Turbine Generators

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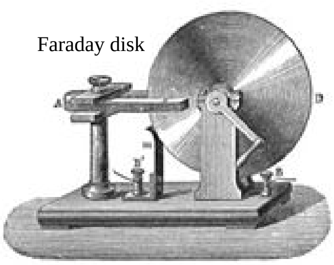
Outline

- Generators
- Synchronous machines
- Number of poles
- Asynchronous machines
- Changing number of poles
- Variable slip
- Indirect grid connection
- Gearboxes
- Controllers
- Power quality

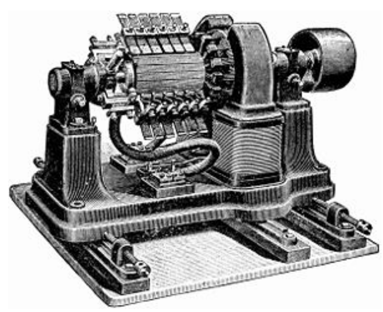
Generator History

Faraday disk



Michael Faraday discovered the principle of electromagnetic generators - a potential difference is generated between the ends of an electrical conductor that moves perpendicular to a magnetic field

Generator History

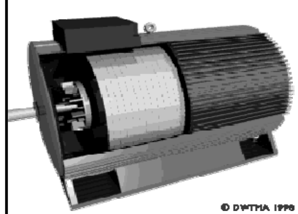


Dynamo was the first (belt driven) electrical generator capable of delivering power for industry

Turbine Generator

http://seattlepi.nwsource.com/photos/photo.asp?PhotoID=27489

Wind Turbine Generators



- ✓ The wind turbine generator converts mechanical energy (torque) into electrical energy
- ✓ Wind turbine generators differ from ordinary generating units found in an electrical grid
- ✓ The main reason is that the generator works with a power source (the wind turbine rotor) supplying highly fluctuating mechanical power (torque)

Turbine Classification

Based on the rotor-generator systems, turbines are classified into four types:

- ✓ Type A: Fixed speed
- ✓ Type B: Limited variable speed
- ✓ Type C: Variable speed with partial scale energy converter
- ✓ Type D: Variable speed with full scale energy converter

Turbine Classification

Speed control		Power control		
		Stall	Pitch	Active stall
Fixed speed	Type A	Type A0	Type A1	Type A2
Variable speed	Type B	Type B0	Type B1	Type B2
	Type C	Type C0	Type C1	Type C2
	Type D	Type D0	Type D1	Type D2

Note: The grey zones indicate combinations that are not in use in the wind turbine industry today.

- ✓ Examples: GE 1.5 MW turbine is type C1, 3.2 MW is type C1
  Gemesa 2 MW turbine is type C1
  Vestas 1.8 MW turbine is type B1, 2MW is type C1

T. Ackermann (2005), p. 57

Turbine Classification

Generator-rotor

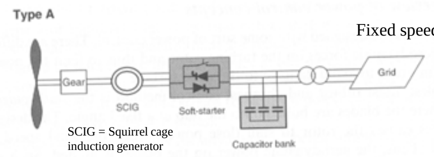
Speed control		Power control		
		Stall	Pitch	Active stall
Fixed speed	Type A	Type A0	Type A1	Type A2
Variable speed	Type B	Type B0	Type B1	Type B2
	Type C	Type C0	Type C1	Type C2
	Type D	Type D0	Type D1	Type D2

Note: The grey zones indicate combinations that are not in use in the wind turbine industry today.

Turbine-wind parameters

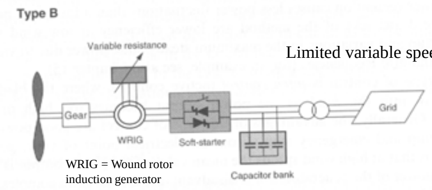
WT Classes		I	II	III	IV	S
$v_{e\,ref}$ (m/s)		50	42.5	37.5	30	
$\bar{v}_w$ (m/s)		10	8.5	7.5	6.0	
$v_{G50} = 1.4 v_{e\,ref}$		70	59.5	52.5	42	values to be
$v_{G1} = 1.05 v_{G50}$		52.5	44.6	39.4	31.5	specified by
A	I_{15}	0.18	0.18	0.18	0.18	the designer
	a	2	2	2	2	
B	I_{15}	0.16	0.16	0.16	0.16	
	a	3	3	3	3	

Turbine Classification



Fixed speed

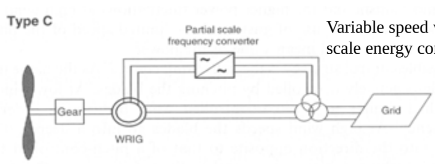
SCIG = Squirrel cage induction generator



Limited variable speed

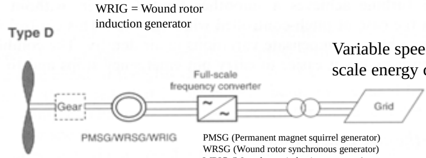
WRIG = Wound rotor induction generator

Turbine Classification



Variable speed with partial scale energy converter

WRIG = Wound rotor induction generator



Variable speed with full scale energy converter

PMSG (Permanent magnet squirrel generator)
WRSG (Wound rotor synchronous generator)
WRIG (Wound rotor induction generator)

Type A: Fixed Speed

- ✓ SCIG (Squirrel cage induction generator) directly connected to the grid via a transformer
- ✓ SCIG draws reactive power from the grid that is compensated by the capacitor bank (in the absence of the capacitor bank voltage fluctuations and power line losses inevitable)
- ✓ Wind speed variability imposes high stresses on the turbine structure

Type B: Limited Variable Speed

- ✓ WRIG (Wound rotor induction generator) directly connected to the grid and it uses a capacitor bank
- ✓ Soft-starter ensures smother grid connection
- ✓ The rotor resistance is controllable and thus the power output is controlled
- ✓ The rotor resistance is changed by an optically controlled converter mounted on the rotor shaft (the OptiSlip concept)
- ✓ The rotor controllable speed range is 0% to 10% over the synchronous speed and it is rotor size dependent

Type C: Variable Speed With Partial Scale Energy Converter

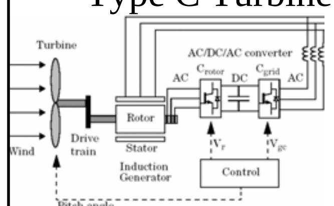
- ✓ The configuration known as DFIG (Double fed induction generator) correspond to the WRIG (Wound rotor induction generator) with partial scale frequency converter
- ✓ The partial scale frequency converter performs the reactive power compensation and ensures smoother grid connection
- ✓ The generator has a wider range of speed control, e.g., (-40% to +30%) around the synchronous speed (wider than OptiSlip)
- ✓ The use of slip rings and protection in case of grid faults is a major drawback

Type D: Variable Speed with Full Scale Energy Converter

- ✓ May use:
  - o PMSG (Permanent magnet squirrel generator) or
  - o WRSG (Wound rotor synchronous generator) or
  - o WRIG (Wound rotor induction generator)
- ✓ The full-scale frequency converter performs the reactive power compensation and ensures smoother grid connection
- ✓ May not use a gearbox at all
- ✓ Turbine examples: Enercon, Made, and Lagerwey

~~Gearbox~~

Type C Turbine: Discussion (1)



The ac*/dc/ac converter consists the rotor-side converter* (*Crotor) and the grid-side converter (Cgrid). Both Crotor and Cgrid converters are voltage-sourced converters using forced* commutated power electronic devices to synthesize an ac voltage from a dc voltage source.

A capacitor connected on the dc side acts as the dc voltage source and a coupling inductor *L is used to connect the grid-side converter to the grid. The* three-phase rotor winding is connected to *Crotor by slip rings* and brushes, and the three-phase stator winding is directly connected to the grid.

Type C Turbine: Discussion (2)

The pitch angle command and the voltage command signals *Vr and Vgc for Crotor and Cgrid converters, respectively, are* generated by the control system controlling the power of the wind turbine, the dc bus voltage, and the voltage at the grid terminals.
The rotor-side converter is used to control the wind turbine output power and the voltage measured at the grid terminals. The power is controlled in order to follow a predefined power–speed characteristic, named tracking characteristic. The converter *Cgrid is used to regulate the voltage of the dc bus capacitor.*
In addition, this model allows using *Cgrid converter* to generate or absorb reactive power.

Vincenzo Galdi *et al.*, IEEE TRANSACTIONS ON ENERGY CONVERSION, VOL. 23, NO. 2, JUNE 2008. p. 559.

Examples

Turbine, by manufacturer	Concept[a]	Power and speed control features	Comments
Vestas, Denmark:			
V80, 2.0 MW	Type C1	Pitch Limited variable speed	WRIG (DFIG concept) Generator voltage: 690 V Generator speed range: 905–1915 rpm Rotor speed range: 9–19 rpm
V80, 1.8 MW	Type B1	Pitch Limited variable speed	WRIG Generator voltage: 690 V Generator speed range: 1800–1980 rpm Rotor speed range: 15.3–16.8 rpm
Enercon, Germany:			
E112, 4.5 MW	Type D1	Pitch Full variable speed	Multiple WRIG Generator voltage: 440 V Generator and rotor speed range: 8–13 rpm
E66, 2 MW	Type D1	Pitch Full variable speed	Multiple WRIG Generator voltage: 440 V Generator and rotor speed range: 10–22 rpm
NEG Micon, Denmark:			
NM80, 2.75 MW	Type C1	Pitch Limited variable speed	WRIG (DFIG concept) Generator stator/rotor voltage: 960 V/690 V Generator speed range: 756–1103 rpm Rotor speed range: 12–17.5 rpm
NM72, 2 MW	Type A2	Active stall Fixed speed	SCIG Generator voltage: 960 V Two generator speeds: 1002.4 rpm and 1503.6 rpm Two rotor speeds: 12 rpm and 18 rpm
Gamesa, Spain:			
G83, 2.0 MW	Type C1	Pitch Limited variable speed	WRIG Generator voltage: 690 V Generator speed range: 900–1900 rpm Rotor speed range: 9–19 rpm

Examples

Gamesa, Spain:			
G83, 2.0 MW	Type C1	Pitch Limited variable speed	WRIG Generator voltage: 690 V Generator speed range: 900–1900 rpm Rotor speed range: 9–19 rpm
G80, 1.8 MW	Type B1	Pitch Limited variable speed	WRIG (OptiSlip® concept) Generator voltage: 690 V Generator speed range: 1818–1944 rpm Rotor speed range: 15.1–16.1 rpm
(GE) GE Wind, USA:			
GE 104, 3.2 MW	Type C1	Pitch Limited variable speed	WRIG (DFIG concept) Generator stator/rotor voltage: 3.3 kV/690 V Rotor speed range: 7.5–13.5 rpm Generator speed range: 1000–1800 rpm
(GE) GE 77, 1.5 MW	Type C1	Pitch Limited variable speed	WRIG Generator voltage: 690 V Rotor speed range: 10.1–20.4 rpm Generator speed range: 1000–2000 rpm
Bonus, Denmark:			
Bonus 82, 2.3 MW	Type A2	Active stall Fixed speed	SCIG Generator voltage: 690 V Two generator speeds: 1000 rpm and 1500 rpm Two rotor speeds: 11 rpm and 17 rpm
Bonus 76, 2 MW	Type A2	Active stall Fixed speed	SCIG Generator voltage: 690 V Two generator speeds: 1000 rpm and 1500 rpm Two rotor speeds: 11 rpm and 17 rpm

Examples

Turbine, by manufacturer	Concept[a]	Power and speed control features	Comments
Nordex, Germany:			
N80, 2.5 MW	Type C1	Pitch Limited variable speed	WRIG (DFIG concept) Generator voltage: 660 V Generator speed range: 700–1300 rpm Rotor speed range: 10.9–19.1 rpm
S77, 1.5 MW	Type C1	Pitch Limited variable speed	WRIG (DFIG concept) Generator voltage: 690 V Generator speed range: 1000–1800 rpm Rotor speed range: 9.9–17.3 rpm
Made, Spain:			
Made AE-90, 2 MW	Type D1	Pitch Full variable speed	WRSG Generator voltage: 1000 V Generator speed range: 747–1495 rpm Rotor speed range: 7.4–14.8 rpm
Made AE-61, 1.32 MW	Type A0	Stall Fixed speed	SCIG Generator voltage: 690 V Two generator speeds: 1010 rpm and 1519 rpm Two rotor speeds: 12.5 rpm and 18.8 rpm
Repower, Germany:			
MM 82, 2 MW	Type C1	Pitch Limited variable speed	WRIG (DFIG concept) Generator voltage: 690 V Generator speed range: 900–1800 rpm Rotor speed range: 10–20 rpm
MD 77, 1.5 MW	Type C1	Pitch Limited variable speed	WRIG (DFIG concept) Generator voltage: 690 V Generator speed range: 1000–1800 rpm Rotor speed range: 9.6–17.3 rpm
Ecotecnia, Spain:			
Ecotecnia 74, 1.67 MW	Type C1	Pitch Limited variable speed	WRIG (DFIG concept) Generator voltage: 690 V Generator speed range: 1000–1950 rpm Rotor speed range: 10–19 rpm
Ecotecnia 62, 1.25 MW	Type A0	Stall Fixed speed	SCIG Generator voltage: 690 V Two generator speeds: 1012 rpm and 1518 rpm Two rotor speeds: 12.4 rpm and 18.6 rpm

Generating Voltage

- ✓ For larger wind turbines (above 100 - 150 kW) the voltage generated by the turbine is usually 475 V - 690 V three-phase alternating current (AC)
- ✓ A transformer raises the voltage to 10,000 - 30,000 volts, depending on the standard in the local electrical grid
- ✓ Large manufacturers supply both 50 Hz wind turbine models (for the electrical grids in most of the world) and 60 Hz models (for the electrical grid in America)

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Generator Types and Grid Connection

Generator Types

- ✓ Synchronous
- ✓ Asynchronous (induction) generators

- ✓ Direct grid connection *or*
- ✓ Indirect grid connection

Mode of turbine operations

- ✓ Grid connected turbine
- ✓ Off-the grid

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Grid Connection

- ✓ Direct grid connection means that the generator connected directly to the (usually 3-phase) alternating current (AC) grid
- ✓ *Indirect grid connection* means that the current from the turbine passes through a series of electric devices which adjust the current to conform the grid
- ✓ For an asynchronous generator the grid frequency occurs automatically

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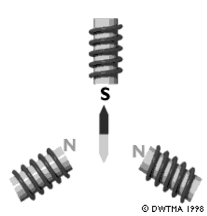
Synchronous Generators

3-Phase Generator (or Motor) Principles



- ✓ A 3-phase generator (or a motor) uses a rotating magnetic field
- ✓ Each of the three magnets is connected to its own phase in the three phase electrical grid
- ✓ The dark letter S indicates when the magnetism is strong

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Synchronous Generators

- ✓ The fluctuation in magnetism corresponds exactly to the fluctuation in voltage of each phase
- ✓ When one phase is at its peak, the other two have the current running in the opposite direction
- ✓ Since the timing of the current in the three magnets is one third of a cycle apart, the magnetic field makes one complete revolution per cycle

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Synchronous Generator Operation

- ✓ The compass needle (with the North pole painted red) follow the magnetic field exactly, and make one revolution per cycle
- ✓ With a 60 Hz grid, the needle makes 60 revolutions per second, i.e., 60 times 60 = 3600 rpm (revolutions per minute)

n_s = f/p
n_s = rotational speed [1/s]
f = grid frequency [Hz]
p = number of pole pairs

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Synchronous Generator Operations

- ✓ The compass needle in the centre is called the rotor, because it rotates
- ✓The permanent magnets have not frequently used due to demagnetization by working in the powerful magnetic fields inside a generator, however, a renewed interest emerges
- ✓ Another reason is that powerful magnets (made of rare earth metals, e.g., Neodynium) are expensive
- ✓ Some generator use an electromagnet maintaining its magnetism through a coil (wound around an iron core) which is fed with direct current)
- ✓ The setup of the three electromagnets is called a stator as it remains static (remains in the same place)

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Wind Turbines With Synchronous Generators

- ✓ Wind turbines with synchronous generators may use electromagnets in the rotor fed by direct current from the electrical grid
- ✓ Since the grid supplies alternating current (AC), the alternating current is converted into direct current (DC) before it is sent to the coil windings around the electromagnets in the rotor
- ✓ The rotor electromagnets are connected to the current by brushes and slip rings on the axle (shaft) of the generator

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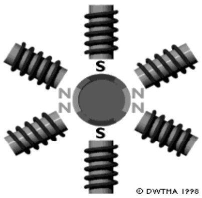
Changing Generator Rotational Speed



- The speed of a synchronous generator connected to a three-phase grid is constant and dictated by the frequency of the grid
- Doubling the number of magnets in the stator results in the magnetic field rotating at half the speed
- The term "synchronous generator speed" refers to the speed of the generator when it is running synchronously with the grid frequency. In the case of asynchronous (induction) generators it is equivalent to the idle speed of the generator

High or Low Speed Generators?

Number of poles	50 Hz	60 Hz
2 (1 pair)	3000	3600
4 (2 pairs)	1500	1800
6 (3 pairs)	1000	1200
8	750	900
10	600	720
12	500	600

Synchronous Generator Speeds (rpm)

$n_s = f/p$
n_s = rotational speed [1/s]
f = grid frequency [Hz]
p = number of pole pairs

- Usually synchronous generators have four or six poles to save on the size and cost
- The maximum force (torque) a generator can handle depends on the rotor size
- For a given power output, the selection is made between a slow-moving, large (expensive) generator, or a high-speed (lower cost) smaller generator

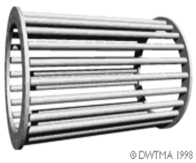
Asynchronous (Induction) Generators

Mostly the rotor is different from the synchronous generator

- Most wind turbines use three phase asynchronous (squirrel cage wound) generators, also called induction generators to generate alternating current
- The concept has been known to the industry at large for many years

Asynchronous (Induction) Generators

- Originally designed as an electric motor
- About 1/3 of the world's electricity is consumed by the induction motors driving machinery, e.g., pumps, fans, compressors, elevators
- One reason for choosing this type of a generator is that it is reliable, and tends to be relatively inexpensive
- The generator has some mechanical properties that are useful for wind turbines (generator slip and a certain overload capability)



The Squirrel Cage Rotor

- ✓ The key component of the asynchronous generator is the cage rotor (called a squirrel cage rotor)
- ✓ The rotor it different from the synchronous generator
- ✓ The rotor consists of a number of copper or aluminum bars connected electrically by aluminum end rings
- ✓ The rotor is placed in the center of the stator. In this case, is a 3-pole pair stator connected to the three phases of the electrical grid

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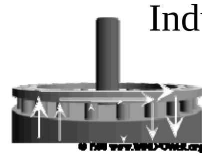
Induction Motor Operation



- ✓ When the current is connected to a stator, the rotor turns like a motor at a *speed slightly below* the synchronous speed of the rotating magnetic field from the stator
- ✓ The magnetic field which moves relative to the rotor induces a strong current in the rotor bars which offer little resistance to the current as they are short circuited by the end rings
- ✓ The rotor then develops its own magnetic poles, which in turn become dragged along by the electromagnetic force from the rotating magnetic field in the stator

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Induction Generator Operation

- ✓ Rotating the rotor around at exactly the synchronous speed of the generator, e.g., 1500 or 1800 rpm (as for the 4-pole synchronous generator), *there is no action*
- ✓ When the magnetic field rotates at exactly the same speed as the rotor, no induction phenomena in the rotor takes place (not interaction with the stator)
- ✓ At the speed *above* 1500/1800 rpm, the rotor moves faster than the rotating magnetic field of the stator, thus the stator induces a current in the rotor
- ✓ The harder we turn the rotor, the more power will be transferred as an electromagnetic force to the stator, and thus converted into electricity fed into the electrical grid

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Induction Generator Slip

- ✓ The speed of the asynchronous generator varies with the turning force (torque) applied to it
- ✓ In practice, the difference between the rotational speed at peak idle power is small (about 1%)
- ✓ This difference expressed in % of the synchronous speed, is called *the generator slip*
- ✓ Thus a 4-pole generator runs idle at 1500/1800 rpm when attached to the 50/60 Hz grid
- ✓ If the generator is producing maximum power, it runs at 1515/1818 rpm
- ✓ This is a useful mechanical property that the generator increases or decreases its speed slightly if the torque varies
- ✓ This implies less tear and wear on the gearbox

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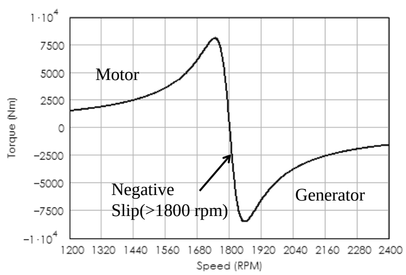
Induction Generator

Torque vs. speed characteristics for a squirrel cage induction generator



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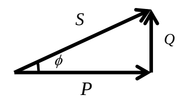
Power quality improvement

$$PF = \frac{P}{S}$$

$$S^2 = P^2 + Q^2$$

$$P = S\left|\cos\phi\right|$$



- ✓ PF : power factor; P : active power measured in W (Watts);
- ✓ S : apparent power measured in volt-amperes (VA);
- ✓ Q : reactive power measured in reactive volt-amperes (Var);
- ✓ ϕ : phase angle between current and voltage.

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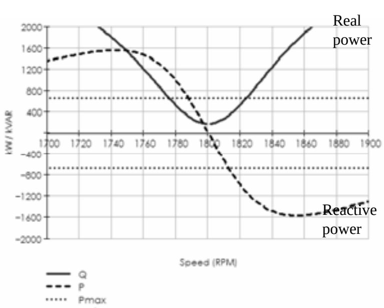
Induction Generator



Variation of the real (solid red) and reactive (dash blue) power with the slip for a squirrel-cage induction generator

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Asynchronous Generator

Low starting torque is one of the most important reasons for using an asynchronous (inductive) generator rather than a synchronous generator on a wind turbine which is directly connected to the electrical grid

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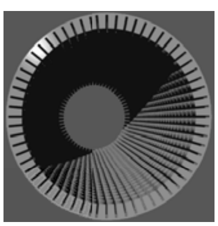
Automatic Pole Adjustment of the Rotor

- ✓ The number of poles in the stator may vary
- ✓ The squirrel cage rotor adapts itself to the number of poles in the stator automatically
- ✓ The same rotor can therefore be used with a different number of poles in the stator

Grid Connection Required

- ✓ The permanent magnet synchronous generator can run as a generator without connection to the electric grid
- ✓ The asynchronous generator is different, as it requires the stator to be magnetized from the grid before its operation
- ✓ An asynchronous generator can function stand alone, when connected to the capacitors supplying the necessary magnetization current
- ✓ It also requires that there be some reminiscence in the rotor iron, i.e., some leftover magnetism at the start of the turbine
- ✓ Otherwise external power is needed to start the system

Changing the Number of Generator Poles



Industrial stator of a generator consists of large number of electromagnets

- ✓ Syn generators (and motors) usually have a large number of stator magnets as the price does not vary too much
- ✓ The reason for this is creating minimal air gap between the rotor and the stator
- ✓ At the same time the magnets needs to be cooled
- ✓ Usually a large number of thin (0.5 mm) insulated steel sheets forms the stator iron

Two Speed, Pole Changing Generators

- ✓ Some turbines ahve two generators, a small one for low winds, and a large one for high winds
- ✓ A newer design is a pole changing generator, i.e., generator which (depending on how their stator magnets are connected) runs with a different number of poles, and thus a different rotational speed
- ✓ Some generators are custom built as two-in-one, i.e., they run as e.g., either 400 kW or 2000 kW generators, and at two different speeds

Two Speed, Pole Changing Generators

- ✓ Incidentally, washing machines usually have pole changing motors, one low speed for washing and at high speed for spinning
- ✓ Also, kitchen exhaust fans in your may two or three different speeds
- ✓ Note about a variable speed fan: Moving twice as much air out of the house per minute using the same fan, uses about eight times as much electricity

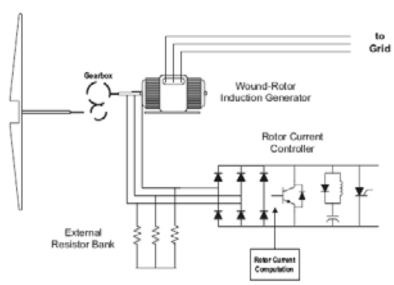
Variable Slip (Speed) Generators for Wind Turbines

- ✓ Electric motors can only run at certain almost fixed speeds determined by the number of poles in the motor
- ✓ The motor (or generator) slip in an asynchronous (induction) machine is usually very small for reasons of efficiency, so the rotational speed varies around 1% between the idle and full load
- ✓ The slip, however is a function of the (DC) resistance (measured in ohms) in the rotor windings of the generator
- ✓ The higher the resistance, the larger the slip

Variable Slip (Speed) Generators for Wind Turbines

- ✓ A way of varying the slip is to vary the resistance in the rotor
- ✓ One may increase generator slip to, e.g., 20 %
- ✓ For motors, this is usually done by having a wound rotor, i.e., a rotor with copper wire windings which make a star configuration, and connected with external variable resistors, plus an electronic control system to operate the resistors
- ✓ The connection has usually been done with brushes and slip rings, which is a drawback over the simple design of a cage wound rotor machine
- ✓ This also introduces parts which wear down in the generator, and thus the generator requires extra maintenance

Wound Rotor Induction Generator

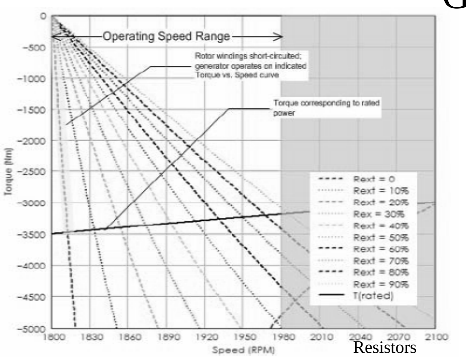


Wind turbine electrical generator with variable slip control

- ✓ Wound-rotor induction generator with scalar control of rotor current
- ✓ Vestas turbines for domestic application (e.g., V47 and V80) utilize such a system

AWEA (2005)

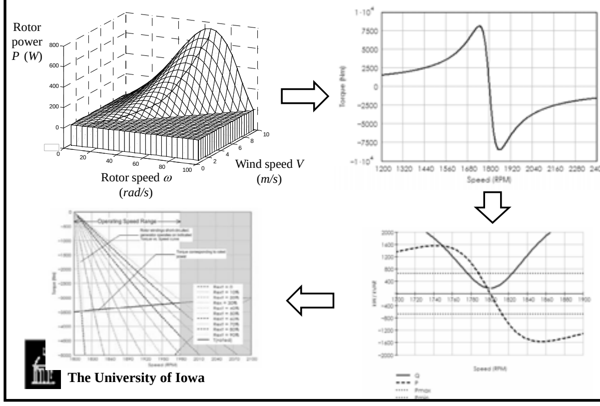
Wound Rotor Induction Generator



Resistors

Operating characteristics of a turbine generator with slip control

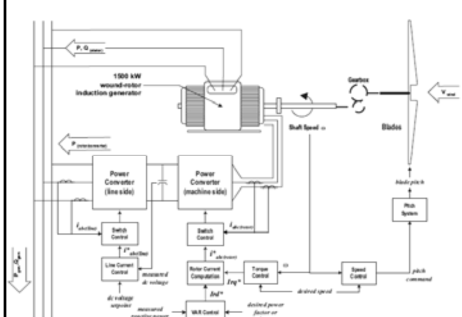
Rotor – Generator Interaction



Opti Slip®

- ✓ An interesting variation of the variable slip induction generator that avoids the problem of introducing slip rings, brushes, external resistors, and maintenance altogether
- ✓ By mounting the external resistors on the rotor itself, and mounting the electronic control system on the rotor as well, there is a problem of how to communicate the amount of slip needed by the rotor
- ✓ This communication using fiber optics communications. The signal is sent across to the rotor electronics each time it passes a stationary optical fiber

Double Fed Induction Generator



Double-fed induction generator with vector control of rotor current

Slip range, e.g., +/- 20% or more

Running a Pitch Controlled Turbine at Variable Speed

- ✓ It is advantageous to run a wind turbine at variable speeds
- ✓ One reason is that of pitch control
- ✓ Controlling the torque by pitching the blades does not overload the gearbox and the generator
- ✓ This means that the reaction time of the pitch mechanism becomes a critical factor in turbine design
- ✓ A variable slip generator allows to increase its slip once the turbine is close to its rated power

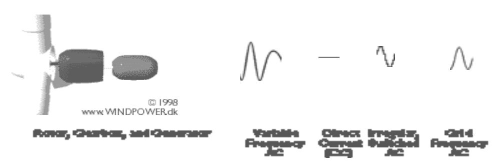
Running a Pitch Controlled Turbine at Variable Speed

- ✓ One control strategy in some turbine designs, e.g., Vestas, is to run the generator at half of its maximum slip when the turbine is operating near the rated power
- ✓ When a wind gust occurs, the control mechanism increases the generator slip to allow the rotor to run a bit faster while the pitch mechanism pitches the blades more out of the wind
- ✓ Once the pitch mechanism has done its work, the slip decreases again
- ✓ In case the wind suddenly drops, the process is applied in reverse
- ✓ It sound simple, however, it is quite difficult to coordinate the two control loops

Improving Power Quality

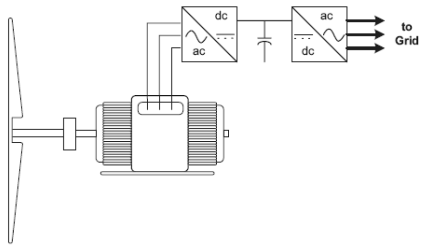
- ✓ Running a generator at high slip releases more heat from the generator as it runs less efficiently
- ✓ That is not a problem in itself, and yet the only alternative left is to waste the excess wind energy by pitching the blades out of the wind
- ✓ One of the benefits of using the pitch-slip control strategy is an improved power quality as the fluctuations in power output are "eaten up" or "topped up" by varying the generator slip and storing or releasing part of the energy as rotational energy in the wind turbine rotor

Indirect Grid Connection of Wind Turbines



- ✓ Most wind turbines are with a direct grid connection
- ✓ In case of indirect grid connection, the wind turbine generator runs on its own, separate mini AC-grid (animated above)

Generator with Full Power Conversion



Electrical generator with full power conversion

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Generating Alternating Current (AC) at Variable Frequency

- ✓ The power is controlled electronically (using an inverter), so that the frequency of the alternating current in the generator's stator of the may vary
- ✓ This way the turbine may run at various speeds
- ✓ The turbine generate alternating current at variable frequency
- ✓ The generator may be either a synchronous or an asynchronous, and the turbine may have a gearbox, or run without a gearbox provided the generator has sufficient number of poles

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Conversion to Direct Current (DC)

- ✓ AC current with a variable frequency cannot be handled by the public electrical grid
- ✓ The variable frequency current can be converted into direct current (DC)
- ✓ The conversion from variable frequency AC to DC can be done using thyristors or more recently large power transistors

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Conversion to Fixed Frequency AC

- ✓ An inverter converts the (fluctuating) direct current (DC) to AC current alternating with the frequency of the public electrical grid
- ✓ Usually thyristors (or recently power transistors) are used
- ✓ A thyristor is a large semiconductor switch that operates without mechanical parts
- ✓ The kind of alternating current one gets out of an inverter involves a series of sudden jumps in the voltage and current, as seen in the animation

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Advantages of Indirect Grid Connection: Variable Speed

- ✓ The advantage of indirect grid connection is that it is possible to run the wind turbine at variable speeds
- ✓ The primary advantage is that gusts may turn the rotor faster, thus storing part of the excess energy as rotational energy until the gust is over
- ✓ Obviously, this requires an intelligent control strategy, since one has to differentiate between gusts and persistently higher wind speeds
- ✓ It is important to reduce the peak torque (to reduce wear of the gearbox and the generator), as well as reduce the fatigue loads on the tower and the turbine blades

Advantages of Indirect Grid Connection: Variable Speed

- ✓ The secondary advantage is that with power electronics one may control reactive power (i.e., a phase shift of current relative to voltage in the AC grid), thus improving the power quality in the electrical grid
- ✓ This may is useful, particularly if a turbine is running in a weak electrical grid
- ✓ Theoretically, variable speed may also provide a slight advantage in annual production, as it is possible to run the turbine at rotational speed changing with the wind speed
- ✓ From an economic point of view that advantage is small

Disadvantages of Indirect Grid Connection

- ✓ The basic disadvantage of indirect grid connection is the cost
- ✓ The turbine needs a rectifier and two inverters, one to control the stator current, and another to generate the output current
- ✓ The cost of power electronics could exceed the gains from building lighter turbines, but this is changing as the cost of power electronics decreases
- ✓ Looking at operating statistics of wind turbines using power electronics, it appears that availability rates for such turbines tend to be somewhat lower than conventional turbines due to failures of the power electronics

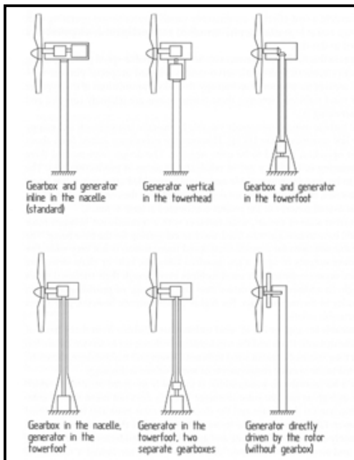
Disadvantages of Indirect Grid Connection

- ✓ Other disadvantages are the energy lost in the AC-DC-AC conversion process, and the fact that power electronics may introduce harmonic distortions of the alternating current in the electric grid, thus reducing power quality
- ✓ The problem of harmonic distortions arises because the filtering process mentioned previously is not perfect, and it may leave some "overtones" (multiples of the grid frequency) in the output current

Cooling System

- ✓ Generators need cooling while they work
- ✓ Air cooling most widely used, however, use water cooled generators also used
- ✓ Water cooled generators are more compact, but they require a radiator in the nacelle to get rid of the heat from the liquid cooling system

Drive Train Configurations



Hau (2006), p. 256

Acknowledgement

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