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Introduction to Wind Energy

Module 2.1

Module Presentation
Lecture 0

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Objectives

The purpose of this module is to introduce the main aspects of wind turbines and wind farms for Master Students in Engineering, focusing on up to date technologies that are particularly relevant for South Mediterranean countries.

ECTS: 3

EQF level: 7

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Learning Outcomes

The main objective of the course is to acquire the necessary knowledge on wind source and technology, making the students able to :

O1. Understand physical quantities and the principles characterizing the wind source and energy;

O2. Understand the different components and types of wind turbines and as their work;

O3. Be familiar with the different conversion technologies needed in wind energy systems;

O4. Be able to select wind turbines and to design (at preliminary project level) a wind farm in a South-Mediterranean location;

O5. Analyze the commercial feasibility of wind energy installations.

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Technical Contents

1. Basic concepts of Wind Energy: source, site, measurement.
2. Energy conversion of Wind: limits on the efficiency; coefficient of performance of a turbine.
3. Availability of Wind Energy and estimation of Wind Energy Potential.
4. Wind Farms. IEC Standards for site selection and design.
5. Types of wind turbines (HAWT, VAWT); on-shore and off-shore configurations
6. Wind turbine components: selection and specifications of rotor blades, gearbox, tower, etc.
7. Onshore Wind Farms equipment: selection and specifications.
8. Control schemes of wind turbines.
9. Wind Energy Converters: Analysis and Selection
10. Performance evaluation for Wind Farms.
11. Integration of Wind Energy into the Power Grid.
12. Economics of Wind Energy: the Levellised Cost of Energy.
13. Sustainability of Wind and environmental aspects.

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Recommended literature

Books:

1. Wind energy engineering. New York: McGraw-Hill, Jain, P. (2011).
2. Understanding wind power technology: Theory, Deployment and Optimisation. John Wiley & Sons. Schaffarczyk, A. (Ed.). (2014).
3. Renewable Energy Systems, the choice and modelling of 100 % renewable solutions", Henrik Lund , Elsevier, 2010.
4. Alternative Energy Systems, B. K. Hodge, John Wiley & Sons, 2009.
5. Fundamental of Aerodynamics, John D. Anderson, Jr., McGraw-Hill, 2001.

Review articles:

1) Herbert, G. J., Iniyan, S., Sreevalsan, E., & Rajapandian, S. (2007). A review of wind energy technologies. Renewable and sustainable energy Reviews, 11(6), 1117-1145.

2) Leung, D. Y., & Yang, Y. (2012). Wind energy development and its environmental impact: a review. Renewable and sustainable energy reviews, 16(1), 1031-1039.

Web links:

[1] www.ewea.org European Wind Energy Association
[2] wwindea.org World Wind Energy Association
[3] www.awea.org American Wind Energy Association

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Introduction to Wind Energy

Module 2.1

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Introduction to Wind Energy

Module 2.1

Basic Concepts of Wind Energy

Lesson 1

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Objective

The purpose of this lesson is to introduce the general aspects of wind energy, and the main parameters affecting the available power depending on local characteristics.

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Learning Outcomes

At the end of this lesson the students will be able to :

O1. Understand physical quantities and the principles characterizing the wind source and energy

O2. Understand statistical presentation of wind parameters

O3. Estimate the average energy available at one particular site

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Technical Contents

1) Basic Concepts of Wind Energy
2) Statistical Distribution of Wind Speed
3) The Effect of Wind Shear
4) Availability of Wind Energy and Estimation of Wind Energy Potential

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Properties of Wind

Contents

- How wind is created.
- Basic properties of wind and air
- Annual average wind speed.
- Statistical properties of wind speed
- Probability density function
- Average energy density.
- Wind shear
- Air density

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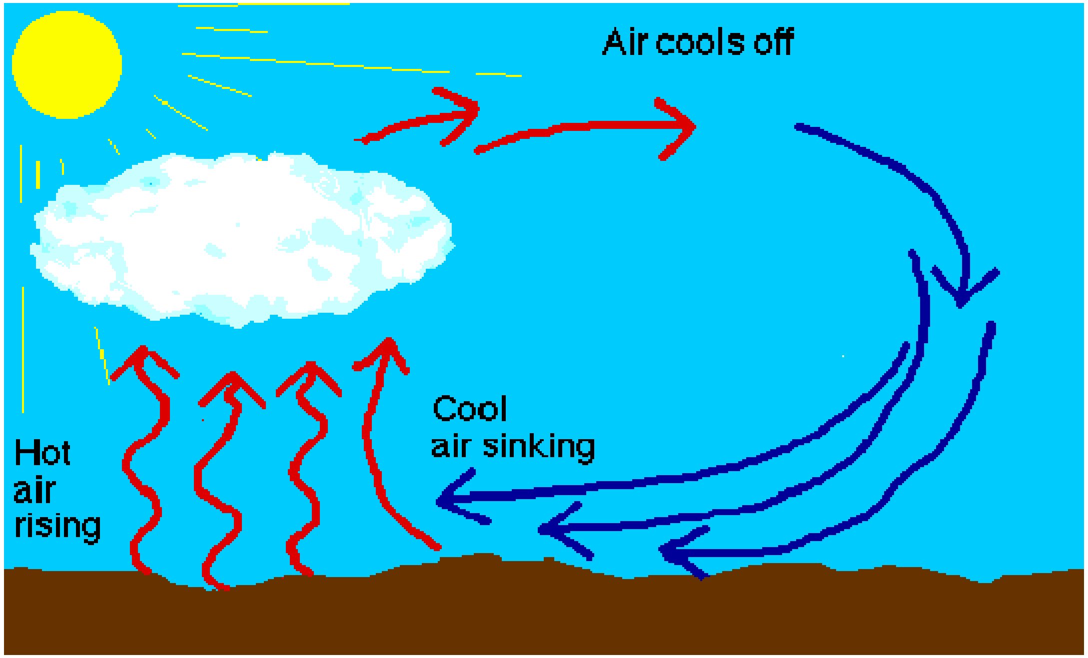
Inroduction

What is wind?

Wind is air in motion. It is produced by the uneven heating of the earth's surface by the sun. Since the earth's surface is made of various land and water formations, it absorbs the sun's radiation unevenly.
Two factors are necessary to specify wind: speed anddirection.



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How Is Wind Generated?

As the sun warms the Earth's surface, the atmosphere warms too. Some parts of the Earth receive direct rays from the sun all year and are always warm. Other places receive indirect rays, so the climate is colder. Warm air, which weighs less than cold air, rises. Then cool air moves in and replaces the rising warm air. This movement of air is what makes the wind blow

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How Is Wind Generated?

Wind is moving air. We can use the energy in wind to do work.

Examples:
1. wind to sail ships.

Photo taken from: https://en.wikipedia.org/wiki/Flettner_rotor

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How Is Wind Generated?

Examples:
2. Flettner rotor. (11)

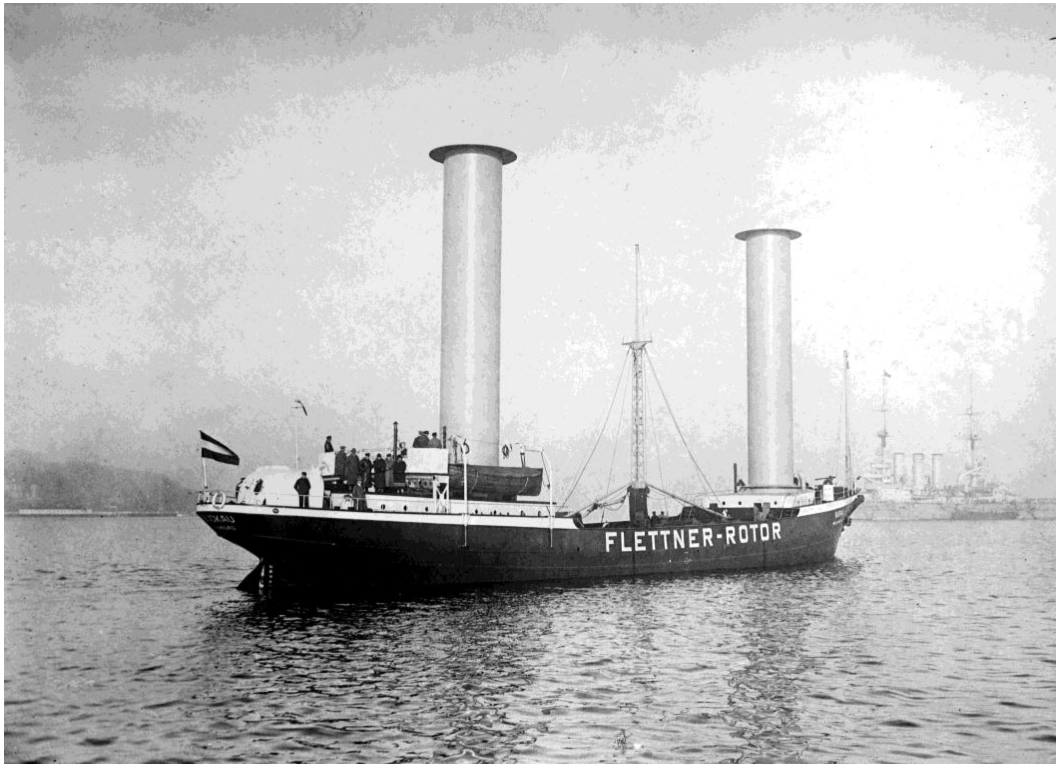

Photo taken from :
http://www.imcbrokers.com/blog/overview/detail/e-ship-1

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How Is Wind Generated?

Examples
3. Windmills to grind wheat.

Photo taken from https://pixabay.com/photos/windmill-wind-mill-wing-grind-879613/

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How Is Wind Generated?

Photo taken from: https://en.globes.co.il/en/article-enlight-buys-rights-to-kosovo-wind-farm-project-1001227695

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Statistical Distribution of Wind Speed

Wind speed is a **stochastic** quantity. The most common density function used to represent wind speed is **Weibull,** whose probability density function pd(*v*) is:

$$\mathrm{pd}(v) = (k/A)(v/A)^{k-1} e^{-(v/A)^k} \text{ for } v > 0$$

Where:

v (m/s)	wind speed,
k (-)	shape factor (the shape of the curve), and
A (m/s)	scale factor the scale of the curve)

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Statistical Distribution of Wind Speed

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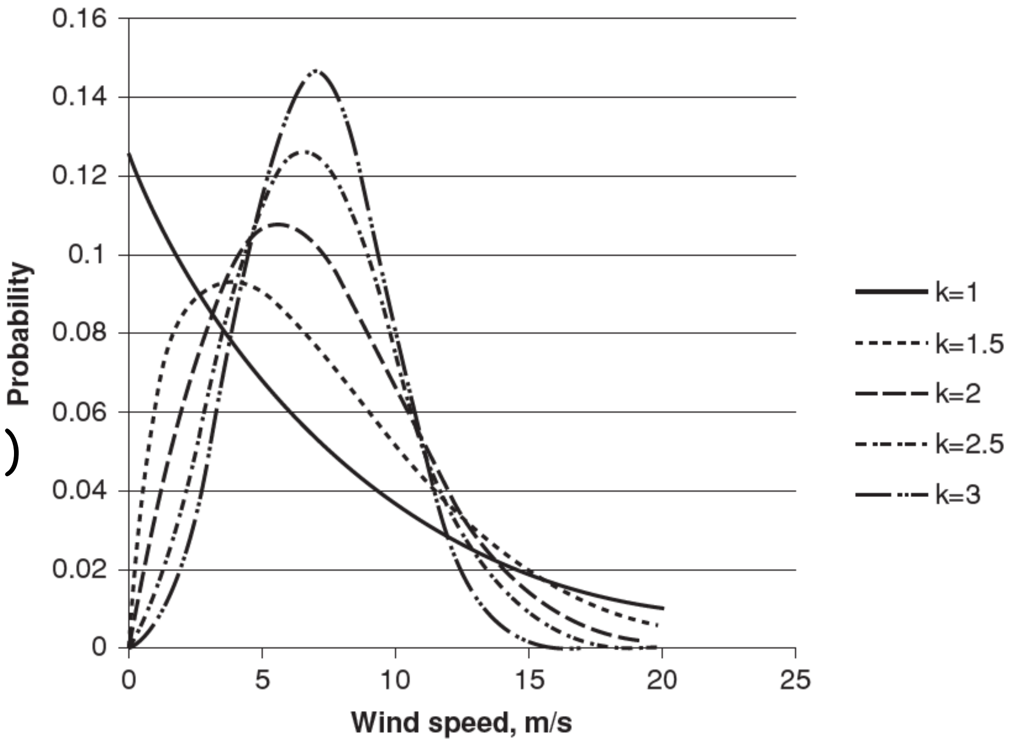
Question: How does this Weibull function look like ?

Answer: It takes several shapes pending on both k, and A. Typical examples are shown on the figure for A=8

- *k* = 1 (exponential distribution.)
- *k* = 2 (Rayleigh distribution)
- *k* > 3 (Gaussian distribution.



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Statistical Distribution of Wind Speed

Notes on Weibull density function

- Wind speed *v* is the 10-min average. In a wind measurement campaign, for each 10-min interval the average wind speed and standard deviation are recorded.

- The Weibull probability density function is a model that represents the 10-min average wind speed. This assumes that over the 10-min interval the wind conditions are stationary.

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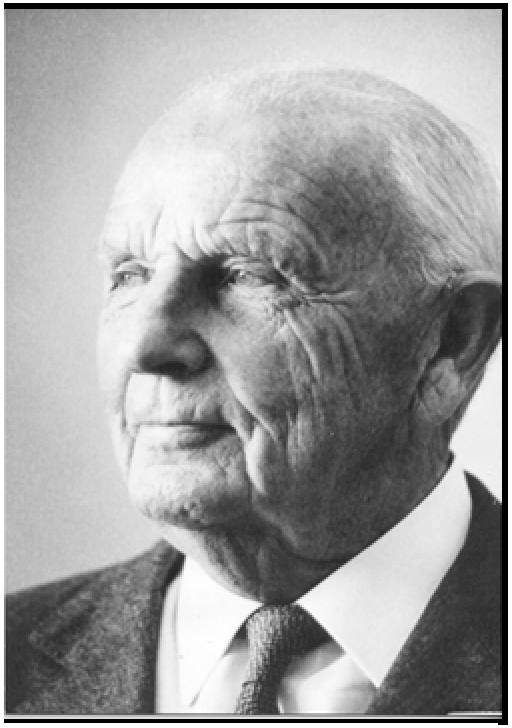
Statistical Distribution of Wind Speed

It is named after Swedish engineer, scientist, and mathematician **Waloddi Weibull**, who described it in detail in 1951.



Wallodi Weibull 1887-1979
Photo by Sam C. Saunders

Photo taken from : https://en.wikipedia.org/wiki/Waloddi_Weibull

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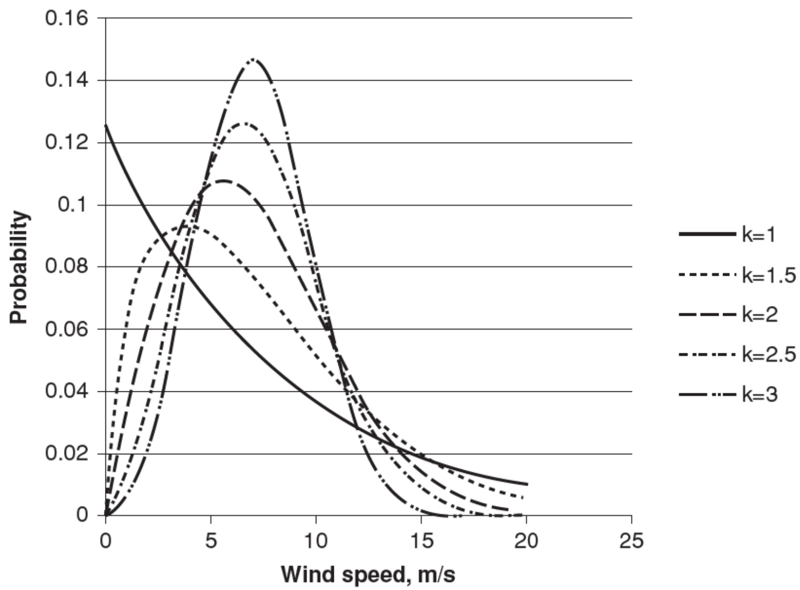
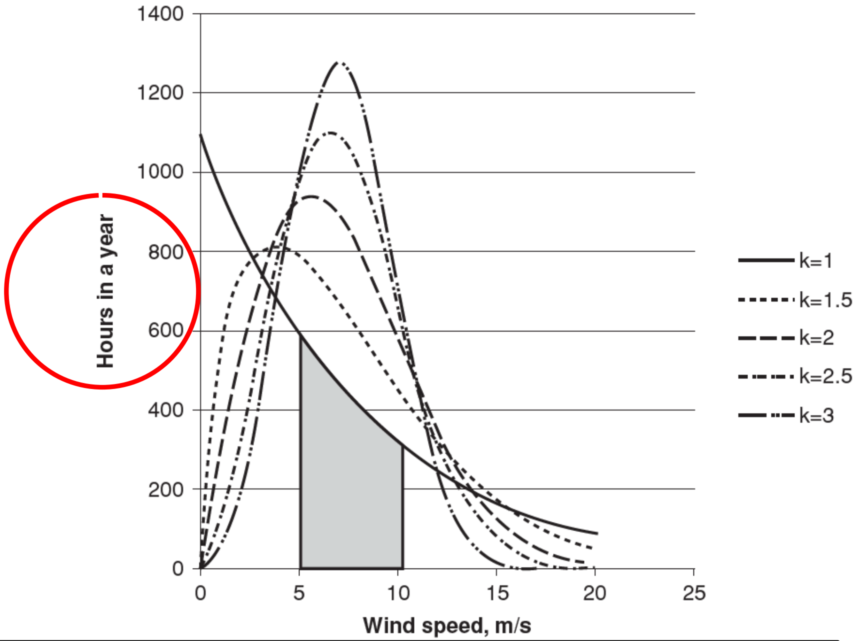
Statistical Distribution of Wind Speed





Instead of a probability density function that represents the fraction of time wind speed is at *v*, it is sometimes customary to speak in terms of hours in a year. That is, pd(*v*) is multiplied by **8760** (number of hours in a year).

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Statistical Distribution of Wind Speed

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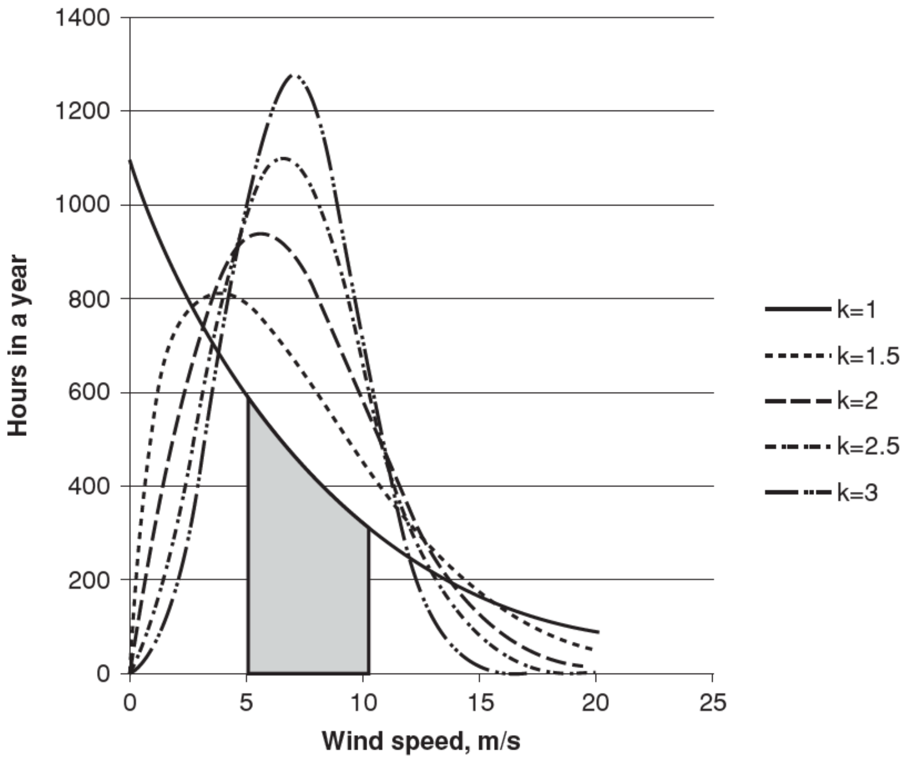
The area under the curve between 5 and 10 m/s represents the total number of hours in a year the wind speed is likely to be in that wind speed range.



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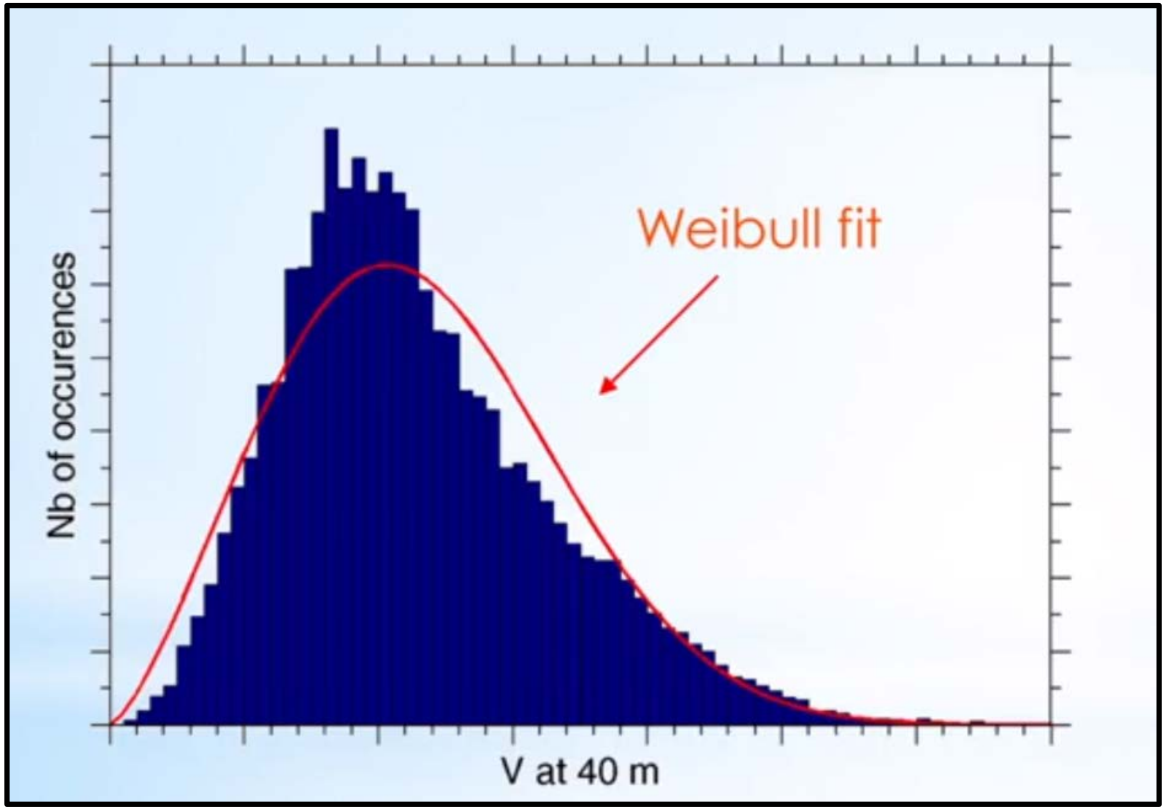
Statistical Distribution of Wind Speed

Empirically, it has been observed that wind speed in most locations is a Weibull distribution. Furthermore, the value of *k* is approximately 2 for most wind profiles.



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Statistical Distribution of Wind Speed

Mean and variance of Weibull Distribution for Wind Speed

If the wind speed data is presented by a Weibull distribution, we can find the mean wind speed as:

$$\mathrm{pd}(v) = (k/A)(v/A)^{k-1} e^{-(v/A)^k} \text{ for } v > 0$$

$$\text{Mean} = \bar{v} = A\Gamma\left(1 + \frac{1}{k}\right)$$

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Statistical Distribution of Wind Speed

Variance

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

where $\Gamma(x)$ is the gamma function

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Statistical Distribution of Wind Speed

The **gamma function** is an extension of the factorial function, with its argument shifted down by 1, to real and complex numbers.
If *n* is a positive integer,

$$\Gamma(n) = (n-1)!$$

For complex numbers with a positive real part, it is defined via a convergent improper integral:

$$\Gamma(z) = \int_0^\infty x^{z-1} e^{-x}\, dx$$

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Statistical Distribution of Wind Speed

Example 1

Wind measurements data collected over one year period was modeled using Weibull distribution. With shape factor k=2 and scale factor A=8

a. Plot the Weibull distribution for ten minutes average velocity range 0 -20 m/s
b. Calculate the annual mean velocity for the measured data

$$\mathrm{pd}(v) = (k/A)(v/A)^{k-1}e^{-(v/A)^k} \text{ for } v > 0$$

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Statistical Distribution of Wind Speed

Solution

The Weibull model is given by :

$$pd(v) = \frac{k}{A}\left(\frac{v}{A}\right)^{k-1} e^{\left(\frac{-v}{A}\right)^{k}}$$

Substituting k=2 and A=8:

$$pd(v) = \frac{2}{8}\left(\frac{v}{8}\right)^{2-1} e^{-\left(\frac{v}{8}\right)^{2}}$$

Reducing:

$$pd(v) = 0.03125ve^{-0.125v^2}$$

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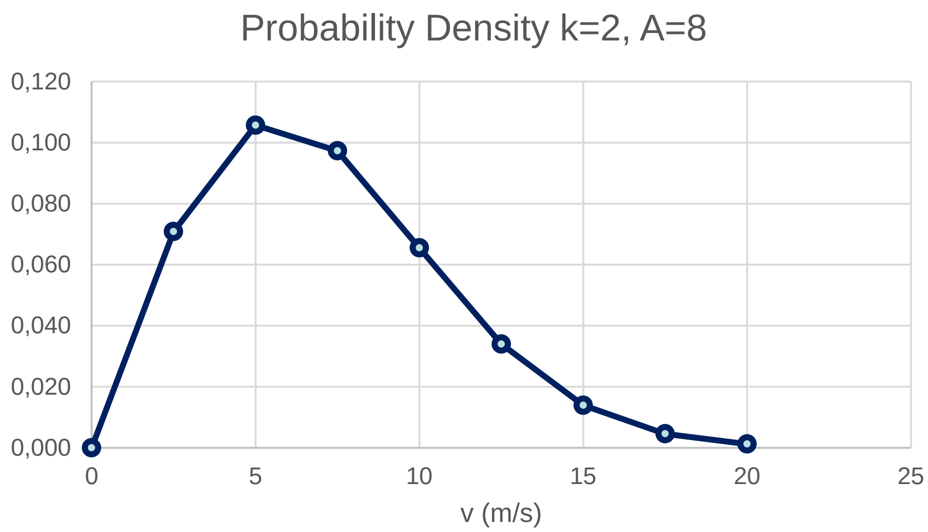
Statistical Distribution of Wind Speed

Solution (Cont.)

$$pd(v) = 0.03125ve^{-0.125v^2}$$

For the velocity range required the probability density values are generated in the shown Table and plotted below



v (m/s)	Probability Density
0	0.000
2.5	0.071
5	0.106
7.5	0.097
10	0.066
12.5	0.034
15	0.014
17.5	0.005
20	0.001

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Statistical Distribution of Wind Speed

Solution (Cont.)

The mean velocity is given by

$$\bar{v} = A\Gamma\left(1 + \frac{1}{k}\right)$$

The $\Gamma(1.5)$ is calculated from:

$$\Gamma(z) = \int_0^{\infty} x^{z-1} e^{-x}\, dx$$

This can be done numerically and yield a value for $\Gamma(1.5)$=0.837895

Substituting in the velocity expression:

$$\bar{v} = 7.09\ m/s$$

x	Gama	sm	fa
0	0	1	0
0.5	0.4288819	4	1.715528
1	0.3678794	2	0.735759
1.5	0.2732775	4	1.09311
2	0.191393	2	0.382786
2.5	0.1297878	4	0.519151
3	0.0862337	2	0.172467
3.5	0.0564941	4	0.225977
4	0.0366313	2	0.073263
4.5	0.0235657	4	0.094263
5	0.0150665	1	0.015067
		sum	5.02737
		area	0.837895
Gama(1.5)=	0.837895		

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Power Density,

In order to understand the impact on power generation of statistical distribution of wind speed, consider the impact on power density. Power density is defined as:

$$\text{PD} = \frac{\text{Power}}{\text{Area}} = \frac{1}{2}\rho v^3, \text{ units are } \frac{W}{m^2}$$

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Statistical Distribution of Wind Speed

If the statistical distribution of wind is ignored and it is assumed that there is no variation in wind speed, then the power density is **incorrectly** computed as:

$$\text{Power Density} = \frac{1}{2}\rho(\bar{v})^3$$

where $\bar{v}$ is the average wind speed.

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Statistical Distribution of Wind Speed

However, if the energy density is computed correctly while taking into account probability density of wind speed, then the power density numbers are very different.

$$\text{Correct Power Density} = \int_0^{\infty} \frac{1}{2}\,\rho\, v^3\, \mathrm{pd}(v)dv$$

where pd(*v*) is the Weibull probability density function explained earlier

The power density of rotor is <u>underestimated</u> if computed based on average wind speed

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Statistical Distribution of Wind Speed

Example 2

For the wind measurements data modeled using Weibull distribution. With shape factor k=2 and scale factor A=8

a. Calculate the power density expected
b. Compare the values calculated in (a) with that based on average wind speed

$$\text{Correct Power Density} = \int_0^{\infty} \frac{1}{2}\,\rho\, v^3\, \mathrm{pd}(v)dv$$

where pd(v) is the Weibull probability density function in Example 1.

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Statistical Distribution of Wind Speed

Solution

The power density in w/m^2 is given by is

$$\text{Power Density} = \int_0^\infty \frac{1}{2}\,\rho\, v^3\, \mathrm{pd}(v)dv$$

where pd(v) is the Weibull probability density calculated in Example 1

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Statistical Distribution of Wind Speed

Solution (Cont.)

The integration expression for the power density is numerically executed as shown on the side Table :

Hence, the power density at 7.09 m/s mean velocity is 406 w/m^2

v (m/s)	Probability Density	PowerDenisty	SM		f(A)
0	0.000	0	1	0	0
2.5	0.071	9.575	4	0.6784491	2.713796
5	0.106	76.6	2	8.0984613	16.19692
7.5	0.097	258.525	4	25.159946	100.6398
10	0.066	612.8	2	40.140581	80.28116
12.5	0.034	1196.875	4	40.692987	162.7719
15	0.014	2068.2	2	28.821546	57.64309
17.5	0.005	3284.225	4	15.002168	60.00867
20	0.001	4902.4	1	5.9149115	5.914911
			Sig(fnArea)		486.1703
	Area under the curve		405.1419 w/m2		

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Statistical Distribution of Wind Speed

Solution (Cont.)

If the power density is calculated based on mean wind speed (7.09 m/s) ignoring the statistical distribution we get

$$PD = \frac{1}{2}\rho v^3 = 0.5 * 1.2265 * (7.09)^3 = 218.4 \text{ w/m}^2$$

Hence, the power density is underestimated if the statistical distribution is ignored.

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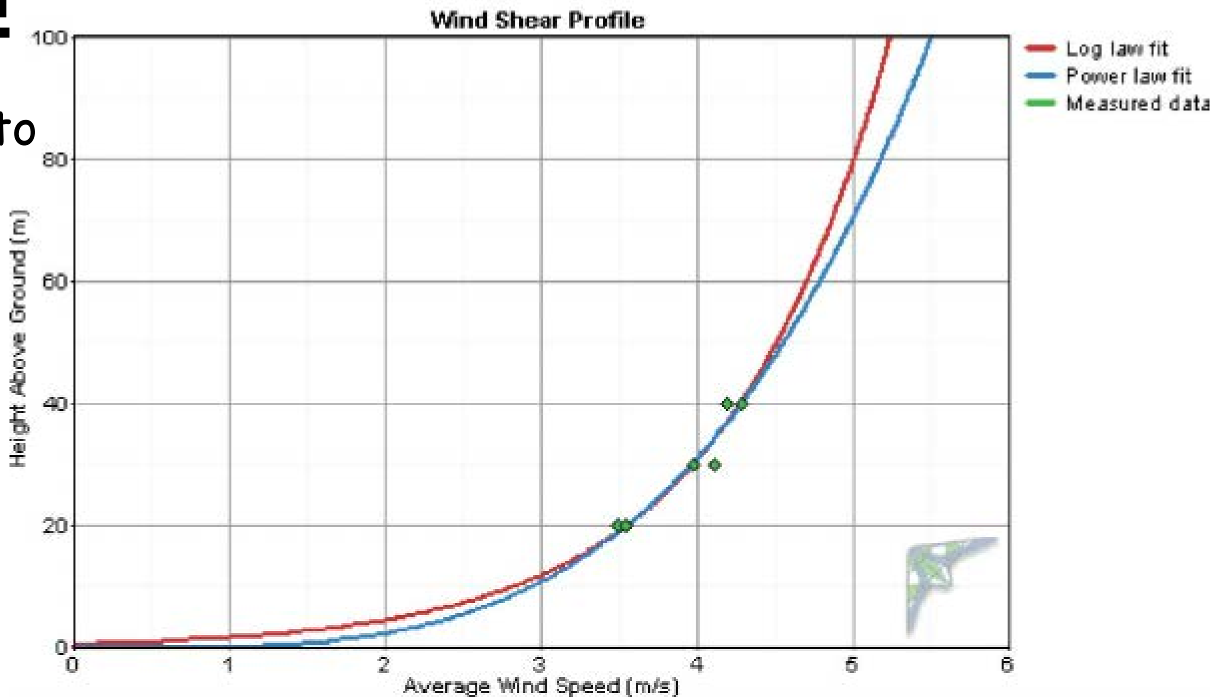
The effect of Wind Shear

Wind Shear

There are two methods to describe shear:

- Power law profile and
- logarithm profile.



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The effect of Wind Shear

Power law

The power law is the most common method to describe the relationship of wind speed and height. This is an engineering approximation and must be used with caution.

$$\frac{v_2}{v_1} = \left(\frac{h_2}{h_1}\right)^{\gamma}$$

where v_2 and v_1 are wind speeds at heights h_2 and h_1, and exponent γ is called wind shear.

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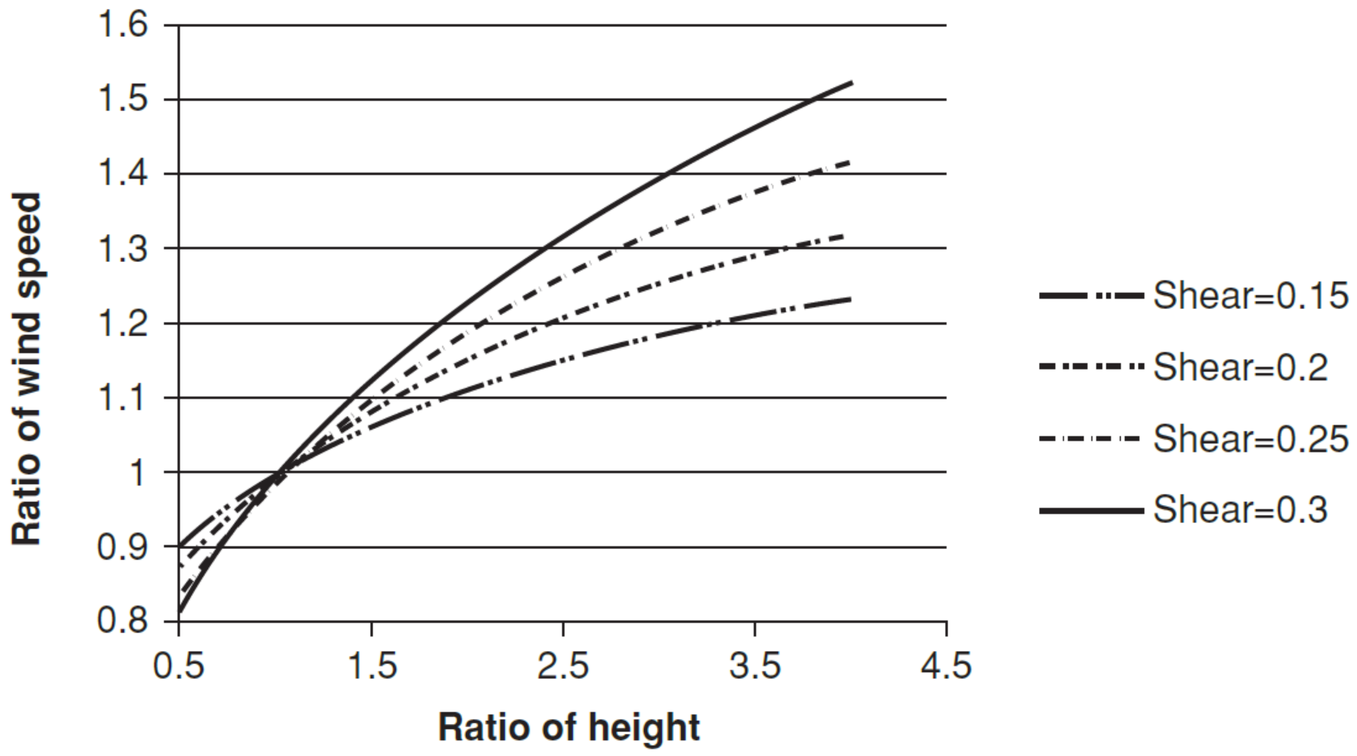
The effect of Wind Shear

The figure below is a plot of the wind speed ratio and height ratio for different values of shear.



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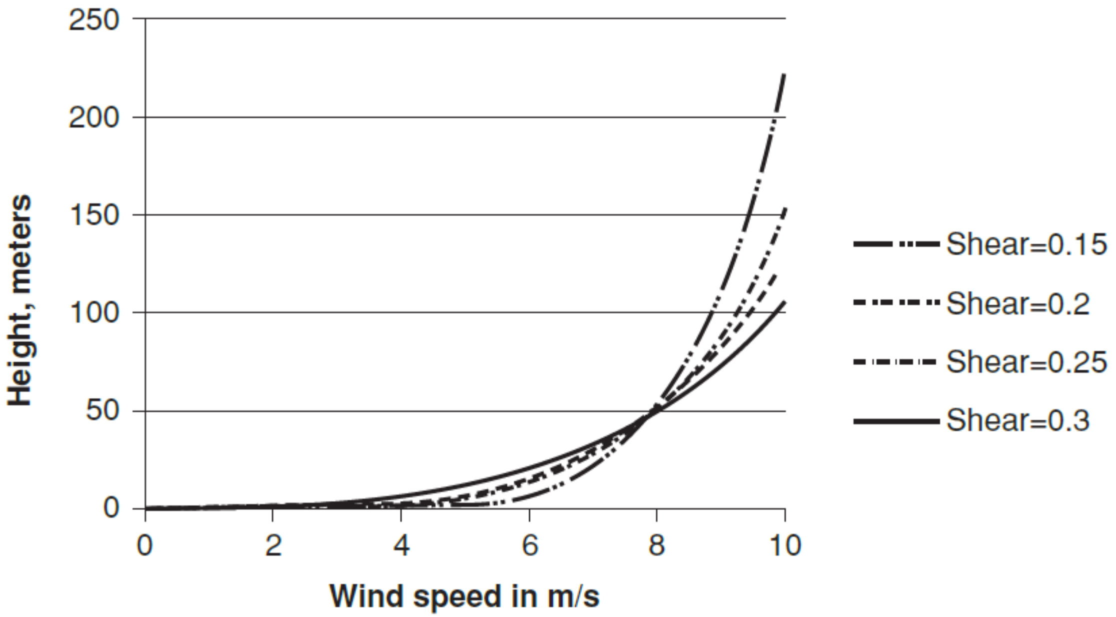
The effect of Wind Shear

The figure below is a plot of height versus wind speed for different values of shear.



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The effect of Wind Shear

Logarithmic profile

An alternate method to extrapolate wind speed is to use the logarithmic profile, which uses roughness of the surface.[4]

$$\frac{v_2}{v_1} = \frac{\ln(h_2/z_0)}{\ln(h_1/z_0)}$$

where z_0 is called the roughness length. If wind speed v_1 is available at h_1 = 10 m, then the above equation may be used to compute v_2.

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The effect of Wind Shear

The value of shear can then be derived from:

$$\gamma = \ln\left(\ln\frac{h_2}{z_0} \Big/ \ln\frac{h_1}{z_0}\right) \Big/ \ln(h_2/h_1)$$

Shear, therefore, depends on the heights and roughness length.

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The effect of Wind Shear

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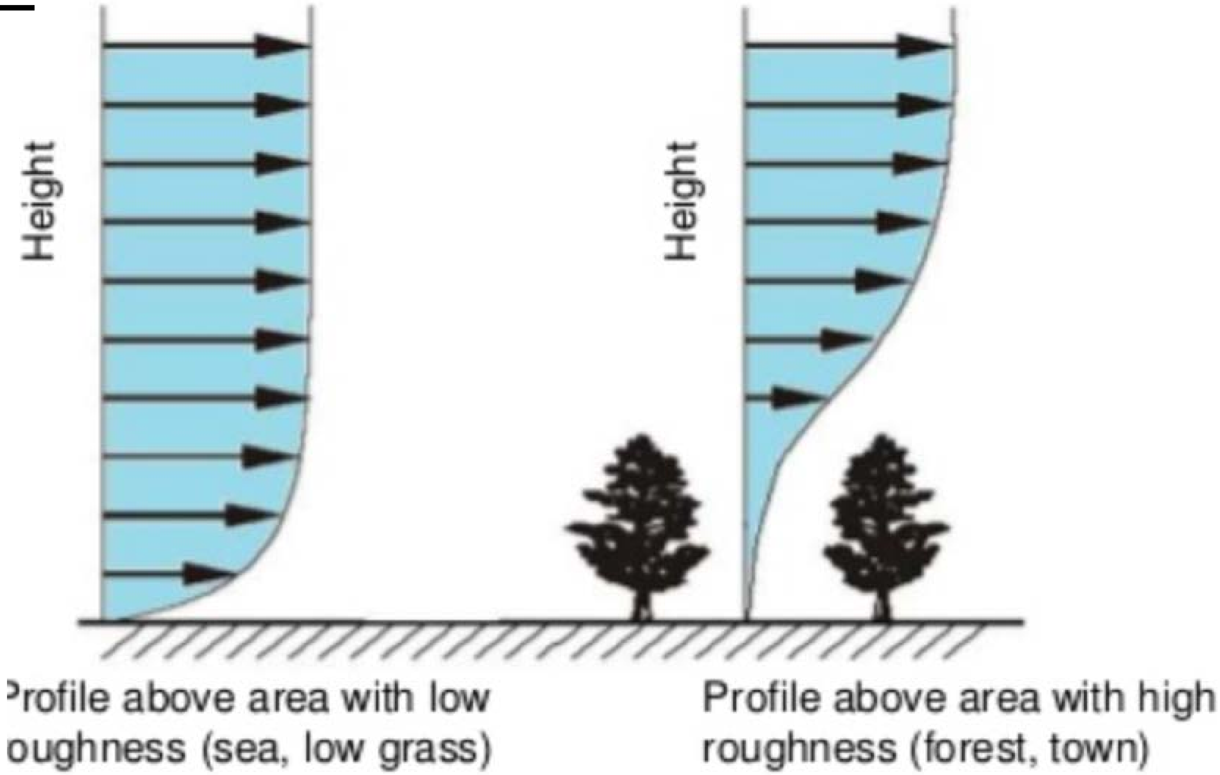
Roughness length

Roughness length is the extrapolated height above the surface at which the mean wind speed is zero.



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The effect of Wind Shear

The Table shown describes classes of roughness, roughness length, and shear.

Description	Roughness Class	Roughness Length, m	Shear
Open sea	0	0.0001–0.003	0.08
Open terrain with a smooth surface, like concrete runway, mowed grass	0.5	0.0024	0.11
Open agricultural area without fences and hedgerows and very scattered buildings. Only softly rounded hills	1	0.03	0.15
Agricultural land with some houses and 8-m-tall sheltering hedgerows with a distance of approx. 1250 m	1.5	0.055	0.17
Agricultural land with some houses and 8-m-tall sheltering hedgerows with a distance of approx. 500 m	2	0.1	0.19
Agricultural land with many houses, shrubs and plants, or 8-m tall sheltering hedgerows with a distance of approx. 250 m	2.5	0.2	0.21
Villages, small towns, agricultural land with many or tall sheltering hedgerows, forests, and very rough and uneven terrain	3	0.4	0.25
Larger cities with tall buildings	3.5	0.8	0.31
Very large cities with tall buildings and skyscrapers	4	1.6	0.39

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The effect of Wind Shear

Useful Approximation

1. Shear = 1/7 = 0.14

This is the most widely used value when wind speed is available at single height.

2: Extrapolating 10-m wind speed data to 50m or higher using a constant shear value. The shear formula shown is most accurate when it is used to extrapolate wind speeds at heights that satisfy:

$$\frac{v_2}{v_1} = \left(\frac{h_2}{h_1}\right)^{\gamma}$$

$$0.5 < h_2/h_1 < 2$$

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The effect of Wind Shear

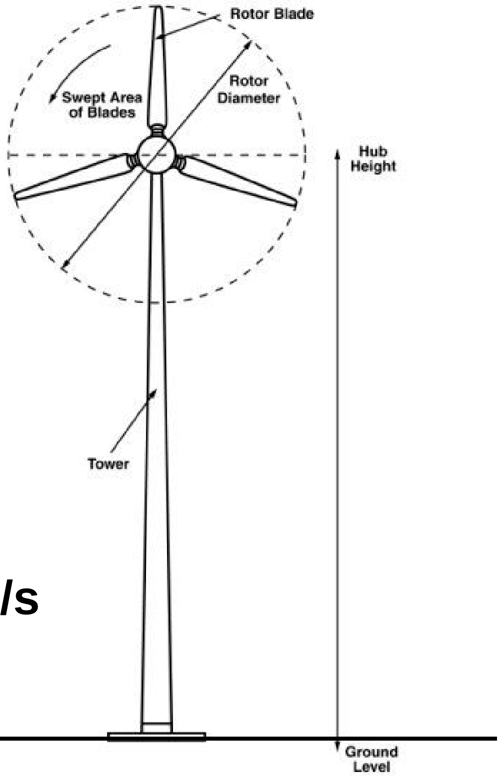
Example 3

For a suggested wind energy project the mean wind speed is 4 m/s wind speed at 10 m in the desert with low roughness. Calculate the wind speed at 80 m hub height.

V(80m)=?

V(10m)=4 m/s

Desert (low roughness)



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The effect of Wind Shear

Solution

From the roughness table choose 0.15 shear value for the desert location

Description	Roughness Class	Roughness Length, m	Shear
Open sea	0	0.0001–0.003	0.08
Open terrain with a smooth surface, like concrete runway, mowed grass	0.5	0.0024	0.11
Open agricultural area without fences and hedgerows and very scattered buildings. Only softly rounded hills	1	0.03	0.15
Agricultural land with some houses and 8 m tall sheltering	1.5	0.055	0.17

$$\frac{v_2}{v_1} = \left(\frac{h_2}{h_1}\right)^{\gamma}$$

$$\frac{v_2}{4} = \left(\frac{80}{10}\right)^{0.15}$$

height h1	10	m
wind speed v1	4	m/s
wind shear γ	0.15	
height h2	80	m
wind speed v2	5.464161	m/s

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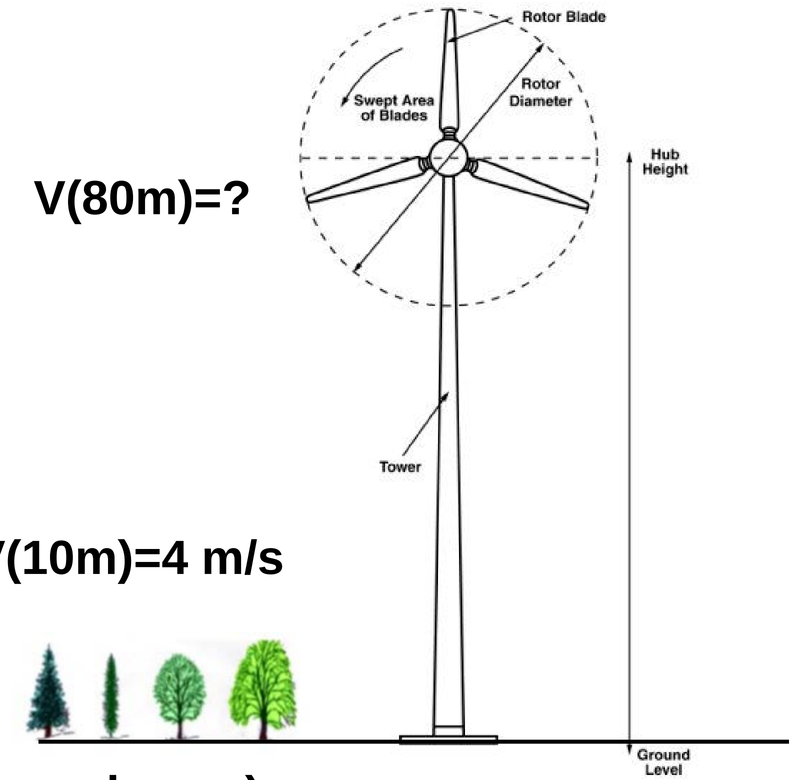
The effect of Wind Shear

Example 4

For another suggested wind energy project the mean wind speed is 4 m/s wind speed at 10 m in a forested area with high roughness. Calculate the wind speed at 80 m hub height



Forested area (high roughness)

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The effect of Wind Shear

Solution

From the roughness table choose 0.25 shear value for the forest area location

8-m tall sheltering hedgerows with a distance of approx. 250 m			
Villages, small towns, agricultural land with many or tall sheltering hedgerows, forests, and very rough and uneven terrain	3	0.4	0.25
Larger cities with tall buildings	3.5	0.8	0.31

$$\frac{v_2}{v_1} = \left(\frac{h_2}{h_1}\right)^{\gamma}$$

$$\frac{v_2}{4} = \left(\frac{80}{10}\right)^{0.25}$$

height h1	10	m
wind speed v1	4	m/s
wind shear γ	0.25	
height h2	80	m
wind speed v2	6.727171	m/s

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The effect of Wind Shear

Example 5

Wind measurements data reported in Examples 1 and 2 are collected at 10 m. The Weibull fit for these data was obtained where k=2, and A=8

a. Find the mean velocity at 80 m height
b. Plot the new k and A for the probability density at the new hub height.
c. Find the power density expected at 80 m hub height

$$\text{pd}(v) = (k/A)(v/A)^{k-1}e^{-(v/A)^k} \text{ for } v > 0$$

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The effect of Wind Shear

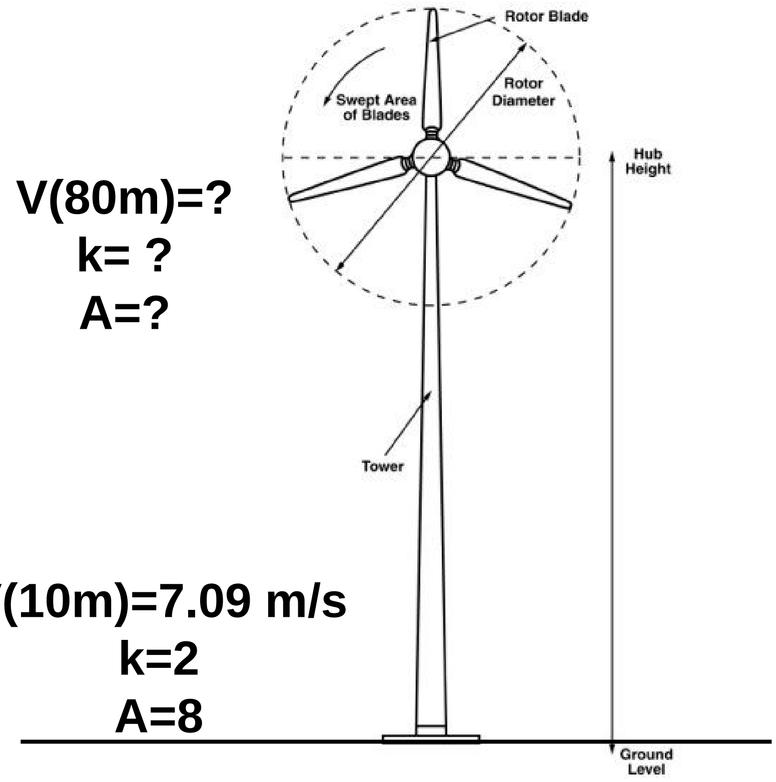
Solution

$$\frac{v_2}{v_1} = \left(\frac{h_2}{h_1}\right)^{\gamma}$$

$$\frac{k_2}{k_1} = \left(\frac{h_2}{h_1}\right)^{\gamma}$$

$$\frac{A_2}{A_1} = \left(\frac{h_2}{h_1}\right)^{\gamma}$$

V(80m)=?
k= ?
A=?



V(10m)=7.09 m/s
k=2
A=8

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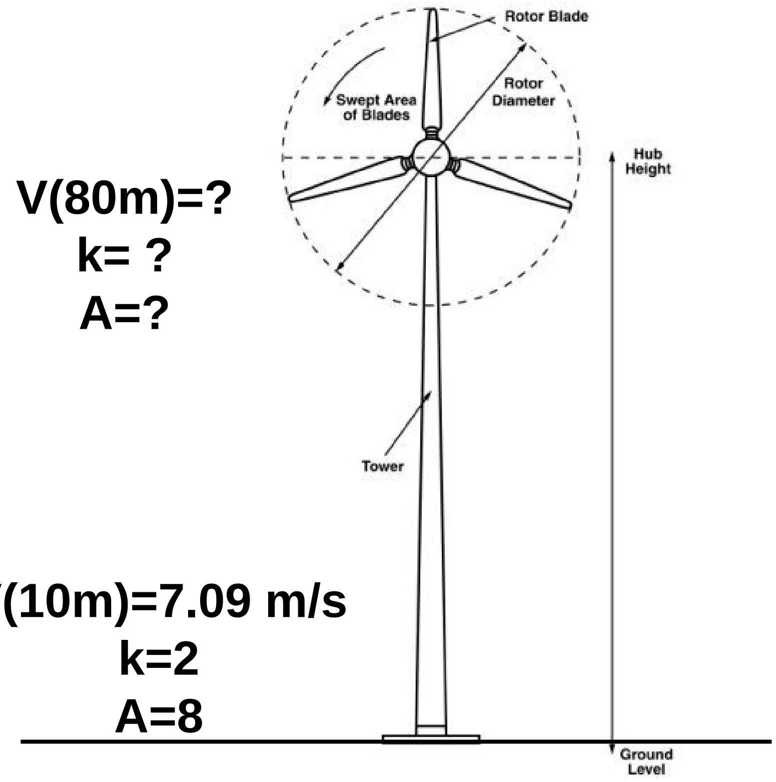
The effect of Wind Shear

Solution (Cont.)

New values for mean velocity, shape factor and scale factors are obtained using the above relations and summarized in the table below

height h1	10	m
wind speed v1	7.09	m/s
wind shear γ	0.14	
Shape factor k1	2	
Scale factor A1	8	
height h2	80	m
wind speed v2	9.485906	m/s
Shape factor k2	2.675855	
Scale factor A2	10.70342	

V(80m)=?
k= ?
A=?



V(10m)=7.09 m/s
k=2
A=8

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The effect of Wind Shear

Solution

The Weibull model is given by :

$$pd(v) = \frac{k}{A}\left(\frac{v}{A}\right)^{k-1} e^{\left(\frac{-v}{A}\right)^{k}}$$

Substituting k=2 and A=8:

$$pd(v) = \frac{2}{8}\left(\frac{v}{8}\right)^{2-1} e^{-\left(\frac{v}{8}\right)^{2}}$$

Reducing:

$$pd(v) = 0.03125ve^{-0.125v^2}$$

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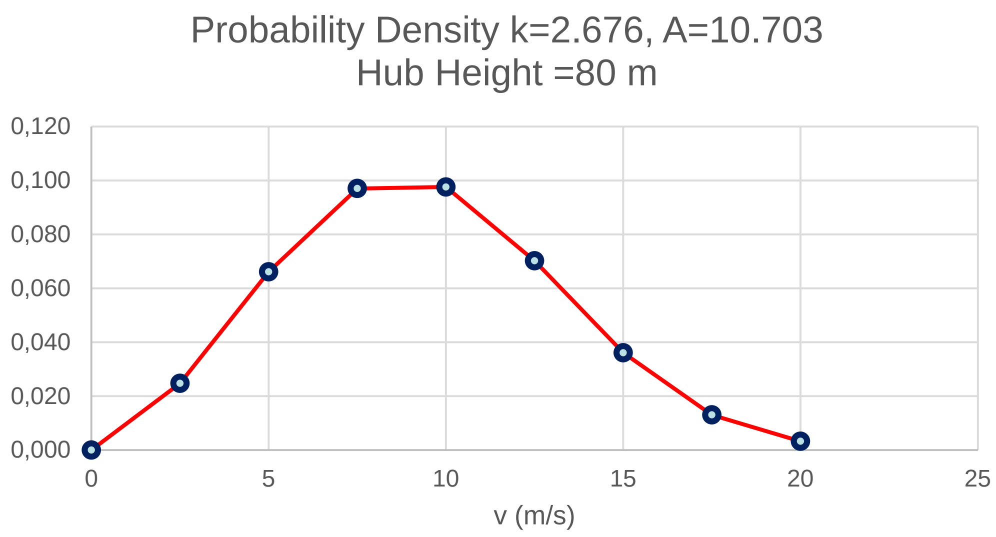
The effect of Wind Shear

Solution (Cont.)

With the new k and A values , the probability density values are generated in the shown Table and plotted below



v (m/s)	Probability Density
0	0.000
2.5	0.025
5	0.066
7.5	0.097
10	0.098
12.5	0.070
15	0.036
17.5	0.013
20	0.003

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The effect of Wind Shear

Solution (Cont.)

The integration expression for the power density is numerically executed as shown on the side Table :

v (m/s)	Probability Density	PowerDenisty	SM		f(A)
0	0.000	0	1	0	0
2.5	0.025	9.575	4	0.2370863	0.948345
5	0.066	76.6	2	5.0655437	10.13109
7.5	0.097	258.525	4	25.083899	100.3356
10	0.098	612.8	2	59.799763	119.5995
12.5	0.070	1196.875	4	84.015733	336.0629
15	0.036	2068.2	2	74.637167	149.2743
17.5	0.013	3284.225	4	42.867216	171.4689
20	0.003	4902.4	1	15.929531	15.92953
			Sig(fnArea)		903.7502
	Area under the curve		753.12518 w/m2		

Hence, the power density at (hub height 80 m) and 9.49 m/s mean velocity is 753 w/m^2

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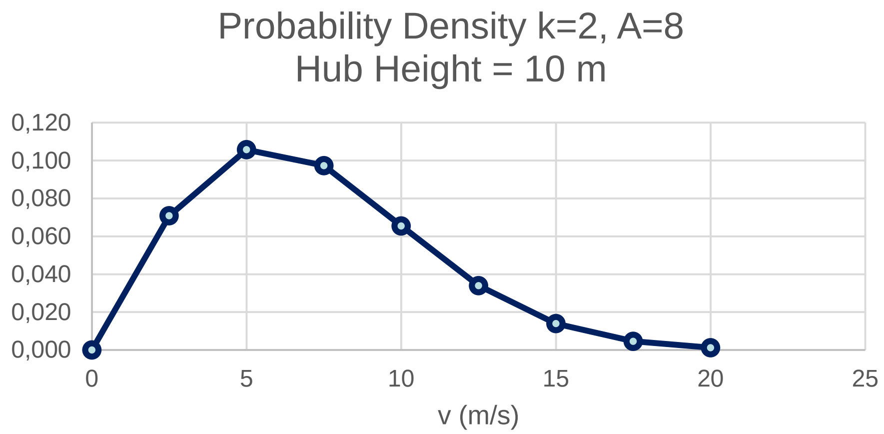
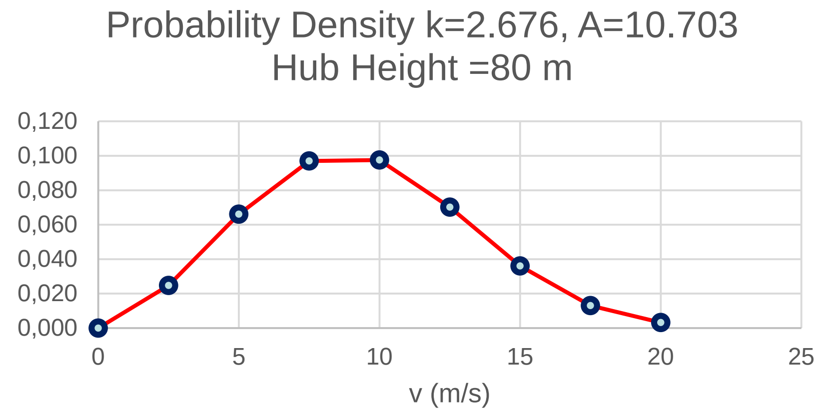
Availability of Wind Energy and estimation of Wind Energy Potential.

Probability density function at two different hub heights





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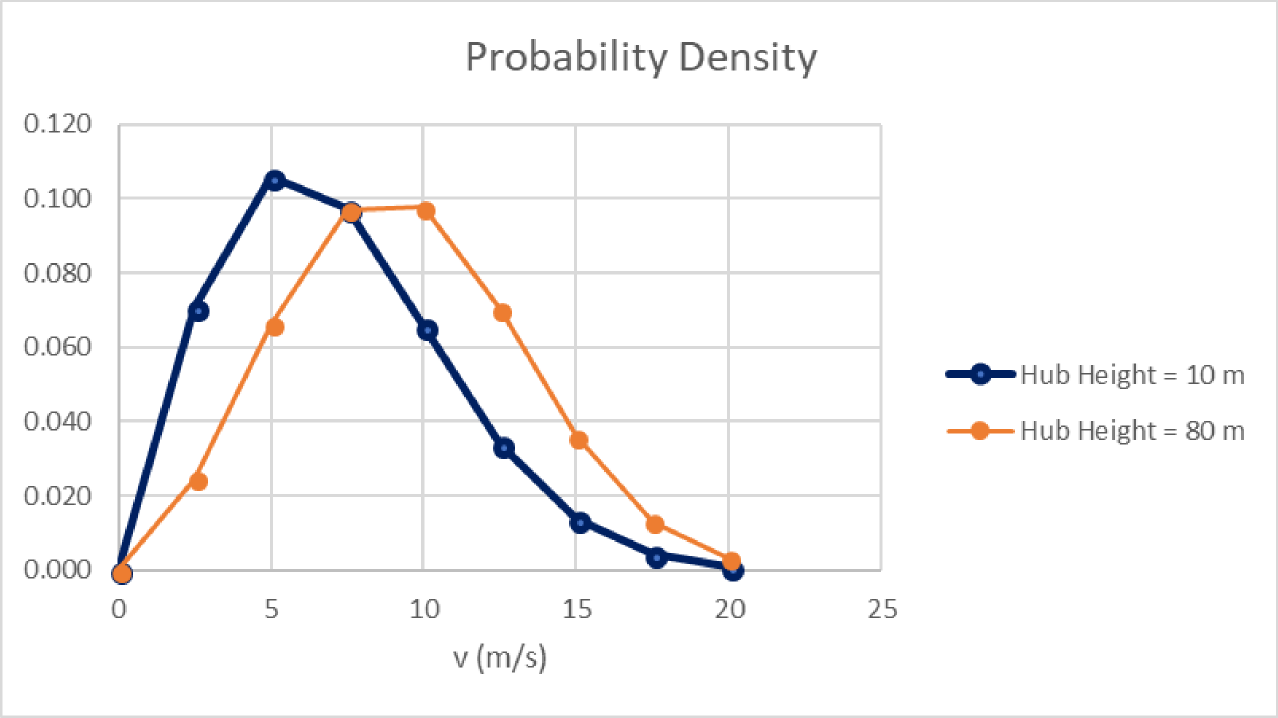
Availability of Wind Energy and estimation of Wind Energy Potential.

Probability density function at two different hub heights



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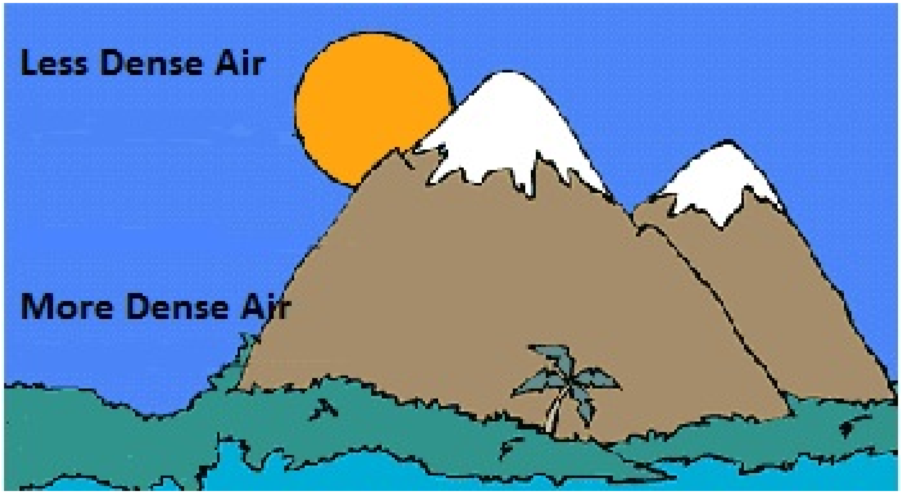
Density of Air as a Function of Elevation

The other parameter that influences power is air density. The relationship between Power (*P*) and density (*ρ*) is linear.

$$P = \rho A v^3 / 2.$$



If *ρ*, the air density is lower by 10%, then the power will be lower by 10%.

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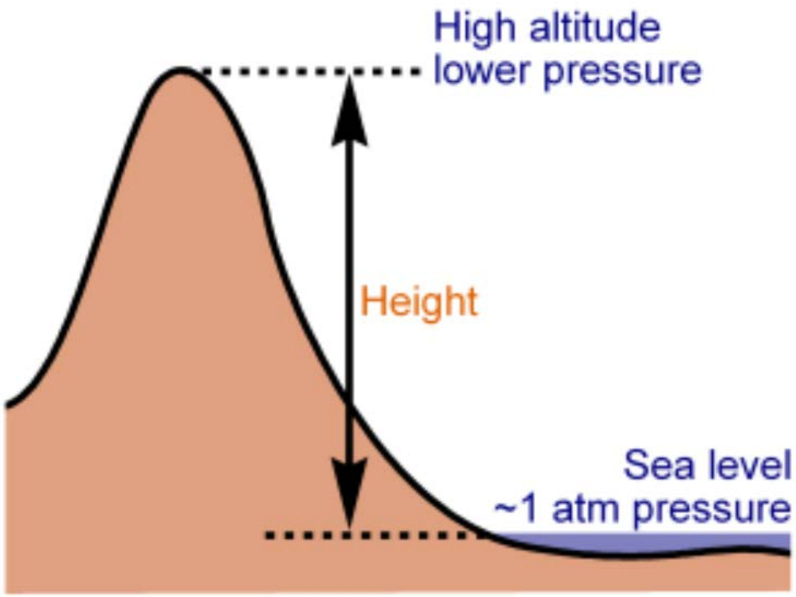
Density of Air as a Function of Elevation (Cont.)

Air density depends on **pressure**, **temperature**, and **relative humidity**. As elevation increases, both pressure and temperature decrease. Based on ideal gas law and variation of both pressure and temperature with altitude the following formula can be used for density variation with height:



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Availability of Wind Energy and estimation of Wind Energy Potential.

$$\rho = p_0 \left(1 - \frac{Lh}{T_0}\right)^{\frac{gM}{RL}} \frac{1}{R\,(T_0 - Lh)} \frac{M}{1000}$$

Where:

p_0	Atmospheric pressure at sea level =101,325 Pa,
L,	Temperature lapse rate = 6.5 K/km,
T_0,	Temperature at sea level = 288.15 K, (K = °C + 273.15)
h	Elevation from sea level in kilometers
g	Gravitational constant, 9.80665 m/s^2.
M	Molecular weight of dry air in grams=28.9644
R	Gas constant which is 287.05 J/(kg · K)

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Availability of Wind Energy and estimation of Wind Energy Potential.

The Table shown contains values of density. Density is lower by 2% at 200 m and 17.8% lower at 2000 m

Height, m	Density, kg/m^3
0	1.224999
5	1.224411
10	1.223824
50	1.21913
100	1.213282
150	1.207456
200	1.201651
250	1.195867
500	1.167268
1000	1.111642
1500	1.058067
2000	1.00649

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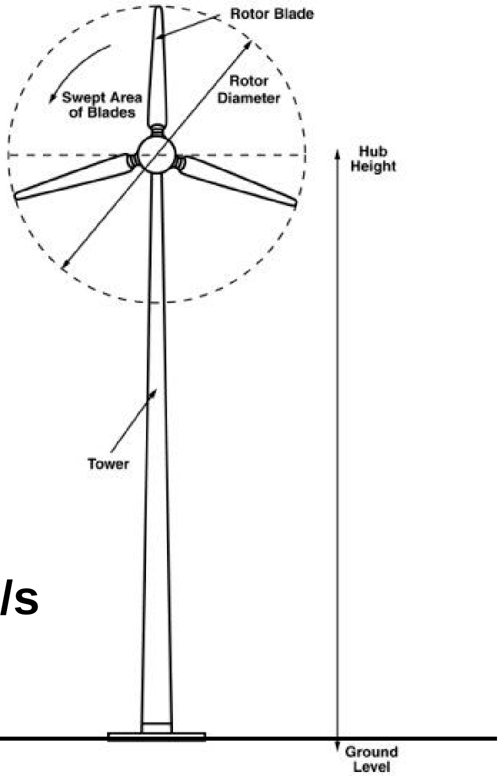
Availability of Wind Energy and estimation of Wind Energy Potential.

Conclusion

Since power is directly proportional to air density, there will be a 2 to 17.8% drop in power depending on elevation of the site. The change in density measured at the ground level versus density at a 100mrotor hub is less than 1%.

V(80m)=?



V(10m)=4 m/s

Desert (low roughness)

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Density of Air as a Function of Humidity

The density of mixture of dry air and water vapor is:

$$\rho = \left(\frac{p}{R_d T}\right)\left(1 - \frac{0.378\, p_v}{p}\right)$$

An approximation for p_v is:

$$p_v = RH * 610.78 * 10^{\frac{7.5T_c}{237.3+T_c}}$$

where

p_v	partial pressure of water vapor,
R_d	gas constant for dry air = 287.05,
RH	relative humidity,
T_c	temperature in degrees Celsius.

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Availability of Wind Energy and estimation of Wind Energy Potential.

The Table shown contains Air Density as a Function of Relative Humidity for p = 101,325 Pa, T_c = 15°C

Relative Humidity, %	Density, kg/m^3
0	1.225012
10	1.224233
20	1.223454
30	1.222674
40	1.221895
50	1.221116
60	1.220337
70	1.219557
80	1.218778
90	1.217999
100	1.217219

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References

Books:

[1] Wind energy engineering. New York: McGraw-Hill, Jain, P. (2011).
[2] Fundamental of Aerodynamics, John D. Anderson, Jr., McGraw-Hill, 2001.

Web links:

[3] www.ewea.org European Wind Energy Association
[4] wwindea.org World Wind Energy Association
[5] www.awea.org American Wind Energy Association

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Thank You for Your Attention!

Contact: info@weset-project.eu *Fernando.Tadeo@uva.es*

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Introduction to Wind Energy

Module 2.1

Estimation of Useful Wind Power
Lesson 2

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Objectives

The purpose of this lesson is to introduce the concept of useful power for wind energy.

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Learning Outcomes

At the end of this lesson, the students would be able to :

O1. Calculate kinetic energy available per unit area of incident wind

O2. Apply basic conservation laws to wind energy systems

O3. Estimate useful power that can be extracted from wind

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Technical Contents

1. *Calculation of the Kinetic Energy of Wind.*
2. *Conservation of mass and momentum in Wind Turbines.*
3. *The Betz limit of Wind Turbines.*
4. *Estimation of Useful Power for Wind turbines.*

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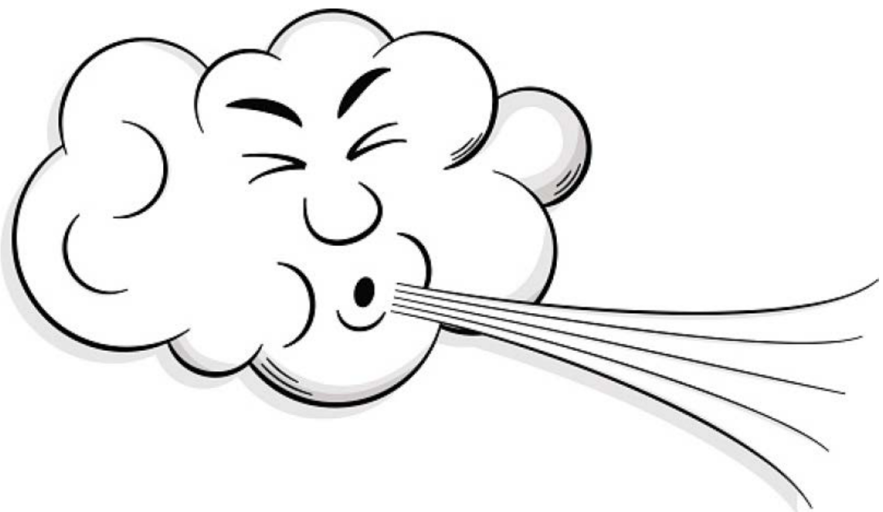
Kinetic Energy of Wind

The kinetic energy contained in wind is:



$$E = \frac{1}{2}mv^2$$

where *m* is mass and *v* is speed; units of energy are kg m^2/s^2 = Joule.

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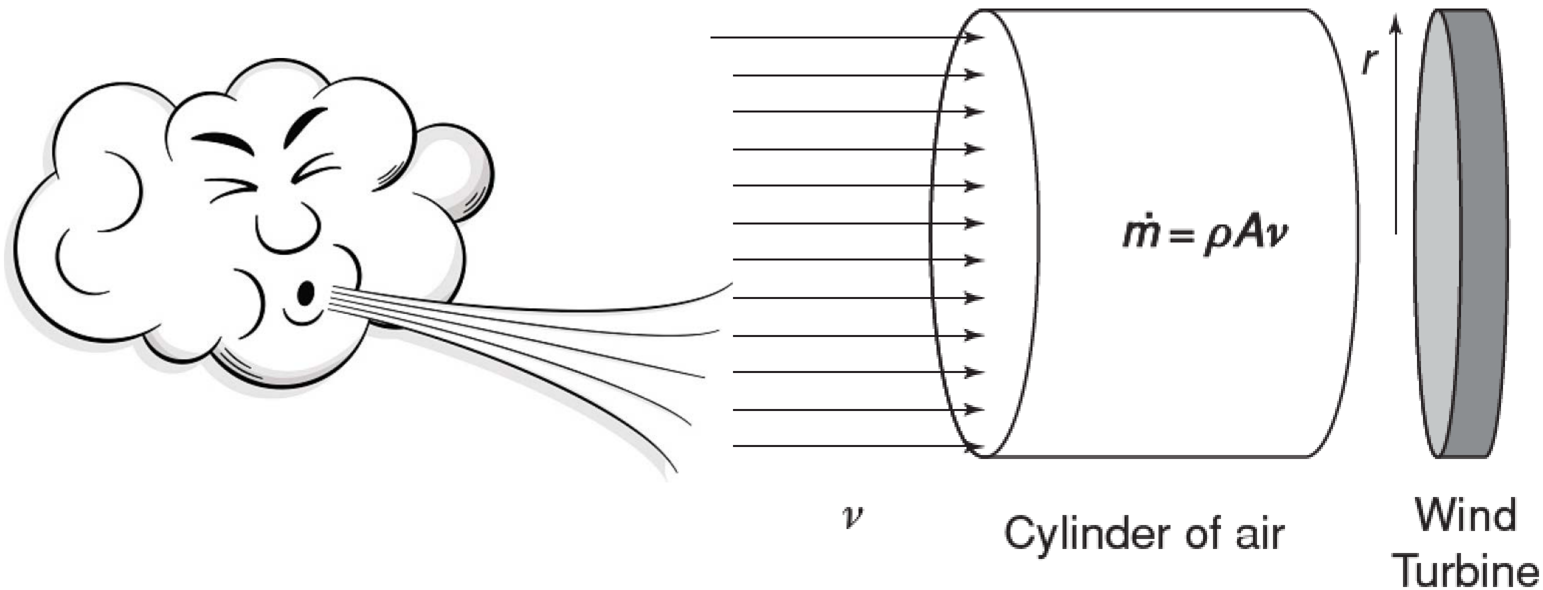
Calculation of the Kinetic Energy of Wind

The mass (m) from which energy is extracted is the mass contained in the volume of air that will flow through the rotor. For a horizontal axis wind turbine (HAWT), the volume of air is cylindrical, as shown in the figure below



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Calculation of the Kinetic Energy of Wind

The Energy per unit time is calculated as:

$$\dot{E} = \frac{1}{2}\dot{m}v^2$$

$$\dot{m} = \rho A v$$

where

ρ	air density and
A	cross-section area.
$m^{\cdot}$	amount of matter contained in a cylinder of air of length v. ˙
E	energy per second, which is the same as power P

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Calculation of the Kinetic Energy of Wind

$$\dot{E} = P = \frac{1}{2}\rho A v v^2 = \frac{1}{2}\rho A v^3$$

Units of power are Watts.

For a HAWT, $A = \pi r^2$, where r is the radius of the rotor, therefore:

$$P = \dot{E} = \frac{1}{2}\rho \pi r^2 v^3$$

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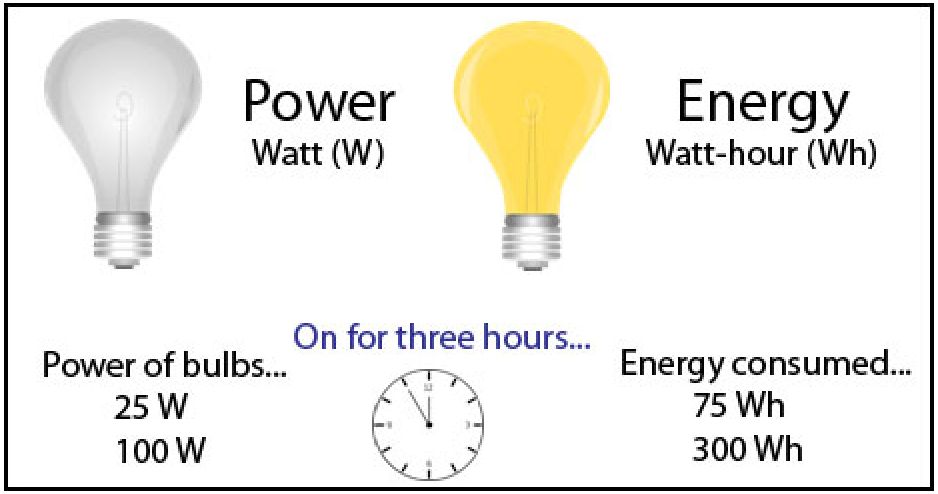
Calculation of the Kinetic Energy of Wind

RK: The distinction between power and energy is important. If a wind turbine operates at a constant power of 10 kW for 2 h, then it will produce 20 kWh of energy, which is 72 million J (or Watt-seconds).



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Sensitivity of Power to Rotor Radius

The impact of change in radius by a small amount *r* , while all else is constant, can be expressed as:

$$\Delta P / P = 2 \, \Delta r / r$$

This means that if the radius is increased/decreased by 1%, power will increase/decrease by 2%. For larger changes in radius, the above formula does not apply; for instance, a 10% increase in radius will lead to increase by 21% in power. A 20% increase in radius will lead to 44% increase in power.

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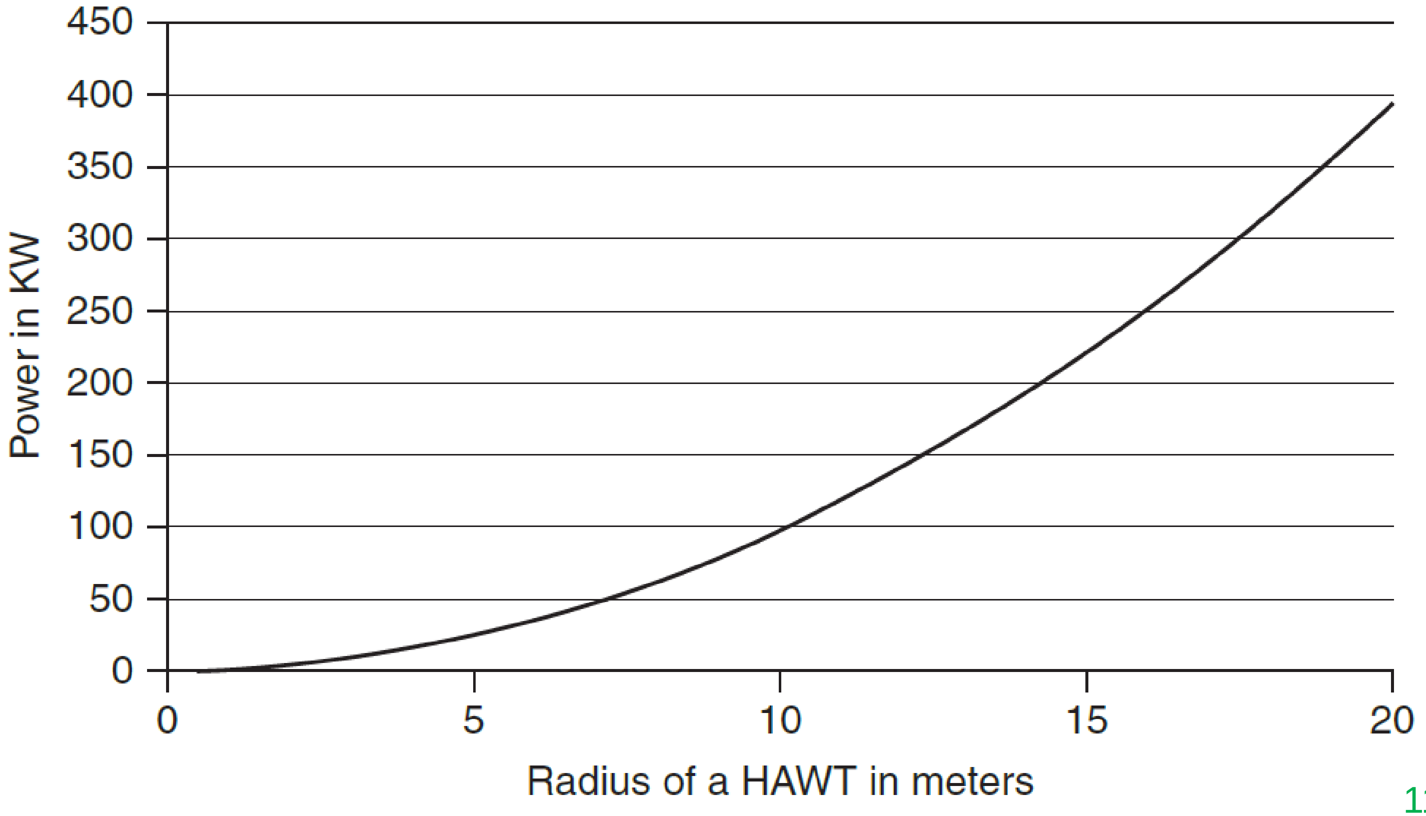
Calculation of the Kinetic Energy of Wind

The relationship between power and rotor diameter are shown below



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Sensitivity of Power to Wind Speed

If speed is changed $\Delta P/P = 3\Delta v/v$ is constant, then

This means that if the speed is increased/decreased by 1%, energy will increase/decrease by 3%. However, if the wind speed is increased by 20%, the power will increase by:

$$\frac{P_1}{P_2} = \frac{v_1^3}{v_2^3} = (1.2)^3 = 1.728$$

This is a 72.8% increase in power

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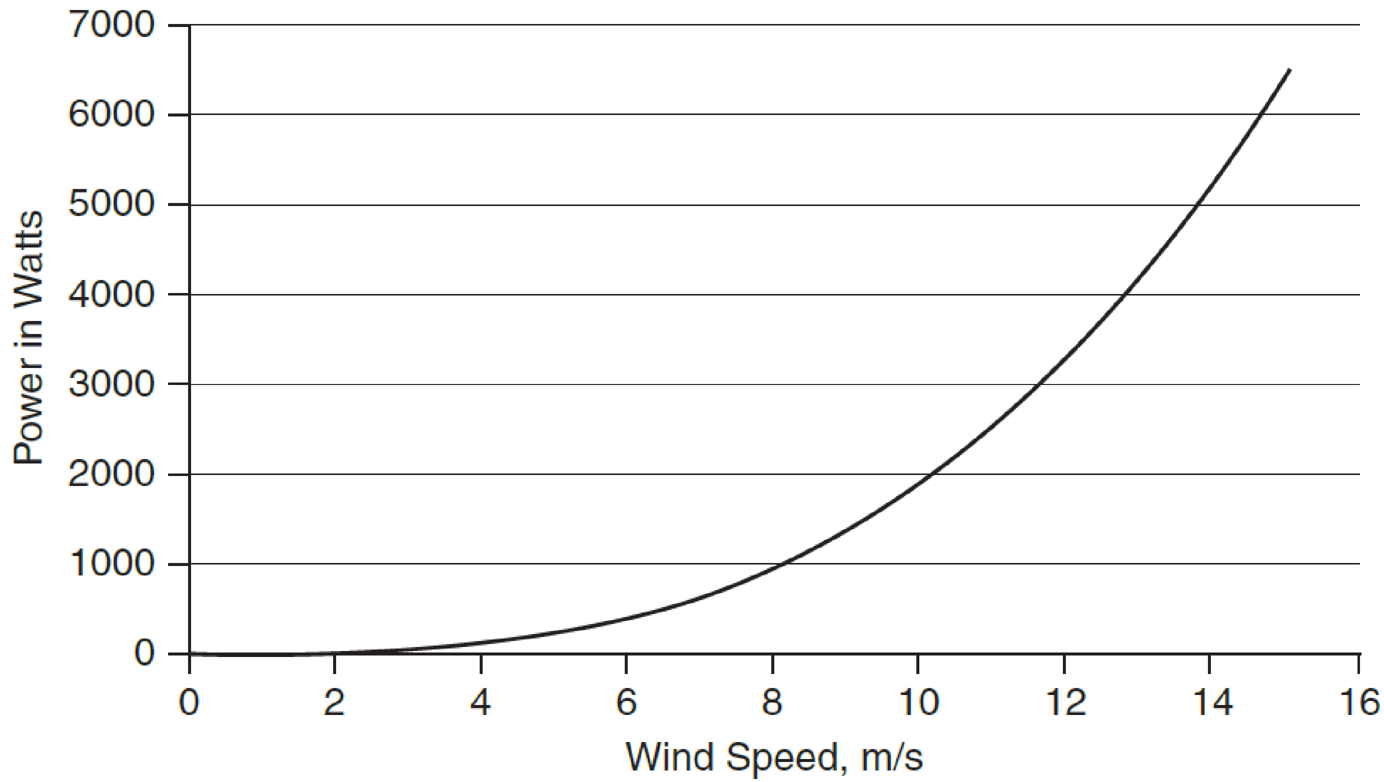
Calculation of the Kinetic Energy of Wind

The relationship between power and wind speed, are shown below



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Basic Concepts/Equations

Three basic principles of physics are often used while studying wind energy extractors; these are :

- Conservation of mass,
- conservation of energy, and
- conservation of momentum.

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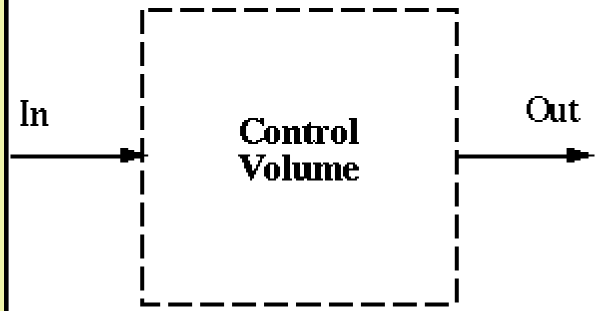
Basic Concepts/Equations

The conservation principles must be applied in a defined control volume. The right and left side of the equation must be referring to the same control volume; in a derivation as one moves from one equation to another, all the equations must refer to the same control volume. This initial control volume may be of any shape;



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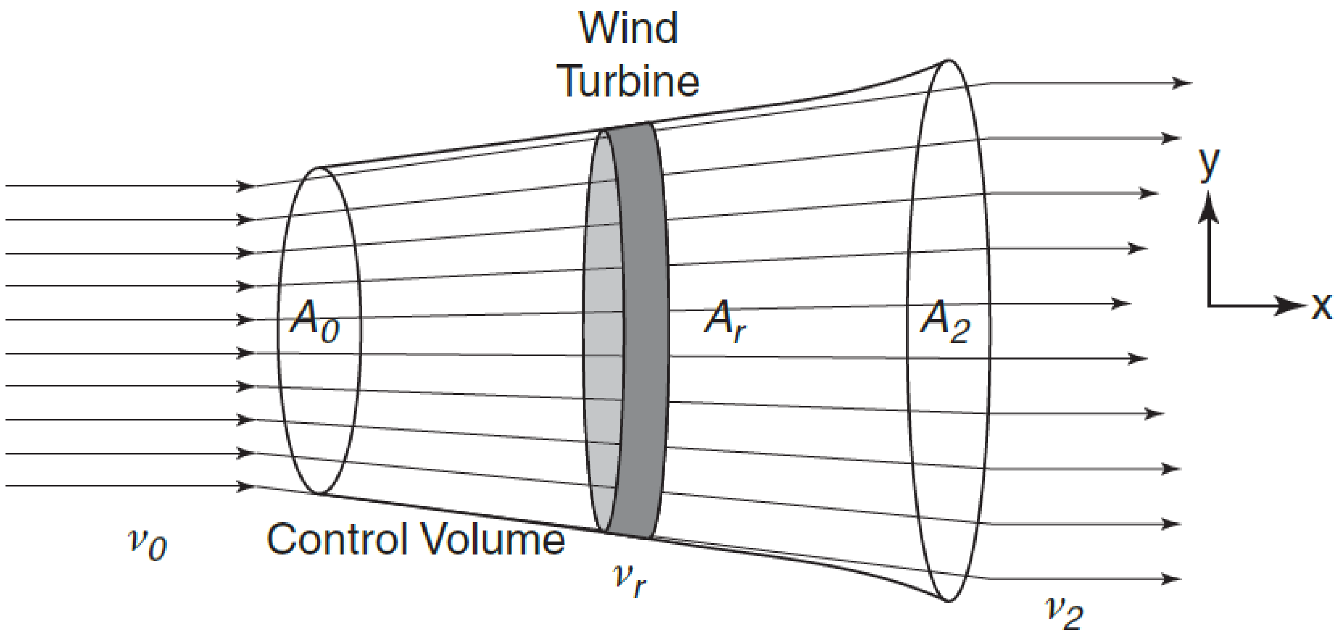
Calculation of the Kinetic Energy of Wind

Typical Control Volume around a wind rotor



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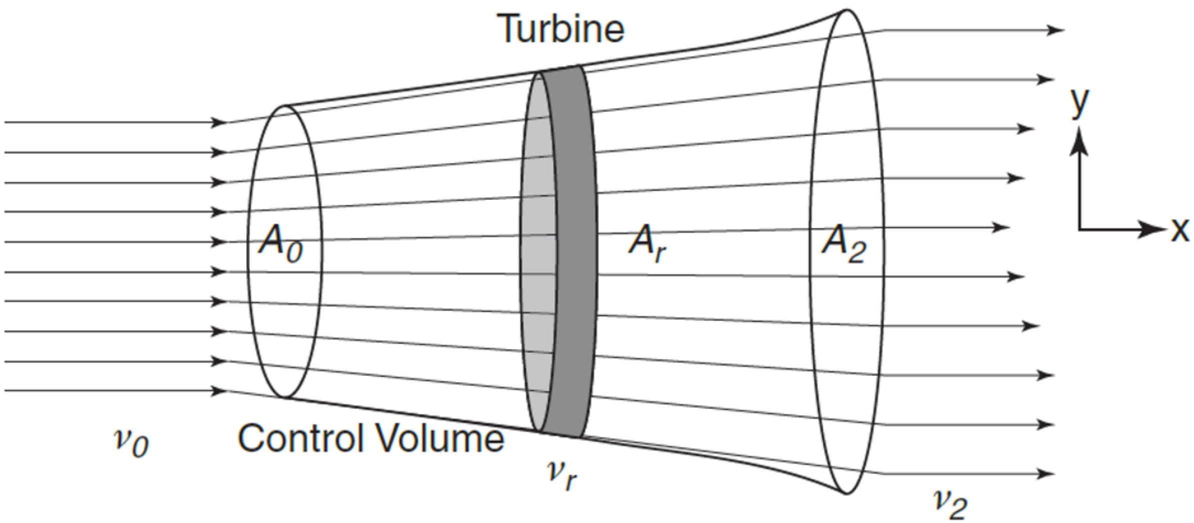
Conservation of mass and momentum in Wind Turbines

Conservation of Mass



Assumptions:

a. Air enters at A_0
b. Air leaves from A_2.
c. Fluid flow is streamlined
and so there is no loss of mass from the surface of the control volume.
d. Fluid is incompressible, that is, there is no change in density.

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Conservation of mass and momentum in Wind Turbines

Under these assumptions, conservation of mass is:

$$\dot{m} = \rho A_0 v_0 = \rho A_r v_r = \rho A_2 \overline{v}_2$$

v_0, v_r, and v_2 are the average wind speeds, taken over cross-sectional A_0;A_r and A_2 respectively.

Since the rotor of turbine is extracting energy from air, the kinetic energy of air will reduce, so, $v_0 > v_r > v_2$.

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Conservation of Energy

A simplified conservation of energy equation is used initially, under the assumptions listed below.

Total energy = Kinetic energy + Pressure energy + Potential energy

The kinetic energy is because of the directed motion of the fluid; pressure energy is because of the random motion of particles in the fluid; potential energy is because of relative position of the fluid.

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Conservation of Energy

Assumptions:

- Fluid is incompressible, meaning the density does not change.
- Note that pressure can change.
- Fluid flow is inviscid, meaning the equation applies to fluid flow outside a boundary layer.
- There is no heat exchange.
- There is no mass transfer.
- Relative position of fluid with respect to the earth's surface does not change, that is, the potential energy remains constant.

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Conservation of mass and momentum in Wind Turbines

The first two assumptions define an ideal fluid.
The above assumptions lead to Bernoulli's equation:
Total energy per unit volume

$$\text{Total energy per unit volume} = \rho \frac{v^2}{2} + p = \text{constant}$$

kinetic energy (dynamic pressure) — $\rho \frac{v^2}{2}$

static pressure — p

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Conservation of mass and momentum in Wind Turbines

Bernoulli's equation, therefore, states that along a streamline when speed increases, then pressure decreases and when speed decreases, then pressure increases. The magnitude of change in pressure is governed by the quadratic relationship.

Daniel Bernoulli

Photo taken from : https://www.alamy.com/stock-photo-daniel-bernoulli-49973531.html

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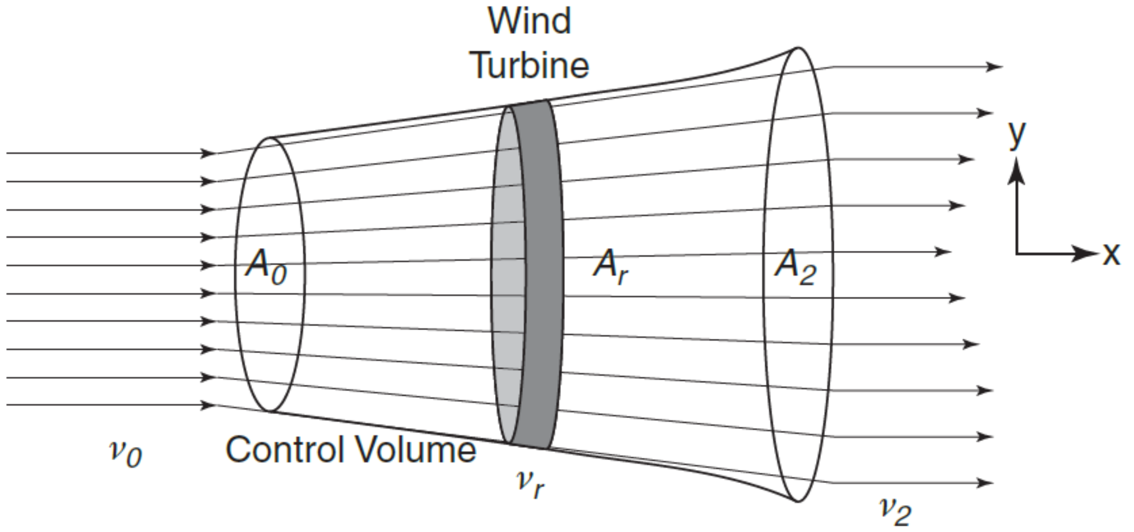
Conservation of mass and momentum in Wind Turbines



Note that Bernoulli's law can be applied from A_0 to the left of the rotor; and then from right of the rotor to A_2. Bernoulli's law cannot be applied across the device that extracts energy; the equation constant in will be different for the two regions.

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Conservation of Momentum

Since the wind rotor is a machine that works by extracting kinetic energy from wind, the wind speed is reduced. Since momentum is mass multiplied by speed, there is a change in momentum.

According to Newton's second law, the rate of change of momentum in a control volume is equal to the sum of all the forces acting.

$$\dot{m}_0 v_0 - \dot{m}_2 v_2 = F$$

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Conservation of Momentum (Cont.)

In order to simplify the equations, the following **assumptions** are required:

- There are no shear forces in the *x*-direction.
- The pressure forces on edges A_0 and A_2 are equal.
- There is no momentum loss or gain other than from A_0 and A_2.
- The equation for Newton's second law along the *x*-axis becomes:

$$\dot{m}_0 v_0 - \dot{m}_2 v_2 = F$$

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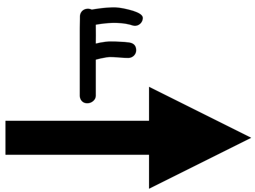
Conservation of Momentum (Cont.)

Because of change in momentum in the control volume, there must be **external force** acting. In this case, rotor provides the external force.

> According to **Newton's third law**, there must be an equal, but opposite, force that acts on the rotor. This force is exerted by wind.



$$F = \Delta p$$

Because wind is exerting a force on the rotor, there must be a **pressure difference** across the rotor equal to the force divided by the area of rotor.

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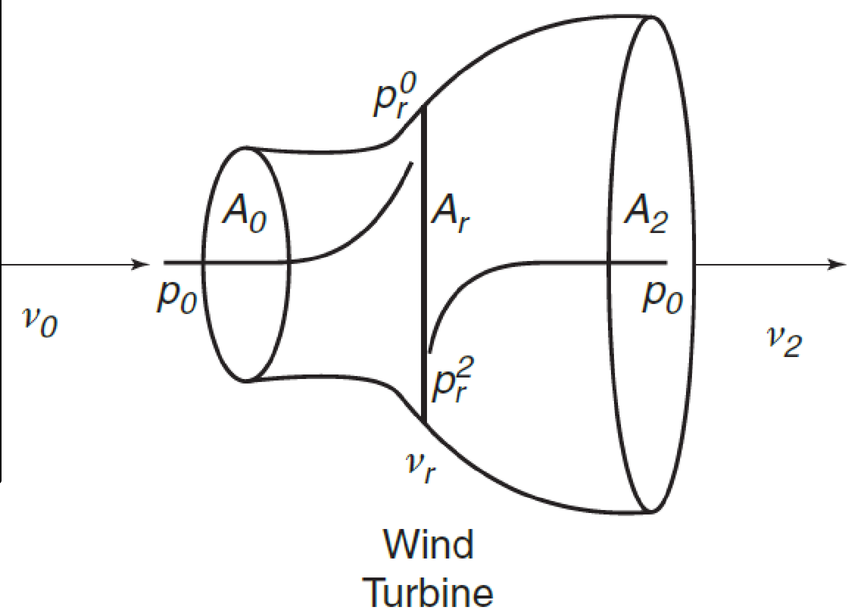
Conservation of Momentum (Cont.)

Since the rotor hinders the flow of air, the pressure at the front of the rotor (p_{0r}) is higher than the free-stream pressure (p_0); the pressure at the back surface of rotor (p_{2r}) is below the free-stream pressure (see next slide).



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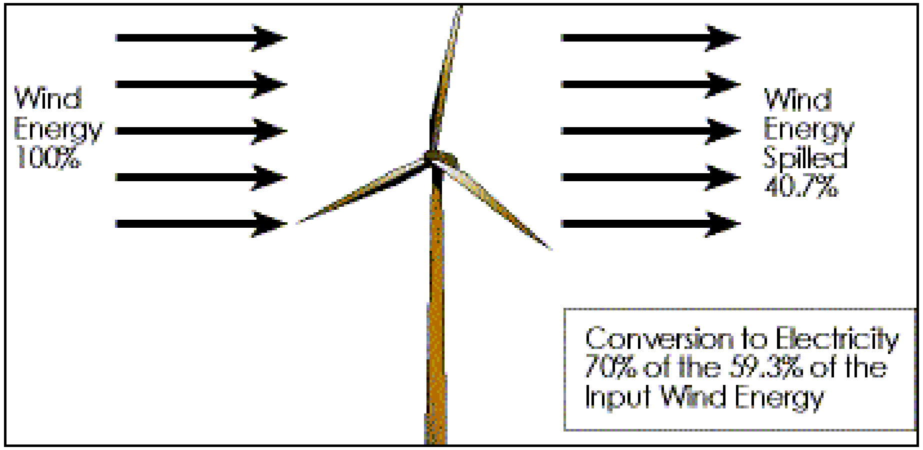
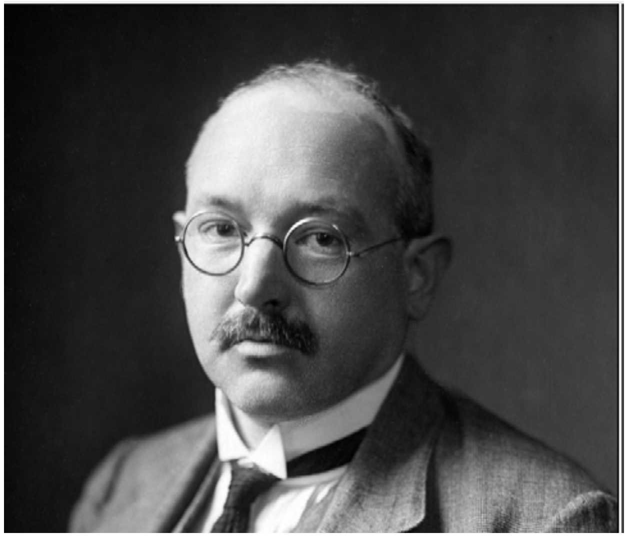
The Betz limit of Wind Turbines

Betz Limit

In 1919, Albert Betz a German physicist postulated a theory about the efficiency of rotor based turbines.





Albert Betz

(25 December 1885 – 16 April 1968)

Photo taken from: https://en.wikipedia.org/wiki/Albert_Betz

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Betz Limit

Using simple concepts of conservation of mass, momentum, and energy, he postulated that a wind turbine with a disc-like rotor **cannot capture more than 59.3% of energy** contained in a mass of air that will pass through the rotor.

$$\frac{16}{27}$$

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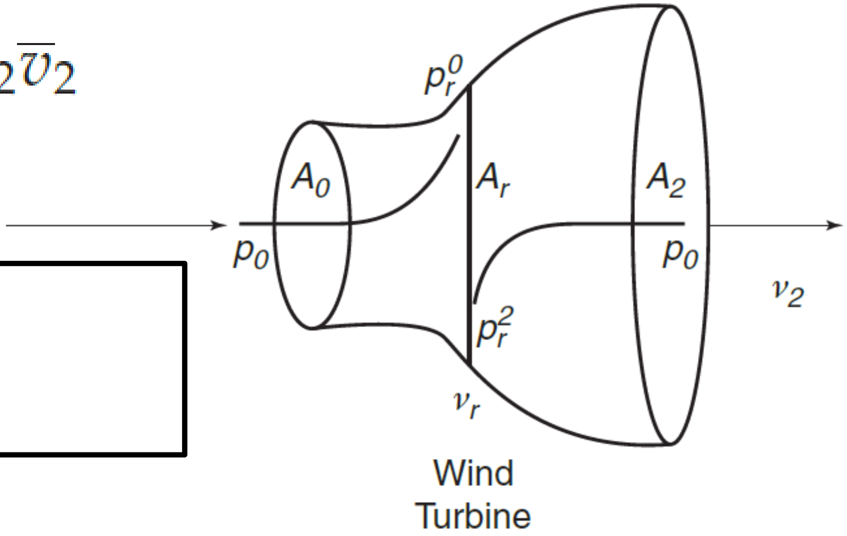
Derivation of Betz Limit

Applying conservation of mass, in control volume A_0, A_r, and A_2 with constant density:

$$\dot{m} = \rho A_0 v_0 = \rho A_r v_r = \rho A_2 \overline{v}_2$$



$$A_0 v_0 = A_r v_r = A_2 v_2$$

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Derivation of Betz Limit

Applying Newton's second law, force exerted on rotor by wind:

$$\dot{m}_0 v_0 - \dot{m}_2 v_2 = F$$

$$F = \dot{m}_r \left(v_0 - v_2\right) = \rho A_r v_r \left(v_0 - v_2\right)$$

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Estimation of Useful Power for Wind turbines

The force exerted on the rotor is also because of the **pressure difference** across the rotor:

$$F = A_r(p_r^0 - p_r^2)$$

Equating the two force expressions

$$F = A_r\left(p_r^0 - p_r^2\right) = \rho A_r v_r\left(v_0 - v_2\right)$$

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Derivation of Betz Limit

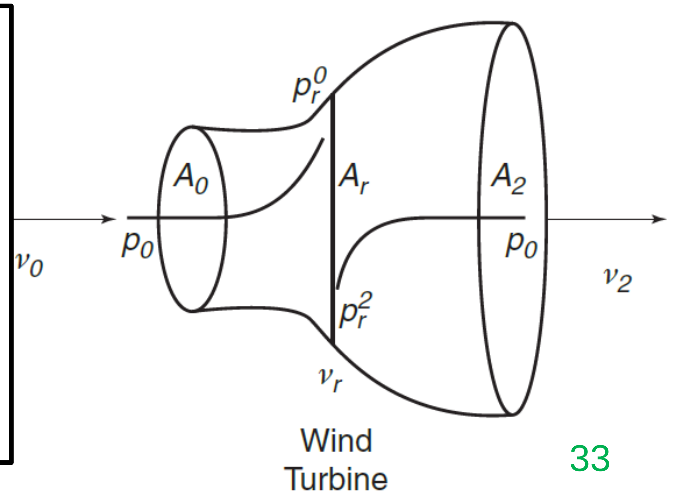
Applying conservation of energy, or Bernoulli's law is next applied in two volumes:

(a) Flow along streamlines from A_0 to the front face of the rotor; and

(b) flow from the back surface of rotor to A_2.

$$p_0 + \frac{1}{2}\rho v_0^2 = p_r^0 + \frac{1}{2}\rho v_r^2$$

$$p_r^2 + \frac{1}{2}\rho v_r^2 = p_0 + \frac{1}{2}\rho v_2^2$$



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Derivation of Betz Limit

Subtracting to get the **pressure difference** across the rotor :

$$p_r^0 - p_r^2 = \frac{1}{2}\rho\left(v_0^2 - v_2^2\right)$$

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Estimation of Useful Power for Wind turbines

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Pressure difference across the rotor can also be obtained from the momentum equation

Momentum eq. Bernoulli's eq.

$$\frac{F}{A_r} = p_r^0 - p_r^2 = \rho v_r (v_0 - v_2) = \frac{\rho}{2}\left(v_0^2 - v_2^2\right)$$

Hence

$$v_r = \frac{(v_0 + v_2)}{2}$$

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Conclusion:

$$v_r = \frac{(v_0 + v_2)}{2}$$

- The Equation above implies that v_r, the wind speed at the rotor, is average of the free-stream wind speed and the wind speed in the wake.
- Note, the wind speed in wake (v_2) is where the pressure reaches freestream pressure (p_0).
- The Equation also implies that **one-half** the wind speed loss occurs in front of the rotor and the other one-half occurs downstream.
- The power is delivered (or work is done) by the force exerted because of pressure difference across the rotor. Power is defined as force multiplied by speed = Fv_r.

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Estimation of Useful Power for Wind turbines

The power delivered to the idealized rotor by the wind is:

$$P = Fv_r = (p_r^0 - p_r^2)A_r v_r$$

Pressure difference was computed earlier as:

$$p_r^0 - p_r^2 = \rho v_r (v_0 - v_2) = \frac{\rho}{2}(v_0^2 - v_2^2)$$

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Estimation of Useful Power for Wind turbines

Hence, the power delivered to the idealized rotor by the wind is:

$$P = \frac{1}{2}\rho A_r v_r \left(v_0^2 - v_2^2\right)$$

$$P = \frac{1}{2}\rho A_r v_r \left(v_0 - v_2\right)\left(v_0 + v_2\right)$$

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Estimation of Useful Power for Wind turbines

Note that

$$P = \frac{1}{2}\rho A_r v_r \left(v_0^2 - v_2^2\right) = \frac{1}{2}\dot{m}\left(v_0^2 - v_2^2\right)$$

which is change in kinetic energy applied to the flow of mass per unit time through the rotor. That is, the work done by force due to pressure difference is equal to the change in kinetic energy.

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Estimation of Useful Power for Wind turbines

Referring to power expression:

$$P = \frac{1}{2}\rho A_r v_r \left(v_0 - v_2\right)\left(v_0 + v_2\right)$$

And the average velocity at the rotor : $v_r = \frac{(v_0 + v_2)}{2}$

The power equation can be reduced to

$$P = \rho A_r v_r^2 \left(v_0 - v_2\right) = 2\rho A_r v_r^2 \left(v_0 - v_r\right)$$

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Estimation of Useful Power for Wind turbines

Maximum power is realized when:

$$\frac{\partial P}{\partial v_r} = 0 = 2v_r v_0 - 3v_r^2$$

Which yields the following expression:

$$\boxed{v_r = \frac{2}{3} v_0}$$

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Estimation of Useful Power for Wind turbines

This implies:

$$v_2 = \frac{1}{3} v_0$$

And the power expression will be:

$$P = 2\rho A_r v_r^2 (v_0 - v_r) = \rho A_r v_0^3 \left(\frac{8}{27}\right)$$

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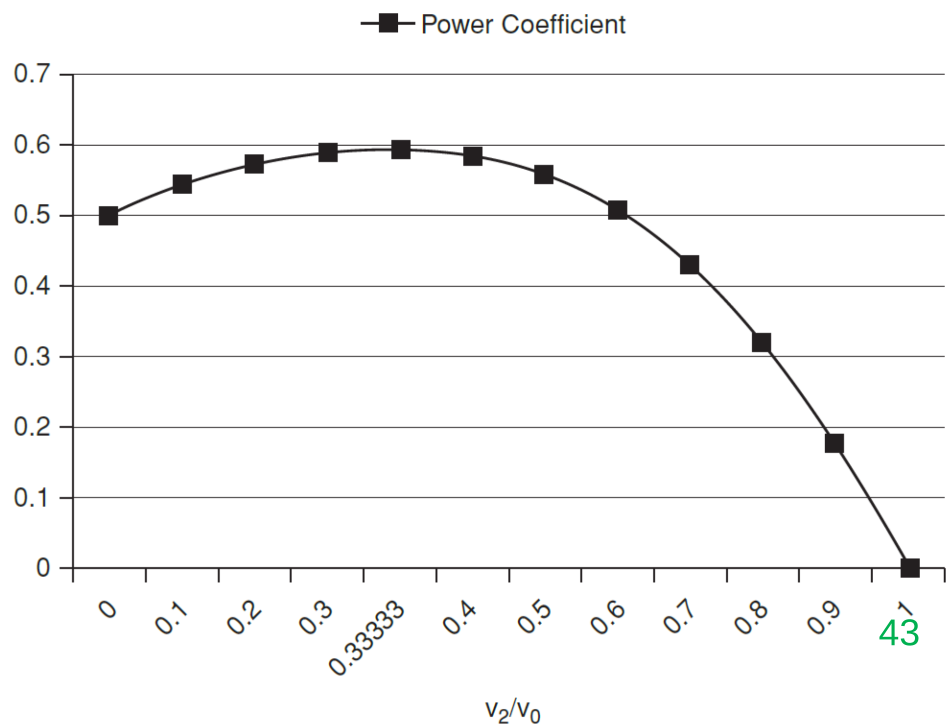
Estimation of Useful Power for Wind turbines

$$\frac{\text{Max power extracted}}{\text{Power available}} = P/\frac{1}{2}\rho A_r v_0^3 = \frac{16}{27} = 0.593 = C_p$$

The figure represent Cp versus v_2/v_0 ratio .



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Estimation of Useful Power for Wind turbines

C_p is called the **power coefficient**. A related concept is the thrust coefficient, C_T, which i-

$$\frac{F}{\frac{1}{2}\rho A_r v_0^2} = \frac{8}{9} = C_T$$

C_p is referred to as the **Betz limit** and states that the maximum power an ideal rotor can extract from wind is 59.3%.

An ideal rotor of the type described above is called an "actuator disk." The actuator disk induces a reduction of the free-stream wind

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Estimation of Useful Power for Wind turbines

If *a* is the induction factor, then: $v_r = (1 - a)v_0$

In terms of *a* the wake wind speed, force and power are:

$$v_2 = (1 - 2a)v_0$$

$$F = 2\rho A_r v_0^2 a\,(1 - a)$$

$$P = 2\rho A_r v_0^3 a\,(1 - a)^2 = \left(\frac{1}{2}\rho A_r v_0^3\right) 4\,a\,(1 - a)^2$$

Note, *a* must be less than 0.5 otherwise, v2 < 0.
Therefore, the above derivation does not apply when *a* > 0.5

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Estimation of Useful Power for Wind turbines

The Meaning of Betz Limit

Wind rotors in idealized conditions can extract, at most, 59.3% of energy contained in the wind. This is an important limit because it defines the upper limit of the efficiency of any rotor disk type energy extracting device that is placed in the flow of a fluid.

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Estimation of Useful Power for Wind turbines

Example 1

Consider 1-MW rated wind turbine with rotor diameter = 70 m and power curve, provided by the turbine manufacturer is given in a Table form shown in the next slide.

a. Calculate the turbine swept area
b. Plot the turbine power curve
c. Generate the Betz limit power expected at the wind velocity range shown on the given table
d. Plot the Betz limit curve
e. Check if the turbine is within the Betz limit at all wind speeds.

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Estimation of Useful Power for Wind turbines

Example 1

m/s	kw
WindSpeed	**UsefullPower**
2	5
4	50
6	150
8	400
10	660
12	900
14	1000

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Estimation of Useful Power for Wind turbines

Solution

Diameter	70	m		
Swept Area	3850	m2	large WTG	>200 m2
Density	1.22	kg/m3		

$$P_{Betz}(v_0) = \frac{16}{27}\frac{\rho A_r v_0^3}{2}$$

m/s	kw	kw
WindSpeed	**UsefullPower**	**BetzLimit**
2	5	11.13
4	50	89.07
6	150	300.61
8	400	712.55
10	660	1391.70
12	900	2404.86
14	1000	3818.83

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Estimation of Useful Power for Wind turbines

Solution (Cont.)

m/s	kw	kw	
WindSpeed	**UsefullPower**	**BetzLimit**	Cp
2	5	11.13	0.44909
4	50	89.07	0.561362
6	150	300.61	0.498989
8	400	712.55	0.561362
10	660	1391.70	0.474239
12	900	2404.86	0.374242
14	1000	3818.83	0.26186

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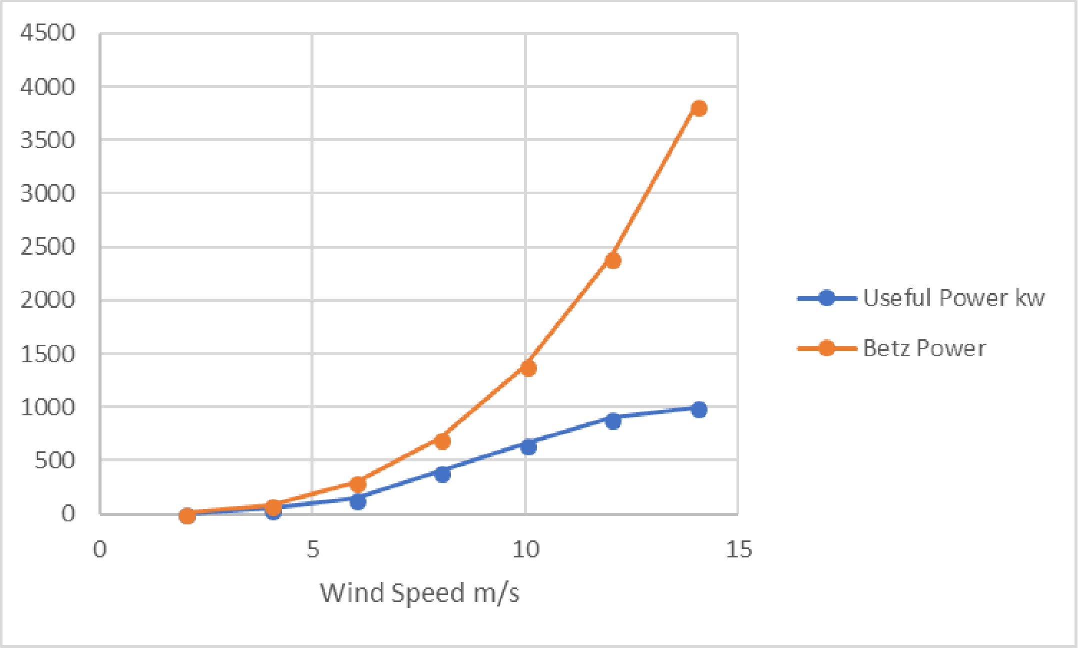
Estimation of Useful Power for Wind turbines

Blue line is the power curve of 1-MW wind turbine generator (WTG) with rotor diameter = 70 m. The brown curve is the Betz limit curve for the same rotor



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Estimation of Useful Power for Wind turbines

Example 2

Consider a turbine with rotor diameter = 2 m and power rating of 2 KW at 12 m/s.
Check if this turbine will pass the Betz limit test at 12 m/s wind speed

Solution

$$P_{ideal} = \frac{\rho A_r v_0^3}{2} = \frac{1.22\pi\left(\frac{2}{2}\right)^2 12^3}{2} = 3.3 \text{ kW}$$

$$P_{Betz} = 0.59 \; P_{ideal} = 1.953 \text{ kW}$$

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Estimation of Useful Power for Wind turbines

Solution (Cont.)

Since the power rating of turbine is greater than the maximum power that can be extracted, this turbine rotor, therefore, **does not pass the Betz limit test;** at 12 m/s, the turbine cannot produce 2 KW of power, unless it uses a shroud or some other means to enhance axial wind speed.

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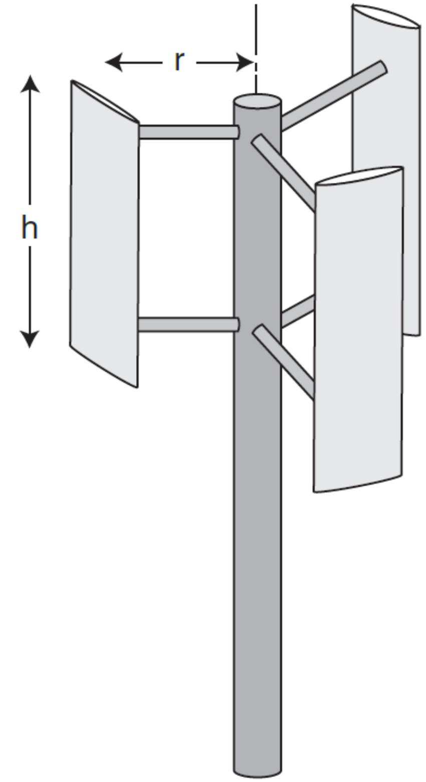
Estimation of Useful Power for Wind turbines

<u>Example 3</u>

consider a vertical axis wind turbine .
The height (h) = 6.1 m, diameter (d) = 1.2 m, and swept area = $h \cdot d$ = 7.43 m^2.
Power rating of rotor at 12 m/s = 1.2 kW.
Check if this turbine will pass the Betz limit test at 12 m/s wind speed



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Estimation of Useful Power for Wind turbines

Solution

$$P_{ideal} = \frac{\rho A_r v_0^3}{2} = \frac{1.22\pi \cdot 7.43 \cdot 12^3}{2} = 7.8\ \text{kW}$$

$$P_{Betz} = 0.59\ P_{ideal} = 4.6\ \text{kW}$$

This VAWT passes the Betz limit test.

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References

Books:
[1] Wind Energy Engineering. New York: McGraw-Hill, Jain, P. (2011).
[2] Fundamental of Aerodynamics, John D. Anderson, Jr., McGraw-Hill, 2001.

Web links:
[3] www.ewea.org European Wind Energy Association
[4] wwindea.org World Wind Energy Association
[5] www.awea.org American Wind Energy Association

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Thank You for Your Attention!

Contact: info@weset-project.eu

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Introduction to Wind Energy

Module 2.1

Wind as a Source of Useful Energy
Lesson 3

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Objectives

The purpose of this lesson is to introduce the main aspects of wind turbines and wind farms for Master Students in Engineering, focusing on up to date technologies that are particularly relevant for South Mediterranean countries.

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Learning Outcomes

This lessons to the students being able to :

O1. Understand how wind energy was developed and utilized throughout history

O2. Understand the potential of wind as renewable energy source

O3. Understand the advantages of using wind energy as power source

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Technical Contents

1. *A short history of Wind as source of energy*
2. *The potential of wind as renewable energy source*
3. *The advantages of using wind energy as power source*

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Why Wind Energy?

CLIMATE CHANGE

Today with the specter of global warming and climate change looming over us, there is a need for the energy industry to find energy sources free of carbon dioxide pollution.

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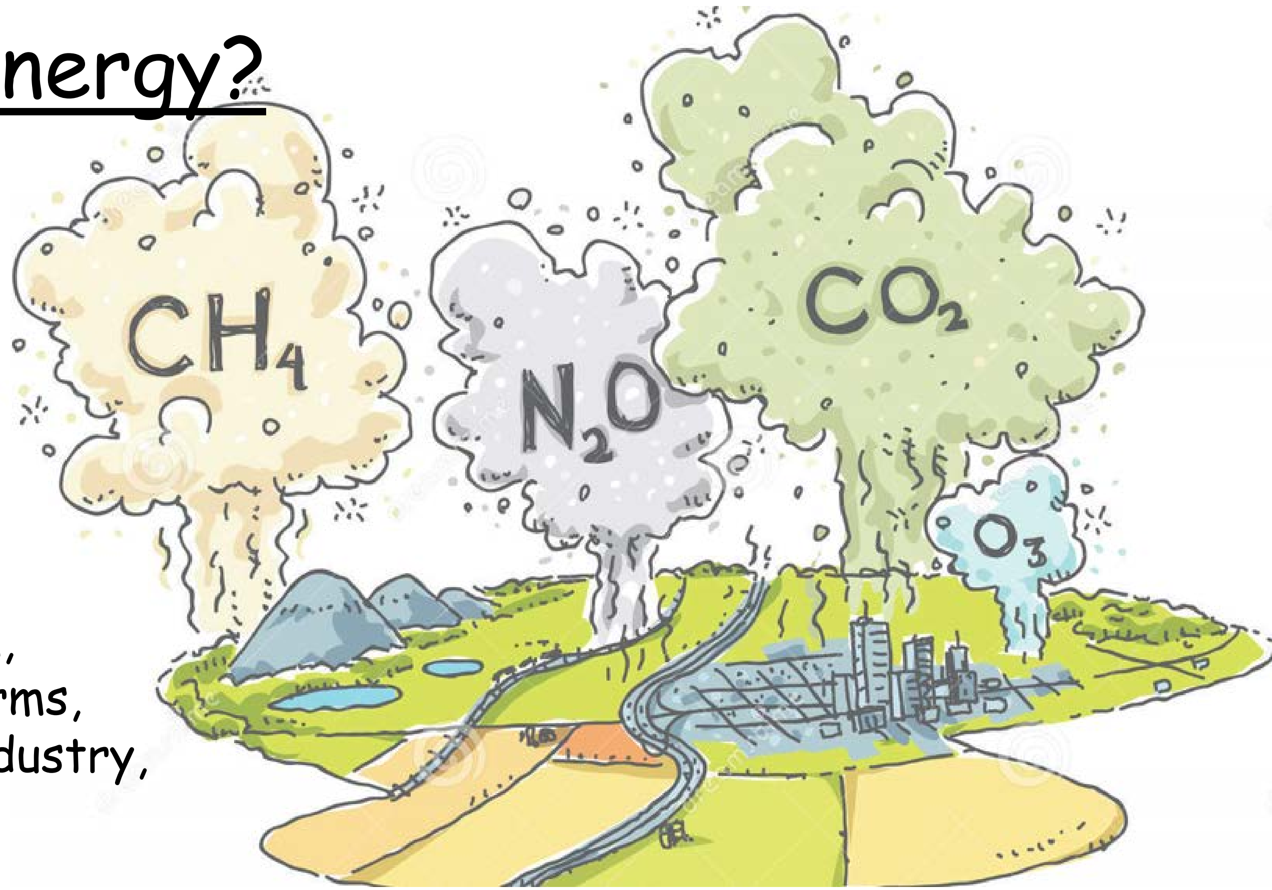
A short history of Wind as source of energy

Why Wind Energy?

Energy-related carbon
(CO_2) emissions contribu
the majority of global
greenhouse gas (GHG)
emissions (66%); these
include:



- electricity production,
- transport in all its forms,
- cement making and industry,

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A short history of Wind as source of energy

Will we be to reach the level of keeping global warming to just 2C above the preindustrial level by 2035. ?

Options:

- International agreements, protocols, conferences, …etc ?

  (are not enough)
- to reduce our consumption of energy and consequently our standard of living

  (natural reticence toward lowering our standard of living, the aspirations of all to a life with available electricity, and the increasing rise in the population of the world)
- to capture CO_2 and bury it in caverns or under the sea (capture and storage, CCS).

  the cost of CCS

A. it is unlikely that these two options will prevail.

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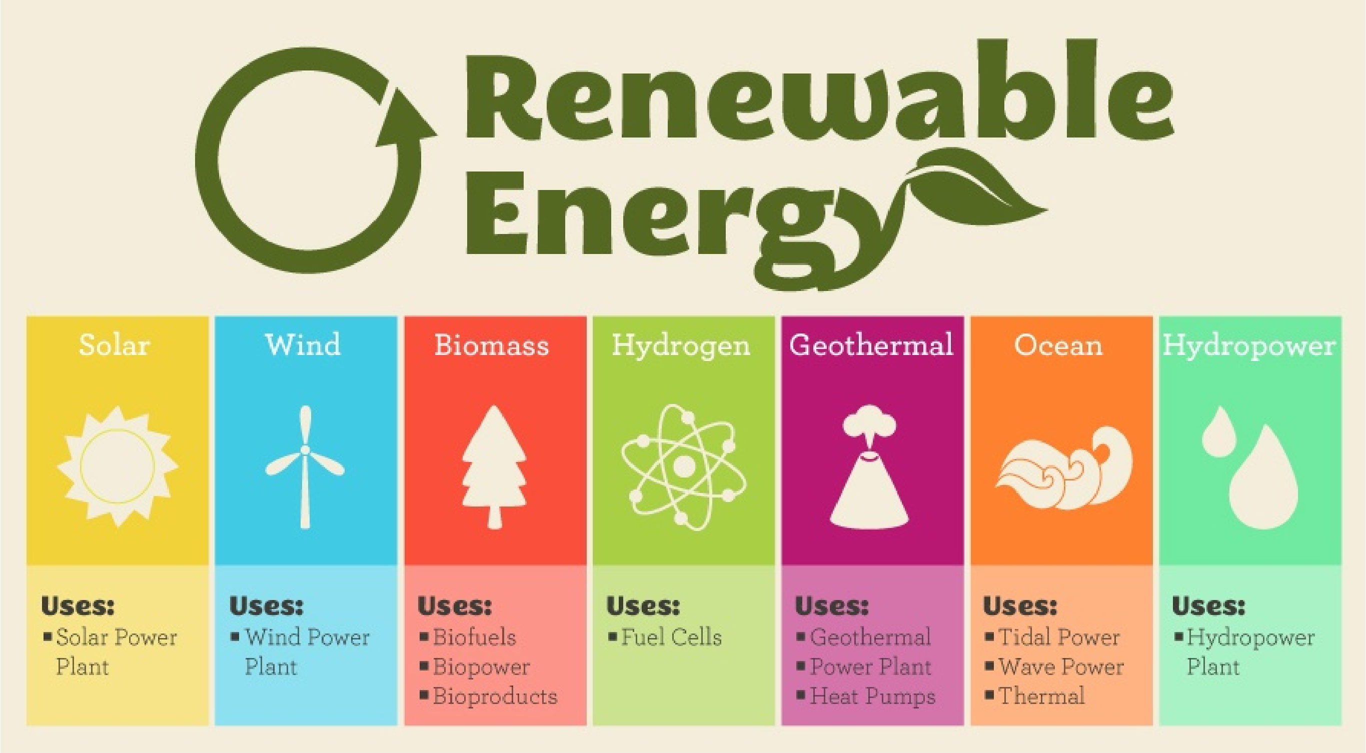
<u>**The spotlight is on the renewable energy industry to find energy sources free of carbon dioxide pollution.**</u>



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A short history of Wind as source of energy

<u>Remark</u>

The production of electricity worldwide is responsible for 26% of the global GHGs (mainly CO_2 and CH_4).

Fossil fuel was responsible for producing 65% of global electricity (coal 38%, gas 22%, and oil 5%)

Energy Source	World/%
Coal	38
Natural gas	22
Hydroelectric	17
Nuclear	11
Oil	5
Biomass, solar, tides	4
Wind	4

Total World Electricity Production in 2014

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A short history of Wind as source of energy

In this course we will focus our attention on electricity generation from wind energy.

Wind and solar energy are at the forefront of the drive to significantly reduce the GHGs to meet the 2C limit. This is largely because we know that if we can replace fossil fuel with wind and solar energy for generated electricity, ***we can significantly reduce CO_2 emissions.***

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A short history of Wind as source of energy

At the moment wind turbines (433 GW in 2015) have a greater installed capacity, worldwide, than do solar photovoltaics (242 GW in 2016), but this is still a mere drop in the ocean.

Wind and solar energy produce only 4% of the global supply of electricity,. There is much work to be done.

Unfortunately, coal, the worst of the fossil fuel polluters, is still the main energy source for generating electricity. The chief culprits are China, the United States, and Australia; coal produces 72% of China's electricity and 38% of the USA's Electricity.

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A short history of Wind as source of energy

BACKGROUND

The extraction of kinetic energy from wind and its conversion to useful types of energy is a process which has been used for centuries. It is believed that the first windmills were invented 2000 years ago by the Persians and also by the Chinese and were used to grind corn and also to lift water.

Later the Dutch would develop windmills to drain their land in the 14th century and, by the 19th century, millions of small windmills were installed in the United States.
In the following few slides a brief history of wind energy

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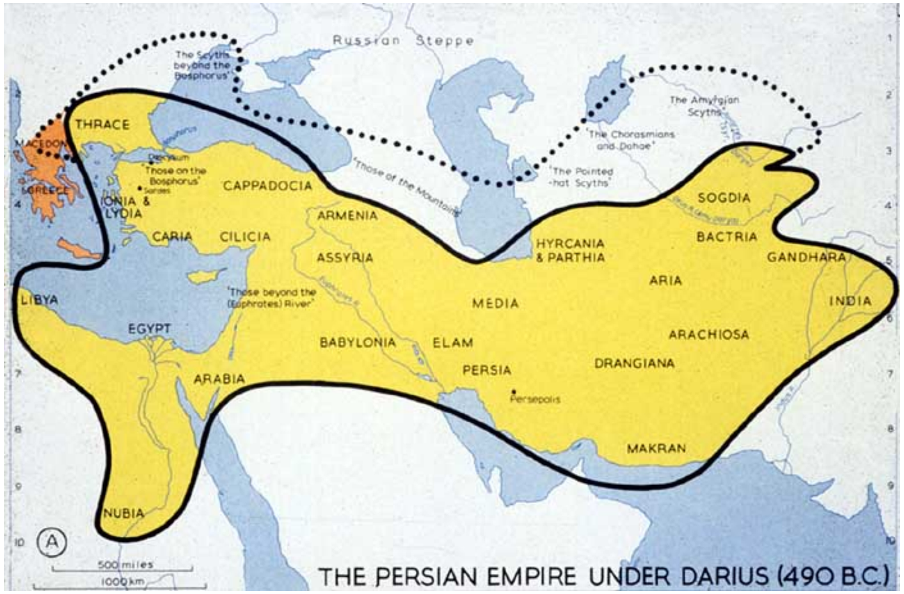
A short history of Wind as source of energy

Wind Energy History

- Extensive application of wind turbines seems to have originated in Persia where it was used for grinding wheat.

It was invented in eastern Persia as recorded by the Persian geographer Estakhr in the 9th century



Source: http://www.utexas.edu/courses/clubmed/92908dariusmap.jpg

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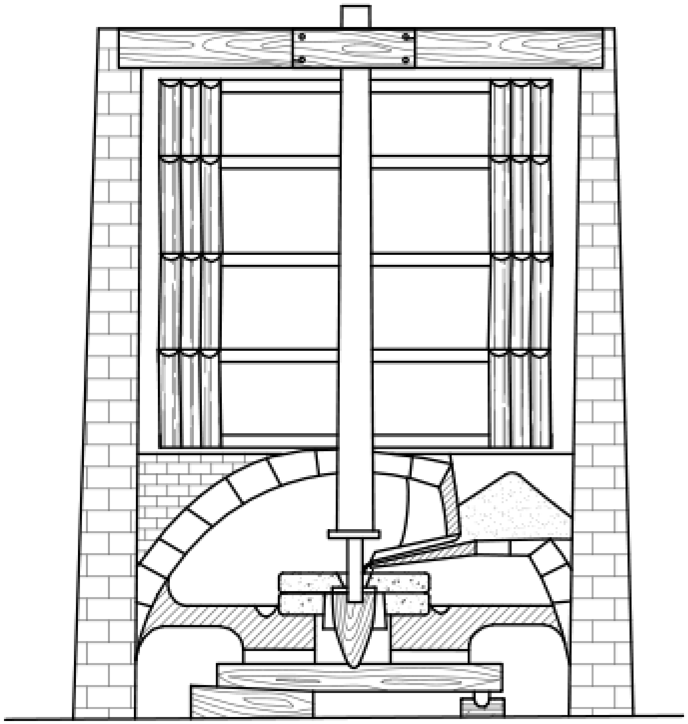
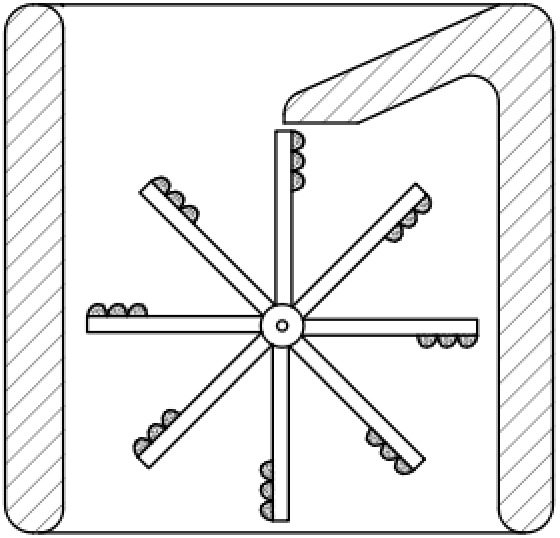
Wind Energy History





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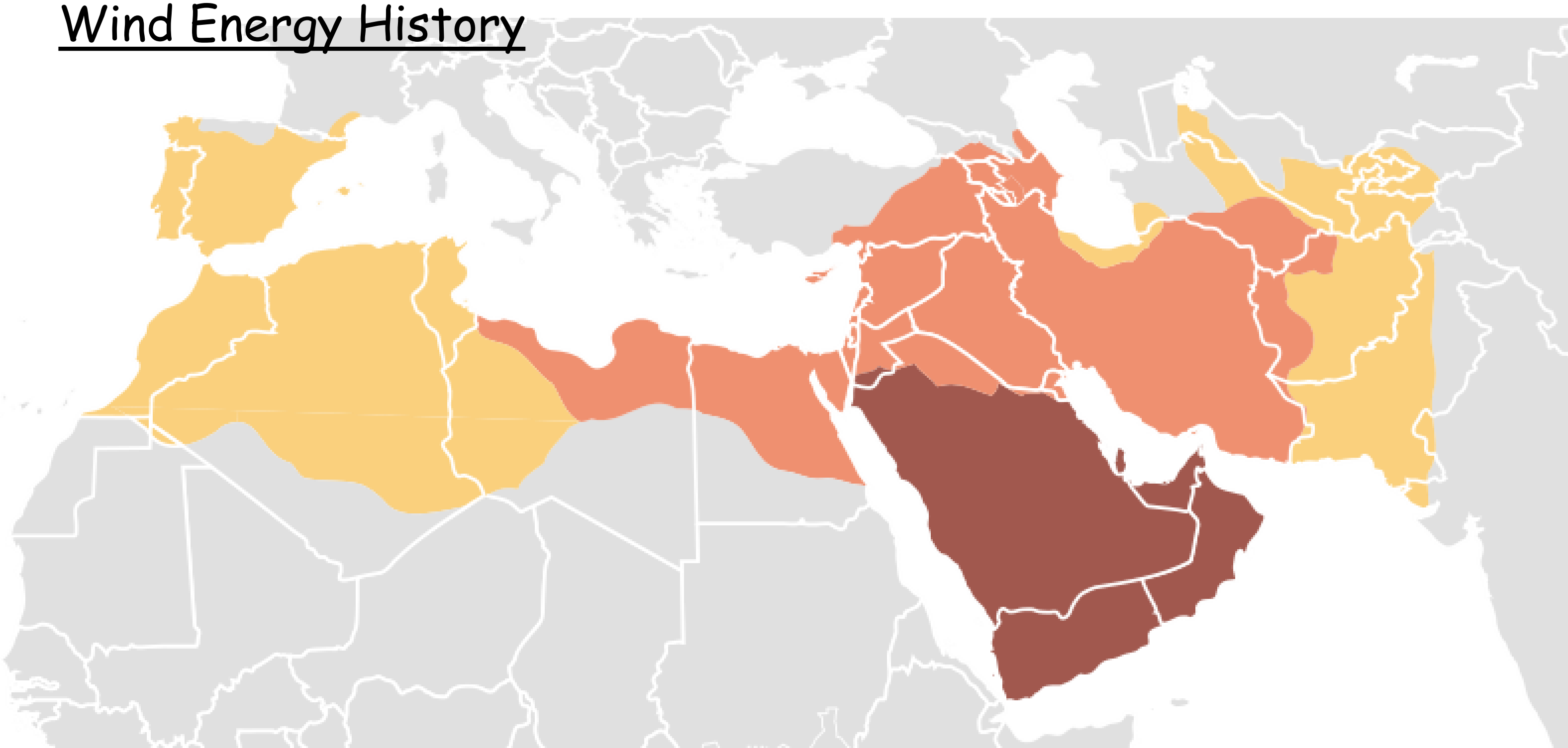
A short history of Wind as source of energy

Wind Energy History



- The Arab conquest spread this technology throughout the Islamic world and China.

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A short history of Wind as source of energy

Wind Energy History

- In Europe, the wind turbine made its appearance in the eleventh century.
- Two centuries later had become an important tool, especially in Holland.

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A short history of Wind as source of energy

Wind Energy History

The Dutch have become very innovative when it comes to keeping out the water.

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Wind Energy History

The Dutch have built dykes, fortifications and last but not least wind and watermills to create new land.

The oldest mill is a watermill that dates back to the eighth century. These techniques were used to pump dry hundreds of lakes and swamps and to prevent land from flooding. Today, windmills are characteristic of the Dutch landscape and a symbol of the Dutch struggle with water.

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Wind Energy History

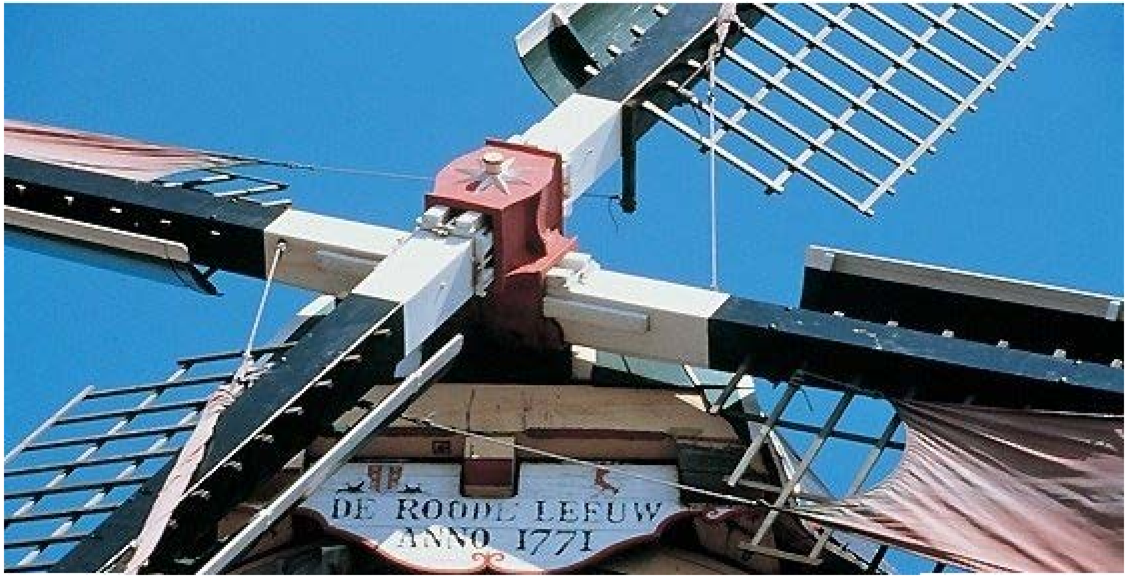

Photo taken from https://www.holland.com/global/tourism/discover-holland/traditional/dutch-windmills.htm

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A short history of Wind as source of energy

American West

The development of the American West was aided by wind-driven pumps.

1854 Dani Halladay invented a windmill for pumping water. Hlladay's company, the US Wind Engine & Pump Co., went on to become the largest manufacturer of windmills in America for a time.

Livestock business benefitted from windmill in ensuring satisfactory supply of water

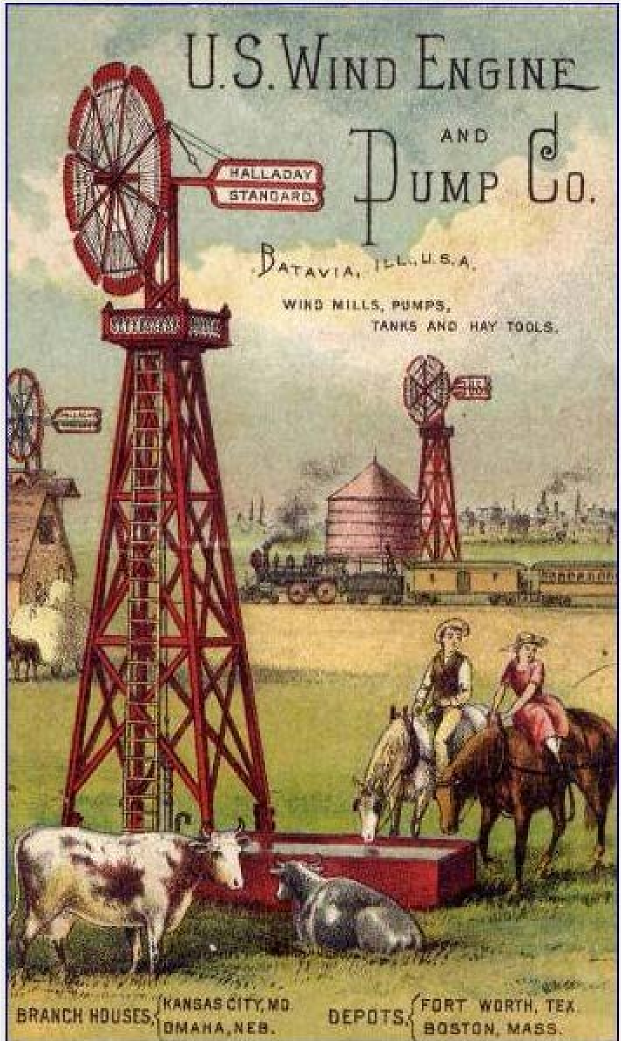

***Photo taken from: Fundamentals of Renewable Energy Processes**, By Aldo V. da Rosa*

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<u>Daniel Halladay</u>

- son of David Halladay and Nancy (Carpenter) Halladay
- born in Marlboro, Vermont. on 24 Nov. 1826.
- At the age of 19 he was apprenticed as a machinist at Ludlow, Massachusetts,
- at 21 was in charge of building machinery for the government armory at Harper's Ferry, Virginia.

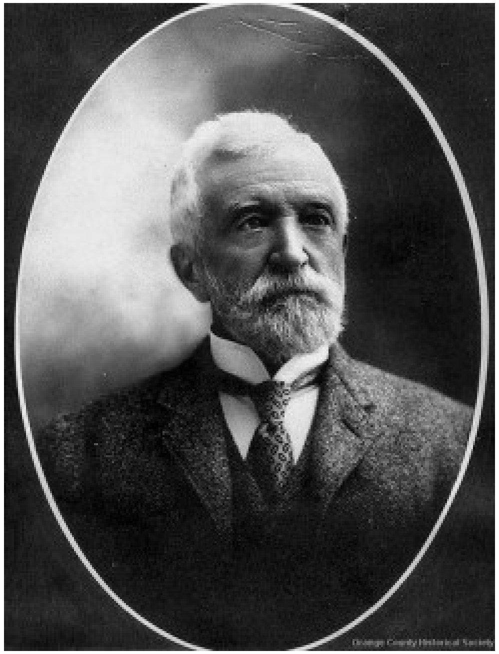

Photo taken from : https://en.wikipedia.org/wiki/Daniel_Halladay

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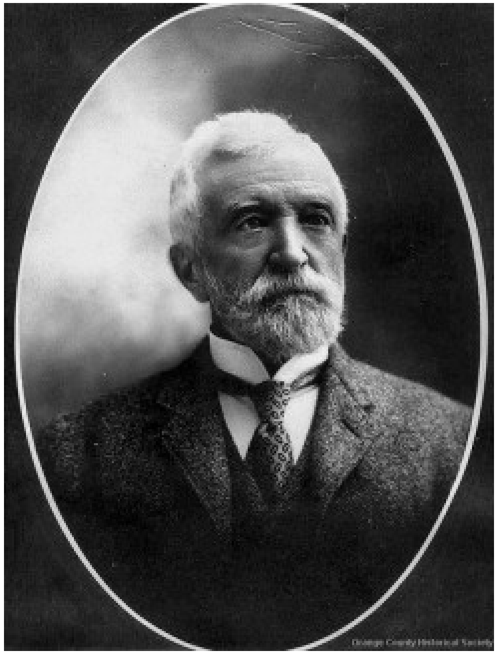
Daniel Halladay

- He married Susan M. Spooner at Ludlow, Massachusetts.
- They had a son who died in infancy and they adopted a daughter.
- In Connecticutt, developed his self-governing wind engine.
- In 1863 he moved his business to Batavia, Illinois changing the name to U. S. Wind Engine and Pump Company. At one time, he employed over 200 people in his windmill factory.



Daniel Halladay, Father of American Windmills.

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More development to windmill took place ..as

- Windmill designs capable of higher pumping capacity
- Iron and steel replaced wooden windmill parts
- The first all steel windmill and tower produced in America by the US Wind Engines and Pump Co. (This work was due to scientific development and testing by the famous windmill and designer Thomas Perry).

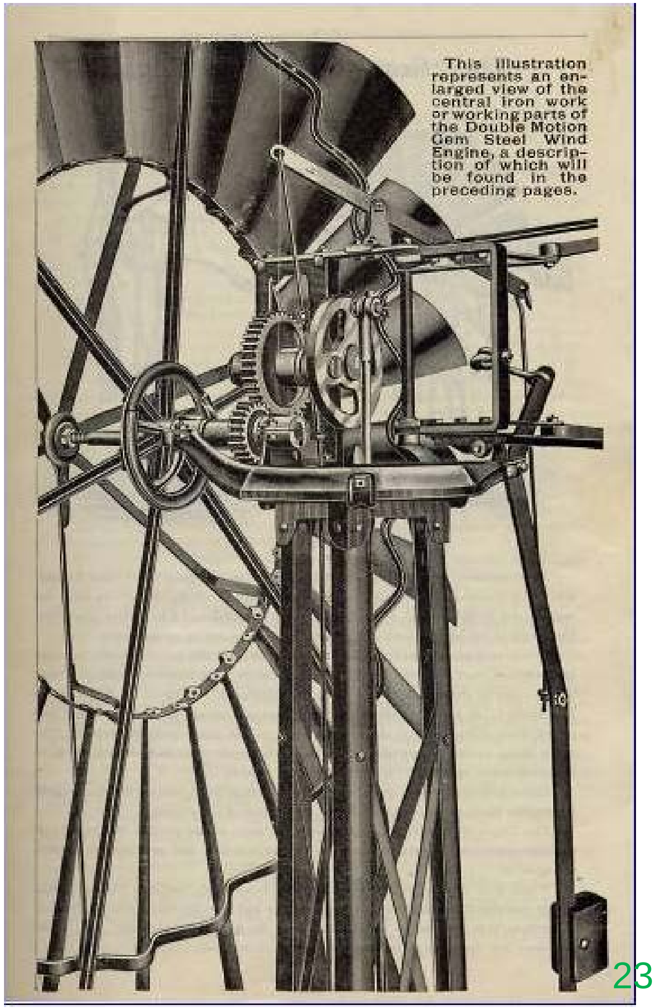

Photo taken from: http://www.ironmanwindmill.com/windmill-history.htm

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- The US Wind Engines and Pump Co. gave up on the marketing of the all metal windmills after early disappointment caused by **poor market acceptance** and continued to produce **their wooden windmills**.
- Eventually, the steel windmills won popularity and went on to dominate the market, but by other manufacturers.
- US Wind Engines and Pump Co. finally **closed** its doors.
- Aermotor began building improved forms of the original all metal mill … and the race went on …

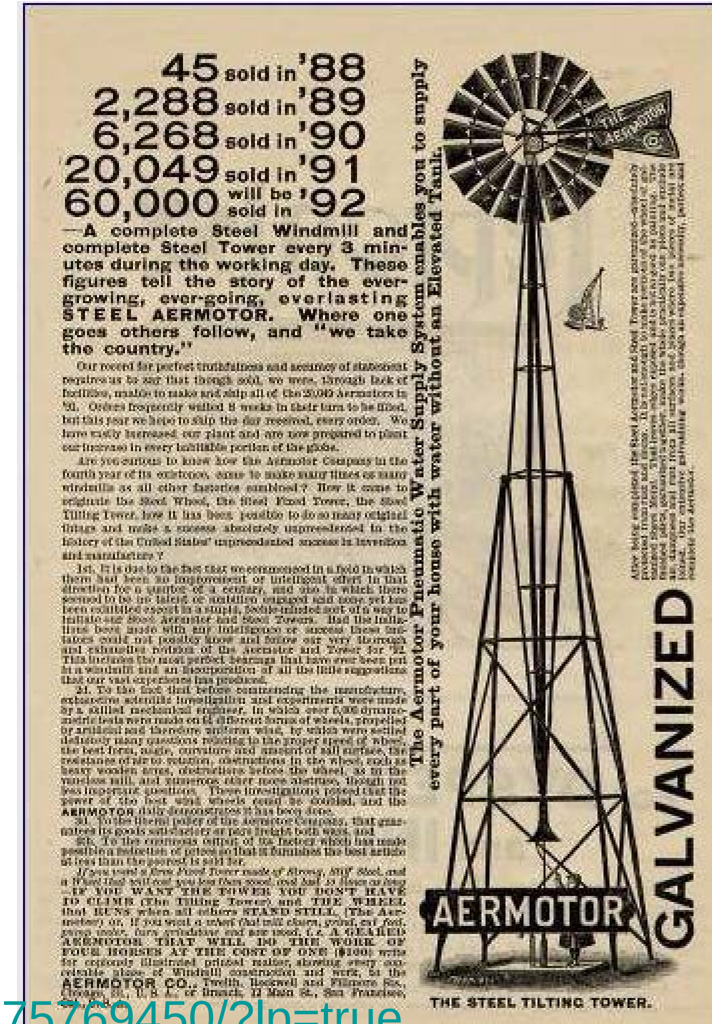

Photo taken from: https://www.pinterest.com/pin/351280839675769450/?lp=true

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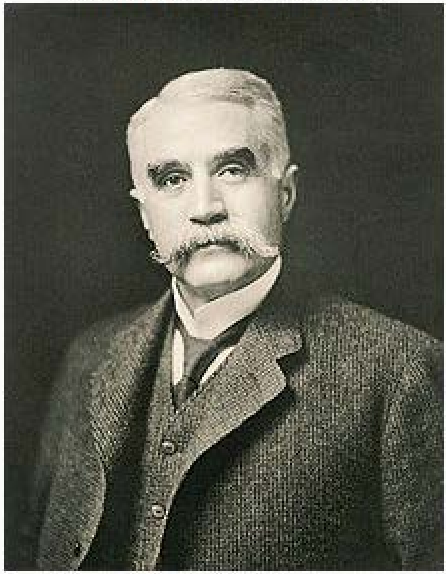
A short history of Wind as source of energy

<u>Wind turbines for **electricity** generation</u>
The first significant wind turbine designed specifically for the generation of electricity was built by <u>Charles Brush</u> in Cleveland, Ohio. It operated for 12 years, from 1888 to 1900 supplying the needs of his mansion.

Charles Francis Brush



Born	March 17, 1849 Euclid, Ohio
Died	June 15, 1929 (aged 80)

Photo taken from: https://en.wikipedia.org/wiki/Charles_F._Brush

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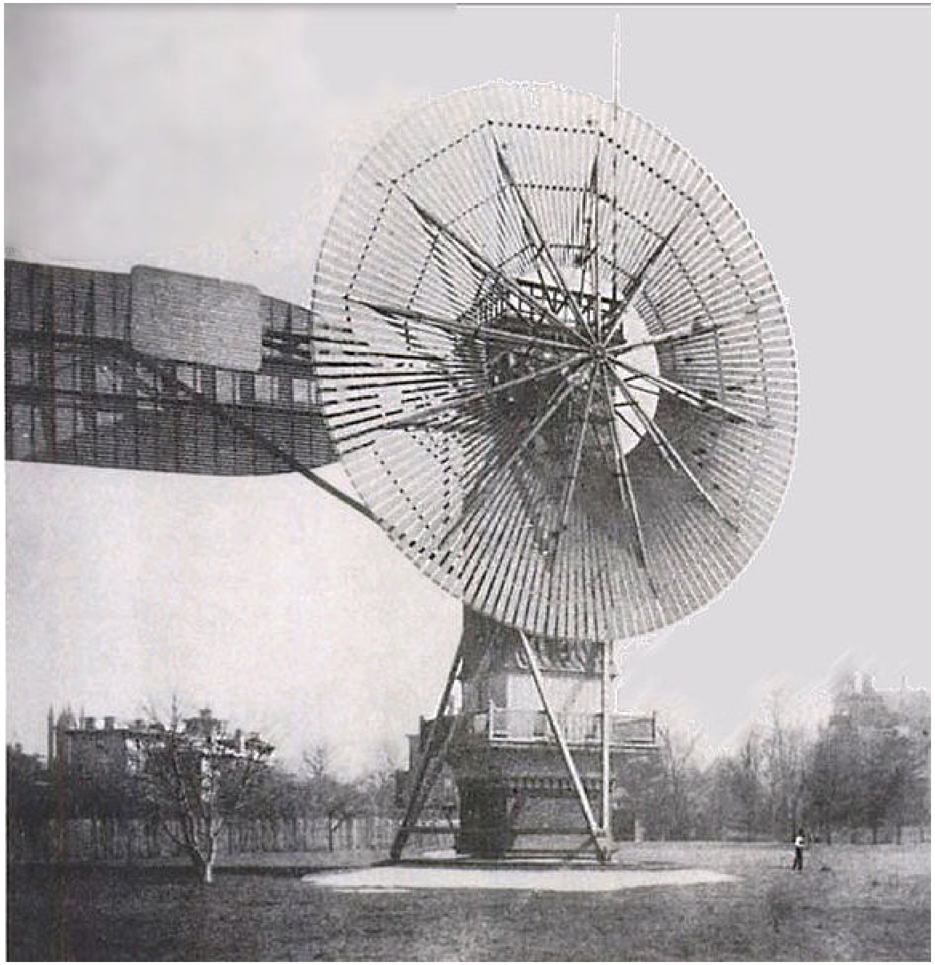
A short history of Wind as source of energy



Wind turbines for electricity generation

His wind turbine was of the then familiar **multi-vane type** (it sported **144 blades**) and, owing to its large solidity, rotated rather slowly and required gears and transmission belts to speed up the rotation by a factor of 50 so as to match the specifications of the electric generator.

Photo taken from: https://en.wikipedia.org/wiki/Charles_F._Brush

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A short history of Wind as source of energy

The wind turbine itself had a diameter of **18.3 meters** and its hub was mounted 16.8 meters above ground. The tower was mounted on a vertical metal pivot so that it **could orient** itself to face the wind. The whole construction massed some 40 tons, and had a **12kW** dynamo

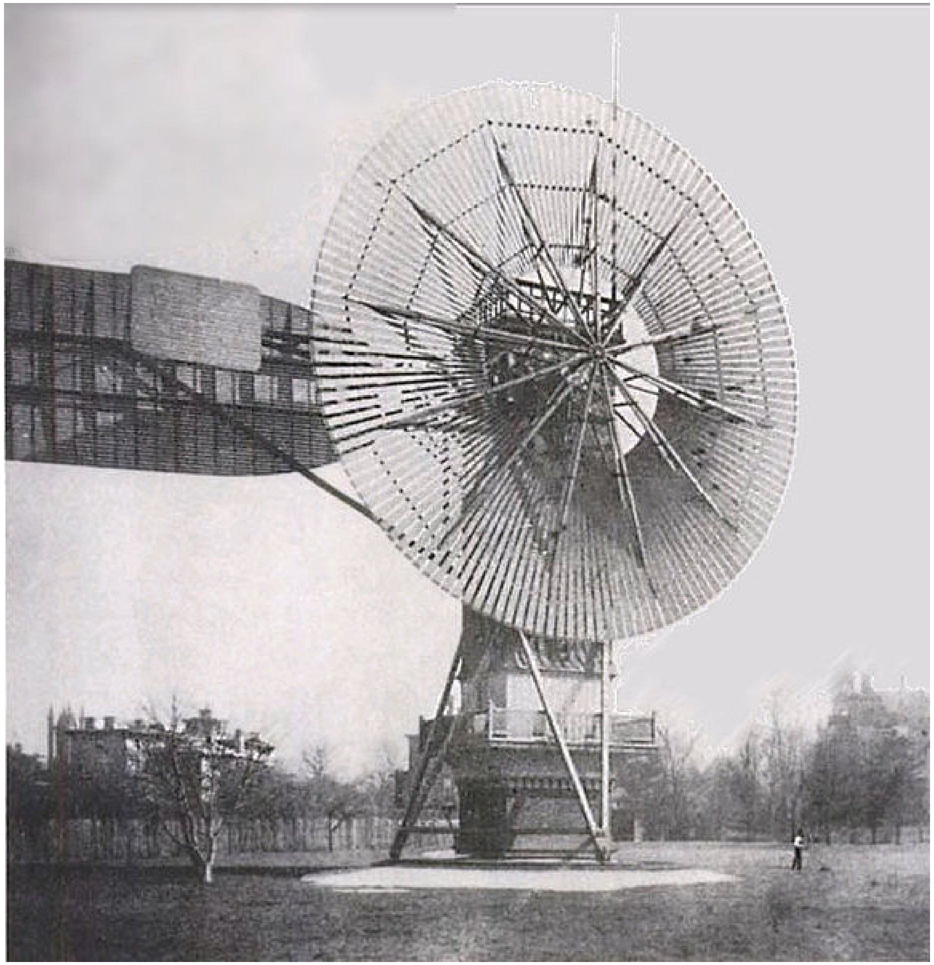

Photo taken from: https://en.wikipedia.org/wiki/Charles_F._Brush

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A short history of Wind as source of energy

In 1884, Brush built a mansion on Euclid Avenue in Cleveland that show cased many of his inventions. There he raised his family and lived the remainder of his life. The basement housed Brush's private laboratory. In 1888, he powered the mansion with the world's first automatically operated wind turbine generator which charged the home's **12 batteries**. **It was the first home in Cleveland to have electricity**. Over its 20 year life, the turbine never failed to keep the home continuously powered.

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A short history of Wind as source of energy

What Next ?

Although the wind is free, the investment and maintenance of the plant caused the **cost** of electricity to be much **higher** than that produced by steam plants. Consequently, the operation was discontinued in 1900 and from then on the Brush mansion was supplied by the Cleveland utility.

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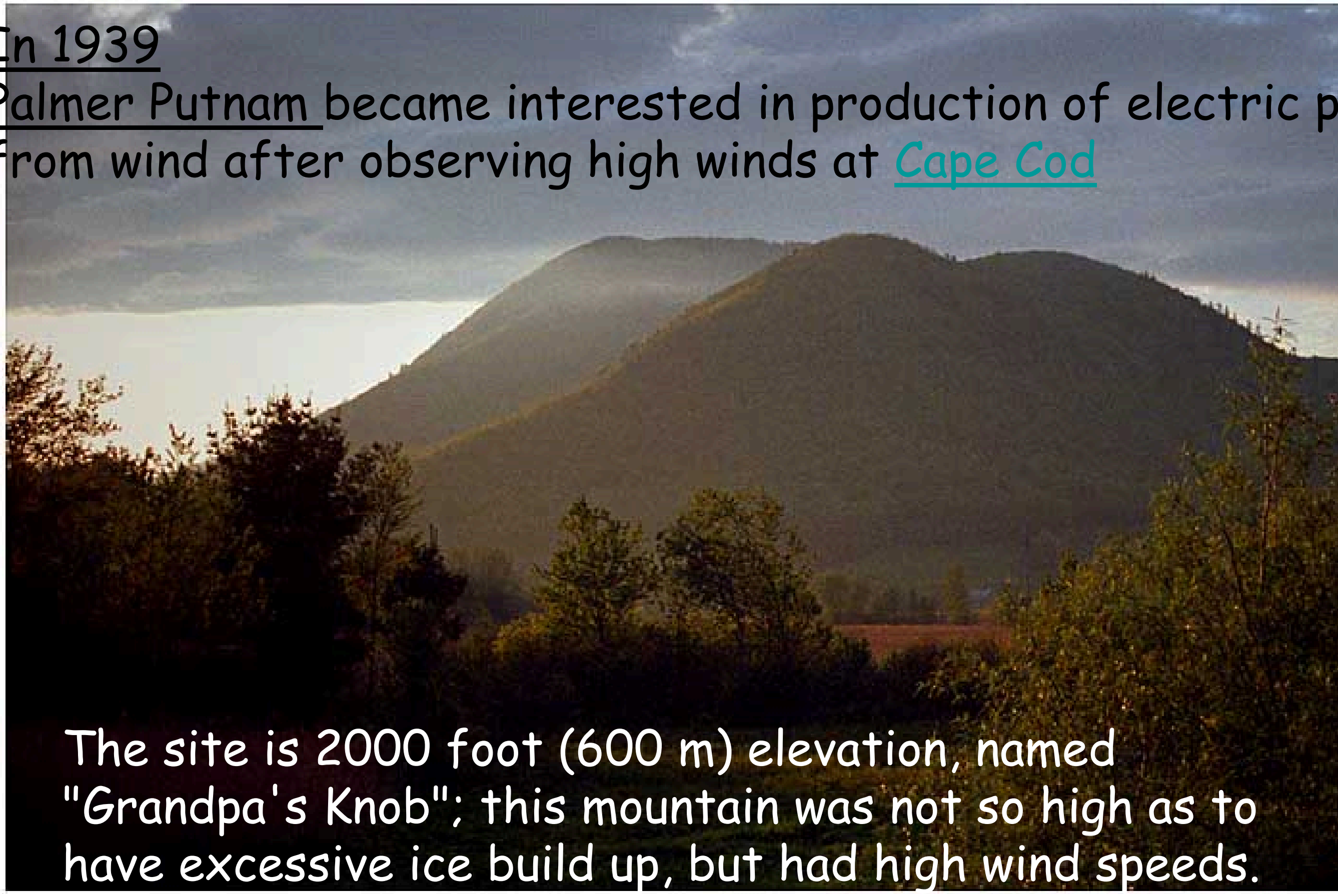
A short history of Wind as source of energy

In 1939
Palmer Putnam became interested in production of electric power from wind after observing high winds at Cape Cod



The site is 2000 foot (600 m) elevation, named "Grandpa's Knob"; this mountain was not so high as to have excessive ice build up, but had high wind speeds.

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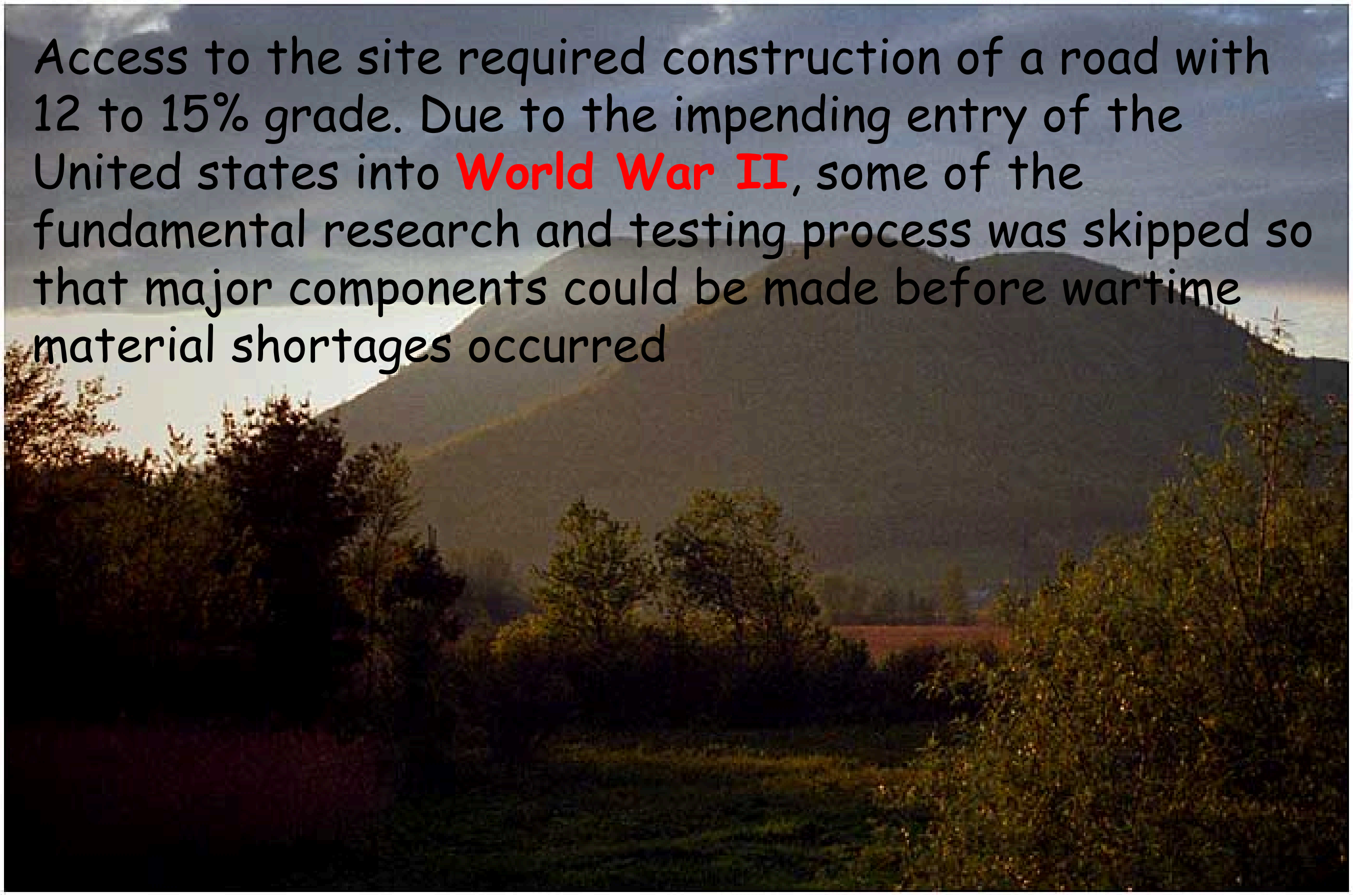
A short history of Wind as source of energy



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A short history of Wind as source of energy

In 1939
construction of a large wind generator was started in **Vermont**. This was the famous Smith-Putnam machine. It was a propeller-type device with a rated power of **1.3 MW** at a wind speed of 15 m/s. Rotor diameter was **53 m**. The machine started operation in 1941, feeding energy synchronously directly into the power network.

Photo taken from https://en.wikipedia.org/wiki/Smith%E2%80%93Putnam_wind_turbine

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A short history of Wind as source of energy

Description

The turbine had two blades, 175 feet in diameter, on the down-wind side of a 120 foot steel lattice tower. Each blade was approximately 8 feet wide and 66 feet long, and weighed eight tons. The blades were built on steel spars and covered with a stainless steel skin. The blade spars were hinged at their root attachment to the hub, allowing them to assume a slight cone shape.

The generator was a 1250 kW 600 RPM synchronous generator made by General Electric, producing 2,400 V at 60 cycles. The generator and rotor hub were mounted on a pintle beam, which allowed the rotor to capture wind from varying directions. The pitch of the blades was controlled by hydraulic cylinders to maintain constant speed.

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A short history of Wind as source of energy

Due to the impending entry of the United states into World War II, some of the fundamental research and testing process was skipped so that major components could be made before wartime material shortages occurred

In the early morning of **March 26, 1945**, the operator on duty in the nacelle of the turbine was thrown down by vibrations. He stopped the turbine.

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A short history of Wind as source of energy

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On investigation, it was found one turbine blade had **broken off** and fallen about 750 feet (229 m) away. The blade had failed at a previously repaired weak point in the spar; due to wartime shortages, it had been impractical to complete a full repair and reinforcement of the blade root

Fig. 2. The blade that failed.

Photo taken from : https://en.wikipedia.org/wiki/Smith%E2%80%93Putnam_wind_turbine

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A short history of Wind as source of energy

Owing to blade failure, in March 1945, operation was discontinued. It ought to be mentioned that the blade failure had been predicted but during World War II there was no opportunity to redesign

Photo taken from; https://en.wikipedia.org/wiki/Smith%E2%80%93Putnam_wind_turbine

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A short history of Wind as source of energy

After World War II, the **low cost of oil** discouraged much of the alternate energy research and ……….

wind turbines were no exception.

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A short history of Wind as source of energy

In 1973 Syria and Egypt attacked Israel Oct. 5, 1973, marking the start of the Yom Kippur War.

When the U.S. and other countries supported Israel, several Arab exporting countries imposed an embargo on the countries supporting Israel. This led to a net loss in production of 4 million barrels of oil per day through March 1974, and during that six-month period, prices increased 400 percent.

Photo taken from: https://do617.com/events/2019/3/1/no-gas-we-take-a-week-off-see-you-next-week

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A short history of Wind as source of energy

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The 1973 oil crises re-spurred interest in wind power as attested by the rapid growth in federal funding.

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A short history of Wind as source of energy

This led to the establishment of wind farms . Early machines used in such farms proved disappointing in performance and expensive to maintain..

Nevertheless, the experience accumulated led to an approximately **5-fold reduction** in the cost of wind-generated electricity

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Photo taken from: https://www.energyjobline.com/landingpage/386943/wind-farm-jobs/

A short history of Wind as source of energy

In the beginning of 1980, the cost of 1 kWh was around 25 cents; in 1996 it was, in some installations, down to 5 cents. To be sure, the determination of energy costs is, at best, an unreliable art. Depending on the assumptions made and the accounting models used, the costs may vary considerably.

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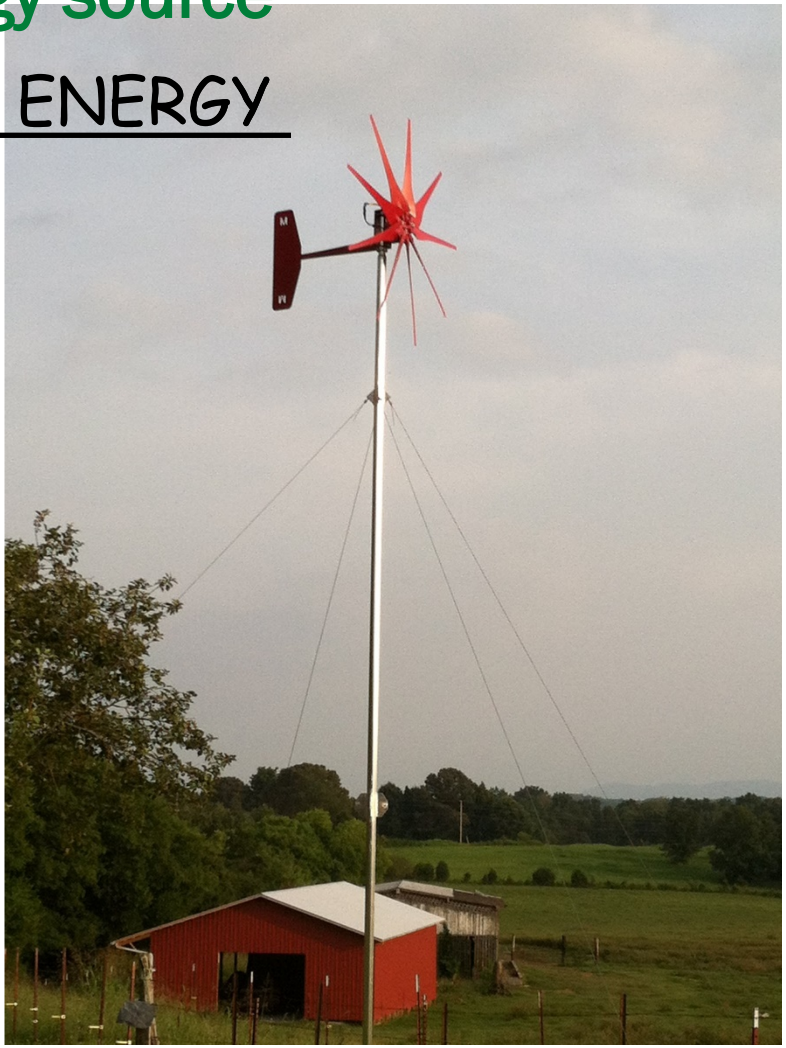
The potential of wind as renewable energy source

THE POTENTIAL OF WIND ENERGY WORLDWIDE

The potential for wind energy is enormous, especially in developing countries.

1. This is particularly true in rural communities which are not yet linked to grid electricity. For these regions it is an economically viable alternative to diesel engines and even coal-fired power stations. In many cases it would save on buying fuel from other countries and instead that could enjoy the luxury of **free fuel** in the form of wind



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The potential of wind as renewable energy source

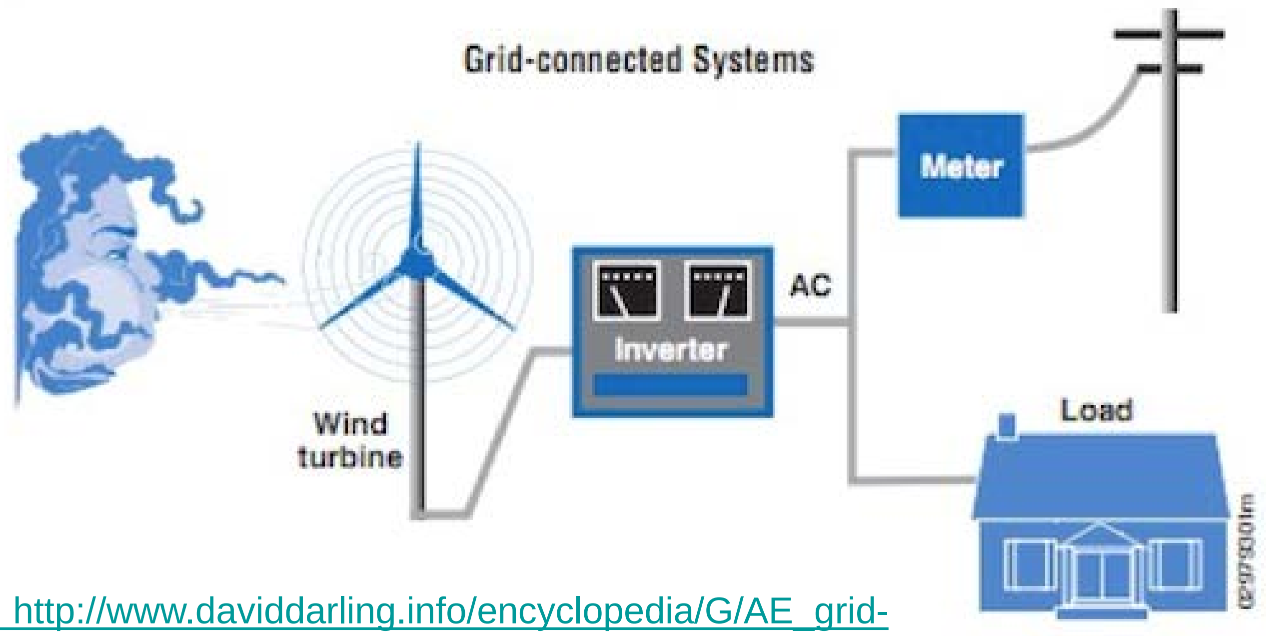

Photo taken from: http://www.daviddarling.info/encyclopedia/G/AE_grid-connected_small_wind_electric_system.html

2. One issue we must not overlook and that is the linking of wind turbine farms and national grids. This has been part of the success story of the wind industry

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The potential of wind as renewable energy source

3. The next major advancement could well be more effective **energy storage** for times when the wind is blowing and electricity is not required

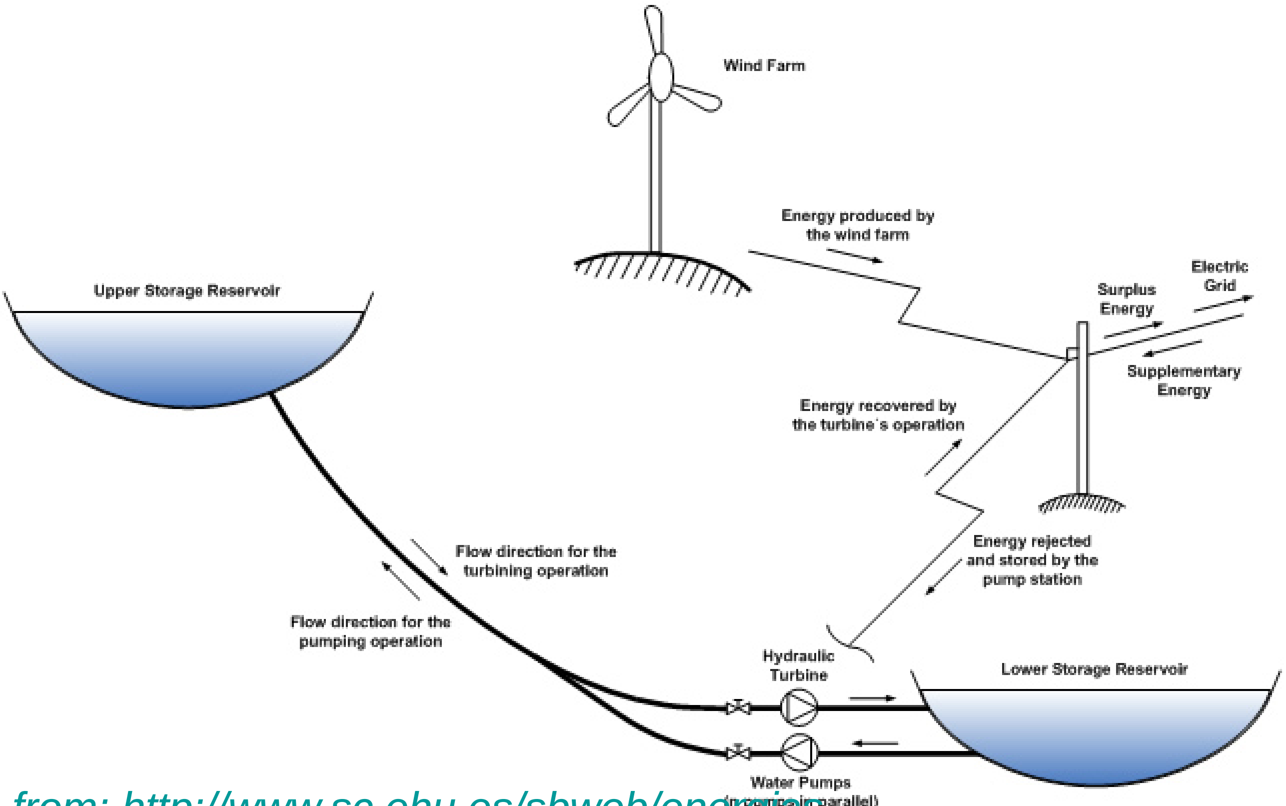

Photo taken from: http://www.sc.ehu.es/sbweb/energias-renovables/temas/almacenamiento/almacenamiento.html

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The potential of wind as renewable energy source

4. Even in developed and industrialized countries wind is becoming a major player

a. A Norwegian island is showing the way for rural communities. It has a population of 4000 and is totally dependent on wind energy for all its electricity. The 21 wind turbines, most of which are part-owned by the islanders, supply the island with almost 30310$_{6}$ kW h of energy and on top of that 80310$_{6}$ kW h is sold to the national grid.

b. In Denmark 39% of the electricity produced is from wind power. This stems from a decision in 1985 to abandon nuclear power and invest in renewable energy. This initiated the beginning of the Danish domination of turbine manufacturing in Europe.

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The potential of wind as renewable energy source

5. For many developed countries, the incentive to invest heavily in wind energy has been dictated by the need to reduce CO_2 emissions. However, today, with the competitive price of wind energy and the rising cost of fossil fuel exploration and the political drive to close coal-fired power stations, the future looks very bright for the wind turbine industry.

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The advantages of using wind energy as power source

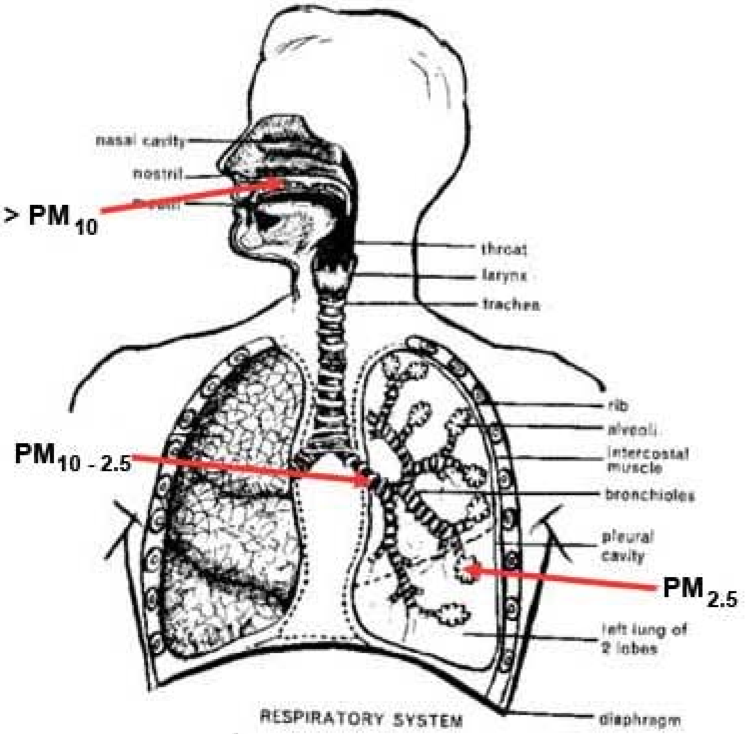
ADVANTAGES OF WIND ENERGY

There are many advantages to using wind turbines to generate electricity and these advantages have been the driving force behind their rapid development.

1. Provision for a clean pollution free source of energy. It delivers electricity without producing carbon dioxide.

The advantages of using wind energy as power source

1. It is also **free of particulate matters.** Particulates have been blamed for the rise of asthma and possibly Alzheimer's disease in our society.



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The advantages of using wind energy as power source

Another atmospheric pollutant that comes with coal- or oil-fired power stations is sulfur dioxide, formed from the burning of sulfur impurities. It is this SO_2 that is largely responsible for acid rain and also climate change; replacing fossil fuel power stations with wind energy and other renewable energy can **rid the planet of this dangerous pollutant.**

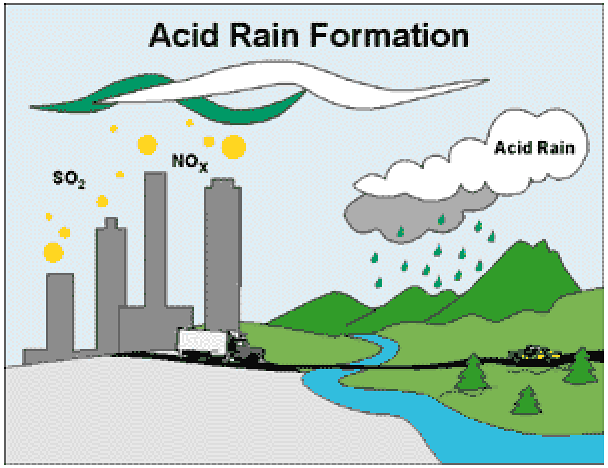

Photo taken from: http://www.geography.learnontheinternet.co.uk/topics/acidrain.html

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The advantages of using wind energy as power source

5. Sustainability.
Whenever the Sun shines and the wind blows, energy can be harnessed and sent to the grid. This makes wind a **sustainable source of energy** and another good reason to invest in wind farms.

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The advantages of using wind energy as power source

6. **Location.** Wind turbines can be erected almost anywhere, e.g., on existing farms. Very often good windy sites are not in competition with urban development or other land usage; such areas include:

- the tops of mountains or in gullies between hills.

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The advantages of using wind energy as power source

- ➢ Off the coast area

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The advantages of using wind energy as power source

7. **Compatibility with other land uses**. Wind turbines can be erected on pastureland with little disturbance to the animals and the general farming activities

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The advantages of using wind energy as power source

7. **Compatibility with other land uses.** Other areas such as near landfills sites, the sides of motorways and major roads, where urban development is unlikely to take place, are ideal locations to consider for wind farms.

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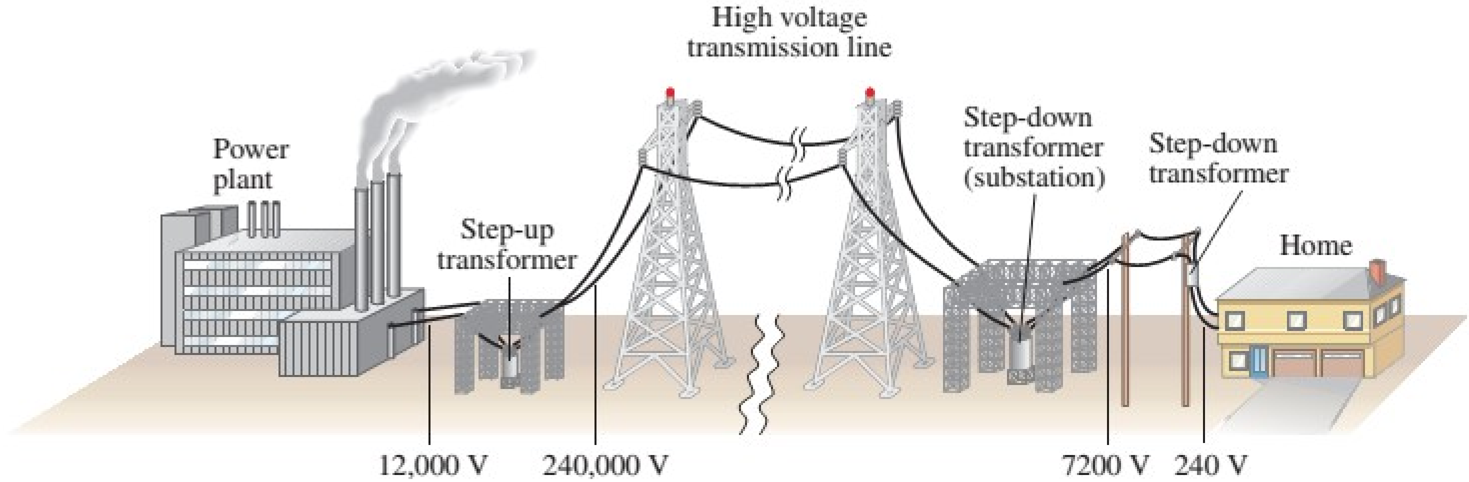
The advantages of using wind energy as power source

8. **Reduction of costly transport costs of electricity from far-away power stations**. Transporting alternating current electricity great distances is expensive because of the cost of the cables and pylons and also because of the loss of power due to the electrical resistance of the cables.



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The advantages of using wind energy as power source

9. National security. The wind is a free source of energy. Being independent of foreign sources of fuel (e.g., fossil fuel and indeed of electricity) is a great advantage. It means no price hikes over which we have no control and no embargoes on importing fuel or even electricity from foreign countries.

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The advantages of using wind energy as power source

10. **Conservation of water**. Traditional power stations using coal, oil, gas, or nuclear fuel all use large volumes of water. Wind farms use no water.

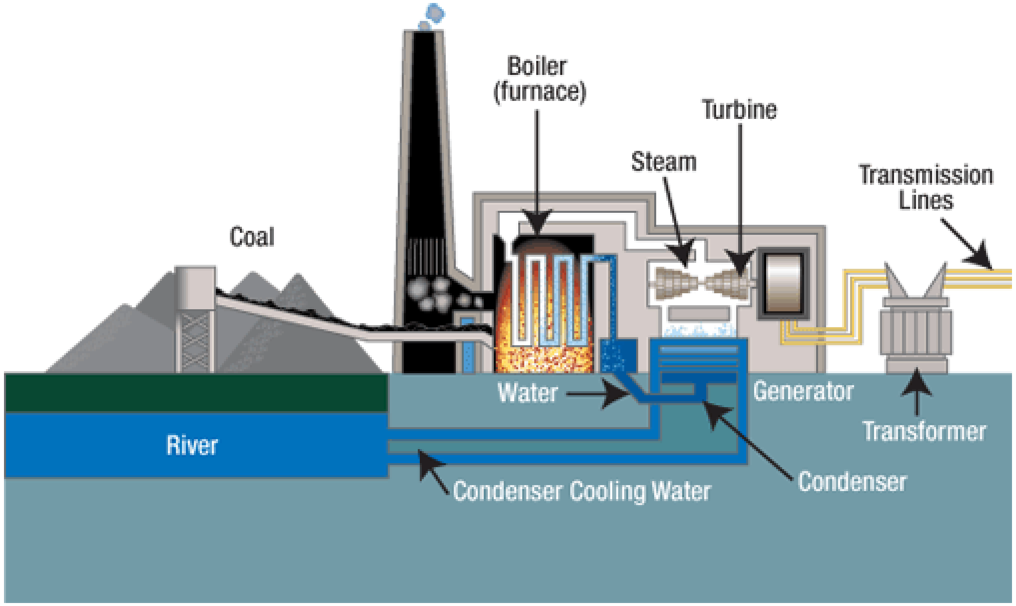

Photo taken from: https://en.wikipedia.org/wiki/Fossil_fuel_power_station

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The advantages of using wind energy as power source

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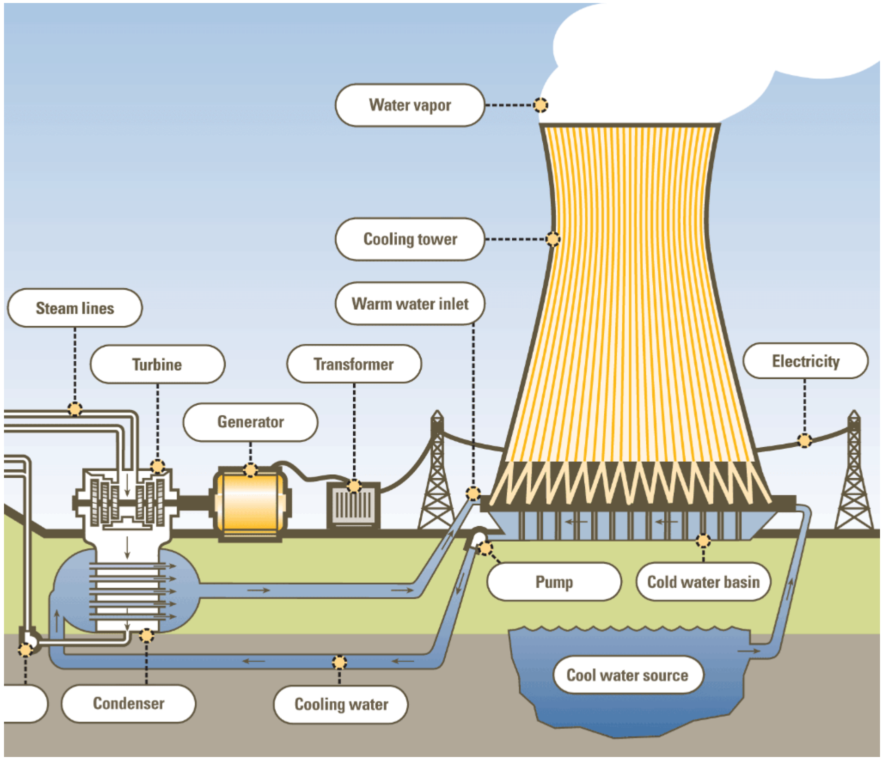

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The advantages of using wind energy as power source

11. **Reduction of destructive mining**. The pumping of oil and gas (especially from ocean beds) and the mining of coal or uranium all have serious environmental impacts on the sea or land. Wind farms are relatively benign in this respect and farming and other activities can take place around the turbines as the real action is over a hundred meters above the ground or sea.

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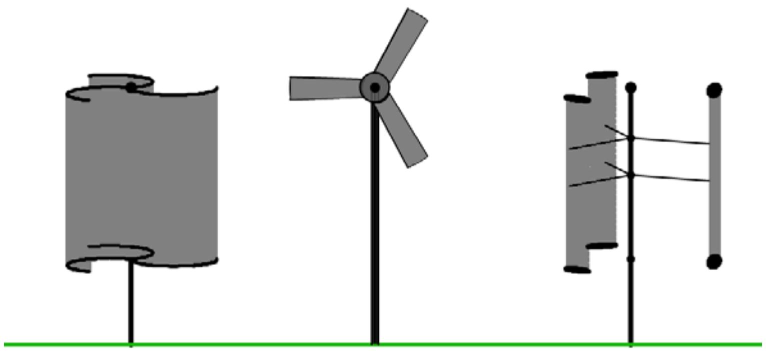
ADVANTAGES OF WIND ENERGY

12. **Short commissioning time**. Wind farms can be commissioned over a relatively short time, and 2 or 3 years from conception to electricity production is not impossible.
This can be compared to the many decades it takes to design, build, and commission a nuclear power station .
The fast rate of growth of the wind energy industry over the past 40 years could well be due to the speed at which wind farms can be commissioned.



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The advantages of using wind energy as power source

13. **Cost effectiveness**. Over the past decade, the cost of turbines has decreased significantly as a result of improved designs and mass production, so that today the cost of producing electricity from wind farms is now very competitive with fossil fuel-derived electricity.

gg71208903 www.gograph.com

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The advantages of using wind energy as power source

13. **Cost effectiveness**. It has been estimated that the energy used in the production of a turbine is recouped in the 7 months of operation and when one considers that the lifespan of a turbine is over 30 years the energy and financial gain is significant

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The advantages of using wind energy as power source

14. **Creation of jobs and local resources**. The wind turbine industry is a rapidly growing industry and employs thousands of workers in the manufacture processes, transport of turbines, erection of turbines, and in servicing working turbines.

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The advantages of using wind energy as power source

15. **Rapid instigation of power**. National grids supply a steady level of electricity (the base load) to meet the needs of a country. If for some reason the supply of electricity needs to be suddenly increased that is not always possible as it can take days to start up a new power station. If the wind is blowing or if the wind energy has been stored then the supply can take just minutes to feed into the national grid.

www.alamy.com - HRAFNR

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The advantages of using wind energy as power source

16. **Diversification of power supply**. With our total reliance on electricity it is well worth diversifying our energy sources so that we are not reliant on one type of energy,

- fossil fuel (which is at the mercy of foreign governments which can raise prices suddenly),
- nuclear (again we are at the mercy of countries supplying uranium), or
- solar (the Sun does not always shine).

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The advantages of using wind energy as power source

17. **Stability of cost of electricity**. Once the wind farm is in place the cost of the electricity to customers should be stable. It is not a function of the price of imported fuels.

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[2] Fundamentals of Renewable Energy Processes, Aldo Vieira da Rosa Stanford University, Elsevier Academic Press, 2012

[3] Wind Energy Engineering, A Handbook for Onshore and Offshore Wind Turbines, Edited by Trevor M. Letcher, Academic press Elsiever, 2017

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[4] www.ewea.org European Wind Energy Association

[5] wwindea.org World Wind Energy Association

[6] www.awea.org American Wind Energy Association

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Thank You for Your Attention!

Contact: info@weset-project.eu

Fernando.Tadeo@uva.es

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Introduction to Wind Energy

Module 2.1

Wind Resource Assessment
Lesson 4

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Objectives

The purpose of this lesson is to discuss the methodology for Assessment of Wind Power, to evaluate the potential of wind power production in possible sites.

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Learning Outcomes

By the end of this lesson the students should be able to:

O1. understand the concept of wind energy resources assessment wind

O2. use wind Atlas and deduce the data pertaining to a particular site

O3. estimate the annual energy production

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Technical Contents

1. *General concepts for Assessment of Wind Resources*
2. *The use of Wind Atlas.*
3. *Local Measurements for assessment of Wind Resources*
4. *Estimation of the Annual Energy Production.*

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Wind resource assessment (WRA)

WRA is the process by which windpower developers estimate the future energy production of a wind farm. In other words it is the discipline of estimating the strength of wind resources at a planned wind project site.

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General concepts for Assesment of Wind Resources

Wind Resource Assessment (WRA)

The output of wind resource assessment is wind conditions and annual energy production at a project site.
A financial model uses this data to compute the financial performance of the wind project. WRA is, therefore, the core activity that determines viability of a wind project.

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General concepts for Assesment of Wind Resources

WRA History

Modern wind resource assessments have been conducted since the first wind farms were developed in the late 1970s. The methods used were pioneered by developers and researchers in **Denmark**, where the modern wind power industry first developed.

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Photo taken from: https://www.dtu.dk/english

General concepts for Assesment of Wind Resources

Overview of WRA

The Figure contains an overview of the WRA process.

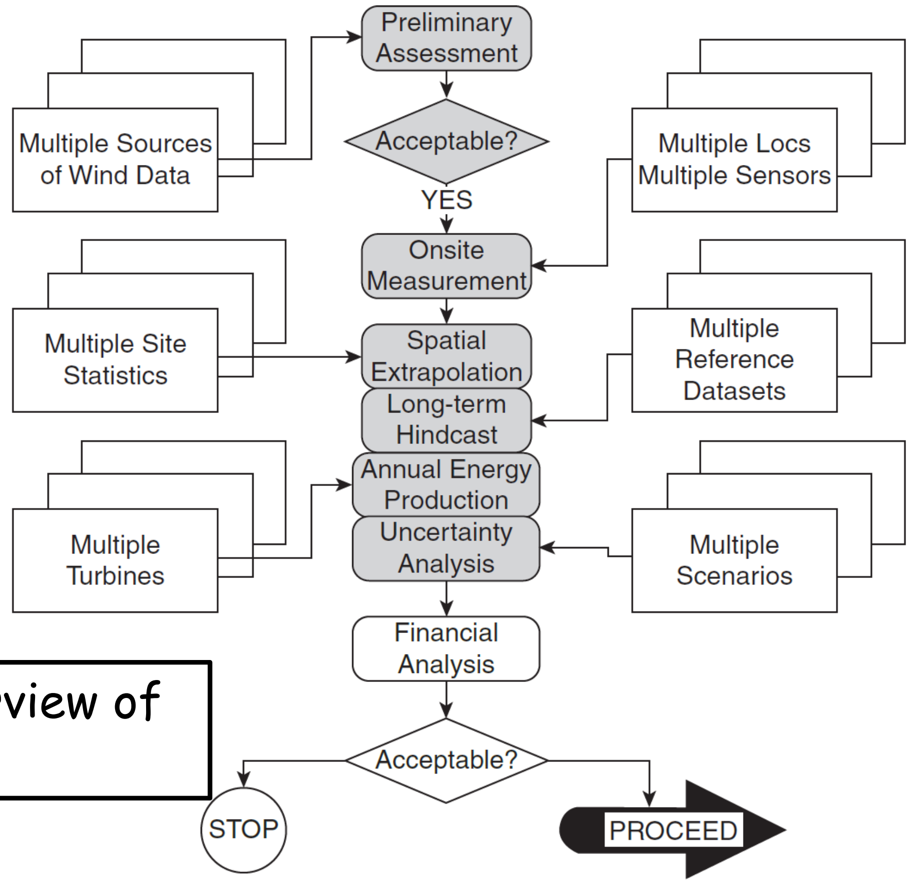

Figure taken from :
Chapter 7, Wind energy engineering. New York: McGraw-Hill, Jain, P. (2011).

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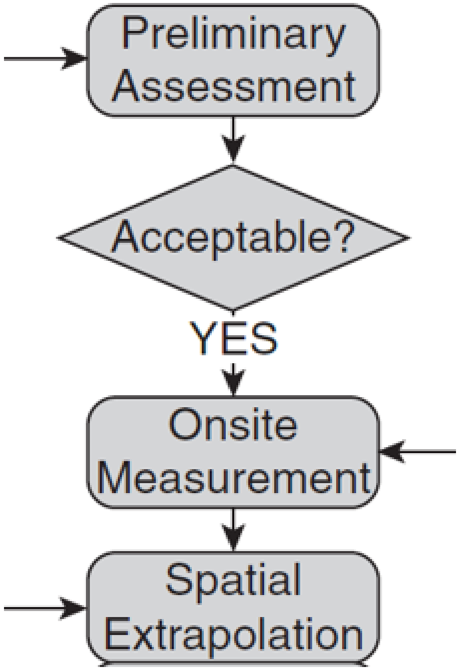
General concepts for Assesment of Wind Resources

Overview of WRA

1. WRA starts with ***a preliminary*** assessment or prospecting. In this step, alternate sites are evaluated for adequate wind speed based on publicly available wind resource maps and wind data.
2. If the site is acceptable, then an onsite wind measurement campaign is conducted.



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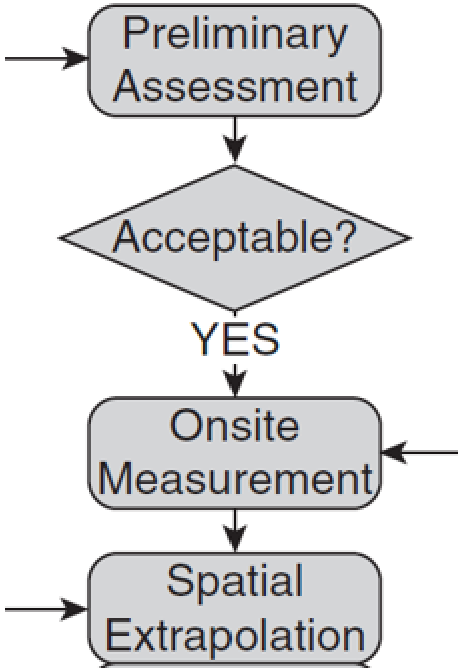
General concepts for Assesment of Wind Resources

Overview of WRA

3. After wind data has been collected for sufficient period, typically one year or more, then a process of detailed WRA begins.
4. It begins with spatial extrapolation, in which measured data at multiple locations within the project area are used to estimate wind speeds over the entire project area.
This is extrapolation along the spatial dimension.



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General concepts for Assesment of Wind Resources

5. The next step in the detailed WRA is to extrapolate along the temporal dimension. A process called ***measure-correlate-predict*** (MCP) is used with multiple reference datasets as input. Reference datasets are long-term wind data from a variety of sources like reanalysis data from National Center for Atmospheric Research (NCAR), airports, and others.
6. MCP extrapolates onsite measured data and generates a long-term dataset that covers the time period covered by the reference dataset.

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Local Measurements for assessment of Wind Resources

Measure-Correlate-Predict Methodology

The method involves acquisition of :

1. wind speed and, optionally, other atmospheric data at the site under investigation, hereafter referred to as the target site (See next slide).
2. Concurrently, a geographically proximate meteorological station with a long historical record, referred to as the reference site, must remain in operation.

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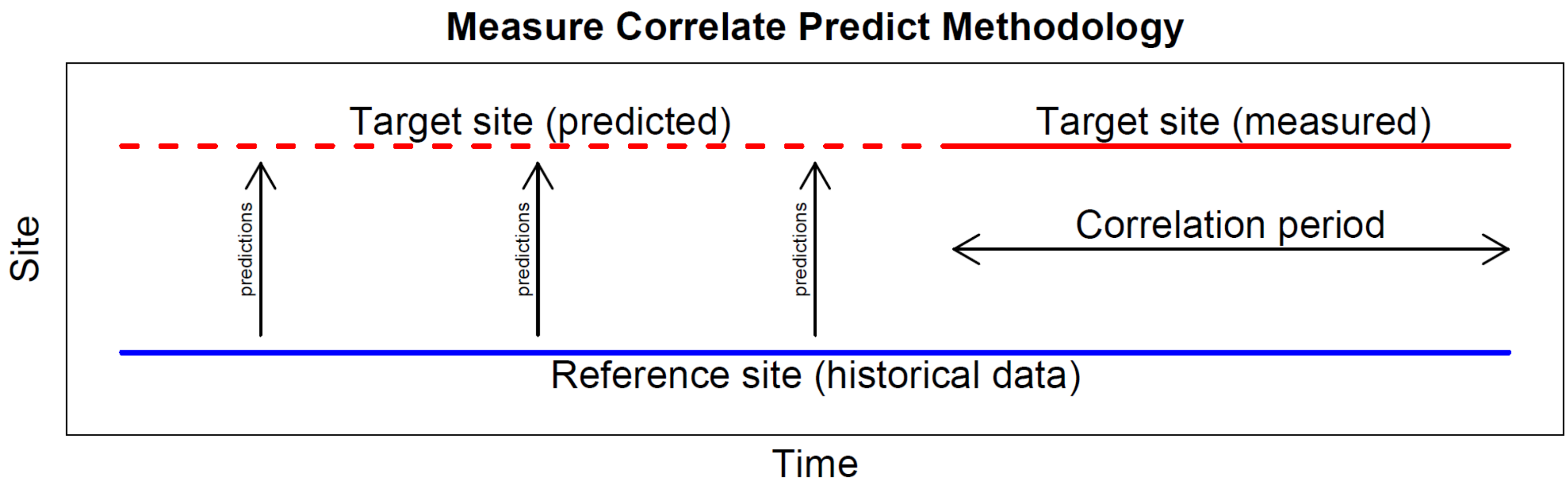
Local Measurements for assessment of Wind Resources

Measure-Correlate-Predict Methodology



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Local Measurements for assessment of Wind Resources

Measure-Correlate-Predict Methodology

Some correlation technique is applied to develop a predictive relationship between the reference and the target site, using the concurrent data set. With this relationship, a “backcast” is produced to estimate the wind speed at the target site based on the historical record at the reference site.

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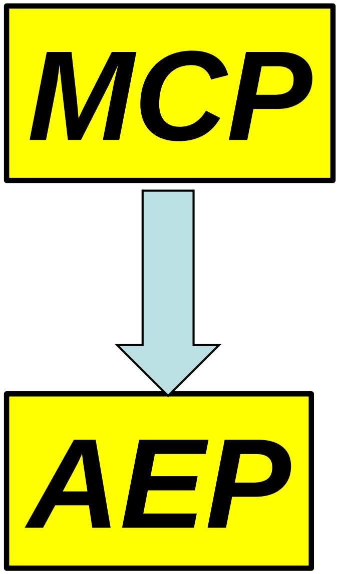
Local Measurements for assessment of Wind Resources

7. Next, ***annual energy production*** (AEP) is computed with several power production curves from different turbines.
8. The last step is to compute uncertainty of AEP, which consolidates the uncertainty in each factor that influences AEP.



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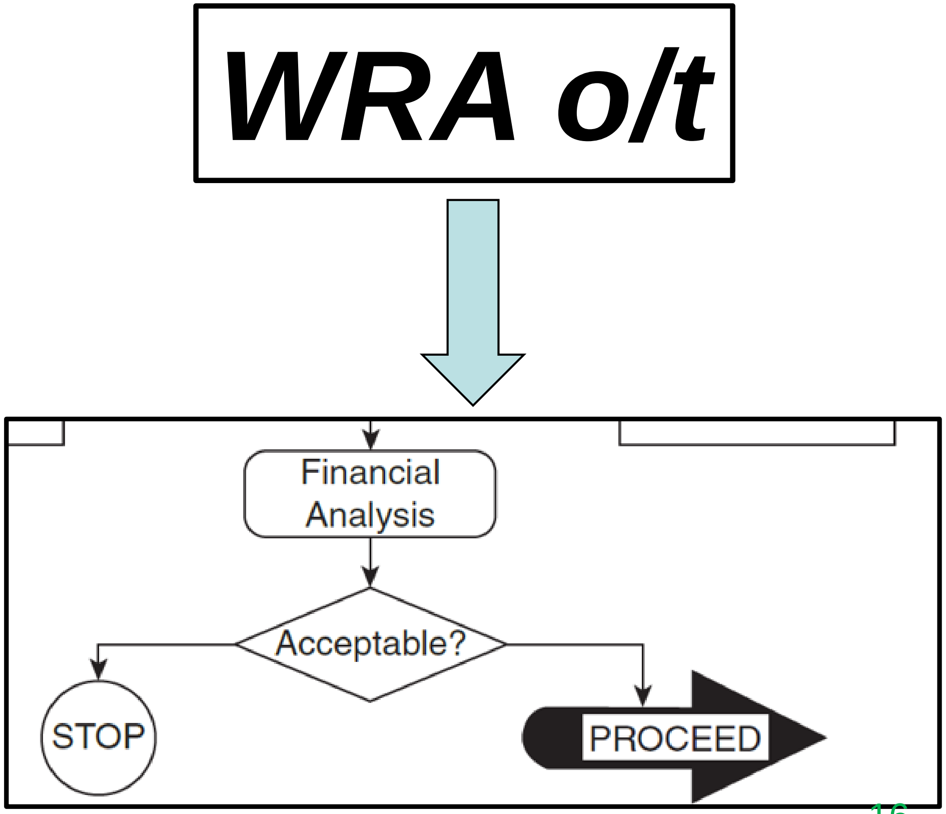
Local Measurements for assessment of Wind Resources

The output of the WRA is input to the financial analysis step, in which the financial viability of the project is assessed.



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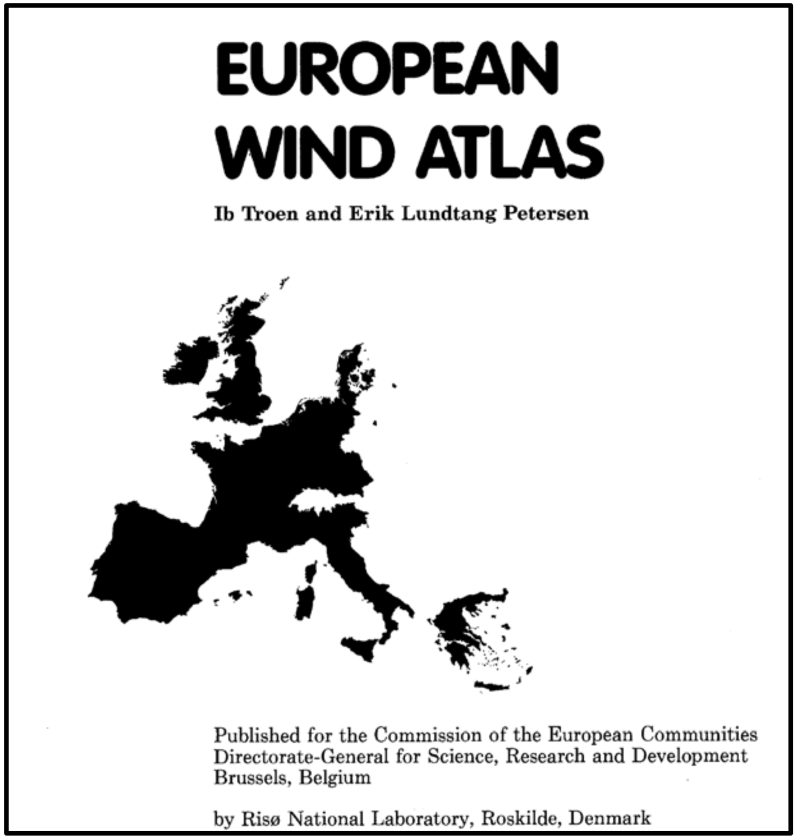
The use of Wind Atlas

Wind resource maps

These are maps published by Government agencies (national 'wind atlas') of estimated wind resources, which serve to inform policy-making and encourage wind power development.
Examples include :

- the Canadian Wind Atlas,
- the European Wind Atlas, and
- the Wind Resource Atlas of the United States.



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The use of Wind Atlas

Example of Wind Speed Maps

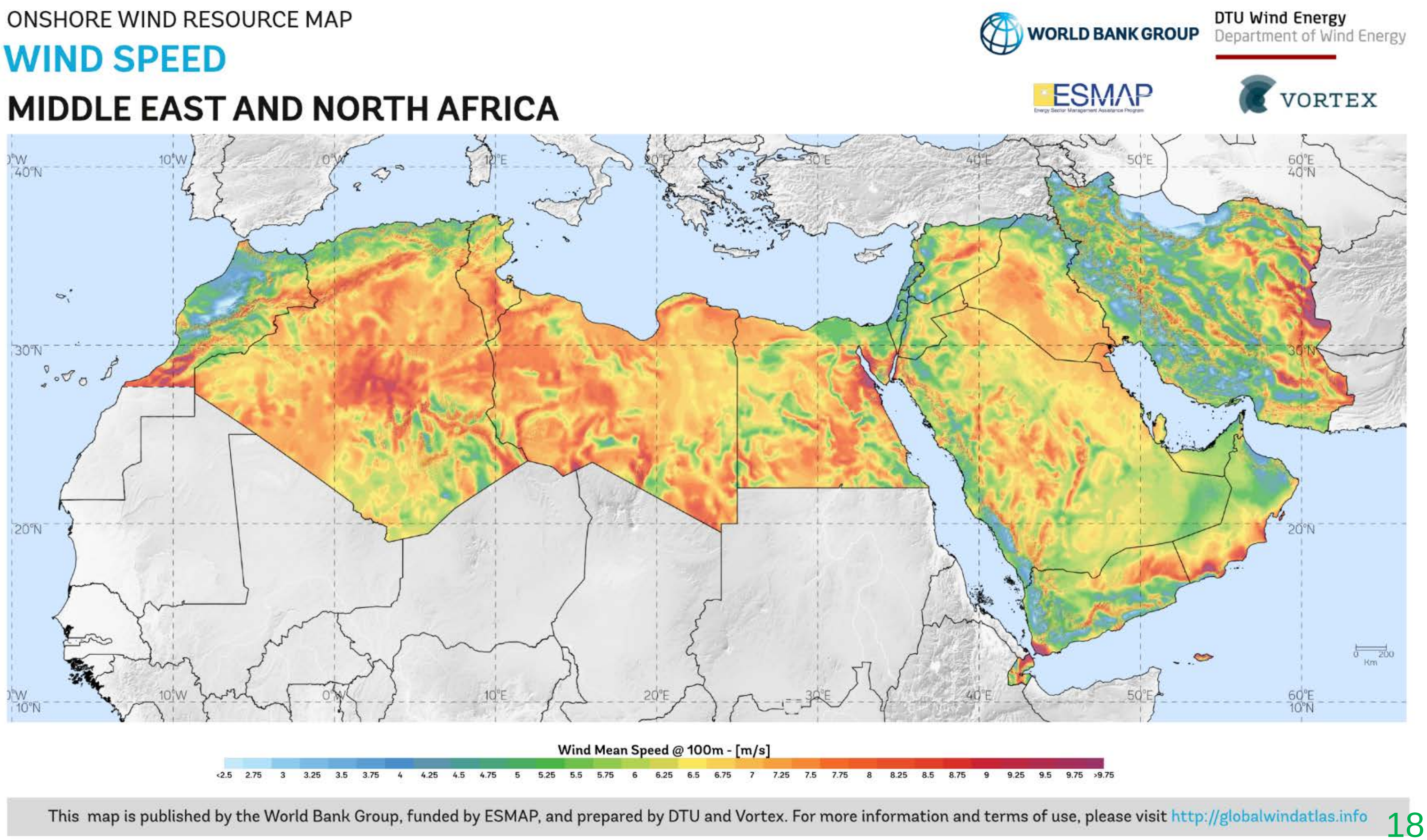

Figure taken from :
World bank Group, http://globalwindatlas.info

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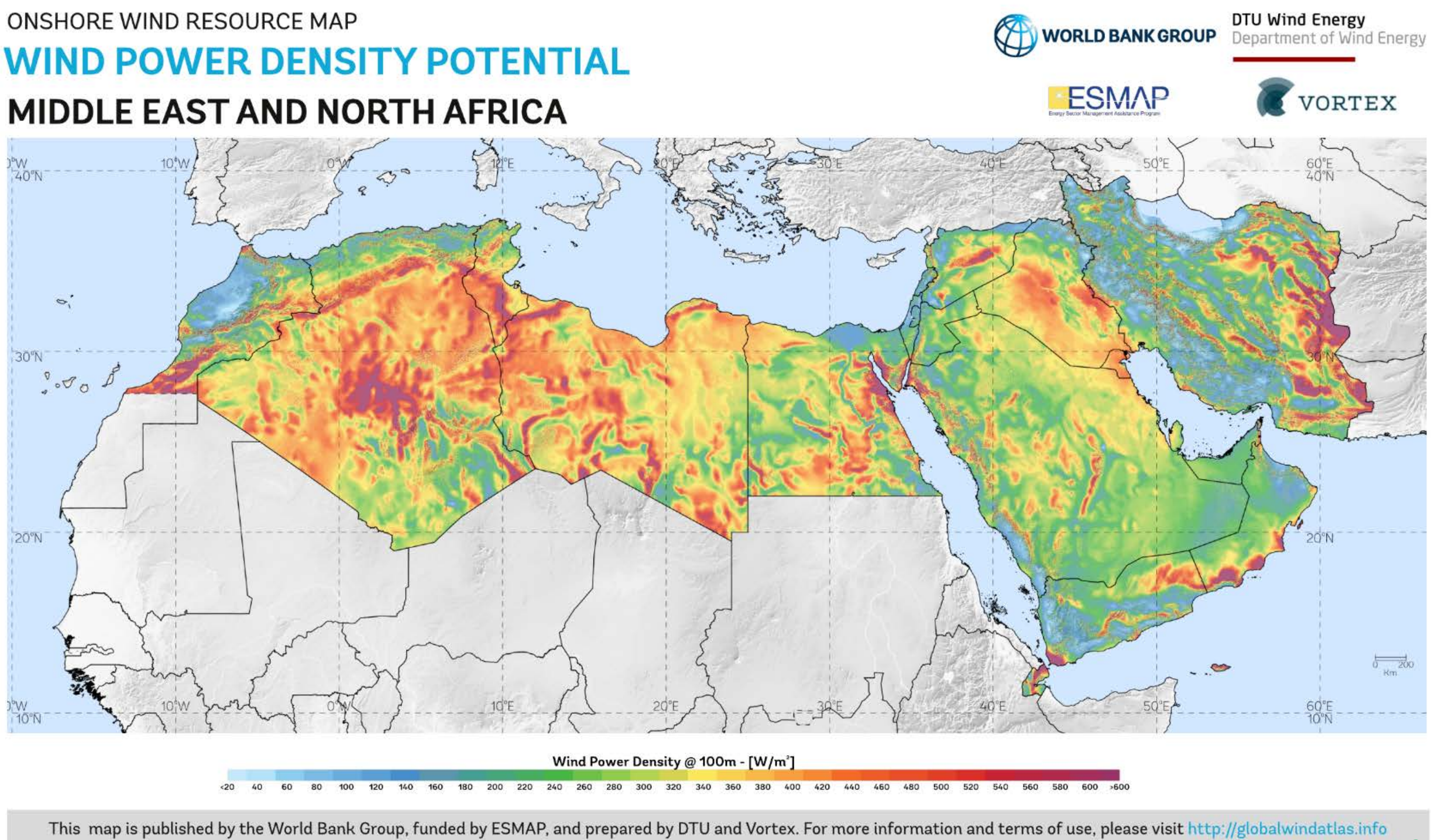
The use of Wind Atlas

Example of Wind Power Maps



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The use of Wind Atlas

Wind prospecting can begin with the use of such maps, but the lack of accuracy and fine detail make them useful only for preliminary selection of sites for collecting wind speed data.
With increasing numbers of ground-based measurements from specially installed anemometer stations, as well as operating data from commissioned wind farms, the accuracy of wind resource maps in many countries has improved over time.

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The use of Wind Atlas

Although the accuracy has improved, it is unlikely that wind resource maps, whether public or commercial, will eliminate the need for on-site measurements for utility-scale wind generation projects.

However, mapping can help speed up the process of site identification and the existence of high quality, ground-based data can shorten the amount of time that on-site measurements need to be collected.

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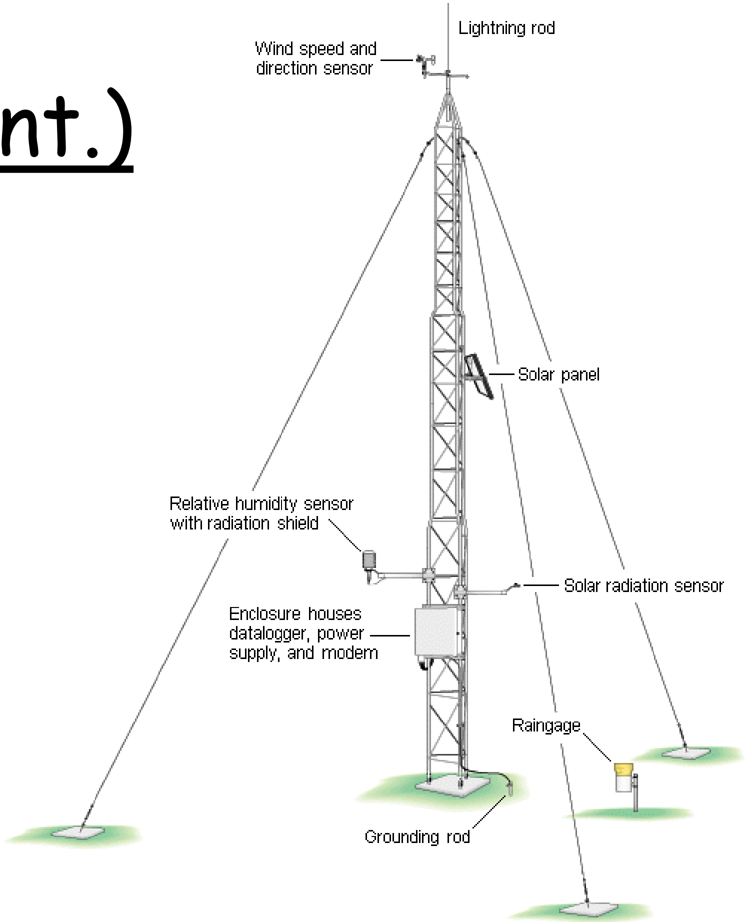
Local Measurements for assessment of Wind Resources

Measurements (Cont.)

To estimate the energy production of a wind farm, developers must first measure the wind on site using Meteorological towers



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Local Measurements for assessment of Wind Resources

Measurements

Meteorological towers are usually equipped with:

- Anemometers,
- Wind vanes,
- Temperature sensors,
- Pressure sensors , and
- relative humidity sensors

Data from these towers must be recorded for at least one year to calculate an annually representative wind speed frequency distribution.

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Measurements (Cont.)

Since onsite measurements are usually only available for a short period, data is also collected from nearby long-term *reference stations* (usually at airports).
This data is used to adjust the onsite measured data so that the mean wind speeds are representative of a long-term period for which onsite measurements are not available.

Note: Versions of these maps can be seen and used with software applications such as windNavigator.

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Estimation of the Annual Energy Production

Calculations

The following calculations are needed to accurately estimate the energy production of a proposed wind farm project:

1. Correlations between onsite meteorological towers:
   Multiple meteorological towers are usually installed on large wind farm sites. For each tower, there will be periods of time where data is missing but has been recorded at another onsite tower. Least squares linear regressions and other methods can be used to fill in the missing data. These correlations are more accurate if the towers are located near each other, the sensors on the different towers are of the same type, and are mounted at the same height above the ground.

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Estimation of the Annual Energy Production

Calculations (Cont.)

2. Correlations between long term weather stations and onsite meteorological towers:

Because wind is variable year to year, and power produced is related to the cube of windspeed, short-term (< 5 years) onsite measurements can result in highly inaccurate energy estimates. Therefore, wind speed data from nearby longer term weather stations (usually located at airports) are used to adjust the onsite data. Least squares linear regressions are usually used, although several other methods exist as well.

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Estimation of the Annual Energy Production

Calculations (Cont.)

3. Vertical shear to extrapolate measured wind speeds to turbine hub height:

The hub heights of modern wind turbines are usually 80 m or greater. The power law and log law vertical shear profiles are the most common methods of extrapolating measured wind speed to hub height.

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Estimation of the Annual Energy Production

Calculations (Cont.)

4. Wind flow modeling to extrapolate wind speeds across a site:

- Wind speeds can vary considerably across a wind farm site if the terrain is *complex* (hilly) or there are changes in *roughness* (the height of vegetation or buildings). Wind flow modeling software, based on either the traditional WAsP linear approach or the newer CFD approach, is used to calculate these variations in wind speed.

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Estimation of the Annual Energy Production

Calculations (Cont.)

5. Energy production using a wind turbine manufacturer's power curve:

- When the long term hub height wind speeds have been calculated, the manufacturer's ***power curve*** is used to calculate the gross electrical energy production of each turbine in the wind farm.

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Estimation of the Annual Energy Production

Calculations (Cont.)

6. Application of energy loss factors:
To calculate the net energy production of a wind farm, the following loss factors are applied to the gross energy production:

- wind turbine wake loss
- wind turbine availability
- electrical losses
- blade degradation from ice/dirt/insects
- high/low temperature shutdown
- high wind speed shutdown
- curtailments due to grid issues

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Estimation of the Annual Energy Production

Software applications

Wind power developers use various types of software applications to assess wind resources.
Ref. https://en.wikipedia.org/wiki/Wind_energy_software

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[1] Wind energy engineering. New York: McGraw-Hill, Jain, P. (2011).
[2] Fundamental of Aerodynamics, John D. Anderson, Jr., McGraw-Hill, 2001.
[3] www.ewea.org European Wind Energy Association
[4] wwindea.org World Wind Energy Association
[5] www.awea.org American Wind Energy Association

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Introduction to Wind Energy

Module 2.1

Components of Commercial Wind Turbine Generators

Lesson 5

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Objectives

The purpose of this lesson is to present and analyze the main components of state-of-the-art Wind Turbine Generators: The Rotor Systems, Nacelle, Tower and Foundations.

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Learning Outcomes

This lesson will contribute to the students to:

O1. Understand the different components and types of wind turbines and as their work;

O2. Be familiar with the different conversion technologies needed in wind energy systems;

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Technical Contents

1. *Structure of a Wind Turbine Generator*
2. *The Rotor System,*
3. *The Nacelle*
4. *The Tower*
5. *The Foundations.*

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Structure of a Wind Turbine Generator

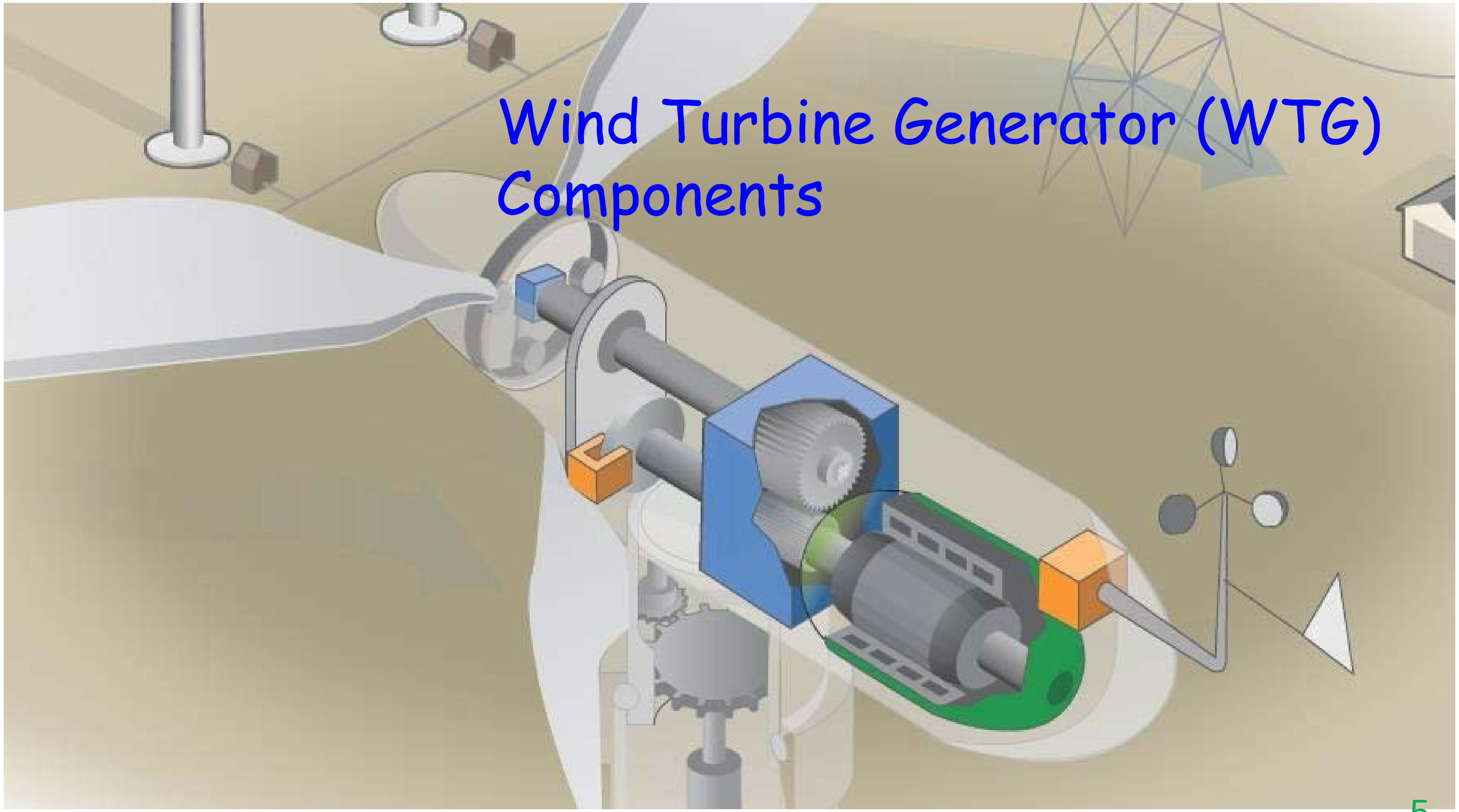

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Photo is taken from:
https://www.energy.gov/eere/wind/inside-wind-turbine

Structure of a Wind Turbine Generator

Wind turbine generator (WTG) has three major systems:

1. ***Rotor system***. This includes blades that capture energy and a rotor hub that connects the blades to the shaft, along with pitch mechanism that assists in efficient capture of energy.

2. ***Nacelle***. This contains all the components that sit on top of the tower, except the rotor system. It includes main shaft, gearbox, generator, brake, bearings, nacelle frame, yaw mechanism, auxiliary crane, hydraulic system, and cooling system.

3. ***Tower and foundation***. These structural elements carry all the forces and moments to the ground

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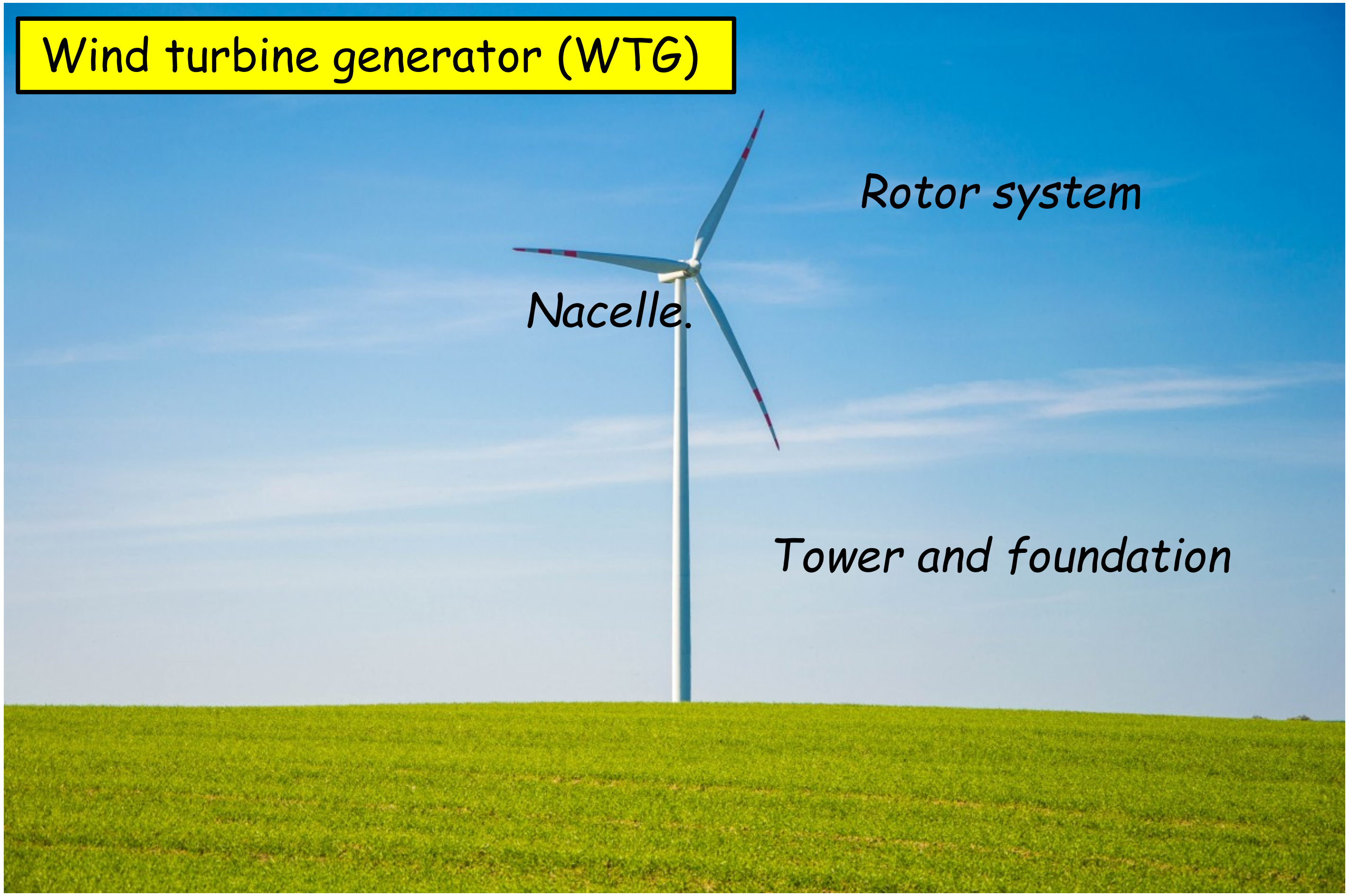
Structure of a Wind Turbine Generator



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Structure of a Wind Turbine Generator

Wind turbine generator (WTG)
Components

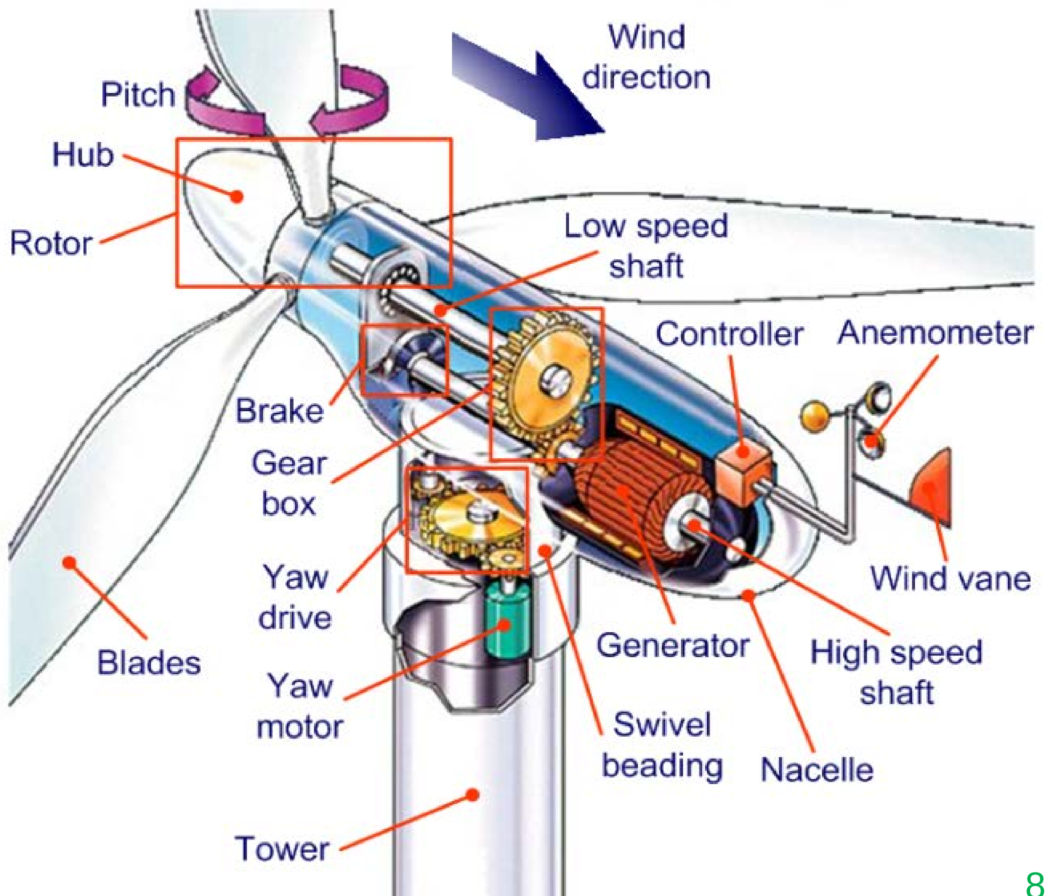

Photo taken from:
https://www.horizoncurriculum.com/supportmaterial/parts-of-a-wind-turbine/

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Wind turbine components :

1-Foundation
2- Connection to the electric grid
3-Tower
4-Access ladder
5- Wind orientation control (Yaw control)
6- Nacelle
7- Generator
8- Anemometer
9- Electric or Mechanical Brake
10- Gearbox
11- Rotor blade
12- Blade pitch control
13- Rotor hub

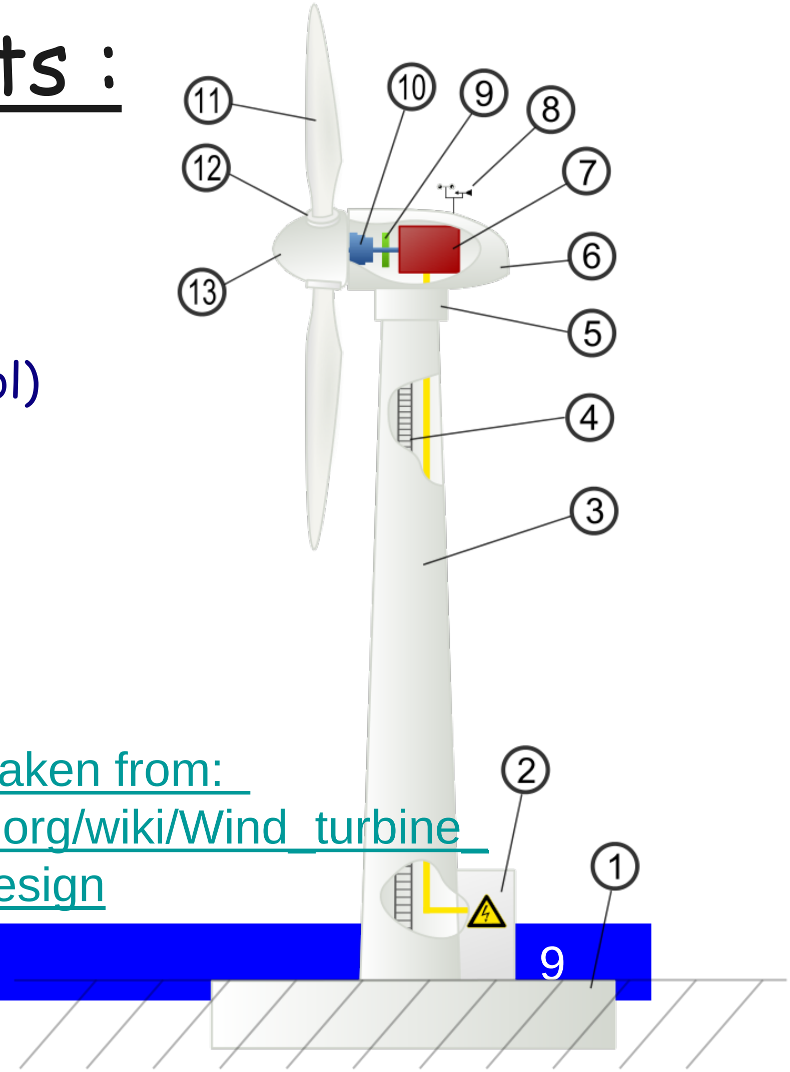

Photo taken from: https://en.wikipedia.org/wiki/Wind_turbine_design

1. Rotor System

The rotor system captures wind energy and converts into rotational kinetic energy. This is accomplished through :

1. blades
2. rotor hub that is connected to the main shaft. In large utility-scale turbines, the rotor hub has mechanisms to pitch the blade, that is, rotate along the longitudinal axis of the blade.

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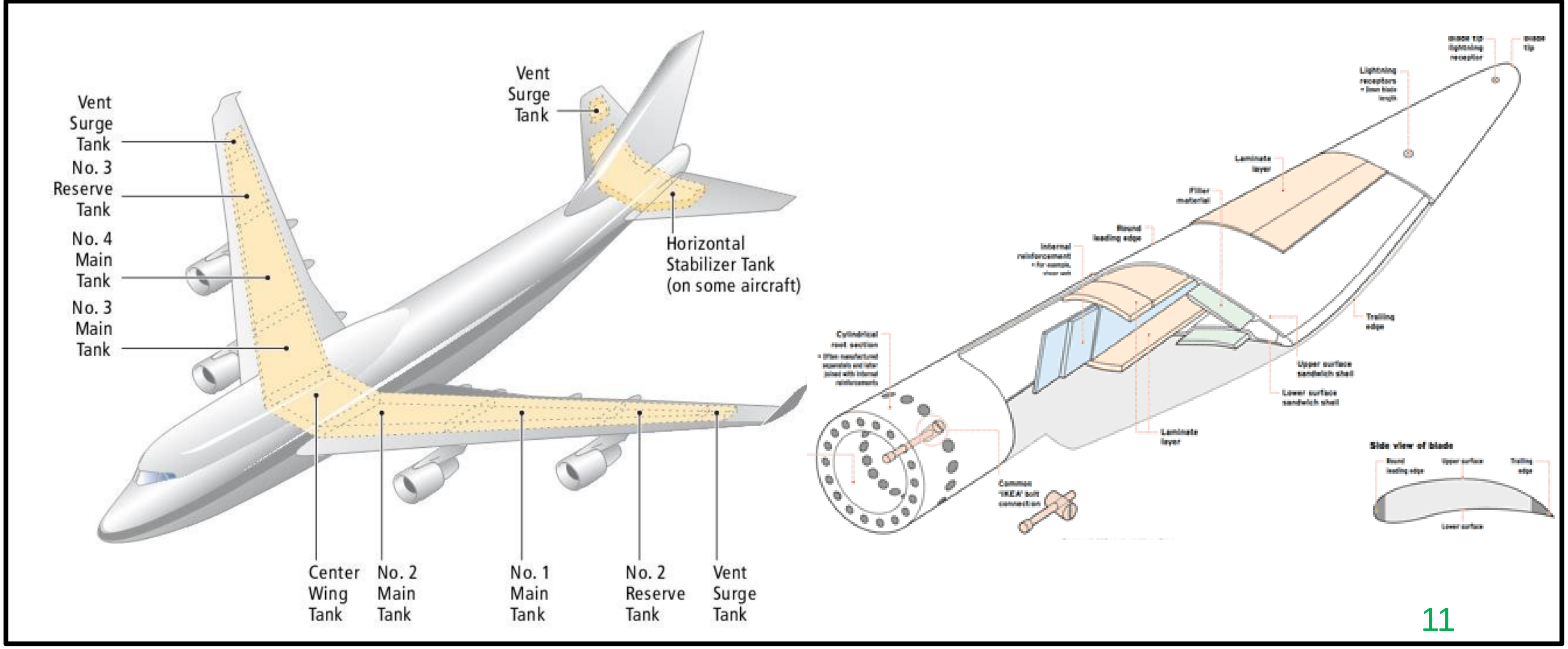
1.1 Blades

turbine blades are, in principle, similar to airplane wings in terms of generating lift.



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1.1 Blades (Cont.)

The cross section of a turbine blade is shown on the figure below

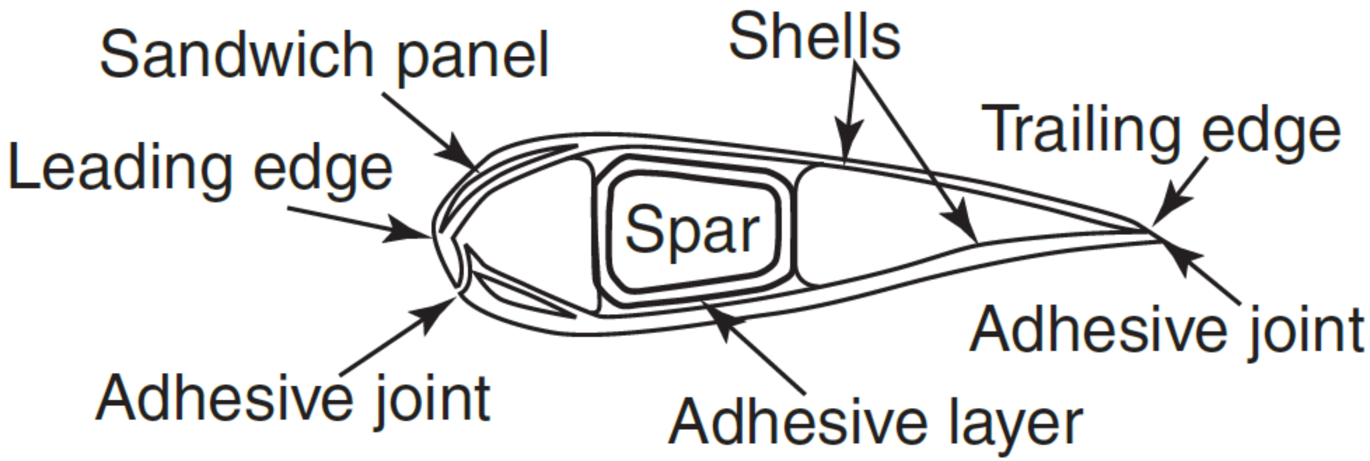

Photo taken from
Wind energy engineering. New York: McGraw-Hill, Jain, P. (2011).

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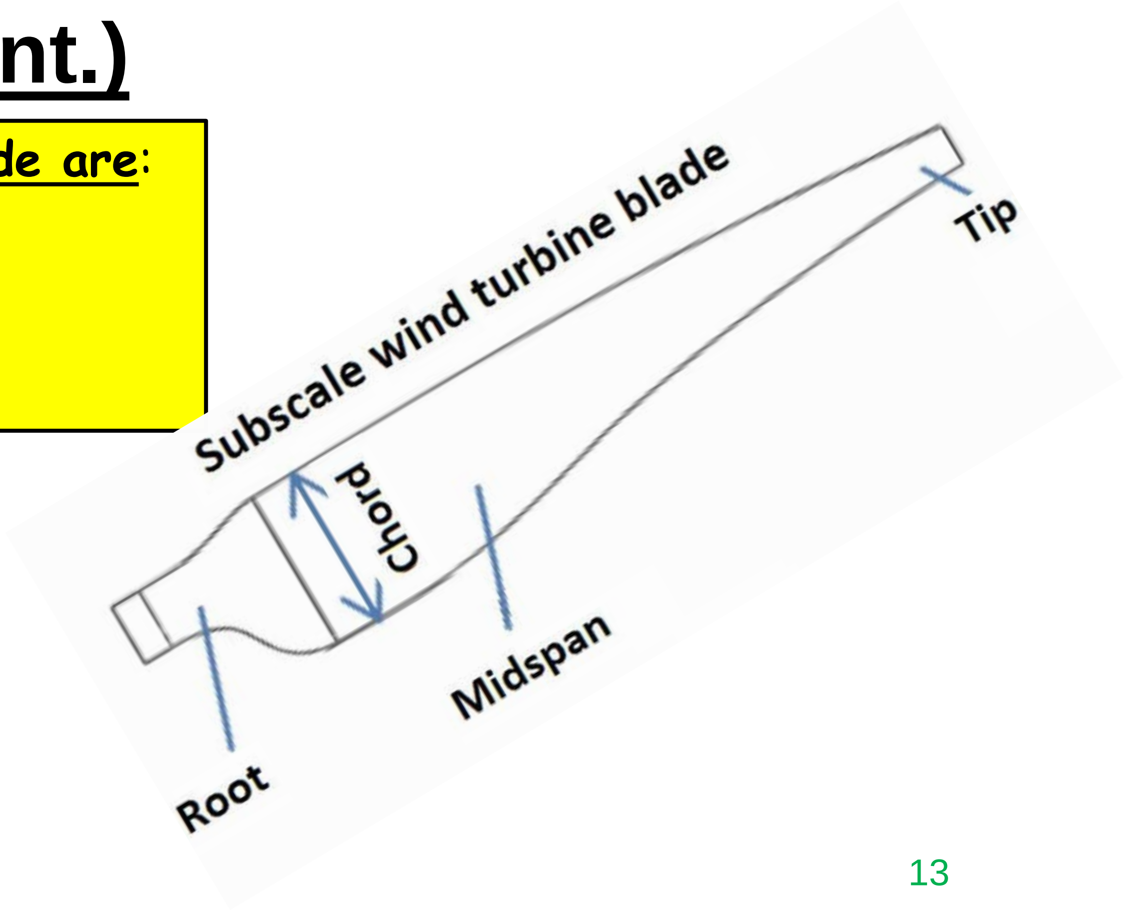
The Rotor

1.1 Blades (Cont.)

The components of a blade are:

1. Core
2. Aerodynamic shell
3. Root
4. Sensors



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1.1 Blades (Cont.)

The components of a blade are:

1. The **core** of the blade is made of balsa wood or foam; the core gives the blade its shape. This is also called the spar, which is like a long tubular beam along the length of the blade.
2. Upwind and downwind **aerodynamic shell** made of fiberglass and epoxy resins. These two are glued at the leading and at the trailing edge. The shells are glued to the spar with an adhesive.
3. **Root** of the blade is a metallic cylinder with bolts to connect the blade to the rotor hub.
4. **Sensors** in the blade to monitor stress, strain, acoustic emissions, and other signals.

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1.1 Blades (Cont.)

In general, ideal ***blade materials*** should meet the following criteria:
- wide availability and easy processing to reduce cost and maintenance
- low weight or density to reduce gravitational forces
- high strength to withstand strong loading of wind and gravitational force of the blade itself
- high fatigue resistance to withstand cyclic loading
- high stiffness to ensure stability of the optimal shape and orientation of the blade and clearance with the tower
- high fracture toughness
- the ability to withstand environmental impacts such as lightning strikes, humidity, and temperature]

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1.1 Blades (Cont.)

Options

1. Metals: vulnerability to fatigue.
2. Ceramics: have low fracture toughness, which could result in early blade failure.
3. Traditional polymers: are not stiff enough to be useful, and
4. wood has problems with repeatability, especially considering the length of the blade.

That leaves fiber-reinforced composites, which have high strength and stiffness and low density, as a very attractive class of materials for the design of wind turbines.

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The Rotor

Fiberglass-reinforced epoxy blades of Siemens SWT-2.3-101 wind turbines. The blade size of 49 meters

Photo taken from: https://en.wikipedia.org/wiki/Wind_turbine_design

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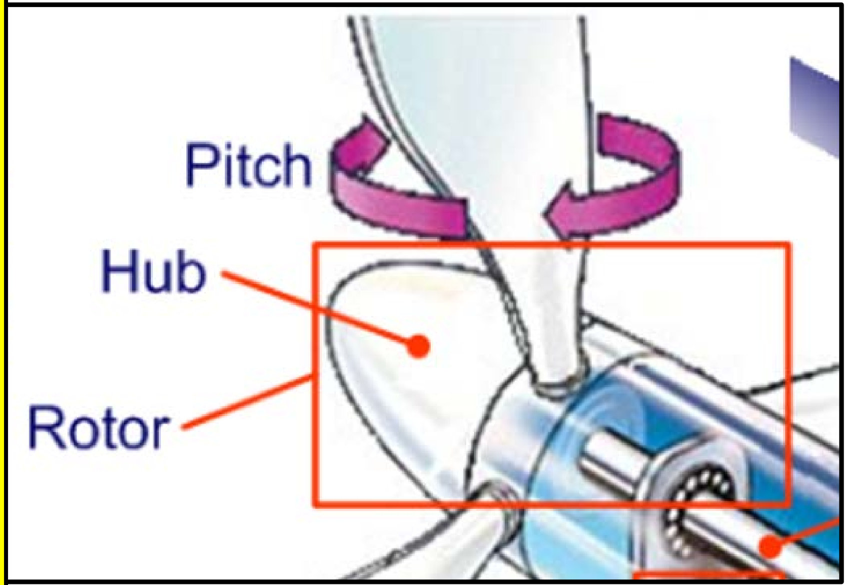
The Rotor

1.2 Rotor Hub

Blades are radially bolted to the hub. On the axial end, the rotor hub is connected to the drive train. The hub is made of high-quality cast iron. It transfers load from the blades to the nacelle frame and to the drive train. The manner of transferring loads from the hub to rest of the components in the nacelle depends on the turbine configuration—direct drive or with gearbox.



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The Rotor

1.2 Rotor Hub

In other more sophisticated designs, they are bolted to the pitch bearing, which adjusts their angle of attack with the help of a pitch system according to the wind speed to control their rotational speed.
The pitch bearing is itself bolted to the hub. The hub is fixed to the rotor shaft which drives the generator directly or through a gearbox.

Photo taken from https://en.wikipedia.org/wiki/Wind_turbine_design

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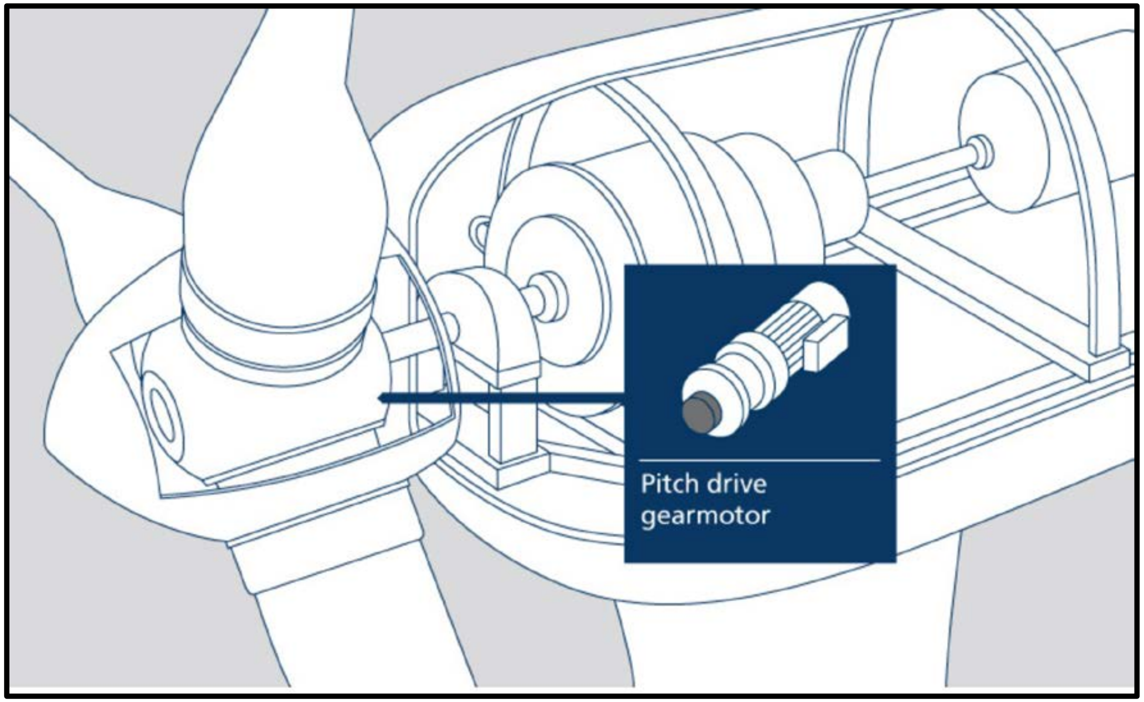
The Rotor

1.3 Pitch Control

Pitch control gearboxes serve the essential purpose of setting wind turbine blades at the best angle to the wind to turn the rotor.



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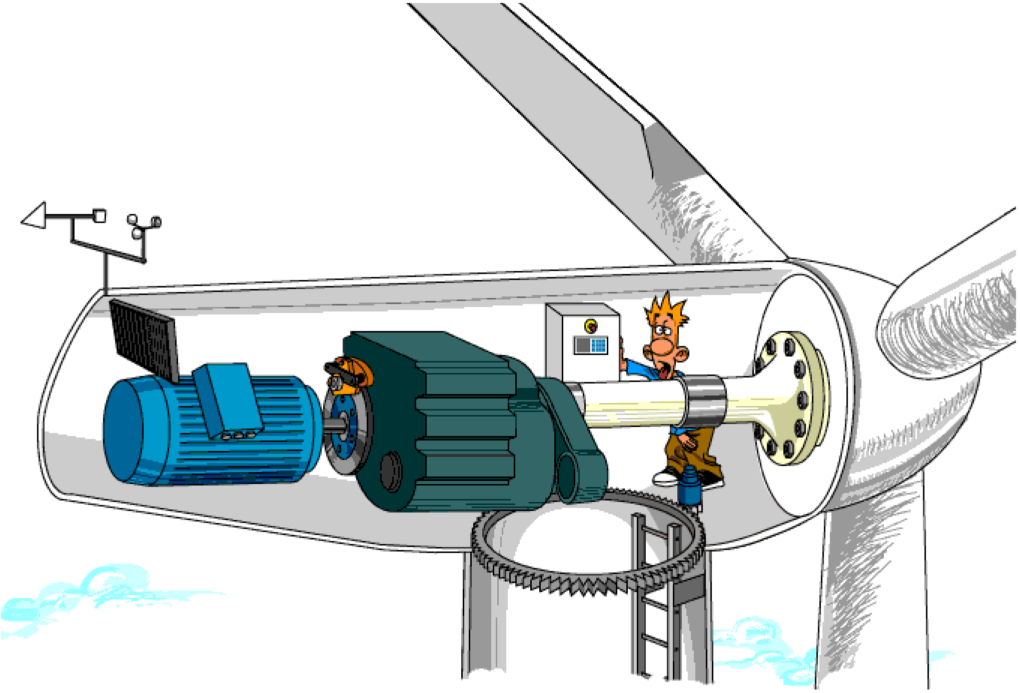
The Nacelle

2. Nacelle

The nacelle is a housing for the gearbox and generator connecting the tower and rotor. Sensors detect the wind speed and direction, and motors turn the nacelle .
Other components inside the nacelle are brake, nacelle frame, hydraulic systems for brakes and lubrication, and cooling systems.



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The Nacelle

2.1 Gearbox

In conventional wind turbines, the blades spin a shaft that is connected through a gearbox to the generator. The gearbox converts the turning speed of the blades 15 to 20 rotations per minute for a large, one-megawatt turbine into the faster 1,800 revolutions per minute that the generator needs to generate electricity.

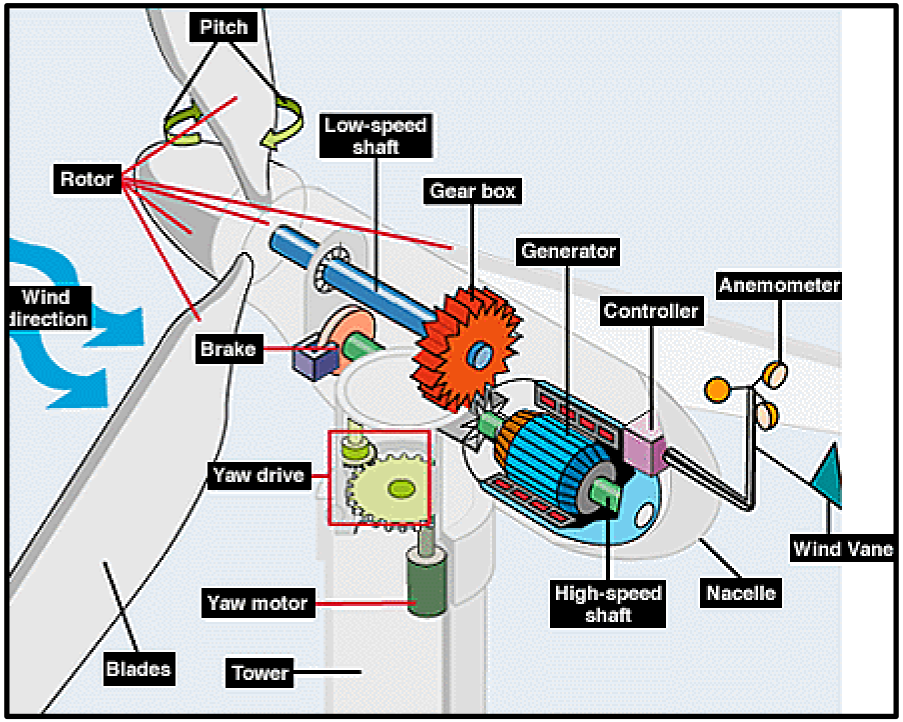

Photo taken from: http://www.climatewarmingcentral.com/wind_page.html

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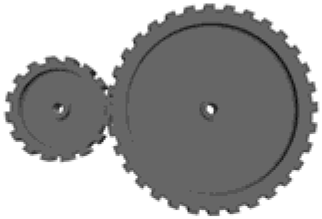
The Nacelle

2.1 Gearbox (Cont.)

A gearbox is typically used in a wind turbine to increase rotational speed from a low-speed rotor to a higher speed electrical generator. A common ratio is about 90:1, with a rate 16.7 rpm input from the rotor to 1,500 rpm output for the generator.



The multiple wheels and bearings in a gearbox suffer tremendous stress because of wind turbulence and any defect in a single component can bring the turbine to a halt. This makes the gearbox the highest-maintenance part of a turbine.

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2.2 Electrical Generator

The electrical generator is mounted inside the nacelle at the top of a tower, behind the hub of the turbine rotor. Usually the rotational speed of the wind turbine is slower than the equivalent rotation speed of the electrical network: typical rotation speeds for wind generators are 5–20 rpm while a directly connected machine will have an electrical speed between 750 and 3600 rpm. Therefore, a gearbox is inserted between the rotor hub and the generator. This also reduces the generator cost and weight.

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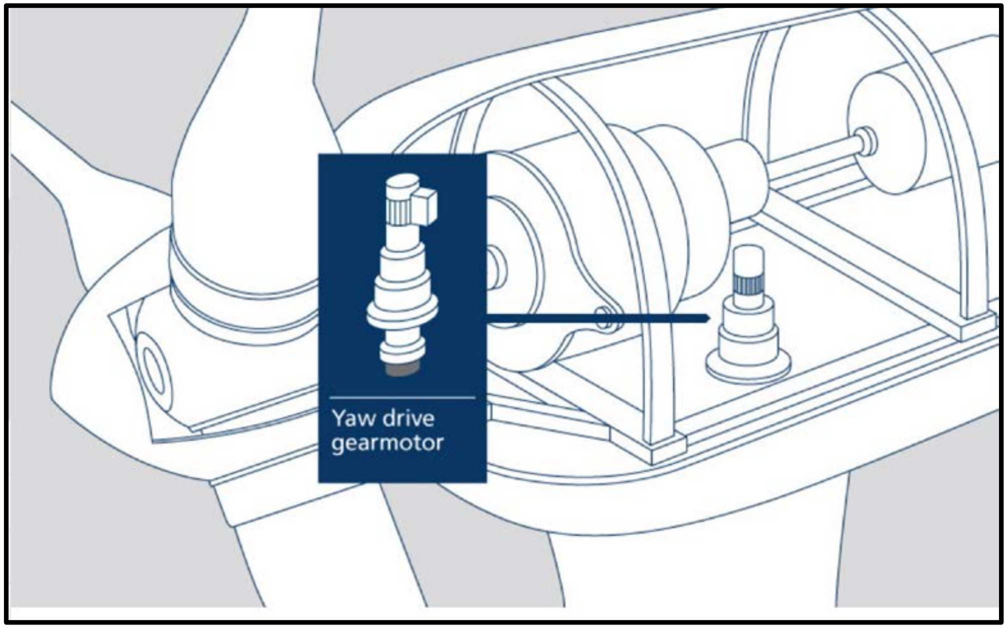
The Nacelle

2.3 Yaw Control

Yaw is the angle of rotation of the nacelle around its vertical axis. Efficient yaw control is essential to ensure that wind turbines always face directly into the wind. Modern large wind turbines are typically actively controlled to face the wind direction measured by a wind vane situated on the back of the nacelle.



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The Nacelle

2.3 Yaw Control (Cont.)

Yawing can make a significant reduction in turbine output The power output losses can simply be approximated to fall with (cos(yaw angle))^3.

Photo taken from: https://www.en.wind-turbine-models.com/turbines

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The Nacelle

2.3 Yaw Control (Cont.)

Smaller turbines (and some older large turbines) use **a passive yaw**,
which are of two types: Tail vane to orient the plane of rotation and
downwind turbine where the wind flows over the nacelle before turning the blades.

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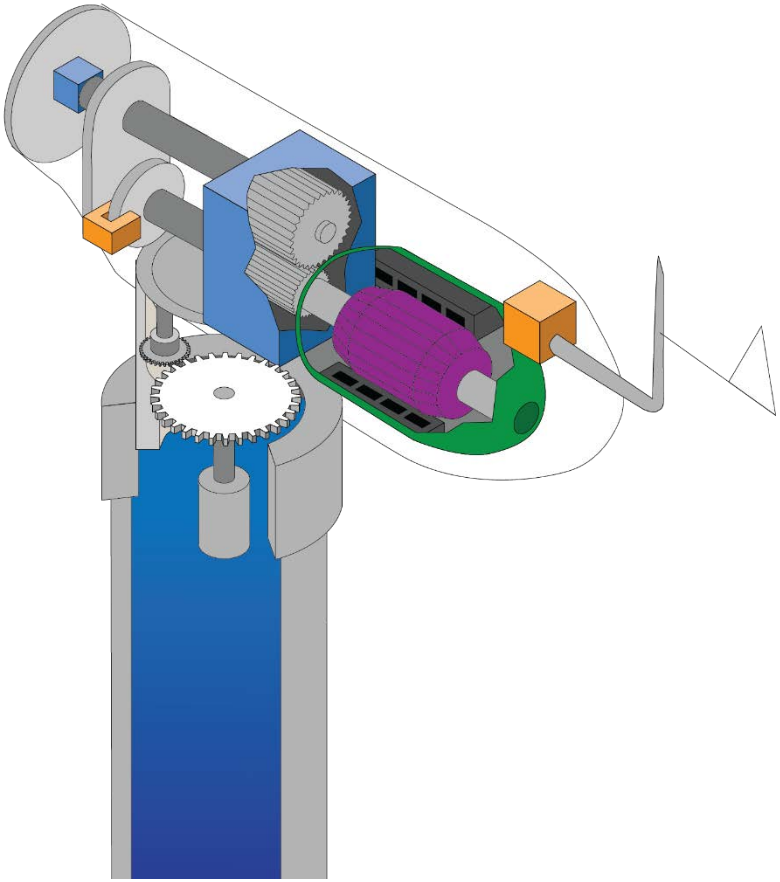
2.3 Yaw Control (Cont.)

Almost all large utility-scale turbines are upwind turbines with **active yaw**. Active yaw is more expensive because it controls the yaw using an electromechanical drive and a control system that monitors wind direction. The yaw motor is in the nacelle frame and its gear connects to a large gear that connects the nacelle to the tower. The yaw mechanism also has yaw brakes to lock the position of the yaw.



The Tower

3. Towers

The tower of the wind turbine carries the nacelle and the rotor.
Towers for large wind turbines may be either:

- Tubular steel towers,
- Lattice towers, or
- Concrete towers.
- Guyed tubular towers are only used for small wind turbines (battery chargers etc.)

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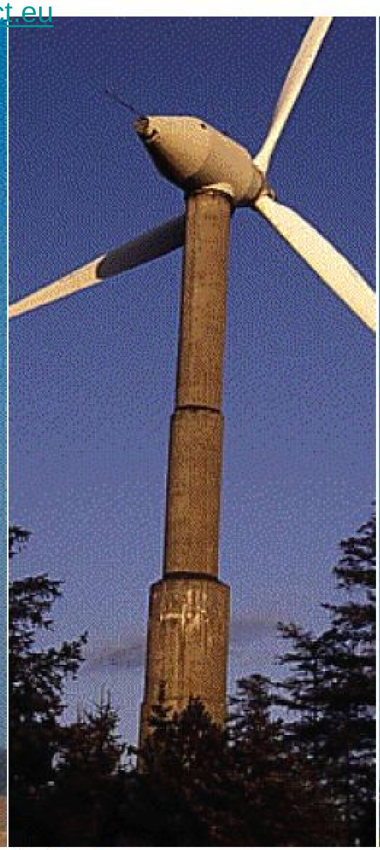
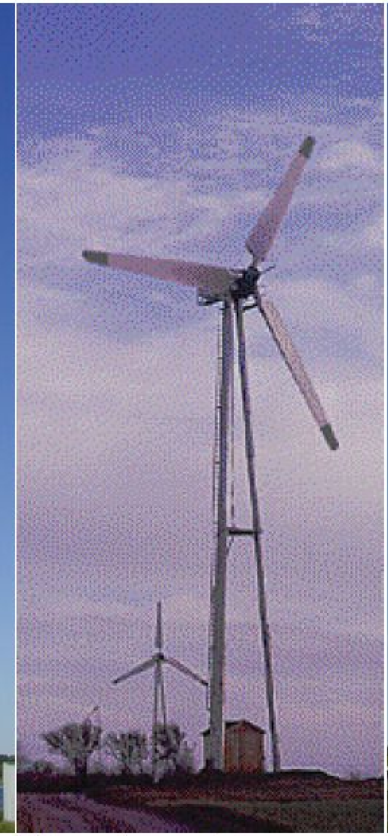
The Tower


Tubular steel tower


Tubular concrete


Lattice tower


Three-legged tower


Guy-wired pole tower

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The Tower

3. Towers (Cont.)

Tubular Steel Towers

Most large wind turbines are delivered with tubular steel towers, which are manufactured in sections of 20-30 metres 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 at the same time.

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The Tower

3. Towers (Cont.)

Lattice towers

Lattice towers are manufactured using welded steel profiles. The basic advantage of lattice towers is cost, since a lattice tower requires only half as much material as a freely standing tubular tower with a similar stiffness. The basic disadvantage of lattice towers is their visual appearance . For aesthetic reasons lattice towers have almost disappeared from use for large, modern wind turbines.

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The Tower

3. Towers (Cont.)

Guyed Pole Towers

Many small wind turbines are built with narrow pole towers supported by guy wires. The advantage is weight savings, and thus cost. The disadvantages are difficult access around the towers which make them less suitable in farm areas. Finally, this type of tower is more prone to vandalism, thus compromising overall safety.

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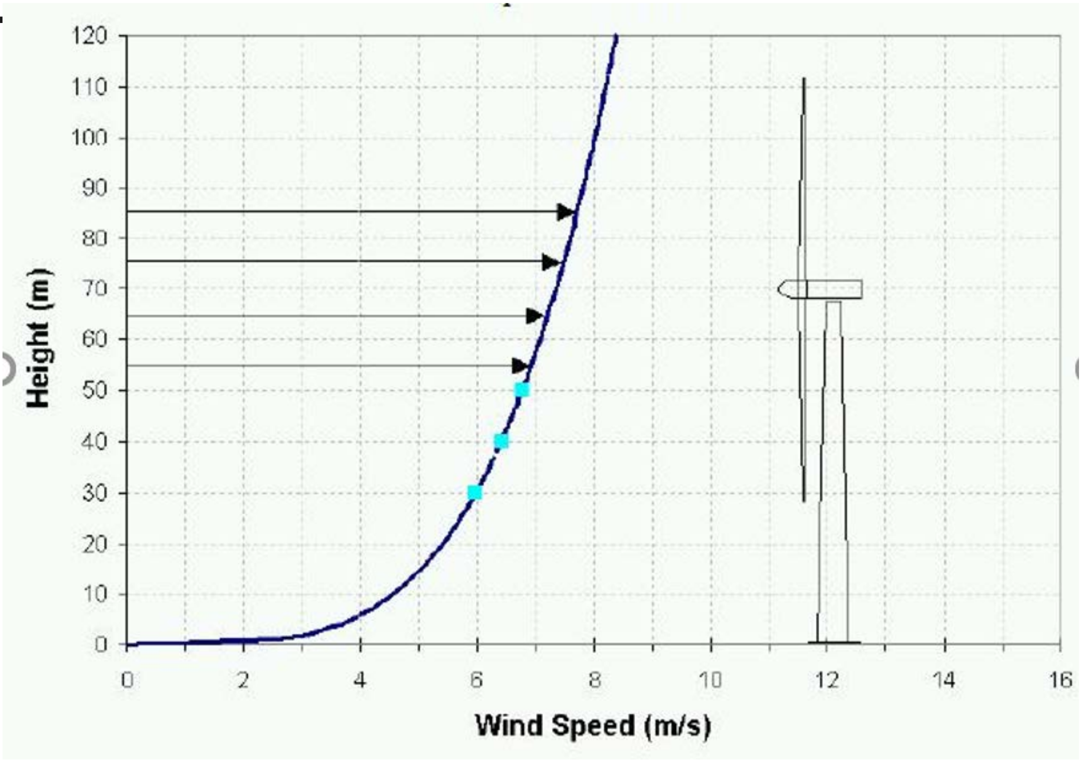
3. Towers (Cont.)

Tower height
Wind velocities increase at higher altitudes due to surface aerodynamic drag and the viscosity of the air.
The variation in velocity with altitude, called **wind shear**



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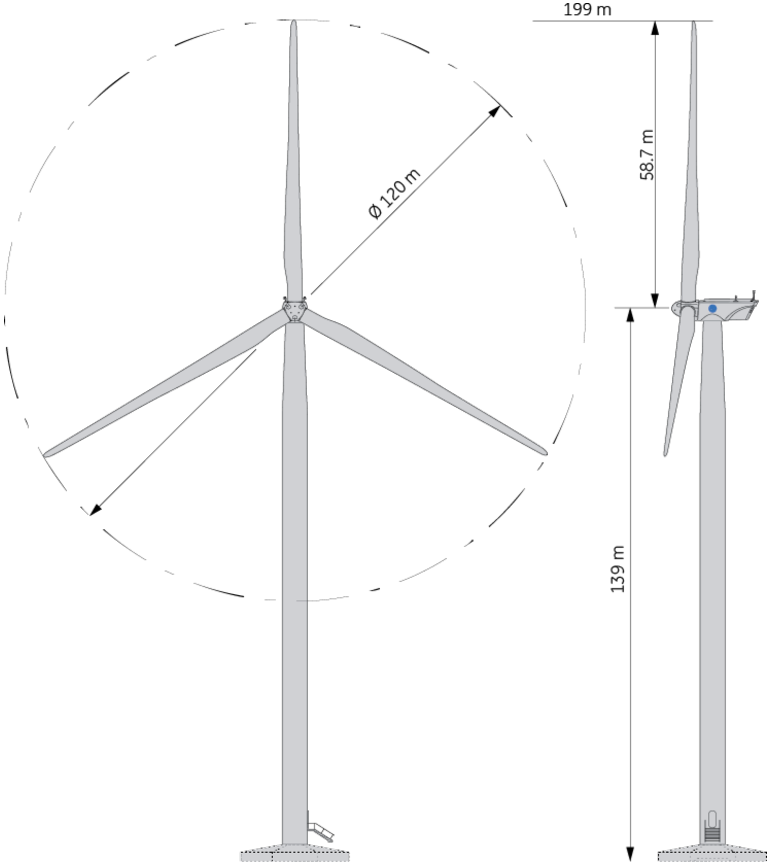
3. Towers (Cont.)

For **HAWTs**, tower heights approximately two to three times the blade length.



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3. Towers (Cont.)

Tower materials

- Higher grade S500 **steel** costs 20%-25% more than S335 steel but it requires 30% less material because of its improved strength. Therefore, replacing wind turbine towers with S500 steel would result in a net savings in both weight and cost.
- A hybrid of **prestressed concrete** and steel has shown improved performance over standard tubular steel at tower heights of 120 meters. Concrete also gives the benefit of allowing for small precast sections to be assembled on site, avoiding the challenges steel faces during transportation.

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The Foundations

4. Foundations

Wind turbines, by their nature, are very tall slender structures, this can cause a number of issues when the structural design of the foundations are considered.

Wind turbine foundations

Photo taken from: https://en.wikipedia.org/wiki/Wind_turbine_design

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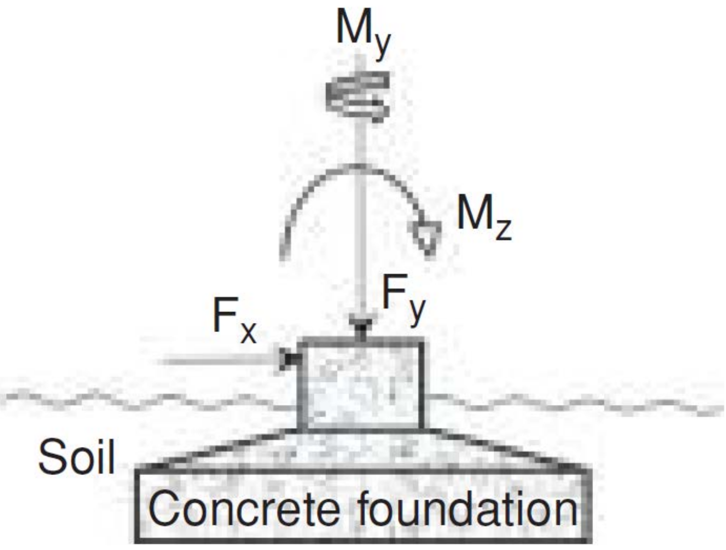
The Foundations

4. Foundations (Cont.)

Weight of the structure is the largest force that must be overcome by foundation. The bending moment because of thrust force applied at the hub height is a large moment that must be overcome. The bending moment acts to overturn the entire turbine; the foundation provides the necessary resistance. This bending moment causes the upwind side of the foundation to be tension and the downwind side to be in compression.



[3] Wind energy engineering. New McGraw-Hill, Jain, P. (2011).

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[3] Wind energy engineering. New York: McGraw-Hill, Jain, P. (2011). [5] Fundamental of Aerodynamics, John D. Anderson, Jr., McGraw-Hill, 2001.

Review articles:Web links:
[4] www.ewea.org European Wind Energy Association
[5] wwindea.org World Wind Energy Association
[6] www.awea.org American Wind Energy Association

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Introduction to Wind Energy

Module 2.1

Aerodynamics of Wind Turbine Blades.
Lesson 6

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Objectives

The purpose of this lesson is to present the aerodynamic theories as applied to wind energy rotors and explain the lift and drag forces

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Learning Outcomes

This lesson will contribute to the students to:

O1. Understand the flow field around wind turbine

O2. Understand the reasons behind using aerofoil section for rotor blades

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Technical Contents

1. *Airfoils*
2. *Relative Velocity of Wind*
3. *Lift and Draft forces*

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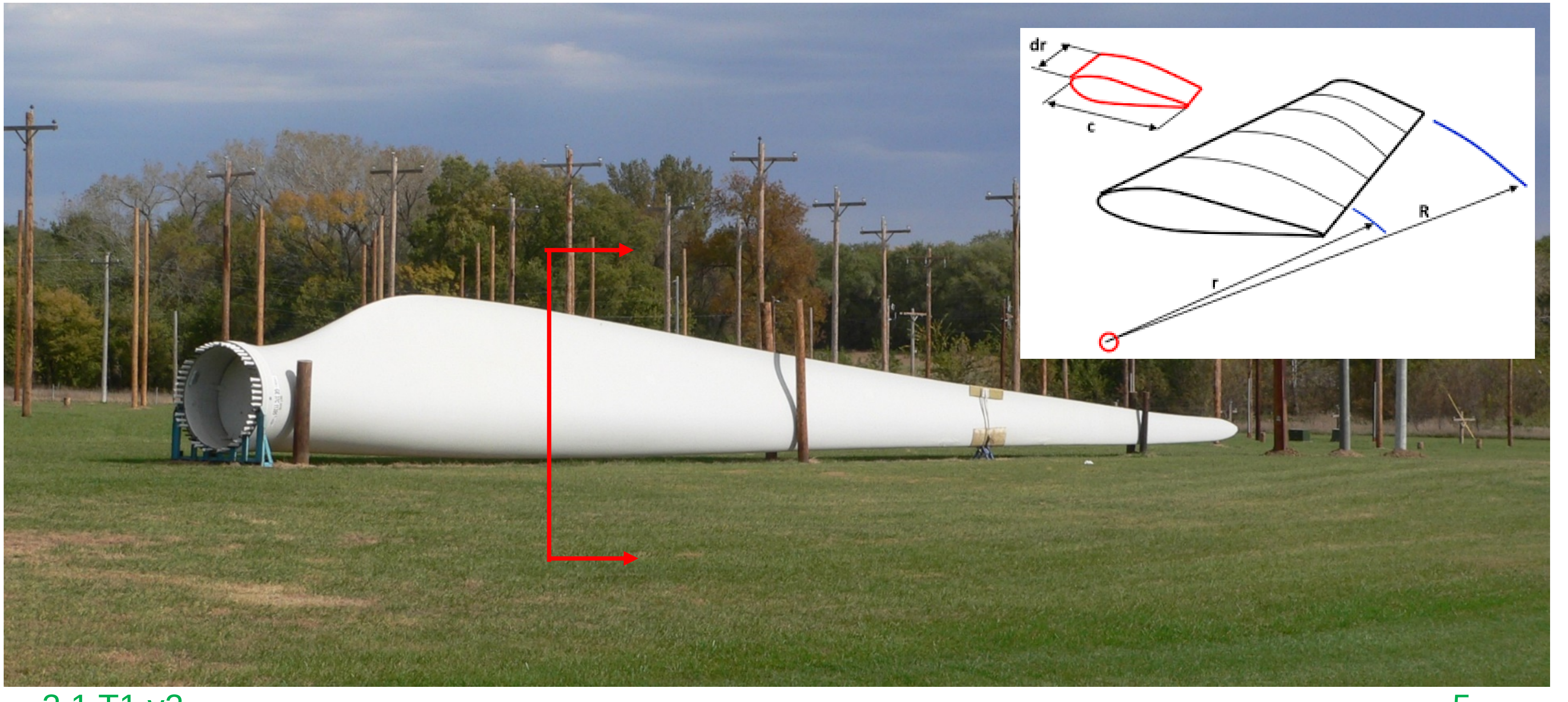
Blade Section

The cross-section of a wind turbine blade is an airfoil.



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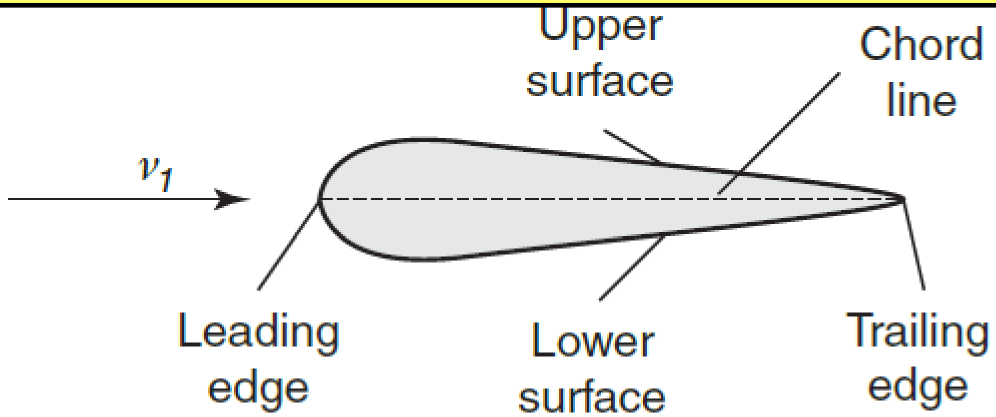
Airfoils

The figure below is a schematic of a symmetrical airfoil. Chord line connects the leading to the trailing edge. Most airfoils used in wind turbines have a larger area above compared to below the chord line. A line connecting the leading and trailing edge that bisects the area of an airfoil is called a camber line.



Ref. Wind Energy Engineering By Pramod Jain

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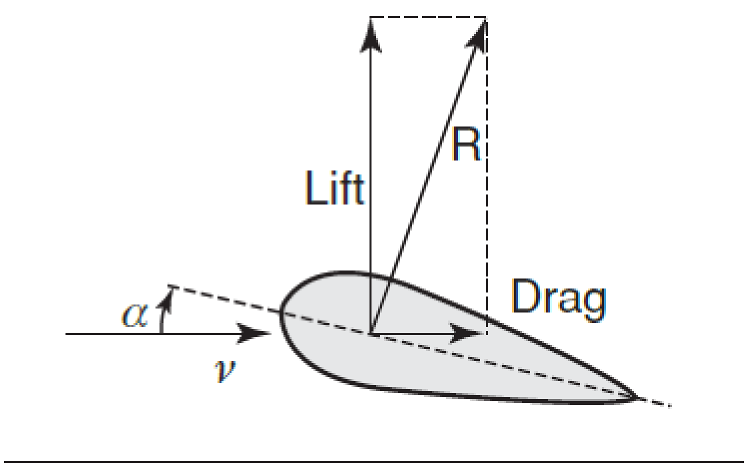
Airfoils

Symmetrical Airfoils

When the airfoil is tilted at an angle to the fluid flow, as shown, then there is an imbalance in the pressure along the *y*-axis resulting in **a lift force**. In an ideal fluid, the pressure remains balanced along the *x*-axis and, therefore, there is no net force along the *x*-axis. *α* is called the angle of attack.



Ref. Wind Energy Engineering By Pramod Jain

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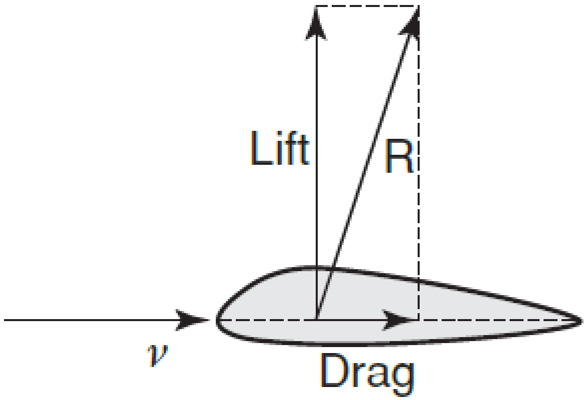
Airfoils

Asymmetrical Airfoils

When the airfoil is not symmetrical and the upper surface is curved more than the lower surface, then **a lift force** occurs because the pressure decrease and speed increase in the upper surface is larger than the pressure decrease and speed increase in the lower surface.



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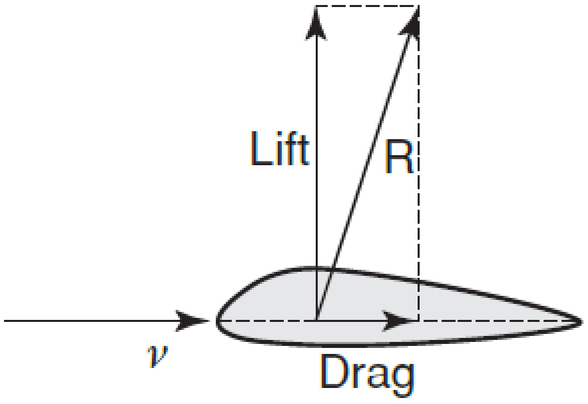
Airfoils

As a convention, :

- lift force is *perpendicular* to the direction of wind and

- drag force is *parallel* to the direction of wind.



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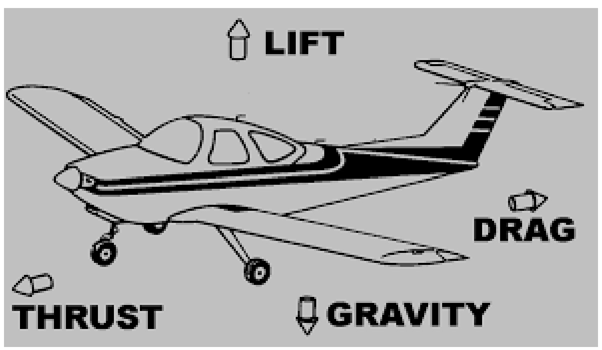
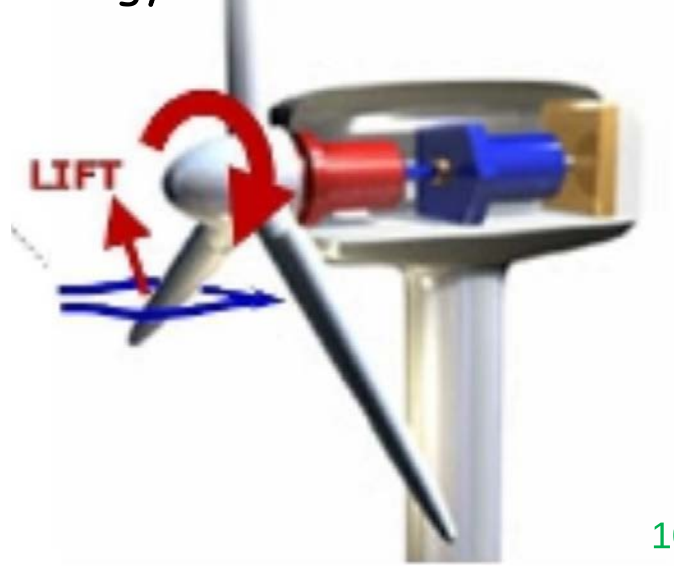
Airfoils

Positive angle of attack (α) on nonsymmetrical airfoils cause :

airplanes to fly



and wind turbines to produce energy



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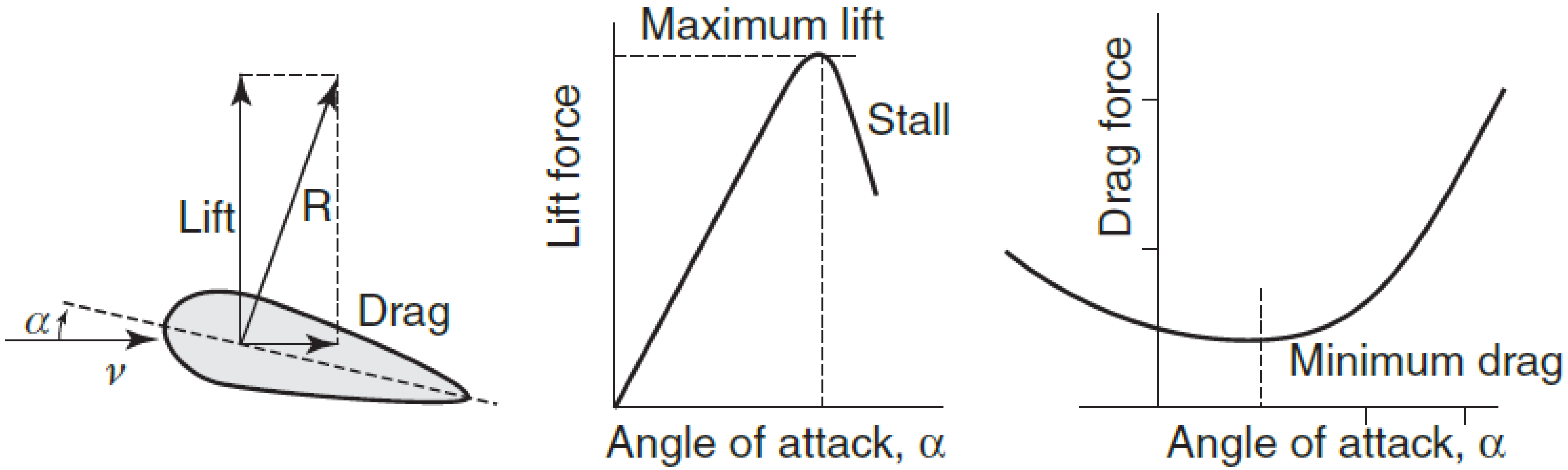
Airfoils

Each type of aerofoil has an optimal value of α that produces maximum lift and minimal drag.



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Relative Velocity of Wind

<u>In case of airplane</u>, the angle of attack of wind is constant along most of the length of the wing of an aircraft.

Photo is taken from: https://fineartamerica.com/featured/view-out-of-airplane-airplane-wing-in-flight-preecha-wannalert-.html

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Relative Velocity of Wind

<u>In the case of wind turbines</u>, the angle of attack changes along the length of a blade. The angle of attack is with respect to the blade, meaning, it is the angle at which wind strikes a blade as seen by an observer on the blade.

Photo is taken from: https://phys.org/news/2017-04-radar-scanner-turbine-blades-defects.html

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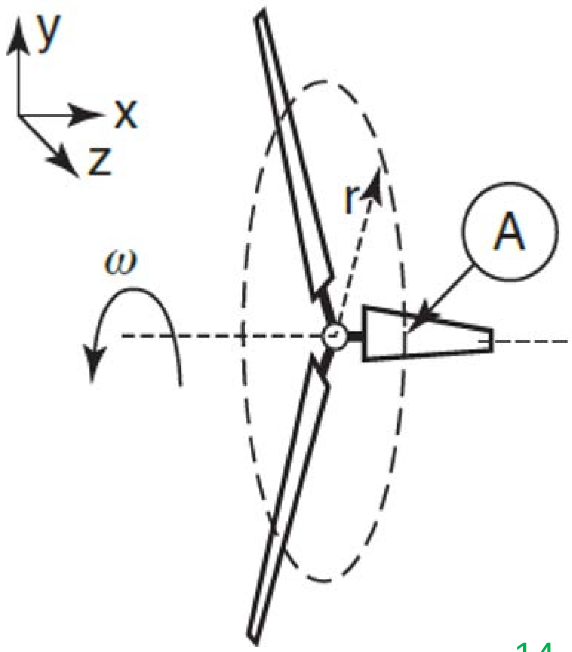
Relative Velocity of Wind

The axis of rotation is parallel to the *x*-axis and the blades move in the *y*-*z* plane. Consider point labeled *A* in the schematic, which is a point at a distance *r* from the center when the longitudinal axis of the blade is parallel to the *z*-axis.



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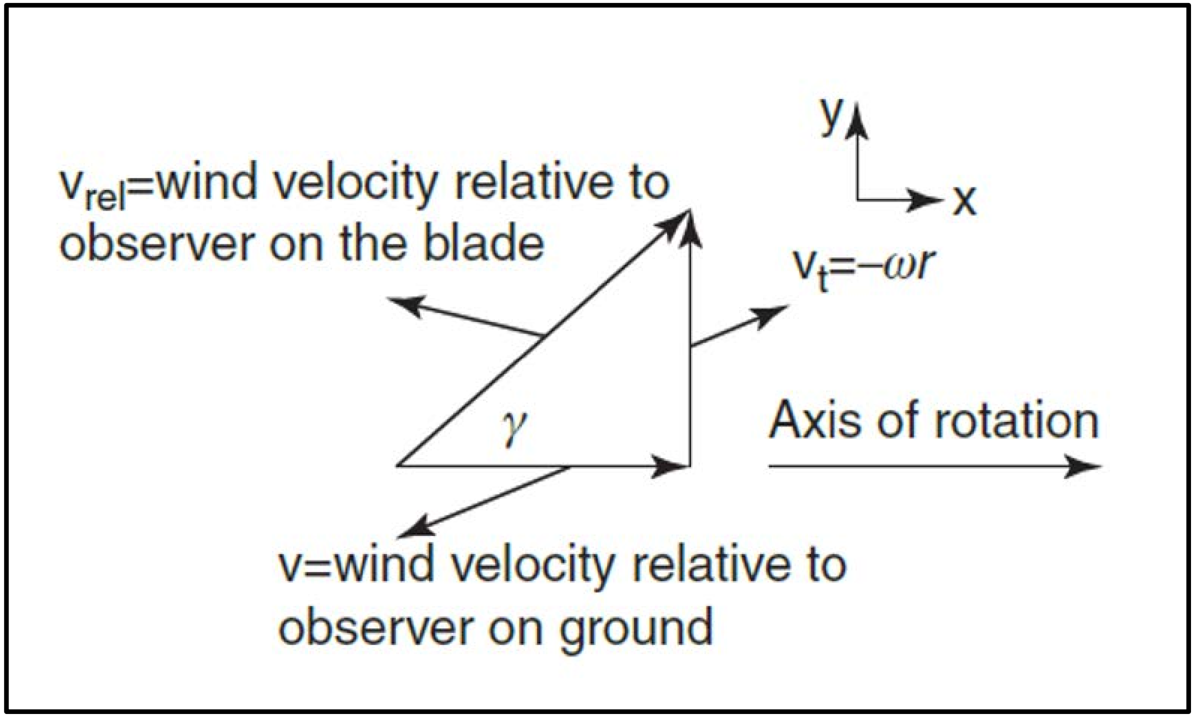
Relative Velocity of Wind

The velocity diagram is drawn for point A and is shown in the schematic to the right. The wind relative velocity of v_{rel}.



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Relative Velocity of Wind

The wind relative velocity is v_{rel}. This relative velocity is at an angle of γ , calculated as:

$$v_{rel} = \sqrt{v^2 + (\omega r)^2}$$

$$\gamma = \tan^{-1} \frac{\omega r}{v}$$

The magnitude and direction of the relative velocity of wind, changes with radius r , the distance from the hub.

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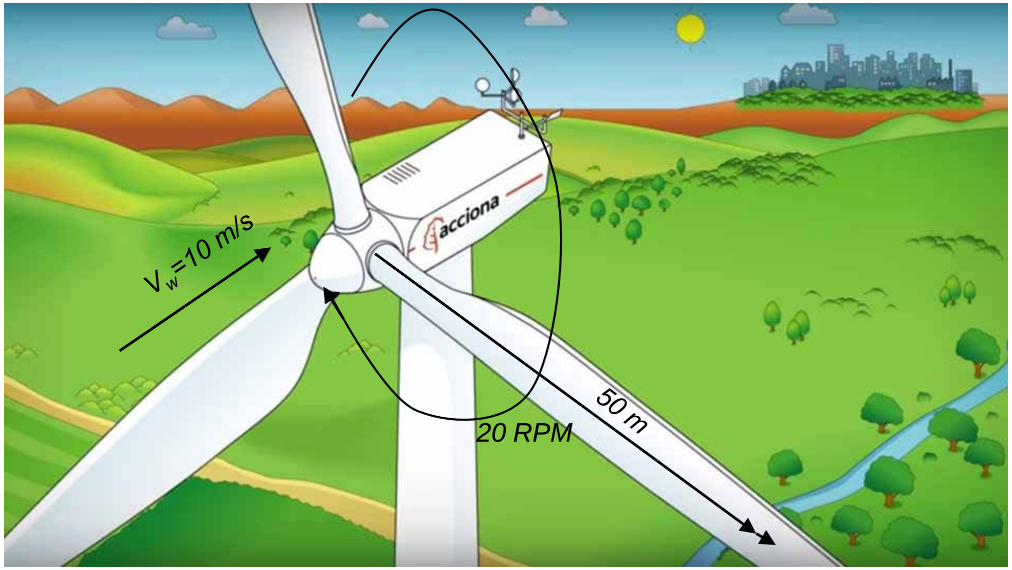
Relative Velocity of Wind

Example 1

Consider a turbine turning at 20 revolutions per minute (rpm), wind speed of 10 m/s and blade of length 50 m. Calculate the following parameters along the blade length :

a. Angular velocity
b. Relative velocity
c. Relative angle



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Relative Velocity of Wind

Example 1
Solution

Input data

Rotor Diameter	100	m
wind Speed	10	m/s
Rotor Rpm	20	
Angular velocity	2.10	rad/s

Formulae

$\omega = 2\pi(RPM)/60$ Angular velocity in rad/s

$V_t = \omega r$ Tangential velocity at radius r

$V_{rel} = \sqrt{V_t^2 + V_W^2}$ Relevant velocity at radius r

$\gamma = tan^{-1}(\frac{V_t}{V_W})$ Relative angle w.r.t. wind direction at radius r

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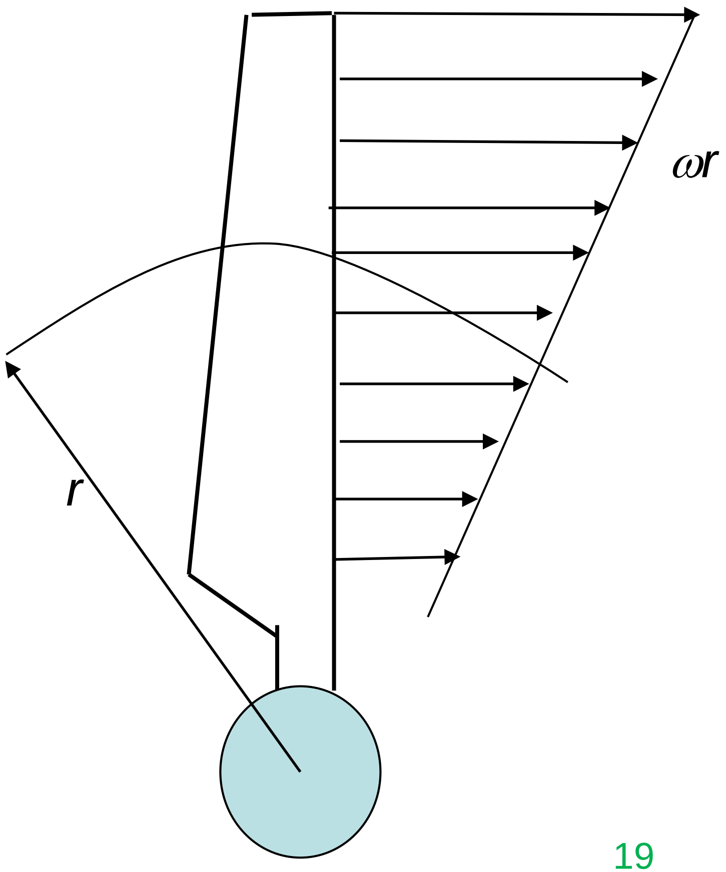
Relative Velocity of Wind

Example 1

Solution

the Table and Figure show the tangential velocity at different values of *r* . *ωr values* increase with distance from the hub of the rotor.

r/R	r (m)	ωr(m/s)
0.1	5	10.48
0.2	10	20.95
0.3	15	31.43
0.4	20	41.90
0.5	25	52.38
0.6	30	62.85
0.7	35	73.33
0.8	40	83.80
0.9	45	94.28
1	50	104.75



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Relative Velocity of Wind

Example 1
Solution (Cont.)

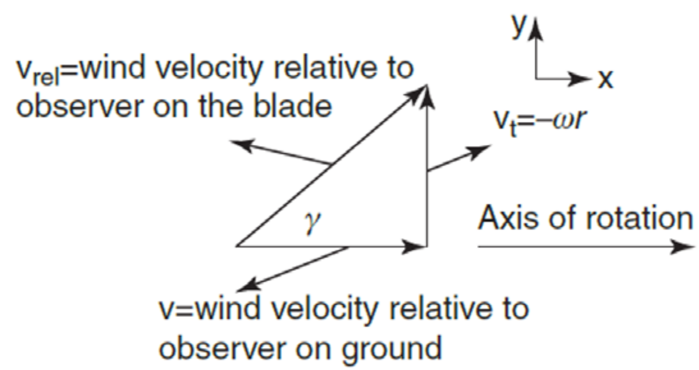
The total or relative velocity to each blade element is obtained as:

$$V_{rel} = \sqrt{V_t^2 + V_w^2}$$

The direction of the relative velocity is calculated from:

$$\gamma = tan^{-1}\left(\frac{V_t}{V_w}\right)$$

r/R	r (m)	ωr(m/s)	Vrel(m/s)	γ (deg)
0.1	5	10.48	14.48	46.31
0.2	10	20.95	23.21	64.46
0.3	15	31.43	32.98	72.32
0.4	20	41.90	43.08	76.55
0.5	25	52.38	53.32	79.16
0.6	30	62.85	63.64	80.93
0.7	35	73.33	74.00	82.20
0.8	40	83.80	84.39	83.16
0.9	45	94.28	94.80	83.91
1	50	104.75	105.23	84.51



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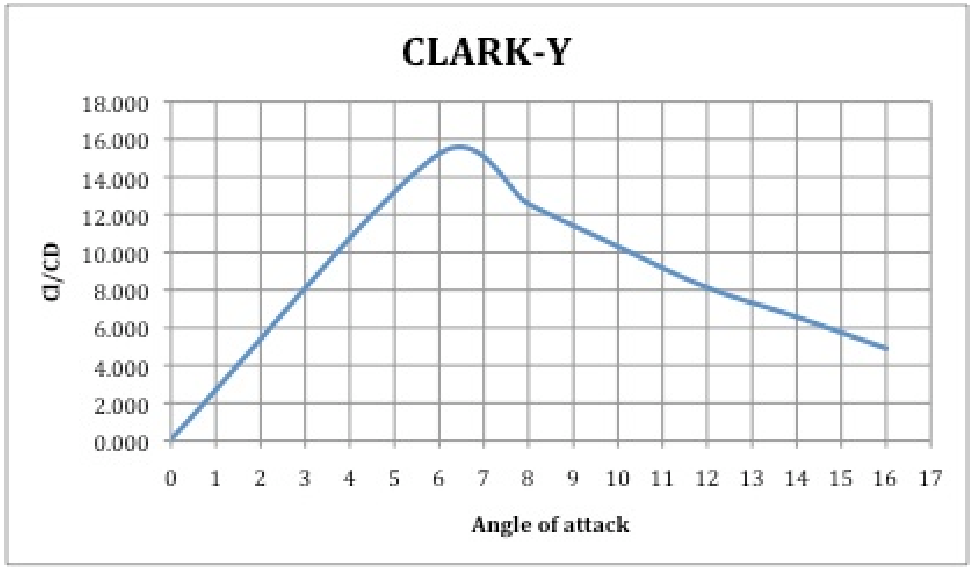
Lift and Draft forces

Blade twist

There is an optimal angle of attack, which is the angle between the chord of the airfoil and the relative velocity vector v_{rel}.
This optimal angle of attack will yield **high lift** and **low drag** forces.



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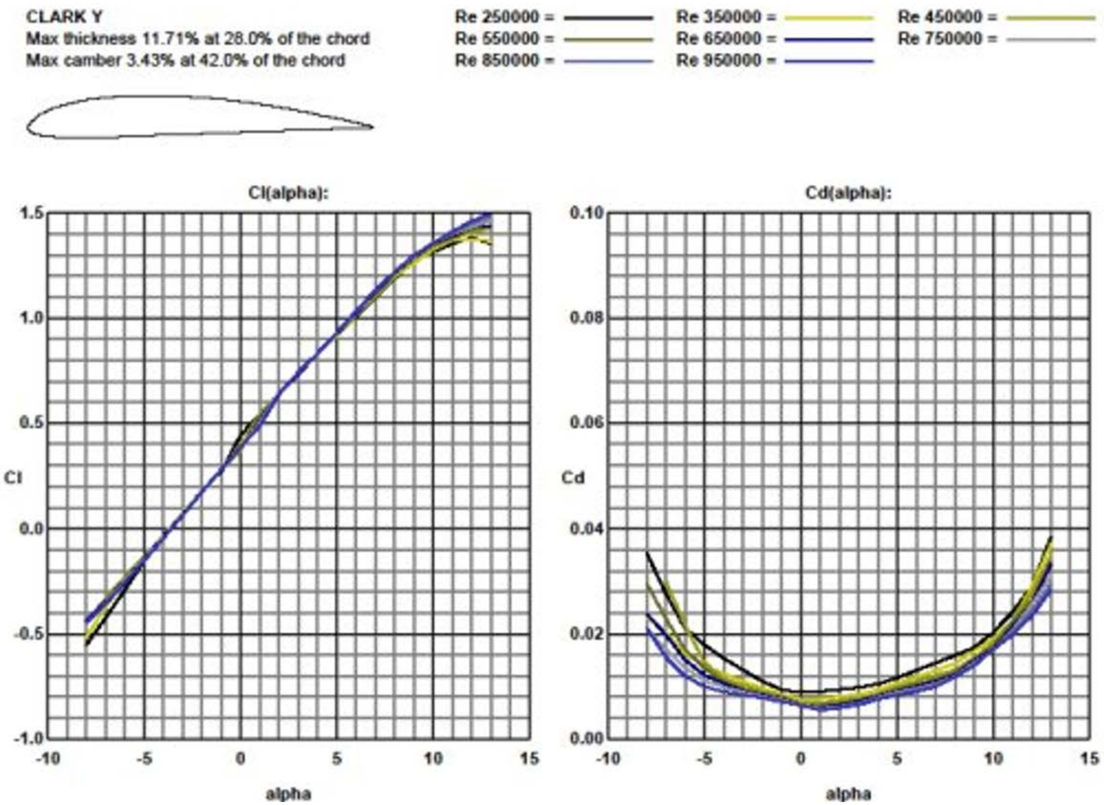
Lift and Draft forces

Recall



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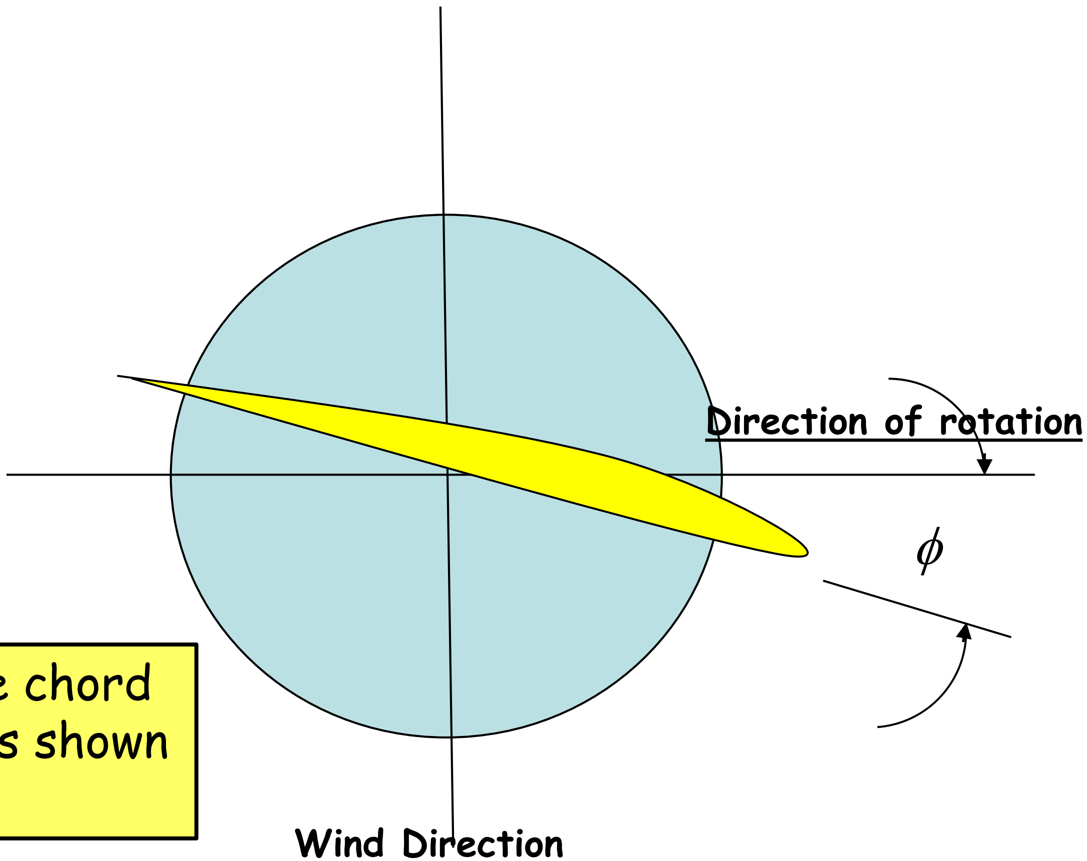
Lift and Draft forces

Blade twist

In order to maintain an optimal angle of attack α along the entire length of the blade while γ changes as a function of radius, the orientation of chord has to change along the length of blade. This orientation is called **the pitch**, φ.



Pitch is the angle between the chord and the direction of motion, as shown in the next slide

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Lift and Draft forces

If the angle of attack is held constant, then the pitch of the blade has to decrease from the root of the blade to the tip of the blade. Close to the root of the blade, the pitch (φ) is approximately 90-α. As the distance from root, *r* , increases, the value of φ decreases.

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Lift and Draft forces

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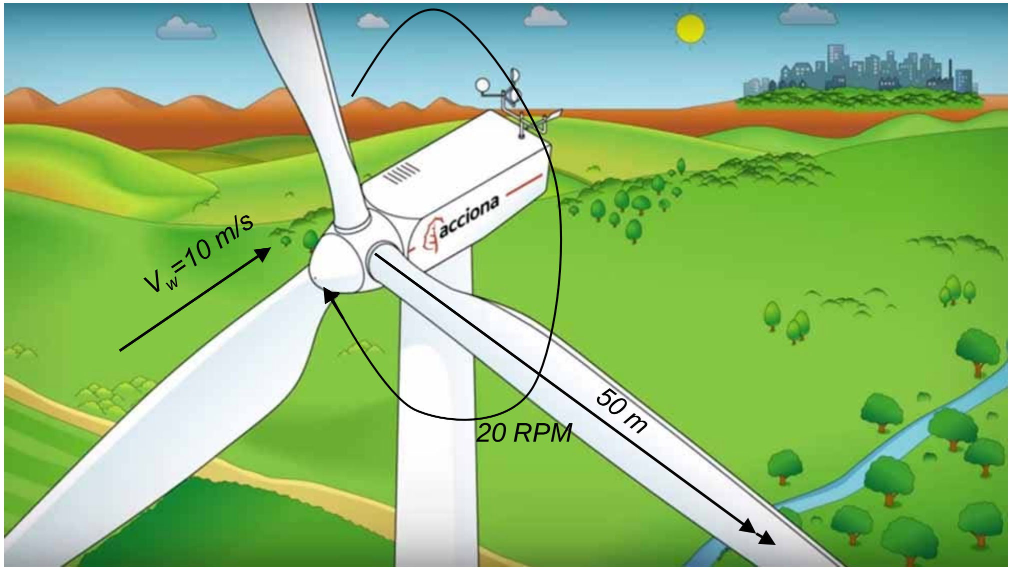
Example 2

If the optimum blade section angle of attack in Example 1 is 6^0 calculate the blade radial twist distribution in degrees



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Lift and Draft forces

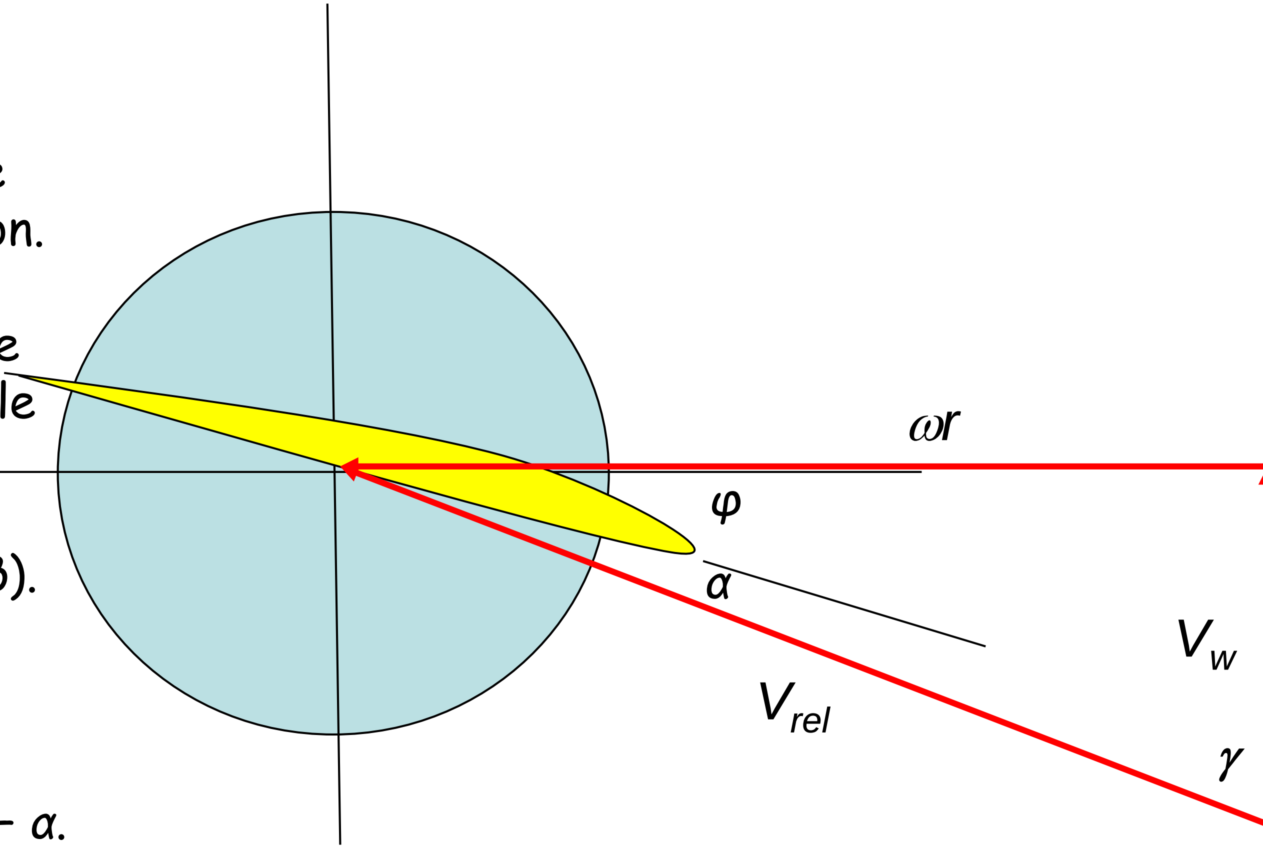
<u>Example 2</u>

<u>Solution</u>

Relative velocity angle and twist angle relation. The angle of attack (α) plus the pitch angle (φ) is equal to the angle of relative velocity with the direction of motion of the blade (β).

$$90 - \gamma = \beta = \alpha + \varphi$$

Therefore, $\varphi = 90 - \gamma - \alpha$.



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Lift and Draft forces

Example 2

Solution

Table shows values of pitch angles at different blade sections

$$\varphi = 90 - \gamma - \alpha.$$

r/R	r (m)	ωr(m/s)	Vrel(m/s)	γ (deg)	ϕ (deg)
0.1	5	10.48	14.48	46.31	37.69
0.2	10	20.95	23.21	64.46	19.54
0.3	15	31.43	32.98	72.32	11.68
0.4	20	41.90	43.08	76.55	7.45
0.5	25	52.38	53.32	79.16	4.84
0.6	30	62.85	63.64	80.93	3.07
0.7	35	73.33	74.00	82.20	1.80
0.8	40	83.80	84.39	83.16	0.84
0.9	45	94.28	94.80	83.91	0.09
1	50	104.75	105.23	84.51	-0.51

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Lift and Draft forces

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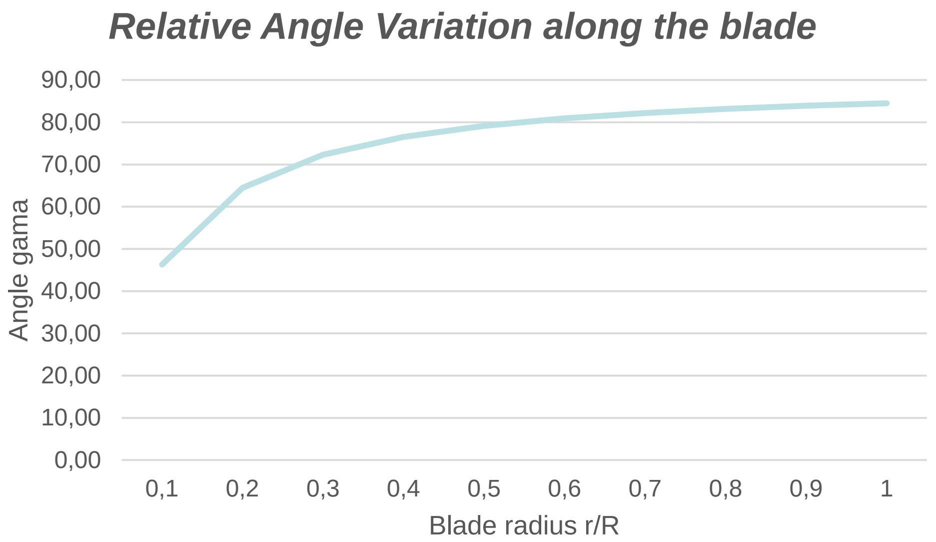
Example 2
Solution



Flow angle radial distribution

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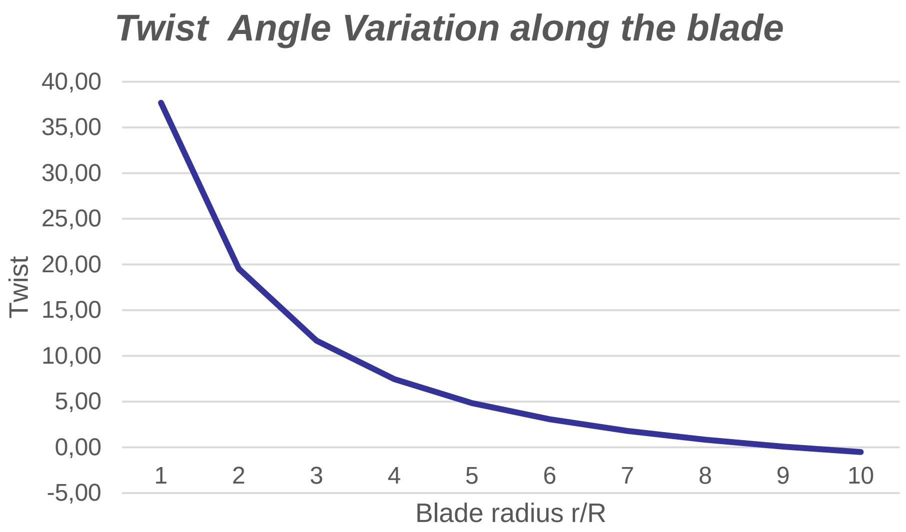
Lift and Draft forces



Blade twist angle radial distribution

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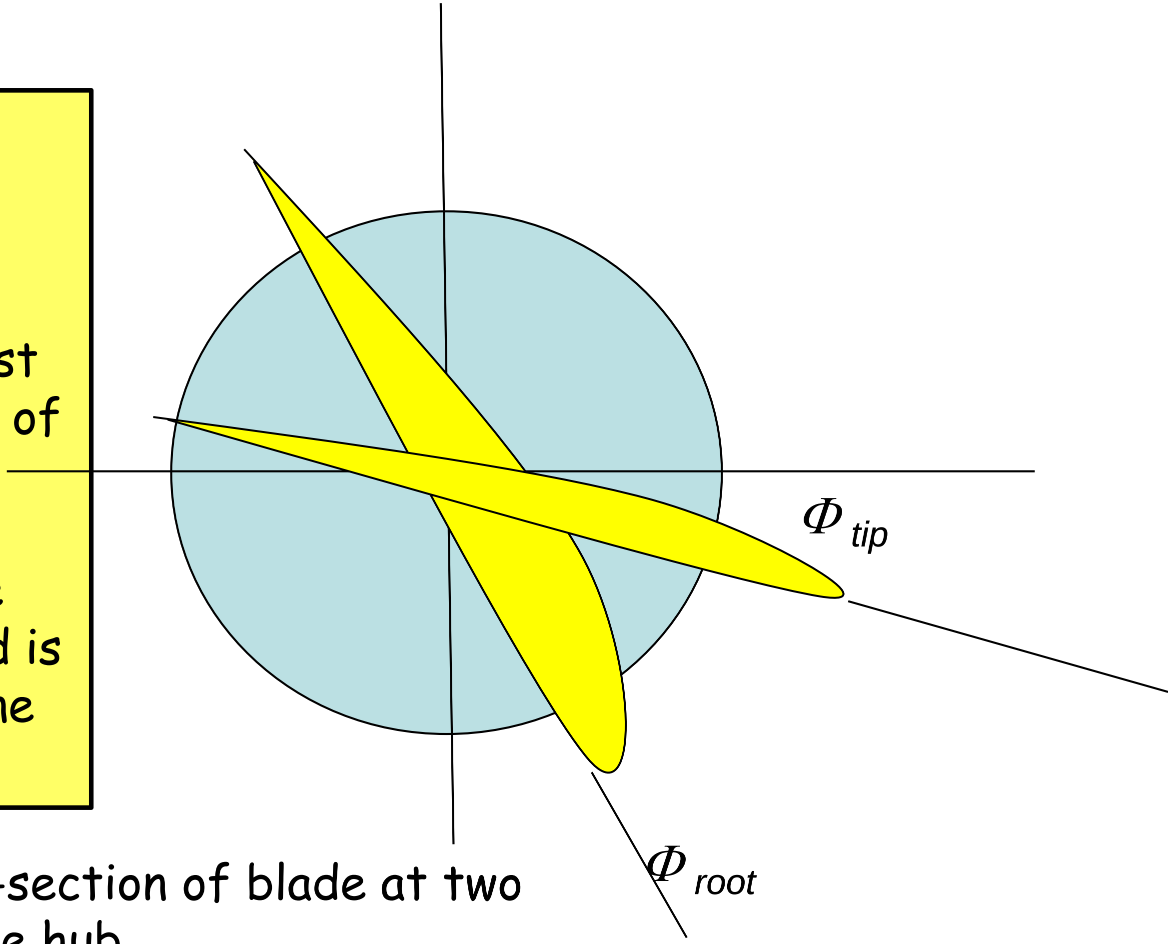
Lift and Draft forces

Remarks:
1. Blades of most large turbines have a twist.
2. Close to the hub, the blade airfoil chord is almost perpendicular to the plane of rotation.
3. At the farthest point from the hub, which is the tip of the blade, the chord is at a small angle to the plane of rotation.



The Figure shows the cross-section of blade at two different distances from the hub.

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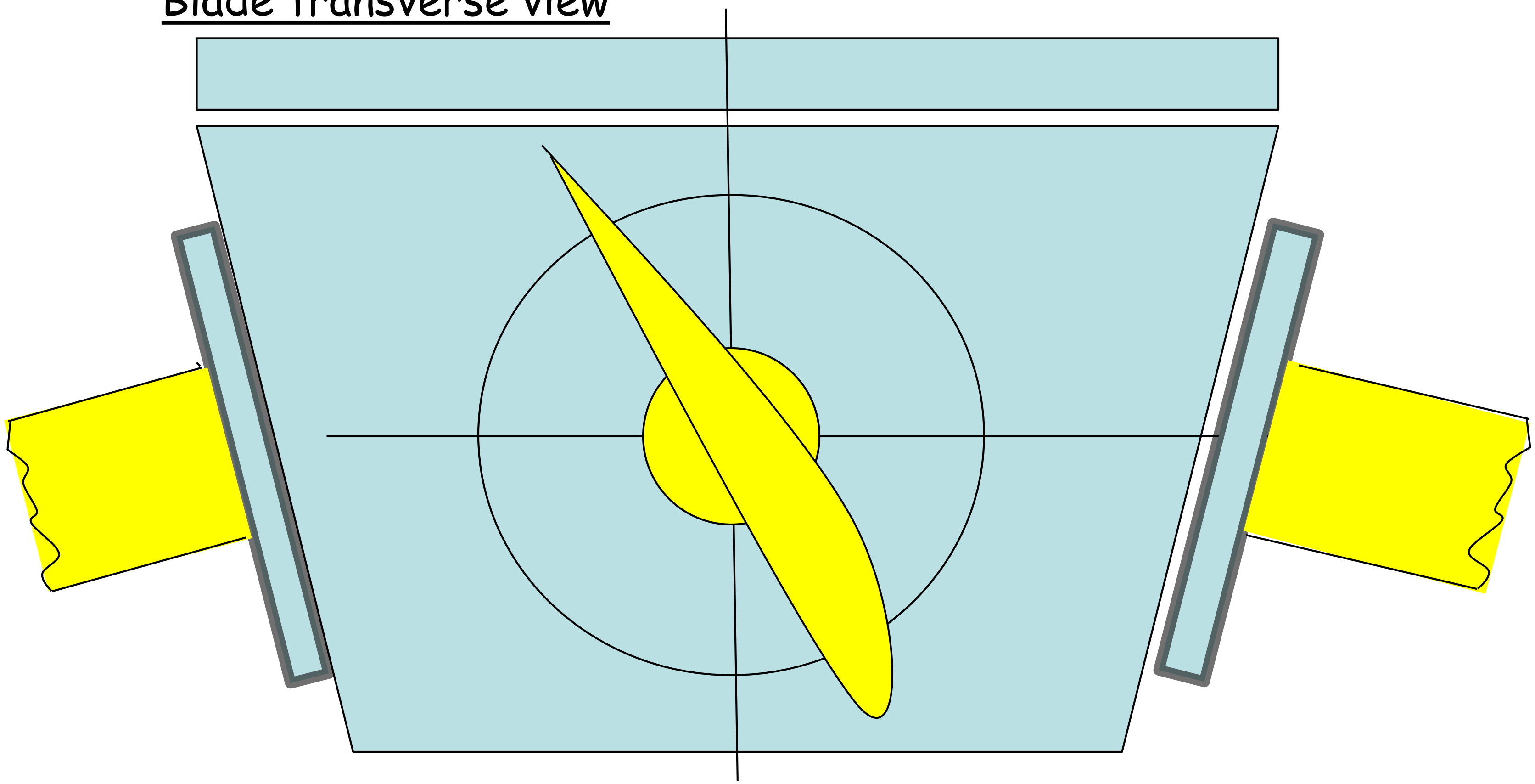
Lift and Draft forces

Blade transverse view



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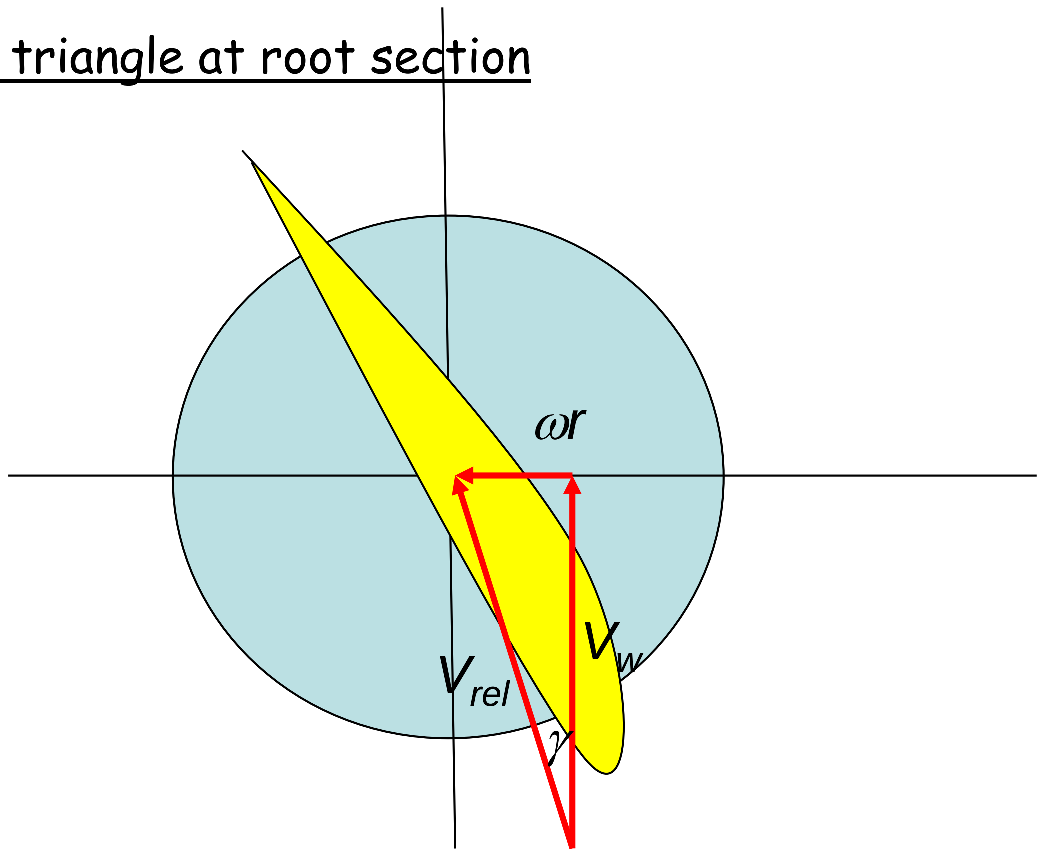
Lift and Draft forces

Velocity triangle at root section



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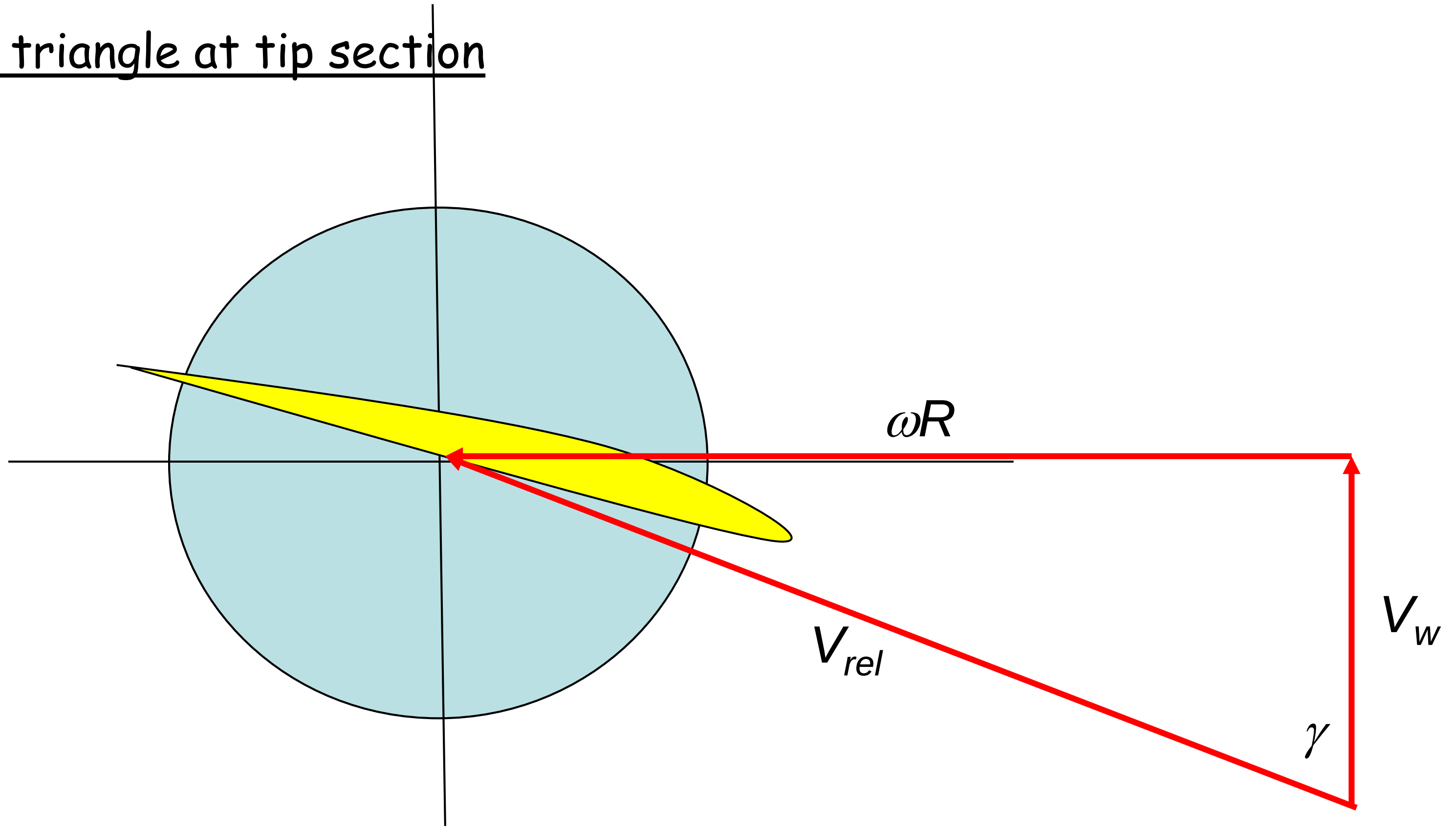
Lift and Draft forces

Velocity triangle at tip section



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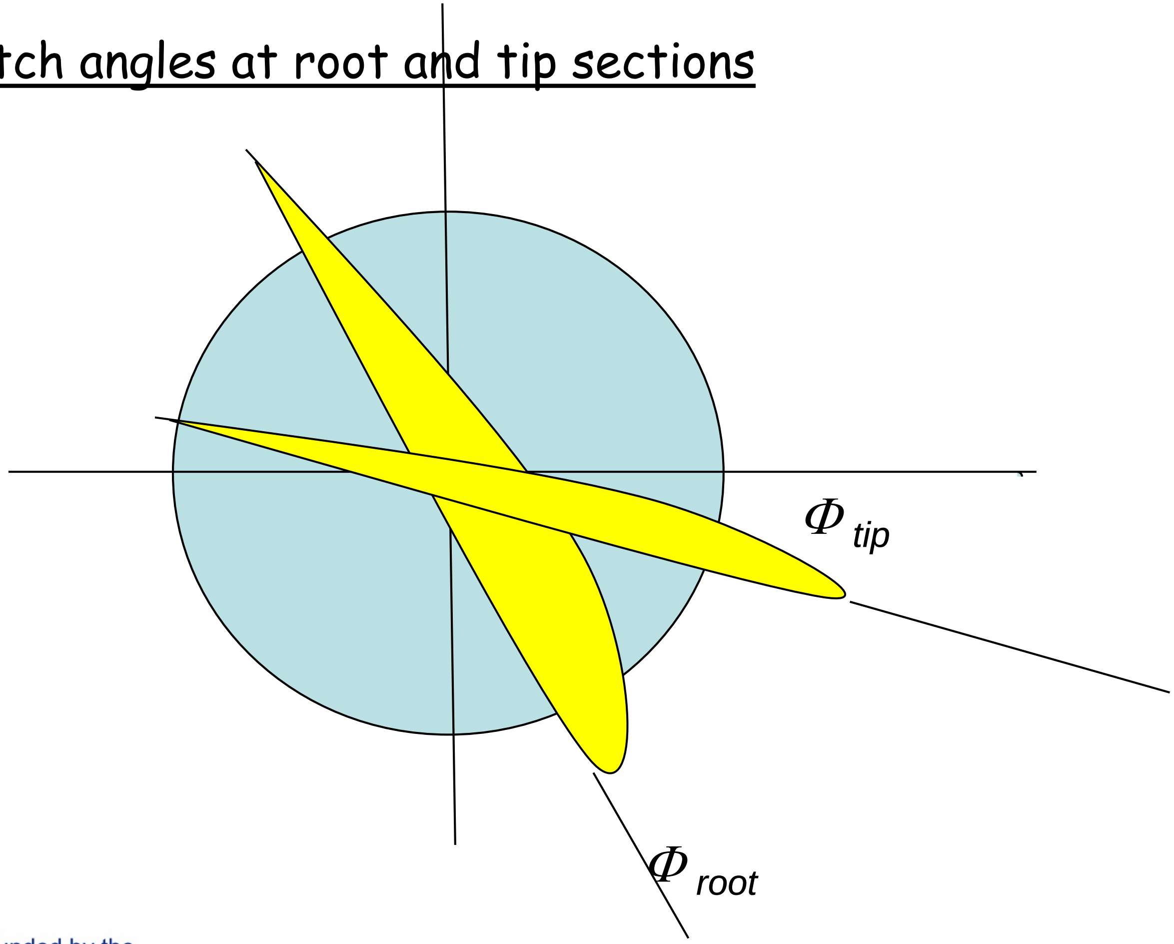
Lift and Draft forces

Blade Pitch angles at root and tip sections



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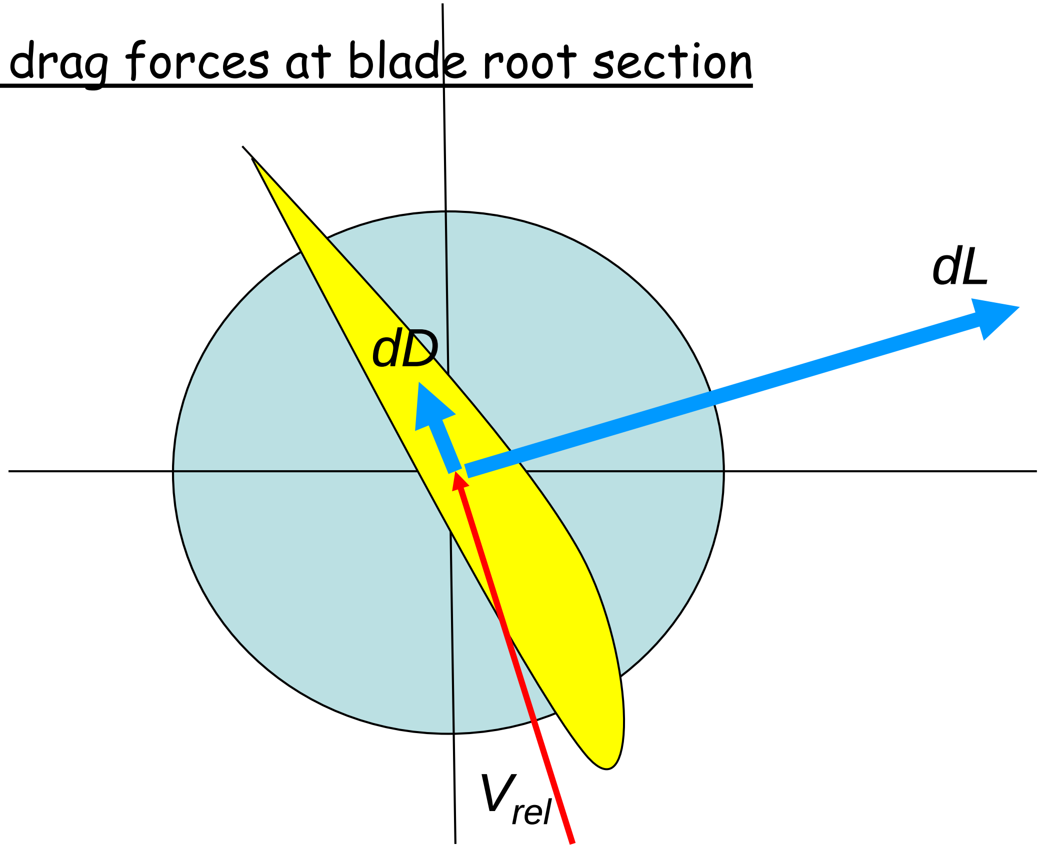
Lift and Draft forces

Lift and drag forces at blade root section



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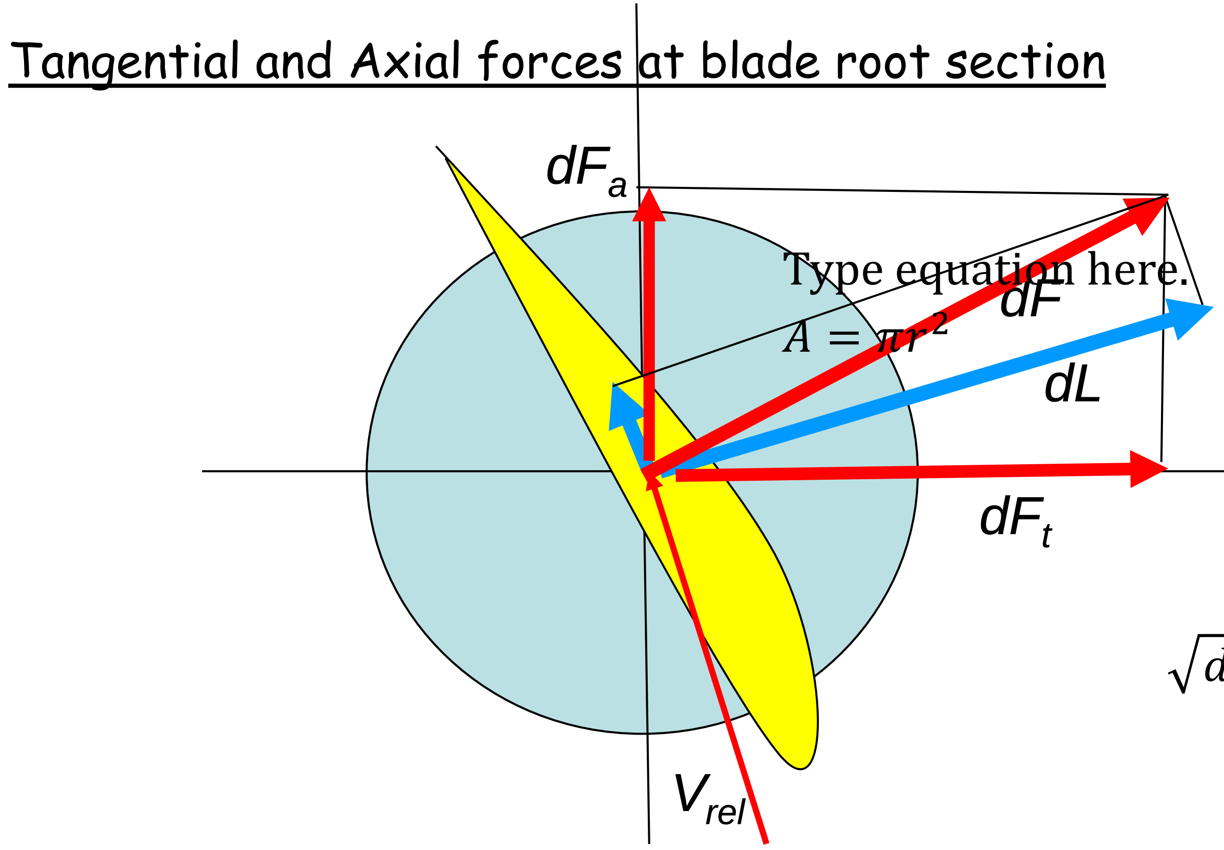
Lift and Draft forces



dF=$\sqrt{dL^2 + dD^2}$

dF= $\sqrt{dF_t^2 + dF^{tD}2}$

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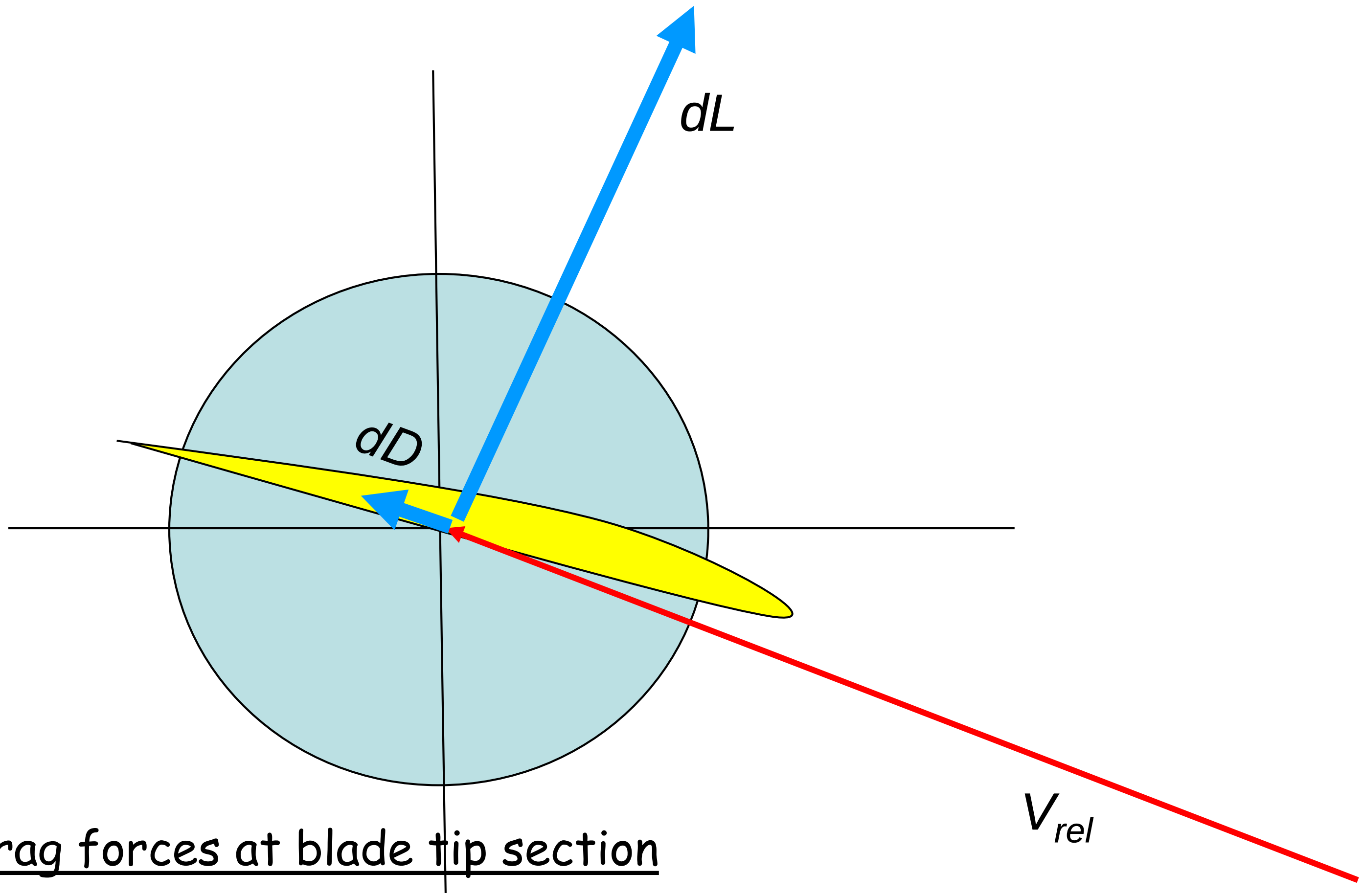
Lift and Draft forces



Lift and drag forces at blade tip section

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References

Books:

[1] Wind energy engineering. New York: McGraw-Hill, Jain, P. (2011).

[2] Fundamental of Aerodynamics, John D. Anderson, Jr., McGraw-Hill, 2001.

Web links:

[3] www.ewea.org European Wind Energy Association

[4] wwindea.org World Wind Energy Association

[5] www.awea.org American Wind Energy Association

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Thank You for Your Attention!

Contact: info@weset-project.eu

Fernando.Tadeo@uva.es

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Module 2.1

International standards for Classification, design and operation of wind turbines. Lesson 7

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Objectives

The purpose of this lesson is to present and to analyze the main standards for Wind Turbine Generators and Farms, focusing on IEC 61400 for wind turbine classification, design specifications and noise limitations.

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Learning Outcomes

This lesson will contribute to the students to:

O1. Understand the different specifications and standards that classify wind turbines

O2. Be familiar with the international entities and regulations that pertain to wind turbine systems

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Technical Contents

1. *Review of existing standards*
2. *IEC 61400: Wind Turbine Classification, Design specifications and noise requirements.*
3. *API RP 2A-WSD*
4. *ISO Standards*
5. *DNV-GL Standards*
6. *Wind Turbine Classification*
7. *Wind Turbine Design requirement*

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Review of existing standards

Introduction

A set of design requirements are needed to ensure that wind turbines are appropriately engineered against damage from hazards within the planned lifetime. These requirements concern most aspects of the turbine life from site conditions before construction, to turbine components being tested, assembled and operated.

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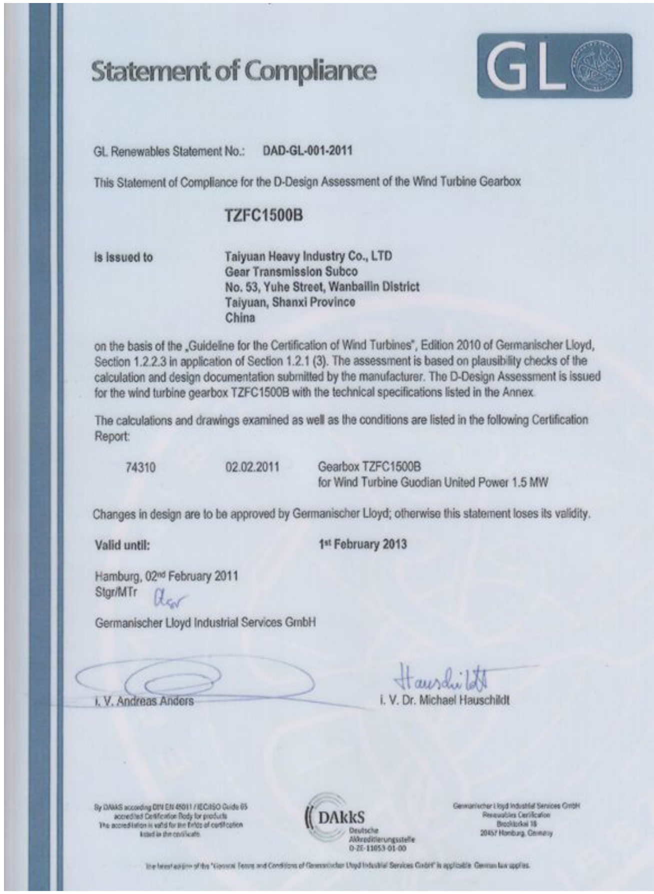
Review of existing standards

Example of Statement of Compliance Issued by GL


Statement of Compliance

GL Renewables Statement No.: DAD-GL-001-2011

This Statement of Compliance for the D-Design Assessment of the Wind Turbine Gearbox

TZFC1500B

is issued to Taiyuan Heavy Industry Co., LTD
Gear Transmission Subco
No. 53, Yuhe Street, Wanbailin District
Taiyuan, Shanxi Province
China

on the basis of the „Guideline for the Certification of Wind Turbines", Edition 2010 of Germanischer Lloyd, Section 1.2.2.3 in application of Section 1.2.1 (3). The assessment is based on plausibility checks of the calculation and design documentation submitted by the manufacturer. The D-Design Assessment is issued for the wind turbine gearbox TZFC1500B with the technical specifications listed in the Annex.

The calculations and drawings examined as well as the conditions are listed in the following Certification Report:

74310 02.02.2011 Gearbox TZFC1500B for Wind Turbine Guodian United Power 1.5 MW

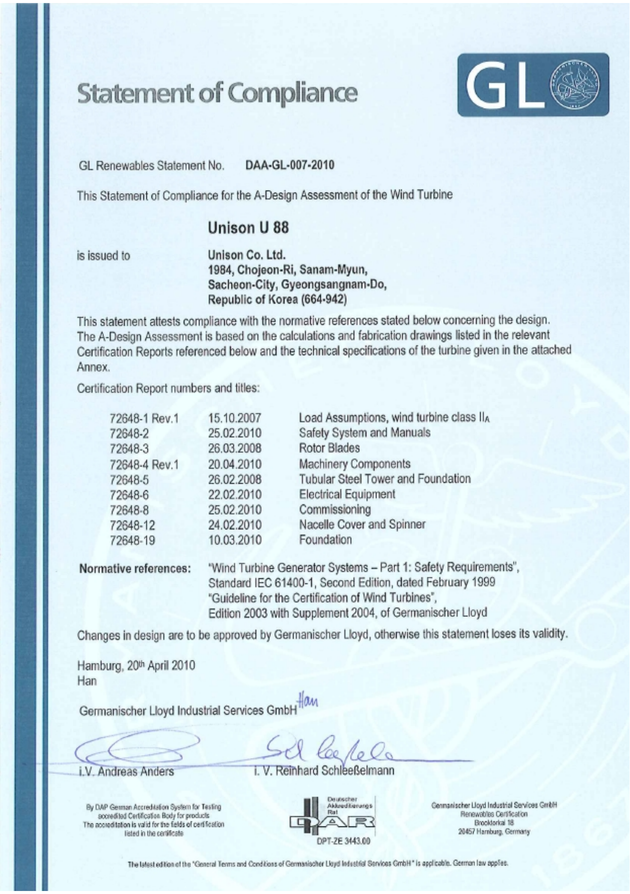
Changes in design are to be approved by Germanischer Lloyd; otherwise this statement loses its validity.

Valid until: 1st February 2013

Hamburg, 02nd February 2011
StgrMTr

Germanischer Lloyd Industrial Services GmbH

i. V. Andreas Anders i. V. Dr. Michael Hauschildt


Statement of Compliance

GL Renewables Statement No. DAA-GL-007-2010

This Statement of Compliance for the A-Design Assessment of the Wind Turbine

Unison U 88

is issued to Unison Co. Ltd.
1984, Chojeon-Ri, Sanam-Myun,
Sacheon-City, Gyeongsangnam-Do,
Republic of Korea (664-942)

This statement attests compliance with the normative references stated below concerning the design. The A-Design Assessment is based on the calculations and fabrication drawings listed in the relevant Certification Reports referenced below and the technical specifications of the turbine given in the attached Annex.

Certification Report numbers and titles:

72648-1 Rev.1	15.10.2007	Load Assumptions, wind turbine class II_A
72648-2	25.02.2010	Safety System and Manuals
72648-3	26.03.2008	Rotor Blades
72648-4 Rev.1	20.04.2010	Machinery Components
72648-5	26.02.2008	Tubular Steel Tower and Foundation
72648-6	22.02.2010	Electrical Equipment
72648-8	25.02.2010	Commissioning
72648-12	24.02.2010	Nacelle Cover and Spinner
72648-19	10.03.2010	Foundation

Normative references: "Wind Turbine Generator Systems – Part 1: Safety Requirements", Standard IEC 61400-1, Second Edition, dated February 1999
"Guideline for the Certification of Wind Turbines", Edition 2003 with Supplement 2004, of Germanischer Lloyd

Changes in design are to be approved by Germanischer Lloyd, otherwise this statement loses its validity.

Hamburg, 20th April 2010
Han

Germanischer Lloyd Industrial Services GmbH

i.V. Andreas Anders i. V. Reinhard Schleeßelmann

DPT-ZE 3443.00

http://www.unison.co.kr/2009/Eng2/Company/Cert/cert.asp

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Review of existing standards

Introduction (Cont.)

These requirements concern most aspects of the turbine life from site conditions before construction, to turbine components being tested, assembled and operated.

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Review of existing standards

Introduction (Cont.)

Some of these requirements provide technical conditions verifiable by an **independent, third party**, and as such are necessary in order to make business agreements so wind turbines can be financed and erected. Wind turbine standards address design requirements and considerations, as well as covering associated components, systems, and technologies that have an impact on the reliable functioning of wind turbines.


格式/Form: CI1101R05

中国船级社
CHINA CLASSIFICATION SOCIETY

设计评估证书
CERTIFICATE FOR DESIGN ASSESSMENT

编号 No. BJ11DA00001

兹证明根据本社《产品认证规则》的规定要求，按照下述认证模式，本社对下述产品的设计报告进行了评审，其结果符合下述标准、规范的要求。

This is to certify that, pursuant to CCS Regulations for Product Certification and the certification model below, design report of the following product has been reviewed and assessed in compliance with the requirements of the following standards and rules.

申请人/地址
APPLICANT/ADDRESS

太原重工股份有限公司
山西省太原市万柏林区玉河街 53 号
Taiyuan Heavy Industry Co., Ltd.
No.53, Yuhe Street, Wanbolin District, Taiyuan City, Shanxi Province, 030024, P.R.China

产品名称/型号/规格（产品技术规格见下页）
DESCRIPTION/MODEL/SPECIFICATIONS (SEE NEXT PAGE)

TZ2000/87 ⅡA 70mHH 双馈变速恒频风力发电机组
TZ2000/87 ⅡA 70mHH
Doubly-fed Variable Speed Constant Frequency Wind Turbine

产品标准及技术要求
PRODUCT STANDARDS AND TECHNICAL REQUIREMENTS

中国船级社《风力发电机组规范》（2008）/CCS Rules for Wind Turbine Generator Systems (2008)
JB/T 10300-2001《风力发电机组 设计要求》/Wind Turbine Generator Systems - Design Requirements
GB 18451.1-2001《风力发电机组 安全要求》/Wind turbine generator systems - Safety requirements

认证模式
CERTIFICATION MODE
设计评估
Design Assessment

发证地点：北 京/Issued in Beijing

本证书是在编号为 BJ10C3008 的设计评估报告的基础上颁发的。若上述型号产品的设计发生任何修改，应重新提交本社批准。

This certificate is issued based on Design Assessment Report No.BJ10C3008. If there are any design modifications after assessment, a new application should be resubmitted to CCS for review and approval.

发证日期：2011 年 01 月 10 日
Issued on January 10, 2011

签 发
Issued by Huang Shiyuan

No 08519566

第 1 页 共 5 页/Page 1 of 5

http://www.tyhi.com/R_D_and_QA/QA/Wind_Power_Equipment_Certificate.htm

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Review of existing standards

A set of **rules** or **principles** are needed as a basis for judgement on design, operation, maintenance of wind turbines. These are called **Standards**

Wind turbine standards address design requirements and considerations, as well as covering associated components, systems, and technologies that have an impact on the reliable functioning of wind turbines.

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Review of existing standards

Examples of such standards are issued by the following entities as related to wind turbines:

- IEC
- ISO
- API
- ABS
- GL-DNV
- IBS
- Others

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Review of existing standards

With the extensive **IEC 61400** series covering topics as far ranging as full-scale structural testing and acoustic noise measurement, as well as a 6-part information model for communications for monitoring and control of wind power plants, the standardization of wind turbines is then further complemented by efforts from **ISO**, **ANSI**, and other national standards bodies.


Intertek

Certificate

for European Product Safety

Intertek

Reference No. 1125698

Wind turbine

Type designation	WindEn 45
Certificate holder	WindEn Sweden AB Theres Svenssons Gata 10 417 55 Göteborg SWEDEN
The product complies with the standard(s)	IEC 61400-2: 2006 EN 61400-2: 2006
Date of expiry	28 October 2018

Additional information in Appendix.

Certification Body	Intertek Semko AB, Product Certification	Place	Kista - Stockholm
Signed	Pär Iggström	Date	28 October 2013

Page 1 of 3

This certificate is issued in accordance with the terms and conditions set out in the Appendix.

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IEC 61400: Wind Turbine Classification, Design specifications and noise requirements

The International Electrotechnical Commission (IEC) 61400 is a set of design requirements made to ensure that wind turbines are appropriately engineered against damage from hazards within the planned lifetime.


NORME INTERNATIONALE
INTERNATIONAL STANDARD

CEI
IEC
61400-2

Aérogénérateurs –

Partie 2:
Exigences en matière de conception des petits aérogénérateurs

Wind turbines –

Part 2:
Design requirements for small wind turbines

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IEC 61400: Wind Turbine Classification, Design specifications and noise requirements

IEC started standardizing international certification on the subject in 1995, and the first standard appeared in 2001.
The common set of standards sometimes replace the various national standards, forming a basis for ***global certification***

Type certification

IEC 61400
BUREAU VERITAS
Certification

Component certification

IEC 61400
BUREAU VERITAS
Certification

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IEC 61400: Wind Turbine Classification, Design specifications and noise requirements

IEC standards cover a wide range of wind turbine types:

- *Small wind turbine*

2.1 T1 v2

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IEC 61400: Wind Turbine Classification, Design specifications and noise requirements

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IEC 61400: Wind Turbine Classification, Design specifications and noise requirements

Photo taken from; https://www.pinterest.com/pin/830491987505941413/?lp=true

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IEC 61400: Wind Turbine Classification, Design specifications and noise requirements

Photo taken from https://www.greentechmedia.com/articles/read/norway-

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IEC 61400: Wind Turbine Classification, Design specifications and noise requirements

Samples of IEC Standards Publications

International Electrotechnical Commission (IEC)

- **IEC 61400-1**
General design requirements for wind turbines
- **IEC 61400-2**
Design requirements for small wind turbines
- **IEC 61400-3**
Design requirements for offshore wind turbines
- **IEC 61400-3-2**
Design requirements for floating offshore wind turbines

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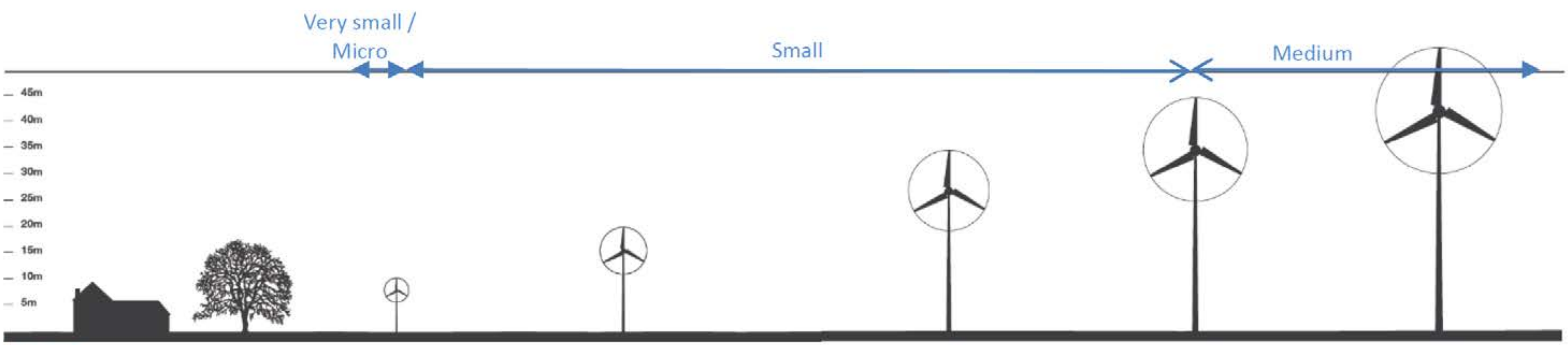
IEC 61400: Wind Turbine Classification, Design specifications and noise requirements

Small Wind Turbine



Size (metres)	2–18	12–25	20–50	35–55	45–65
Capacity (kW)	0–1.5	1.5–15	15–50	50–200	200–500
Typical on-site electricity use	Up to 100% used on-site	Up to 90% used on-site	Up to 80% used on-site	Up to 70% used on-site	Up to 70% used on-site
Typical annual energy production (kWh)	Up to 1000	Up to 60,000	Up to 250,000	Up to 700,000	Up to 2,400,000
Typically connected to:	House	House or farm	House or small business	Farm or large business	Community, farm or large business

Small wind turbines are generally single turbine installations principally owned by private individuals, agricultural farms or small enterprises for on-site consumption only exporting unused capacity to the grid.

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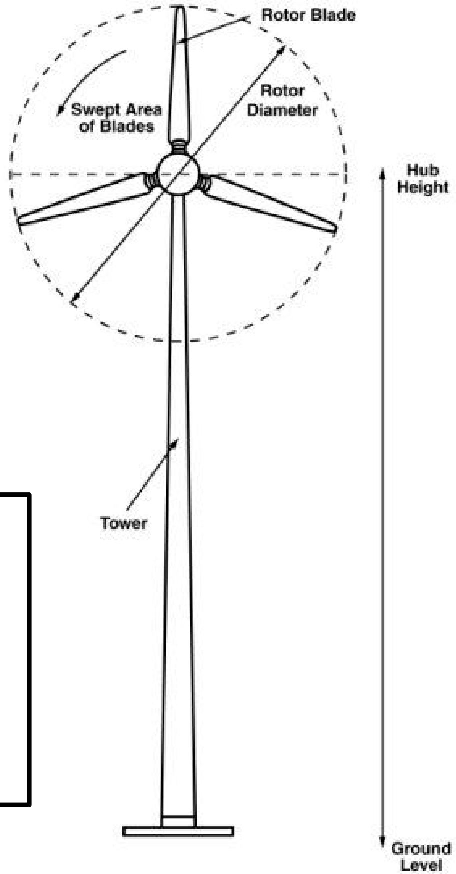
IEC 61400: Wind Turbine Classification, Design specifications and noise requirements

Small Wind Turbine

The IEC-61400-2:2006 Standard defines small wind turbines as wind turbines with a rotor swept area smaller than 200 m^2, generating at a voltage below 1000 Va.c. or 1500 Vd.c.



Example: Anything under, say, 10 meters rotor diameter (30 feet) is well within the "small wind" category. That works out to wind turbines with a rated power up to around 20 kW (at 11 m/s, or 25 mph).

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IEC 61400: Wind Turbine Classification, Design specifications and noise requirements

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Large Wind Turbine

At the other extreme, large wind farms owned by major utility companies may comprise many tens of turbines, of the order of 160m high, each generating some 5 - 6 MW and specifically installed to provide power to the grid

(turbines 220m high and with a capacity of 8MW are now available).

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IEC 61400: Wind Turbine Classification, Design specifications and noise requirements

More Samples of IEC Standards publications

- **IEC 61400-4:2012**
  Design requirements for wind turbine gearboxes
- **IEC 61400-11:2012**
  Acoustic noise measurement techniques
- **IEC 61400-12-1:2005**
  Power performance measurements of electricity producing wind turbines
- **IEC 61400-12-2:2013/COR1:2016**
  Power performance of electricity-producing wind turbines based on nacelle anemometry / Corrigendum 1

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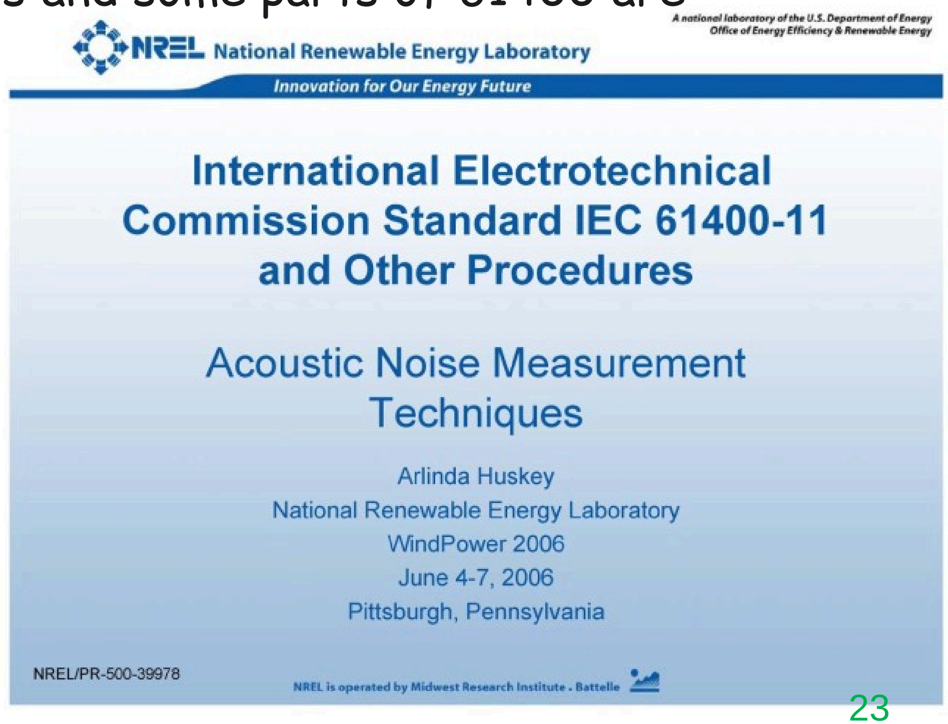
IEC 61400: Wind Turbine Classification, Design specifications and noise requirements

Standards Harmonization

Local standards in different countries are intended to be **compatible** with IEC standards and some parts of 61400 are required documentation.

- The U.S. **National Renewable Energy Laboratory** participates in IEC standards development work and tests equipment according to these standards



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API RP 2A-WSD

API RP 2A-WSD,
Recommended practice for planning, designing and constructing fixed offshore steel platforms - working stress design.

Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms—Working Stress Design

API RECOMMENDED PRACTICE 2A-WSD (RP 2A-WSD)
TWENTY-FIRST EDITION, DECEMBER 2000
ERRATA AND SUPPLEMENT 1, DECEMBER 2002
ERRATA AND SUPPLEMENT 2, SEPTEMBER 2005
ERRATA AND SUPPLEMENT 3, OCTOBER 2007

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ISO Standards

For U.S. **offshore turbines**, more standards are needed, and the most important are :

- ISO 19900, General requirements for offshore structures
- ISO 19902, Fixed steel offshore structures
- ISO 19903, Fixed concrete offshore structures
- ISO 19904-1, Floating offshore structures – mono-hulls, semisubmersibles and spars
- ISO 19904-2, Floating offshore structures - tension-leg platforms

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DNV-GL Standards

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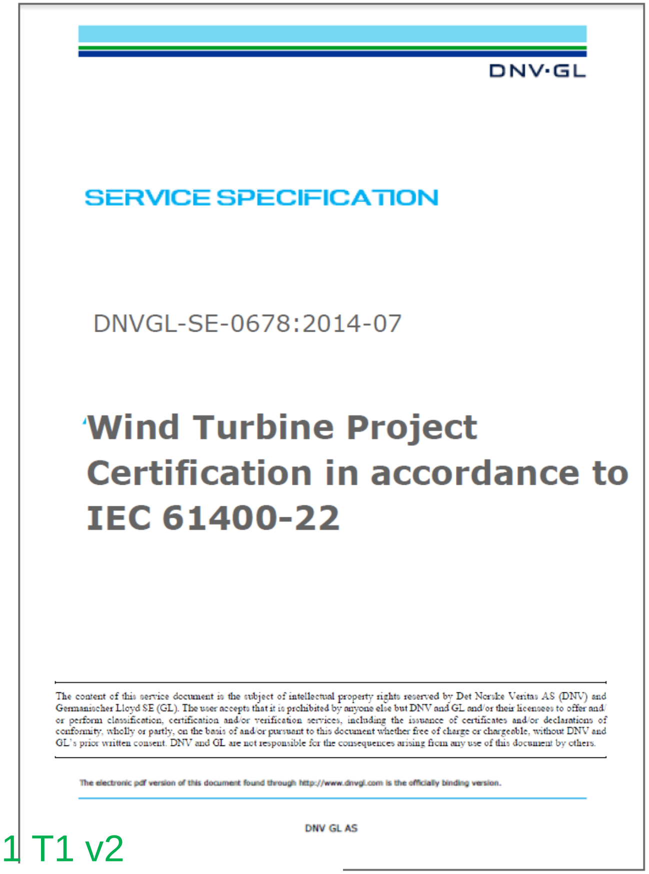


DNV·GL

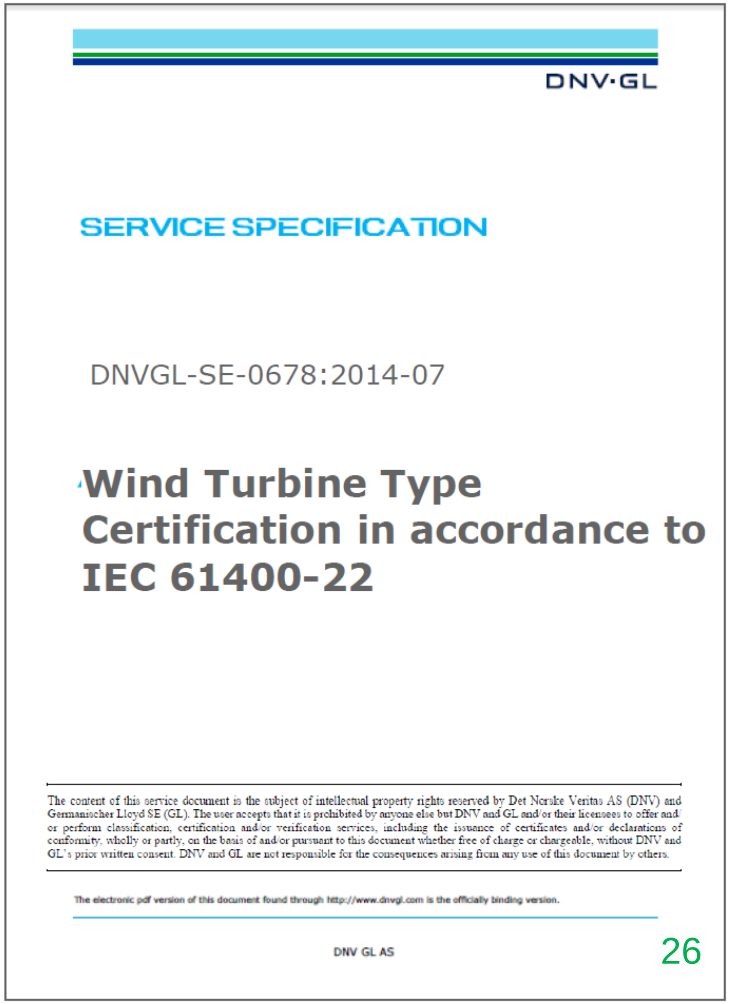
SERVICE SPECIFICATION

DNVGL-SE-0678:2014-07

Wind Turbine Project Certification in accordance to IEC 61400-22

The electronic pdf version of this document found through http://www.dnvgl.com is the officially binding version.

DNV GL AS



DNV·GL

SERVICE SPECIFICATION

DNVGL-SE-0678:2014-07

Wind Turbine Type Certification in accordance to IEC 61400-22

The electronic pdf version of this document found through http://www.dnvgl.com is the officially binding version.

DNV GL AS

Ref. DNVGL.com

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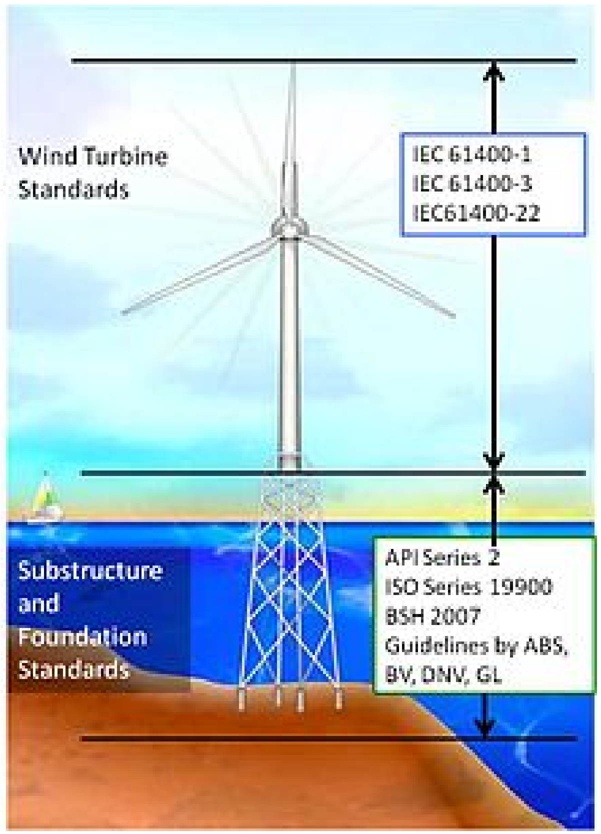
Wind Turbine Standards



IEC

energy API AMERICAN PETROLEUM INSTITUTE

DNV·GL

ISO

https://ipfs.io/ipfs/QmXoypizjW3WknFiJnKLwHCnL72vedxjQkDDP1mXWo6uco/I/m/US_certification_standards_for_offshore_wind_turbines.jpg

Wind Turbine Classification

Before deciding to build a wind turbine in a particular site, there are a few critical questions the developer needs to answer:

1. What is the average annual wind speed in this location?
2. What are the extreme gusts that could occur within a 50 year period?
3. How turbulent is the wind at the site?

These three dimensions — wind speed, extreme gusts, and turbulence — encompass the wind class of a wind turbine.

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Wind Turbine Classification

Wind Turbine Generator (WTG) classes

The International Electrotechnical Commission (IEC) sets international standards for the wind speeds each wind class must withstand, as seen in the table in the next slide

Turbine classes are determined by three parameters:

- the average wind speed,
- extreme 50-year gust, and
- turbulence

V_{avg}
Extreme Gust
Turbulence

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Wind Turbine Classification

Wind Turbine Classification

IEC Classification of Wind Turbines
Ref.: (IEC61400-1: 2005): Appendix II
Rayleigh distribution is assumed, i.e. k = 2.

Wind turbine class		I	II	III	S
V_{ave} (m/s)		10	8.5	7.5	User defined
V_{ref} (m/s)		50	42.5	37.5	
$V_{50,gust}$ (m/s)		70	59.5	52.5	
I_{ref}	A	0.16			
	B	0.14			
	C	0.12			

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Wind Turbine Classification

Where:

V_{ave}	annual mean wind speed at hub height;
V_{ref}	50-year extreme wind speed over 10 minutes;
V50,gust	50-year extreme gust over 3 seconds;
I_{ref}	mean turbulence intensity at 15 m/s.
A, B and C	categories of higher, medium and lower turbulence intensity characteristics respectively

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Wind Turbine Classification

Wind Class/Turbulence	Annual average wind speed at hub-height (m/s)	Extreme 50-year gust in meters/second (miles/hour)
Ia High wind - Higher Turbulence 18%	10.0	70 (156)
Ib High wind - Lower Turbulence 16%	10.0	70 (156)
IIa Medium wind - Higher Turbulence 18%	8.5	59.5 (133)
IIb Medium wind - Lower Turbulence 16%	8.5	59.5 (133)
IIIa Low wind - Higher Turbulence 18%	7.5	52.5 (117)
IIIb Low wind - Lower Turbulence 16%	7.5	52.5 (117)
IV	6.0	42.0 (94)

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Wind Turbine Classification

Wind Turbine classes impacts on blade design

- A Wind Class 3 turbine is designed for an easy life with average wind speeds up to 7.5 m/s, and these turbines typically have extra-large rotors to allow them to capture as much energy as possible from the lower wind speeds they are subjected to.
- Wind Class 2 turbines are for windier sites up to 8.5 m/s average, and are the most common class of wind turbines available.
- Wind Class 1 turbines are designed to cope with the tough operating conditions experienced at sites with average wind speeds above 8.5 m/s. Typically these turbines have smaller rotors (i.e. shorter blades) and are on shorter towers to minimize structural loads. They are also heavier-duty in design, which makes them more expensive.

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Wind Turbine Classification

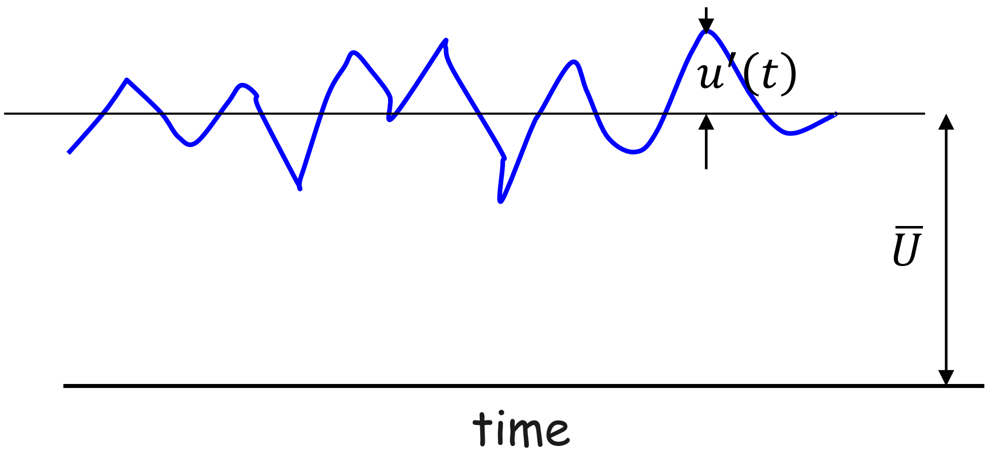
Turbulence intensity

Turbulence intensity quantifies how much the wind varies typically within 10 minutes.

$$U(t) = \overline{U} + u'(t)$$

$$rms = \sqrt{\sum (u')^2}$$

$$TI = \frac{rms}{\overline{U}}$$



Because the **fatigue loads** of a number of major components in a wind turbine are mainly caused by turbulence, the knowledge of how turbulent a site is of crucial importance.

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Wind Turbine Classification

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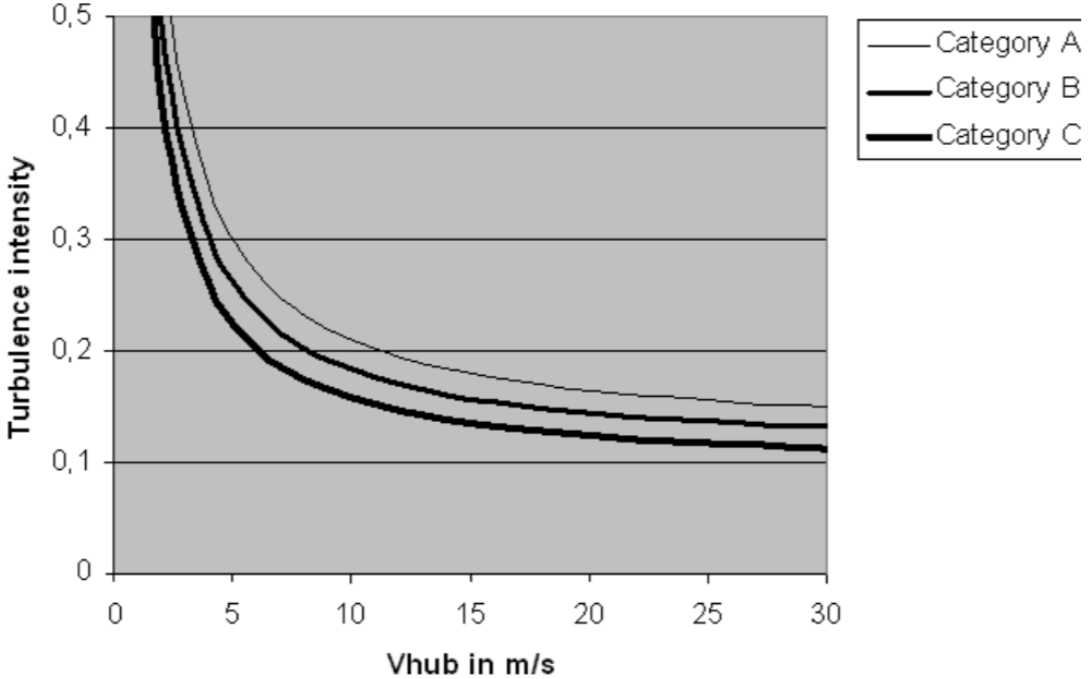

Categories of higher, medium and lower turbulence intensity characteristics respectively

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Wind Turbine Classification

Extreme wind speeds

The extreme wind speeds are based on the 3 second average wind speed. Turbulence is measured at 15 m/s wind speed. This is the definition in IEC 61400-1 edition 2.

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Wind Turbine Classification

Wind Class/Turbulence	Annual average wind speed at hub-height (m/s)	Extreme 50-year gust in meters/second (miles/hour)
Ia High wind - Higher Turbulence 18%	10.0	70 (156)
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Wind Turbine Design Requirement

Design requirements

IEC 61400-1 Ed. 3.0 b:2005

Wind turbines - Part 1: Design requirements

"Specifies essential design requirements to ensure the engineering integrity of wind turbines. Provides an appropriate level of protection against damage from all hazards during the planned lifetime. Is concerned with all subsystems of wind turbines such as control and protection mechanisms, internal electrical systems, mechanical systems and support structures. Applies to wind turbines of all sizes

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Wind Turbine Design Requirement

Small wind turbines

IEC 61400-2 Ed. 3.0 b:2013

Wind turbines Part 2 Small wind turbines

deals with safety philosophy quality assurance and engineering integrity and specifies requirements for the safety of small wind turbines SWTs including design installation maintenance and operation under specified external conditions. It provides the appropriate level of protection against damage from hazards from these systems during their planned lifetime. While this standard is similar to IEC 61400 1 it does **simplify** and **make significant changes** in order to be applicable to small wind turbines

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Wind Turbine Design Requirement

Design requirements for offshore wind turbines

IEC 61400-3 Ed. 1.0 b:2009

Wind turbines - Part 3: Design requirements for **offshore wind turbines**

"specifies **additional requirements** for assessment of the external conditions at an offshore wind turbine site and specifies essential design requirements to ensure the engineering integrity of offshore wind turbines. Its purpose is to provide an appropriate level of protection against damage from all hazards during the planned lifetime. Itis also concerned with subsystems such as control and protection mechanisms, internal electrical systems and mechanical systems. It should be used together with the appropriate IEC and ISO standards, in particular with IEC 61400-1."

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Wind Turbine Design Requirement

Design requirements for wind turbine gearboxes

IEC 61400-4 Ed. 1.0 en:2012 (Cont.)

Wind turbines - Part 4: Design requirements for wind turbine gearboxes

- is applicable to enclosed speed increasing gearboxes for horizontal axis wind turbine drivetrains with a power rating in excess of 500 kW.
- This standard applies to wind turbines installed onshore or offshore. It provides guidance on the analysis of the wind turbine loads in relation to the design of the gear and gearbox elements.
- The gearing elements covered by this standard include such gears as spur, helical or double helical and their combinations in parallel and epicyclic arrangements in the main power path.

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Wind Turbine Design Requirement

Design requirements for wind turbine gearboxes

IEC 61400-4 Ed. 1.0 en:2012

Wind turbines - Part 4: Design requirements for wind turbine gearboxes (Cont.)

- The standard is based on gearbox designs using rolling element bearings.
- Also included is guidance on the engineering of shafts, shaft hub interfaces, bearings and the gear case structure in the development of a fully integrated design that meets the rigorous of the operating conditions.
- Lubrication of the transmission is covered along with prototype and production testing. Finally, guidance is provided on the operation and maintenance of the gearbox.

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Wind Turbine Design Requirement

Acoustic noise measurement techniques

IEC 61400-11 Ed. 3.0 en:2012

Wind turbines - Part 11: Acoustic noise measurement techniques

presents measurement procedures that enable noise emissions of a wind turbine to be characterized. This involves using measurement methods appropriate to noise emission assessment at locations close to the machine, in order to avoid errors due to sound propagation, but far away enough to allow for the finite source size. They are intended to facilitate characterization of wind turbine noise with respect to a range of wind speeds and directions.

Standardization of measurement procedures will also facilitate comparisons between different wind turbines. This new edition constitutes a technical revision, introducing new principles for data reduction procedures

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Wind Turbine Design Requirement

Measurement of mechanical loads

IEC 61400-13 Ed. 1.0 b:2015

Wind turbines - Part 13: Measurement of mechanical loads

IEC 61400-13:2015(B) describes the measurement of fundamental structural loads on wind turbines for the purpose of the load simulation model validation. The standard prescribes the requirements and recommendations for site selection, signal selection, data acquisition, calibration, data verification, measurement load cases, capture matrix, post-processing, uncertainty determination and reporting. Informative annexes are also provided to improve understanding of testing methods. This standard replaces IEC TS 61400-13 published in 2001; it constitutes a technical revision and transition from technical specification to International Standard.

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References

[1] API Recommended Practice 2A-WSD Planning, Designing, and Constructing Fixed Offshore Platforms—Working Stress Design TWENTY-SECOND EDITION | NOVEMBER 2014 | 310 PAGES PRODUCT NO. G2AWSD22

[2] British Standards Wind turbines, Part 3: Design requirements for offshore wind turbines BS EN 61400-3:2009 Licensed

[3] INTERNATIONAL STANDARD IEC 61400-1 Third edition 2005-08 Wind turbines – Part 1: Design requirements

[4]http://www.cesos.ntnu.no/attachments/083_Kimon_Argyriadis_certification_&_standards.pdf

[5] https://en.wikipedia.org/wiki/IEC_61400

[6] www.glgroup.com, "Certification and Standards for Wind Turbines September 2013, Kimon Argyriadis

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Thank You for Your Attention!

Contact: info@weset-project.eu

Fernando.Tadeo@uva.es

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Introduction to Wind Energy

Module 2.1

Maximum Power Point Tracking
Lesson 9

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Objective

The purpose of this lesson is to present the importance of Maximum Power Point Tracking in grid-connected systems, and analyze some frequent techniques.

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Learning Outcomes

This lesson will contribute to the students to:

O2. Understand the different components and types of wind turbines and as their work;

O4. Be able to select wind turbines and to design (at preliminary project level) a wind farm in a South-Mediterranean location.

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Technical Contents

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AGENDA

Wind Energy Conversion systems

1.wind turbine mathematical model

2.wind power curves

AGENDA

Wind Energy Conversion systems

1.wind turbine mathematical model

2.wind power curves

WIND TURBINE MATHEMATICAL MODEL

Under constant acceleration a, the kinetic energy E of an object having mass m and velocity v is equal to the work done W in displacing that object from rest to a distance s under a force F, i.e. $E = W = Fs$. According to Newton's second law of motion

$$F = ma \tag{1}$$

thus, the kinetic energy becomes

$$E = mas \tag{2}$$

From kinematics of solid motion, $v^2 = u^2 + 2as$ where u is the initial velocity of the object. This implies that $a = \frac{v^2 - u^2}{2s}$. Assuming the initial velocity of the object is zero, we have that $a = \frac{v^2}{2s}$. Hence from equation (2) we have that

$$E = \frac{1}{2}mv^2 \tag{3}$$

WIND TURBINE MATHEMATICAL MODEL

This kinetic energy formulation is based on the fact that the mass of the solid is a constant. However, if we consider wind (air in motion) as a fluid, both density and velocity can change and hence no constant mass. For this reason Reccab et. al[5] formulate the kinetic energy law with a factor of $\frac{2}{3}$ instead of $\frac{1}{2}$. In this paper we shall assume that the density of air does not vary considerably even with variation in altitude or temperature and use the kinetic energy law in the form of equation (3). Hence the kinetic energy(in joules) in air of mass m moving with velocity v_w(wind) can be calculated from equation (3) above. The power P in the wind is given by the rate of change of kinetic energy, i.e.

$$P = \frac{dE}{dt} = \frac{1}{2}\frac{dm}{dt}v_w^2 \qquad (4)$$

WIND TURBINE MATHEMATICAL MODEL

But mass flow rate $\frac{dm}{dt}$ is given by $\frac{dm}{dt} = \rho A v_w$ where A is the area through which the wind in this case is flowing and ρ is the density of air. With this expression, equation (4) becomes

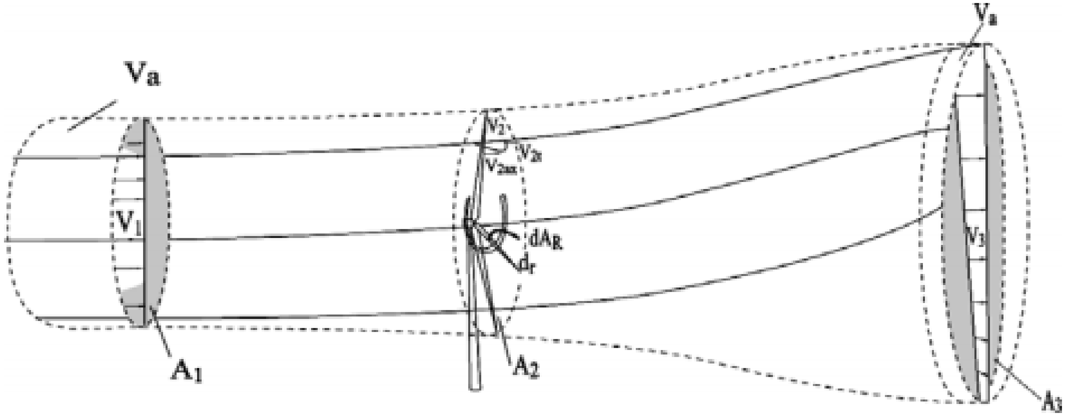
$$P = \frac{1}{2}\rho A v_w^3 \tag{5}$$

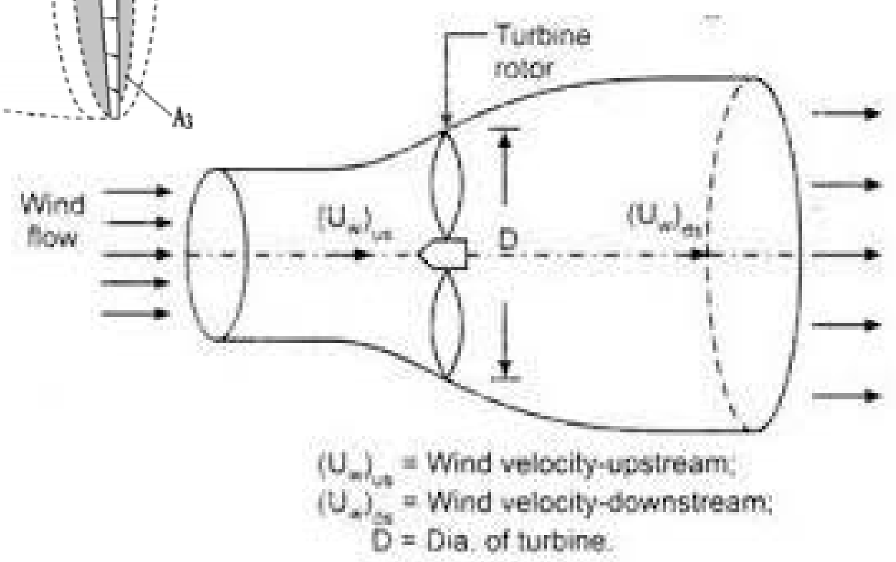
The actual mechanical power P_w extracted by the rotor blades in watts is the difference between the upstream and the downstream wind powers[1], i.e.

$$P_w = \frac{1}{2}\rho A v_w (v_u^2 - v_d^2) \tag{6}$$

REPORT

WIND TURBINE MATHEMATICAL MODEL





WIND TURBINE MATHEMATICAL MODEL

where v_u is the upstream wind velocity at the entrance of the rotor blades in m/s and v_d is the downstream wind velocity at the exit of the rotor blades in m/s. We shall see later that these two velocities give rise to the blade tip speed ratio. Now from the mass flow rate, we may write

$$\rho A v_w = \frac{\rho A(v_u + v_d)}{2} \tag{7}$$

v_w being the average of the velocities at the entry and exit of rotor blades of turbine. With this expression, equation(6) becomes $P_w = \frac{1}{2}\rho A(v_u^2 - v_d^2)\frac{(v_u+v_d)}{2}$ which may be simplified as follows:

$$P_w = \frac{1}{2}\left[\rho A\left\{\frac{v_u}{2}(v_u^2 - v_d^2) + \frac{v_d}{2}(v_u^2 - v_d^2)\right\}\right]$$

$$= \frac{1}{2}\left[\rho A\left\{\frac{v_u^3}{2} - \frac{v_u v_d^2}{2} + \frac{v_d v_u^2}{2} - \frac{v_d^3}{2}\right\}\right]$$

$$= \frac{1}{2}\left[\rho A v_u^3\left\{\frac{1 - (\frac{v_d}{v_u})^2 + (\frac{v_d}{v_u}) - (\frac{v_d}{v_u})^3}{2}\right\}\right]$$

WIND TURBINE MATHEMATICAL MODEL

$$P_w = \frac{1}{2}\left[\rho A\left\{\frac{v_u}{2}(v_u^2 - v_d^2) + \frac{v_d}{2}(v_u^2 - v_d^2)\right\}\right]$$

$$= \frac{1}{2}\left[\rho A\left\{\frac{v_u^3}{2} - \frac{v_u v_d^2}{2} + \frac{v_d v_u^2}{2} - \frac{v_d^3}{2}\right\}\right]$$

$$= \frac{1}{2}\left[\rho A v_u^3\left\{\frac{1 - (\frac{v_d}{v_u})^2 + (\frac{v_d}{v_u}) - (\frac{v_d}{v_u})^3}{2}\right\}\right]$$

or

$$P_w = \frac{1}{2}\rho A V_u^3 C_p \qquad (8)$$

where $C_p = \frac{1-(\frac{v_d}{v_u})^2+(\frac{v_d}{v_u})-(\frac{v_d}{v_u})^3}{2}$ or

$$C_p = \frac{(1 + \frac{v_d}{v_u})(1 - (\frac{v_d}{v_u})^2)}{2} \qquad (9)$$

WIND TURBINE MATHEMATICAL MODEL

$$C_p = \frac{(1+\frac{v_d}{v_u})(1-(\frac{v_d}{v_u})^2)}{2} \quad (9)$$

The expression for C_p in equation (9) is the fraction of upstream wind power captured by the rotor blades. C_p is often called the Betz limit after the Germany physicist Albert Betz who worked it out in 1919. Other names for this quantity are the power coefficient of the rotor or rotor efficiency. The power coefficient is not a static value. It varies with tip speed ratio of the wind turbine. Let λ represent the ratio of wind speed v_d downstream to wind speed v_u upstream of the turbine, i.e.

$$\lambda = \frac{v_d}{v_u} \quad (10)$$

or

$$\lambda = \frac{\text{blade tip speed}}{\text{wind speed}} \quad (11)$$

WIND TURBINE MATHEMATICAL MODEL

λ is called the tip speed ratio of the wind turbine. The blade tip speed in metres per second can be calculated from the rotational speed of the turbine and the length of the blades used in the turbine, i.e.

$$\text{blade tip speed} = \frac{\text{angular speed of turbine}(\omega) \times R}{\text{wind speed}} \tag{12}$$

where R is the radius of the turbine and ω is measured in radian per second. Substitution of equation (10) into equation (9) leads to

$$C_p = \frac{(1+\lambda)(1-\lambda^2)}{2} \tag{13}$$

WIND TURBINE MATHEMATICAL MODEL

$$C_p = \frac{(1+\lambda)(1-\lambda^2)}{2} \qquad (13)$$

Differentiate C_p with respect to λ and equate to zero to find value of λ that makes C_p a maximum, i.e. $\frac{dC_p}{d\lambda} = \frac{(1+\lambda).(-2\lambda)+(1-\lambda^2).1}{2} = 0$ yielding $\lambda = -1$ or $\lambda = \frac{1}{3}$. Now $\lambda = \frac{1}{3}$ makes the value of C_p a maximum. This maximum value is $\frac{16}{27}$. Thus the Betz limit says that no wind turbine can convert more than $\frac{16}{27}$ (59.3%) of the kinetic energy of the wind into mechanical energy turning a rotor, i.e $C_{pmax} = 0.59$. Wind turbines cannot operate at this maximum limit though. The real world is well below the Betz limit with values of $0.35 - 0.45$ common even in best designed wind turbines.

WIND TURBINE MATHEMATICAL MODEL

Tip-Speed Ratio

Tip-speed ratio is the ratio of the speed of the rotating blade tip to the speed of the relative wind.

$$TSR = \frac{\omega r}{v}$$

Where,

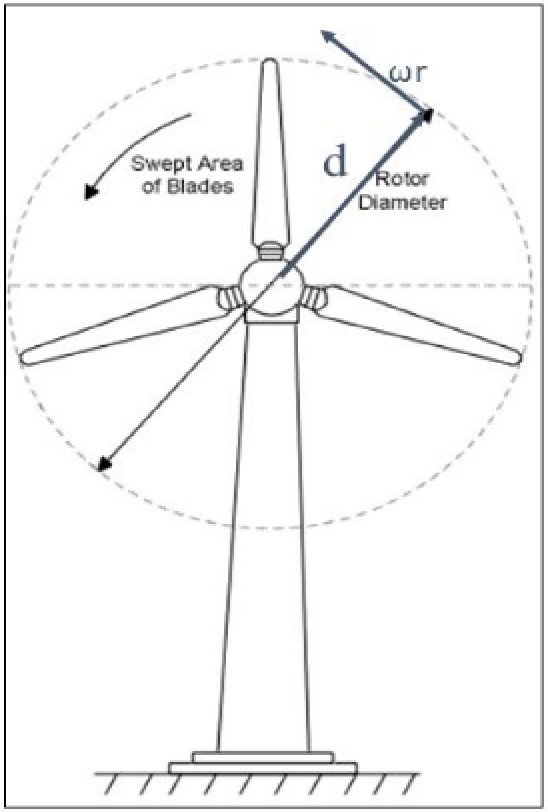
ω = rotational speed in radians /sec

π radians = 180°

2π radians = 360°

r = rotor radius

v = speed of relative wind



WIND TURBINE MATHEMATICAL MODEL

If the rotor of a wind turbine turns too slowly most of the wind will pass through the openings between blades with little power extraction. If on the other hand the rotor turns too fast, the rotating blades act as a solid wall obstructing the wind flow again reducing the power extraction. The turbines must be designed to operate at their optimal wind tip speed ratio λ in order to extract as much power as possible from the wind stream. Theoretically the higher the λ the better in terms of efficient operation of the generator. There are disadvantages however. High λ causes erosion of leading edges of the blades due to impact of dust or sand particles found in the air. This would require use of special erosion resistant coating material that may increase the cost of energy. Higher λ also leads to noise generation, vibration, reduced rotor efficiency due to drag and tip losses and excessive rotor speeds can lead to turbine failure.

WIND TURBINE MATHEMATICAL MODEL

$$P_w = \frac{1}{2}\rho A V_u^3 C_p \qquad (8)$$

Equation (8) relates the parameters that are required in power production by a wind turbine. The power coefficient C_p is the most important parameter in the case of power regulation[4]. It is a non-linear function whose value is unique to each turbine type and is a function of wind speed that the turbine is operating in. Each turbine manufacturer provides look up tables for C_p for operation purposes. Other than look up tables from turbine manufactures, models for power coefficient have been developed. For example [3] models C_p as a function of the tip speed ratio and the blade pitch angle θ in degrees as

$$C_p(\lambda, \theta) = C_1(C_2\frac{1}{\beta} - C_3\beta\theta - C_4\theta^x - C_5)e^{-C_6\frac{1}{\beta}} \qquad (16)$$

where the values of the coefficients $C_1 - C_6$ and x depend on turbine type. θ is defined as the angle between the plane of rotation and the blade cross section chord.

WIND TURBINE MATHEMATICAL MODEL

For a particular turbine type $C_1 = 0.5, C_2 = 116, C_3 = 0.4, C_4 = 0, C_5 = 5, C_6 = 21$ and β is defined by

$$\frac{1}{\beta} = \frac{1}{\lambda + 0.08\theta} - \frac{0.035}{1 + \theta^3} \qquad (17)$$

Anderson and Bose [3] suggested the following empirical relation for C_p

$$C_p = \frac{1}{2}(\lambda - 0.022\theta^2 - 5.6)e^{-0.17\lambda} \qquad (18)$$

where θ is the pitch angle of the blade in degrees, λ is the tip speed ratio of the turbine defined by $\lambda = \frac{v_w(mph)}{\omega_b(rads^{-1})}$ where ω_b is the turbine angular speed.

AGENDA

Wind Energy Conversion systems

1.wind turbine mathematical model

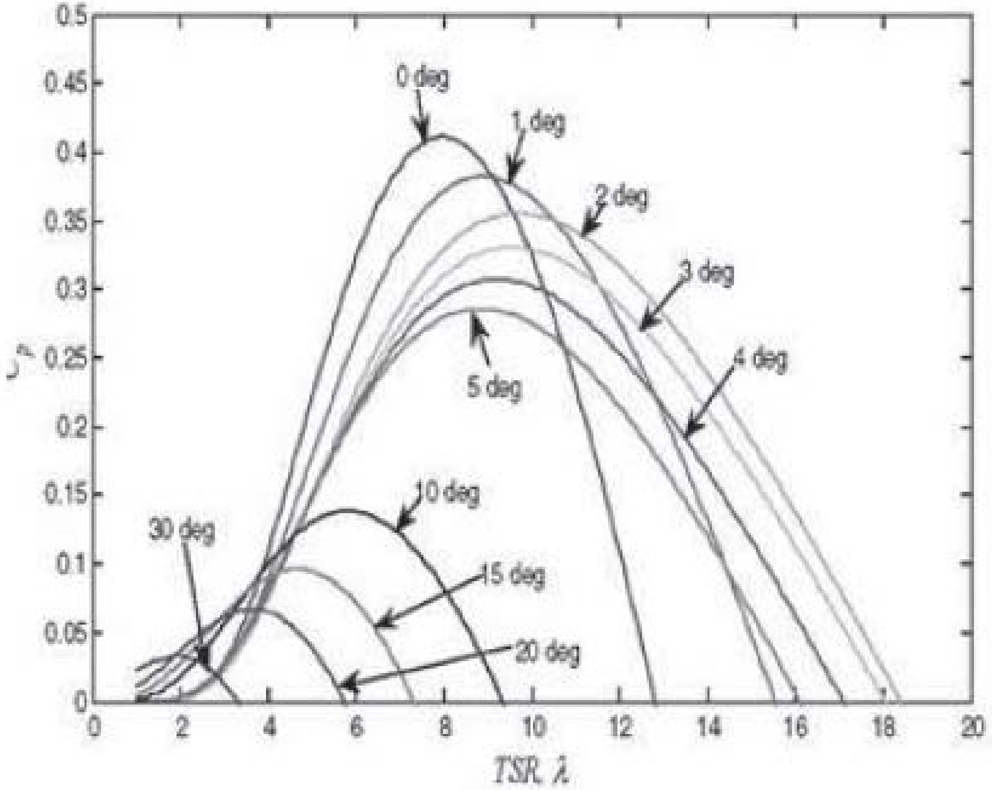
2.wind power curves

WIND TURBINE POWER CURVES

The power output of a turbine as we have mentioned is determined by the area of the rotor blades, wind speed and the power coefficient. The output power of the turbine can be varied by changing the area and flow conditions at the rotor system and this forms the basis of the control system. C_p is achieved at a particular λ which is specific to the design of the turbine.

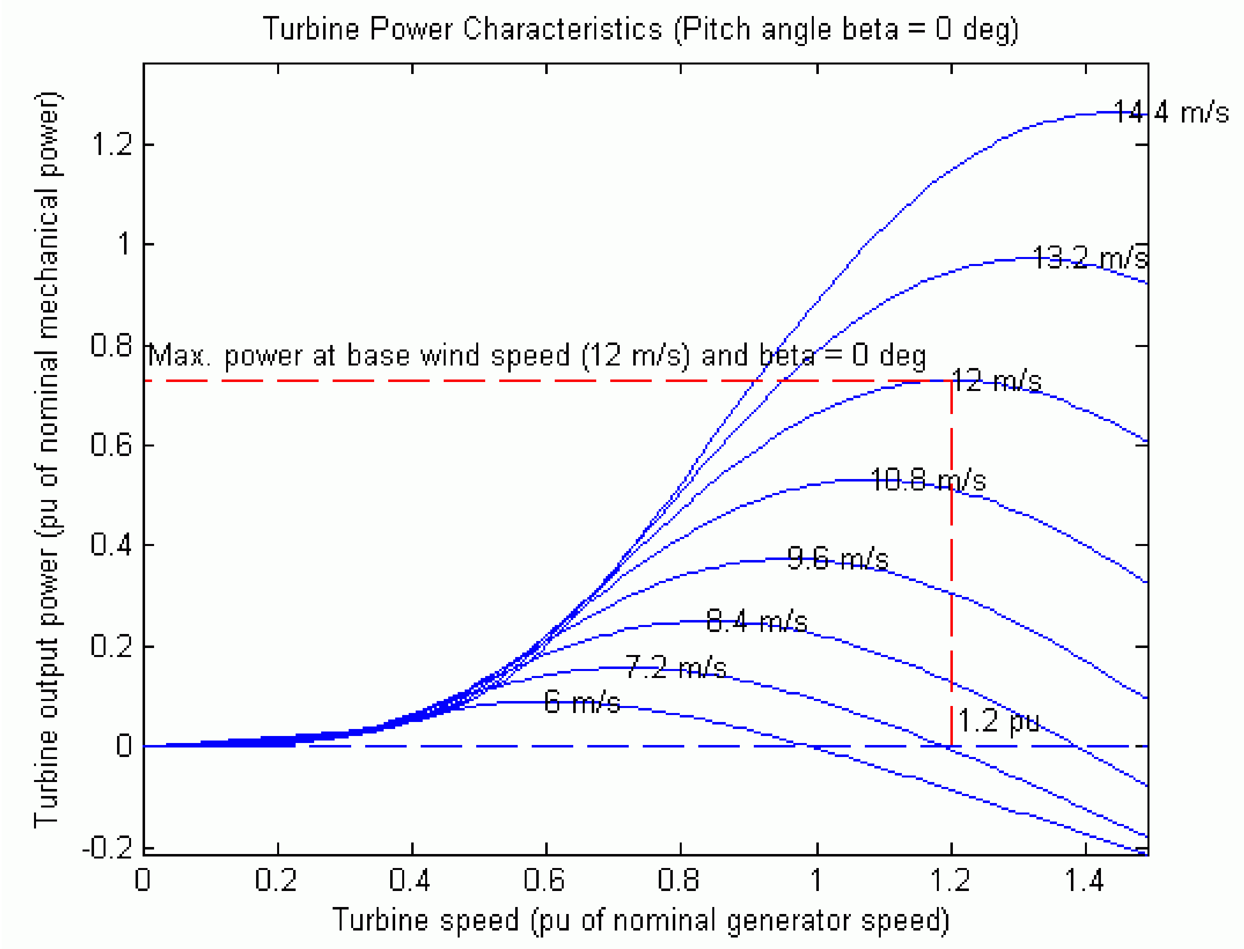
Hence the model turbine consists of equations (5), power in the wind, equation (8), power captured by the turbine, equation(10), he tip speed ratio of the turbine and the power coefficient equation (16). Control of out put of wind energy lies in a number of parameters. The rotor area and flow conditions at the rotor system(v_w, ρ, C_p), the rotor torque and pitch angle control. Fixed speed stall-regulated turbines have no options for control input. However, variable speed wind turbines use generator torque to control and optimize power output.

WIND TURBINE POWER CURVES



. **Cp – λ characteristics of the WECS at different pitch angles (θ)**

WIND TURBINE POWER CURVES



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Recommended literature

Books:

1. Wind energy engineering. New York: McGraw-Hill, Jain, P. (2011).
2. Understanding wind power technology: Theory, Deployment and Optimisation. John Wiley & Sons. Schaffarczyk, A. (Ed.). (2014).
3. Renewable Energy Systems, the choice and modelling of 100 % renewable solutions", Henrik Lund , Elsevier, 2010.
4. Alternative Energy Systems, B. K. Hodge, John Wiley & Sons, 2009.
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2) Leung, D. Y., & Yang, Y. (2012). Wind energy development and its environmental impact: a review. Renewable and sustainable energy reviews, 16(1), 1031-1039.

Web links:

[1] www.ewea.org European Wind Energy Association
[2] wwindea.org World Wind Energy Association
[3] www.awea.org American Wind Energy Association

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Introduction to Wind Energy

Module 2.1

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Introduction to Wind Energy

Module 2.1

Maximum Power Point Tracking
Lesson 9

Co-funded by the
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Objective

The purpose of this lesson is to present the importance of Maximum Power Point Tracking in grid-connected systems, and analyze some frequent techniques.

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Learning Outcomes

This lesson will contribute to the students to:

O2. Understand the different components and types of wind turbines and as their work;

O4. Be able to select wind turbines and to design (at preliminary project level) a wind farm in a South-Mediterranean location.

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Technical Contents

1. The importance of Maximum Power Point Tracking (MPPT)

2. MPPT of wind energy:

2.1 Tip speed ratio technique

2.2 Power signal feedback technique

2.3 Hill climbing technique

2.4 Other techniques

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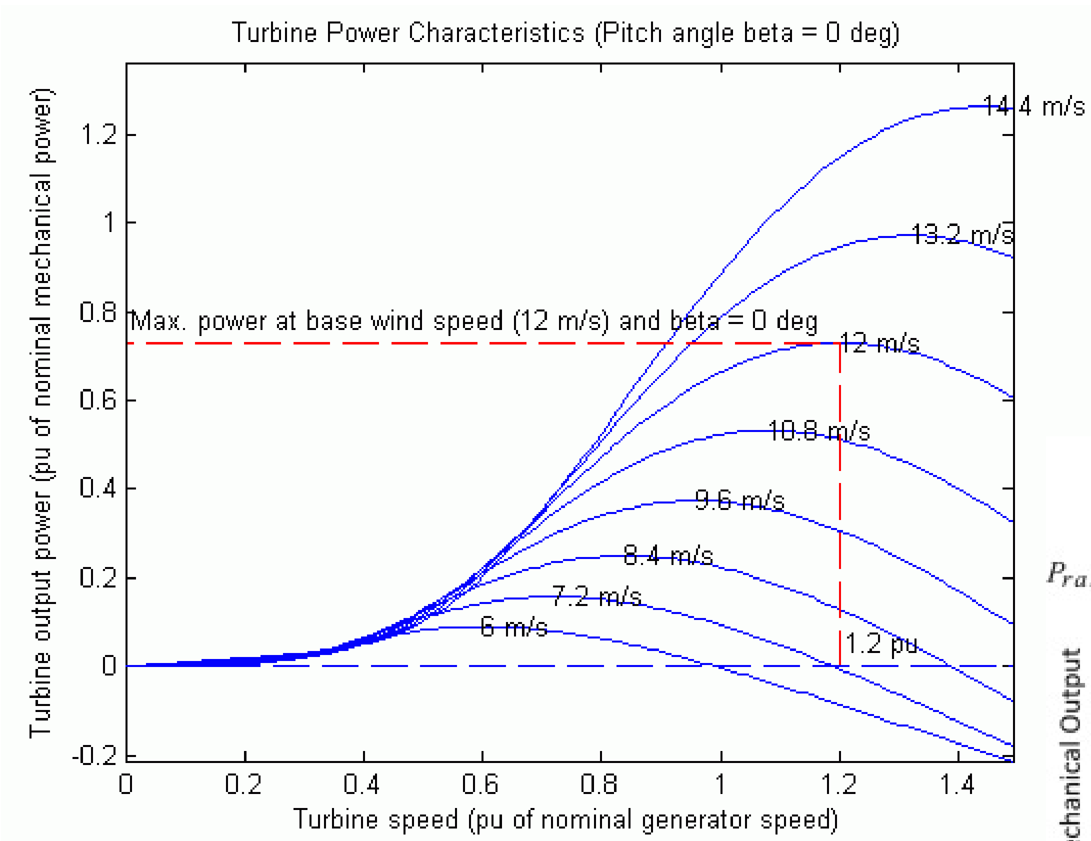
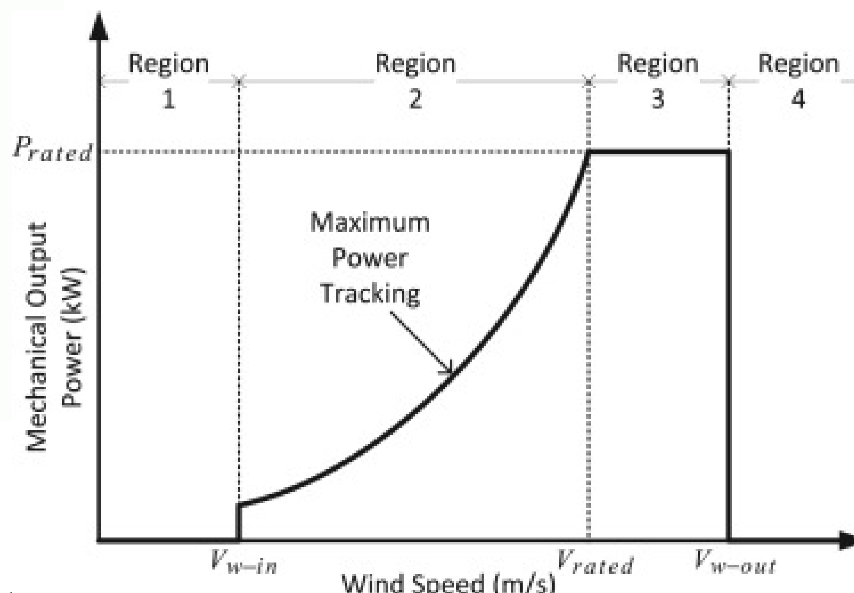
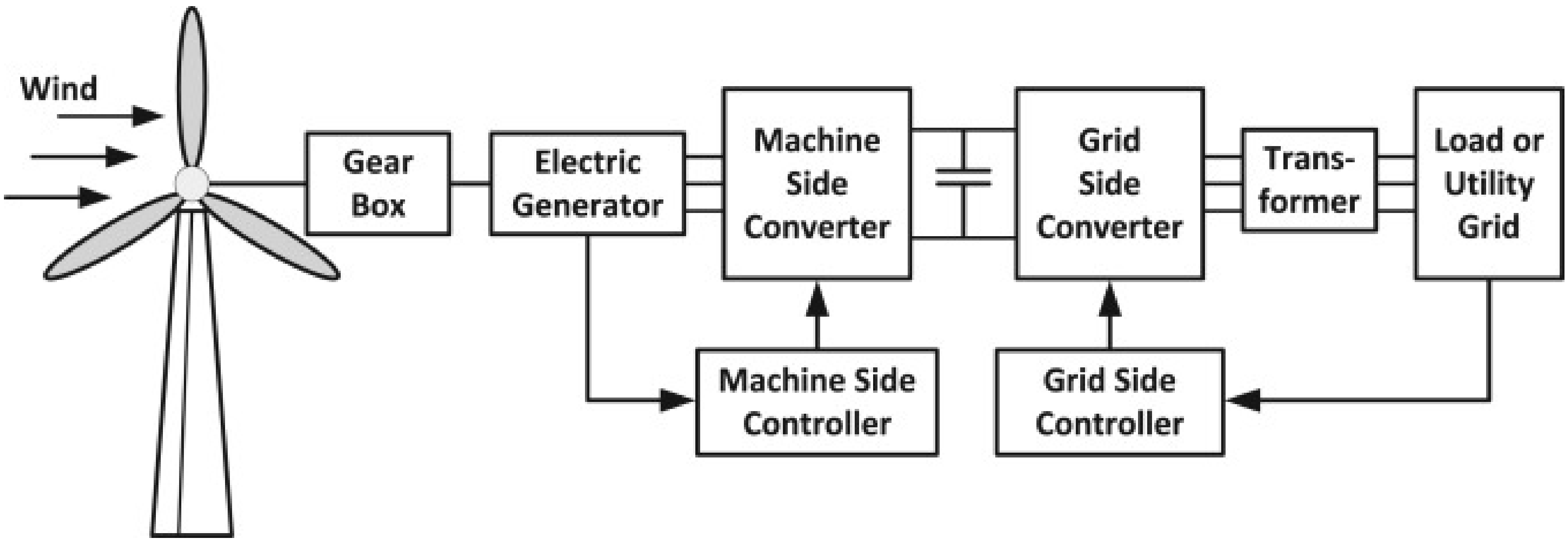
Why MPPT is mandatory





Why MPPT is mandatory



AGENDA

Wind Energy Conversion systems

1.why MPPT is mandatory

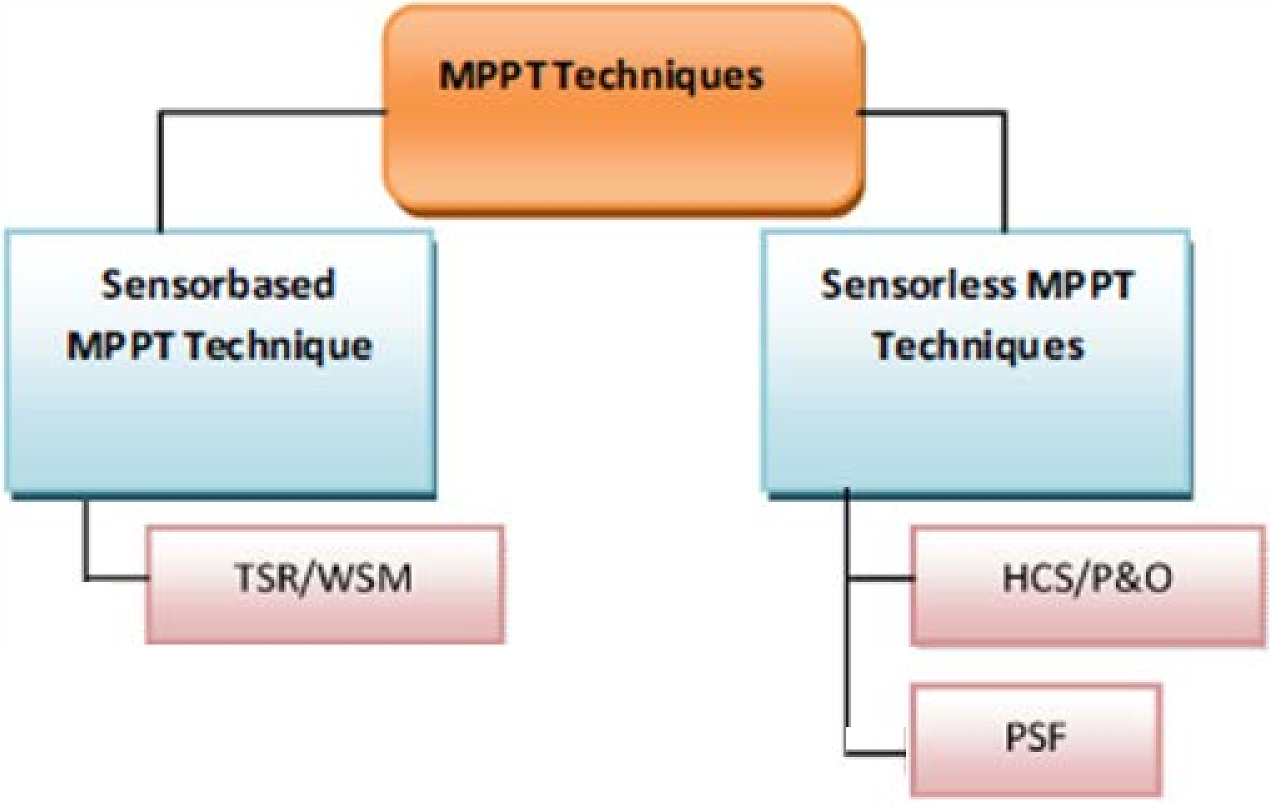
2.wind energy MPPT techniques

2.1 Tip speed ratio technique

2.2 Power signal feedback technique

2.3 Hill climbing technique

Wind Energy MPPT techniques



AGENDA

Wind Energy Conversion systems

1.why MPPT is mandatory

2.wind energy MPPT techniques

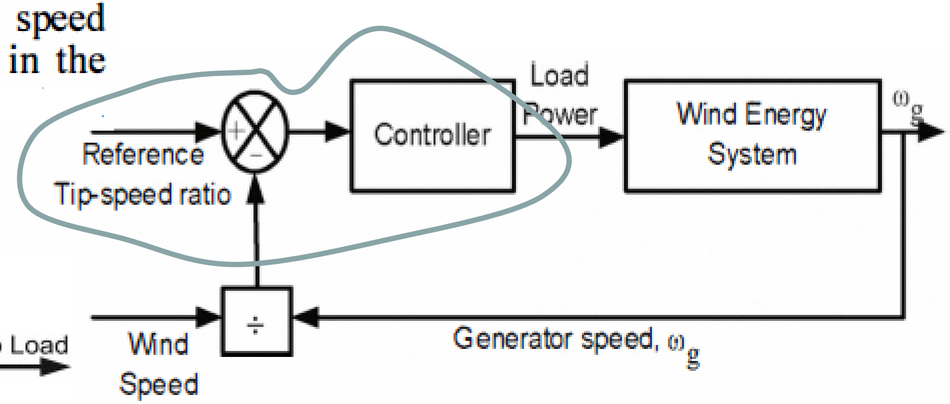
2.1 Tip speed ratio technique

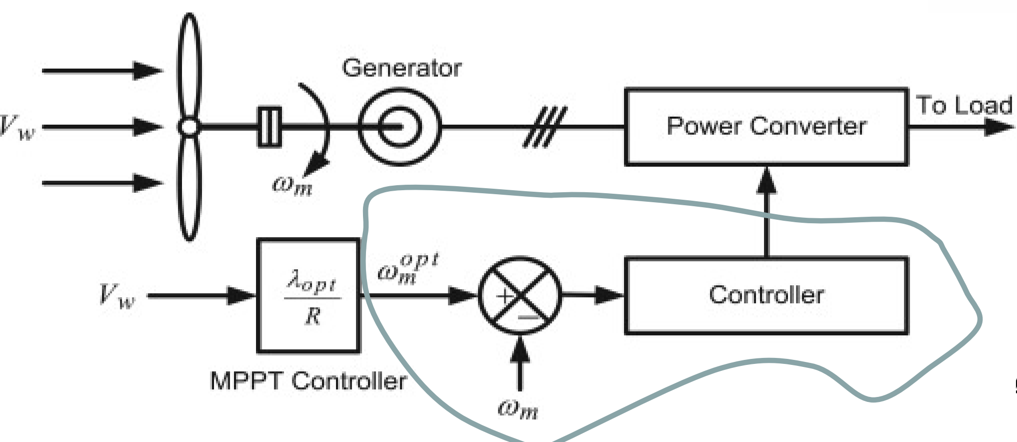
2.2 Power signal feedback technique

2.3 Hill climbing technique

TSR MPPT technique

The optimal TSR for a given wind turbine is constant regardless of the wind speed. If the TSR is maintained constantly at its optimal value, this ensures that the energy extracted is in its maximum operating point too. Therefore, this method seeks to force the energy conversion system to work at this point continuously by comparing it with the actual value and feeding this difference to the controller. That, in turn, changes the speed of the generator to reduce this error. The optimal point of the TSR can be determined experimentally or theoretically and stored as a reference. This method is simple, however, it requires the measurement of wind speed consistently and accurately which complicates its use in the reality, as well as increases the system cost





TSR MPPT technique

$$\text{TSR}\ (\lambda) = \frac{\text{Tip Speed of Blade}}{\text{Wind Speed}}$$

Why is This Important???

Knowing the tip speed ratio of your turbine will help you maximize the power output and efficiency of your wind turbine. Remember that if your rotor spins too slowly, a lot of wind will pass through the gaps between the blades rather than giving energy to your turbine. But if your blades spin too quickly, they could create too much turbulent air or act as a solid wall against the wind. So, if you want to maximize your turbine's efficiency, you've got to calculate the perfect Tip Speed Ratio.

TSR MPPT technique

$$\text{Tip speed ratio: } \lambda = \frac{\text{speed of rotor tip}}{\text{wind speed}} = \frac{v}{V} = \frac{\omega r}{V} \qquad (1)$$

where:

V	is the wind speed [m/sec]
$v = \omega r$	is velocity of rotor tip [m/sec]
r	is rotor radius [m]
$\omega = 2\pi f$	is the angular velocity [radian/sec]
f	is the frequency of rotation [Hz], [sec^{-1}]

This dimensionless factor arises from the detailed treatment of the aerodynamic theory of wind power extraction.

EXAMPLE

TSR MPPT technique

The Suzlon S.66/1250, 1.25 MW rated power at 12 m/s rated wind speed wind turbine design has a rotor diameter of 66 meters and a rotational speed of 13.9-20.8 rpm. Its angular speed range is:

$$\omega = 2\pi f$$
$$= 2\pi \frac{13.9 - 20.8}{60}[\text{radian}.\frac{\text{revolutions}}{\text{minute}}.\frac{\text{minute}}{\text{second}}]$$
$$= 1.46 - 2.18[\frac{\text{radian}}{\text{sec}}]$$

The range of its rotor's tip speed can be estimated as:

$$= (1.46 - 2.18)\frac{66}{2}$$
$$= 48.18 - 71.94[\frac{\text{m}}{\text{sec}}]$$

The range of its tip speed ratio is thus:

$$\lambda = \frac{\omega r}{V}$$
$$= \frac{48.18 - 71.94}{12}$$
$$\simeq 4 - 6$$

TSR MPPT technique

HOW DO YOU KNOW THE PERFECT TIP SPEED RATIO???

If you want the optimum Tip Speed Ratio for maximum power output, this formula has been empirically proven:

$$\lambda \text{ (max power)} = \frac{4\pi}{n} \qquad \textit{(n = number of blades)}$$

Of course, there is always a cheat sheet if you're feeling lazy:

# of Blades		Optimum TSR
2	—	Around 6
3	—	Around 4—5
4	—	Around 3
6	—	Around 2

TSR MPPT technique

OPTIMAL ROTOR TIP SPEED RATIO

The optimal tip speed ratio for maximum power extraction is inferred by relating the time taken for the disturbed wind to reestablish itself t_w to the time taken for a rotor blade of rotational frequency ω to move into the position occupied by its predecessor t_s .

For an n bladed rotor, the time period for the blade to move to its predecessor's position is given by:

$$t_s = \frac{2\pi}{n\omega}[\text{sec}] \qquad (2)$$

If the length of the strongly disturbed air stream upwind and downwind of the rotor is s, then the time period for the wind to return to normal is given by:

$$t_w = \frac{s}{V}[\text{sec}] \qquad (3)$$

TSR MPPT technique

If $t_s > t_w$, then some wind is unaffected. If $t_w > t_s$, then some wind is not allowed to flow through the rotor. The maximum power extraction occurs when these two time periods are about equal:

$$t_s \approx t_w$$

$$\frac{2\pi}{n\omega} \approx \frac{s}{V} \Rightarrow \frac{n\omega}{V} \approx \frac{2\pi}{s} \qquad (4)$$

From which the optimal rotational frequency is:

Consequently, for optimal power extraction, the rotor blade must rotate at a rotational frequency that is related to the speed of the incoming wind. This rotor rotational frequency decreases as the radius of the rotor increases and can be characterized by calculating the optimal tip ratio as:

$$\lambda_{opt} \approx \frac{\omega_{opt} r}{V} \approx \frac{2\pi}{n}\left(\frac{r}{s}\right) \qquad (6)$$

TSR MPPT technique

Consequently, for optimal power extraction, the rotor blade must rotate at a rotational frequency that is related to the speed of the incoming wind. This rotor rotational frequency decreases as the radius of the rotor increases and can be characterized by calculating the optimal tip ratio as:

$$\lambda_{opt} \approx \frac{\omega_{opt} r}{V} \approx \frac{2\pi}{n}\left(\frac{r}{s}\right) \qquad (6)$$

The optimal tip speed ratio depends on the number of rotor blades n of the wind turbine. The smaller the number of blades, the faster the wind turbine has to rotate to extract maximum power from the wind.

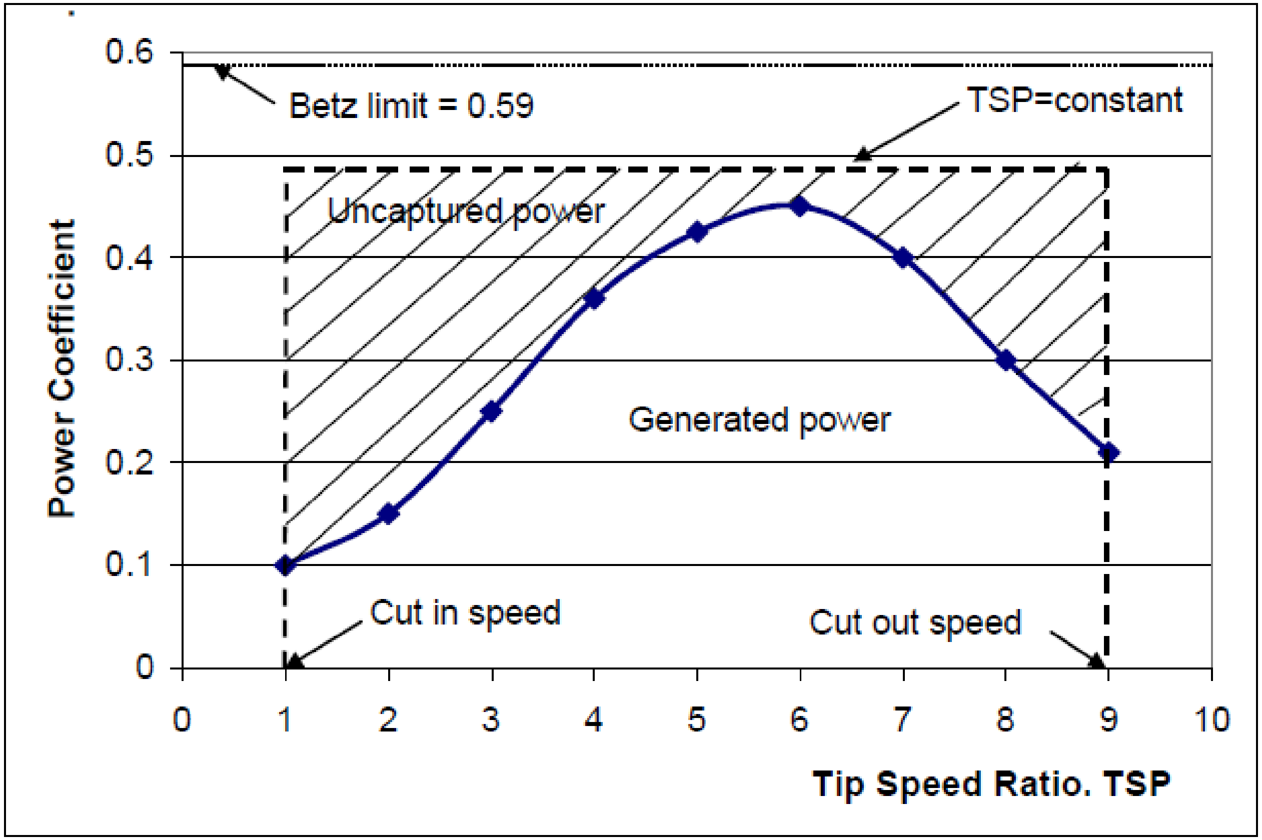
For an n bladed machine it has been empirically observed that s is equal to about half a rotor radius or:

$$\frac{s}{r} \approx \frac{1}{2}$$

or the ratio (s/r) is approximately equal to 0.5, thus we can write:

$$\lambda_{opt} \approx \frac{2\pi}{n}\left(\frac{r}{s}\right) \approx \frac{4\pi}{n} \qquad (7)$$

TSR MPPT technique



The maximum achievable power factor is 59.26 percent, and is designated as the Betz limit. In practice, values of obtainable power coefficients are in the range of 45 percent. This value below the theoretical limit is caused by the inefficiencies and losses attributed to different configurations, rotor blades and turbine designs.

AGENDA

Wind Energy Conversion systems

1.why MPPT is mandatory

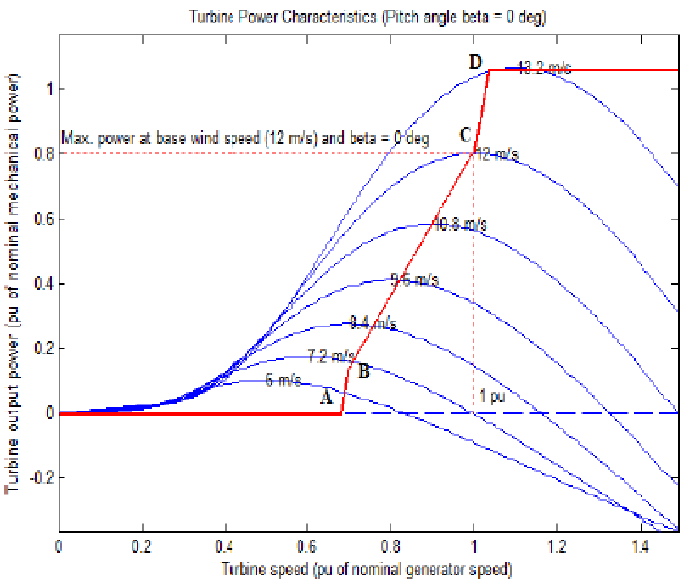
2.wind energy MPPT techniques

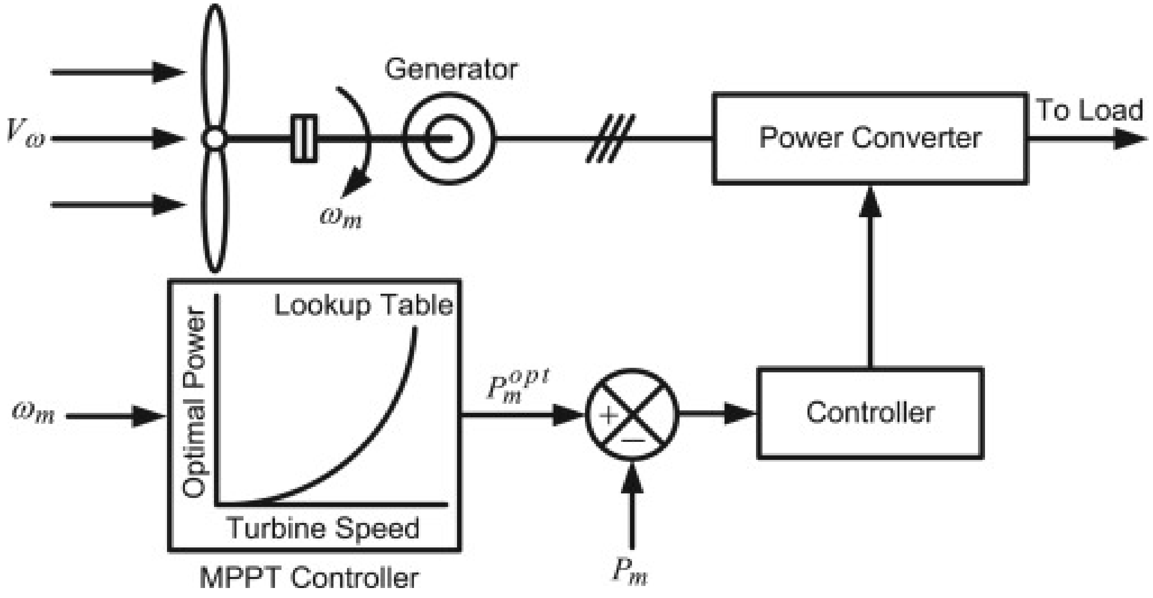
2.1 Tip speed ratio technique

2.2 Power signal feedback technique

2.3 Hill climbing technique

PSF MPPT technique





AGENDA

Wind Energy Conversion systems

1.why MPPT is mandatory

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2.1 Tip speed ratio technique

2.2 Power signal feedback technique

2.3 Hill climbing technique

Hill Climbing MPPT technique

The perturbation and observation (P&O) or hill-climb searching (HCS) method is a mathematical optimization technique used to search for the local maxima points of a given function. It is widely used in wind energy systems to get the optimal operating point that maximizes the extracted energy. This method is based on perturbing a control parameter in small step-size and observing the resulting changes in the target function, until the slope becomes zero. As shown in Fig. , if the operating point is to the left of the peak point, the controller must move the operating point to the right to be closer for the MPP, and vice versa if the operating point is on the other side.

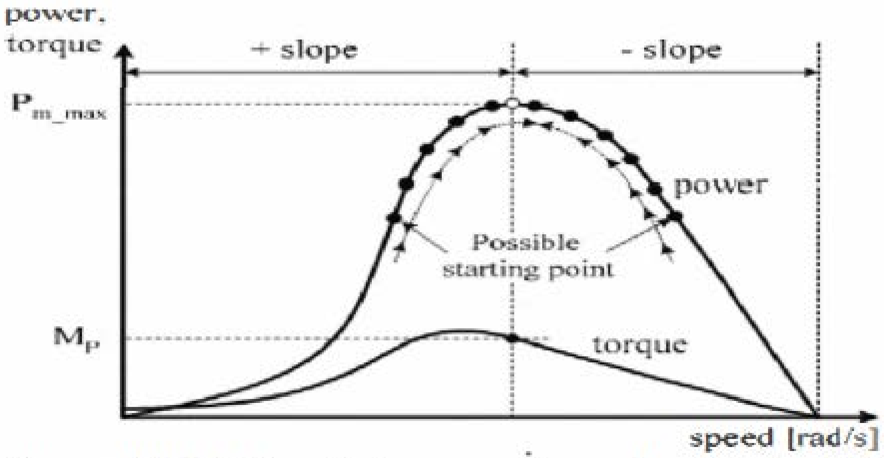
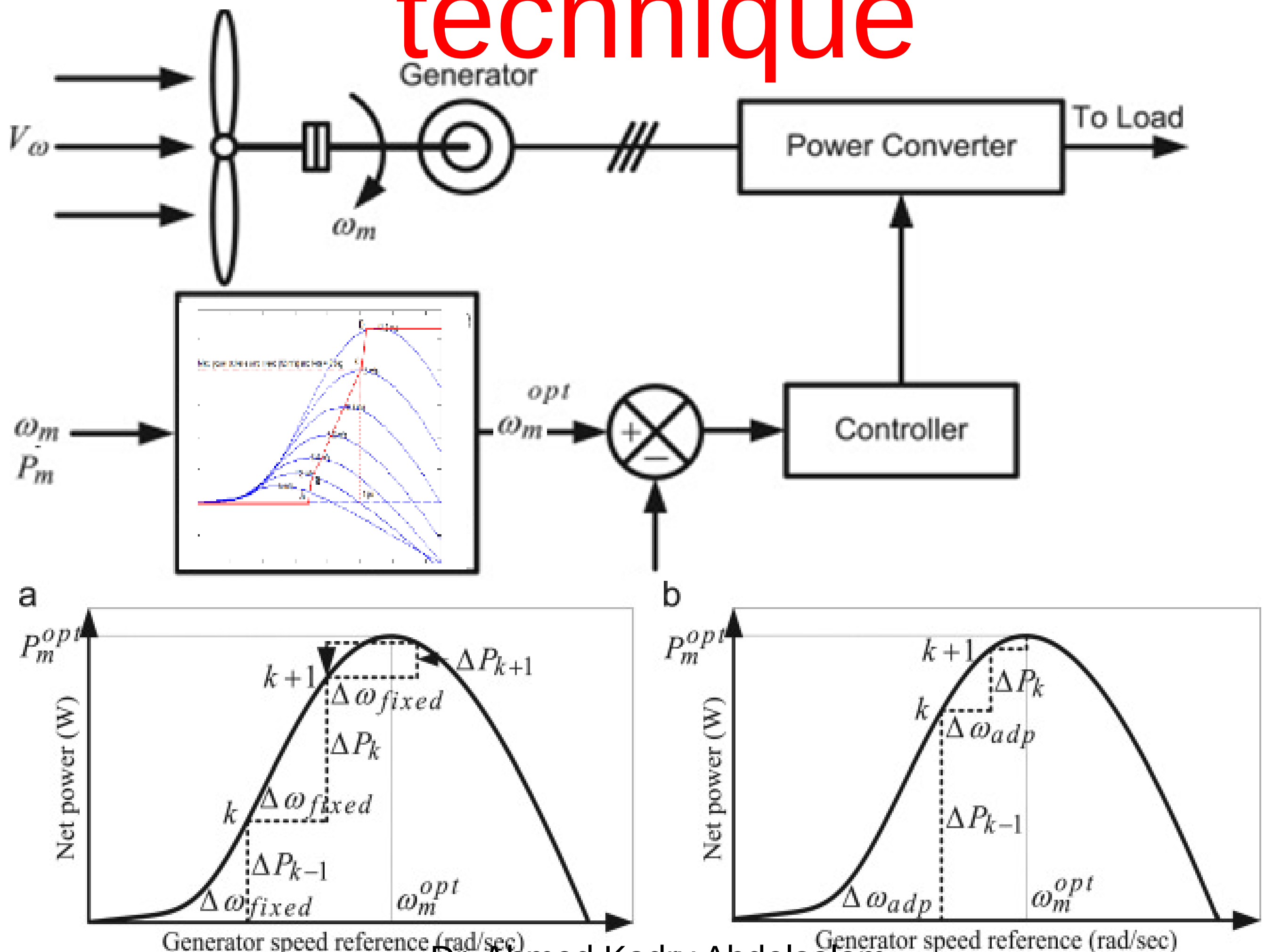
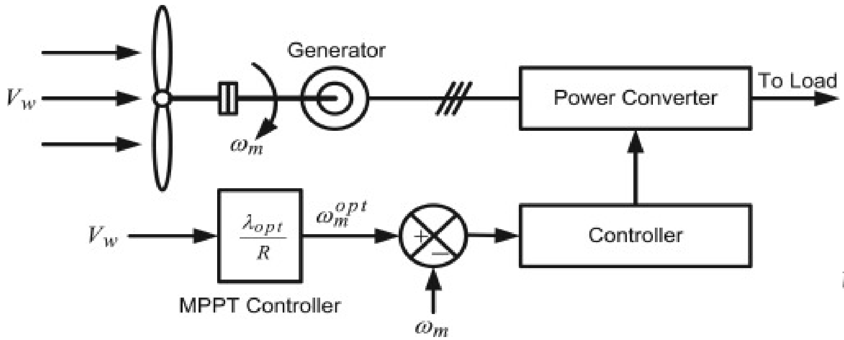


Figure Wind turbine output power and torque characteristics with MPP tracking process

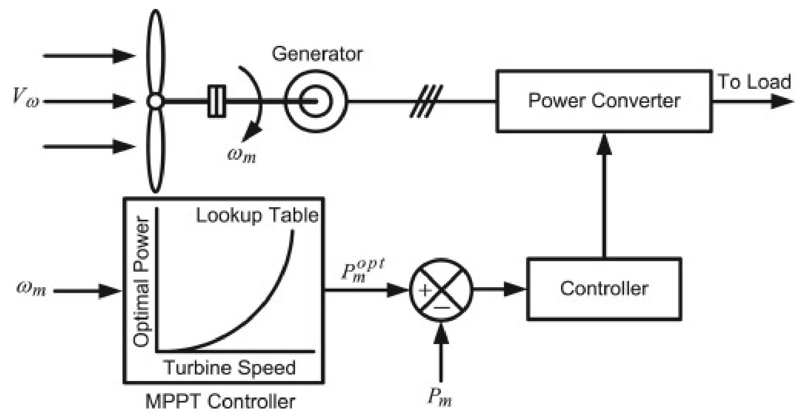
Hill Climbing (P&O) MPPT technique



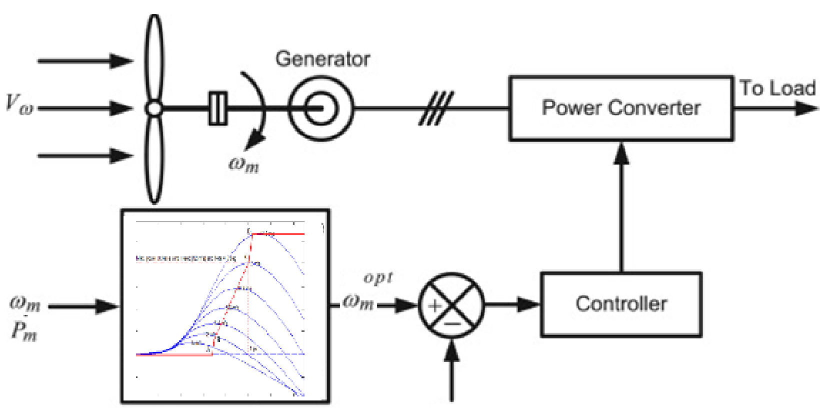
MPPT techniques Summary



TSR MPPT



PSF MPPT



P&O MPPT

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Recommended literature

Books:

1. **Wind energy engineering. New York: McGraw-Hill, Jain, P. (2011).**
2. **Understanding wind power technology: Theory, Deployment and Optimisation. John Wiley & Sons. Schaffarczyk, A. (Ed.). (2014).**
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[3] www.awea.org American Wind Energy Association

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Introduction to Wind Energy

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Module 2.1

Configurations of Wind Energy Conversion Systems
Lesson 10

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Objective

The purpose of this lesson is to present the state-of-the-art of different configurations used in the Wind Energy industry for the power generation components.

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Learning Outcomes

This lesson will contribute to the students to:

O2. Understand the different components and types of wind turbines and as their work;

O4. Be able to select wind turbines and to design (at preliminary project level) a wind farm in a South-Mediterranean location.

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Technical Contents

1. *Single-Speed WECS*
2. *Wound-Rotor Induction Generator (WRIG) with External Rotor Resistances*
3. *Doubly Fed Induction Generator WECS with Reduced-Capacity Power Converter*
4. *SCIG Wind Energy Systems with Full-Capacity Power Converters*
5. *with Full-Capacity Back-to-Back Power Converters*
6. *with Diode Rectifier and DC/DC Converters*

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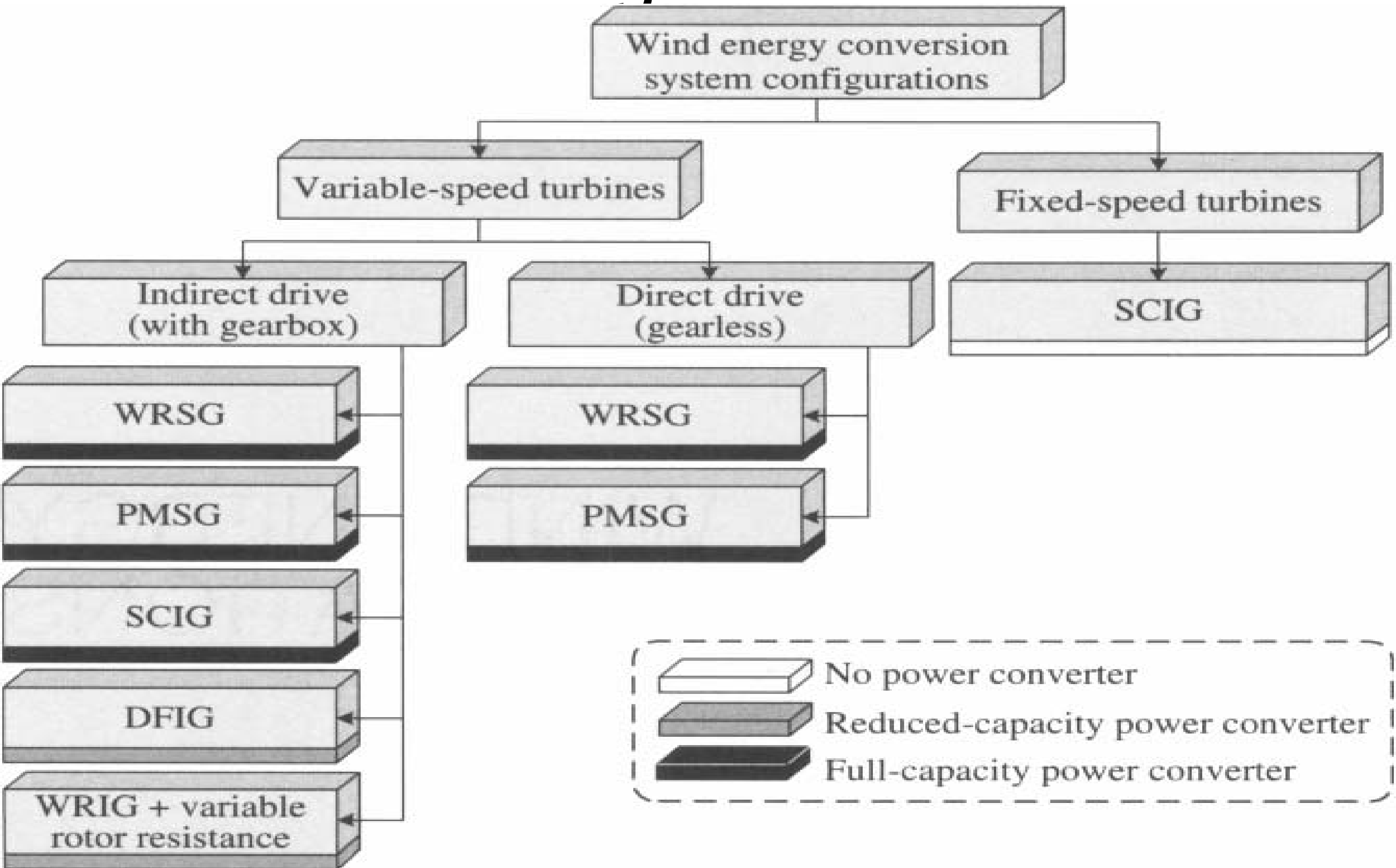
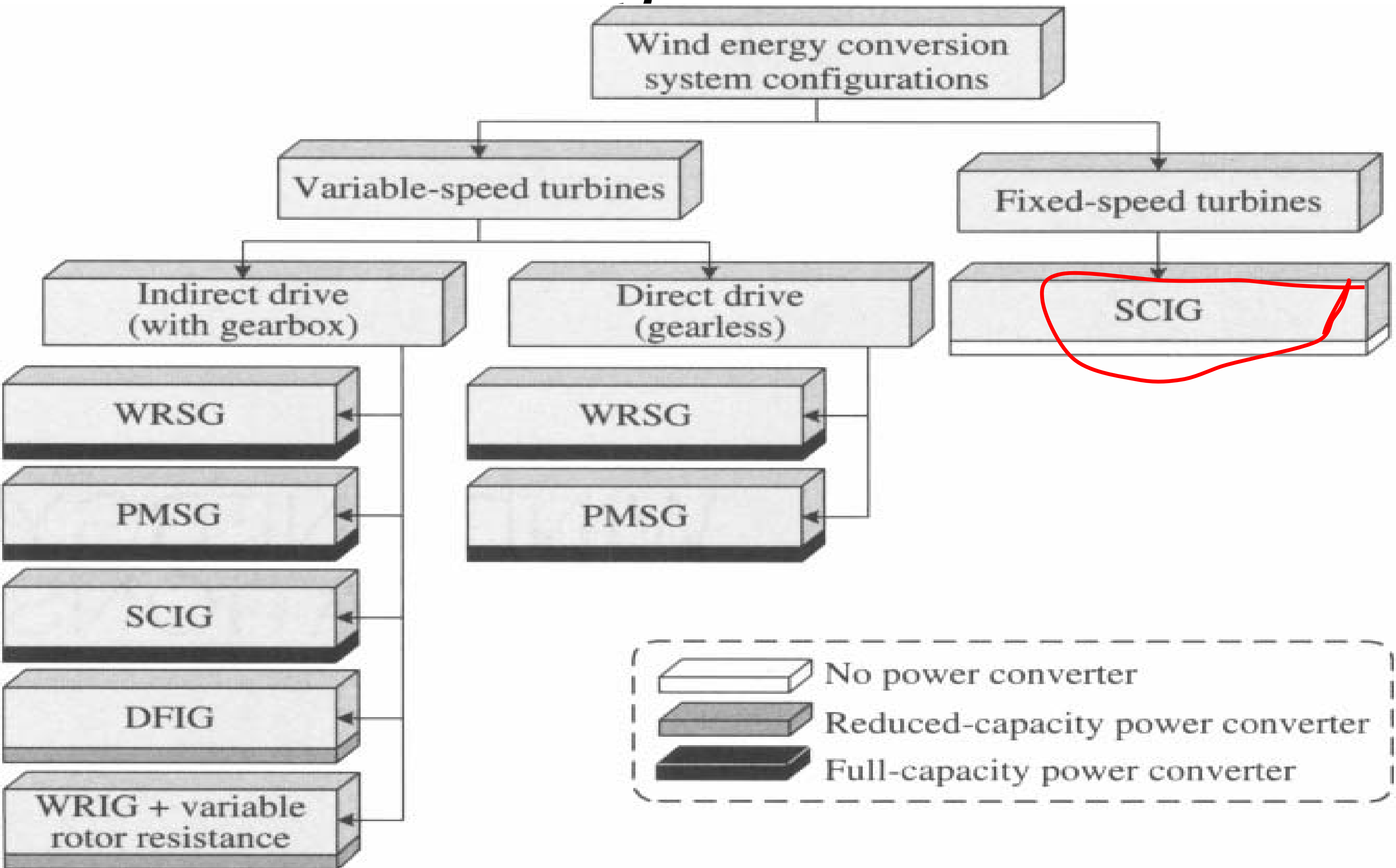
Wind Energy System Configurations



Wind Energy System Configurations



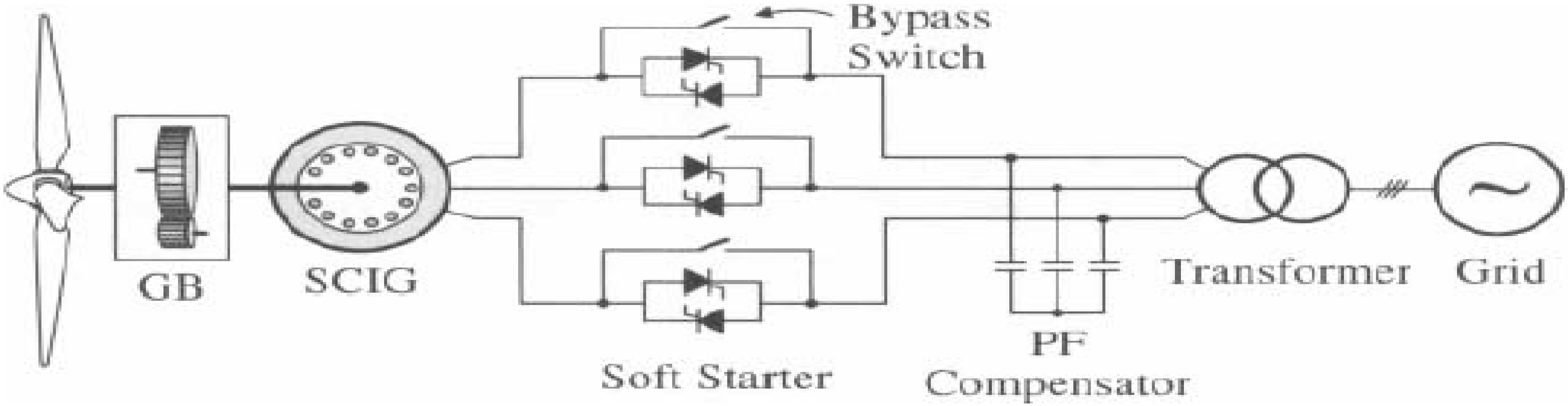
Fixed-Speed WECS without Power Converter Interface

- **FIXED-SPEED WECS**

The fixed-speed wind energy systems can be divided into

- Single-speed WECS, in which the generator operates at only one fixed speed; and
- Two-speed WECS, in which the generator can operate at two fixed speeds.

(1) Single-Speed WECS



- A typical configuration for a high-power (MWs), fixed-speed wind energy system is shown in the figure.
- The turbine is normally of horizontal-axis type with three rotor blades rotating at low speeds, for example, 15 rpm as the rated speed.

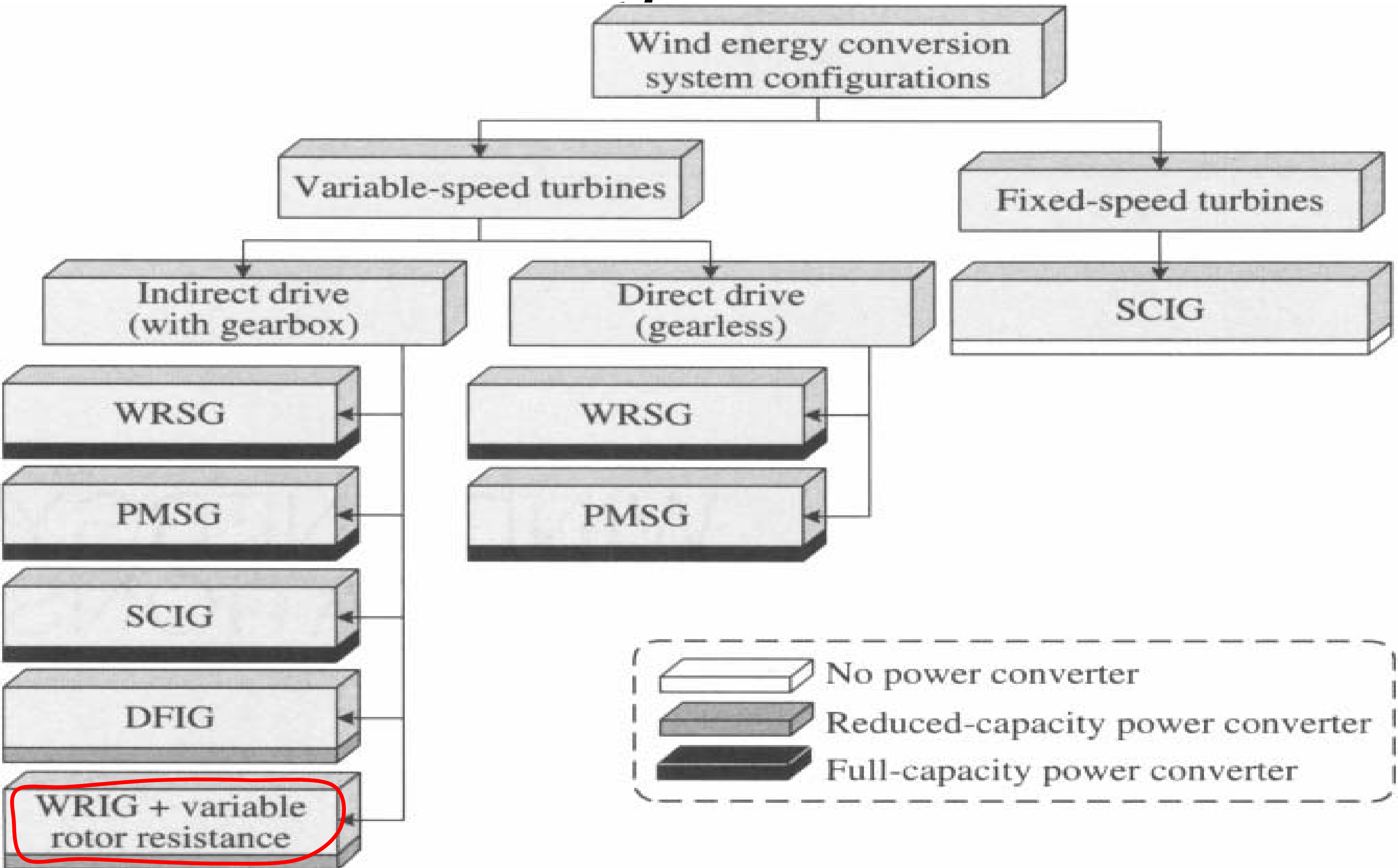
Single-Speed WECS

- Squirrel cage induction generators are exclusively used in the system. Assuming that a four pole generator is connected to a 50 Hz grid, its speed is slightly higher than 1500 rpm, for which a gear ratio of about 100:1 is required.
- To assist the start-up of the turbine, a soft starter is used to limit the inrush current in the generator winding. The soft starter is essentially a three-phase AC voltage controller. It is composed of three pairs of bidirectional thyristor switches. To start the system, the firing angle of the thyristors is gradually adjusted such that the voltage applied to the generator is increased gradually from zero to the grid voltage level. As a result, the stator current is effectively limited. Once the startup process is over, the soft starter is bypassed by a switch, and the WECS is then connected to the grid through a transformer.

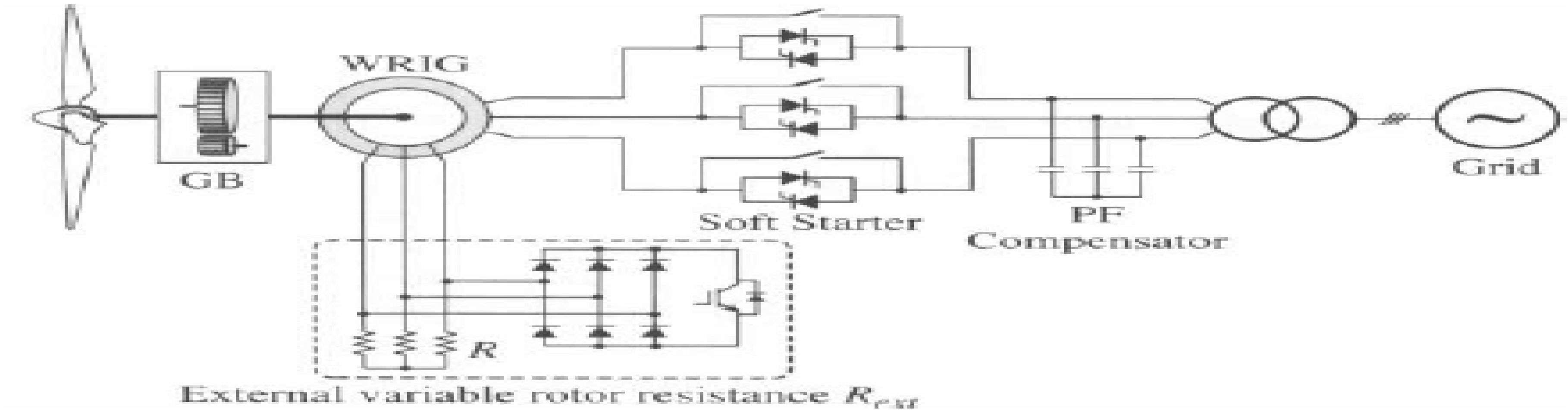
Single-Speed WECS

- To compensate for the inductive reactive power consumed by the induction generator, a capacitor-based power-factor (PF) compensator is normally used. In practice, the compensator is composed of multiple capacitor banks, which can be switched into or out of the system individually to provide an optimal compensation according to the operating conditions of the generator.
- Due to the use of a cost-effective and robust squirrel-cage induction generator with inexpensive soft starter, the fixed-speed WECS features simple structure, low cost, and reliable operation. However, compared to the variable-speed WECS, the fixed-speed system has a lower energy conversion efficiency since it can achieve the maximum efficiency only at one given wind speed.

Wind Energy System Configurations



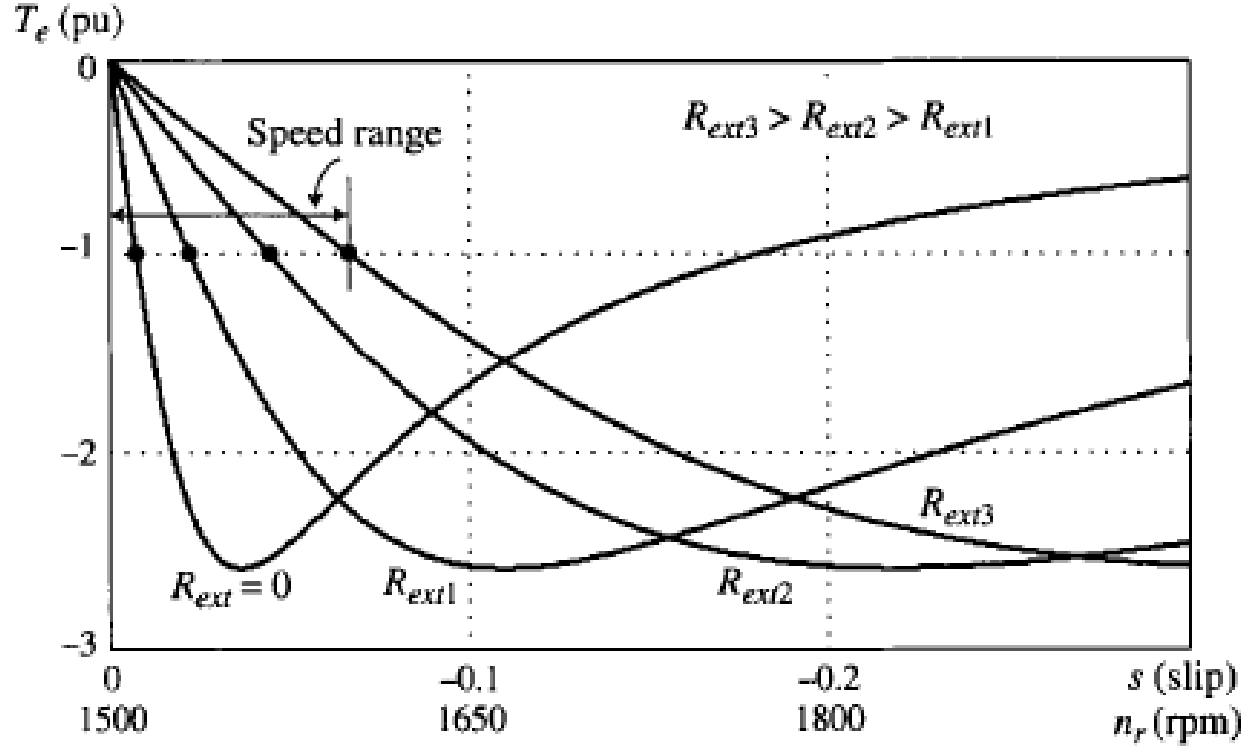
(3) Wound-Rotor Induction Generator (WRIG) with External Rotor Resistances



- The system configuration is the same as that of the fixed-speed wind energy system except that the SCIG is replaced with the WRIG. The external rotor resistance, is made adjustable by a converter composed of a diode bridge and an IGBT chopper. The equivalent value of R_{ex}, seen by the rotor varies with the duty cycle of the chopper.

Wound-Rotor Induction Generator (WRIG) with External Rotor Resistances

- The torque-slip characteristics of the generator vary with the external rotor resistance R_{ext}. With different values of R_{ext}, the generator can operate at different operating points. This introduces a moderate speed range, usually less than 10% of the rated speed.



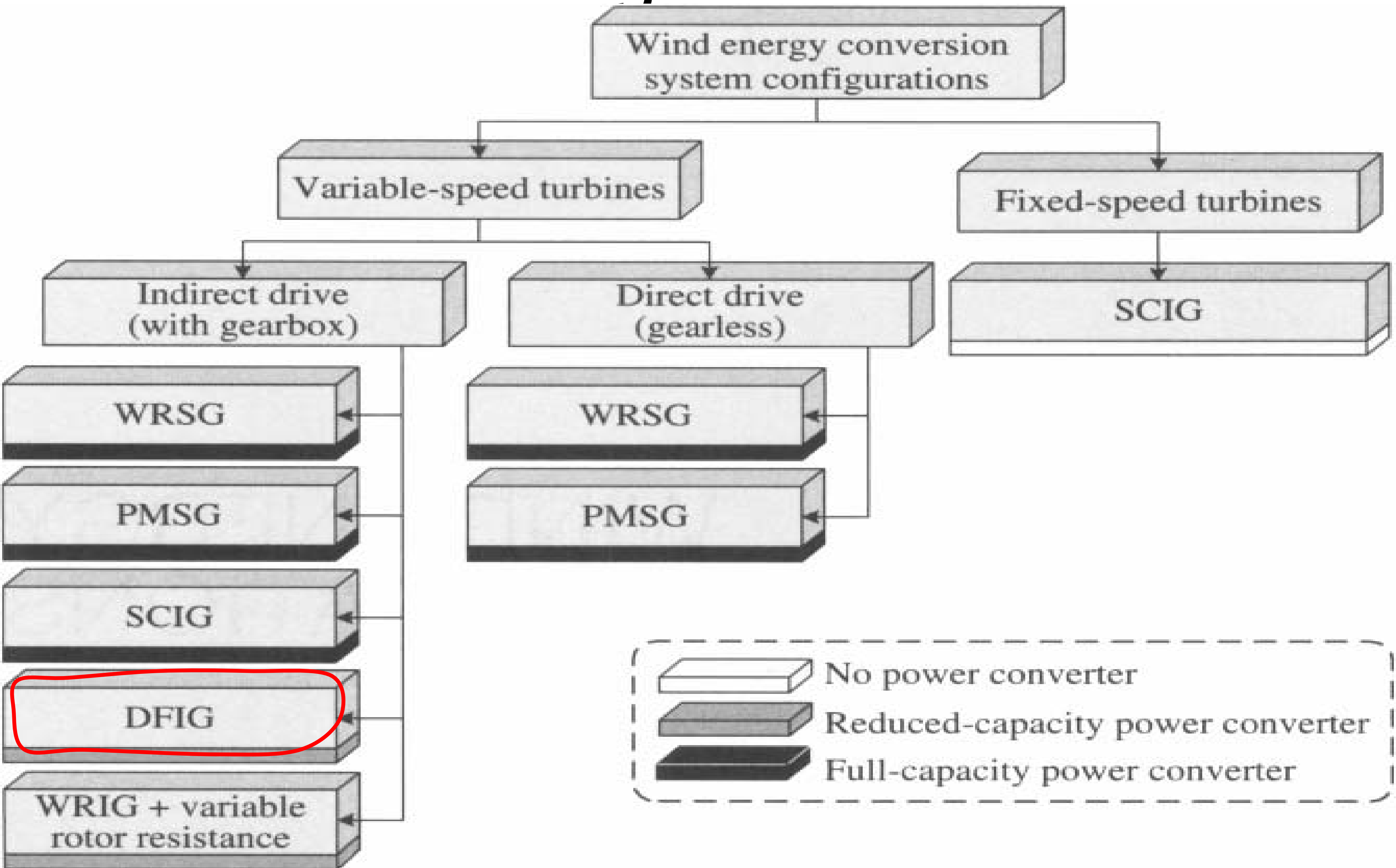
Wound-Rotor Induction Generator (WRIG) with External Rotor Resistances

- Slip rings and brushes of the WRIG can be avoided in some practical WECS by mounting the external rotor resistance circuit on the rotor shaft. This reduces maintenance needs, but introduces additional heat dissipation inside the generator.

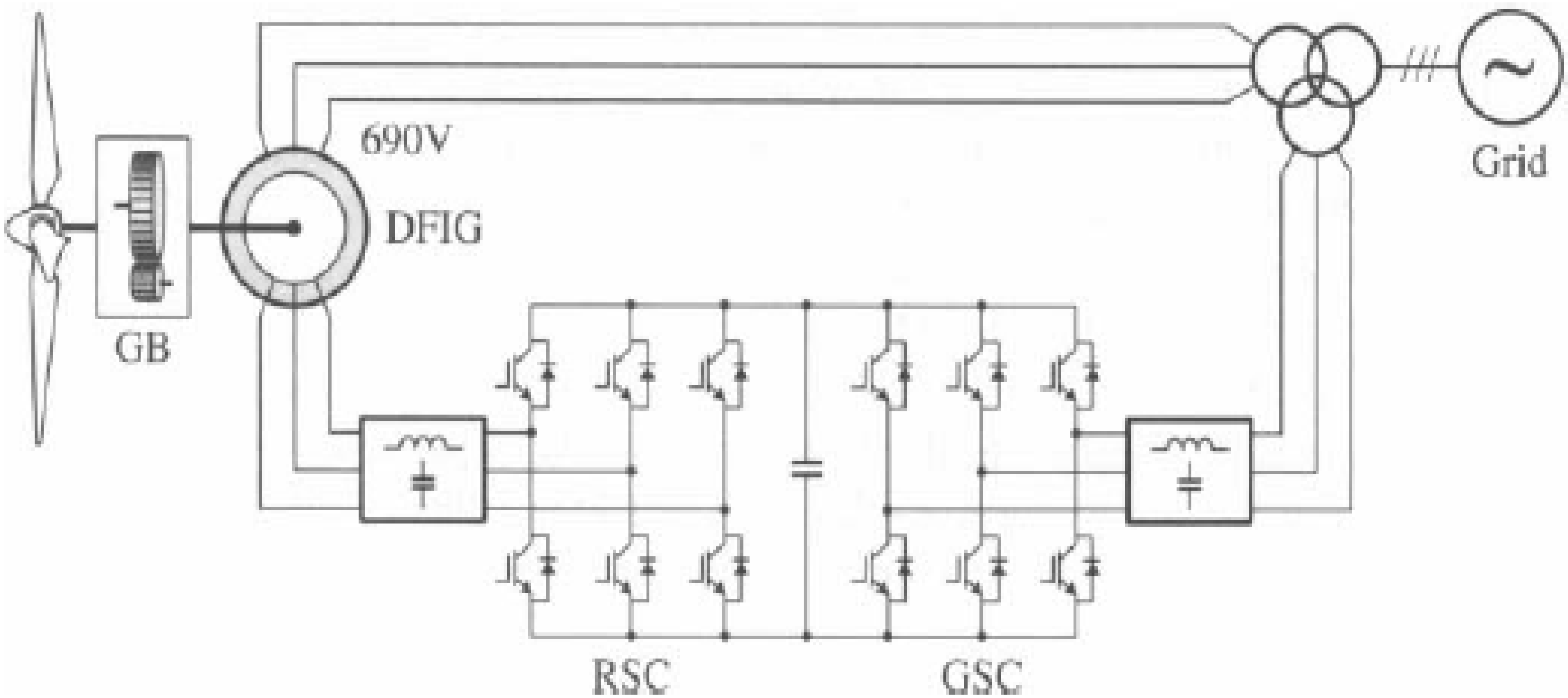
- The main advantage of this configuration compared to the variable-speed WECS is the low cost and simplicity.

- The major drawbacks include limited speed range, inability to control grid-side reactive power, and reduced efficiency due to the resistive losses

Wind Energy System Configurations



(4) Doubly Fed Induction Generator WECS with Reduced- Capacity Power Converter



- The variable-speed DFIG wind energy system is one of the main WECS configurations in today's wind power industry.

Doubly Fed Induction Generator WECS with Reduced- Capacity Power Converter

- The stator is connected to the grid directly, whereas the rotor is connected to the grid via reduced-capacity power converters.
- A two-level IGBT voltage source converter (VSC) system in a back-to-back configuration is normally used. Since both stator and rotor can feed energy to the grid, the generator is known as a doubly fed generator.
- The typical stator voltage for the commercial DFIG is 690 V and power rating is from a few hundred kilowatts to several megawatts

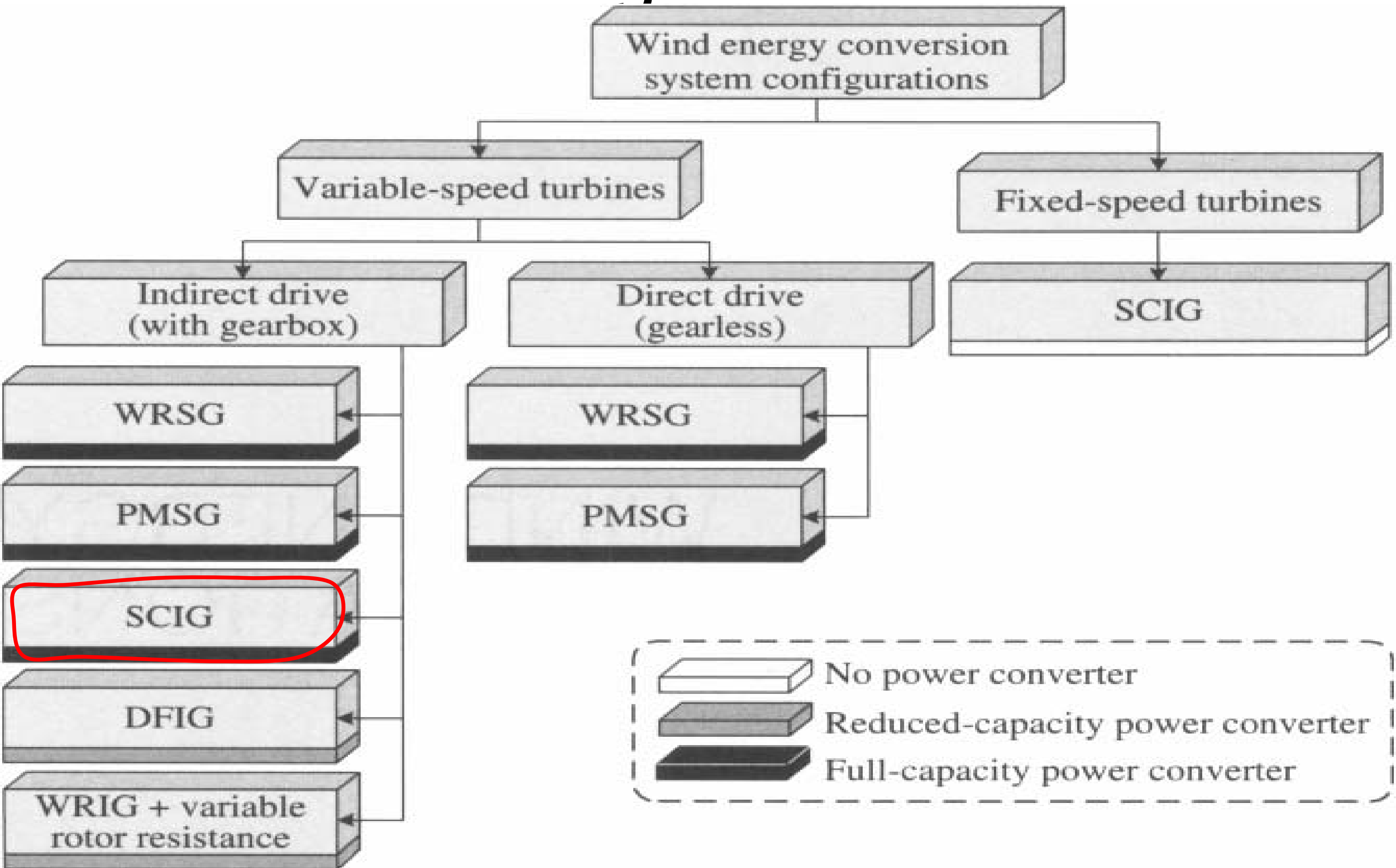
Doubly Fed Induction Generator WECS with Reduced- Capacity Power Converter

- The rotor-side converter (RSC) controls the torque or active/reactive power of the generator while the grid-side converter (GSC) controls the DC-link voltage and its AC-side reactive power. Since the system has the capability to control the reactive power, external reactive power compensation is not needed.
- The speed range of the DFIG wind energy system is around ±30%, which is 30% above and 30% below synchronous speed. The speed range of 60% can normally meet all the wind conditions and, therefore, it is sufficient for the variable-speed operation of the wind turbine. The maximum slip determines the maximum power to be processed by the rotor circuit, which is around 30% of the rated power.

Doubly Fed Induction Generator WECS with Reduced- Capacity Power Converter

- Therefore, the power flow in the rotor circuit is bidirectional: it can flow from the grid to the rotor or vice versa. This requires a four-quadrant converter system.
- However, the converter system needs to process only around 30% of the rated power. The use of reduced-capacity converters results in reduction in cost, weight, and physical size as well. Compared with the fixed-speed systems, the energy conversion efficiency of the DFIG wind turbine is greatly enhanced.
- Power converters normally generate switching harmonics. To solve the problems caused by the harmonics, different types of harmonic filters are used in practical wind energy conversion systems

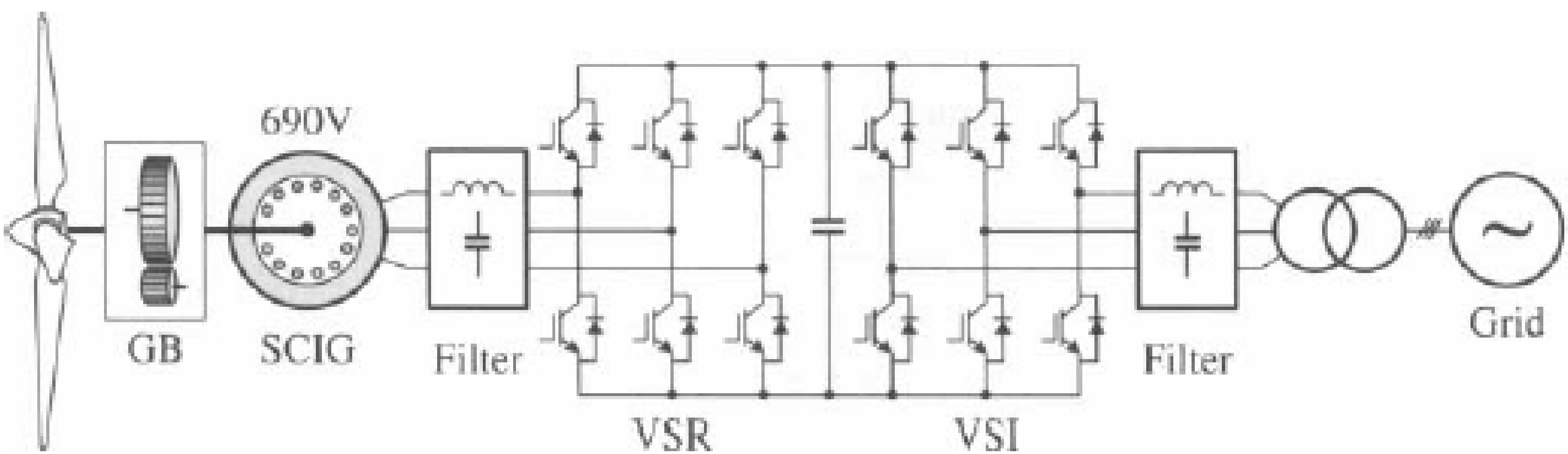
Wind Energy System Configurations



(5) SCIG Wind Energy Systems with Full-Capacity Power Converters

- ***With Two-Level Voltage Source Converters.***

The two converters are identical in topology and linked by a DC-link capacitive filter. The generator and converters are typically rated for 690 V, and each converter can handle up to 0.75 MW.

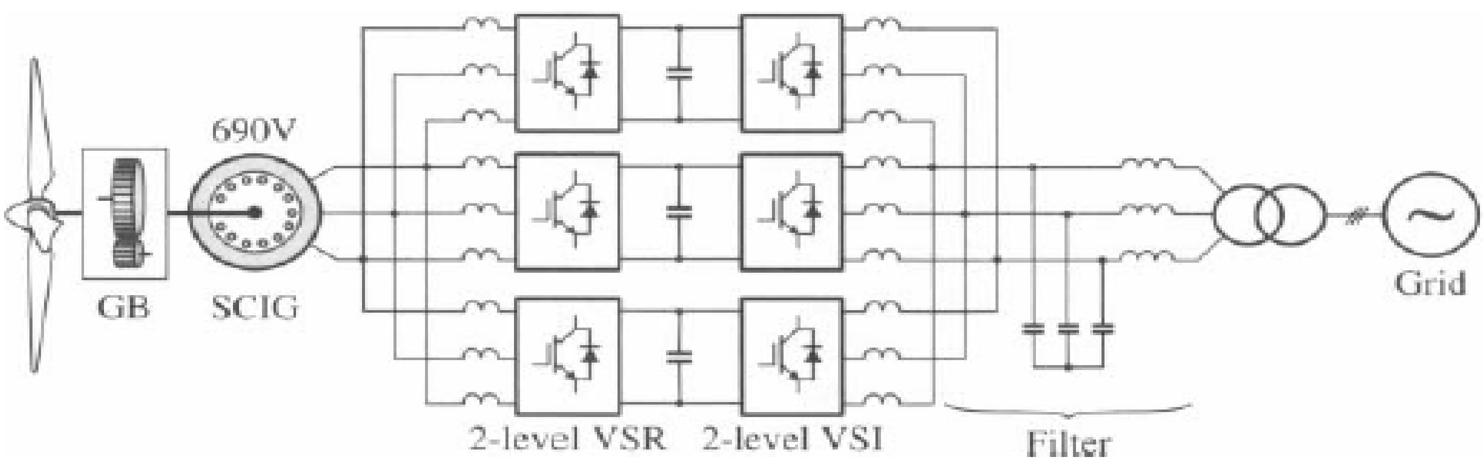


SCIG Wind Energy Systems with Full-Capacity Power Converters

- For wind turbines larger than 0.75 MW, the power rating of the converter can be increased by paralleling IGBT modules. Measures should be taken to ensure minimum circulating current among the parallel modules.
- To minimize the circulating current, issues such as dynamic and static characteristics of IGBTs, design and arrangement of gate driver circuits, and physical layout of IGBT modules and DC bus should be considered.
- Some semiconductor manufacturers provide IGBT modules for parallel operation to achieve a power rating of several megawatts.

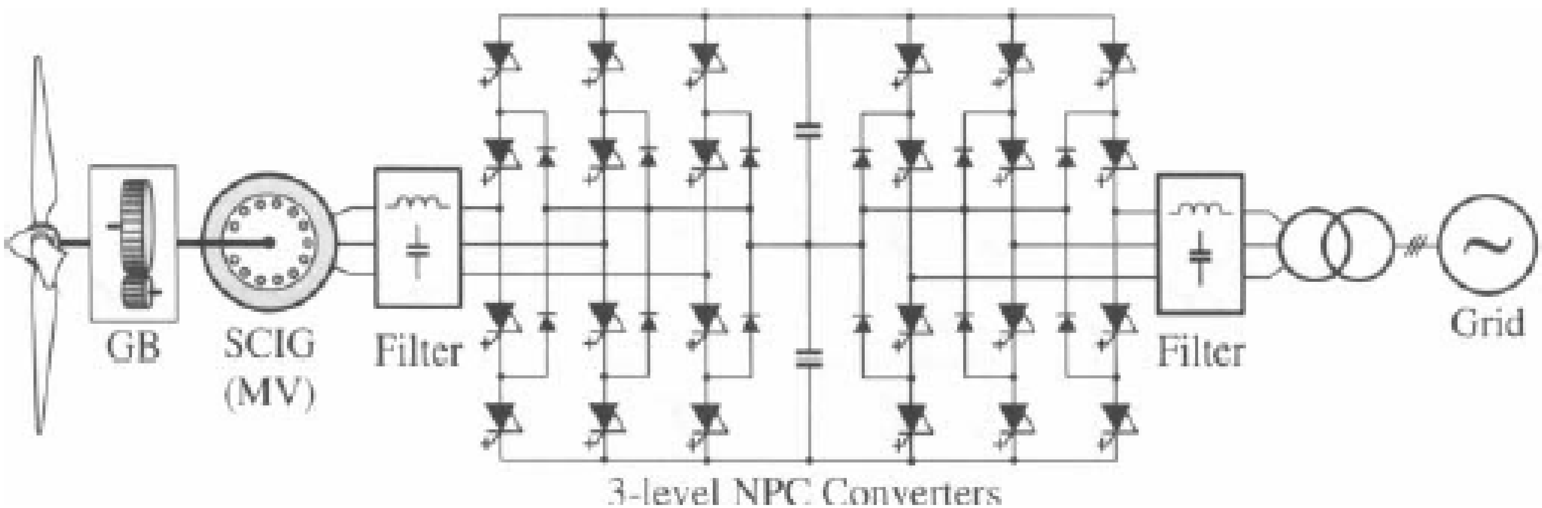
SCIG Wind Energy Systems with Full-Capacity Power Converters

- An alternative approach to the paralleled converter channels is illustrated in the figure, where three converter channels are in parallel for a megawatt IG wind turbine. Each converter channel is mainly composed of two-level voltage source converters in a back-to-back configuration with harmonic filters. An additional benefit of the paralleled converter channels is the improvement of energy efficiency.

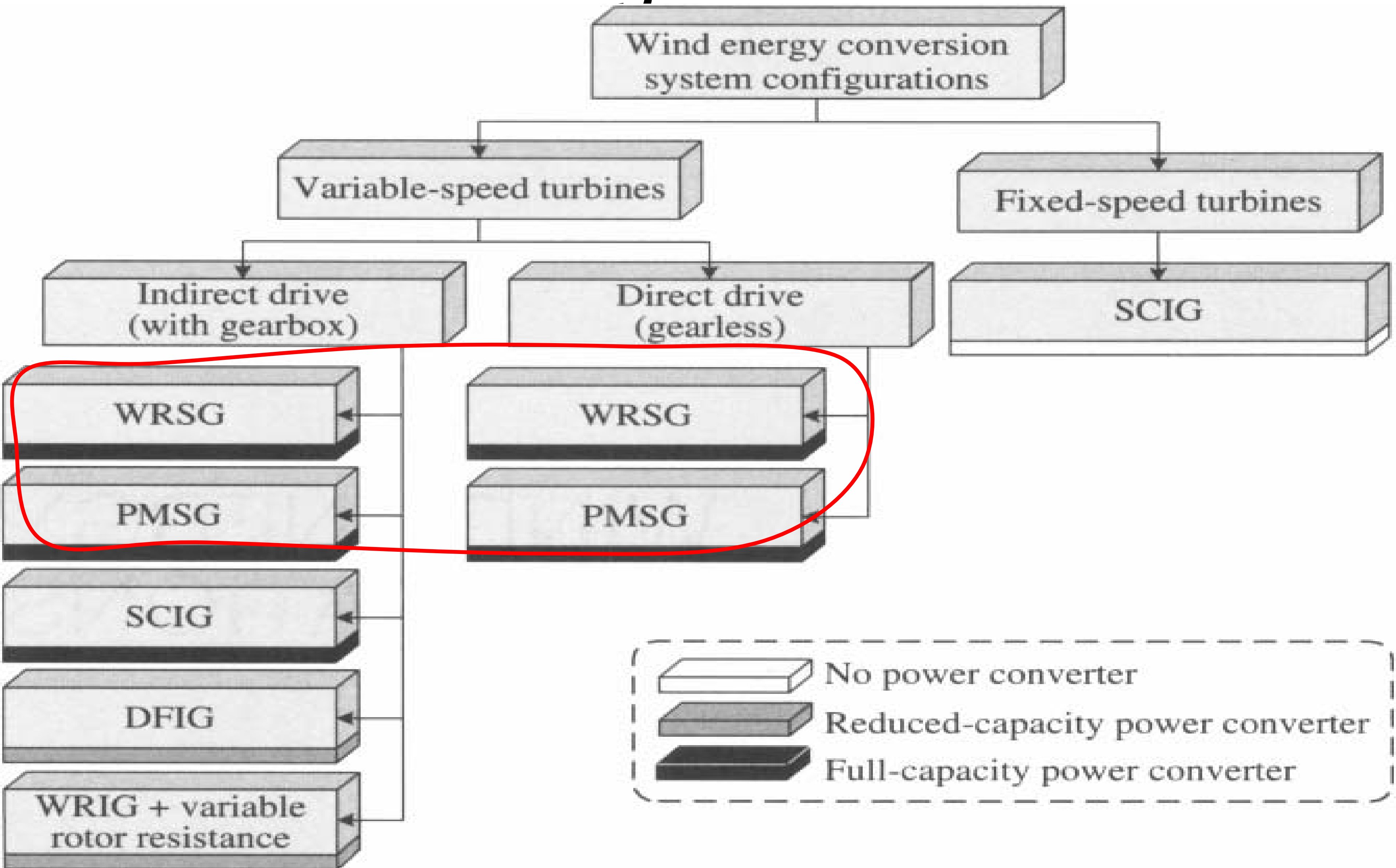


SCIG Wind Energy Systems with Full-Capacity Power Converters

- ***With Three-Level NPC Converters.***
- The low-voltage converters discussed before are cost-effective at low power levels. As the power rating of wind turbines increases to several megawatts, medium-voltage (MV) wind energy systems of 3 kV or 4 kV become competitive.



Wind Energy System Configurations

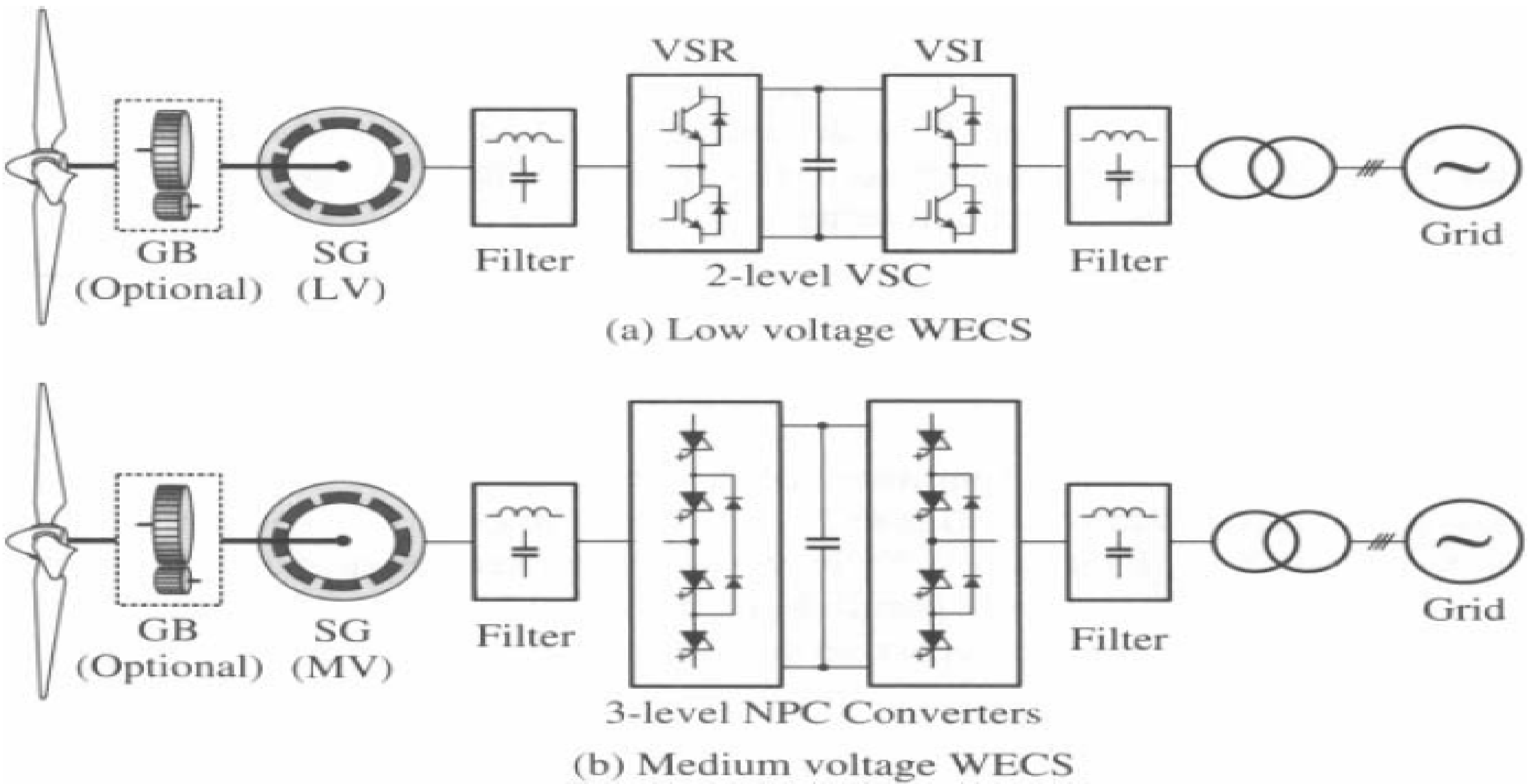


VARIABLE-SPEED SYNCHRONOUS GENERATOR WECS

- Synchronous generator wind energy systems have many more configurations than the induction generator WECS. This is mainly due to the fact that (1) the synchronous generator provides the rotor flux by itself through permanent magnets or rotor field winding and, thus, diode rectifiers can be used as generator-side converters, which is impossible in the induction generator WECS, and (2) it is easier and more cost-effective for the synchronous generator to have multiple-pole (e.g., 72 poles) and multiple-phase (e.g., six phases) configurations than its counterpart.

(6) Configuration with Full-Capacity Back-to-Back Power Converters

- ***With Two-Level VSC and Three-Level***

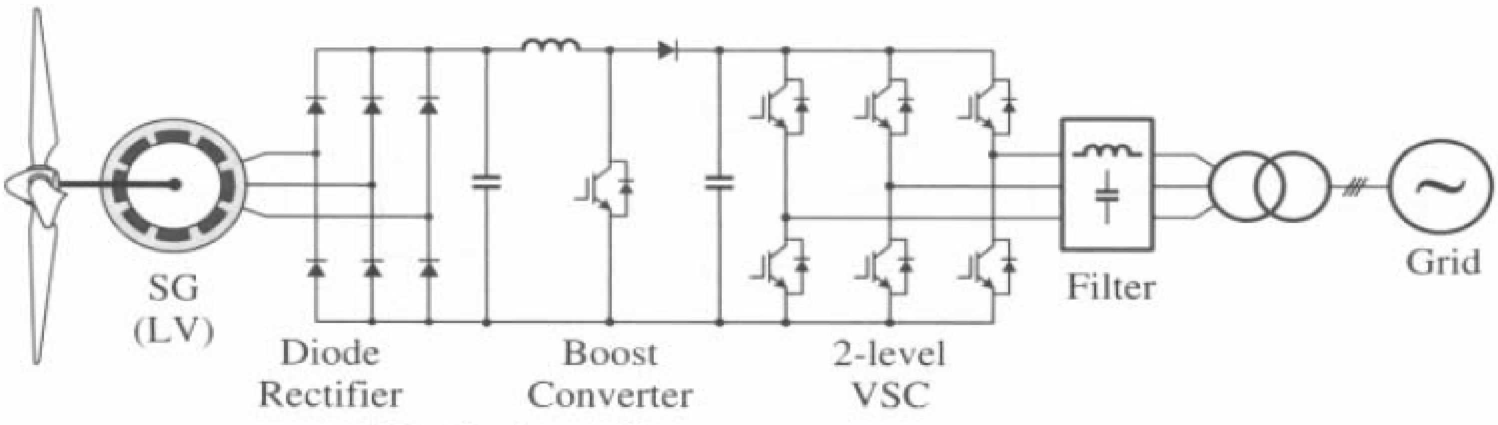


(6) Configuration with Full-Capacity Back-to-Back Power Converters

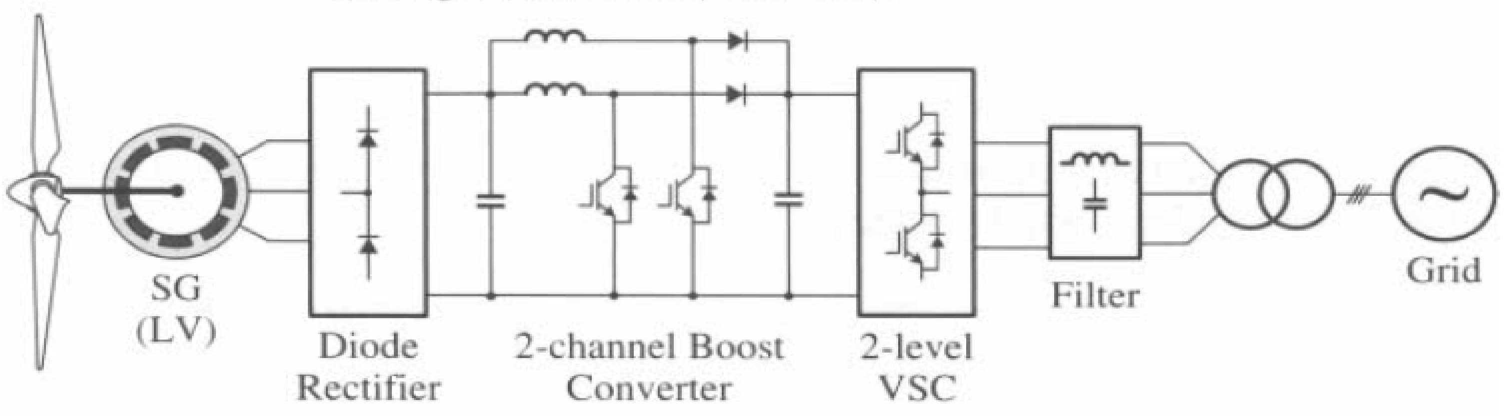
- The configuration of SG wind energy systems with full-capacity power converters utilizes back-to-back two-level voltage source converters are employed in low-voltage wind energy systems and three-level NPC converters are used in medium voltage wind turbines. Similar to the SCIG system presented earlier, parallel modules or converter channels are required in the LV systems for generators of more than 0.75 MW, whereas in the MV systems a single NPC converter can handle power up to a few megawatts.
- Not all the SG wind turbines need a gearbox. When a low-speed generator with high number of poles is employed, the gearbox can be eliminated. The gearless wind turbine is attractive due to the reduction in cost, weight, and maintenance.

(7) Configuration with Diode Rectifier and DC/DC Converters

- ***With Diode Rectifier and Multichannel***



(a) Single-channel boost converter



(b) Two-channel boost converter

(7) Configuration with Diode Rectifier and DC/DC Converters

- To reduce the cost of the wind energy systems, the two-level voltage source rectifier can be replaced by a diode rectifier and a boost converter.
- This converter configuration cannot be used for SCIG wind turbines since the diode rectifier cannot provide the magnetizing current needed for the induction generator.
- The diode rectifier converts variable generator voltage to a DC voltage, which is boosted to a higher DC voltage by the boost converter. It is important that the generator voltage at low wind speeds be boosted to a sufficiently high level for the inverters, which ensures the delivery of the maximum captured power to the grid in the full wind speed range.

(7) Configuration with Diode Rectifier and DC/DC Converters

- The two-level inverter controls the DC link voltage and grid-side reactive power. The power rating of the system is in the range of a few kilowatts to several hundred kilowatts, and can be further increased to the megawatt level by using a two-channel or three-channel interleaved boost converter as shown in figure b.
- Compared with the PWM voltage source rectifier, the diode rectifier and boost converter are simpler and more cost-effective. However, the stator current waveform is distorted due to the use of the diode rectifier, which increases the losses in the generator and causes torque ripple as well. Both system configurations illustrated in the figure are used in practical systems.

What is a wind plant? Towers, Rotors, Gens, Blades

Manu-facturer	Capacity	Hub Height	Rotor Diameter	Gen type	Weight (s-tons)		
					Nacelle	Rotor	Tower
	0.5 MW	50 m	40 m				
Vestas	0.85 MW	44 m, 49 m, 55 m, 65 m, 74 m	52m	DFIG/Asynch	22	10	45/50/60/75/95, wrt to hub hgt
GE (1.5sle)	1.5 MW	61-100 m	70.5-77 m	DFIG	50	31	
Vestas	1.65 MW	70,80 m	82 m	Asynch water cooled	57(52)	47 (43)	138 (105/125)
Vestas	1.8-2.0 MW	80m, 95,105m	90m	DFIG/ Asynch	68	38	150/200/225
Enercon	2.0 MW		82 m	Synchronous	66	43	232
Gamesa (G90)	2.0 MW	67-100m	89.6m	DFIG	65	48.9	153-286
Suzlon	2.1 MW	79m	88 m	Asynch			
Siemens (82-VS)	2.3 MW	70, 80 m	101 m	Asynch	82	54	82-282
Clipper	2.5 MW	80m	89-100m	4xPMSG	113		209
GE (2.5xl)	2.5 MW	75-100m	100 m	PMSG	85	52.4	241
Vestas	3.0 MW	80, 105m	90m	DFIG/Asynch	70	41	160/285
Acciona	3.0 MW	100-120m	100-116m	DFIG	118	66	850/1150
GE (3.6sl)	3.6 MW	Site specific	104 m	DFIG	185	83	
Siemens (107-vs)	3.6 MW	80-90m	107m	Asynch	125	95	255
Gamesa	4.5 MW		128 m				
REpower (Suzlon)	5.0 MW	100–120 m Onshore 90–100 m Offshore	126 m	DFIG/Asynch	290	120	
Enercon	6.0 MW	135 m	126 m	Electrical excited SG	329	176	2500
Clipper	7.5 MW	120m	150m				

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Recommended literature

Books:

1. **Wind energy engineering. New York: McGraw-Hill, Jain, P. (2011).**
2. **Understanding wind power technology: Theory, Deployment and Optimisation. John Wiley & Sons. Schaffarczyk, A. (Ed.). (2014).**
3. **Renewable Energy Systems, the choice and modelling of 100 % renewable solutions", Henrik Lund , Elsevier, 2010.**
4. **Alternative Energy Systems, B. K. Hodge, John Wiley & Sons, 2009.**
5. **Fundamental of Aerodynamics, John D. Anderson, Jr., McGraw-Hill, 2001.**

Review articles:

1) Herbert, G. J., Iniyan, S., Sreevalsan, E., & Rajapandian, S. (2007). A review of wind energy technologies. Renewable and sustainable energy Reviews, 11(6), 1117-1145.

2) Leung, D. Y., & Yang, Y. (2012). Wind energy development and its environmental impact: a review. Renewable and sustainable energy reviews, 16(1), 1031-1039.

Web links:

[1] www.ewea.org European Wind Energy Association
[2] wwindea.org World Wind Energy Association
[3] www.awea.org American Wind Energy Association

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Module 2.1

Further information:

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Introduction to Wind Energy

Module 2.1

Induction Generator: modelling and dynamics
Lesson 11

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Objective

The purpose of this lesson is to present the models of induction generator used in industry to analyze, simulate and design the power section of Wind Energy Converters.

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Learning Outcomes

This lesson will contribute to the students to:

O2. Understand the different components and types of wind turbines and as their work;

O4. Be able to select wind turbines and to design (at preliminary project level) a wind farm in a South-Mediterranean location.

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Technical Contents

1. Modelling of induction generators

2. Analysis of Transient characteristics

3. Case Study

The students are advised to have the following reference as several equations and figures are cited from it:

Reference Book:

Power conversion and control of wind energy systems, B. Wu *et al.* , John Wiley & Sons, 2011

For more details regarding this lecture, kindly refer to ch3 in the reference book mentioned above

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AGENDA

Wind Generators Modelling

1.Induction generator Modelling

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Induction Generator Types and Models

There are two types of induction generators in the wind energy industry:

1) doubly fed induction generators (DFIGs) and
2) squirrel-cage induction generators (SCIGs).

These generators have the same stator structure and differ only in the rotor structure.

Figure 11-1a shows the construction of a squirrel-cage induction generator. The stator is made of thin silicon steel laminations. The laminations are insulated to minimize iron losses caused by induced eddy currents. The laminations are basically flat rings with openings disposed along the inner perimeter of the ring. When the laminations are stacked together with the openings aligned, a canal is formed, in which a three-phase copper winding is placed.

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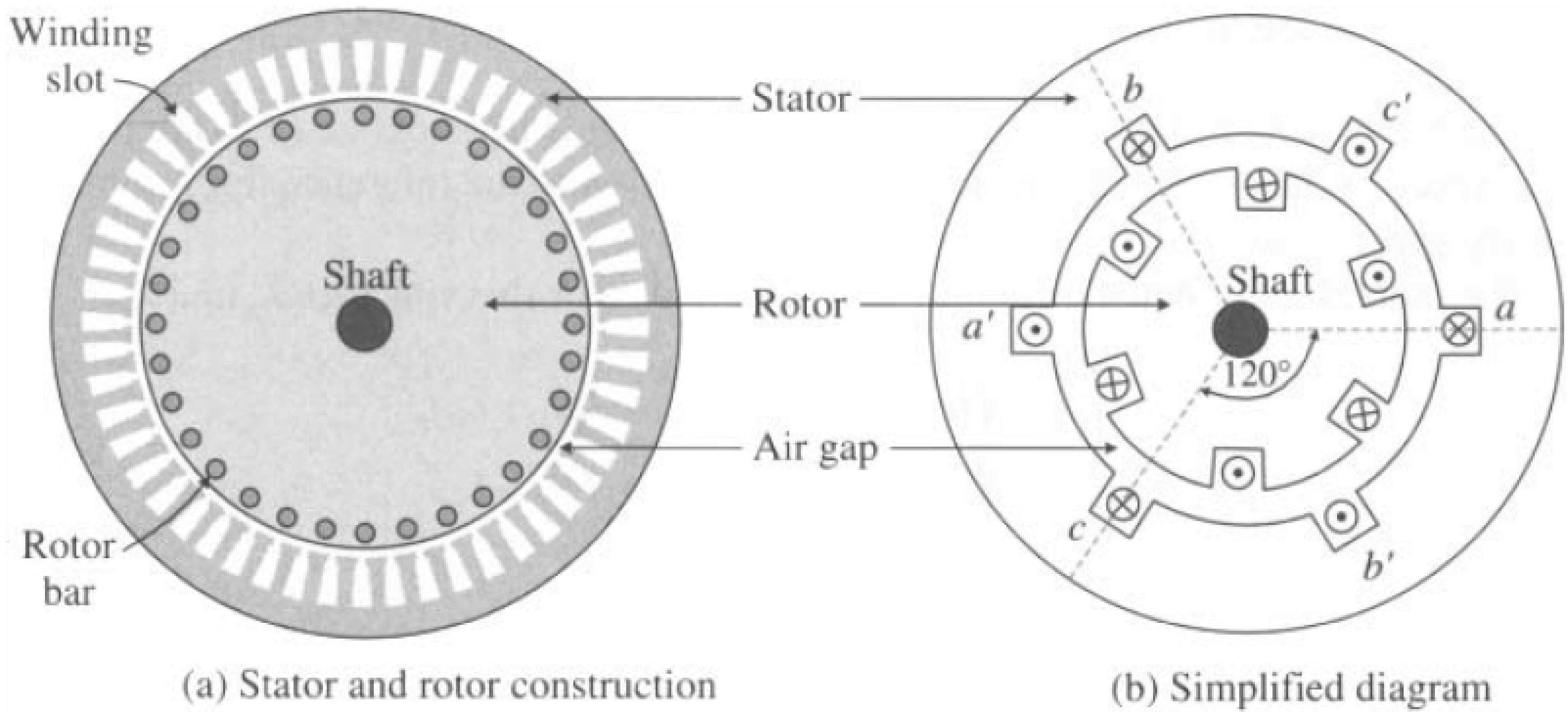

Figure 11.1 Cross-Sectional View of an SCIG [1]

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The rotor of the SCIG is composed of the laminated core and rotor bars. The rotor bars are embedded in slots inside the rotor laminations and are shorted on both ends by end rings.

When the stator winding is connected to a three-phase supply, a rotating magnetic field is generated in the air gap. The rotating field induces a three-phase voltage in the rotor bars.
Since the rotor bars are shorted, the induced rotor voltage produces a rotor current, which interacts with the rotating field to produce the electromagnetic torque.

The rotor of the DFIG has a three-phase winding similar to the stator winding. The rotor winding is embedded in the rotor laminations but in the exterior perimeter. This winding is usually fed through slip-rings mounted on the rotor shaft both ends by end rings.

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State space Model of Induction Generator

The equivalent circuit of IG is represented as shown in Figure 11.2 .

The voltage equations of rotor and stator with in the arbitrary reference frame are given by

$$\begin{cases} \vec{v}_s = R_s \vec{i}_s + p\vec{\lambda}_s + j\omega\vec{\lambda}_s \\ \vec{v}_r = R_r \vec{i}_r + p\vec{\lambda}_r + j(\omega - \omega_r)\vec{\lambda}_r \end{cases} \quad (11.1)$$

where

$\vec{v}_s$, $\vec{v}_r$—stator and rotor voltage vectors (V)
$\vec{i}_s$, $\vec{i}_r$—stator and rotor current vectors (A)
$\vec{\lambda}_s$, $\vec{\lambda}_r$—stator and rotor flux-linkage vectors (Wb)
R_s, R_r—stator and rotor winding resistances (Λ)
ω—rotating speed of the arbitrary reference frame (rad/s)
ω_r—rotor electrical angular speed (rad/s)
p—derivative operator ($p = d/dt$).

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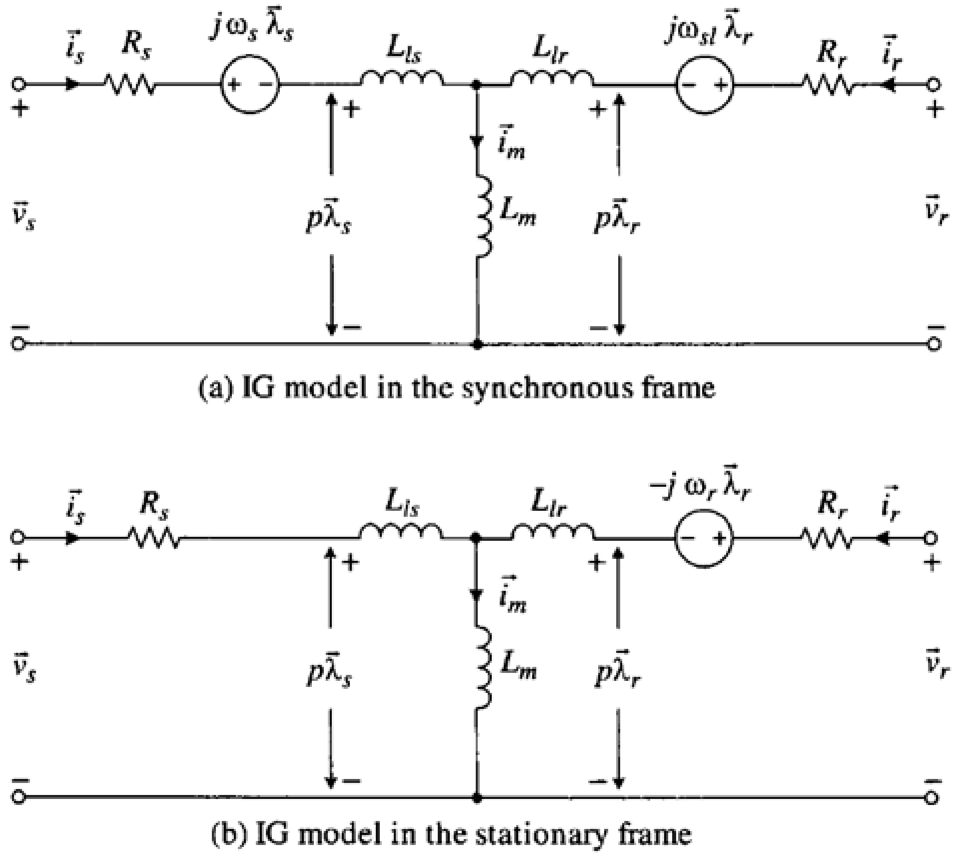
dq Model of Induction Generator



(a) IG model in the synchronous frame

(b) IG model in the stationary frame

Figure 11.2. Space-vector models for induction generator in the synchronous and stationary reference frames [1]

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dq Model of Induction Generator

The *dq-axis model of the induction generator can be obtained by decomposing the* space-vectors into their corresponding *d- and q-axis components, that is,*

$$\begin{cases} \vec{v}_s = v_{ds} + j\,v_{qs};\ \ \vec{i}_s = i_{ds} + j\,i_{qs};\ \ \vec{\lambda}_s = \lambda_{ds} + j\,\lambda_{qs} \\ \vec{v}_r = v_{dr} + j\,v_{qr};\ \ \vec{i}_r = i_{dr} + j\,i_{qr};\ \ \vec{\lambda}_r = \lambda_{dr} + j\,\lambda_{qr} \end{cases} \tag{11.2}$$

Substituting equation (11.2) into equation (11.1)

$$\begin{cases} v_{ds} = R_s\,i_{ds} + p\lambda_{ds} - \omega\lambda_{qs} \\ v_{qs} = R_s\,i_{qs} + p\lambda_{qs} + \omega\lambda_{ds} \\ v_{dr} = R_r\,i_{dr} + p\lambda_{dr} - (\omega - \omega_r)\lambda_{qr} \\ v_{qr} = R_r\,i_{qr} + p\lambda_{qr} + (\omega - \omega_r)\lambda_{dr} \end{cases} \tag{11.3}$$

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dq Model of Induction Generator

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The *dq-axis flux linkages* re obtained:

$$\begin{cases} \lambda_{ds} = (L_{ls} + L_m)i_{ds} + L_m i_{dr} = L_s i_{ds} + L_m i_{dr} \\ \lambda_{qs} = (L_{ls} + L_m)i_{qs} + L_m i_{qr} = L_s i_{qs} + L_m i_{qr} \\ \lambda_{dr} = (L_{lr} + L_m)i_{dr} + L_m i_{ds} = L_r i_{dr} + L_m i_{ds} \\ \lambda_{qr} = (L_{lr} + L_m)i_{qr} + L_m i_{qs} = L_r i_{qr} + L_m i_{qs} \end{cases} \quad (11.4)$$

The electromagnetic torque equation is obtained

$$T_e = \begin{cases} \frac{3P}{2}(i_{qs}\lambda_{ds} - i_{ds}\lambda_{qs}) & \text{(a)} \\ \frac{3PL_m}{2}(i_{qs}i_{dr} - i_{ds}i_{qr}) & \text{(b)} \\ \frac{3PL_m}{2L_r}(i_{qs}\lambda_{dr} - i_{ds}\lambda_{qr}) & \text{(c)} \end{cases} \quad (11.5)$$

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Simulation Model of Induction Generator

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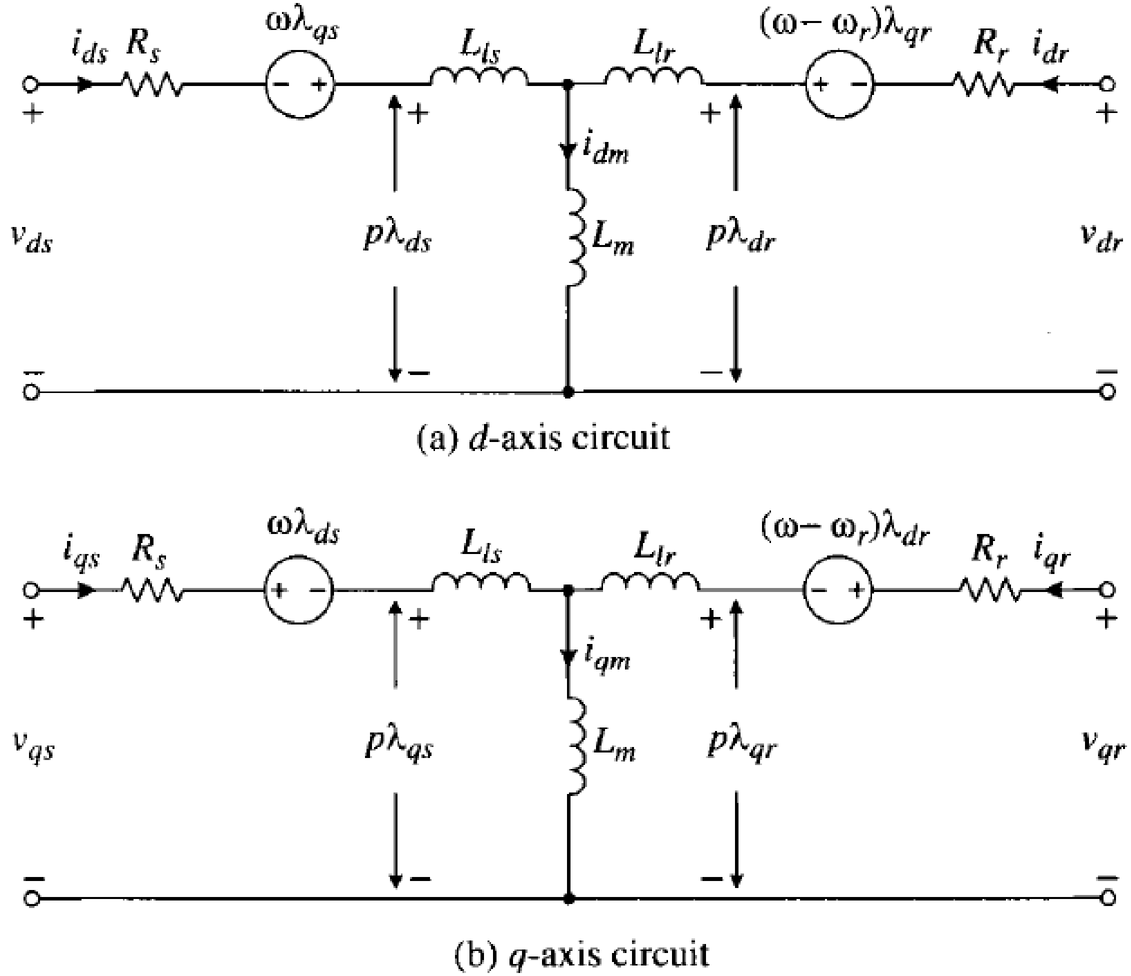

Figure 11.3 Induction generator *dq-axis model in the arbitrary reference frame [1]*

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To build the simulation model, the equations derived previously should be rearranged. Equation (11.4) can be rewritten as

$$\begin{cases} \lambda_{ds} = \left(v_{ds} - R_s i_{ds} + \omega\lambda_{qs}\right)/S \\ \lambda_{qs} = \left(v_{qs} - R_s i_{qs} - \omega\lambda_{ds}\right)/S \\ \lambda_{dr} = \left(v_{dr} - R_r i_{dr} + (\omega-\omega_r)\lambda_{qr}\right)/S \\ \lambda_{qr} = \left(v_{qr} - R_r i_{qr} - (\omega-\omega_r)\lambda_{dr}\right)/S \end{cases} \quad (11.6)$$

where the derivative operator p in Equation (11.4) is replaced by the Laplace operator *S, and 1/S represents an integrator. The flux linking is represented in matrix form*

$$\begin{bmatrix} \lambda_{ds} \\ \lambda_{qs} \\ \lambda_{dr} \\ \lambda_{qr} \end{bmatrix} = \begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix} \cdot \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} \quad (11.7)$$

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To build the simulation model, the equations derived previously should be rearranged. Equation (11.4) can be rewritten as

$$\begin{cases} \lambda_{ds} = \left(v_{ds} - R_s i_{ds} + \omega \lambda_{qs}\right)/S \\ \lambda_{qs} = \left(v_{qs} - R_s i_{qs} - \omega \lambda_{ds}\right)/S \\ \lambda_{dr} = \left(v_{dr} - R_r i_{dr} + (\omega - \omega_r)\lambda_{qr}\right)/S \\ \lambda_{qr} = \left(v_{qr} - R_r i_{qr} - (\omega - \omega_r)\lambda_{dr}\right)/S \end{cases} \tag{11.6}$$

where the derivative operator p in Equation (11.4) is replaced by the Laplace operator *S, and 1/S represents an integrator. The flux linking is represented in matrix form*

$$\begin{bmatrix} \lambda_{ds} \\ \lambda_{qs} \\ \lambda_{dr} \\ \lambda_{qr} \end{bmatrix} = \begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix} \cdot \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} \tag{11.7}$$

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By using the following matrix manipulation:

$$[\lambda]=[L][i] \quad \rightarrow \quad [L]^{-1}[\lambda]=[L]^{-1}[L][i] \quad \rightarrow \quad [i]=[L]^{-1}[\lambda] \tag{11.8}$$

$$\begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} = \frac{1}{D_1} \begin{bmatrix} L_r & 0 & -L_m & 0 \\ 0 & L_r & 0 & -L_m \\ -L_m & 0 & L_s & 0 \\ 0 & -L_m & 0 & L_s \end{bmatrix} \cdot \begin{bmatrix} \lambda_{ds} \\ \lambda_{qs} \\ \lambda_{dr} \\ \lambda_{qr} \end{bmatrix} \tag{11.9}$$

where $D_1 = L_s L_r - L_m^2$

The torque equations for the simulation model are given by

$$\begin{cases} \omega_r = \dfrac{P}{JS}\left(T_e - T_m\right) & \text{(a)} \\ T_e = \dfrac{3P}{2}\left(i_{qs}\lambda_{ds} - i_{ds}\lambda_{qs}\right) & \text{(b)} \end{cases} \tag{11.10}$$

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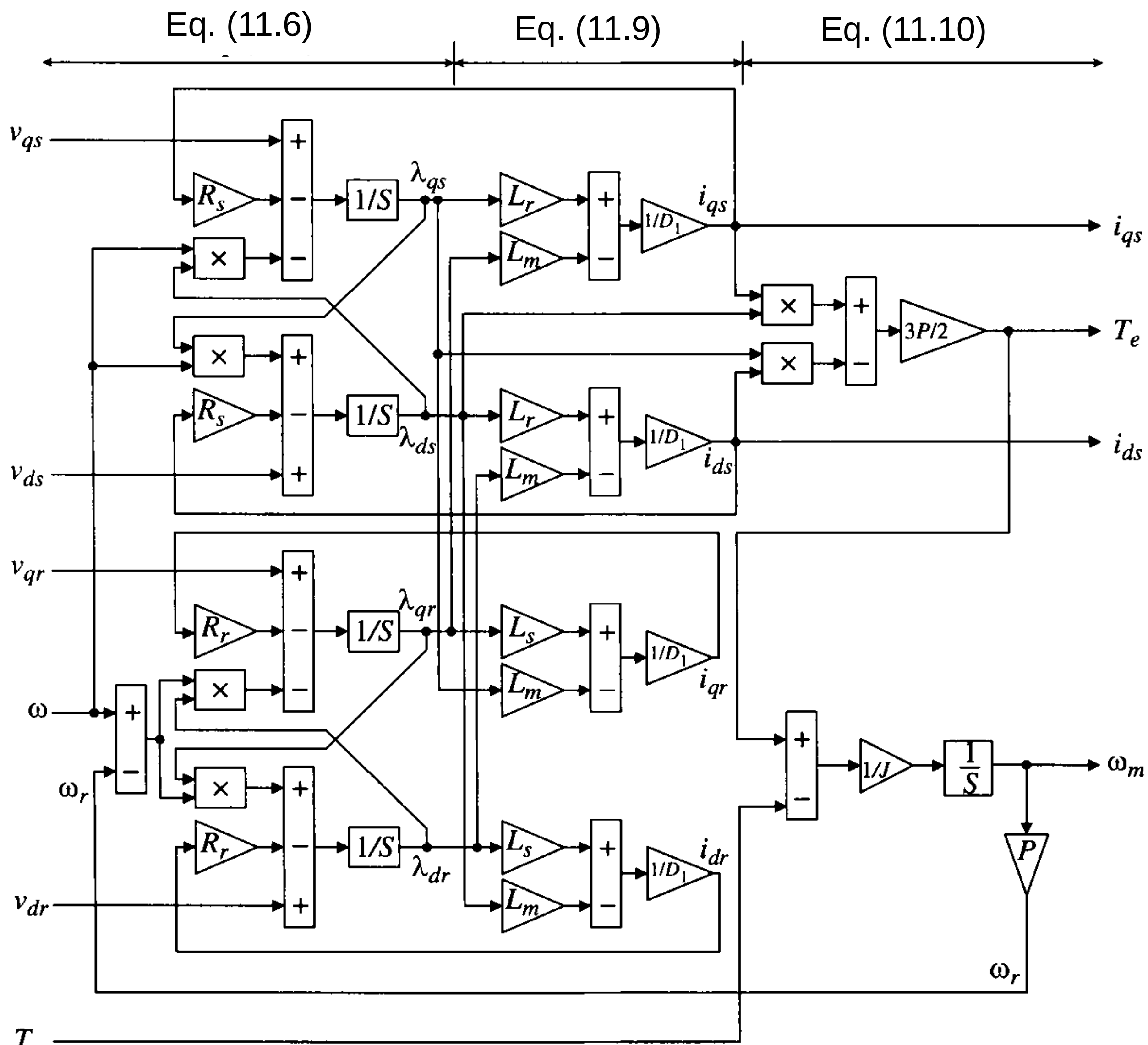

Figure 11.4 Block diagram for IM dynamic Model simulation in the arbitrary reference frame [1]

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Induction Generator Transient Characteristics

The transient characteristics of an induction-generator can be investigated using Figure 11.4.
The grid voltages v_{as}, v_{bs}, *and* v_{cs} *in the stationary* frame are transformed to the two-phase voltages v_α and v_β in the $\alpha\beta$ *stationary frame. In this case, the IG model in the stationary reference* frame should be used, which can be realized by setting the speed of the arbitrary reference frame to zero (w = 0).

Case Study 3-1—Direct Grid Connection of SCIG during System Startup.

This case study investigates the dynamic performance of a SCIG wind energy system during system start-up

Consider a 2.3 MW, 690 V, 50 Hz, 1512 rpm squirrel-cage induction generator. Its nameplate and parameters are listed in Appendix B Table B1 [1].

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Induction Generator Transient Characteristics

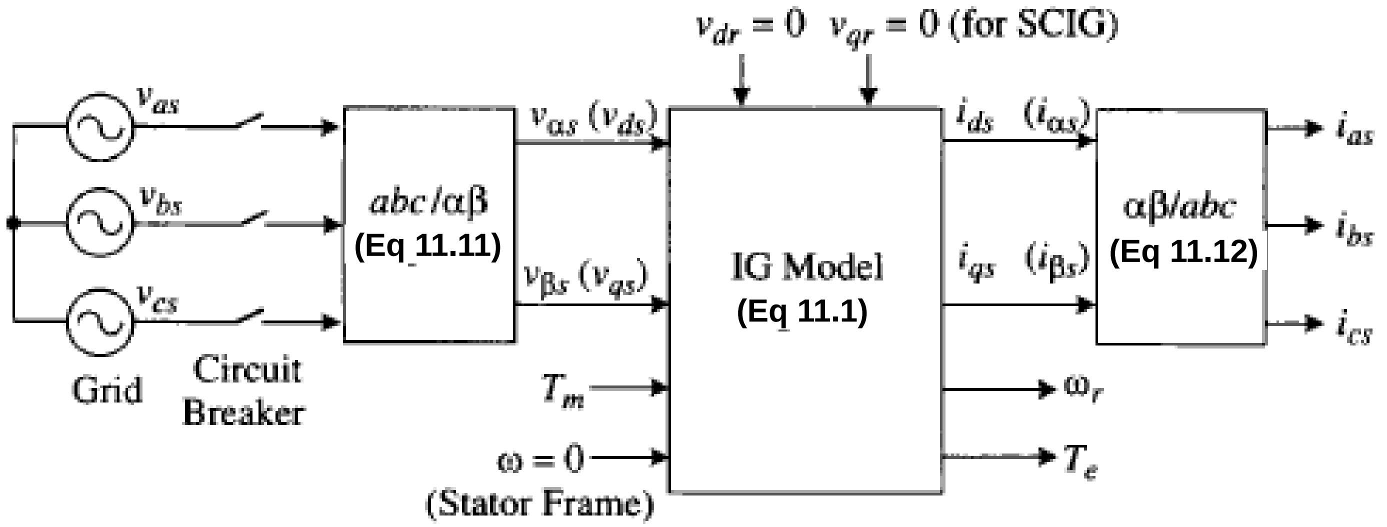

Figure 11.5 Block diagram for dynamic simulation of SCIG with direct grid connection [1]

$$abc/\alpha\beta \longrightarrow \begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \quad \textbf{(11.11)}$$

$$\alpha\beta/abc \longrightarrow \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} \quad \textbf{(11.12)}$$

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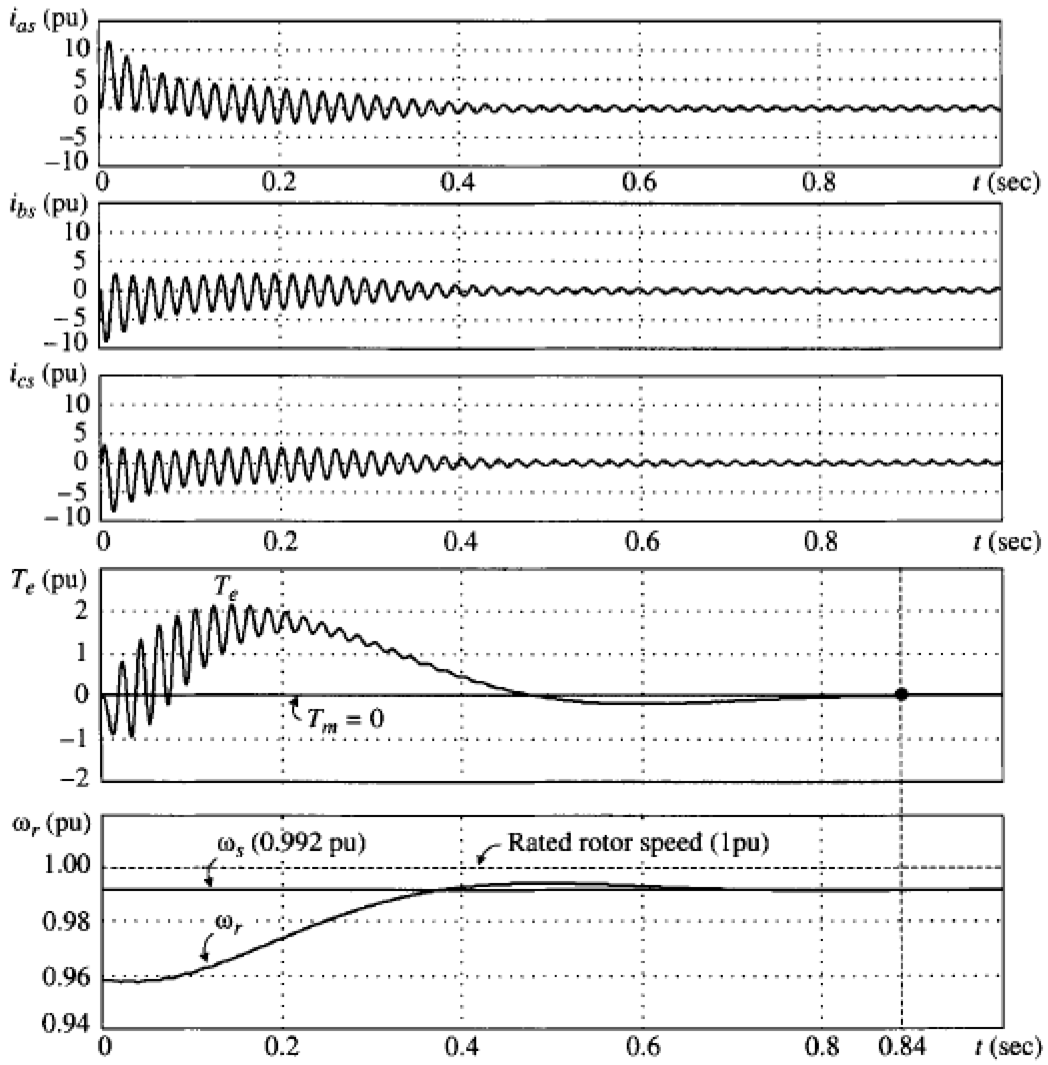

Figure 11.6 Dynamic response of SCIG with direct grid connection [1]

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It is clear the inrush current reach 10 time steady state as shown in Figure 11.6 and 117

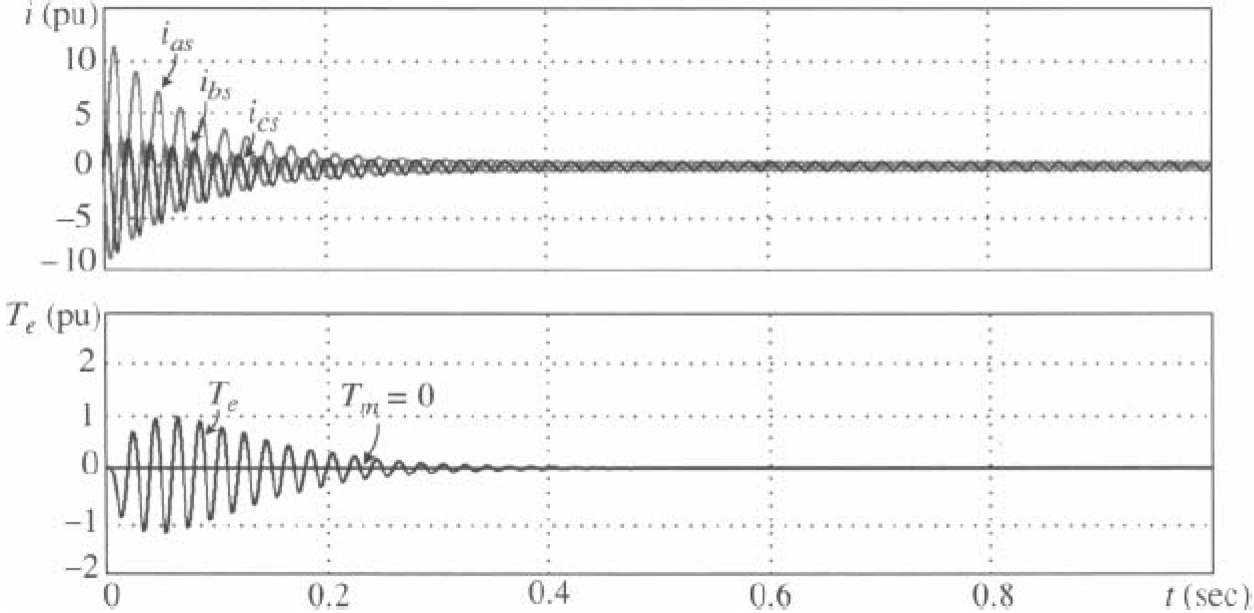

Figure 11.6 Dynamic response of SCIG with a fixed rotor speed during direct grid connection [1]

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Steady-State Equivalent Circuit

The steady-state equivalent circuit can be driven from the IG space-vector model described by Equation (11.1) according to the following steps

Set the arbitrary w in Equation (11.1) to the synchronous speed ws.

- Set the derivative terms to zero (*p*=0)
- Replace all space vectors in Equation (11.1) with their corresponding phasors.
- Reverse the rotor current direction, that is, the rotor current flows out of the rotor circuit instead of into the rotor circuit shown in Figure 11-2.

The equations for the steady-state analysis of the induction generator are then given by

$$\begin{cases} \overline{V}_s = R_s \overline{I}_s + j\omega \overline{\Lambda}_s \\ \overline{V}_r = -R_r \overline{I}_r + j(\omega_s - \omega_r)\overline{\Lambda}_r \end{cases} \quad (11.12)$$

where $\overline{\Lambda}_s$ *and* $\overline{\Lambda}_r$ are the phasors for the stator and rotor flux linkages λ_s *and* , λ_r, *respectively*

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Equation (11.12) cab be rewritten in the form

$$\begin{cases} \overline{V}_s = R_s \overline{I}_s + j\omega_s (L_{ls}\overline{I}_s + L_m \overline{I}_m) \\ \overline{V}_r = -R_r \overline{I}_r + j\omega_{sl}(-L_{lr}\overline{I}_r + L_m \overline{I}_m) \end{cases} \qquad (11.13)$$

where ω_{ls} *is the angular slip frequency, given by* $\omega_{ls} = \omega_s - \omega_r$.

The slip is given by $s = \dfrac{\omega_{sl}}{\omega_s}$

Then eq. (11.13) is rearranged as:

$$\begin{cases} \overline{V}_s = R_s \overline{I}_s + j\omega_s (L_{ls}\overline{I}_s + L_m \overline{I}_m) = R_s \overline{I}_s + jX_{ls}\overline{I}_s + jX_m \overline{I}_m \\ \dfrac{\overline{V}_r}{s} = -\dfrac{R_r}{s}\overline{I}_r + j\omega_s(-L_{lr}\overline{I}_r + L_m \overline{I}_m) = -\dfrac{R_r}{s}\overline{I}_r - jX_{lr}\overline{I}_r + jX_m \overline{I}_m \end{cases} \qquad (11.14)$$

where $\begin{cases} X_{ls} = \omega_s L_{ls} \\ X_{lr} = \omega_s L_{lr} \\ X_m = \omega_s L_m \end{cases}$

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Steady-State Power Flow

The rotor resistance can be represented in the form $\frac{R_r}{s} = R_r + \frac{1-s}{s} R_r$ then the eq. circuit will be as shown in Figure 11.7

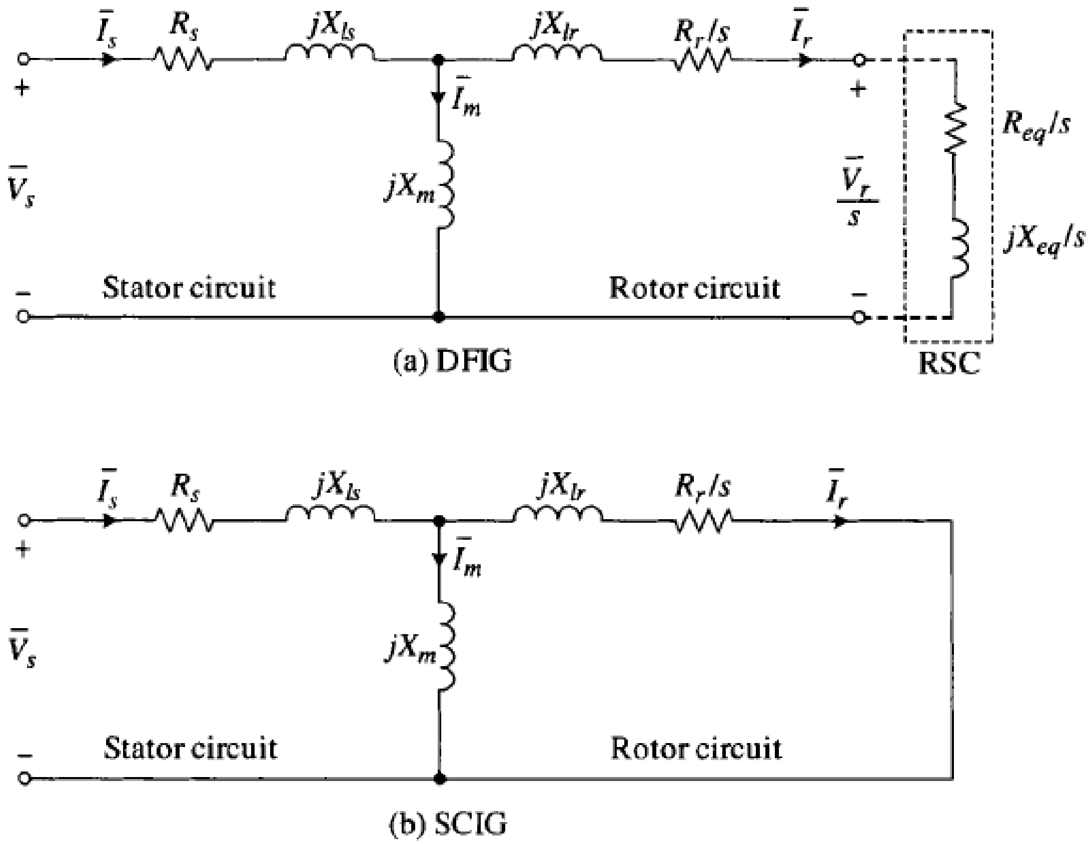

Figure 11.7 Steady-state equivalent circuits of an induction generator [1]

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The mechanical power of the shaft can be calculated by

$$P_m = 3I_r^2 \frac{(1-s)}{s} R_r \qquad (11.15)$$

Then the copper losses

$$\begin{cases} P_{cu,r} = 3I_s^2 R_r \\ P_{cu,s} = 3I_s^2 R_s \end{cases} \qquad (11.16)$$

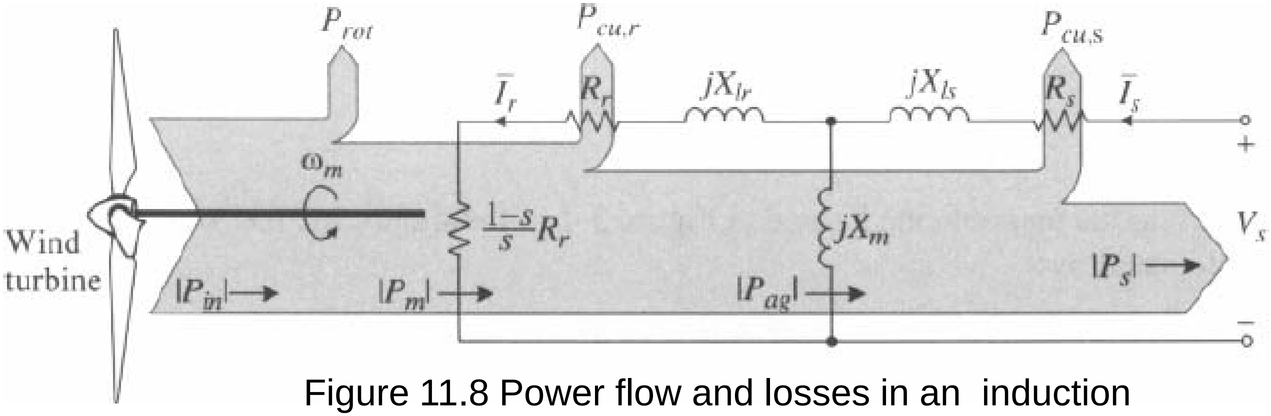

Figure 11.8 Power flow and losses in an induction generator [1]

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The stator output power can be obtained from

$$|P_s| = |P_m| - P_{cu,r} - P_{cu,s} \qquad (11.17)$$

Which can be obtained also from $P_s = 3V_s I_s \cos\varphi_s$

where $\varphi_s = \angle\overline{V}_s - \angle\overline{I}_s$

The mechanical power is given by

$$P_m = T_m \omega_m \qquad (11.18)$$

Substitute in eq. (11. 15), the mechanical torque

$$T_m = \frac{1}{\omega_m}\left(3I_r^2 \frac{1-s}{s} R_r\right) = \frac{1}{\omega_r / P}\left(3I_r^2 \frac{1-s}{s} R_r\right) \qquad (11.19)$$

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Substitute $(1-s)=\omega_r/\omega_s$ then

$$T_m = \frac{1}{\omega_s / P}\left(3I_r^2 \frac{R_r}{s}\right) = \frac{P_{ag}}{\omega_s / P} \qquad (11.20)$$

where

$$P_{ag} = 3I_r^2 \frac{R_r}{s} \qquad (11.21)$$

The rotor current is obtained

$$I_r = \frac{V_s}{\sqrt{\left(R_s + \frac{R_r}{s}\right)^2 + \left(X_{ls} + X_{lr}\right)^2}} \qquad (11.22)$$

Then the torque

$$T_m = \frac{3P}{\omega_s} \cdot \frac{R_r}{s} \cdot \frac{V_s^2}{\left(R_s + \frac{R_r}{s}\right)^2 + \left(X_{ls} + X_{lr}\right)^2} \qquad (11.23)$$

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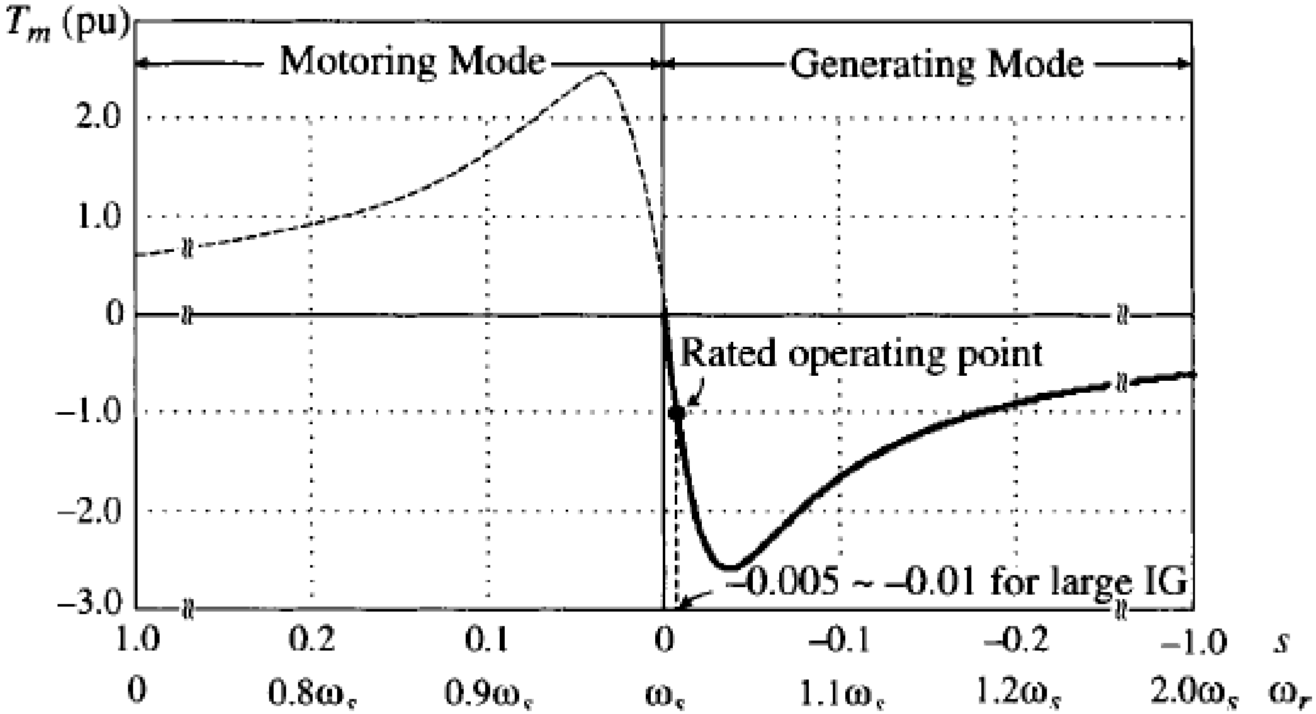

Figure 11.9 Typical torque-slip curve of squirrel-cage induction generator [1]

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References

Books:

[1] Power conversion and control of wind energy systems, B. Wu *et al.* , John Wiley & Sons, 2011

[2] Wind energy engineering. New York: McGraw-Hill, Jain, P. (2011).

[3] Understanding wind power technology: Theory, Deployment and Optimisation. John Wiley & Sons. Schaffarczyk, A. (Ed.). (2014).

[4] Renewable Energy Systems, the choice and modelling of 100 % renewable solutions", Henrik Lund , Elsevier, 2010.

Review articles:

[5] Herbert, G. J., Iniyan, S., Sreevalsan, E., & Rajapandian, S. (2007). A review of wind energy technologies. Renewable and sustainable energy Reviews, 11(6), 1117-1145.

[6] Leung, D. Y., & Yang, Y. (2012). Wind energy development and its environmental impact: a review. Renewable and sustainable energy reviews, 16(1), 1031-1039.

Web links:

[7] www.ewea.org European Wind Energy Association

[8] www.indea.org World Wind Energy Association

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Introduction to Wind Energy

Module 2.1

Synchronous Generator: modelling and dynamics
Lesson 12

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Objective

The purpose of this lesson is to present the dynamic models of synchronous generators, which are used in industry to analyze, simulate and design the power section of this Wind Energy Converters.

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Learning Outcomes

This lesson will contribute to the students to:

O2. Understand the different components and types of wind turbines and as their work;

O4. Be able to select wind turbines and to design (at preliminary project level) a wind farm in a South-Mediterranean location.

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Technical Contents

1. Dynamic Modelling of synchronous generators

2. Analysis of Transient characteristics

3. Case Study

The students are advised to have the following reference as several equations and figures are cited from it:

Reference Book:
Power conversion and control of wind energy systems, B. Wu *et al.* , John Wiley & Sons, 2011

For more details regarding this lecture, kindly refer to ch3 in the reference book mentioned above

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AGENDA

Wind Generators Modelling

1.Synchronous Generator Modelling

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Synchronous Generator s

Synchronous generators (SGs) are widely used in wind energy conversion systems from the range of kilowatts to megawatts. The synchronous generators can be classified into two categories:

- wound-rotor synchronous generators (WRSGs) and
- permanent-magnet synchronous generators (PMSGs).

In the WRSG the rotor flux is generated by the rotor field winding, whereas the PMSG uses permanent magnets to produce the rotor flux.

In addition, the SG can be classified based on the rotor shape and air gap into salient-pole and nonsalient-pole types.

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Wound-Rotor Synchronous Generators

the WRSG has a wound-rotor configuration to generate the rotor magnetic flux as shown in Figure 12.1 with salient-pole WRSG. It has twelve poles. The field winding is wound around pole shoes, which are placed symmetrically on the perimeter of the rotor in a radial configuration around the shaft to accommodate large number of poles.

The synchronous generators with a high number of poles (e.g., 72 poles) operating at low rotational speeds can be used in direct-driven megawatt wind energy systems where there is no need for a gearbox. This leads to a reduction in power losses and maintenance cost [1].

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The rotor-field winding of the synchronous generator requires DC excitation through brushes

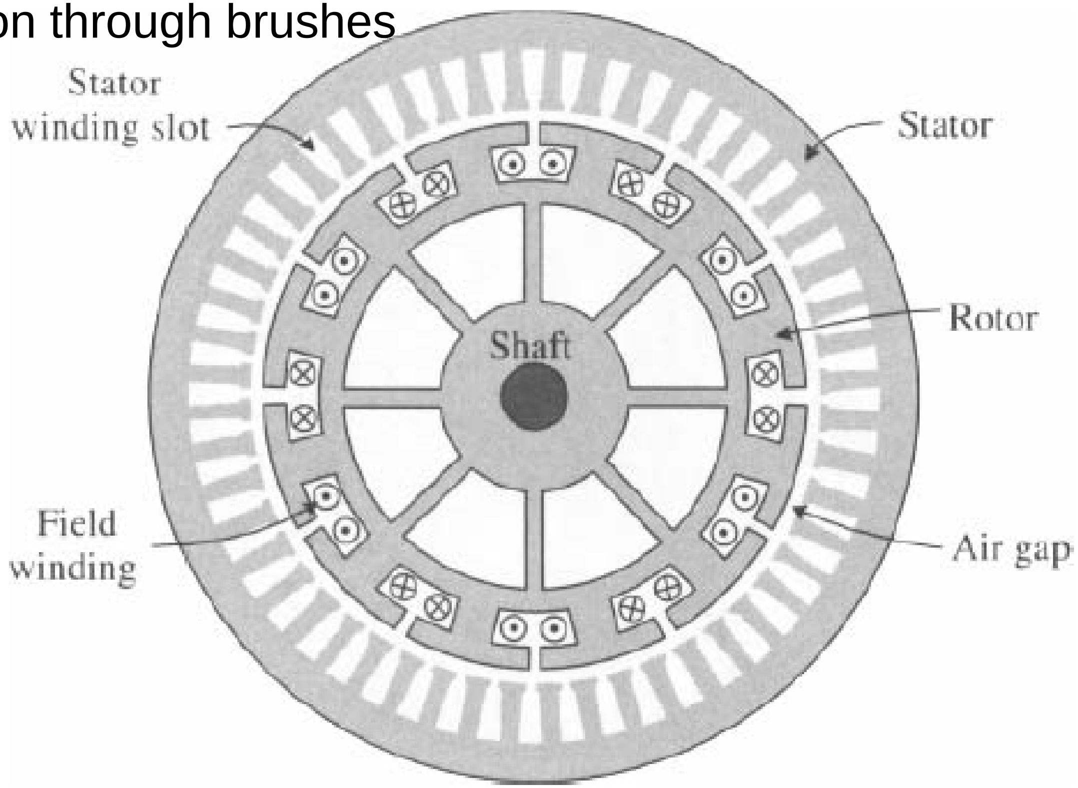

Figure 12.1 Salient-pole, wound-rotor synchronous generator (twelve-pole configuration [1]

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Permanent-Magnet Synchronous Generators

The rotor magnetic flux is generated by permanent magnets which called brushless.

This configuration leas to :

A high power density can be achieved,

low size and weight of the generator,

no rotor winding losses, and low thermal stress on the rotor.

The drawbacks of these generators are 1) permanent magnets are more expensive and 2) prone to demagnetization.

It can be classified into surface-mounted and inset PM generators .

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Surface Mounted PMSG

In the surface-mounted PMSG, the permanent magnets are placed on the rotor surface as shown in Figure 12.2. The figure shows PMSG with 6 magnets mounted on the surface of the rotor core, separated by nonferrite materials

The main advantages of this configuration is its simplicity and low construction cost. However, its application is limited to low speed to avoid the detachment from the rotor due to centrifugal forces.

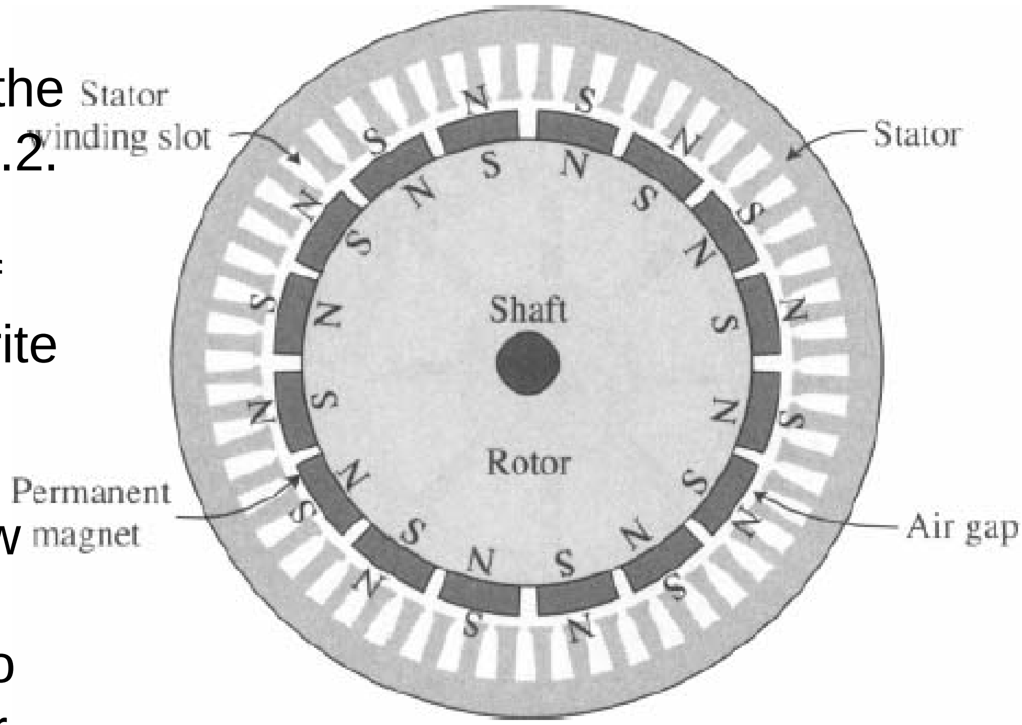

Figure 12.2 Surface-mounted nonsalient PMSG (sixteen-pole configuration [1]

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Insert PMSG

the permanent magnets are inset into the rotor surface as shown in Figure 12.3.

The saliency is created by the different permeability of the rotor core material and magnets.

This configuration also reduces rotational stress associated with centrifugal forces

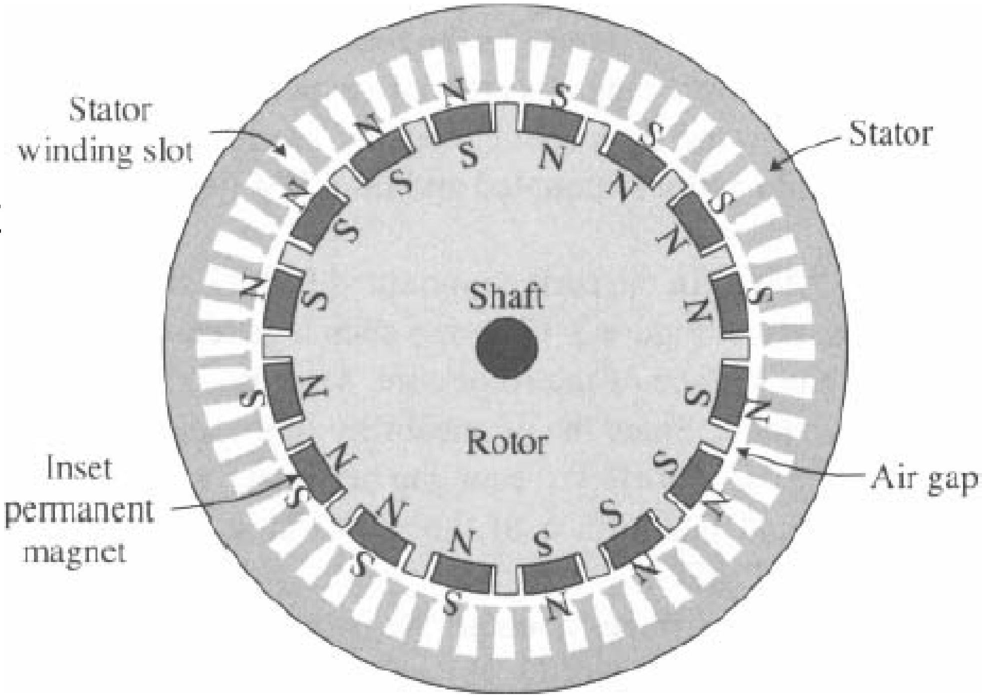

Figure 12.3 Insert PMSG with salient poles (four-pole configuration [1]

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Dynamic Model of SG

The dq-axis model of a synchronous generator is shown in Figure 12.4*.* The SG is normally modeled in the rotor field synchronous reference frame. The stator circuit of the *dq-axis model is similar to induction* generator except that [1]

1. The speed of the arbitrary reference frame w in the IG model is replaced by the rotor speed w_r *in the synchronous frame*
2. The magnetizing inductance *L_m is replaced by the dq-axis magnetizing inductances L_{dm} and L_{qm} of the synchronous generator. In a nonsalient SG, the d- and q-axis magnetizing inductances are equal ($L_{dm} = L_{qm}$), whereas in the salient pole* generators, *d-axis magnetizing inductance is normally lower than the q-axis* magnetizing inductance *($L_{dm} < L_{qm}$).*
3. The *dq-axis stator currents, i_{ds} and i_{qs}, flow out of the stator.*

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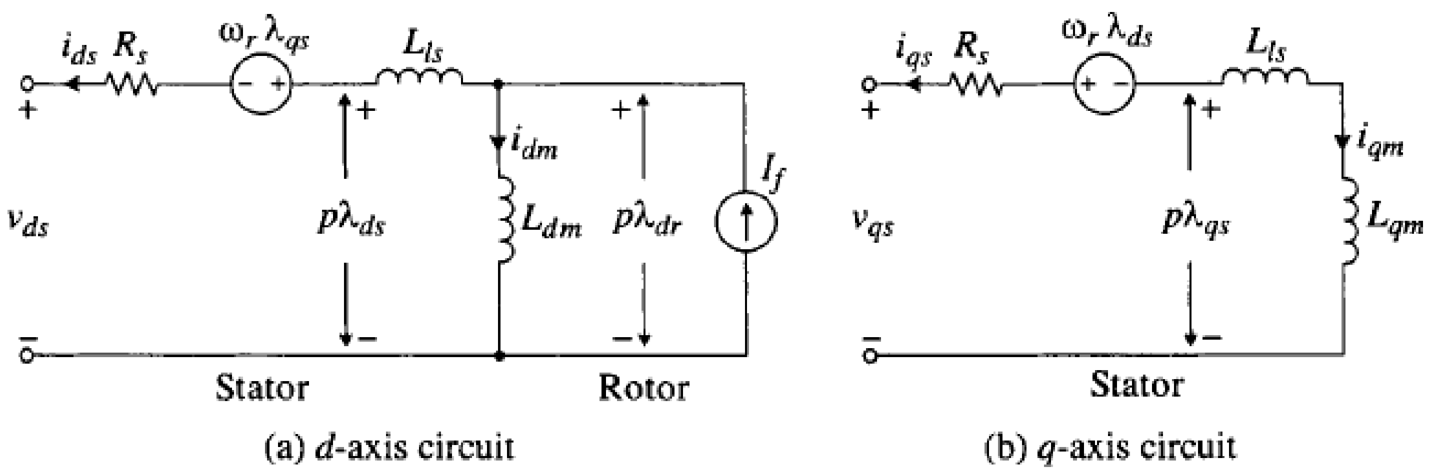

Figure 12.4 General *dq-axis model of SG in the rotor field synchronous reference frame [1]*

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The voltage equations for the synchronous generator are given by

$$\begin{cases} v_{ds} = -R_s i_{ds} - \omega_r \lambda_{qs} + p\lambda_{ds} \\ v_{qs} = -R_s i_{qs} + \omega_r \lambda_{ds} + p\lambda_{qs} \end{cases} \quad (12.1)$$

where λ_{ds} *and* λ_{qs} *are the d- and g-axis stator flux linkages, given by*

$$\begin{cases} \lambda_{ds} = -L_{ls} i_{ds} + L_{dm}\left(I_f - i_{ds}\right) = -(L_{ls} + L_{dm})i_{ds} + L_{dm} I_f = -L_d i_{ds} + \lambda_r \\ \lambda_{qs} = -(L_{ls} + L_{qm}) i_{qs} = -L_q i_{qs} \end{cases} \quad (12.2)$$

Where λ_r is the rotor flux, and L_d *and* L_q *are the stator dq-axis self-inductances, defined* by

$$\begin{cases} \lambda_r = L_{dm} I_f \\ L_d = L_{ls} + L_{dm} \\ L_q = L_{ls} + L_{qm} \end{cases} \quad (12.3)$$

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Substitute from (12.3) into (12.1) and consider that $d\lambda_r/dt = 0$ then

$$\begin{cases} v_{ds} = -R_s i_{ds} + \omega_r L_q i_{qs} - L_d p i_{ds} \\ v_{qs} = -R_s i_{qs} - \omega_r L_d i_{ds} + \omega_r \lambda_r - L_q p i_{qs} \end{cases} \quad (12.4)$$

Then the simplified model will be

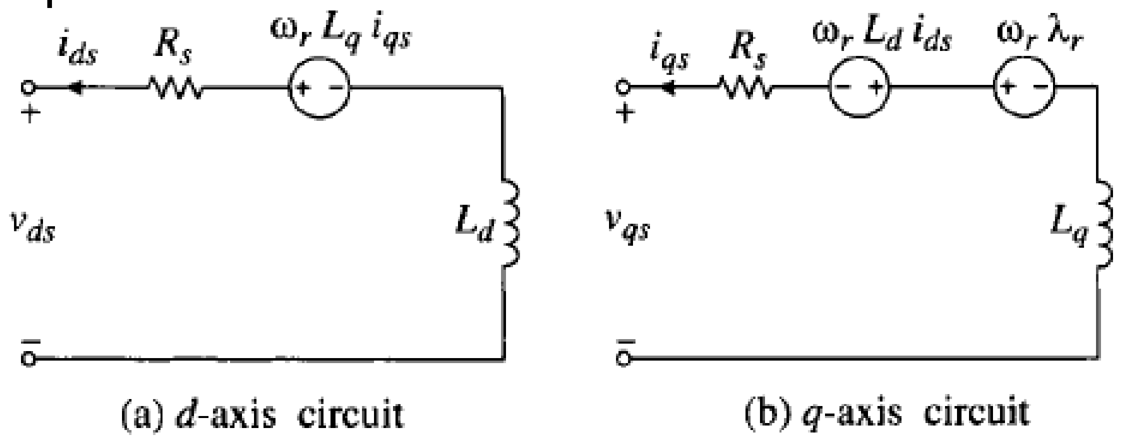

Figure 12.5 Simplified *dq-axis model of SG in the rotor-field synchronous reference frame [1]*

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The electromagnetic torque

$$T_e = \frac{3P}{2}\left(i_{qs}\lambda_{ds} - i_{ds}\lambda_{qs}\right)$$

Substitute by (12.2) into torque equation then

$$T_e = \frac{3P}{2}\left[\lambda_r i_{qs} - \left(L_d - L_q\right) i_{ds} i_{qs}\right] \qquad (12.5)$$

The rotor speed based on the mechanical motion is given by

$$\omega_r = \frac{P}{JS}\left(T_e - T_m\right) \qquad (12.6)$$

Then the dynamic model of stator current is represented as

$$\begin{cases} i_{ds} = \frac{1}{S}\left(-v_{ds} - R_s i_{ds} + \omega_r L_q i_{qs}\right) / L_d \\ i_{qs} = \frac{1}{S}\left(-v_{qs} - R_s i_{qs} - \omega_r L_d i_{ds} + \omega_r \lambda_r\right) / L_q \end{cases} \qquad (12.7)$$

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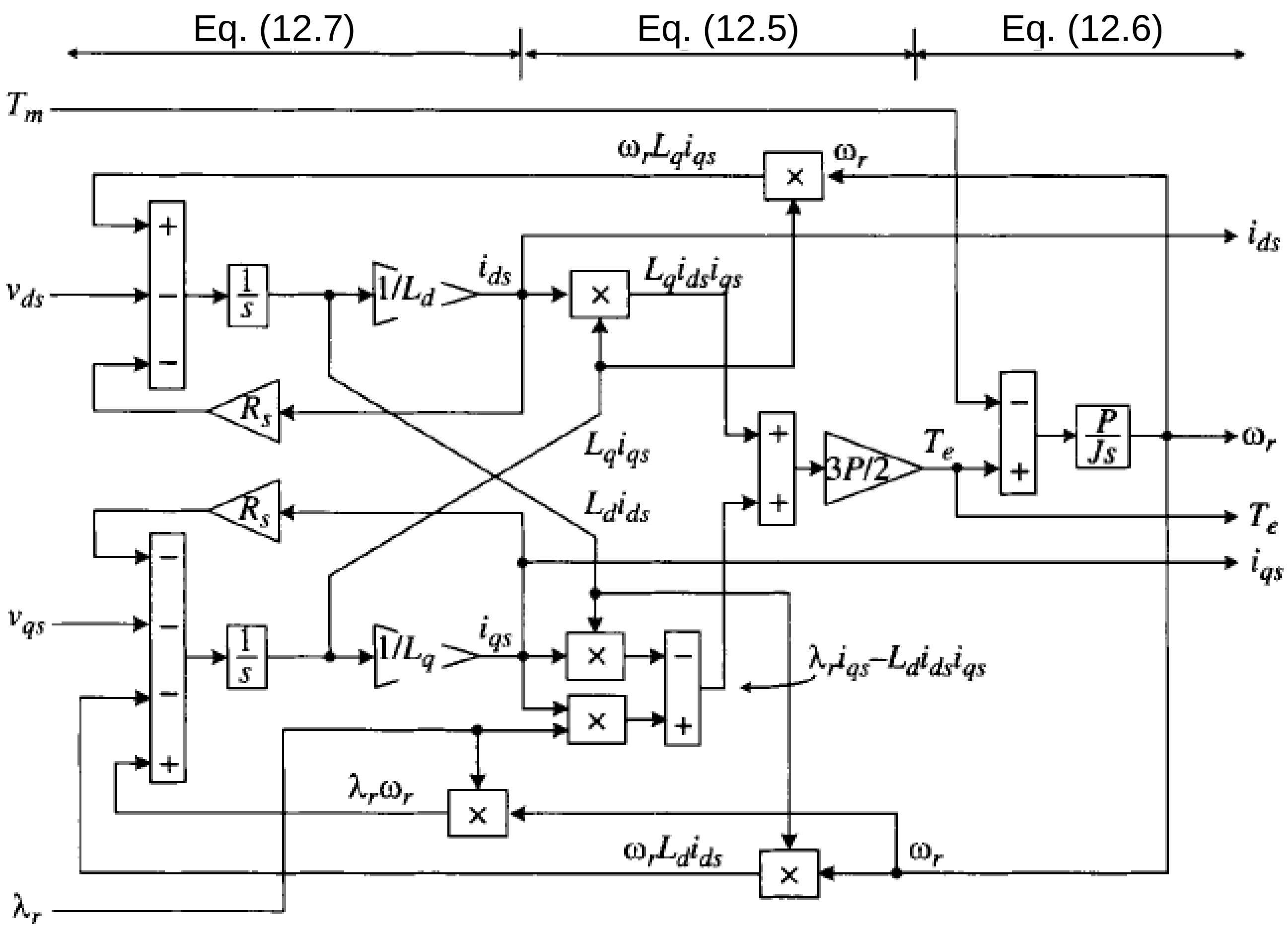

Figure 12.6 Block diagram for dynamic simulation of synchronous generators [1]

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Case Study —Analysis of Synchronous Generator in Standalone Operation.

The purpose of the case study is to

- Investigate the operation of a stand-alone SG wind energy system feeding a three-phase resistive load
- Illustrate how to effectively use the simulation model of Figure 12.6 for the simulation of synchronous generators
- Reveal the relationship between the three-phase *abc variables in the stationary* frame and the *dq variables in the synchronous frame [1]*

The generator used in the study is a 2.45 MW, 4000 V, 53.33 Hz, 400 rpm nonsalient pole PMSG, whose parameters are given in Table B-10 in Appendix B of [1] .

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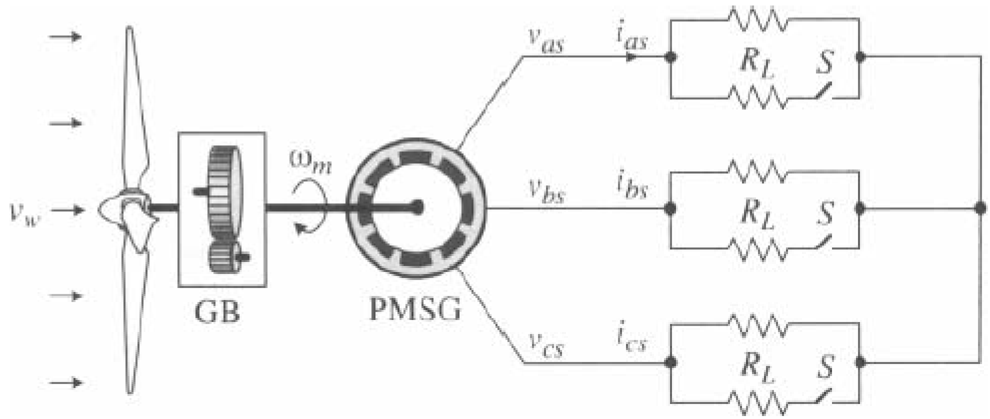
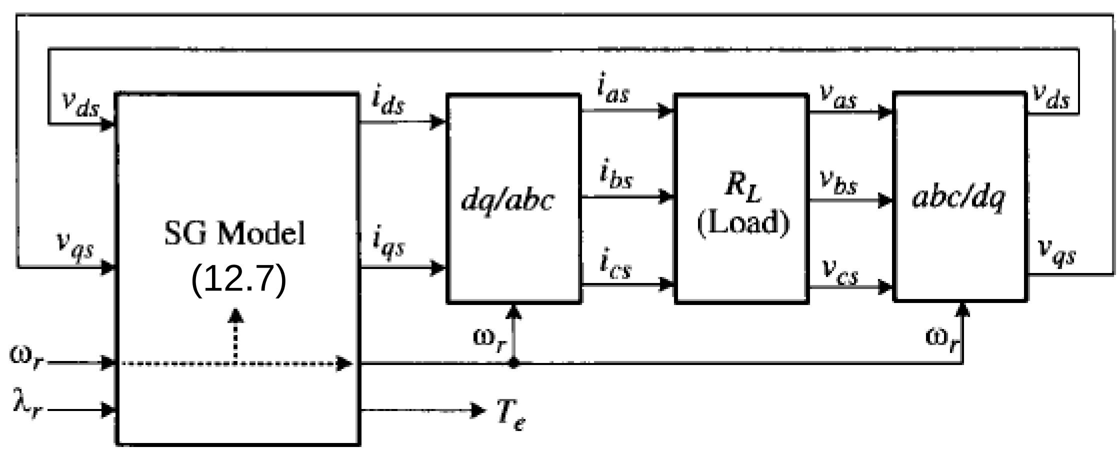


(a) SG with a three-phase resistive load



(b) Block diagram for simulation

Figure 12.7 Block diagram of a stand-alone SG configuration with a three-phase resistive load [1].

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with a three-phase balanced resistive load R_L *and operates at 320 rpm (0.8* pu) at a given wind speed. The loading of the generator can be changed by switch *S.* When *S is closed at t=0.015sec , the load resistance is reduced to* $R_L/2$ *per phase.*

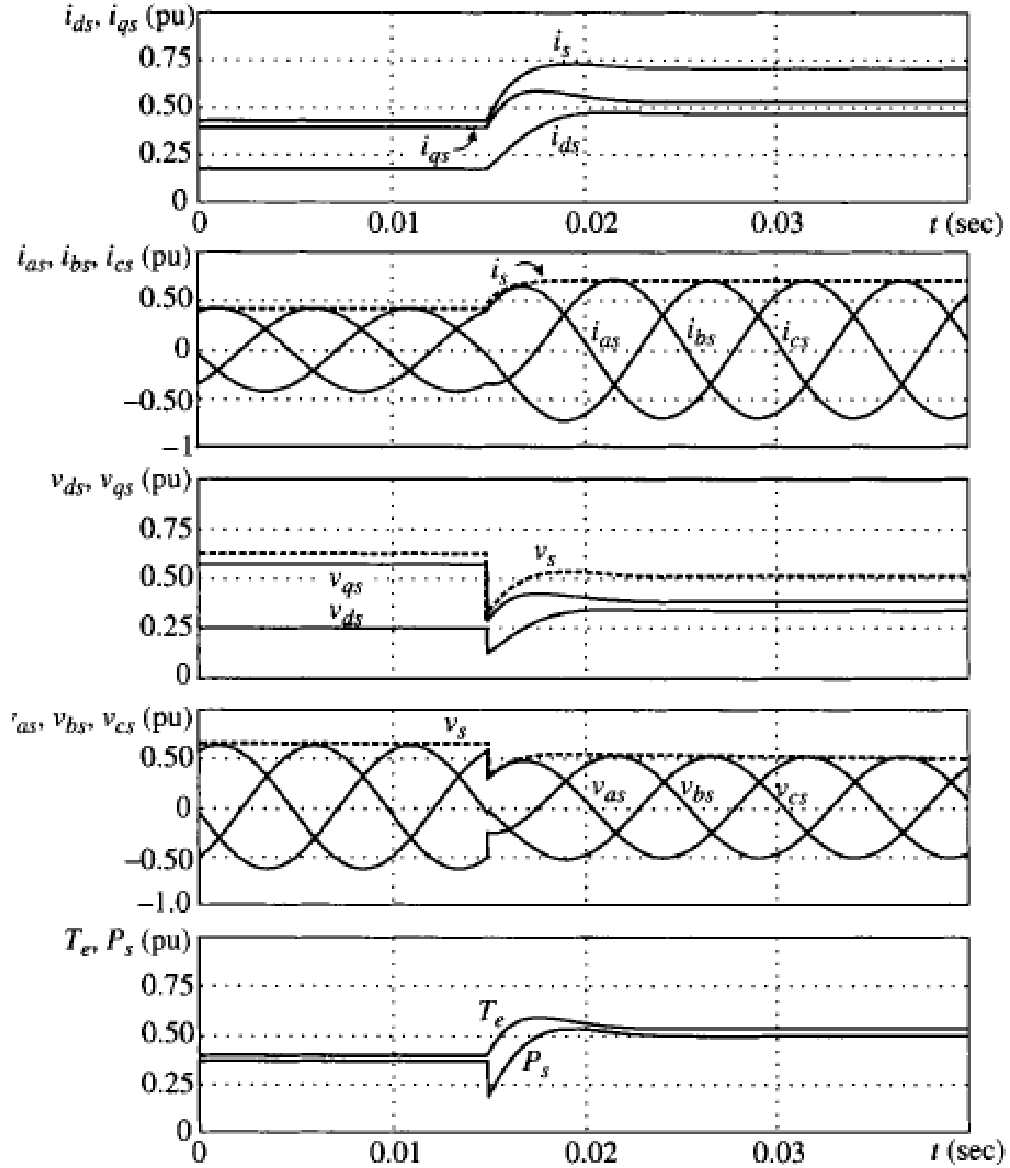

Figure 12.8 Simulated waveforms for a stand-alone PMSG system with resistive load [1]

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Steady-State Equivalent Circuits

the steady state equations of the synchronous generator are given by

$$\begin{cases} v_{ds} = -R_s i_{ds} + \omega_r L_q i_{qs} \\ v_{qs} = -R_s i_{qs} - \omega_r L_d i_{ds} + \omega_r \lambda_r \end{cases} \quad (12.8)$$

and the equivalent circuit is shown in Figure 12.9

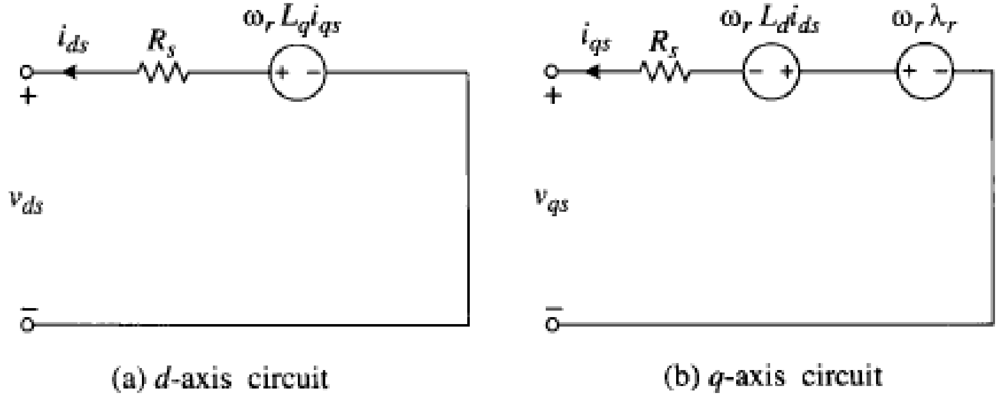

Figure 12.9 Steady-state model of synchronous generator[1]

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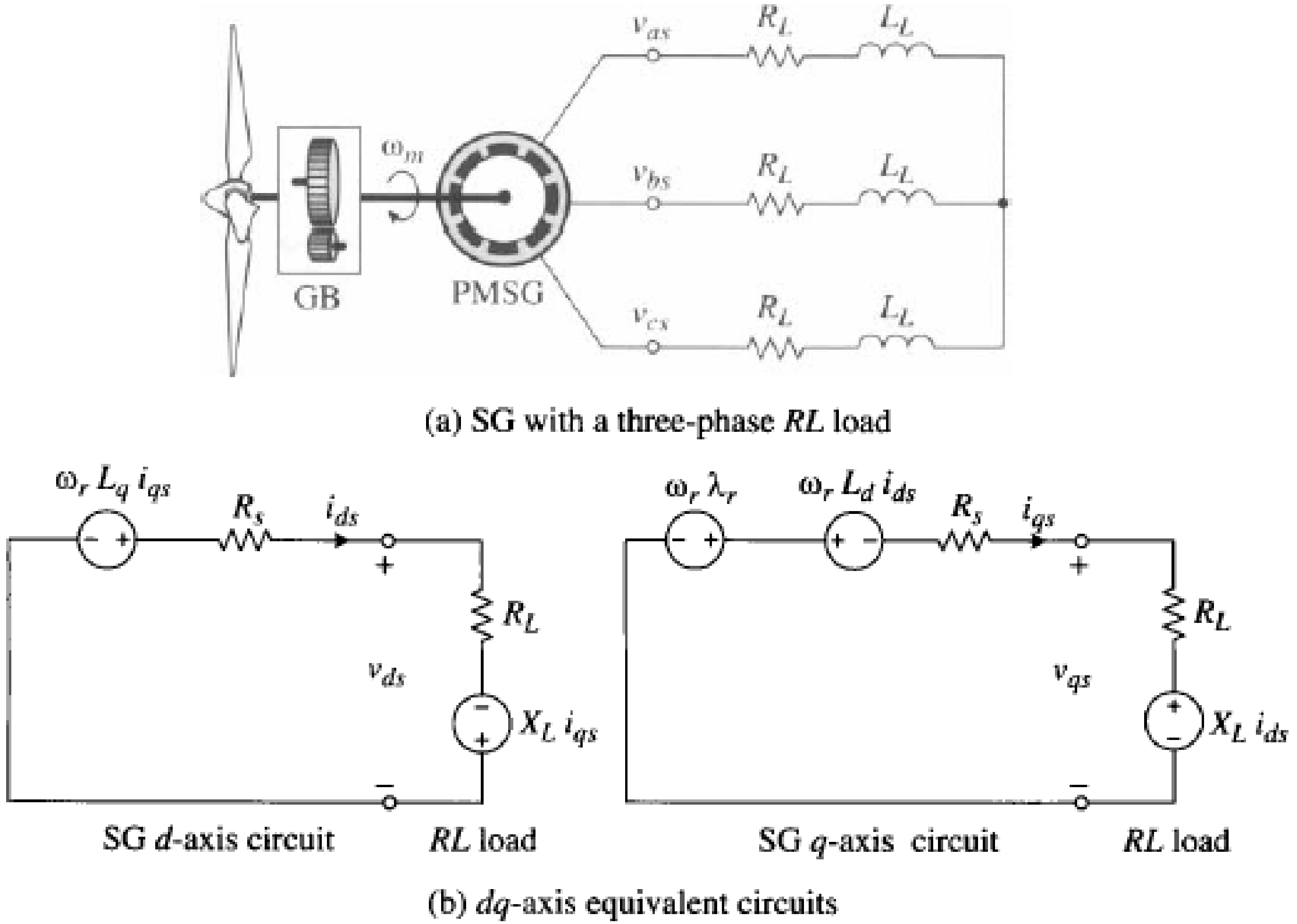

Figure 12.10 Steady-state analysis of PMSG
with an *RL load[1]*

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References

Books:

[1] Power conversion and control of wind energy systems, B. Wu *et al.* , John Wiley & Sons, 2011

[2] Wind energy engineering. New York: McGraw-Hill, Jain, P. (2011).

[3] Understanding wind power technology: Theory, Deployment and Optimisation. John Wiley & Sons. Schaffarczyk, A. (Ed.). (2014).

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[6] Leung, D. Y., & Yang, Y. (2012). Wind energy development and its environmental impact: a review. Renewable and sustainable energy reviews, 16(1), 1031-1039.

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Introduction to Wind Energy

Module 2.1

Fixed Speed WECS based on Squirrel Cage Induction Generator

Lesson 13

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Objective

The purpose of this lesson is to analyze and model WECS based on Squirrel Cage Induction Generator, to analyze, simulate and design the power section of these Wind Energy Converters.

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Learning Outcomes

This lesson will contribute to the students to:

O2. Understand the different components and types of wind turbines and as their work;

O4. Be able to select wind turbines and to design (at preliminary project level) a wind farm in a South-Mediterranean location.

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Technical Contents

1. *Fixed Speed operation of Squirrel Cage Induction Generators*
2. *Two Speed operation of Squirrel Cage Induction Generators*
3. *Case Study*

The students are advised to have the following reference as several equations and figures are cited from it:

Reference Book:
Power conversion and control of wind energy systems, B. Wu *et al.* , John Wiley & Sons, 2011

For more details regarding this lecture, kindly refer to ch6 in the reference book mentioned above

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AGENDA

Fixed Speed WECS based on Squirrel Cage Induction Generator

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Introduction

- The rotor is normally a squirrel-cage induction generator (SCIG).
- The generator shaft is driven by the wind turbine and its stator is directly connected to the grid.
- Under normal operating conditions, the stator frequency is fixed to that of the grid and the slip is very low (less than 1% for megawatt generators).
- Its advantages are simple configuration, reliable operation, and low costs for manufacturing, installation, and maintenance.
- However, it causes higher mechanical stress and higher power fluctuation. It has a lower overall energy conversion efficiency since the generator speed cannot be adjusted to achieve maximum power operation at different wind speeds.
- Moreover, it unable to control the reactive power to the grid without using additional devices

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Configuration of Fixed-speed SCIG Wind Energy

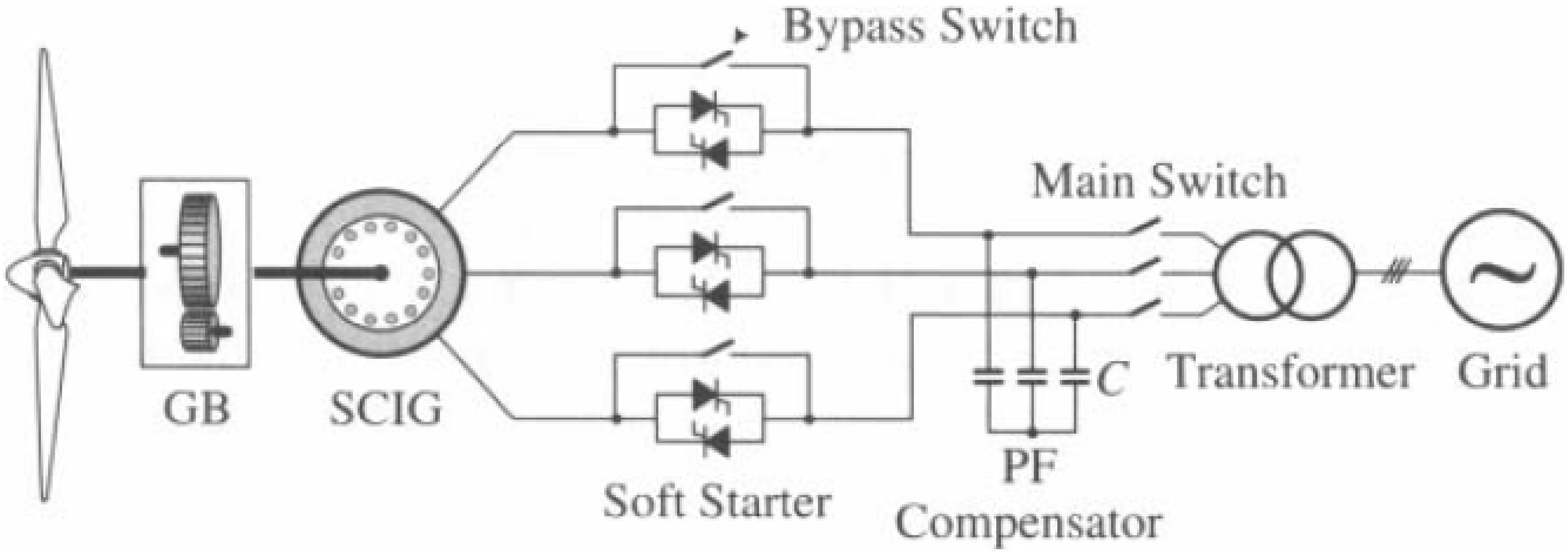

Figure 13.1 Configuration of fixed-speed SCIG wind energy conversion system [1]

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1. Wind Turbine

- The wind power is captured by the blades, which convert the wind kinetic energy into rotational mechanical energy. The three-blade wind turbine is preferred for large (megawatt) fixed-speed wind energy systems.
- The generated output power starts when the wind speed is higher than the cut-in speed, around 3-4 m/s.
- If the wind speed is higher than the rated speed, around 12-15 m/sec, the power captured by the turbine is limited either by passive aerodynamic stall, active stall, or pitch control of the blades.
- If the wind speed exceeds the cut-out speed of around 25 m/s, the turbine is stopped by either full stall or full pitch of the blades to protect the turbine and generator from possible damage

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2. Wind Turbine

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2. Gearbox

- The rotating speed of large fixed-speed wind turbines is normally in the 6 to 25 rpm range. The generator operating speed is determined by the grid frequency and the number of poles.
- For instance, for a four-pole generator connected to a grid of 50 Hz, the synchronous speed is 1500 rpm.
- A gearbox with a high gear ratio is required to match the low speed of the turbine to the high speed of the generator.
- A multiple- stage gearbox is usually required to achieve the high gear ratio

Table 13.1 Examples of gear ratios for fixed-speed WECS (rated slip = -1 %) [1]

Rated turbine speed (rpm)	Gear ratio					
	50 Hz grid			60 Hz grid		
	4-pole	6-pole	8-pole	4-pole	6-pole	8-pole
12	126	84	63	152	101	76
14	108	72	54	130	87	65
16	94	63	47	114	76	57

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3. Generator

- Squirrel-cage induction generators are exclusively used in the fixed-speed WECS.
- When the generator is connected to the grid of 50 Hz or 60 Hz, the synchronous speed of the generator is fixed, and the rotor speed varies slightly with the system operating conditions.
- Figure 13.2 shows a torque-versus-speed curve of a 2.3 MW, 690 V, 50 Hz SCIG [1]. When this four-pole generator delivers the rated power to the grid of 50 Hz, its rated rotor speed is 1512 rpm, which is only 0.8% higher than the synchronous speed of 1500 rpm.
- The speed range for the generator is from 1500 rpm to 1512 rpm under normal operation conditions. The speed range is so narrow that this type of wind energy system is known as the fixed-speed WECS

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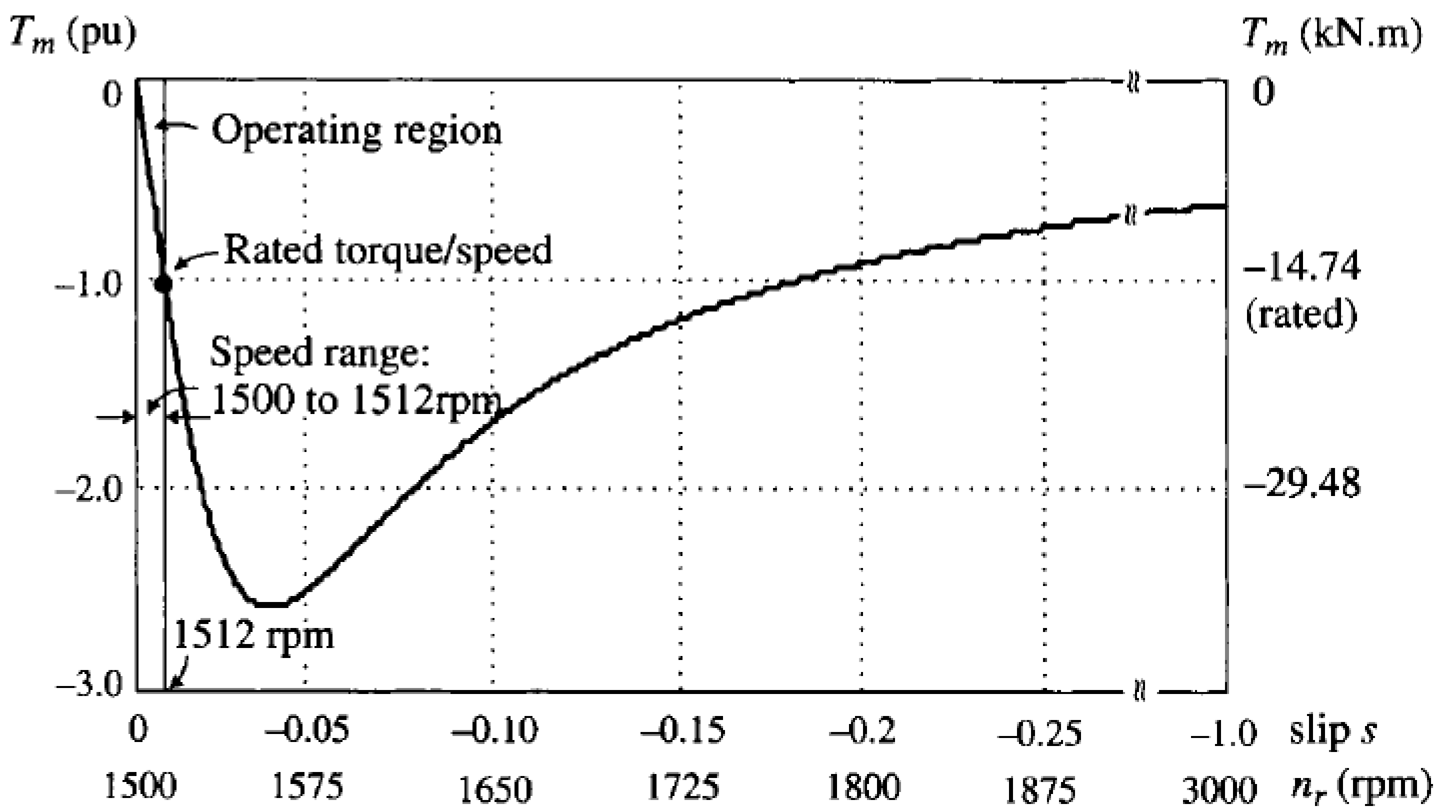

Figure 13.2. Torque-versus-speed curve of a 2.3 MW, 690 V, 50 Hz SCIG [1]

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4. Soft Starter

- A soft starter is normally used between the generator and the grid to limit the high inrush current during the system start-up.
- The soft starter is an AC voltage controller that increases the stator voltage gradually by controlling the firing angles of the SCR devices.
- The firing angles are varied to increase the stator voltage gradually from zero to the full voltage of the grid.
- When the soft starter voltage reaches the grid voltage, it is shorted by a bypass switch to eliminate the conduction losses of the SCR devices.

5. **Reactive Power Compensation**

- The squirrel-cage induction generator draws lagging reactive power from the grid during operation.
- A PF compensator device is normally installed to meet the grid code for reactive power compensation using capacitor banks

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6. Main Features and Drawbacks

a. Features

- It is simpler, more cost-effective, and robust .
- It is directly connected to the grid without the need of a full-capacity power converter system
- It does not need sophisticated control system

b. Drawbacks

- It has low power conversion efficiency
- The fixed-speed operation and uncontrolled generator do not allow the system to react quickly to wind gusts
- Inability to control active and reactive power which limits its application in weak grid.

- Table 13.2 summarize the main features and drawbacks

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Table 13.2 Sumarry of Fixed Speed SCIG Features [1]

Advantages	Description
Simple system and low costs	No PWM power converters No closed-loop controls Cost-effective generator (SCIG)
Reliable generator and low maintenance	Squirrel-cage rotor, no rotor winding No slip rings or brushes Compact size and light weight
Disadvantages	**Description**
Low conversion efficiency	Fixed-speed operation, unable to implement MPPT
Low power quality	No reactive power compensation capability Fluctuation in output power No voltage ride-through capability
High mechanical stress	Caused by gusts of wind and inability to control active power Reduction in life span of mechanical components

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Operation Principles of Fixed Speed SCIG

Figure 13.3 shows the operating condition of SCIG. It is clear if the wind speed operates beyond the rated generator speed, the extracted is lower than the maximum (MPP)

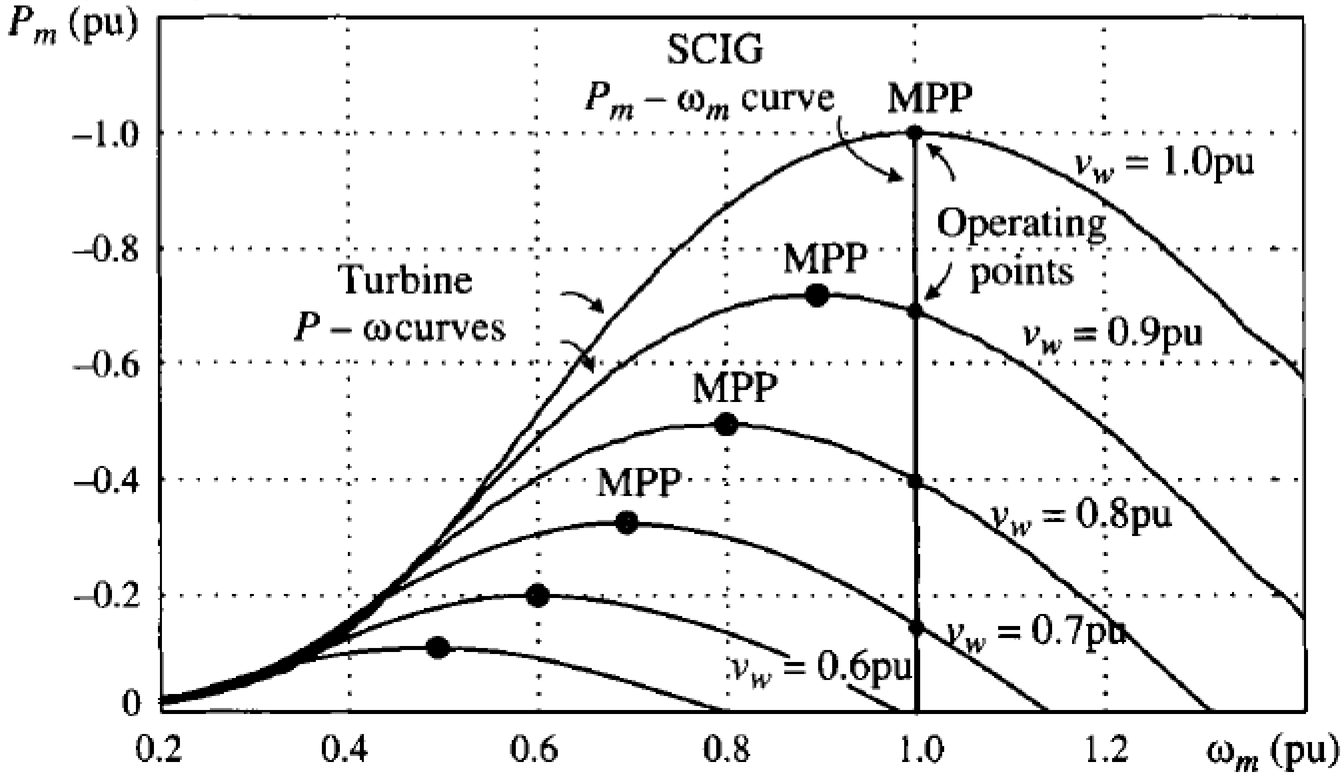

Figure 13.3 System operating points and maximum power points (MPP) at different wind Speeds [1]

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Two-Speed Operation of Fixed-Speed WECS

- To improve power conversion efficiency of the fixed-speed WECS, two-speed SCIG wind energy systems is used.
- The two-speed operation is realized by changing the number of poles of the stator winding.
- For example, the synchronous speed of a generator connected to a grid of 60 Hz is 1800 rpm and 1200 rpm with four pole and six-pole configurations, respectively.
- The stator winding can be reconfigured through a switch.
- For example, changing from the four-pole to eight-pole configuration, and vice versa, is performed by switch *S* through connecting the winding in parallel (high # of poles) or series configuration (low # of poles) as illustrated in Figure 13.4.
- Figure 13.5 and 13.6 show the characteristics of two speed configuration

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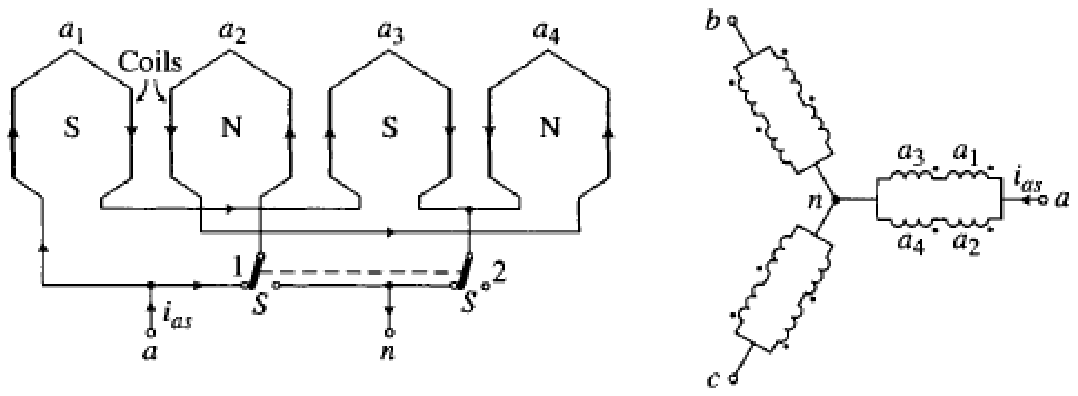
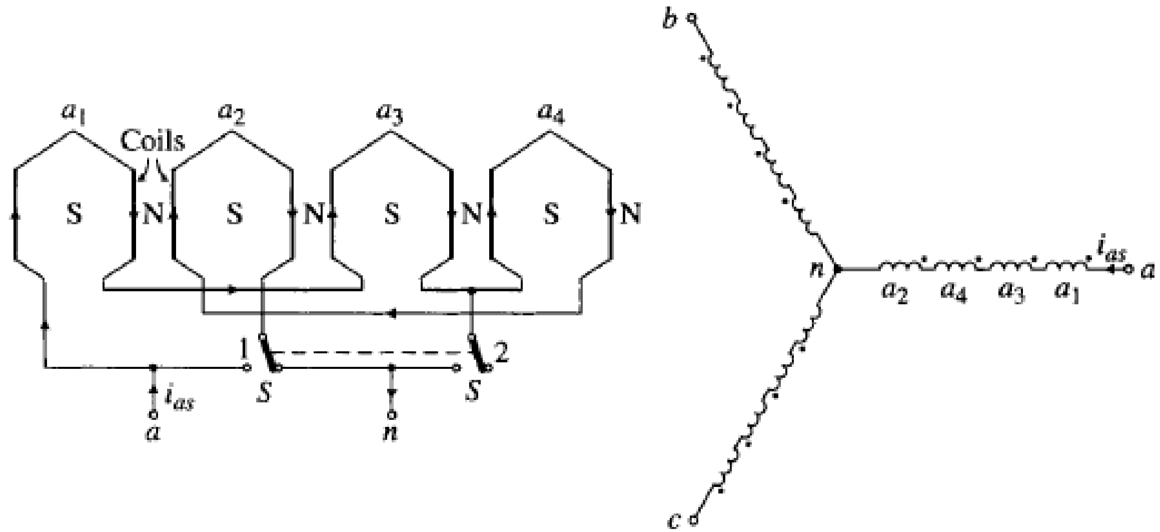


(a) 4-pole configuration



(b) 8-pole configuration

Figure 13.4 Induction generator with four-pole and eight-pole configurations [1]

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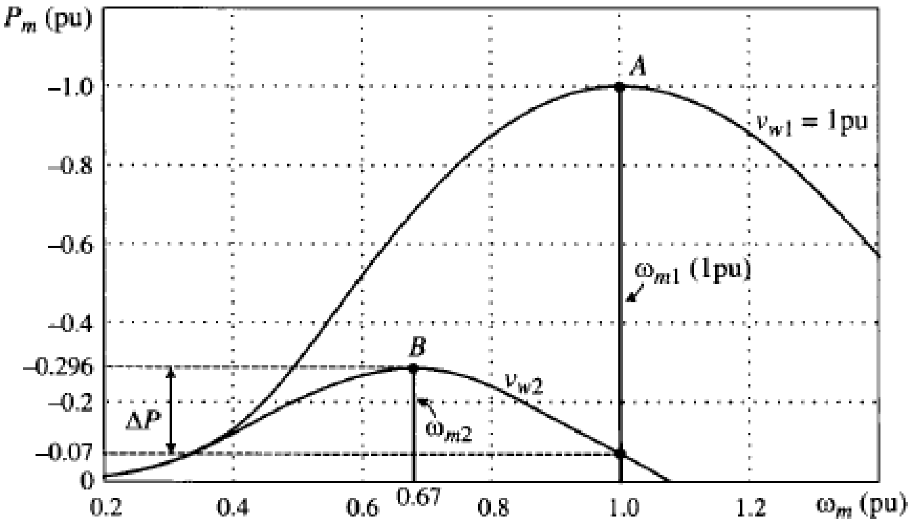

Figure 13.5 Power versus rotor speed characteristics of SCIG WECS with two fixed rotor speeds [1].

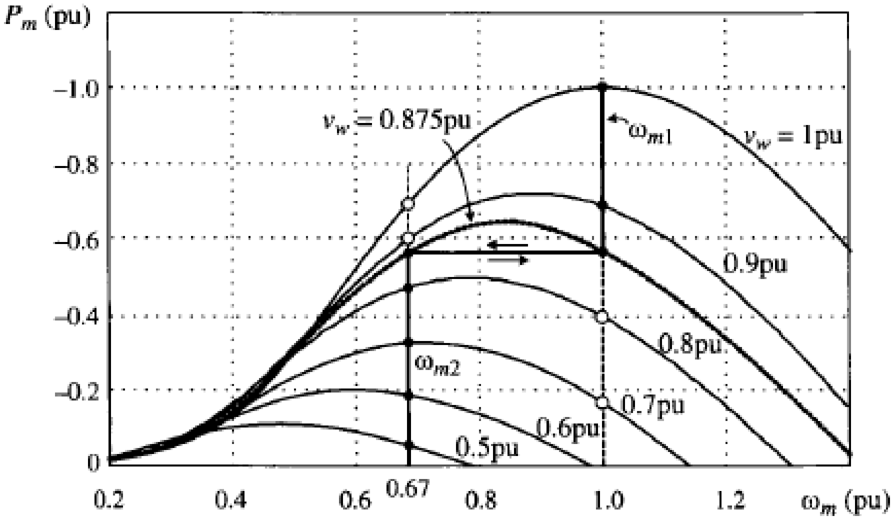

Figure 13.6 Switch between the two fixed rotor speeds ω_{ml} and ω_{m2} [1]

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Case Study –Grid Connected with Soft Starter

It is clear that at starting the turbine work as motor then it start to operate as generator

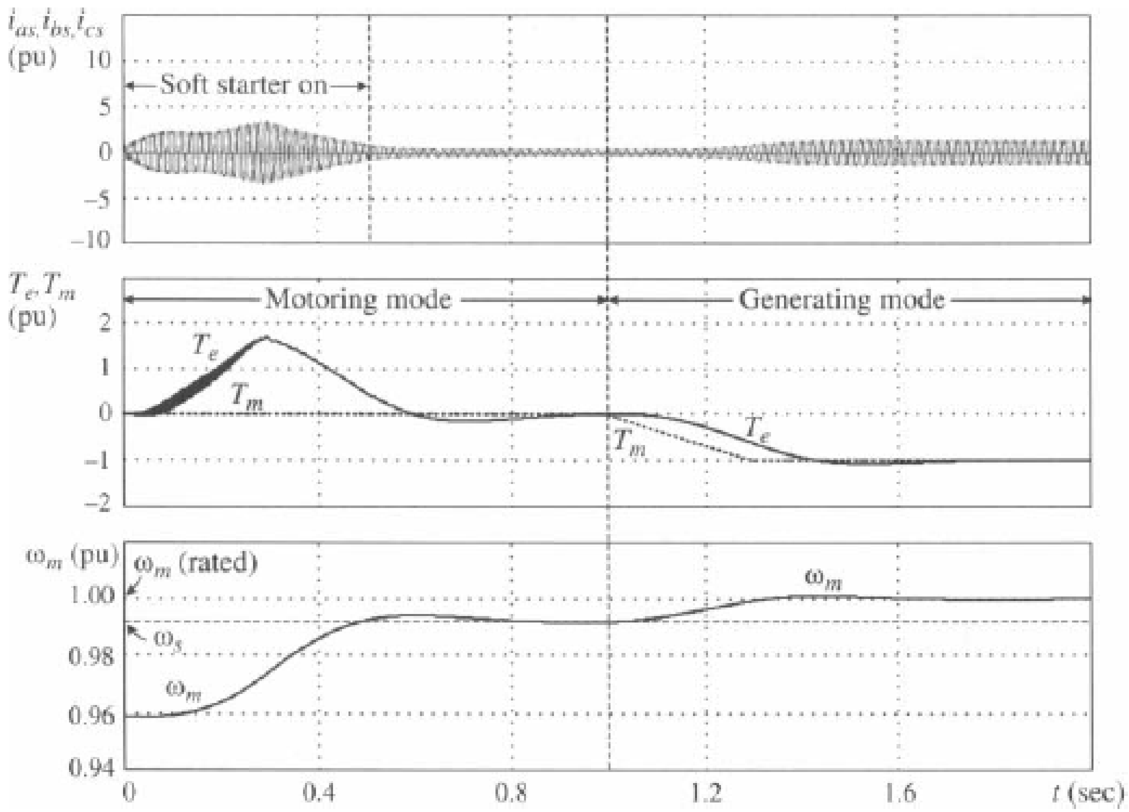

Figure 13.7 Startup transients of fixed-speed WECS with a soft starter [1]

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Reactive Power Compensation

Case Study —Reactive Power Compensation

The design procedure is used to select the values capacitors to compensate for the reactive power of the generator over its full operating range.

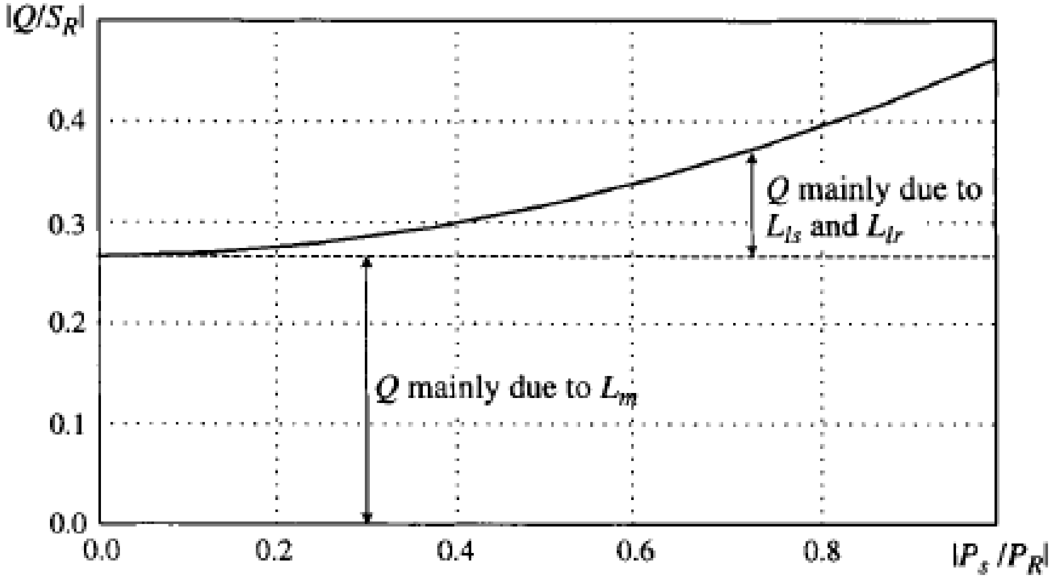

Figure 13.8Typical characteristics of reactive versus active power of a squirrel-cage induction generator [1]

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Consider a 2.3 MW, 690 V, 50 Hz, 1512 rpm SCIG fixed-speed wind energy system with parameters in Table B-I of Appendix B [1].
The system is connected to a grid of 690 V/50 Hz and its rated condition speed of 1512 rpm.
The generator slip is

$$s = \frac{1500 - 1512}{1500} = -0.008 \qquad (13.1)$$

then the impedance of IG will be

$$\bar{\bar{Z}}_s = R_s + jX_{ls} + jX_m \left(\frac{R_r}{s} + jX_{lr} \right) = 0.1837 \angle 152.58^\circ \, \Omega$$

and the power factor is $PF_s = \cos\varphi_s = -0.888$

$$\begin{cases} S_s = 3V_s I_s = 3 \times 398.4 \times 2168 = 2.591 \text{ MVA} \\ P_s = S_s \cos(\phi_s) = -2.3 \text{ MW} \\ Q_s = S_s \sin(\phi_s) = 1.193 \text{ MVAR} \end{cases}$$

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To compensate for the lagging reactive power drawn by the induction generator, a three-phase capacitor C_1 *is connected to the system. Then the capacitor reactive power will be*

$$Q_c = 3V_c I_c = 3(V_s)^2 \omega_s C_1$$

To achieve a unity power factor, the capacitor should provide a reactive power of 1.193 MVAR, that is

$$Q_c = 3(V_s)^2 \omega_s C_1 = 1.193\ \text{MVAR}$$

$$C_1 = \frac{Q_c}{3(V_s)^2 \omega_s} = \frac{1.193 \times 10^6}{3 \times (398.4)^2 \times (2\pi \times 50)} = 7{,}975\ \mu\text{F}$$

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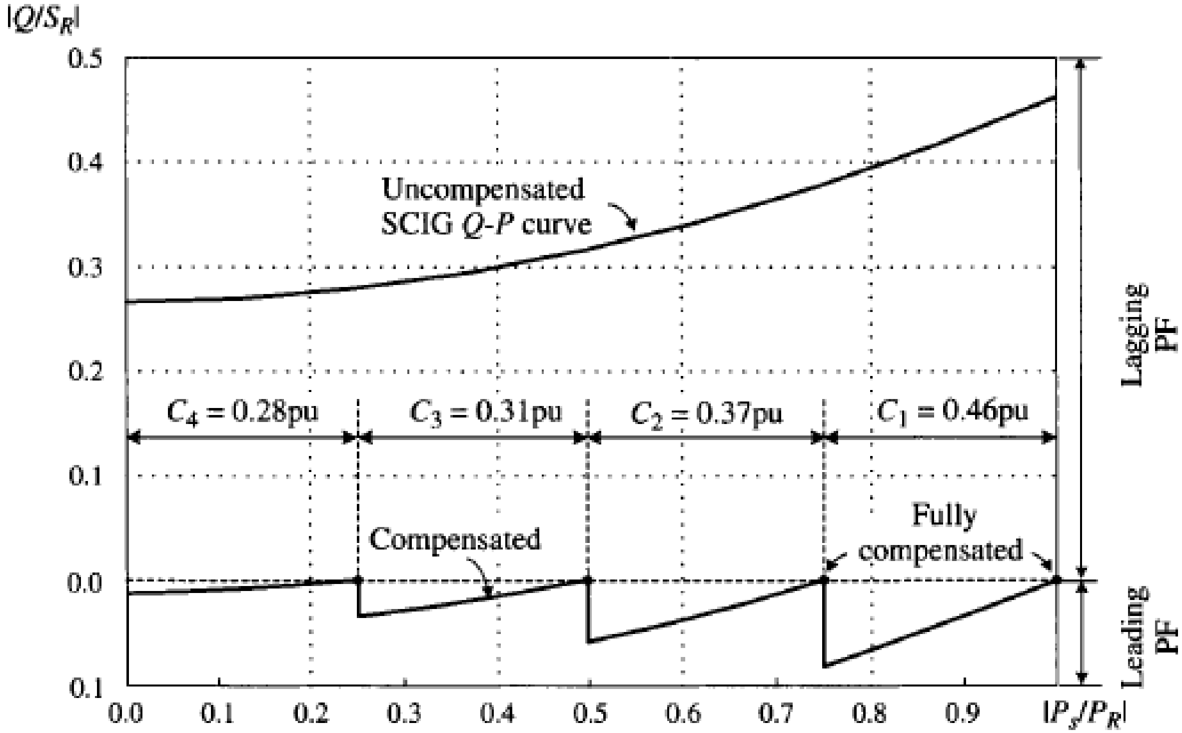

Figure 13.9 Reactive power compensation by capacitor banks [1]

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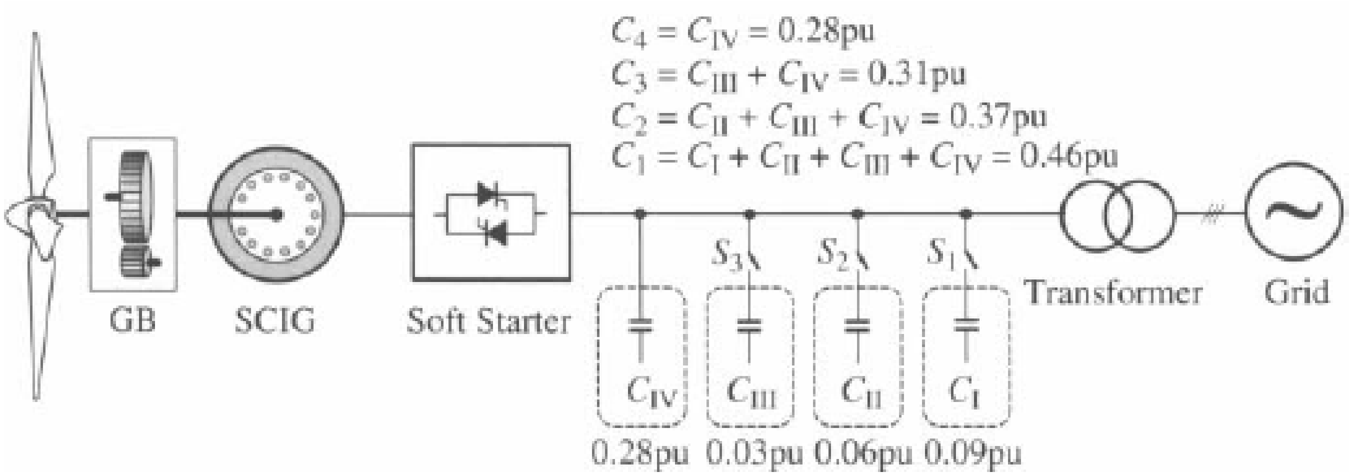

Figure 13. 10Connection of capacitors for reactive power compensation over the full operating range [1].

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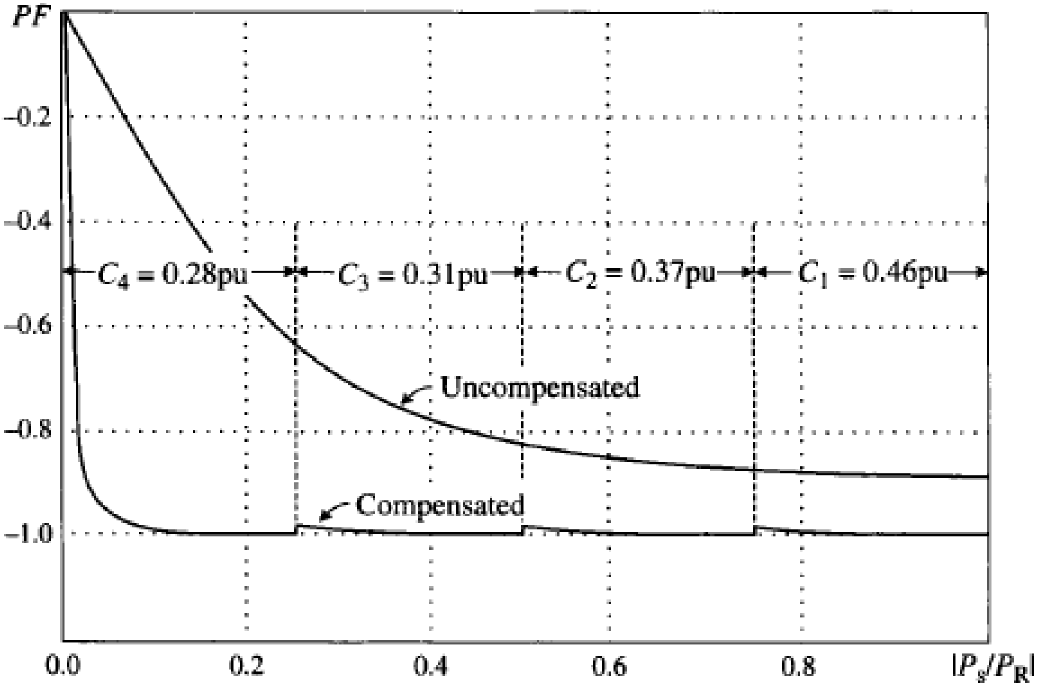

Figure 13.11 Power factor improvement through reactive power compensation by capacitor banks [1].

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References

Books:

[1] Power conversion and control of wind energy systems, B. Wu *et al.* , John Wiley & Sons, 2011

[2] Wind energy engineering. New York: McGraw-Hill, Jain, P. (2011).

[3] Understanding wind power technology: Theory, Deployment and Optimisation. John Wiley & Sons. Schaffarczyk, A. (Ed.). (2014).

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[4] Herbert, G. J., Iniyan, S., Sreevalsan, E., & Rajapandian, S. (2007). A review of wind energy technologies. Renewable and sustainable energy Reviews, 11(6), 1117-1145.

[5] Leung, D. Y., & Yang, Y. (2012). Wind energy development and its environmental impact: a review. Renewable and sustainable energy reviews, 16(1), 1031-1039.

Web links:

[6] www.ewea.org European Wind Energy Association

[7] www.indea.org World Wind Energy Association

[8] www.awea.org American Wind Energy Association

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Module 2.1

DFIG Variable Speed Wind Energy Conversion Systems

Lesson 14

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Objective

The purpose of this lesson is to analyze the operation of WECS based on variable-speeds, in particular DFIG-based systems. Emphasis will be given to the Operation and Control of these systems..

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Learning Outcomes

This lesson will contribute to the students to:

O2. Understand the different components and types of wind turbines and as their work;

O4. Be able to select wind turbines and to design (at preliminary project level) a wind farm in a South-Mediterranean location.

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Technical Contents

1. Operation of DFIG WEC systems

2. Stator Voltage Control of DFIG WEC systems

3. Start Up of DFIG WEC systems

The students are advised to have the following reference as several equations and figures are cited from it:

Reference Book:
Power conversion and control of wind energy systems, B. Wu *et al.* , John Wiley & Sons, 2011

For more details regarding this lecture, kindly refer to ch8 in the reference book mentioned above

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AGENDA

DFIG based Variable Speed Wind Energy Conversion Systems

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INTRODUCTION

The doubly fed induction generator (DFIG) is essentially a wound rotor induction generator in which the rotor circuit can be controlled by external devices to achieve variable speed operation.

Figure 14.1 shows a typical block diagram of the DFIG wind energy system. The power can be delivered from the rotor to the grid and vice versa through rotor-side converter (RSCs) and grid-side converters (GSCs

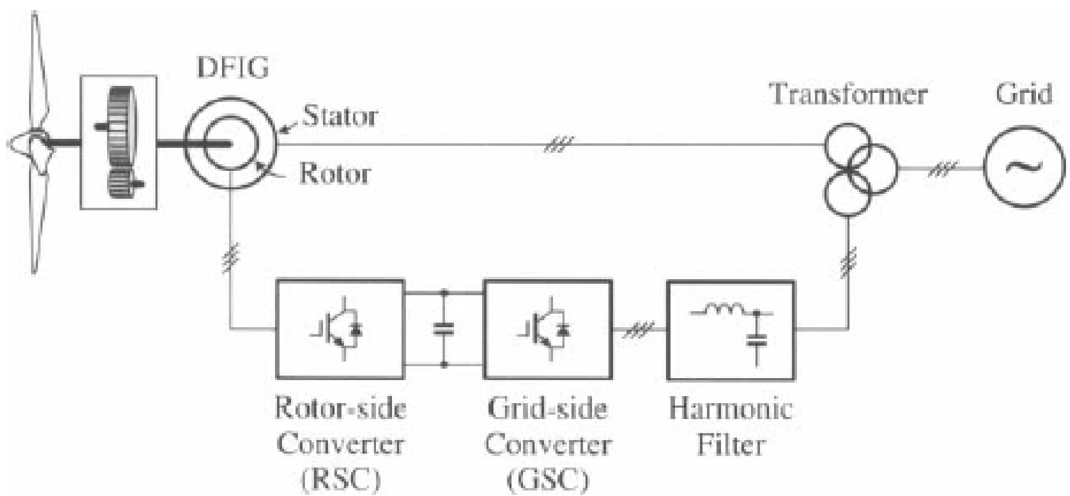

Figure 14.1 Simplified block diagram for DFIG wind energy conversion system [1]

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Super-Subsynchronous Operation of DFIG

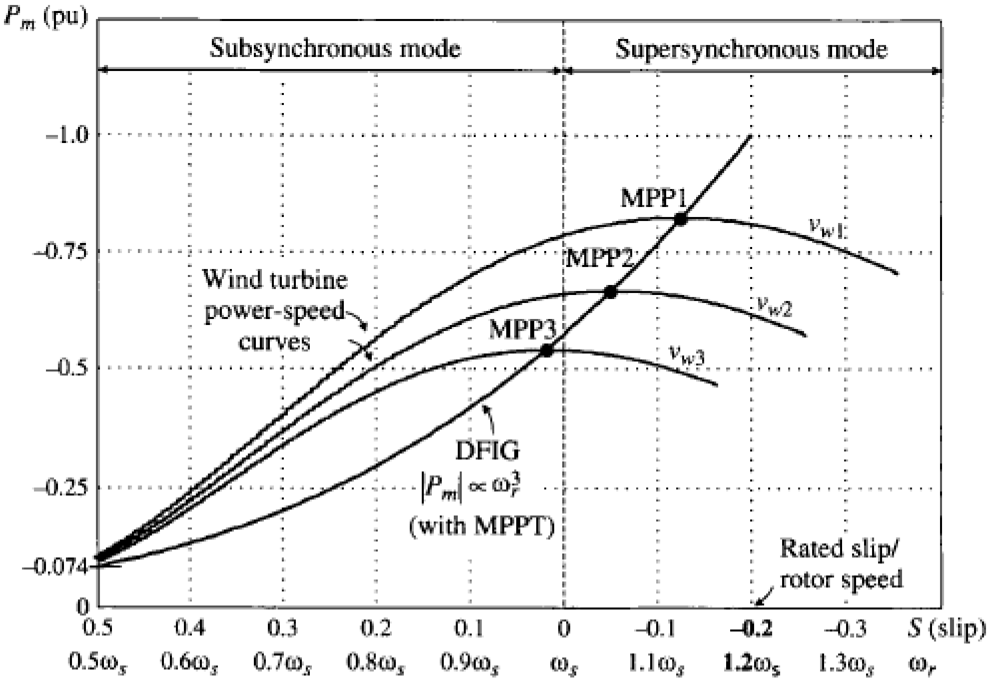

Figure 14.2 An example of power-speed characteristics in a DFIG wind energy system with MPPT control [1].

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The rotor speed of the generator in Figure 14.2 is in the range of 0.5 ω_s *to l.2* ω_s which corresponds to about 58% of the full speed range (zero to *l.2* ω_s*). This speed* range is normally sufficient for a wind energy system since the power generated at
42% of the rated speed is equal to 0.074 pu (0.423), only 7.4% of the rated power.
The power flow of DFIG is shown in Figure 14.3.

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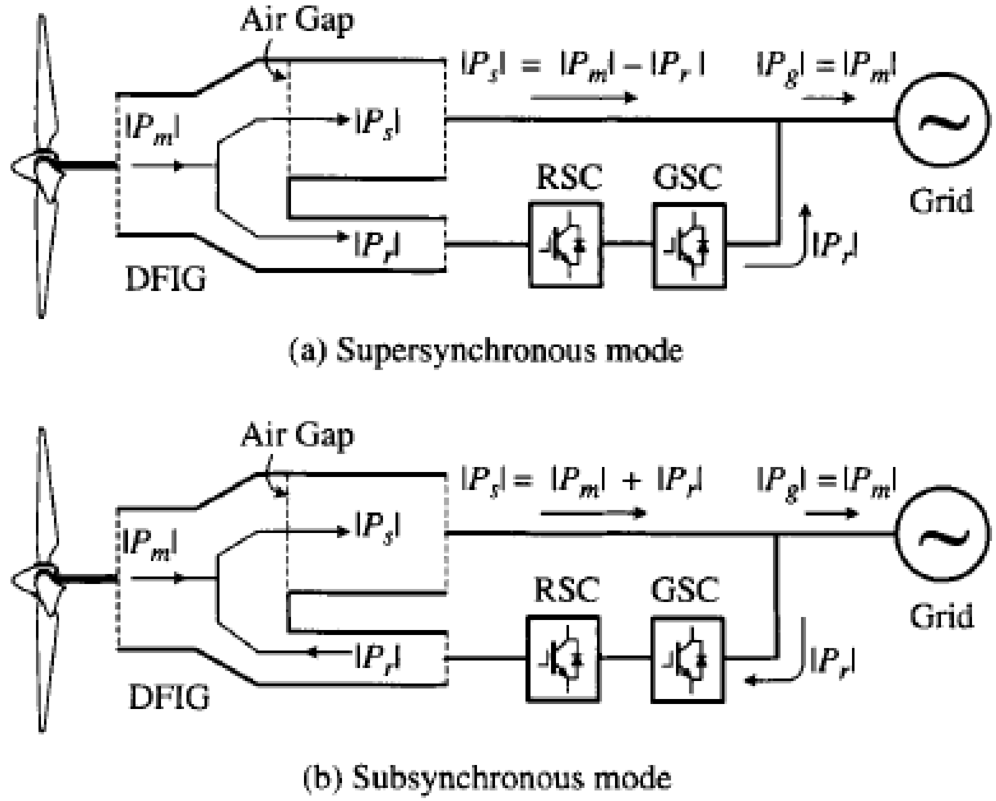

Figure 14.3 Power flow in DFIG wind energy conversion system [1]

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Steady-State Equivalent Circuit of DFIG with Rotor-Side Converter

the equivalent circuit of DFIF is shown in Figure 14.4. the equivalent impedance is given by

$$\overline{Z}_{eq} = R_{eq} + jX_{eq} = R_{eq} + j\omega_{sl}L_{eq}$$

$$\overline{Z}_{eq} / s = R_{eq} / s + j\omega_{sl}L_{eq} / s = R_{eq} / s + j\omega_s L_{eq}$$

where $\omega_{sl} = s\omega_s$

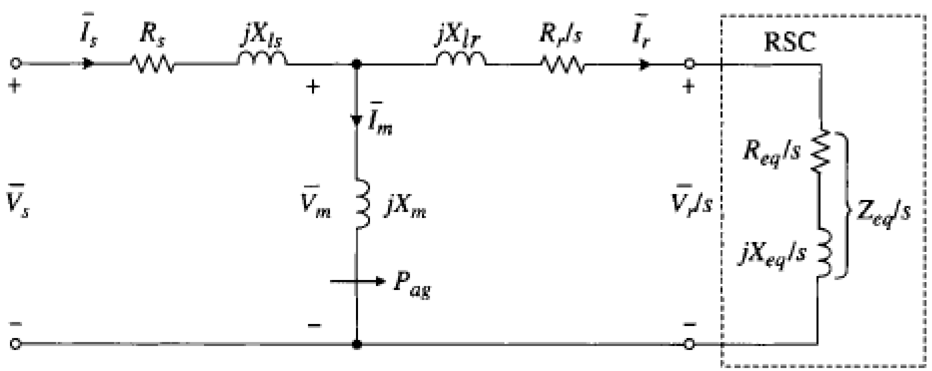

Figure 14.4 Steady-state equivalent circuit of DFIG with the rotor-side converter [1]

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The air gap power is obtained from

$$P_{ag} = 3(V_s - I_s R_s) I_s$$

which is also obtained

$$P_{ag} = \frac{\omega_s T_m}{P}$$

therefore,

$$\frac{\omega_s T_m}{P} = 3(V_s - I_s R_s) I_s$$

Then the stator current will be

$$I_s = \frac{V_s \pm \sqrt{V_s^2 - \frac{4 R_s \omega_s T_m}{3P}}}{2R_s}$$

The stator voltage and current have $\bar{V}_s = V_s \angle 0°$ and $\bar{I}_s = I_s \angle 180°$

Then based on circuit Figure 14.4 then

$$\frac{\bar{V}_r / s}{\bar{I}_r} = R_{eq} / s + jX_{eq} / s$$

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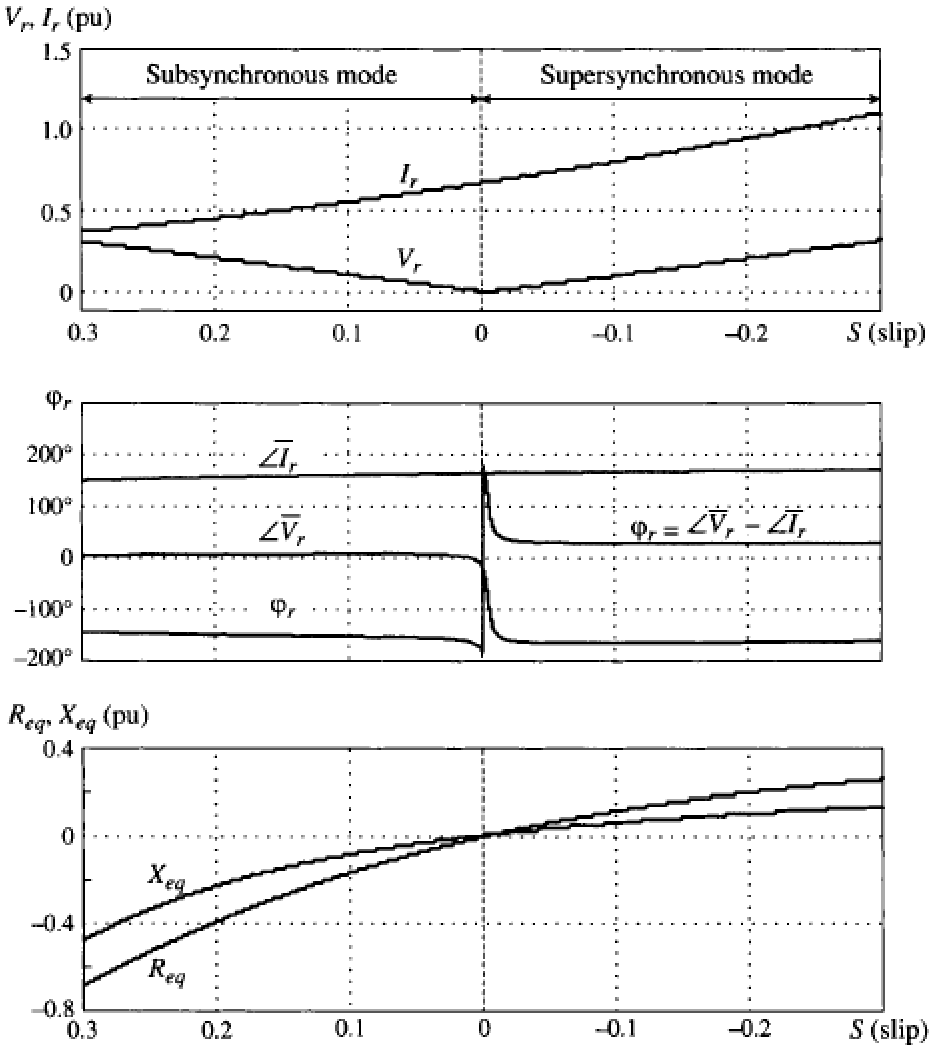

Figure 14.5 Rotor-side converter equivalent impedance *(PFS = 1) [1].*

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Torque-Slip Characteristics of DFIG WECS

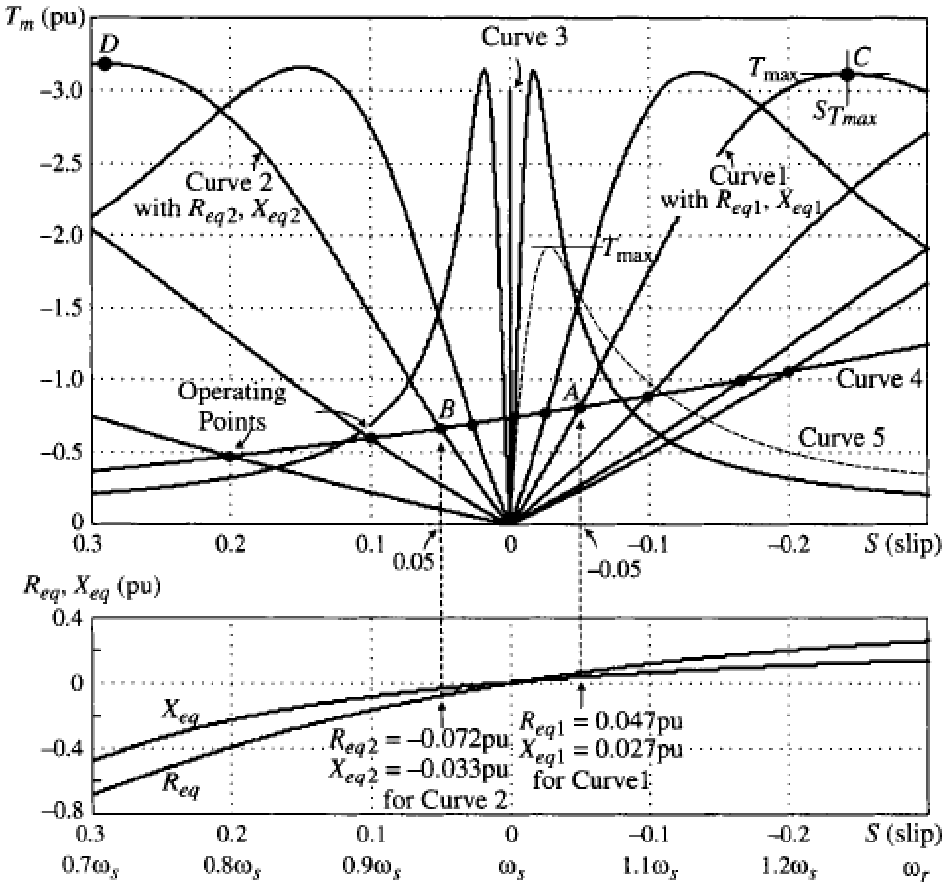

Figure 14.6 Torque-slip characteristics of DFIG wind energy system *(PFS = 1) [1].*

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Figure 14.6 shows the torque speed characteristics of 1.5Mw 690v DFIG. Table 14.1 show the equivalent impedance at different rotor speed

Table 14.1 Equivalent impedance in 1.5 MW/690 V DFIG WECS *(PFS = 1) [1]*

Rotor speed (rpm)	1200	1350	1500	1650	1750 (rated)
Slip	0.2	0.1	0	–0.1	–0.1667 (rated)
T_m (kN·m)	–3.849	–4.871	–6.014	–7.276	–8.185
$\overline{V}_r$ (V)	83.756∠6.2°	43.068∠7.4°	2.218∠–16.0°	39.711∠–165.8°	67.965∠–164.9°
$\overline{I}_r$ (A)	569.285∠155.9°	697.103∠160.5°	843.281∠164.0°	1006.991∠166.6°	1125.566∠168.0°
R_{eq} (Ω)	–0.126989	–0.055113	–0.00263	0.034942	0.053751
X_{eq} (Ω)	–0.074293	–0.027918	0	0.018281	0.027513

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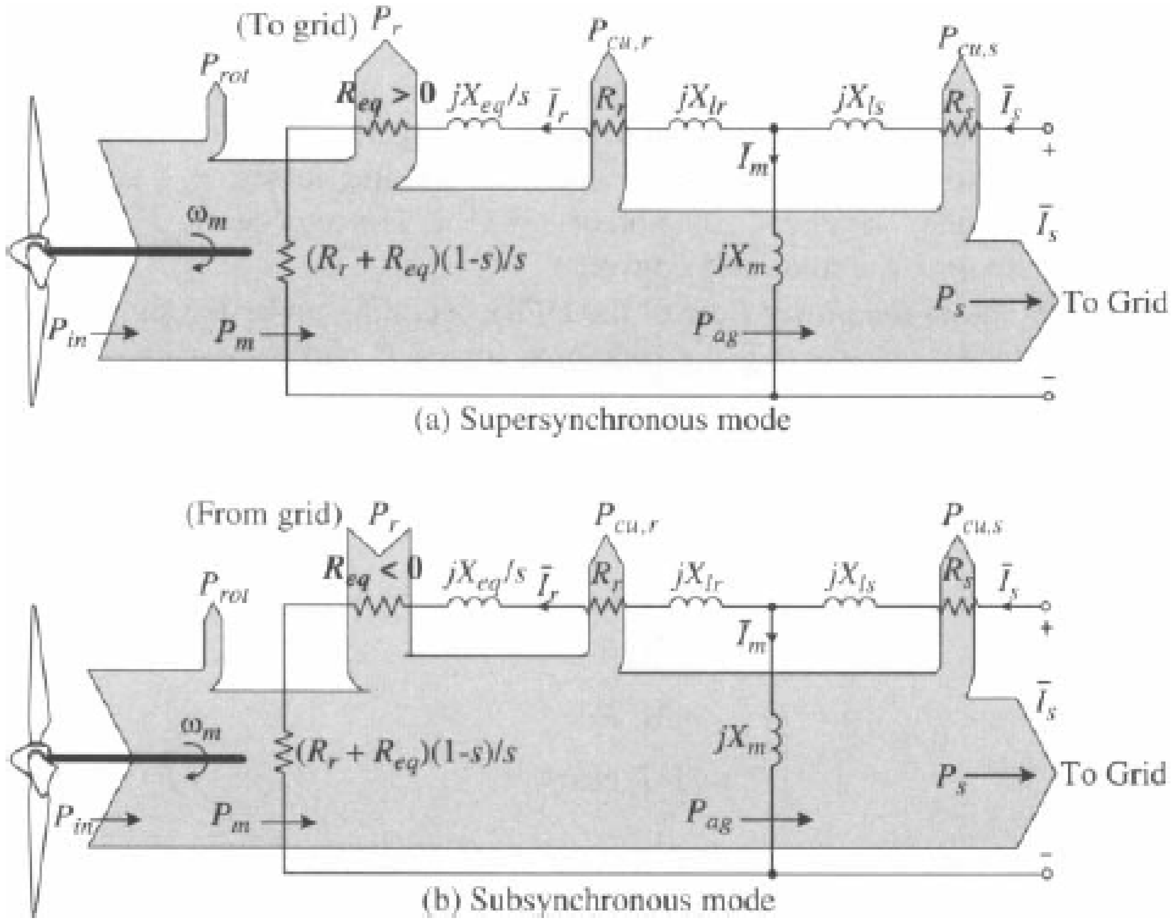

Figure 14.7 Power flow of DFIG with rotor-side converter represented by R_{eq} *and* X_{eq} [1]

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Table 14.2 Three operating modes of 1.5 MW/690 V DFIG WECS *(PFS = 1)[1]*

Operating mode	Subsynchronous operation	Synchronous operation	Supersynchronous operation
ω_m (rpm)	1200	1500	1750 (rated)
s Slip	0.2	0	–0.1667 (rated)
$\lvert T_m \rvert$ (kN·m)	3.849	6.014	8.1851
R_{eq} (Ω)	–0.126989	–0.002630	0.053751
X_{eq} (Ω)	–0.074293	0	0.027513
I_s (A)	504.16	786.28	1068.22
I_r (A)	569.29	843.28	1125.57
V_r (V)	83.76	2.22	67.97
$\lvert P_m \rvert$ (kW)	483.64	944.61	1500.0
$\lvert P_r \rvert$ (kW)	123.47	5.61	204.29
$P_{cu,r}$ (kW)	2.56	5.61	10.0
$P_{cu,s}$ (kW)	2.02	4.92	9.07
$\lvert P_s \rvert$ (kW)	602.53	939.69	1276.64
$\lvert P_g \rvert$ (kW)	479.06	934.08	1480.93

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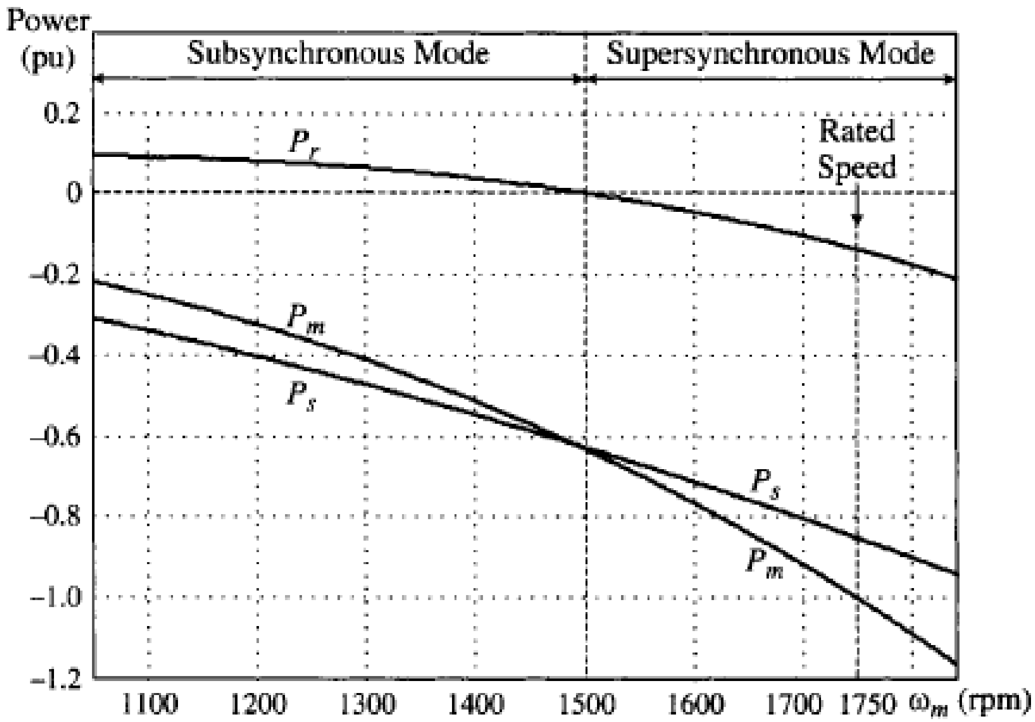

Figure 14.8 Stator, rotor, and mechanical power of the 1.5 MW/690 V DFIG operating at super- and subsynchronous speeds [1]

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Stator Voltage Oriented Control of DFIG WECS

Principle of Stator Voltage Oriented Control (SVOC)

In DFIG wind energy systems, the stator of the generator is directly connected to the grid, and its voltage and frequency can be considered constant under the normal operating conditions. It is, therefore, convenient to use stator voltage oriented control (SVOC) for the DFIG [1].

Figure 14.9 shows a space vector diagram for the DFIG with the stator voltage oriented control operating with unity power factor in supersynchronous mode.

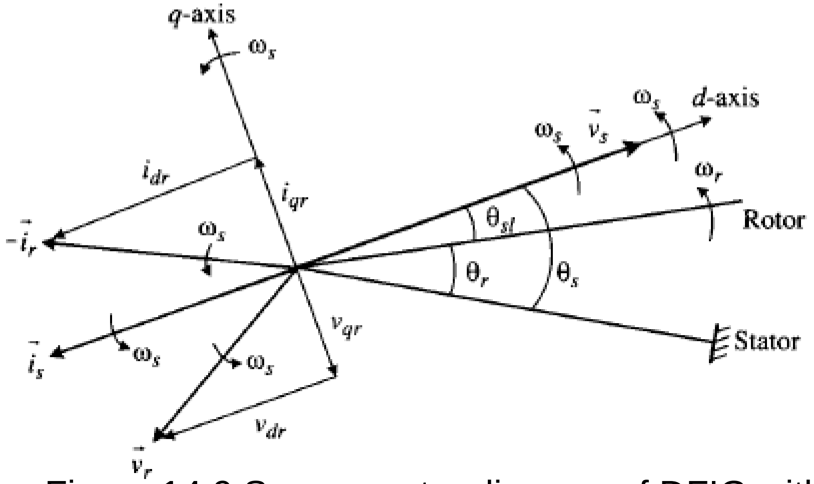

Figure 14.9 Space-vector diagram of DFIG with SVOC in the supersynchronous mode [1]

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The electromechanical torque is obtained

$$T_e = \frac{3P}{2}(i_{qs}\lambda_{ds} - i_{ds}\lambda_{qs})$$

where

$$\begin{cases} \lambda_{ds} = L_s i_{ds} + L_m i_{dr} \\ \lambda_{qs} = L_s i_{qs} + L_m i_{qr} \end{cases}$$

And dq- stator current is obtained

$$\begin{cases} i_{ds} = \dfrac{\lambda_{ds} - L_m i_{dr}}{L_s} \\ i_{qs} = \dfrac{\lambda_{qs} - L_m i_{qr}}{L_s} \end{cases}$$

Then the torque

$$T_e = \frac{3PL_m}{2L_s}(-i_{qr}\lambda_{ds} + i_{dr}\lambda_{qs})$$

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Then the rotor current

$$\begin{cases} i_{dr} = -\frac{2L_s}{3v_{ds}L_m}P_s + \frac{v_{qs} - R_s i_{qs}}{\omega_s L_m} = -\frac{2L_s}{3v_{ds}L_m}P_s - \frac{R_s}{\omega_s L_m}i_{qs} \\ i_{qr} = \frac{2L_s}{3v_{ds}L_m}Q_s - \frac{v_{ds} - R_s i_{ds}}{\omega_s L_m} = \frac{2L_s}{3v_{ds}L_m}Q_s + \frac{R_s}{\omega_s L_m}i_{ds} - \frac{v_{ds}}{\omega_s L_m} \end{cases} \quad \text{for } v_{qs} = 0$$

By neglecting stator resistance

$$\begin{cases} i_{dr} = -\frac{2L_s}{3v_{ds}L_m}P_s & \text{(a)} \\ i_{qr} = \frac{2L_s}{3v_{ds}L_m}Q_s - \frac{v_{ds}}{\omega_s L_m} & \text{(b)} \end{cases}$$

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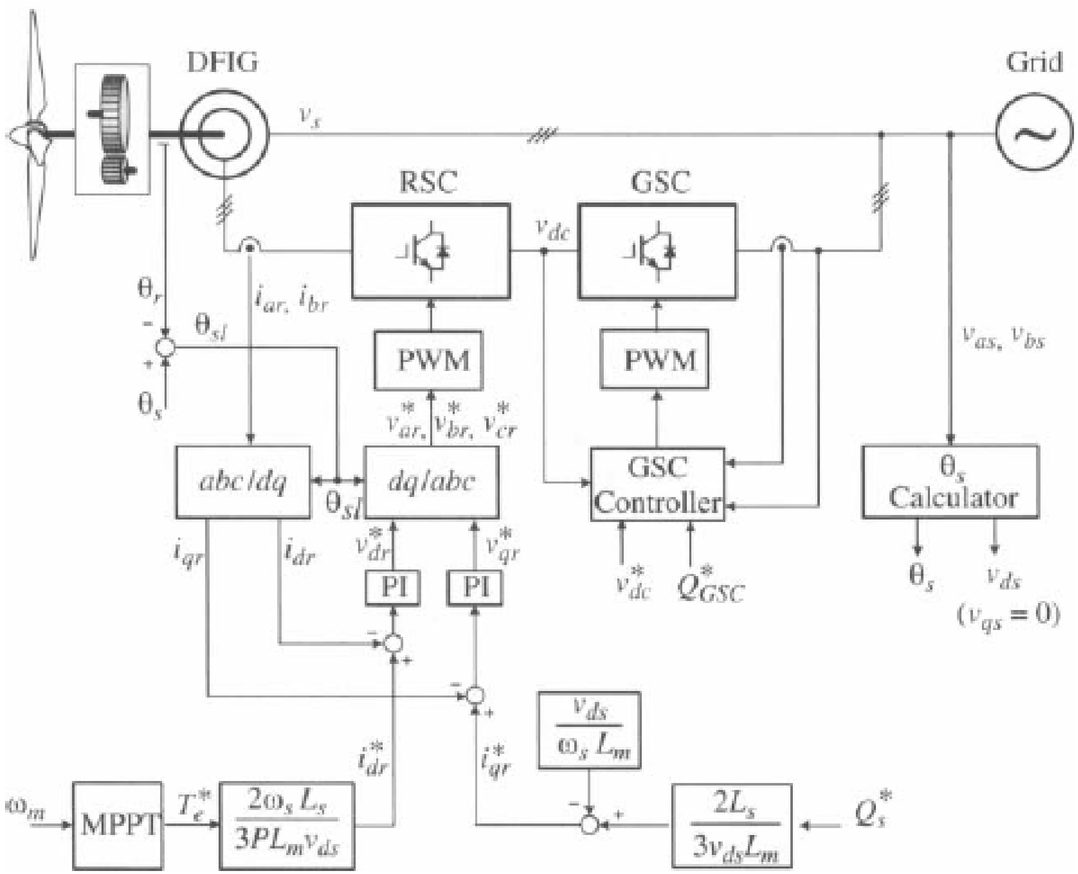

Figure 14.10 Bloc diagram of a DFIG wind energy system with stator voltage oriented control [1]

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Dynamic Performance of DFIG WECS

Case Study —Transients from Supersynchronous to Subsynchronous Operation.

Figure 14.11 illustrates the transients of a 1.5 MW/690 V DFIG wind energy system caused by a step change in wind speed are investigated. The torque and power versus rotor speed characteristics of the system at the wind speeds of 0.7 pu and 1.0 pu is shown in Figure 14.12.

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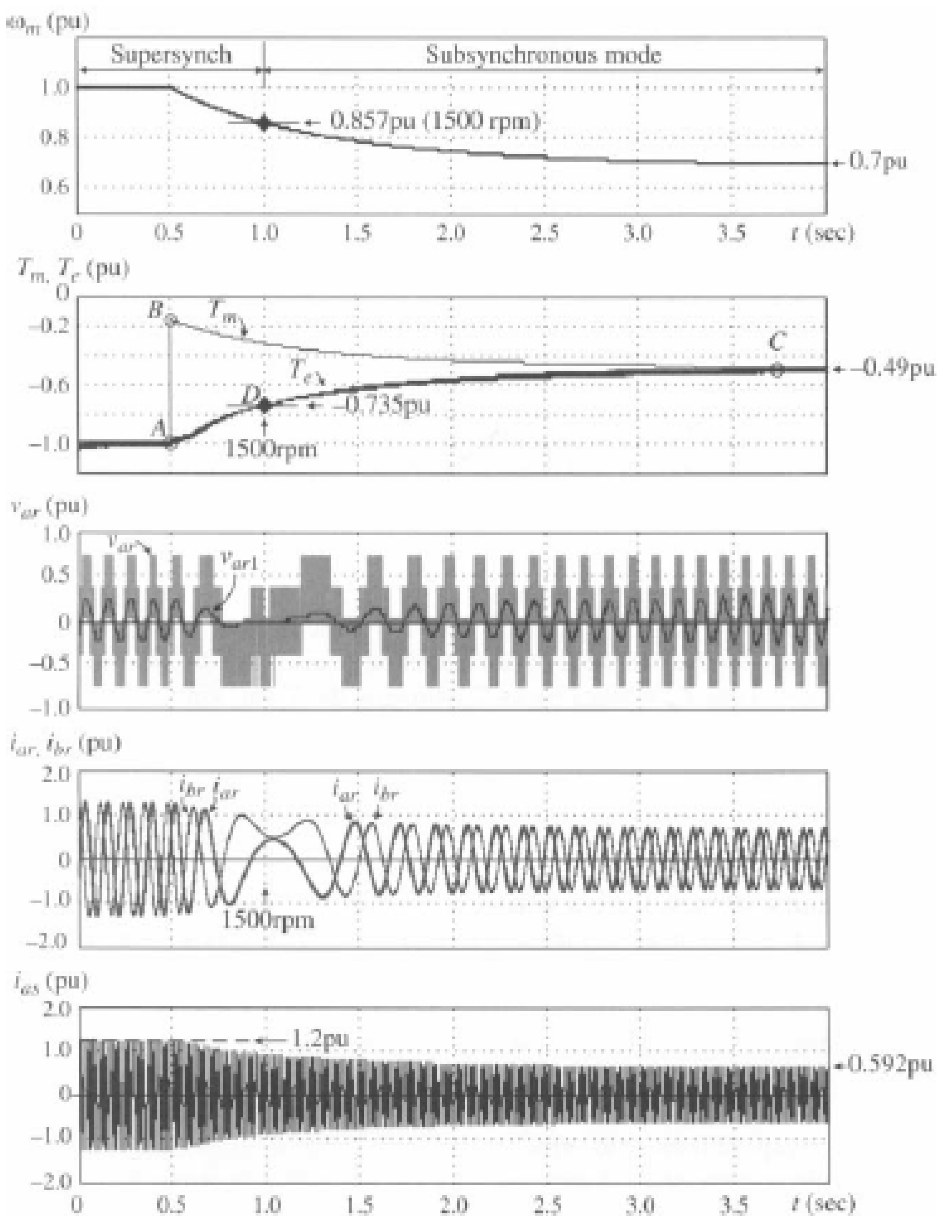

Figure 14.11 Transients of DFIG WECS from supersynchronous to subsynchronous mode [1]

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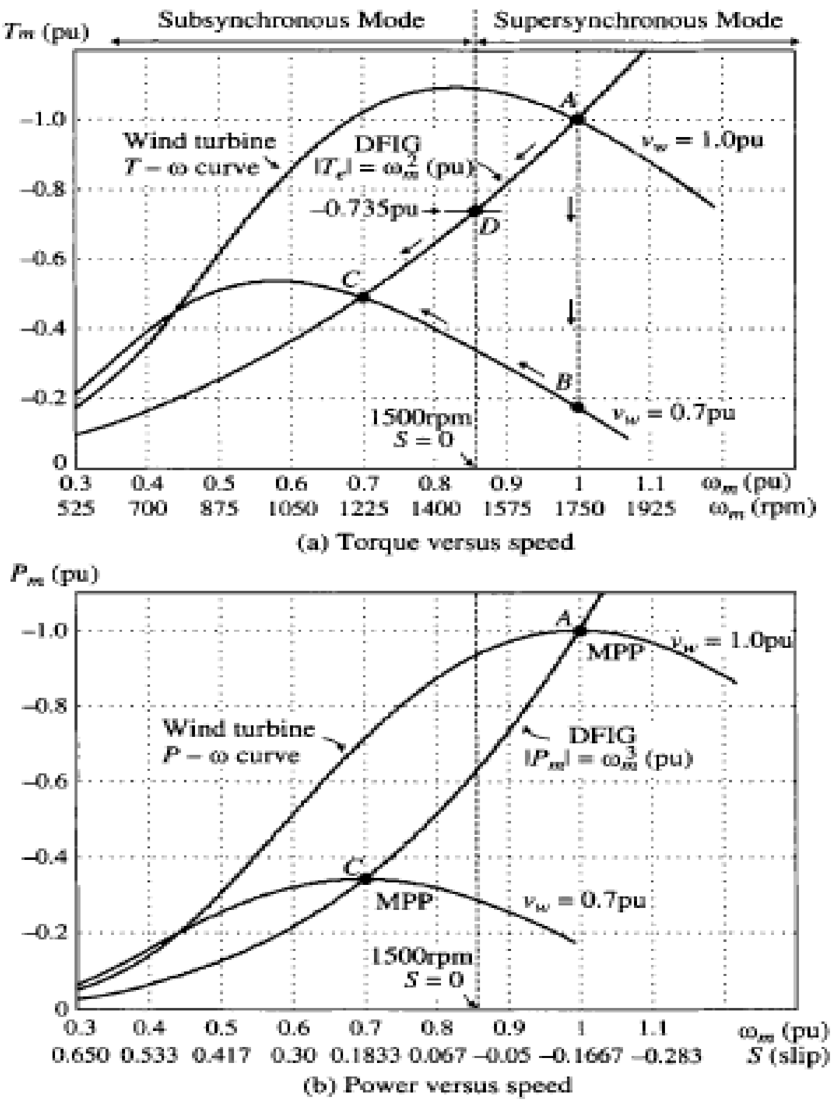

Figure 14.12 Torque and power versus rotor speed of DIFG WECS [1]

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DFIG WECS Start-Up and Experiments

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Consider the block diagram of DFIG in Figure 14.13 [1]

Step 1—Initial parking state. In the initial stage with the wind speed below the cut-in speed, switches SW1 and SW2 are open, and both stator and rotor circuits are disconnected from the grid.

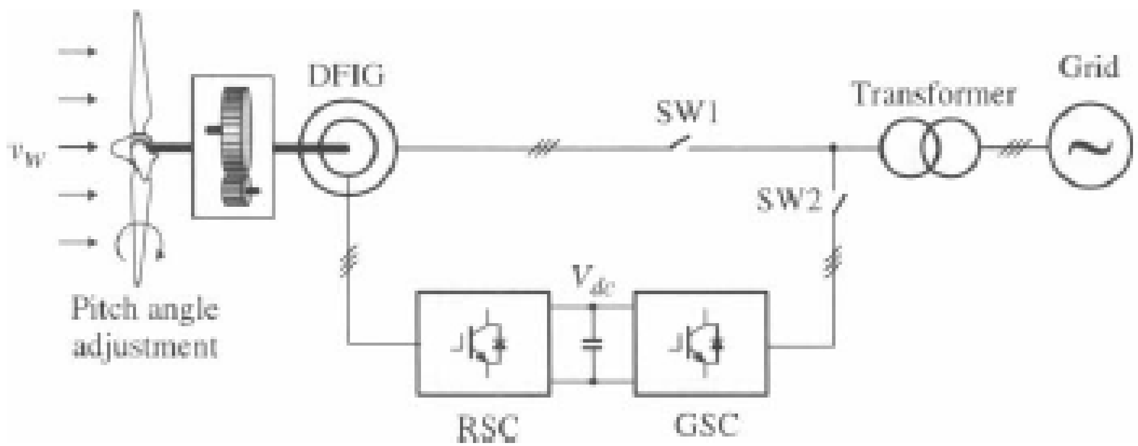

Figure 14.13 Start-up of a DFIG WECS [1]

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Step 2—Turbine/generator acceleration and stator voltage generated.
When the wind speed reaches the cut-in speed, the pitch angle of the blades is adjusted to provide starting torque, and the turbine starts to rotate. Switch SW2 in the rotor circuit is closed and the power converters are energized. The DC link voltage of the converters is controlled by the grid-side converter and kept at a fixed value. The rotor-side converter is controlled to provide excitation current to the DFIG. A three-phase balanced voltage is then induced in the stator, which is monitored for synchronization to the grid. The torque reference in the DFIG controller is set to zero. No power is generated or delivered to the grid.

Step 3—Synchronization of the voltage/frequency with the grid.
During the rotor speed acceleration, both stator voltage and frequency are fully controlled by the rotor-side converter. When the generator accelerates to a speed that is set according to the measured wind speed, the stator voltage, frequency, and phase angle are adjusted to match those of the grid for synchronization. When the synchronization is achieved, SW1 is closed, and the DFIG WECS is connected to the grid.

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Step *4—Power generation and optimal pitch angle.*

Once the DFIG is connected to the grid, the torque or power reference is increased from zero to a value generated from the MPPT algorithm according to the measured wind speed. The blade pitch angle is also adjusted to its optimal value, at which the maximum wind energy conversion efficiency is achieved. The start-up process is completed

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Books:

[1] Power conversion and control of wind energy systems, B. Wu *et al.* , John Wiley & Sons, 2011

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Introduction to Wind Energy

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Module 2.1

PMSG Wind Energy Conversion Systems
Lesson 15

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Objective

The purpose of this lesson is to analyze the operation of WECS based on PMSG. Emphasis will be given to the Operation and Control of these systems.

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Learning Outcomes

This lesson will contribute to the students to:

O2. Understand the different components and types of wind turbines and as their work;

O4. Be able to select wind turbines and to design (at preliminary project level) a wind farm in a South-Mediterranean location.

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Technical Contents

1. Operation of PMSG WEC systems

2. Control of PMSG WEC systems

3. Start Up of PMSG WEC systems

Reference Book:

Power conversion and control of wind energy systems, B. Wu *et al.* , John Wiley & Sons, 2011

For more details regarding this lecture, kindly refer to ch9 in the reference book mentioned above

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AGENDA

PMSG based Variable Speed Wind Energy Conversion Systems

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Introduction

- Synchronous generators (SGs) have been widely used in variable-speed wind energy conversion systems (WECS).
- They are classified such as including permanent magnet and wound rotor generators, salient and nonsalient pole generators, and generators with external and internal rotors.
- The synchronous generator can be constructed with a large number of poles and operate at a speed that directly matches the turbine blade speed. Such a direct-drive system does not need a gearbox.
- The SG wind energy system is normally controlled by full capacity power converters for variable-speed operation, ensuring maximum wind energy conversion efficiency throughout its operating range

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System Configuration

- The block diagram of a typical variable-speed synchronous generator WECS is shown in Figure 15.1
- The system consists of a wind turbine, a gearbox, a synchronous generator, power converters, and a transformer for grid connection.
- The rated speed of the wind turbine depends on its power rating and the number of blades.
- For three-blade horizontal-axis turbines, the rated speed of the turbine is approximately in the range of 20 to 300 rpm for small/medium size and 8 to 30 rpm for large megawatt turbines
- The control of a wind energy system includes generator-side active power control with maximum power point tracking (MPPT), grid-side reactive power control, and DC voltage control for voltage source converters or DC current control for current source converters.

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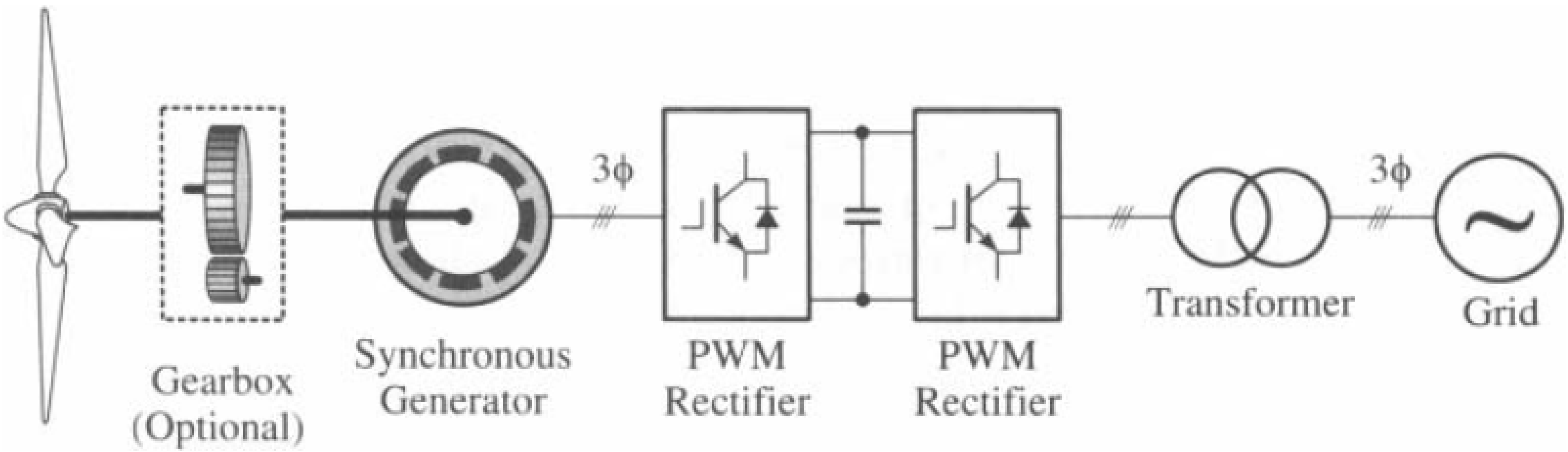

Figure 15.1 Block diagram of variable-speed SG wind energy system [1]

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Control of Synchronous Generators

The synchronous generator can be controlled by different methods to achieve different objectives . For instance,

1. the *d-axis stator current of the generator can be set* to zero during the operation to achieve a linear relationship between the stator current and the electromagnetic torque.
2. the generator can be controlled to produce maximum torque with a minimum stator current.
3. Operate the system with unity power factor

Zero d-Axis Current (ZDC) Control

The zero d-axis current control can be realized by resolving the three-phase stator current in the stationary reference frame into *dq-axis components in the synchronous* reference frame. The d-axis component, i_{ds}, *is then controlled to be zero.*

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$$\begin{cases} \vec{i}_s = i_{ds} + ji_{qs} = ji_{qs} \\ i_s = \sqrt{i_{ds}^2 + i_{qs}^2} = i_{qs} \end{cases} \quad \text{for } \; i_{ds} = 0$$

The electromechanically torque equation is

$$T_e = \frac{3}{2} P \left(\lambda_r i_{qs} - \left(L_d - L_q \right) i_{ds} i_{qs} \right)$$

which can be simplified into

$$T_e = \frac{3}{2} P \lambda_r i_{qs} = \frac{3}{2} P \lambda_r i_s$$

The equivalent circuit and vector diagram of SG in shown in Figure 15.2
The stator voltage

$$v_s = \sqrt{(v_{ds})^2 + (v_{qs})^2} = \sqrt{(\omega_r L_q i_{qs})^2 + (\omega_r \lambda_r)^2}$$

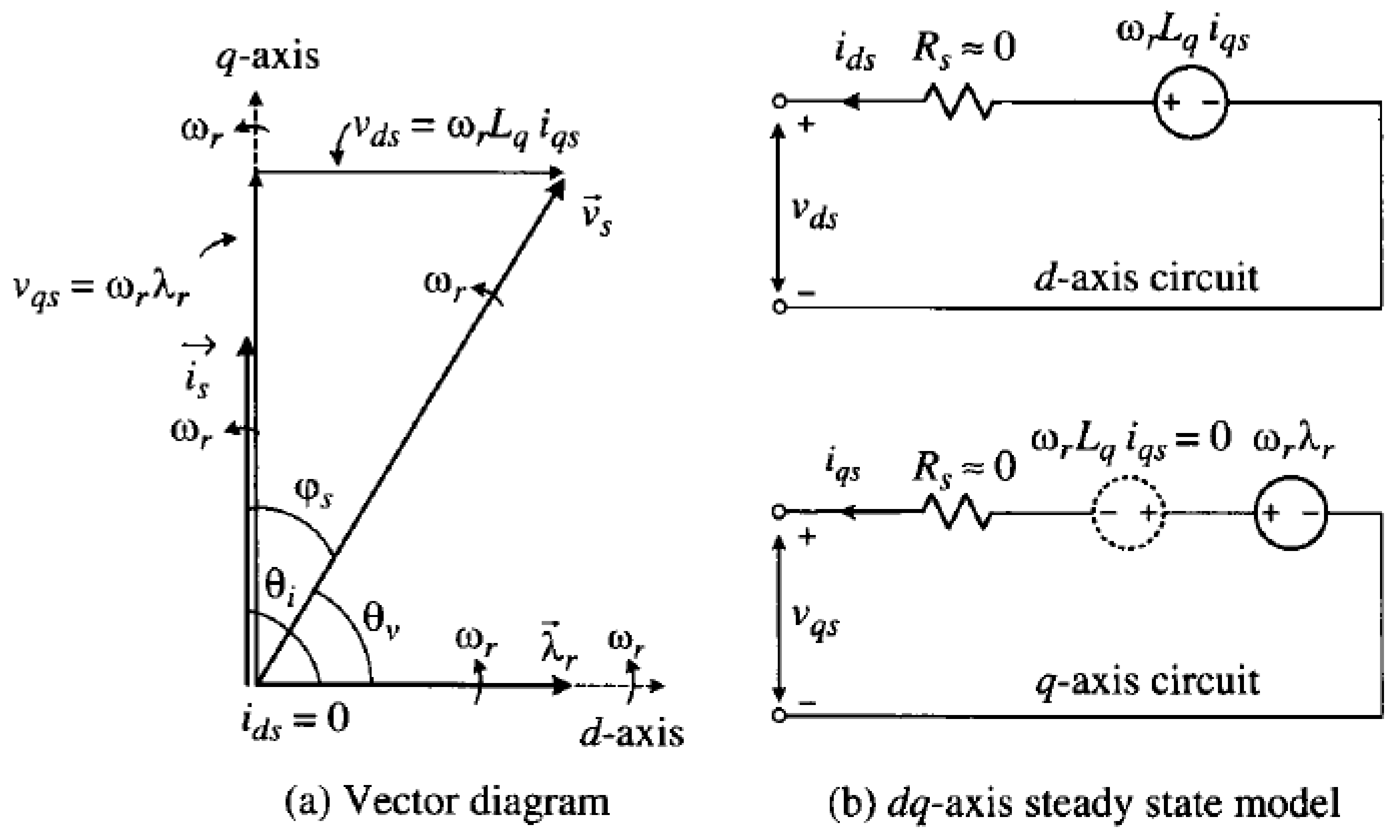

Figure 15.2 Space vector diagram of synchronous generator with ZDC control [1]

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The stator power factor angle is

$$\varphi_s = \theta_v - \theta_i$$

Where

$$\begin{cases} \theta_v = \tan^{-1} \dfrac{v_{qs}}{v_{ds}} \\ \theta_i = \tan^{-1} \dfrac{i_{qs}}{i_{ds}} \end{cases}$$

Then

$$\varphi_s = \theta_v - \theta_i = \left(\tan^{-1} \frac{v_{qs}}{v_{ds}} \right) - \frac{\pi}{2} \qquad \text{for } i_{ds} = 0$$

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Maximum Torque per Ampere (MTPA) Control

The maximum torque per ampere control generates a given torque with a minimum stator current.
This implies that the generator can produce a given torque with different values of i_{ds} and i_{qs}

$$i_{ds} = \sqrt{i_s^2 - i_{qs}^2}$$

Then the torque

$$T_e = \frac{3}{2} P \left(\lambda_r i_{qs} - (L_d - L_q)\left(\sqrt{i_s^2 - i_{qs}^2}\right) i_{qs} \right)$$

For the salient-pole generator, the MTPA scheme can be derived through the following steps.
1- Differentiating T_e

$$\frac{dT_e}{di_{qs}} = \frac{3P}{2}\left(\lambda_r - (L_d - L_q) i_{ds} + (L_d - L_q) i_{qs}^2 \frac{1}{\sqrt{i_s^2 - i_{qs}^2}} \right)$$

Set drivative to zero

$$\lambda_r - (L_d - L_q) i_{ds} + (L_d - L_q)\frac{i_{qs}^2}{i_{ds}} = 0$$

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then $$i_{ds} = \frac{\lambda_r}{2(L_d - L_q)} \pm \sqrt{\frac{\lambda_r^2}{4(L_q - L_d)^2} + i_{qs}^2} \quad \text{for } L_d \neq L_q$$

$$\begin{cases} T_e = \frac{3}{2} P \left(\lambda_r i_{qs} - (L_d - L_q) i_{ds} i_{qs} \right) \\ i_{ds} = \frac{\lambda_r}{2(L_d - L_q)} + \sqrt{\frac{\lambda_r^2}{4(L_q - L_d)^2} + i_{qs}^2} \end{cases} \quad \text{for } L_d \neq L_q$$

The space vector of MTPA is shown in Figure 15.3, where

$$\delta = \tan^{-1} \frac{i_{ds}}{i_{qs}} = \frac{\pi}{2} - \theta_i \qquad \text{for } 0 \leq \theta_i \leq \frac{\pi}{2}$$

Figure 15.4 shows the trajectory torque control of MTPA

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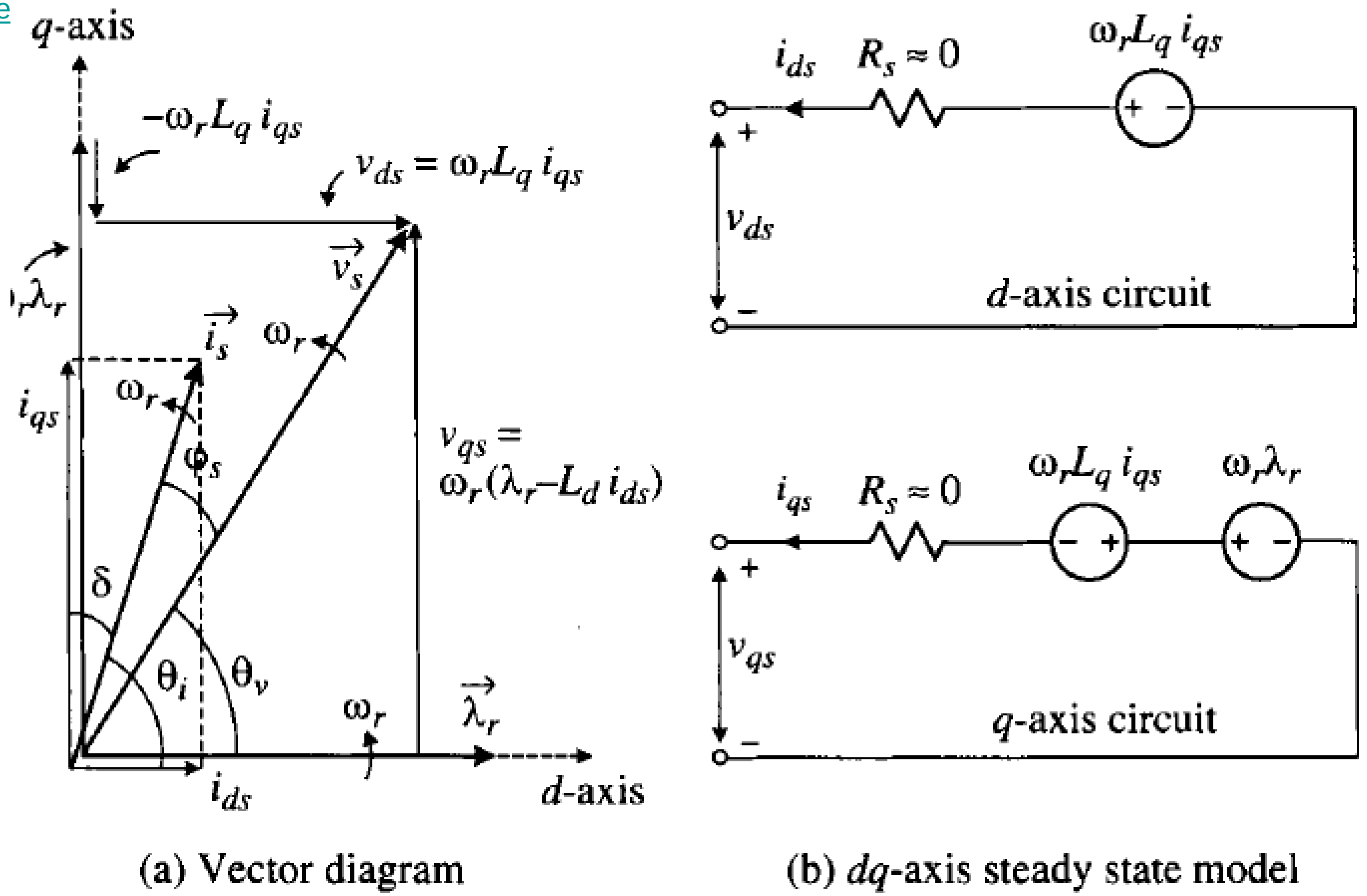

Figure 15.3 Space vector diagram of synchronous generator with MTPA control [1]

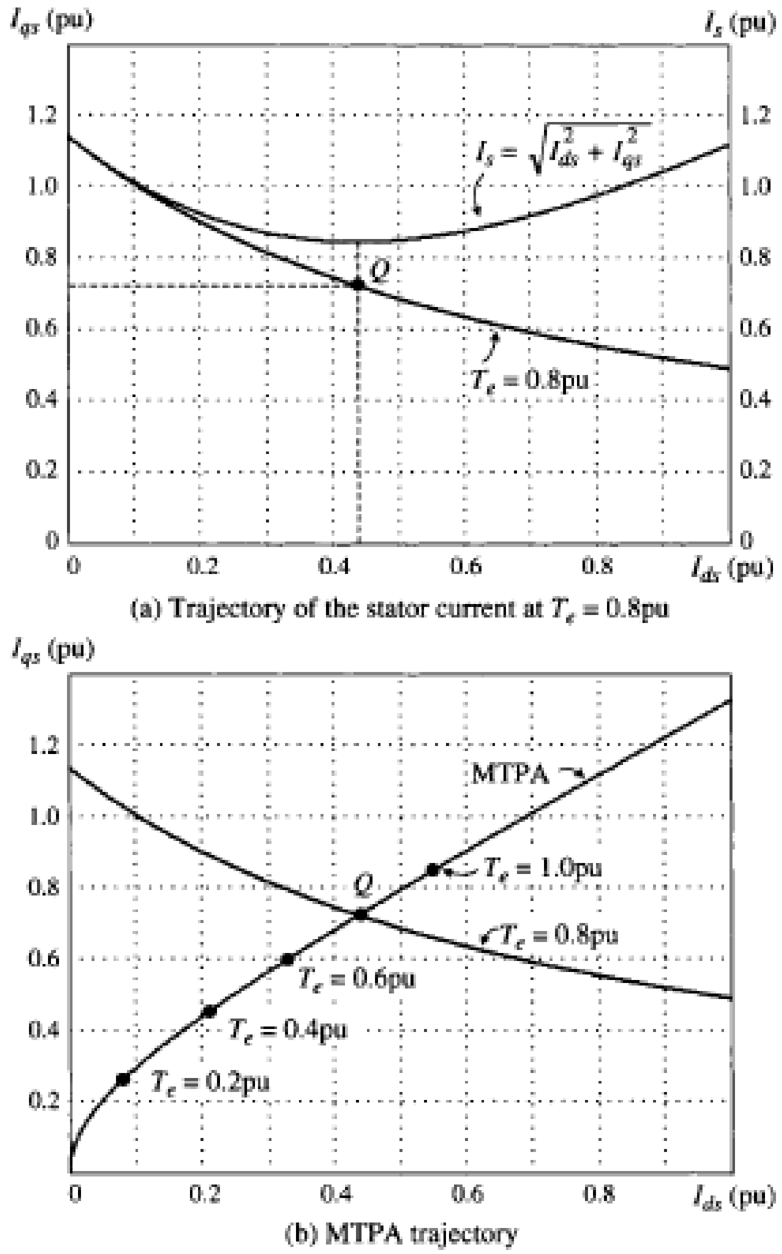

Figure 15.4 Trajectory of maximum torque- per-ampere control[1]

Unity Power Factor (UPF) Control

To simplify the analysis, let us neglect the small voltage drop across the stator resistance Rs. The phase angles of the stator voltage and current can then be calculated by

$$\begin{cases} \theta_v = \tan^{-1}\left(\frac{v_{qs}}{v_{ds}}\right) = \tan^{-1}\frac{\omega_r\lambda_r - \omega_r L_d i_{ds}}{\omega_r L_q i_{qs}} \\ \theta_i = \tan^{-1}\left(\frac{i_{qs}}{i_{ds}}\right) \end{cases}$$

Unity power factor operation can be realized when the stator power factor angle φ_s *between* the stator voltage and current is zero

$$\varphi_s = \theta_v - \theta_i = 0 \qquad 15.1$$

The space vector diagram for the generator with UPF control is shown in Figure 15.5.

Substitute by angle in eq. (15.1) $L_d i_{ds}^2 + L_q i_{qs}^2 - \lambda_r i_{ds} = 0$

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Solve the equation with respect to current then

$$i_{ds} = \begin{cases} \dfrac{\lambda_r + \sqrt{\lambda_r^2 - 4L_d L_q i_{qs}^2}}{2L_d} & \text{(a)} \quad \text{Not valid} \\ \dfrac{\lambda_r - \sqrt{\lambda_r^2 - 4L_d L_q i_{qs}^2}}{2L_d} & \text{(b)} \end{cases}$$

$$i_{qs} \le \frac{\lambda_r}{2\sqrt{L_d L_q}}$$

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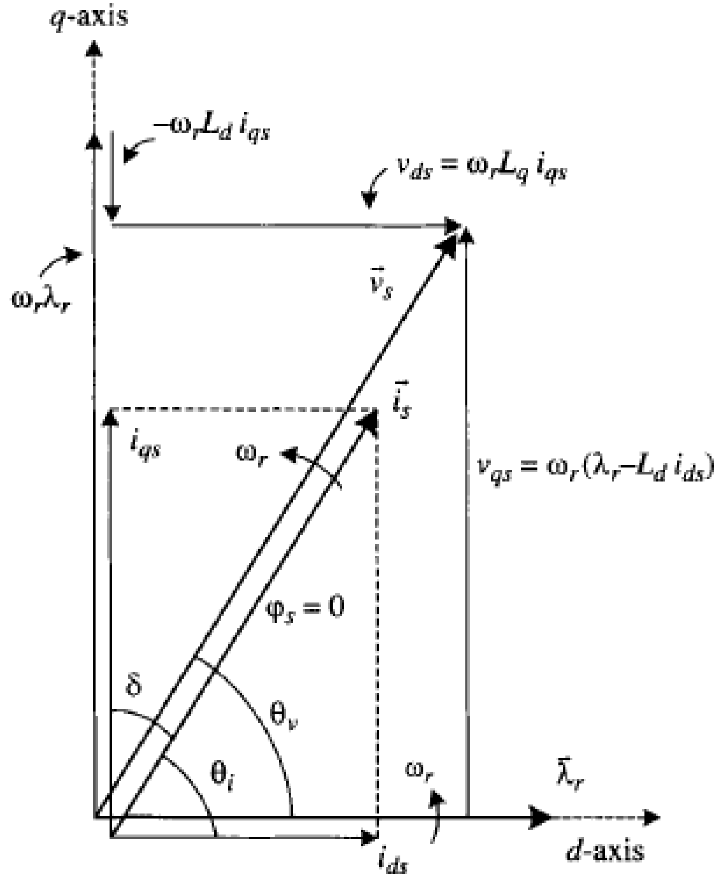

Figure 15.5 Space vector diagram of synchronous generator with UPF control [1]

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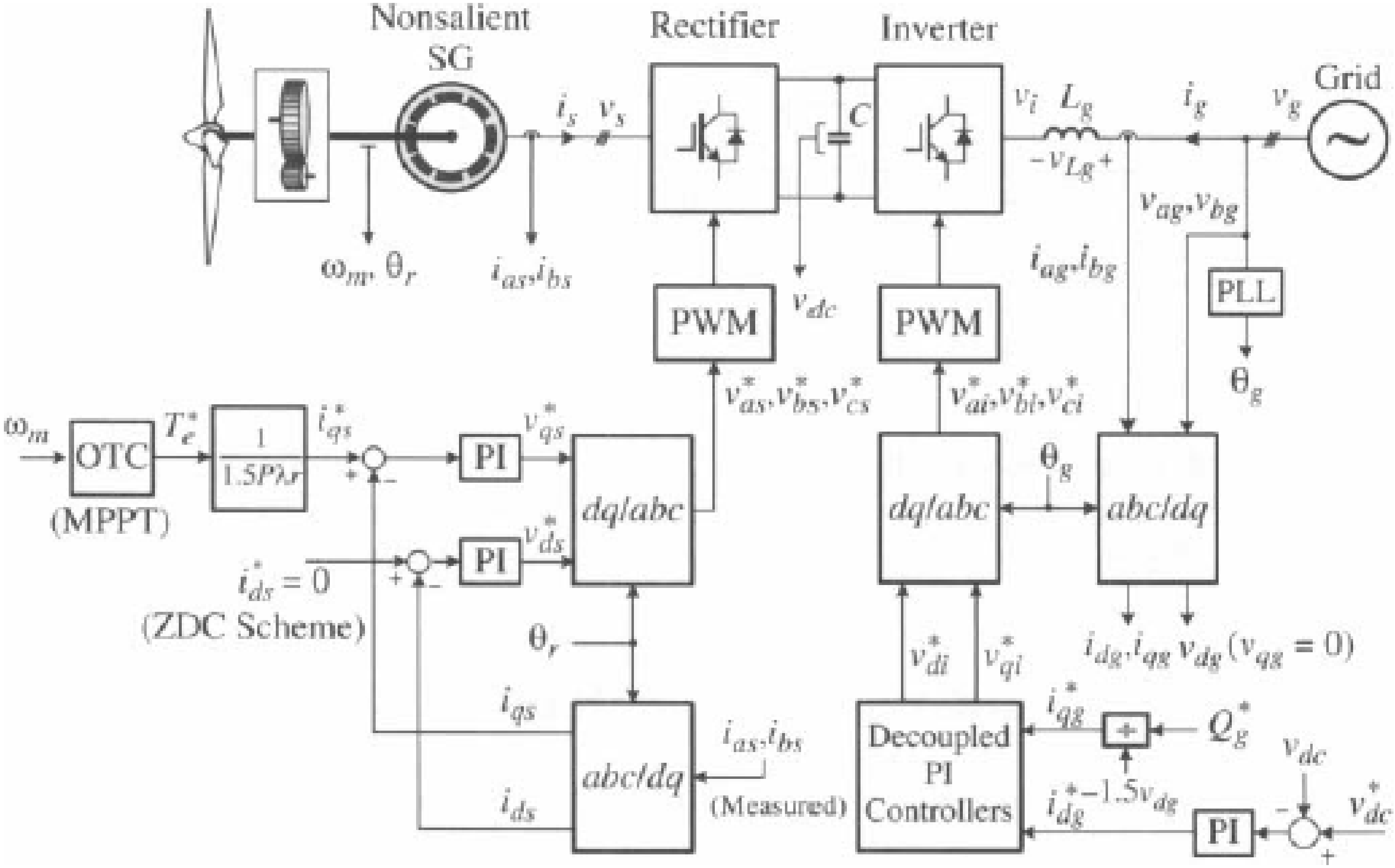

Figure 15.6 Control scheme of nonsalient SG wind energy system with ZDC control [1]

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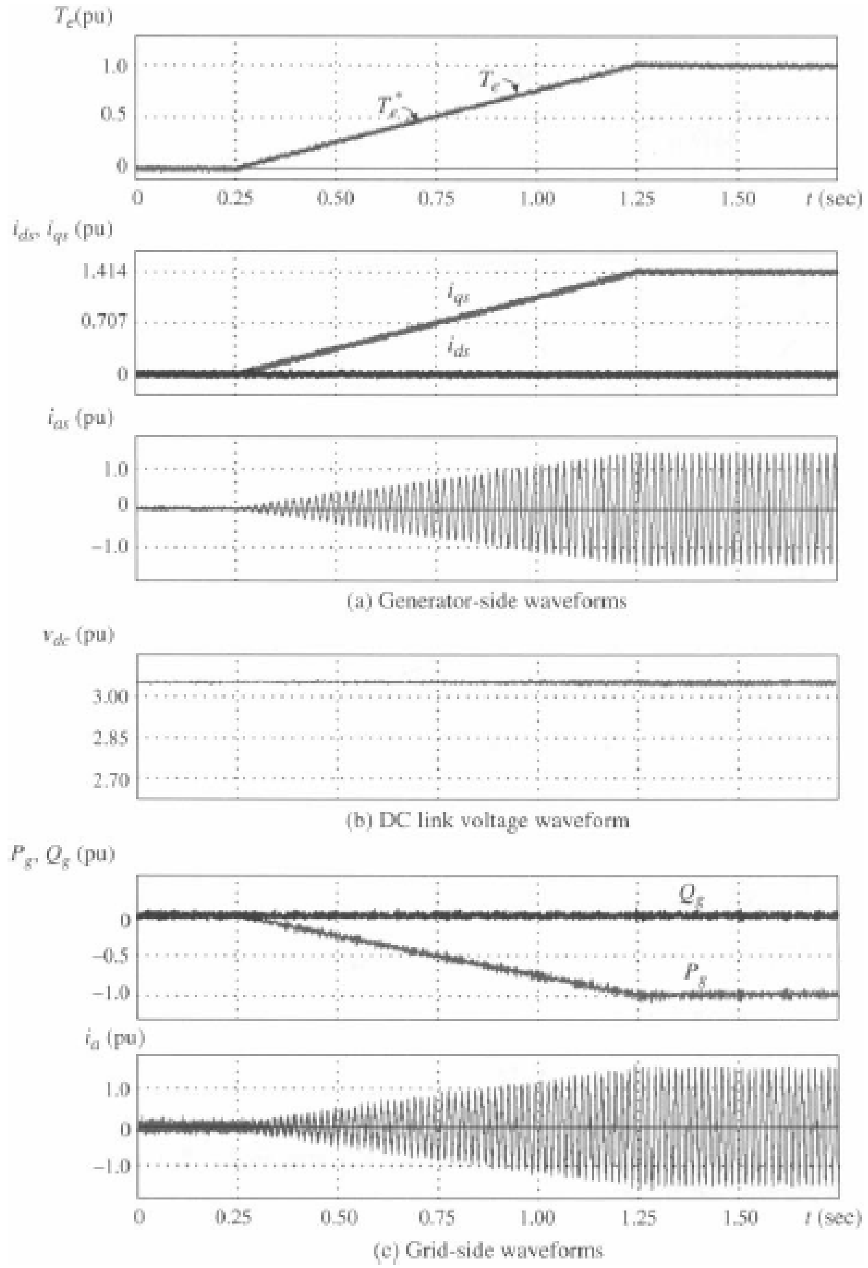

Figure 15.7Simulated waveforms of a nonsalient SG wind energy system during start-up [1]

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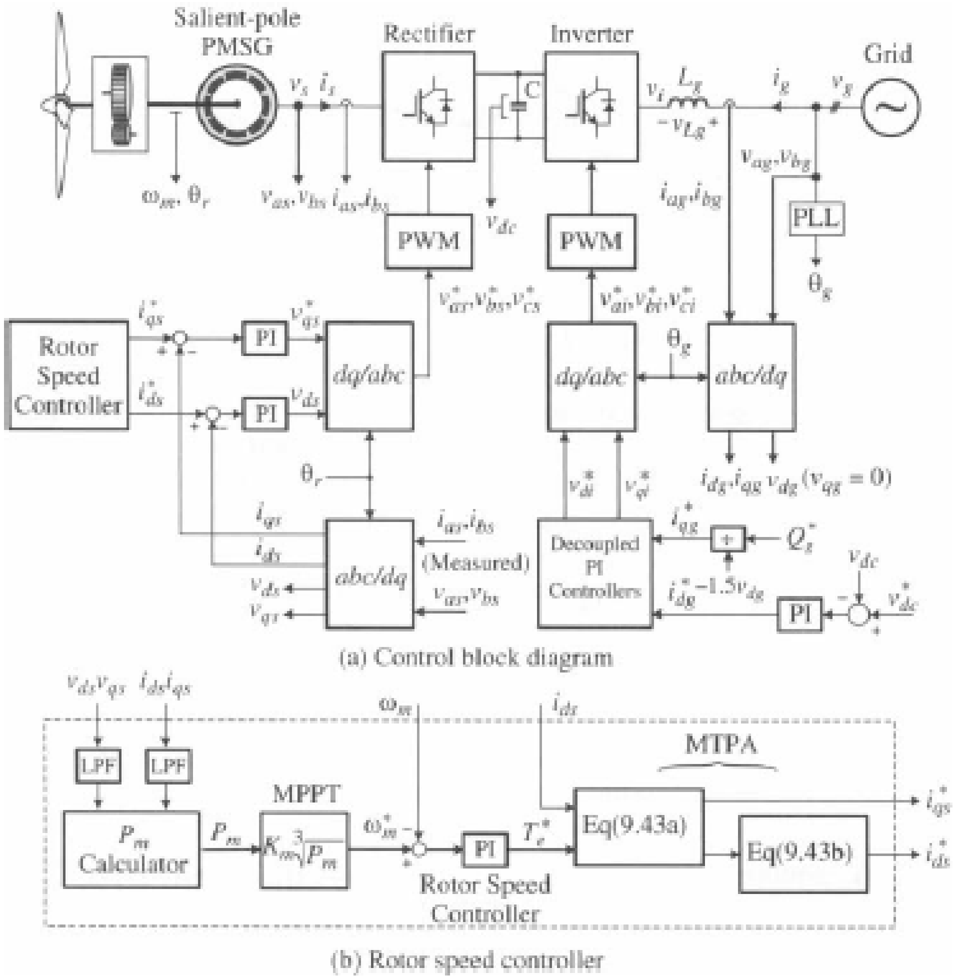

Figure 15.8 Block diagram of salient-pole SG WECS with MTPA and rotor speed feedback controls [1].

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To implement the MTPA for the salient-pole generator, the reference values for the dq-axis currents, i_{ds}^* and i_{qs}^*, are calculate

$$\begin{cases} i_{qs}^* = \dfrac{2T_e^*}{3P\left(\lambda_r - (L_d - L_q)\right)i_{ds}} & \text{(a)} \\ i_{ds}^* = \dfrac{\lambda_r}{2\left(L_d - L_q\right)} + \sqrt{\dfrac{\lambda_r^2}{4\left(L_q - L_d\right)^2} + \left(i_{qs}^*\right)^2} & \text{(b)} \end{cases}$$

The mechanical power

$$P_m = P_s + P_{cu} = \frac{3}{2}\left(v_{ds} i_{ds} + v_{qs} i_{qs}\right) + \frac{3}{2}\left(i_s\right)^2 R_s$$

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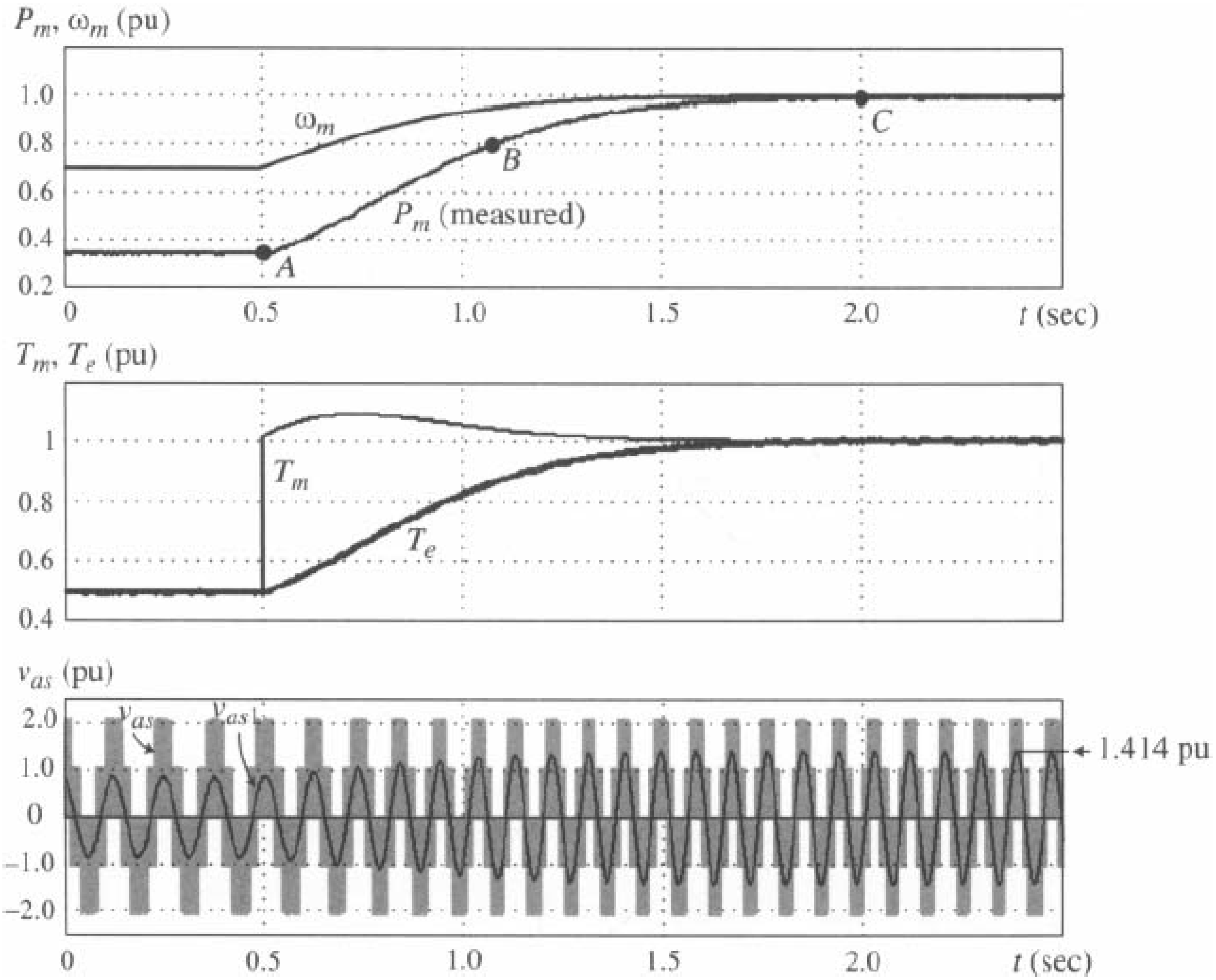

Figure 15.8 Transients of salient-pole SG wind energy system with rotor speed feedback control [1]

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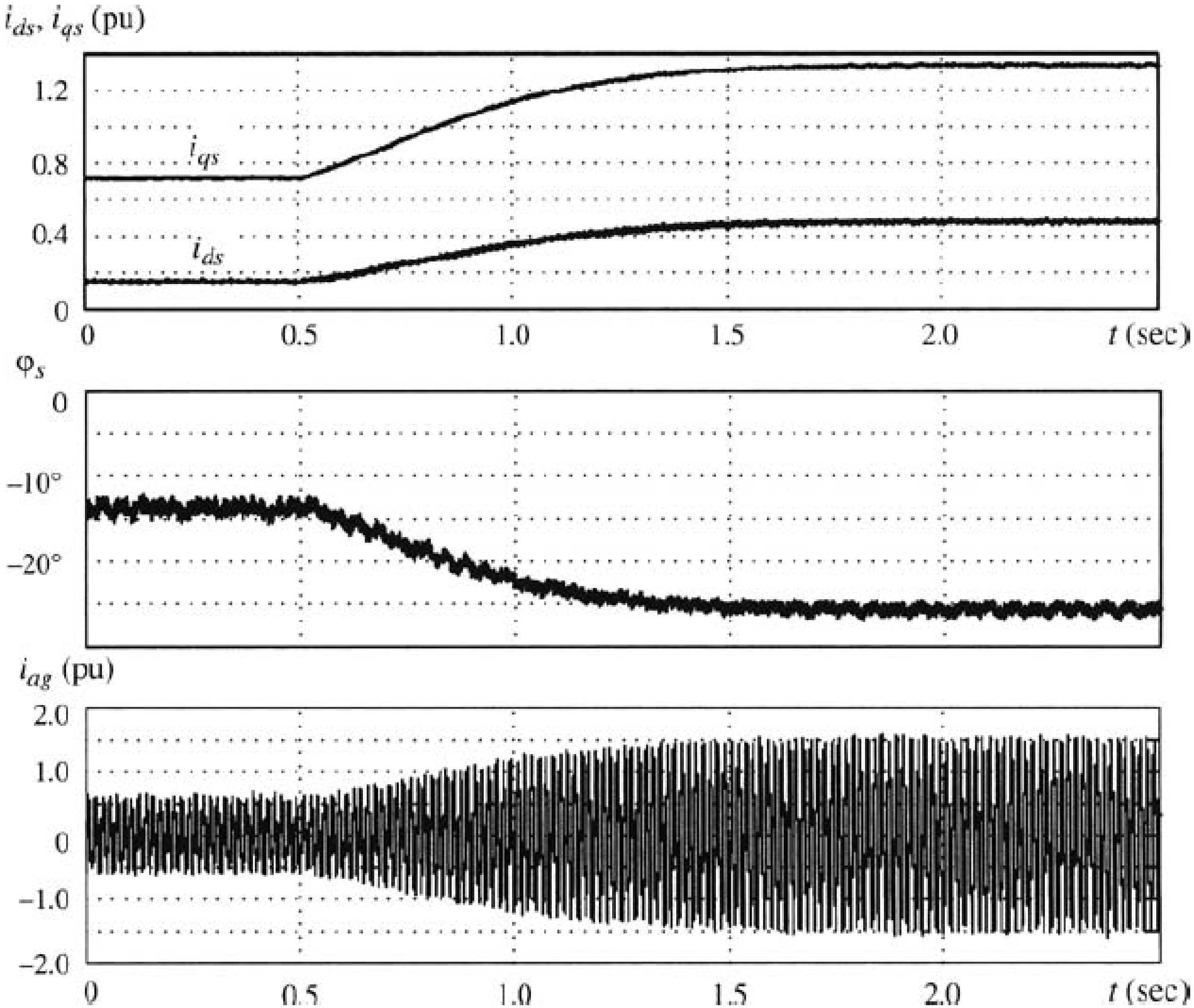

Figure 15.9 Transient waveforms for salient-pole SG WECS with rotor speed feedback control [1]

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