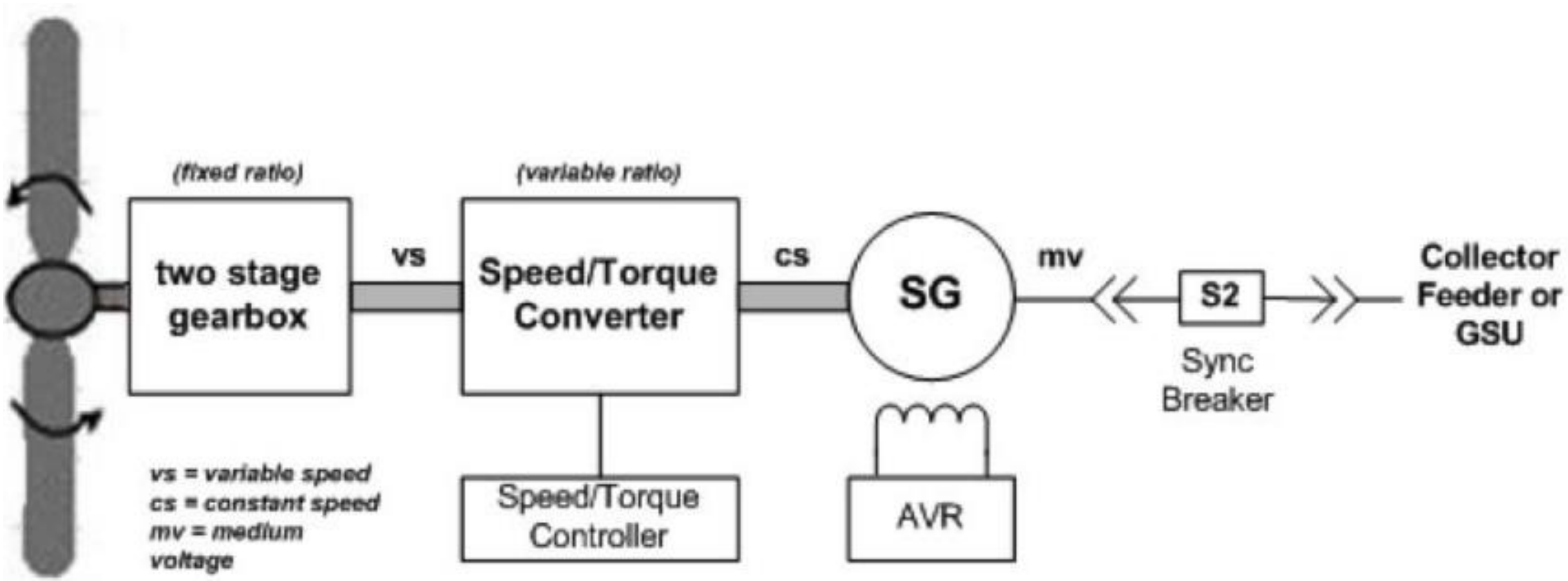
- In addition, the gearbox may be eliminated, such that the machine spins at the slow turbine speed and generates an electrical frequency well below that of the grid.
- This is no problem for a Type 4 turbine, as the inverters convert the power, and offer the possibility of reactive power supply to the grid.
- The rotating machines of this type have been constructed as wound rotor synchronous machines, similar to conventional generators found in hydroelectric plants with control of the field current and high pole numbers, as permanent magnet synchronous machines, or as squirrel cage induction machines.

Type 4 : Variable speed with full power electronic conversion

- However, based upon the ability of the machine side inverter to control real and reactive power flow, any type of machine could be used.
- Advances in power electronic devices and controls in the last decade have made the converters both responsive and efficient.
- It does bear mentioning, however, that the power electronic converters have to be sized to pass the full rating of the rotating machine, plus any capacity to be used for reactive compensation.

Type 5 : Generator speed control via mechanical torque converter in gearbox

- Type 5 turbines consist of a typical wind turbine generator variable-speed drive train connected to a torque/speed converter coupled with a synchronous generator.



Type 5 : Generator speed control via mechanical torque converter in gearbox

- The torque/ speed converter changes the variable speed of the rotor shaft to a constant output shaft speed.
- The closely coupled synchronous generator, operating at a fixed speed (corresponding to grid frequency), can then be directly connected to the grid through a synchronizing circuit breaker.
- The synchronous generator can be designed appropriately for any desired speed (typically 6 pole or 4 pole) and voltage.
- This approach requires speed and torque control of the torque/ speed converter along with the typical voltage regulator (AVR), synchronizing system, and generator protection system inherent with a grid-connected synchronous generator.

Generating Voltage (tension)

- On large wind turbines (above 100-150 kW) the voltage (tension) generated by the turbine is usually 690 V three-phase alternating current (AC).
- The current is sent through a transformer next to the wind turbine to raise the voltage between 10,000 to 33,000 volts, depending on the standard in the local electrical grid.
- Large manufacturers will supply both 50 Hz wind turbine models and 60 Hz models.

Cooling System

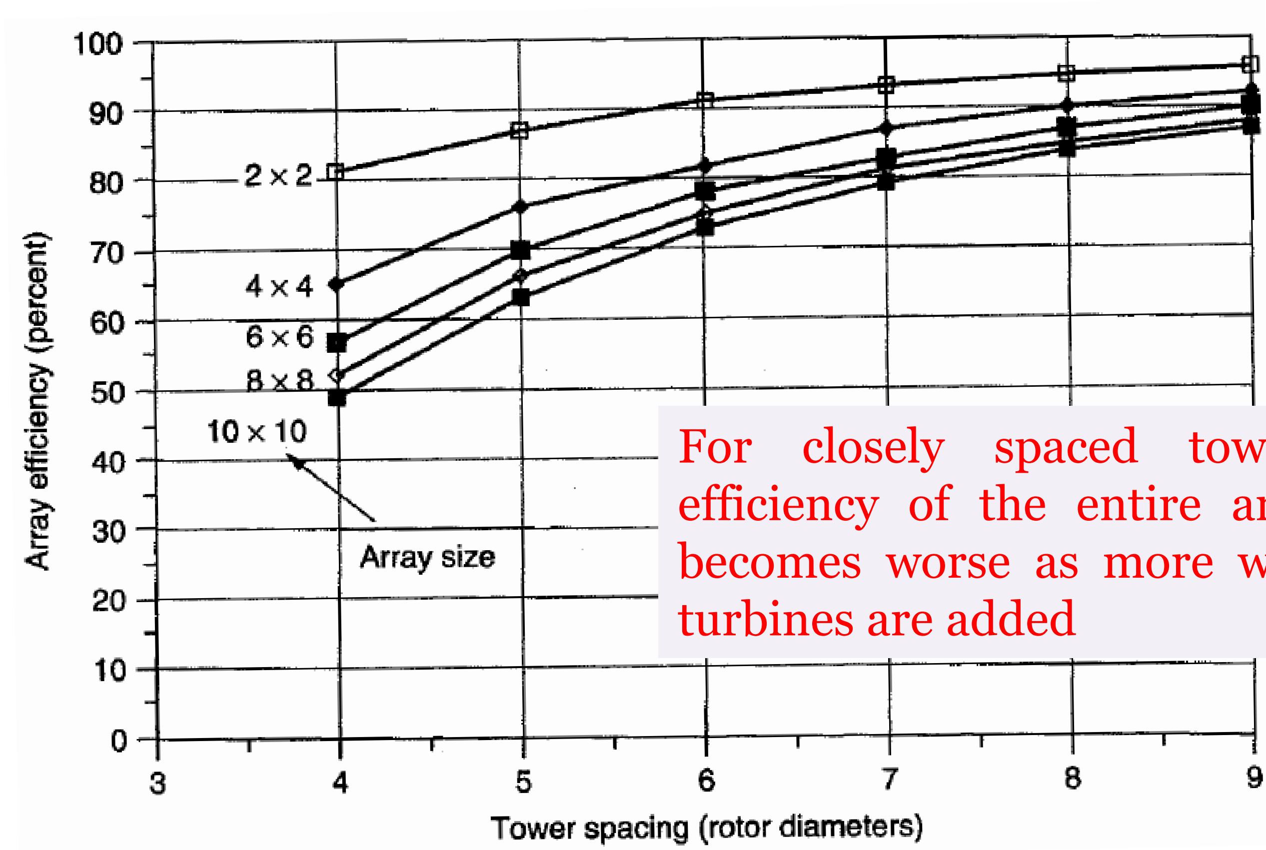
- Generators need cooling while they work.
- On most turbines this is accomplished by encapsulating the generator in a duct, using a large fan for air cooling, but a few manufacturers use water cooled generators.
- Water cooled generators may be built more compactly, which also gives some electrical efficiency advantages, but they require a radiator in the nacelle to get rid of the heat from the liquid cooling system.

Wind Farms

- It makes sense to install a large number of wind turbines in a wind farm or a wind park
- **Benefits**
  1. Able to get the most use out of a good wind site.
  2. Reduced development costs.
  3. Simplified connections to the transmission system.
  4. Centralized access for operations and maintenance.

Wind Farms

- Wind slows down as it passes through the blades.
- Extracting power with the blades reduces the available power to downwind machines.



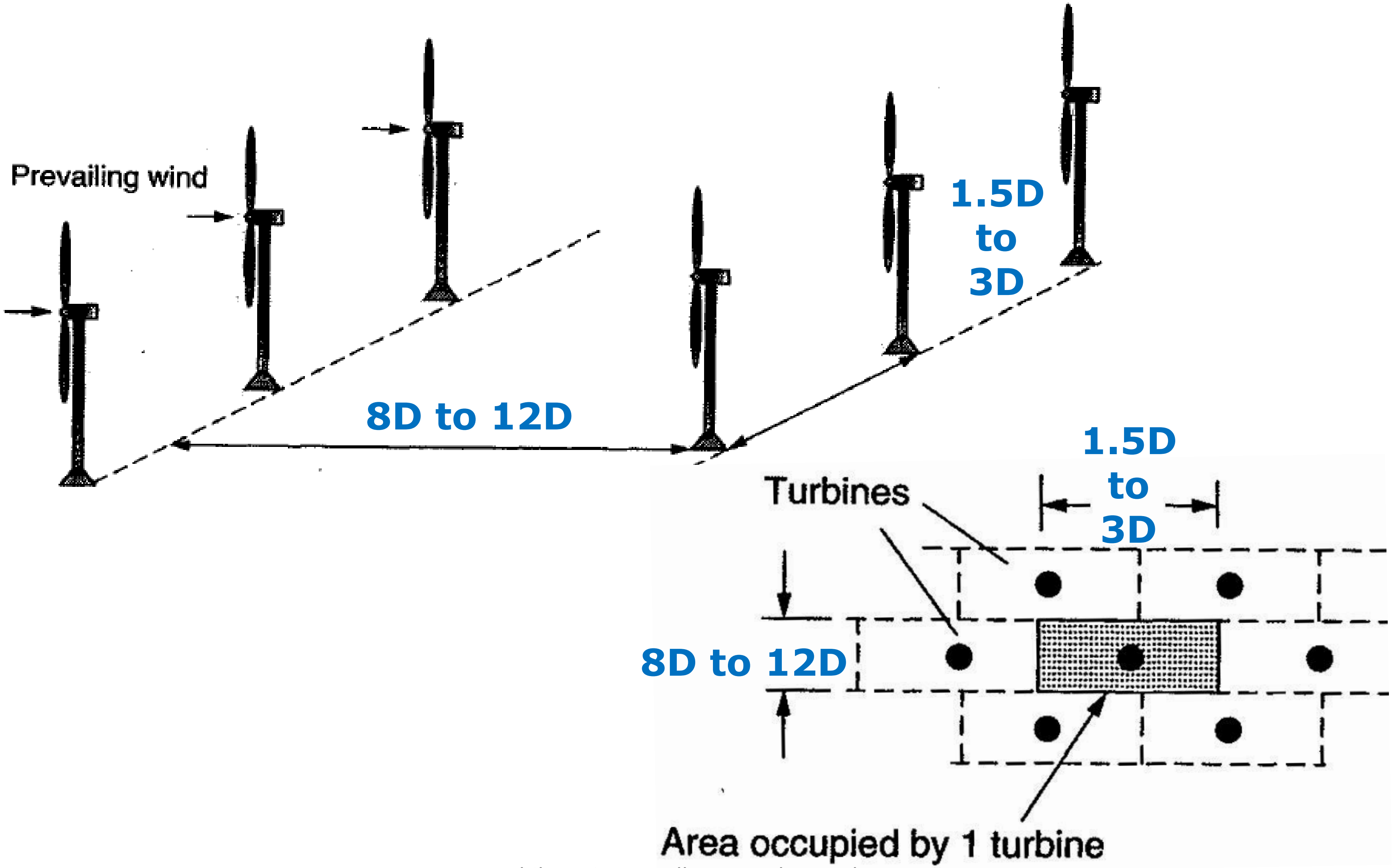
For closely spaced towers, efficiency of the entire array becomes worse as more wind turbines are added

Wind Farms

- The spacing between wind farm towers depends on:
  1. the terrain
  2. the wind direction
  3. the wind speed
  4. the turbine size.

- Rectangular arrays with only a few long rows are better.
- Optimum spacing is 1.5-3 rotor diameters between towers in a row and 8-12 diameters between rows.

Wind Farms – Optimum Spacing



Offshore Wind Farms

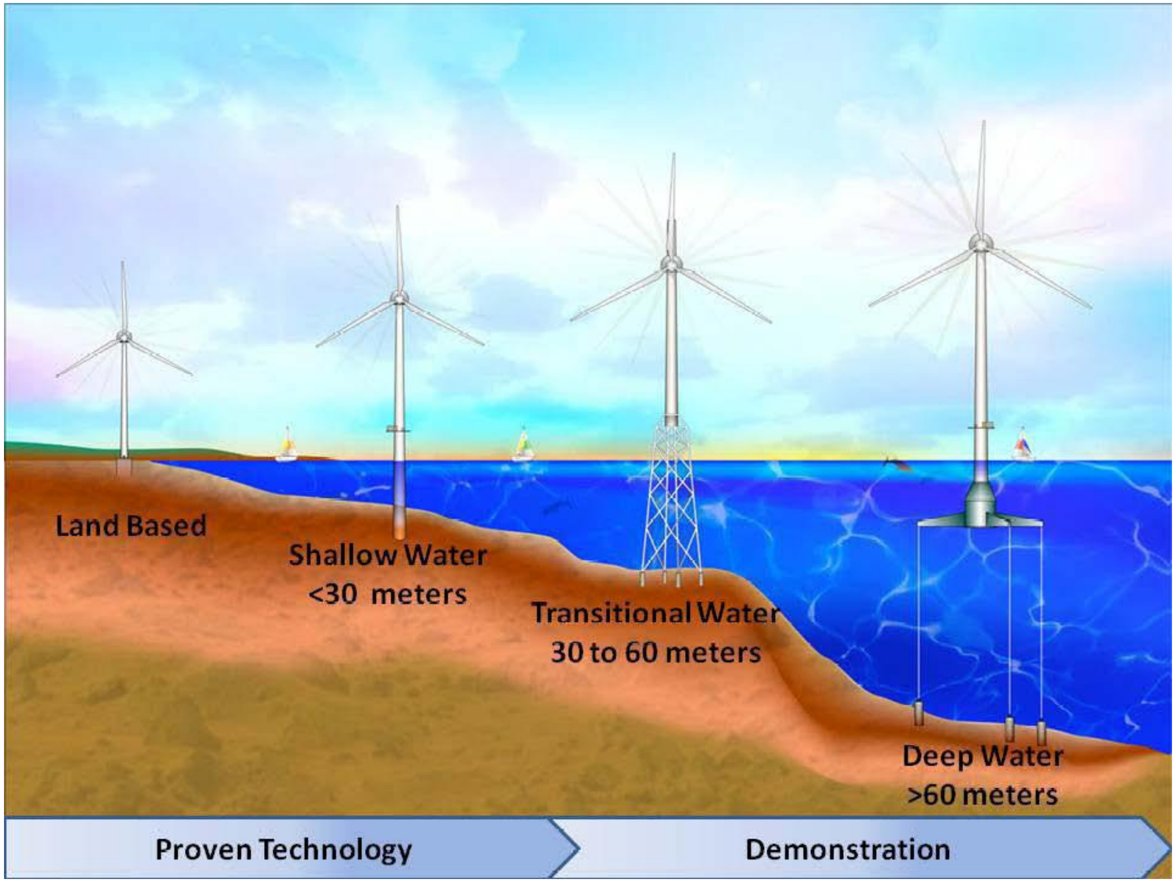
- Offshore wind turbines are the same as the horizontal-axis wind turbine used onshore, only the rotors are much larger.
- Wind offshore blows much faster than on shore, because there are fewer obstructions such as buildings and hills.
- Offshore turbines do not need to be as tall relative to their heights as onshore wind turbines.
- The slight increase in wind velocity means a significant increase in power production for the offshore wind turbines.

Offshore Wind Farms

- Most offshore wind turbines are installed in shallow water, which is no more than 30 meters deep.
- Before, towers can be driven 24 to 30 meters into the seabed, an assessment must be made to protect from environmental damages.
- Recently, more offshore wind turbines have been moving toward the transitional water, which has a depth between 30 and 60 m.
- Simple towers will not stabilize these wind turbines, tripod-like stands or wider- base structures must be installed.

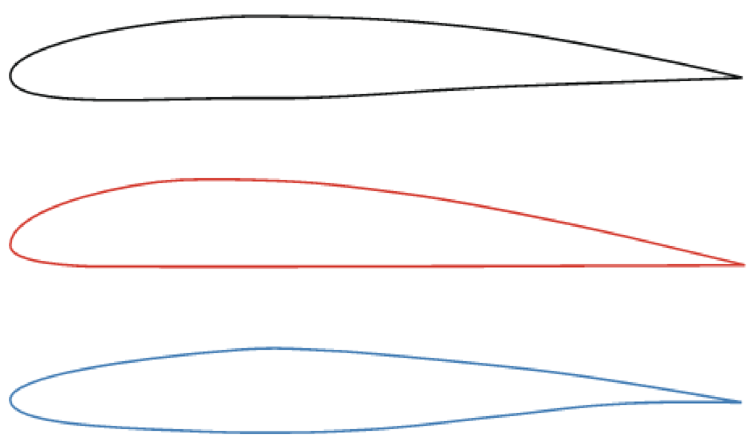
Offshore Wind Farms

- The eventual goal is to have offshore turbines in deep water, which is greater than 60 meters deep.



Blade section shape

- Wind turbine blades have similar requirements to airplane wings, so their cross-sections are usually based on a similar family of shapes.
- In general the best lift/drag characteristics are obtained by an aerofoil that is fairly thin: it's thickness might be only 10-15% of its chord.



Typical aerofoil shapes offering good lift/drag ratio

Designs of Rotor Blades

Materials

The most important material properties for choosing materials for blades are:

1. specific weight (g/cm^3)
2. Strength limit (N/mm^2)
3. Modulus of elasticity (kN/m^2)
4. Breaking strength related to the specific weight, the so-called breaking length (km)
5. Modulus of elasticity related to the specific weight, (10^3 km)
6. Allowable fatigue strength after 10^7 to 10^8 load cycles (N/mm^2).
7. Cost of the material, manufacturing cost.

Designs of Rotor Blades

Materials

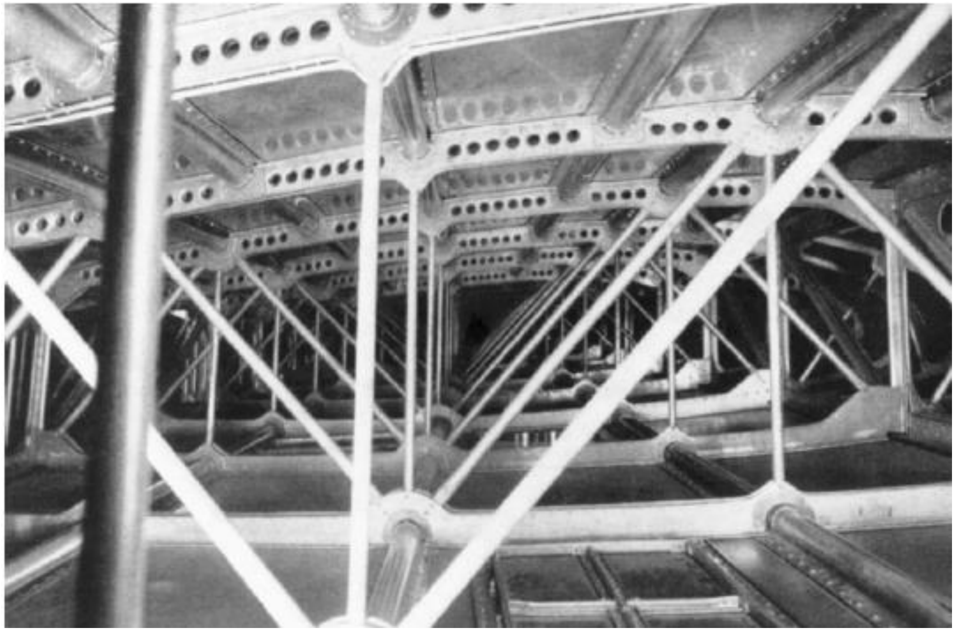
Judging from experience gained in aircraft engineering, the following materials are considered as suitable for wind turbine rotor blades:

1. Titanium
2. Aluminum
3. Steel
4. Fiber composite material (glass, carbon and aramide fibers)
5. Wood

Designs of Rotor Blades

Riveted Aluminum Designs

- Aluminum is a high-strength material with which a weight advantage of approximately 30% can be achieved against comparably loaded steel designs.

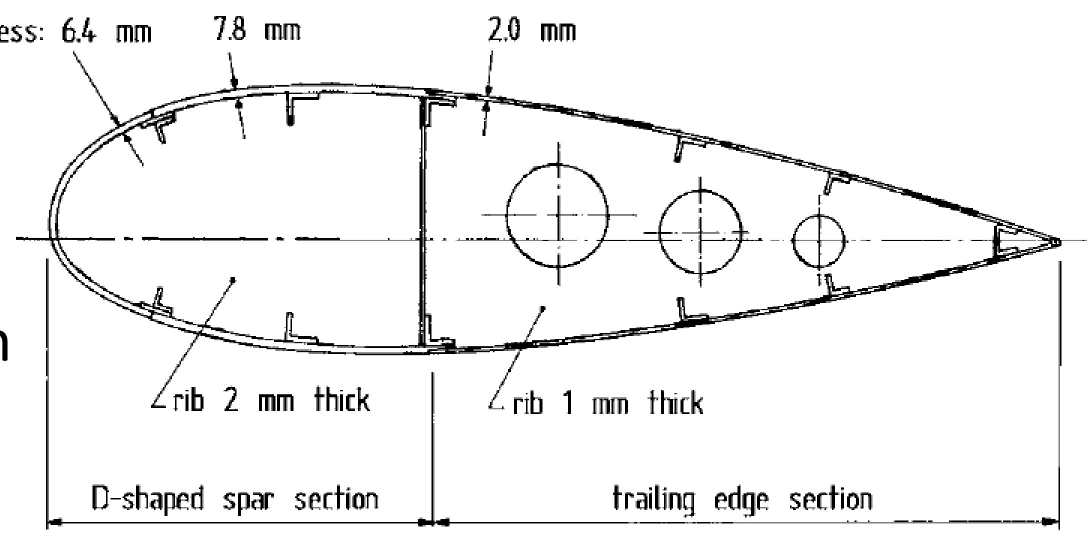


Wind turbine blade in riveted aluminum design

Designs of Rotor Blades

Riveted Aluminum Designs

- **Advantages:** The good strength values and resistance to corrosion.
- **Disadvantage:** costly production and unweldable.
- aluminum sheets and stringers are practically unweldable and must be riveted.

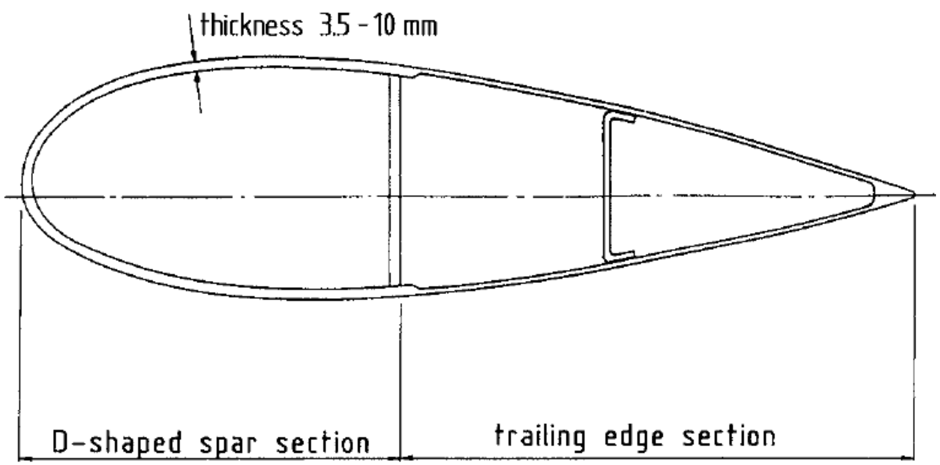


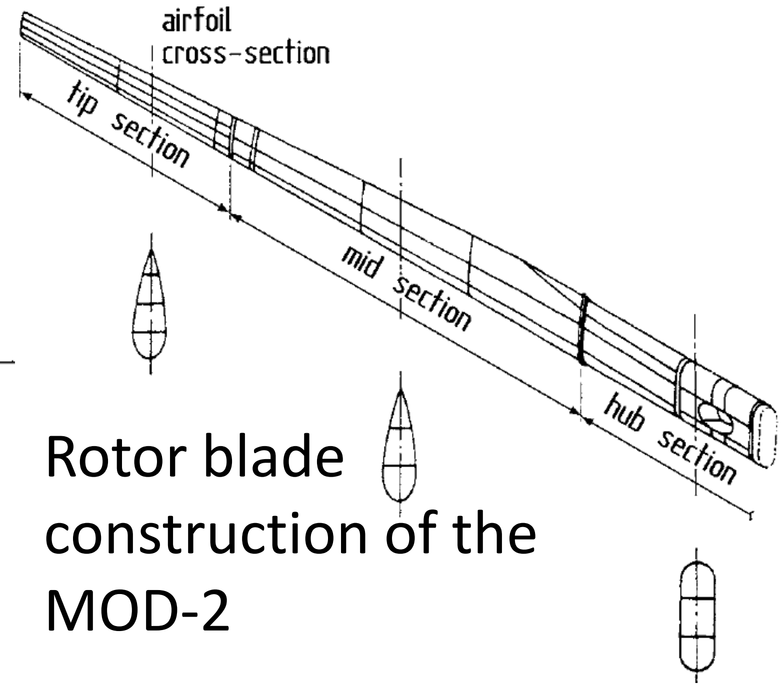
Rotor blade design with riveted aluminum in the American

Designs of Rotor Blades

Steel Designs

- Steel was the prevailing rotor blade material in the large test turbines built in the early eighties.
- This includes the rotor blades of the German Growian turbine, the American MOD-2 turbine and the Swedish WTS-75 turbine.





Rotor blade construction of the MOD-2

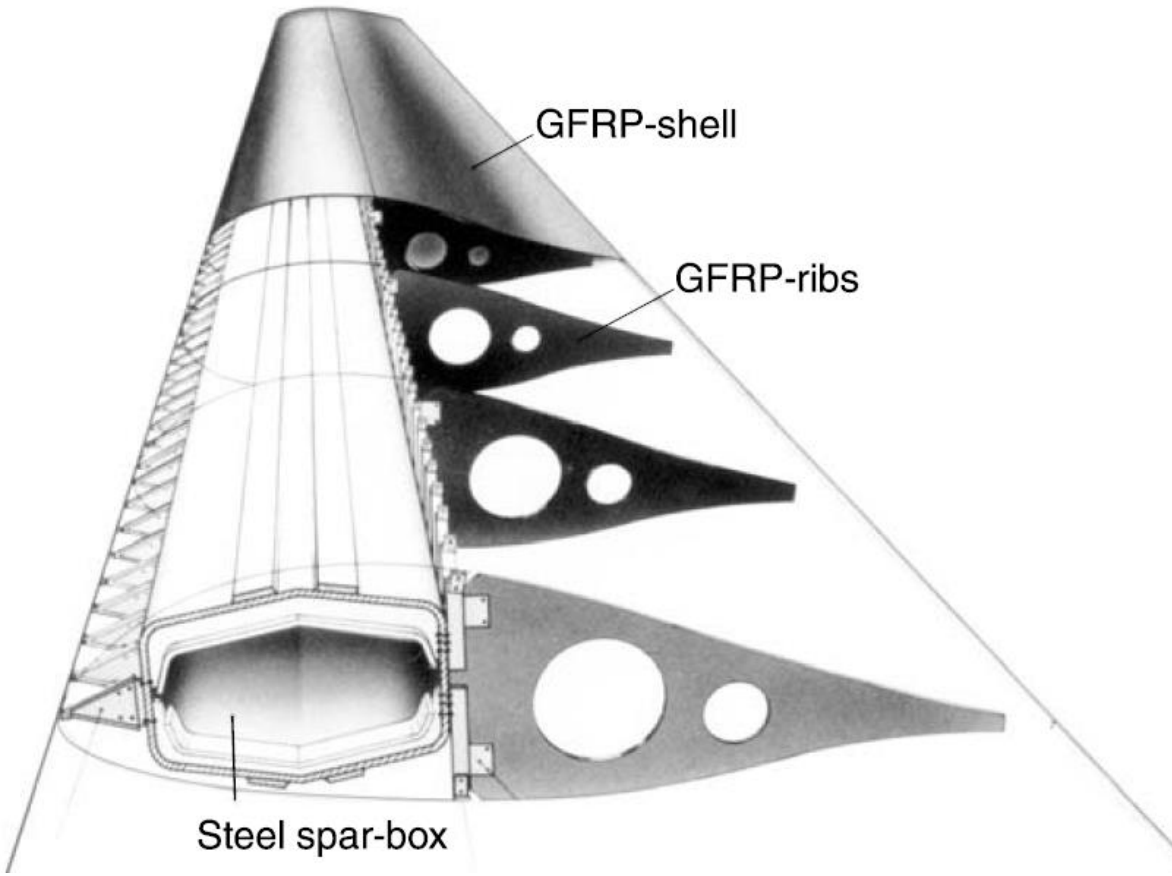
Designs of Rotor Blades

Steel Designs

- **Advantages:**
  1. allowable fatigue-strength values.
  2. Low price of the material.
  3. Low production costs.
  4. Conventional welding techniques.
  5. The well-known material properties.
- **Disadvantages:**
  1. corrosion.
  2. Heavy weight.
  3. Thick steel sheets with great difficulty can be formed into the twisted shape.

Designs of Rotor Blades

Steel Designs

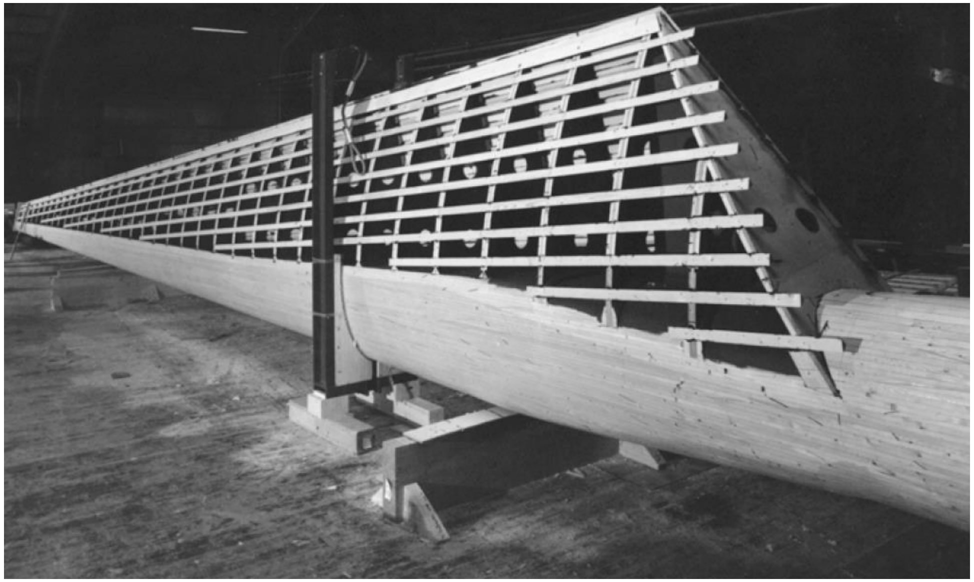


Rotor blade design of the German Growian experimental turbine

Designs of Rotor Blades

Traditional Wood Construction

- Although wood has a tradition of centuries as a material in the construction of windmills, its use in modern wind energy technology was considered.
- Solid wood construction as found in aircraft propellers can still be found today on small wind wheels with a diameter of only a few meters.



Rotor blade of the NIBE-B turbine, in traditional wood design(Denmark)

Designs of Rotor Blades

Modern Fiber-Reinforced Composite Blades

- Components of fiber-reinforced composites have been widely used for a number of decades.
- The basic concept of fiber-reinforced composites consists in reinforcing the well-known synthetic resins by embedding fibers in them which have better strength properties than the basic material.
- Fiber-reinforced composites differ with regard to the type of fiber material used which is essentially responsible for the strength and the stiffness properties of the composite material.
- On the other hand, various resins are used as bonding material, the so-called *matrix*.

Designs of Rotor Blades

Modern Fiber-Reinforced Composite Blades

- **Three different fibers materials are available:**

1. Carbon fiber
2. Glass fiber
3. Organic aramid fibers (*Kevlar*)

Designs of Rotor Blades

Modern Fiber-Reinforced Composite Blades

- **Three different fibers materials are available:**

1. **Carbon fiber**
    1. high modulus of elasticity (Its stiffness is comparable to steel structures)
    2. Their fatigue strength properties are good.
    3. Needs special precautionary measures for protection against lightning.
    4. Expensive.

    This is why carbon fiber is frequently used only in combination with glass fiber material for the areas which are particularly subjected to stress.

Designs of Rotor Blades

Modern Fiber-Reinforced Composite Blades

- **Three different fibers materials are available:**

2. **Glass fiber**
    1. The most widely used
    2. Its strength properties are extraordinarily high
    3. Its specific modulus of elasticity is not so good (Low stiffness) for that cannot be used unreservedly for very large rotor blades.

Designs of Rotor Blades

Modern Fiber-Reinforced Composite Blades

- **Three different fibers materials are available:**

3. Organic aramid fibers (*Kevlar*)

1. Good strength properties.
2. The fatigue strength has not been tested to the present day.
3. They are hygroscopic.

Designs of Rotor Blades

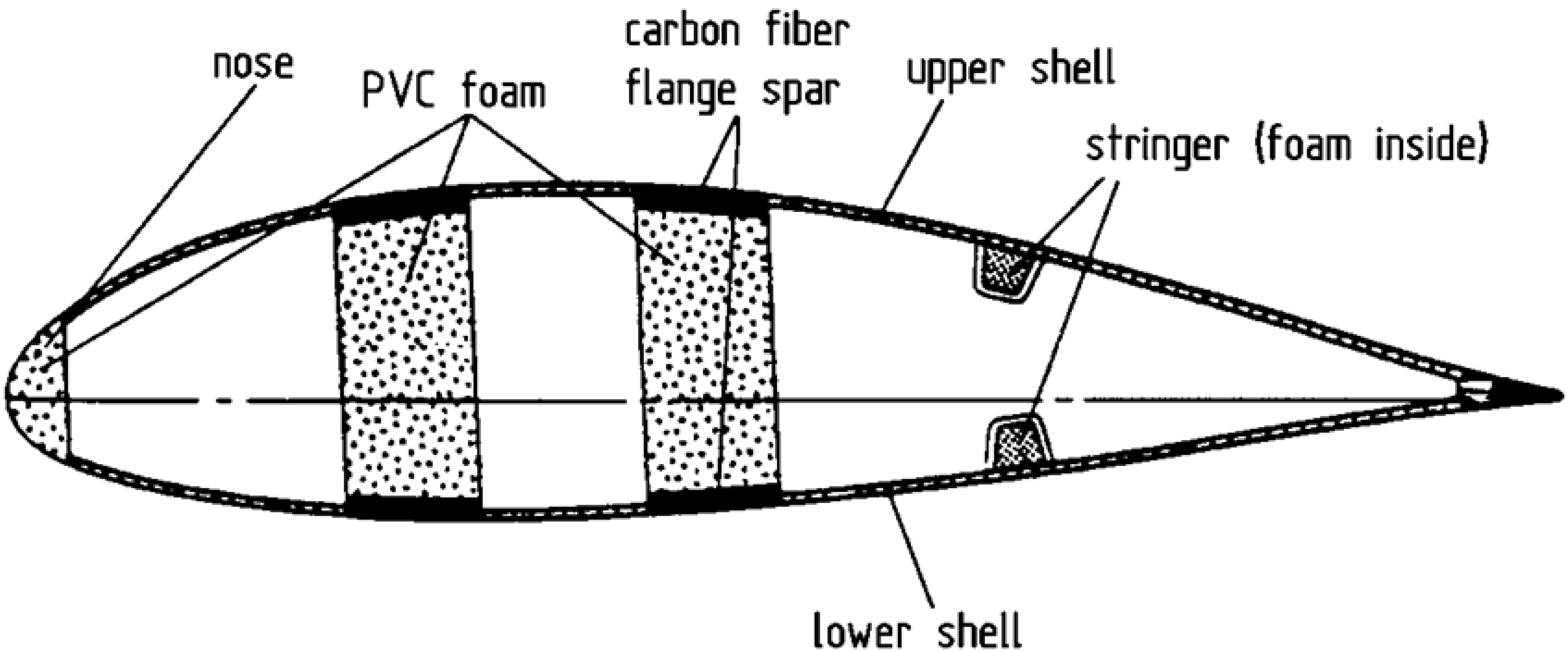
Modern Fiber-Reinforced Composite Blades

- **Considering the practical aspects, the selection of matrix material is restricted to:**

1. **Polyester resins:** They are inexpensive and quite suitable for medium stresses. Most of the earlier rotor blades, especially from Danish production, were manufactured on its basis.
2. **Epoxy resins:** Many rotor blade manufacturers now prefer to use the expensive, high-quality *epoxy resins* which are exclusively used in aircraft construction. Their strength characteristics are better both with regard to the flow properties with high concentrated loads and to the fatigue strength. Moreover, they do not exhibit any shrinkage like the polyester resins.

Designs of Rotor Blades

Modern Fiber-Reinforced Composite Blades



Rotor blade of the experimental Aeolus II turbine in mixed glass fiber/carbon fiber construction

Next Lecture

- Tidal and Wave Energies

Questions and Thank you