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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

Introduction to Wind Energy

Module 2.1

Further information:

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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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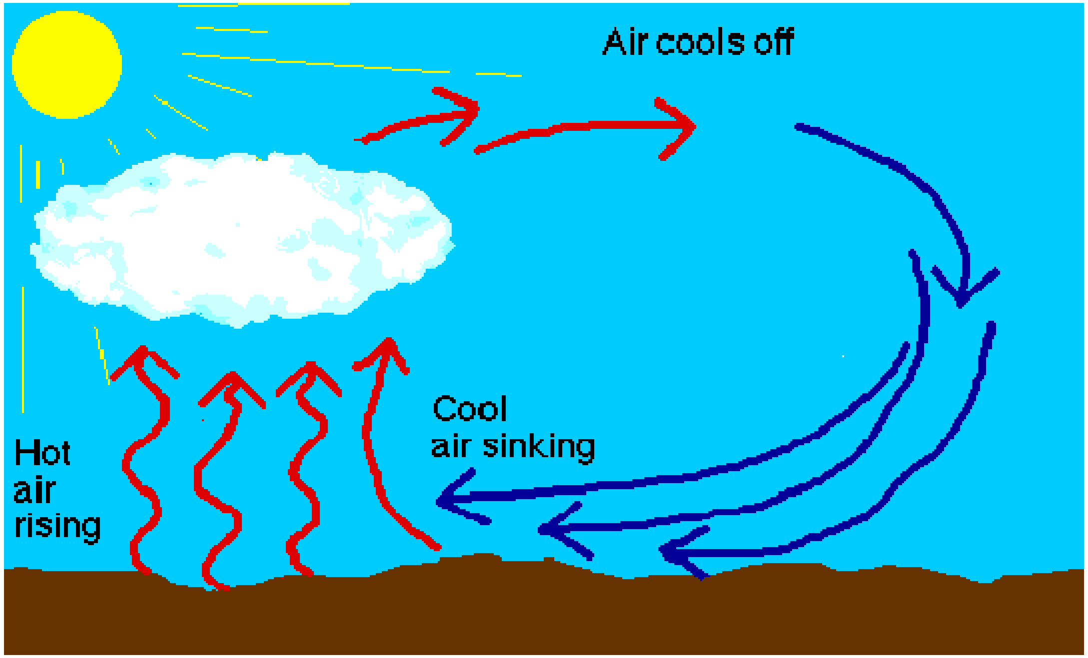
Basic Concepts of Wind Energy

Introduction to Wind Energy

What is wind?

- air in motion.
- produced by the uneven heating of the earth's surface by the sun.
- earth's surface is made of various land and water formations, sun's radiation unevenly absorbed.
- Two factors are necessary to specify wind: **speed** and **direction**.



Source: [2]

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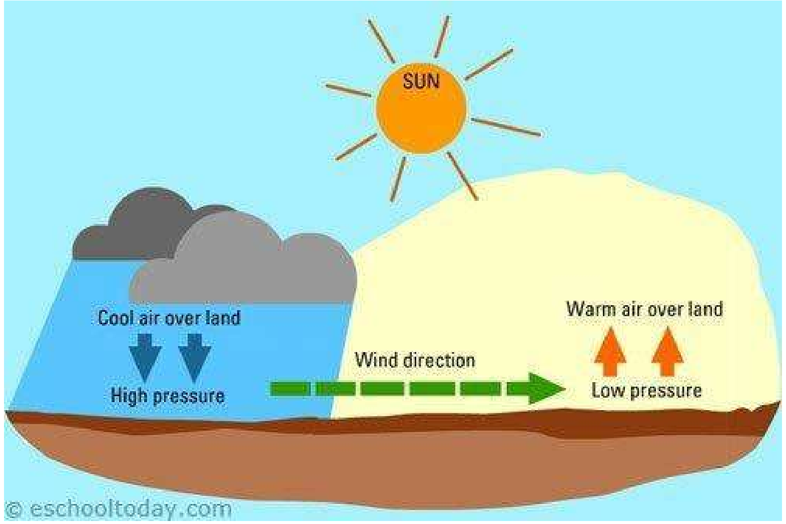
How is wind generated?

- The wind is generated as shown in the Figure
- The sun warms the Earth's surface and the atmosphere
- Some parts of the Earth receive direct rays and be warm
- Other places receive indirect rays and be colder.
- Warm air rises and cool air moves in and replaces the rising warm air.
- This movement of air is what makes the wind blow



Source: [2]

How is wind generated?

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

Examples:
1. wind to sail ships.

Source: [10]

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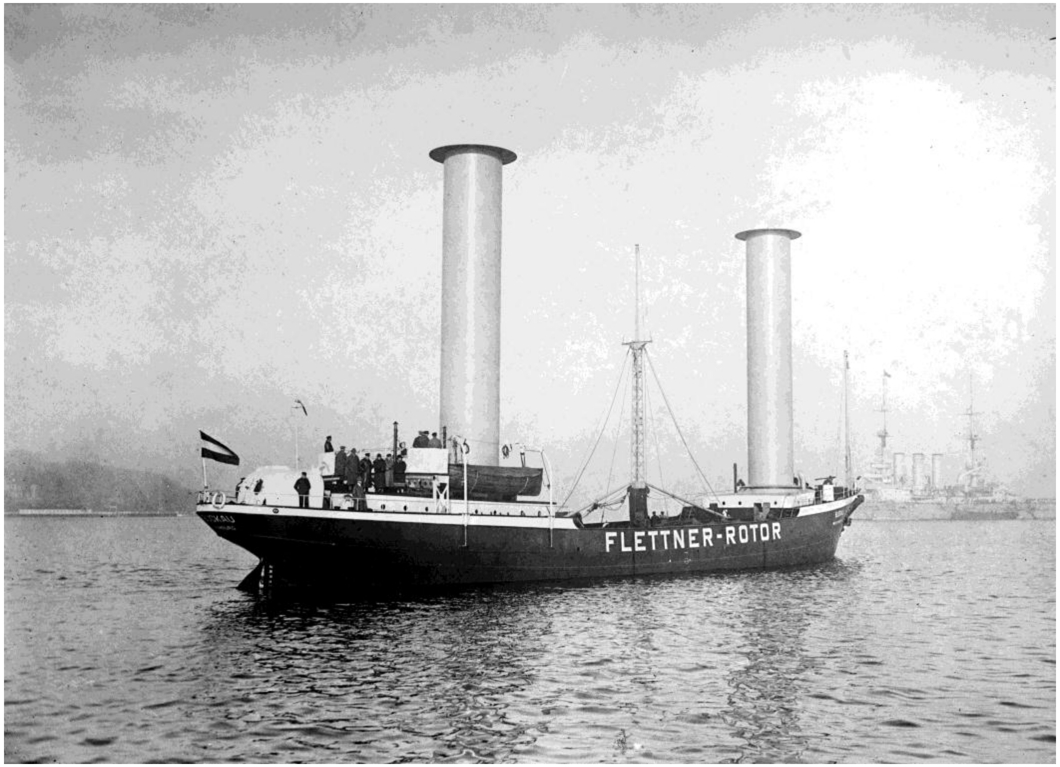
How is wind generated?

Examples:
2. Flettner rotor. (11)



Source: [11]

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How is wind generated?

Examples

3. Windmills to grind wheat.

Source: [12]

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How is wind generated?

Today, we use wind to generate electricity

Source: [13]

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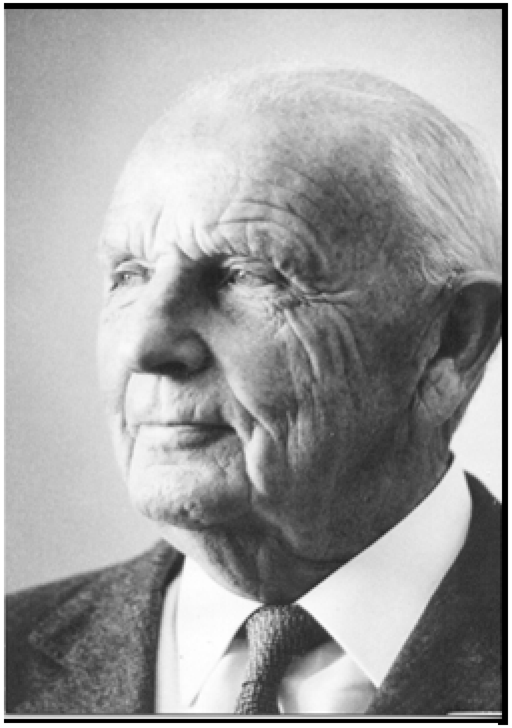
Statistical Distribution of Wind Speed

- Wind speed is a **stochastic** quantity.
- The most common density function used to represent wind speed is **Weibull.**
- 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

Source: [14]

Statistical Distribution of Wind Speed

<u>**Weibull's**</u> 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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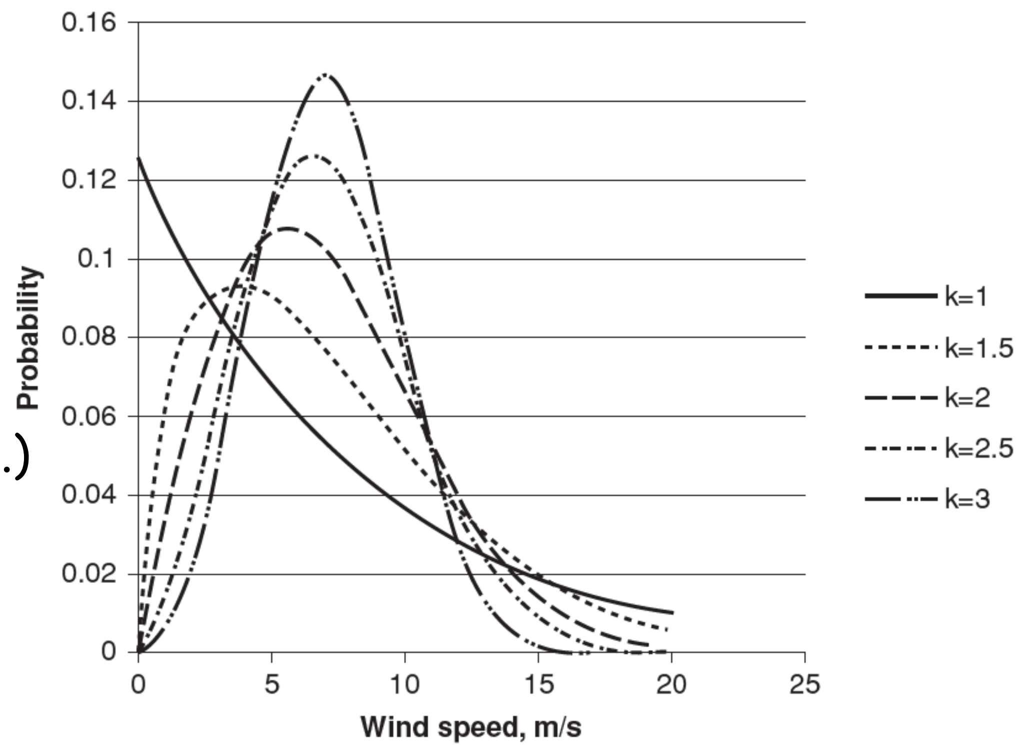
Statistical Distribution of Wind Speed

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.



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

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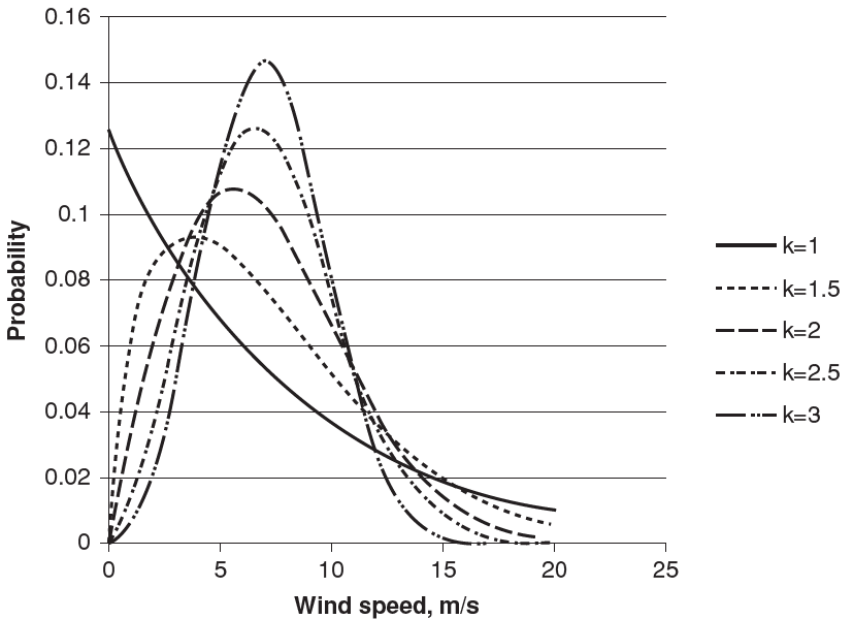

Figure 1

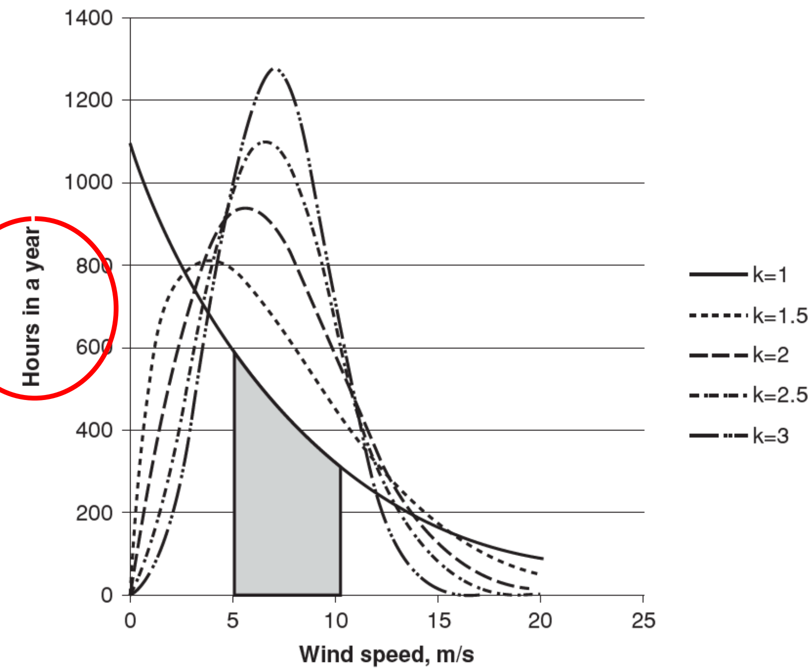

Figure 2

Probability density function represented as:

- Fraction of time wind speed is at v, (Figure 1).
- In terms of hours in a year (Figure 2), $pd(v)$ is multiplied by **8760** (number of hours in a year)

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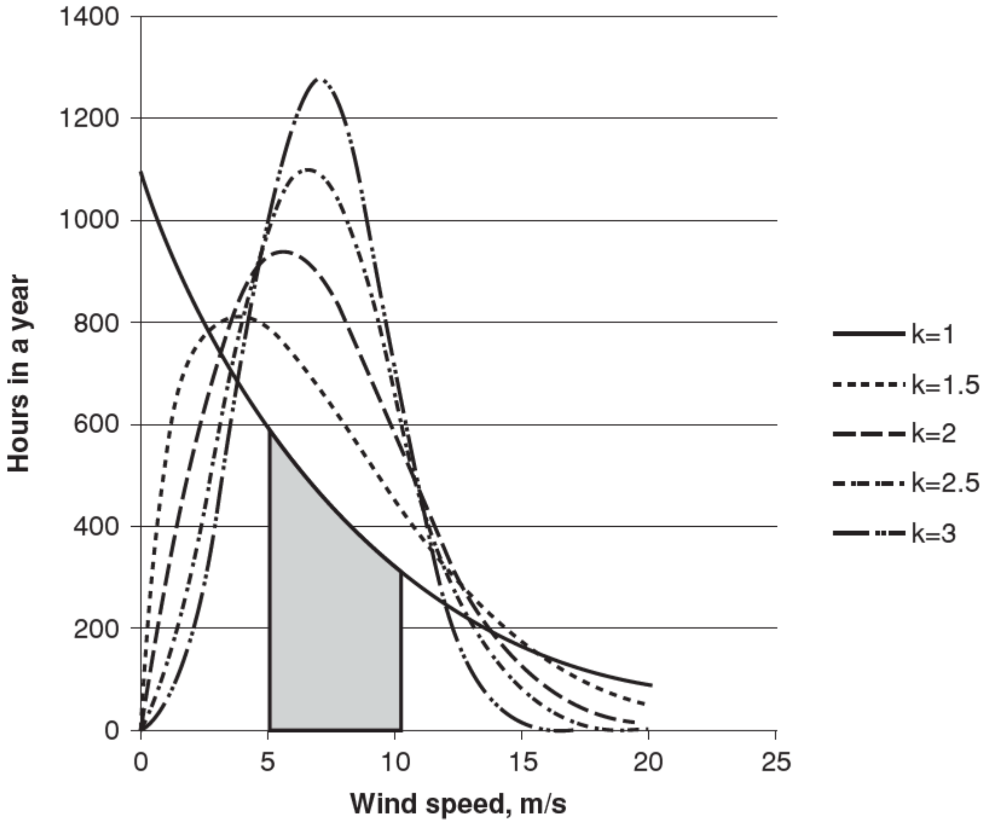
Statistical Distribution of Wind Speed

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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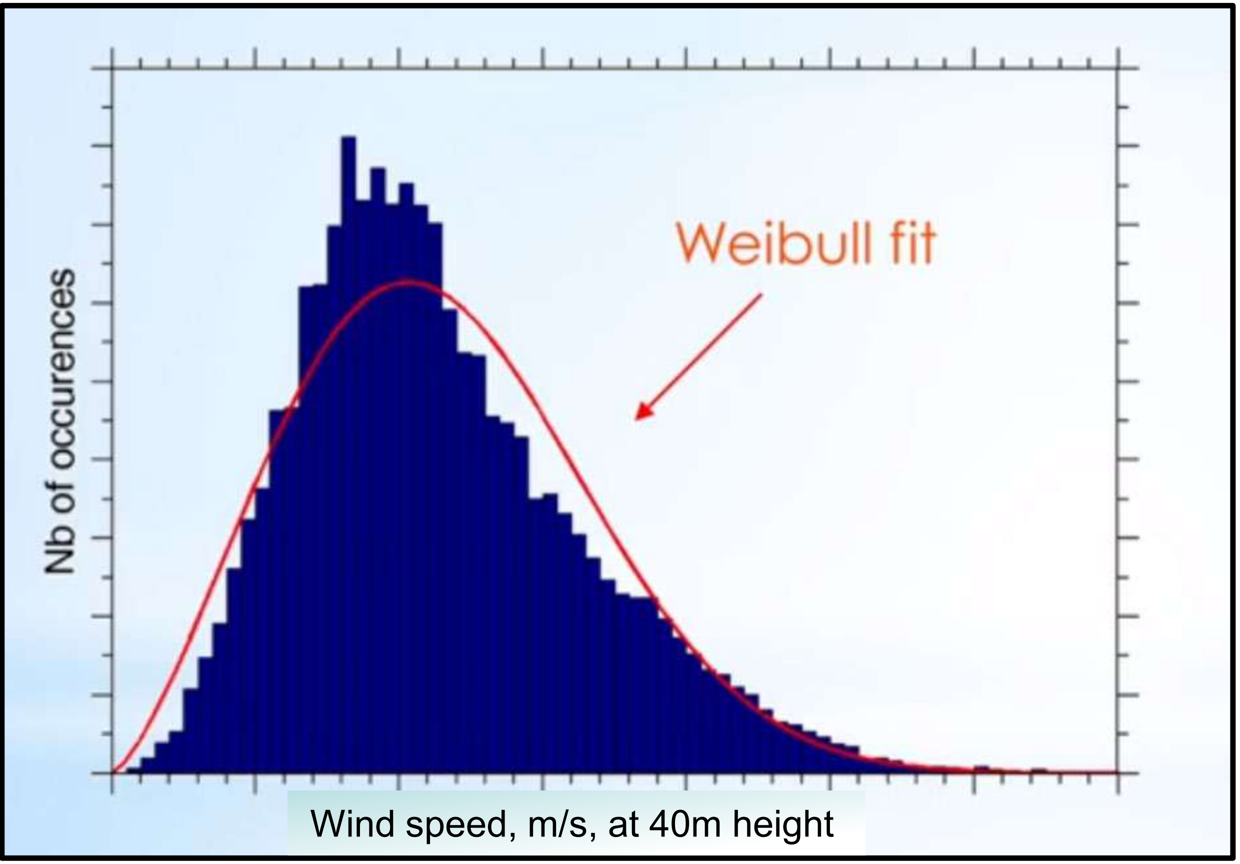
Statistical Distribution of Wind Speed

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:

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

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

where:

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

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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 m/s

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 m/s:

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

Reducing:

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

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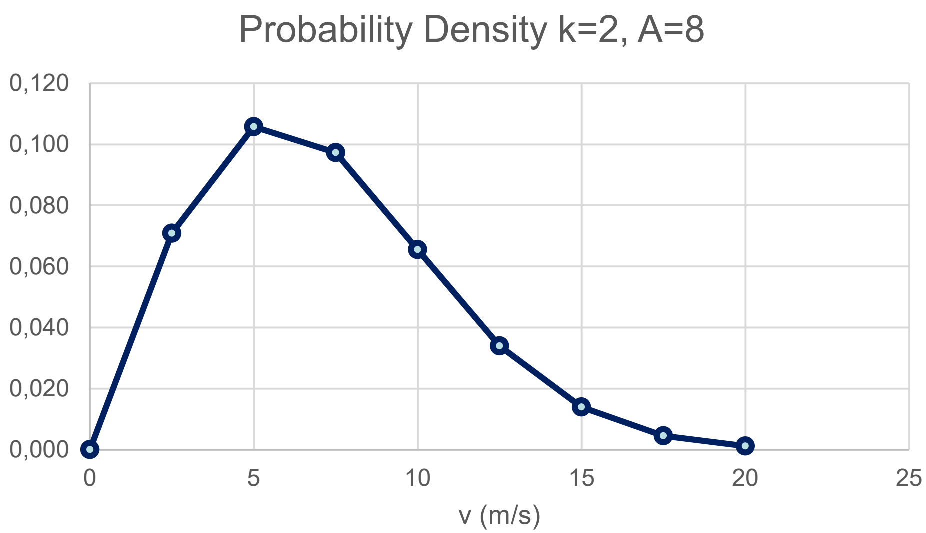
Statistical Distribution of Wind Speed

Solution (Cont.)

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

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 $\Gamma(1.5)$=0.84

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	5.03
		area	0.84
Gama(1.5)=	0.837895		

Substituting in the velocity expression:

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

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Statistical Distribution of Wind Speed

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:

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

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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.

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

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

The power density of rotor is underestimated 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 m/s

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

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

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:

v (m/s)	Probability Density	PowerDenisty	SM		f(A)
0	0.000	0.00	1	0.00	0.00
2.5	0.071	9.58	4	0.68	2.71
5	0.106	76.60	2	8.10	16.20
7.5	0.097	258.53	4	25.16	100.64
10	0.066	612.80	2	40.14	80.28
12.5	0.034	1196.88	4	40.69	162.77
15	0.014	2068.20	2	28.82	57.64
17.5	0.005	3284.23	4	15.00	60.01
20	0.001	4902.40	1	5.91	5.91
			Sig(fnArea)		486.17
	Area under the curve		405.1419042 W/m2		

Hence, the power density is 406 W/m^2 at mean wind speed of 7.09 m/s

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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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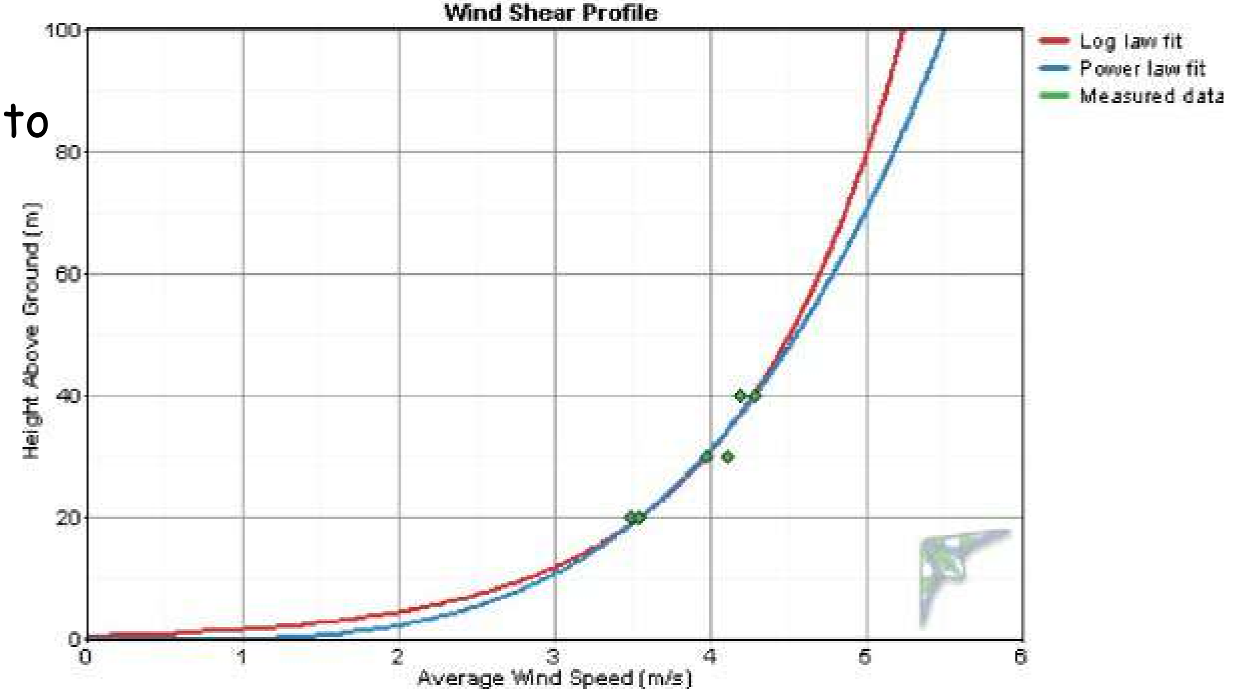
The effect of Wind Shear

Wind Shear

There are two methods to describe shear:

- Power law profile
- logarithm profile



Source: [2]

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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

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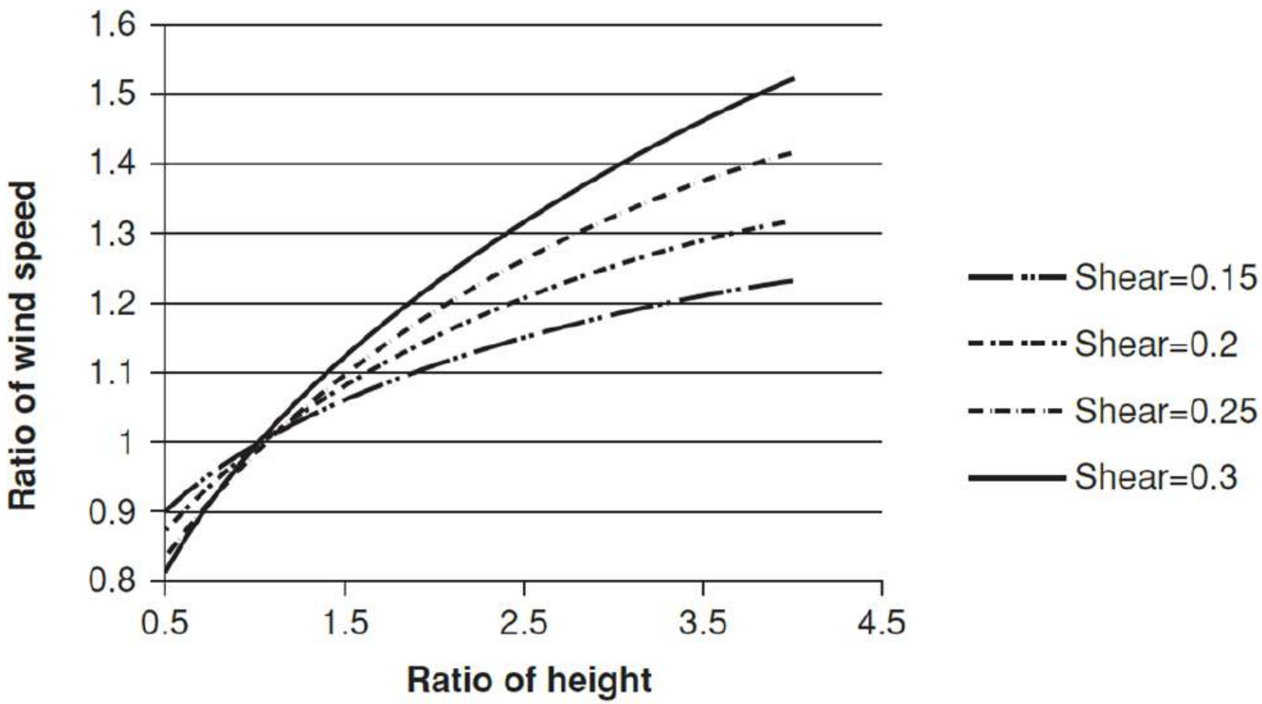
The figure below is a plot of the wind speed ratio and height ratio for different values of shear.



Source: [2]

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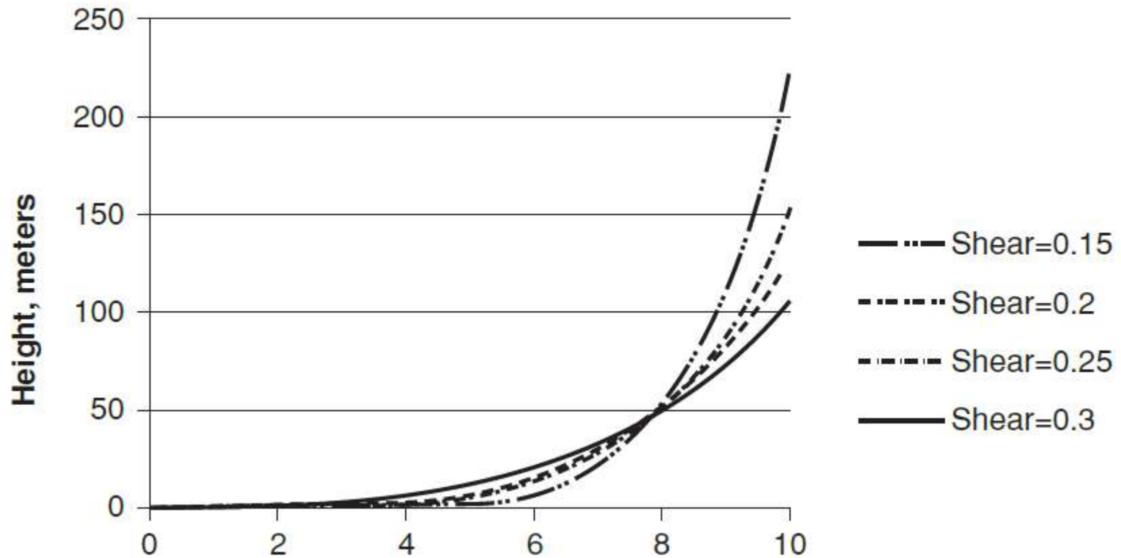
The effect of Wind Shear

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



Wind speed, m/s

Source: [2]

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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.

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

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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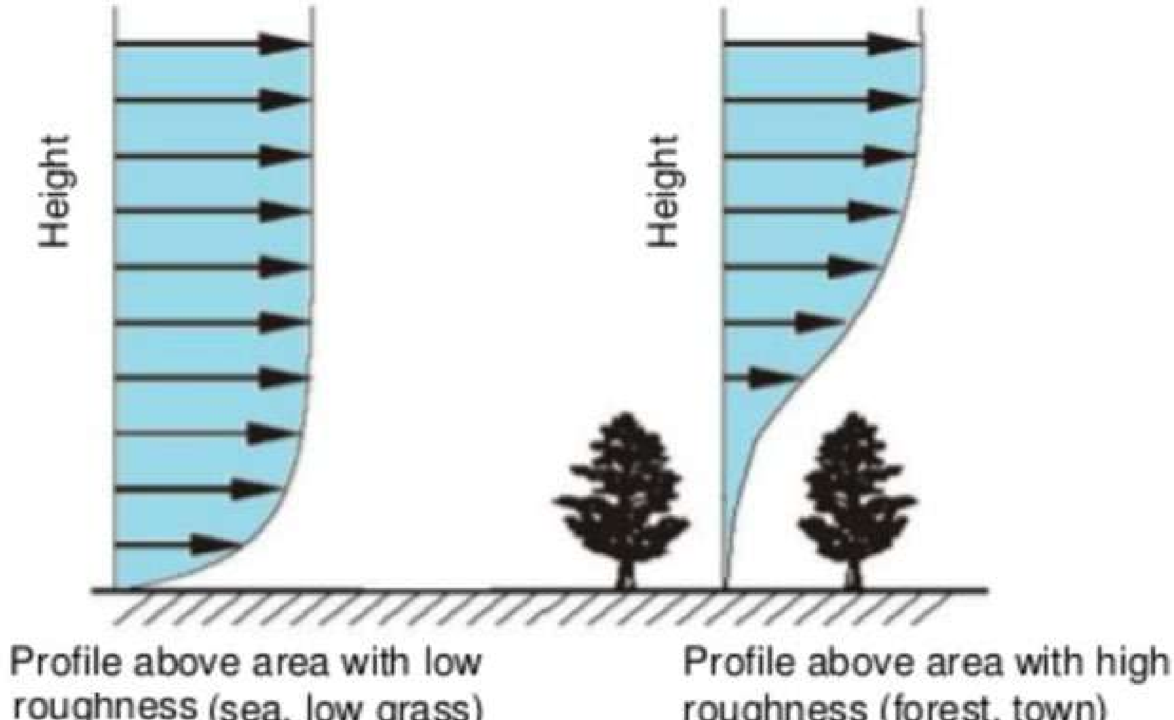
The effect of Wind Shear

Roughness length

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



Source: [4]

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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

Source: [4]

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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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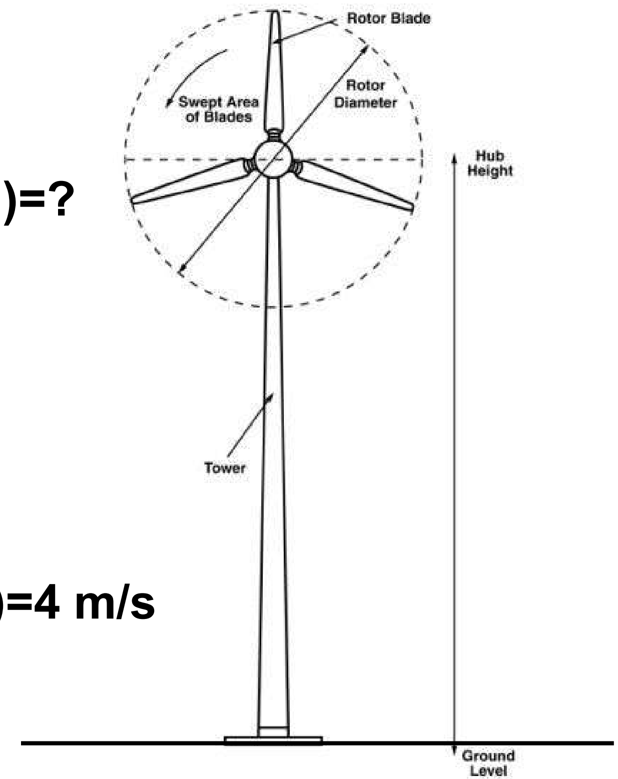
The effect of Wind Shear

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)

Source: [4]

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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	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	5.46	m/s

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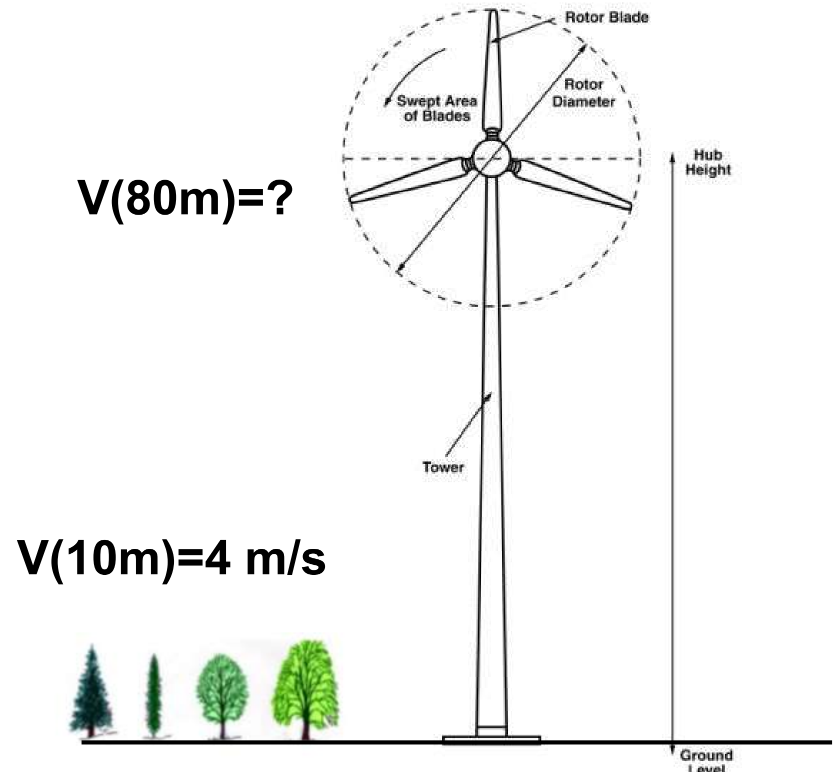
The effect of Wind Shear

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)

Source: [4]

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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	10.00	m
wind speed v1	4.00	m/s
wind shear γ	0.25	
height h2	80.00	m
wind speed v2	6.73	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 m/s

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

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

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The effect of Wind Shear

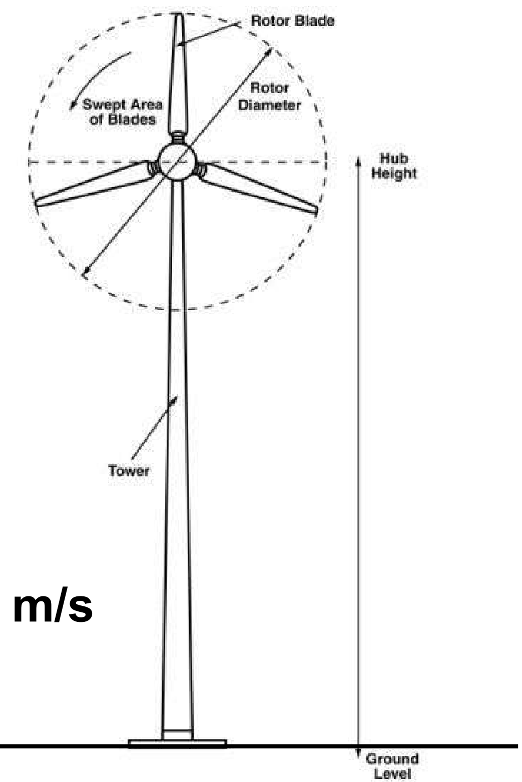
Solution

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

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

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

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



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

Source: [4]

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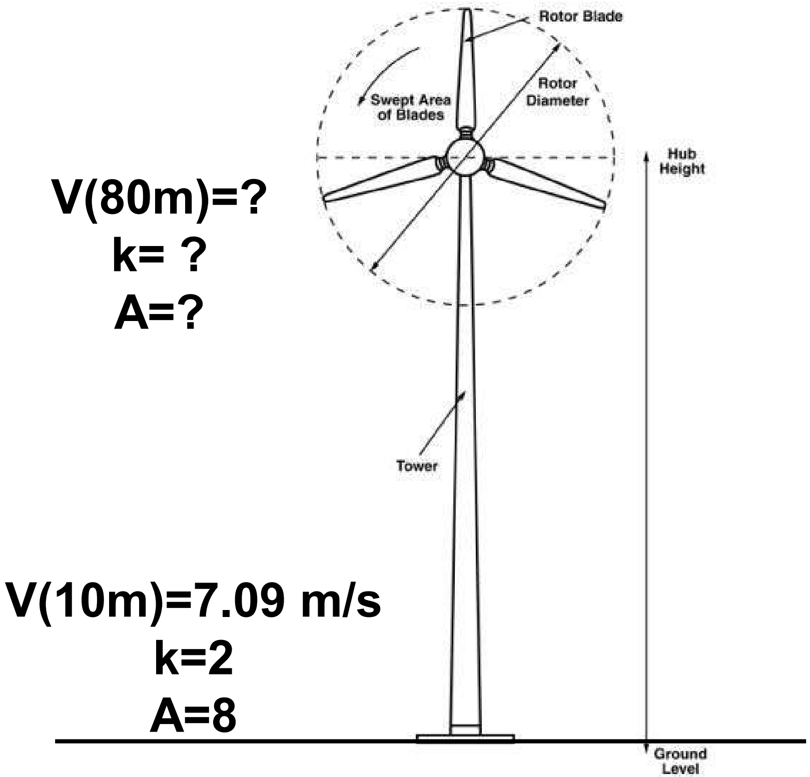
The effect of Wind Shear

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	10.00	m
wind speed v1	7.09	m/s
wind shear γ	0.14	
Shape factor k1	2.00	
Scale factor A1	8.00	
height h2	80.00	m
wind speed v2	9.49	m/s
Shape factor k2	2.68	
Scale factor A2	10.70	



Source: [4]

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 m/s:

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

Reducing:

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

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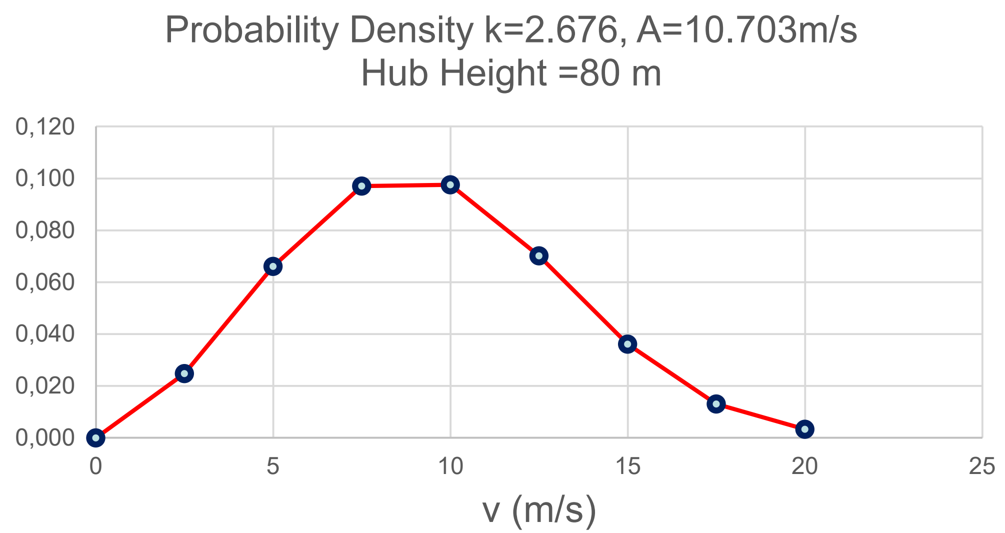
The effect of Wind Shear

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 :

Hence, the power density at (hub height 80 m) and 9.49 m/s mean velocity is 753 W/m²

v (m/s)	Probability Density	PowerDenisty	SM	
0	0.000	0.00	1	0.00
2.5	0.025	9.58	4	0.24
5	0.066	76.60	2	5.07
7.5	0.097	258.53	4	25.08
10	0.098	612.80	2	59.80
12.5	0.070	1196.88	4	84.02
15	0.036	2068.20	2	74.64
17.5	0.013	3284.23	4	42.87
20	0.003	4902.40	1	15.93
			Sig(fnArea)	

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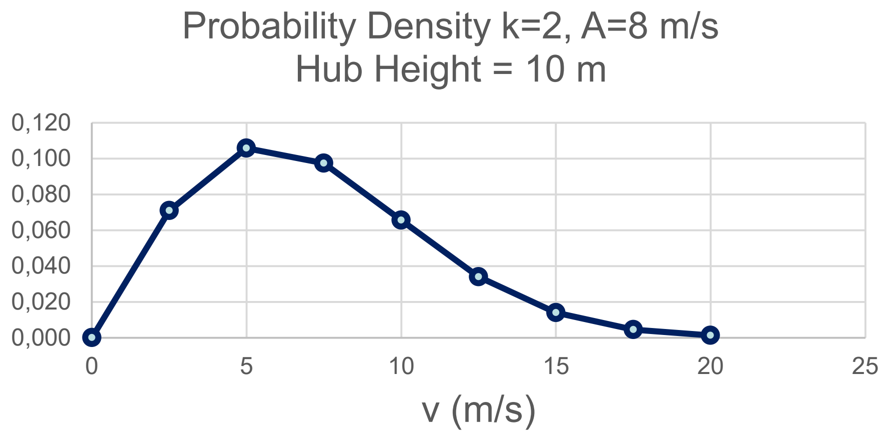
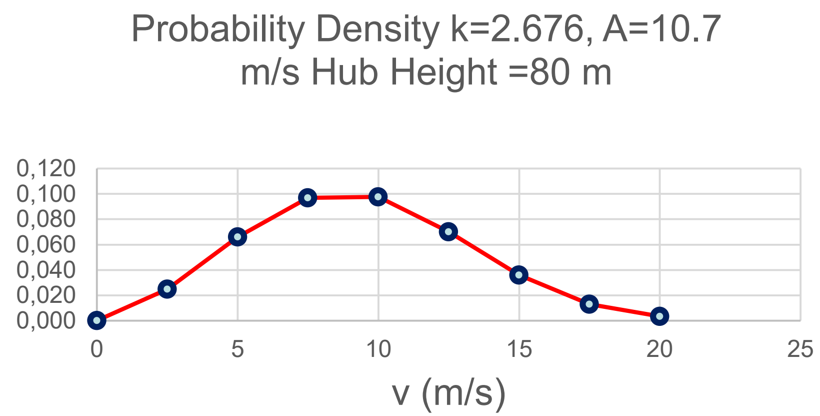
Availability of Wind Energy and estimation of Wind Energy Potential

Probability density function at two different hub heights





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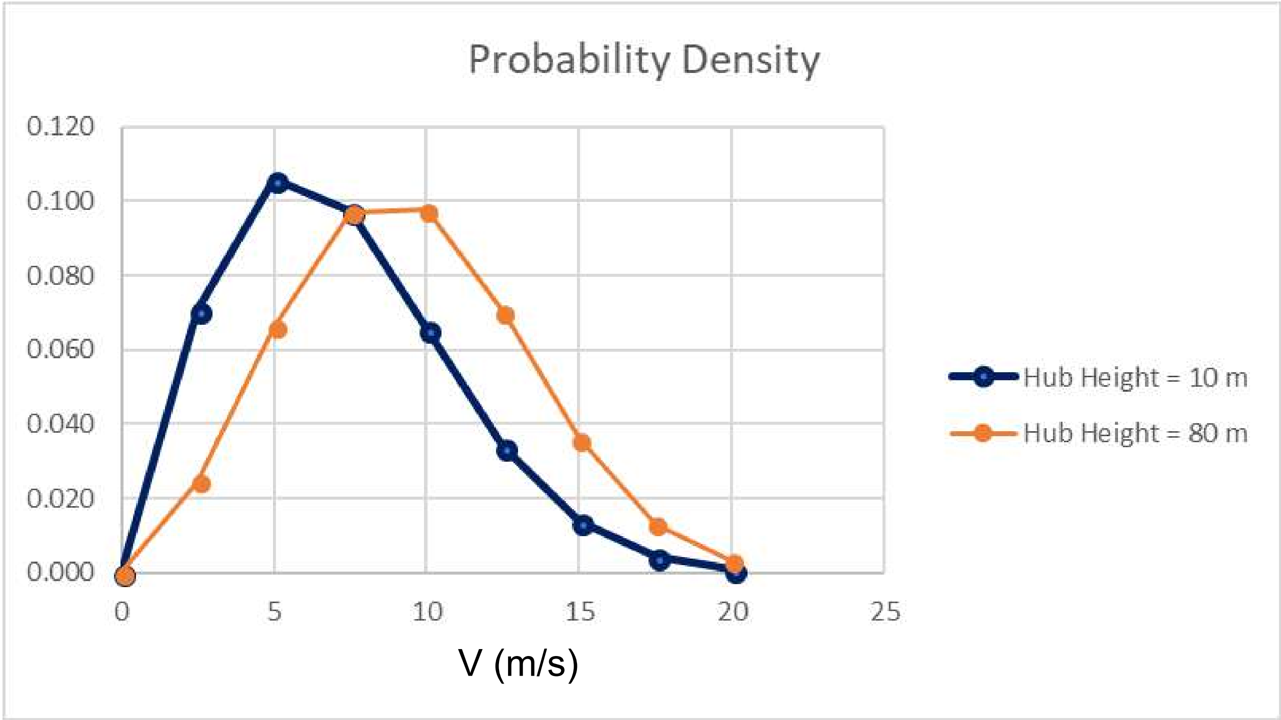
Availability of Wind Energy and estimation of Wind Energy Potential

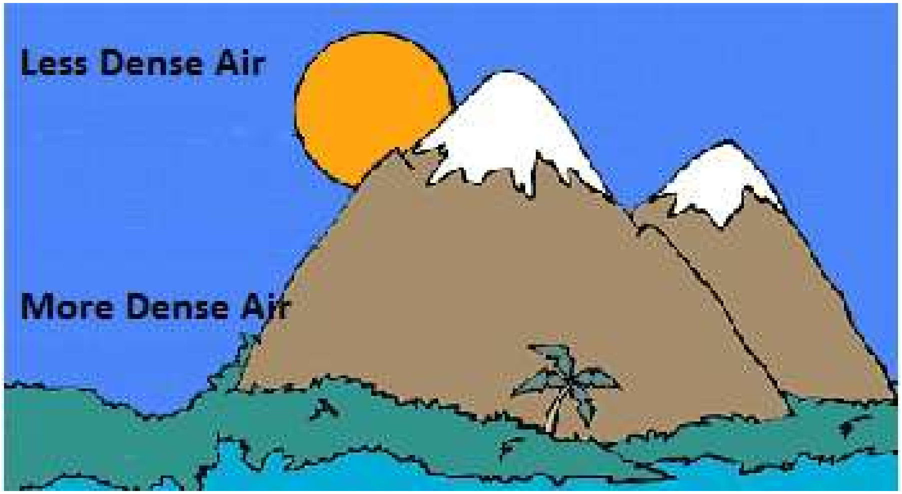
Probability density function at two different hub heights



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.

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



Source: [2]

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

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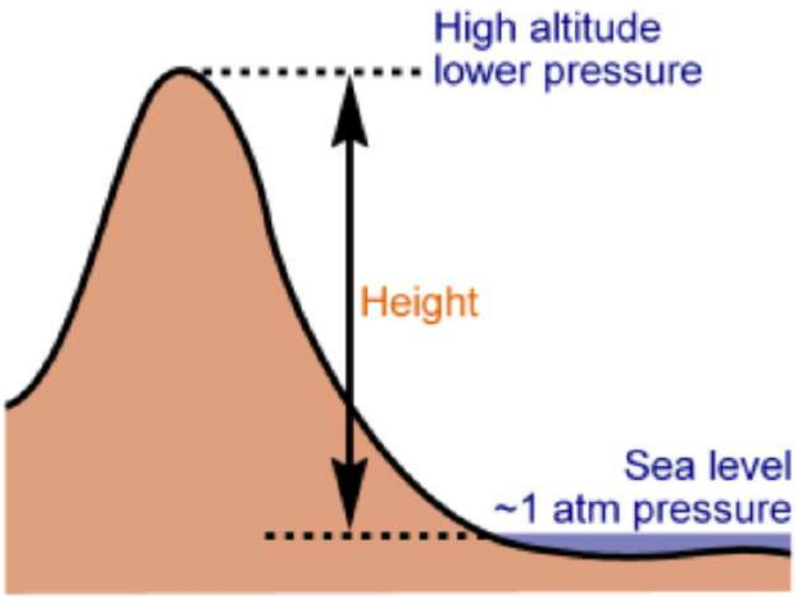
Density of Air as a Function of Elevation (Cont.)

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:



Source: [2]

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
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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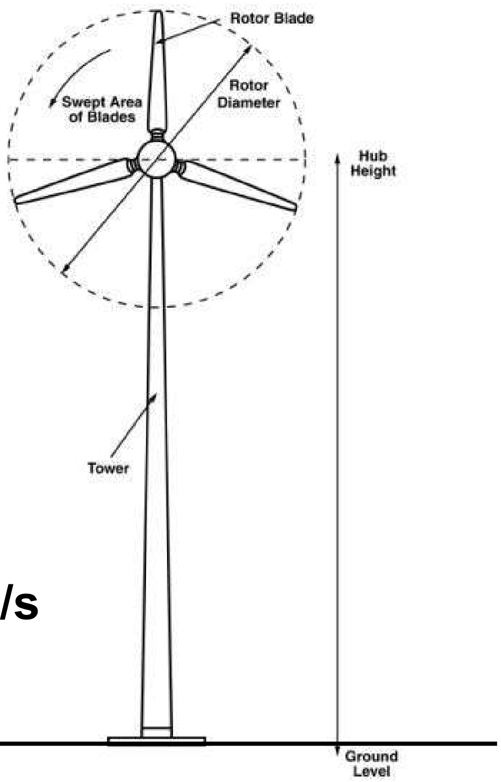
Availability of Wind Energy and estimation of Wind Energy Potential

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)

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:

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

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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Recommended literature

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

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

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

[10 https://en.wikipedia.org/wiki/Flettner_rotor

[11] http://www.imcbrokers.com/blog/overview/detail/e-ship-1

[12] https://pixabay.com/photos/windmill-wind-mill-wing-grind- 879613

[13] https://en.globes.co.il/en/article-enlight-buys-rights-to-kosovo-wind-farm-project-1001227695

[14] https://en.wikipedia.org/wiki/Waloddi_Weibull

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Introduction to Wind Energy

Module 2.1

Further information:

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info@weset-project.eu

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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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Calculation of the Kinetic Energy of Wind

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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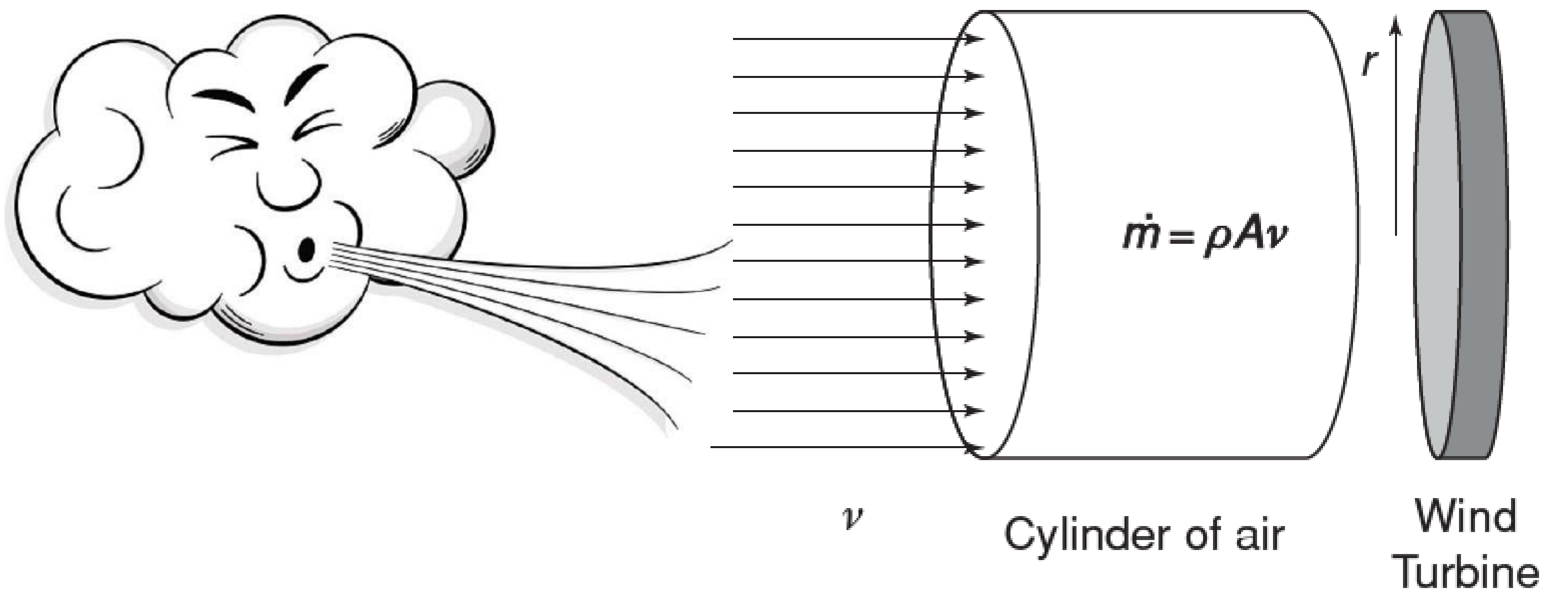
Calculation of the Kinetic Energy of Wind

- 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˙	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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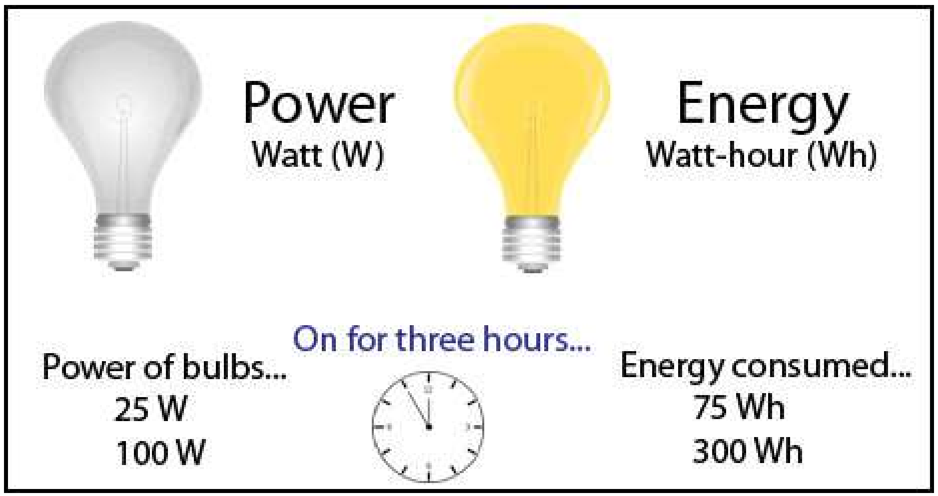
Calculation of the Kinetic Energy of Wind

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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Calculation of the Kinetic Energy of Wind

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

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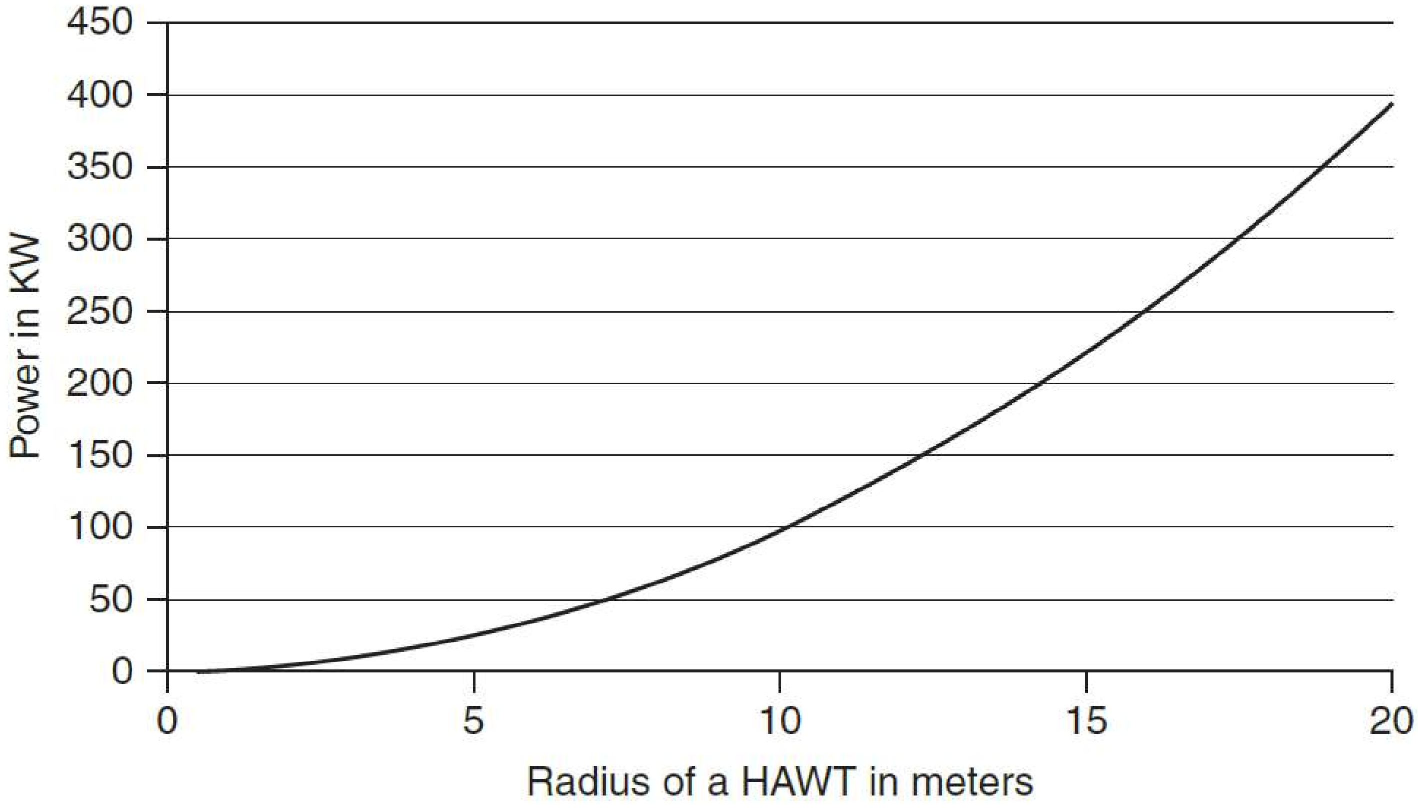
The relationship between power and rotor diameter are shown below



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Calculation of the Kinetic Energy of Wind

Sensitivity of Power to Wind Speed

- If speed is changed by a small amount and all else is constant, then

$$\Delta P / P = 3 \Delta v / v$$

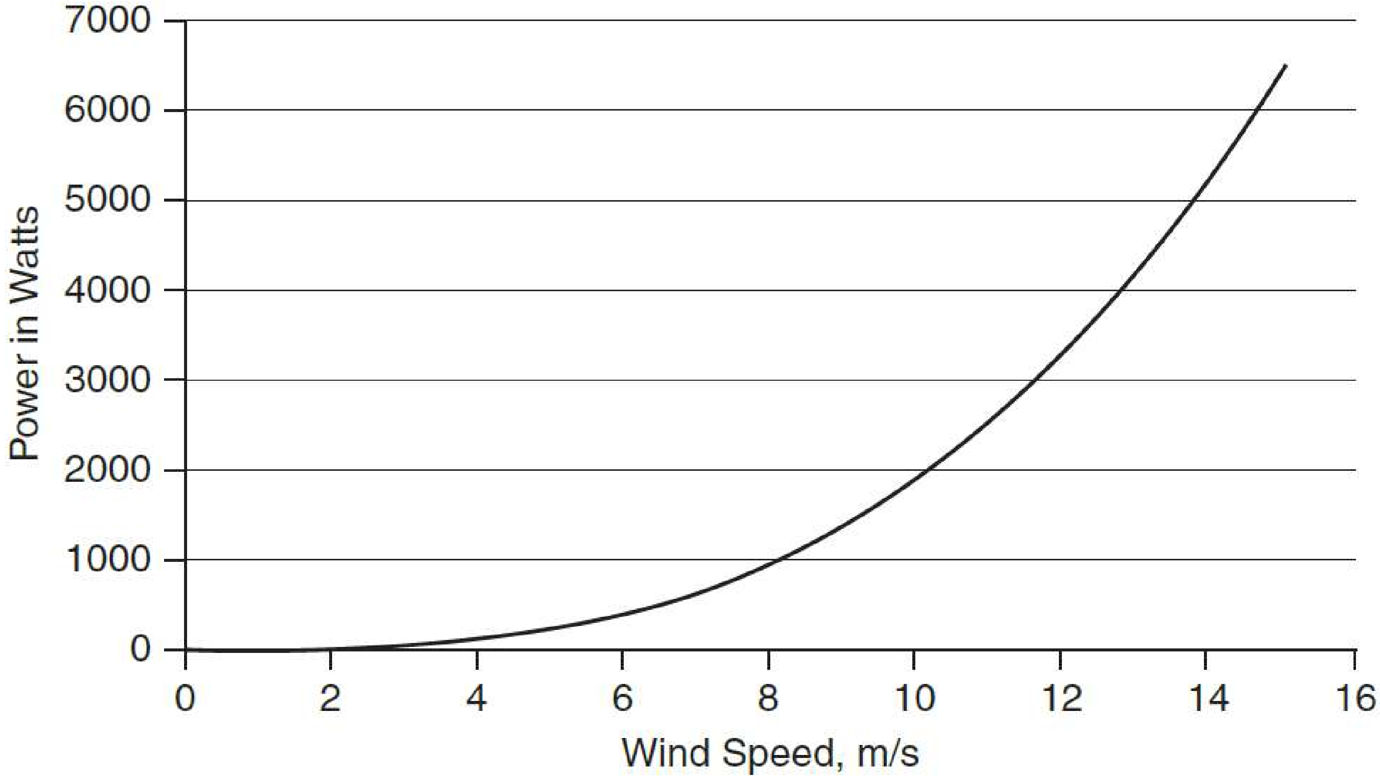
- This means that if the speed is increased/decreased by 1%, energy will increase/decrease by 3%
- However, if the wind speed is increased by 20%, the power will increase by:

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

- This is a 72.8% increase in power

Calculation of the Kinetic Energy of Wind

The relationship between power and wind speed, are shown below



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Calculation of the Kinetic Energy of Wind

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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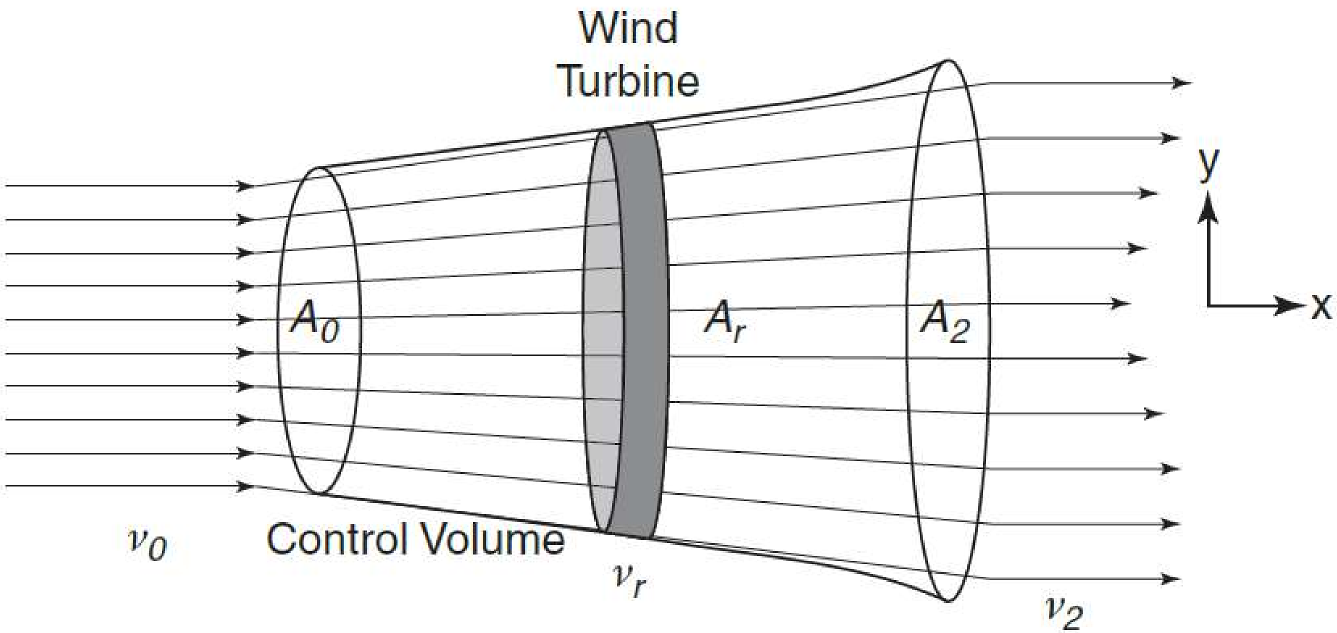
Calculation of the Kinetic Energy of Wind

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

Calculation of the Kinetic Energy of Wind

Typical Control Volume around a wind rotor



Source: [4]

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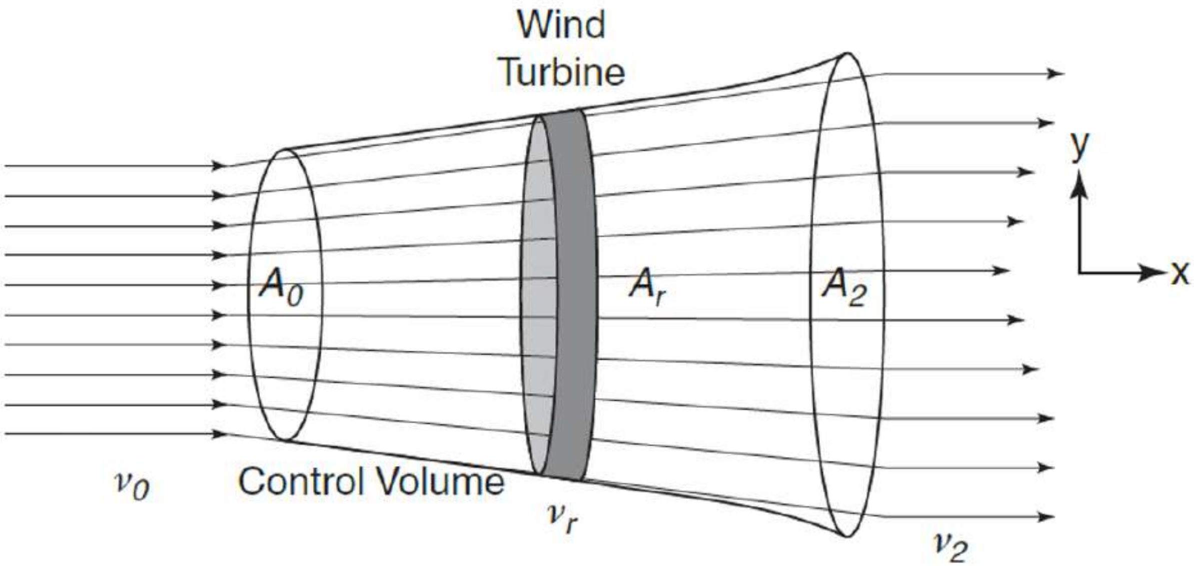
Conservation of mass and momentum in Wind Turbines

Conservation of Mass



Source: [4]

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, $v_0 > v_r > v_2$.

Conservation of mass and momentum in Wind Turbines

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
- Ppotential energy is because of relative position of the fluid.

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Conservation of mass and momentum in Wind Turbines

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 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

Source: [10]

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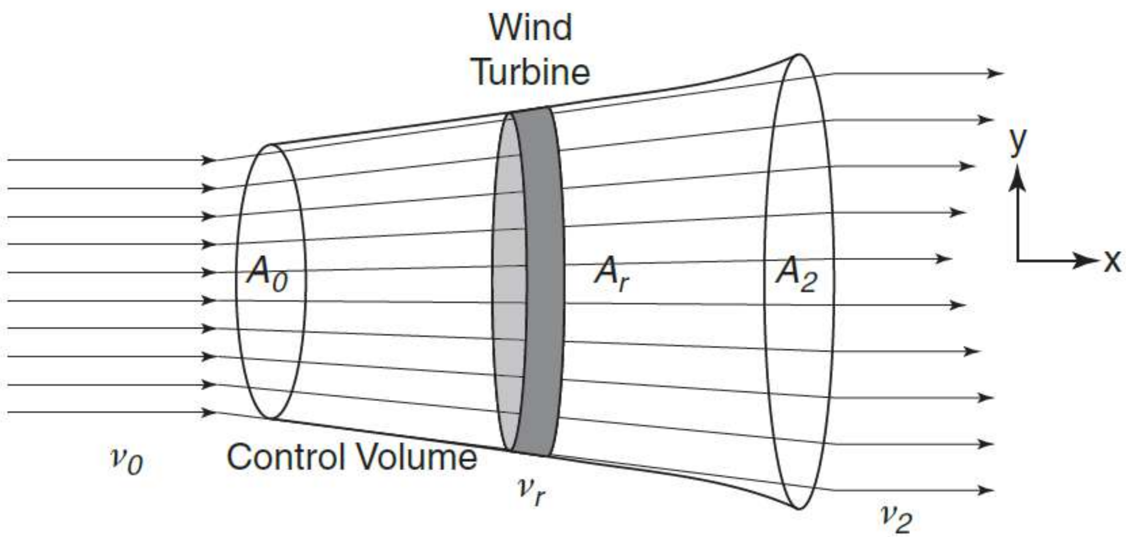
Conservation of mass and momentum in Wind Turbines



Source: [4]

- 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 mass and momentum in Wind Turbines

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 mass and momentum in Wind Turbines

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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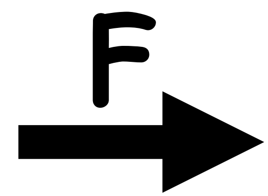
Conservation of mass and momentum in Wind Turbines

Conservation of Momentum (Cont.)

- The change in momentum in the control volume means that there is an **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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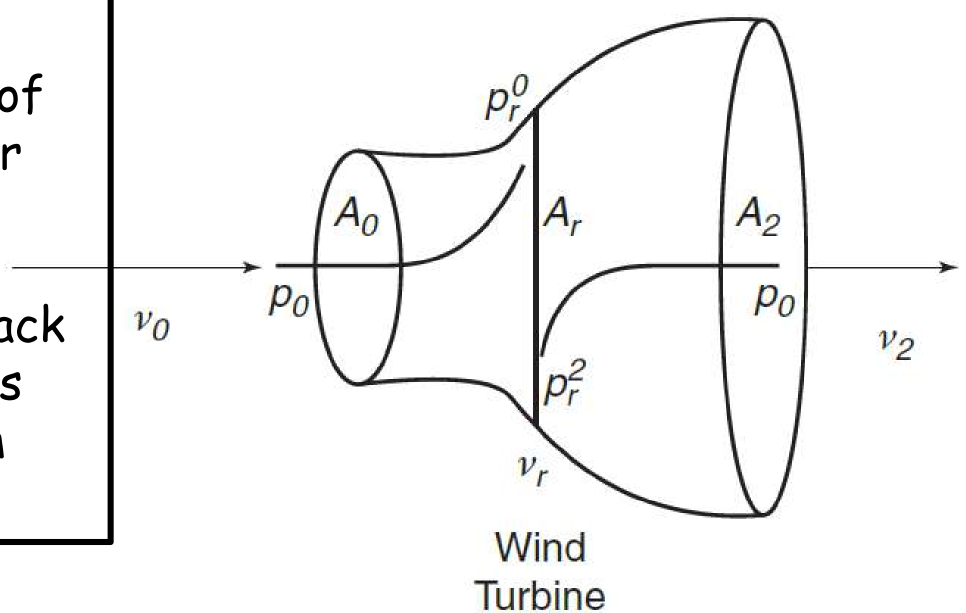
Conservation of mass and momentum in Wind Turbines

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



Source: [4]

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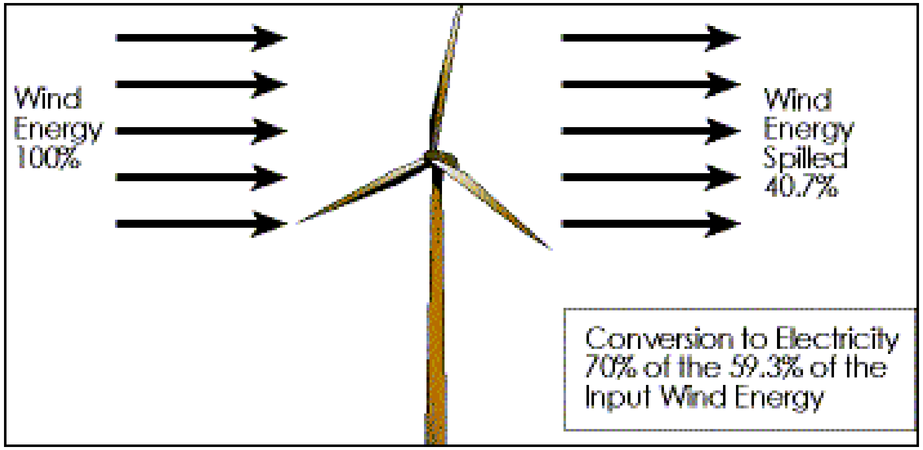
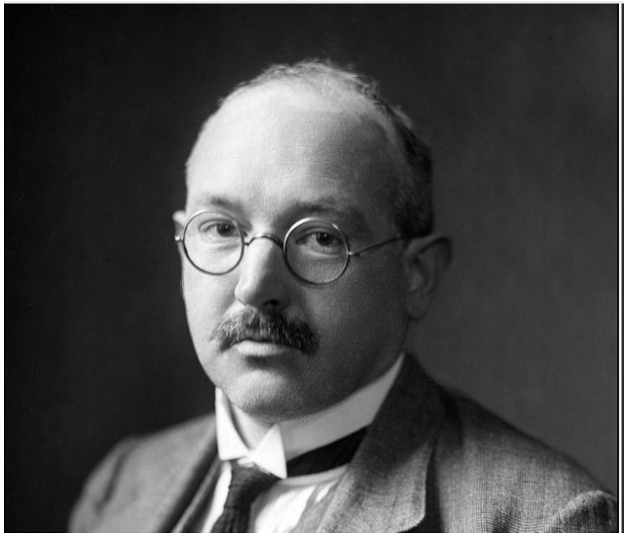
The Betz limit of Wind Turbines

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)

Source: [12]

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The Betz limit of Wind Turbines

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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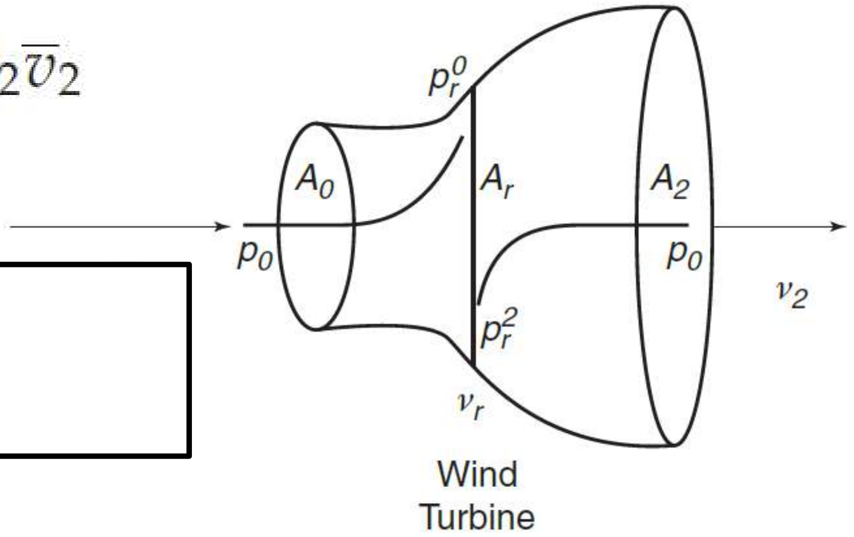
The Betz limit of Wind Turbines

Derivation of Betz Limit

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

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

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



Source: [4]

The Betz limit of Wind Turbines

Derivation of Betz Limit

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

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

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

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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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Estimation of Useful Power for Wind turbines

Derivation of Betz Limit

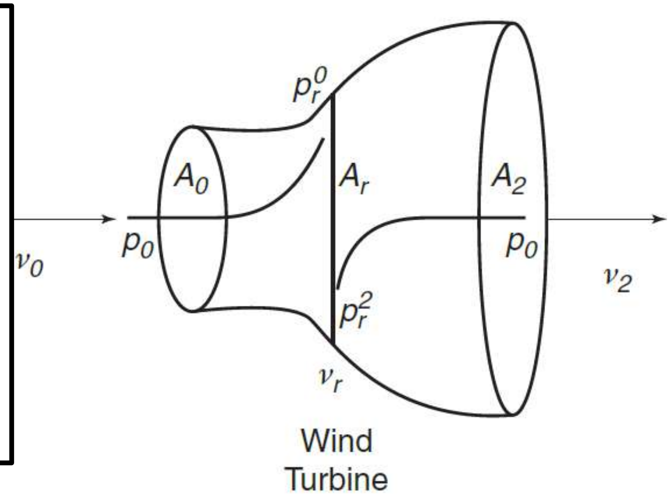
Applying conservation of energy, or Bernoulli's law is next applied in two volumes:

(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.

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

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



Source: [4]

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Estimation of Useful Power for Wind turbines

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

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

Momentum eq. Bernoulli's eq.

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

Hence

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

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Estimation of Useful Power for Wind turbines

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:

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

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

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:

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

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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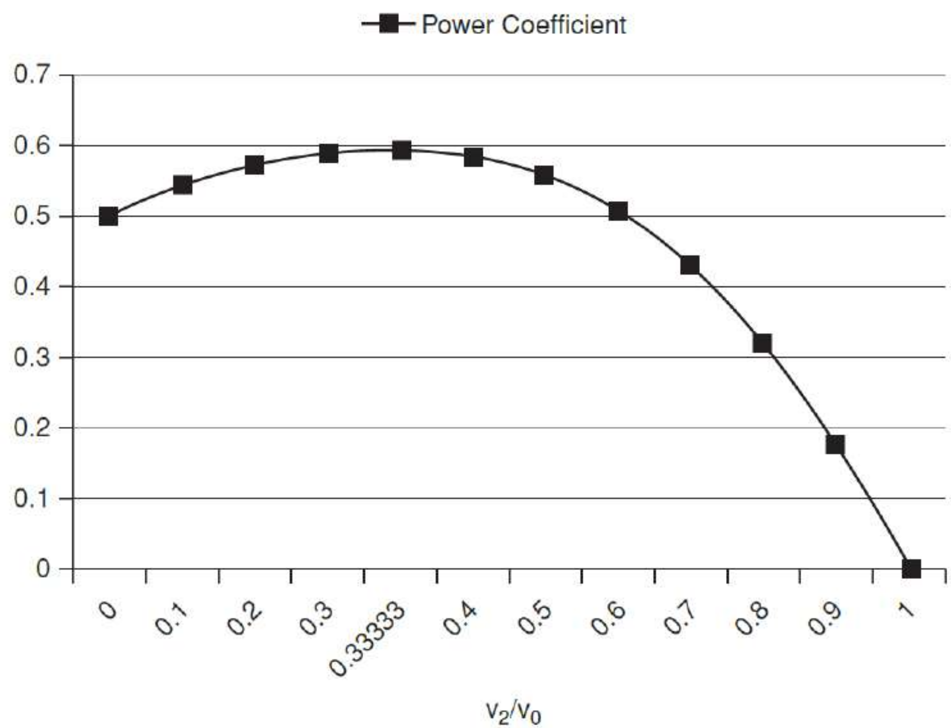
Estimation of Useful Power for Wind turbines

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

The figure represent Cp versus v_2/v_0 ratio [1] .



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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	Usefull Power
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	m^2	large WTG	>200 m2
Density	1.22	kg/m^3		

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

m/s	kW	kW
Wind Speed	**Usefull Power**	**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	
Wind Speed	**Usefull Power**	**BetzLimit**	Cp
2	5	11.13	0.45
4	50	89.07	0.56
6	150	300.61	0.50
8	400	712.55	0.56
10	660	1391.70	0.47
12	900	2404.86	0.37
14	1000	3818.83	0.26

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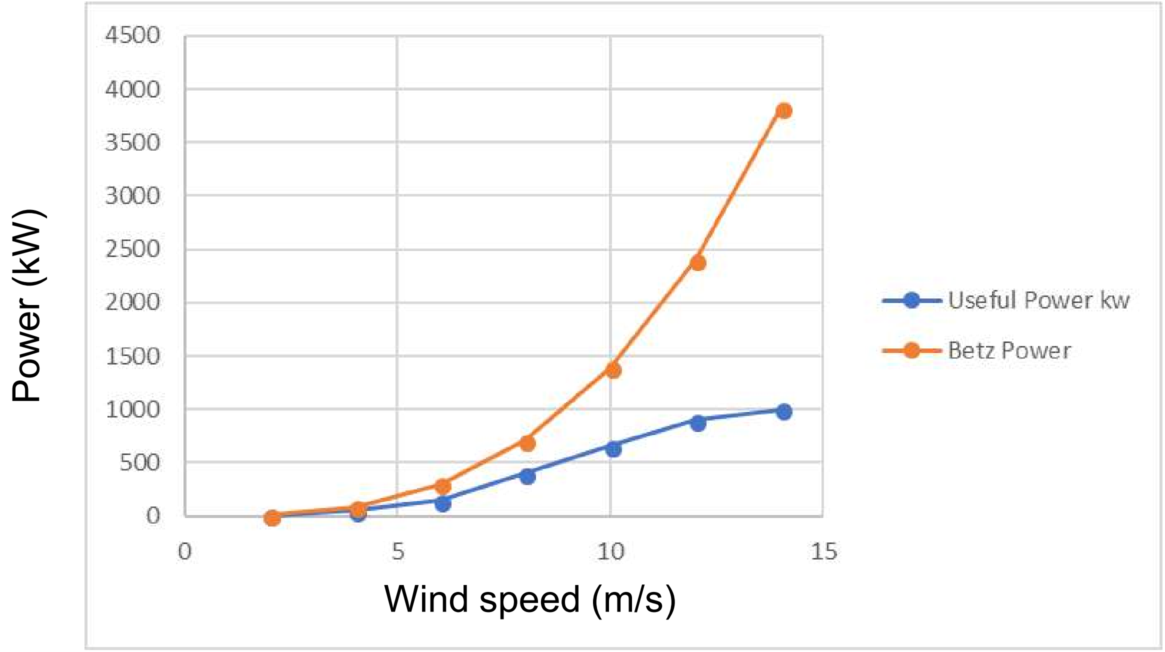
Estimation of Useful Power for Wind turbines

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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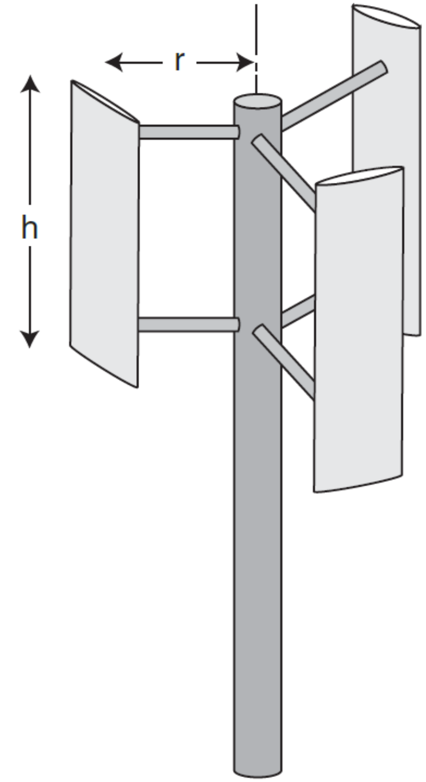
Estimation of Useful Power for Wind turbines

Example 3

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



Source: [2]

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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Recommended literature

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

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
[9] www.awea.org American Wind Energy Association
[10] https://www.alamy.com/stock-photo-daniel-bernoulli-49973531.html
[11] https://en.wikipedia.org/wiki/Albert_Betz

Introduction to Wind Energy

Module 2.1

Further information:

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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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A short history of Wind as source of energy

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.

Source: [12]

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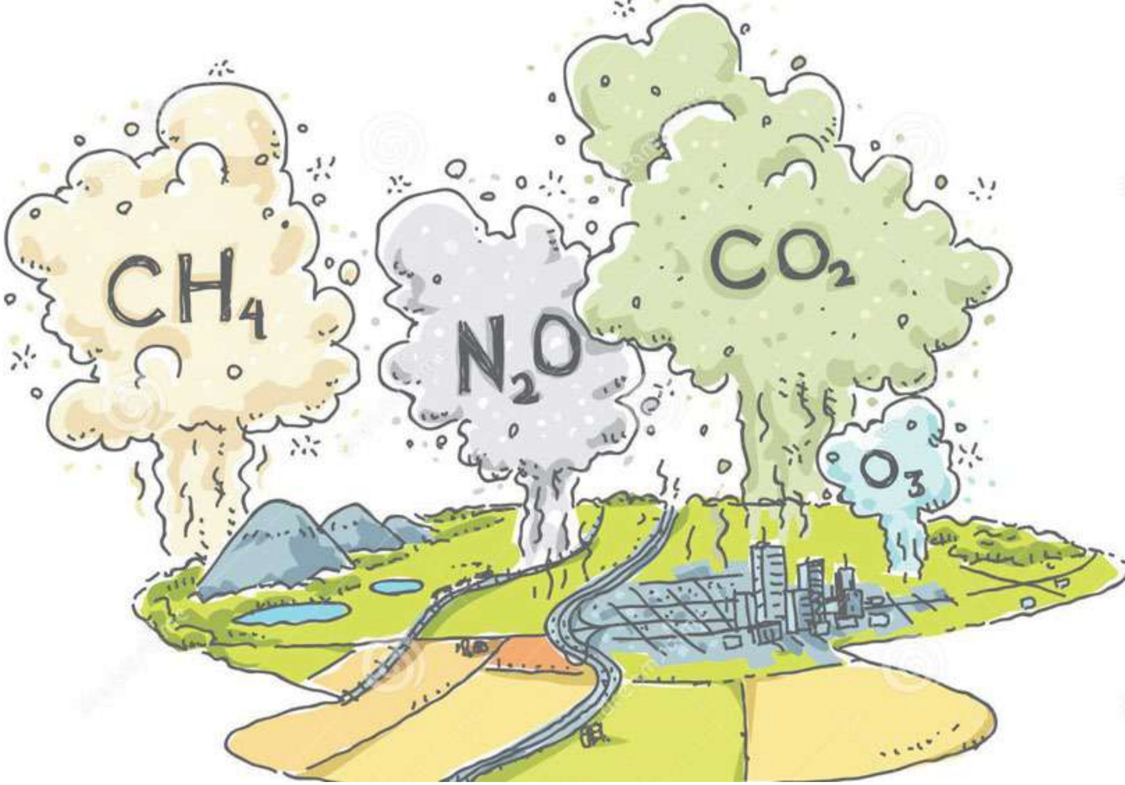
A short history of Wind as source of energy

Why Wind Energy?

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

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



Source: [3]

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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 **2°C** 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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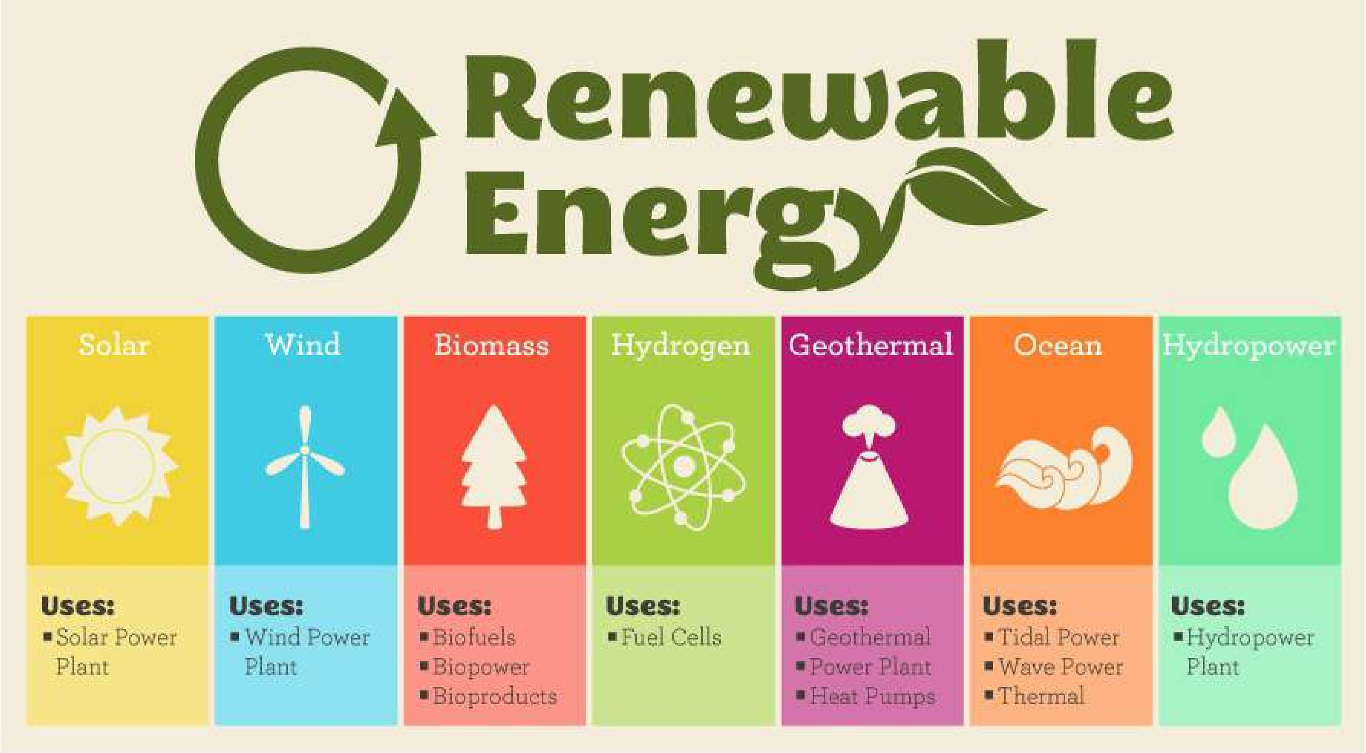
A short history of Wind as source of energy

The spotlight is on the renewable energy industry to find energy sources free of carbon dioxide pollution[1]



Source: [1]

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A short history of Wind as source of energy

Remark

- 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 [1]

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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 **2°C** 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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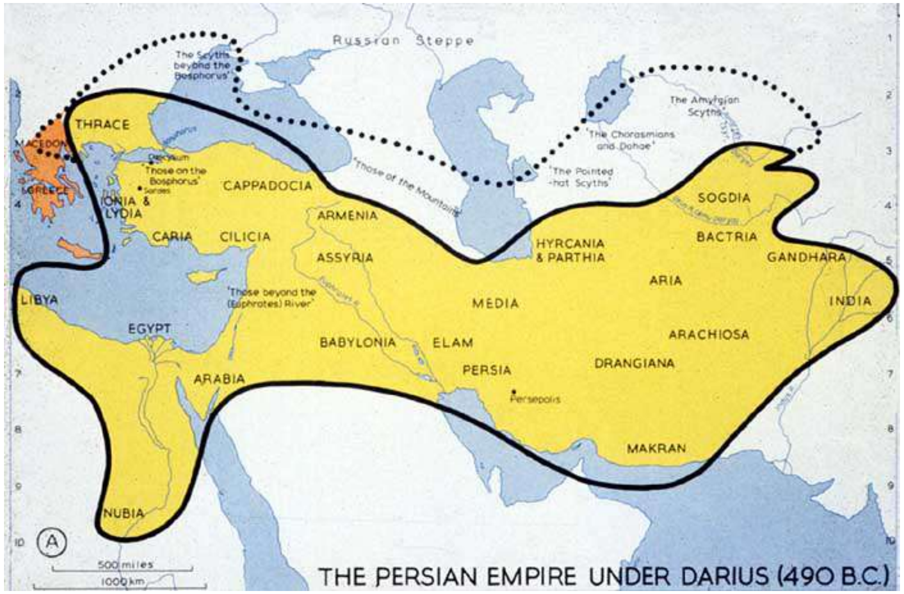
Wind Energy History

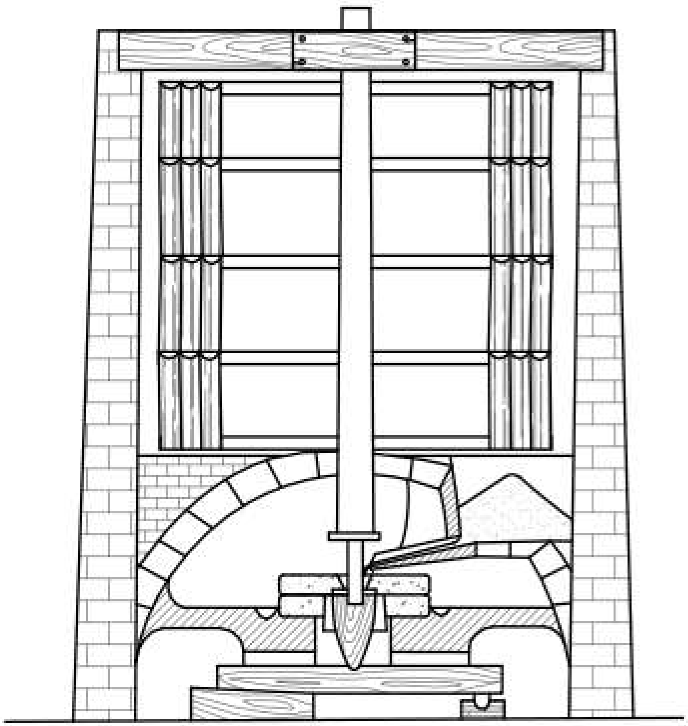
- Extensive application of wind turbines seems to have originated in Persia where it was used for grinding wheat
- It was invented in eastern Persia as recorded bythe Persian geographer Es takhr in the 9th century

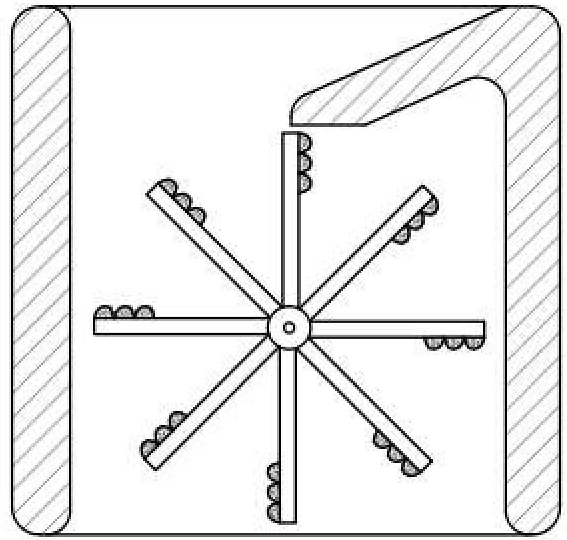


Source: [10]

A short history of Wind as source of energy

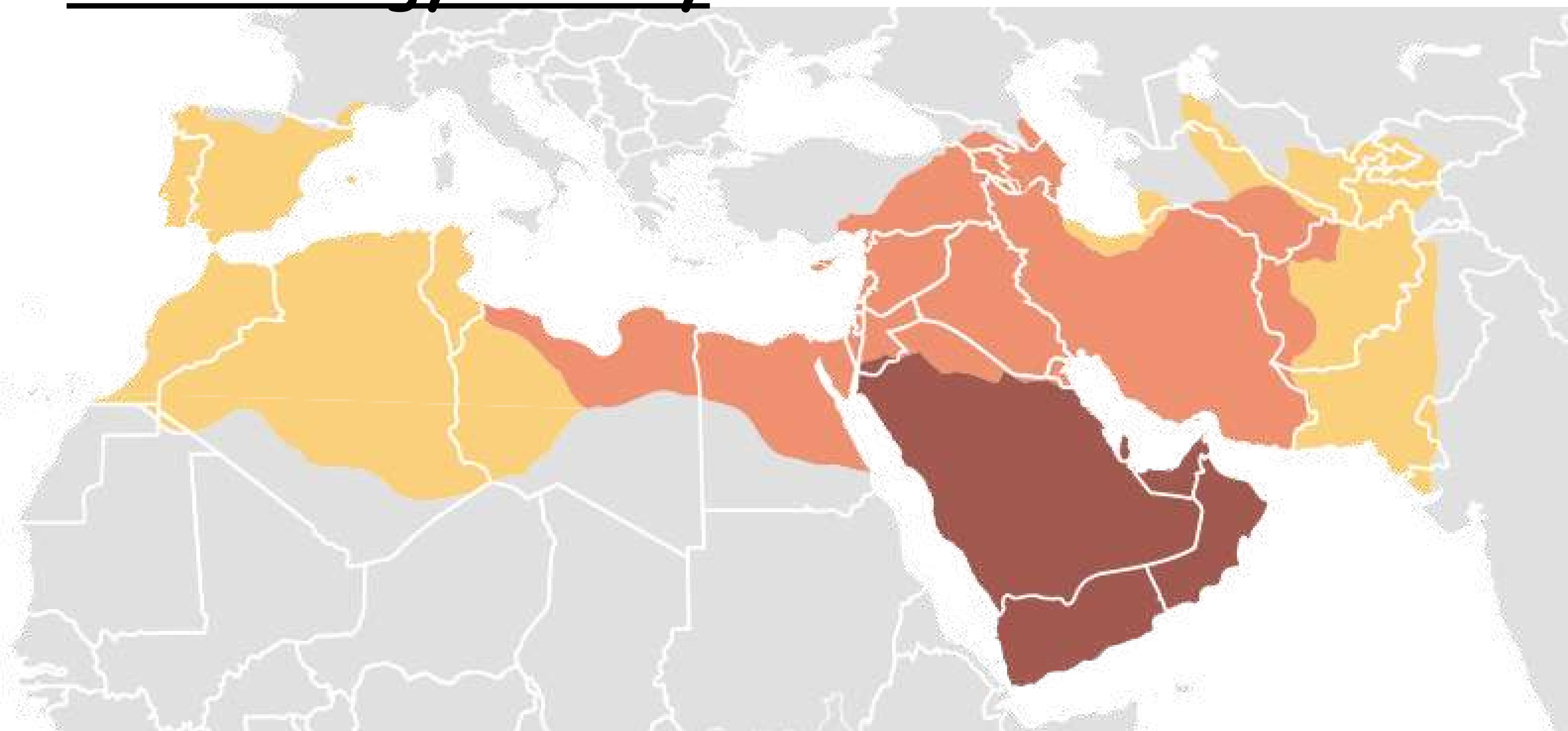
Wind Energy History [2]





Source: [2]

Wind Energy History



Source: [20]

- 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 it had become an important tool, especially in Holland

Source: [11]

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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

Source: [15]

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A short history of Wind as source of energy

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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A short history of Wind as source of energy

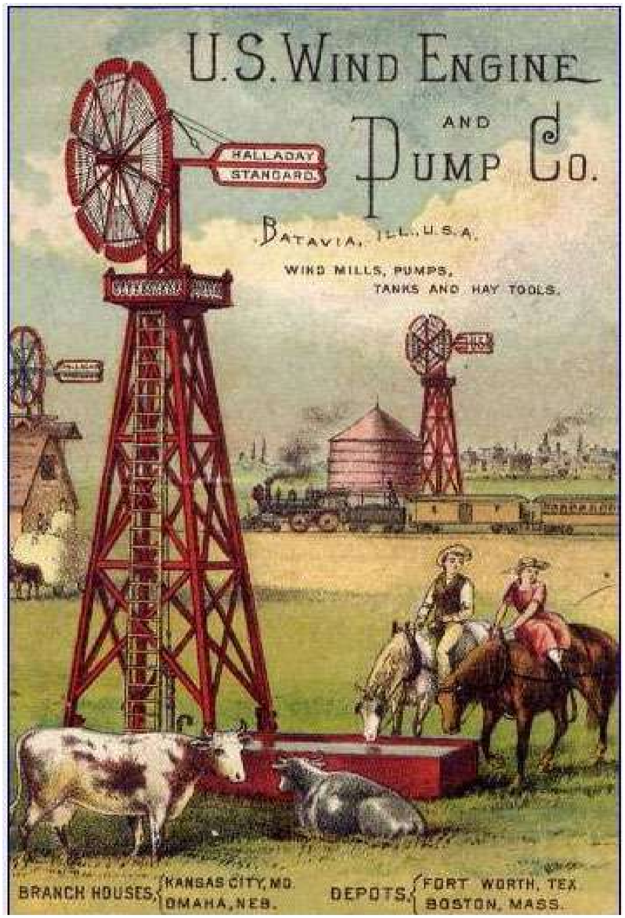
Wind Energy History

Source: [11]

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



Source: [2]

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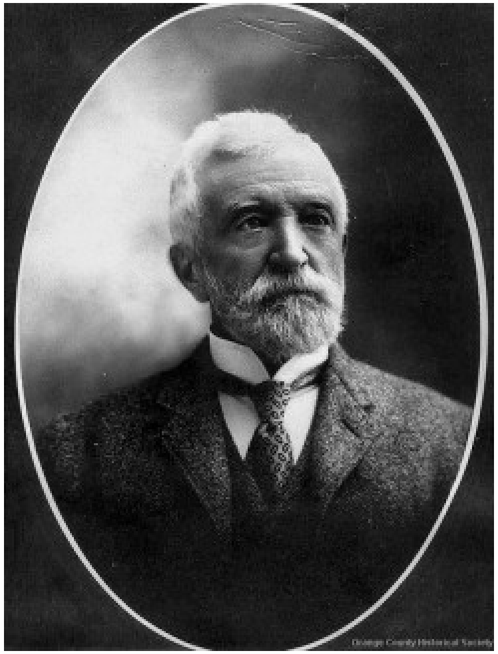
A short history of Wind as source of energy

Daniel Halladay

- 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



Source: [13]

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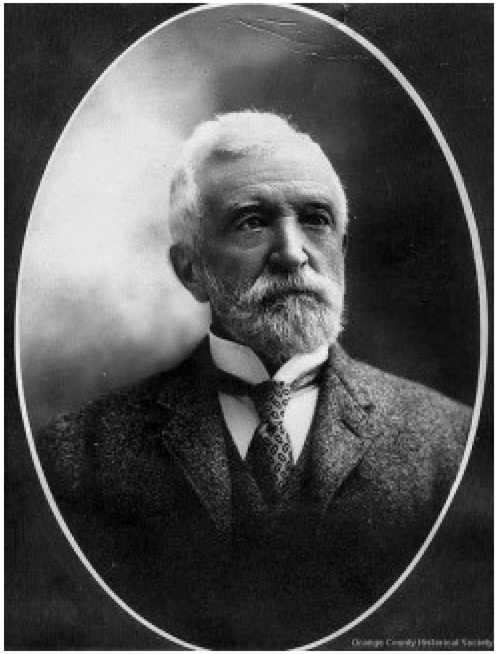
A short history of Wind as source of energy

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 [13]

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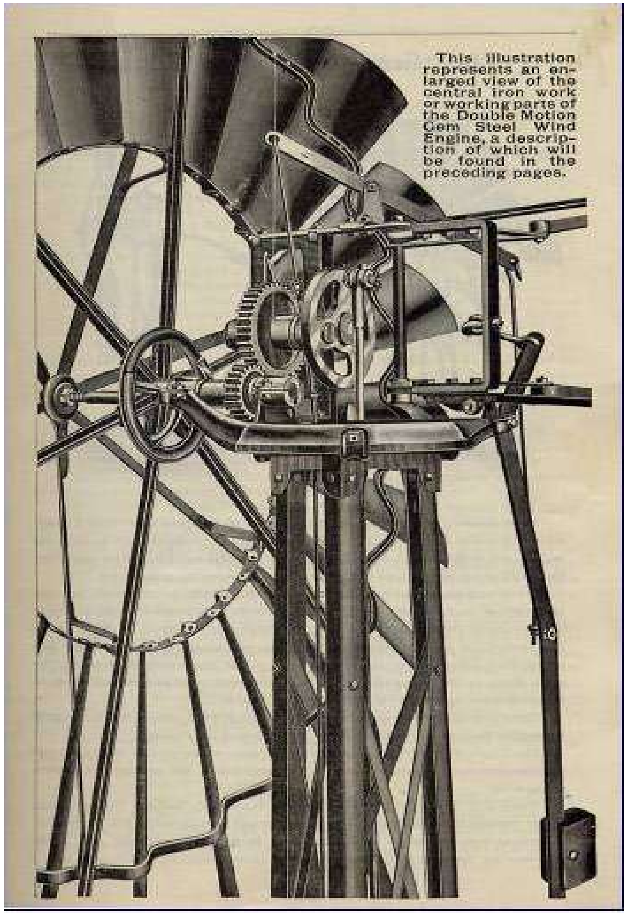
A short history of Wind as source of energy

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



Source: [14]

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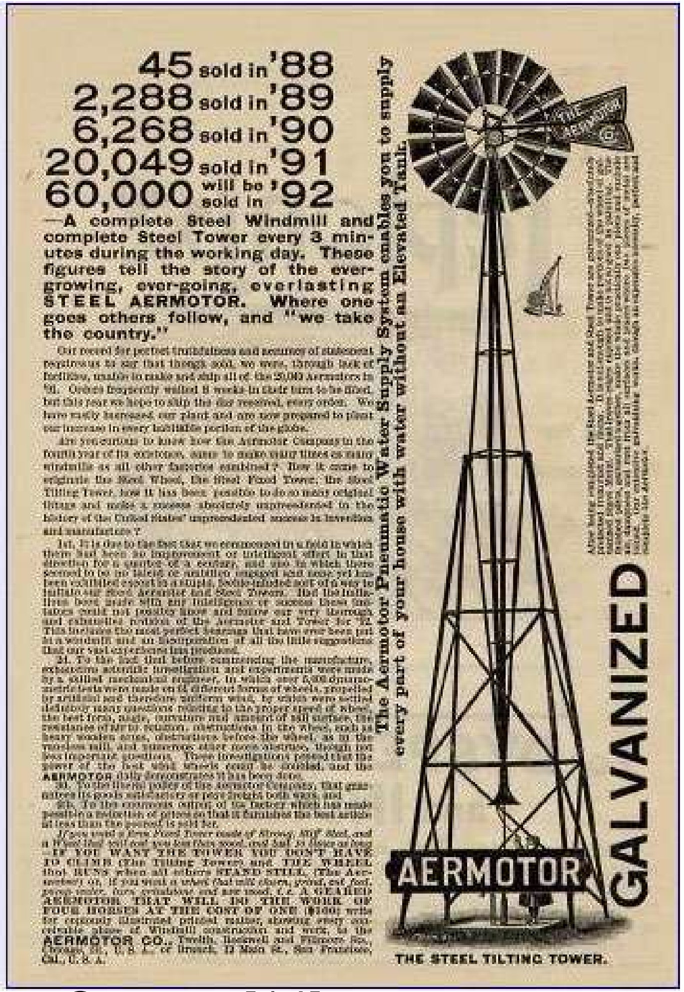
A short history of Wind as source of energy

- 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 …



Source: [14]

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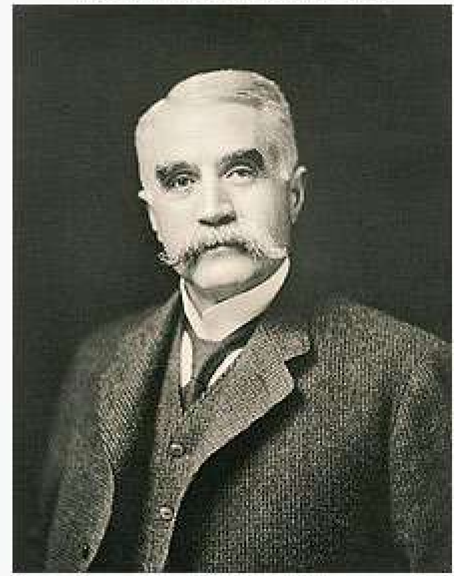
A short history of Wind as source of energy

Wind turbines for electricity generation

- The first significant wind turbine designed specifically for the generation of electricity was built by Charles Brush 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)

Source: [21]

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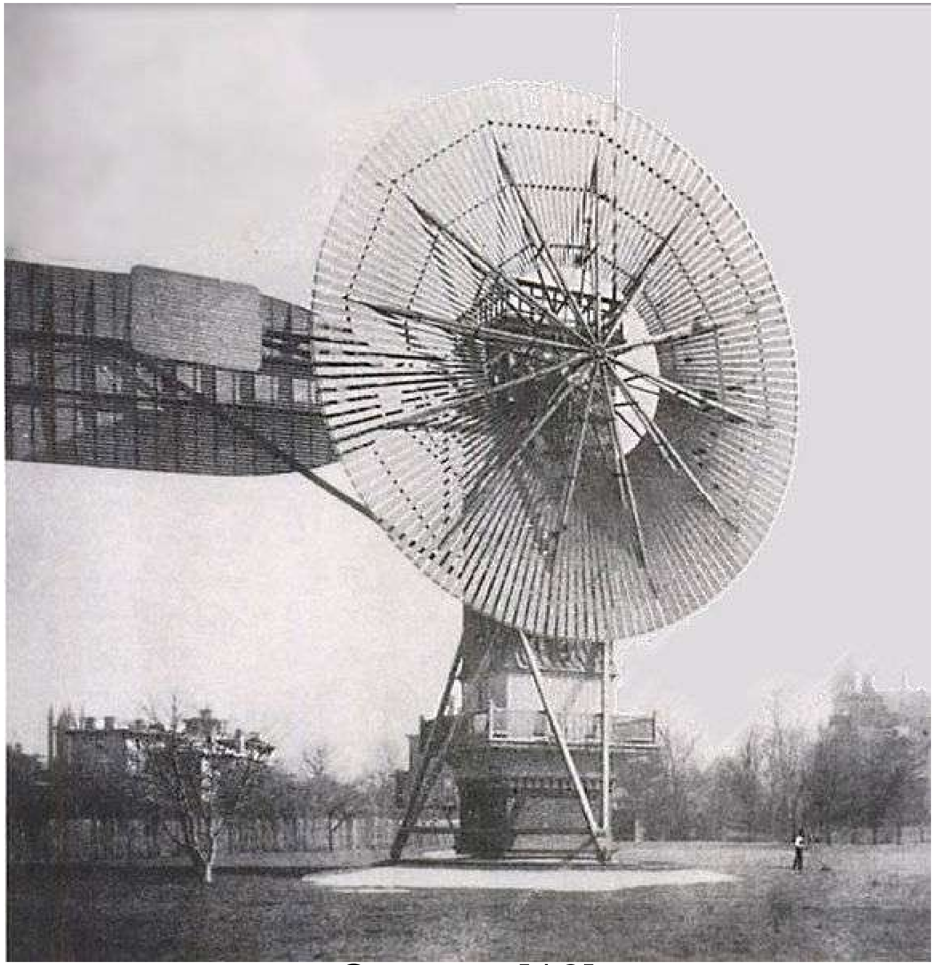
A short history of Wind as source of energy

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.



Source: [16]

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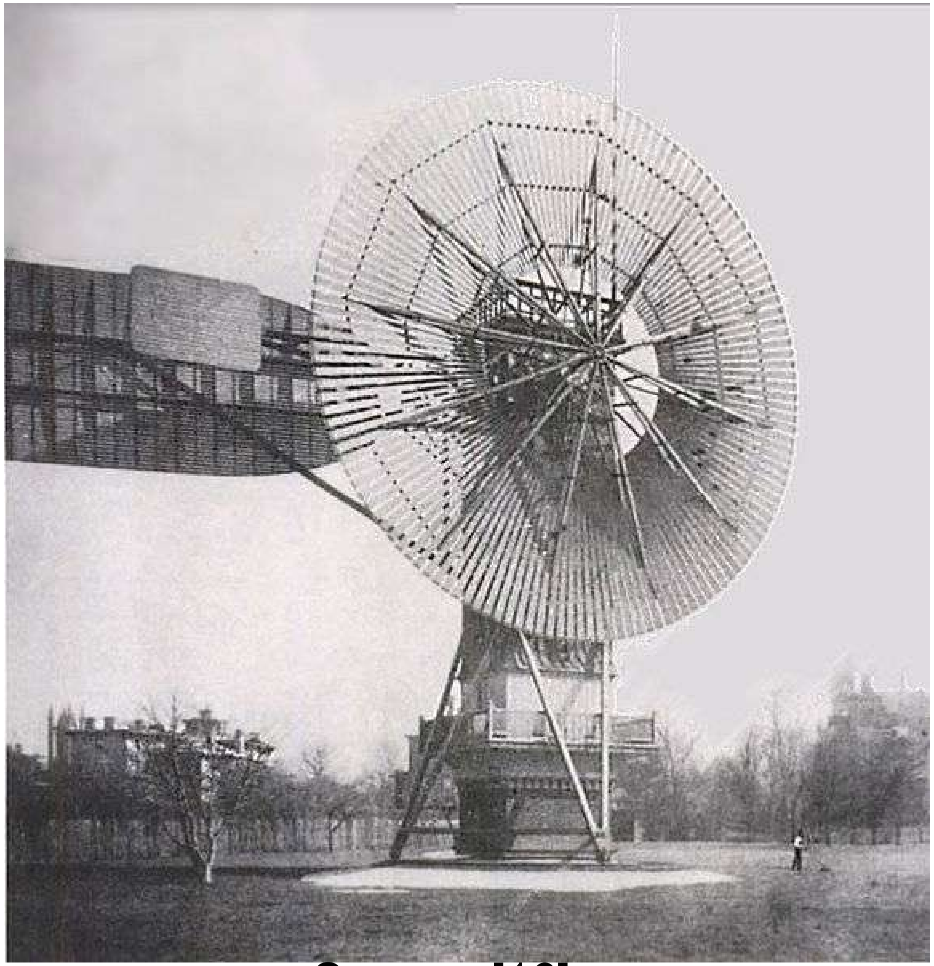
A short history of Wind as source of energy

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



Source: [16]

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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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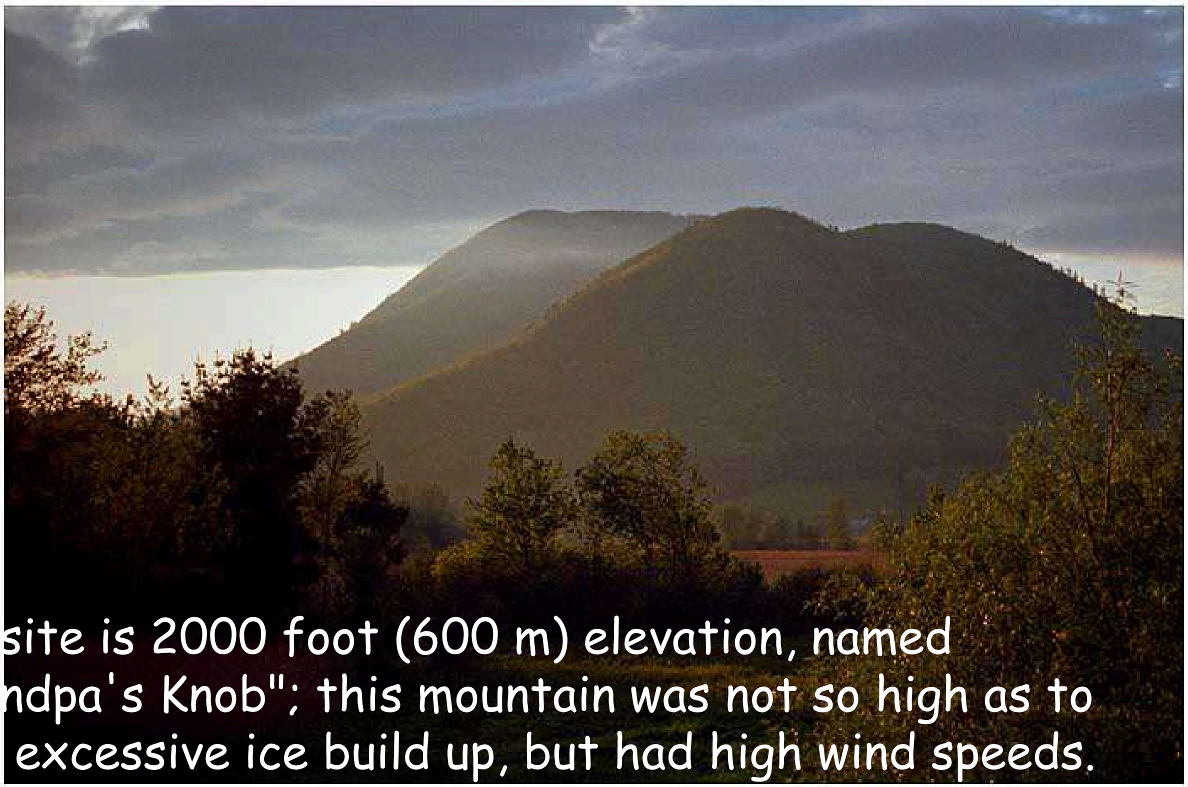
WE SET

A short history of Wind as source of energy

www.weset-project.eu

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



A short history of Wind as source of energy

- Access to the site required construction of a road with 12 to 15% grade
- 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

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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

Source: [16]

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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

Source: [16]

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A short history of Wind as source of energy

- 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
- 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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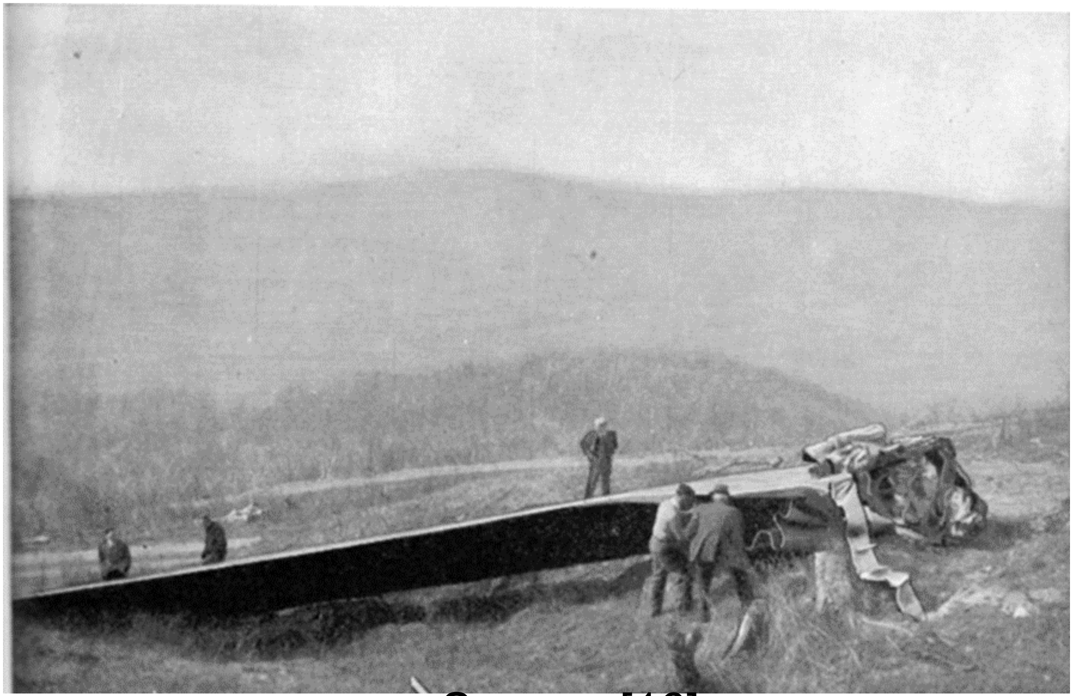
A short history of Wind as source of energy

- 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



Source: [16]

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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

Source: [16]

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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

Source: [17]

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A short history of Wind as source of energy

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

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

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A short history of Wind as source of energy

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

Source: [18]

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 considerable

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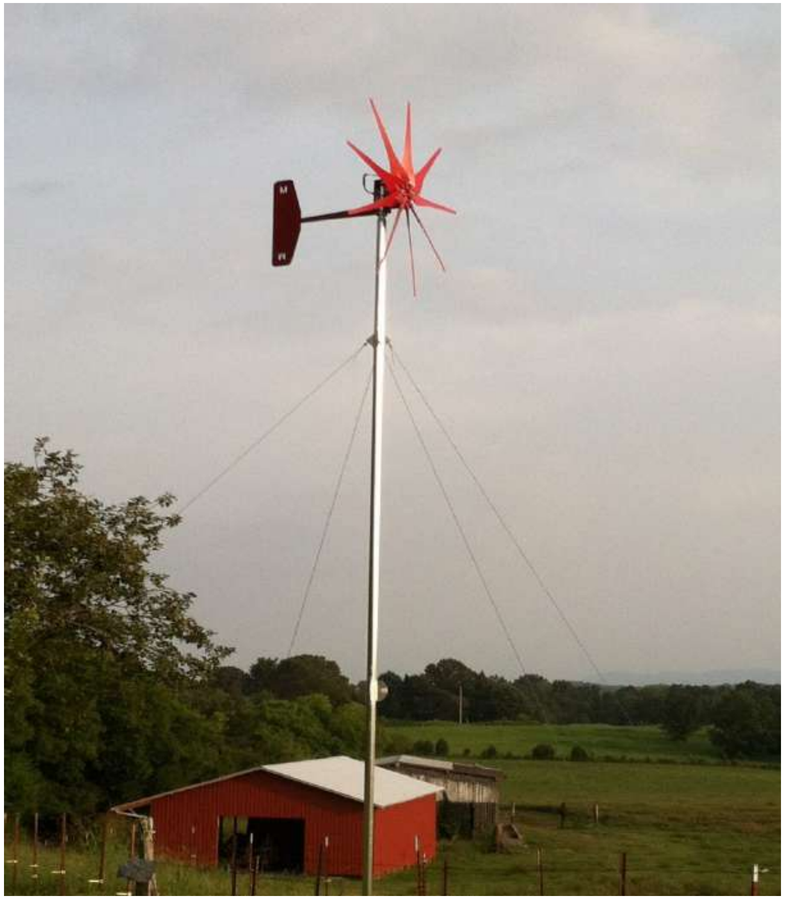
The potential of wind as renewable energy source

THE POTENTIAL OF WIND ENERGY WORLDWIDE



- The potential for wind energy is enormous, especially in developing countries
- 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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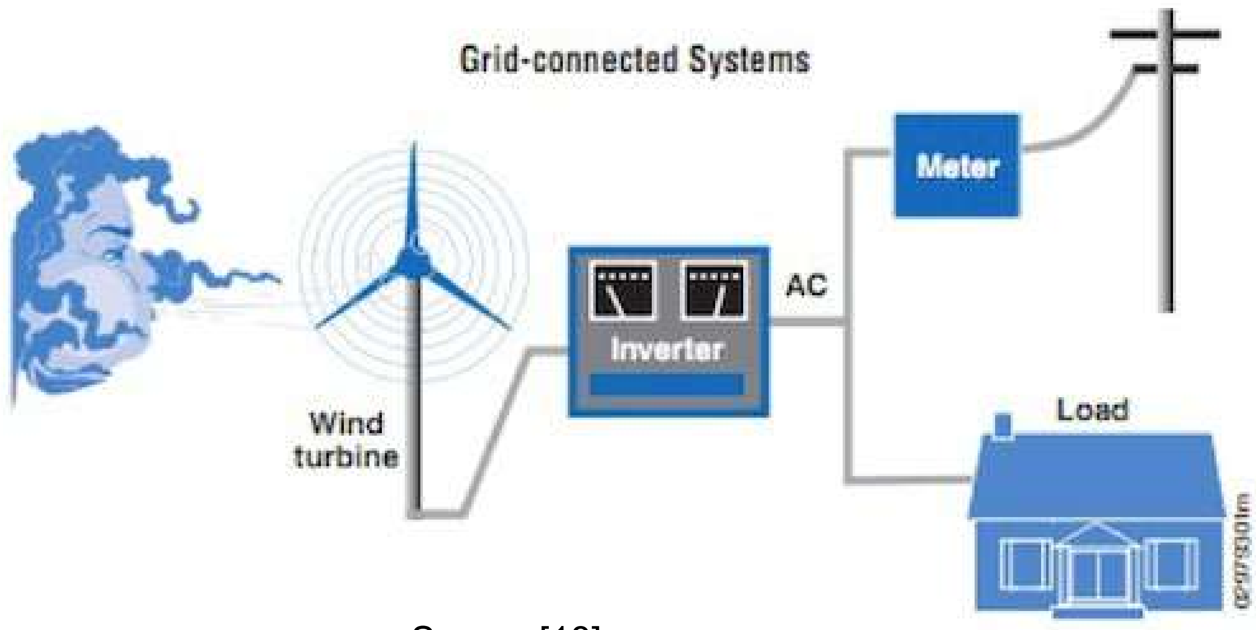
The potential of wind as renewable energy source



Source [18]

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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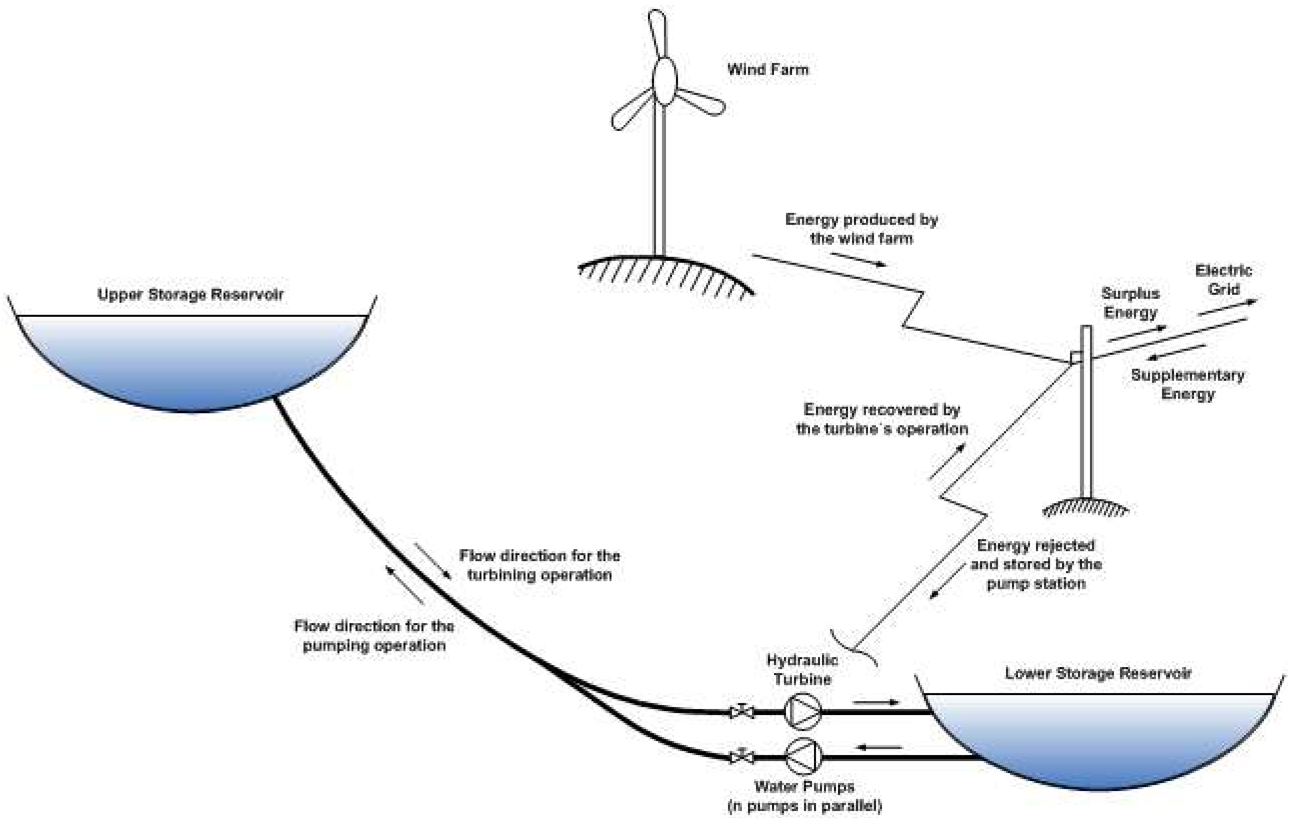
The potential of wind as renewable energy source

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



Source: [19]

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The potential of wind as renewable energy source

- Even in developed and industrialized countries wind is becoming a major player
- 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 kW h of energy and on top of that 80310 kW h is sold to the national grid
- 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

- 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

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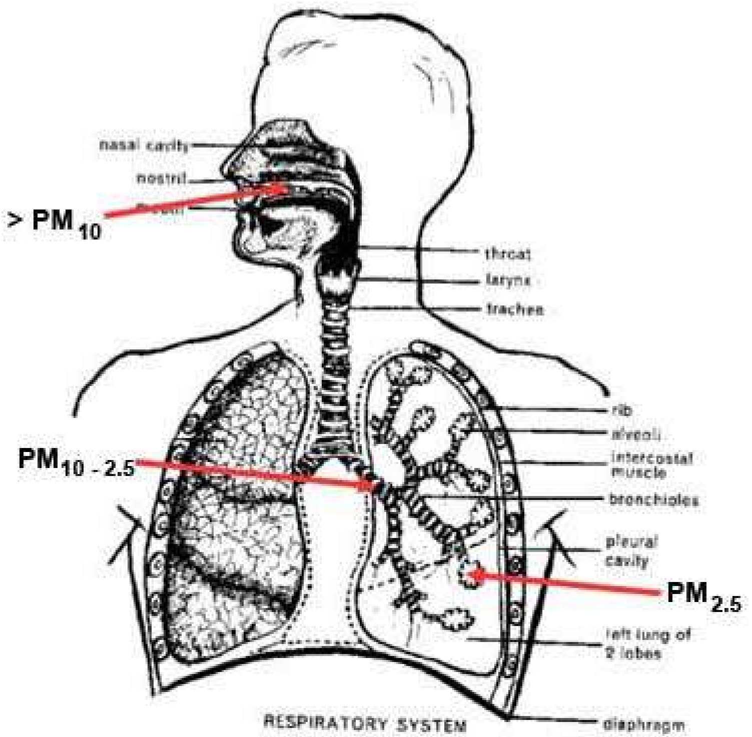
The advantages of using wind energy as power source

1. Provision for a clean pollution free source of energy.

- It delivers electricity without producing carbon dioxide

2. Free of particulate matters.

- Particulates have been blamed for the rise of asthma and possibly Alzheimer's disease in our society



Source: [3]

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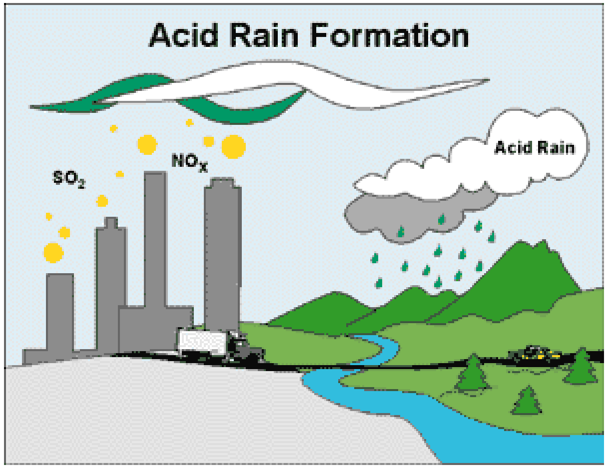
The advantages of using wind energy as power source

3. 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**



Source: [25]

The advantages of using wind energy as power source

4. 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

Source: [22]

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The advantages of using wind energy as power source

5. 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

Source: [23]

The advantages of using wind energy as power source

Off the coast area

Source: [23]

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The advantages of using wind energy as power source

6. **Compatibility with other land uses:**

- Wind turbines can be erected on pastureland with little disturbance to the animals and the general farming activities

Source: [23]

The advantages of using wind energy as power source

- 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

Source: [23]

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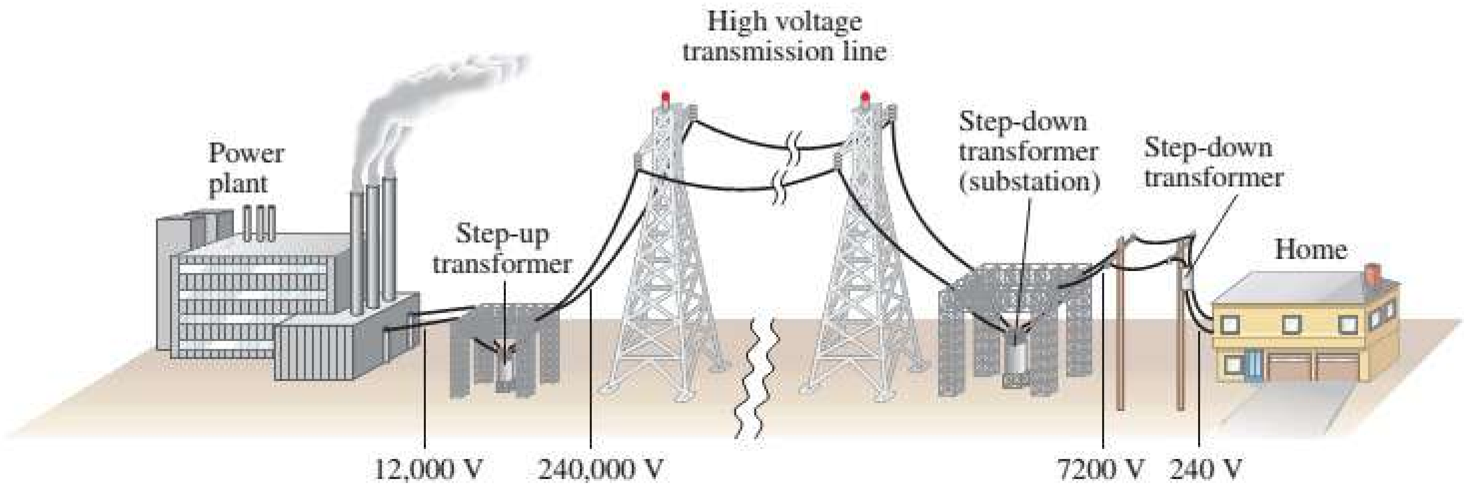
The advantages of using wind energy as power source

7. **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



Source: [24]

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The advantages of using wind energy as power source

8. 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

Source: [3]

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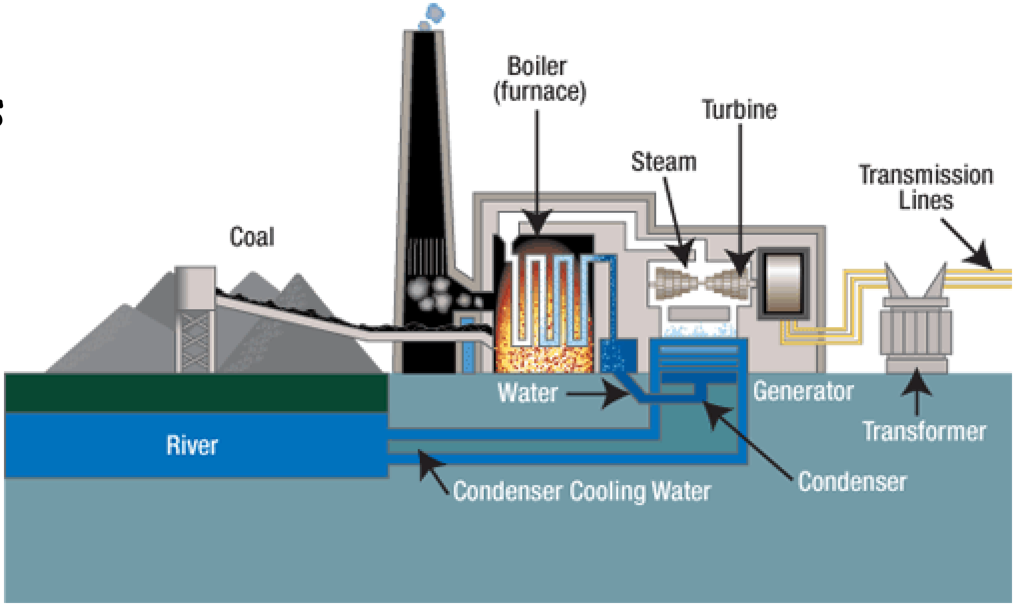
The advantages of using wind energy as power source

9. **Conservation of water**:

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



Source: [24]

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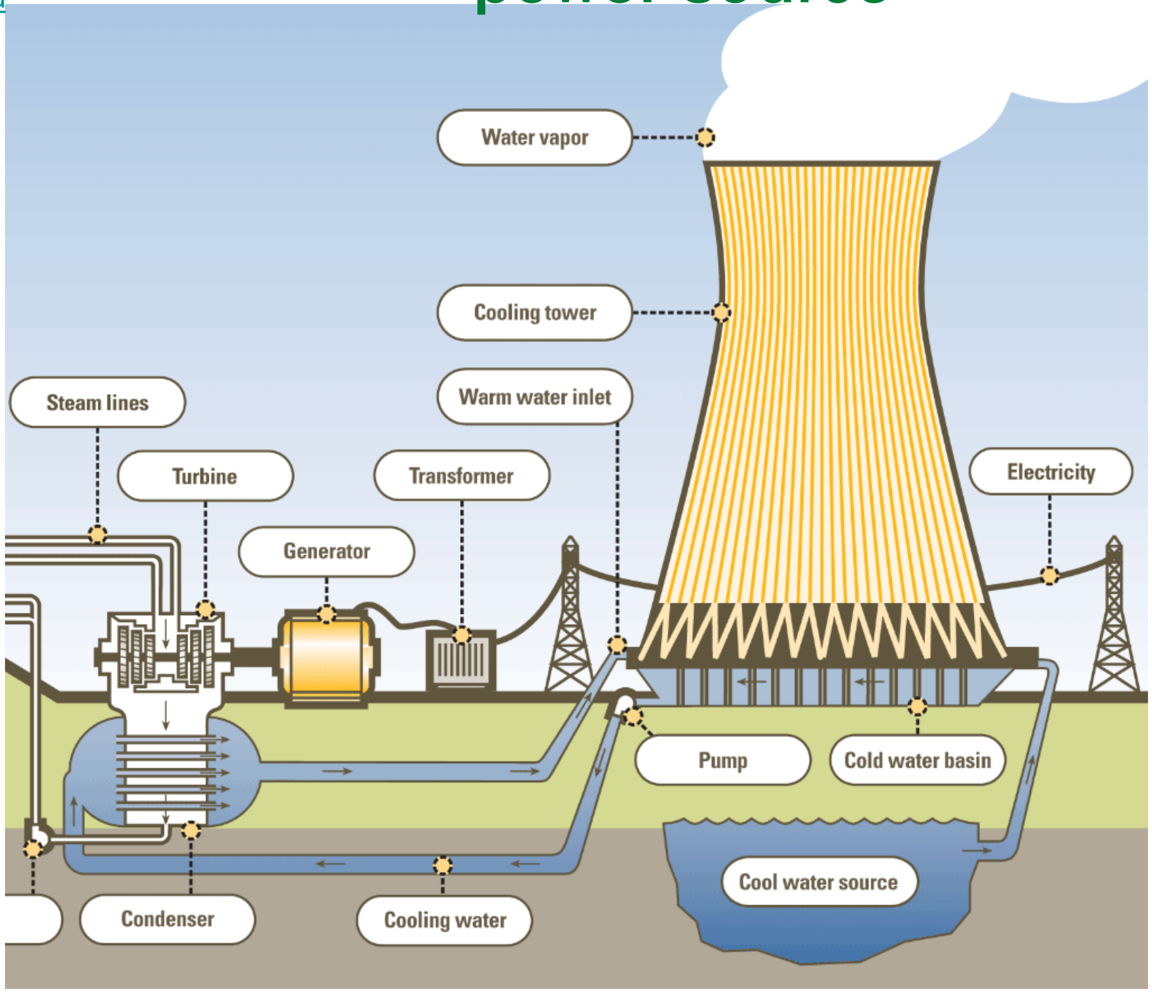
The advantages of using wind energy as power source



Source: [24]

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The advantages of using wind energy as power source

10. **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

Source: [3]

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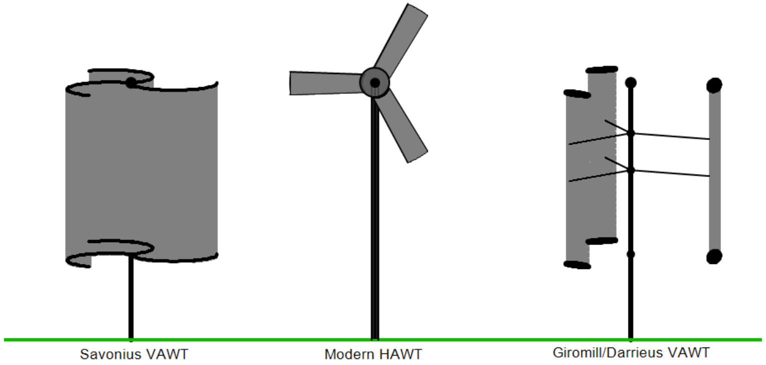
The advantages of using wind energy as power source

ADVANTAGES OF WIND ENERGY

11. **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



Source: [26]

The advantages of using wind energy as power source

12. **Cost effectiveness**:

- Over the past decade, the cost of turbines has decreased significantly as 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

12. **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

Source: [27]

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The advantages of using wind energy as power source

13. **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

Source: [28]

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The advantages of using wind energy as power source

14. **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

15. **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

Source: [29]

- 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

16. **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

Source: [30]

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Recommended literature

Books:

[1] Renewable Power Generation Costs in 2017, IRENA InternationalRenewable Energy Agency, Abu Dhabi, 2018, ISBN 978-92-9260 -040-2, report available at www.irena.org/publications

[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

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

[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] https://www.ewea.org European Wind Energy Association
[8] https://www.indea.org World Wind Energy Association
[9] https:// www.awea.org American Wind Energy Association
[10] https://www.utexas.edu/courses/clubmed/92908dariusmap.jpg
[11] https://www.holland.com/global/tourism/discover- holland/traditional/dutch-windmills.htm
[12] https://pixabay.com/illustrations/earth-hour-climate-change-globe-4776711/

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Recommended literature

[13] https://valleynewsnow.com/2011/09/daniel-halladay-the-remarkable-connecticut-inventor-i%E2%80%99ll-bet-you-never-heard-of/

[14] http://www.ironmanwindmill.com/windmill-history.htm

[15] https://www.pinterest.com/pin/351280839675769450/?lp=true

[16] https://www.renewableenergyworld.com/storage/history-of-wind-turbines/#gref

[17] https://www.energyjobline.com/landingpage/386943/wind-farm-jobs/

[18] http://www.daviddarling.info/encyclopedia/G/AE_grid-connected

[19] http://www.sc.ehu.es/sbweb/energias-renovables/temas/*almacenamiento/almacenamiento.html*

[20] https://ha.wikipedia.org/wiki/Khulafa%27hur-Rashidun

[21] https://ece.umich.edu/alumni/awards/bicentennial/brush.html

[22] https://www.shutterstock.com/image-vector/open-cartoon-hand-holding-planet-earth-364049948

[23] https://www.nationalgeographic.org/encyclopedia/wind-energy/

[24] https://en.wikipedia.org/wiki/Fossil_fuel_power_station

[25] *http://www.geography.learnontheinternet.co.uk/topics/acidrain.html*

[26] https://upload.wikimedia.org/wikipedia/commons/c/ce/HAWT_and_VAWTs_in_operation_medium.gif

[27] https://blog.commlabindia.com/elearning-design/elearning-projects-cost-effective-tips

[28] https://thefinancialexpress.com.bd/views/creating-jobs-for-the-unemployed-youths-1600268383

[29] https://www.whitelabelworldexpo.de/news/blog.asp?blog_id=25440

[30] https://thefinancialexpress.com.bd/views/the-dangerous-delusion-of-price-stability-1514555999

Introduction to Wind Energy

Module 2.1

Further information:

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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

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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General concepts for Assessment of Wind Resources

Wind resource assessment (WRA)

- WRA is the process by which wind power 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

Source: [13]

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General concepts for Assessment 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

Source: [4

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General concepts for Assessment 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.

Source: [10]

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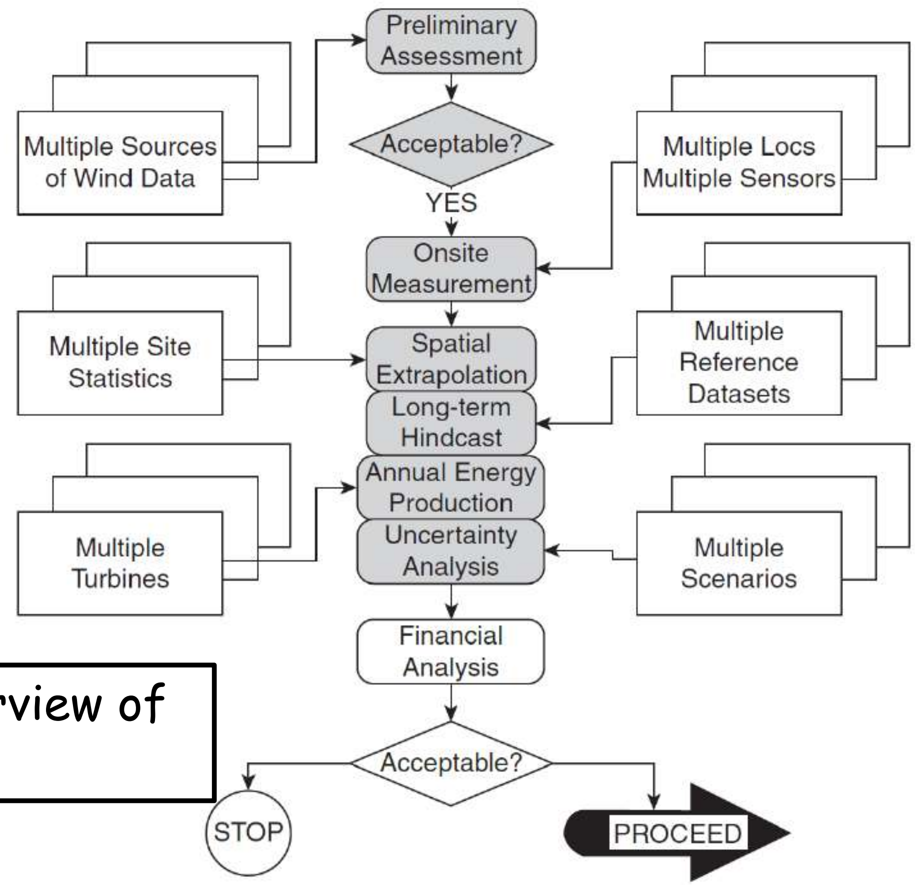
General concepts for Assessment of Wind Resources

Overview of WRA



The Figure contains an overview of the WRA process.

Source: Chapter 7, Wind energy engineering [2]

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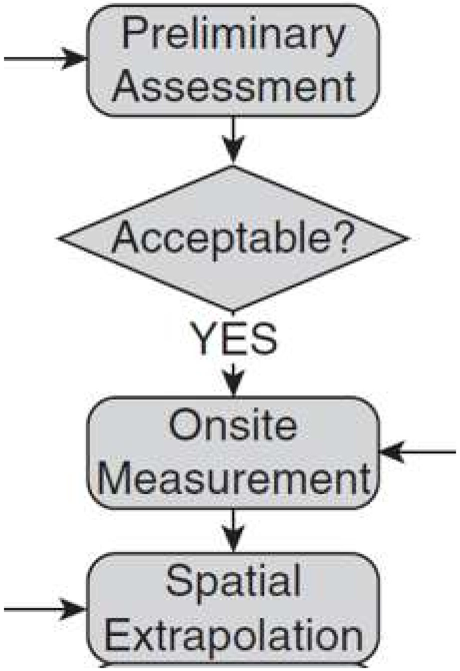
General concepts for Assesment of Wind Resources

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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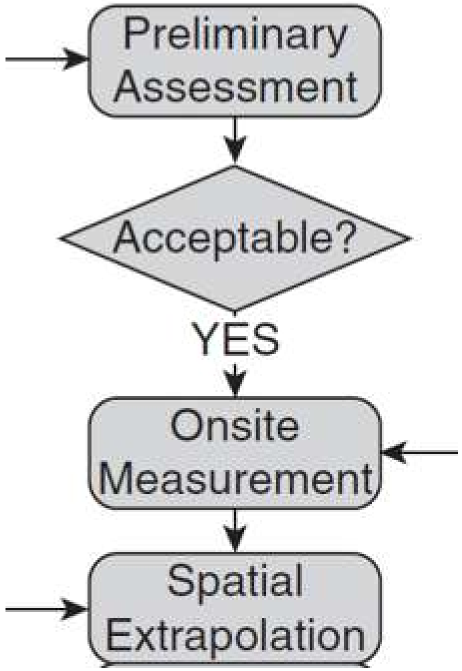
General concepts for Assesement of Wind Resources

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.



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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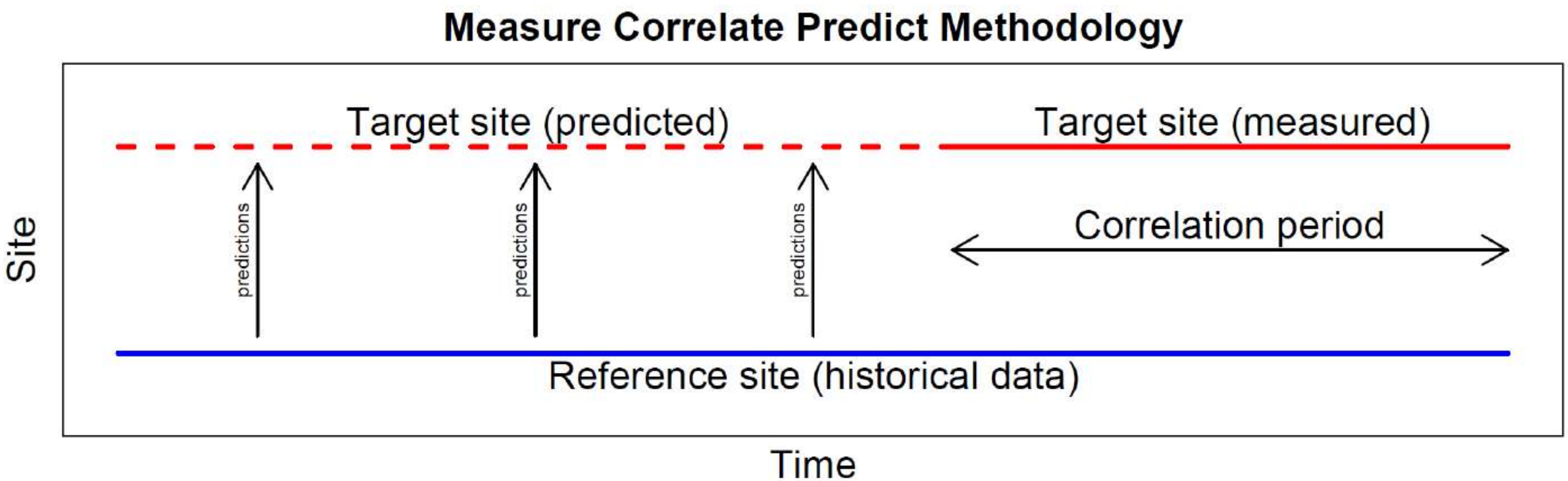
Local Measurements for assessment of Wind Resources

Measure-Correlate-Predict Methodology



Source: [15]

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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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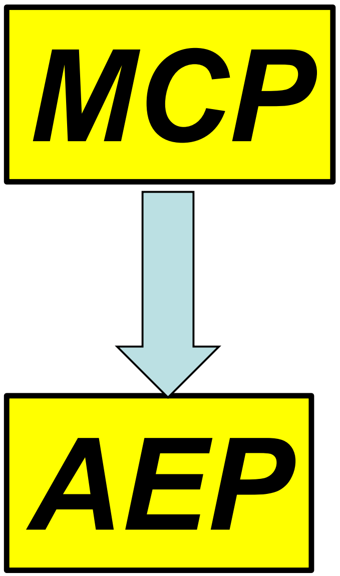
Local Measurements for assessment of Wind Resources

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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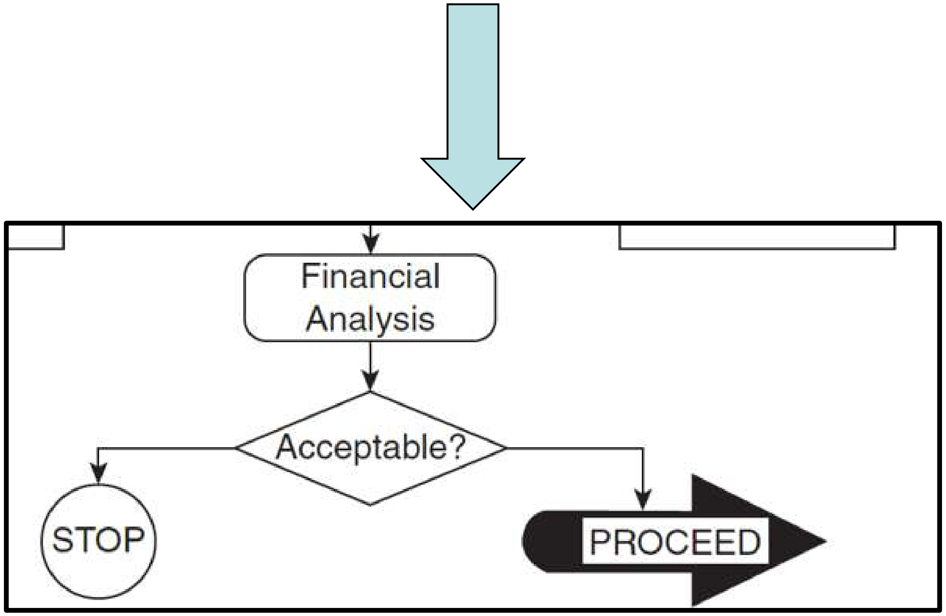
Local Measurements for assessment of Wind Resources

WRA o/t



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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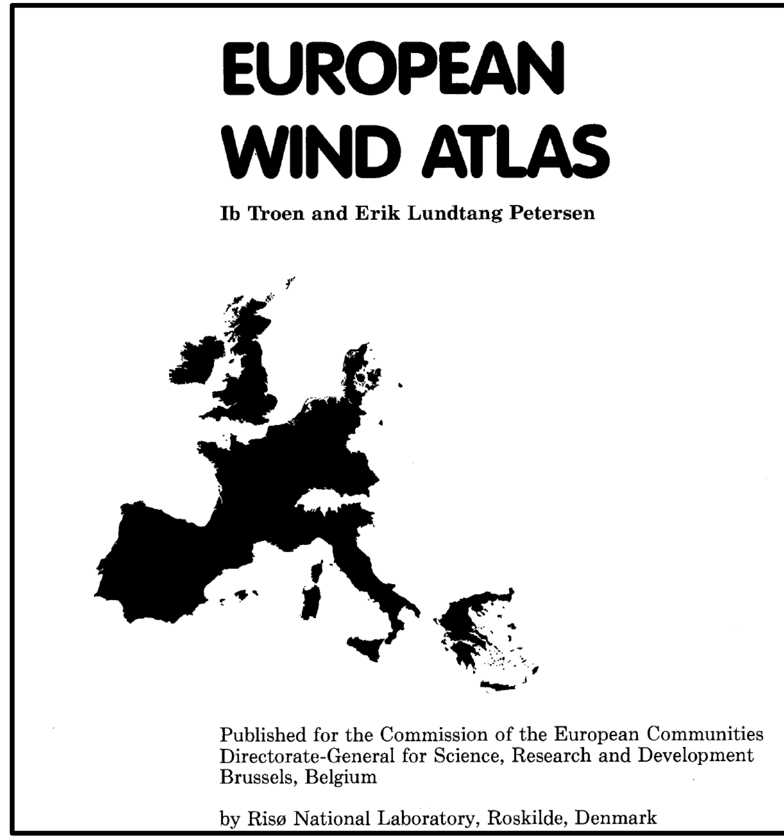
The use of Wind Atlas

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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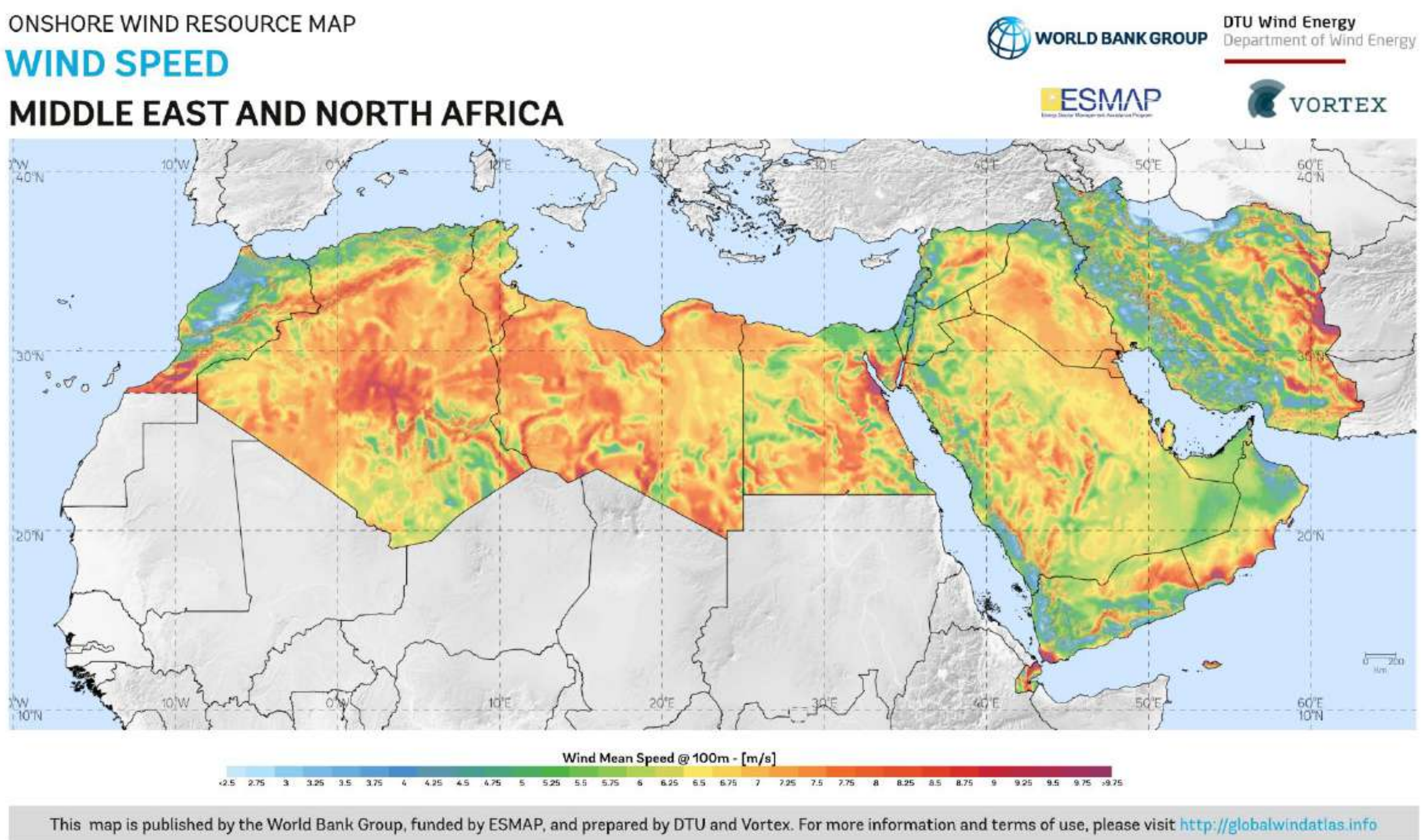
The use of Wind Atlas

Example of Wind Speed Maps



Source: [11]

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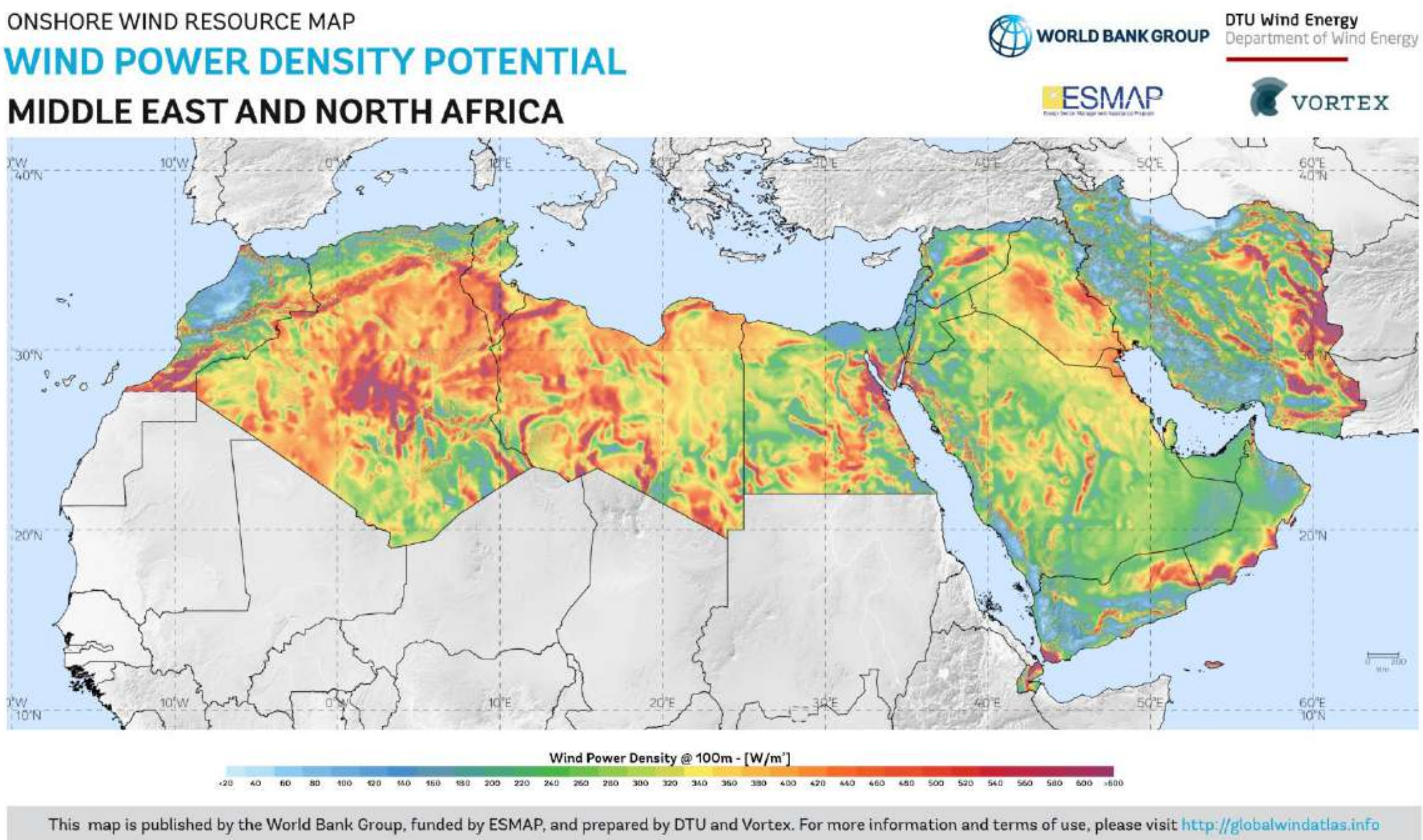
The use of Wind Atlas

Example of Wind Power Maps



Source [11]

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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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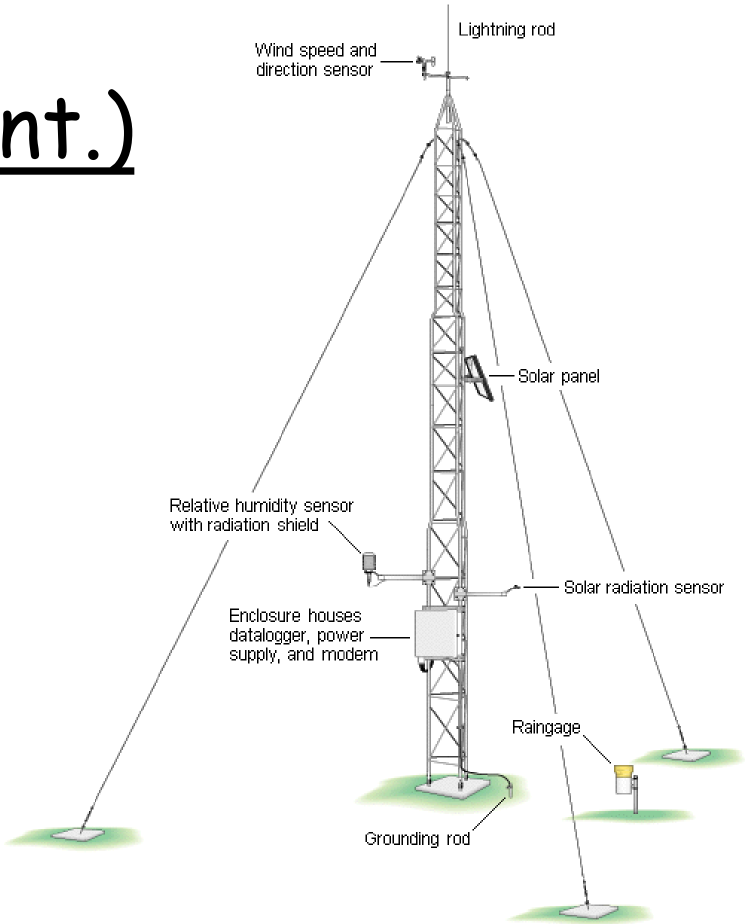
Local Measurements for assessment of Wind Resources

Measurements (Cont.)

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



Source [16]

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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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Local Measurements for assessment of Wind Resources

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 [12]

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Recommended literature

Books:

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

[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] https:// **www.ewea.org European Wind Energy Association**
[8] https://**www.indea.org World Wind Energy Association**
[9] https:// **www.awea.org American Wind Energy Association**
[10] https://www.dtu.dk/english
[11] **World bank Group, http://globalwindatlas.info**
[12] https://en.wikipedia.org/wiki/Wind_energy_software
[13] https://www.latimes.com/politics/story/2021-05-25/biden-administration-unveils-an-offshore-wind-plan-for-californias-coast

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Recommended literature

[14] https://maritime-executive.com/article/australia-s-first-offshore-wind-farm-a-step-closer

[15] https://www.semanticscholar.org/paper/Analysis-of-the-measure-correlate-predict-for-wind-Sheppard/2a5a2aa29365ea6f7fb0009e2bd6d07be583aa17

[16] https://www.adamsenvsys.com/10MTower.htm

Module 2.1

Further information:

www.weset-project.eu

info@weset-project.eu

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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

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This lesson will contribute to the students to:

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

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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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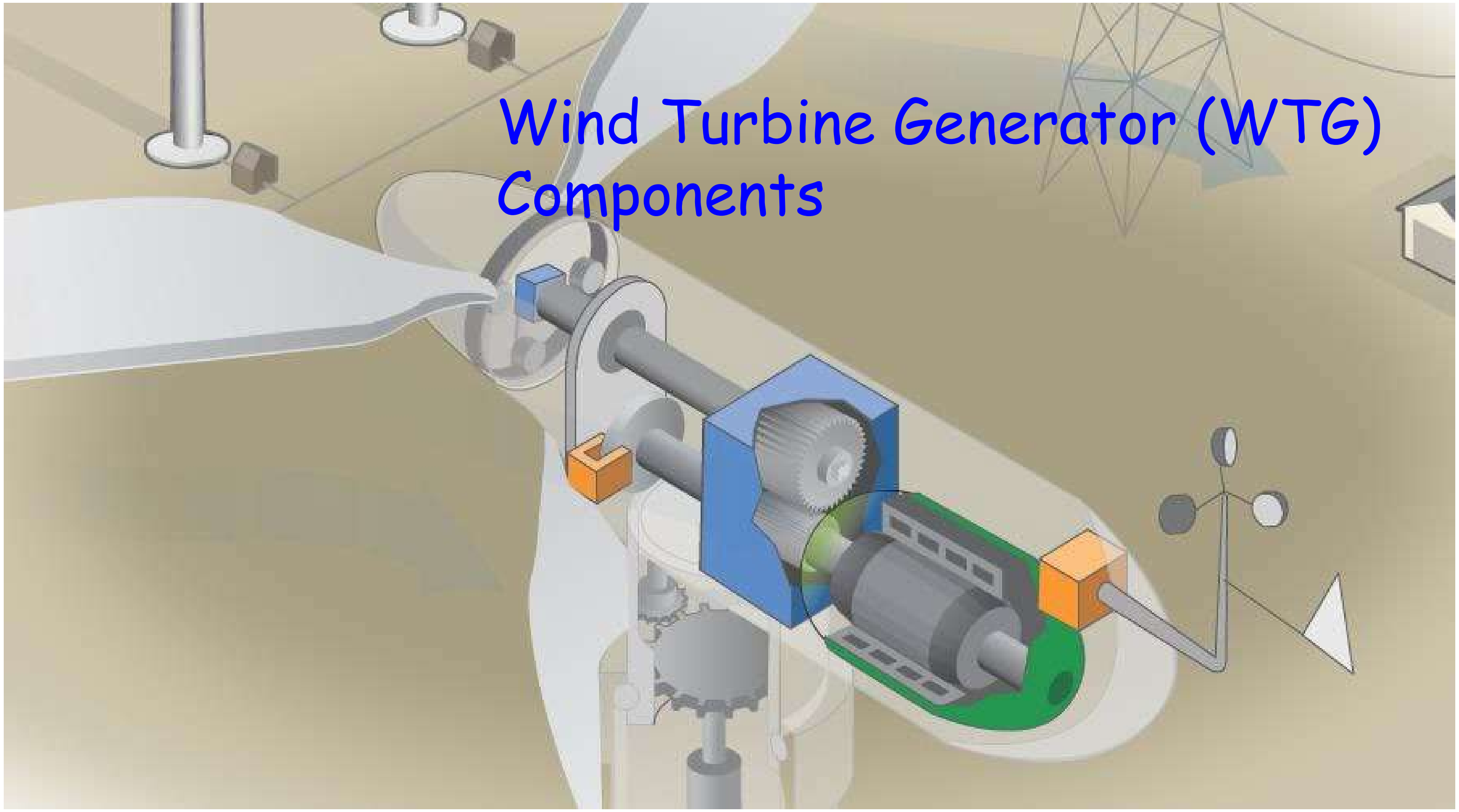
Structure of a Wind Turbine Generator



Source: [4]

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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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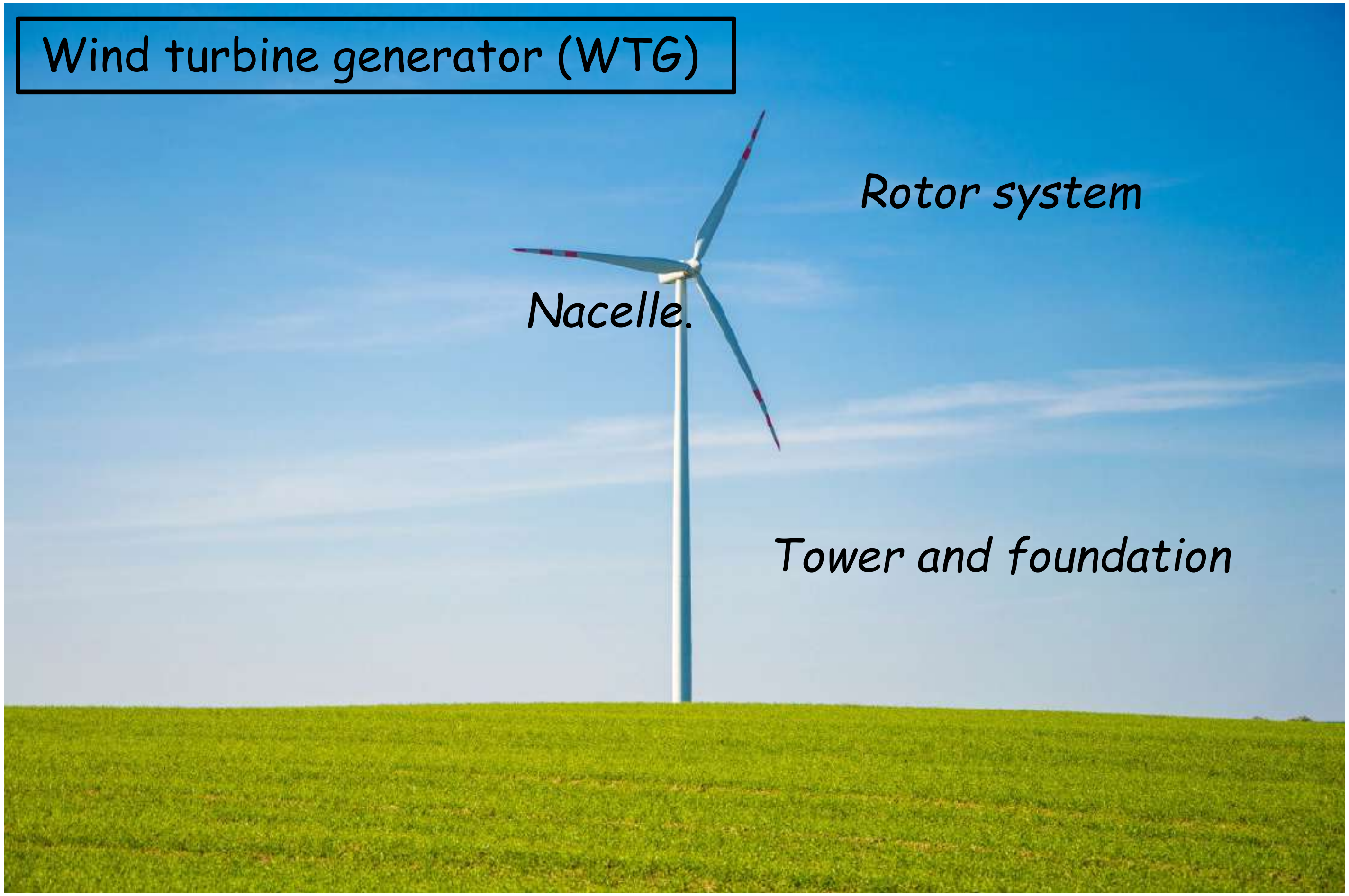
Structure of a Wind Turbine Generator



Source: [8]

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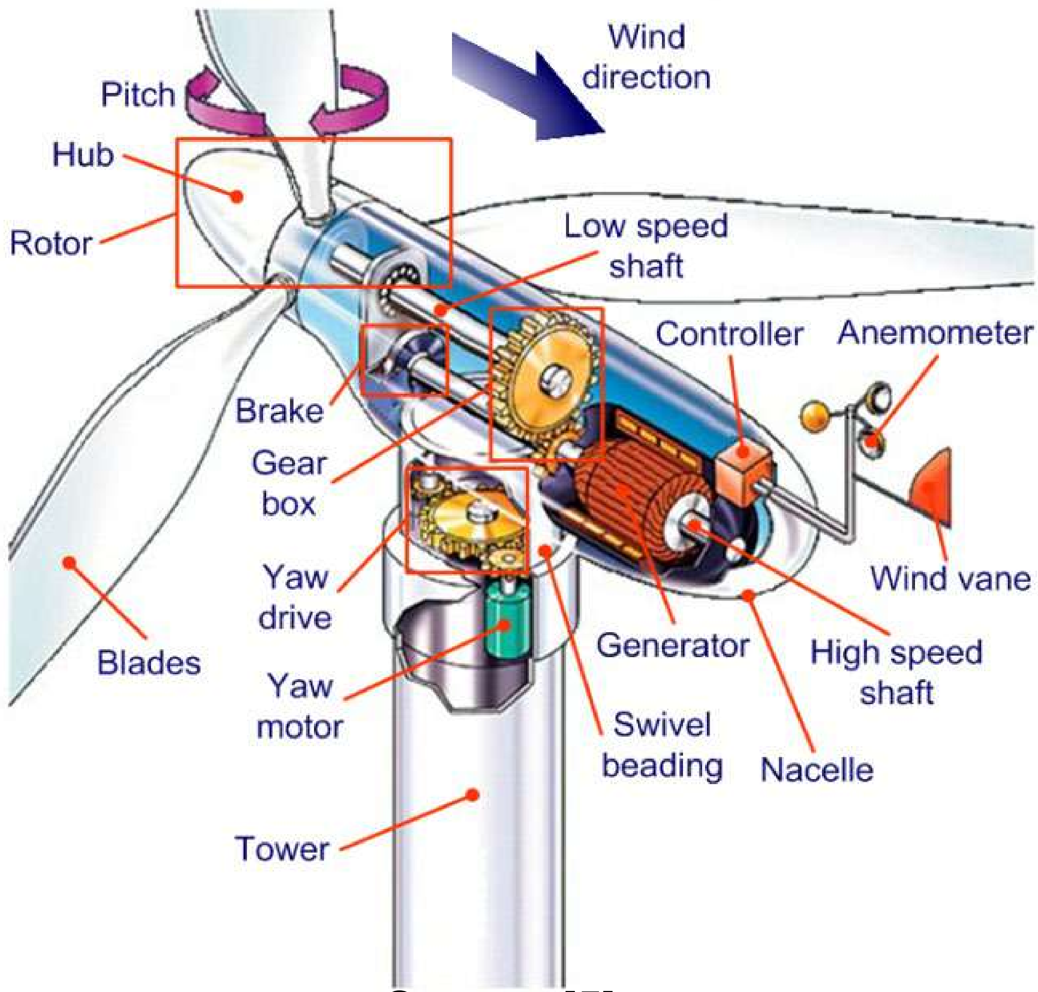
Structure of a Wind Turbine Generator

www.weset-project.eu

Wind turbine generator (WTG)
Components

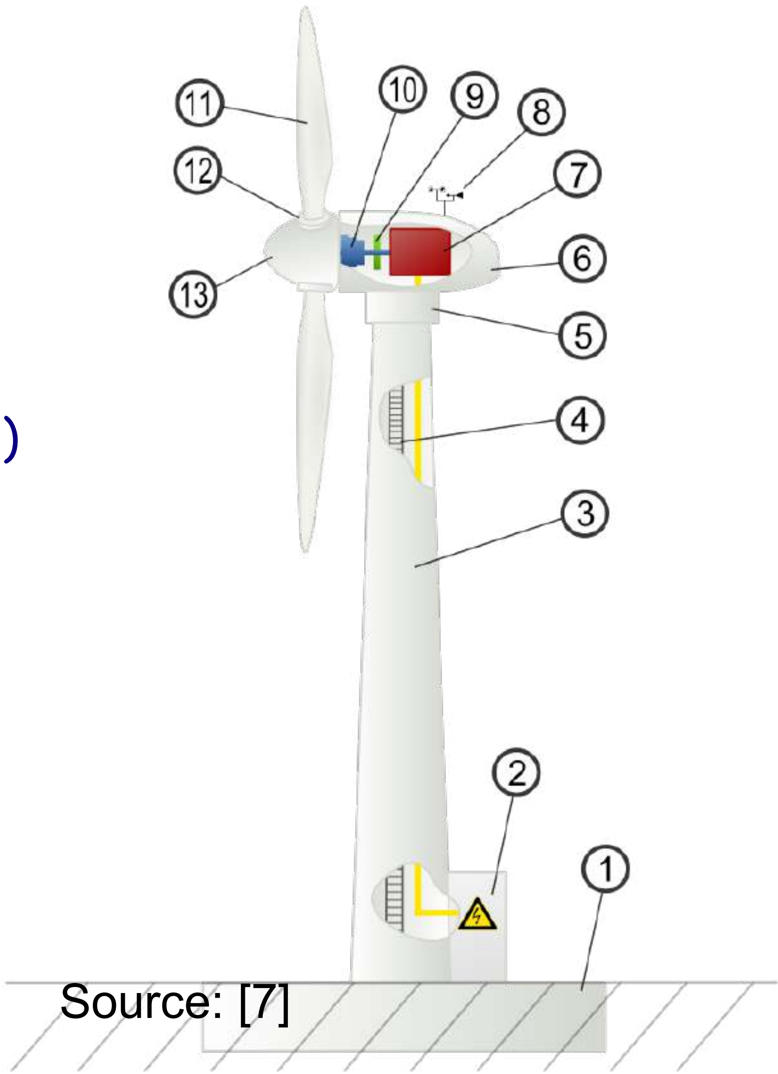


Source: [5]

Introduction to Wind Energy

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



Source: [7]

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The Rotor

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.

Source: [8]

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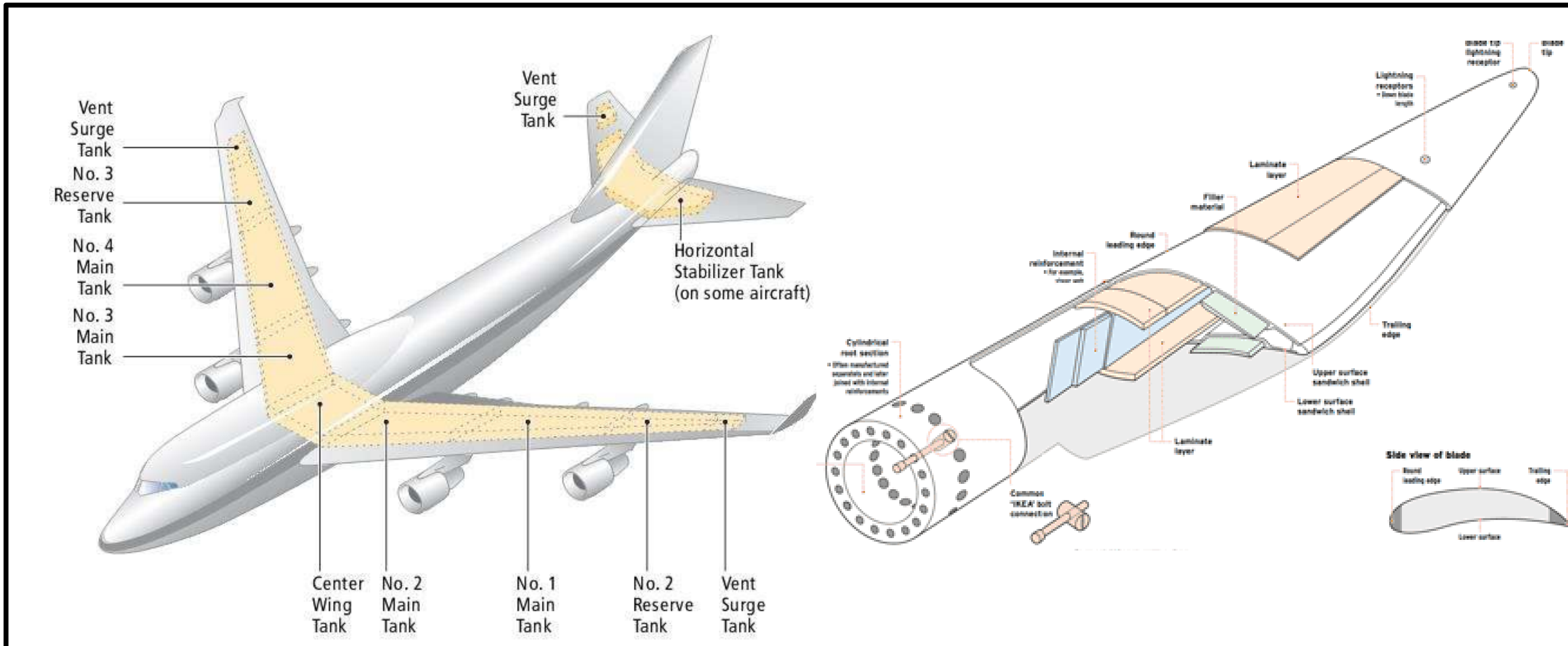
1.1 Blades

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



Source: [7]

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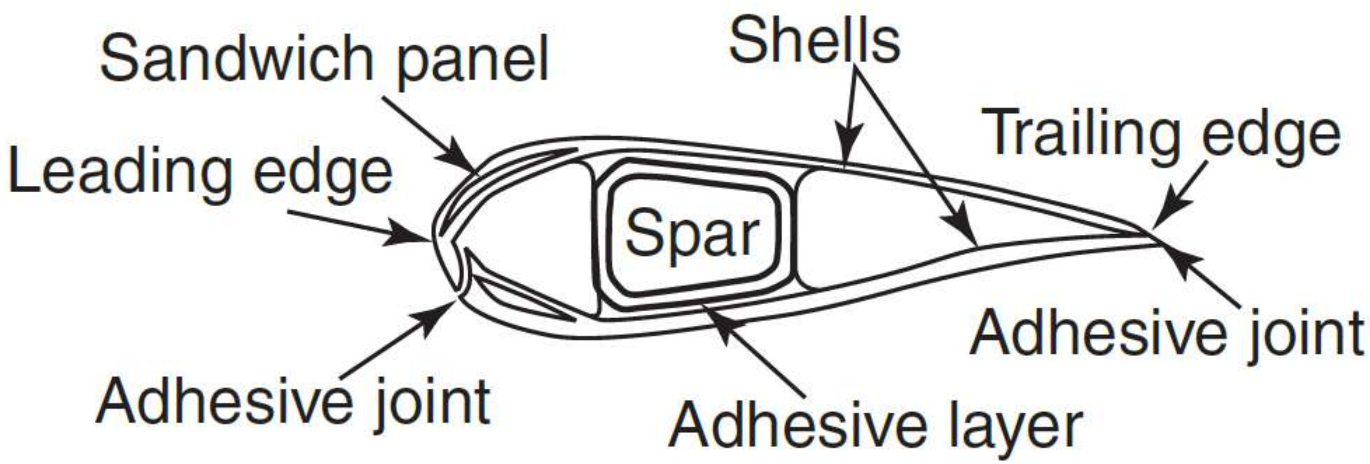
The Rotor

1.1 Blades (Cont.)

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

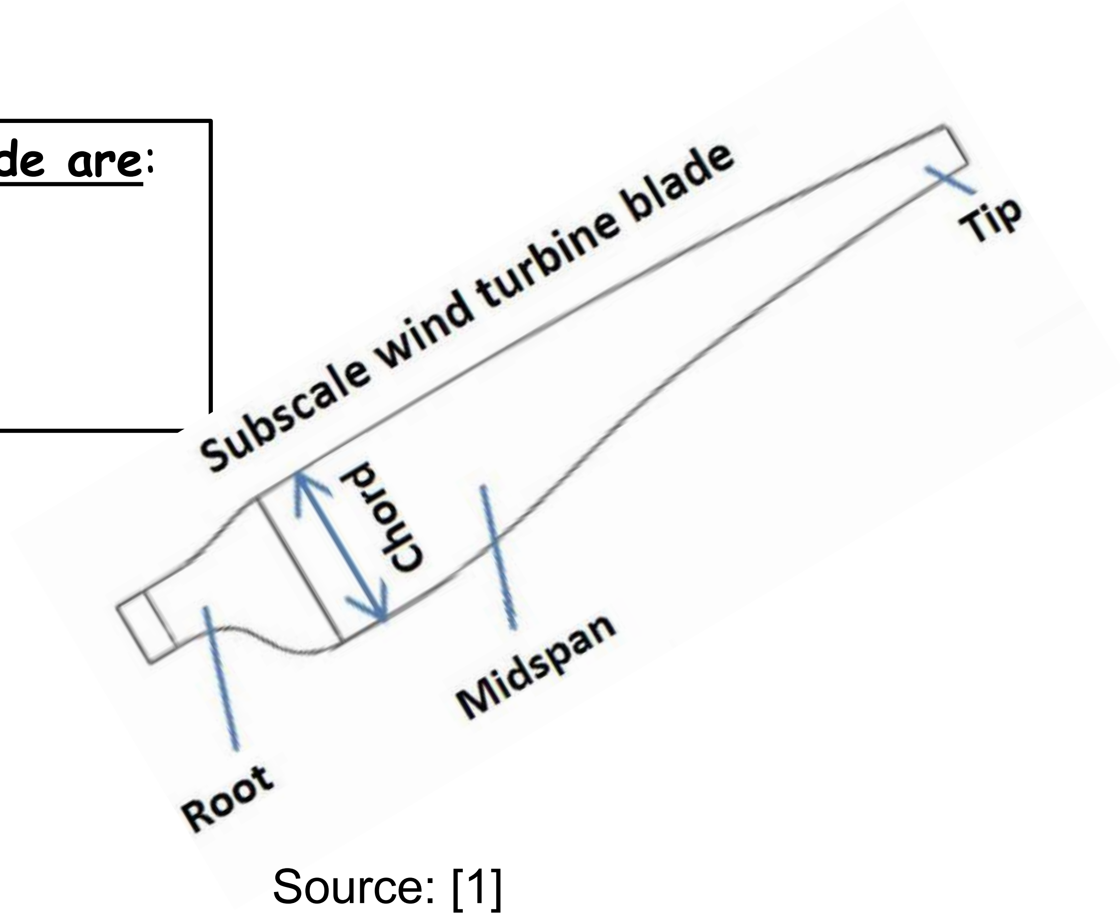


Source: [1]

The Rotor

1.1 Blades (Cont.)

The components of a blade are:
1. Core
2. Aerodynamic shell
3. Root
4. Sensors



Source: [1]

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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

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

Source: [6]

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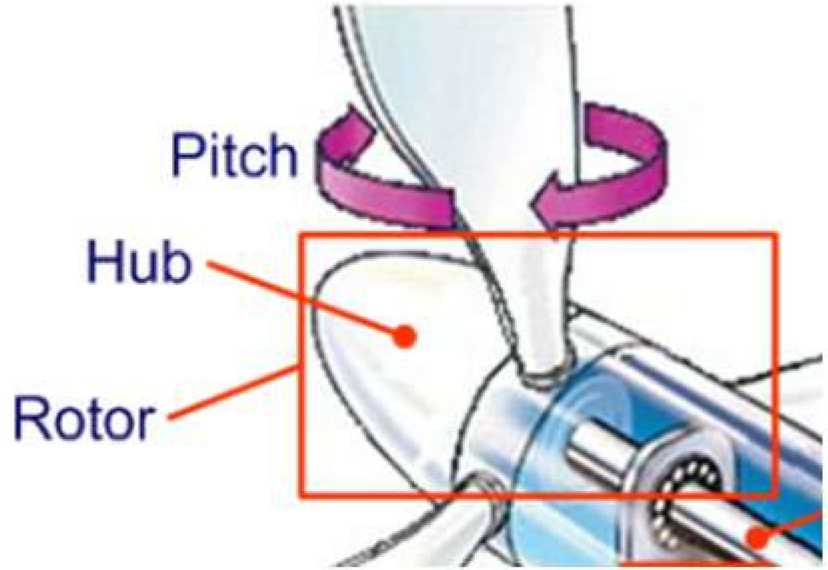
The Rotor

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.



Source: [7]

The Rotor

1.2 Rotor Hub

- In 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

Source: [7]

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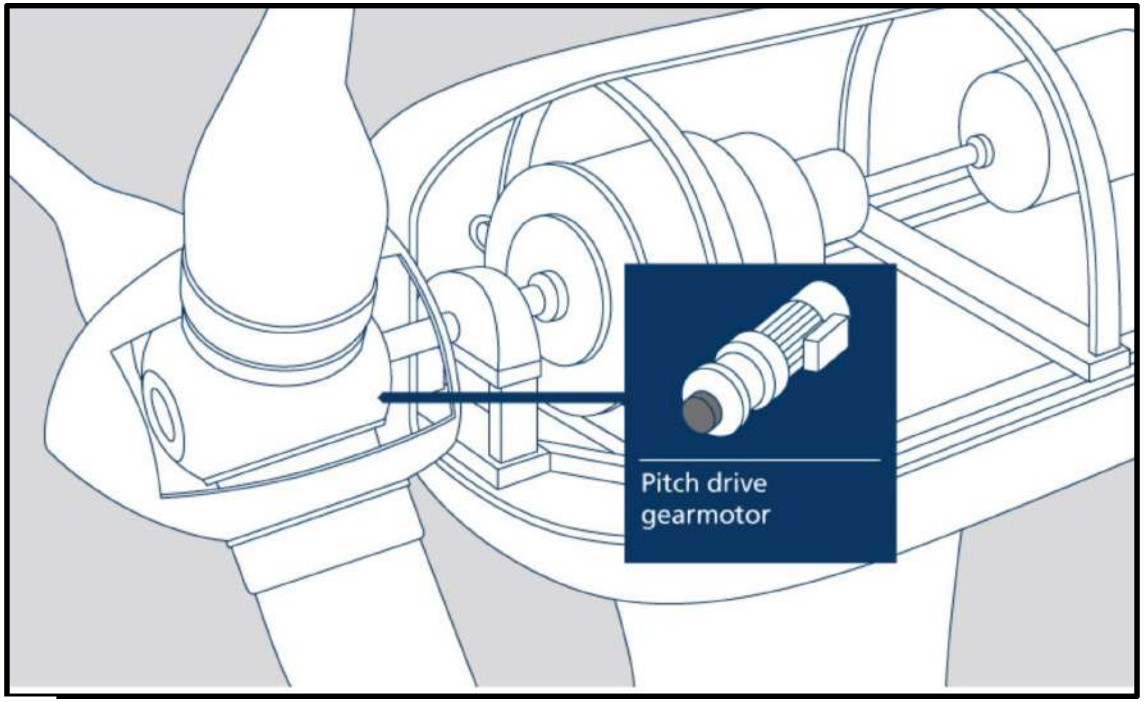
1.3 Pitch Control

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



Source: [7]

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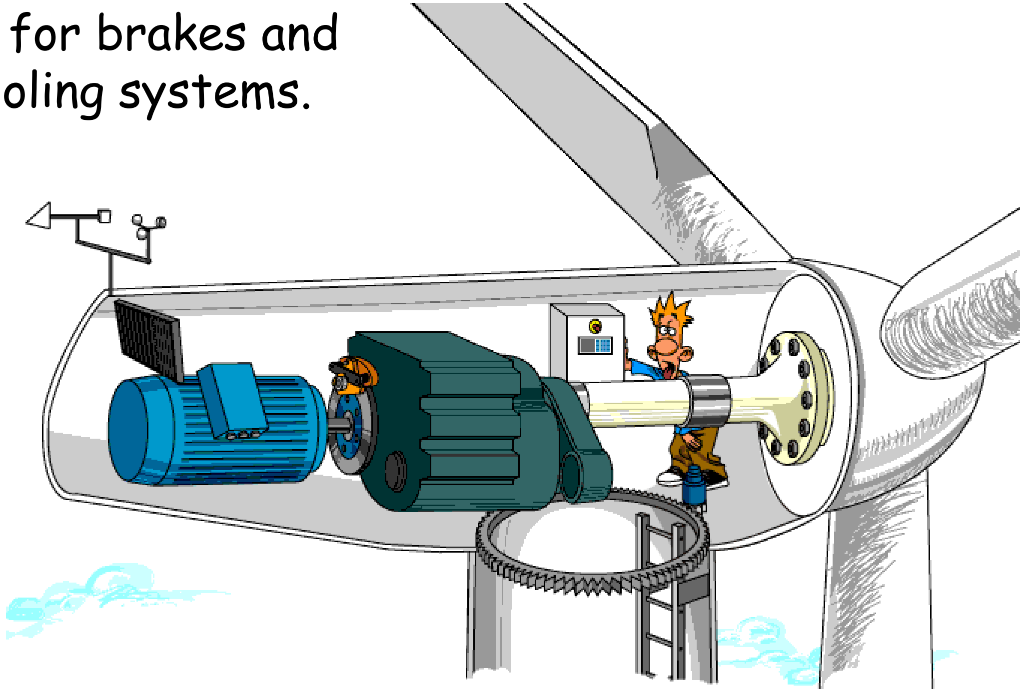
2. Nacelle

- 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.



Source: [9]

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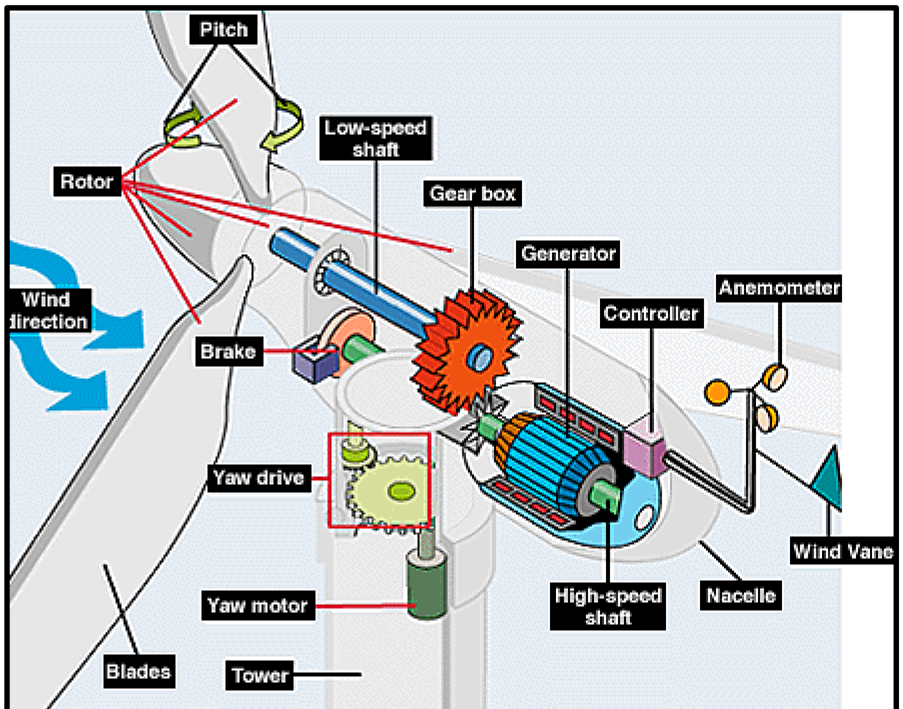
The Nacelle

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



Source: [7]

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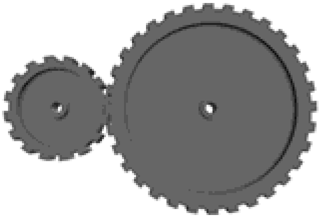
The Nacelle



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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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The Nacelle

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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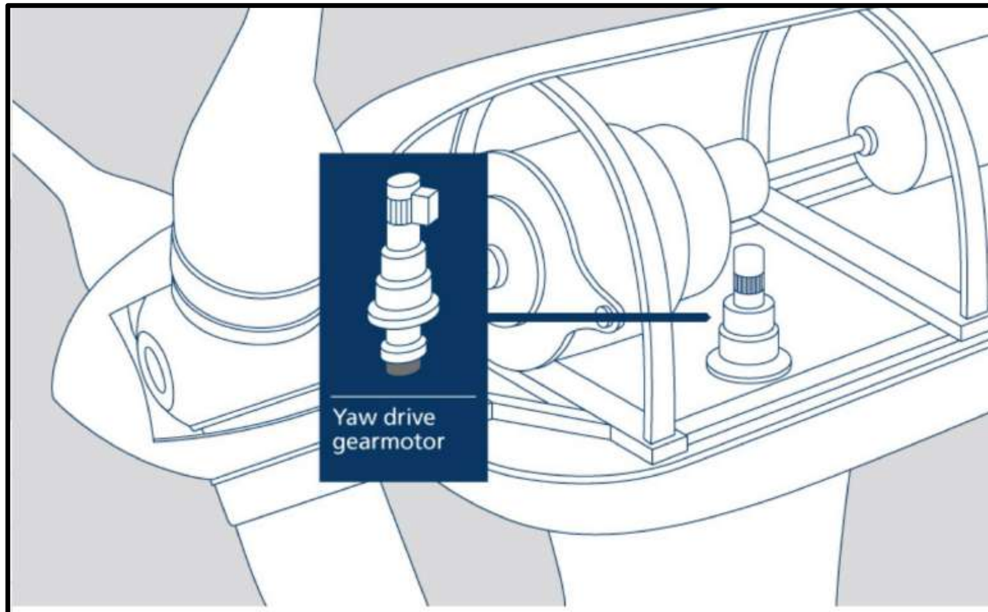
The Nacelle

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.



Source: [9]

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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 $(\cos(\text{yaw angle}))^3$

Source: [7]

The Nacelle

2.3 Yaw Control (Cont.)

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

Source: [7]

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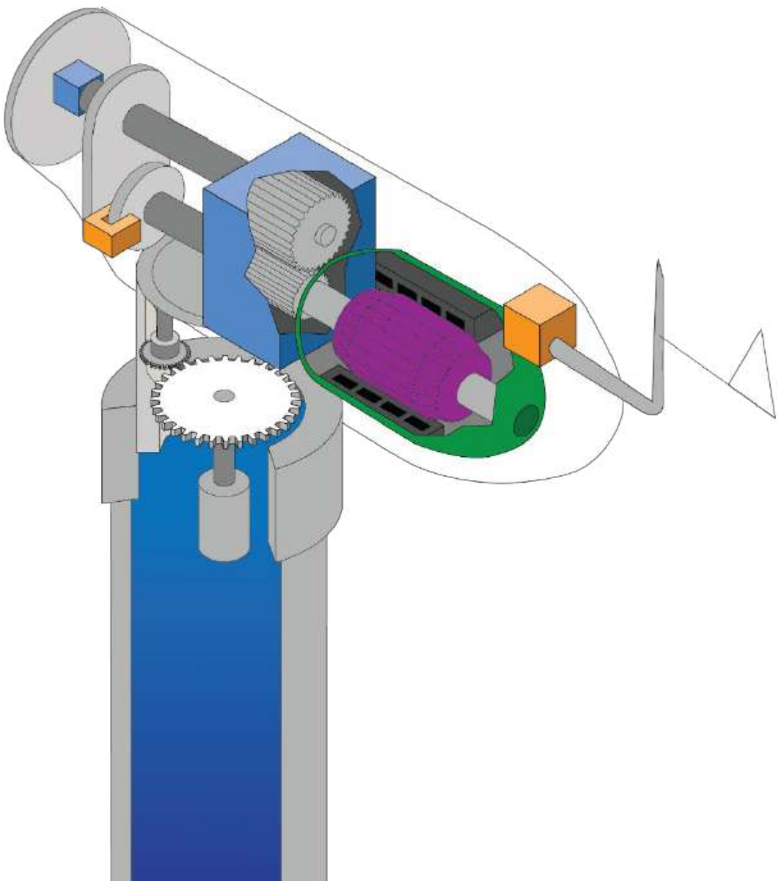
The Nacelle

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



Source: [9]

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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.)

Source: [10]

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The Tower

Tubular steel tower | Tubular concrete | Lattice tower | Three-legged tower | Guy-wired pole tower

Source: [10]

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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.

Source: [10]

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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.

Source: [10]

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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

Source: [9]

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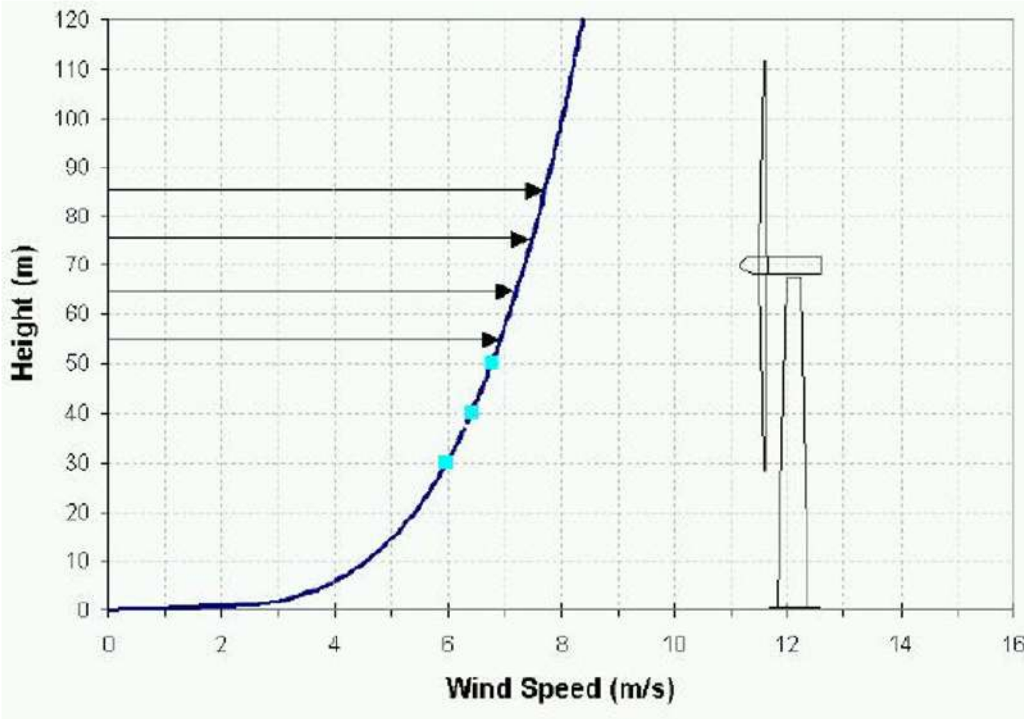
The Tower

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**



Source: [9]

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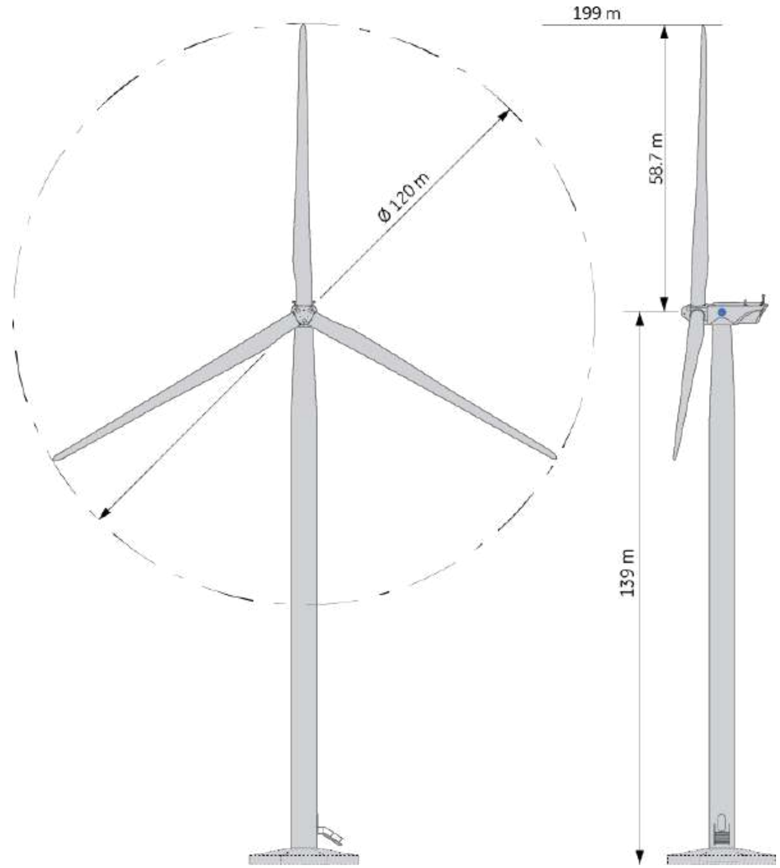
The Tower

3. Towers (Cont.)

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



Source: [9]

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The Tower

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 cos.
- 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

Source: [1]

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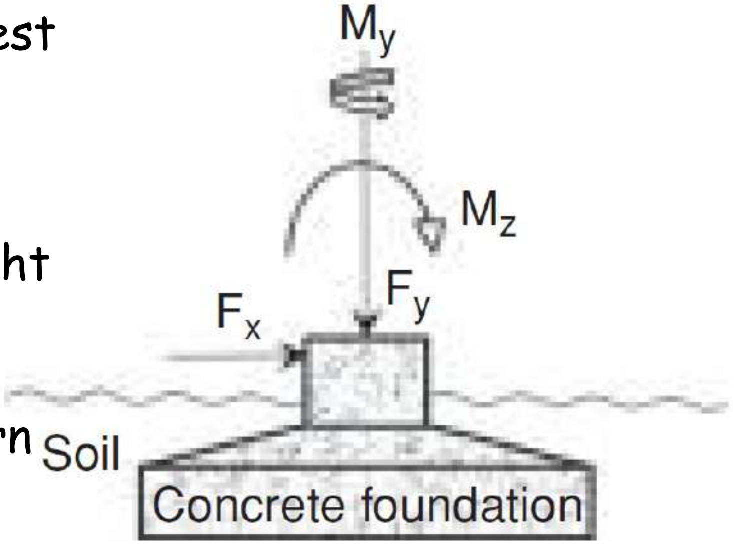
The Foundations

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 resistanc
- This bending moment causes the upwind side of the foundation to be tension and the downwind side to be in compression.



Source: [1]

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Recommended literature

www.weset-project.eu

Books:

1. **Wind energy engineering. New York: McGraw-Hill, Jain, P. (2011).**
2. Mechanical Drive Train and Nacelle – Springer, Hau. (2013), https://link.springer.com/content/pdf/10.1007%2F978-3-642-27151-9_9.pdf
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.**
5. **Alternative Energy Systems, B. K. Hodge, John Wiley & Sons, 2009.**
6. Fundamental of Aerodynamics, John D. Anderson, Jr., McGraw-Hill, 2001.

   "Aerodynamic and Performance Measurements on a SWT-2.3- 101 Wind Turbine"

Web links:

[1] www.ewea.org **European Wind Energy Association**
[2] www.wwindea.org **World Wind Energy Association**
[3] www.awea.org **American Wind Energy Association**
[4] https://www.energy.gov/eere/wind/inside-wind-turbine
[5] https://www.horizoncurriculum.com/supportmaterial/parts-of-a-wind-turbine
[6] https://www.en.wind-turbine-models.com/turbines
[7] https://energyeducation.ca/encyclopedia/Wind_turbine
[8] https://www.windenergy.org.nz/wind-energy/the-facts
[9] https://www.slideshare.net/akkaa/wind-farms-2985162
[10] https://www.windfarmbop.com/wind-turbine-tower/

Introduction to Wind Energy

Module 2.1

Further information:

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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 airfoil 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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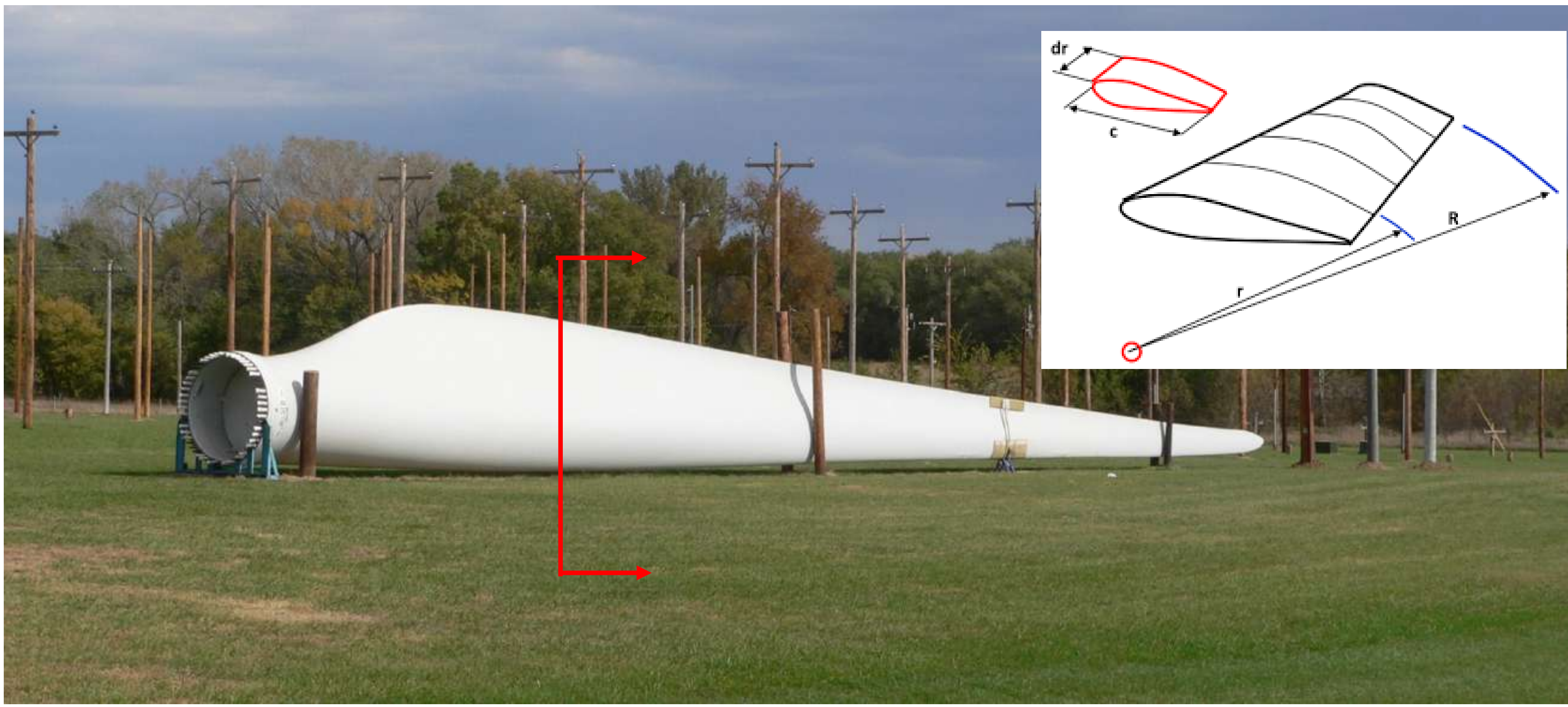
Airfoils

Blade Section

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



Source: [6]

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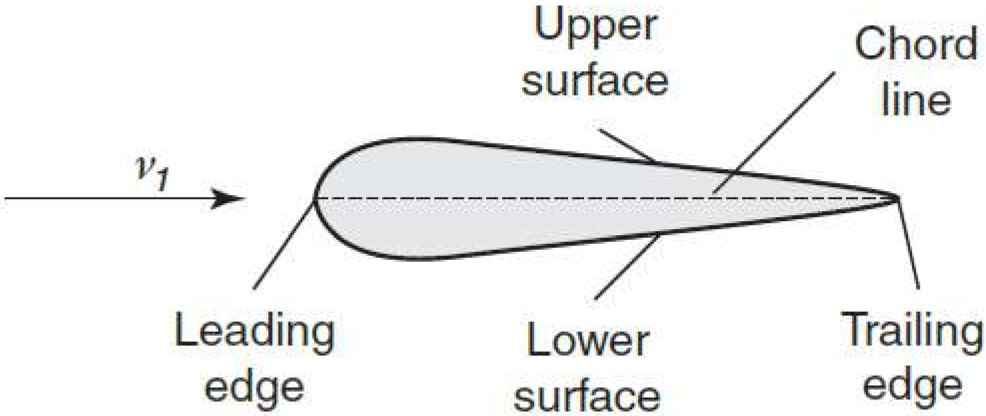
Airfoils

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



Source: [1]

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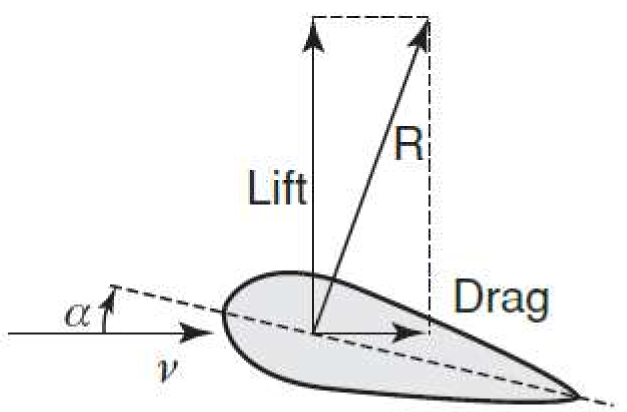
Airfoils

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



Source: [1]

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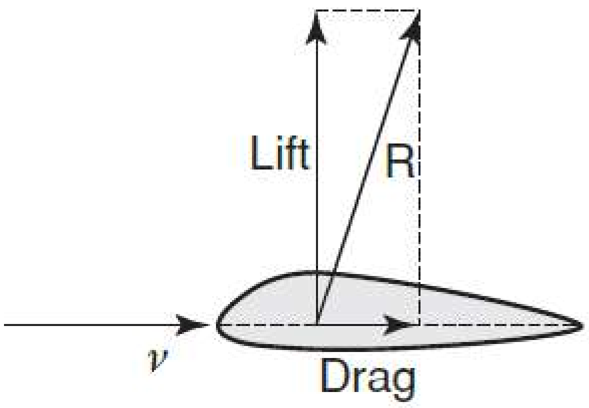
Airfoils

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.



Source: [1]

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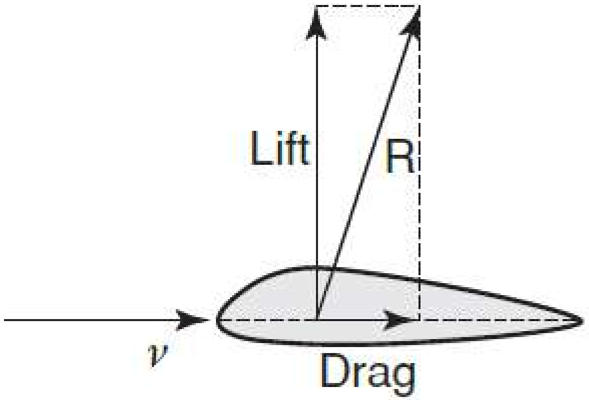
Airfoils

As a convention :

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



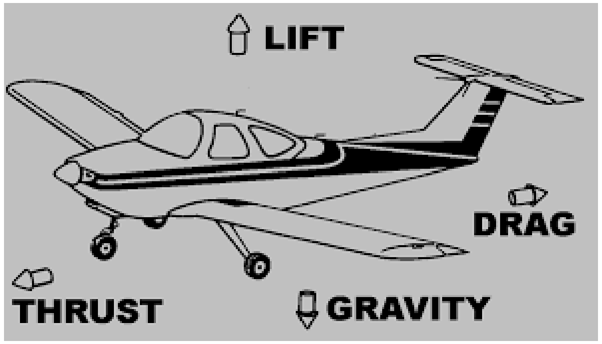
Source: [1]

Airfoils

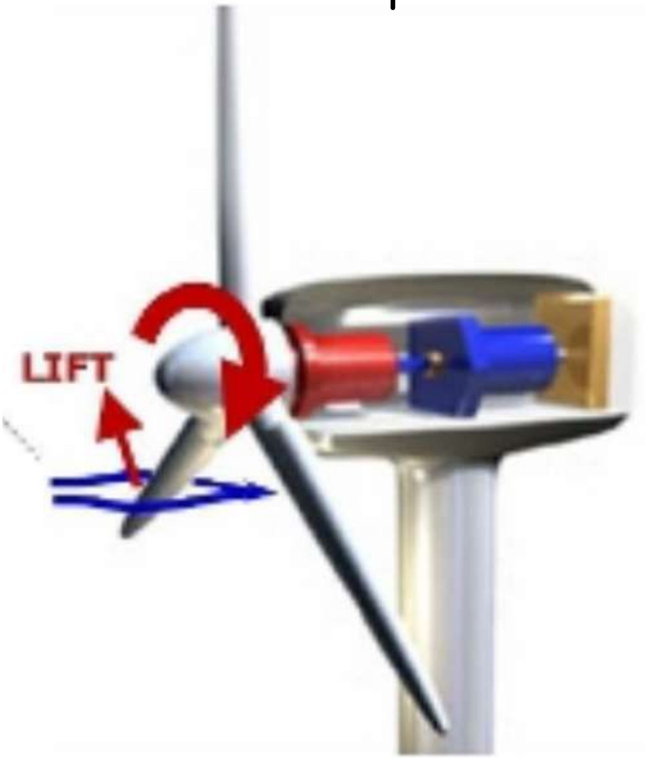
Positive angle of attack (α) on nonsymmetrical airfoils cause :

wind turbines to produce energy

airplanes to fly



Source: [1]



Source: [7]

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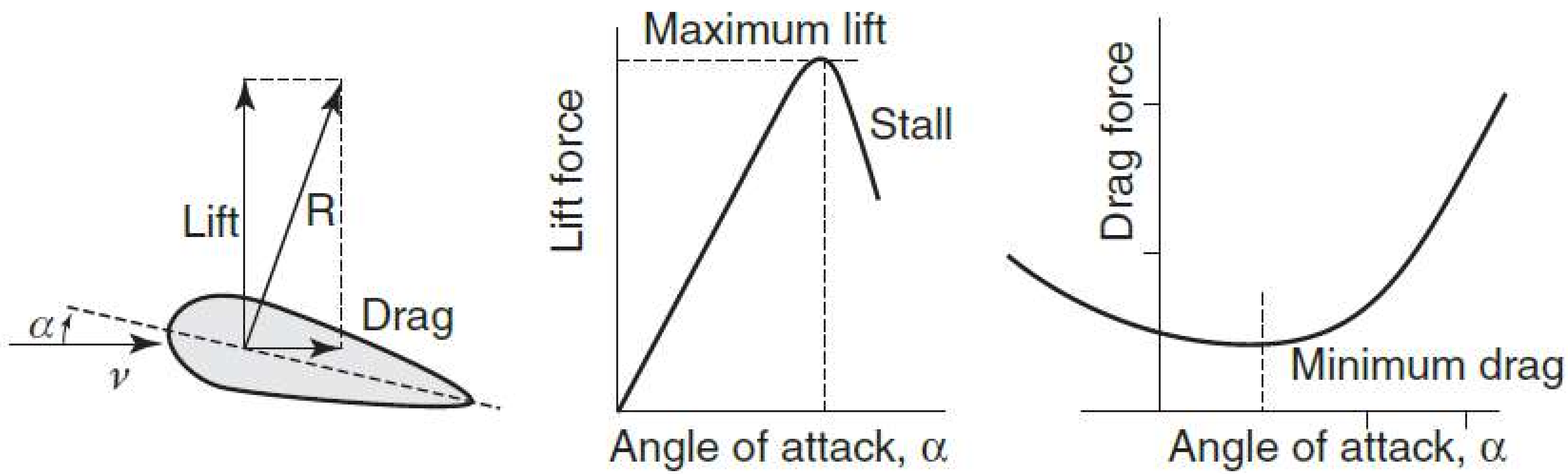
Airfoils

Each type of airfoil has <u>an optimal</u> value of α that produces optimum lift and minimal drag.



Source: [1]

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Relative Velocity of Wind

In case of airplane, the angle of attack of wind is constant along most of the length of the wing of an aircraft

Source: [4]

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Relative Velocity of Wind

- In the case of wind turbines, 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.

Source: [5]

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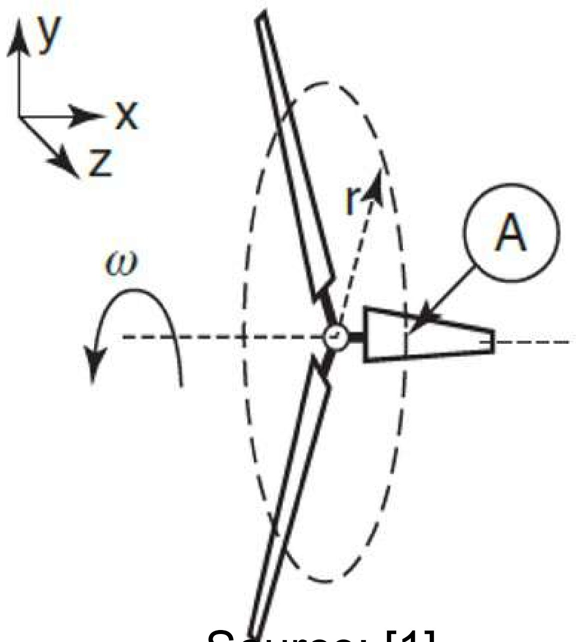
Relative Velocity of Wind

- 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.



Source: [1]

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Relative Velocity of Wind

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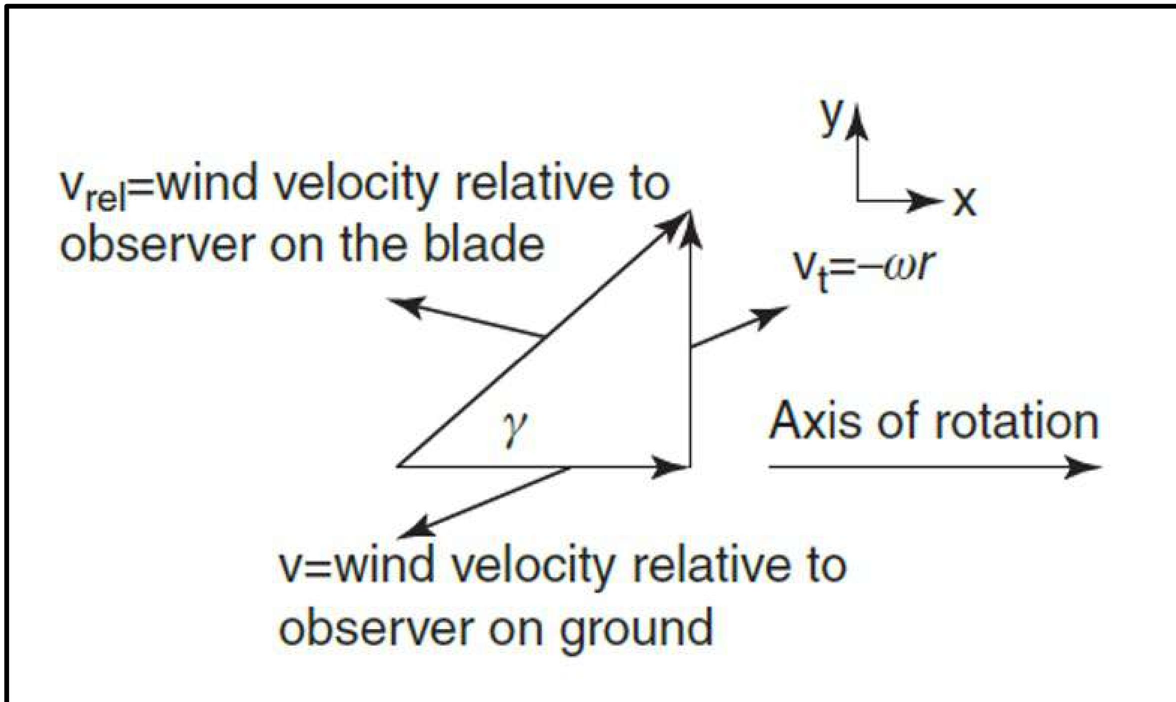
- The velocity diagram is drawn for point *A* and is shown in the schematic to the right
- The wind relative velocity of v_{rel}.



Source: [1]

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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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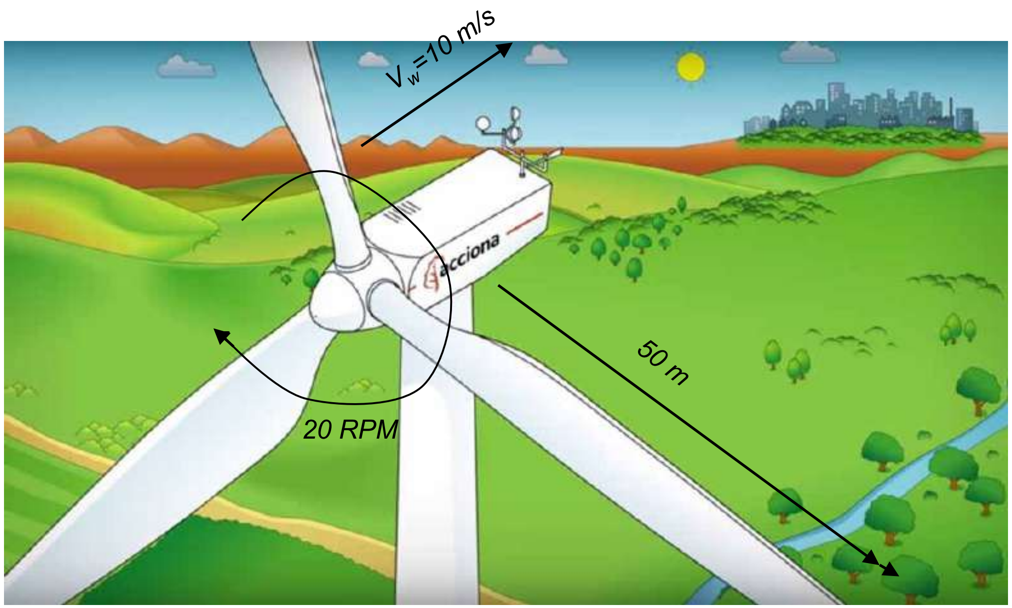
Relative Velocity of Wind

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



Source: [8]

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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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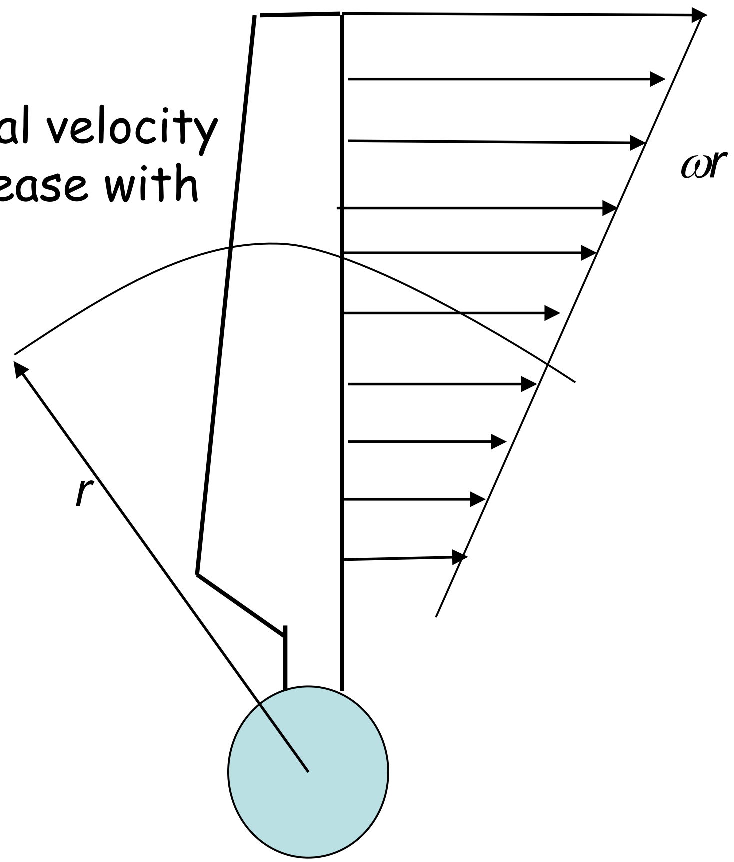
Relative Velocity of Wind

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.)

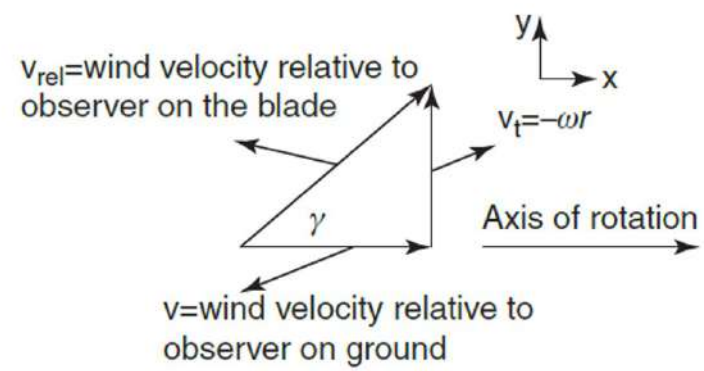
The total or relative velocity to each blade element is obtained as:

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

The direction of the relative velocity is calculated from:

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

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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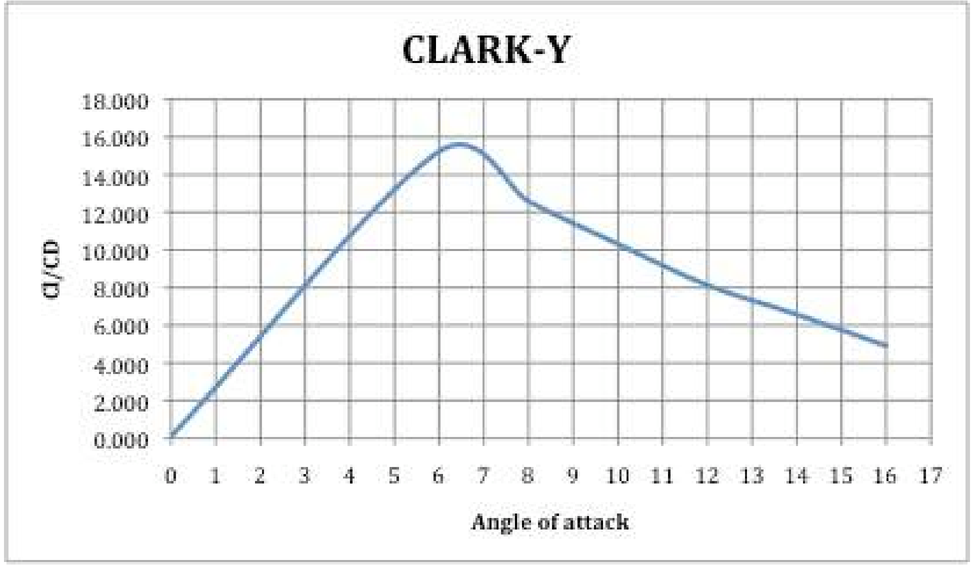
Lift and Draft Forces

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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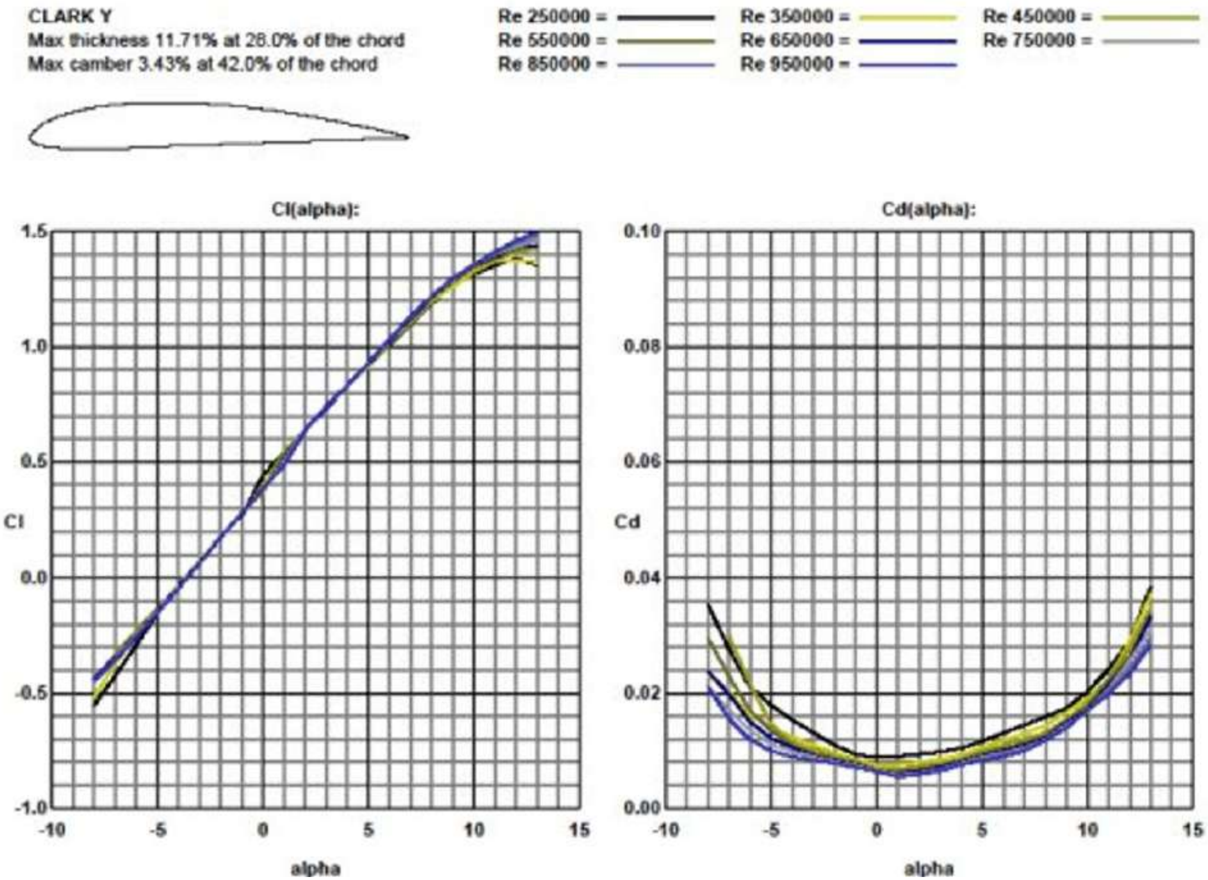
Lift and Draft Forces

Recall

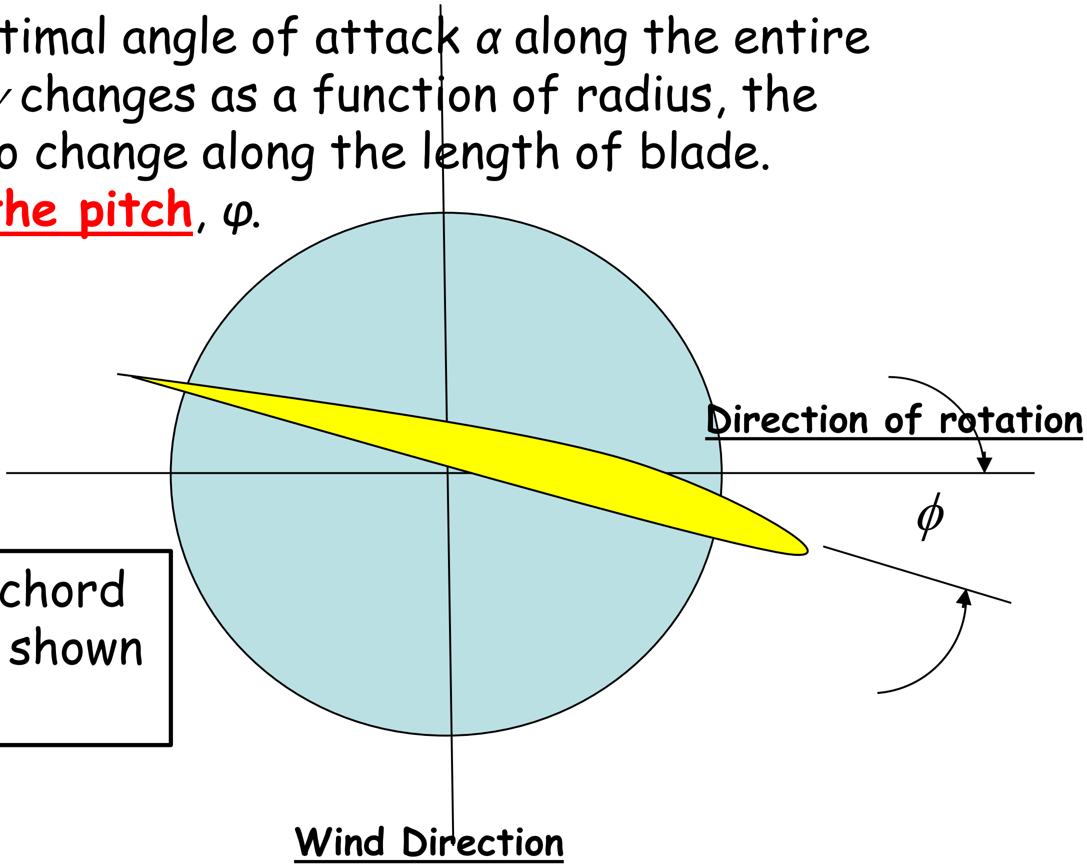


Source: [1]

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

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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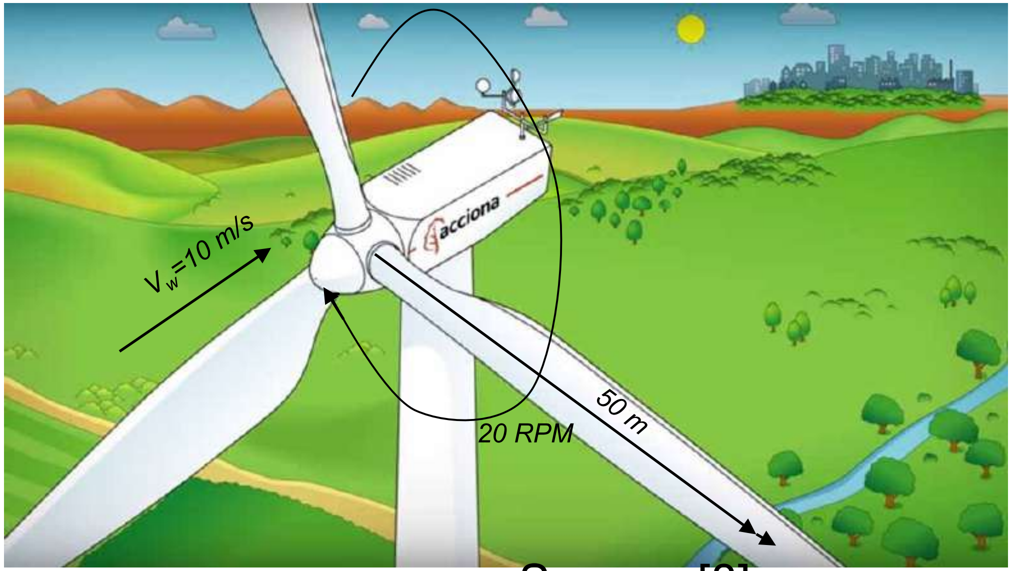
Lift and Draft Forces

Example 2

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



Source: [8]

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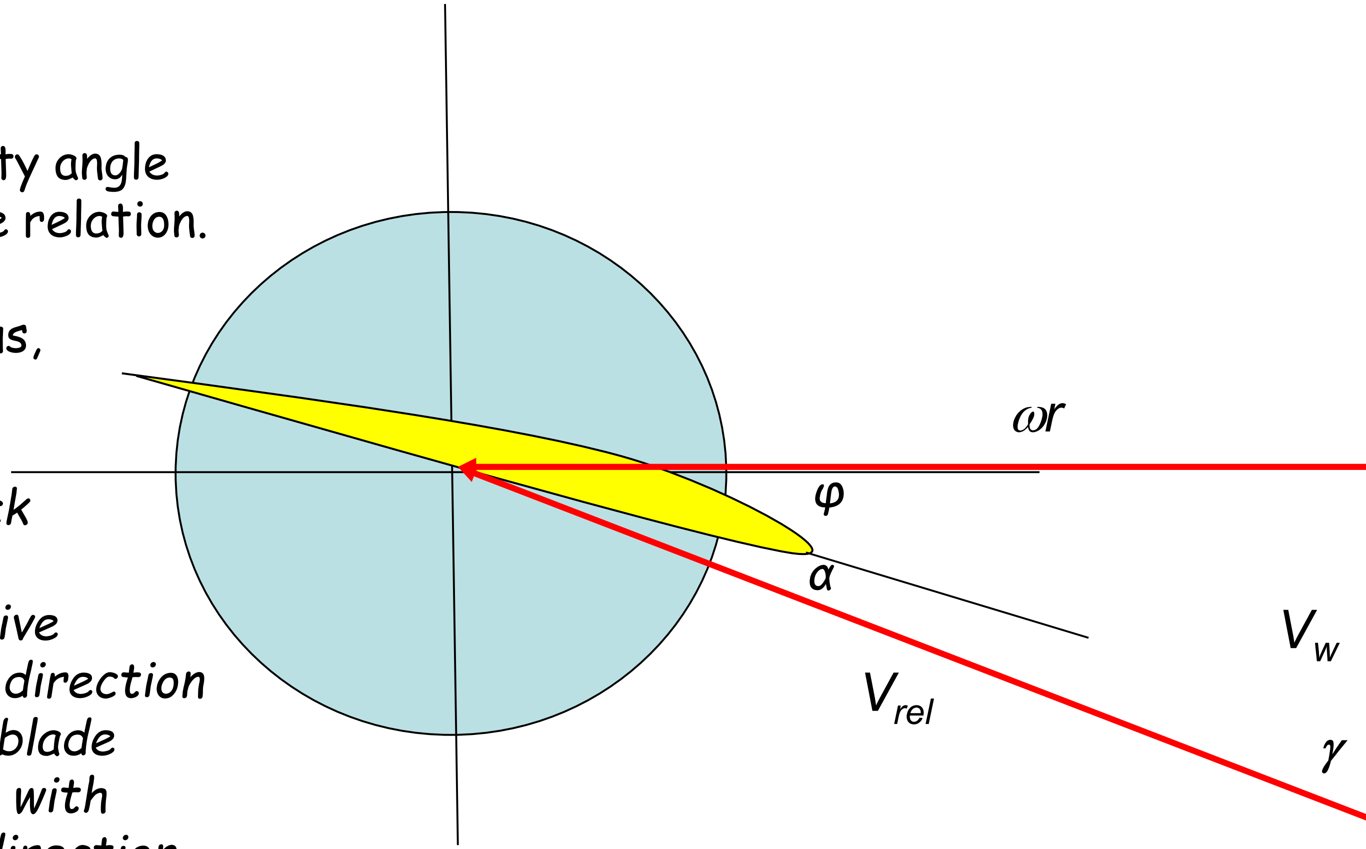
Lift and Draft Forces

Example 2 Solution

- Relative velocity angle and twist angle relation.
- $\beta = \alpha + \varphi$ and
- $\beta = 90 - \gamma$ thus,
- $\varphi = 90 - \gamma - \alpha$

Where:

α = angle of attack
φ = pitch angle
β = angle of relative velocity with the direction of motion of the blade
γ = Relative angle with respect to wind direction at radius r



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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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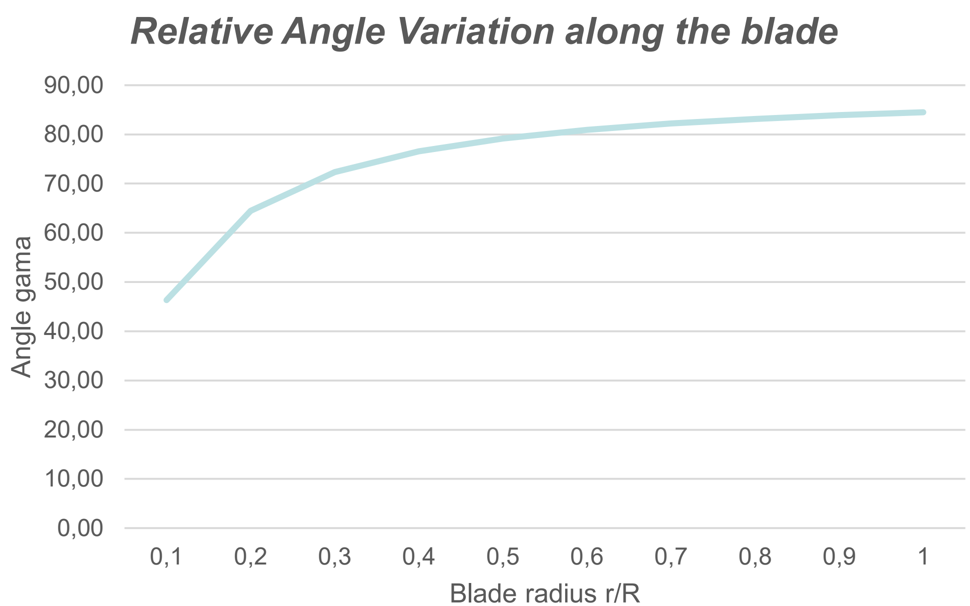
Lift and Draft Forces

Example 2 Solution



Flow angle radial distribution

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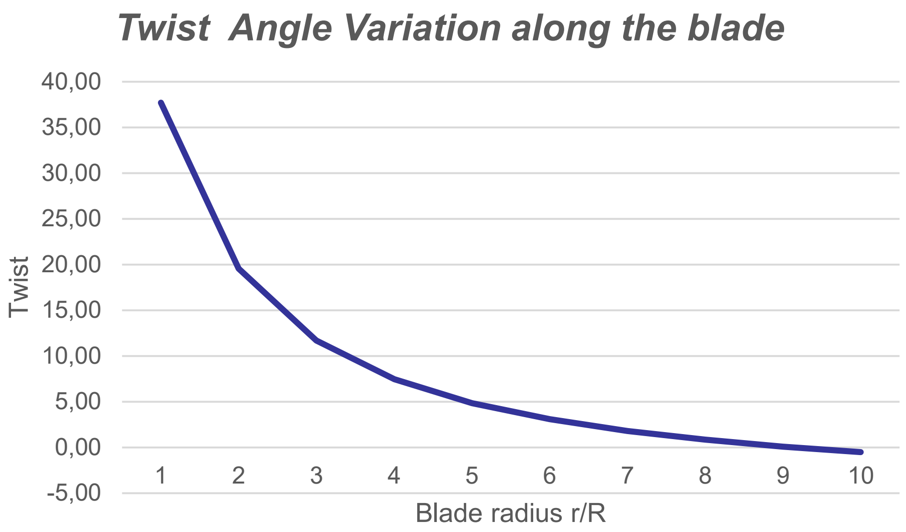
Lift and Draft Forces



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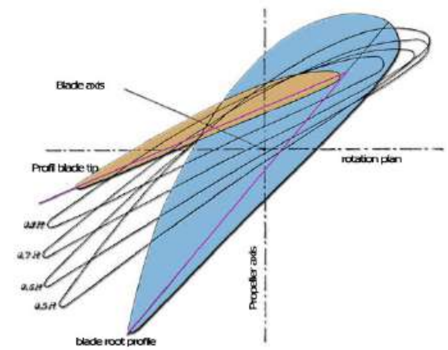
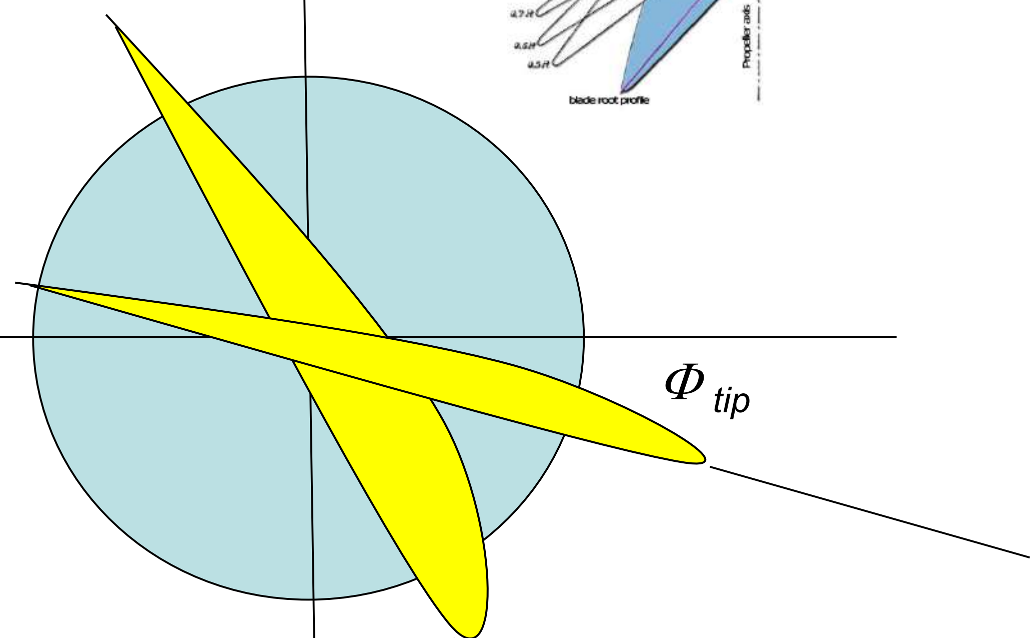
Lift and Draft Forces



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

Source: [1]

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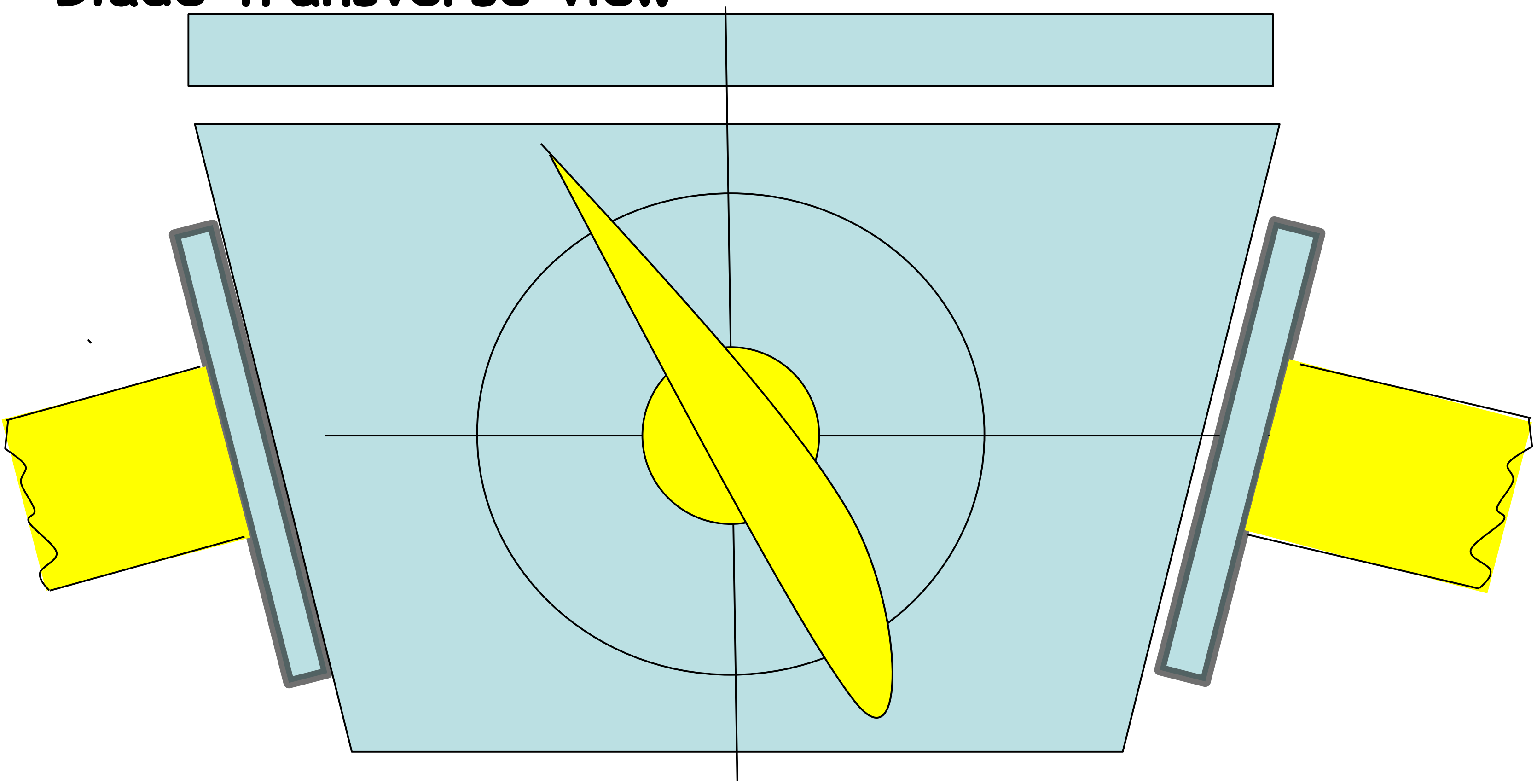
Lift and Draft Forces

Blade transverse view



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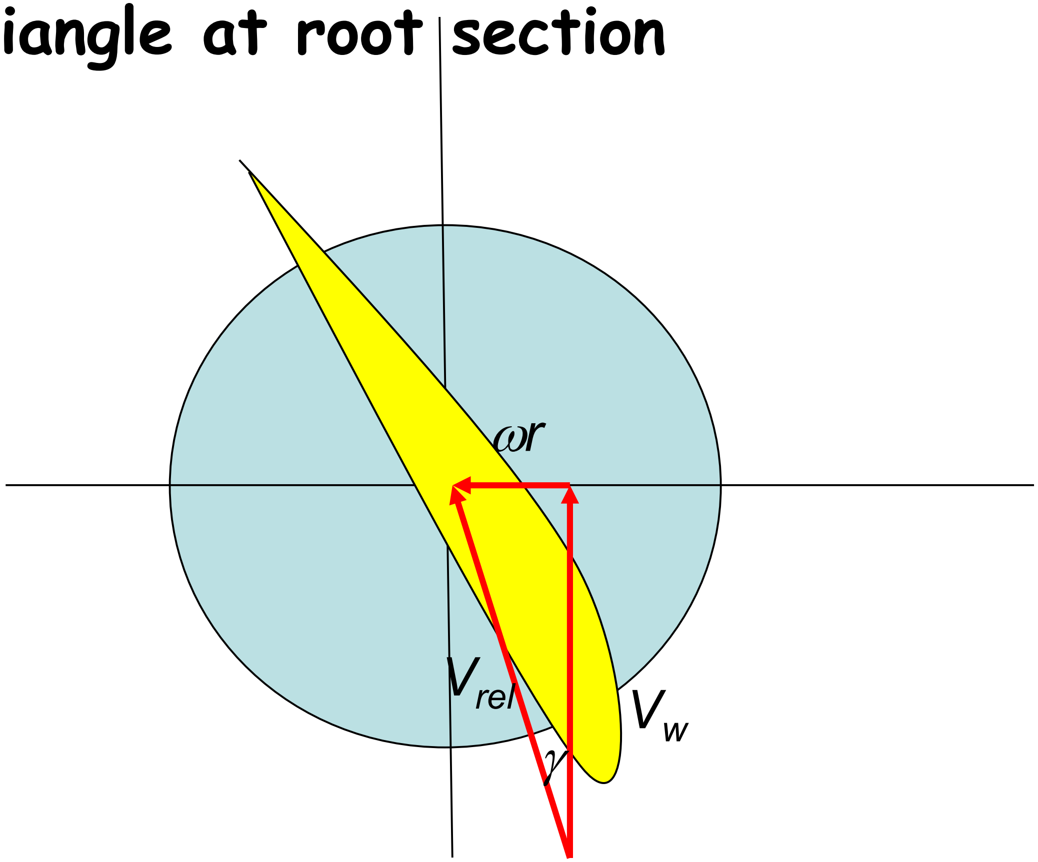
Lift and Draft Forces

Velocity triangle at root section



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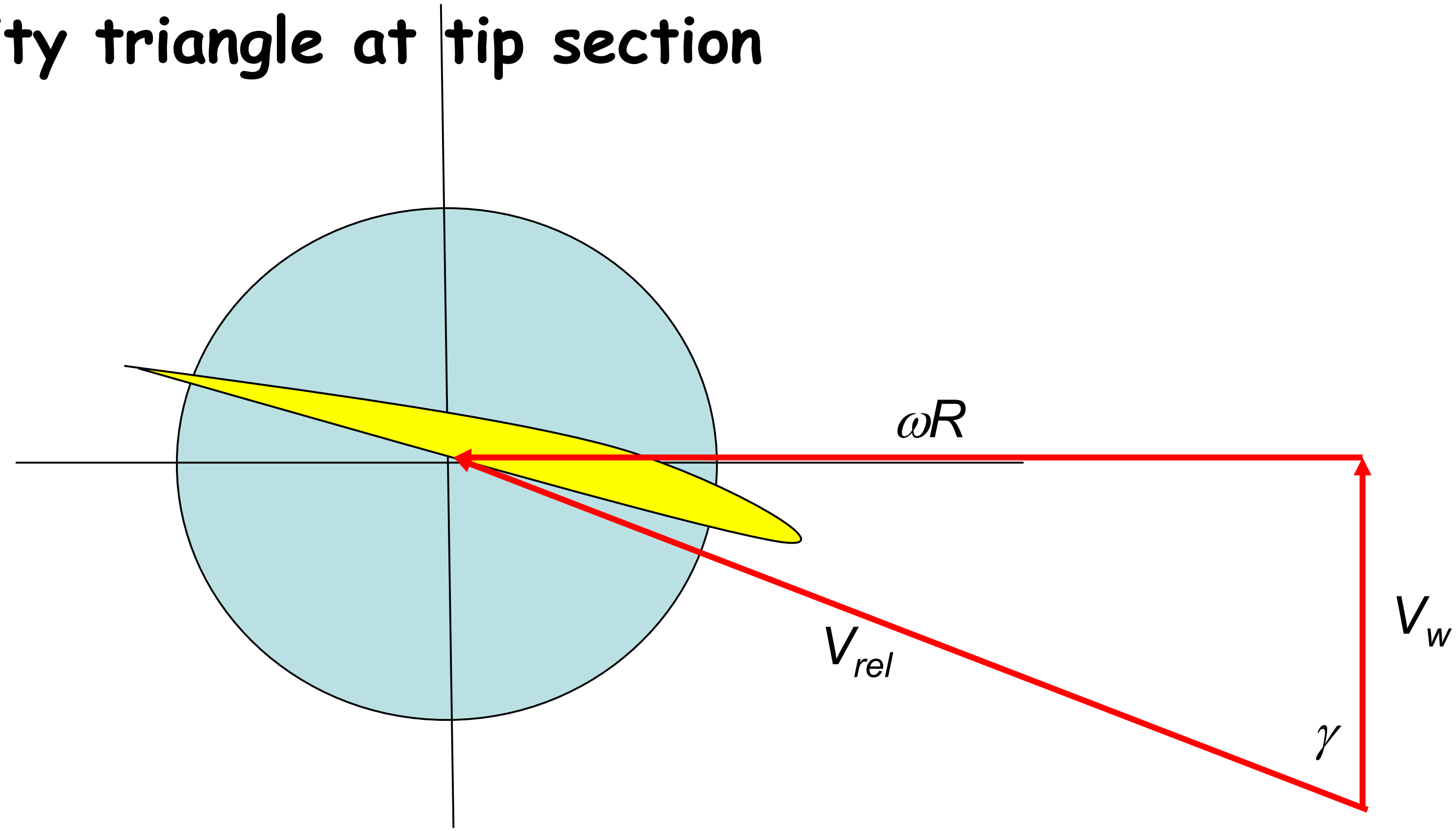
Lift and Draft Forces

Velocity triangle at tip section



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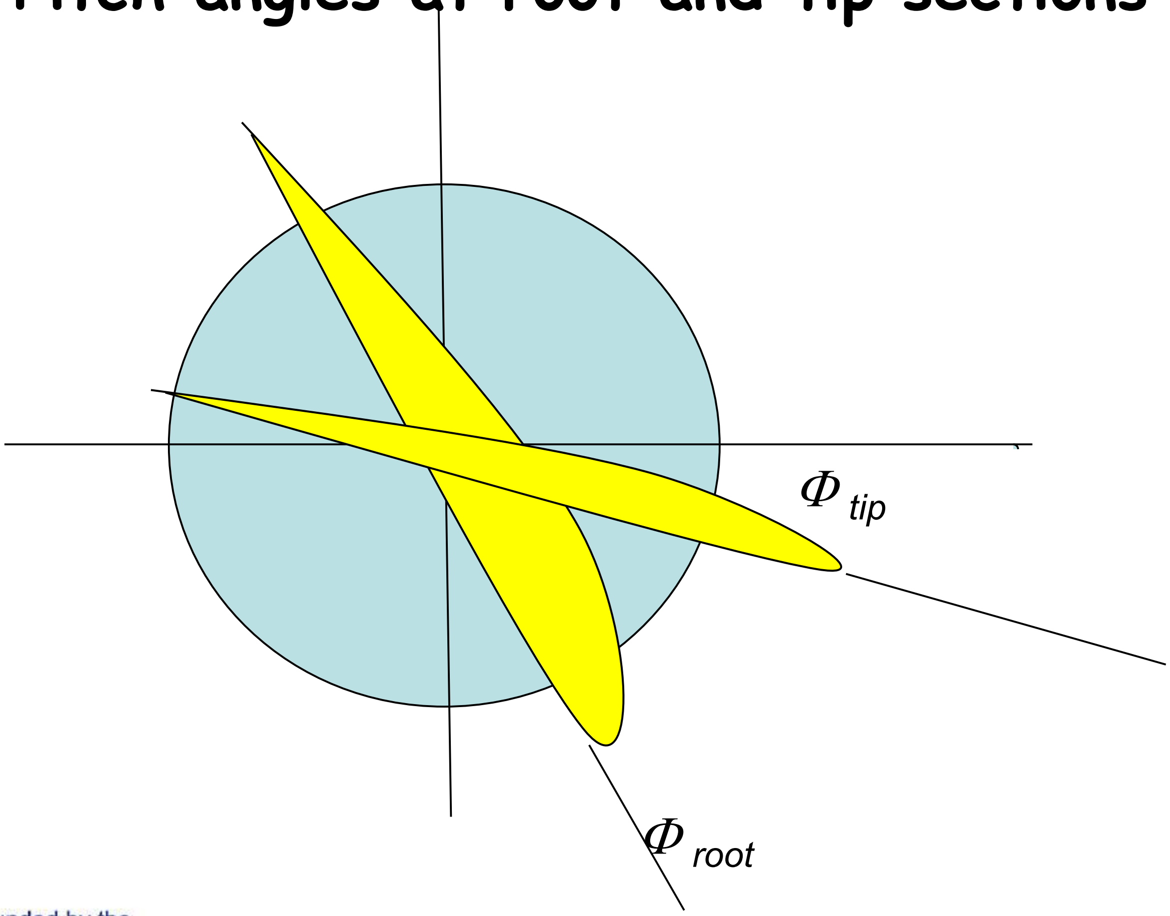
Lift and Draft Forces

Blade Pitch angles at root and tip sections



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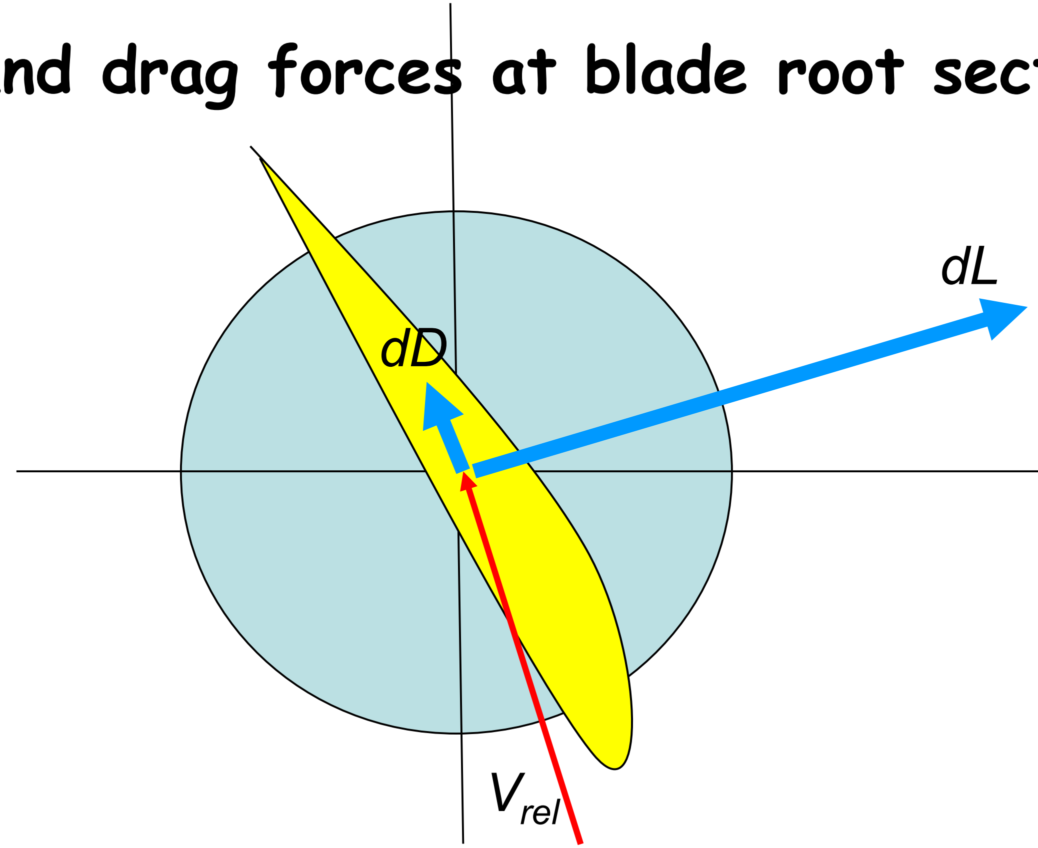
Lift and Draft Forces

Lift and drag forces at blade root section



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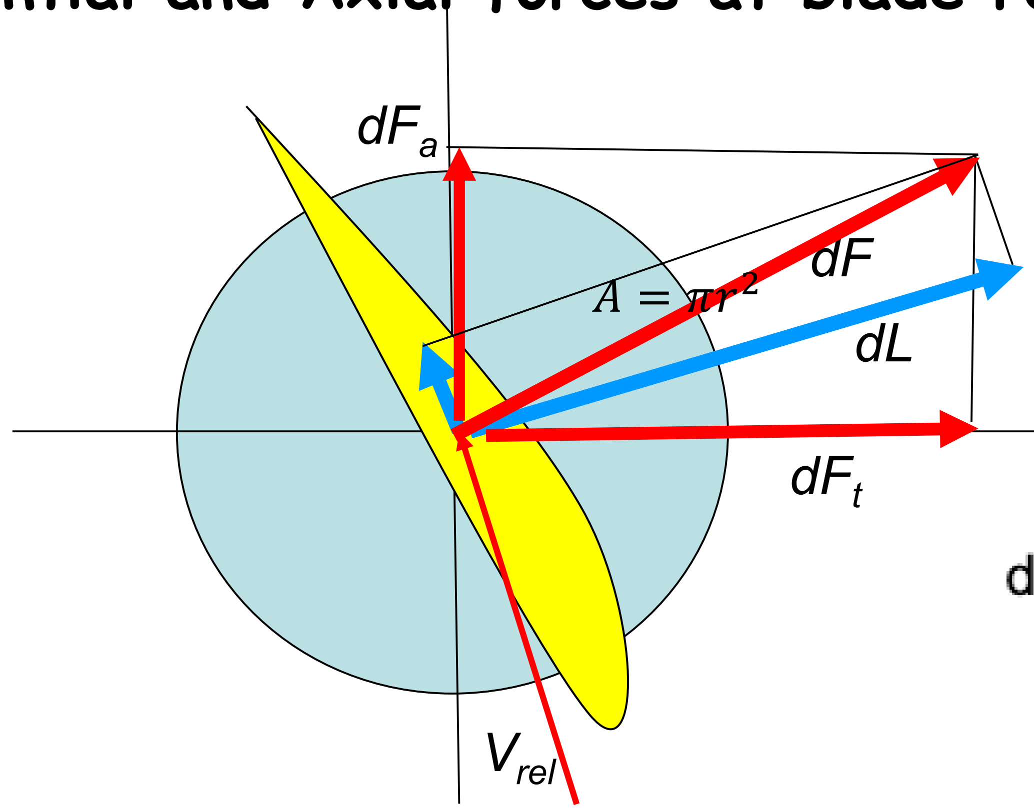
Lift and Draft Forces

Tangential and Axial forces at blade root section



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

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

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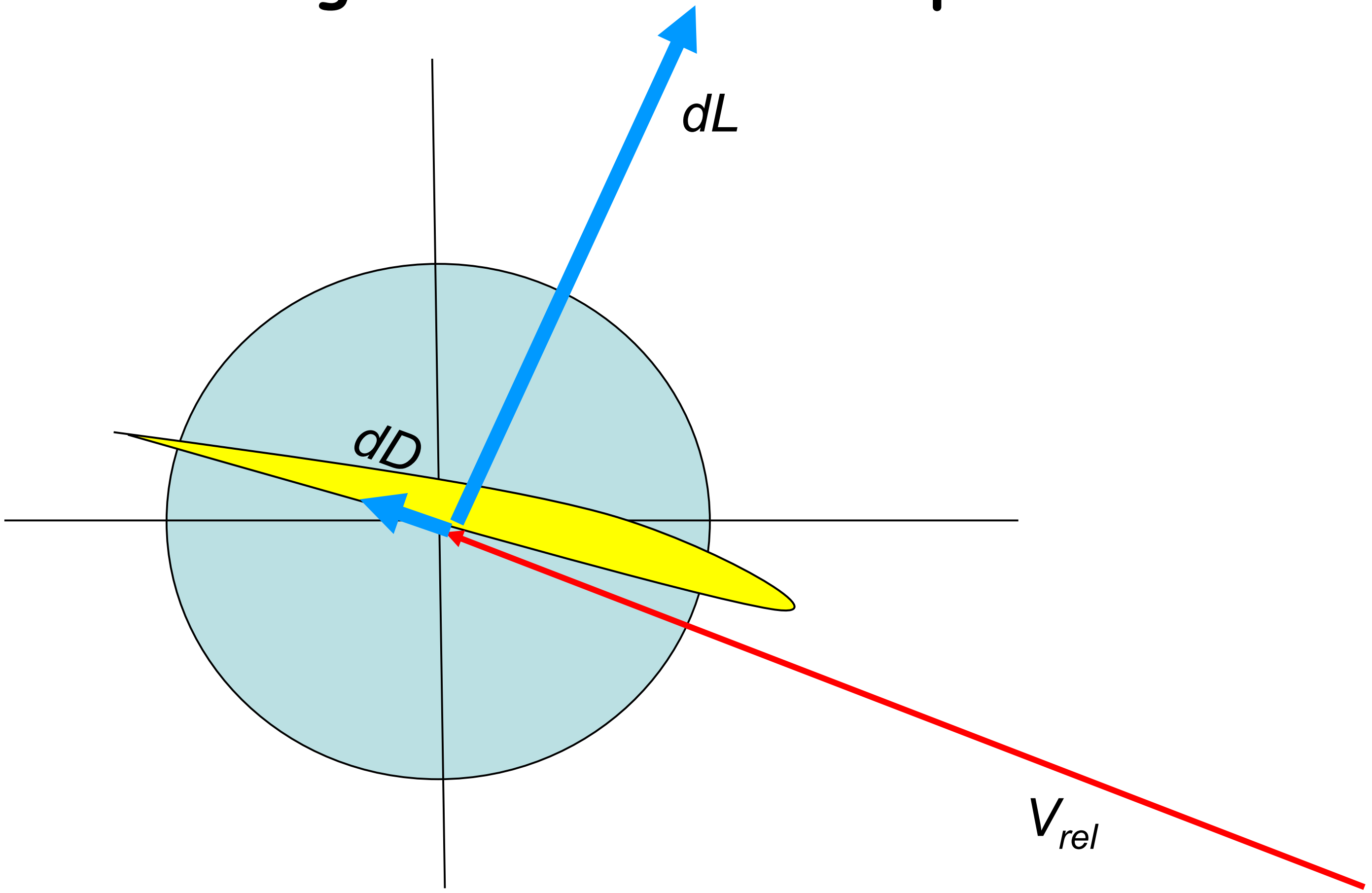
Lift and Draft forces

Lift and drag forces at blade tip section



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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] www.wwindea.org World Wind Energy Association
[3] www.awea.org American Wind Energy Association
[4] https://fineartamerica.com/featured/view-out-of-airplane-airplane-wing-in-flight-preecha-wannalert-
[5] https://phys.org/news/2017-04-radar-scanner-turbine-blades-defects.html
[6] https://www.powerblanket.com/blog/tag/wind-turbine-blades/
[7] http://people.bu.edu/dew11/liftanddrag.html
[8] https://www.acciona.com/solutions/energy/

Module 2.1

Further information:

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Introduction to Wind Energy

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.

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

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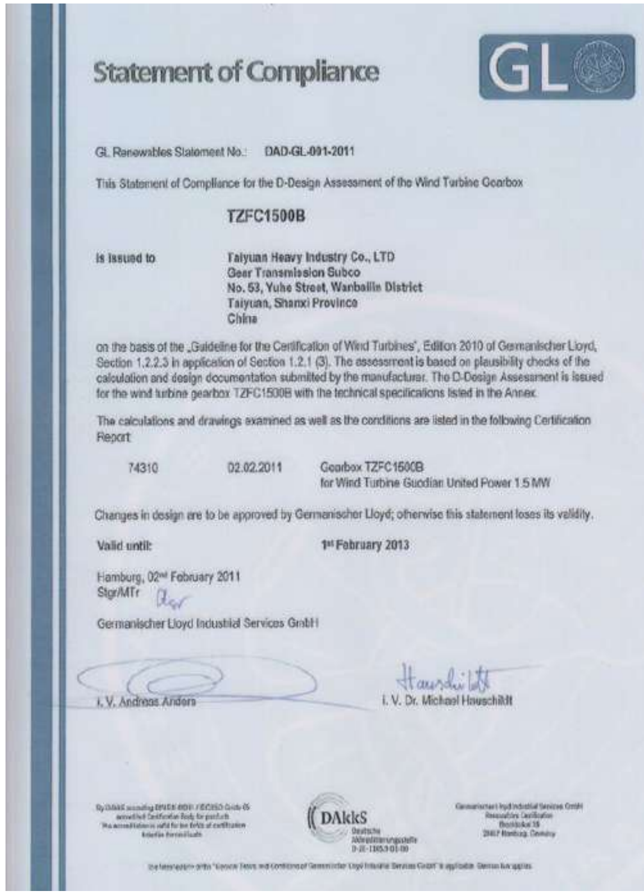
Review of existing standards

Example of Statement of Compliance Issued by GL


Statement of Compliance

GL

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.

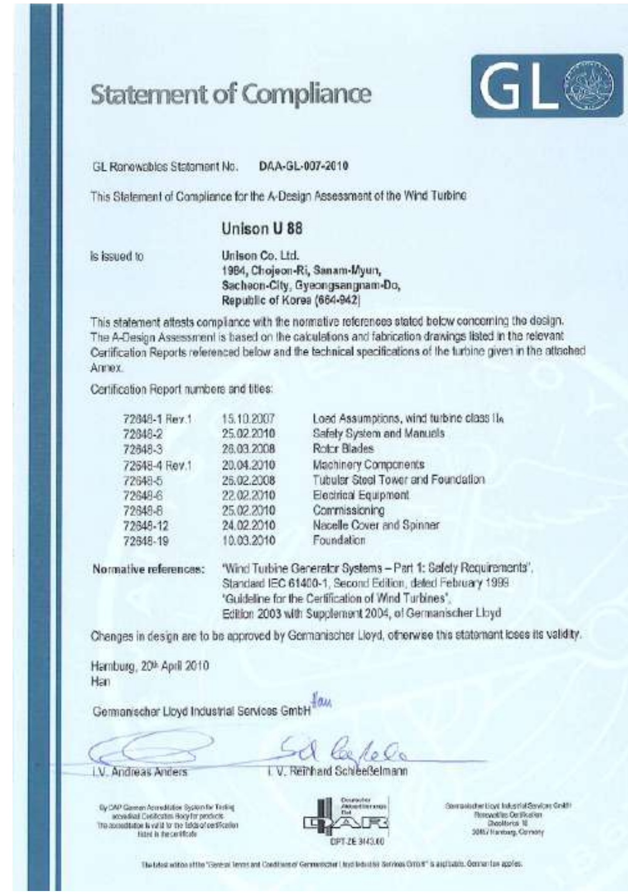
Valid until: 1st February 2013

Hamburg, 02nd February 2011
StgrMTr

Germanischer Lloyd Industrial Services GmbH

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

DAkkS


Statement of Compliance

GL

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 IIA
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 Schießelmann

DAR

Source: [7]

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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.

Source: [13]

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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.

Source: [8]

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Review of existing standards

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

Source: [14]

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	Par Iggstrom	Date	28 October 2013 Page 1 of 3

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

Source: [15]

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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

www.weset-project.eu

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*

Source: [16]

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

- Wind turbine in farms

Source: [17]

Co-funded by the Erasmus+ Programme of the European Union

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

- Offshore fixed wind turbine

Source: [9]

Co-funded by the Erasmus+ Programme of the European Union

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

- Offshore floating wind turbine

Source: [10]

Co-funded by the Erasmus+ Programme of the European Union

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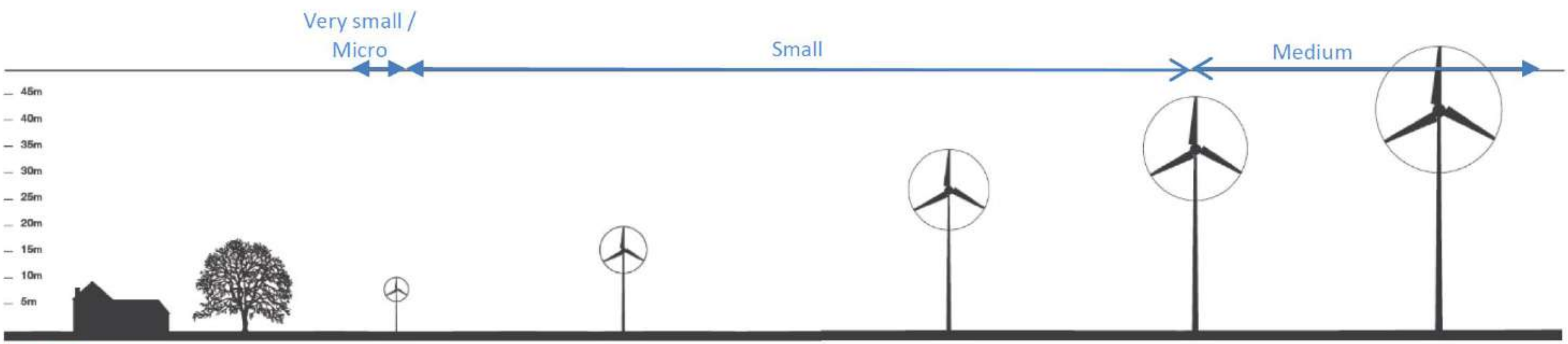
IEC 61400: Wind Turbine Classification, Design specifications and noise requirements

Small Wind Turbine

- 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



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

Source: [17]

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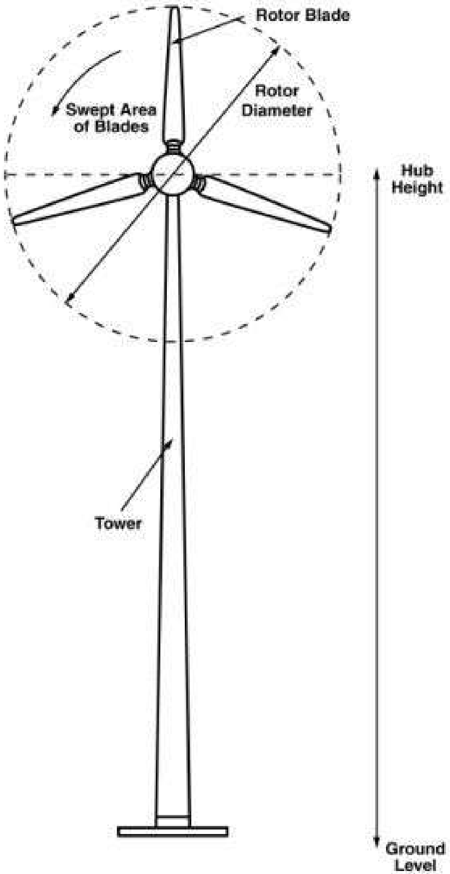
IEC 61400: Wind Turbine Classification, Design specifications and noise requirements

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).



Source: [17]

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

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).

Source: [17]

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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

energy API
AMERICAN PETROLEUM INSTITUTE

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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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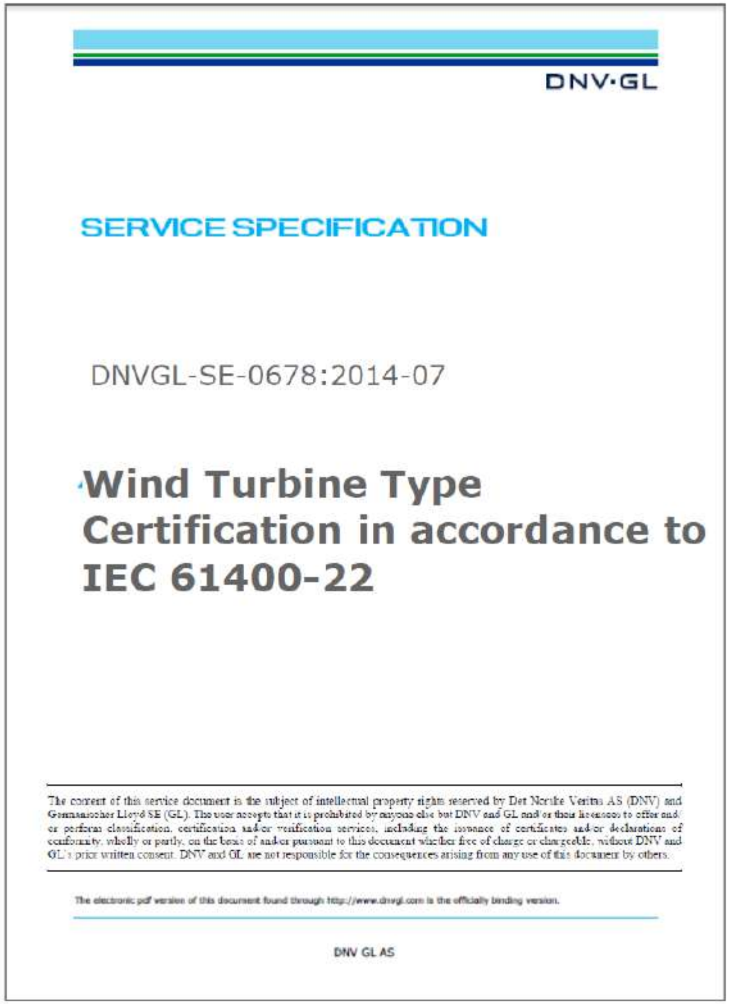
DNV·GL

SERVICE SPECIFICATION

DNVGL-SE-0678:2014-07

Wind Turbine Project Certification in accordance to IEC 61400-22

DNV GL AS


DNV·GL

SERVICE SPECIFICATION

DNVGL-SE-0678:2014-07

Wind Turbine Type Certification in accordance to IEC 61400-22

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

DNV GL AS

Source: [11]

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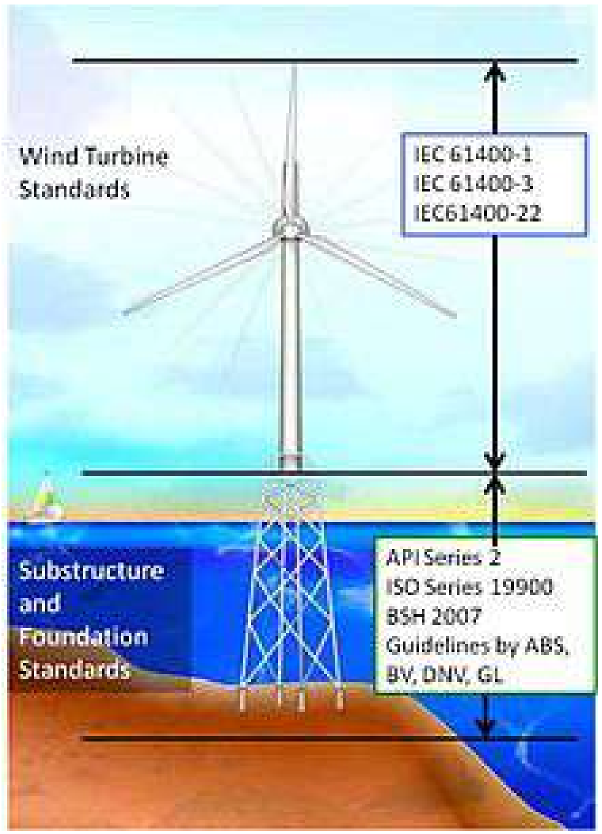
Wind Turbine Standards



Source: [12]

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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

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

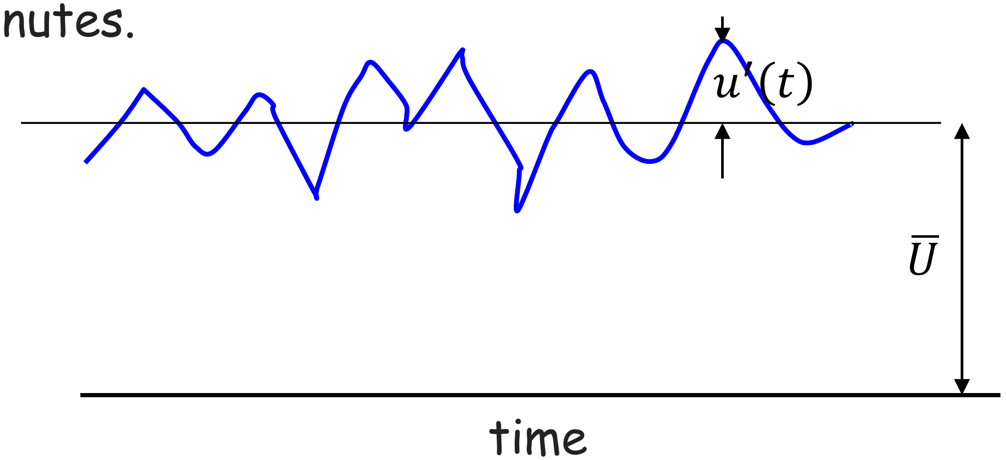
Turbulence intensity

- 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.

Wind Turbine Classification

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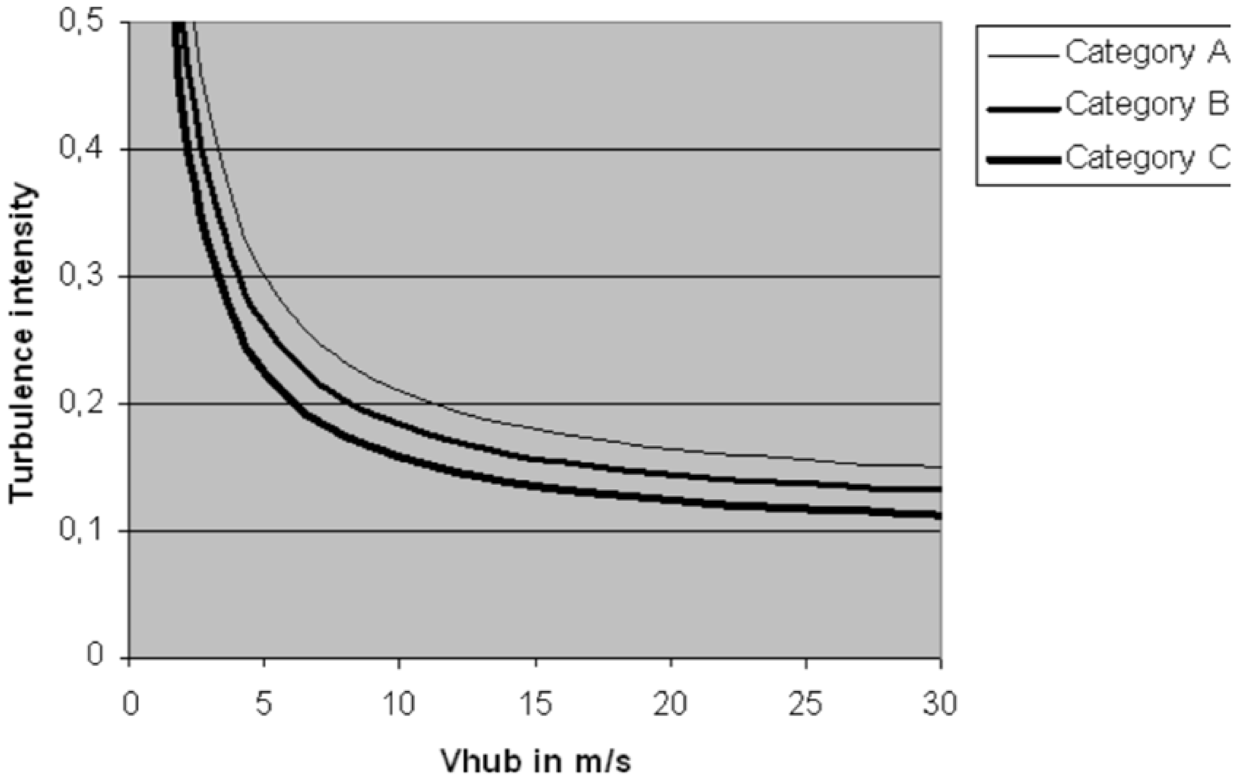
- Categories of higher, medium and lower turbulence intensity characteristics respectively



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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 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

<u>IEC 61400-4 Ed. 1.0 en:2012</u>

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 turbine
- This new edition constitutes a technical revision, introducing new principles for data reduction procedures

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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Recommended literature

Books:
1. **Wind energy engineering. New York: McGraw-Hill, Jain, P. (2011).**
2. **Fundamental of Aerodynamics, John D. Anderson, Jr., McGraw-Hill, 2001.**
3. **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**
4. **British Standards Wind turbines, Part 3: Design requirements for offshore wind turbines BS EN 61400-3:2009 Licensed**
5. **INTERNATIONAL STANDARD IEC 61400-1 Third edition 2005-08 Wind turbines – Part 1: Design requirements**

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] www.wwindea.org **World Wind Energy Association**
[3] www.awea.org **American Wind Energy Association**
[4] http://www.cesos.ntnu.no/attachments/083_Kimon_Argyriadis_certification_&_standards.pdf

www.weset-project.eu

Recommended literature

[5] https://en.wikipedia.org/wiki/IEC_61400
[6] www.glgroup.com, “Certification and Standards for Wind Turbines September 2013, Kimon Argyriadis
[7] http://www.unison.co.kr/2009/Eng2/Company/Cert/cert.asp
[8] http://www.tyhi.com/R_D_and_QA/QA/Wind_Power_Equipment_Certificate.htm
[9] https://www.pinterest.com/pin/830491987505941413/?lp=true
[10] https://www.greentechmedia.com/articles/read/norway-advances-in-floating-offshore-wind-race#gs.qo5lcl
[11] DNVGL.com
[12] https://ipfs.io/ipfs/QmXoypizjW3WknFiJnKLwHCnL72vedxjQkDDP1mXWo6uco/I/m/US_certification_standards_for_offshore_wind_turbines.jpg
[13] https://www.dnv.com/services/wind-turbine-type-certification-70124
[14] https://innerreign.com/2018/03/28/what-you-accept-becomes-your-standard/
[15] http://www.winden.se/en/products/certification.html
[16] https://www.indiamart.com/proddetail/domestic-solar-wind-hybrid-system-16026761848.html
[17] https://blog.greenangelsyndicate.com/blog/investing-in-small-scale-wind-energy

Introduction to Wind Energy

Module 2.1

Further information:

www.weset-project.eu

info@weset-project.eu

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

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Introduction to Wind Energy

Module 2.1

Wind Energy Conversion Systems
Lesson 8

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Objective

The purpose of this lesson is to present the mathematical relation between the wind speed and turbine speed and power. In addition two illustrate the wind speed power curve as an introduction to the importance of Maximum Power Point Tracking in grid-connected systems.

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Learning Outcomes

This lesson will contribute to the students to:

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

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Technical Contents

1. *Wind turbine mathematical model.*
2. *Wind power curves*

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Wind Turbine Mathematical Model

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Under constant acceleration, a, the Kinetic Energy, E, of an object having a mass, m, and velocity ,v, is the work done W to displacing that object a distance, s, under a force ,F, according to Newton second law

$$F = ma \qquad (1)$$

The kinetic energy

$$E = mas \qquad (2)$$

The velocity of moving object, v, with initial velocity u is given by

$$v^2 = u^2 + 2as$$

If $u=0$ then the kinetic energy will be

$$E = \frac{1}{2}mv^2 \qquad (3)$$

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Wind Turbine Mathematical Model

- The Wind is considered as a fluid, hence its velocity and densities can change and its mass is not constant
- Here, the density of air is assumed to constant.
- The power is defined as the rate of change of Kinetic energy then the power is calculated based on Kinetic energy in equation (3) as

$$P = \frac{dE}{dt} = \frac{1}{2}\frac{dm}{dt}v_w^2 \tag{4}$$

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Wind Turbine Mathematical Model

The mass flow rate $\frac{dm}{dt}$ is given by

$$\frac{dm}{dt} = \rho A v_w$$

where A is the area of air flow and is the density of air

$$P = \frac{1}{2}\rho A v_w^3 \qquad (5)$$

The actual mechanical power P_w extracted by the wind blade is the difference between upstream and down stream wind power.

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

REPORT

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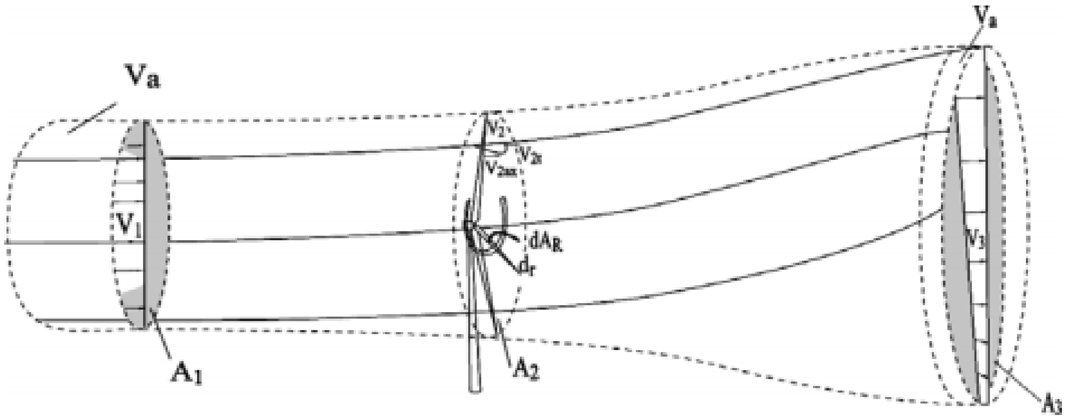
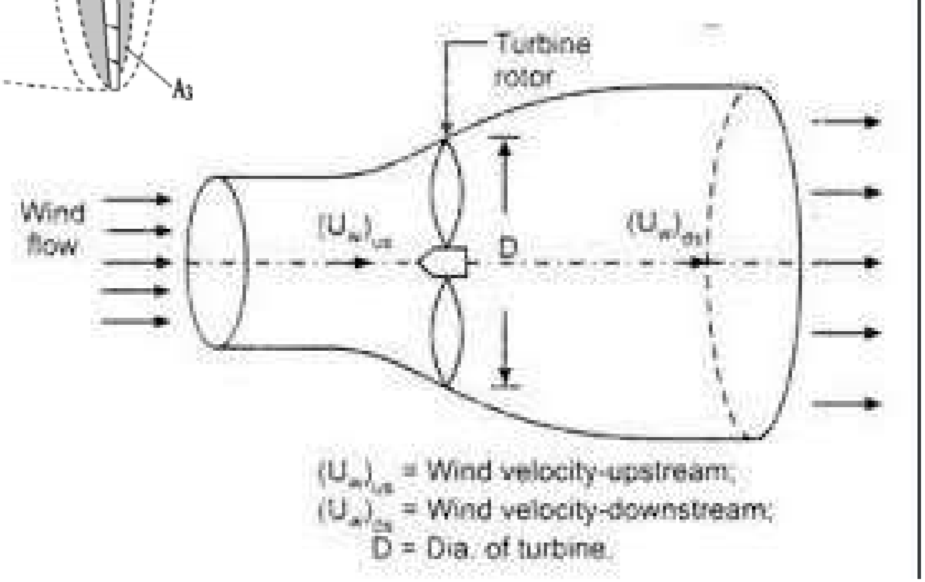
Wind Turbine Mathematical Model





[1-3]

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Wind Turbine Mathematical Model

- where v_u is the upstream wind velocity at entrance of rotor blade in *m/s* and v_d is the downstream wind velocity at the exist of the blade in *m/s*
- The mass flow rate

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

- and v_w is the average speed between the upstream and downstream
- The power in equation (6) becomes $P_w = \frac{1}{2}\rho A(v_u^2 - v_d^2)\frac{(v_u+v_d)}{2}$
- That can be simplified as

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

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

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

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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

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

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

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

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Wind Turbine Mathematical Model

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

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.

$$\lambda = \frac{v_d}{v_u} \tag{10}$$

or

$$\lambda = \frac{\text{blade tip speed}}{\text{wind speed}} \tag{11}$$

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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

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

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Wind Turbine Mathematical Model

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

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.

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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,

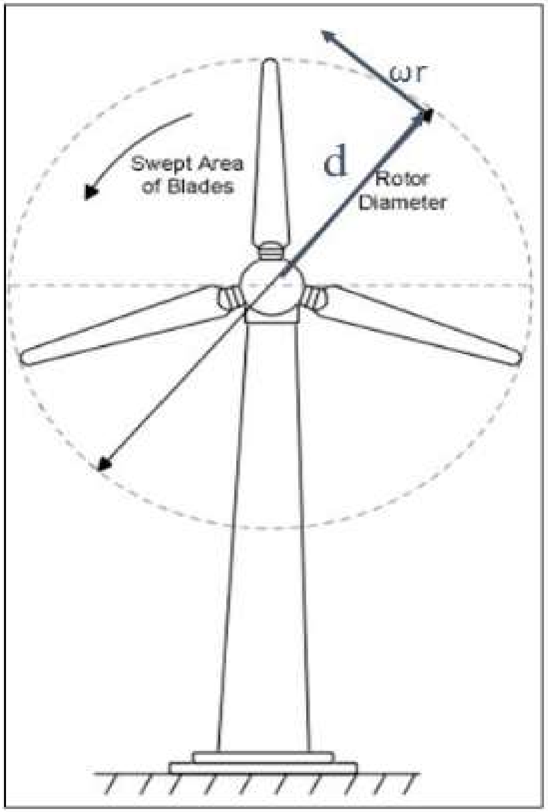
ω = rotational speed in radians /sec

π radians = 180°

2π radians = 360°

r = rotor radius

v = speed of relative wind



[3]

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Wind Turbine Mathematical Model

- If the rotor of a wind turbine turns too slow, the extracted power will be very small
- If the rotor turns too fast, rotating blade act as a solid wall abstracting the wind flow and reducing the extracted power
- The turbine must operate at optimal tip speed ration in order to extract maximum power
- High λ causes erosion of leading edge of the blade and noise generation and vibration

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Wind Turbine Mathematical Model

- Equation (8) shows the parameters affecting the extracted power of wind turbine

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

- The power coefficient C_p is a very important parameter
- It is a function of tip speed ration and the blade pitch angle θ

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

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

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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

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

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

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

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.

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Wind power curves

- Control of the output power of wind energy depends on a number of parameters
- The rotor area and flow condition at rotor system, the rotor torque and pitch angle
- Fixed speed stall-regulated turbine have no option for control input
- Variable speed wind turbine use generator torque to control and optimize power output.
- The pitch control is used to control the output power.

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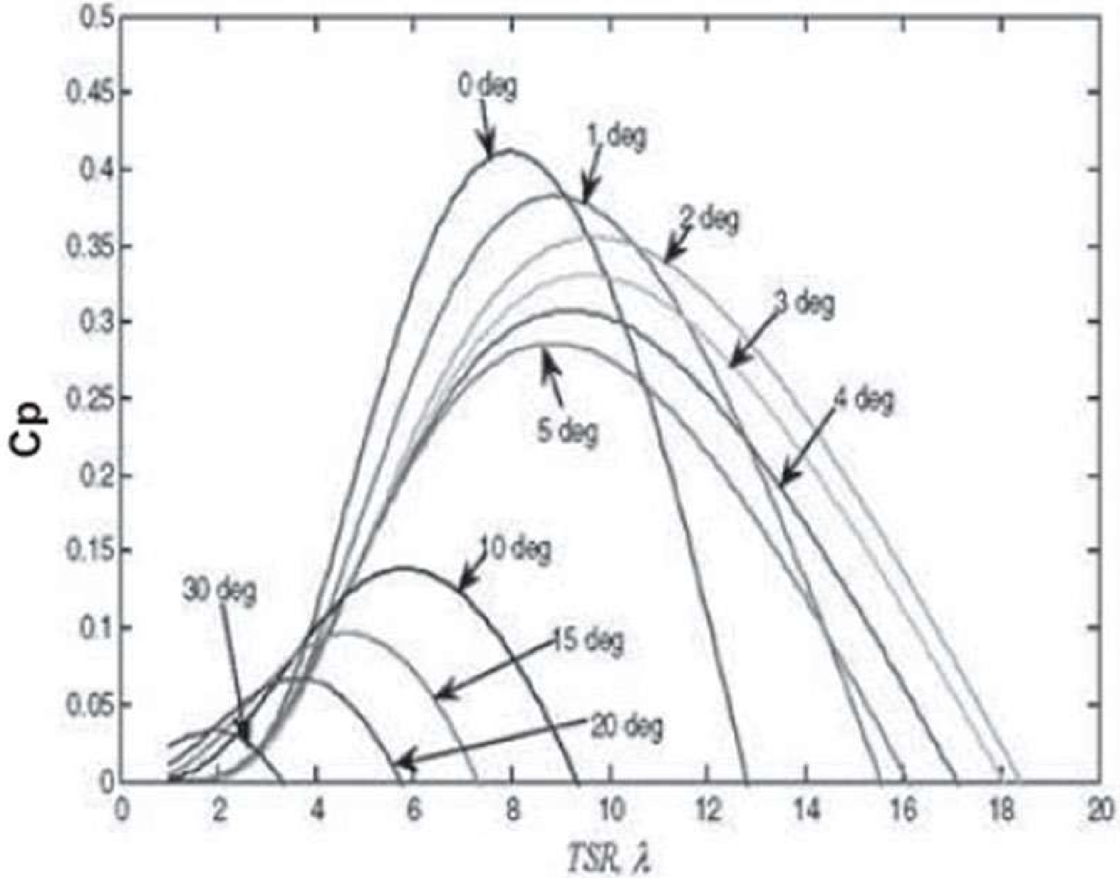
Wind power curves



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

[1-2]

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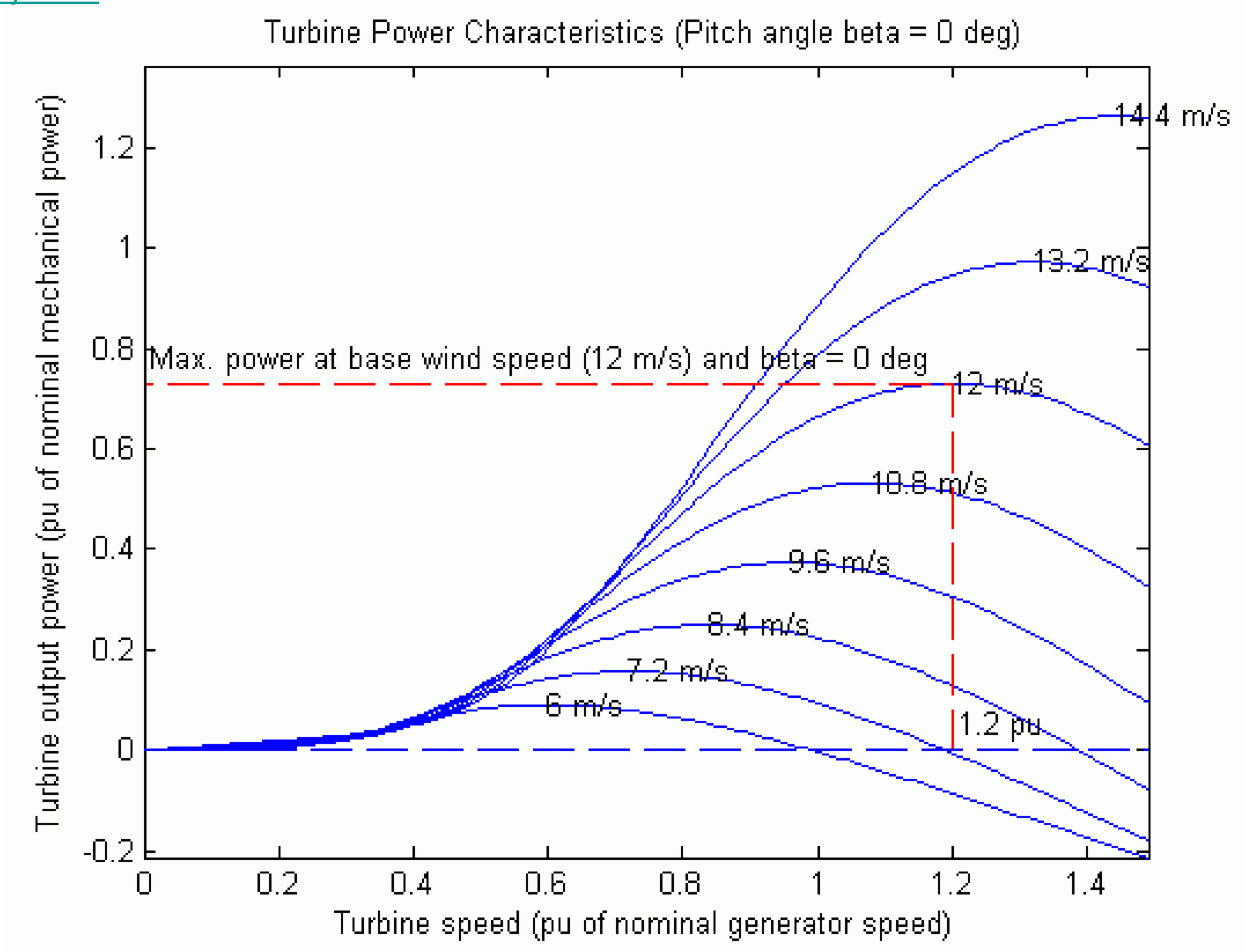
Wind power curves



[1-3]

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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] www.wwindea.org **World Wind Energy Association**
[3] www.awea.org **American Wind Energy Association**

Introduction to Wind Energy

Module 2.1

Further information:

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info@weset-project.eu

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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:

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

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

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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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The importance of Maximum Power Point Tracking (MPPT)

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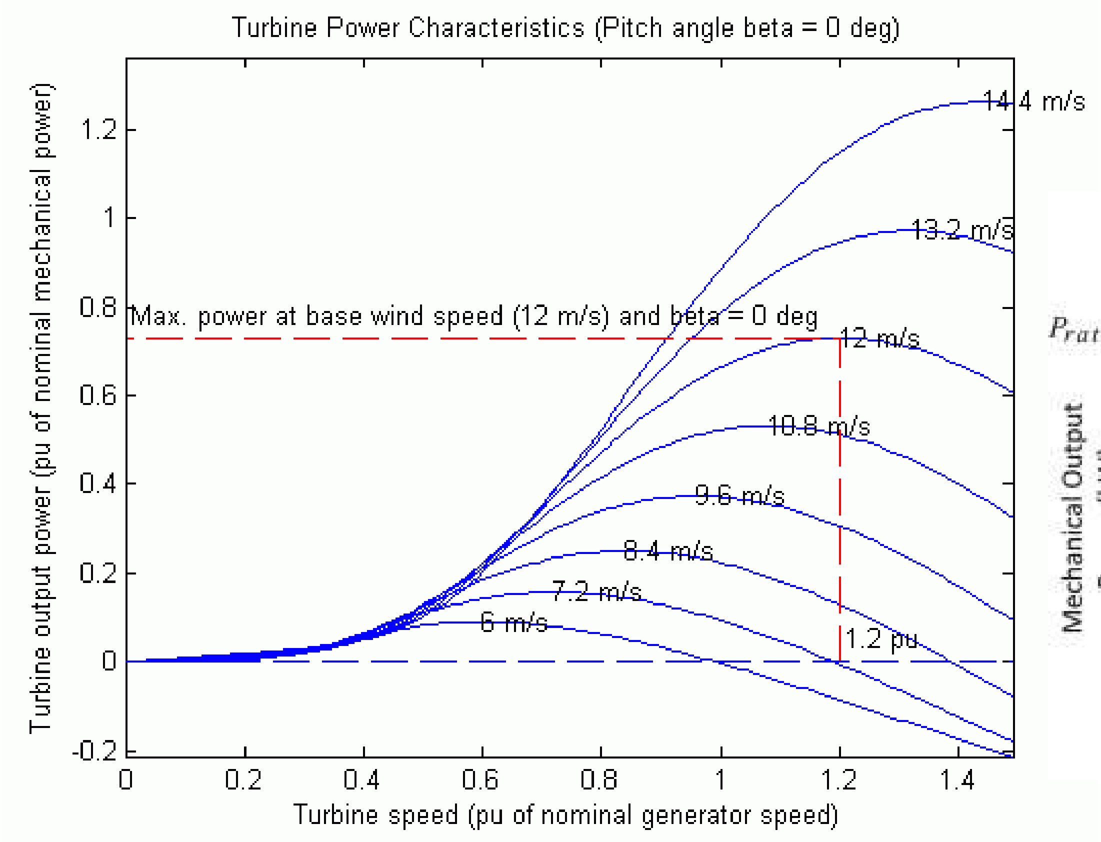
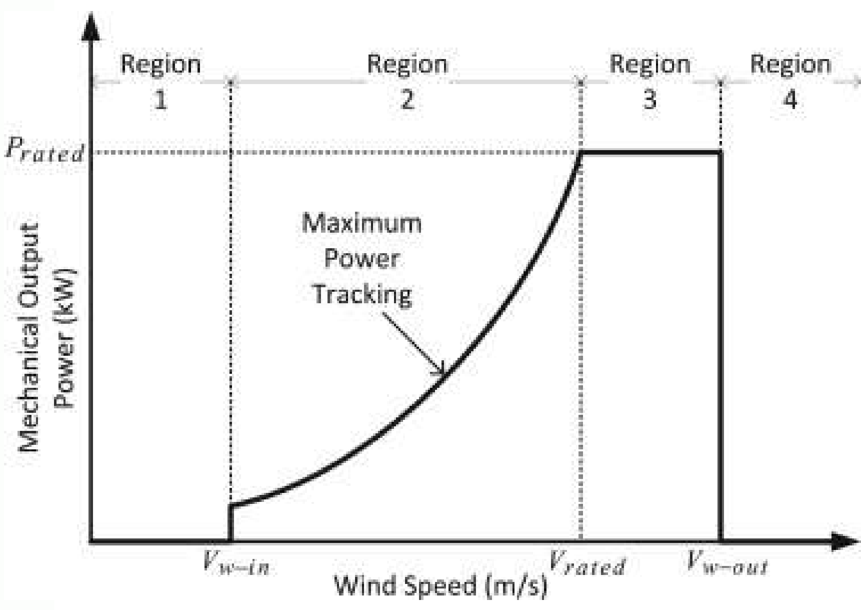
Why MPPT is mandatory





[1-3]

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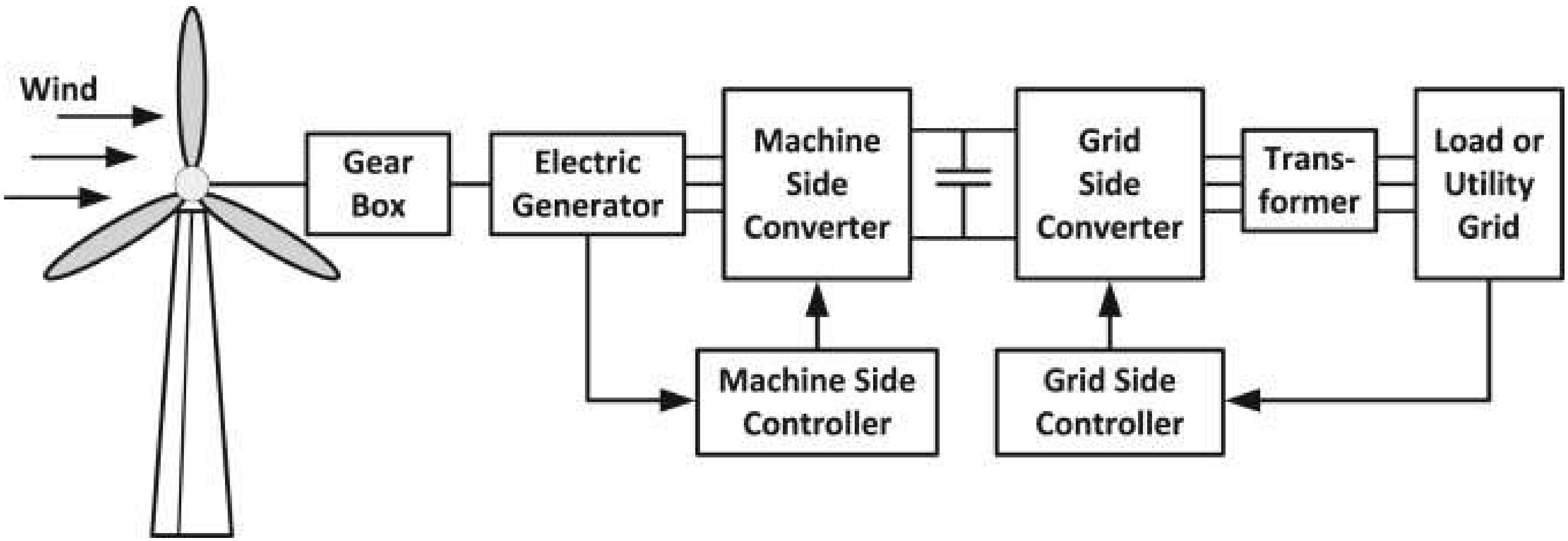
The importance of Maximum Power Point Tracking (MPPT)



[1-3, 6, 7]

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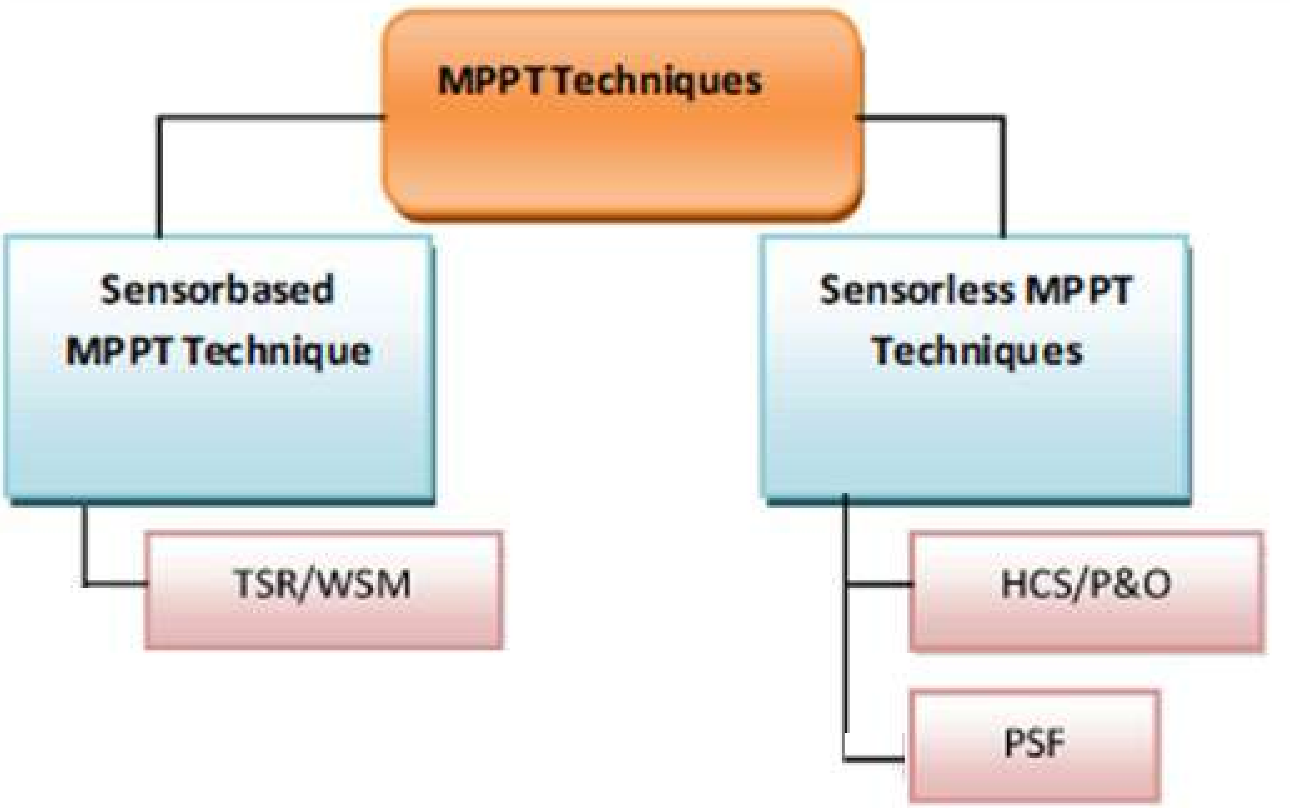
Wind Energy MPPT techniques



[6,7]

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MPPT of wind energy:
Tip Speed Ratio (TSR) technique

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

Why is This Important???

- By knowing TSR will maximize the wind power and efficiency
- If the rotor spins too slow, less power will be extracted because a large amount of power pass through the gap between blades
- Other wise if the rotor spins too fast it will cause turbulence
- So it is important to calculate the perfect TSR.

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MPPT of wind energy:
Tip Speed Ratio (TSR) technique

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

where

V	is the wind speed [m/s]
$v = \omega r$	is the velocity of rotor tip [m/s]
r	is the rotor radius [m]
$\omega = 2\pi f$	is the angular velocity [radian/s]
f	is the frequency of the rotor [Hz]

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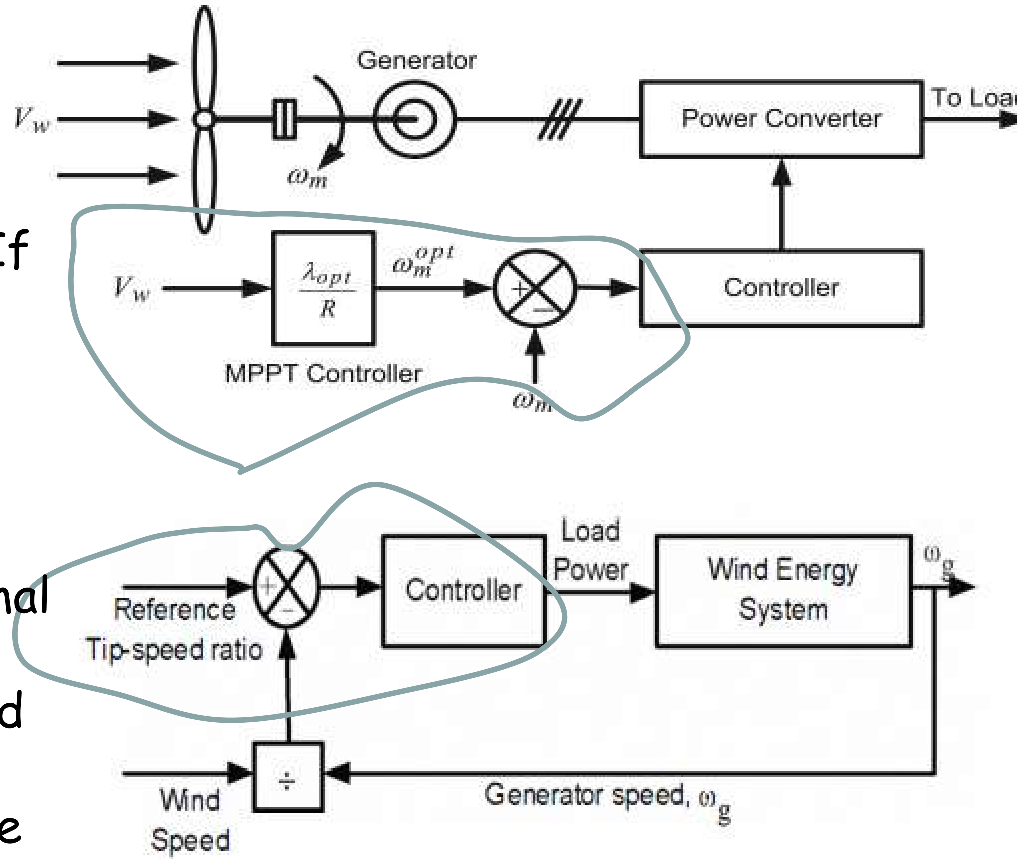
MPPT of wind energy:
Tip Speed Ratio (TSR) technique

- The optimal TSR is constant regardless of wind speed
- The extracted power is maximum If TSR is maintained at optimal value
- In this technique the difference between the optimal TSR and the actual will be manipulated by the controller to force the energy conversion system to work at optimal TSR
- The optimal TSR can be determined experimentally or theoretically
- This method is simple but it require to measure the wind speed



[2-3]

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MPPT of wind energy: Tip Speed Ratio (TSR) technique

EXAMPLE

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:

Source:[2]

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MPPT of wind energy:
Tip Speed Ratio (TSR) technique

$$
\begin{aligned}
v &= \omega r \\
&= (1.46 - 2.18)\frac{66}{2} \\
&= 48.18 - 71.94[\frac{\mathrm{m}}{\mathrm{sec}}]
\end{aligned}
$$

The range of its tip speed ratio is thus:

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

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MPPT of wind energy:
Tip Speed Ratio (TSR) 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:

$$\lambda\ (\text{max power}) = \frac{4\pi}{n}$$ *(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

Source: [2]

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MPPT of wind energy:
Tip Speed Ratio (TSR) technique

Optimal Rotor Tip Speed Ratio

The optimal TSR for maximum power extraction is inferred by the establishing time after disturbance *tw*.

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

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

If the length of strong distrusted air stream upward and downward is *s* then the time period to return to normal is given by

$$t_w = \frac{s}{V}[\text{sec}]$$

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MPPT of wind energy:
Tip Speed Ratio (TSR) technique

The maximum power extraction occurs when

$$t_s \approx t_w$$

$$\frac{2\pi}{n\omega} \approx \frac{s}{V} \Rightarrow \frac{n\omega}{V} \approx \frac{2\pi}{s}$$

Then the optimal speed

$$\omega_{opt} \approx \frac{2\pi V}{ns}$$

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MPPT of wind energy:
Tip Speed Ratio (TSR) technique

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Hence the optimal TSR is

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

For n bladed machine it has been observed that

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

then

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

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MPPT of wind energy:
Tip Speed Ratio (TSR) technique

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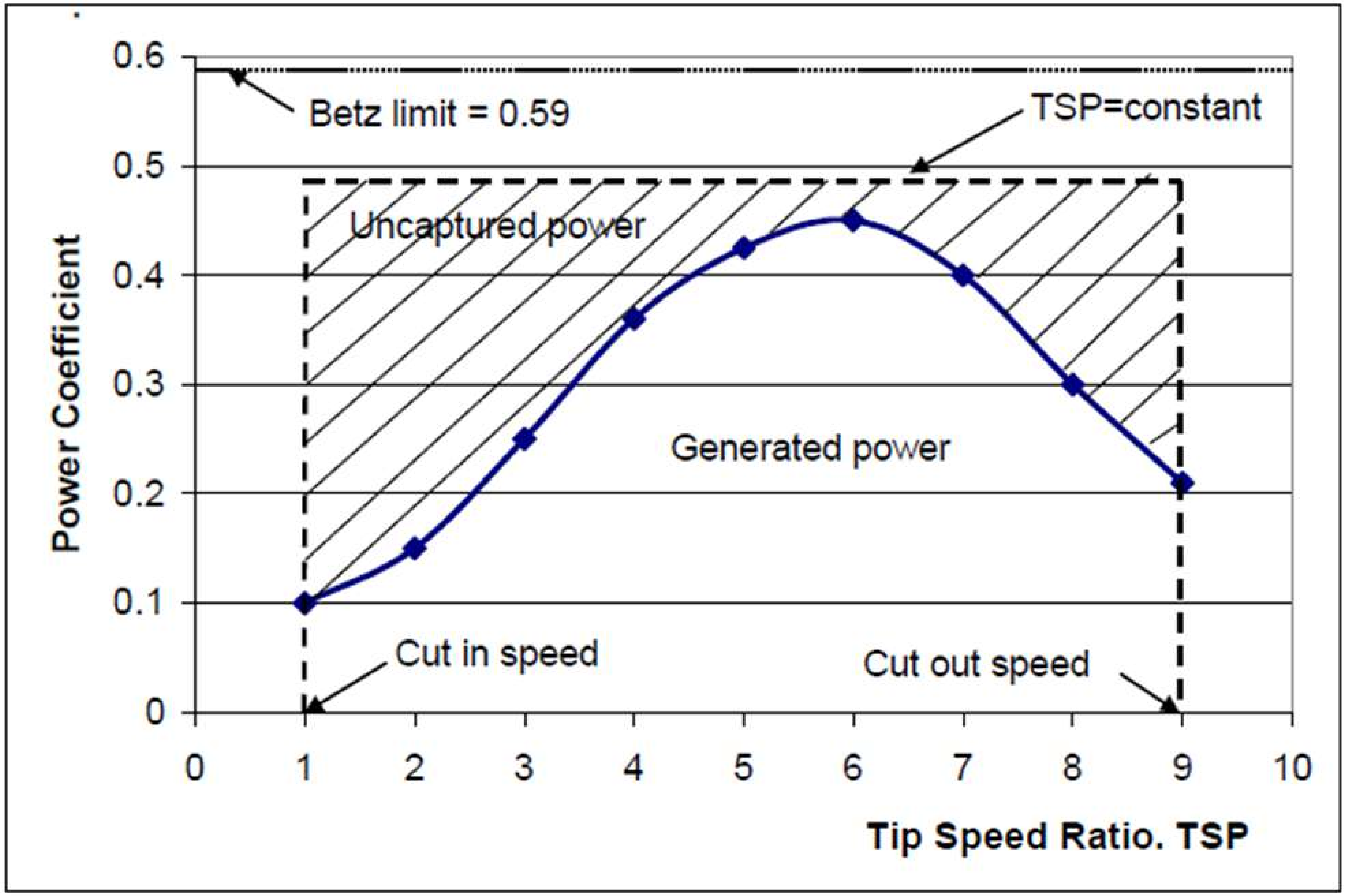

Source: [2]

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MPPT of wind energy:
Tip Speed Ratio (TSR) technique

It is clear from the power coefficient that,

- Maximum Power Extraction occurs at the optimal tip speed ratio,
- The uncaptured power is caused due to
  - the tip speed ration is not constant as well as
  - the inherent inefficient and losses in different turbine design
- The maximum available power factor is 59.26 %, Betz Limit
- In Practice, values of obtainable power coefficient are in the range of 45%
- Therefor, it is necessary to operate at the maximum power coefficient at different wind speed as illustrated in the following Figure

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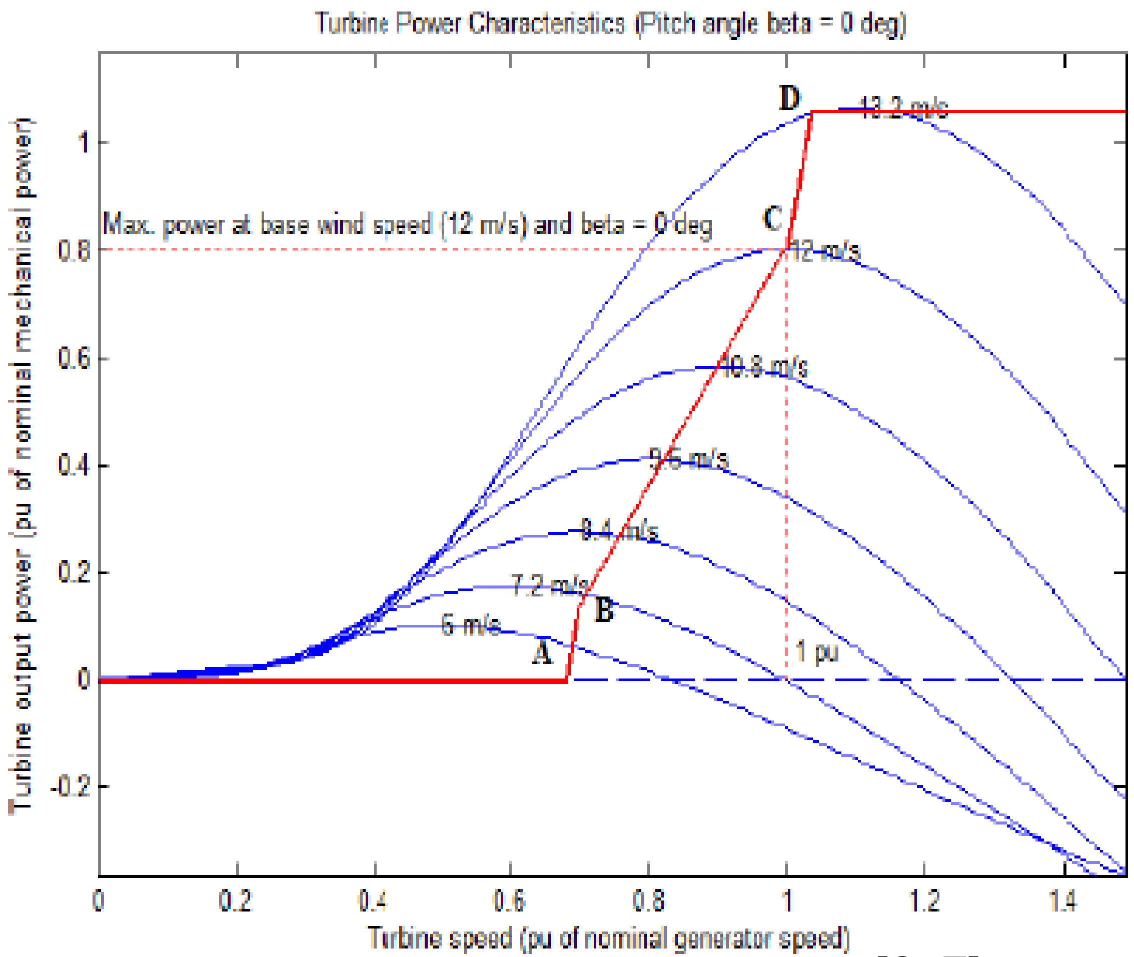
MPPT of wind energy:
Power Signal Feedback (PSF) Technique



[6, 7]

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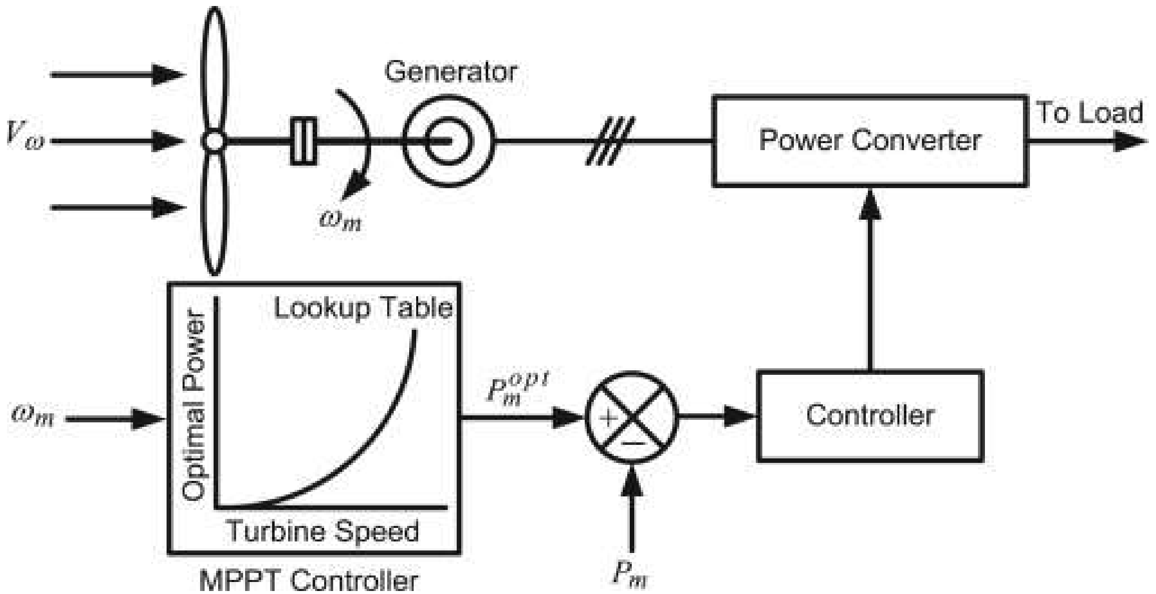
MPPT of wind energy:
Power Signal Feedback (PSF) Technique

- The maximum power operation at different speed can be obtained by implementing PSF technique as shown bellow



[6, 7]

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MPPT of wind energy:
Hill Climbing (P&O) Technique

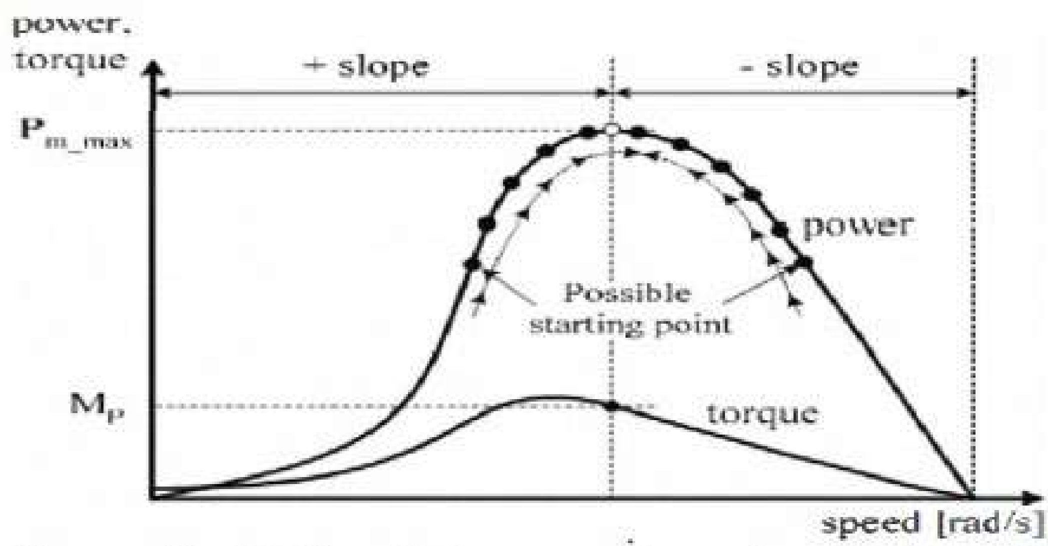
- The perturbation an observation (P&O) or Hill-Climb searching (HCS) technique is an optimization method based on numerical searching technique for local maxima.
- It is widely used in renewable energy by perturbing a control parameter and observe the resulting change until the slop of change becomes zero as illustrated in the Figure
- 

Figure Wind turbine output power and torque characteristics with MPP tracking process [1-6]

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MPPT of wind energy:
Hill Climbing (P&O) Technique

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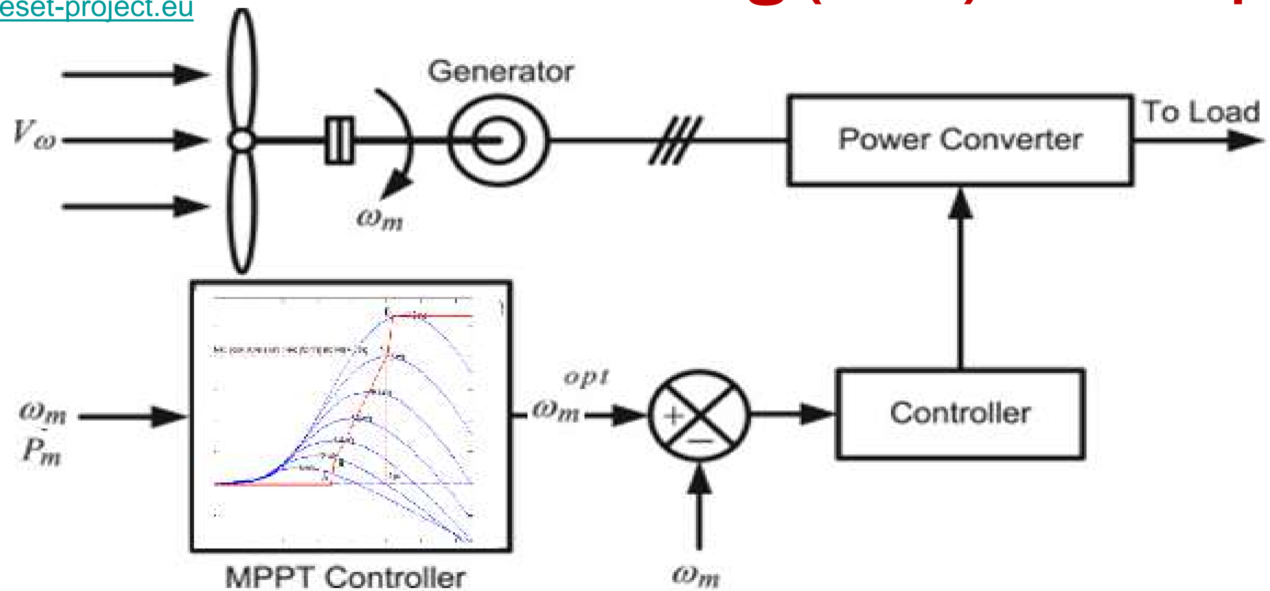

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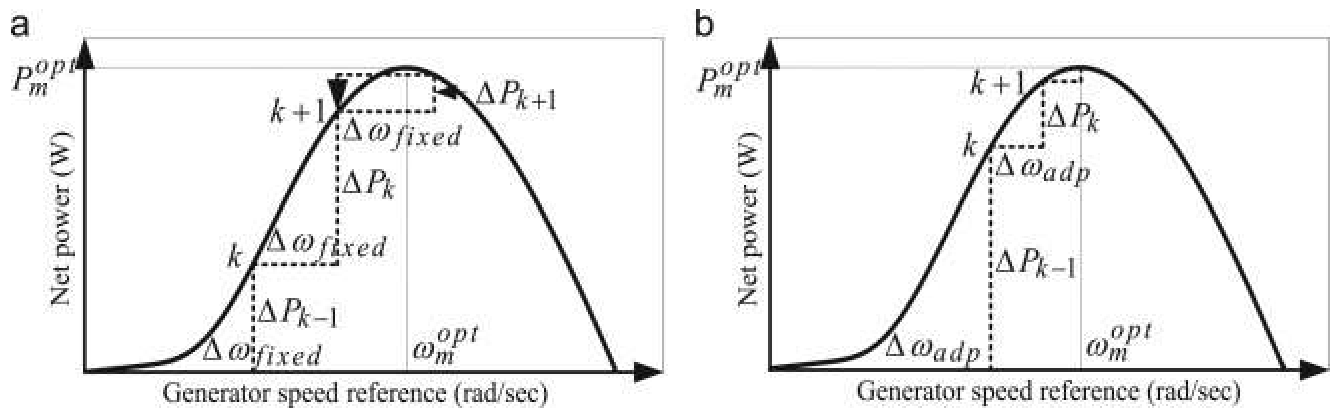

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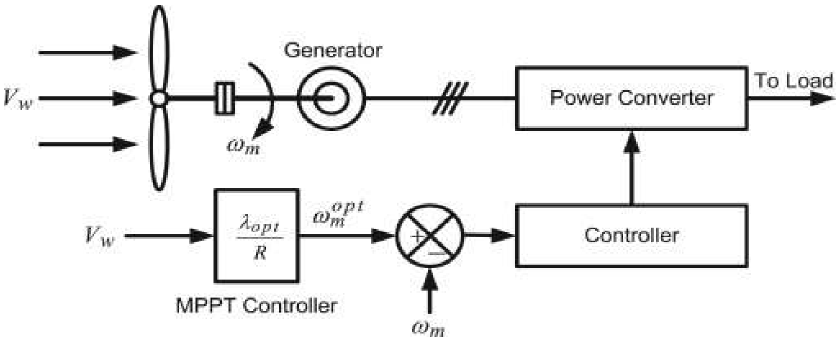
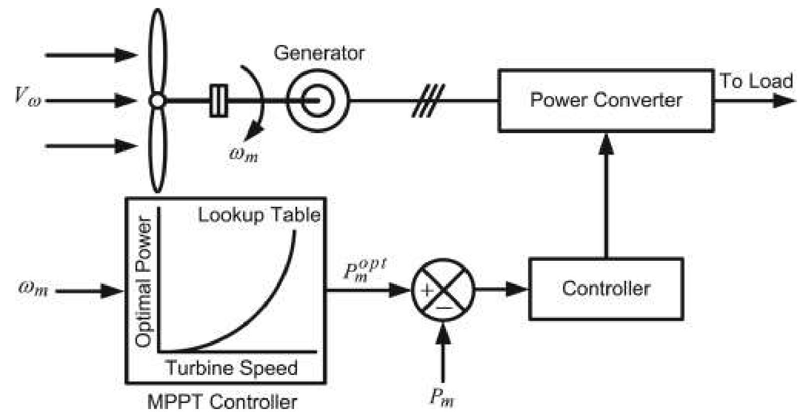
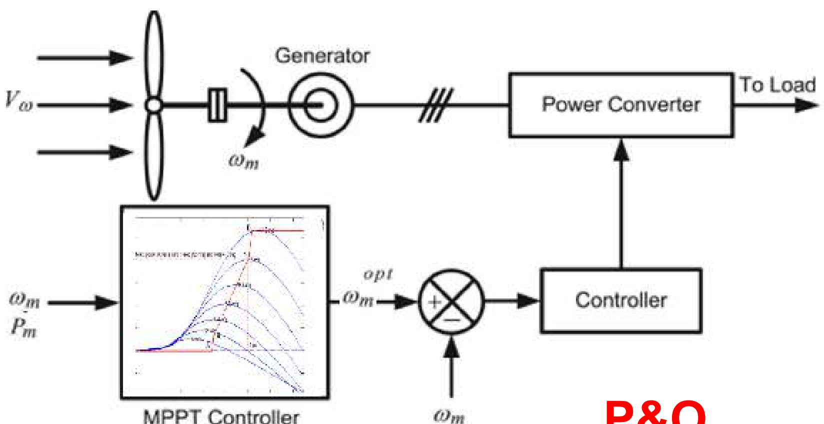
MPPT Technique summary



TSR MPPT



PSF MPPT



P&O MPPT

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Recommended literature

Books:

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4. **Alternative Energy Systems, B. K. Hodge, John Wiley & Sons, 2009.**
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6. **Power conversion and control of wind energy systems, B. Wu *et al.* , John Wiley & Sons, 2011**

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] www.wwindea.org **World Wind Energy Association**
[3] www.awea.org **American Wind Energy Association**

Module 2.1

Further information:

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Introduction to Wind Energy

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:

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. *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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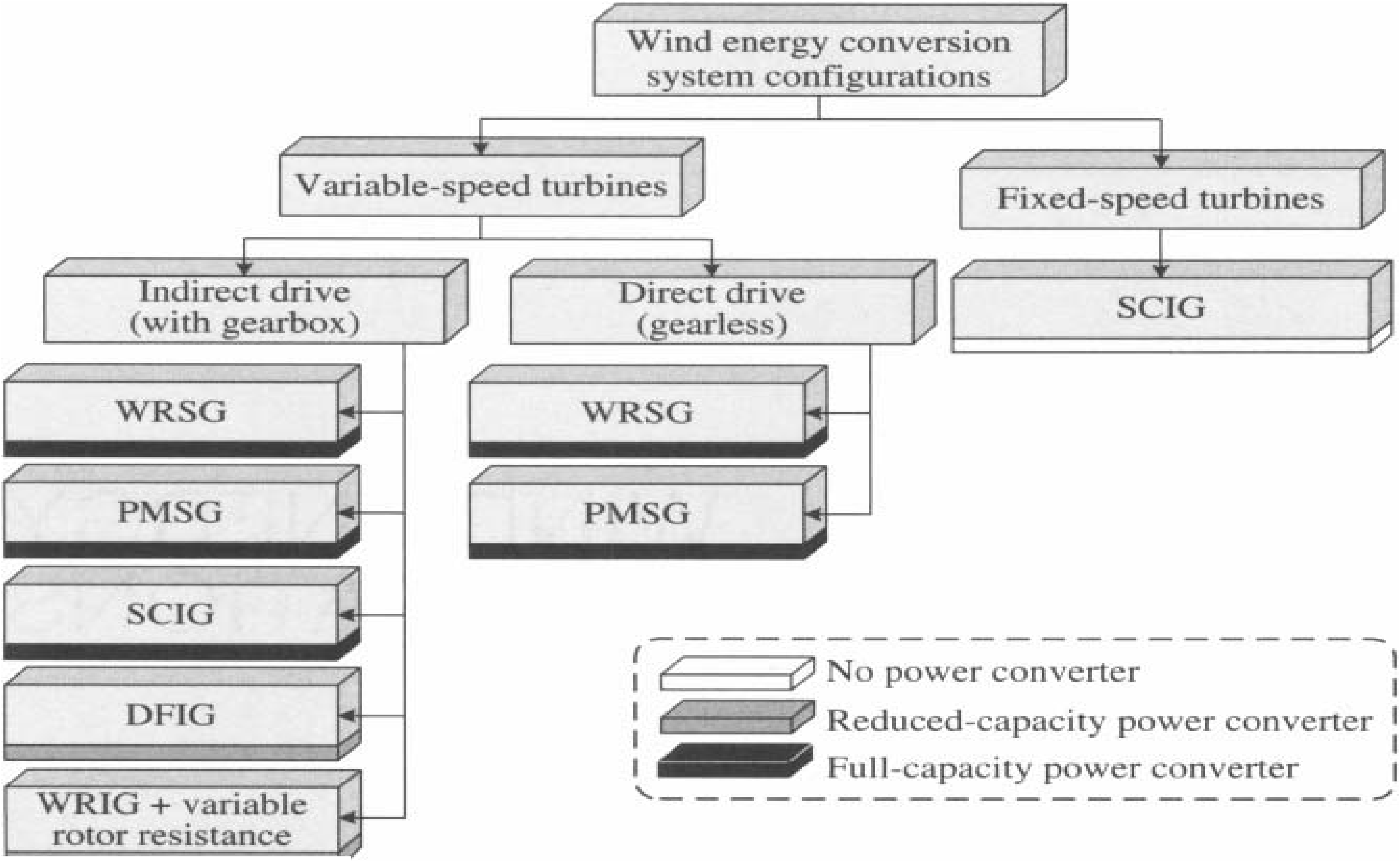
Introduction



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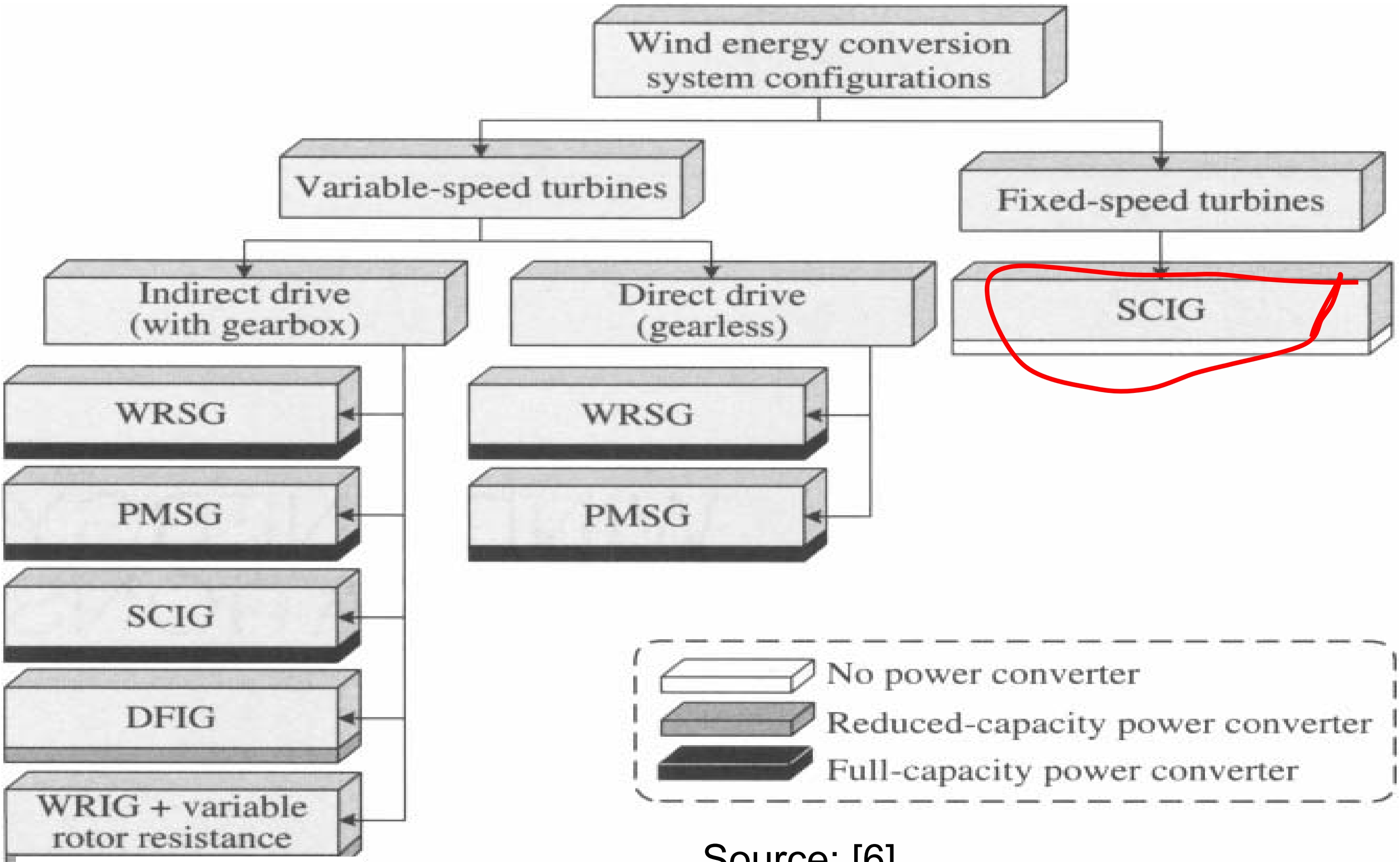
Introduction



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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
- Two-speed WECS, in which the generator can operate at two fixed speeds.

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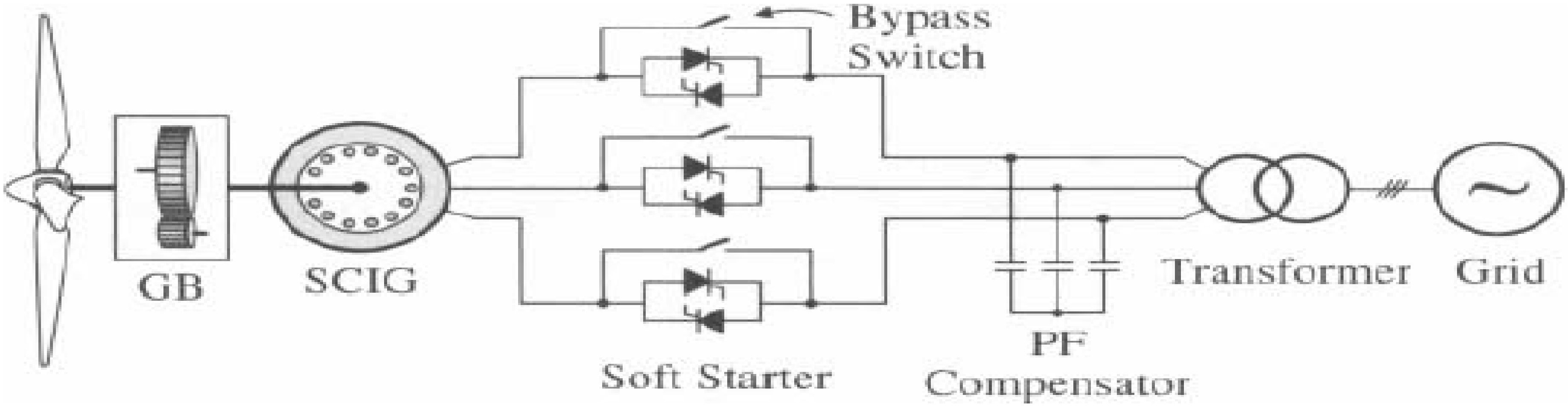
(1) Single-Speed WECS



[3, 11]

- 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

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(1) 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.

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(1) 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

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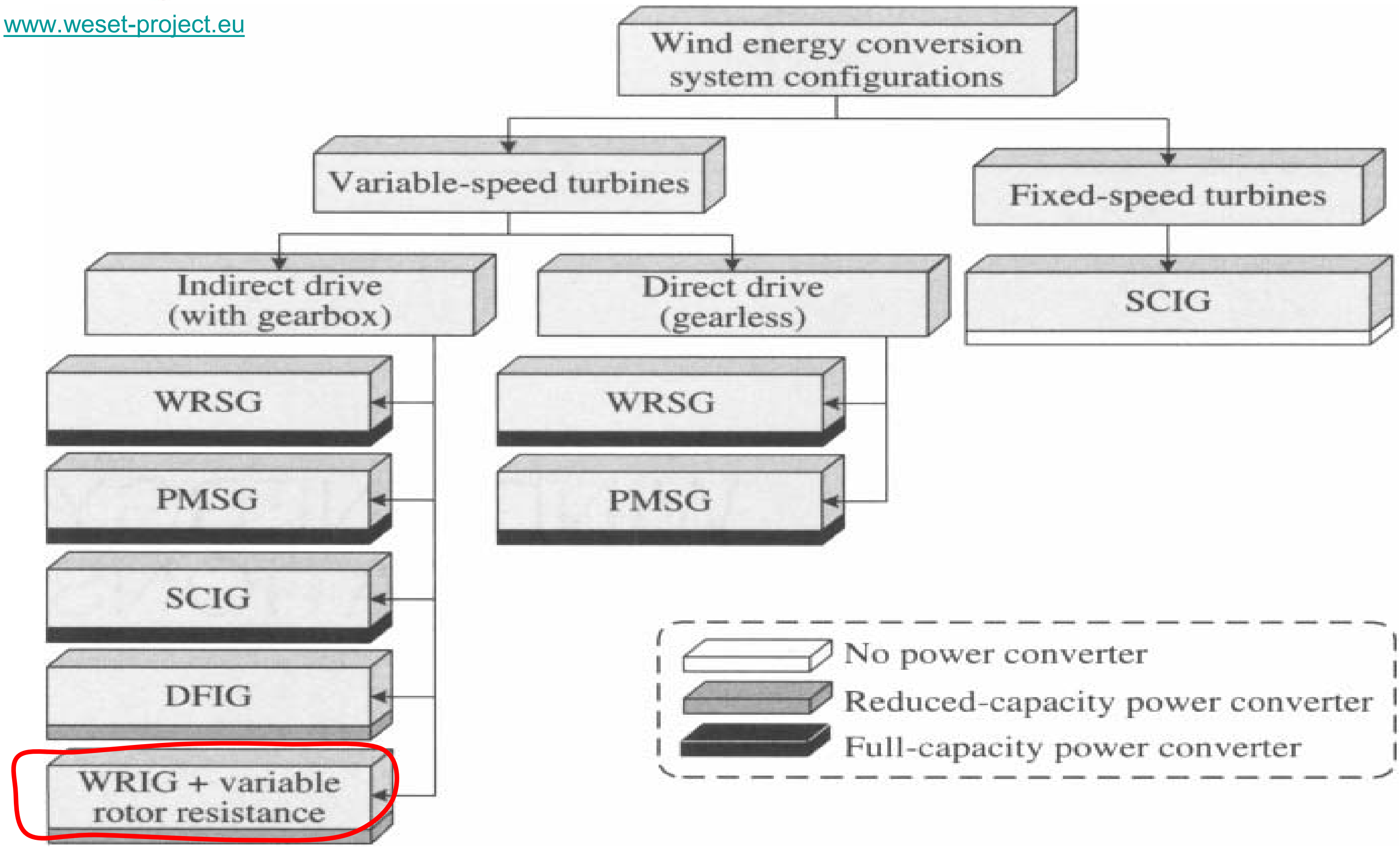
WECS



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

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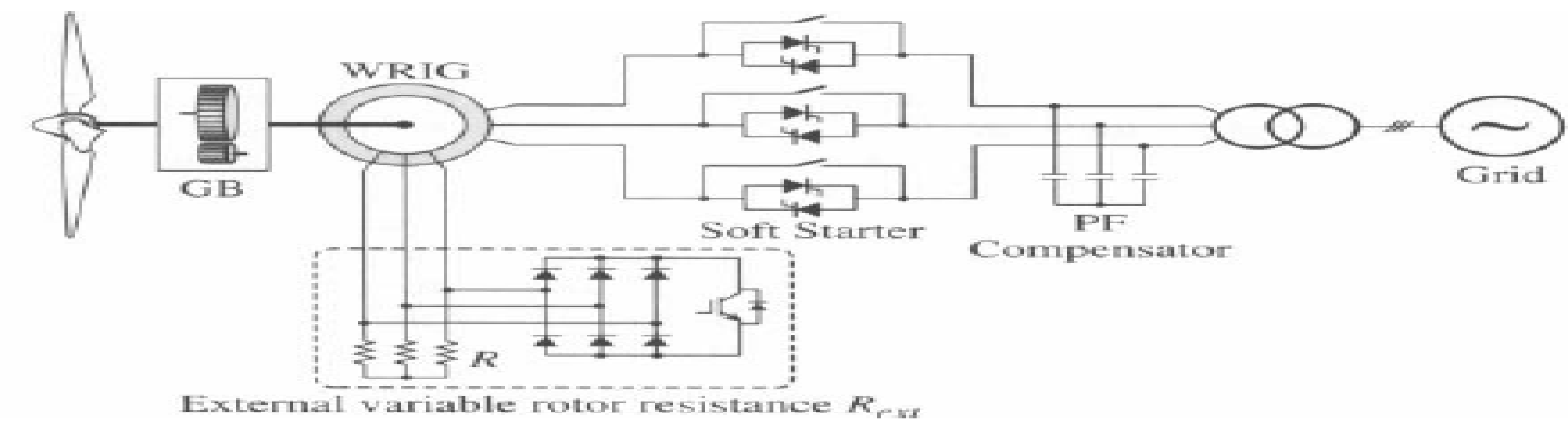
- The system configuration is the same as that of the fixed-speed wind energy system except that the SCIG is replaced with the WRIG.
- The external rotor resistance, is made adjustable by a converter composed of a diode bridge and an IGBT chopper
- The equivalent value of R_{ex}, seen by the rotor varies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



[1, 3, 11]

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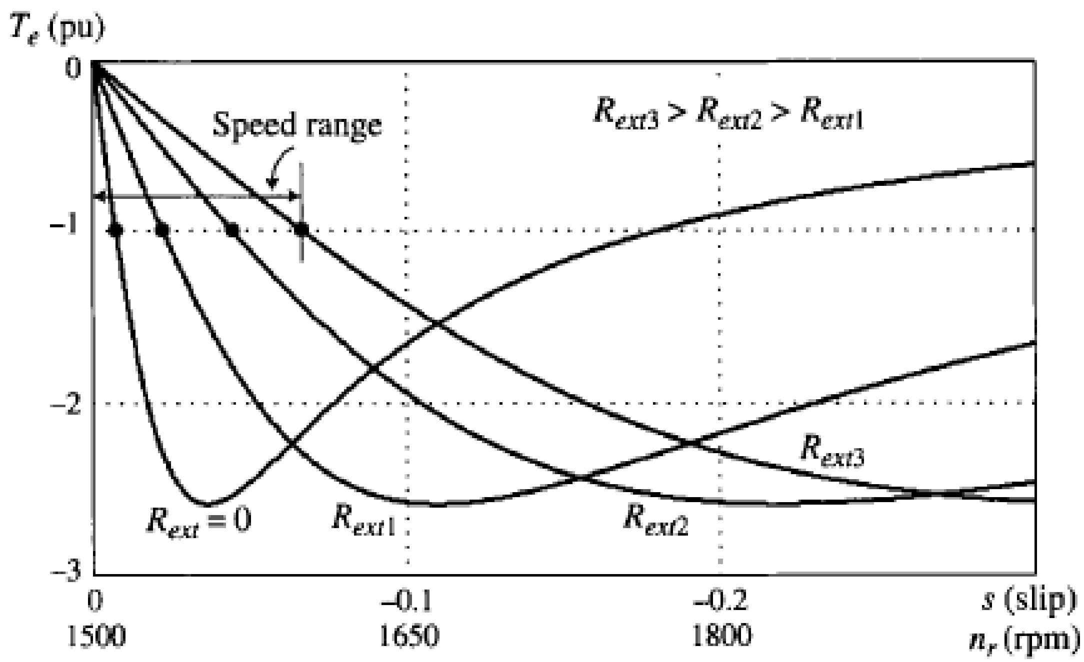
(3) Wound-Rotor Induction Generator (WRIG) with External Rotor Resistances

- 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.



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(3) 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

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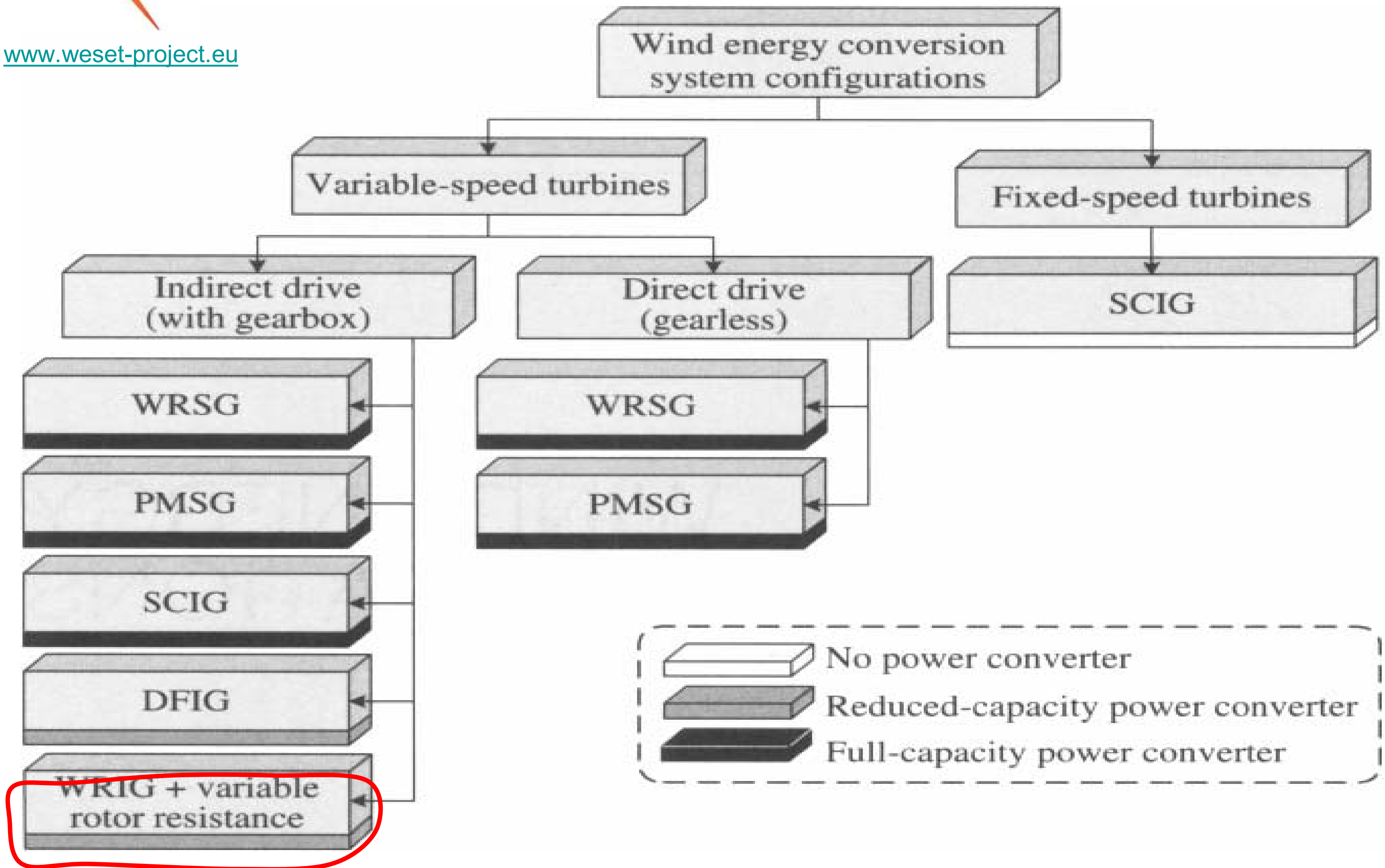
WECS



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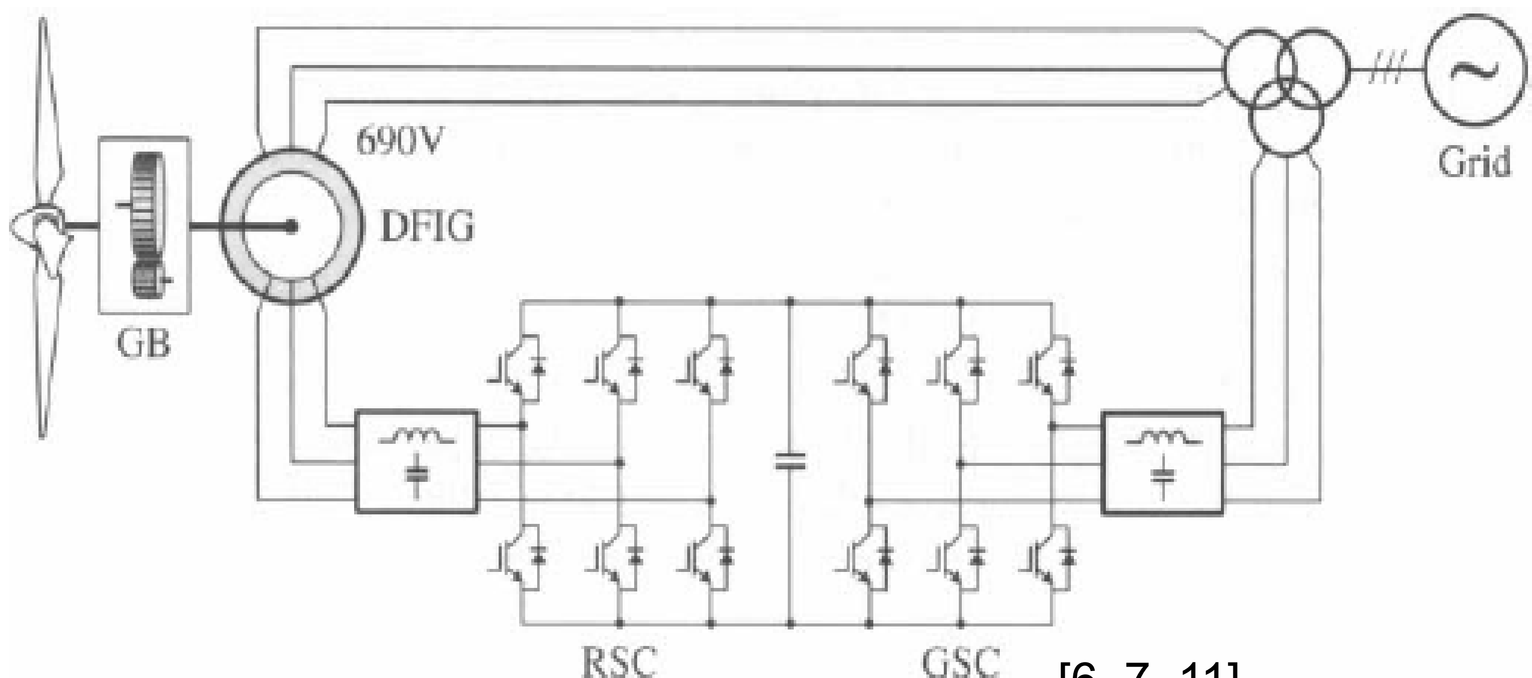
(4) Doubly Fed Induction Generator WECS with Reduced- Capacity Power Converter

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



[6, 7, 11]

(4) 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

(4) 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.

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(4) 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

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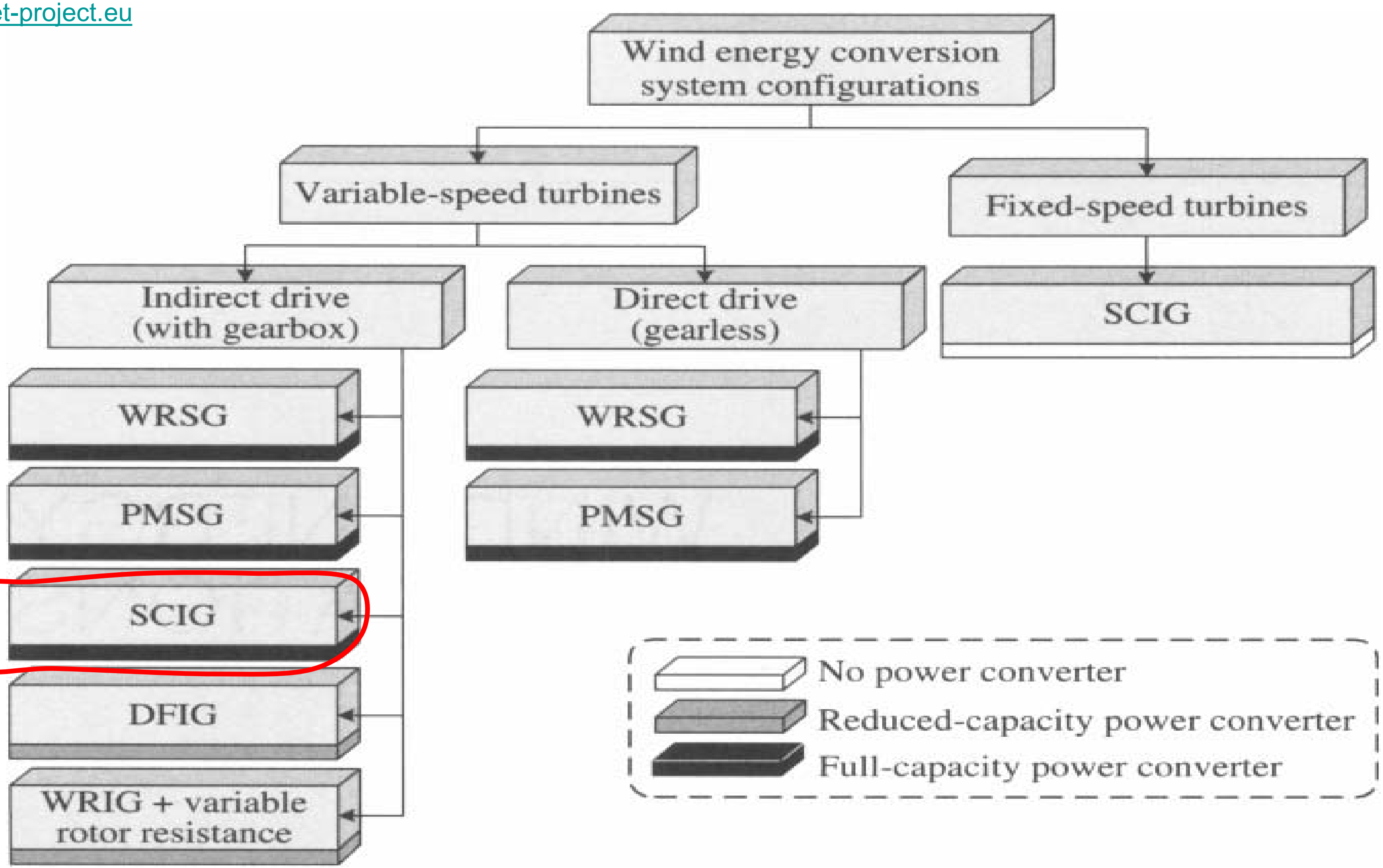
WECS



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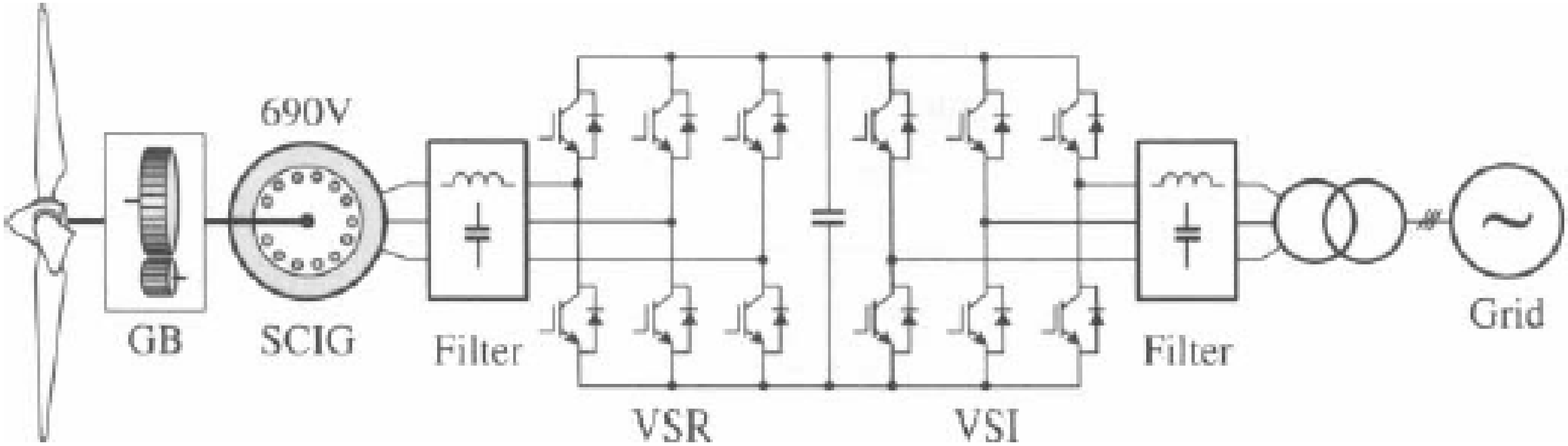
(4) SCIG Wind Energy Systems with Full-Capacity Power Converters

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



[3, 7, 11]

(4) 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.

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

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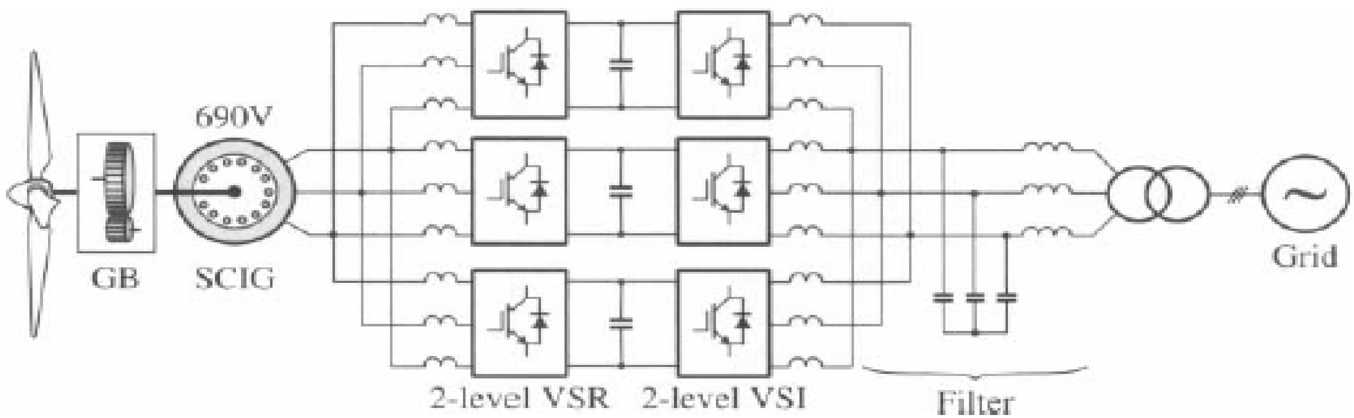
- An alternative approach to the paralleled converter channels is illustrated in the figure, where three converter channels are in parallel for a megawatt IG wind turbine
- Each converter channel is mainly composed of two-level voltage source converters in a back-to-back configuration with harmonic filters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



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

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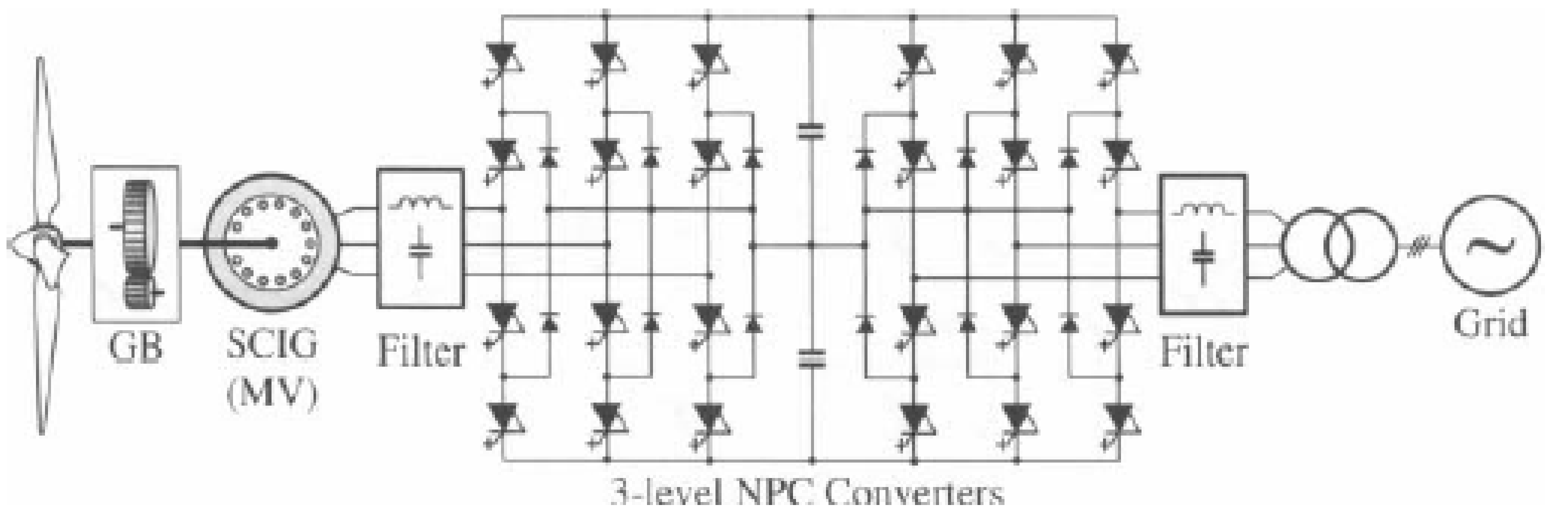
With Three-Level NPC Converters

- 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.



[1, 11]

WECS

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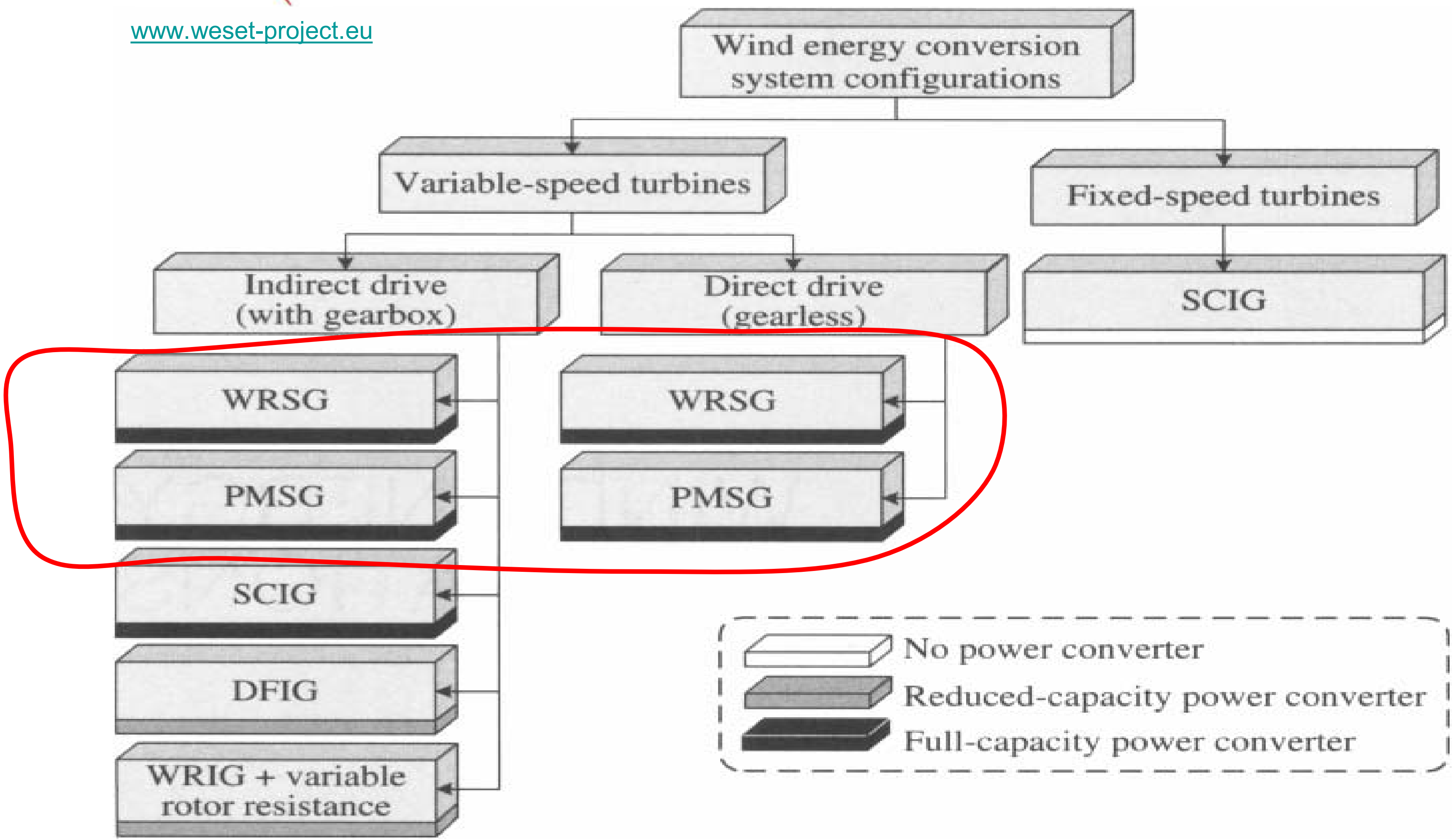

Source: [6]

(5) 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,
  2. thus, diode rectifiers can be used as generator-side converters, which is impossible in the induction generator WECS, and
  3. 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.

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

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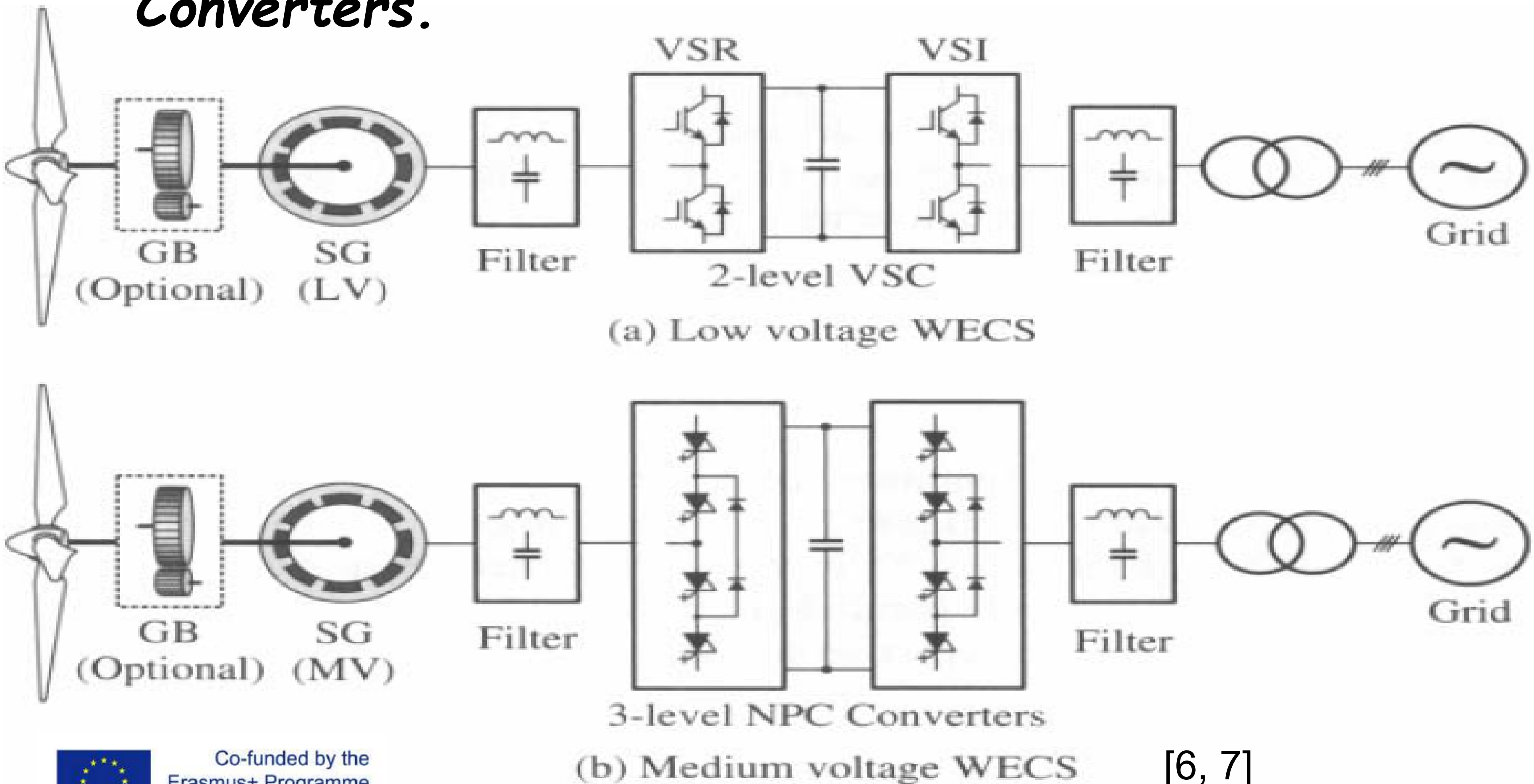
- ***With Two-Level VSC and Three-Level NPC Converters.***



[6, 7]

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(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

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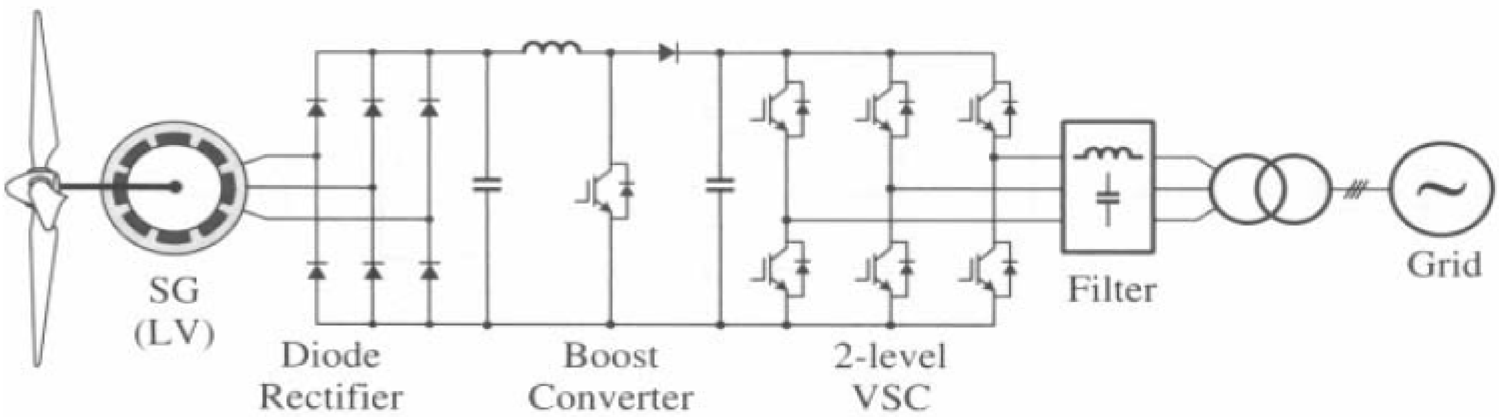
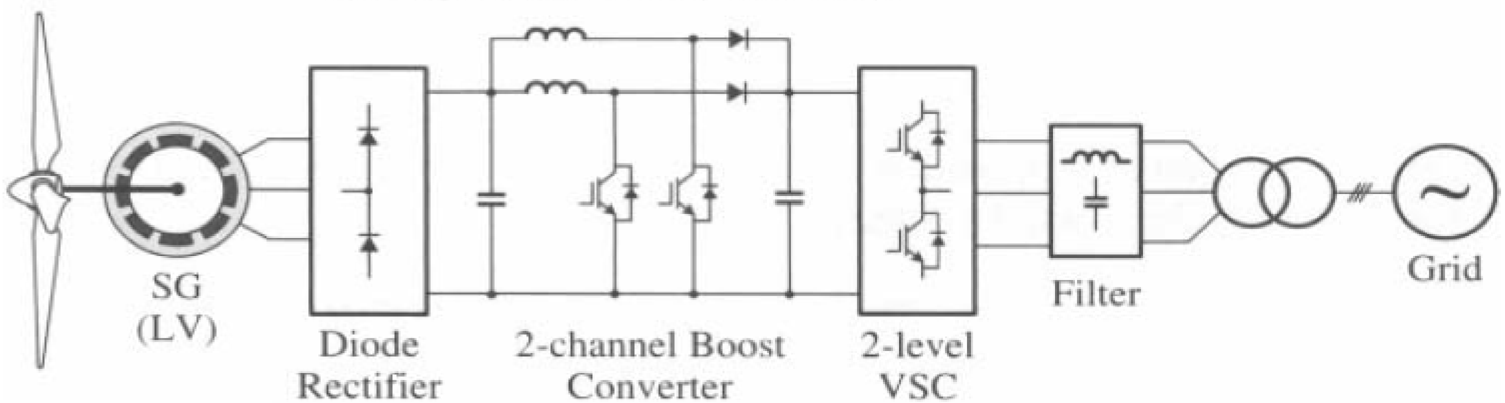
(7) Configuration with Diode Rectifier and DC/DC Converters

With Diode Rectifier and Multichannel Boost Converters



(a) Single-channel boost converter



(b) Two-channel boost converter

[6, 7, 11]

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(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

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(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

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

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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.**

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Introduction to Wind Energy

Module 2.1

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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:

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. Modelling of induction generators

1. Analysis of Transient characteristics

2. Case Study

3. Steady Sate Equivalent Circuit

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Modelling of induction generators

- There are two types of induction generators in the wind energy industry:
    1. Doubly fed induction generators (DFIGs)
    2. squirrel-cage induction generators (SCIGs)
- Both have the same stator structure and differ only in the rotor structure
- Construction of a squirrel-cage induction generator:
- Stator is made of thin silicon steel laminations
- Laminations are insulated to minimize iron losses caused by induced eddy currents 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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Modelling of induction generators

- 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

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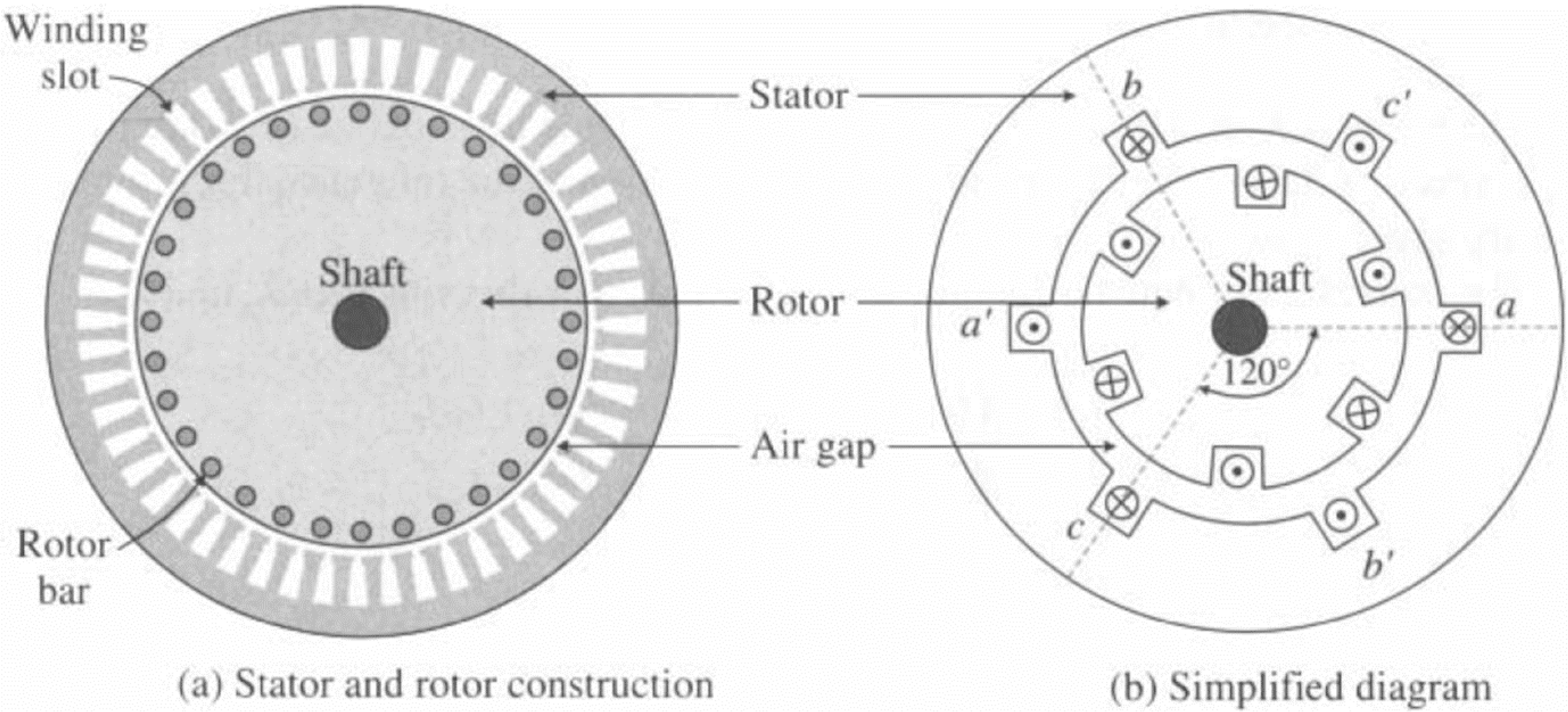
Modelling of Induction Generators



Cross-section view of SCIG
Source: [1]

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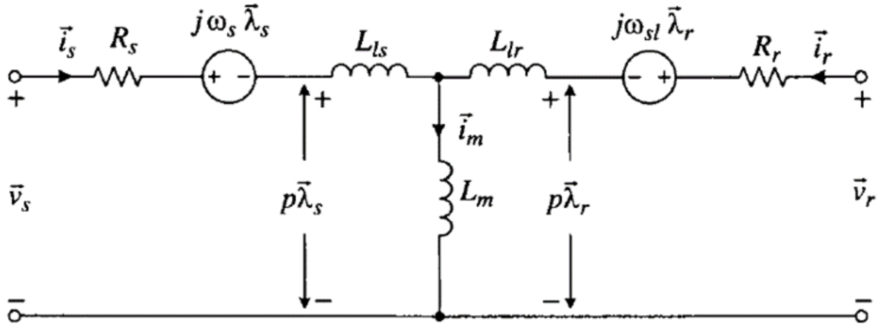
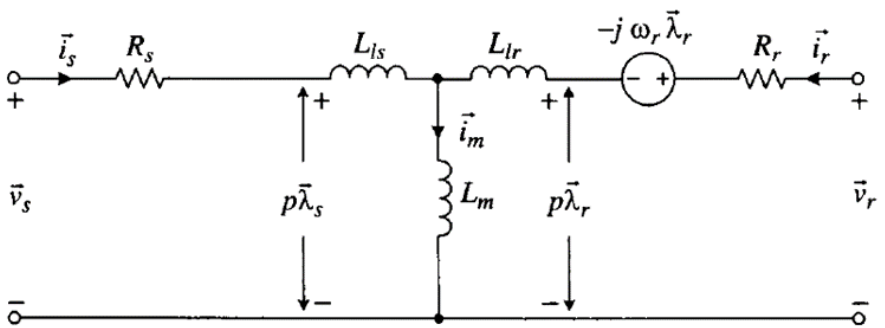
Modelling of Induction Generators

dq Reference Frame Model

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



(a) IG model in the synchronous frame



(b) IG model in the stationary frame

Induction Generator Model, Arbitrary Reference Frame [1]

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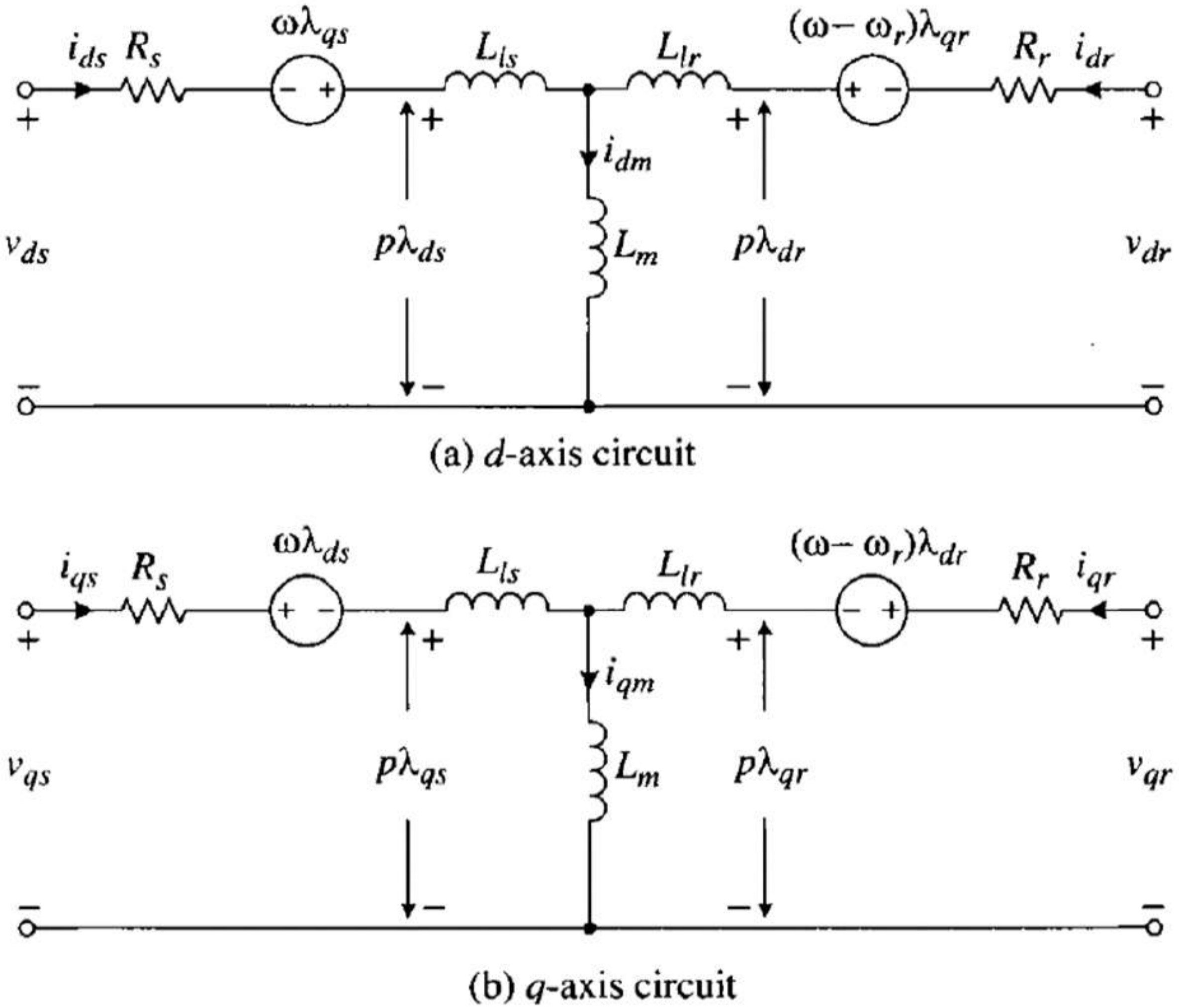
Modelling of Induction Generators



Induction Generator Model, Stationary Reference Frame [1]

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Modelling of Induction Generators

The stator and rotor equation of the equivalent circuit

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

The *dq*-axis voltage equations are obtained from

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

The *dq*-flux linkage equations are obtained from

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

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Modelling of Induction Generators

The Generator torque equation

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

The flux linkage in stationary frame

$$\begin{cases} \lambda_{ds} = \left(v_{ds} - R_s i_{ds} + \omega\lambda_{qs}\right)/ S \\ \lambda_{qs} = \left(v_{qs} - R_s i_{qs} - \omega\lambda_{ds}\right)/ S \\ \lambda_{dr} = \left(v_{dr} - R_r i_{dr} + (\omega - \omega_r)\lambda_{qr}\right)/ S \\ \lambda_{qr} = \left(v_{qr} - R_r i_{qr} - (\omega - \omega_r)\lambda_{dr}\right)/ S \end{cases} \qquad (1)$$

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Modelling of Induction Generators

The flux linkage can be represented as

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

The mathematical relation between current and flux

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

Modelling of Induction Generators

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Therefore, the stator and rotor current

$$\begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} = \frac{1}{D_1} \begin{bmatrix} L_r & 0 & -L_m & 0 \\ 0 & L_r & 0 & -L_m \\ -L_m & 0 & L_s & 0 \\ 0 & -L_m & 0 & L_s \end{bmatrix} \cdot \begin{bmatrix} \lambda_{ds} \\ \lambda_{qs} \\ \lambda_{dr} \\ \lambda_{qr} \end{bmatrix} \quad (2)$$

where $D_1 = L_s L_r - L_m^2$ [1]

The motion and toque equations

$$\begin{cases} \omega_r = \frac{P}{JS}(T_e - T_m) & \text{(a)} \\ T_e = \frac{3P}{2}\left(i_{qs}\lambda_{ds} - i_{ds}\lambda_{qs}\right) & \text{(b)} \end{cases} \quad (3)$$

The input variables of the model include the dq-axis stator voltages v_{ds}, and v_{qs}, rotor volages v_{dr} and v_{qr}. The mechanical torque T_m and speed of arbitrary reference frame w, whereas the output variables are dq-axis stator current, i_{ds} and i_{qs}, electromagnetic torque T_e, and the mechanical speed w_m.

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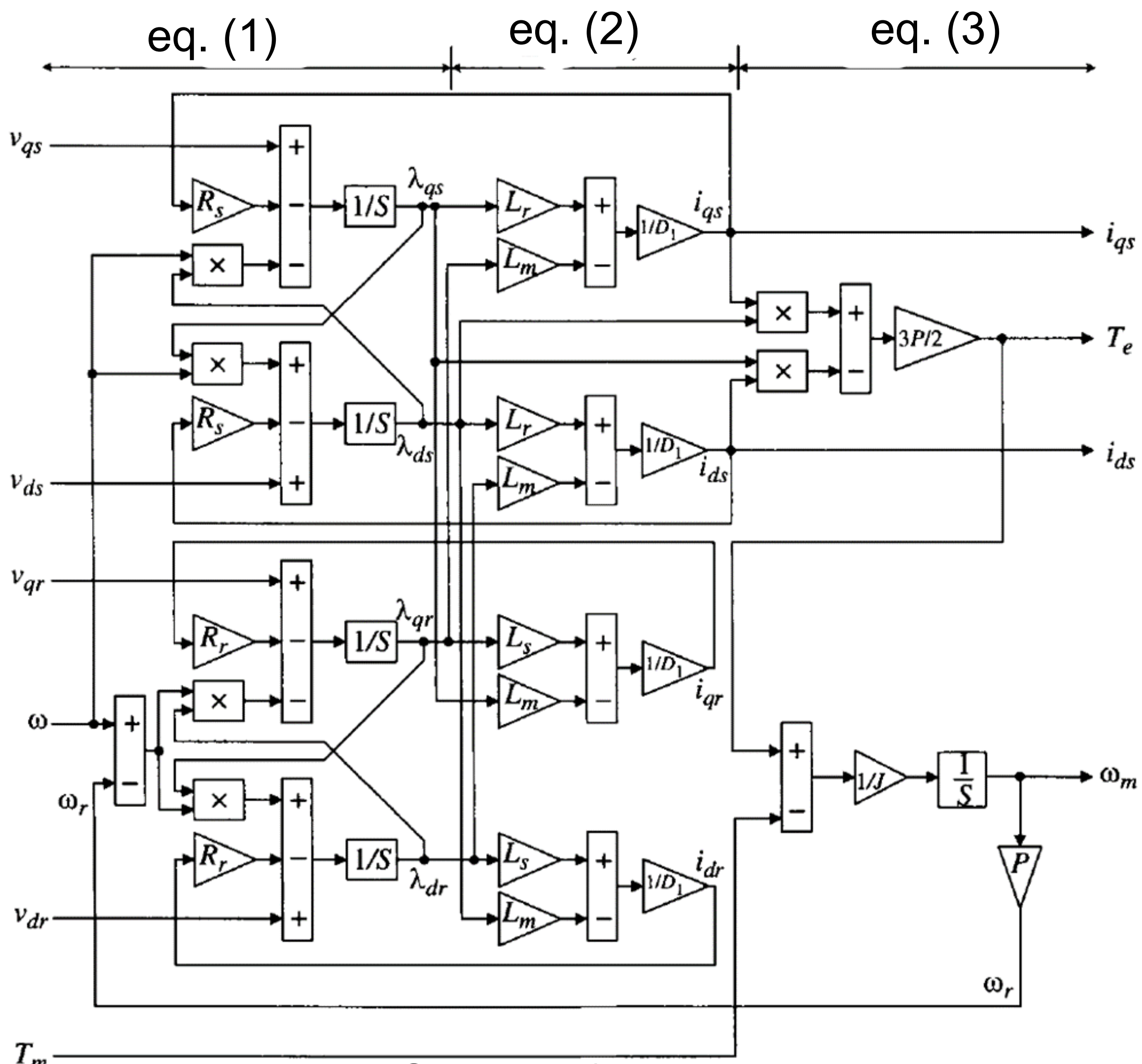
Modelling of Induction Generators



Source: [1]

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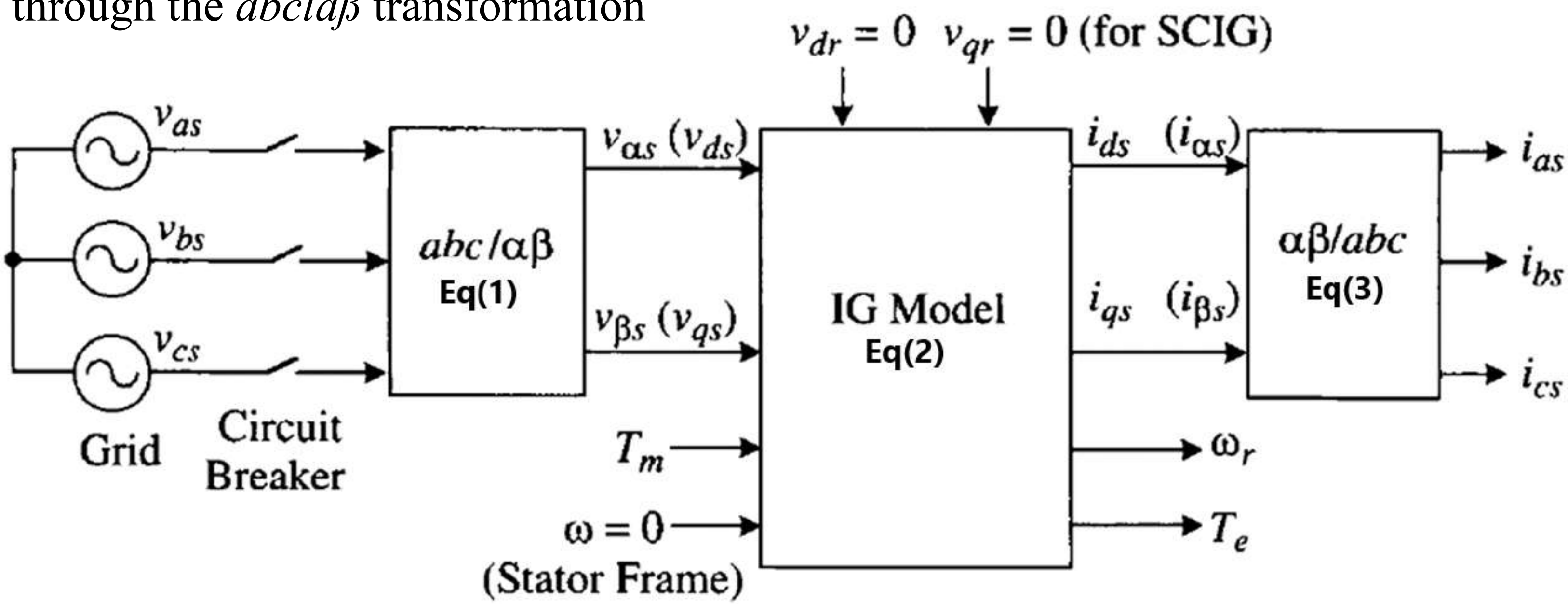
Induction Generator Transient Characteristic

The transient characteristics of an induction-generator-based WECS with direct grid connection can be investigated using the simulation block diagram shown below. Assuming a three-phase balanced grid, the grid voltages *vas, vbs,* and *vcs* in the stationary frame are transformed to the two-phase voltages $v_{\alpha s}$ and $v_{\beta s}$ in the *aß* stationary frame through the *abc/aß* transformation



Block diagram for dynamic simulation of SCIG with direct grid connection.

Source: [1]

Induction Generator Transient Characteristic

abc/αβ transformation

$$\begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix}$$ Eq(1)

Stator model of IG

$$\begin{cases} \vec{v}_s = R_s \vec{i}_s + p\vec{\lambda}_s + j\omega\vec{\lambda}_s \\ \vec{v}_r = R_r \vec{i}_r + p\vec{\lambda}_r + j(\omega - \omega_r)\vec{\lambda}_r \end{cases}$$ Eq(2)

Aβ/abc transformation

$$\begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix}$$ Eq(3)

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Case Study 3-1—Direct Grid Connection of SCIG during System Startup.

- It case study investigates the dynamic performance of a SCIG wind energy system during system start-up, and verifies that a large SCIG cannot be directly connected to the grid due to the excessive inrush current and torque oscillations.
- Consider a 2.3 MW, 690 V, 50 Hz, 1512 rpm squirrel-cage induction generator. Its nameplate and parameters are listed in Table B-l.
- The shaft of the generator is coupled to the wind turbine through a gearbox.
- During the system start-up, the turbine and generator are brought by the wind to a certain speed, at which the generator is connected to the grid of 690 V/50 Hz by the circuit breaker shown in Figure of slide 15. The investigation is carried out in the following two cases [1].

Case Study

Table B-1. 2.3 MW, 690 V, 50 Hz squirrel cage induction generator (SCIG) parameters

Generator Type	SCIG, 2.3 MW, 690 V, 50 Hz	
Rated Output Power	2.30 MW	
Rated Mechanical Power	2.3339 MW	1.0 pu
Rated Apparent Power	2.59 MVA	1.0 pu
Rated Line-to-line Voltage	690 V (rms)	
Rated Phase Voltage	398.4 V (rms)	1.0 pu
Rated Stator Current	2168 A (rms)	1.0 pu
Rated Stator Frequency	50 Hz	1.0 pu
Rated Power Factor	0.888	
Rated Rotor Speed	1512 rpm	1.0 pu
Rated Slip	–0.008	
Number of Pole Pairs	2	
Rated Mechanical Torque	14.74 kN·m	1.0 pu

(continued)

Source: [1]

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Case Study

Table B-1. *Continued*

Generator Type	SCIG, 2.3 MW, 690 V, 50 Hz	
Rated Stator Flux Linkage	1.2748 Wb (rms)	1.0053 pu
Rated Rotor Flux Linkage	1.2096 Wb (rms)	0.9539 pu
Stator Winding Resistance, R_s	1.102 mΩ	0.006 pu
Rotor Winding Resistance, R_r	1.497 mΩ	0.008 pu
Stator Leakage Inductance, L_{ls}	0.06492 mH	0.111 pu
Rotor Leakage Inductance, L_{lr}	0.06492 mH	0.111 pu
Magnetizing Inductance, L_m	2.13461 mH	3.6481 pu
Moment of Inertia, J	1200 kg·m²	
Inertia Time Constant, H	5.8078 sec	
Base Flux Linkage, Λ_B	1.2681 Wb (rms)	1.0 pu
Base Impedance, Z_B	0.1838 Ω	1.0 pu
Base Inductance, L_B	0.58513 mH	1.0 pu
Base Capacitance, C_B	17316.17 µF	1.0 pu

Note: $H = J(\omega_m)^2/(2S_R)$

Source: [1]

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Case Study

- **DYNAMIC PERFORMANCE OF SCIG WITH DIRECT GRID CONNECTION.**
- The wind turbine is initially in a parking mode with the blades pitched out of the wind
- When the wind speed reaches an operative level, the blades are pitched into the wind slightly, and wind turbine and generator start to rotate slowly
- When the generator is accelerated close to the rated speed—1450 rpm (0.959 pu)—the circuit breaker is closed and the generator is directly connected to the grid.
- The simulated waveforms for the generator are illustrated in the following Figure
- During the system transients, a high inrush current flows into the generator and a DC offset current appears in each of the stator currents i_{as}, i_{bs}, and i_{cs},
- The generator finally reaches the synchronous speed of 1500 rpm (0.992 pu) at t = 0.84

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Case Study

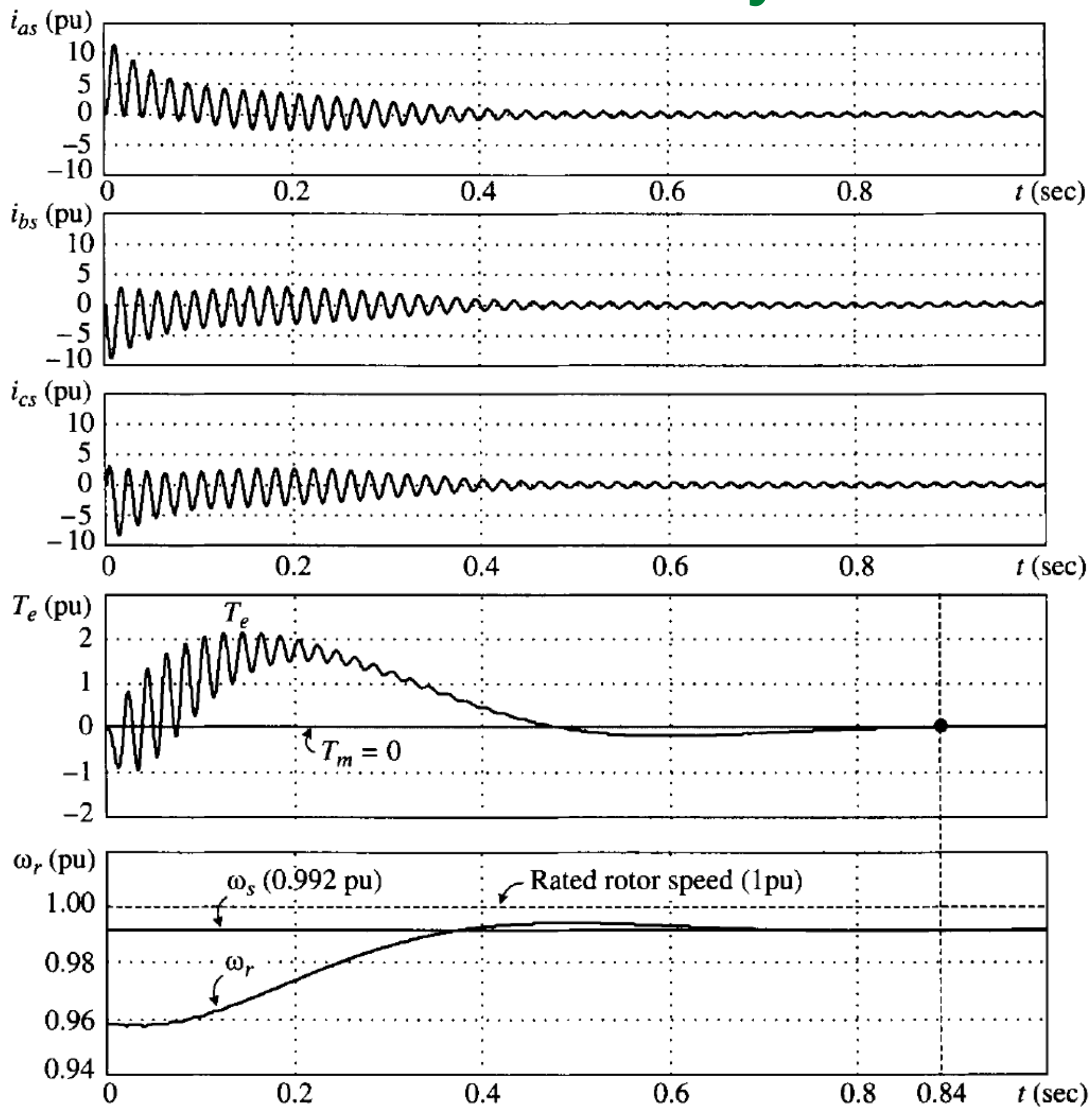

Figure 3-11. Dynamic response of SCIG with direct grid connection.

Source: [1]

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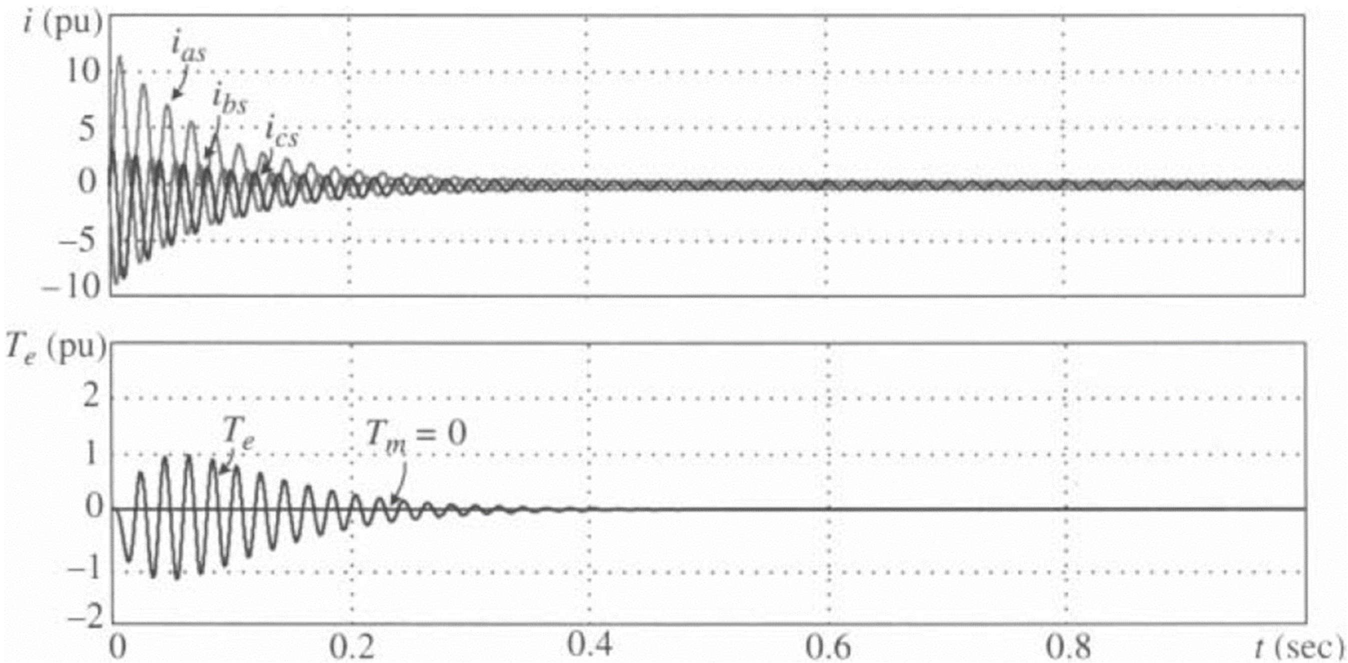
Case Study

The dynamic response at the moment the SCIG is connected to the grid is depicted in Figure 3-12.



Source: [1]

Case Study

- A high inrush current is drawn by the generator, and its peak value is more than 10 pu
- The high amplitude of the stator currents causes oscillations in the
- generator torque T_e
- Compared with the previous case, the transient process is faster due to the constant rotor speed that eliminates the motion equation in the simulation
- It can be concluded that the direct connection of a SCIG to the grid is not allowed in practice due to the excessive stator current and torque oscillations

Source: [1]

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Steady Sate Equivalent Circuit

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- To investigate the steady-state performance of induction generators, the steady-state equivalent circuit is a useful tool. The steady-state equivalent circuit can be derived from the IG space-vector model described by Eq (3)
- To obtain the steady state equivalent circuit, the IG space-vector model in the synchronous frame is used, and the following steps are taken:
  - Set the arbitrary ω in Eq (3) to the synchronous speed ωs.
  - Set the derivative terms in Eq (3) to zero
  - Replace all space vectors Eq (3) with their corresponding phasors
  - Reverse the rotor current direction,
  - The steady state equation will be

$$\begin{cases} \bar{V}_s = R_s \bar{I}_s + j\omega \bar{\Lambda}_s \\ \bar{V}_r = -R_r \bar{I}_r + j(\omega_s - \omega_r)\bar{\Lambda}_r \end{cases}$$

where

$\bar{\Lambda}_s$ and $\bar{\Lambda}_r$ are the phasors for the stator and rotor flux linkages X_s and A_r, respectively

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Source: [1]

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Steady Sate Equivalent Circuit

Then the steady state voltage equation will be

$$\begin{cases} \overline{V}_s = R_s \overline{I}_s + j\omega_s (L_{ls} \overline{I}_s + L_m \overline{I}_m) \\ \overline{V}_r = -R_r \overline{I}_r + j\omega_{sl} (-L_{lr} \overline{I}_r + L_m \overline{I}_m) \end{cases}$$

where ω_{sl} is the angular slip frequency, given by

$$\omega_{ls} = \omega_s - \omega_r.$$

The rotor slip

$$s = \frac{\omega_{sl}}{\omega_s}$$

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Steady Sate Equivalent Circuit

By rearrange the previous equation

$$\begin{cases} \bar{V}_s = R_s \bar{I}_s + j\omega_s (L_{ls}\bar{I}_s + L_m \bar{I}_m) = R_s \bar{I}_s + jX_{ls}\bar{I}_s + jX_m \bar{I}_m \\ \dfrac{\bar{V}_r}{s} = -\dfrac{R_r}{s}\bar{I}_r + j\omega_s(-L_{lr}\bar{I}_r + L_m \bar{I}_m) = -\dfrac{R_r}{s}\bar{I}_r - jX_{lr}\bar{I}_r + jX_m \bar{I}_m \end{cases}$$

where

$$\begin{cases} X_{ls} = \omega_s L_{ls} \\ X_{lr} = \omega_s L_{lr} \\ X_m = \omega_s L_m \end{cases}$$

The equivalent circuit of steady state IG is shown in the following Figure

Steady Sate Equivalent Circuit

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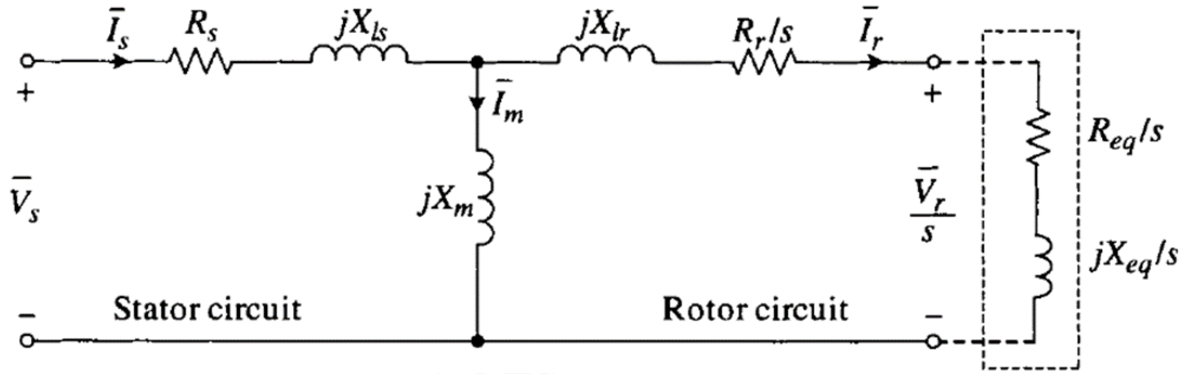
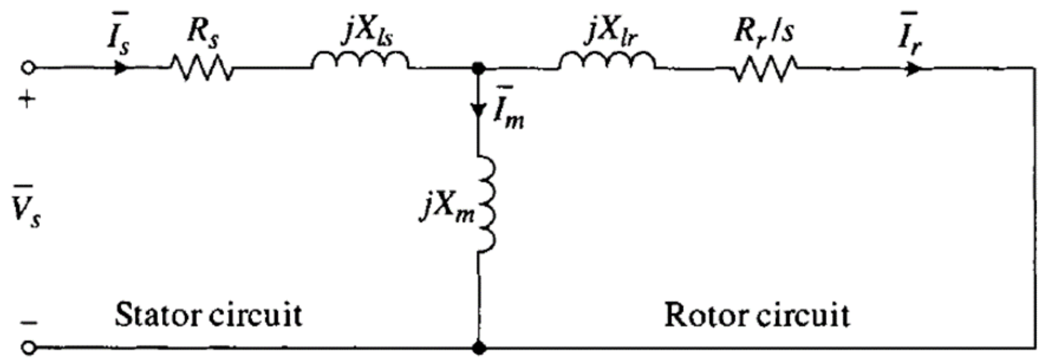


(a) DFIG



(b) SCIG

Source: [1]

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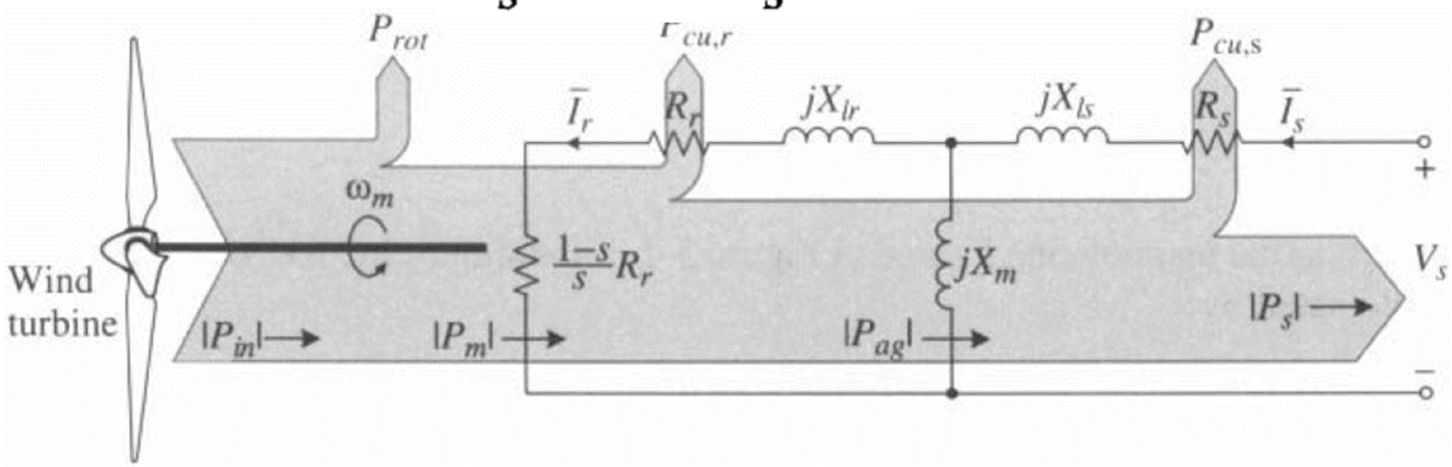
Steady Sate Equivalent Circuit

Power Flow. To facilitate the power flow analysis for the induction generator, the rotor resistance *Rr/s* is split into two components:

$$\frac{R_r}{s} = R_r + \frac{1-s}{s} R_r$$



Power flow and losses in an induction generator.

Source: [1]

Steady Sate Equivalent Circuit

The mechanical power $$P_m = 3I_r^2 \frac{(1-s)}{s} R_r$$

The rotor and stator copper losses

$$\begin{cases} P_{cu,r} = 3I_s^2 R_r \\ P_{cu,s} = 3I_s^2 R_s \end{cases}$$

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Source: [1]

Steady Sate Equivalent Circuit

The stator output power

$$|P_s| = |P_m| - P_{cu,r} - P_{cu,s}$$

Which can be calculated

$$P_s = 3V_s I_s \cos\varphi_s$$

where

$$\varphi_s = \angle \overline{V}_s - \angle \overline{I}_s$$

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Source: [1]

Steady Sate Equivalent Circuit

Generator Torque-Speed Characteristics

It shows how the torque developed by the generator varies with the speed for a given stator voltage and frequency

The mechanical power of the generator is given by $P_m = T_m \omega_m$

The mechanical torque

$$T_m = \frac{1}{\omega_m}\left(3I_r^2 \frac{1-s}{s} R_r\right) = \frac{1}{\omega_r / P}\left(3I_r^2 \frac{1-s}{s} R_r\right)$$

$$T_m = \frac{1}{\omega_s / P}\left(3I_r^2 \frac{R_r}{s}\right) = \frac{P_{ag}}{\omega_s / P}$$

where air gap power $P_{ag} = 3I_r^2 \frac{R_r}{s}$

The rotor current

$$I_r = \frac{V_s}{\sqrt{\left(R_s + \frac{R_r}{s}\right)^2 + (X_{ls} + X_{lr})^2}}$$

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Source: [1]

Steady Sate Equivalent Circuit

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Sub. The current in torque equation then

$$T_m = \frac{3P}{\omega_s} \cdot \frac{R_r}{s} \cdot \frac{V_s^2}{\left(R_s + \frac{R_r}{s}\right)^2 + (X_{ls} + X_{lr})^2}$$

- This relates the mechanical torque T_m with slip s for a given stator voltage V_s and stator frequency ω_s
- This relation is shown in the Figure
- There are two operating modes: motoring and generating modes.
- When the generator operates in the motoring mode, the rotor speed ω_r is below the synchronous speed ω_s, and both mechanical torque and slip are positive ($Tm > 0, s > 0$).
- When the generator operates in the generating mode, the rotor speed is higher than the synchronous speed and both torque and slip are negative ($Tm < 0$, $s < 0$)

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Source: [1]

Steady Sate Equivalent Circuit

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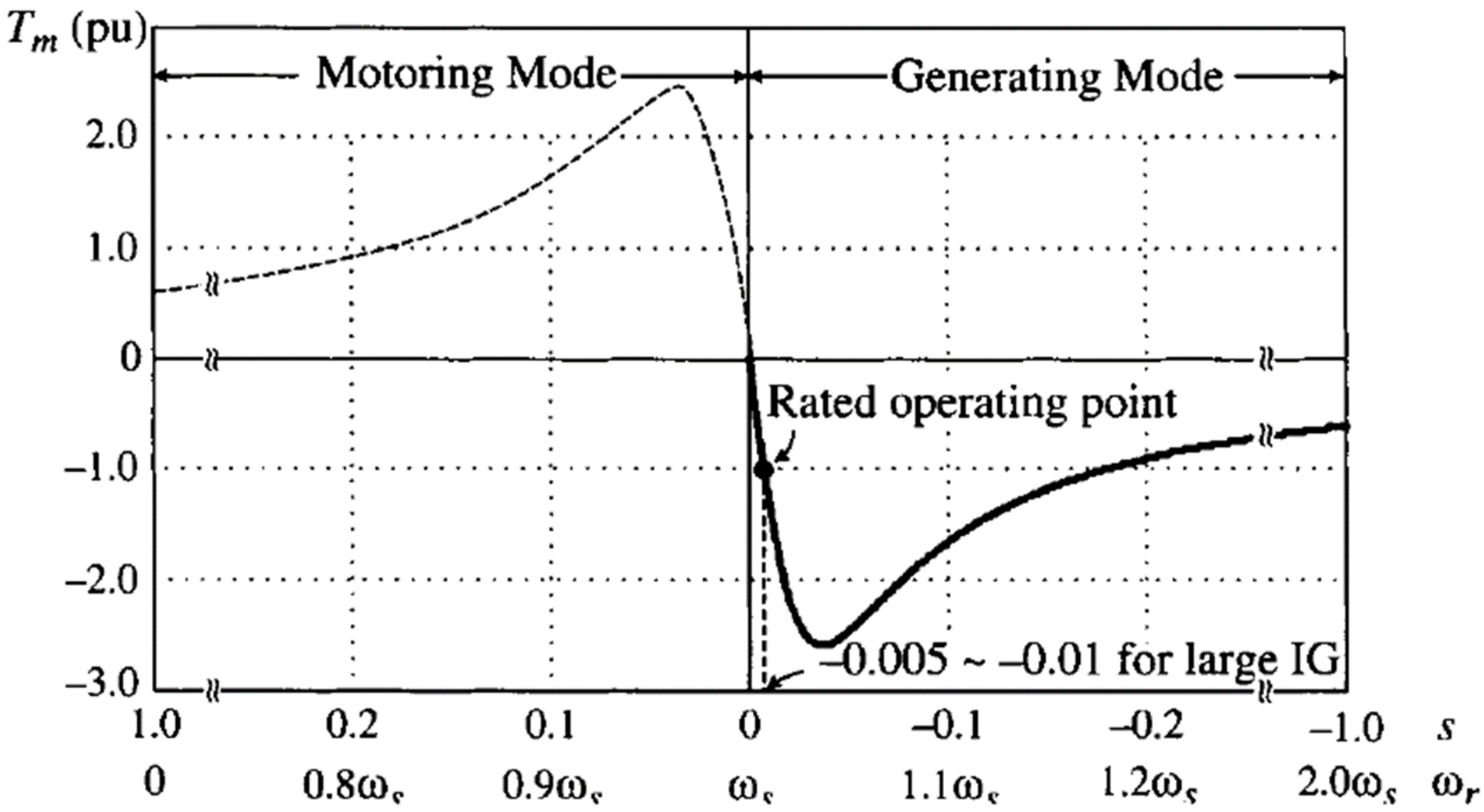

Typical torque-slip curve of squirrel-cage induction generator.

Source: [1]

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Recommended literature

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] https://www.ewea.org European Wind Energy Association

[8] https://www.indea.org World Wind Energy Association

[9] https://www.awea.org American Wind Energy Association

Recommended literature

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

Introduction to Wind Energy

Module 2.1

Further information:

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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:

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. *Dynamic Modelling of synchronous generators*
2. *Analysis of Transient characteristics*
3. *Case Study*
4. *Steady State Model*

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Synchronous Generator

- Synchronous generators (SGs) are widely used in wind energy conversion systems of a few kilowatts to a few 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,
- In the PMSG uses permanent magnets to produce the rotor flux
- Depending on the shape of the rotor and the distribution of the air gap along the perimeter of the rotor, synchronous generators can be categorized into salient-pole and nonsalient-pole types
- The construction of WRSGs and PMSGs in wind energy systems is presented, the dynamic and steady-state models for both types of synchronous generators are derived [1]

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Synchronous Generator

Wound-Rotor Synchronous Generators

- The wound-rotor synchronous generator has a wound-rotor configuration to generate the rotor magnetic flux
- 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 generator has an uneven air gap flux distribution due to the salient structure of the rotor
- 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
- The rotor-field winding of the synchronous generator requires DC excitation though brushes [1]

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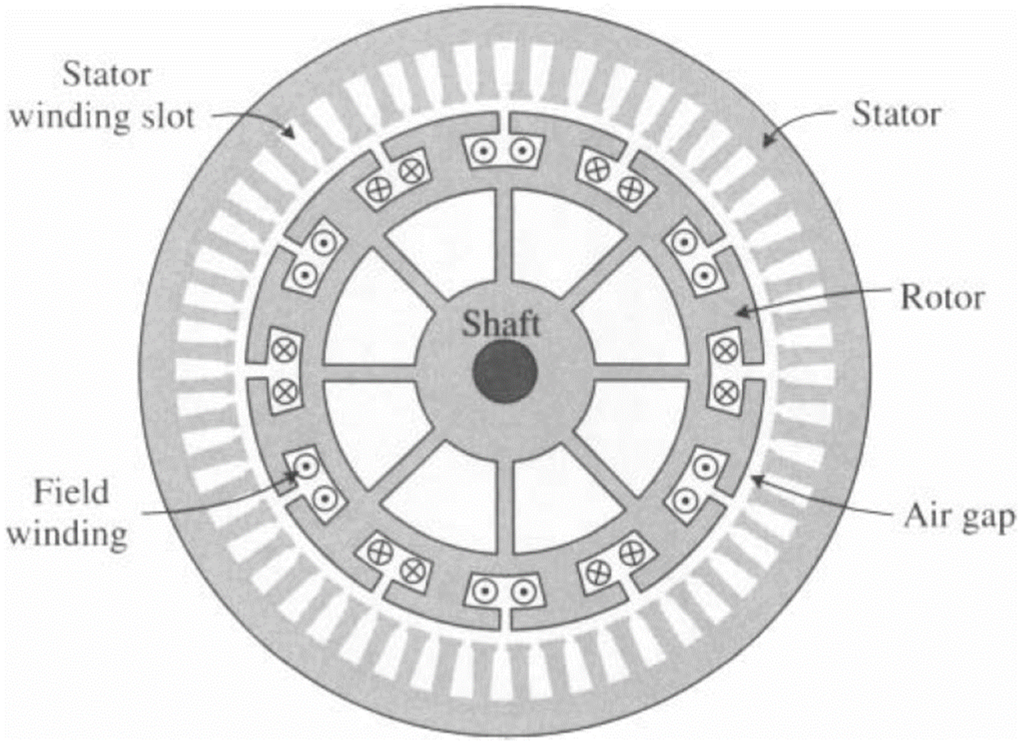
Synchronous Generator

- Salient-pole, wound-rotor synchronous generator (twelve-pole configuration



Source : [1]

Synchronous Generator

Permanent-Magnet Synchronous Generators

- In the PMSG, the rotor magnetic flux is generated by permanent magnets,
- Because of the absence of the rotor windings, a high power density can be achieved, reducing the size and weight of the generator.
- In addition, there are no rotor winding losses, reducing the thermal stress on the rotor
- The drawbacks of these generators lie in the fact that permanent magnets are more expensive and prone to demagnetization
- The PMSG can be classified into surface-mounted and inset PM generators.
- In the surface-mounted PMSG, the permanent magnets are placed on the rotor surface
- Since the permeability of the magnets is very close to that of the nonfemte materials, the effective air gap between the rotor core and stator is uniformly distributed around the surface of the rotor.
- This type of configuration is known as a nonsalient-pole PMSG [1]

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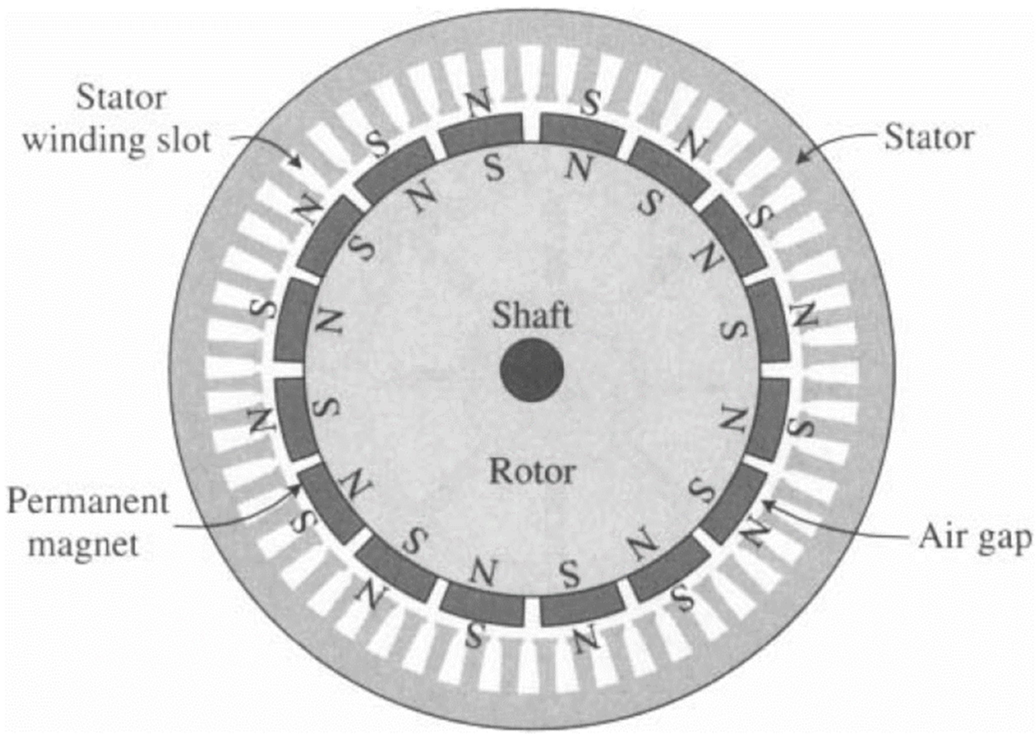
Synchronous Generator

- Surface-mounted nonsalient PMSG (sixteen-pole configuration



Source : [1]

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Synchronous Generator

- The main advantage of the surface-mounted SG is :
  - its simplicity and low construction cost in comparison to the inset PMSG.
- However, the magnets are subject to centrifugal forces that can cause their detachment from the rotor and,
- therefore, the surface-mounted PMSGs are mainly used in low-speed applications
- In a direct-driven WECS, the synchronous generator with a high number of poles is used.
- In the inset PMSG, the permanent magnets are inset into the rotor surface
- 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 in comparison to the surface-mounted PMSG and,
- Therefore, this type of generator can operate at higher rotor speeds

Source : [1]

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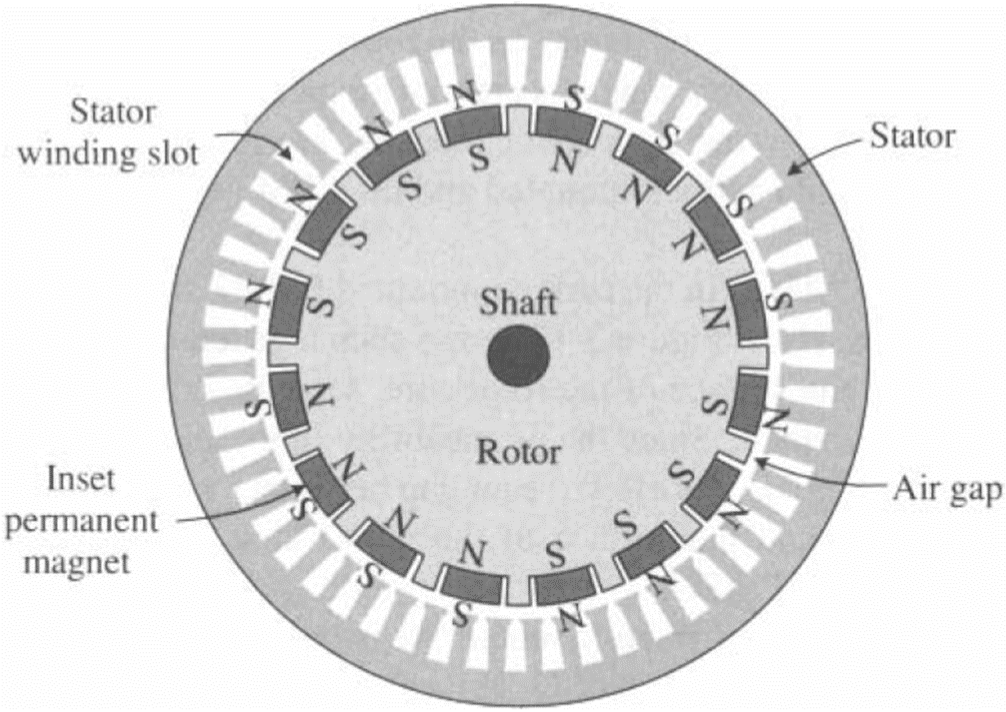
Synchronous Generator

Inset PMSG with salient poles (four-pole configuration

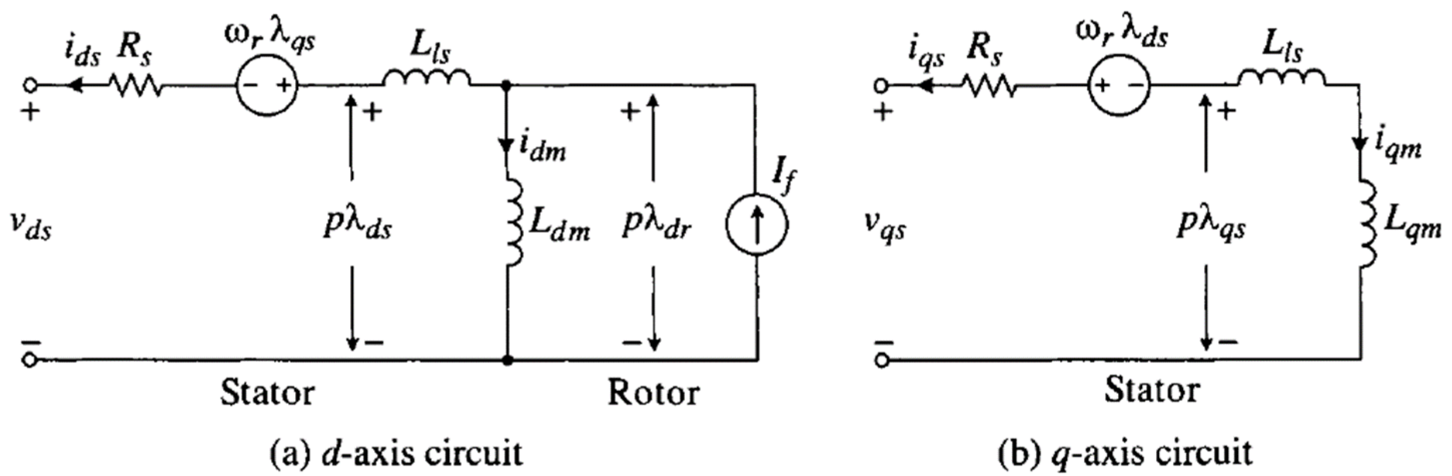


Source : [1]

Modeling of Synchronous Generator

Dynamic Model of SG

- The following Figure shows a general *dq-axis* model of a synchronous generator.
- To simplify the analysis, the SG is normally modeled in the rotor field synchronous reference frame.



General *dq*-axis model of SG in the rotor field synchronous reference frame.

Source : [1]

Modeling of Synchronous Generator

Dynamic Model of SG

- The stator circuit of the *dq-axis* model is essentially the same as that of the induction generator except that
  - The speed of the arbitrary reference frame ω in the IG model is replaced by the rotor speed ω_r in the synchronous frame
  - 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 ($L_{dm} < L_{qm}$).
  - The *dq-axis* stator currents, i_{ds} and i_{qs}, flow out of the stator. This is based on the generator convention since most synchronous machines are used as generators.

Source : [1]

Modeling of Synchronous Generator

To model the rotor circuit, the field current in the rotor winding is represented by a constant current source *If* in the *d*-axis circuit.
In the PMSG, the permanent magnet can be modeled by an equivalent current source *If* with a fixed magnitude.
To simplify the SG model, the voltage equations for the synchronous generator are given

$$\begin{cases} v_{ds} = -R_s i_{ds} - \omega_r \lambda_{qs} + p\lambda_{ds} \\ v_{qs} = -R_s i_{qs} + \omega_r \lambda_{ds} + p\lambda_{qs} \end{cases}$$

where λ_{ds} and λ_{qs} are the *d*- and *q*-axis stator flux linkages, given by

$$\begin{cases} \lambda_{ds} = -L_{ls} i_{ds} + L_{dm}\left(I_f - i_{ds}\right) = -(L_{ls} + L_{dm}) i_{ds} + L_{dm} I_f = -L_d i_{ds} + \lambda_r \\ \lambda_{qs} = -(L_{ls} + L_{qm}) i_{qs} = -L_q i_{qs} \end{cases}$$

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Source : [1]

Modeling of Synchronous Generator

where λ_r is the rotor flux, and L_d and L_q are the stator *dq*-axis self-inductances, defined by

$$\begin{cases} \lambda_r = L_{dm} I_f \\ L_d = L_{ls} + L_{dm} \\ L_q = L_{ls} + L_{qm} \end{cases}$$

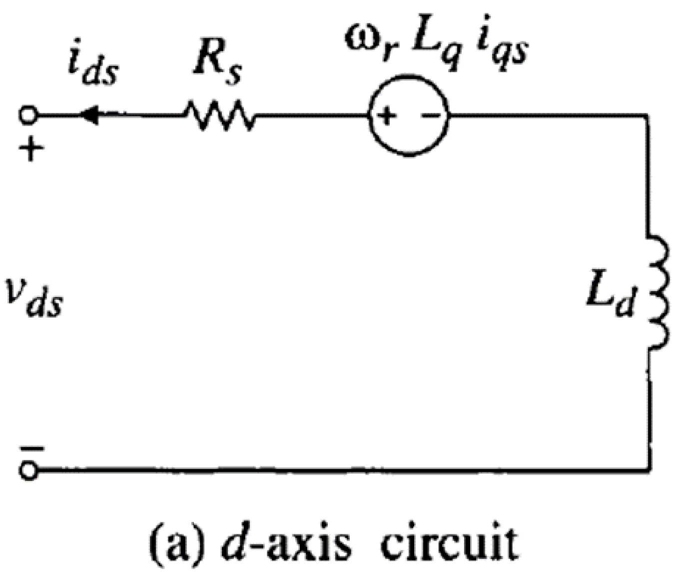
considering $d\lambda r/dt$ = 0 for constant field current If in the WRSG and constant λ_r in the PMSG, we have

$$\begin{cases} v_{ds} = -R_s i_{ds} + \omega_r L_q i_{qs} - L_d p i_{ds} \\ v_{qs} = -R_s i_{qs} - \omega_r L_d i_{ds} + \omega_r \lambda_r - L_q p i_{qs} \end{cases}$$

Source : [1]

Modeling of Synchronous Generator

A simplified model for the synchronous generators is shown as



Simplified dq-axis model of SG in the rotor-field synchronous reference frame.

Source : [1]

Modeling of Synchronous Generator

It should be pointed out that

- The simplified mode is as accurate, since no assumption was made during the derivation of the simplified model. The performance analysis based on the general and simplified models should give identical results
- The SG model is valid for both wound-rotor and permanent-magnet synchronous generators.
    - For a given field current I_f in the WRSG, the rotor flux can be calculated by $\lambda_r = L_{dm} I_f$.
    - For the PMSG, the rotor flux λ_r is produced by permanent magnets and its rated value can be obtained from the nameplate data and generator parameters.
- The model is also valid for both salient- and nonsalient-pole synchronous generators.
    - For a nonsalient generator, the *dq-axis* synchronous inductances, L_d and L_q, are equal
    - The *d-axis* synchronous inductance of PMSG is usually lower than that of the *q-axis* ($L_d < L_q$) [1]

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Modeling of Synchronous Generator

The electromagnetic torque produced by the SG can be calculated by

$$T_e = \frac{3P}{2}\left(i_{qs}\lambda_{ds} - i_{ds}\lambda_{qs}\right)$$

$$T_e = \frac{3P}{2}\left[\lambda_r i_{qs} - \left(L_d - L_q\right) i_{ds} i_{qs}\right]$$

The rotor speed ω_r is governed by motion equation

$$\omega_r = \frac{P}{JS}\left(T_e - T_m\right)$$

Then the motor current

$$\begin{cases} i_{ds} = \frac{1}{S}\left(-v_{ds} - R_s i_{ds} + \omega_r L_q i_{qs}\right) / L_d \\ i_{qs} = \frac{1}{S}\left(-v_{qs} - R_s i_{qs} - \omega_r L_d i_{ds} + \omega_r \lambda_r\right) / L_q \end{cases}$$

Co-fu[illegible]
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Source : [1]

Modeling of Synchronous Generator

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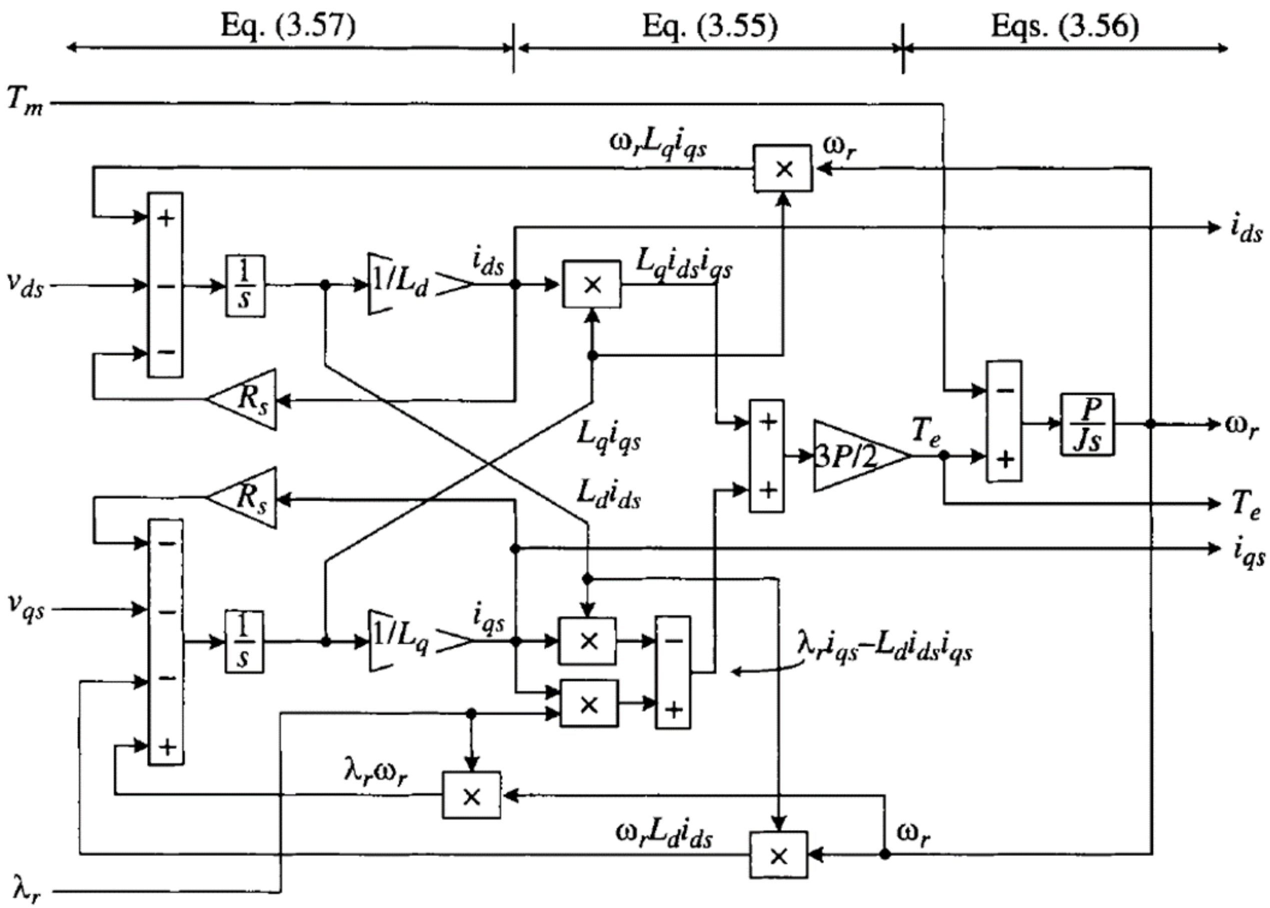

Block diagram for dynamic simulation of synchronous generators.

Source : [1]

Case Study

- ***Case Study 3-3—Analysis of Synchronous Generator in Standalone Operation.***
- The main purpose of this case 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 slide 19 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

- 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-2

Source : [1]

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Case Study

Table B-2. 2.45 MW, 4000 V, 53.33 Hz nonsalient pole PMSG parameters

Generator Type	PMSG, 2.45 MW, 4000 V, 53.33 Hz, nonsalient pole	
Rated Mechanical Power	2.4487 MW	1.0 pu
Rated Apparent Power	3.419 MVA	1.0 pu
Rated Line-to-line Voltage	4000 V (rms)	
Rated Phase Voltage	2309.4 V (rms)	1.0 pu
Rated Stator Current	490 A (rms)	1.0 pu
Rated Stator Frequency	53.33 Hz	1.0 pu
Rated Power Factor	0.7162	
Rated Rotor Speed	400 rpm	1.0 pu
Number of Pole Pairs	8	
Rated Mechanical Torque	58.4585 kN·m	1.0 pu
Rated Rotor Flux Linkage	4.971 Wb (rms)	0.7213 pu
Stator Winding Resistance, R_s	24.21 mΩ	0.00517 pu
d-axis Synchronous Inductance, L_d	9.816 mH	0.7029 pu
q-axis Synchronous Inductance, L_q	9.816 mH	0.7029 pu
Base Flux Linkage, Λ_B	6.892 Wb (rms)	1.0 pu
Base Impedance, Z_B	4.6797 Ω	1.0 pu
Base Inductance, L_B	13.966 mH	1.0 pu
Base Capacitance, C_B	637.72 µF	1.0 pu

Source : [1]

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Case Study

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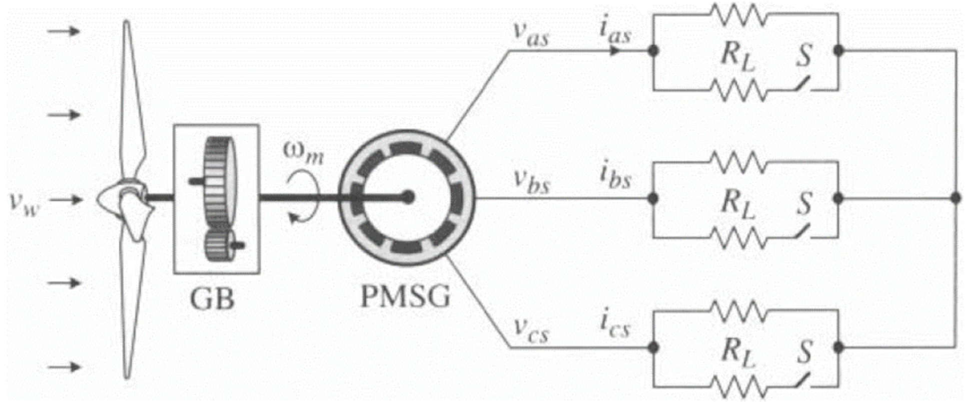
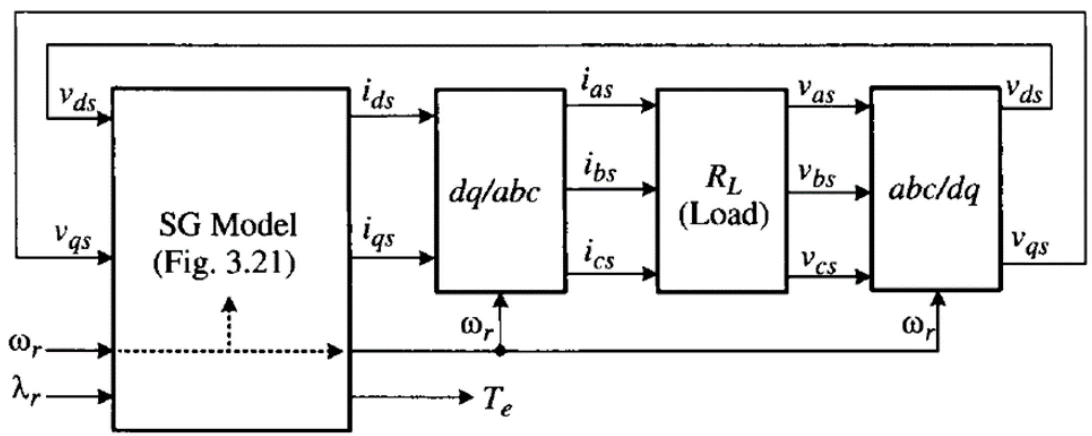


(a) SG with a three-phase resistive load



(b) Block diagram for simulation

Block diagram of a stand-alone SG configuration with a three-phase resistive

Source : [1]

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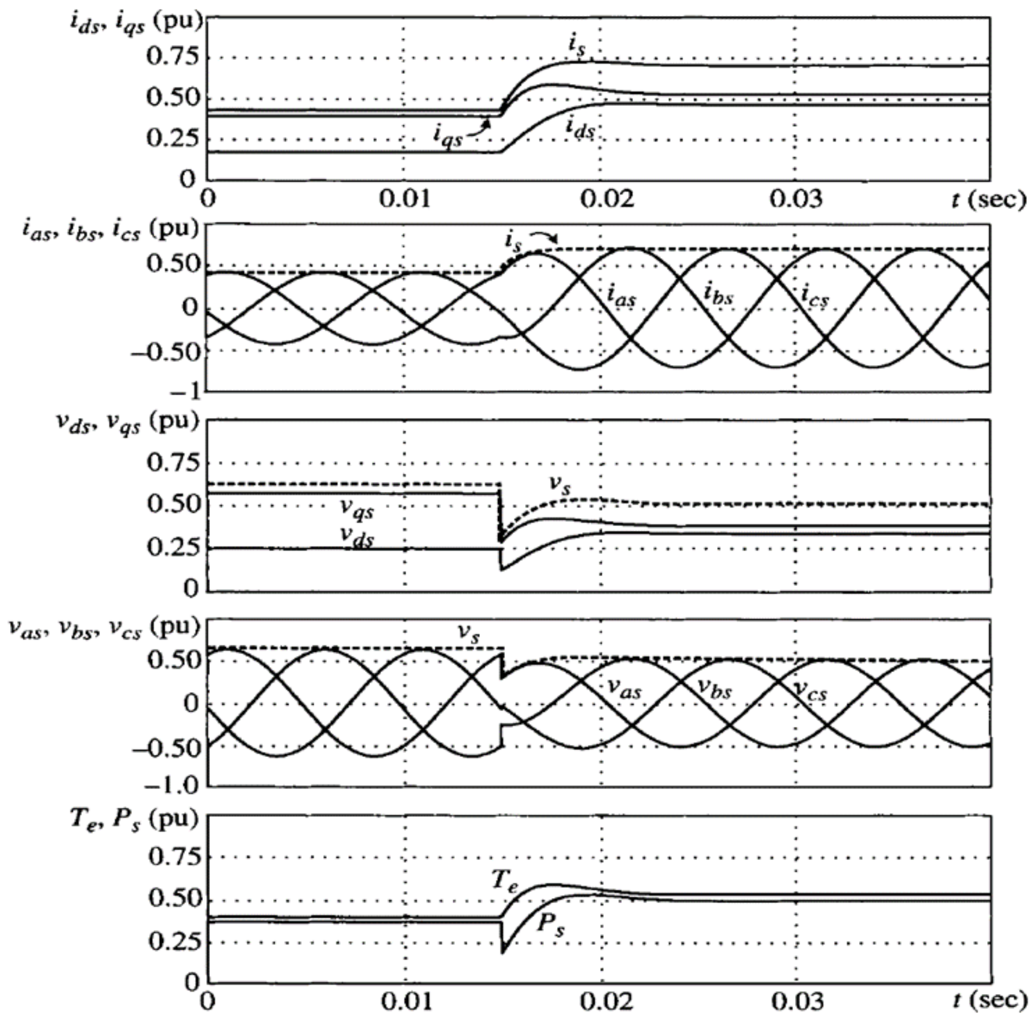
Case Study



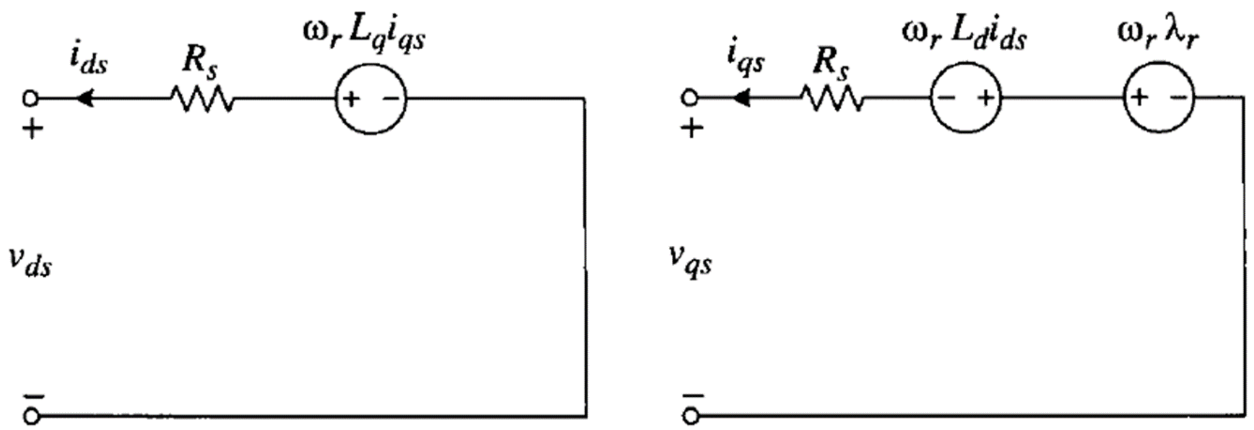
Simulated waveforms for a stand-alone PMSG system with resistive load.

Source : [1]

Steady State Model

The steady state model can be obtained from dynamic by making the derivative term equal zero then

$$\begin{cases} v_{ds} = -R_s i_{ds} + \omega_r L_q i_{qs} \\ v_{qs} = -R_s i_{qs} - \omega_r L_d i_{ds} + \omega_r \lambda_r \end{cases}$$



(a) *d*-axis circuit (b) *q*-axis circuit

Steady-state model of synchronous generator.

Source : [1]

Steady State Model

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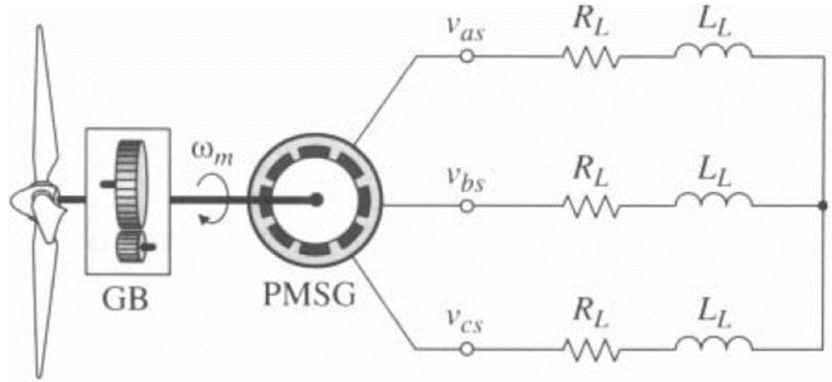
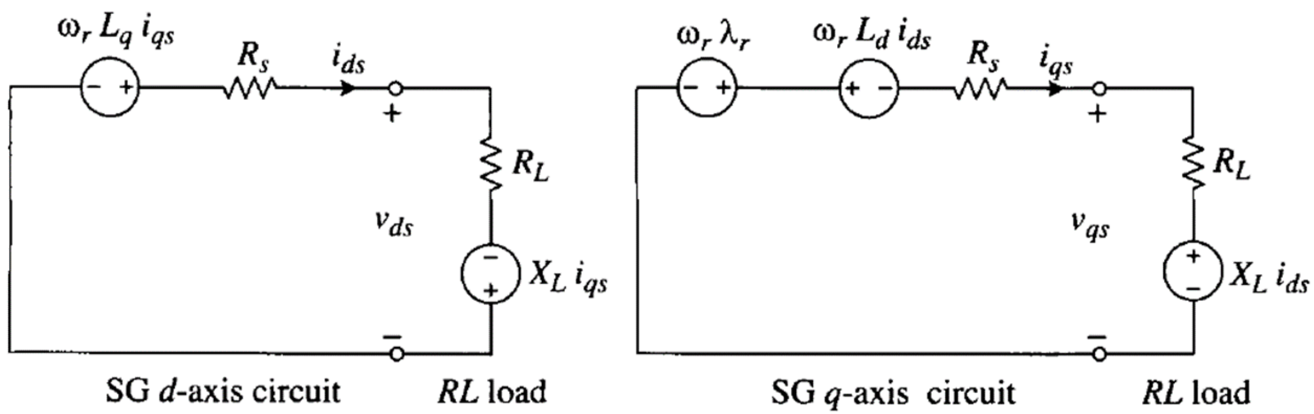
RL Load



(a) SG with a three-phase *RL* load



(b) *dq*-axis equivalent circuits

Steady-state analysis of PMSG with an *RL* load.

Source : [1]

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Recommended literature

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] https://www.ewea.org European Wind Energy Association
[8] https://www.indea.org World Wind Energy Association
[9] https://www.awea.org American Wind Energy Association

Recommended literature

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

Module 2.1

Further information:

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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:

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. *Fixed Speed operation of Squirrel Cage Induction Generators*
2. *Two Speed operation of Squirrel Cage Induction Generators*
3. *Case Study*

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Fixed Speed Square Cage Induction Generator

- Fixed speed Wind Energy Conversion System (WECS) is one of the earliest system paricullary during 1990s, due to Its simplicity and cost
- Square-cage induction generator is the common used
- The generator shaft is driven by the wind its its stator is connected to the grid
- Under normal operating condition, the stator frequency is fixed to the grid and slip frequencies varies little with the wind speed.
- The main advantage of fixed speed WECS is Simple configuration, reliable operation, and low cost of manufacturing, installation and maintenance
- However, it it causes higher mechanical stress and power fluctuation, and it has a low energy conversion efficiency
- Unable to control reactive power to the grid alone

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Fixed Speed Square Cage Induction Generator

- The typical fixed speed WECS configuration is illustrated in the figure below,
- It is composed of three blad wind turbine, a gear box and square-cage IG, 3 phase soft starter, power factor compensator and a transform for grid connection

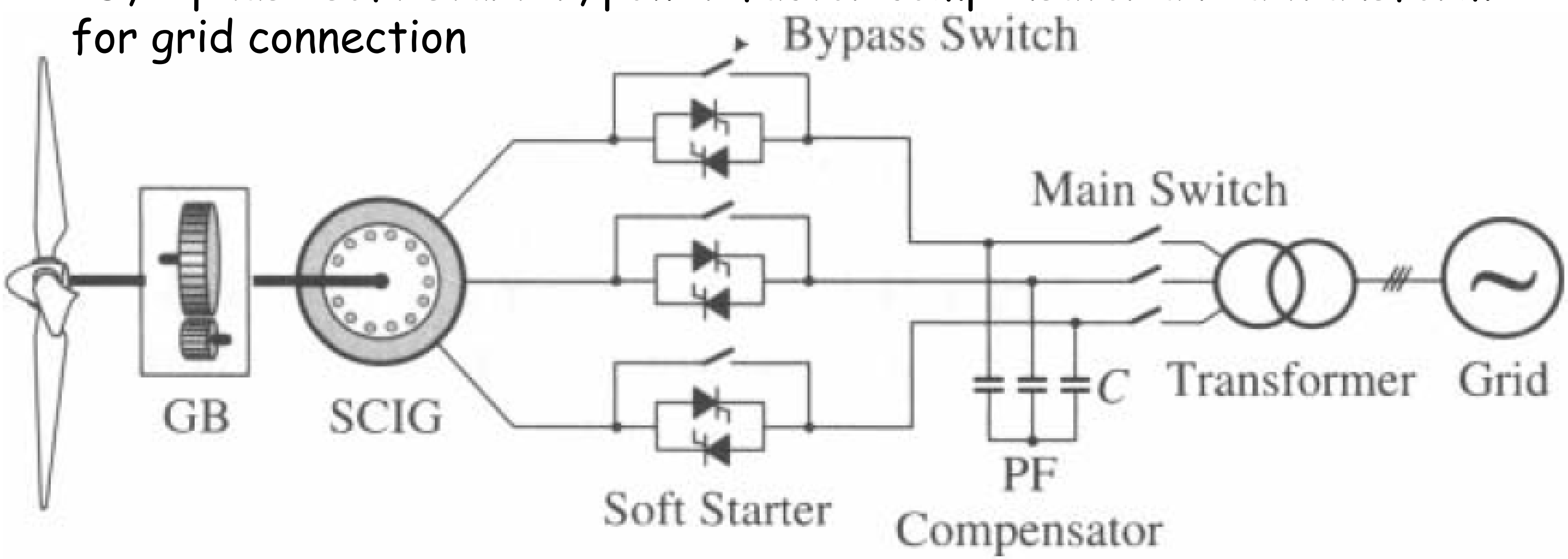

Figure 6-1. Configuration of fixed-speed SCIG wind energy conversion system.

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Source: [1]

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Fixed Speed Square Cage Induction Generator

1. Wind Turbine

- It convert wind energy into rotational mechamnical energy
- It generate power when the speed higher that the cut of speed (3-4m/s)
- The rated speed around 12-15 m/s

2. Gearbox

- The rotating speed of large fixed-speed wind turbine is normally in 6 to 25 rpm range
- Induction generator operate at high speed for example 50 hz, 2 pole induction generator operate at 3000rpm
- Gearbox is necessary to step up the wind turbine speed to thre SCIG speed

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Fixed Speed Square Cage Induction Generator

Table 6-1. Examples of gear ratios for fixed-speed WECS (rated slip = –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

Source: [1]

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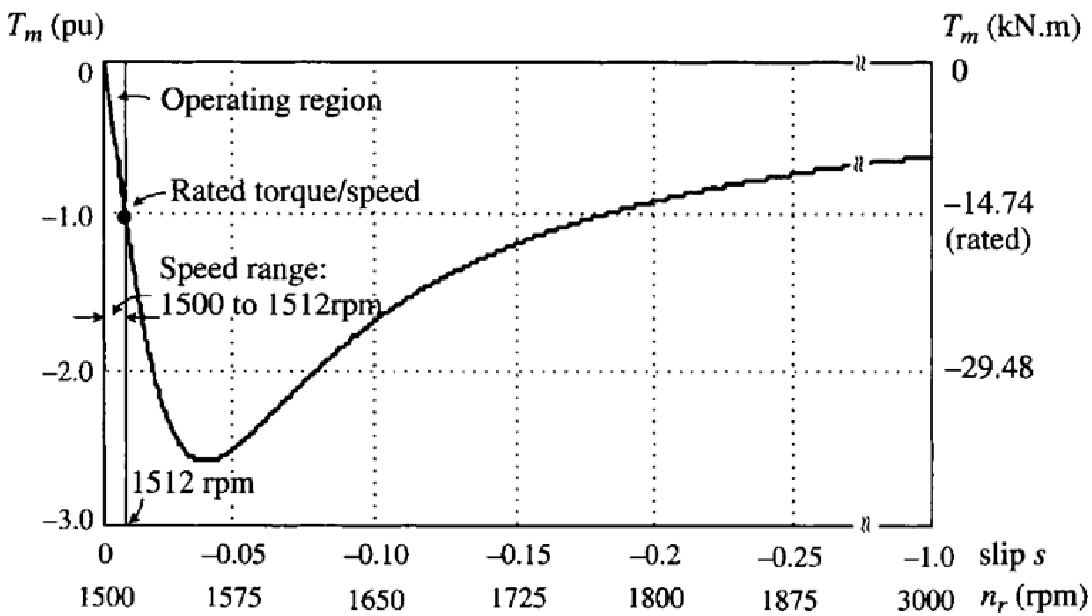
Fixed Speed Square Cage Induction Generator

3. Generator

- Square-cage IG is preferred for fixed speed wind turbine
- It rage from few kilowatts to megawatts
- Torque-versus-speed curve of a 2.3 MW, 690 V, 50 Hz SCIG is shown
-



Source: [1]

Fixed Speed Square Cage Induction Generator

3. 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 basically an AC voltage controller that increases the stator voltage gradually by controlling the firing angles of the SCR devices
- After the full voltage of the grid is applied to the generator,
- the soft starter is shorted by a bypass switch to eliminate the conduction losses of the SCR devices.

Source: [1]

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Fixed Speed Square Cage Induction Generator

3. Reactive Power Compensation

- The squirrel-cage induction generator draws lagging (inductive) reactive power from the grid during operation.
- A PF compensator device is normally installed to meet the grid code for reactive power compensation.
- The most commonly used PF compensator for the fixed-speed wind energy system is a power capacitor
- To effectively compensate the reactive power of the system over the full operating range, a number of capacitor banks can be used,
- which can be switched in or out of the system for optimal results

Source: [1]

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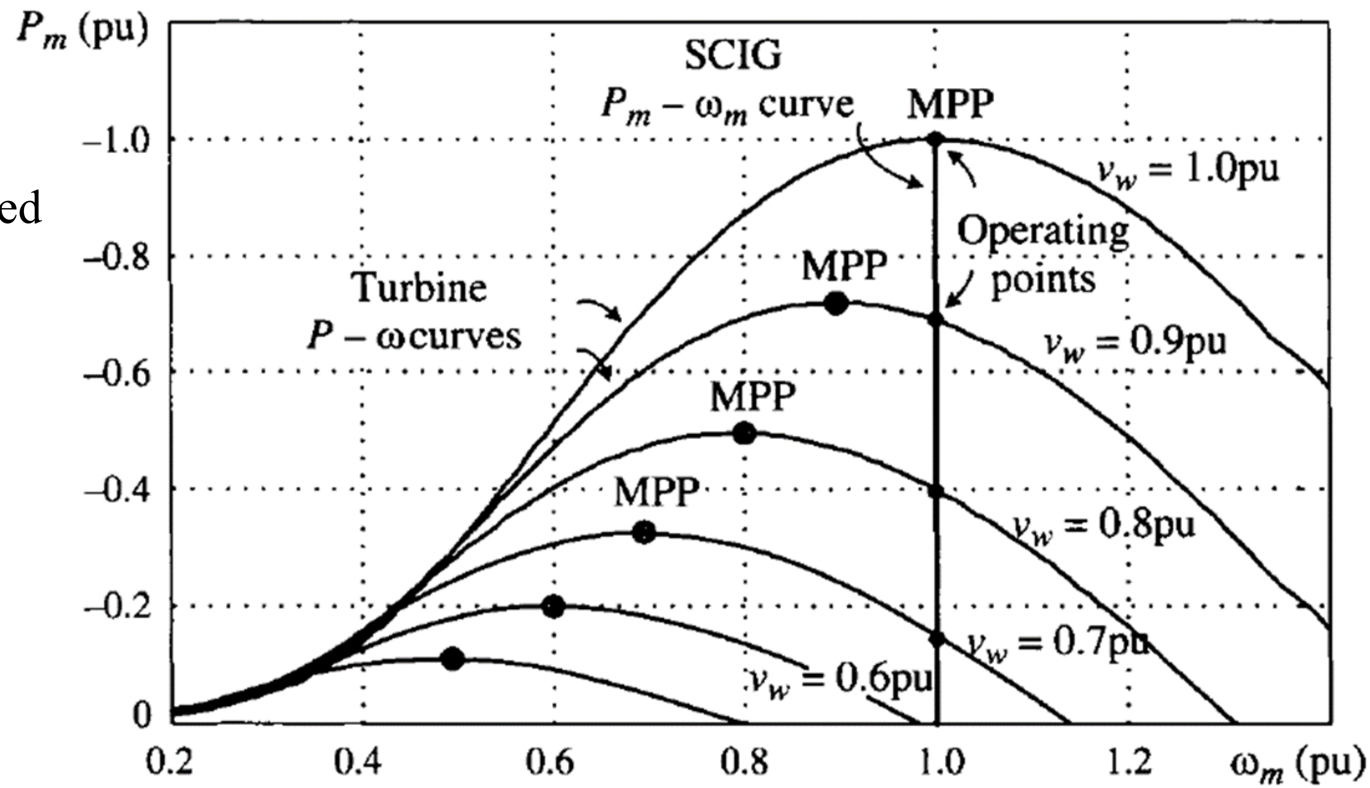
Fixed Speed Induction Generator Operation

Fixed-Speed Operation of SCIG

- the power-versus-speed characteristics of both wind turbine and generator are illustrated

where *Pm* is the mechanical power applied to the shaft of the generator and *wm* is the mechanical speed of the generator



Source: [1]

Fixed Speed Induction Generator Operation

Fixed-Speed Operation of SCIG

- For the fixed-speed WECS, the system can operate only at one MPP, which is at the rated wind speed of 1.0 pu
- At the other wind speeds, the system operates at the points that are lower than MPP and,
- therefore, cannot capture the maximum power available from the wind,
- leading to lower power-conversion efficiency.
- In particular, when the wind speed is below 0.6 pu, no power can be captured by the system [1]

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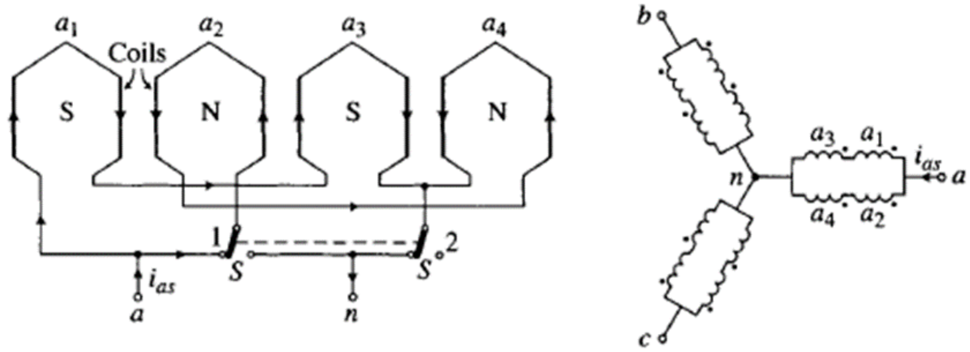
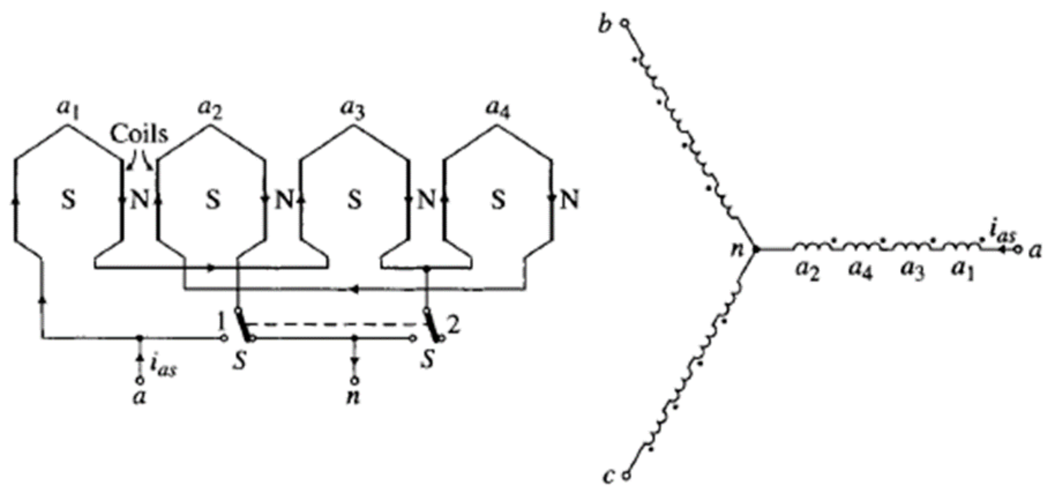
Fixed Speed Induction Generator Operation

Two Speed Operation of Fixed-Speed WECS

- By changing number of poles, the generator can operate at two different rotor speeds that are slightly higher than its synchronous speed.



(a) 4-pole configuration



Source: [1]

(b) 8-pole configuration

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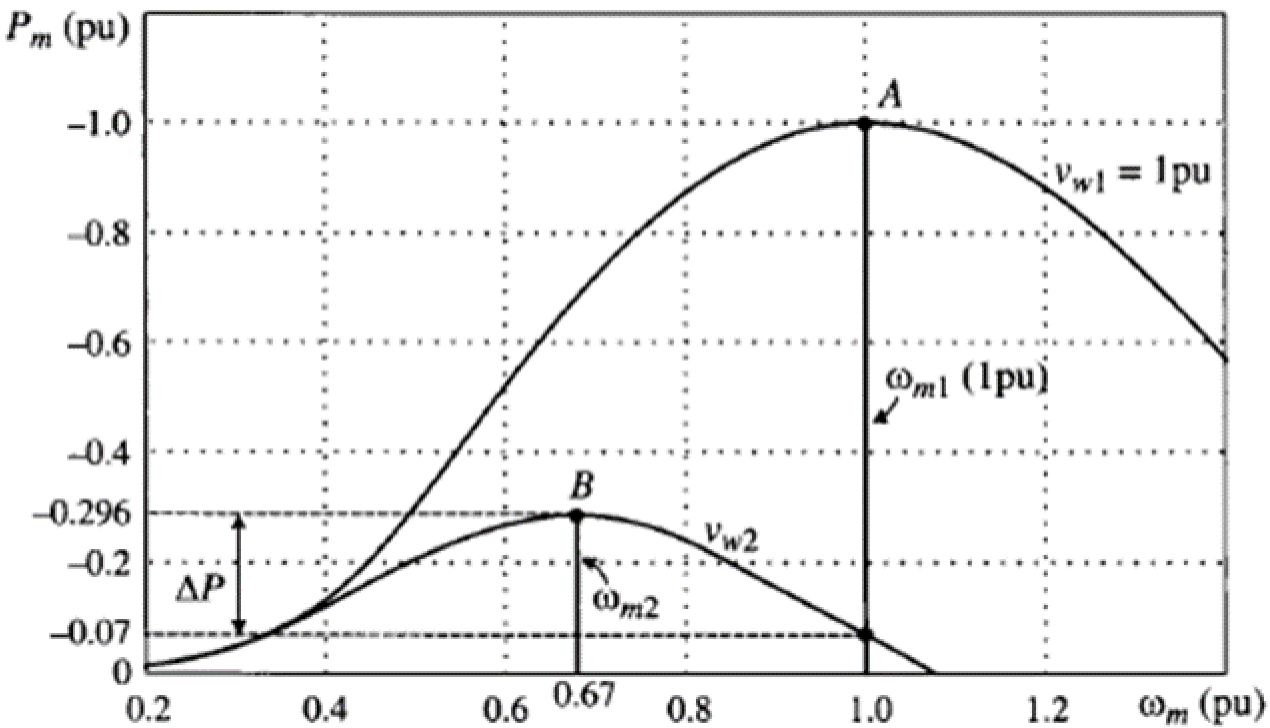
Fixed Speed Induction Generator Operation

Two Speed Operation of Fixed-Speed WECS

- Power versus rotor speed characteristics of SCIG WECS with two fixed rotor speeds

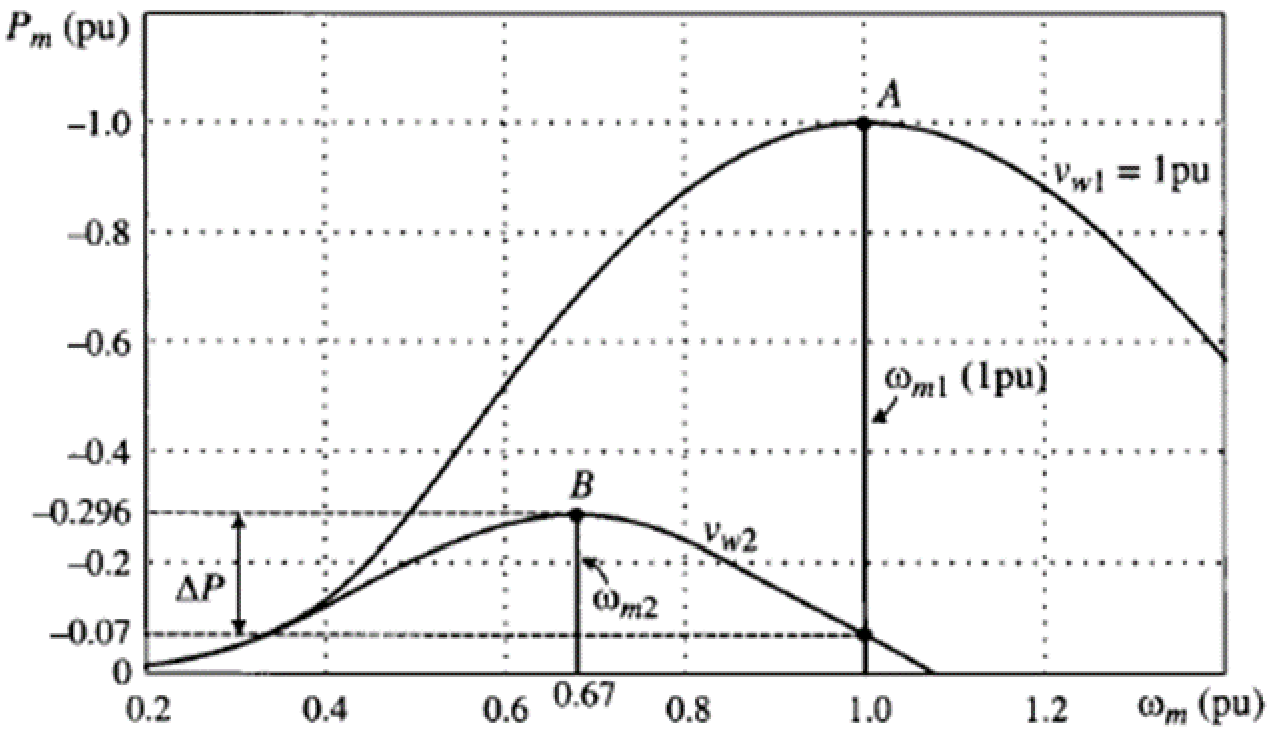


Source: [1]

Fixed Speed Induction Generator Operation

Two Speed Operation of Fixed-Speed WECS

- Power versus rotor speed characteristics of SCIG WECS with two fixed rotor speeds



Source: [1]

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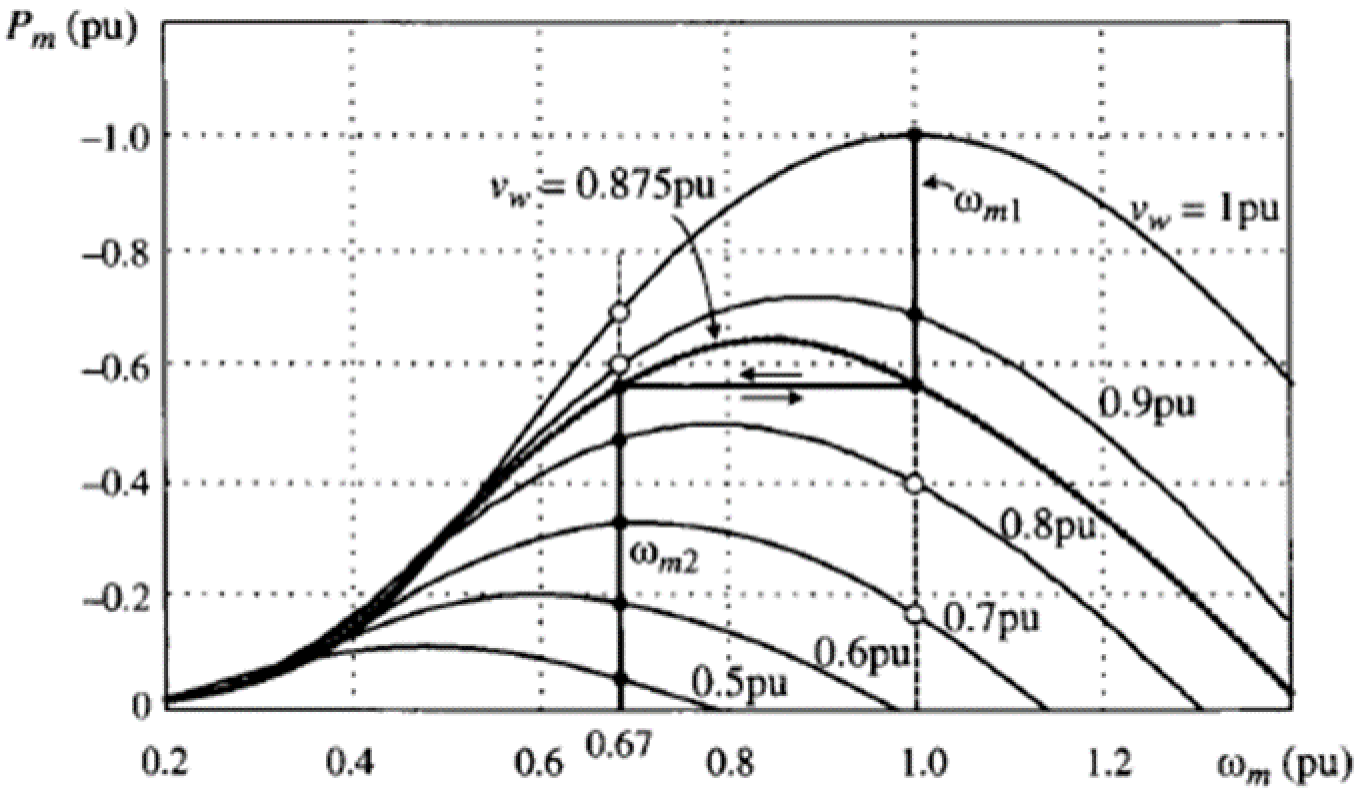
Fixed Speed Induction Generator Operation

Two Speed Operation of Fixed-Speed WECS

- Switch between the two fixed rotor speeds ω_{m1} and ω_{m2}



Source: [1]

Case Study

Soft Start of Fixed-Speed WECS

- A 2.3 MW, 690 V, 50 Hz, 1512 rpm squirrel-cage induction generator is used in the study
- When the wind speed is higher than its cut-in speed, the pitch angle of the blade is slightly adjusted, and a small amount of torque is produced to accelerate the turbine and the generator
- Although the generator is rotating during the acceleration period, no stator voltage is induced due to the lack of magnetizing current to produce a magnetic flux that is needed to generate the stator voltage.
- When the rotor speed is close to its synchronous speed (0.959 pu, 1450 rpm), the generator is connected to the grid by the main switch
- At the same time, the soft starter is activated with a large firing angle of 120°
- The firing angle is then decreased gradually from 120° to 0° in 0.5 sec, at which the full grid voltage is applied to the generator

Source: [1]

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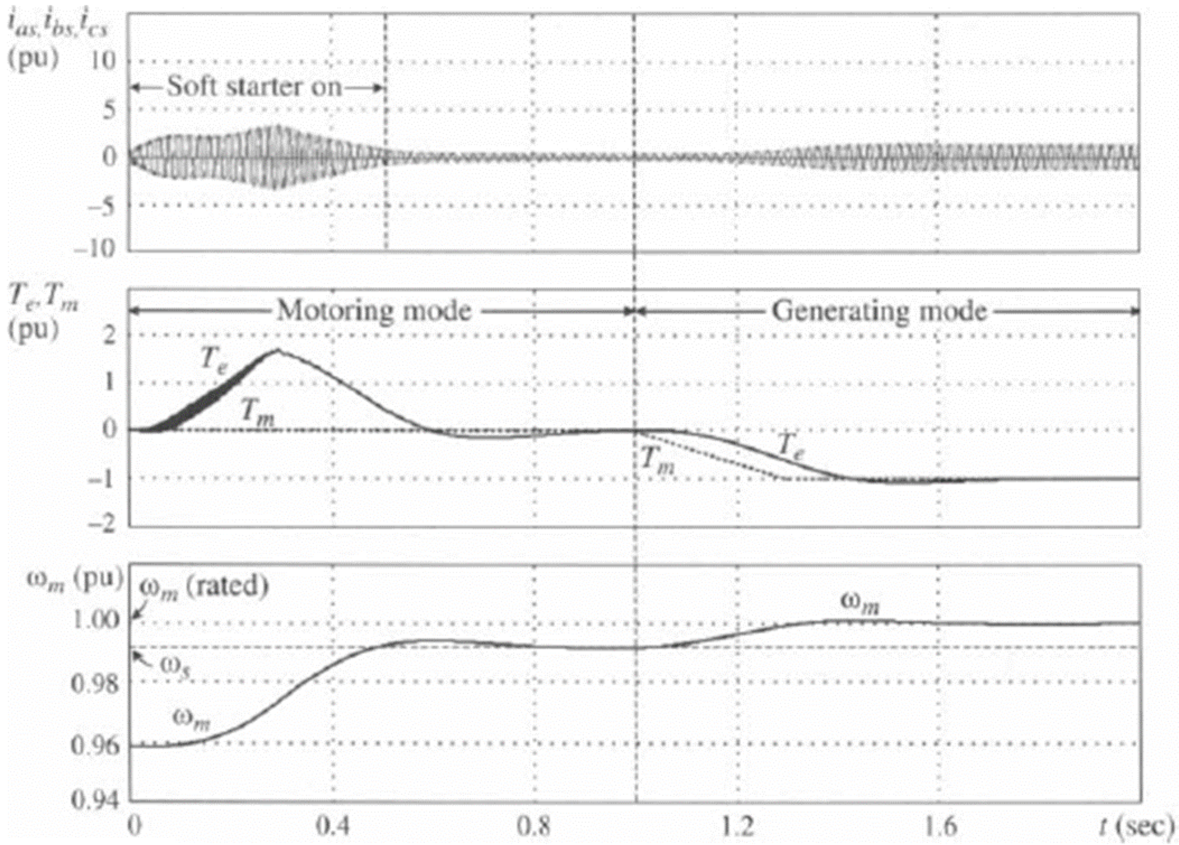
Case Study

Soft Start of Fixed-Speed WECS

- Startup transients of fixed-speed WECS with a soft starter



Source: [1]

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Case Study

- **REACTIVE POWER COMPENSATION**
- The induction generator in a fixed-speed wind energy system draws reactive power from the grid.
- In a variable-speed WECS, the reactive power control is usually realized by power converters that connect the generator to grid.
- However, this method is not applicable in fixed-speed WECS.
- To meet the grid code, the reactive power of fixed speed wind energy systems has to be compensated
- The amount of reactive power Q drawn by an induction generator varies with the active stator power *Ps* or the slip of the generator.
- The generator draws reactive power close to a third of the total power rating when it is not delivering any active power to the grid.

Source: [1]

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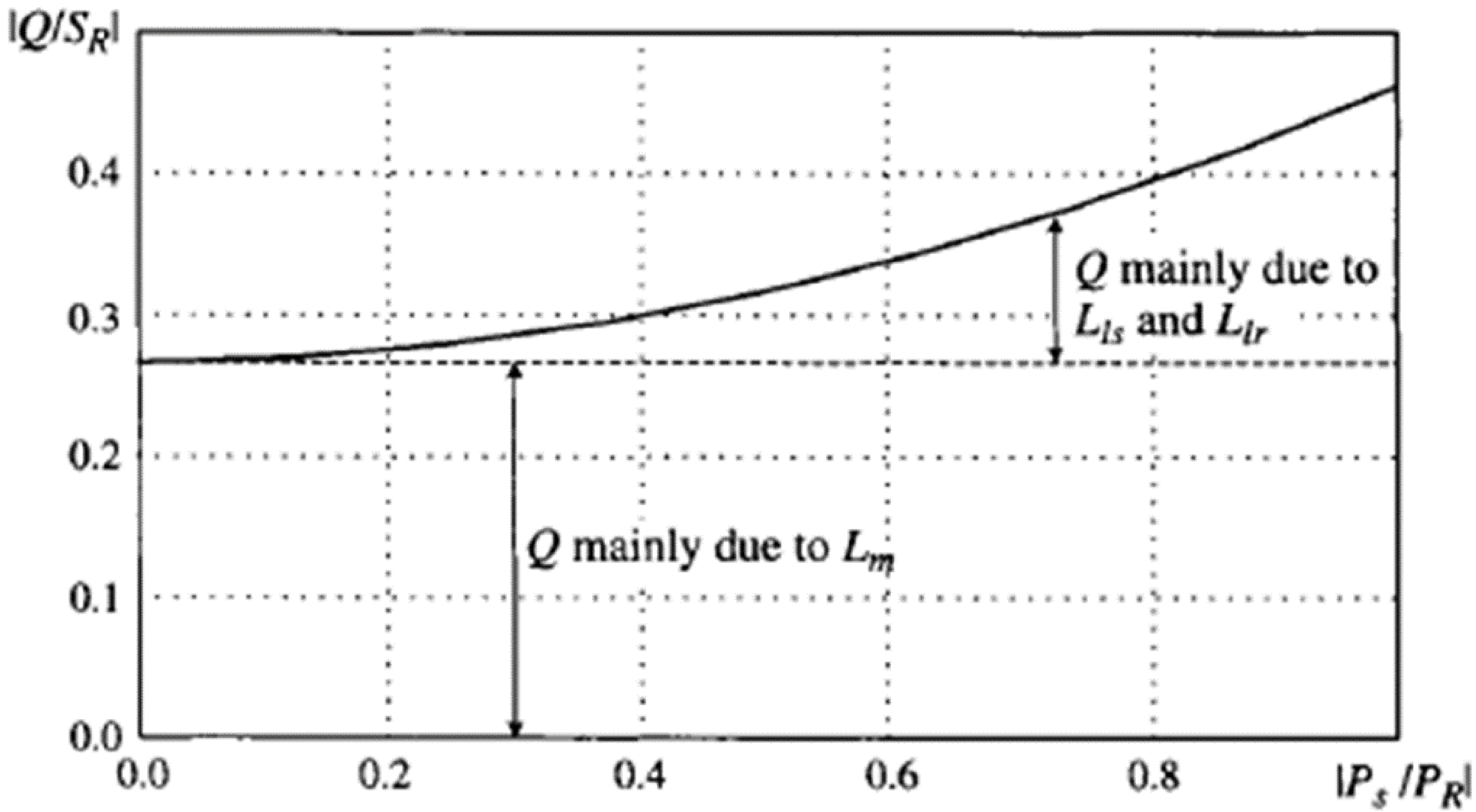
Case Study

- **REACTIVE POWER COMPENSATION**
- Typical characteristics of reactive versus active power of a squirrel-cage induction generator



Source: [1]

REACTIVE POWER COMPENSATION

- Consider a 2.3 MW, 690 V, 50 Hz, 1512 rpm SCIG fixed-speed wind energy system. The generator parameters are given in Table B-l of Appendix B [1]. The system is connected to a grid of 690 V/50 Hz (assuming the transformer turns ratio of 1:1 for simplicity).
- The generator operates under the rated conditions with its rated speed of 1512 rpm, based on which the slip of the generator is

$$s = \frac{1500 - 1512}{1500} = -0.008$$

- the impedance of the induction generator can be calculated by

$$\bar{Z}_s = R_s + jX_{ls} + jX_m \left(\frac{R_r}{s} + jX_{lr} \right) = 0.1837\angle 152.58°\ \Omega$$

- The stator current is then determined by

$$\bar{I}_s = \frac{\bar{V}_s}{\bar{Z}_s} = \frac{690/\sqrt{3}\angle 0°}{0.1837\angle 152.58°} = 2168\angle -152.58°\ \text{A}\ \ (1\ \text{pu}) \qquad PF_s = \cos\varphi_s = -0.888$$

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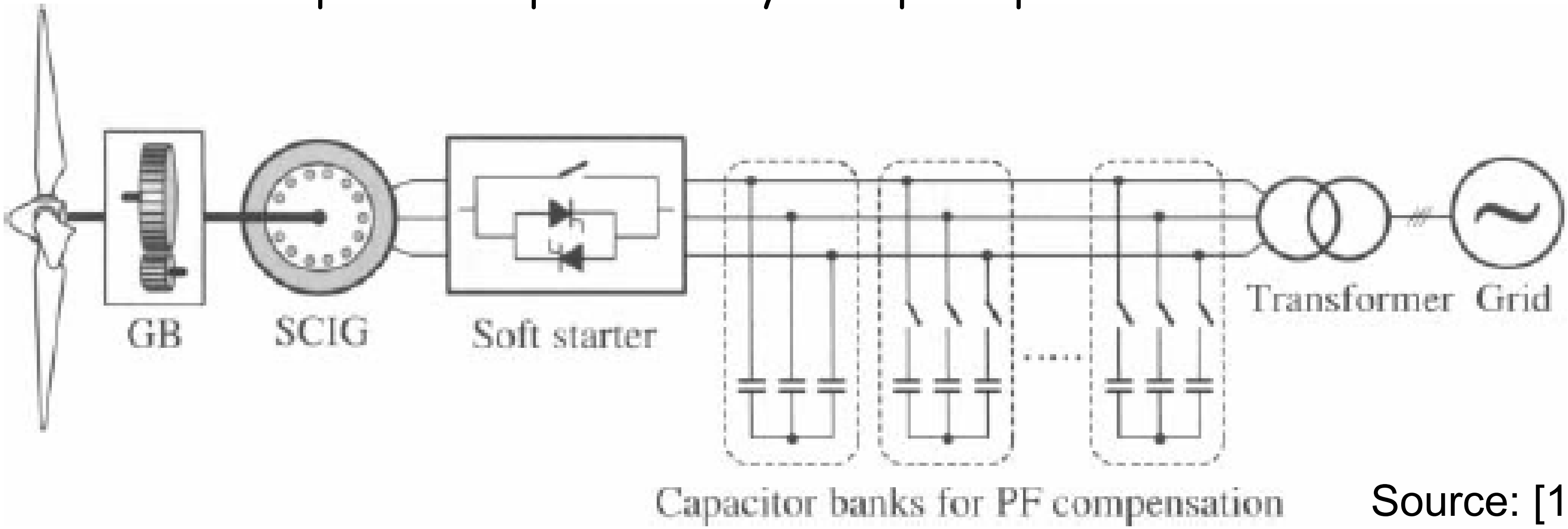
Source: [1]

Case Study

- **REACTIVE POWER COMPENSATION**
  - Reactive power compensation by multiple capacitor banks



Source: [1]

The stator apparent, active, and reactive power are calculated by

$$\begin{cases} S_s = 3V_sI_s = 3\times 398.4\times 2168 = 2.591\ \text{MVA} \\ P_s = S_s\cos(\phi_s) = -2.3\ \text{MW} \\ Q_s = S_s\sin(\phi_s) = 1.193\ \text{MVAR} \end{cases}$$

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Case Study

REACTIVE POWER COMPENSATION

- To compensate for the lagging reactive power drawn by the induction generator, a three-phase capacitor *Cx* is connected to the system
- The reactive power provided by the capacitor can be calculated by

$$Q_c = 3V_c I_c = 3(V_s)^2 \omega_s C_1$$

- where *Ic* is the capacitor current; *Vc* is the capacitor voltage,; and *ωs* is the stator/grid angular frequency

$$Q_c = 3(V_s)^2 \omega_s C_1 = 1.193 \text{ MVAR}$$

$$C_1 = \frac{Q_c}{3(V_s)^2 \omega_s} = \frac{1.193 \times 10^6}{3 \times (398.4)^2 \times (2\pi \times 50)} = 7{,}975\ \mu\text{F}$$

Source: [1]

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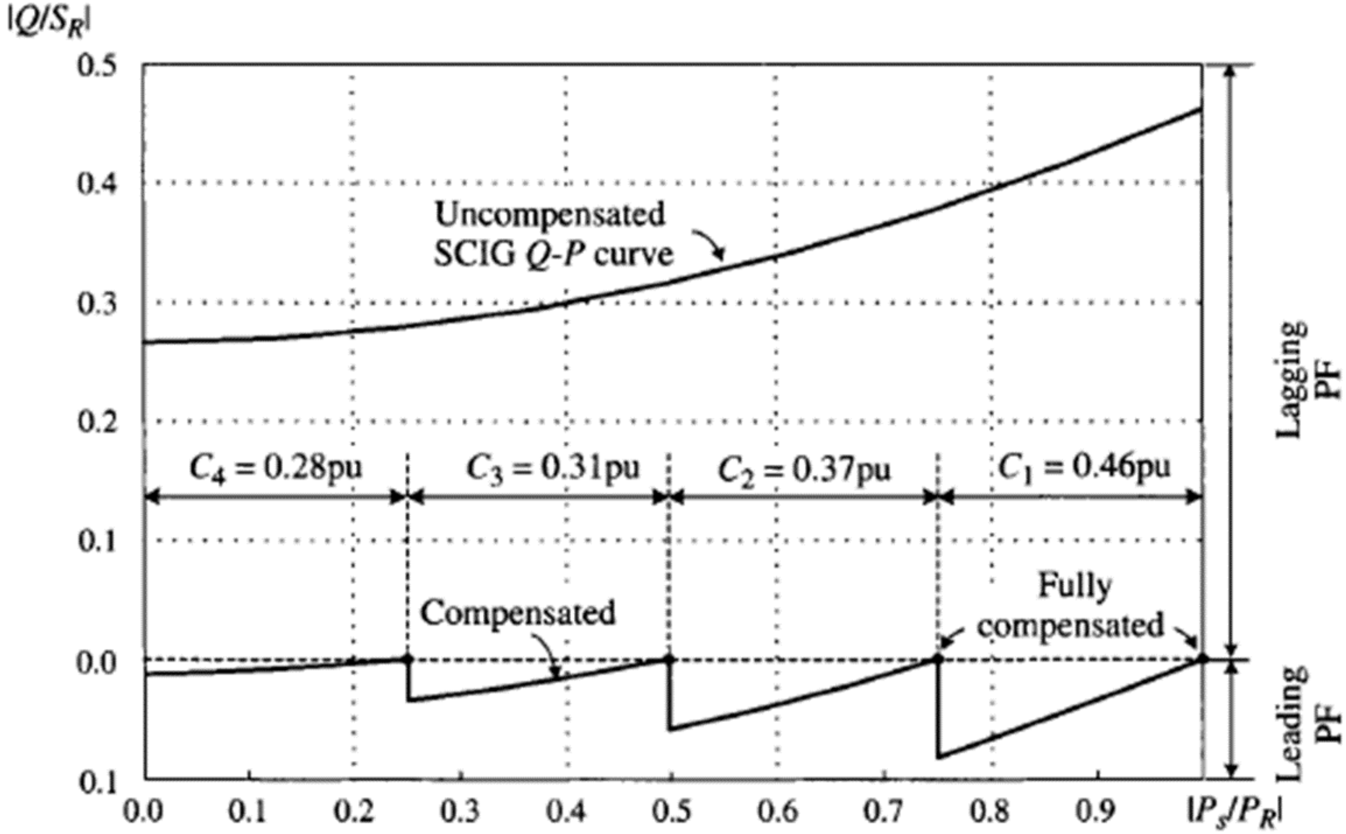
REACTIVE POWER COMPENSATION

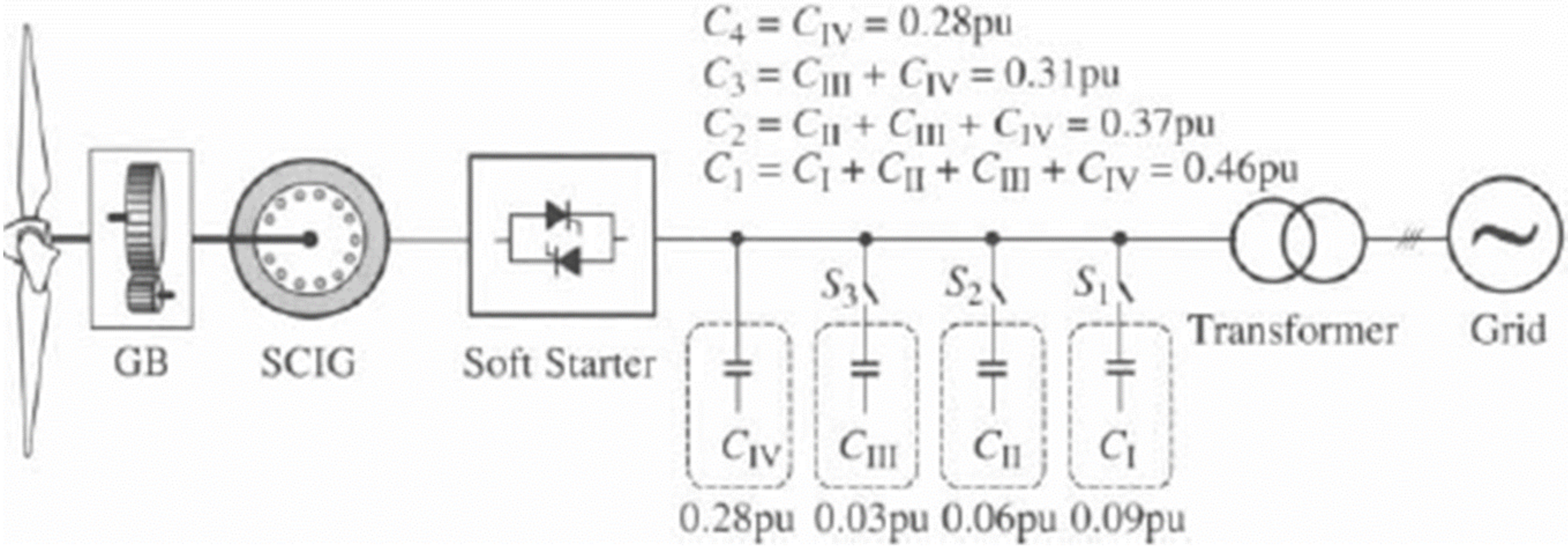
- Reactive power compensation by capacitor banks



Source: [1]

REACTIVE POWER COMPENSATION

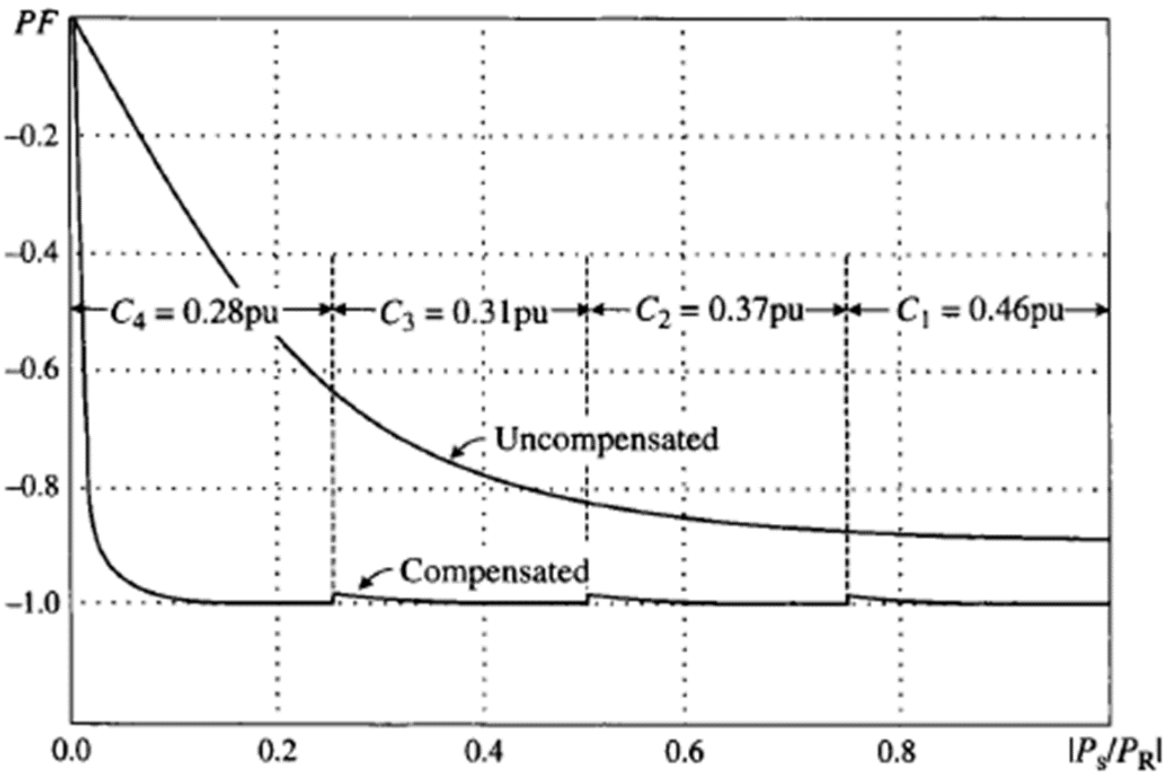
- Connection of capacitors for reactive power compensation over the full operatingrange



Source: [1]

REACTIVE POWER COMPENSATION

- Power factor improvement through reactive power compensation by capacitor banks



Source: [1]

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Recommended literature

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] https://www.ewea.org European Wind Energy Association
[8] https://www.indea.org World Wind Energy Association
[9] https://www.awea.org American Wind Energy Association

Recommended literature

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

Introduction to Wind Energy

Module 2.1

Further information:

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Introduction to Wind Energy

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:

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. *Operation of DFIG WEC systems*
2. *Stator Voltage Control of DFIG WEC systems*
3. *Start Up of DFIG WEC systems*

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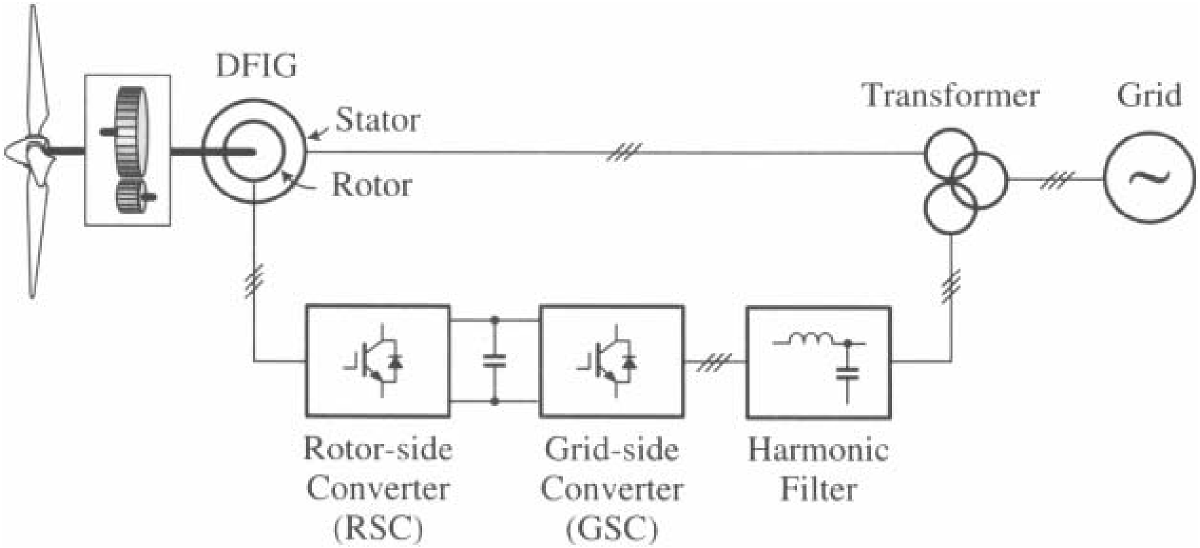
Operation of DFIG WEC systems

- The doubly fed induction generator (DFIG) wind energy system is widely accepted in today's wind energy industry
- The DFIG is essentially a wound rotor induction generator
- The rotor circuit can be controlled by external devices to achieve variable speed operation.
- A typical block diagram of the DFIG wind energy system is shown



Source: [1]

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Operation of DFIG WEC systems

- The stator of the generator is connected to the grid through a transformer, whereas the rotor connection to the grid is done through power converters, harmonic filters, and the transformer.
- The power rating for the DFIG is normally in the range of a few hundred kilowatts to several megawatts.
- The stator of the generator delivers power from the wind turbine to the grid and, therefore, the power flow is unidirectional.
- However, the power flow in the rotor circuit is bidirectional, depending on the operating conditions
- The power can be delivered from the rotor to the grid and vice versa through rotor-side converter (RSCs) and grid-side converters (GSCs)
- Since the maximum rotor power is approximately 30% of the rated stator power, the power rating of the converters is substantially reduced in comparison to the WECS with full-capacity converters

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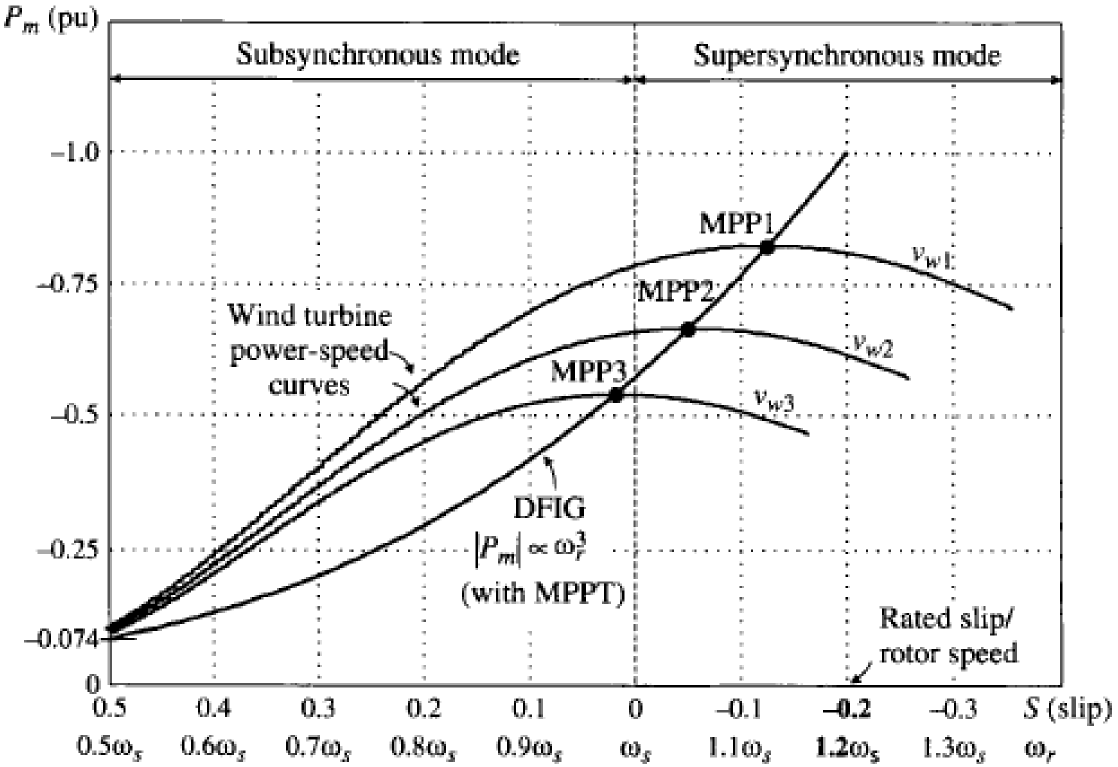
Operation of DFIG WEC systems

SUPER- AND SUBSYNCHRONOUS OPERATION OF DFIG

Mechanical power *Pm* versus slip s characteristics of a DFIG wind energy system.



Source: [1]

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Operation of DFIG WEC systems

SUPER- AND SUBSYNCHRONOUS OPERATION OF DFIG

- The negative value of mechanical power indicates that the DFIG is in the generating mode
- Since the rotor speed of the DFIG is adjustable, one of the maximum power point tracking (MPPT) schemes can be implemented to harvest the maximum available power from the wind turbine
- Depending on the rotor speed, there are two modes of operation in a DFIG WECS :

(1) supersynchronous mode, in which the generator operates above the synchronous speed; and

(2) subsynchronous mode, in which the generator operates below the synchronous speed

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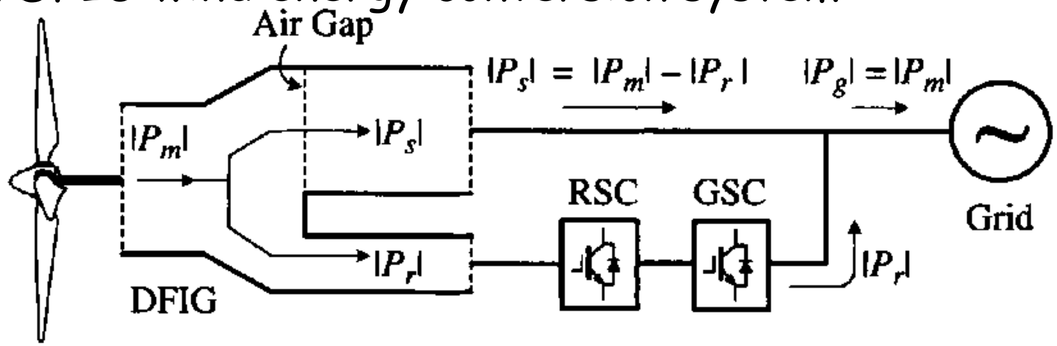
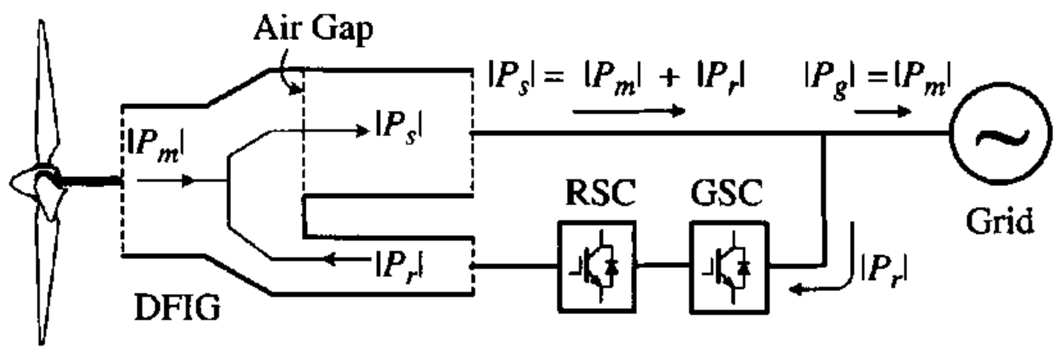
Operation of DFIG WEC systems

SUPER- AND SUBSYNCHRONOUS OPERATION OF DFIG

- Power flow in DFIG wind energy conversion system



(a) Supersynchronous mode



(b) Subsynchronous mode

Source: [1]

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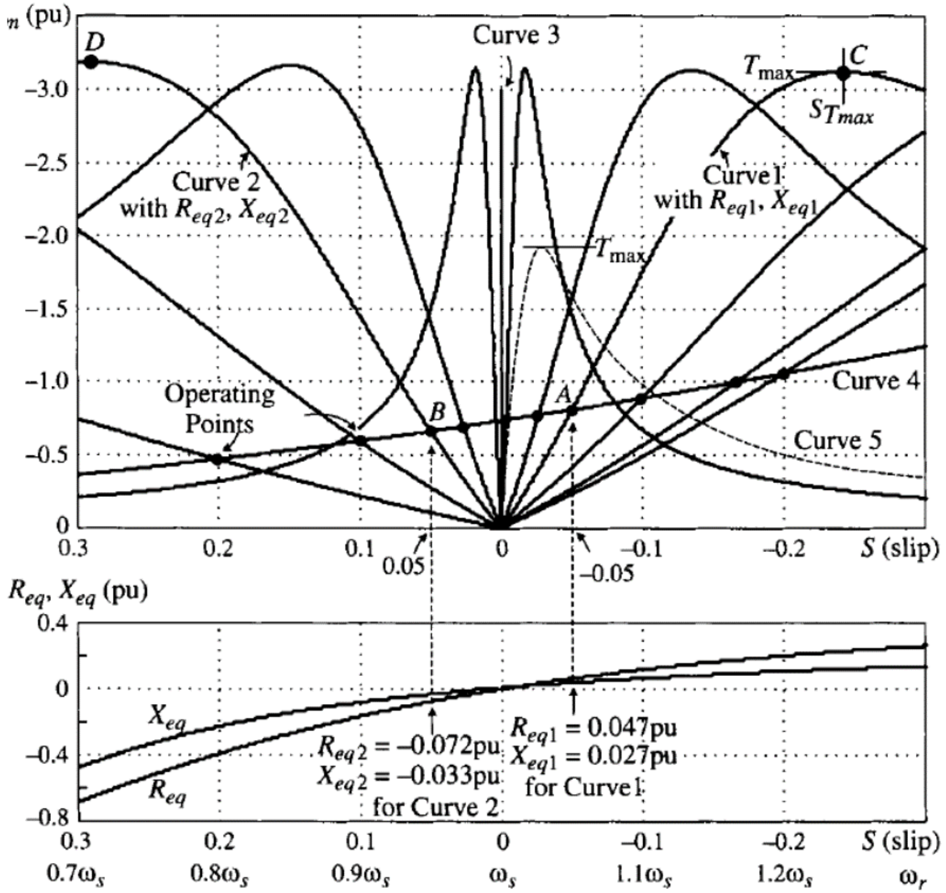
Operation of DFIG WEC systems

Torque-Slip Characteristics of DFIG WECS



Source: [1]

Operation of DFIG WEC systems

Torque-Slip Characteristics of DFIG WECS

Table -1. Equivalent impedance of RSC in 1.5 MW/690 V DFIG WECS ($PF_s = 1$)

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

Source: [1]

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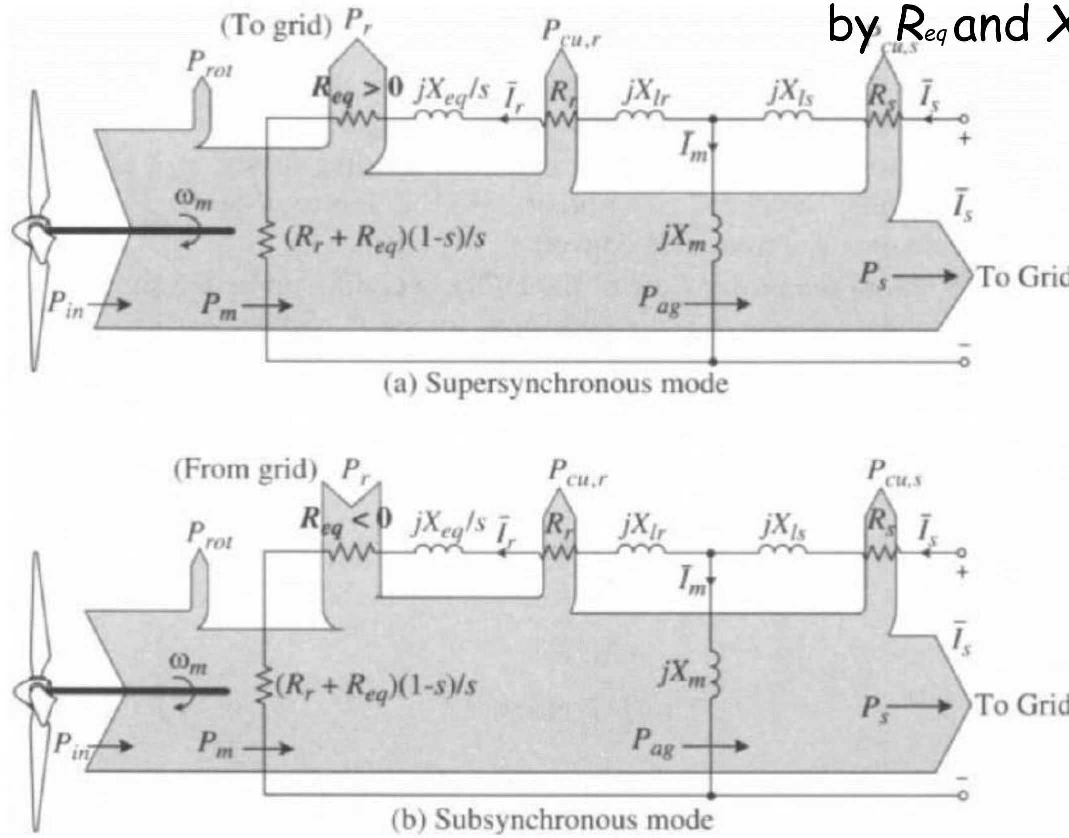
Operation of DFIG WEC systems

Torque-Slip Characteristics of DFIG WECS

- Power flow of DFIG with rotor-side converter represented by R_{eq} and X_{eq}



(a) Supersynchronous mode

(b) Subsynchronous mode

Source: [1]

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Operation of DFIG WEC systems

Torque-Slip Characteristics of DFIG WECS

Table 8-2. Three operating modes of 1.5 MW/690 V DFIG WECS ($PF_s = 1$)

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

Source: [1]

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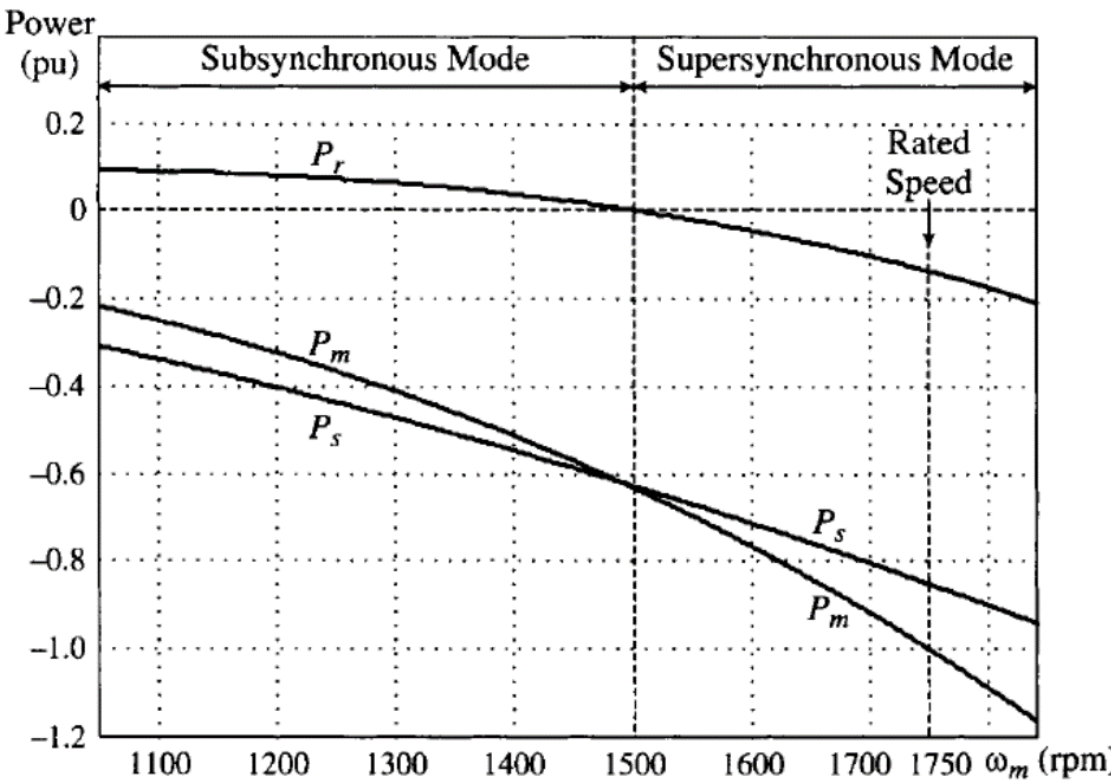
Operation of DFIG WEC systems

Torque-Slip Characteristics of DFIG WECS

- Stator, rotor, and mechanical power of the 1.5 MW/690 V DFIG operating at super-and sub-synchronous speeds.



Source: [1]

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STATOR VOLTAGE ORIENTED CONTROL OF DFIG WECS

Principle of Voltage Oriented

- In DFIG, the stator of the generator is directly connected to the grid,
- its voltage and frequency can be considered constant under the normal operating conditions.
- Stator voltage oriented control (SVOC) for the DFIG is used
- The rotor or stator-flux field oriented controls (FOC) are normally used
- The stator voltage oriented control is achieved by aligning the dq-axis of the synchronous reference frame with the stator
- The resultant d- and q-axis stator voltages are

$$v_{qs} = 0 \quad \text{and} \quad v_{ds} = v_s$$

- The rotating speed o rence frame is given by

$$\omega_s = 2\pi f_s$$

Source: [1]

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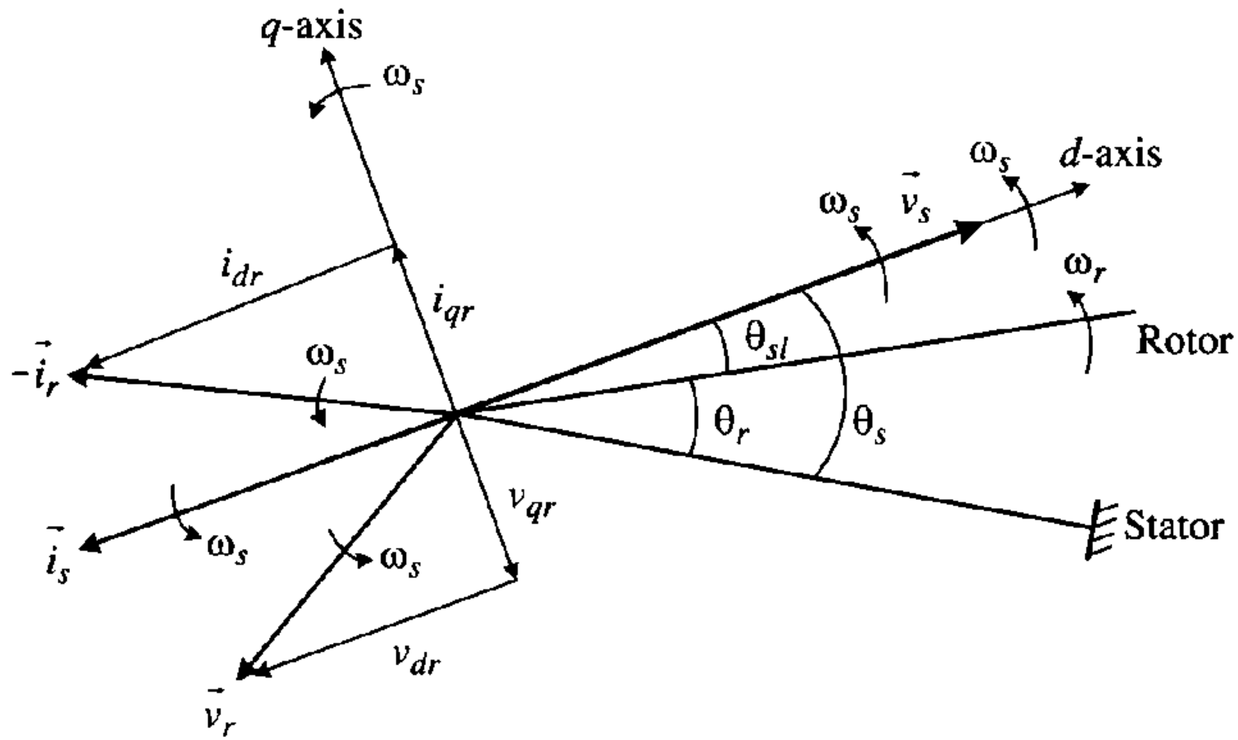
STATOR VOLTAGE ORIENTED CONTROL OF DFIG WECS

Principle of Voltage Oriented

Space-vector diagram of DFIG with SVOC in the supersynchronous mode



Source: [1]

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STATOR VOLTAGE ORIENTED CONTROL OF DFIG WECS

Principle of Voltage Oriented

where v_s is the magnitude of $\vec{v}_s$ (also the peak value of the three-phase stator voltage). The rotating speed of the synchronous reference frame is given by

$$\omega_s = 2\pi f_s$$

where f_s is the stator frequency of the generator (also the frequency of the grid voltage). The stator voltage vector angle θ_s is referenced to the stator frame, which varies from zero to 2π when $\vec{v}_s$ rotates one revolution in space.

The rotor rotates at speed ω_r. The rotor position angle θ_r is also referenced to the stator frame. The angle between the stator voltage vector and the rotor is the slip angle, defined by

$$\theta_{sl} = \theta_s - \theta_r$$

Source: [1]

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STATOR VOLTAGE ORIENTED CONTROL OF DFIG WECS

Principle of Voltage Oriented

- the electromagnetic torque of the generator can be expressed as

$$T_e = \frac{3P}{2}(i_{qs}\lambda_{ds} - i_{ds}\lambda_{qs})$$

where λ_{ds} and λ_{qs} are the *dq*-axis stator flux linkages, given

$$\begin{cases} \lambda_{ds} = L_s i_{ds} + L_m i_{dr} \\ \lambda_{qs} = L_s i_{qs} + L_m i_{qr} \end{cases}$$

from which the *dq*-axis stator currents are calculated to be

$$\begin{cases} i_{ds} = \dfrac{\lambda_{ds} - L_m i_{dr}}{L_s} \\ i_{qs} = \dfrac{\lambda_{qs} - L_m i_{qr}}{L_s} \end{cases} \longrightarrow T_e = \frac{3PL_m}{2L_s}(-i_{qr}\lambda_{ds} + i_{dr}\lambda_{qs})$$

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Source: [1]

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STATOR VOLTAGE ORIENTED CONTROL OF DFIG WECS

Principle of Voltage Oriented

- the stator voltage vector for the steady-state operation of the generator is $\vec{v}_s = R_s\vec{i}_s + j\omega_s\vec{\lambda}_s$

- The representation in *dq-axis* is

$$(v_{ds} + jv_{qs}) = R_s(i_{ds} + ji_{qs}) + j\omega_s(\lambda_{ds} + j\lambda_{qs})$$

$$\begin{cases} \lambda_{ds} = \dfrac{v_{qs} - R_s i_{qs}}{\omega_s} \\ \lambda_{qs} = -\dfrac{v_{ds} - R_s i_{ds}}{\omega_s} \end{cases} \longrightarrow \begin{aligned} T_e &= \frac{3PL_m}{2\omega_s L_s}(-i_{qr}(v_{qs} - R_s i_{qs}) - i_{dr}(v_{ds} - R_s i_{ds})) \\ &= \frac{3PL_m}{2\omega_s L_s}(-i_{qr}v_{qs} + R_s i_{qs} i_{qr} + R_s i_{ds} i_{dr} - i_{dr} v_{ds}) \end{aligned}$$

$$T_e = \frac{3PL_m}{2\omega_s L_s}(R_s i_{qs} i_{qr} + R_s i_{ds} i_{dr} - i_{dr} v_{ds})$$

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Source: [1]

STATOR VOLTAGE ORIENTED CONTROL OF DFIG WECS

Principle of Voltage Oriented

- Ignoring the stator resistance *Rs*, which is normally very low for large DFIG, the torque equation can be further simplified

$$T_e = -\frac{3PL_m}{2\omega_s L_s} i_{dr} v_{ds}$$

- The stator active and reactive power can be calculated by

$$\begin{cases} P_s = \frac{3}{2}(v_{ds}i_{ds} + v_{qs}i_{qs}) \\ Q_s = \frac{3}{2}(v_{qs}i_{ds} - v_{ds}i_{qs}) \end{cases} \longrightarrow \begin{cases} P_s = \frac{3}{2} v_{ds}i_{ds} \\ Q_s = -\frac{3}{2} v_{ds}i_{qs} \end{cases} \quad \text{for } v_{qs} = 0$$

Source: [1]

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STATOR VOLTAGE ORIENTED CONTROL OF DFIG WECS

Principle of Voltage Oriented

$$\begin{cases} P_s = \dfrac{3}{2} v_{ds} \left(\dfrac{\lambda_{ds} - L_m i_{dr}}{L_s} \right) \\ Q_s = -\dfrac{3}{2} v_{ds} \left(\dfrac{\lambda_{qs} - L_m i_{qr}}{L_s} \right) \end{cases}$$

$$\begin{cases} i_{dr} = -\dfrac{2L_s}{3v_{ds}L_m} P_s + \dfrac{1}{L_m} \lambda_{ds} \\ i_{qr} = \dfrac{2L_s}{3v_{ds}L_m} Q_s + \dfrac{1}{L_m} \lambda_{qs} \end{cases}$$

$$\begin{cases} i_{dr} = -\dfrac{2L_s}{3v_{ds}L_m} P_s + \dfrac{v_{qs} - R_s i_{qs}}{\omega_s L_m} = -\dfrac{2L_s}{3v_{ds}L_m} P_s - \dfrac{R_s}{\omega_s L_m} i_{qs} \\ i_{qr} = \dfrac{2L_s}{3v_{ds}L_m} Q_s - \dfrac{v_{ds} - R_s i_{ds}}{\omega_s L_m} = \dfrac{2L_s}{3v_{ds}L_m} Q_s + \dfrac{R_s}{\omega_s L_m} i_{ds} - \dfrac{v_{ds}}{\omega_s L_m} \end{cases} \quad \text{for } v_{qs} = 0$$

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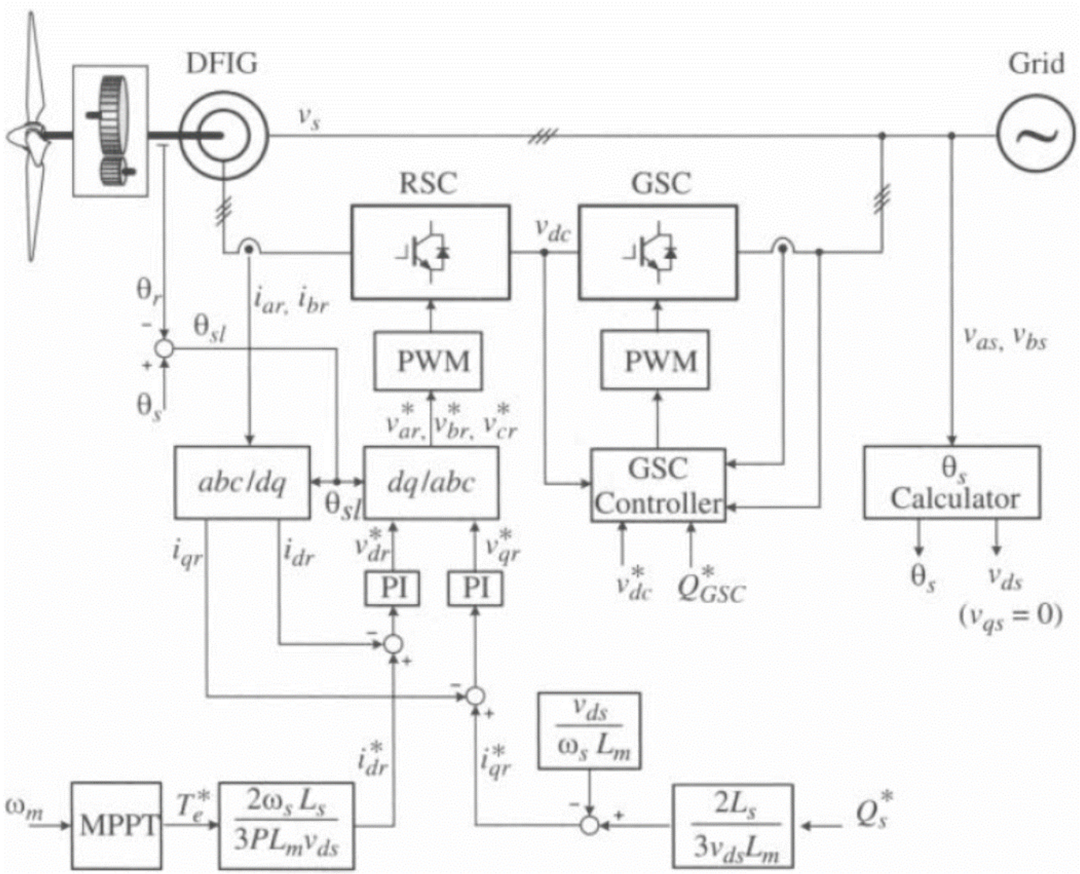
Source: [1]

STATOR VOLTAGE ORIENTED CONTROL OF DFIG WECS

Block Diagram of DFIG



Source: [1]

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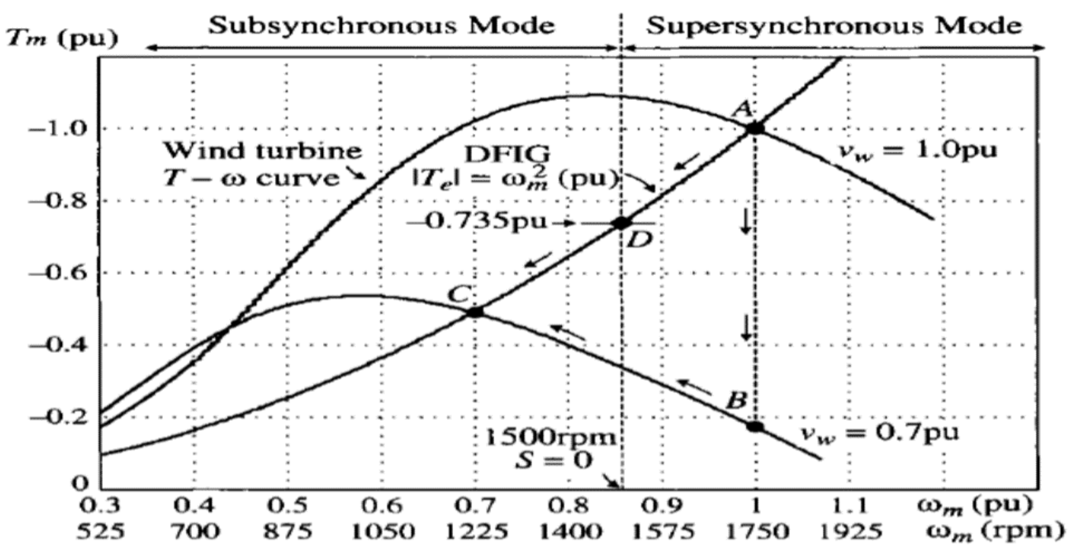
STATOR VOLTAGE ORIENTED CONTROL OF DFIG WECS

Dynamic Performance of DFIG: Case Study

- ***Transients from Supersynchronous to SubsynchronousOperation***
- 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 are illustrated



(a) Torque versus speed

Source: [1]

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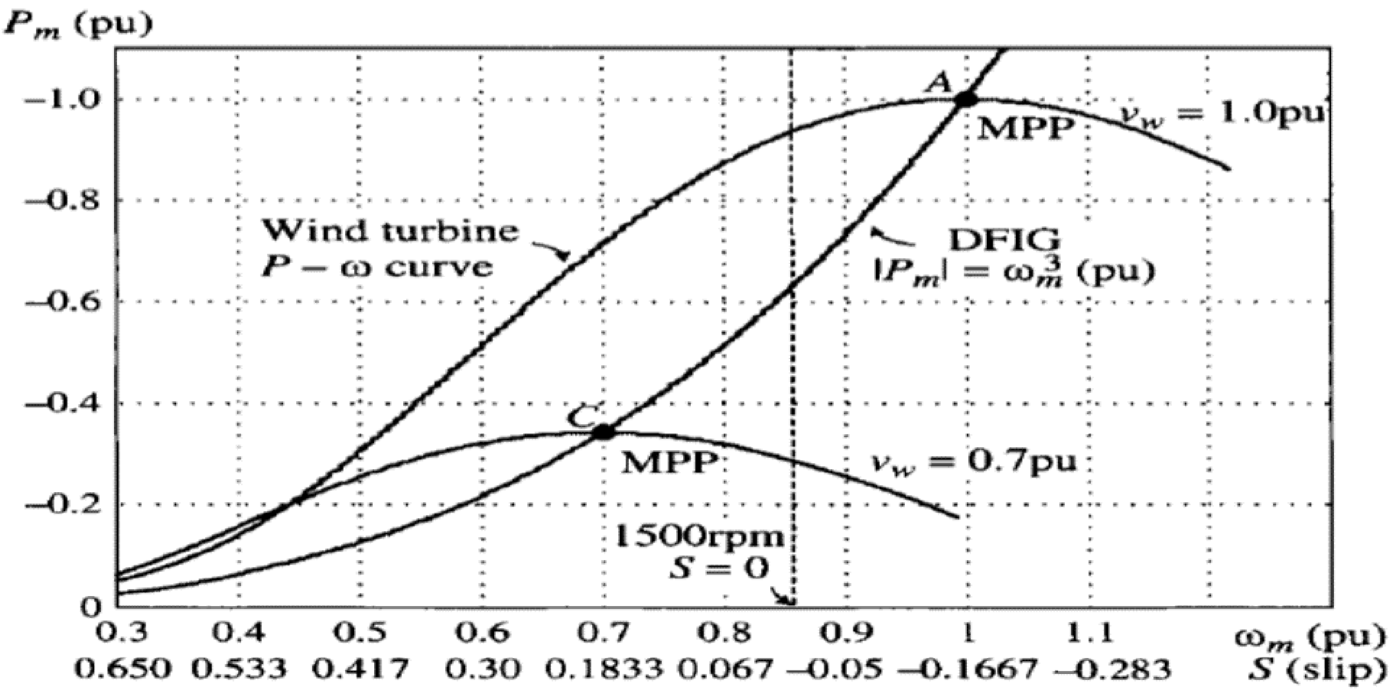
STATOR VOLTAGE ORIENTED CONTROL OF DFIG WECS

Dynamic Performance of DFIG: Case Study



(b) Power versus speed

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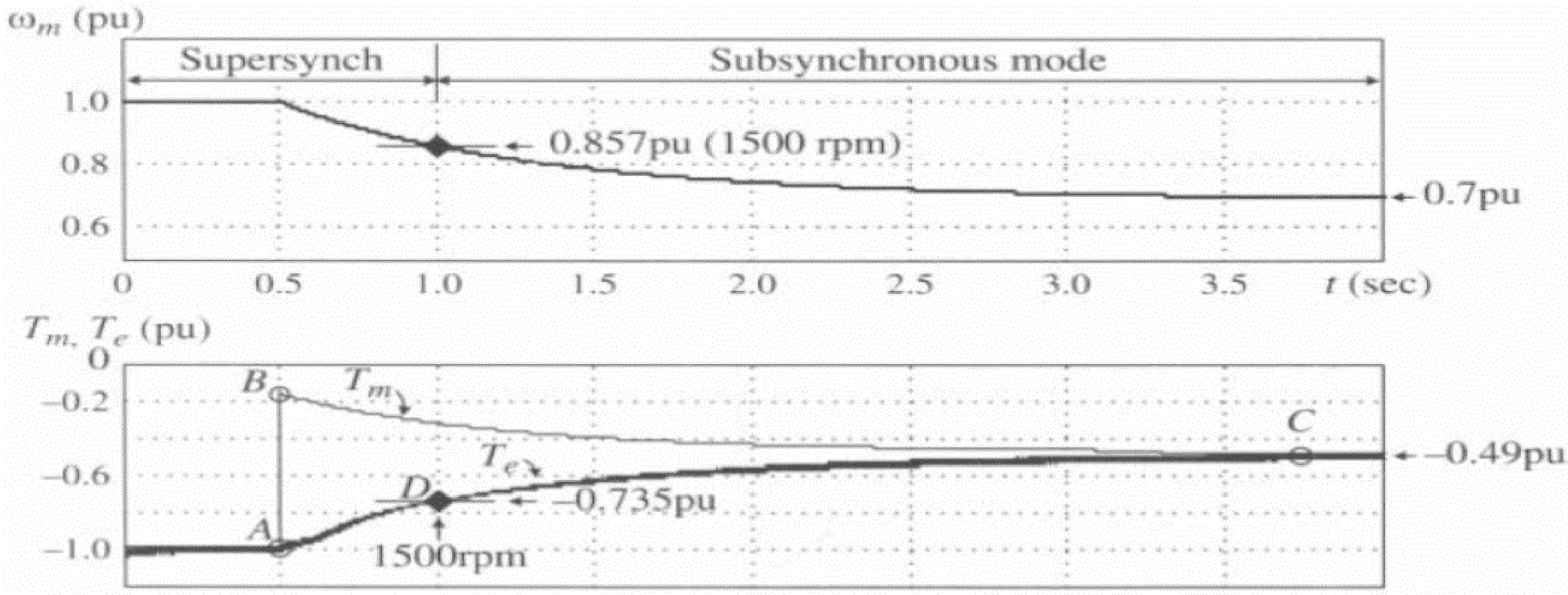
Source: [1]

STATOR VOLTAGE ORIENTED CONTROL OF DFIG WECS

Dynamic Performance of DFIG: Case Study

- Transients of DFIG WECS from supersynchronous to subsynchronous mode

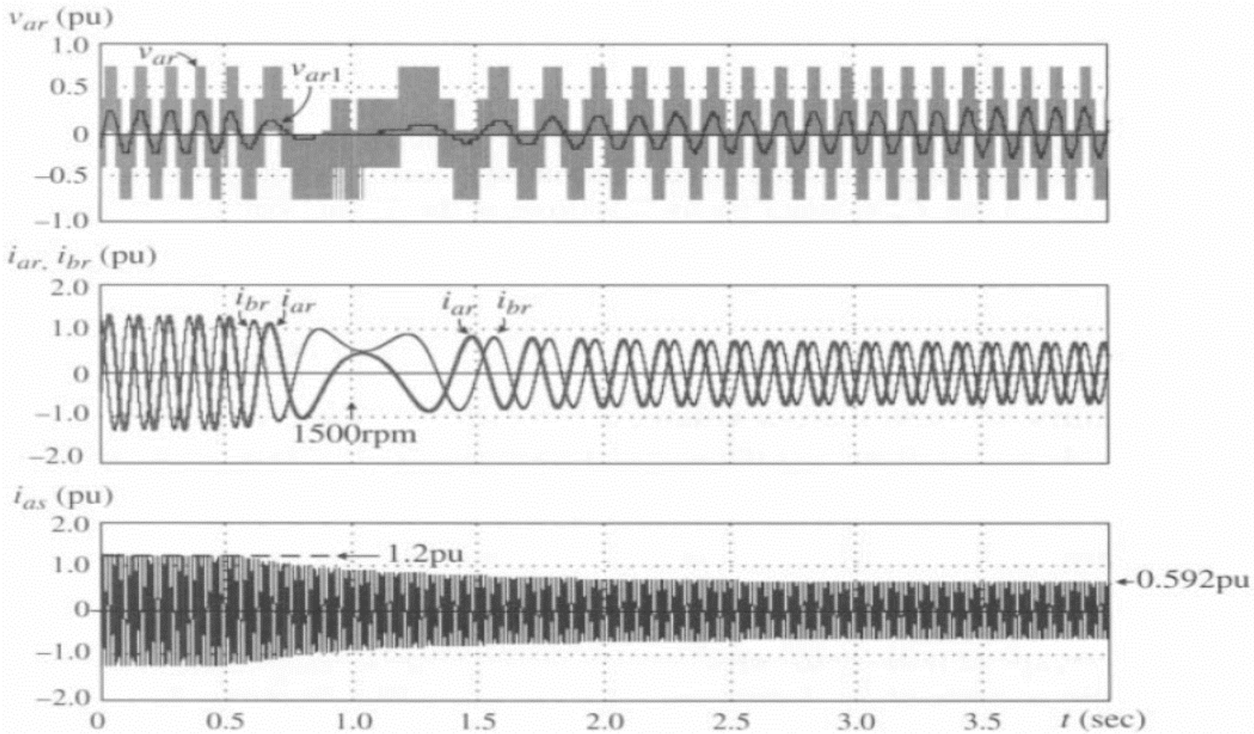


Source: [1]

STATOR VOLTAGE ORIENTED CONTROL OF DFIG WECS

Dynamic Performance of DFIG: Case Study

- Transients of DFIG WECS from supersynchronous to subsynchronous mode



Source: [1]

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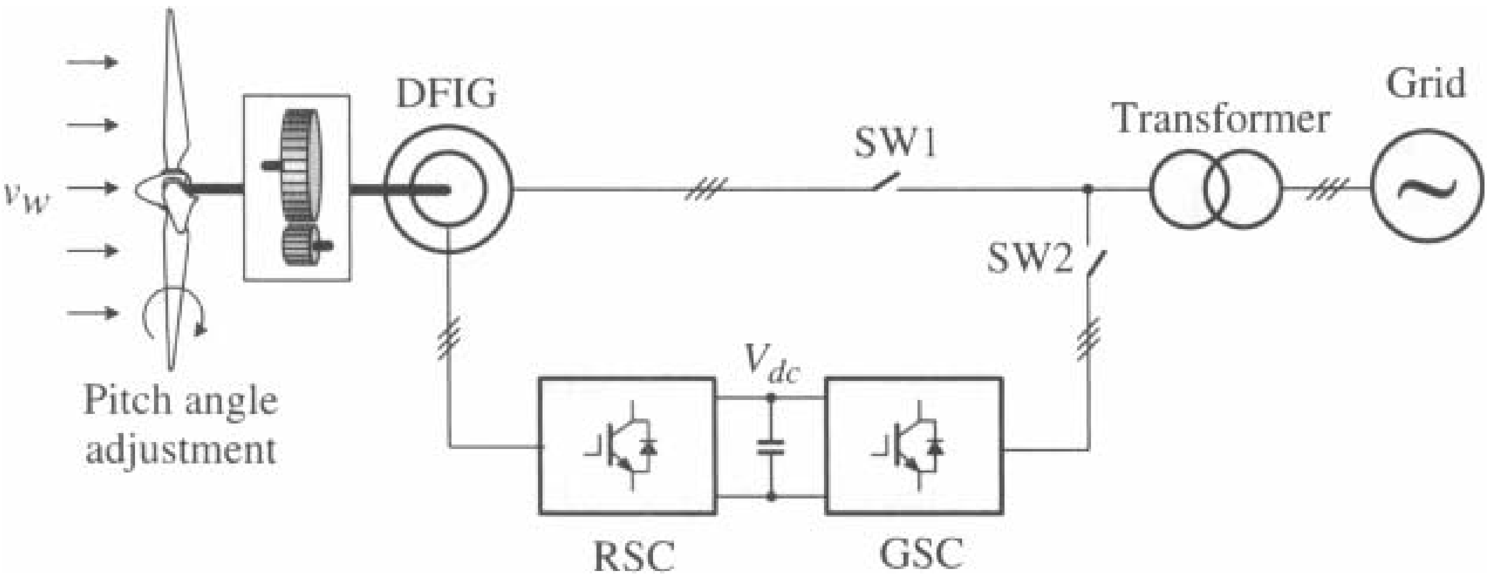
DFIG WECS START-UP

- Start-up of a DFIG WECS



Source: [1]

DFIG WECS START-UP

The system start-up process can be divided into the following steps

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
- The turbine blades are pitched out of the wind, and no torque is generated by the turbine
- The system is in the parking state

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DFIG WECS START-UP

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.

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DFIG WECS START-UP

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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DFIG WECS START-UP

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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Recommended literature

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] https://www.ewea.org European Wind Energy Association
[8] https://www.indea.org World Wind Energy Association
[9] https:// www.awea.org American Wind Energy Association

Recommended literature

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

Introduction to Wind Energy

Module 2.1

Further information:

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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:

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. *Operation of PMSG WEC systems*
2. *Control of PMSG WEC systems*
3. *Start Up of PMSG WEC systems*

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Operation of PMSG WEC systems

- Synchronous generators (SGs) have been widely used in variable-speed wind energy conversion systems (WECS)
- The synchronous generator can be constructed with a large number of poles and operate at a speed that directly matches the turbine blade speed.
- It is a direct-drive system, does not need a gearbox
- This results a reduction in installation and maintenance costs
- 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
- With full-capacity converters, the system is able to meet various grid code, including leading/lagging reactive power control and fault ride-through operation, without the need for additional equipment

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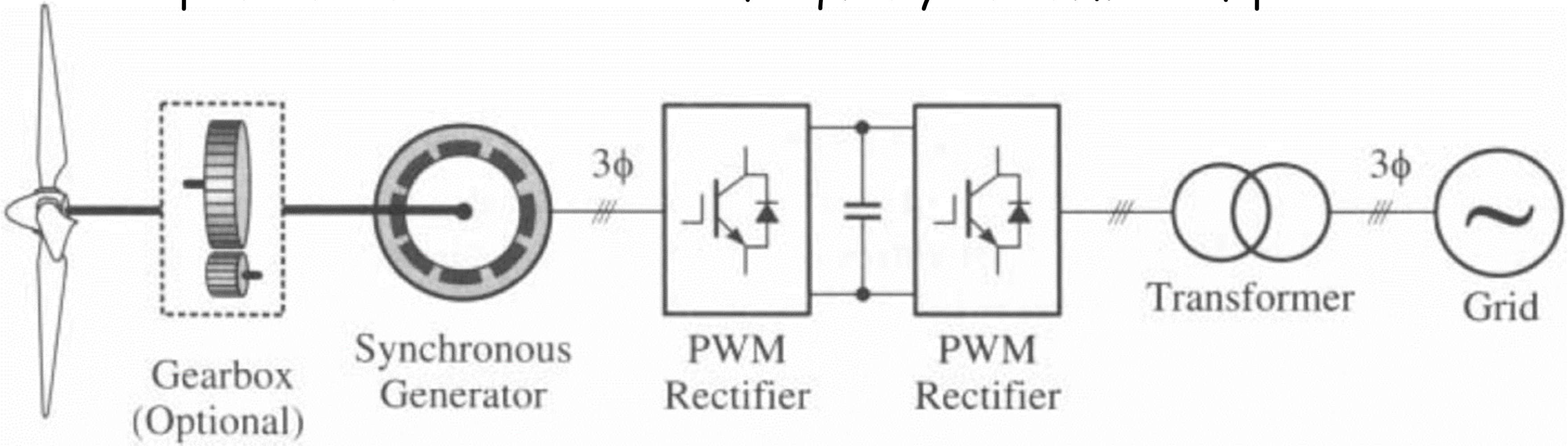
Operation of PMSG WEC systems

- Block Diagram of Variable Speed Synchronous Generators
- 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.
- On the other hand, the rated speed of the synchronous generator
- is dependent on its rated stator frequency and number of poles



Source: [1]

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Control of PMSG WEC systems

- The synchronous generator can be controlled by a number of methods to achieve different objectives
- For instance, 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.
- Alternatively, the generator can be controlled to produce maximum torque with a minimum stator current[1]

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Control of PMSG WEC systems

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 *d*- and q-axis components in the synchronous reference frame.
- The d-axis component, *ids*, is then controlled to be zero.
- With the *d*-axis stator current kept at zero, the stator current is equal to its q-axis component *iqs:*

$$\begin{cases} \vec{i}_s = i_{ds} + j i_{qs} = j i_{qs} \\ i_s = \sqrt{i_{ds}^2 + i_{qs}^2} = i_{qs} \end{cases} \quad \text{for } i_{ds} = 0$$

Source: [1]

where $\vec{i}_s$ is the stator current space vector and i_s represents its magnitude, which is also the peak value of the three-phase stator current in the stationary reference frame.

Control of PMSG WEC systems

Zero d-Axis Current (ZDC) Control

- The electromagnetic torque of the generator:

$$T_e = \frac{3}{2} P \left(\lambda_r i_{qs} - \left(L_d - L_q \right) i_{ds} i_{qs} \right)$$

- Which can be simplified to

$$T_e = \frac{3}{2} P \lambda_r i_{qs} = \frac{3}{2} P \lambda_r i_s$$

- The magnitude of the stator voltage is given by

$$v_s = \sqrt{(v_{ds})^2 + (v_{qs})^2} = \sqrt{(\omega_r L_q i_{qs})^2 + (\omega_r \lambda_r)^2}$$

$$\begin{cases} \theta_v = \tan^{-1} \dfrac{v_{qs}}{v_{ds}} \\ \theta_i = \tan^{-1} \dfrac{i_{qs}}{i_{ds}} \end{cases}$$

Source: [1]

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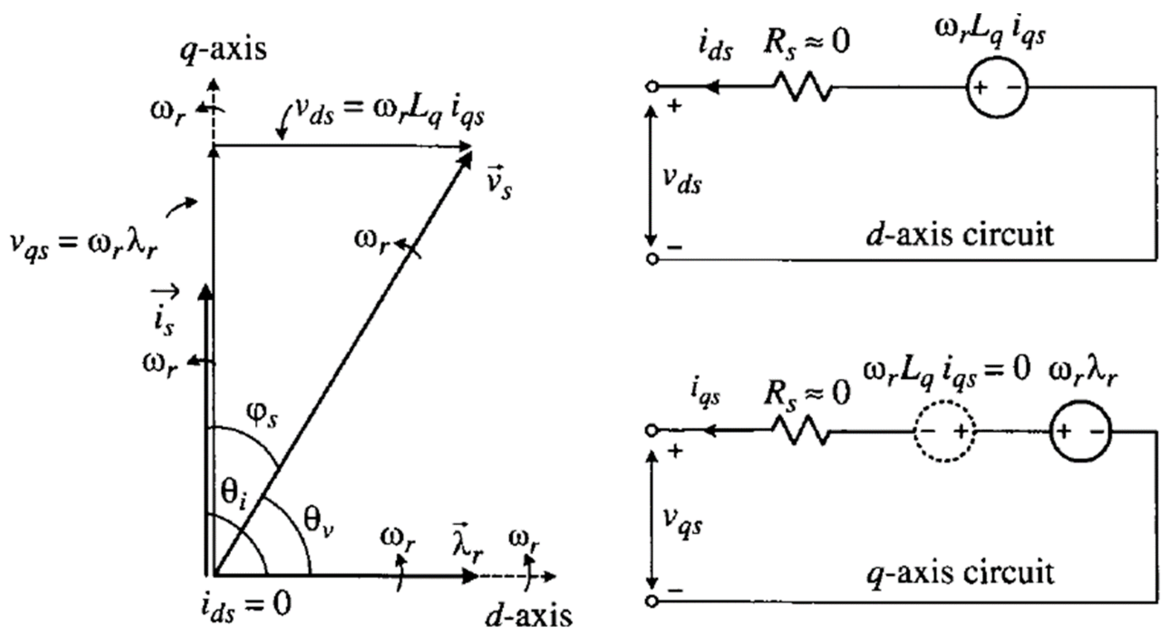
Zero d-Axis Current (ZDC) Control

- For the ZDC scheme, *ids* = 0, the stator power factor angle is given by

$$\varphi_s = \theta_v - \theta_i = \left(\tan^{-1}\frac{v_{qs}}{v_{ds}}\right) - \frac{\pi}{2} \qquad \text{for } i_{ds} = 0$$



(a) Vector diagram (b) *dq*-axis steady state model

Source: [1]

Control of PMSG WEC systems

Maximum Torque per Ampere (MTPA) Control

- The maximum torque per ampere control generates a given torque with a minimum stator current
- For a given stator current *is*, the magnitude of its d-axis current can be calculated by

$$i_{ds} = \sqrt{i_s^2 - i_{qs}^2}$$

$$T_e = \frac{3}{2} P \left(\lambda_r i_{qs} - (L_d - L_q) \left(\sqrt{i_s^2 - i_{qs}^2} \right) i_{qs} \right)$$

$$\frac{dT_e}{di_{qs}} = \frac{3P}{2} \left(\lambda_r - (L_d - L_q) i_{ds} + (L_d - L_q) i_{qs}^2 \frac{1}{\sqrt{i_s^2 - i_{qs}^2}} \right)$$

- To find the maximum torque per ampere, one can set the above derivative to zero:

$$\lambda_r - (L_d - L_q) i_{ds} + (L_d - L_q) \frac{i_{qs}^2}{i_{ds}} = 0$$

Source: [1]

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Control of PMSG WEC systems

Maximum Torque per Ampere (MTPA) Control

then

$$i_{ds} = \frac{\lambda_r}{2\left(L_d - L_q\right)} \pm \sqrt{\frac{\lambda_r^2}{4\left(L_q - L_d\right)^2} + i_{qs}^2} \quad \text{for } L_d \neq L_q$$

$$\begin{cases} T_e = \dfrac{3}{2} P \left(\lambda_r i_{qs} - \left(L_d - L_q\right) i_{ds} i_{qs}\right) \\ i_{ds} = \dfrac{\lambda_r}{2\left(L_d - L_q\right)} + \sqrt{\dfrac{\lambda_r^2}{4\left(L_q - L_d\right)^2} + i_{qs}^2} \end{cases} \quad \text{for } L_d \neq L_q$$

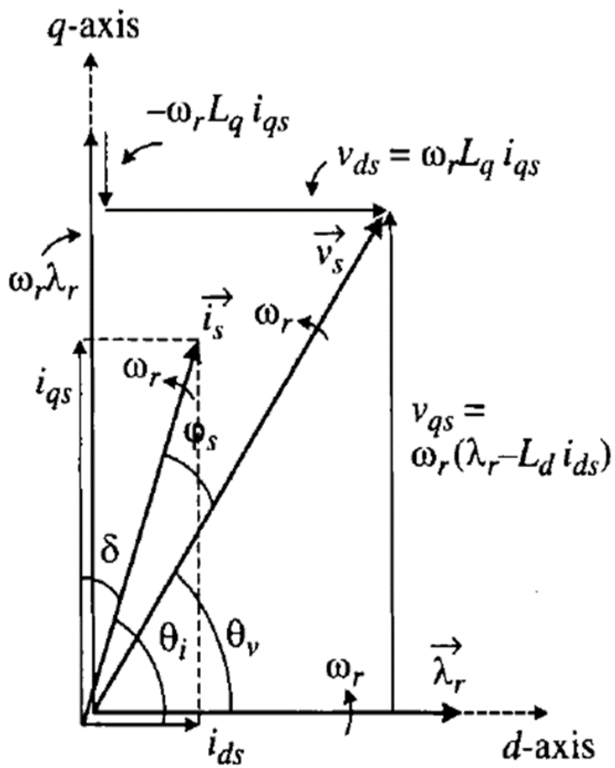
$$\delta = \tan^{-1} \frac{i_{ds}}{i_{qs}} = \frac{\pi}{2} - \theta_i \qquad \text{for } 0 \leq \theta_i \leq \frac{\pi}{2}$$

where δ is angle of the stator current vector with respect to the q-axis

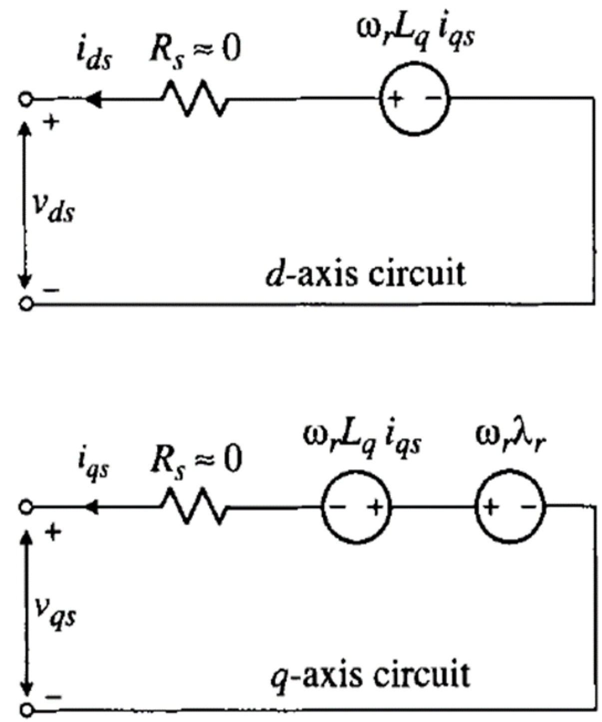
Source: [1]

Control of PMSG WEC systems

Maximum Torque per Ampere (MTPA) Control



(a) Vector diagram



(b) dq-axis steady state model

Source: [1]

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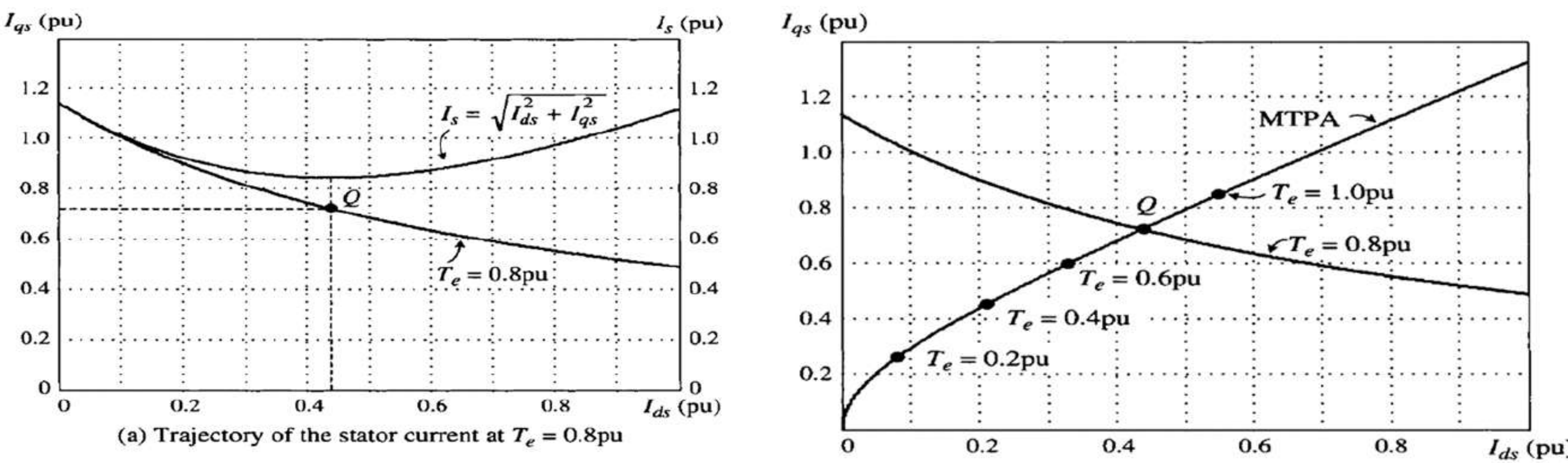
Control of PMSG WEC systems

Maximum Torque per Ampere (MTPA) Control

- Trajectory of maximum torque-per-ampere control



(a) Trajectory of the stator current at $T_e = 0.8$pu

(b) MTPA trajectory

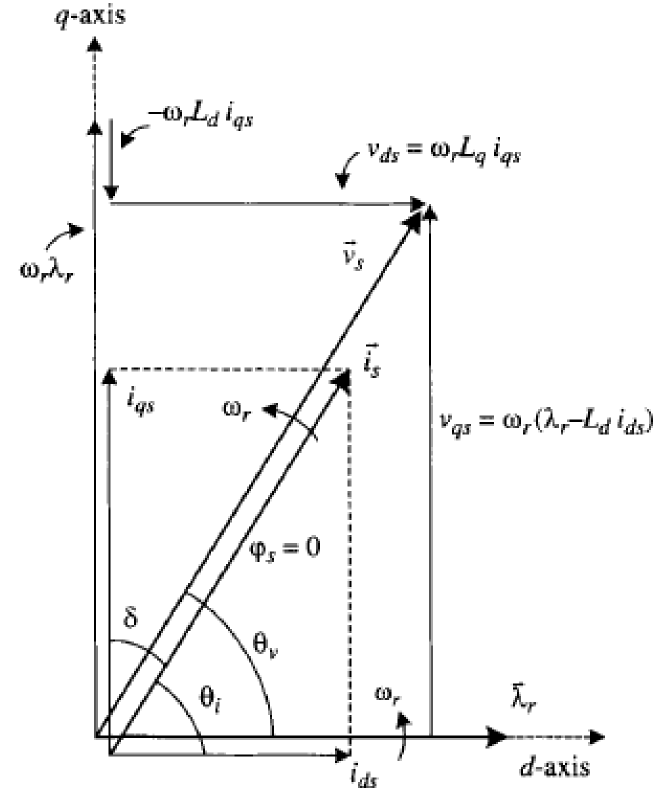
Source: [1]

Control of PMSG WEC systems

Unity Power Factor (UPF) Control

By neglecting the stator resistance *Rs*, the phase angles of the stator voltage and current can then be calculated by

$$\begin{cases} \theta_v = \tan^{-1}\left(\dfrac{v_{qs}}{v_{ds}}\right) = \tan^{-1}\dfrac{\omega_r\lambda_r - \omega_r L_d i_{ds}}{\omega_r L_q i_{qs}} \\ \theta_i = \tan^{-1}\left(\dfrac{i_{qs}}{i_{ds}}\right) \end{cases}$$



Source: [1]

- Unity power factor operation can be realized when the stator power factor angle φ_s between the stator voltage and current is zero: $\varphi_s = \theta_v - \theta_i = 0$

- From the state vector

$$L_d i_{ds}^2 + L_q i_{qs}^2 - \lambda_r i_{ds} = 0$$

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Control of PMSG WEC systems

Unity Power Factor (UPF) Control

Solving the above equation for i_{ds}, we have

$$i_{ds} = \begin{cases} \dfrac{\lambda_r + \sqrt{\lambda_r^2 - 4L_d L_q i_{qs}^2}}{2L_d} & \text{(a) Not valid} \\ \dfrac{\lambda_r - \sqrt{\lambda_r^2 - 4L_d L_q i_{qs}^2}}{2L_d} & \text{(b)} \end{cases}$$

In case of $\lambda_r^2 - 4L_d L_q i_{qs}^2 > 0$

Source: [1]

then $i_{qs} \leq \dfrac{\lambda_r}{2\sqrt{L_d L_q}}$

Control of PMSG WEC systems

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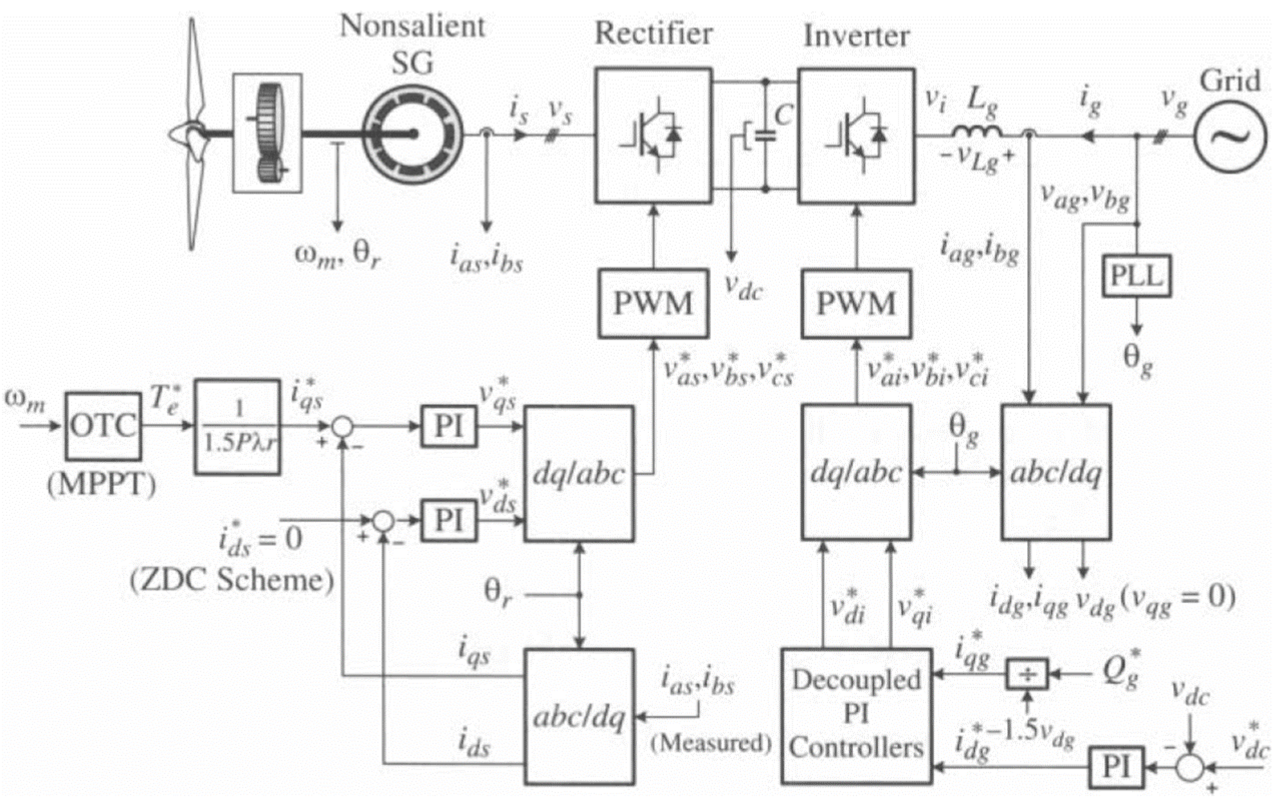
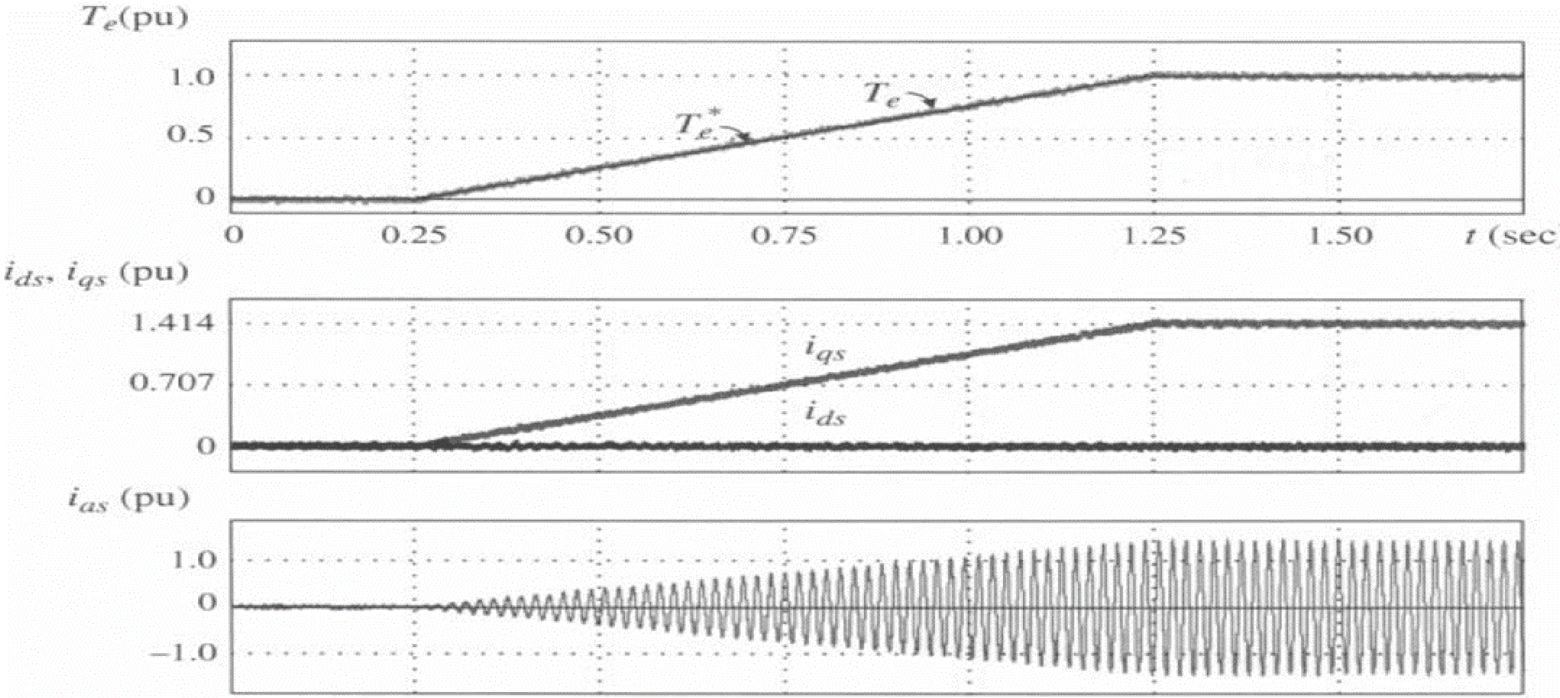
- Control scheme of nonsalient SG wind energy system with ZDC



Source: [1]

Control of PMSG WEC systems

- Simulated waveforms of a nonsalient SG wind energy system during start-up.



(a) Generator-side waveforms

Source: [1]

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Control of PMSG WEC systems

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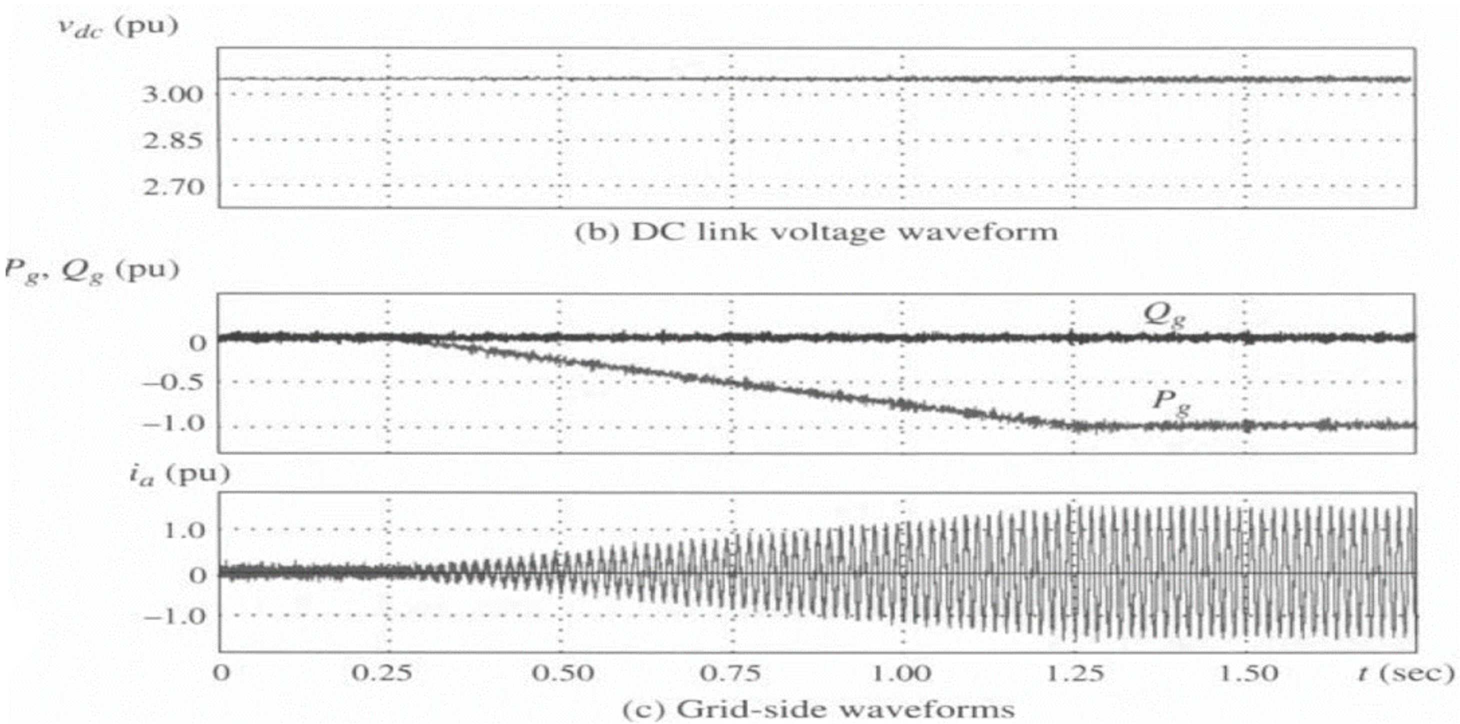
- Simulated waveforms of a nonsalient SG wind energy system during start-up.



Source: [1]

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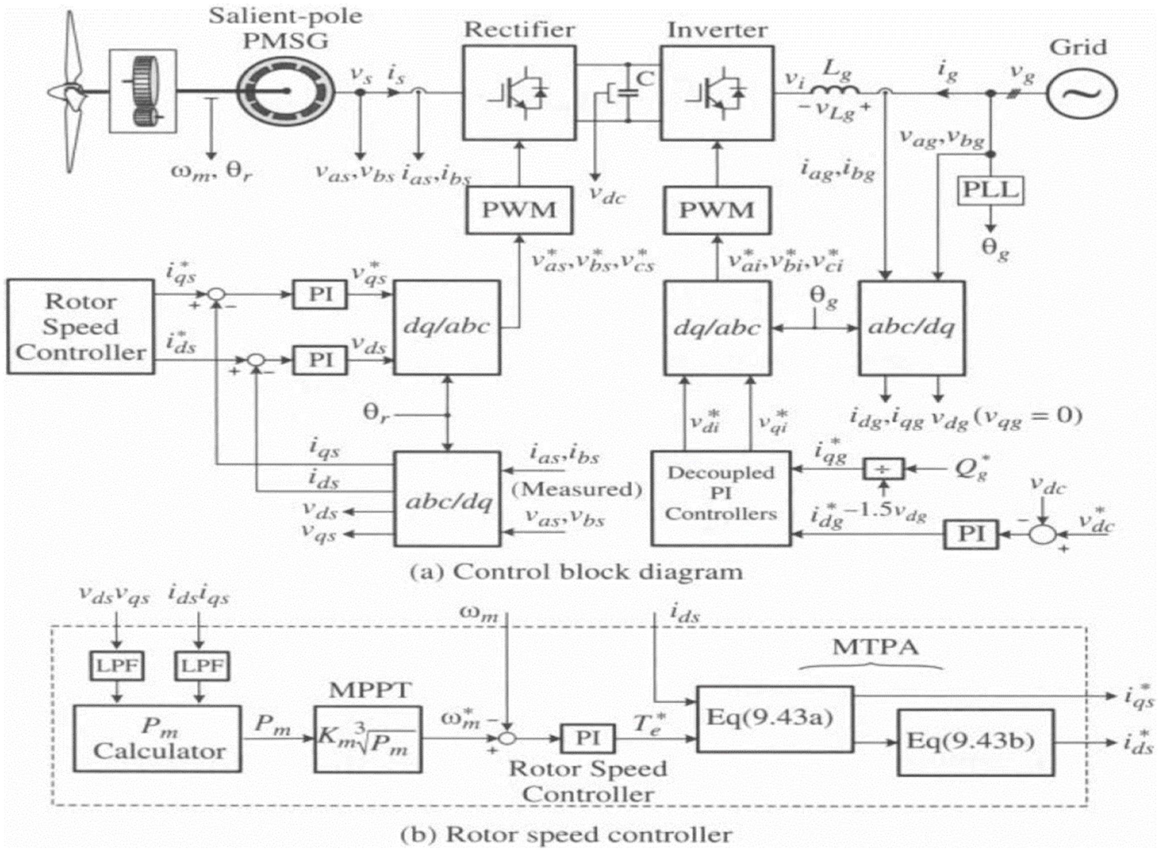
Control of PMSG WEC systems

- Block diagram of salient-pole SG WECS with MTPA and rotor speed feedback controls.



Source: [1]

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Control of PMSG WEC systems

- Salient-pole SG WECS with MTPA

To implement the MTPA for the salient-pole generator, the reference values for the dq-axis currents, i_{ds}^* and i_{qs}^*, are calculated

$$\begin{cases} i_{qs}^* = \dfrac{2T_e^*}{3P\left(\lambda_r - (L_d - L_q)\right)i_{ds}} & \text{(a)} \\ i_{ds}^* = \dfrac{\lambda_r}{2\left(L_d - L_q\right)} + \sqrt{\dfrac{\lambda_r^2}{4\left(L_q - L_d\right)^2} + \left(i_{qs}^*\right)^2} & \text{(b)} \end{cases}$$

where i_{ds} is the measured d-axis stator current, T_e^* is generated by the rotor speed PI controller, and λ_r is rotor flux linkage, a constant value in PMSG.

The main function of the P_m calculator is to calculate the mechanical power of the generator based on measured dq-axis stator voltages and currents

$$P_m = P_s + P_{cu} = \frac{3}{2}\left(v_{ds}i_{ds} + v_{qs}i_{qs}\right) + \frac{3}{2}\left(i_s\right)^2 R_s$$

Source: [1]

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Control of PMSG WEC systems

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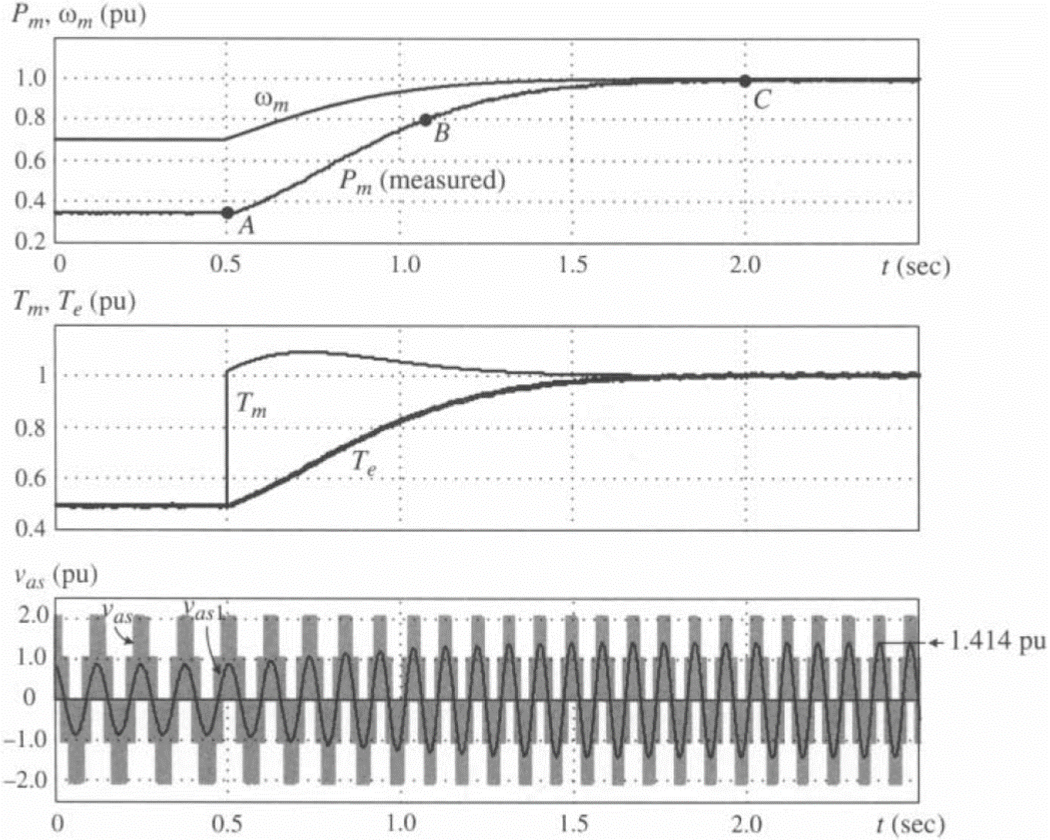
- Transients of salient-pole SG wind energy system with rotor speed feedback control



Source: [1]

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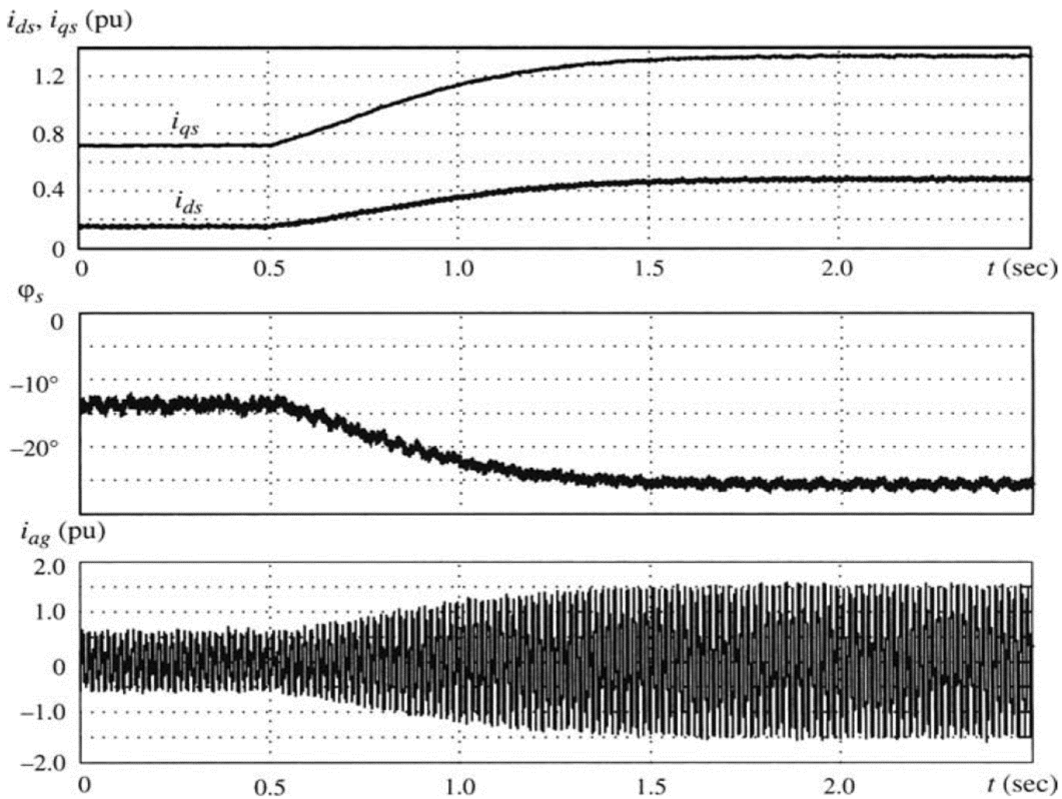
Control of PMSG WEC systems

- Transient waveforms for salient-pole SG WECS with rotor speed feedback control



Source: [1]

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Recommended literature

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] https:// www.ewea.org European Wind Energy Association
[8] https://www.indea.org World Wind Energy Association
[9] https://www.awea.org American Wind Energy Association

Recommended literature

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 ch9 in the reference book mentioned above

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Introduction to Wind Energy

Module 2.1

Further information:

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Research Paper Topics

1- Experimental investigation of different drag devices arrangements on the starting torque of H-Darrius Vertical Axis Wind Turbine.

2- Experimental investigation of pitch angle on the starting torque of H-Darrius Vertical Axis Wind Turbine.

3- Investigating the effect of sinusoidal bumps on power coefficient of H-Darrius Vertical Axis Wind Turbine (VAWT) with NACA 0018 airfoil.

4- Aerodynamic performance experimental investigation of cambered-slotted NACA 0018 airfoil with different pitch angles at low Reynolds Number.

5- Experimental investigation of different inflated lens shapes on performance of small Horizontal Axis Wind Turbines (HAWT)at low Reynolds number.

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MODULE 3. EXAM PROPOSAL

Instructions to Students

- Assume any missing information and state your assumptions clearly.
- Write your answers in the answer book provided, not on the exam paper.
- Submit exam paper with the answer book.
- Equipment allowed: Non-programmable calculator.
- Material allowed: Printed Lecture notes.

This examination is **THREE** hours long.

[Turn Over only when instructed to do so]

QA1 Consider a variable speed pitch regulated direct drive IEC Class I wind turbine. The rotor diameter is 47 meters, the rated rotational speed is 36 r.p.m. The frequencies of different wind speeds as well as the associated power provided from the manufacturer are given in table QA1.

Table QA1

V_{wind} m/s	Frequency days	Power KW
1	8	0.0
2	20	0.0
3	24	0.0
4	25	32
5	30	62
6	36	107
7	38	170
8	45	254
9	30	362
10	25	496
11	18	660
12	16	660
13	12	660
14	10	660
15	9	660
16	8	660
17	4	660
18	3	660
19	2	660
20	2	660
25	0	0

Based on a proper maximum Tip Speed Ratio (TSR), It is required to:

(i). Construct a Weibull wind speed probability density function that describes the above wind speed frequencies.
(ii). Calculate annual energy yield of this wind turbine.
(iii). Determine the capacity factor of the wind site.
(iv). Calculate and plot the angular velocity vs. wind speed.
(v). Calculate and plot the Tip Speed Ratio vs. wind speed.
(vi). Calculate and plot the power coefficient vs. wind speed.
(vii). Set a proper arrangement for this wind turbine to establish a wind power plant of 10 MW to be located at El Gouna village.

QB1a

Consider the wind site of Fig.QB1at Ras Gharib on the Suez Gulf. A wind turbine of 300 KW rated power is to be installed at the shown position. It is required to:

(i). sketch a roughness rose at the location of the wind turbine indicating roughness classes and roughness lengths.
(ii). In your own words give your comments on the importance of roughness rose on wind resources assessment.

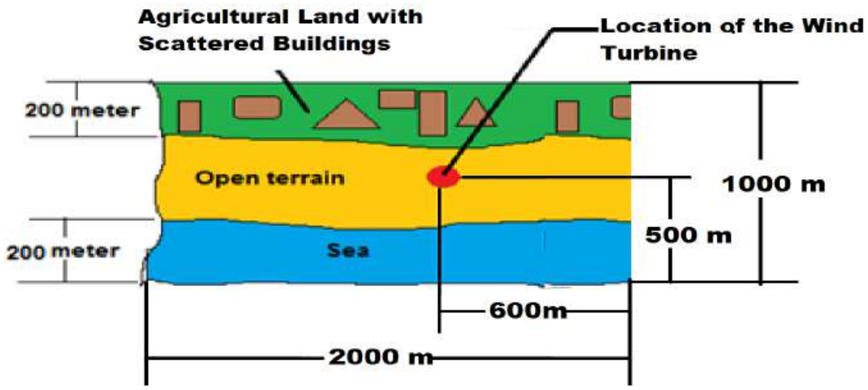

Fig.QB1

[10 Marks]

QB1b Consider a wind turbine operating at angular velocity of 6 rad/s and at a wind speed of 10 m/s. The length of the blade is 14 m. Table QB1b presents the aerodynamic characteristics of the aerofoil section. It is required to:

(i). Construct the velocity triangle along 2m, 6m, 10m and tip of the blade.
(ii). Calculate and plot the flow angle along the same blade locations.
(iii). Calculate and plot the pitch angle along the same blade locations for best wind turbine performance.
(iv). Calculate the tangential force at the same blade locations.

Table QB1b

Angle of Attack (Deg.)	Lift Coefficient (C_L)	Drag Coefficient (C_D)
0	0.2	0.01
2	0.4	0.011
6	0.8	0.014
8	1.03	0.018
10	1.20	0.030
14	1.05	0.040

[20 Marks]

QB2

Fig. QB2 presents a wind site where two identical wind turbines are installed in a row. The rotor diameter is 30 m and the height of tower is 25 m. A third wind turbine of same rotor diameter should be installed in a second raw such that the downstream distance between the two wind turbines rows should not exceed 250 m. It is required to:

(i). Calculate and Plot the change in downwind speed vs tower height.
(ii). Determine a proper tower height for this wind turbine so that the reduction in wind speed would be less than 35 %.
(iii). Assuming a simple rotor disc model, discuss the energy conversion in this wind site.

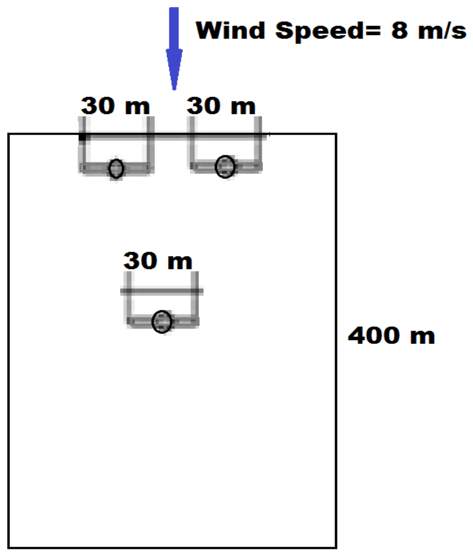

Fig. QB2

[30 Marks]

QB3

Consider a small wind turbine blade of 4 meters length . The wind turbine is to be installed at a site of 7 m/s average wind speed. The angular velocity of the rotor is 7 rad/s. Table QB3 presents the values of axial induction factor as well as angular induction factor at different blade locations. it is required to:

(i). Calculate the local speed ratio at all blade locations.
(ii). Calculate and plot the elemental torque generated at each location of the blade.
(iii). Calculate the total torque generated by the blade.
(iv). Calculate the total generated power by the blade.

Table QB3

Radius (meter)	Axial Induction factor	Angular Induction factor
0.2	0.3	1.845
1	0.35	0.1910
2	0.35	0.0540
3	0.35	0.0247
4	0.35	0.0141

[30 Marks]