Introduction to Wind Energy Systems

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Agenda

- Historical Development of WT
- Current Status and Future Prospects of Wind Energy
- Types of Wind Turbine Generators (WT)
- Orientation of WT
- Sizes and Applications of WT
- Components of WT
- Wind Power Calculations

Historical Development

- Wind has been used by people for over 3000 years for grinding grain, sailboats, and pumping water Windmills were an important part of life for many communities beginning around 1200 BC.
- Wind was first used for electricity generation in the late 19th century.

- The Babylonian emperor Hammurabi planned to use wind power for his ambitious irrigation project during seventeenth century B.C.

- The wind wheel of the Greek engineer Heron of Alexandria in the 1st century AD is the earliest known instance of using a wind-driven wheel to power a machine

- Wind-driven wheel was the prayer wheel, which was used in ancient Tibet and China since the 4th century

➢By the 13th century, grain grinding mills were popular in most of Europe

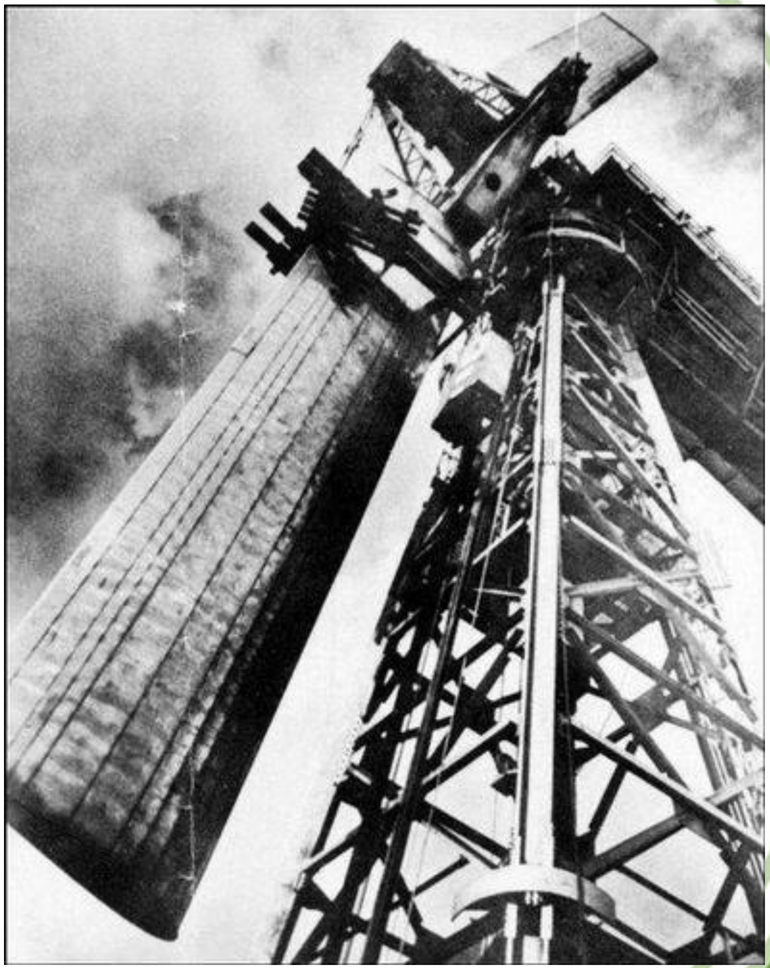
➢French adopted this technology by 1105 A.D. and the English by 1191 A.D

Old windmill.

- The era of wind electric generators began close to 1900’s.
- The first modern wind turbine, specifically designed for electricity generation, was constructed in Denmark in 1890.
- The first utility-scale system was installed in Russia in 1931.
- A significant development in large-scale systems was the 1250 kW turbine fabricated by Palmer C. Putman.

- Built around a central post

- Smith Putnam Machine
- 1941
- Rutland, Vermont
- 1.25 MW
- 53 meters (largest turbine for 40 years)
- Structural steel
- Lost blade in 1945



Mod-5B Horizontal axis wind turbine.

Darrieus wind turbine is vertical axis wind turbine.

Current status and future prospects

Wind is the world's fastest growing energy source today

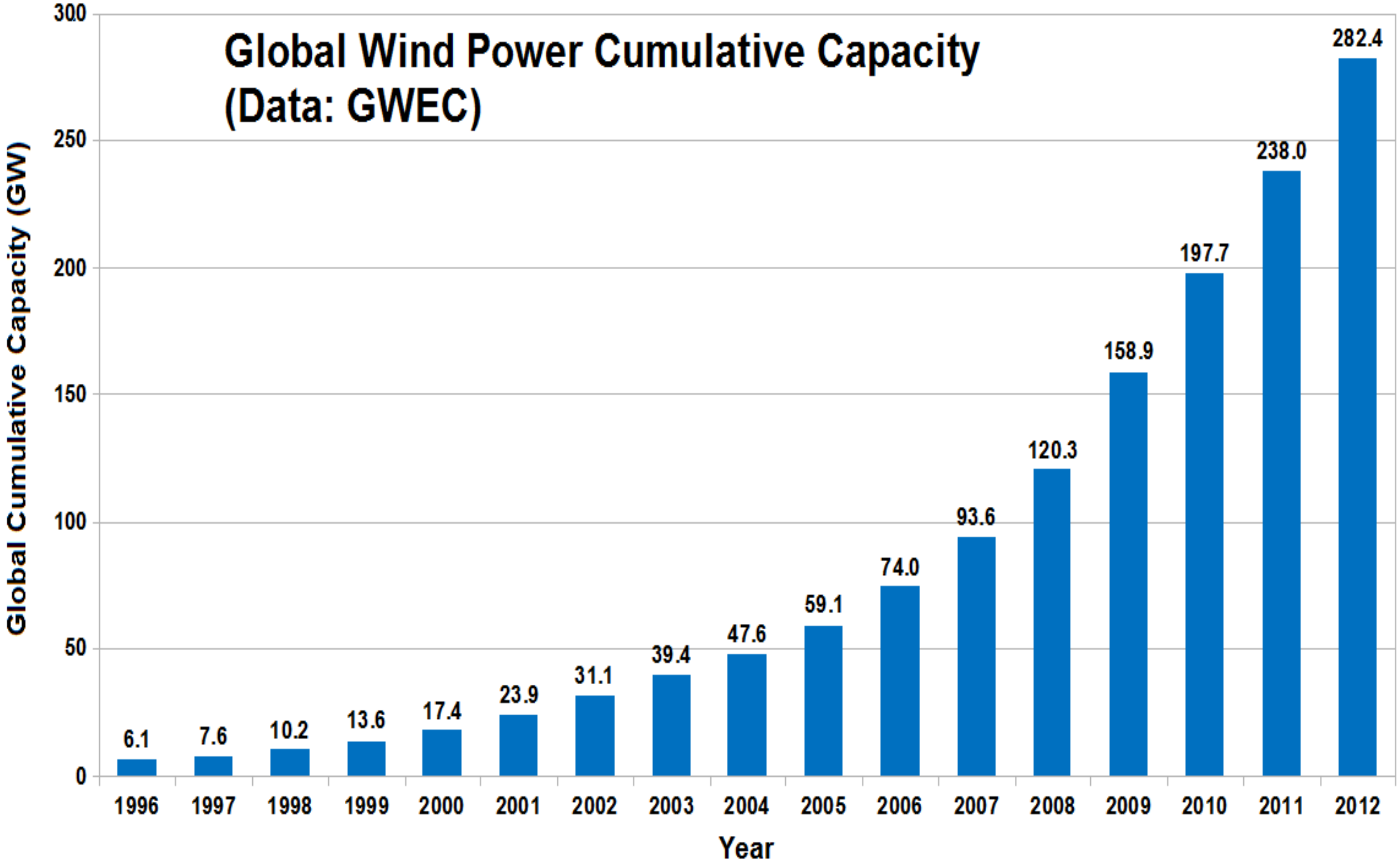
The global wind power capacity increases at least 40% every year.

For example, the European Union targets to meet 25 per cent of their demand from renewable by 2012.

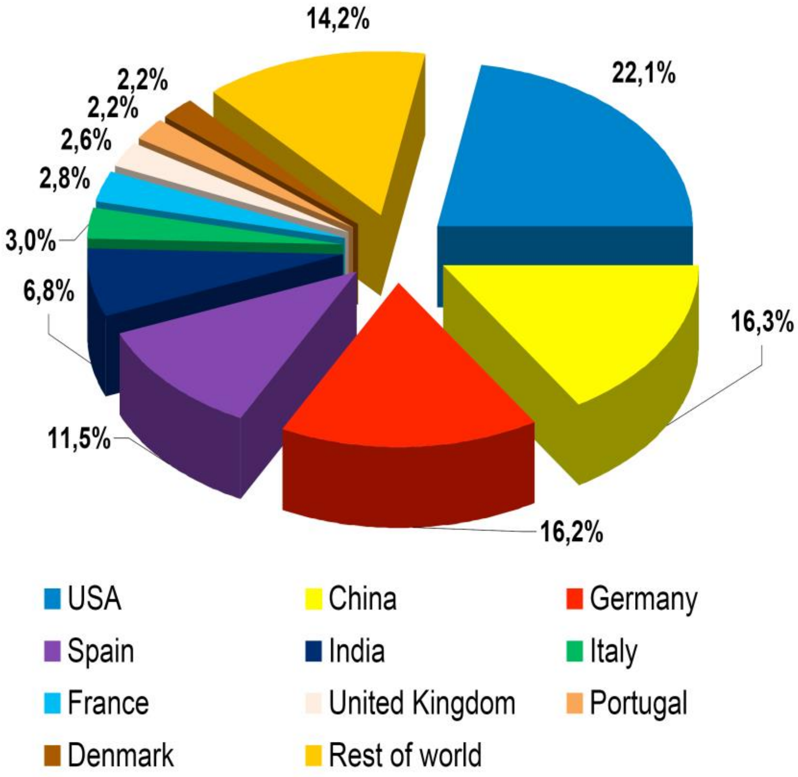
Spain also celebrates in Nov. 10, 2010 when the wind energy resources contribute 53% of the total generation of the electricity.

Over 80 percent of the global installations are in Europe.

Installed capacity may reach a level of 1.2 million MW by 2020



The installed capacity from the wind worldwide.

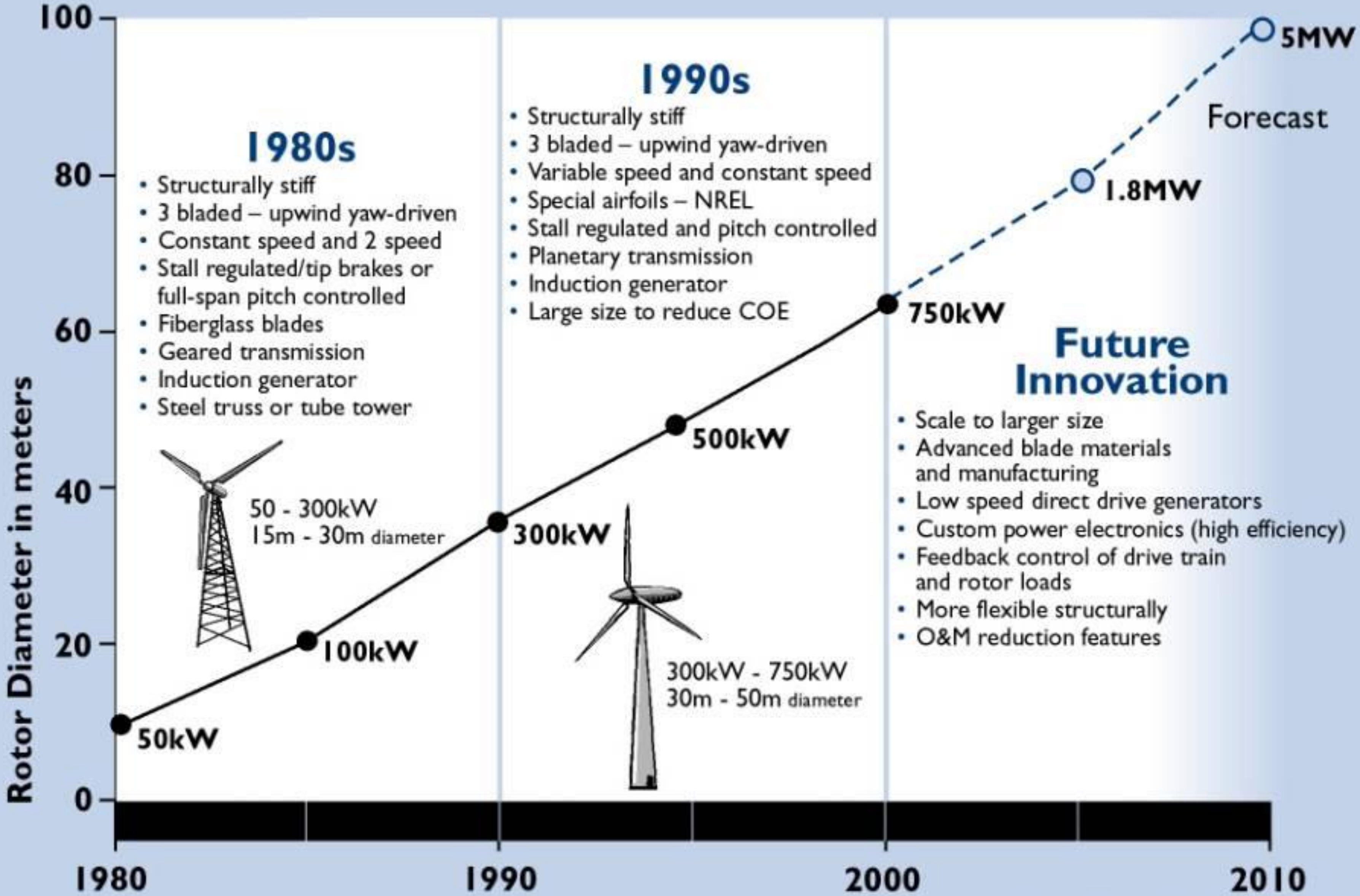


Wind Power Worldwide June 2010

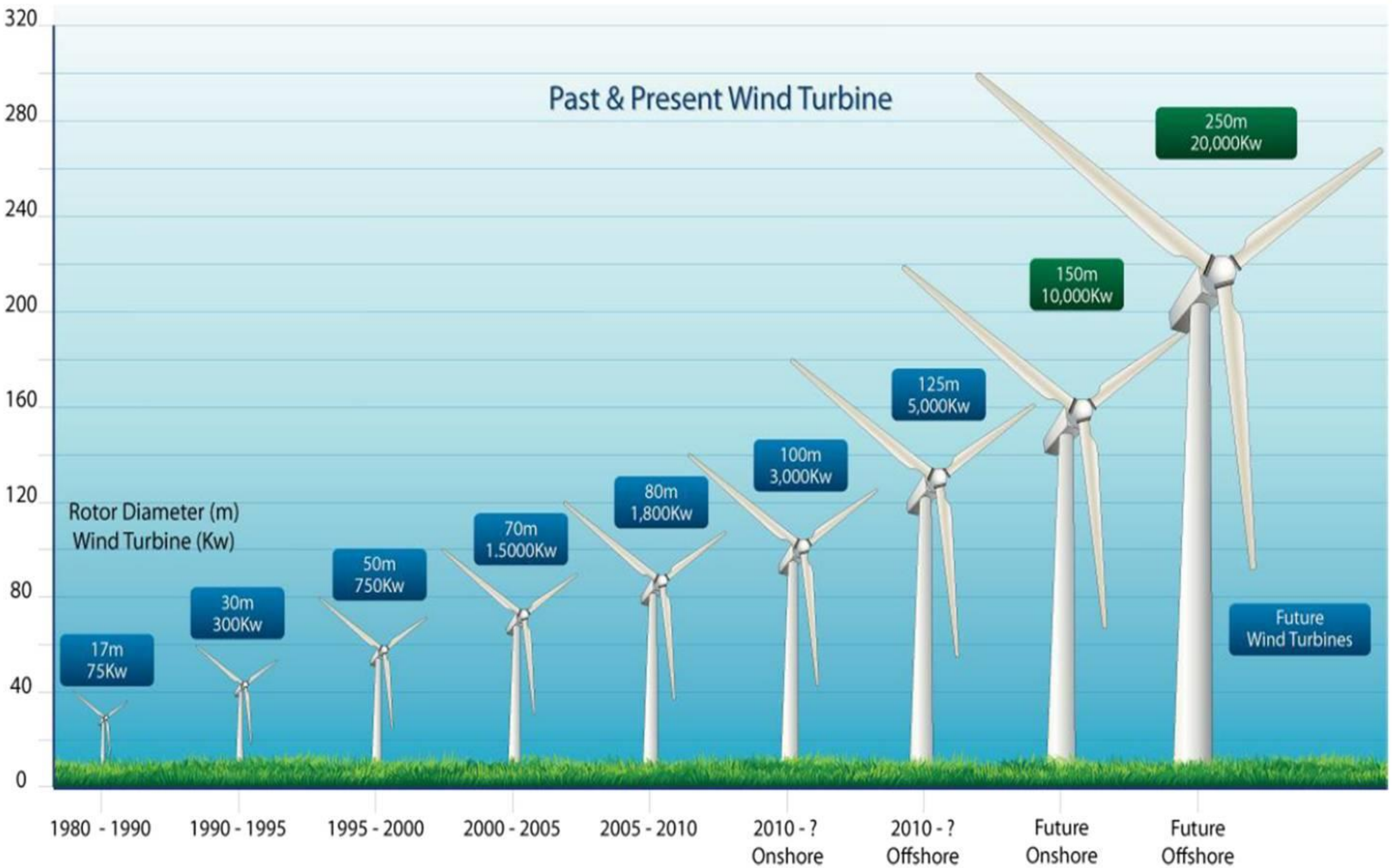
Position	Country	Total capacity June 2010 [MW]	Added capacity June 2010 [MW]	Total capacity end 2009 [MW]
1	USA	**36.300**	1.200	35.159
2	China	**33.800**	7.800	26.010
3	Germany	**26.400**	660	25.777
4	Spain	**19.500**	400	19.149
5	India	**12.100**	1.200	10.925
6	Italy	**5.300**	450	4.850
7	France	**5.000**	500	4.521
8	United Kingdom	**4.600**	500	4.092
9	Portugal	**3.800**	230	3.535
10	Denmark	**3.700**	190	3.497
	Rest of the World	**24.500**	2.870	21.698
Total		**175.000**	**16.000**	**159.213**

Installed capacity in different regions in the world, 2010.

The Evolution of Commercial U.S. Wind Technology



Source: Thresher & Dodge, Wind Energy Journal 1998



Past & Present Wind Turbine
Rotor Diameter (m)
Wind Turbine (Kw)
320
280
240
200
160
120
80
40
0
17m
75Kw
30m
300Kw
50m
750Kw
70m
1.5000Kw
80m
1,800Kw
100m
3,000Kw
125m
5,000Kw
150m
10,000Kw
250m
20,000Kw
Future
Wind Turbines
1980 - 1990
1990 - 1995
1995 - 2000
2000 - 2005
2005 - 2010
2010 - ?
Onshore
2010 - ?
Offshore
Future
Onshore
Future
Offshore

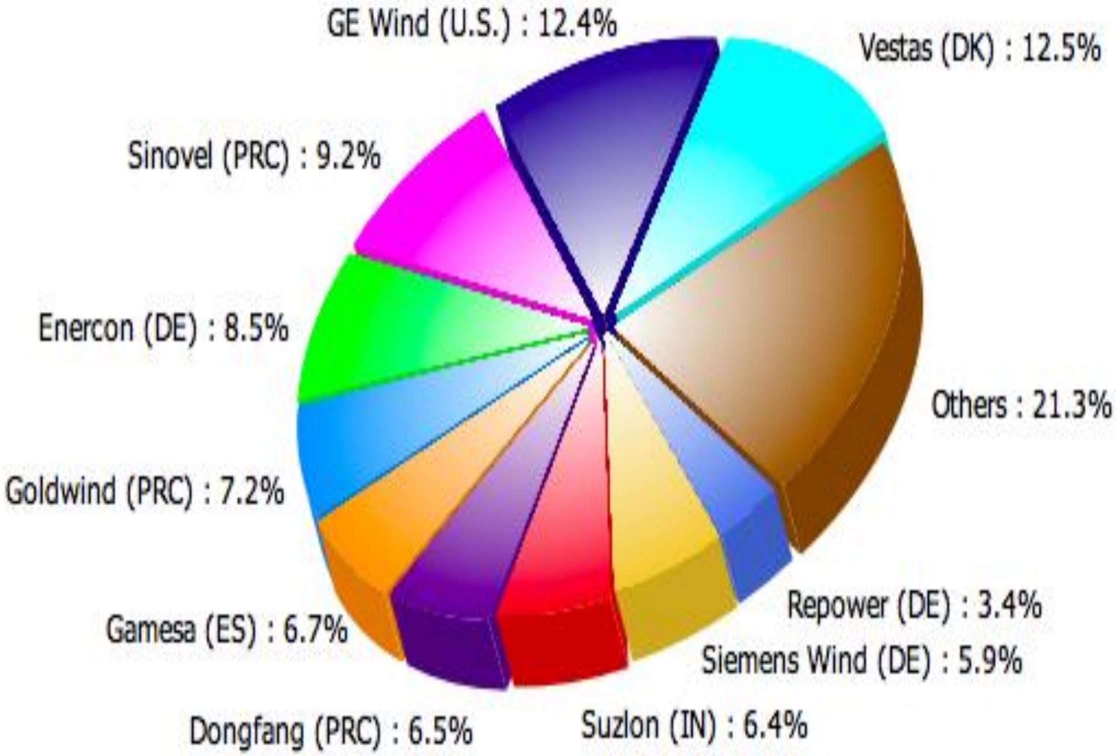
(a) SWAY 10MW.

Enercon E126, 7.5MW, 126 diameter

Table I.3.1: Design choices of leading manufacturers

		Share (%)	Model	Drive train	Power rating (kW)	Diameter (m)	Tip speed (m/s)	Power conversion
1	Vestas	22.8	V90	Geared	3000	90	87	Asynchronous
2	GE Energy	16.6	2.5XL	Geared	2500	100	86	PMG converter
3	Gamesa	15.4	G90	Geared	2000	90	90	DFIG
4	Enercon	14.0	E82	Direct	2000	82	84	Synchronous
5	Suzlon	10.5	S88	Geared	2100	88	71	Asynchronous
6	Siemens	7.1	3.6 SWT	Geared	3600	107	73	Asynchronous
7	Acciona	4.4	AW-119/3000	Geared	3000	116	74.7	DFIG
8	Goldwind	4.2	REpower750	Geared	750	48	58	Induction
9	Nordex	3.4	N100	Geared	2500	99.8	78	DFIG
10	Sinovel	3.4	1500 (Windtec)	Geared	1500	70		

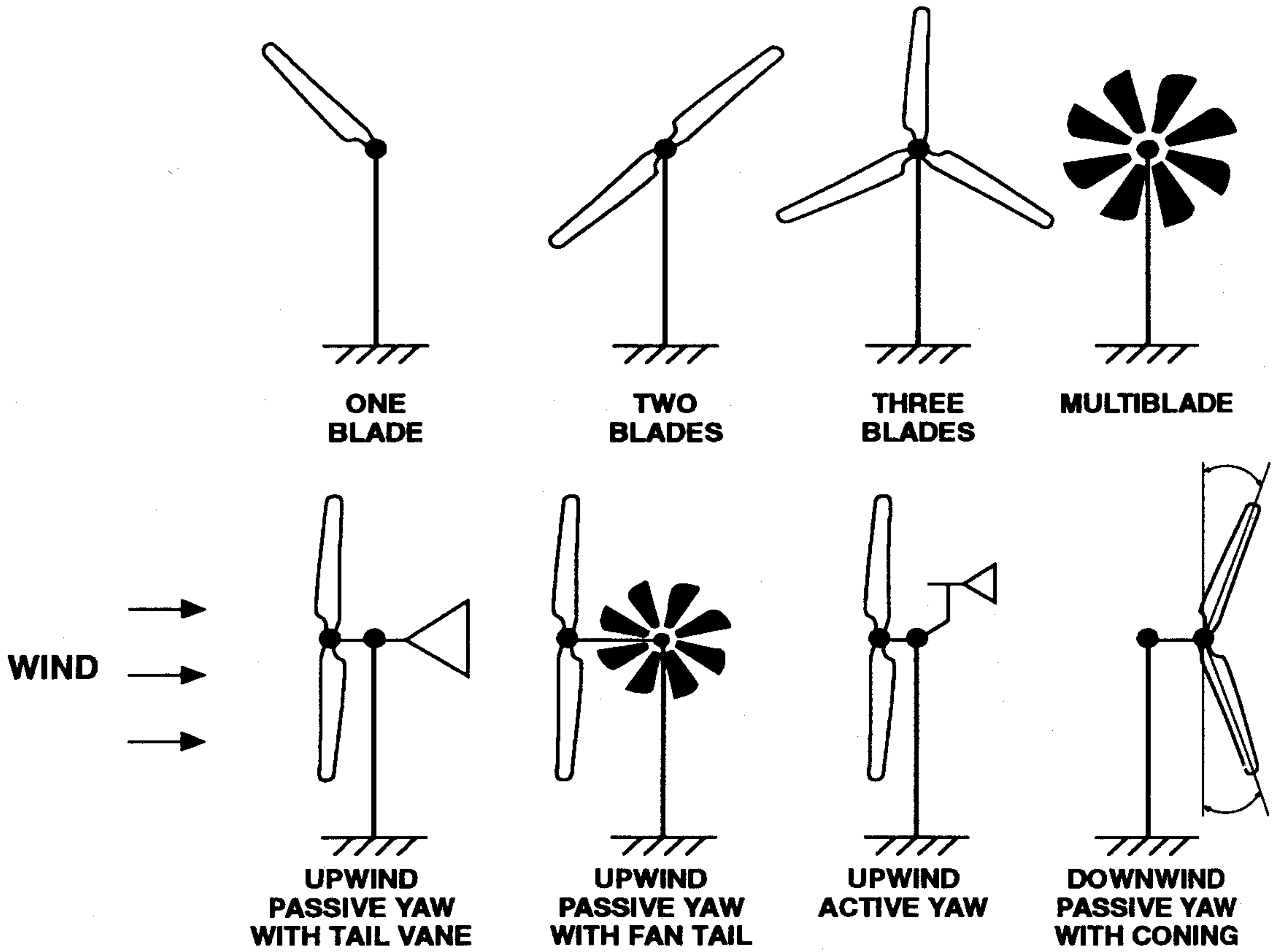
Source: Garrad Hassan



Top ten manufacturers of WTs, 2009.

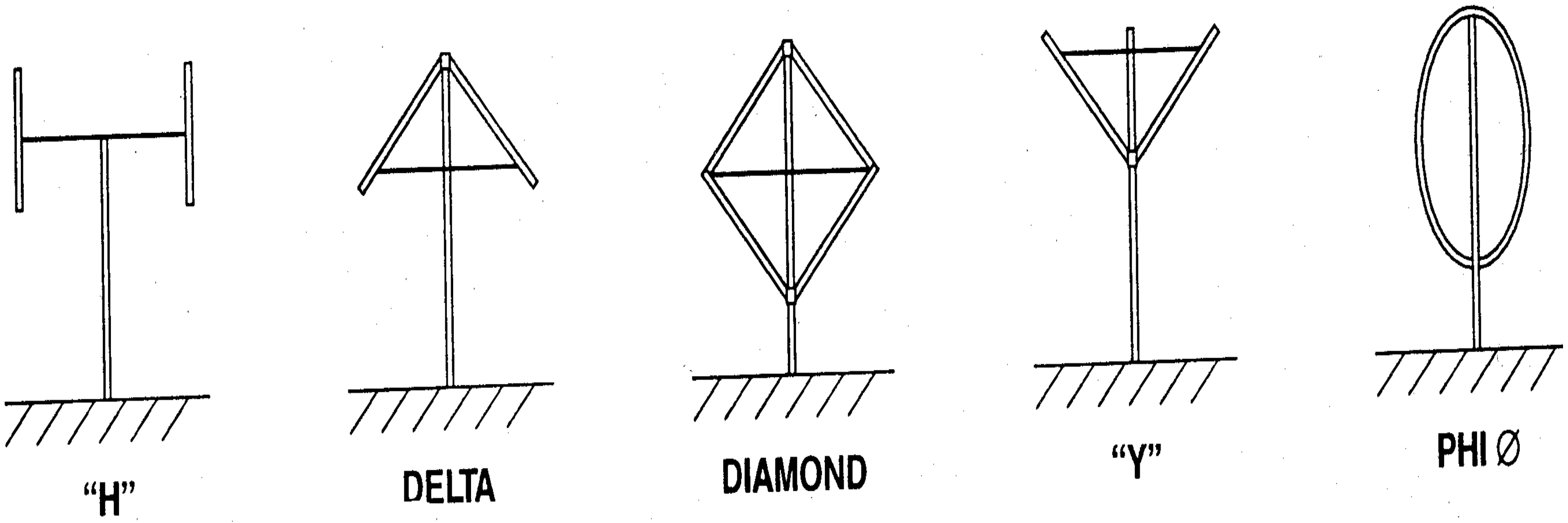
Types of Wind Turbine Generators (WT)

1. Horizontal Axis WTs (HAWTs)



The HAWT configurations

Vertical Axis WTs (VAWTs)



The VA-WTs Configurations

Orientation of WT

Turbines can be categorized into two overarching classes based on the orientation of the rotor

Vertical Axis

Horizontal Axis

Vertical Axis Turbines

Advantages

- Omnidirectional
  - Accepts wind from any angle
- Components can be mounted at ground level
  - Ease of service
  - Lighter weight towers
- Can theoretically use less materials to capture the same amount of wind

Disadvantages

- Rotors generally near ground where wind poorer
- Centrifugal force stresses blades & components
- Poor self-starting capabilities
- Requires support at top of turbine rotor
- Requires entire rotor to be removed to replace bearings
- Overall poor performance and reliability/less efficient
- Have never been commercially successful (large scale)

Windspire

Savonious

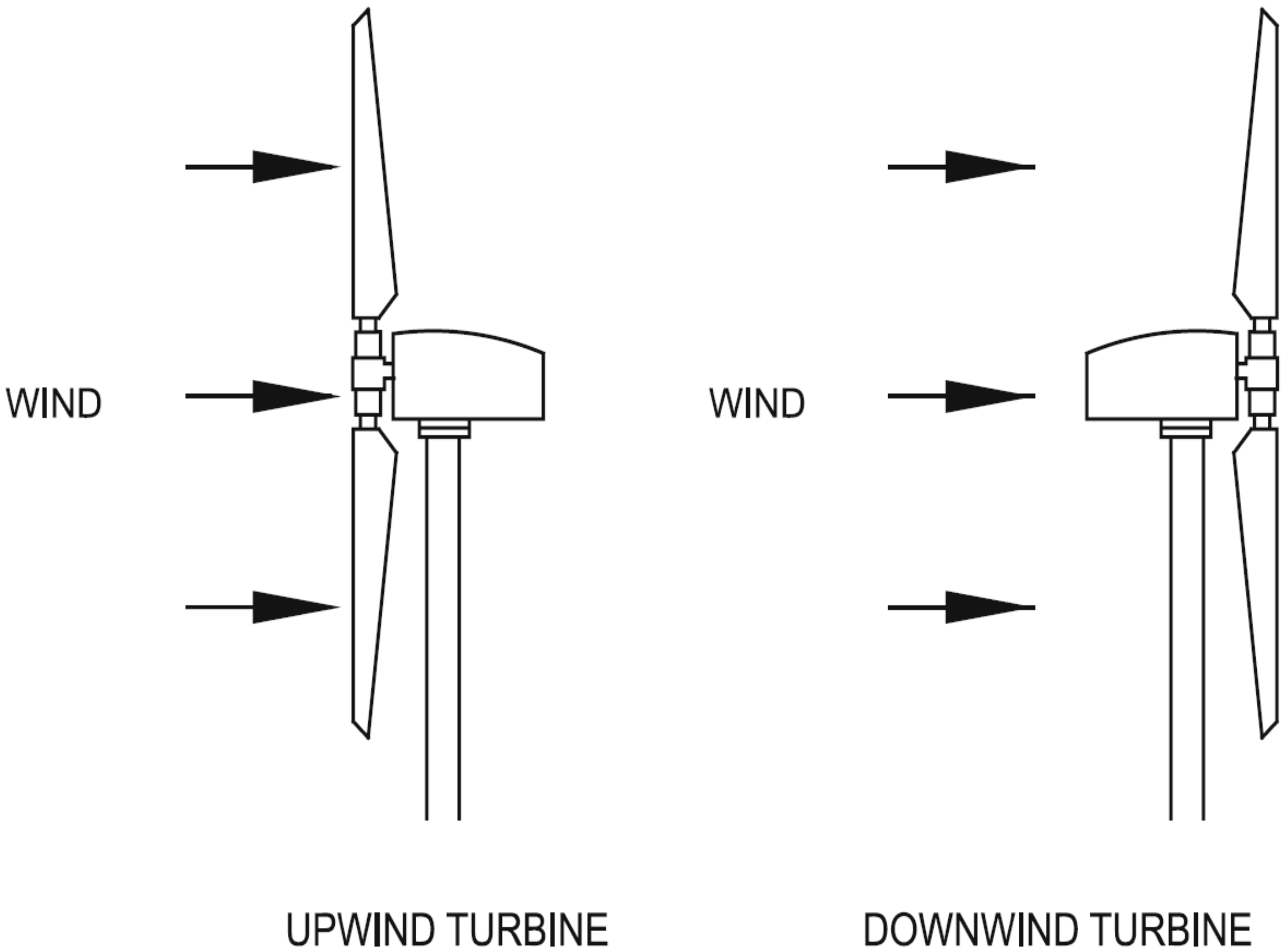
Horizontal Axis Wind Turbines

- Rotors are usually Up-wind of tower
- Some machines have down-wind rotors, but only commercially available ones are small turbines
- Proven, viable technology

Comparison between HA-WTs and VA-WTs.

Items	**HA-WTs**	**VA-WTs**
Output power	Wide range	Narrow range
Starting	Self starting	Need starting means
Efficiency	Higher	Lower
Cost	Lower	Higher
Wind direction	Need redirected when the Wind change its direction	Does not needs redirected into the wind direction
Generator and gear box	At the top of the tower	At the ground level
Maintenance	Difficult	Easy

Upwind and Dawnwind WT



Upwind turbines have the rotor facing the wind as shown in Fig.1.11 (a). This technique has the following features:

- Avoids the wind shade that the tower causes which improve the power quality of the generated voltage and reduces the spicks in power when the blades move in front of the tower specially in constant speed systems.

- Fewer fluctuations in the power output.

- Requires a rigid hub, which has to be away from the tower. Otherwise, if the blades are bending too far, they will hit the tower.

- This is the dominant design for most wind turbines in the MW-range

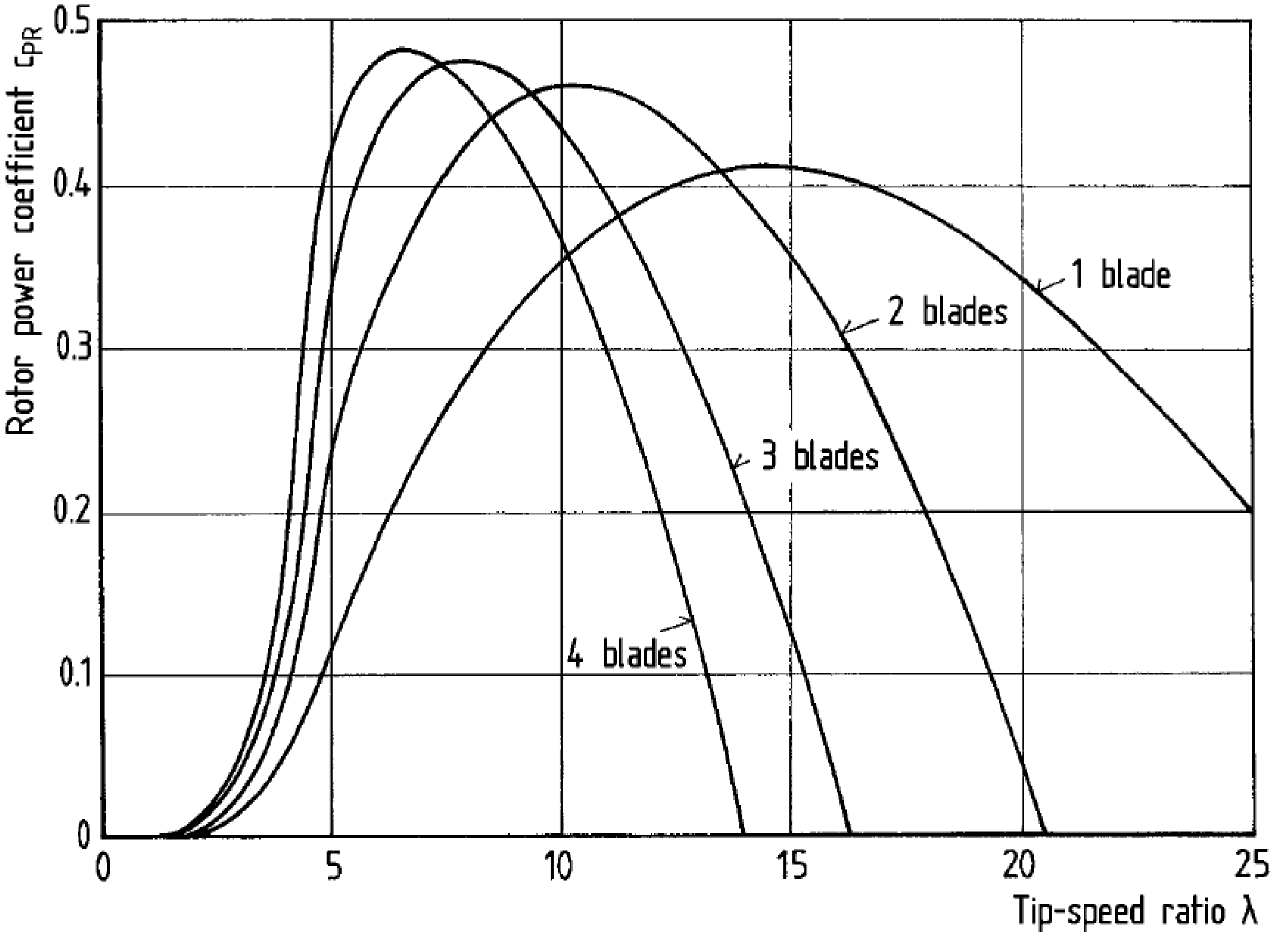
Downwind WT have the rotor on the flow-side as shown in Fig.1.11 (b). It may be built without a yaw mechanism if the nacelle has a streamlined body that will make it follow the wind.

■Rotor can be more flexible: Blades can bend at high speeds, taking load off the tower. Allow for lighter build.

■Increased fluctuations in wind power, as blades are affected by the tower shade.

■Only small wind turbines.

1.3.4 Number of Rotor Blades



Influence of the number of blades on the rotor power coefficient (envelope) and the optimum tip-speed ratio.

shows one blade WT.

Sizes and Applications

Small (≤10 kW)

- Homes
- Farms
- Remote Applications

(e.g. water pumping, telecom sites, icemaking)

Intermediate (10-250 kW)

- Village Power
- Hybrid Systems
- Distributed Power

Large (660 kW - 2+MW)

- Central Station Wind Farms
- Distributed Power
- Community Wind

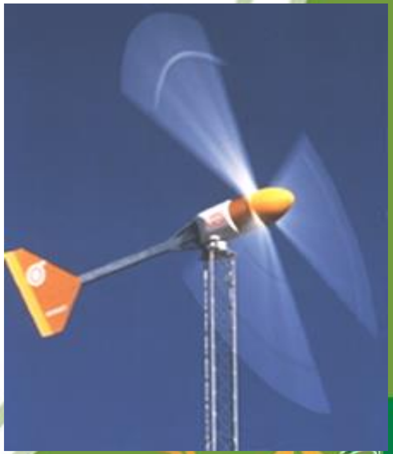
Large and Small Wind Turbines

Large Turbines (600-2000 kW)

- Installed in “Windfarm” arrays totaling 1 - 100 MW
- $1,300/kW
- Designed for low cost of energy (COE)
- Requires 6 m/s (13 mph) average wind speed
- Value of Energy: $0.02 - $0.06 per kWh

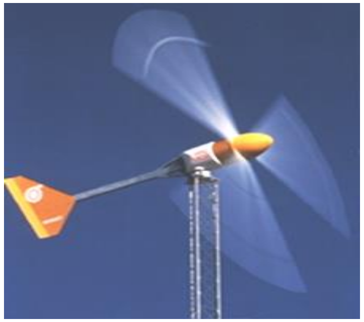
Small Turbines (0.3-100 kW)

- Installed in “rural residential” on-grid and off-grid applications
- $2,500-$8,000/kW
- Designed for reliability / low maintenance
- Requires 4 m/s (9 mph) average wind speed
- Value of energy: $0.06 - $0.26 per kWh

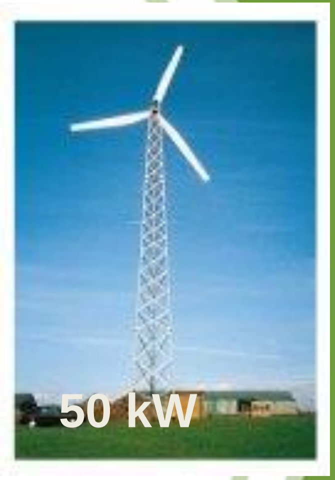


Small Wind Turbines

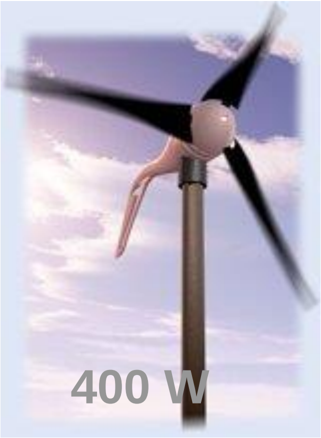
- Blades: Fiber-reinforced plastics, fixed pitch, either twisted/tapered, or straight (pultruded)
- Generator: Direct-drive permanent magnet alternator, no brushes, 3-phase AC, variable-speed operation
- Designed for:
  – Simplicity, reliability
  – Few moving parts
  – Little regular maintenance required



10 kW



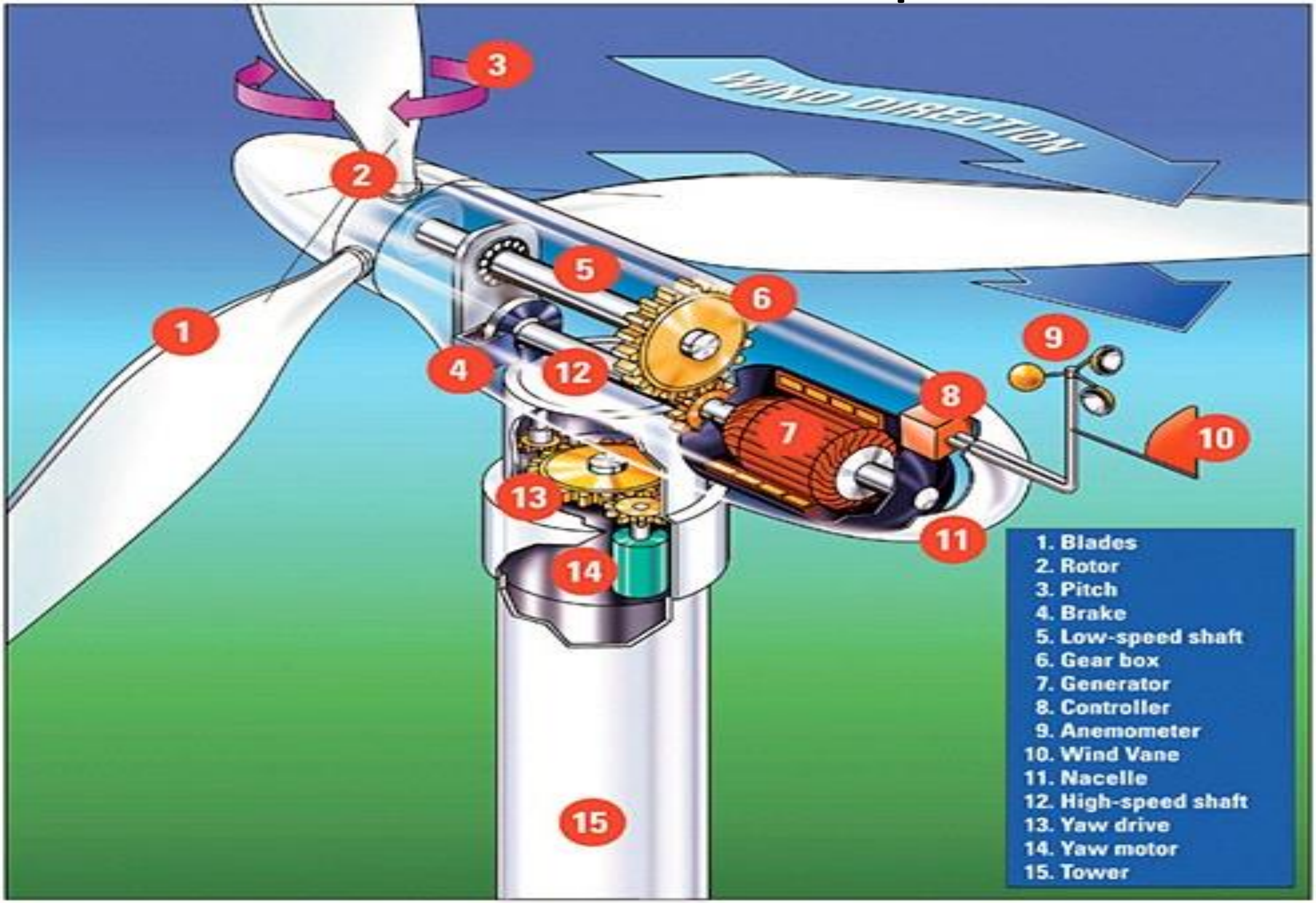
50 kW

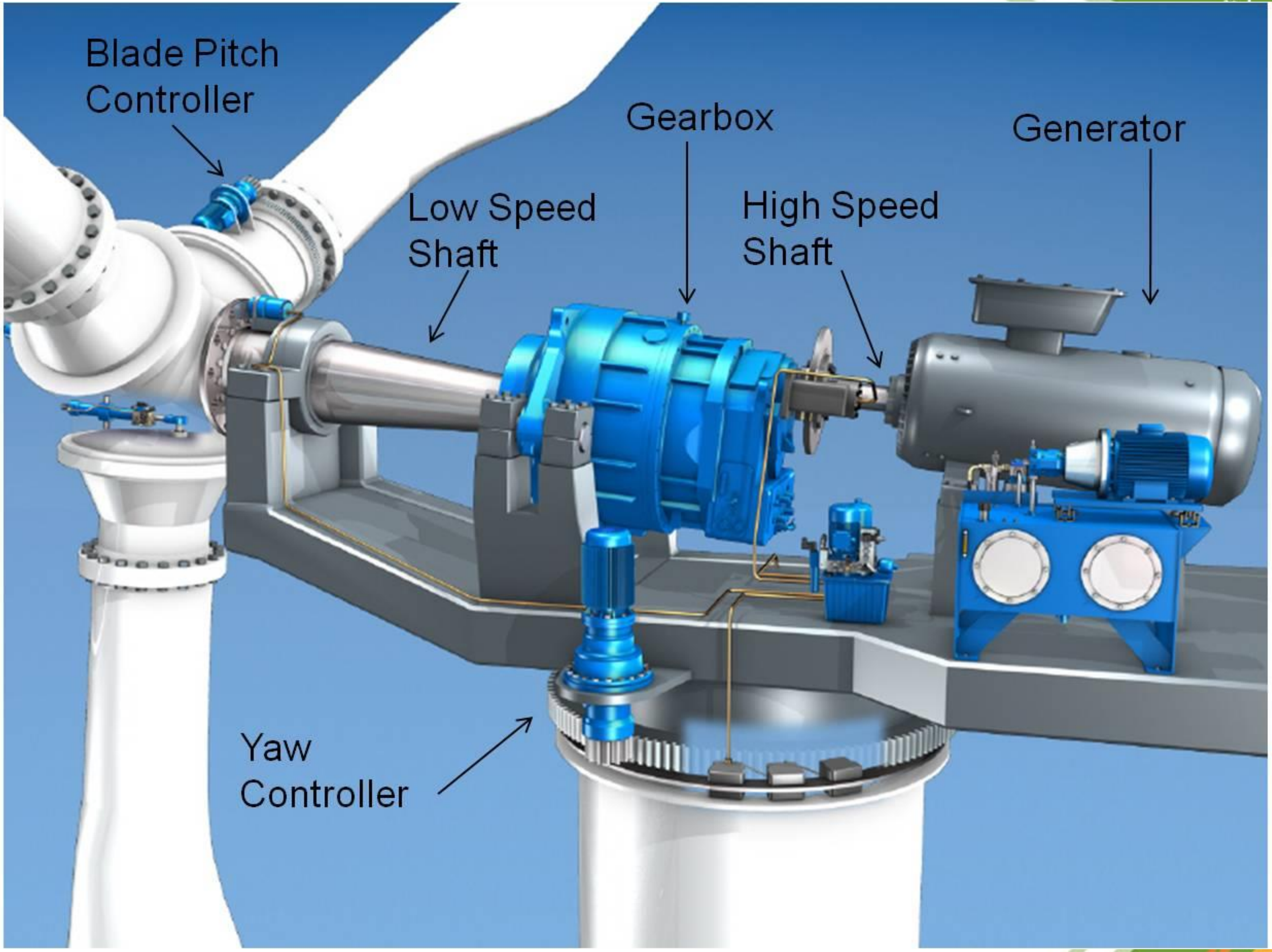


400 W

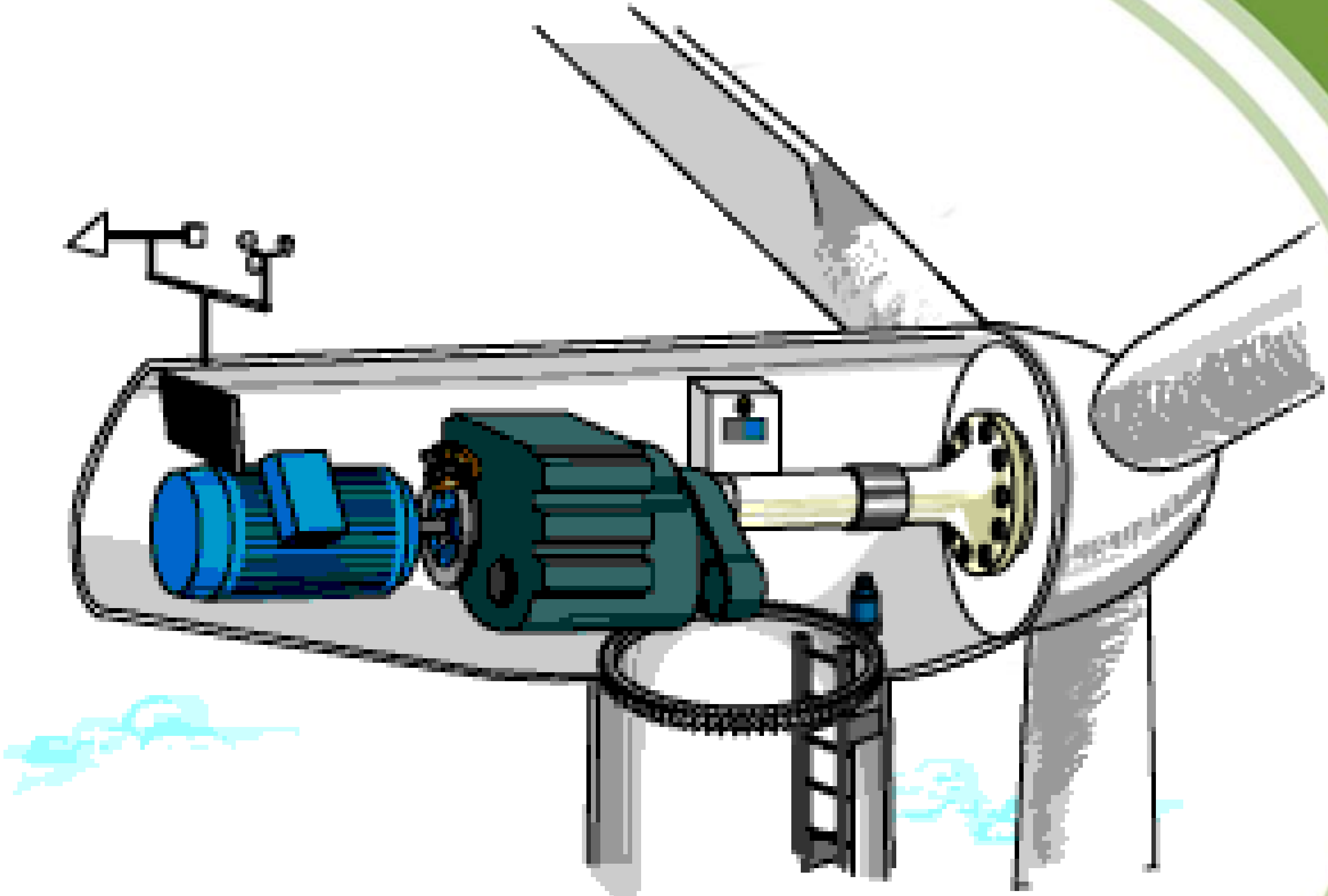
900 W

Wind Turbine components




Blade Pitch
Controller
Gearbox
Generator
Low Speed
Shaft
High Speed
Shaft
Yaw
Controller

Yaw system

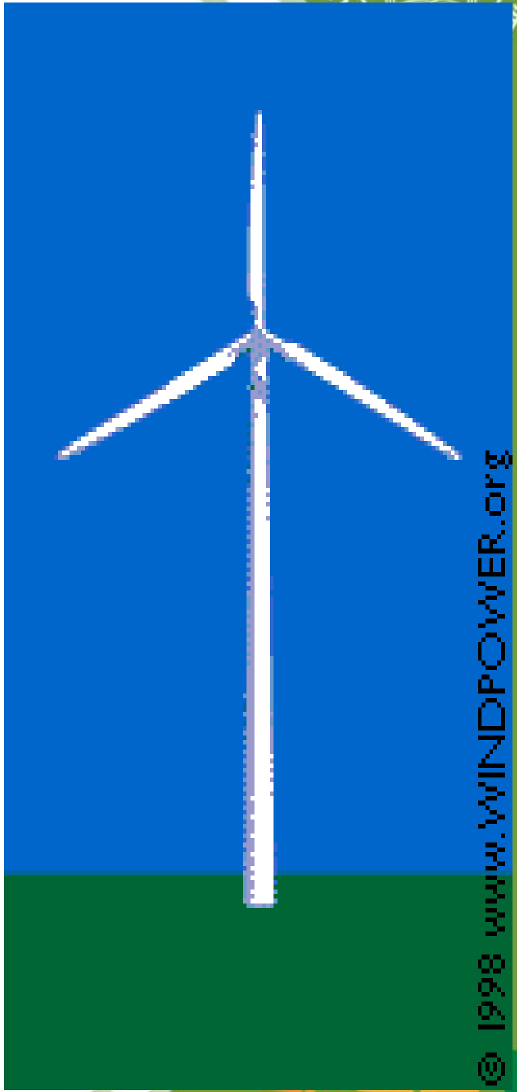


***Yaw drive*: Upwind turbines face into the wind; the yaw drive is used to keep the rotor facing into the wind as the wind direction changes. Downwind turbines don't require a yaw drive, the wind blows the rotor downwind.**

***Yaw motor*: Powers the yaw drive.**

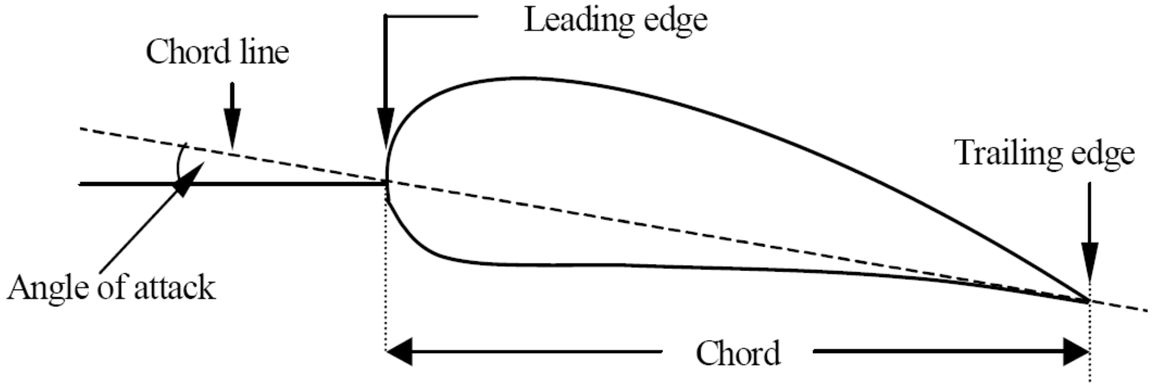
YAW MECHANISM

- It is used to turn the turbine against the wind..
- If the turbine is not perpendicular to the wind, then the power flowing is lower.
- Almost all HAWT use forced yawing, i.e they use electric motors and gearbox.
- Wind turbine running with yaw error are running with hiher fatigue loads.



Yaw mechanism

1.3.5 Aerodynamics of Wind Turbines



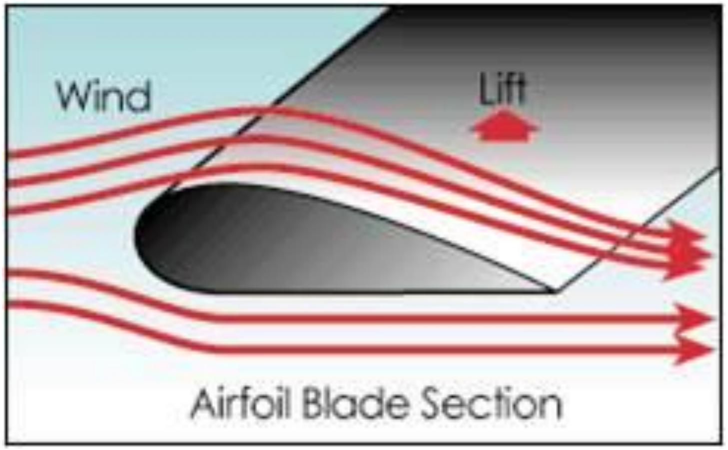
Important parameters of an airfoil

[redacted]

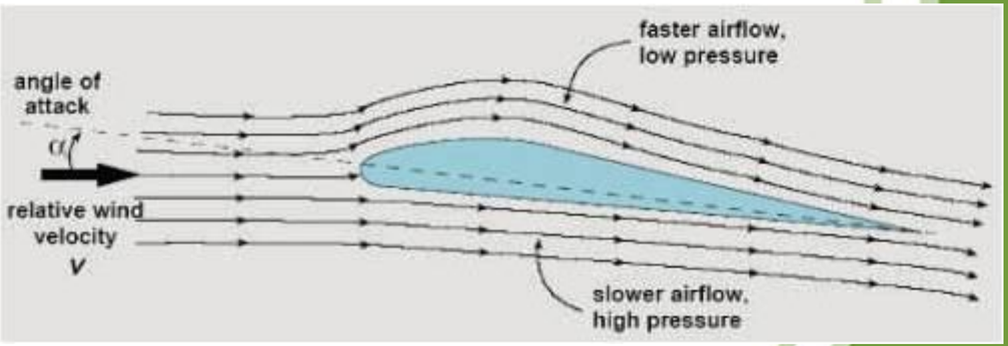
$$D = C_D \frac{1}{2} \rho_a \; A \, V^2$$

where C_L and C_D are the lift and drag coefficients respectively.

Airfoil Shape



Just like the wings of an airplane, wind turbine blades use the airfoil shape to create lift and maximize efficiency.



The Bernoulli Effect

Lift & Drag Forces

- **The *Lift Force* is perpendicular to the direction of motion. We want to make this force BIG.**

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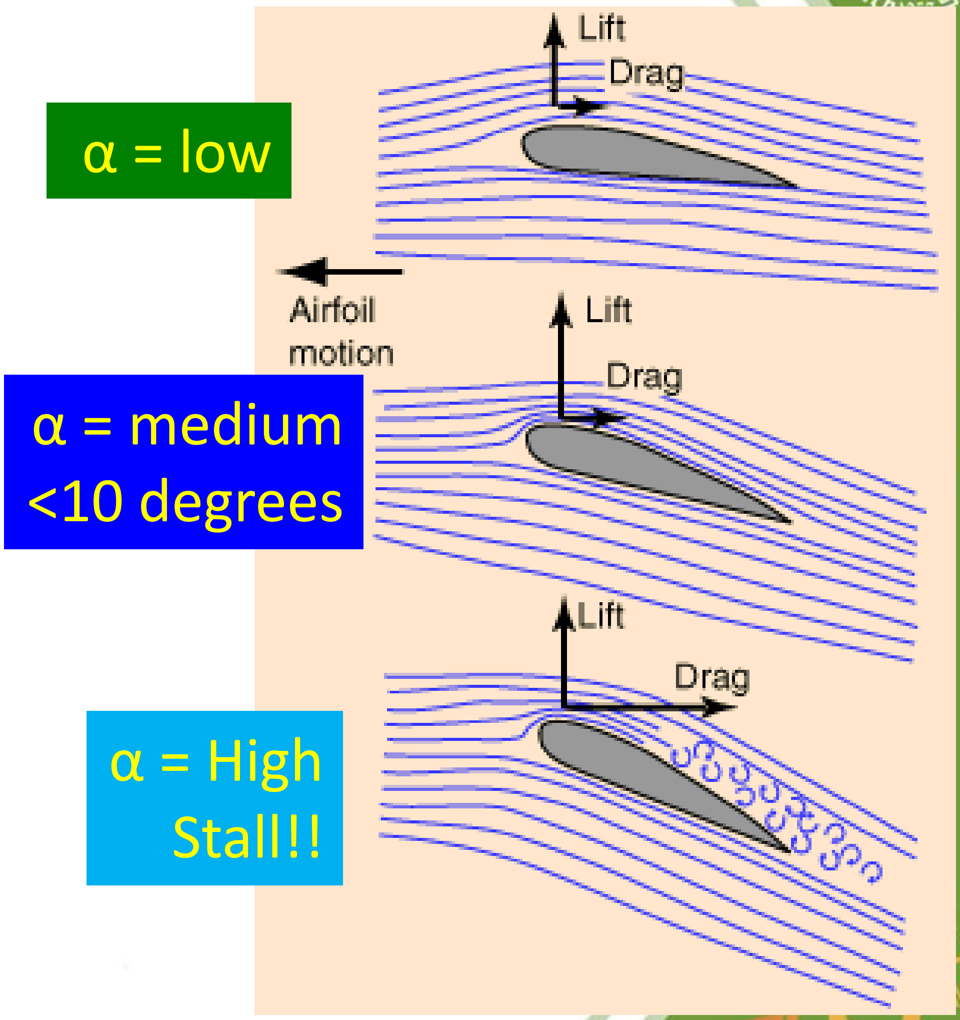
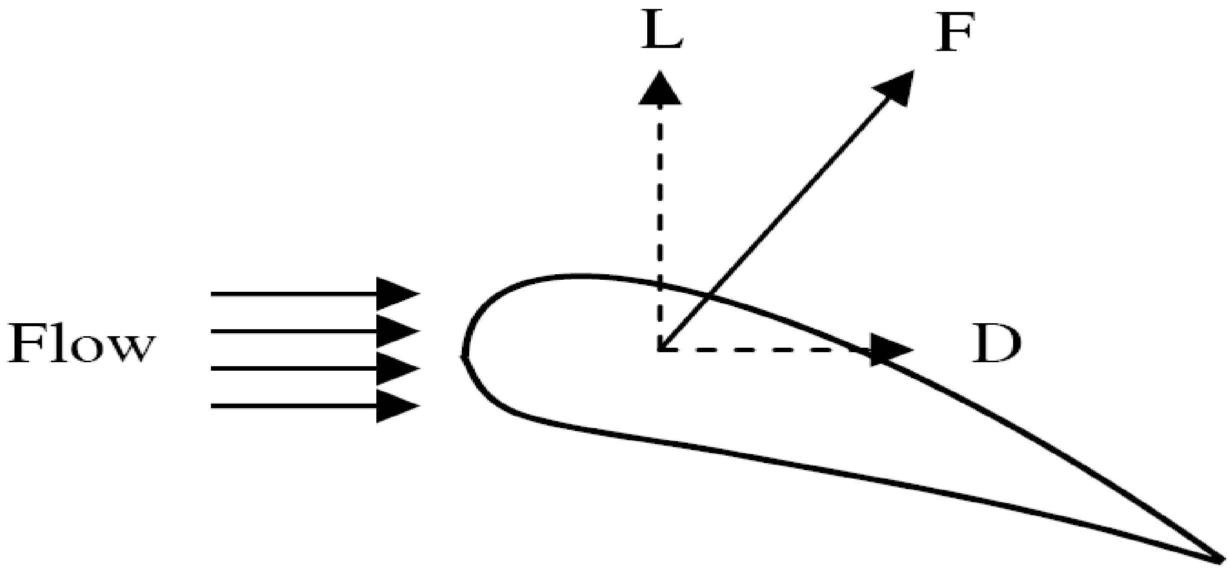
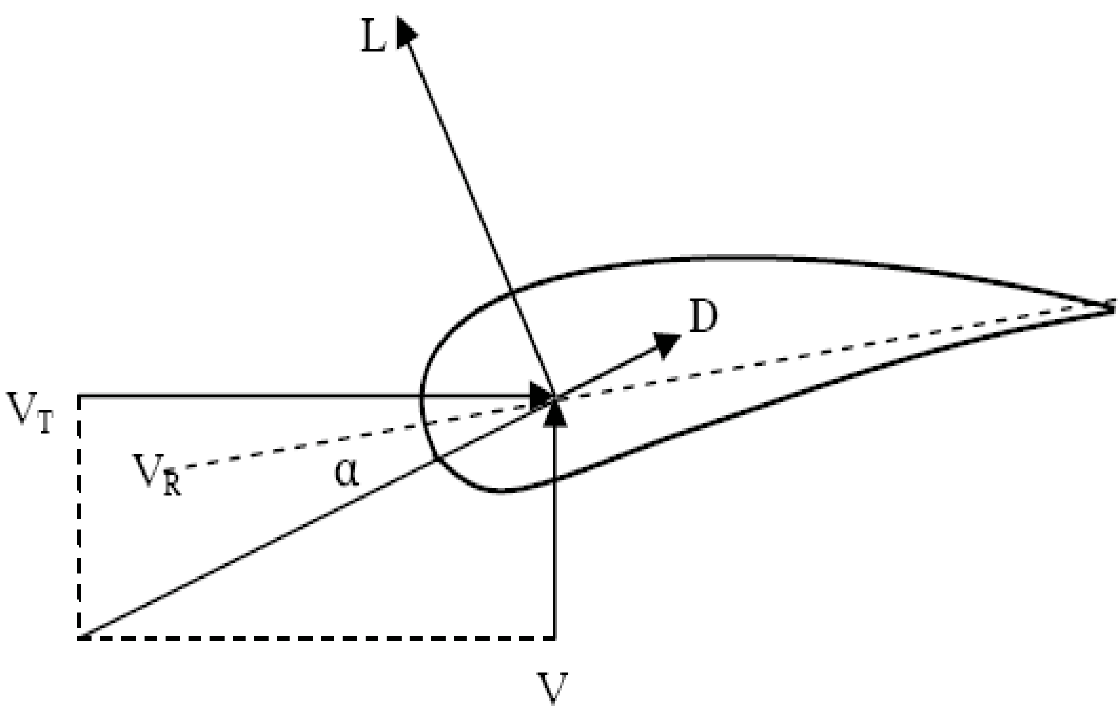
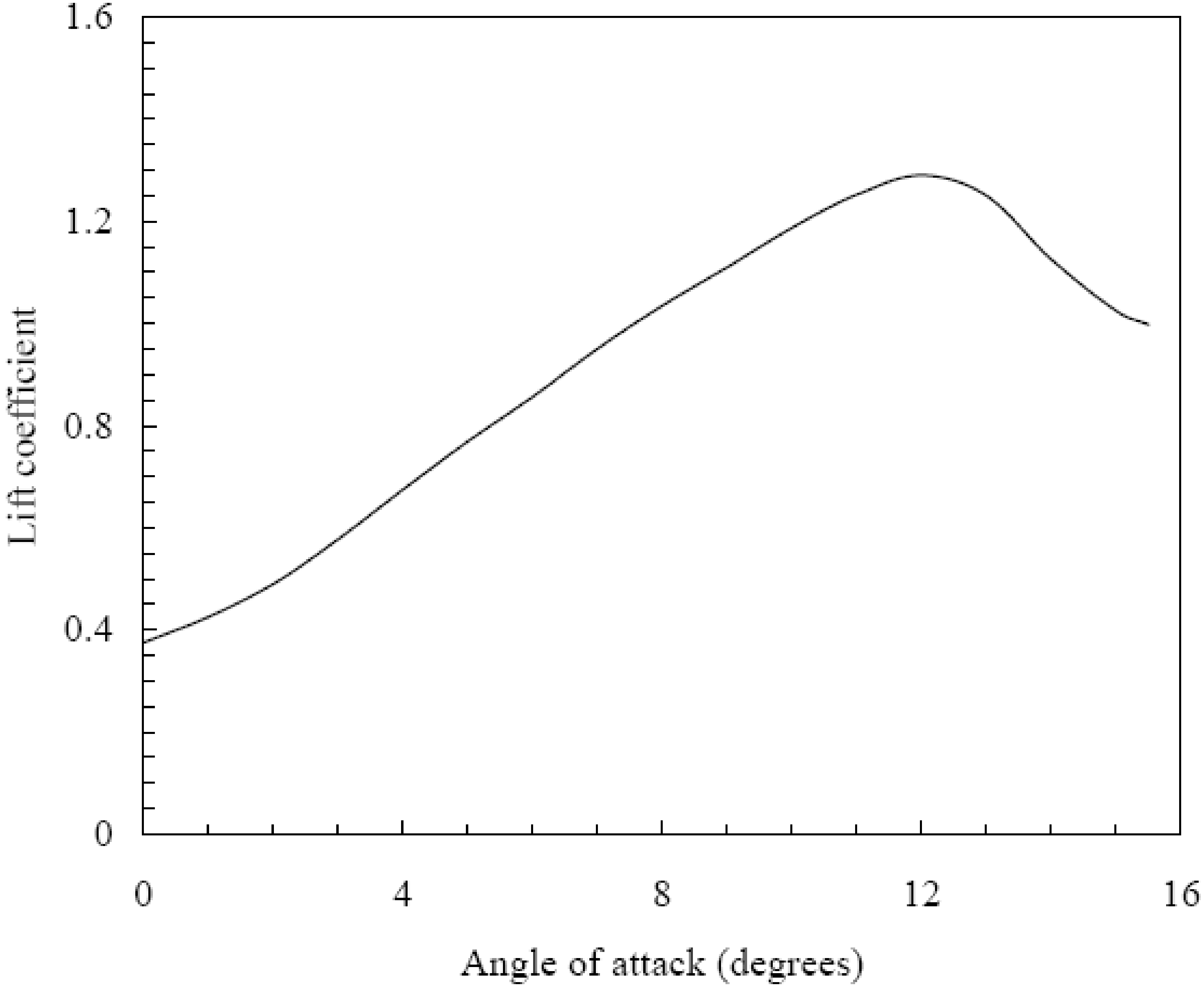
- **The *Drag Force* is parallel to the direction of motion. We want to make this force small.**



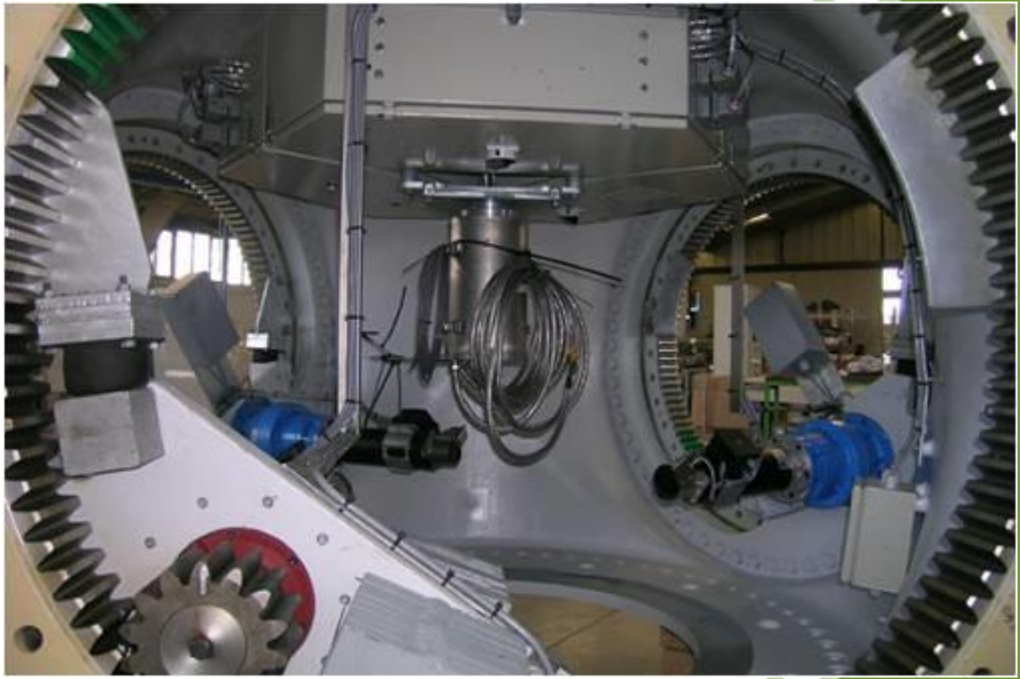

L
F
Flow
D


L
D
V_T
V_R
α
V



Effect of angle of attack on airfoil lift

Pitch Control Mechanisms



BRAKING MECHANISM

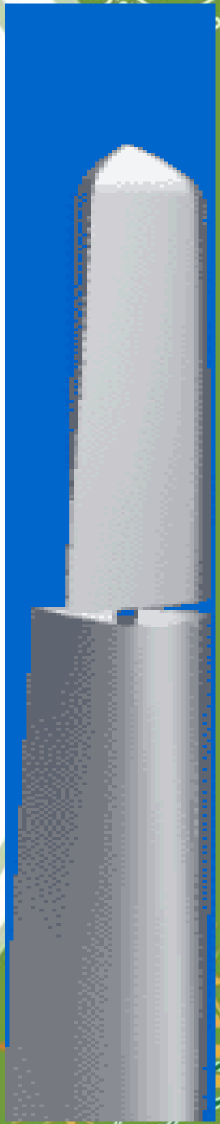
- **It essential for turbines to stop automatically in case malfunction of components.**
- **Thus, it is necessary to have an over speed safety system.**
- **There are two types of braking:-**

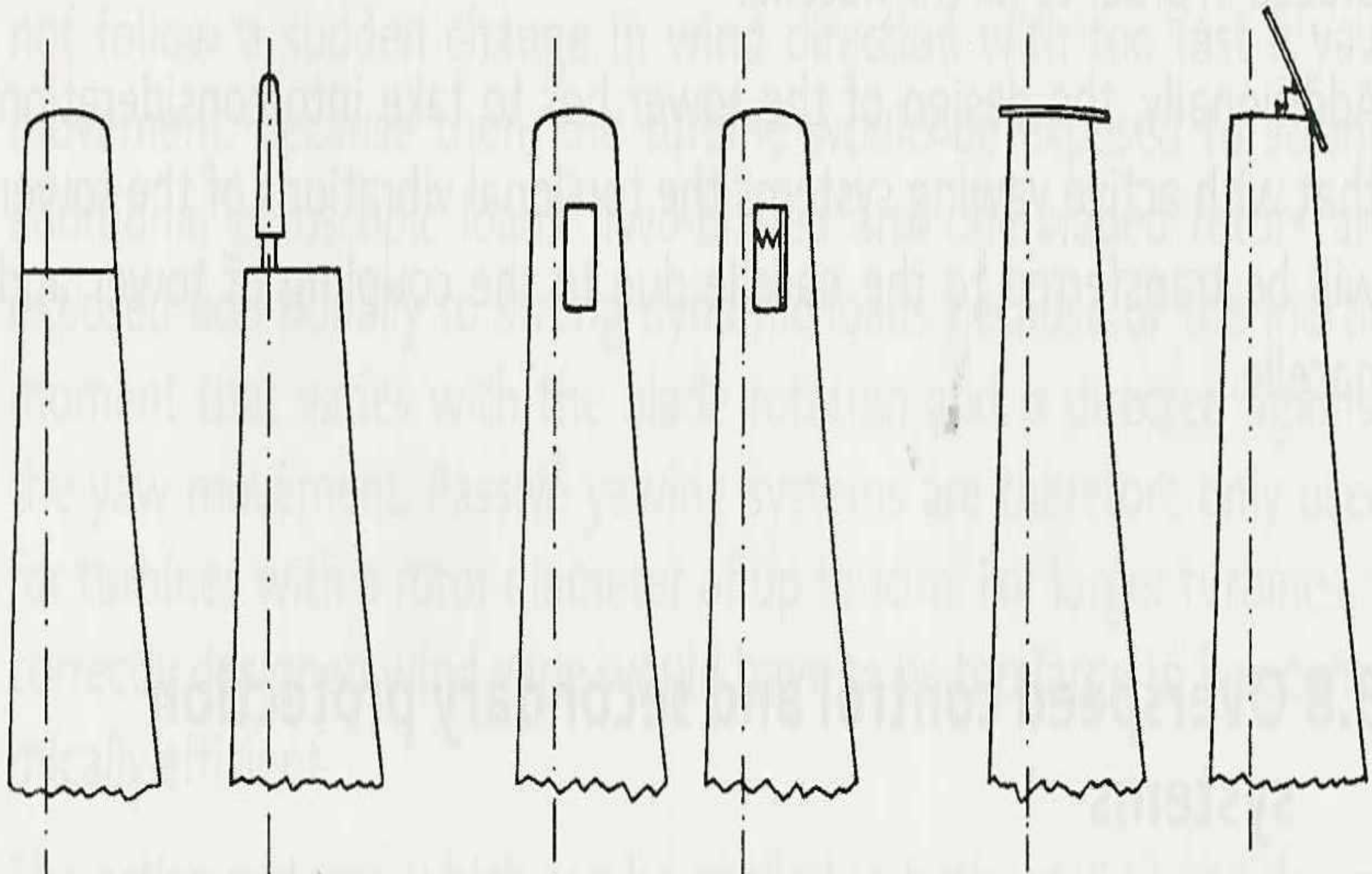
  1.aerodynamic braking system

  2.mechanical breaking system

1.Aerodynamic braking system

- It consists of turning the rotor blades or tips about 90^0 about the longitudinal axis.
- They are spring operated and thus work even in case of power failure.
- They have a very gentle and secure way of stop the rotor thus avoiding the damage.
- They are extremely safe .





MECHANICAL BRAKING SYSEM

- they act as back-up for other mechanism.

Control Mechanisms

Its purpose is to:

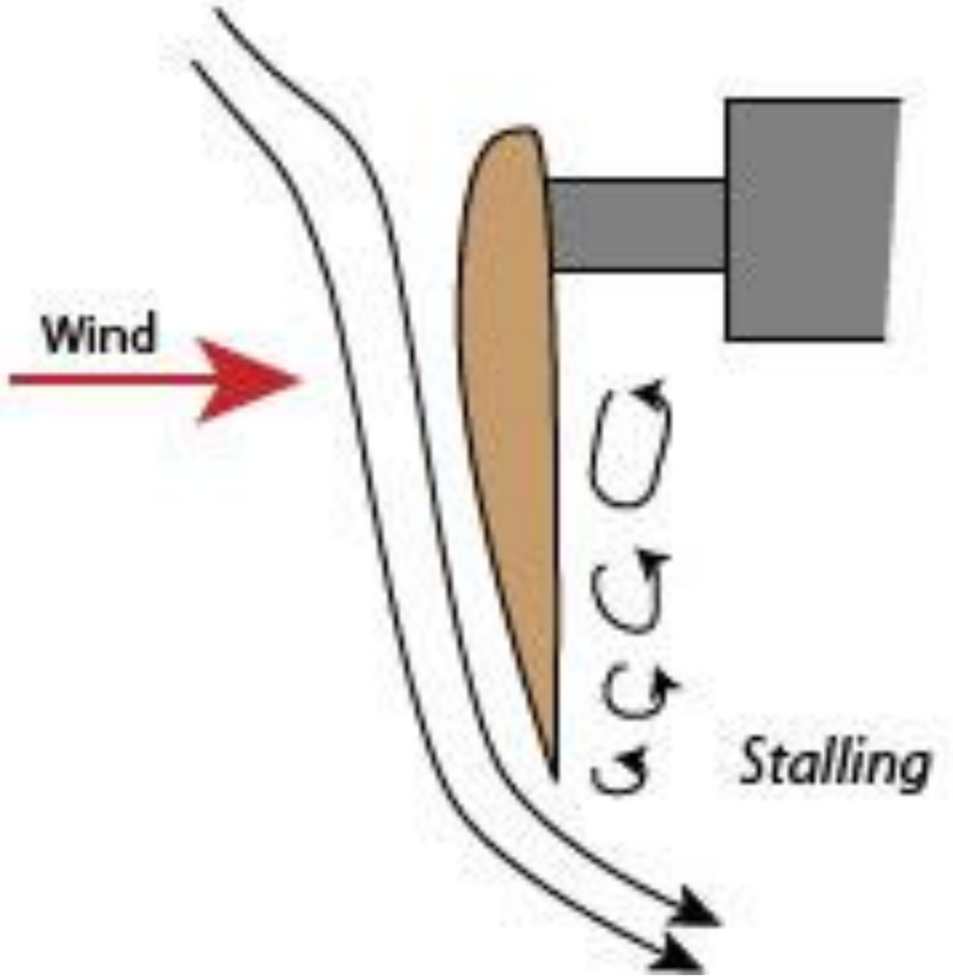
■Optimize aerodynamic efficiency,

■Keep the generator with its speed and torque limits and rotor and tower within strength limits,

■Enable maintenance, and,

■Reduce noise.

Stalling (Losing power) Principle: Increased angle of attack results in decreasing lift-to-drag ratio.



The schematic representing the *Stalling* control regulator.

Passive: Blades are at a fixed pitch that starts to stall when the wind speed is too high.

■Active: motor turns the blades towards stall when wind speeds are too high.

■Hybrid: Pitch can be adjusted manually to reflect site's particular wind regime.

■Disadvantages:

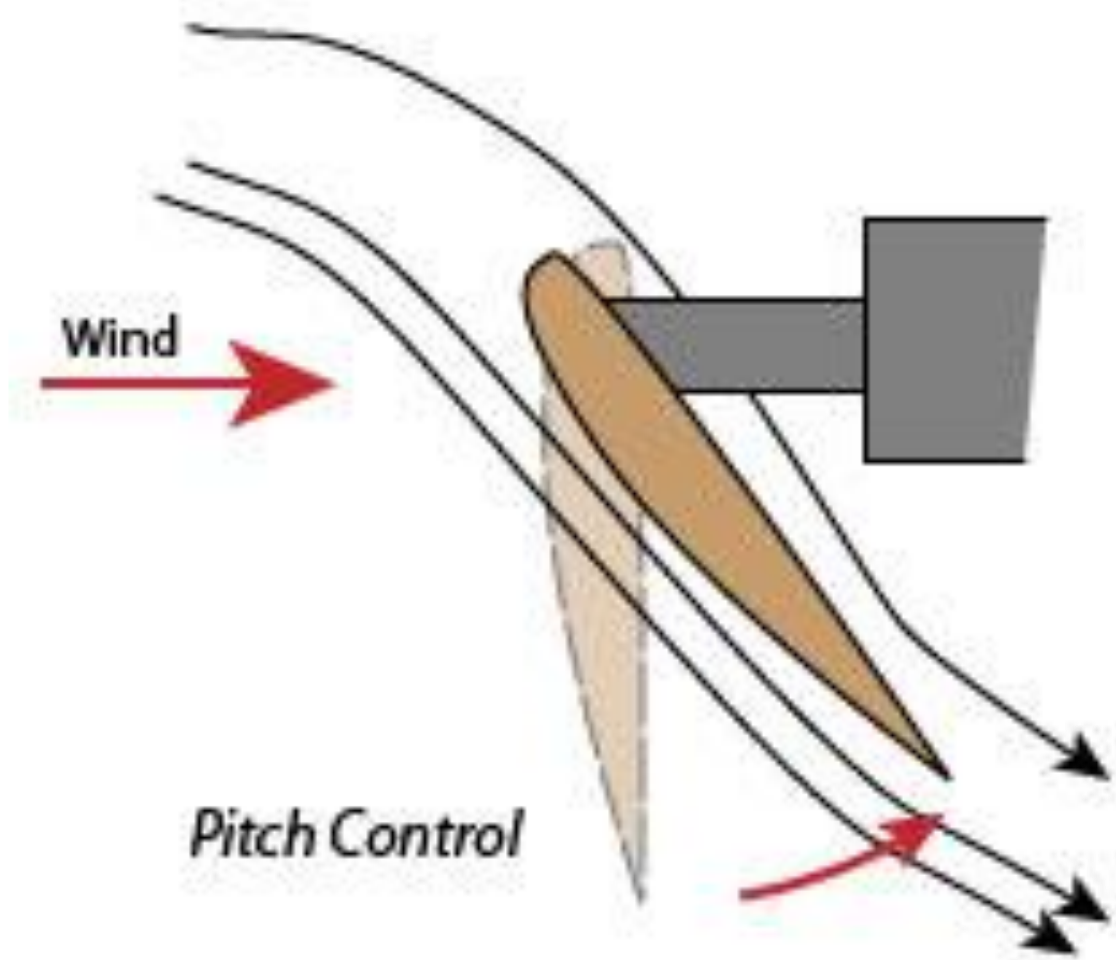
1- Stalled blades cause large vibration and therefore noise.

2- The aerodynamic power on the blades is limited. Such slow aerodynamic
power regulation causes less power fluctuations than a fast-pitch power regulation.

3-lower efficiency at low wind speeds

4- It needs startup means.

***Pitch Control Principle*: Decrease angle of attack also results in decreasing lift-to-drag ratio.**



The schematic representing the pitch control regulator.

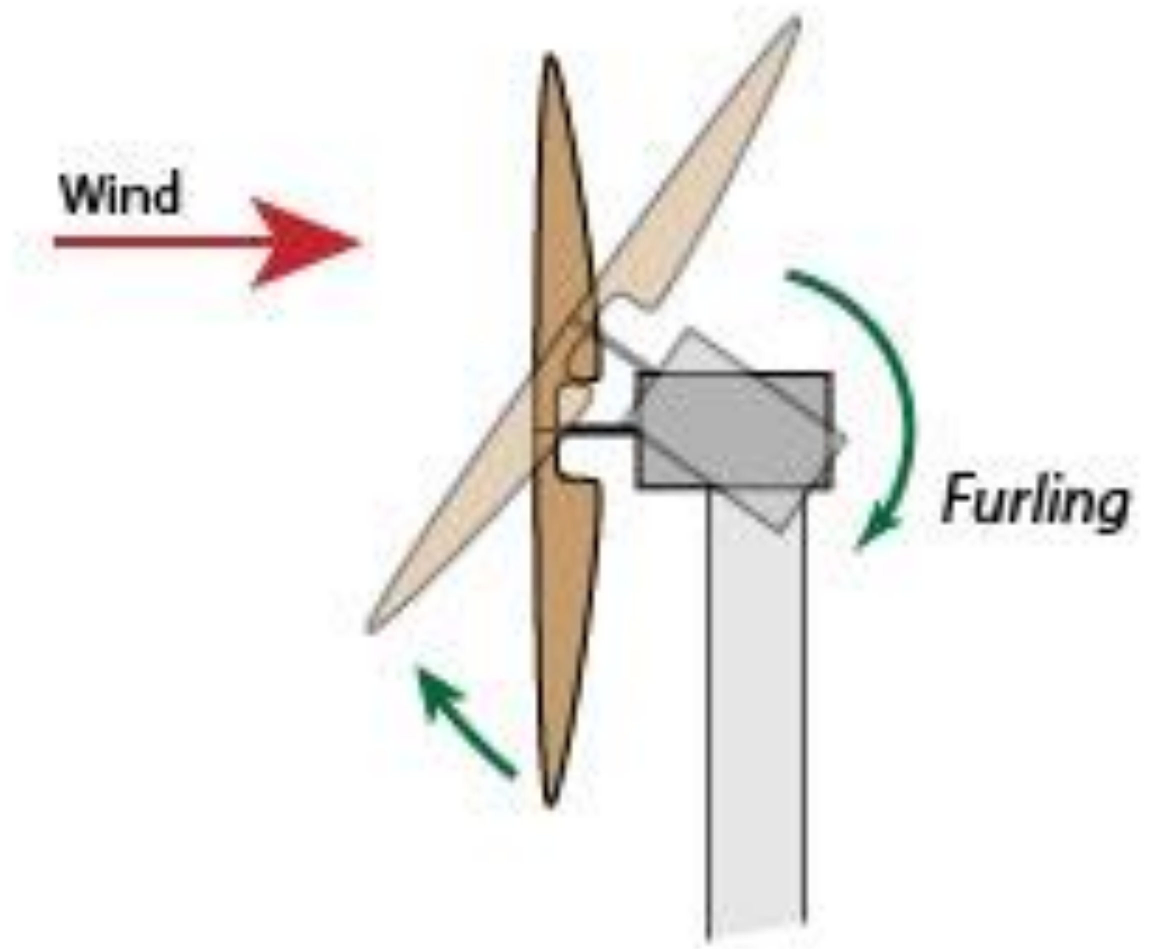
Always active control: Blades rotate out of the wind when wind speeds are too high.

The advantages of this technique are:

- good power control,
- No need for startup means.
- It can be combined with emergency stop means.

The main disadvantage of this technique is the extra complexity arising from the pitch mechanism and the higher power fluctuations at high wind speeds.

Furling Principle: Moving the axis out of the direction of the wind decreases angle of attack and cross-section



The schematic representing the *Furling* control regulator.

■Requires active pitch control: Pitch angle of the blades needs to be minimized first, otherwise the torque on the rotor would be too big for furling.

■Active: Vertical furling (as diagram) with hyrdraulic, spring-loaded or electric motor driven.

■Passive: Horizontal furling with yaw.

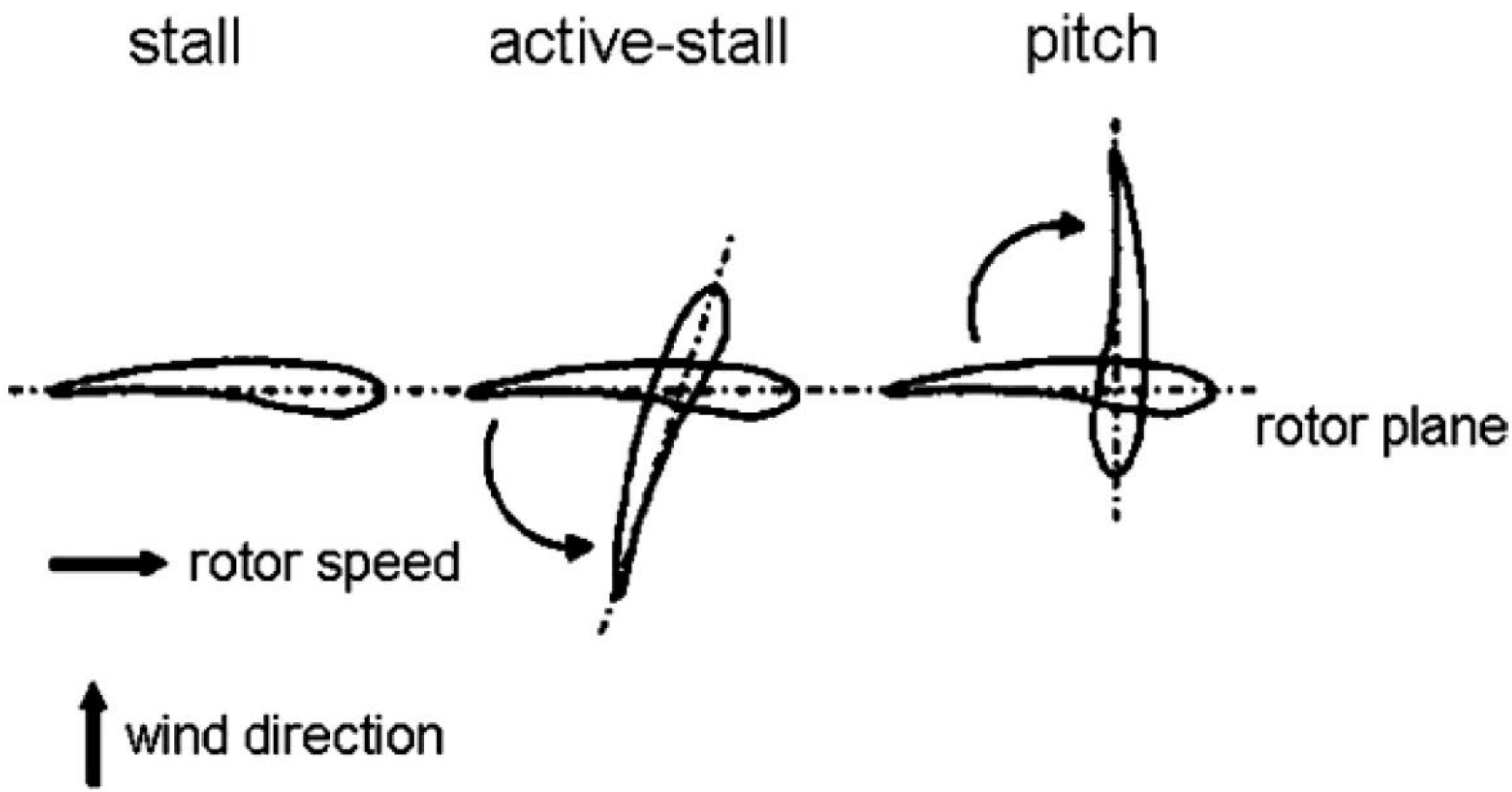
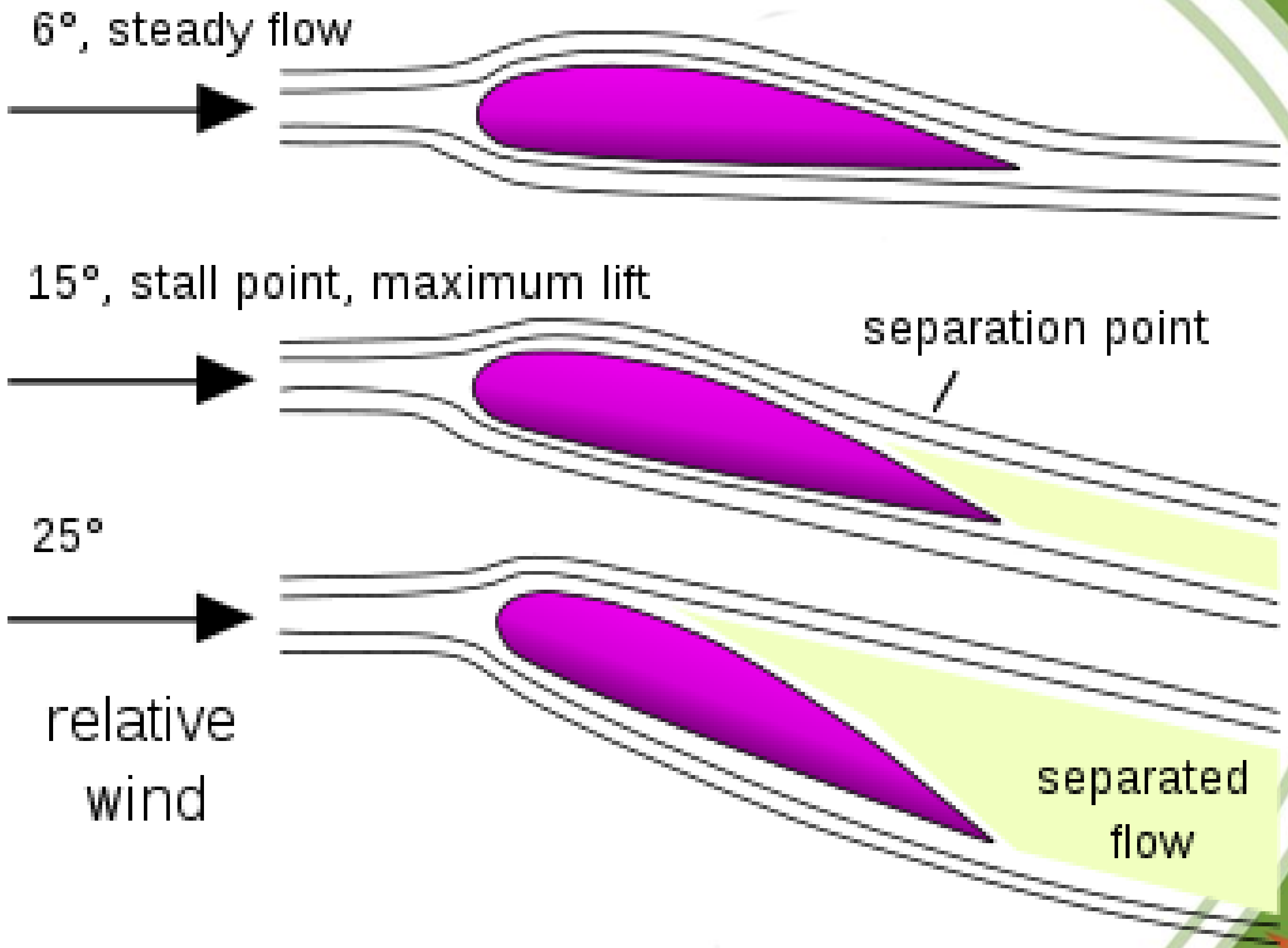
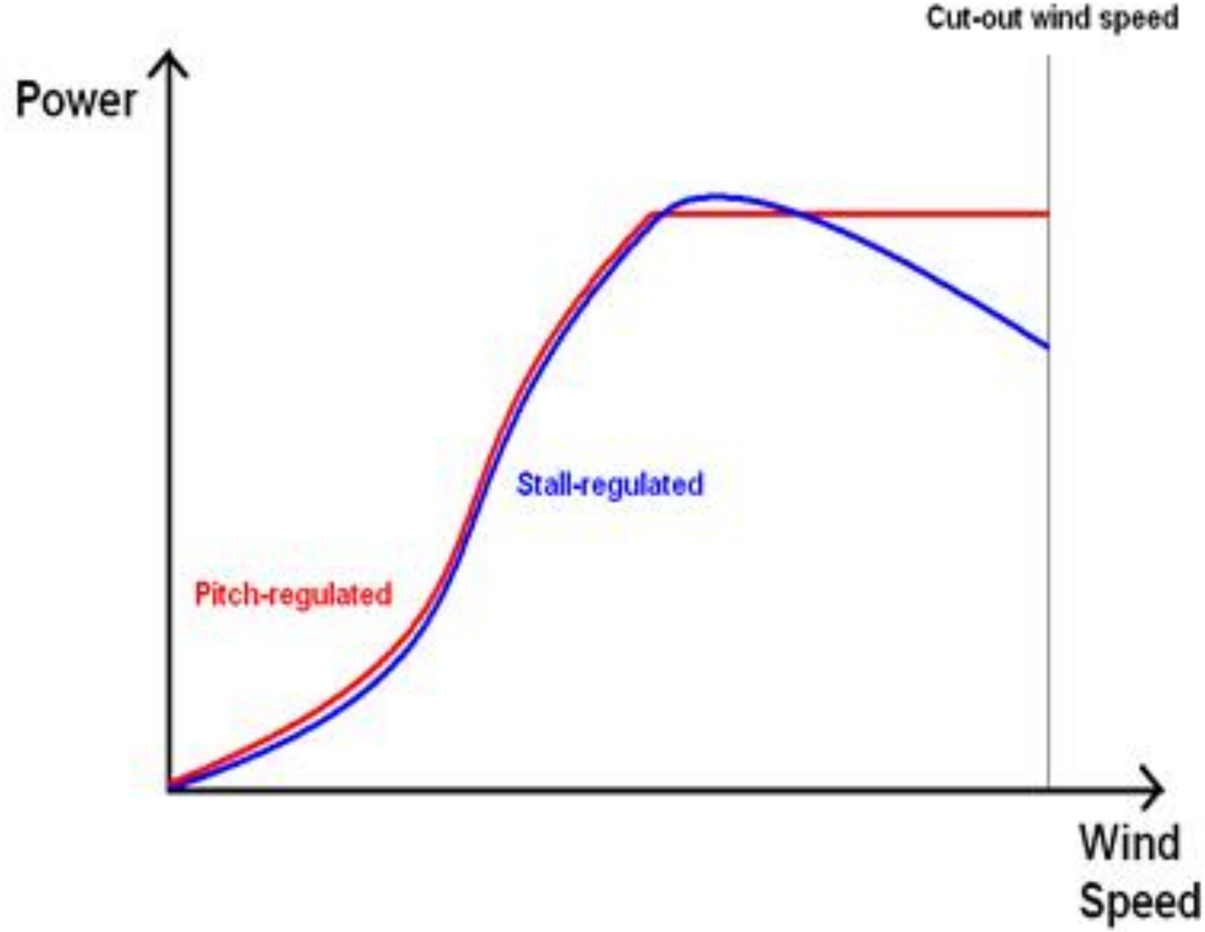


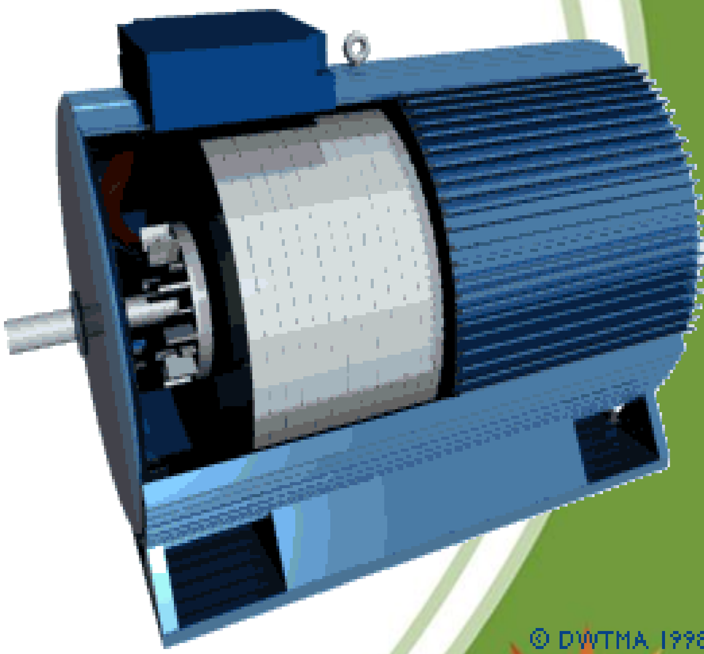
Illustration of stall, active-stall and pitch effects.


6°, steady flow
15°, stall point, maximum lift
separation point
25°
relative wind
separated flow


Cut-out wind speed
Power
Stall-regulated
Pitch-regulated
Wind
Speed

GENERATOR

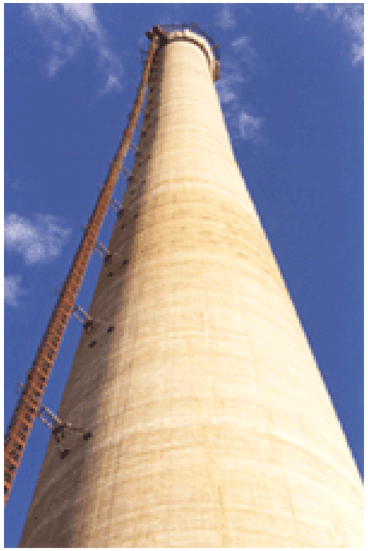
- They are a bit different than other turbines b'coz they have to handle changing mechanical torque.
- They usually produce around 690 V, 50 or 60 Hz, 3 phase ac.



Towers

Lattice tower

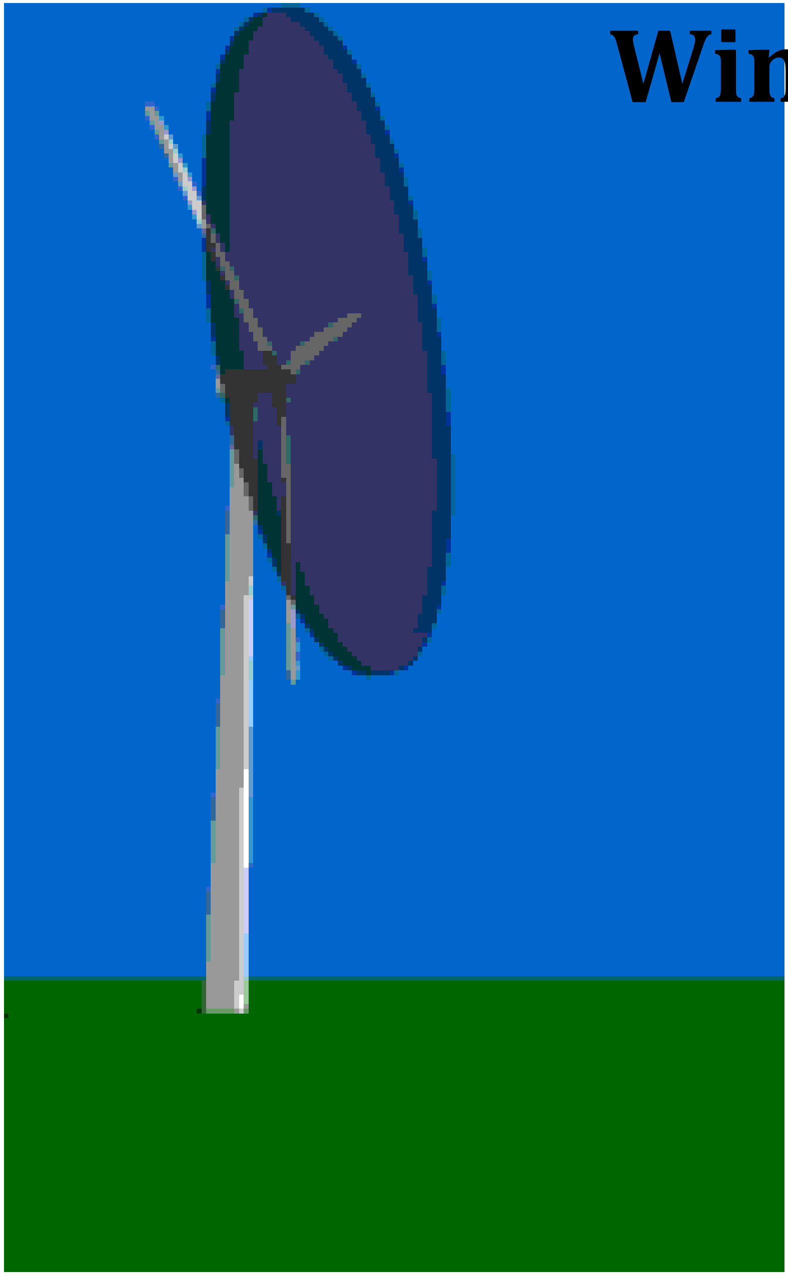
Guyed Pole Tower



Concrete tower

Tubular steel towers,

Wind Power



1.Sitting of Wind Energy Plants

Wind Power

The power in the wind can be defined as follows,

$$P_w = \frac{1}{2}\,\rho_a\;A\,V^3$$

where ρ_a : Air density, kg/m^3.

A: Cross sectional area of wind parcel, m^2.

V: The wind speed, m/sec.

$$V(Z) = V(Zg) * \left(\frac{Z}{Zg}\right)^{\alpha}$$

where Z : The height above the ground level, m.

Zg : The height of where the wind speed is measured, m.

α : The exponent, which depends on the roughness of the ground surface, its average value, is (1/7) [14].

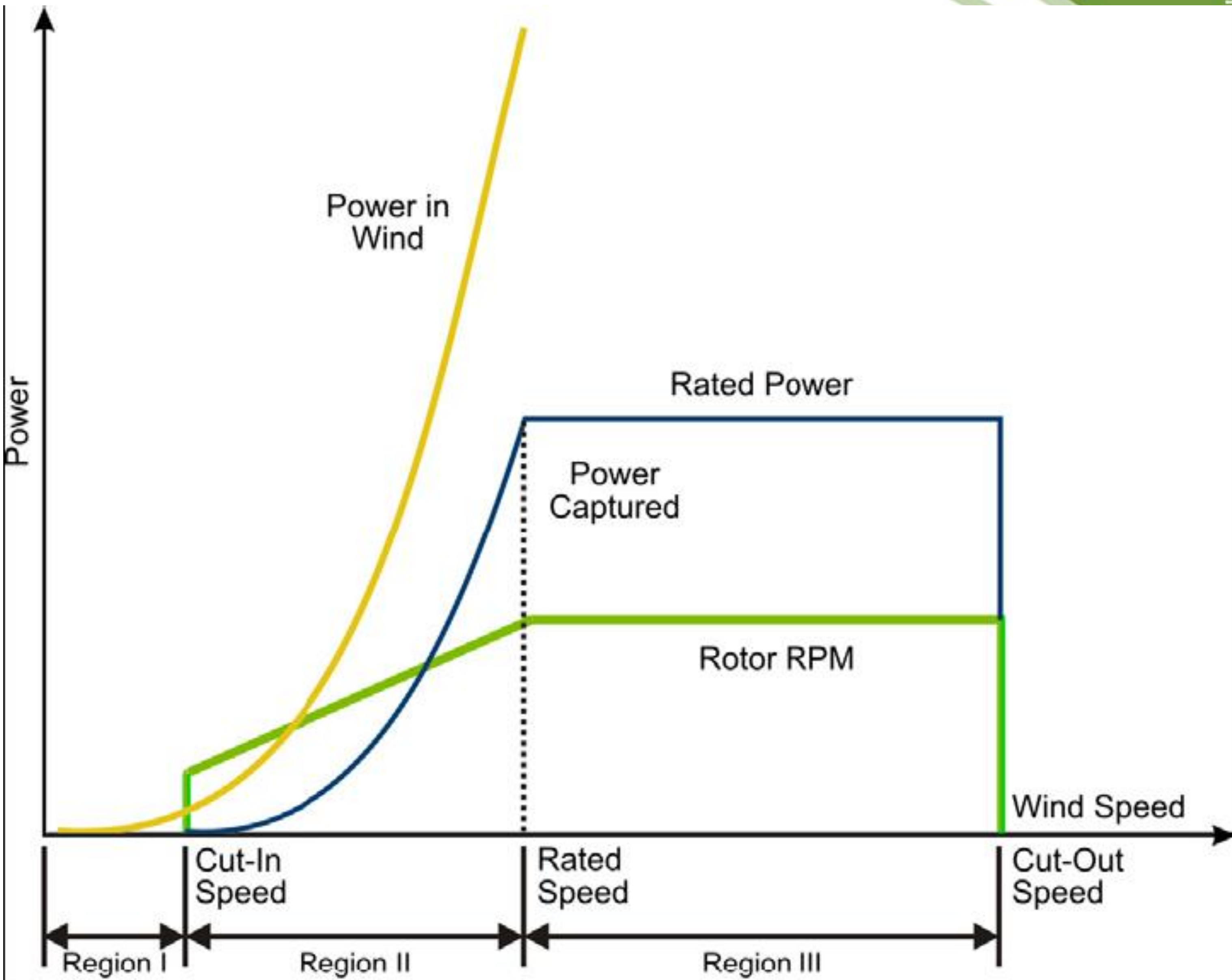
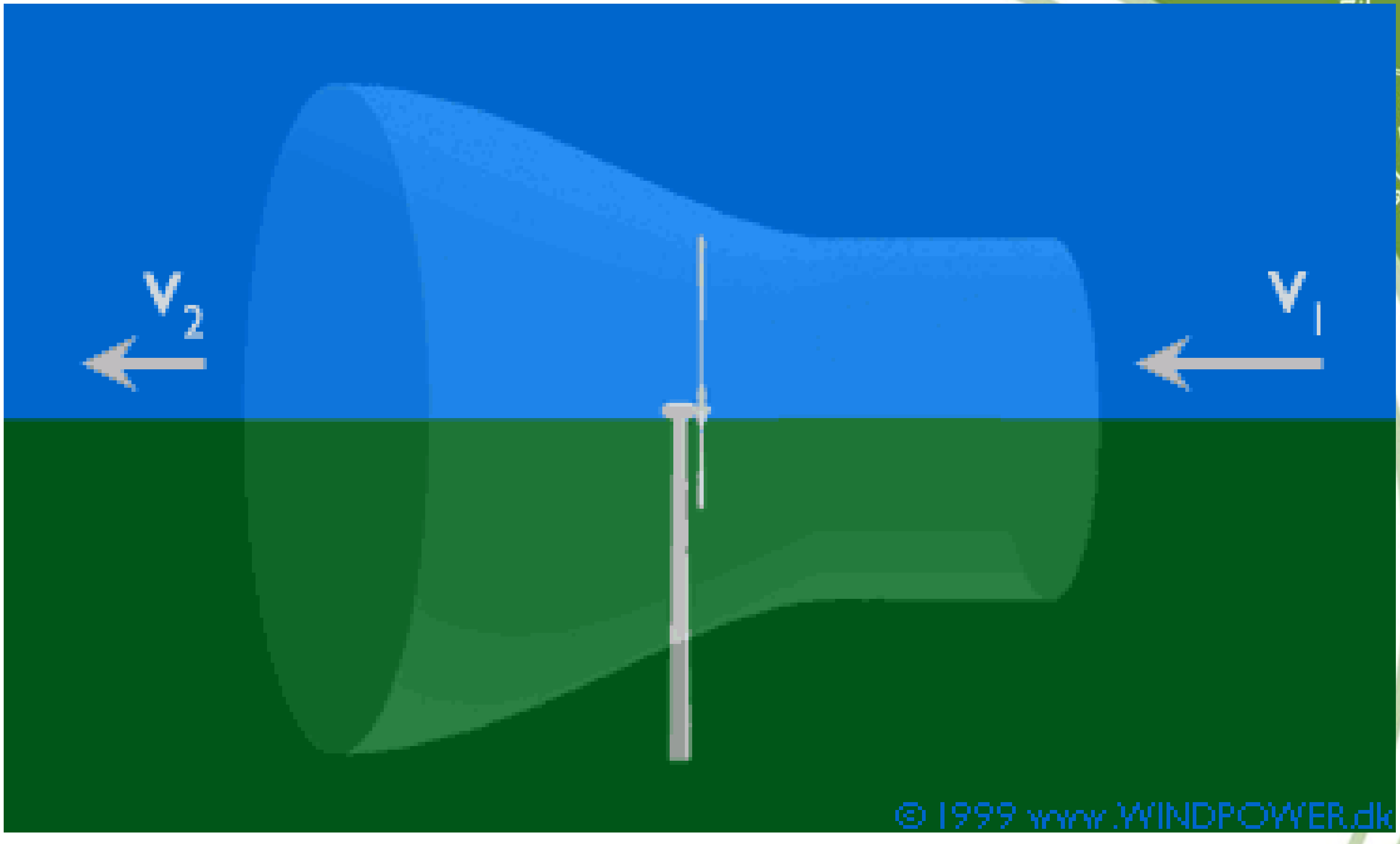


Fig. 1.22 Actual WT output power with the wind speed.

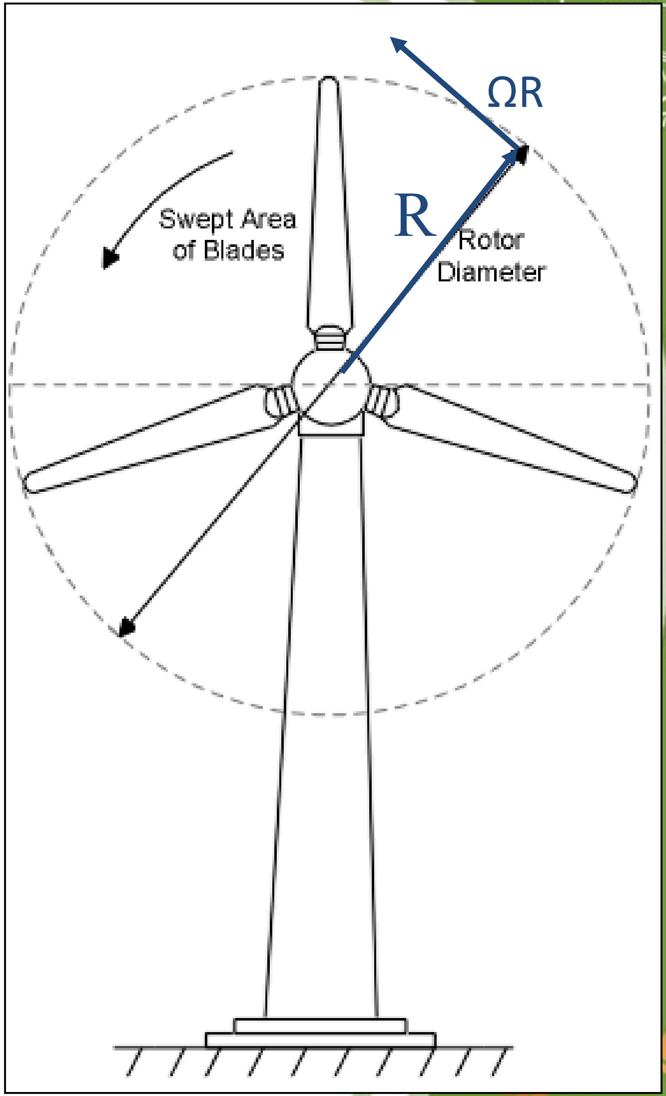


Betz' Law

Betz: law says that you can only convert less than 16/27 (or 59%) of the kinetic energy in the wind to mechanical energy using a wind turbine.

Tip-Speed Ratio

- Tip-speed ratio is the ratio of the speed of the rotating blade tip to the speed of the free stream wind.
- There is an optimum angle of attack which creates the highest lift to drag ratio.
- Because angle of attack is dependant on wind speed, there is an optimum tip-speed ratio



$$TSR = \frac{\Omega R}{V}$$

Where,

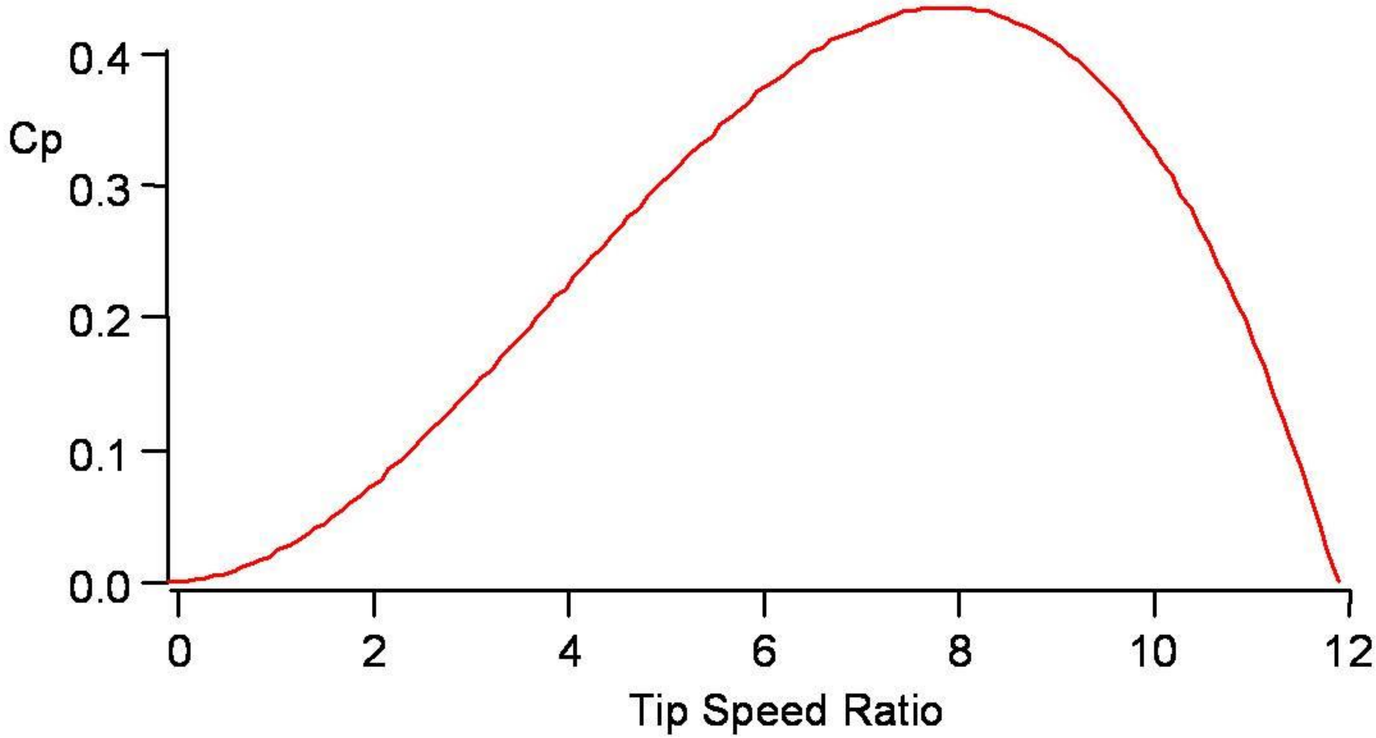
Ω = rotational speed in radians /sec

R = Rotor Radius

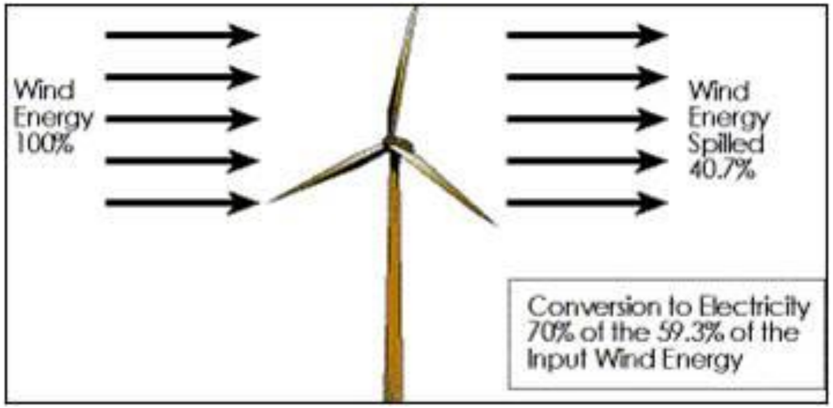
V = Wind "Free Stream" Velocity

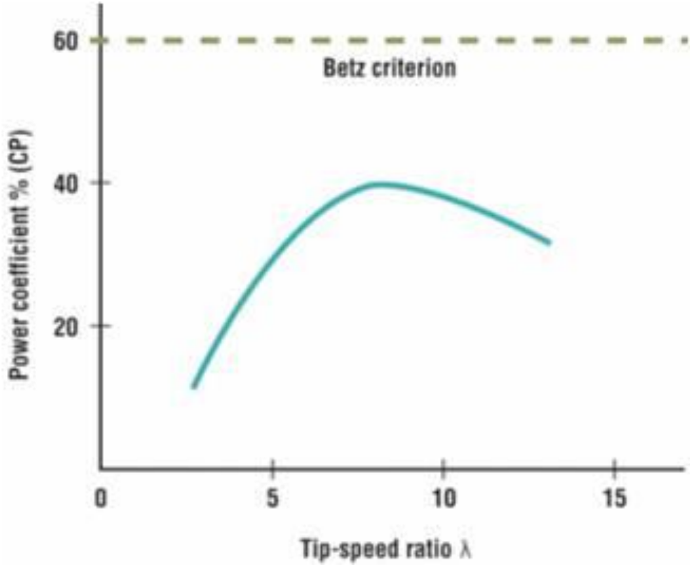
Performance Over Range of Tip Speed Ratios

- Power Coefficient Varies with Tip Speed Ratio
- Characterized by Cp vs Tip Speed Ratio Curve



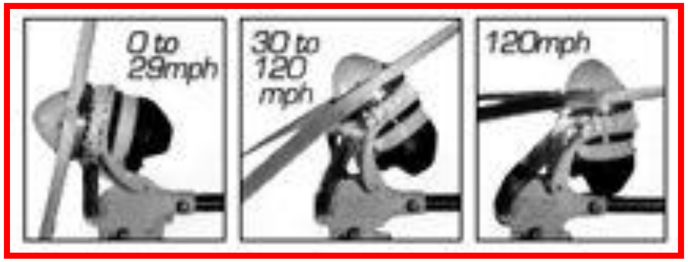
Betz Limit

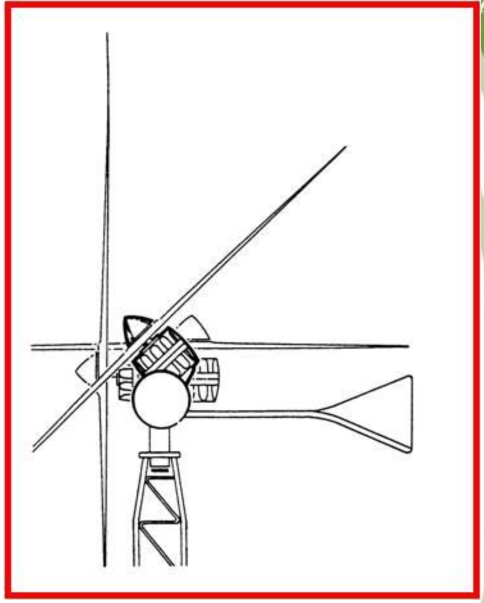




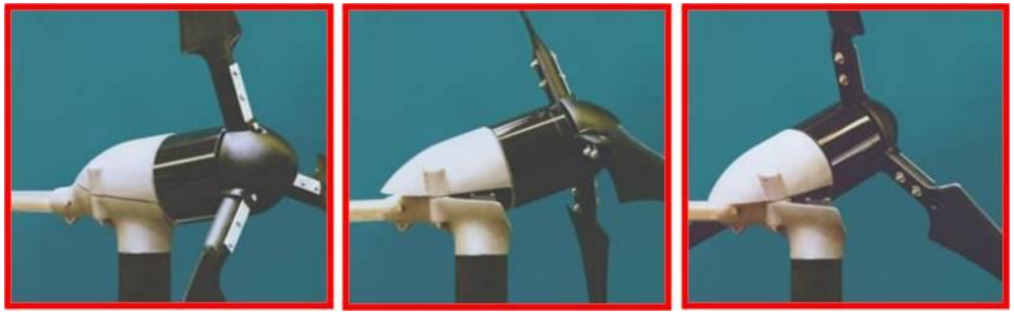
- All wind power cannot be captured by rotor or air would be completely still behind rotor and not allow more wind to pass through.
- Theoretical limit of rotor efficiency is 59%
- Most modern wind turbines are in the 35 – 45% range

Over-Speed Protection During High Winds





Upward Furling: The rotor tilts back during high winds



Angle Governor: The rotor turns up and to one side

Rotor Design

$$P_D = \frac{1}{2} C_{PD} \eta_d \eta_g \rho_a A_T V_D^3$$

$$R = \sqrt{\frac{2P_D}{C_{PD}\eta_d\eta_g\rho_a \pi V_D^3}}$$

$$R = \sqrt{\frac{2E_A}{\eta_s\rho_a \pi V_D^3 T}}$$

1. Radius of the rotor (R)
2. Number of blades (B)
3. Tip speed ratio of the rotor at the design point (λ_D)
4. Design lift coefficient of the airfoil (C_{LD})
5. Angle of attack of the airfoil lift (α)

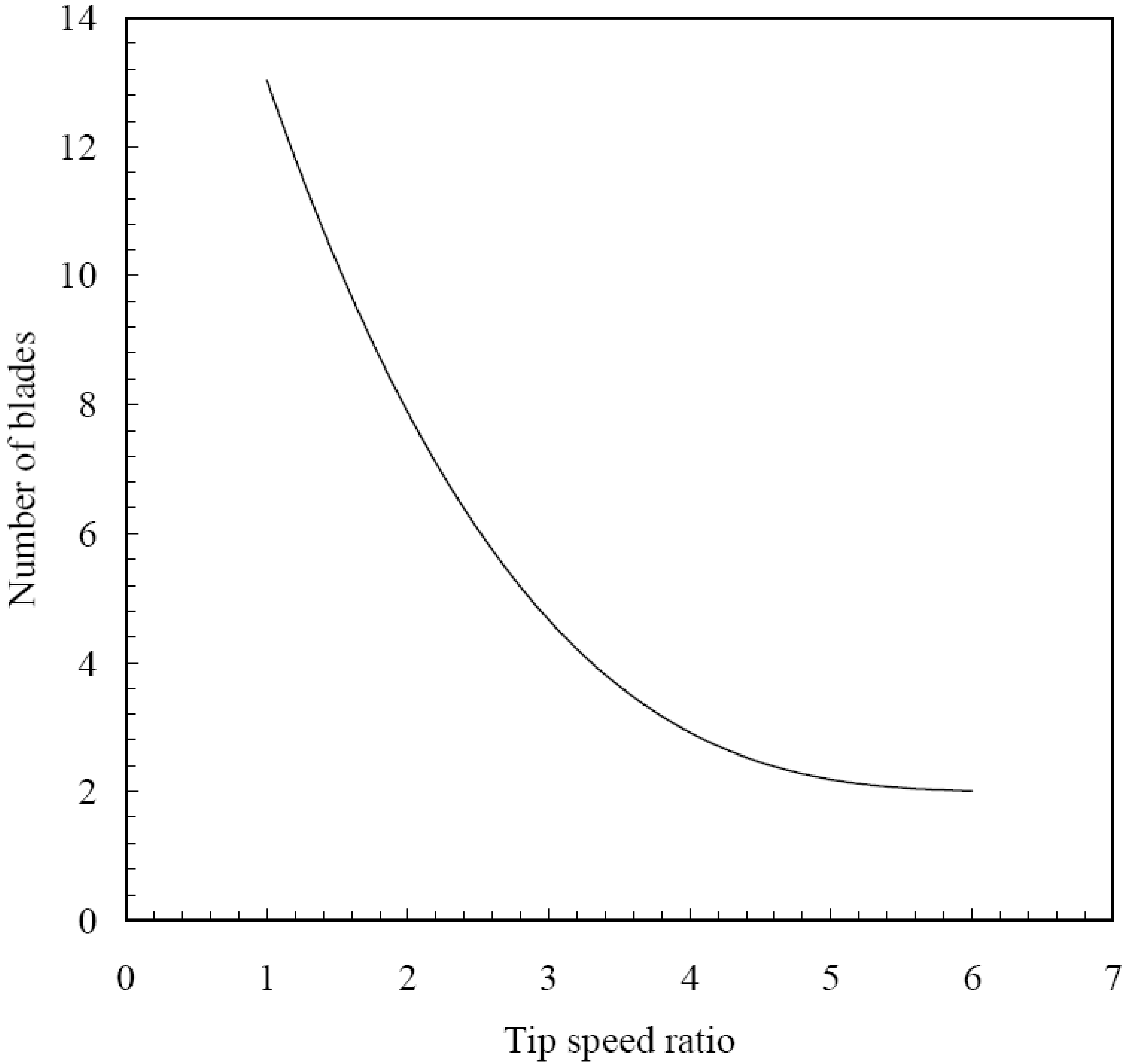


Fig.1.23. Number of blades and design tip speed ratio

Example

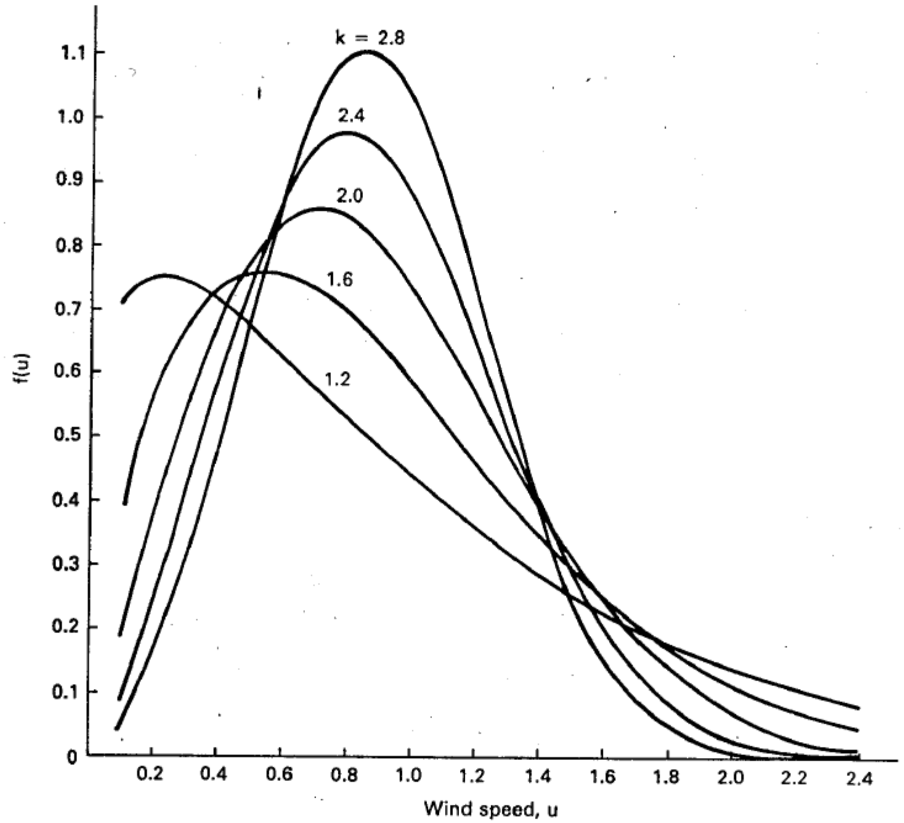
Design the rotor for a WT develop 100 W at a wind speed of 7 m/s. NACA 4412 airfoil may be used for the rotor.

Let us take the design power coefficient as 0.4 and the combined drive train and generator efficiency 0.9. Taking the air density as 1.224 kg/m3, from Equation (1.7), the rotor radius is:

$$R = \left[\frac{2 \times 100}{0.4 \times 0.9 \times 1.224 \times \pi \times 7^3} \right]^{\frac{1}{2}} = 0.65\,m$$

Weibull Statistics

$$f(u) = \frac{k}{c}\left(\frac{u}{c}\right)^{k-1} \exp\left(-\left(\frac{u}{c}\right)^{k}\right), \quad (k > 0, u > 0,\ c > 1)$$



$$c = 1.12\,\bar{u} \qquad (1.5 \le k \le 3.0)$$

Weibull density function $f(u)$ for scale parameter $c = 1$.

Example

The Weibull parameters at a given site are c = 6 m/s and k = 1.8. Estimate the number of hours per year that the wind speed will be between 6.5 and 7.5 m/s. Estimate the number of hours per year that the wind speed is greater than or equal to 15 m/s. From Eq. (1.25), the probability that the wind is between 6.5 and 7.5 m/s is just $f(7)$, which can be evaluated from Eq. (1.21) as:

$$f(7) = \frac{1.8}{6}\left(\frac{7}{6}\right)^{1.8-1} \exp\left(-\left(\frac{7}{6}\right)^{1.8}\right) = 0.0907$$

This means that the wind speed will be in this interval 9.07 % of the time, so the number of hours per year with wind speeds in this interval would be;

0.0907*8760=794 hr.

From Eq. (1.24), the probability that the wind speed is greater than or equal to 15 m/s is

$$P(u \geq 15) = \exp\left(-\left(\frac{15}{6}\right)^{1.8}\right) = 0.0055$$

which represents

0.0055*8760=48 h/year

Determining the Weibull Parameters

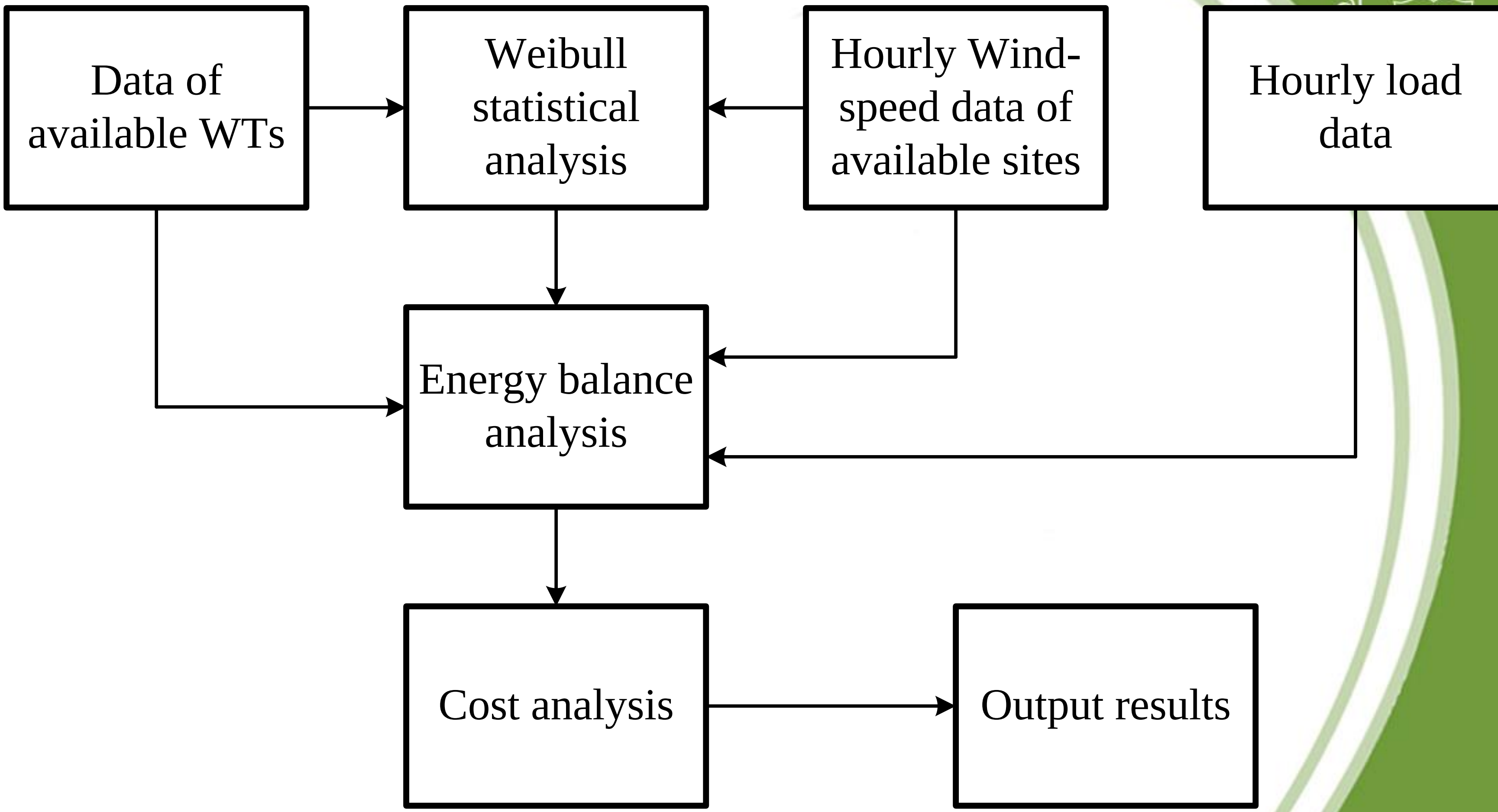
$$k=\left(\frac{\sigma}{\bar{u}}\right)^{-1.086} \qquad \sigma^2=c^2\left[\Gamma\left(1+\frac{2}{k}\right)-\Gamma^2\left(1+\frac{1}{k}\right)\right]=(\bar{u})^2\left[\frac{\Gamma(1+2/k)}{\Gamma^2(1+1/k)}-1\right]$$

$$c=\frac{\bar{u}}{\Gamma(1+1/k)} \qquad c=1.12\bar{u}, \qquad (1.5\le k\le 3.0)$$

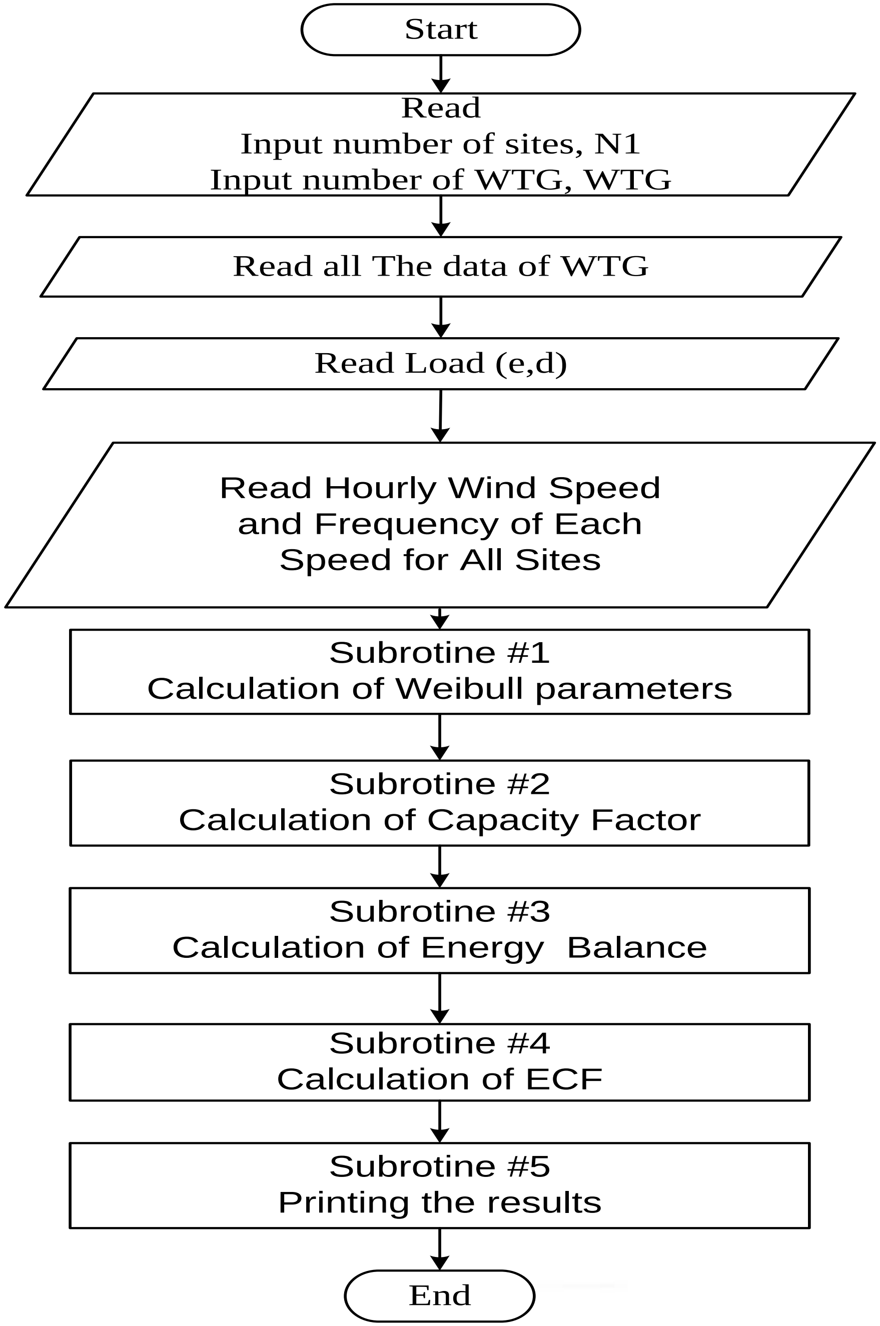
$$P_{eave}=P_{eR}\left\{\frac{\exp\left[-(u_c/c)^k\right]-\exp\left[-(u_R/c)^k\right]}{(u_R/c)^k-(u_c/c)^k}-\exp\left[-(u_F/c)^k\right]\right\}$$

$$NWT=\frac{P_{L\,av}}{P_{eave}}$$

Design of Wind Energy System



Summarized block diagram of the analysis



Flowchart of the main computer program.

Project Development

element of wind farm	% of total cost
Wind Turbines	65
Civil Works	13
Wind farm electrical infrastructure	8
Electrical network connection	6
Project development and management costs	8

Wind Farms


FLOWIND
FLOWIND
INTERACTING WITH MINIATURE RAILROADING 2008

- A '*wind farm* is a group of wind turbines in the same location used for production of electric power.

- Individual turbines are interconnected with a medium voltage (usually 34.5 kV) power collection system and communications network.

- At a substation, this medium-voltage electrical current is increased in voltage with a transformer for connection to the high voltage transmission system

- A large wind farm may consist of a few dozen to several hundred individual wind turbines, and cover an extended area of hundreds of square miles (square kilometers), but the land between the turbines may be used for agricultural or other purposes.

- A wind farm may be located off-shore to take advantage of strong winds blowing over the surface of an ocean or lake.

Factors Affecting A wind Farm

- Location
- Wind speed
- Altitude
- Wind park effect
- Environmental and aesthetic impacts
- Effect on power grid

Types of Wind Farms

- Off-Shore
- On-Shore
- Near-Shore
- Air borne

Off-shore

On-shore

- **Onshore**

Onshore turbine installations in hilly or mountainous regions tend to be on ridgelines generally three kilometers or more inland from the nearest shoreline. This is done to exploit the so called topographic acceleration as the wind accelerates over a ridge.

- **Nearshore**

Nearshore turbine installations are on land within three kilometers of a shoreline or on water within ten kilometers of land. These areas are good sites for turbine installation, because of wind produced by convection due to differential heating of land and sea each day. Wind speeds in these zones share the characteristics of both onshore and offshore wind, depending on the prevailing wind direction.

OffShore

Offshore wind development zones are generally considered to be ten kilometers or more from land. Offshore wind turbines are less obtrusive than turbines on land, as their apparent size and noise is mitigated by distance.

In stormy areas with extended shallow continental shelves, turbines are practical to install.

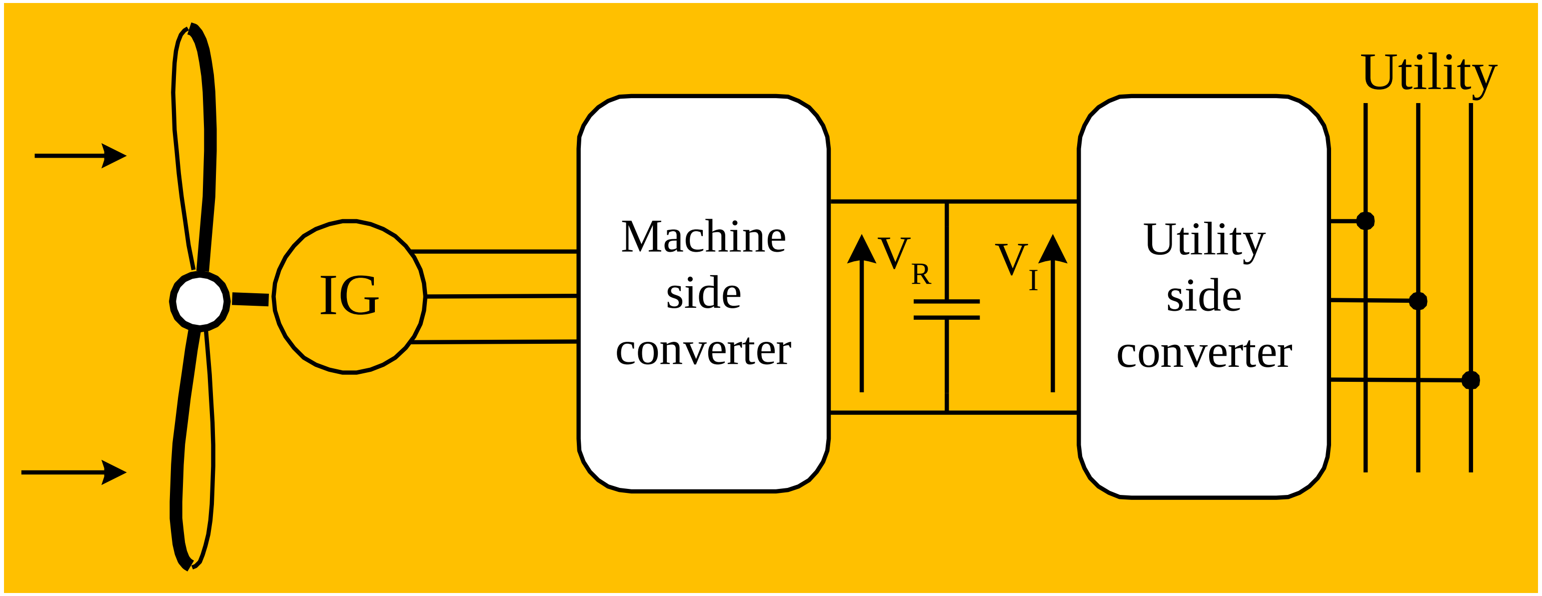
Offshore installation is more expensive than onshore but this depends on the attributes of the site.

Airborne

Airborne wind turbines would eliminate the cost of towers and might also be flown in high speed winds at high altitude. No such systems are in commercial operation.

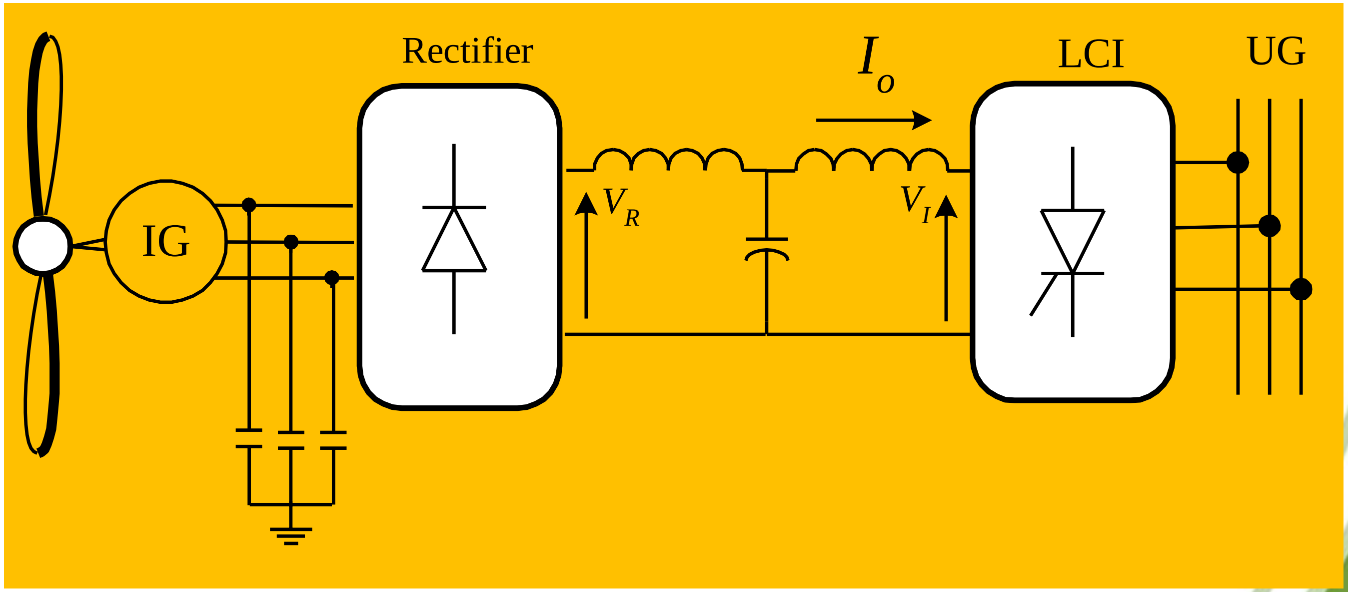
Utility Interface Options for Wind, Photovoltaic and Fuel Cell Energy Systems

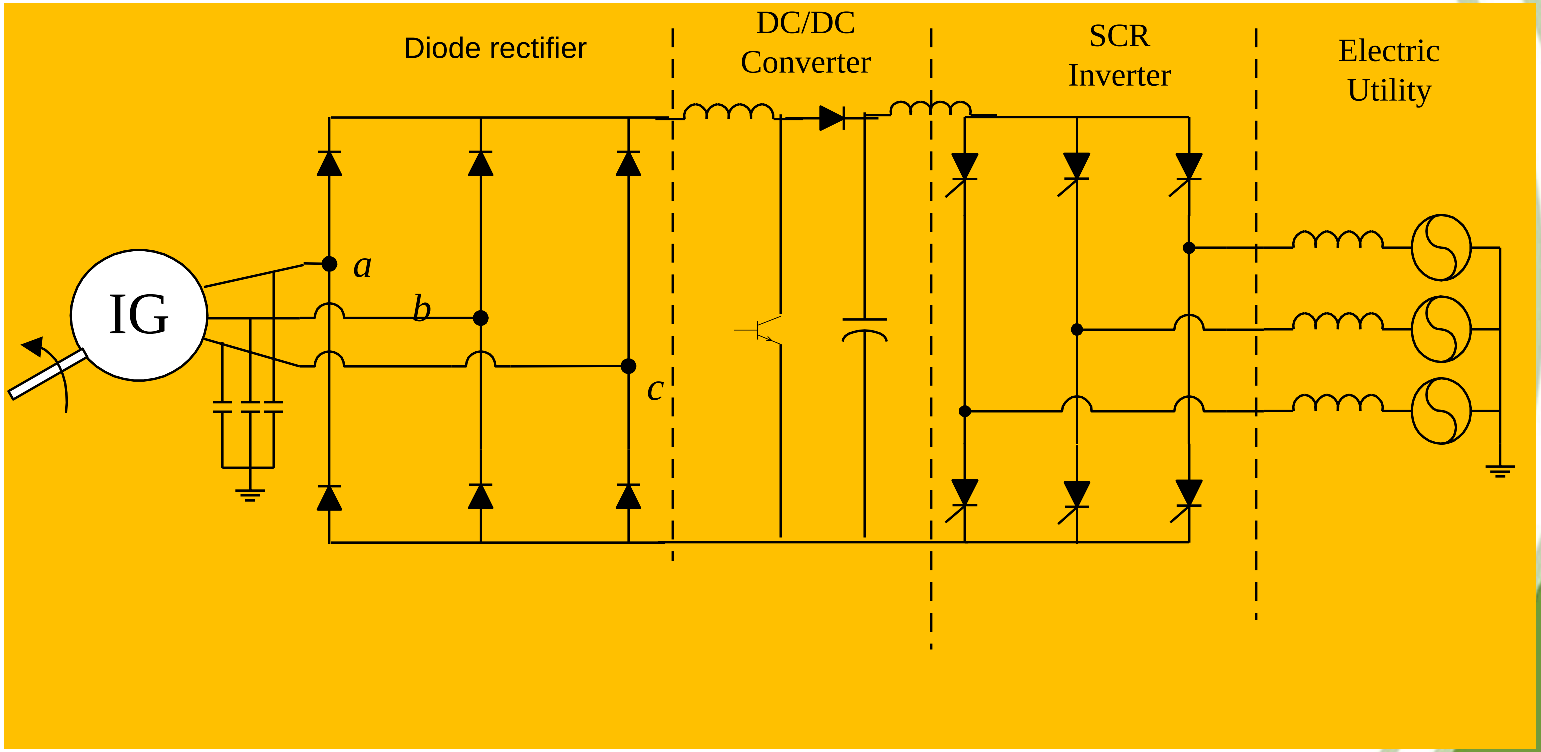
Interconnection of Induction Generator with Electric Utility



Scheme #1

Self Excited Induction Generator Equipped with Diode Rectifier / LCI Inverter

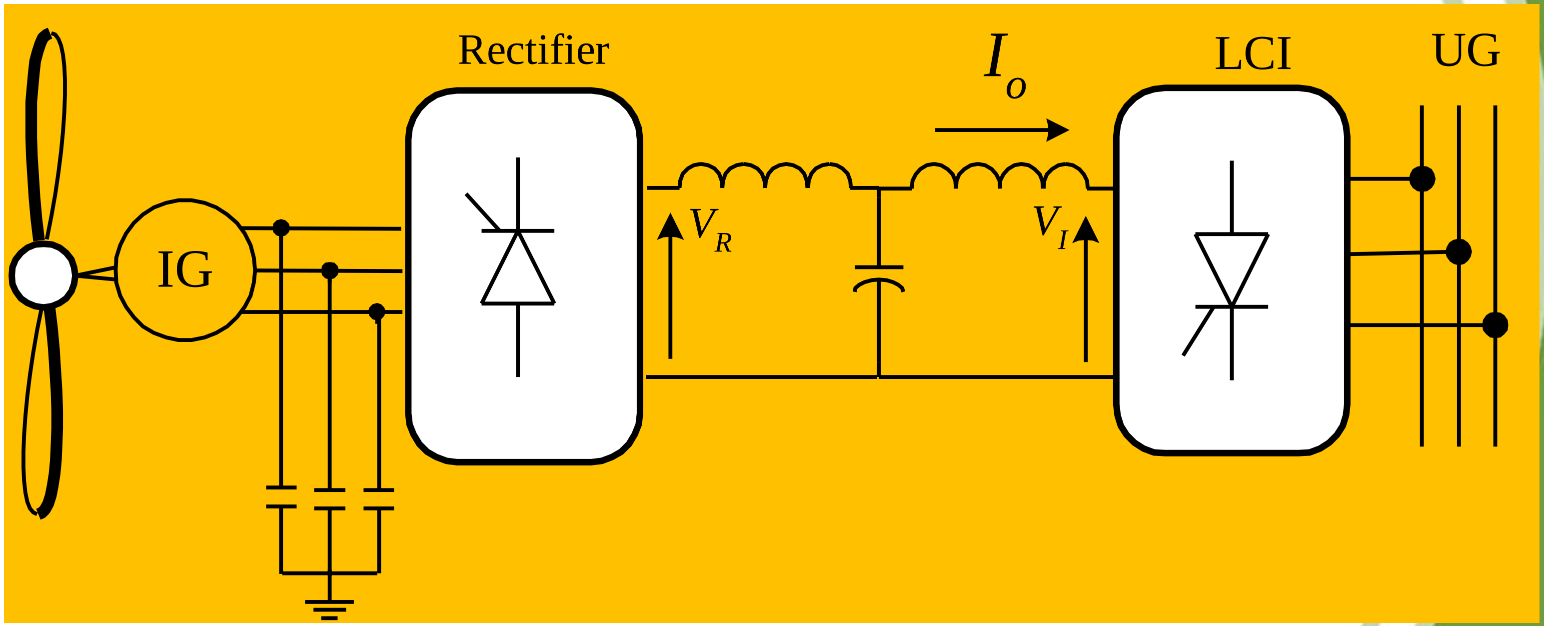


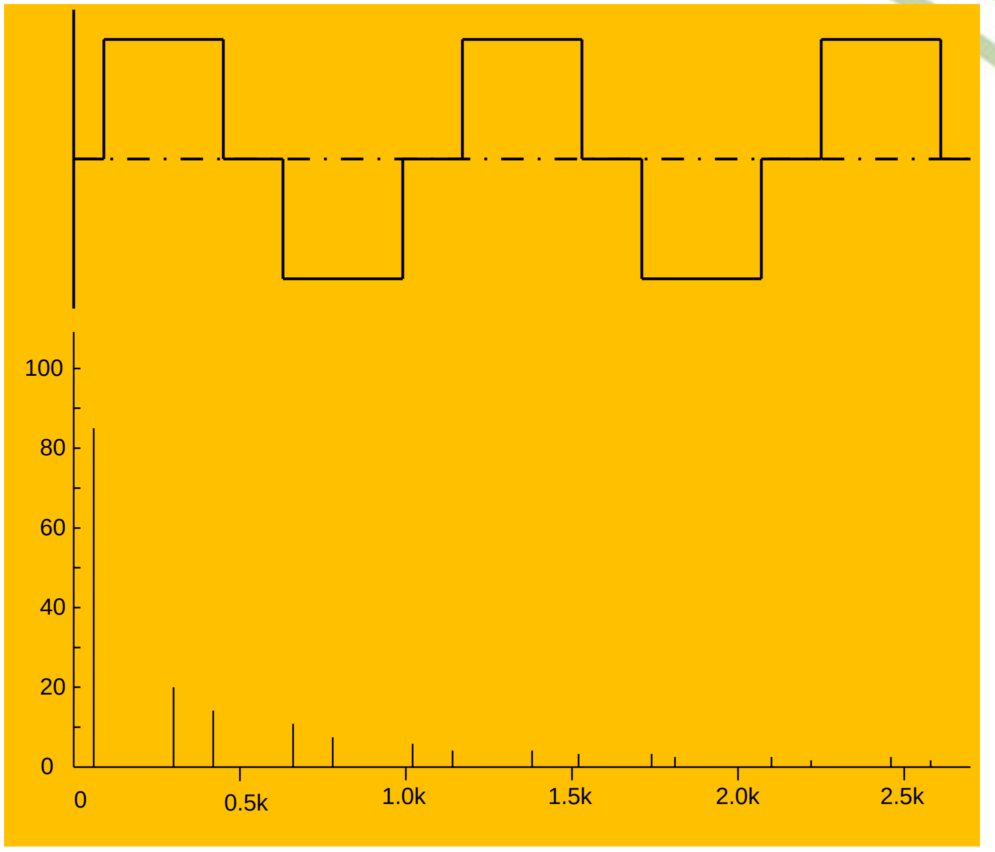


DC-Link Voltage Control

Scheme #2

Self Excited Induction Generator Equipped with SCR Rectifier / LCI Inverter

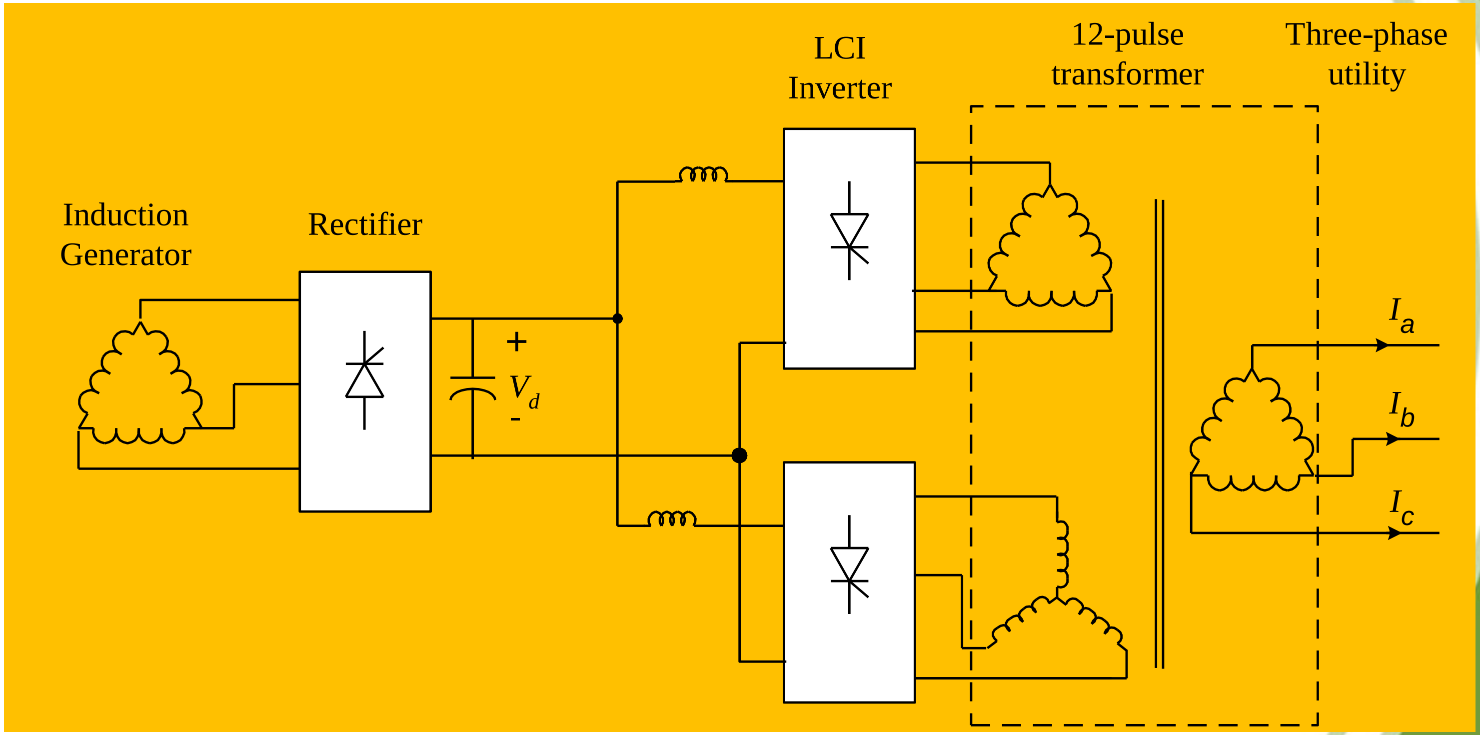


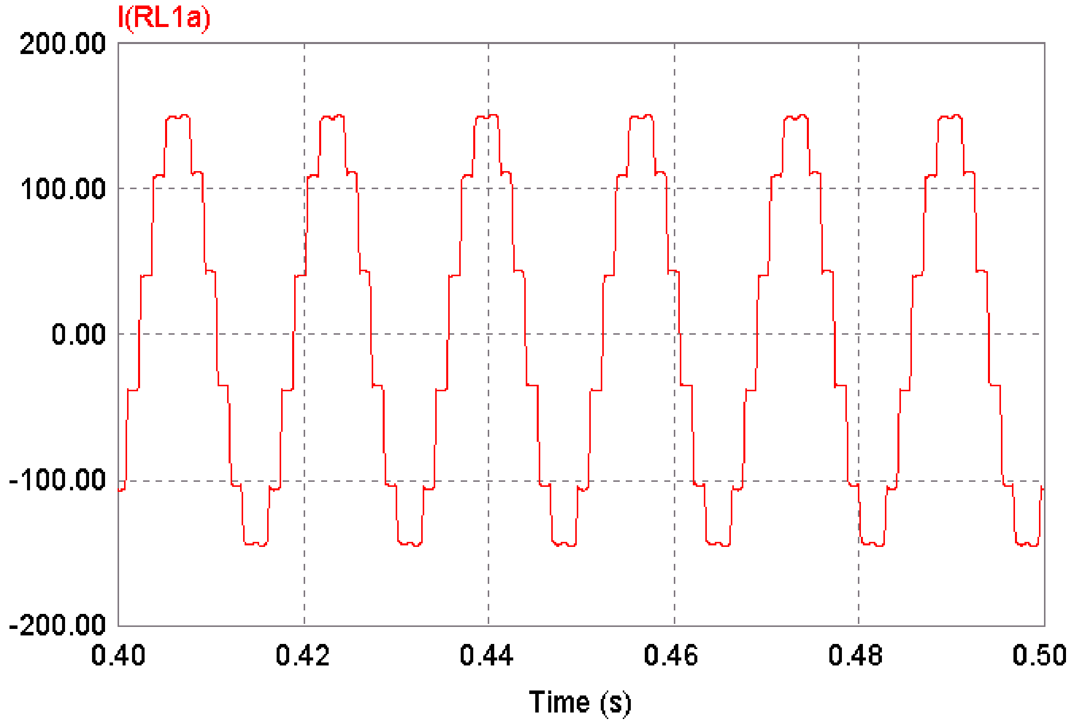


Six-Pulse Line Current Waveform and its Spectrum

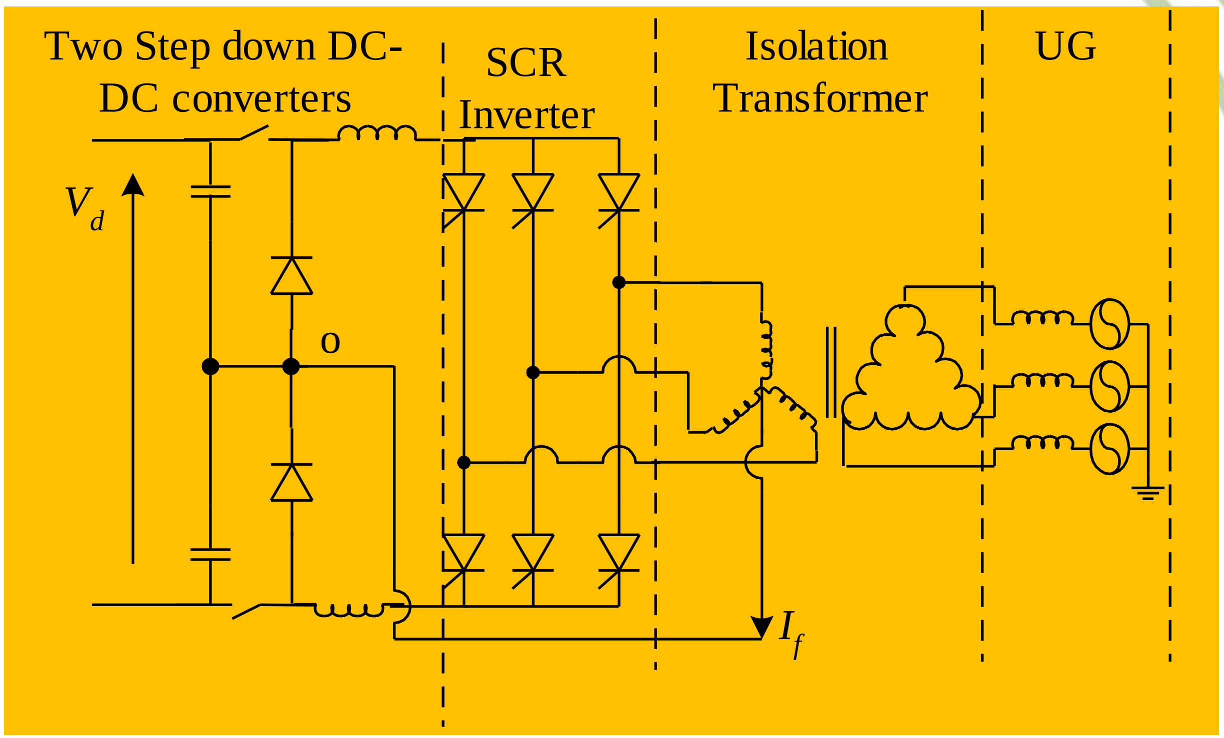
$$i(t) = \frac{2\sqrt{3}}{\pi} I_o \left(\cos(\omega t) - \frac{1}{5}\cos(5\omega t) - \frac{1}{7}\cos(7\omega t) + \frac{1}{11}\cos(5\omega t) + \frac{1}{13}\cos(13\omega t) \cdots\cdots \right)$$

Twelve pulse inverter

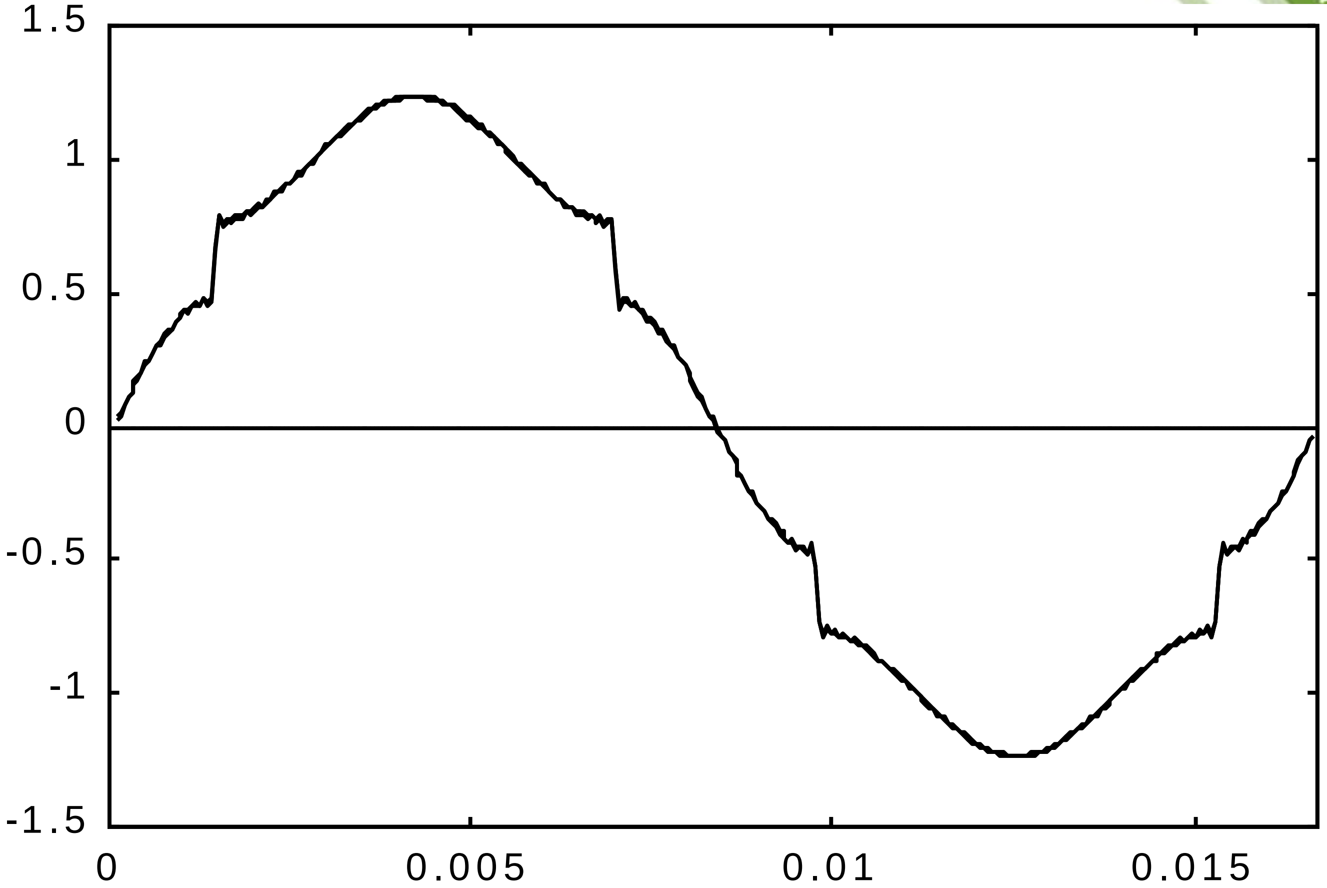




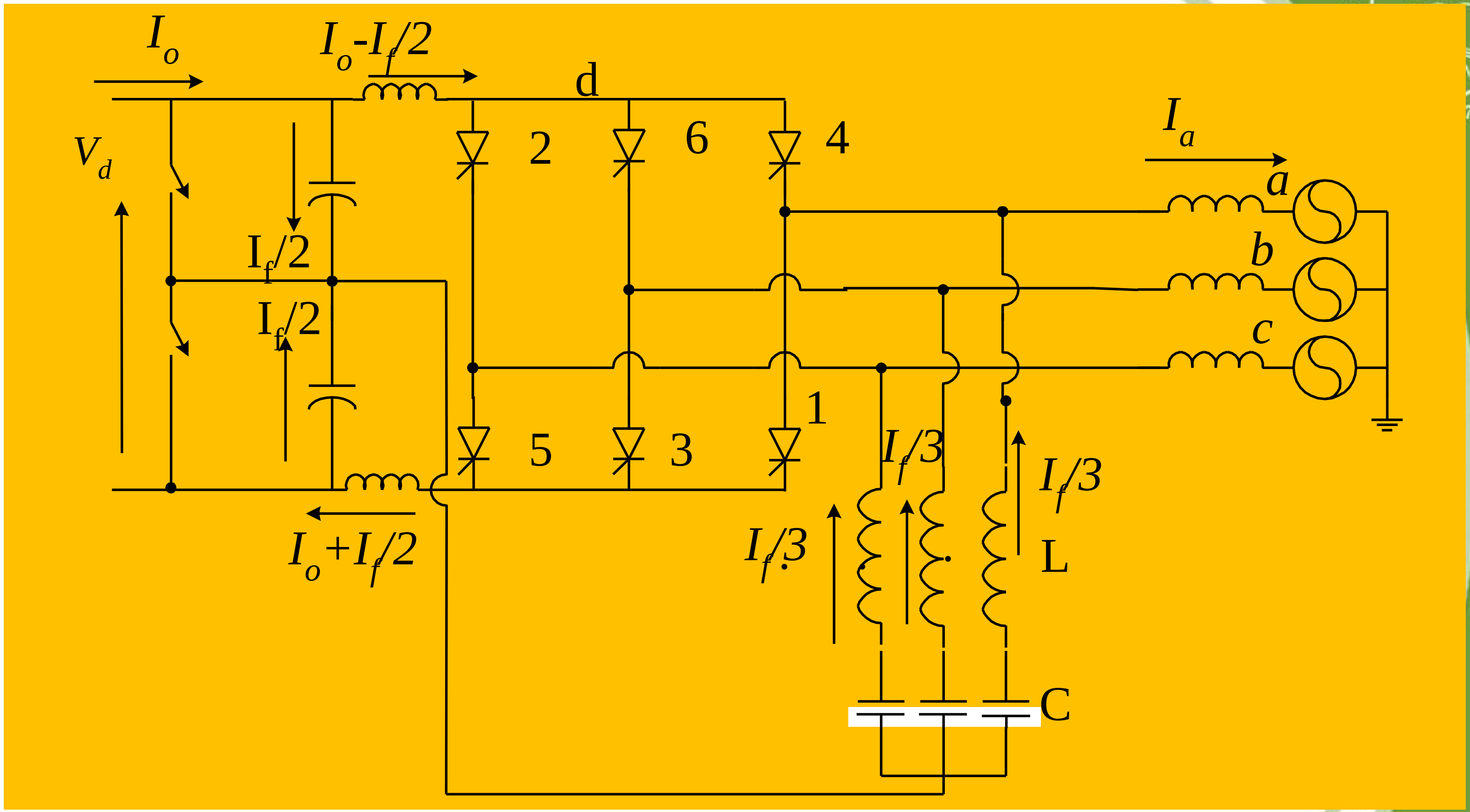
$$I_a = \frac{2\sqrt{3}}{\pi} I_o \left(\sin(\omega t) + \frac{1}{11}\sin(11\omega t) + \frac{1}{13}\sin(13\omega t) + \frac{1}{23}\sin(23\omega t) + \cdots \right)$$



Harmonic reduction in LCI inverter by two-step down DC-DC converters.



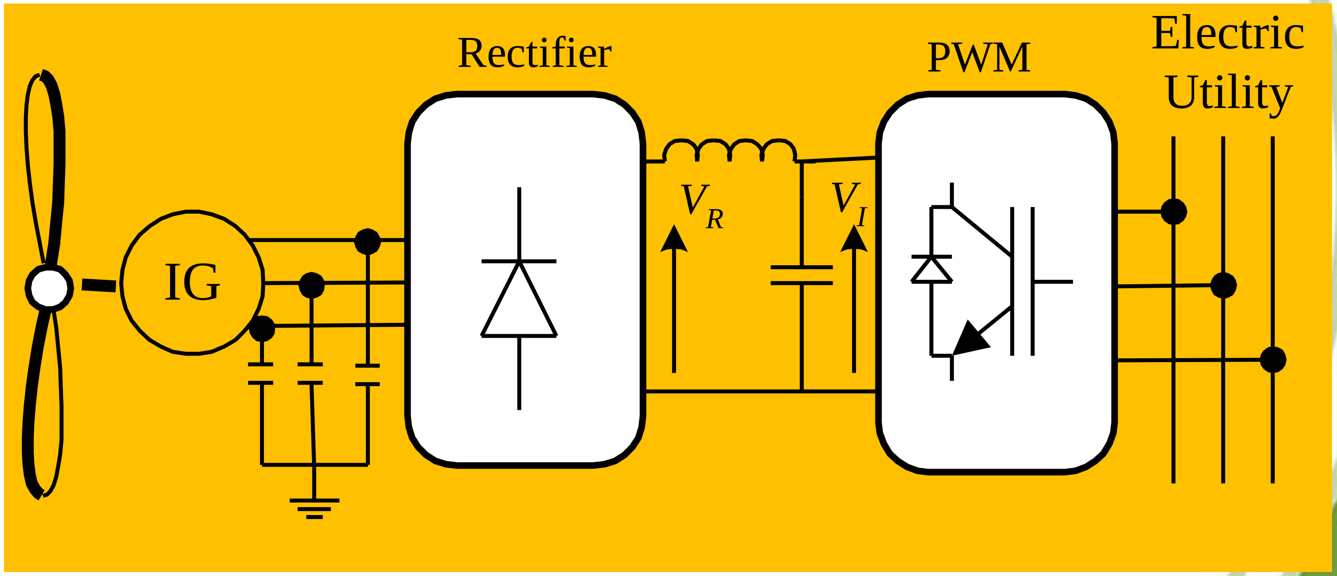
The utility line current with reinjection technique.



The reinjection technique using three-LC branches

Scheme #3

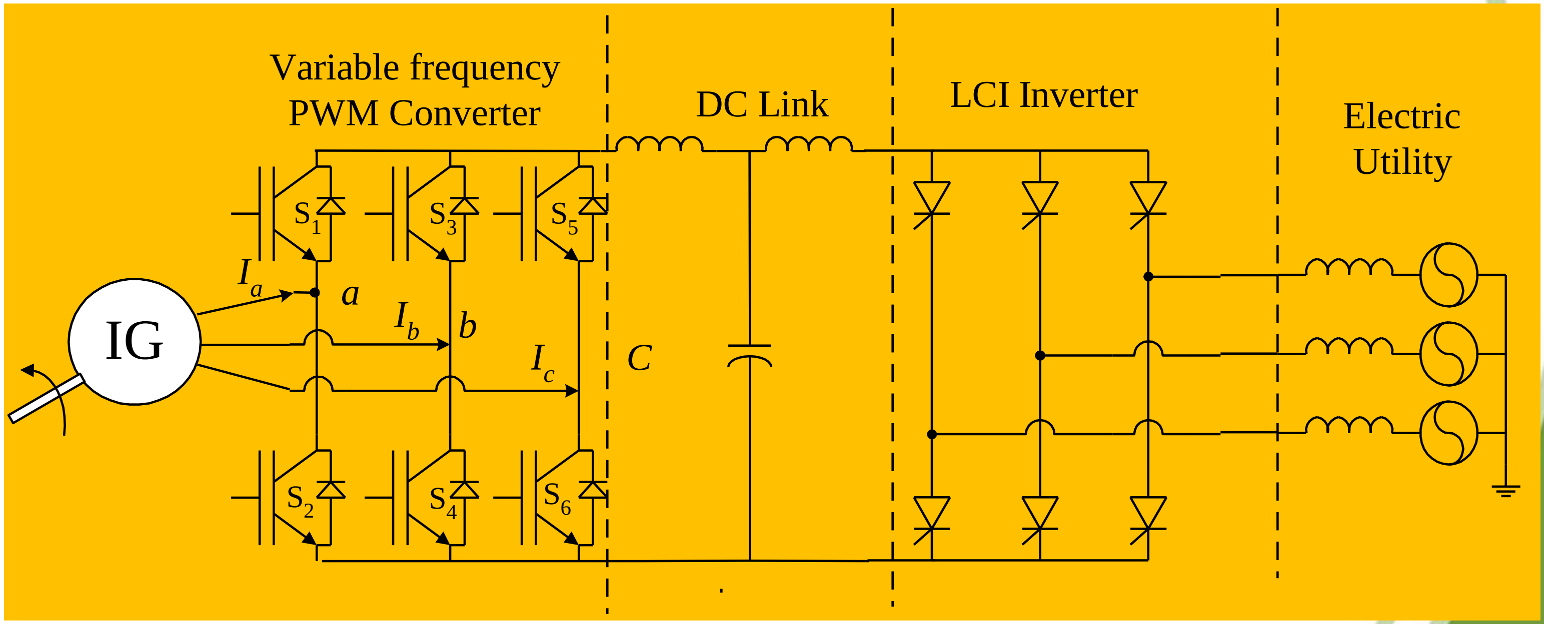
Self Excited Induction Generator Equipped with Diode Rectifier / PWM Inverter



Utility interfacing of SCIG via diode rectifier and PWM inverter

Scheme #4

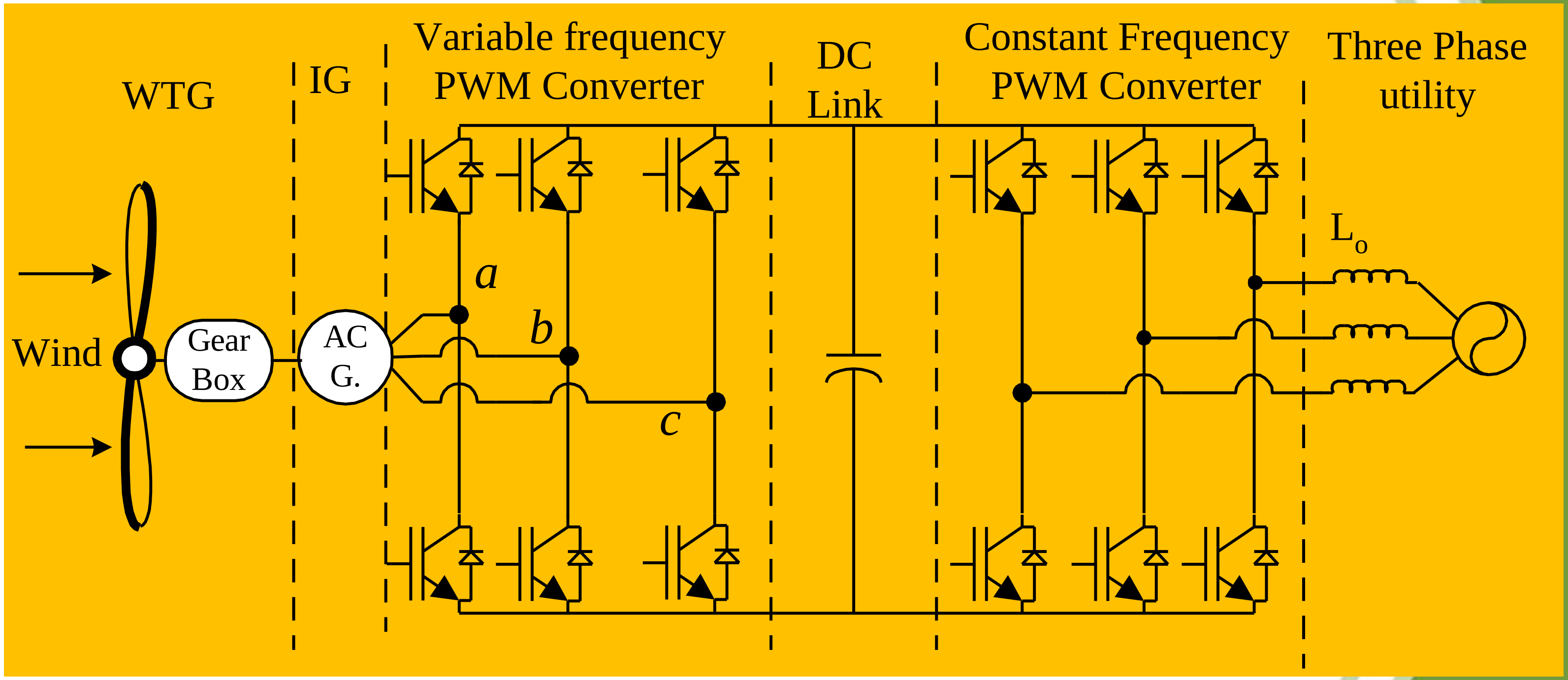
Induction Generator Equipped with PWM Rectifier / LCI Inverter



Variable speed WTG equipped PWM / LCI inverter cascade

Scheme #5

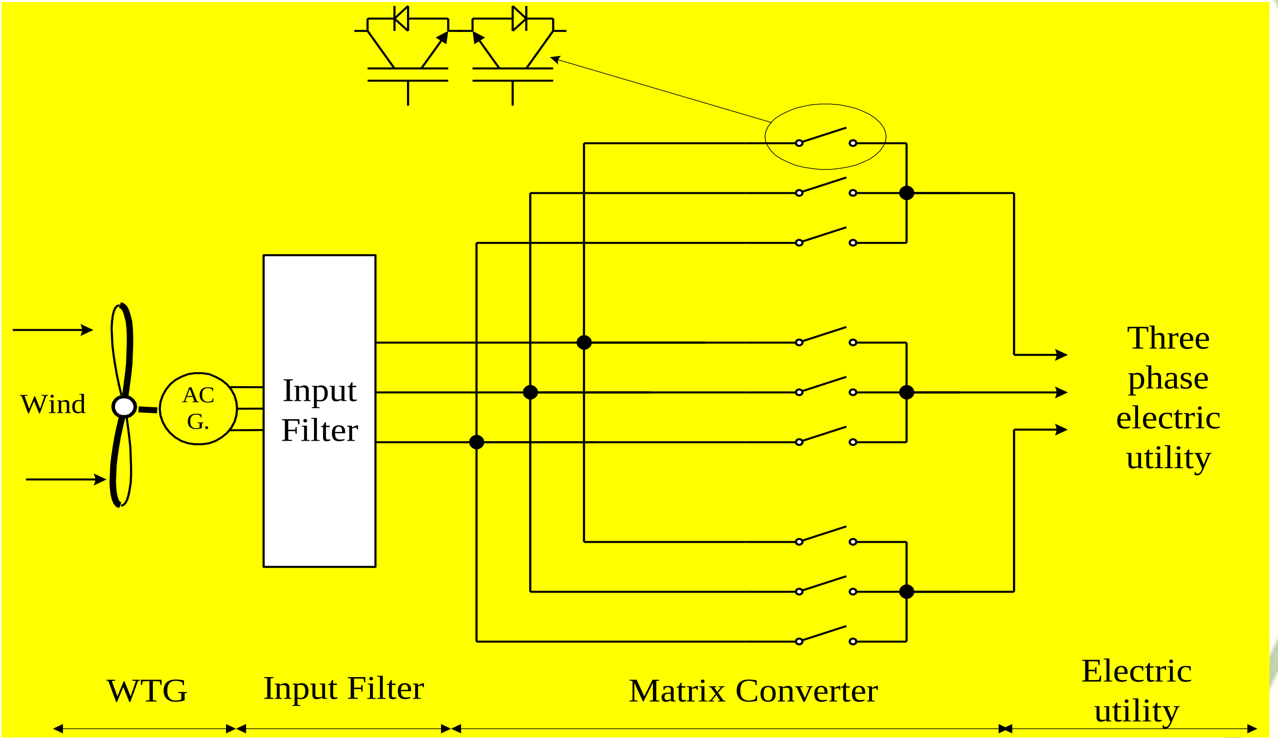
Induction Generator Equipped with PWM Rectifier / PWM Inverter



Connection of Cage IG to electric utility via two voltage sources PWM.

Scheme #6

Induction Generator Equipped with Cycloconverter



Utility interfacing of WTG with electric utility via Cycloconverter.