



ERCOT WOTF Wind Energy 101

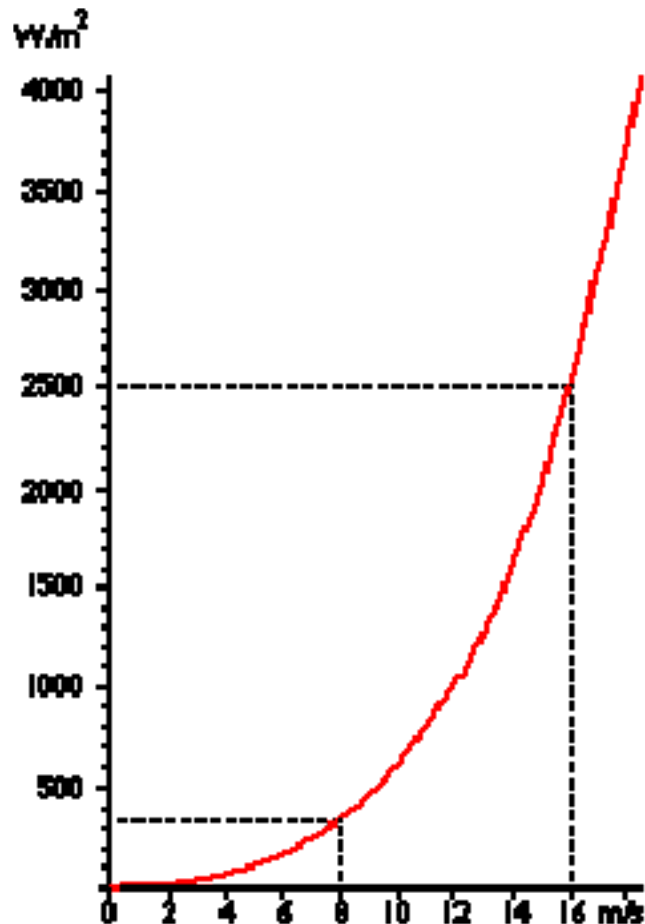
Presented August 22, 2008

By

Robert Sims

AES Wind Generation

The Power of the Wind: Cube of Wind Speed



The energy content of the wind varies with the cube (the third power) of the wind speed, e.g. if the wind speed is twice as high it contains eight times as much energy.

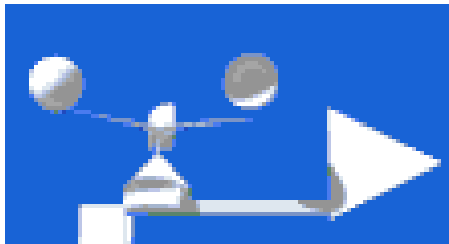
The Ideal Wind Turbine

- The more kinetic energy a wind turbine pulls out of the wind, the more the wind will be slowed down as it leaves the turbine.
- If we tried to extract all the energy from the wind, the air would move away with the speed zero, i.e. the air could not leave the turbine. In that case we would not extract any energy at all, since all of the air would obviously also be prevented from entering the rotor of the turbine.
- In the other extreme case, the wind could pass through the rotor without being hindered at all. In this case we would likewise not have extracted any energy from the wind.

Betz' Law

Betz' law was first formulated by the German Physicist Albert Betz in 1919. Betz' law says that you are limited to a maximum conversion of $\frac{6}{27}$ (or 59%) of the kinetic energy in the wind to mechanical energy using a wind turbine.

Wind Speed Measurement: Anemometers & Wind Vanes



The measurement of wind speeds is usually done using a cup anemometer. The cup anemometer has a vertical axis and three cups which capture the wind. The number of revolutions per minute is registered electronically in a data logger located at the base of the tower.

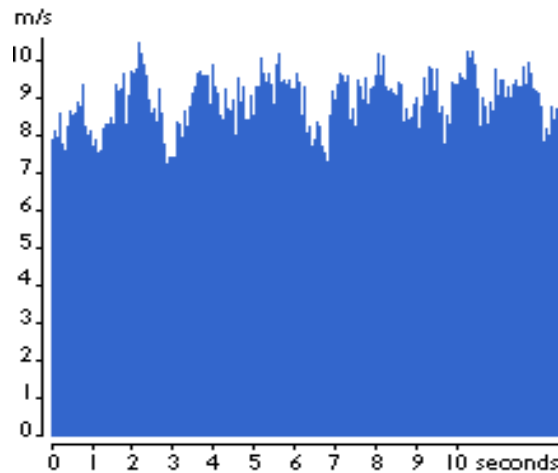


Quality Anemometers are a necessity for wind energy measurement. Inexpensive anemometers are not usable for wind speed measurement since they may be very inaccurate and calibrated poorly. A measurement error of 5 or 10 % from a poor anemometer can result in energy estimate errors as high as 30%.

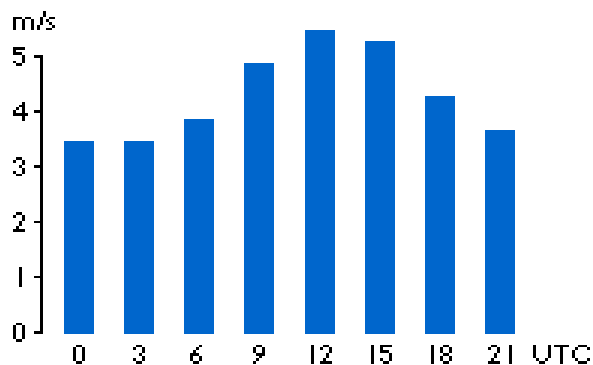
The typical monitoring station is also fitted with a wind vane to detect the wind direction.

Wind speed and direction data is stored on a memory chip and removed monthly or sent via cell phone.

Wind Speed Variability



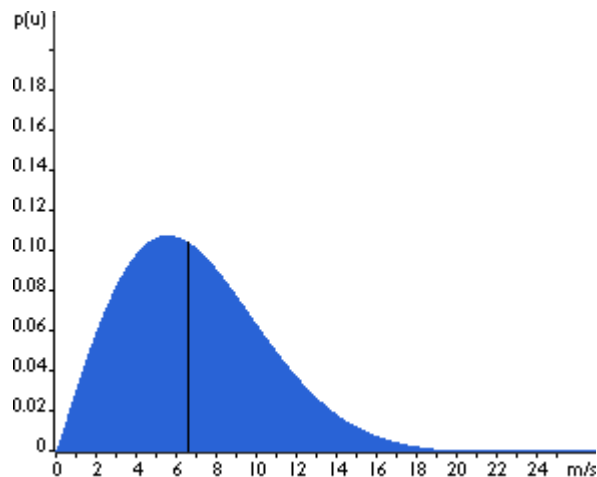
Energy output from a wind turbine will vary as the wind speed varies due to changes in weather and local surface conditions. Much of the very short duration rapid variations will be dampened by the inertia of the wind turbine rotor. Across a large project individual turbine variations will be averaged at the common point of grid connection by the many turbines.



Diurnal (Night and Day) and Seasonal Variations

Energy output will also vary with longer term trends of hours, days and seasons. Measuring and documenting these variation is important in understanding the value of a particular wind resource location.

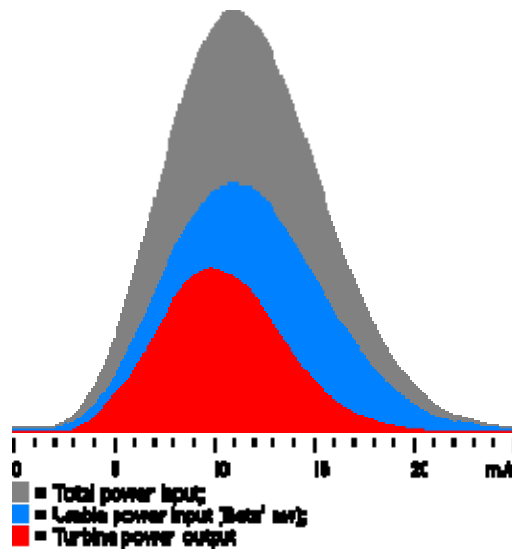
Describing Wind Variations: Weibull Distribution



The Weibull graph is key to understanding the wind speed distribution for a particular site and for the selection of the most efficient and cost effective turbine configuration (IEC Class) for a particular project location.

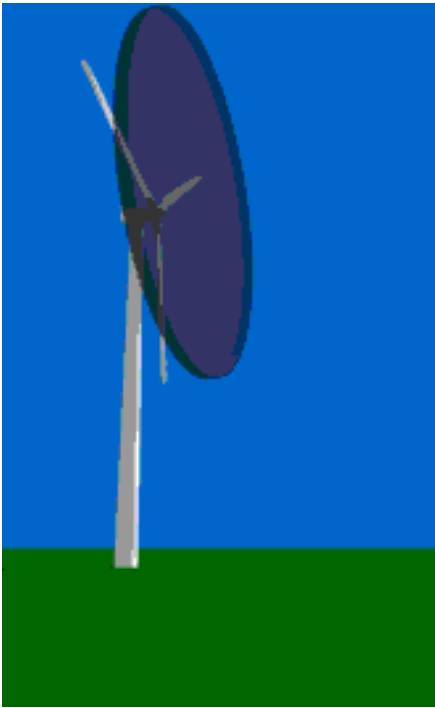
Power of the Wind

The energy potential (the power) varies in proportion to the cube (the third power) of the wind speed, and in proportion to the density of the air. (Its weight per unit of volume).



Gray: Total Potential Wind Power
 Blue, Usable Power (Betz' Law)
 Red: Turbine Power Output

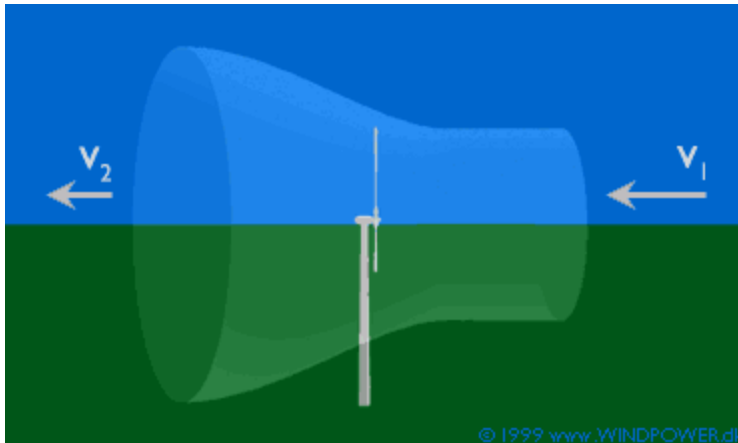
Capturing the Energy: Air Density – Velocity – Rotor Area



A wind turbine obtains its power input by converting the force of the wind into a torque (turning force) acting on the rotor blades. The amount of energy which the wind transfers to the rotor depends on the density of the air, the rotor area, and the wind speed (Velocity).

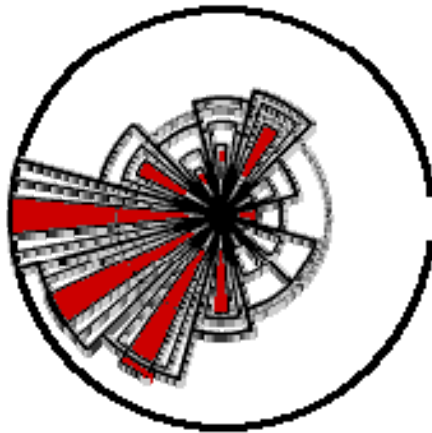
$$\text{Power} = 1/2 (\text{Air Density}) \times (\text{Swept Area}) \times (\text{Velocity})^3$$

Wind Turbines Deflect and Slow the Wind Creating Wake & Turbulence

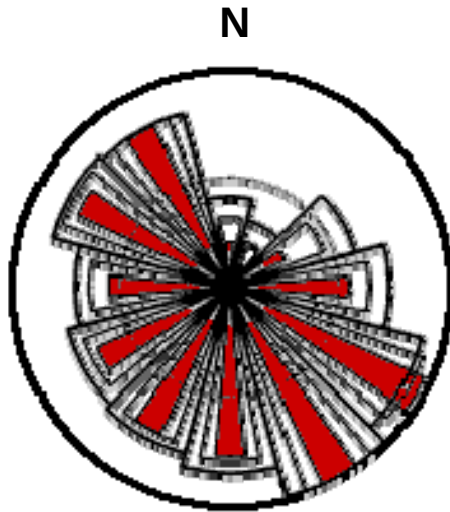


The wind turbine rotor slows down the wind as it captures its kinetic energy and converts it into rotational energy. This means that the wind will be moving more slowly downwind of the rotor than upwind of the rotor. Since the volume of air entering through the swept rotor area must be the same as the amount of air leaving the rotor area to the left, the air will have to occupy a larger cross section (diameter) behind the rotor plane. As the slower air remixes with the higher speed air passing around the rotor significant turbulence is created.

The Wind Rose Diagram

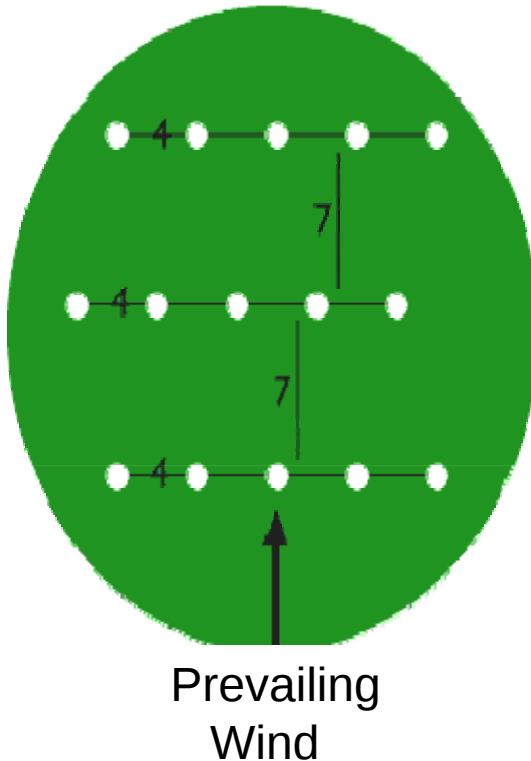


To show the distribution of wind speeds, and wind directions, a wind rose is often prepared based on a long period of the measured wind speeds and directions.



The wind rose is extremely useful for planning the best locations for wind turbines across a project or array to mitigate the losses from wakes and turbulence of up wind turbines.

Cost Effective Project Layout



Each wind turbine slows down the wind behind it as it pulls out energy and converts it to electricity. Ideally, we would therefore like to space turbines as far apart as possible in the prevailing wind direction.

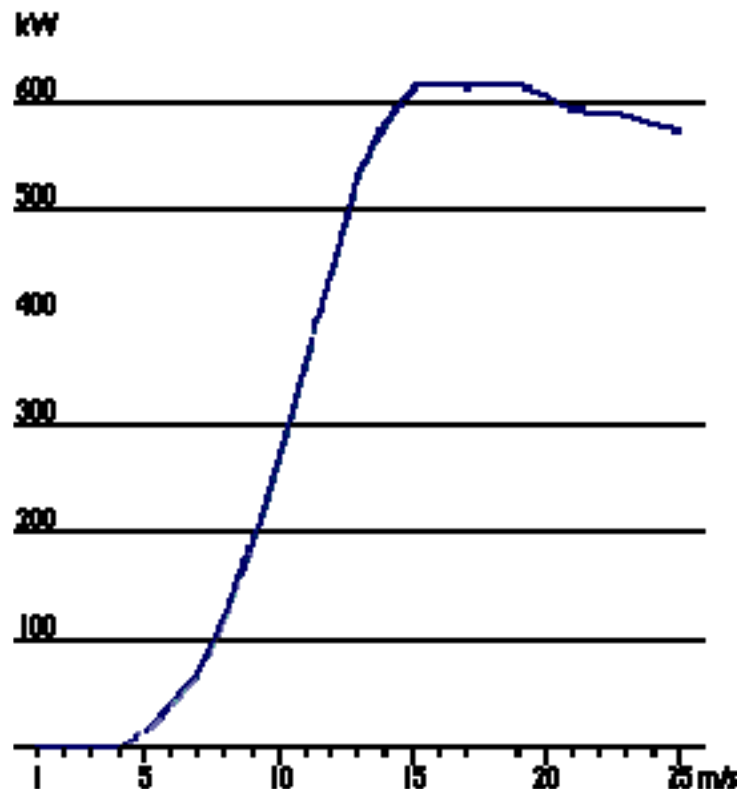
On the other hand, land use, the cost of connecting wind turbines to the power grid and road costs would tell us to space them closer together.

As a rule of thumb, turbines are usually spaced somewhere between 5 and 10 rotor diameters apart in the prevailing wind direction, and between 3 and 5 diameters apart perpendicular to the prevailing winds depending on the Wind Rose data.

With knowledge of the rotor size, wind rose, Weibull distribution, and the roughness in the different directions one can calculate the energy loss due to wind turbines shading one another, typically somewhere around 5%.

The Turbine Power Curve

The power curve of a wind turbine is a graph that indicates the electrical power output for the turbine at different wind speeds.



As part of the acceptance test for a new turbine we normally perform a power curve verification test. This involves the placement of temporary high accuracy anemometer towers immediately up-wind of a selected test turbine to monitor and record wind speeds simultaneously with turbine power output, temperature, & air density over a period of time. The testing is based on a strict IEC procedure.

This graph shows a field measured power curve for a typical Danish 600 kW wind turbine.



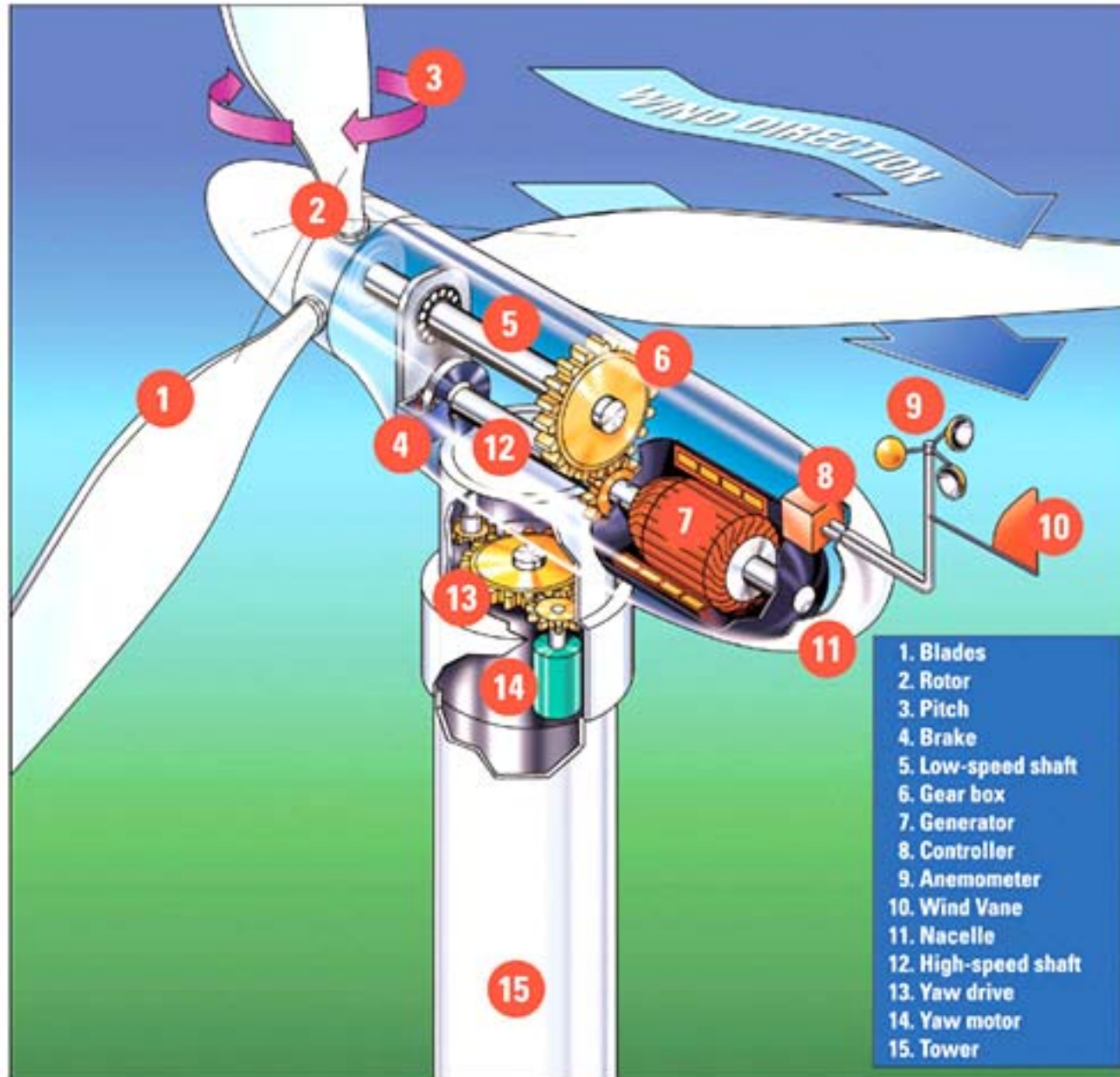
Annual Energy Production

Annual Capacity Factor

A common way of stating the annual energy output from a wind project is the project annual capacity factor. The capacity factor is the actual or estimated annual energy output divided by the theoretical maximum output, (if all the turbines were running at rated (maximum) power for 8760 hours.

Annual Capacity factor can be Gross or Net (Net adjustment for array losses, service down time, electrical collection losses, etc are factored in)

Wind Turbine Components



Wind Turbine Towers

Tubular Towers

Most large wind turbines are supplied with tubular steel towers, which are manufactured in sections of 20-30 meters with flanges at either end, and bolted together on the site. The towers are conical (i.e. with their diameter increasing towards the base) in order to increase their strength and to save materials.



Lattice Towers

Lattice towers are manufactured using welded steel sections similar to a utility transmission line tower. The basic advantage of lattice towers is lower initial cost due to about $\frac{1}{2}$ the steel of a tube tower. due to approximately $\frac{1}{2}$ the steel of a tube tower.



Disadvantages include more maintenance to re-torque the bolts and their visual appearance. Lattice towers have almost disappeared from use for large, modern wind turbines.

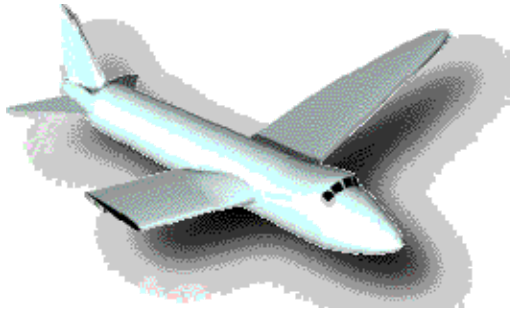
Yaw Control



The wind turbine yaw mechanism is used to turn the wind turbine rotor in to the wind. Most wind turbines use forced yawing utilizing a mechanism which uses electric motors and brakes to keep the turbine yawed against the wind. Almost all manufacturers of upwind machines prefer to brake the yaw mechanism whenever it is unused. The yaw mechanism is activated by the electronic controller that is monitoring the wind vane on the top of the turbine.



Aerodynamics of Wind Turbines:



Lift:

The wind turbine blade actually works like an airplane wing. The high and low pressure areas on the opposite sides of the blade actually push and pull the rotor around in a circle.



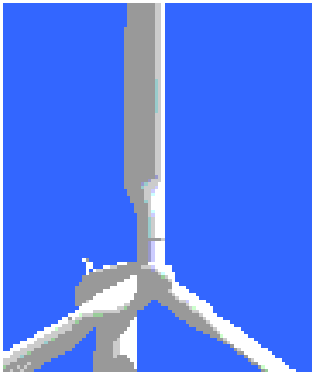
Stall:

When a wing stalls the air flow on the upper surface stops sticking to the surface of the wing. Instead the air whirls around in an irregular vortex (also known as turbulence). All of a sudden the lift from the low pressure on the upper surface of the wing disappears

Turbine Power Control

Stall Controlled Wind Turbines

(Passive) stall controlled wind turbines have the rotor blades bolted onto the hub at a fixed angle. The geometry of the rotor blade profile has been aerodynamically designed to ensure that the moment the wind speed becomes too high, it creates turbulence and loses lift. This configuration was common on turbines < 750 kW thru about 1990.



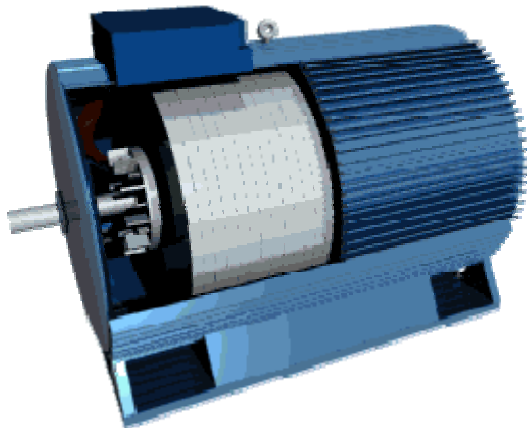
Pitch Controlled Wind Turbines

On a pitch controlled wind turbine the turbine's electronic controller checks the power output of the turbine several times per second. When the power output becomes too high, it sends an order to the blade pitch mechanism which immediately pitches (turns) the rotor blades slightly out of the wind. Conversely, the blades are turned back into the wind whenever the wind speed drops again. During normal operation the blades will pitch a fraction of a degree at a time

Generators

The wind turbine generator converts mechanical energy to electrical energy.

On medium to large wind turbines the voltage (tension) is usually 690 V three-phase alternating current (AC). Although some larger turbines are available with voltages as high as 34.5 kV



The current is subsequently sent through a transformer next to the wind turbine (or inside the tower) to raise the voltage to 20 to 35 kV depending on the voltage of the wind farm collection system.

Design Evolution

1980/90s

- Up to 750 kW
- Stall regulated or variable pitch blades
- Glass-polyester resin
- 1 speed or 2 speed operation
- Asynchronous (induction generators)
- Generator connected to the grid
- Double reduction Gear Box

Today

- Up to 5 MW (1.5 – 2.5 on land)
- Exclusively Variable Pitch
- Epoxy based resins to carbon blades
- Variable Speed operation
- Double fed Asynchronous and Permanent Magnet Generators
- Power electronics used to connect & isolate generator
- Double & Single reduction gear box to direct drive

The debate over which technology combination has the lowest **life cycle cost per KWH is ongoing.**

Four Electrical Wind Turbine Types

1- Direct Connected Asynchronous

- 3 phase asynchronous (induction) generator connected directly across the 60 Hz. line.
- Sometimes configured for two speeds with 4/6 pole operation or two generators
- Absorbs VARs while producing Watts.
- No inherent voltage control capability, tends to pull down voltage as generation increases.
- Switched shunt capacitors used for power factor correction.
- Susceptible to voltage and frequency disturbances.

Superior Technology for A Brighter Future

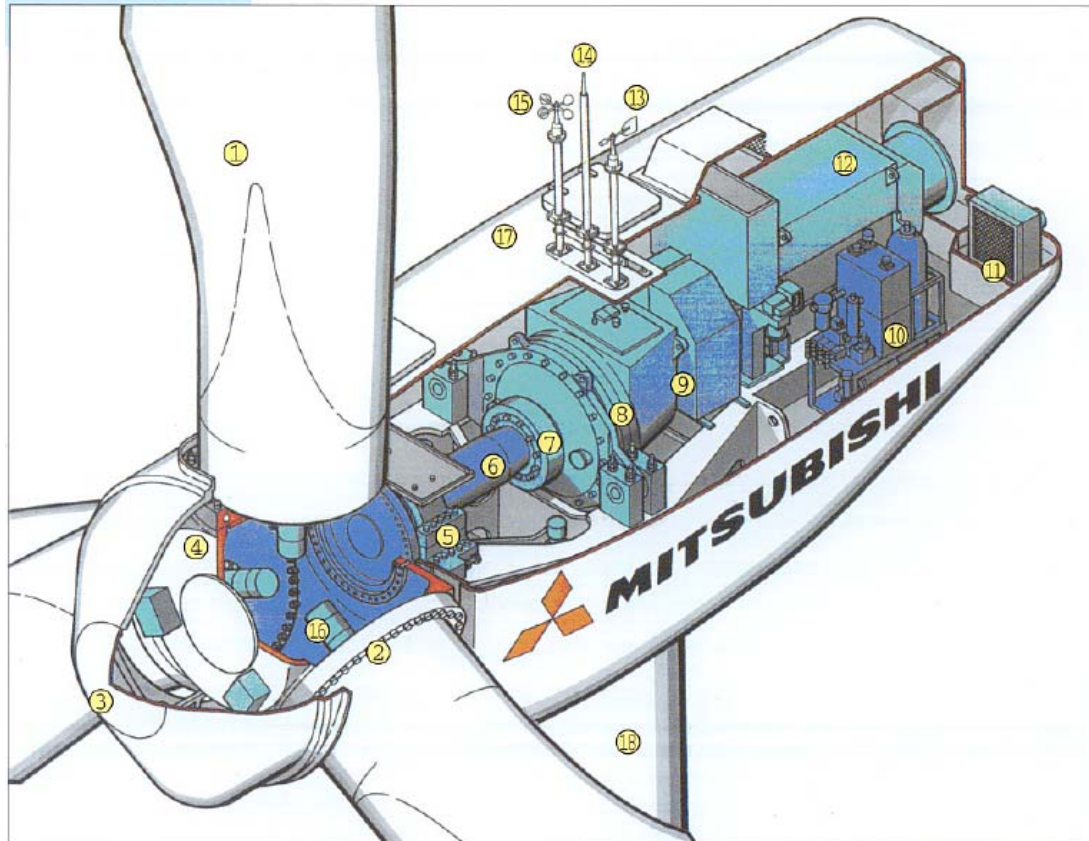
MITSUBISHI WIND TURBINE GENERATOR

MWT-1000

- **Higher Production**
- **Well-proven Technology**

for class 1 wind condition

AES operates these in Palm Springs, Wyoming and Oregon



Schematic Diagram

- | | | | |
|-----------------|-------------------------|--------------------------|-------------------------------|
| ① Blade | ⑥ Main Shaft | ⑪ L.O. Cooler (with Fan) | ⑭ Hydraulic Pitch Link System |
| ② Blade Bearing | ⑦ Coupling (Low Speed) | ⑫ Generator | ⑮ Nacelle |
| ③ Front Capsule | ⑧ Gear Box | ⑬ Wind Vane | ⑯ Tower |
| ④ Rotor Head | ⑨ Coupling (High Speed) | ⑭ Lightning Rod | |
| ⑤ Main Bearing | ⑩ Hydraulic Unit | ⑮ Anemometer | |

MITSUBISHI HEAVY INDUSTRIES, LTD.



Four Electrical Wind Turbine Types

2 - Direct Connected-Variable Resistance Rotor

- 3 phase double-fed asynchronous generator connected across the line with variable resistance control of rotor winding.
- Allows for some variable speed operation by changing slip rating of generator.
- Absorbs VARs while producing Watts.
- No inherent voltage control capability, tends to pull down voltage as generation increases.
- Switched shunt capacitors used for power factor correction.
- Improved power regulation along with better voltage and frequency disturbance ride through capability.

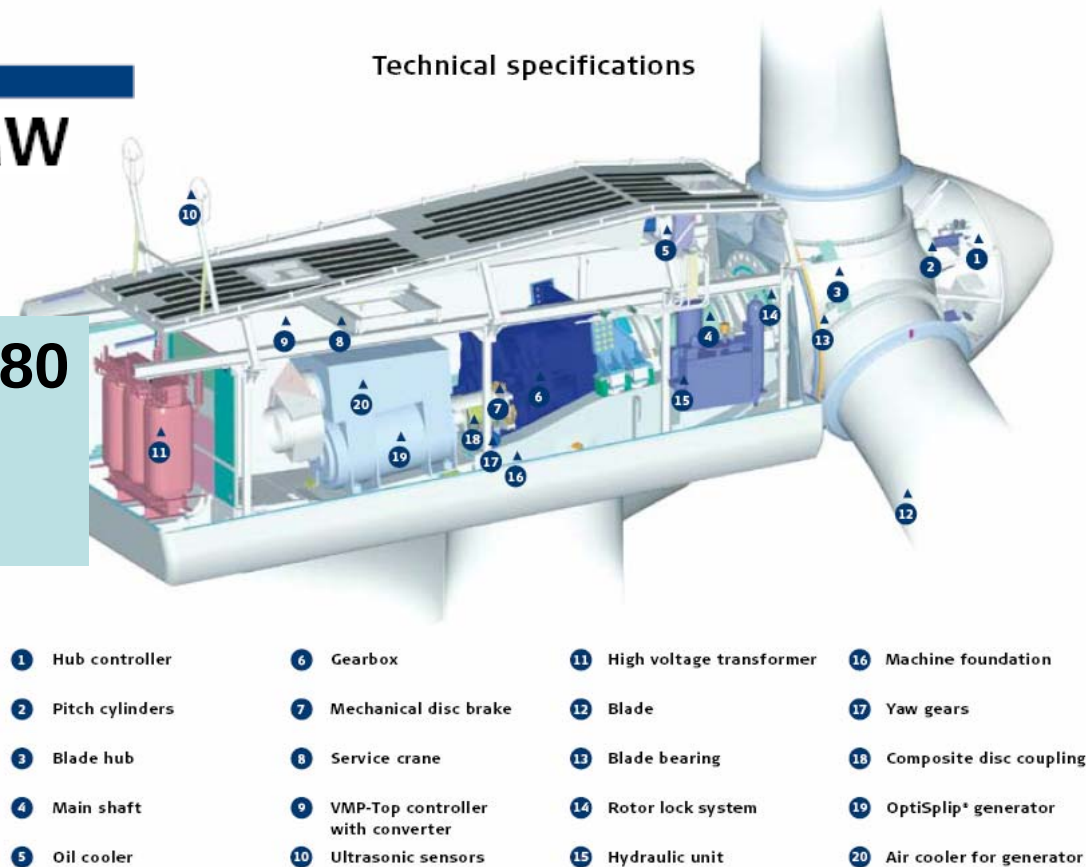


AES Buffalo Gap 1
67 machines
120.6 MW

Vestas
V80-1.8 MW

**Over 2,000 V 80
machines
in operation**

Technical specifications



Four Electrical Wind Turbine Types

3 - Double Fed Asynchronous

- 3 phase double-fed asynchronous generator connected across the line with variable frequency & variable voltage control of rotor winding.
- Requires smaller inverter, but adds slip rings to generator.
- Allows for variable speed and variable frequency operation.
- Good power regulation along with excellent voltage and frequency disturbance ride through capability.



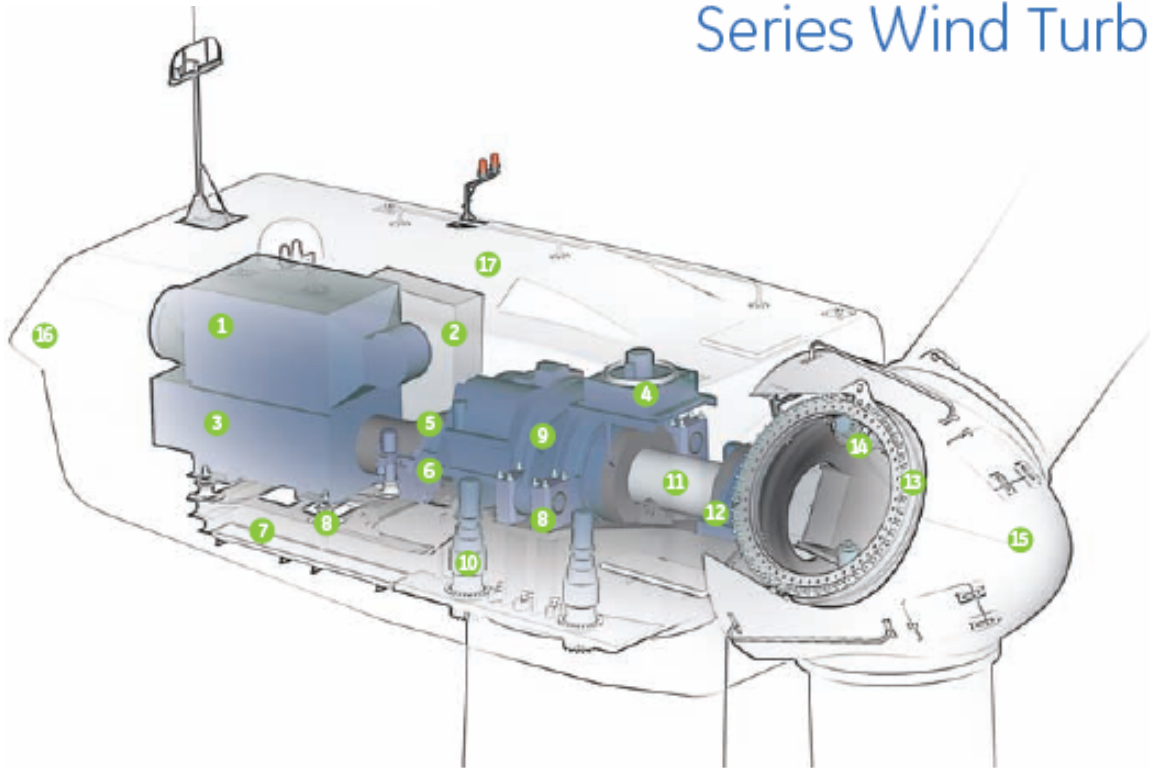
1.5 MW

Series Wind Turbine

AES Buffalo Gap 2

155 machines

232.5 MW

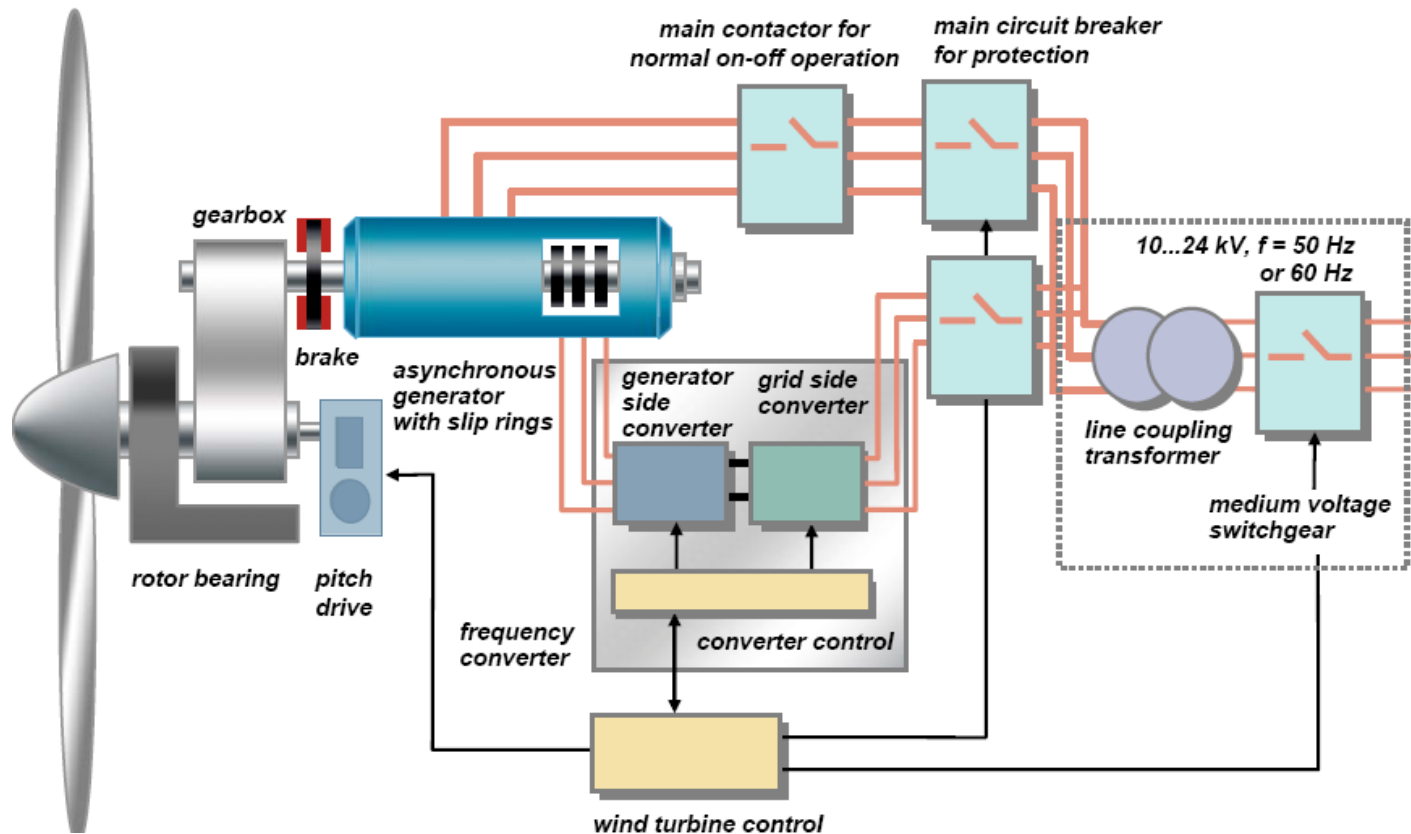


- | | |
|---------------------------|--------------------|
| 1 Heat exchanger | 10 Yaw drive |
| 2 Control panel | 11 Rotor shaft |
| 3 Generator | 12 Bearing housing |
| 4 Oil cooler | 13 Rotor hub |
| 5 Coupling | 14 Pitch drive |
| 6 Hydraulic parking brake | 15 Nose cone |
| 7 Main frame | 16 Ventilation |
| 8 Impact noise insulation | 17 Nacelle |
| 9 Gearbox | |

**Over 5,000 1.5 MW
machines
in operation**



Doubly fed asynchronous generator with slip energy recovery



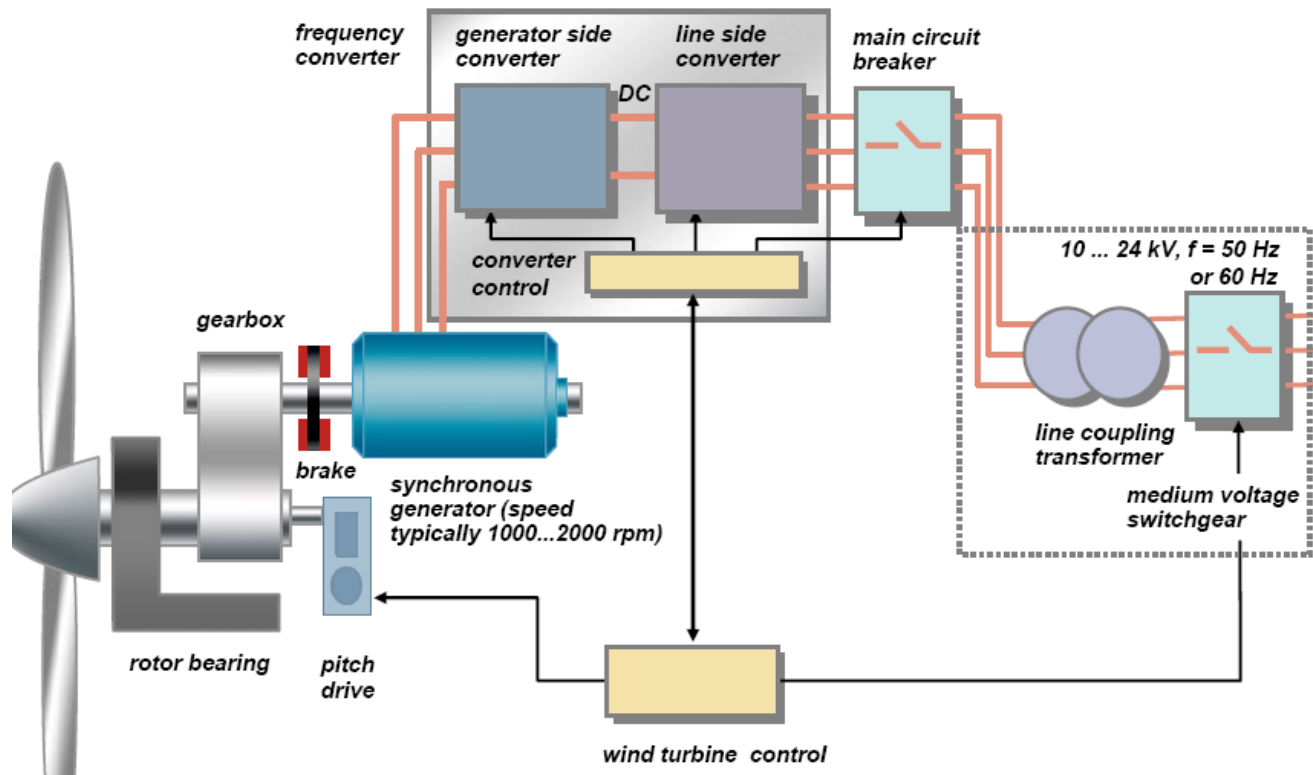
The varying wind speed is managed through **Variable Pitch** blades and the **Converter Control** adjusting the rotor field voltage and frequency to manage drive train torque. In the USA, the GE patent has been an issue, but is being resolved.

Four Electrical Wind Turbine Types

4 - AC-DC-AC Converter Connected

- 3 phase asynchronous (induction) generator connected to (and isolated from) the line by two back-to-back 4-quadrant inverters (AC-DC-AC).
- Requires large full rated inverters, but retains simple generator.
- Mechanical drive train isolated from the electrical grid.
- Full voltage control capability, voltage regulation or power factor regulation modes.
- Switched shunt power factor capacitors not needed.
- Good voltage and frequency disturbance ride through capability.

Full back to back AC-DC-AC Converter Grid Connection



Improvement:

- Eliminates generator slip rings and brushes

Concerns:

- Power electronics are utilized to reconcile the full generator output with the fixed voltage and frequency of the grid and add cost

SIEMENS

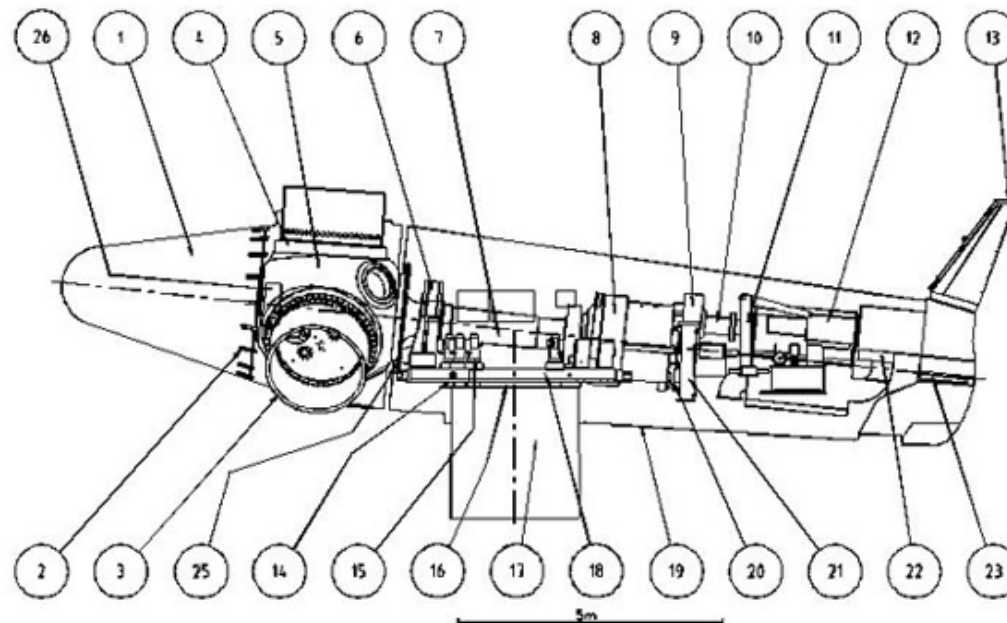


AES Buffalo Gap 3

74 machines

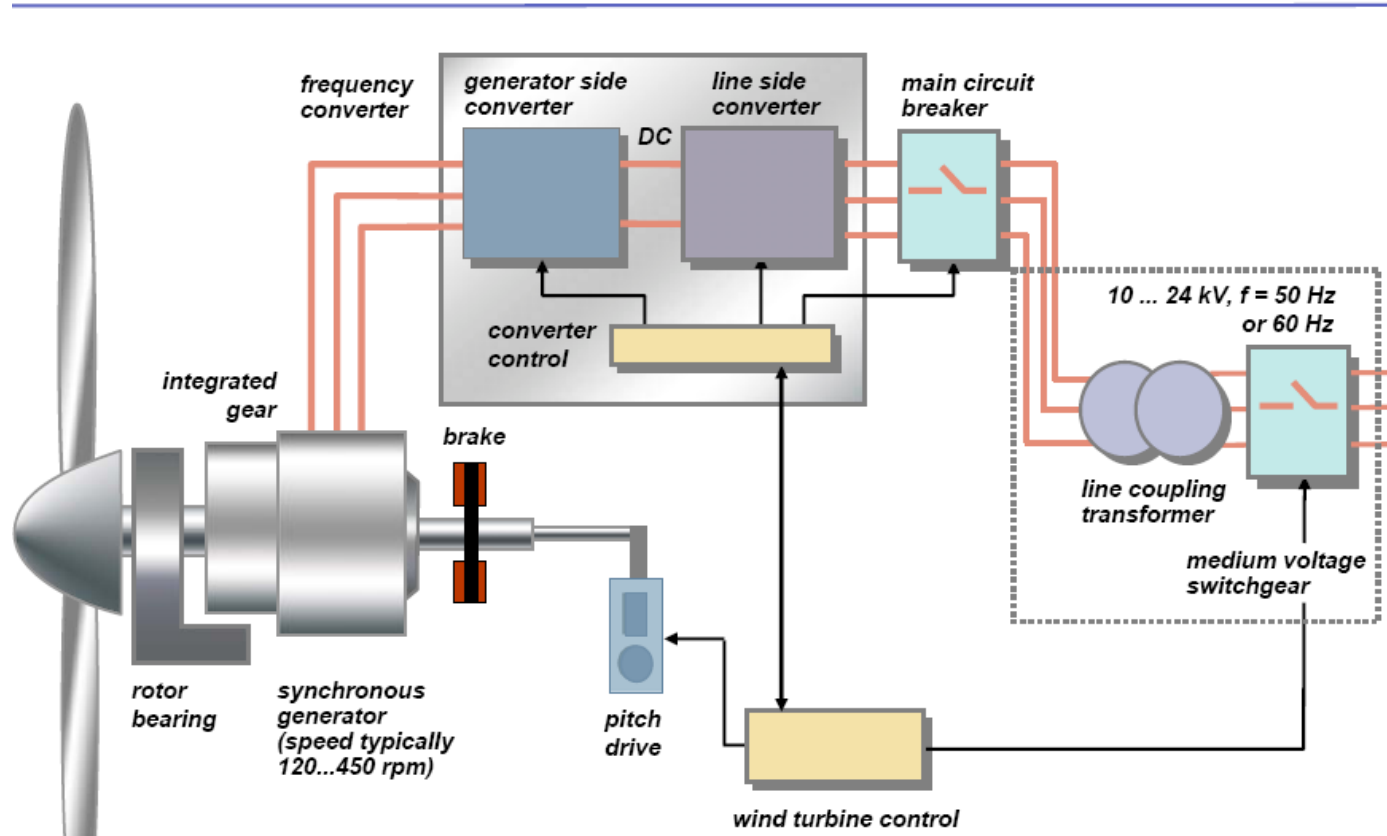
170.2 MW

SWT-2.3-82 Wind Turbine



1 Spinner, 2 Spinner bracket, 3 Blade, 4 Pitch bearing, 5 Rotor hub, 6 Main bearing, 7 Main shaft, 8 Gearbox, 9 Brake disc, 10 Coupling, 11 Service crane, 12 Generator, 13 Meteorological sensors 14 Yaw bearing, 15 Yaw gear, 16 Yaw ring, 17 Tower, 18 Nacelle bedplate, 19 Canopy, 20 Oil filter, 21 Oil filter, 22 Generator fan, 23 Oil cooler, 25 Rotor lock, 26 Hub controller box

Advanced solution: PM generator with integrated low speed gear



Goal:

Improve gear box and generator reliability, while reducing O&M costs, optimizing life cycle cost

Concerns:

- Power electronics are utilized to reconcile the full generator output with the fixed voltage and frequency of the grid



2.5 MW Liberty Wind Turbine



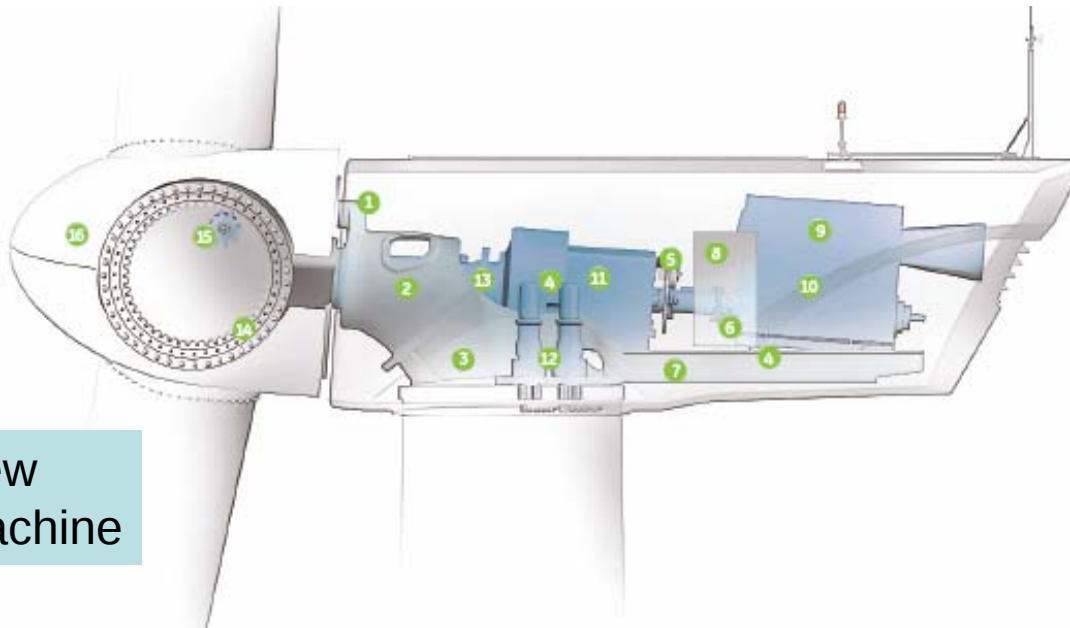
New
Machine

- Integrated gear box and generators. The D-GenQ with 4 high efficiency PM, “Mega-Flux”, generators increases reliability
- Synchronous generator with fully rated power converters



2.5 MW

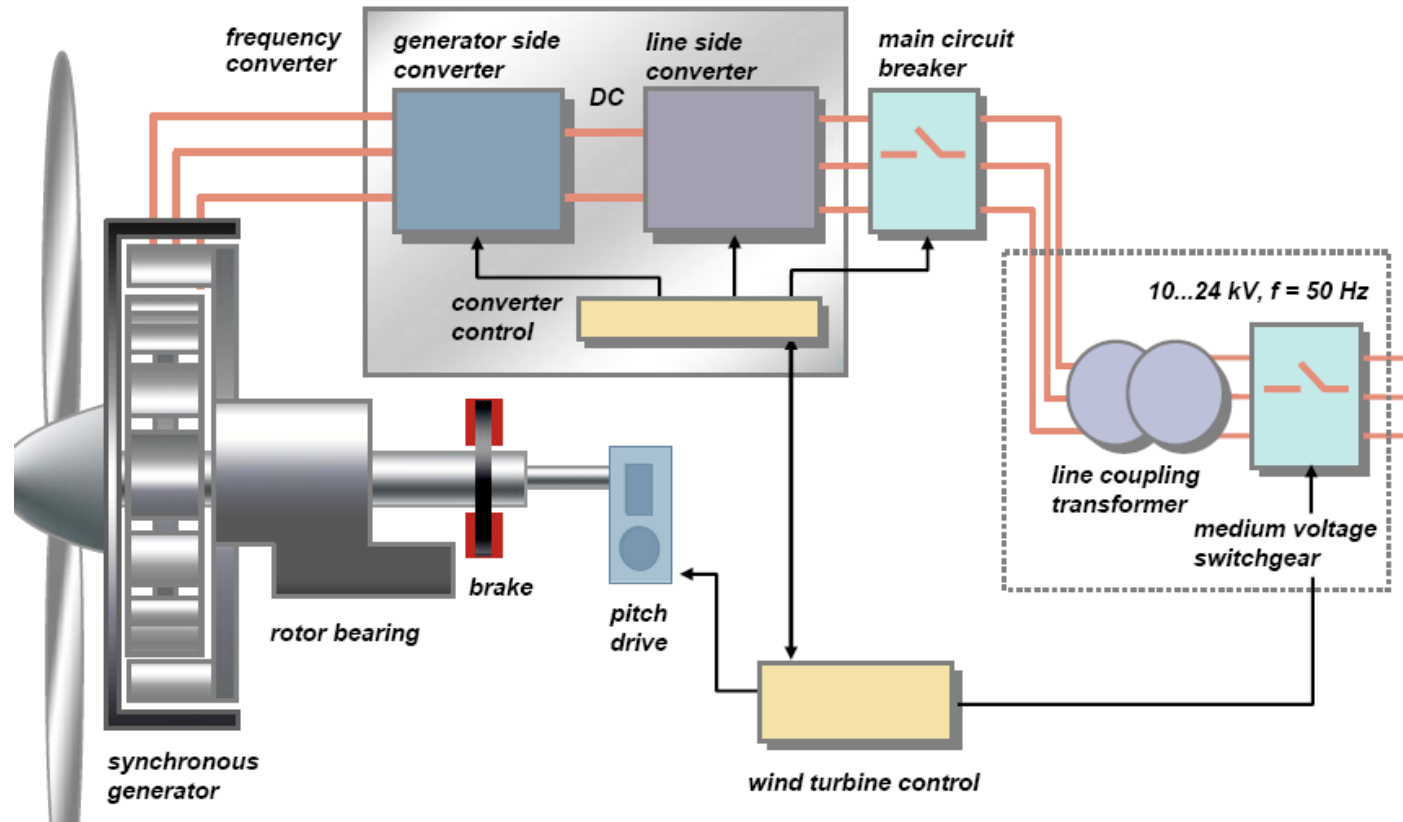
Wind Turbine



- | | |
|---------------------------|------------------|
| 1 Rotor lock | 9 Heat exchanger |
| 2 Pillow block | 10 Generator |
| 3 Main frame | 11 Gearbox |
| 4 Impact noise insulation | 12 Yaw drive |
| 5 Hydraulic parking brake | 13 Rotor shaft |
| 6 Coupling | 14 Rotor hub |
| 7 Generator frame | 15 Pitch drive |
| 8 Control panel | 16 Nose cone |

New
Machine

Advanced solution: gear less with PM generator



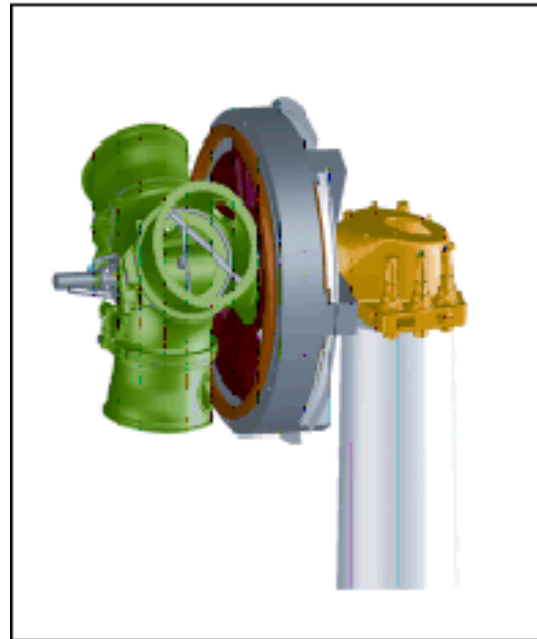
Goals

- Reduce maintenance costs
- Improve reliability

Concerns

- Larger generator makes it heavier, requiring higher upfront cost
- Full converter may increase electrical O&M issues

**10,722 machines
in operation**



Direct Drive Generator

Expensive upfront cost
Very reliable

Not available in USA due
to GE patent fight



AES InnoVent/ France
50 MW operating



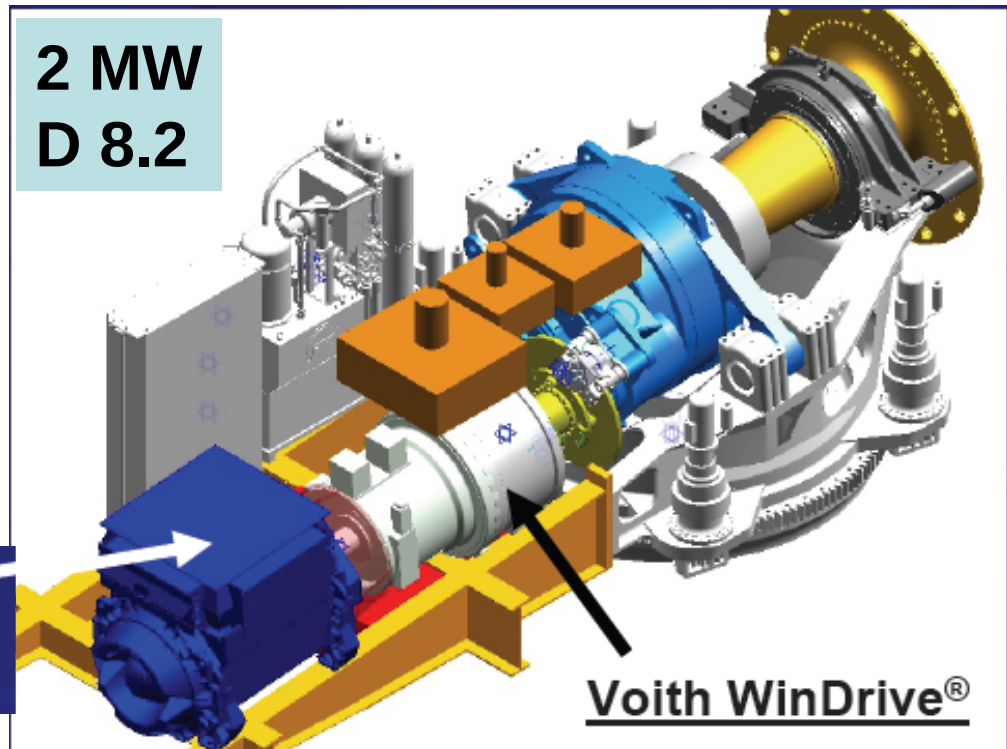
A Mechanical Variation

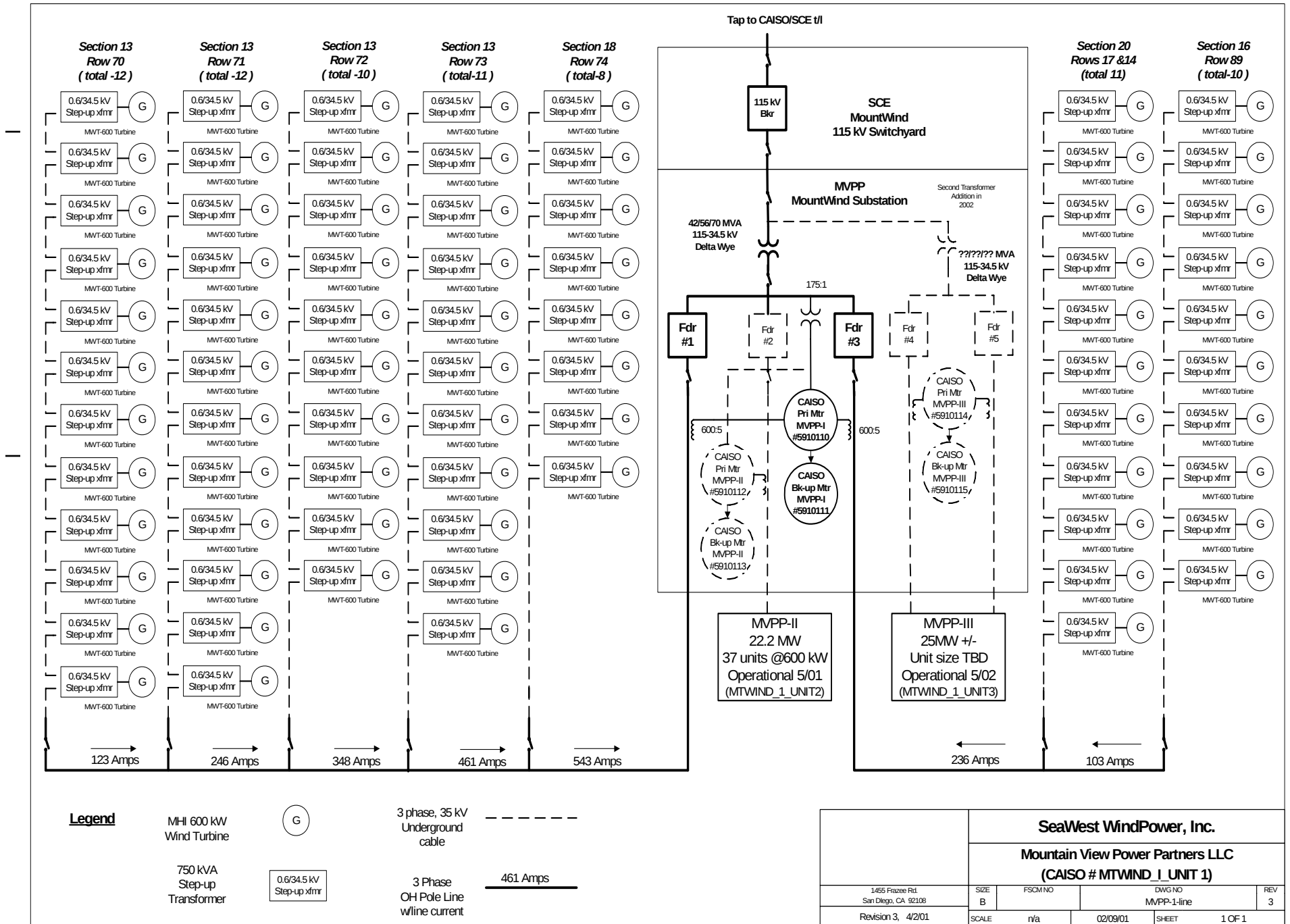
- Dewind is using a Voith hydraulic torque converter to maintain constant generator speed

Goal is to reduce losses from power electronics and improve reliability

Synchronous Generator with High Voltage Output

2 MW
D 8.2







About AES

AES is one of the world's largest global power companies

- 2007 revenues of \$13.6 billion
- Operations in 27 countries on five continents,
- AES's generation and distribution facilities serve 100 million people worldwide
- 14 regulated utilities and 121 generation facilities totaling over 44,000 megawatts
- Global workforce of 30,000 people
- ERCOT generation includes Buffalo Gap 525 MW-Wind, and Deepwater 160 MW-Thermal
- To learn more about AES, please visit www.aes.com



Thank You

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