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Wind Energy: Electrical Generators

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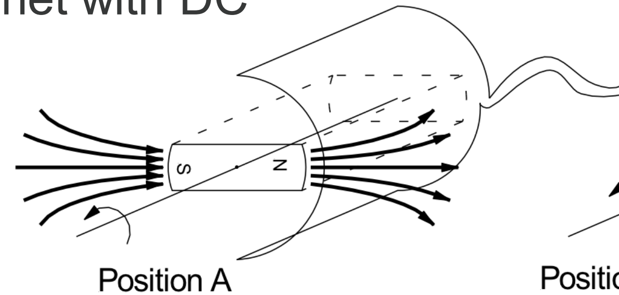
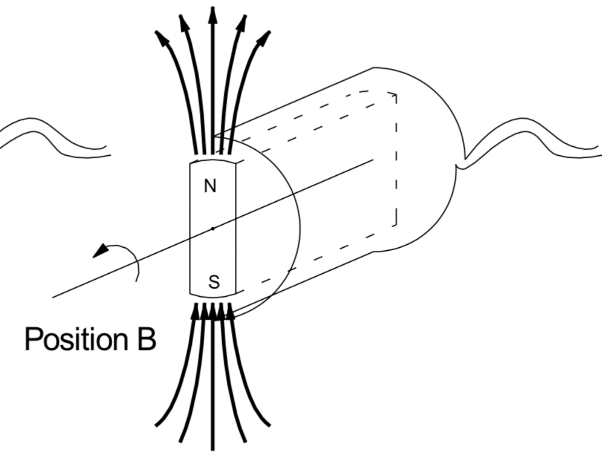
Basic Generator

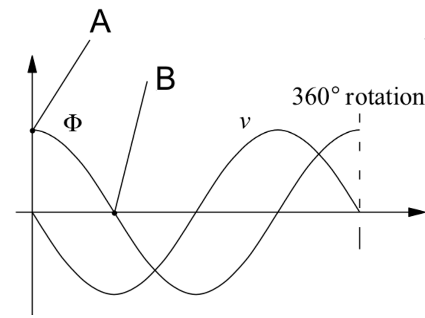
The basic generator is a rotating magnet (either a permanent magnet or an electromagnet with DC current), linked to a stationary coil.





The changing flux linking the coil induces an electro-motive force, EMF

Each passage of a north-pole and then south-pole field over the coil creates a cycle of AC voltage



A simple magnetic field (one north-pole and one south-pole) rotating at *n* revs/min will induces EMF at a frequency of

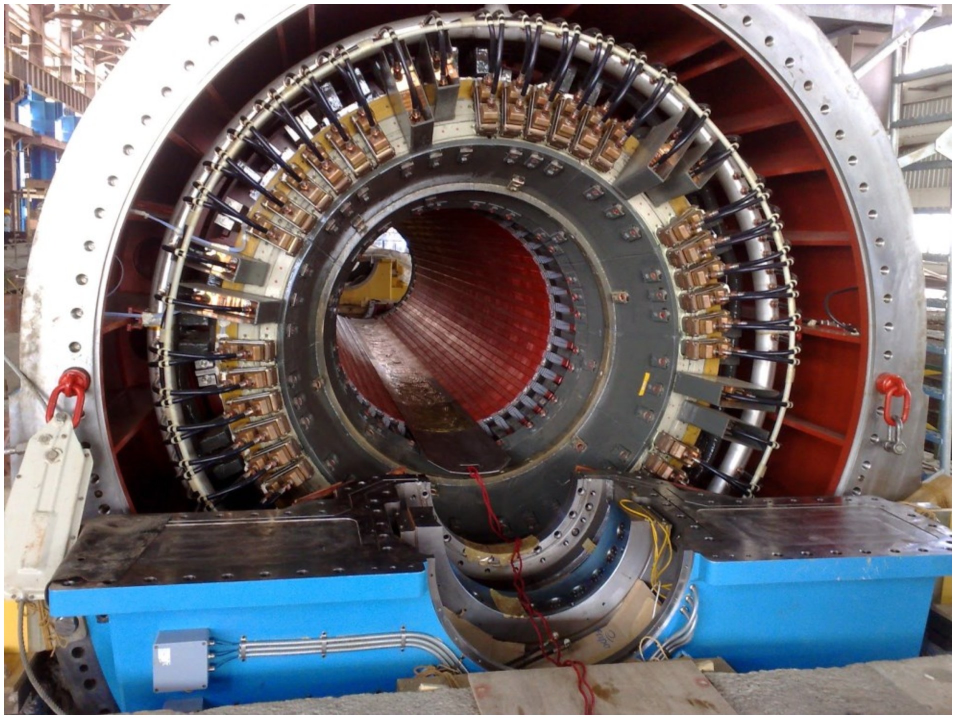
$$f = n/60$$ <Hz>

(or $\omega = 2\pi\, n/60$ <rad/s>)

Generators with more pairs, p, of north and south magnetic poles generate EMFs that are p times higher in frequency

$$f = p\, n/60$$ <Hz>

Real Generators



Both the stator (normally carries the main generator winding) and the rotor (normally carries the magnet or electro-magnet) use a steel structure to provide a low reluctance path for magnetic flux.

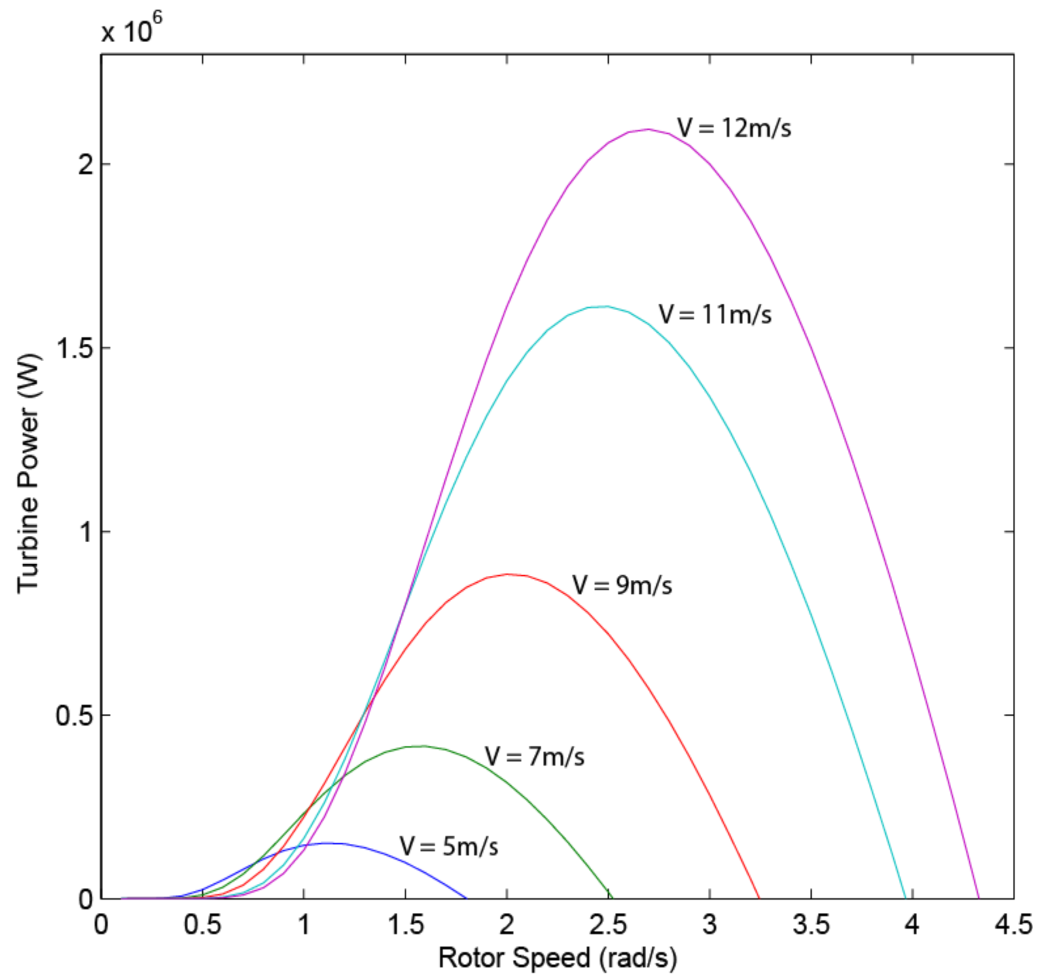
Windings are placed in slots in the stator steel and distributed between many slots around the circumference for better use of space and better cooling

Power as a function of Turbine Speed

If we "de-normalise" the power curves, that is, don't plot against λ but against turbine speed, ω, we get a family of curves

For each wind speed we need to use a different rotational speed to achieve the maximum power (maximum C_P)

This is the case for "variable speed" wind turbines.

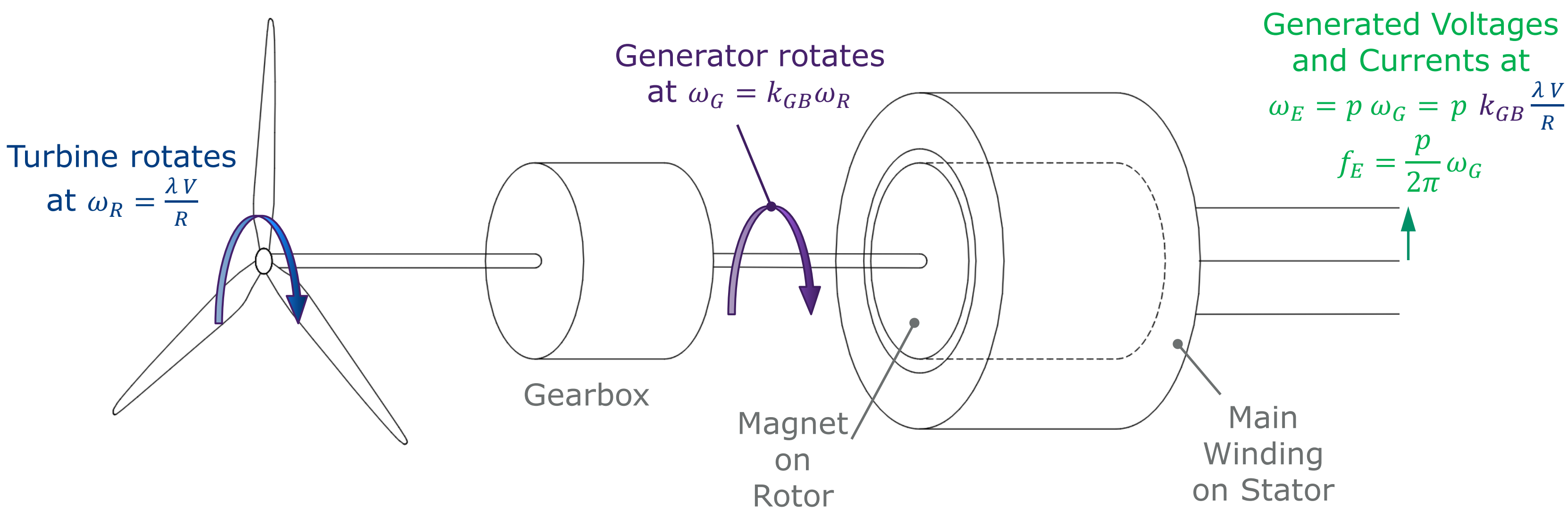


Interfacing a Variable-Speed Generator

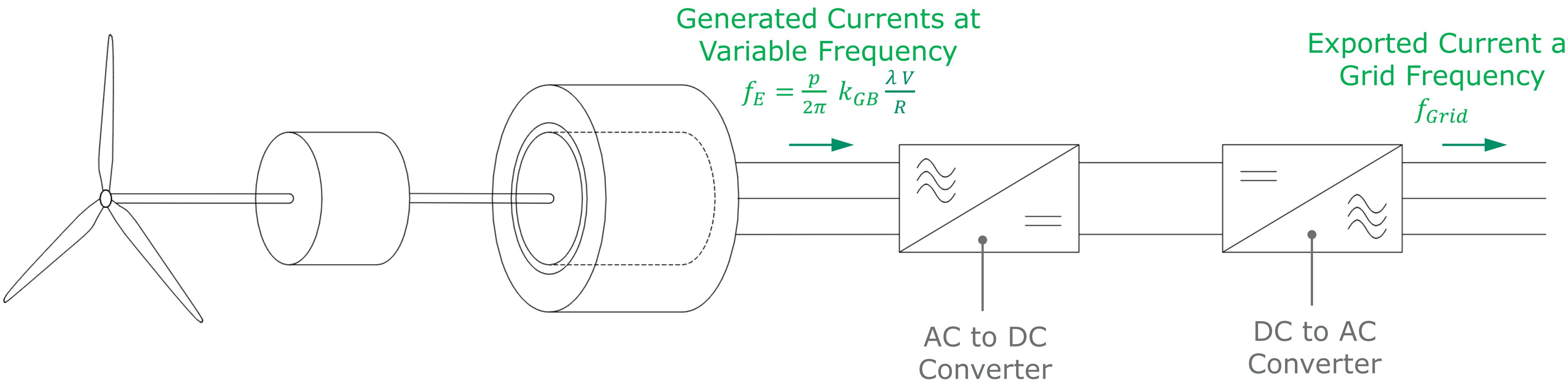
Grid frequencies are (very nearly) constant at either 50 or 60 Hz and conventional (synchronous) generators spin at a speed that matches this frequency (e.g. 3,000 rpm for 50 Hz).

We need to run a wind turbine at variable speed, not constant speed, in order to maximise the power yield and thus a generator driven by a wind turbine will generate at variable frequency.

To match the frequency we can rectify the generator output to DC and then invert the DC at grid frequency.



Full-Converter Interface

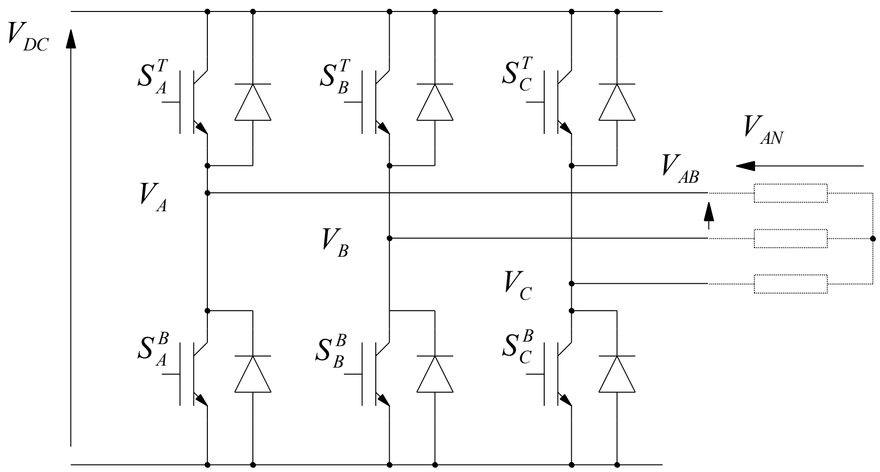


This arrangement is known as a **full-converter interface**: all of the generated power is passed through a power converter uses high-voltage, high-current transistors to process the power and change its frequency.

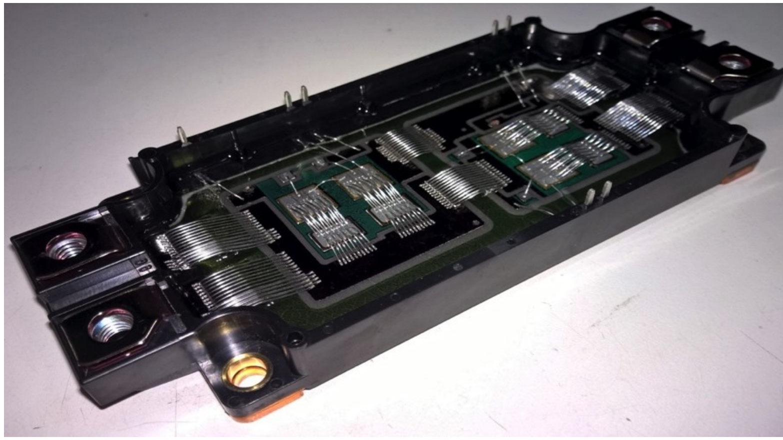
In fact there are two power converters. The first rectifies the variable frequency AC from the turbine to produce DC. The second inverts DC to produce AC of the same frequency as the grid (nominally 50 or 60 Hz).

The power converters are large, costly and produce power losses of maybe 1 - 2% in each. This cost is more than offset by the ability to optimise the aerodynamic efficiency of the turbine.

The Three-Phase Inverter



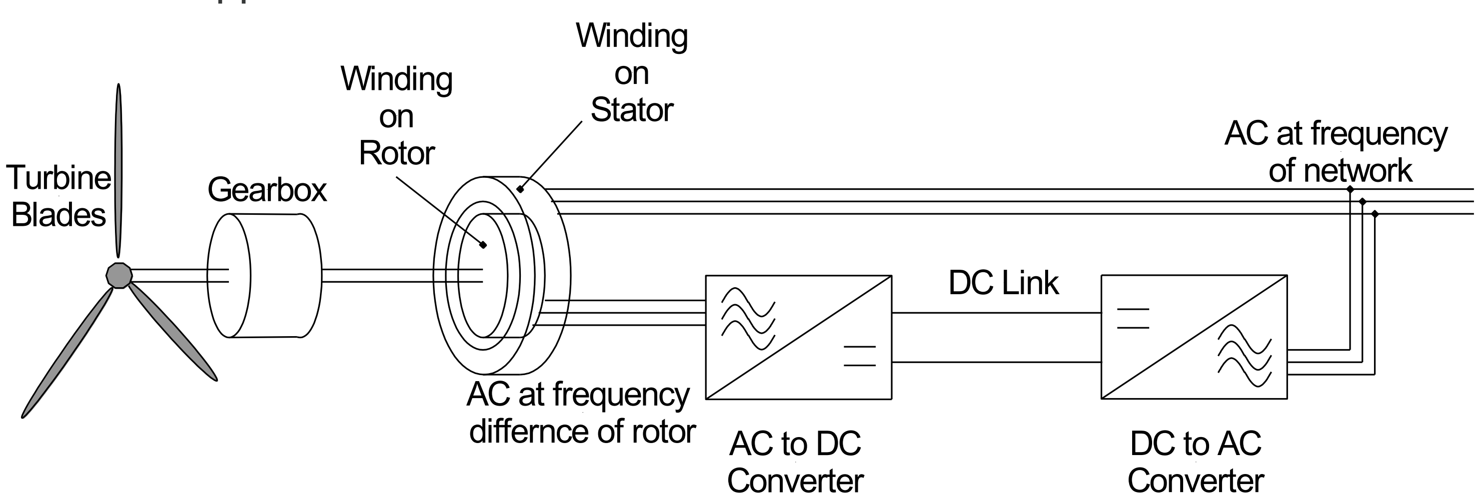
A DC/AC power converter (inverter) uses power transistors to switch the DC voltage to create pulses. Two switches (and diodes) are needed for each AC connection, or phase. This circuit has 3 phases.



The transistors are insulated-gate bipolar transistors (IGBT). Typically they are made as dies (chips) of about 1 -2 cm^2. Several can be connected in parallel to give current ratings up to about 2,000 A. Maximum voltage rating is currently about 4,500 V.

Limited Speed Range

- Compared to other electric machines, wind turbines operate with a rather small range of rotor speeds. A cut in speed of 4 m/s and a base speed of 12 m/s (after which the generator speed is held constant) requires a generator speed range of 3:1.
- The **doubly-fed induction generator** (DFIG) is suitable for limited speed range.
- In a DFIG the rotor is supplied with low frequency AC not DC. This creates a magnetic field on the rotor that rotates a bit faster or a bit slower than the physical rotation of the rotor.
- For instance, if rotor is rotating at 40 rev/s, and we want 50 Hz induced voltages in the stator, we need to make the magnetic field spin 10 rev/s faster than the rotor and so we supply the rotor with a voltage at 10 Hz. This difference frequency is known as the "slip" frequency.
- The rotor is supplied via an AC/DC/AC converter



Operation of Doubly-Fed Induction Generator

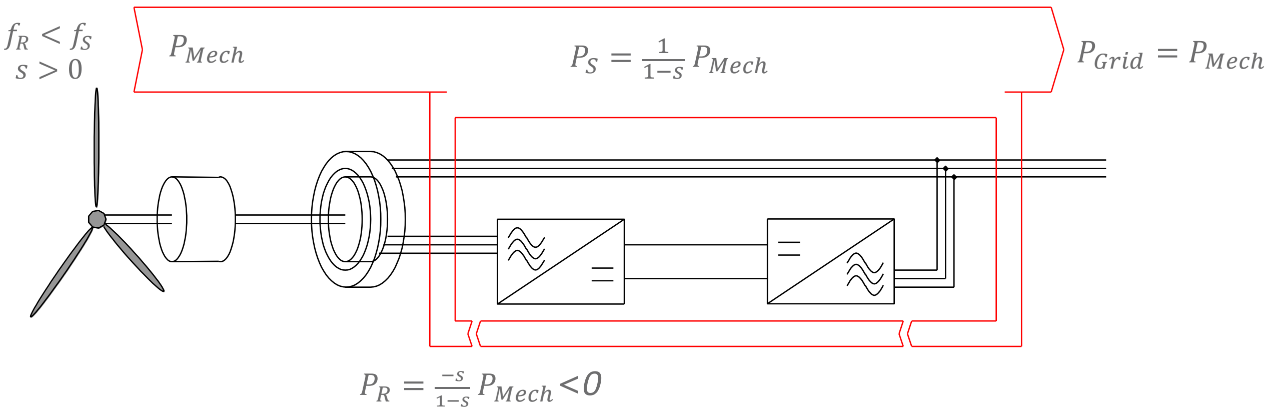
- The mechanical power is processed through both the stator and the rotor
- When turbine is slower than 50Hz (equivalent), power must be injected to the rotor while creating the faster magnetic field (negative P_R).
- When turbine is faster than 50Hz (equivalent), power must be extracted from the rotor while creating the slower magnetic field (positive P_R).
- The amount of power processed through the power converters is proportional to the speed difference expresses in normalised terms, the "slip", s.

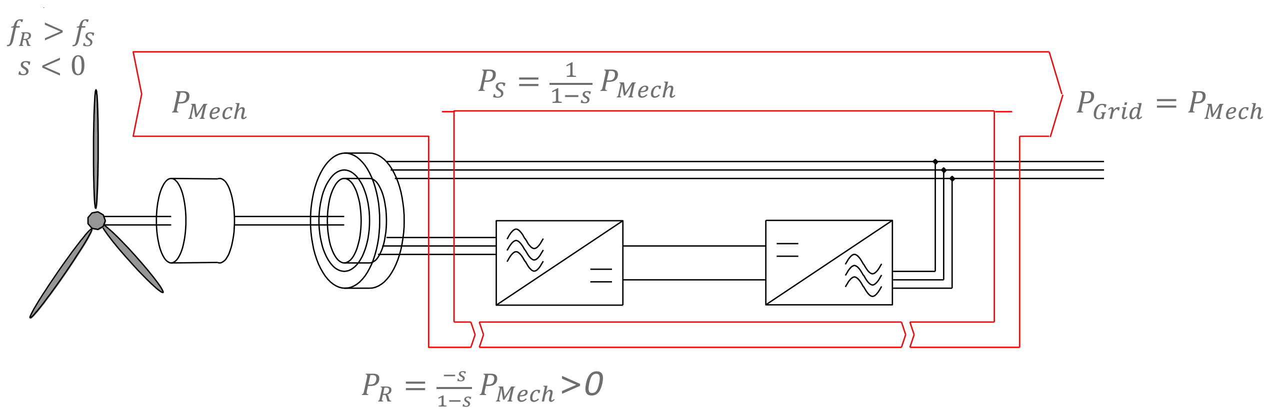
$$P_{Mech} = P_S + P_R$$

$$f_{slip} = f_S - f_R$$

$$s = \frac{f_S - f_R}{f_S}$$

$$P_R = -s\, P_S$$





Choosing s and power rating

For a 3:1 speed range we need f_R to range from say 0.5 to 1.5 f_S.

So, $s = \pm 0.5$

Power converters are rated at 50% of the stator power

This is 0.5/1.5 = 33% of the total power output capability of the turbine

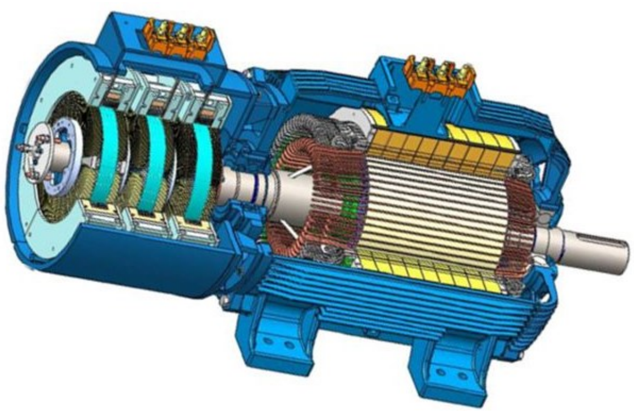
Thus the power converters are 33% of the size used in a full-converter design

Comparison of Full-Converter and DFIG

- DFIG uses converters of about 33% of the power rating of the full-converter.
- Roughly speaking one might expect the DFIG converters to be 33% of the cost, 33% of the physical size and 33% of the power loss of those of the full-converter.

- Power converters of 33% rating allow a 3:1 speed range. To obtain a lower cut-in speed or a higher base-speed means increasing the rating and loosing some of the advantage. A full-converter can work from cut-in at 2.5 m/s to rated at 15 m/s (6:1 speed range) without a penalty.

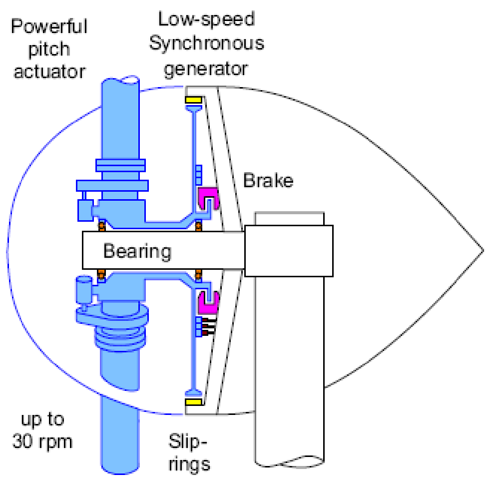
- The DFIG requires slip-rings and brushes to connect to the rotor that are rated at 33% of the power. These are difficult, high-maintenance items. The full-converter requires no slip-rings/brushes if it uses permanent magnets on the rotor and only small ones if using an electro-magnet.



- The partially-rated power converters are unable to control the rotor (and stator) currents during a short-circuit fault on the AC grid and so fault ride-through is problematic.

Gearbox vs. Direct Drive

- Gearboxes are used to convert the slow rotation of the turbine to a higher speed that suits a generator. However, the gearboxes are large and challenging to design given the high level of torque shocks from wind gusts.
- **Direct drive** uses full-converter designs and the freedom to operate at any speed means they do not use a gearbox between the turbine and the generator.
- The generator's low speed means that it must be very high torque to deliver the power. This is achieved with a very large diameter generator.
- The weight of generator is reduced by using an annular structure and a supporting frame



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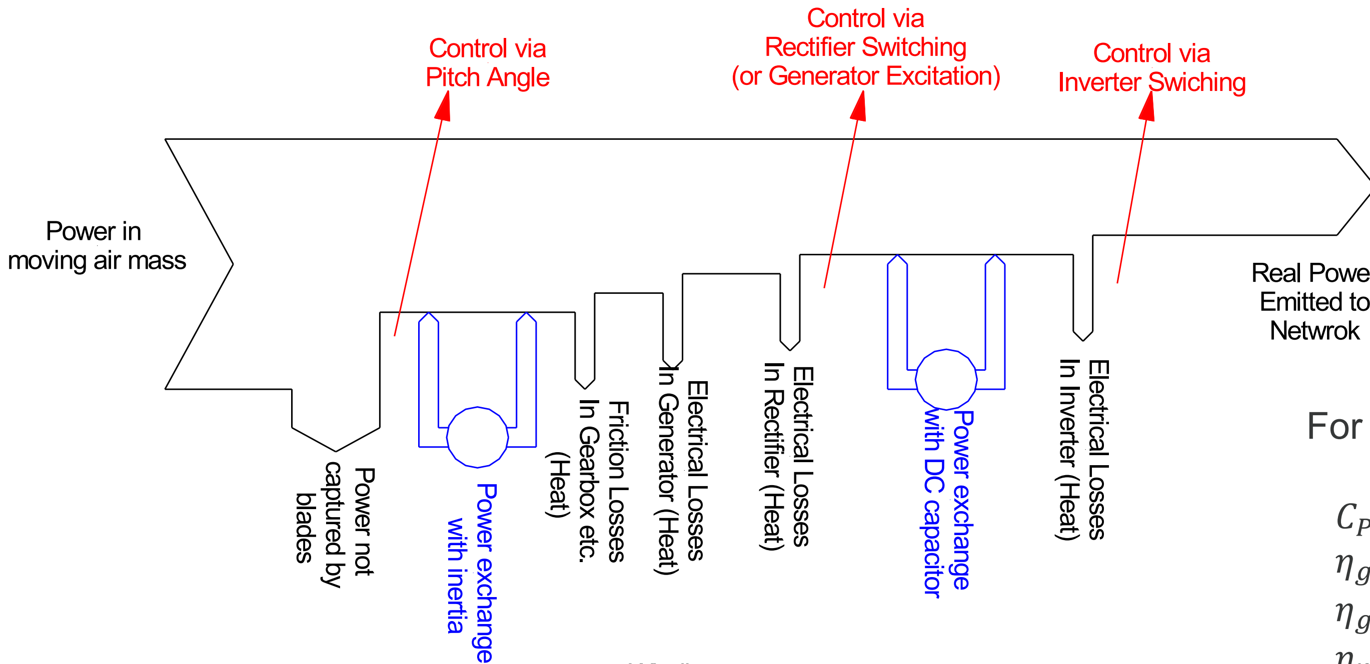
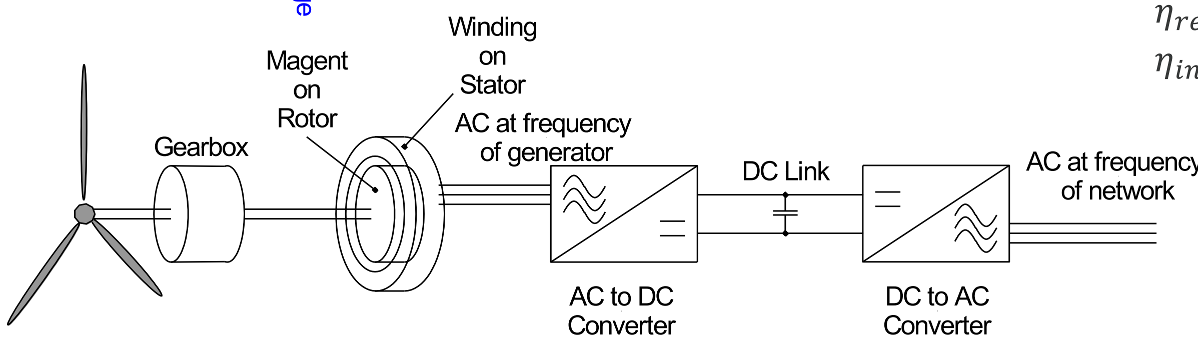
Turbine Drive Train Efficiency





For MW-scale machines, the excepted efficiencies are:

$C_P \simeq 0.45 - 0.55$

$\eta_{gear} \simeq 0.87 - 0.97$

$\eta_{generator} \simeq 0.87 - 0.97$

$\eta_{rectifer} \simeq 0.97 - 0.99$

$\eta_{inverter} \simeq 0.97 - 0.99$

$$P_{out} = P_{blade}\ \eta_{gear}\ \eta_{generator}\ \eta_{rectifer}\ \eta_{inverter}$$

Where $P_{blade} = ½\, C_P\, \rho\, A\, V^3$ and C_P here is for the set of turbine blades alone

C_P can also be defined for combined drive train and blades as $C_P^{sys} = {}^{P_{out}}/_{½\,\rho\, A\, V^3}$

Drive Train Control

- The principal task of the turbine control system is to optimise or limit the power absorbed by the turbine

- The flow of the power through the drive train then needs to be managed

- If the energy input (minus losses) does not match the energy output at each stage (and overall) then something will suffer a rise/fall in stored energy:
  - The turbine may absorb any energy not exported in its inertia; too much would cause an over-speed failure
  - The DC-link may absorb energy not exported in its capacitance; too much would cause and over-voltage failure

- A coordinated set of controllers is needed with references set for exported power, turbine speed and DC-link voltage

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Further Turbine Control Functions

- **Yaw control:** wind direction must be assessed, and the yaw actuators used to rotate the turbine to face into the wind
- **Ramp rate:** rapid fluctuations of torque and power are not good for the turbine or grid. Control references are smoothed
- **Oscillation damping:** the mechanical structure is subject to pulsating forces (such as tower-shadow) and mechanical resonances need to be damped by adding terms to the generator’s power/torque references
- **Noise control:** certain combinations of operating condition (blade pitch and speed) are avoided to reduce acoustic noise. This applies only to on-shore wind turbines