UNIVERSITÀ DI TRENTO

DEPARTMENT OF
INDUSTRIAL ENGINEERING

Renewable Energy Conversion Systems

Lecture 7

Prof. Elisabetta Tedeschi

MSc Degree in Mechatronic Engineering,
Academic Year 2024-2025

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Co-lecturer for the course

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Lecture 5: Outline

Main topic:

Wind Energy Conversion Systems:
electro-mechanical conversion and power electronic conditioning

- Electro-mechanical conversion and power electronic conditioning in wind turbines
- Wind turbines' classification
- Electric generator's choice for wind turbines
- Power converters' choice for wind turbines
- Basics of electrical machines used in wind turbines: focus on the permanent magnet synchronous generator

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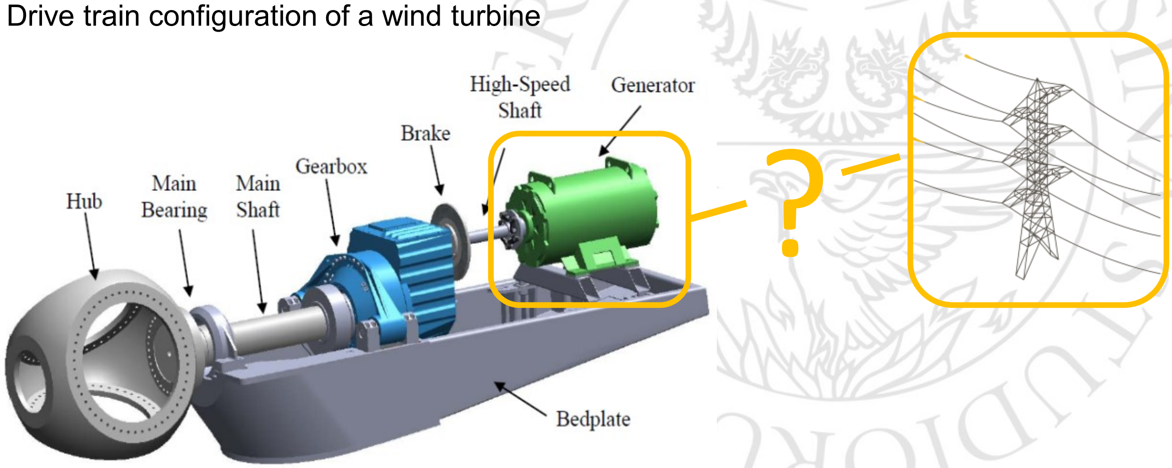
Electro-mechanical energy conversion in a wind turbine

Drive train configuration of a wind turbine



Source: F. Oyague, NREL

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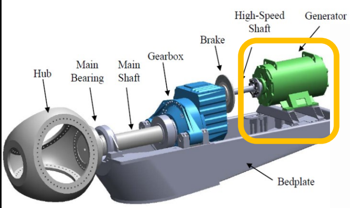
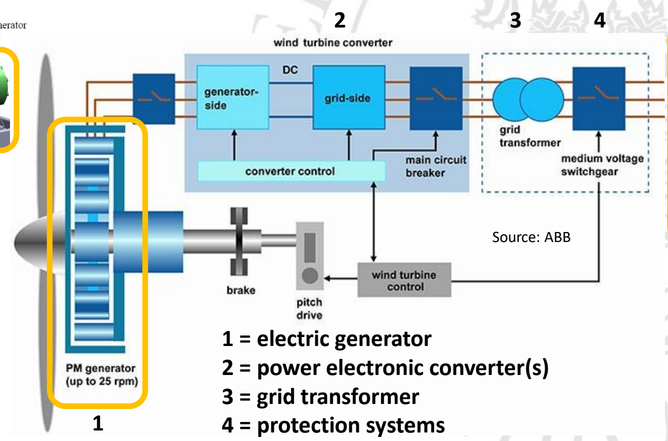
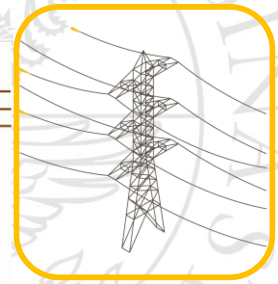
Electro-mechanical energy conversion in a wind turbine

Drive train configuration of a wind turbine







1 = electric generator
2 = power electronic converter(s)
3 = grid transformer
4 = protection systems

Source: F. Oyague, NREL

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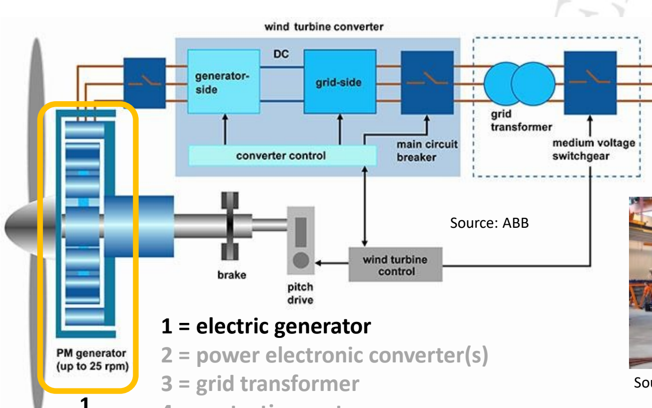
Electro-mechanical energy conversion in a wind turbine

Drive train configuration of a wind turbine



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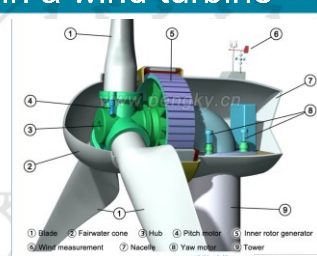
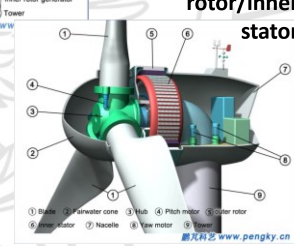


Inner rotor/outer stator

Source: The Switch



Outer rotor/inner stator

Electric generator performs the electro-mechanical conversion

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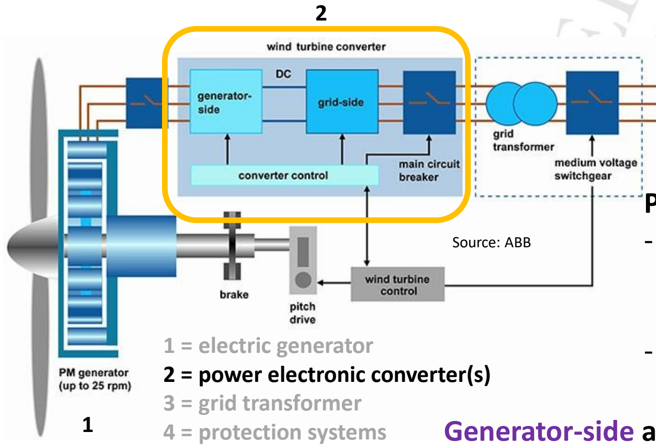
Electro-mechanical energy conversion in a wind turbine

Drive train configuration of a wind turbine



Power electronics is needed for a twofold goal:

- **To regulate torque and speed on the electric generator, to optimize the wind power extraction**
- **To make voltage and current waveforms compliant with the electric grid**

Generator-side and grid-side converters can be distinguished

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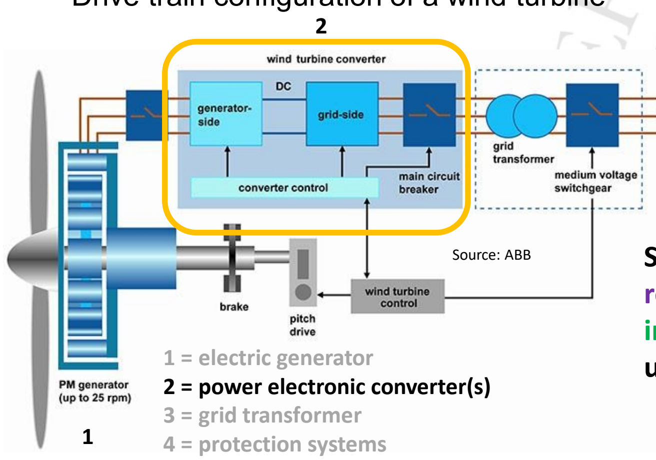
Electro-mechanical energy conversion in a wind turbine

Drive train configuration of a wind turbine



Switching converters, typically including a rectifier (i.e., AC to DC converter) and an inverter (i.e., DC to AC converter) are typically used

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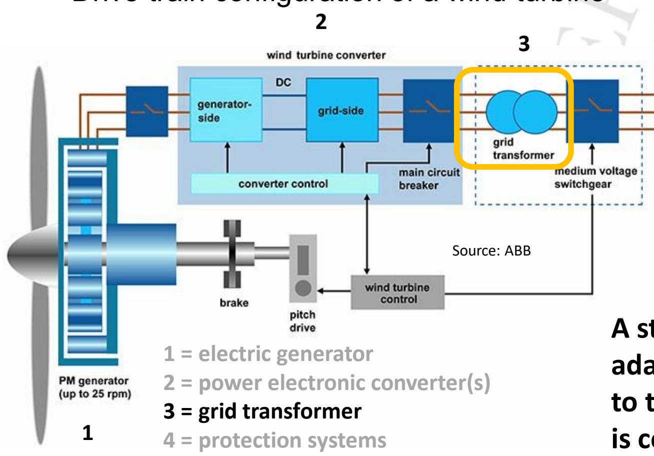
Electro-mechanical energy conversion in a wind turbine

Drive train configuration of a wind turbine



1 = electric generator
2 = power electronic converter(s)
3 = grid transformer
4 = protection systems

Source: ABB

A step-up voltage transformer is required to adapt the voltage level of the electric generator to the one of the electric grid to which the WT is connected

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Electro-mechanical energy conversion in a wind turbine

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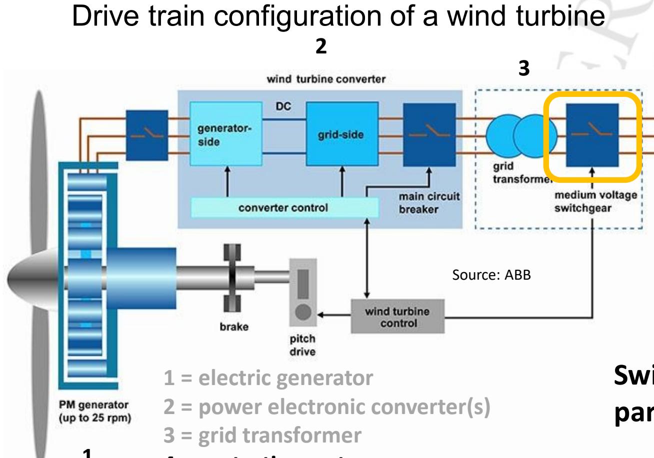

1 = electric generator
2 = power electronic converter(s)
3 = grid transformer
4 = protection systems

Source: Schneider Electric

Switchgears are required to isolate different parts of the system in case a fault occurs

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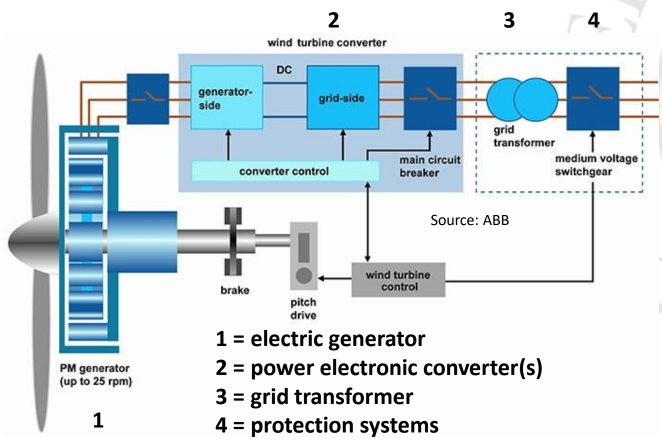
Electro-mechanical energy conversion in a wind turbine

Drive train configuration of a wind turbine



1 = electric generator
2 = power electronic converter(s)
3 = grid transformer
4 = protection systems

Different types of generators and power converters are used, their choices are typically interdependent and evolved over time

Wind turbine solutions without any power electronics are not in use anymore

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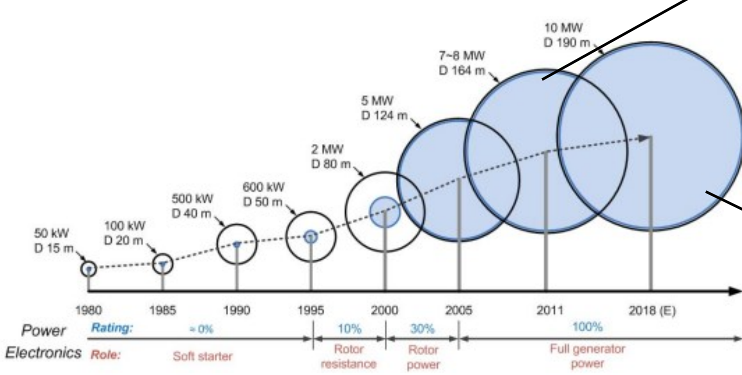
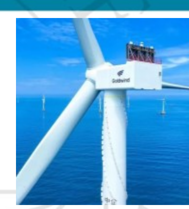
Electro-mechanical energy conversion in a wind turbine

Wind turbine evolution over time



Source: Blabjeerg and Ma (2013)

Vestas V164, 9.5 MW (2017)



Goldwind, 16 MW (2023)

GE Haliade, 12, 13, 14 MW(2020-)

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Wind turbines' classification

Wind turbines are typically categorized in 4 different «types», depending on what kind of combination generator/power electronic interface (if any) that they use

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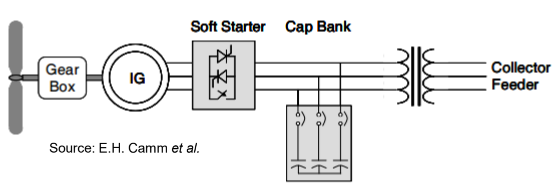
Wind turbines' classification

Type 1 wind turbine generator (WTG)



Source: E.H. Camm *et al.*

Type 1 WTG:
Direct connected
Induction Generator (IG)

- **Use of squirrel case induction generator (for its robustness)**
- **Soft starters are used for start-up**
- **The IM is directly connected to the grid: hence the wind turbine is forced to work at an almost fixed speed (slip between -0.01 and ~0) compatible with the nominal frequency of the local network. This reduces the efficiency of this configuration**
- **It requires capacitors to supply reactive power**

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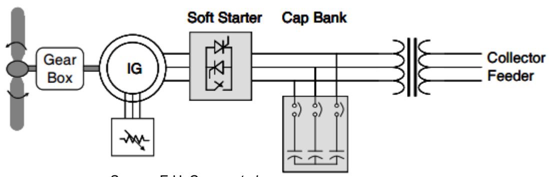
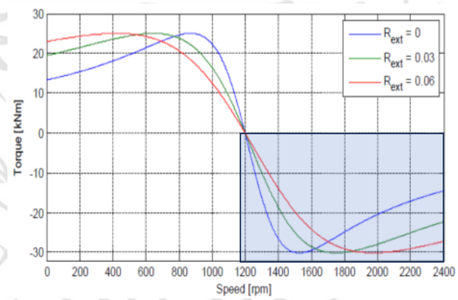
Wind turbines' classification

Type 2 wind turbine generator (WTG)



Source: E.H. Camm *et al.*

Type 2 WTG:
Direct connected induction generator (IG) with variable rotor resistance



- **Similar to Type 1 WT, but with (wounded rotor and) variable rotor resistances**
- **The IG is still directly connected to the grid. The rotor resistances allow to obtain the nominal torque at different speeds**
- **The objective is to maximise power extraction from the wind and prevent the power extracted from exceeding the machine's ratings**

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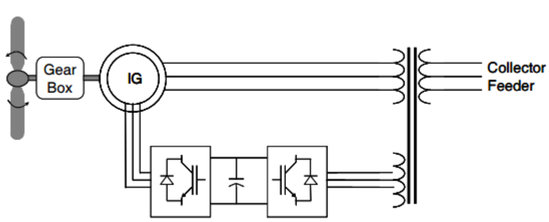
Wind turbines' classification

Type 3 wind turbine generator (WTG)



Source: E.H. Camm *et al.*

Type 3 WTG: Doubly-fed Induction generator with partially rated power electronic converters

- **Doubly-fed induction generator (DFIG) is derived from wounded-rotor IG**
- **The stator has the same 3-phase arrangement as in conventional IG**
- **The 3-phase wounded rotor is externally supplied (through slip rings) by a power electronic (PE) converter**

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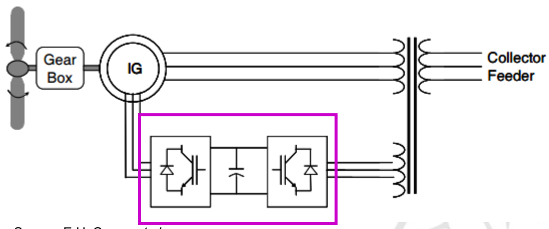
Wind turbines' classification

Type 3 wind turbine generator (WTG)



Source: E.H. Camm *et al.*

Type 3 WTG: Doubly-fed Induction generator with partially rated power electronic converters

- The power electronic (PE) interface is composed of a back-to-back configuration (i.e. 3-ph controlled rectifier and inverter connected through the DC link)
- The PE interface can actively control the current that is supplied to the rotor, and its frequency, so the speed of the generator can be controlled (normally +/-30% range around the synchronous speed)
- The PE interface can generate reactive power on the grid side (which is required by the stator circuit)

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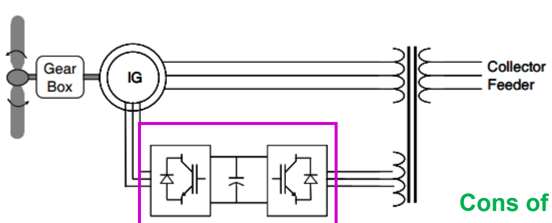
Wind turbines' classification

Type 3 wind turbine generator (WTG)



Source: E.H. Camm *et al.*

Type 3 WTG: Doubly-fed Induction generator with partially rated power electronic converters

Cons of DFIG
More complex structure of the rotor (slip rings)

- Advantages of DFIG
- It allows variable speed operation of the wind turbine
- The power flowing through the converter is a fraction (~30%) of the total power extracted by the wind turbine, thus reducing the cost of the power electronics converter compared to full-scale solution
- Reactive power regulation capability

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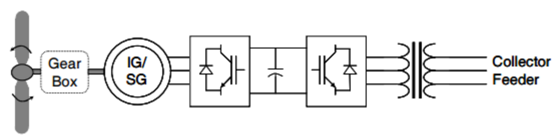
Wind turbines' classification

Type 4 wind turbine generator (WTG)



Type 4 WTG: Full scale back-to-back power converter

Source: E.H. Camm *et al.*

- The generator can be either synchronous or asynchronous
- The back-to-back converter processes the full power of the wind turbine
- This ensures full-decoupling of the wind turbine from the electric grid, hence, the possibility of variable speed operation through converter frequency control
- The converter can also provide reactive power on the grid side, if needed

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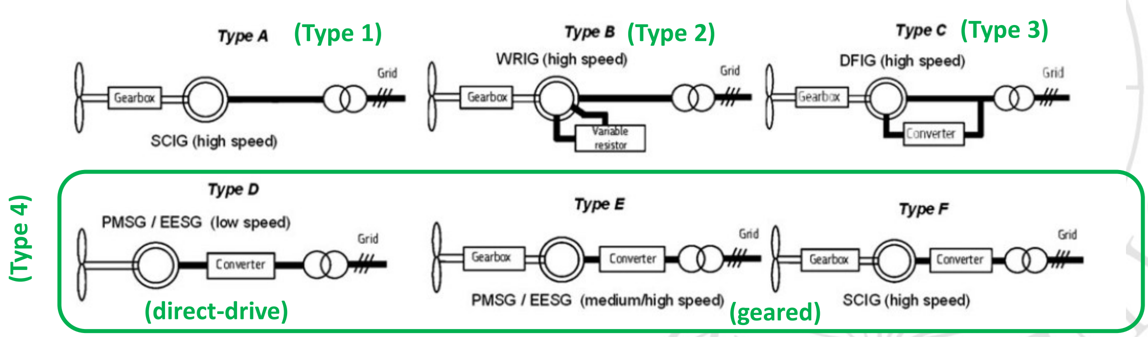
Wind turbines' classification

Extended classification of wind turbine types



Source:J. Serrano-González & R. Lacal-Arántegui (2016)

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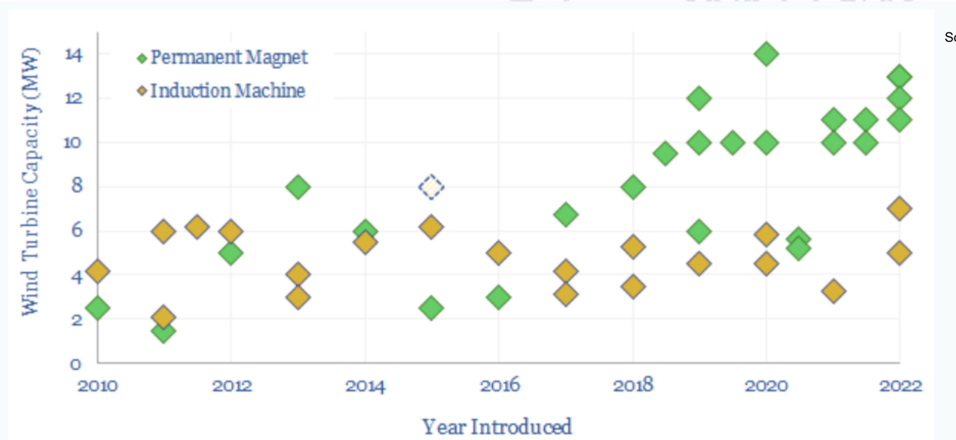
Wind turbine generator’s choice

Use of synchronous vs. asynchronous (i.e., induction) generators



Source:Thunder Said Energy

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Wind turbine generator’s choice

Advantages of different types of generators

(Doubly-fed) Induction generators

- Lower rating of power electronic interfaces (~30% of rated power)
- No use of rare earth material

Direct-drive PMSG

- High efficiency (>96%)
- High reliability due to absence of gearbox
- Lower maintenance requirement that in DFIG and G-PMSG
- No need for rotor power supply

Geared PMSG

- High efficiency (>96%)
- Lower use of rare earth materials than in DD-PMSG
- No need for rotor power supply

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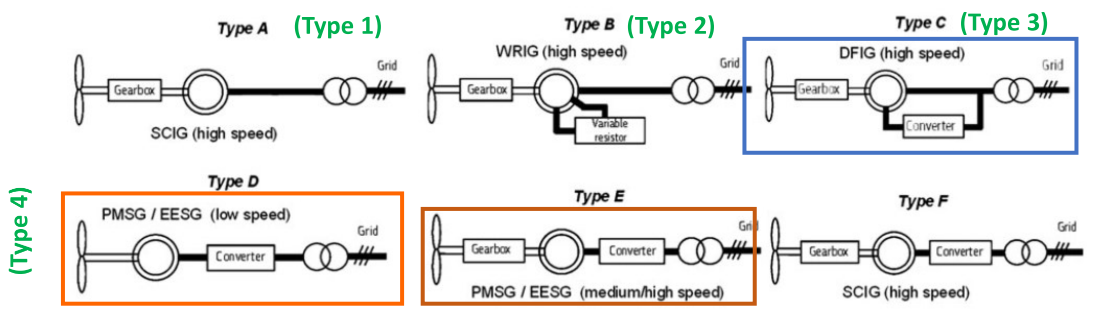
Wind turbine generator’s choice

Extended classification of wind turbine types



Source:J. Serrano-González & R. Lacal-Arántegui (2016)

Doubly-fed induction generators (DFIG) are still dominating the market, **but solutions with fully rated power converters are eroding this supremacy.** Direct drive solutions prevail in the high-power range (6-7 MW), but 20% of the European market is already covered by geared medium speed drive

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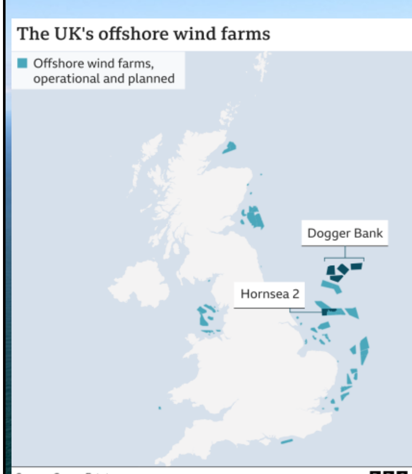
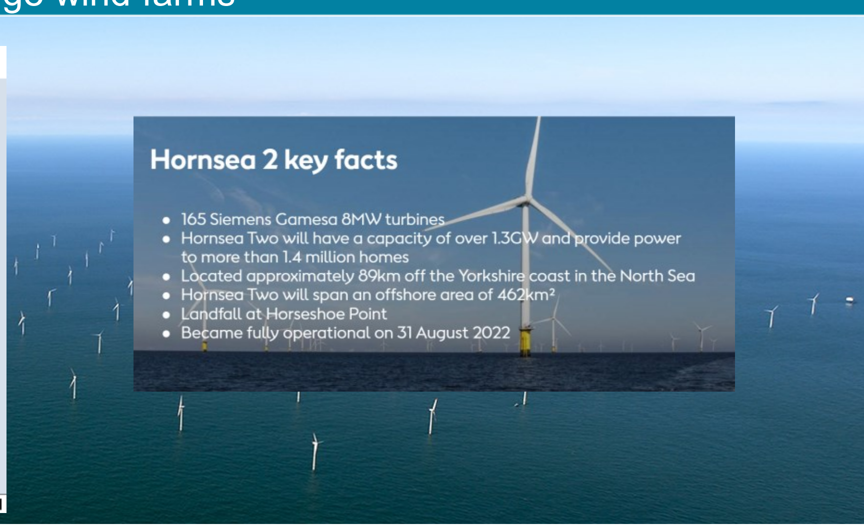
Wind turbines in large wind farms





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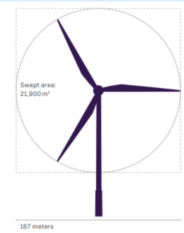
Wind turbines in large wind farms

Wind turbines used in HornSea 2:
Siemens Gamesa SG 8.0-167 DD

Gearbox: - (direct-drive)
Generator: PM synchronous gen.
Generator voltage: 690 V



SG 8.0-167 DD	
Nominal power	8,000 kW
Rotor diameter	167 m
Blade length	81.4 m
Swept area	21,900 m²
Hub height	Site specific
Power regulation	Pitch-regulated, variable speed

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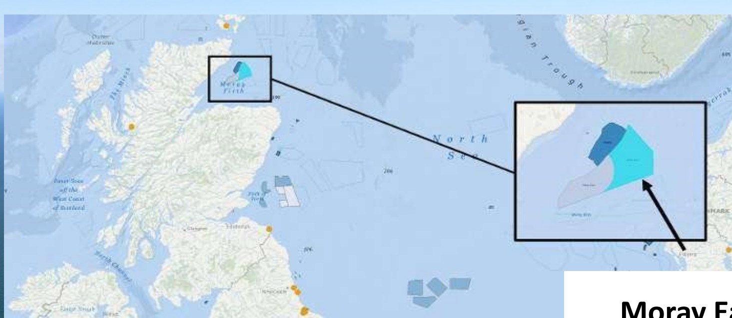
Wind turbines in large wind farms



Moray East wind farm

- 100 Vestas 9.5 MW turbines
- Located the Moray Firth off the coast of Scotland.
- Commissioned in April 2022

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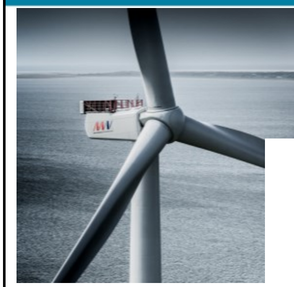
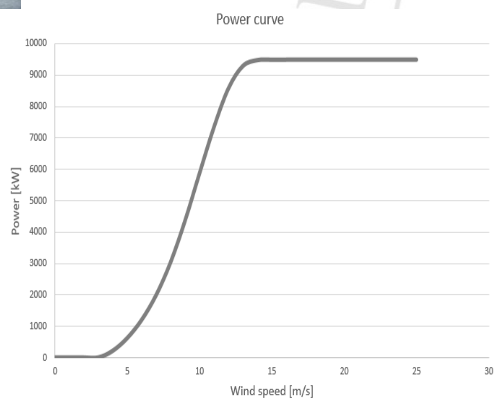
MHI Vestas Offshore V164-9.5 MW





IECRE

IECRE - IEC System for Certification to Standards Relating to Equipment for Use in Renewable Energy Applications

Certificate No.
IECRE.WE.CC.18.0003-R0

COMPONENT CERTIFICATE
Wind Turbine

Machine parameters:

Power regulation:	Pitch-controlled
Rotor orientation:	Upwind
Number of rotor blades:	3
Rotor tilt:	6°
Cone angle:	-6°
Rated power:	9525 kW
Rated wind speed V_r:	12.4 m/s
Rotor diameter:	164 m
Hub height(s):	Reference HH 107 m, please see interfaces below
Hub height operating wind speed range $V_{in} - V_{out}$: Max Storm (High Wind Operation) derating linearly to 4.3 MW at 31 m/s:	3-31 m/s 25-31 m/s
Design life time:	25 years
Software version:	17.08

Wind conditions:

Characteristic turbulence intensity I_{ref} at V_{hub} = 15 m/s:	0.14
Annual average wind speed at hub height V_{ave}:	10 m/s
Reference wind speed V_{ref}:	50 m/s
Mean flow inclination:	0°
Hub height 50-year extreme wind speed V_{e50}:	70 m/s

Electrical network conditions:

Normal supply voltage and range:	Nominal grid voltage: 33, 34, 66 kV
Normal supply frequency and range:	50Hz
Voltage imbalance:	2%
Maximum duration of electrical power network outages:	Not dimensioning
Number of electrical network outages	50

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MHI Vestas Offshore V164-9.5 MW

Gearbox:

Type:	3 stage planetary differential gearbox
Gear Ratio:	1:38.03
Manufacturer:	ZF
Drawing / Data sheet / Part No.:	GPC 842.0 D

Yaw System:

Drive Type:	10 electrical yaw motors incl. gearbox and motor brake
Manufacturer:	Lafert
Drawing / Data sheet / Part No.:	29020308 (motor), Rev. 0
Bearing Type:	Slide bearing
Manufacturer:	MHI Vestas Offshore Wind A/S
Drawing / Data sheet / Part No.:	300010675 (support beam machined), Rev. 0
Gear Type:	Internal ring gear
Manufacturer:	Comer Industries
Drawing / Data sheet / Part No.:	29031015 (yaw gear), Rev. 0
Brake Type:	Braking capacity is based on bearing friction and electrically activated friction brake on motors.
Manufacturer:	MHI Vestas Offshore Wind A/S Lafert
Drawing / Data sheet / Part No.:	29004587 (brake), Rev. -

Generator:

Type:	Medium-speed low voltage 3-phase synchronous permanent magnet generator
Manufacturer:	The Switch

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Certificate No.
…18.0003-R0

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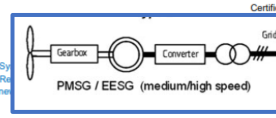

Rated Power:	10 MW
Rated Frequency:	50 Hz
Rated Speed:	400 rpm
Max. speed:	536 rpm
Rated Voltage:	740 V
Rated Current:	9700 A
Insulation Class:	H
Degree of Protection:	IP54
Drawing / Data sheet / Part No.:	PMM1500B09

Converter:

Type:	Full scale converter
Manufacturer:	Vestas Wind Systems A/S
Rated Voltage:	710 VAC machine-side 640 VAC line-side
Rated Current:	2 x 5000 A

Transformer:

Type:	Three-winding three-phase liquid-immersed HV transformer
Manufacturer:	Siemens
Rated Voltage:	Grid voltage: 33 or 34 kV
Rated Power:	9525 kW
Degree of Protection:	IP54
Location:	PCM 1
Drawing / Data sheet / Part No.:	TDU-104K03W6A-99

Transformer:

Type:	Three-winding three-phase liquid-immersed HV transformer
Manufacturer:	ABB Oy Transformers
Rated Voltage:	Grid voltage: 34 or 66 kV
Rated Power:	9525 kW

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MHI Vestas Offshore V164-9.5 M

Gearbox:	
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Brake Type:	Braking capacity is based on bearing friction and electrically activated friction brake on motors.
Manufacturer:	MHI Vestas Offshore Wind A/S Lafert
Drawing / Data sheet / Part No.:	29004587 (brake), Rev. -
Generator:	
Type:	Medium-speed low voltage 3-phase synchronous permanent magnet generator
Manufacturer:	The Switch

Medium-speed permanent magnet generators

The Switch PM generators can easily be adapted to various operational points. All generators are also available for medium voltage.

Technical specifications	PMM 1000	PMM 1500
Power [MW]	2.0 – 6.0	6.0 – 12.5
Speed [rpm]	100 – 600	100 – 500
Shaft height [mm]	1000	1500
Weight[1] [t]	13.3 – 15.6	20.0 – 32.5
Voltage [V]	690 – 750	690 – 750
Current [A]	< 5800	< 12500
Power factor	0.87	0.85
Efficiency[1] [100% load]	97.5	98.0
Efficiency[1] [75% load]	97.3	97.8
Efficiency[1] [50% load]	97.0	97.2
Efficiency[1] [25% load]	96.0	96.5
Protection class	IP54	IP54
Insulation class	F/H	F/H
Thermal class	B/F	B/F
Cooling	Air-to-liquid	Air-to-liquid

[1] Typical values

Please contact us to get precise values for the rated parameters of your turbine.

The exact dimensions depend on the final construction of the unit.

Dimensions	Shaft height (H2) [mm]	Length (L) [mm]	Width (W) [mm]	Height (H1) [mm]
PMM 1000	1000	2515 – 3150	2090	2090 – 2800
PMM 1500	1500	2300 – 2800	2920	2920 – 3800

Rated Power: 9525 kW

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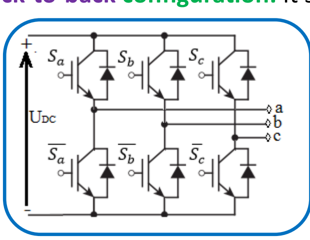
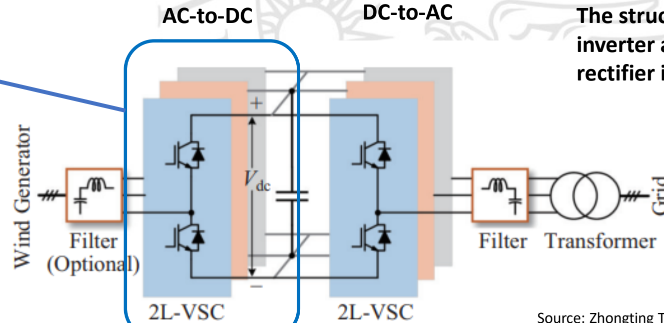
Wind turbine power converters' choice

Power electronic converters for wind turbine applications

Historically, the most used configuration has been the 3-phase, 2 levels Voltage Source Converter in a back-to-back configuration. It's a well-proven, robust, and reliable solution to low-voltage wind power systems



Converters are typically controlled with Pulse Width Modulation (PWM)



The structure of the inverter and the rectifier is the same

Source: Zhongting Tang *et al.* (2022)

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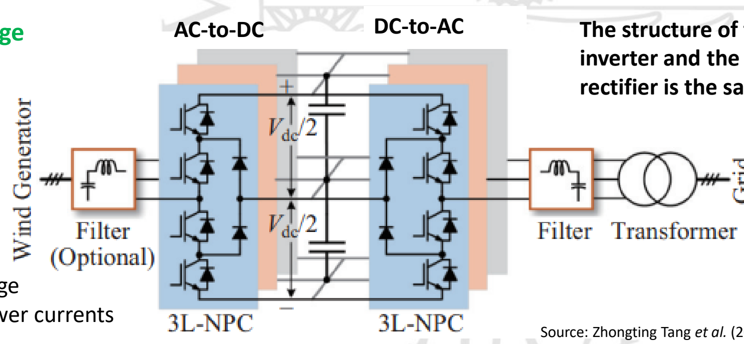
Wind turbine power converters' choice

Power electronic converters for wind turbine applications

With the increase of the power level (> few MW), the 2L-VSC becomes unsuitable due to excess of losses and high distorsion in the AC current/voltage waveforms, requiring bulky filters

Solutions with multi-level Voltage Source Converters are used for higher power WTs

They can achieve less dv/dt stresses on the semiconductor, smaller filter inductors.
Multi-level power converters are suitable to achieve the medium-voltage (MV) level power conversion with lower currents



The structure of the inverter and the rectifier is the same

Source: Zhongting Tang *et al.* (2022)

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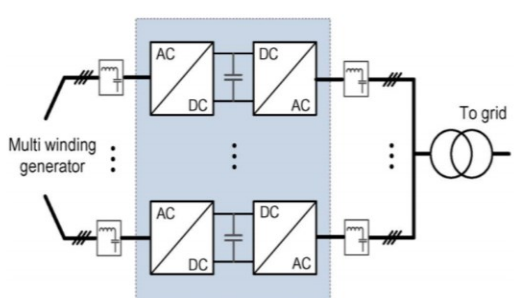
Wind turbine power converters' choice

Power electronic converters for wind turbine applications

In multi-MW wind turbine multiple power conversion lines in parallel can be used.



Source: Blaabjerg *et al.*

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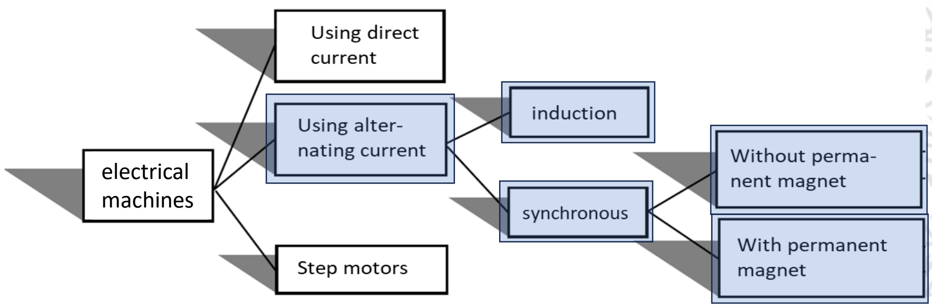
AC generators for WT applications



Source: adapted from Zigliotto

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Basics of AC generators

Electrical machines perform the electro-mechanical conversion exploiting the energy stored in the magnetic field

Both synchronous and asynchronous (i.e. induction) generators base their operation on magnetic induction and the principle of the rotating magnetic field

They also share the same stator structure, while they differ for the rotor structure and working principle

(We will limit our focus to PMSM)

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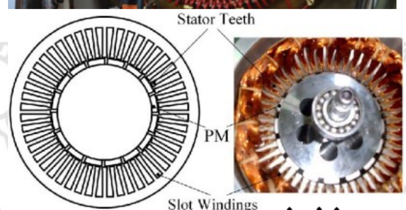
Basics of AC generators

Stator configuration in PMSM (and IM)

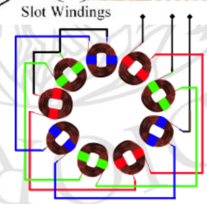
- It is the fixed part of the generator, built of laminated ferromagnetic material.
- Three phase conductors are wounded, being distributed in the stator slots. The 3 phases have the same conductors' number and distribution, but are space-displaced by $2\pi/3$
- They are supplied by 3-phase balanced voltages

Source: https://netaworldjournal.org/



Source: Jang-Young Choi Et al. (2011)

Scheme of 3-phase stator wiring layout



Source: Jimmy of Eirbyte

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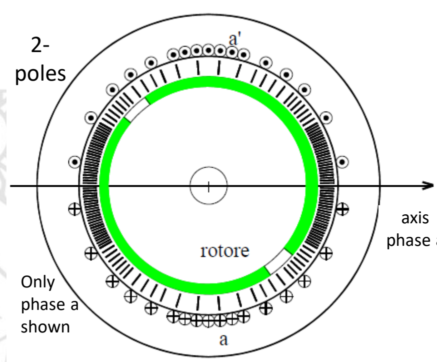
Basics of AC generators

Stator configuration in PMSM (and IM)

- In practice, space distribution of conductors of the same phase is uneven across the stator circumference
- This allows a sinusoidal field distribution (generated based on the Ampere Law) in the airgap of the machine



The same structure must be assumed for phases b and c

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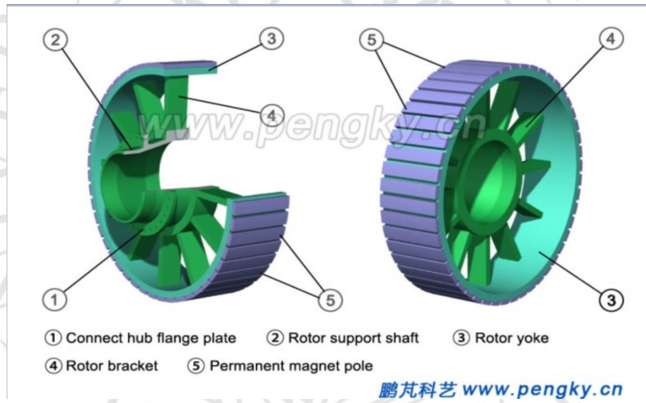
Basics of AC generators

Rotor configuration in PMSM

- it is the rotating part in laminated ferromagnetic material where permanent magnets are hosted. They typically use surface mounted permanent magnets, SM-PMSM, providing magnetic isotropy to the machine



- The magnetic poles in the rotor, coupled in pairs, create a rotating magnetic field crossing the stator winding when the rotor is brought into rotation

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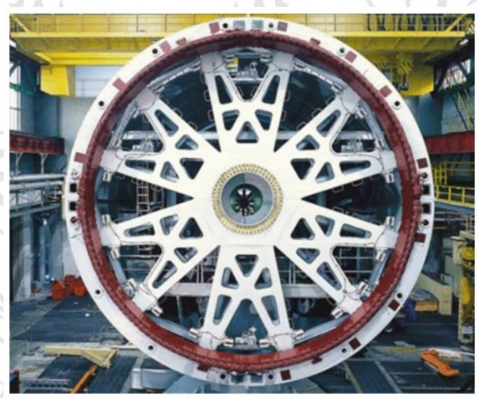
Basics of AC generators

Rotor configuration in EE-SM

- As an alternative to permanent magnets, synchronous generators can be electrically excited, i.e. using electromagnets in the stator supplied by a DC current, which have the same role as PMs in PMSM



EESG in Enercon E-126-7.5 MW
SourceA. Bensala
Et al. (2018)

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Basics of AC generators

(Electro-)Magnetic induction

- According to Faraday's law, an electromotive force (emf, e) will be produced at the terminal of a coil, which is exposed to a time-varying magnetic flux:

$$e(t) = \frac{d}{dt}\lambda(t) = N\frac{d}{dt}\phi(t)$$

- The PM rotation induced by the rotor will hence induce an emf on the stator windings, and being them connected to the power electronic converter/grid, three phase currents will circulate into the stator
- The concurrent presence of voltages and currents in the stator windings is at the basis of the electric power generation (i.e. of the electro-mechanical conversion)

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Basics of AC generators

Rotating Magnetic field

- If we assume a rotation of the rotor at constant angular speed ω_m , due to the geometric distribution of the stator windings across the stator circumference and the (sinusoidal) time-varying currents in the stator windings, the latter will produce a rotating magnetic field at the machine airgap, with rotates at a fixed speed ω_{me}
- Such magnetic field is "locked" to the rotor, i.e., it rotates at the angular speed ω_{me} that corresponds to the angular frequency of the stator currents, which, in turns is dependent on the angular rotating speed of the rotor and the pole pairs of the machine

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Basics of AC generators

Remarks

- The presence of multiple pole pairs (p) in the rotor of the PMSM implies that the angular frequency of the induced fem/currents in the stator winding is proportionally higher than the rotating speed of the rotor
- Hence, in multipole machines, we distinguish the mechanical (rotational) speed of the rotor (ω_m) and the corresponding electrical speed (ω_{me}). In synchronous machines, where the frequency of induced emf/currents (synchronous speed) is strictly proportional to the mechanical speed:

$$\boxed{\omega_{me} = 2\pi f = p\,\omega_m}$$

- Hence the name "synchronous"

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Basics of AC generators

Remarks

- This explains why to be directly connected to the electric grid (f=50 Hz) a synchronous generator must operate a fixed speed

At 50Hz

Number of Individual Poles	2	4	8	12	24	36	48
Rotational Speed (rpm)	3,000	1,500	750	500	250	167	125

- It also clarifies why applications having low mechanical speed, such as direct drive wind turbines, need electrical machines with a high number of poles

$$\boxed{\omega_{me} = 2\pi f = p\,\omega_m}$$

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Video on wind turbine operation

https://www.youtube.com/watch?v=JJr4PIuQp2w

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Thanks for your attention!

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