Introduction to Present Day Wind Energy Technology,
The Wind Power Station

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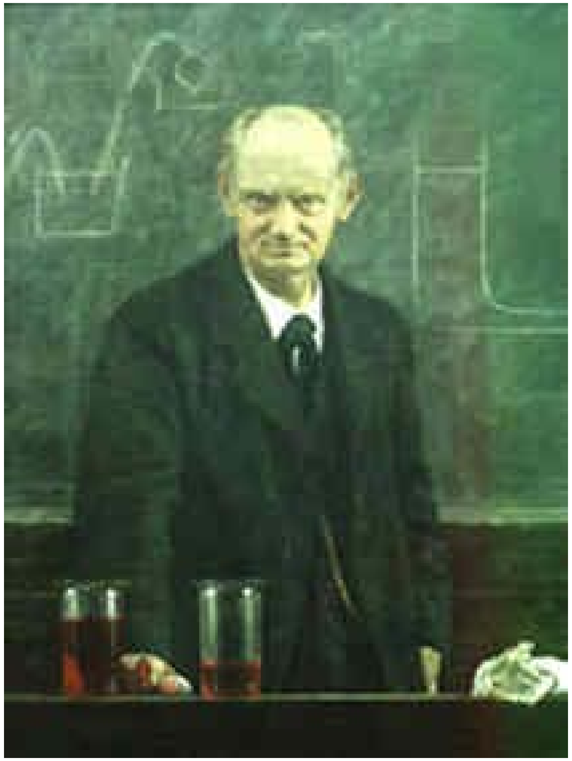
History of Wind

History

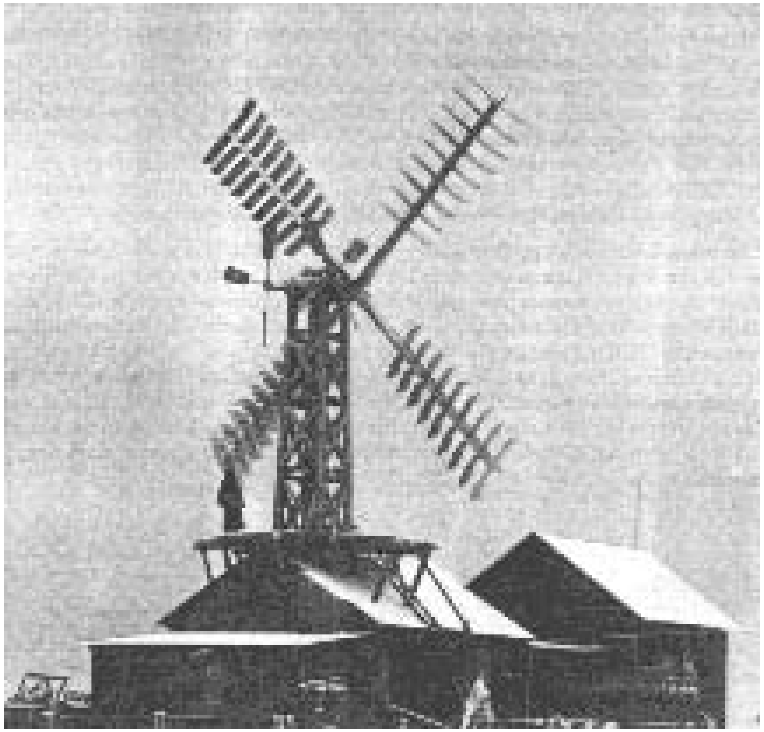
- Man has been using the wind for 4000 years, first to power boats and ships
- Earliest windmills in China and Persia 2000 years ago

- Windmills used for:
  - Pumping water
  - Milling grain
  - Grinding spices & dyes
  - Papermaking
  - Sawing wood
  - Powering textile looms
- First recorded windmill in England 1185 in Weedon, Yorkshire
- Before the Industrial Revolution, at their height, there were 20000 windmills in England

Electric Wind Turbines, 1885, Denmark

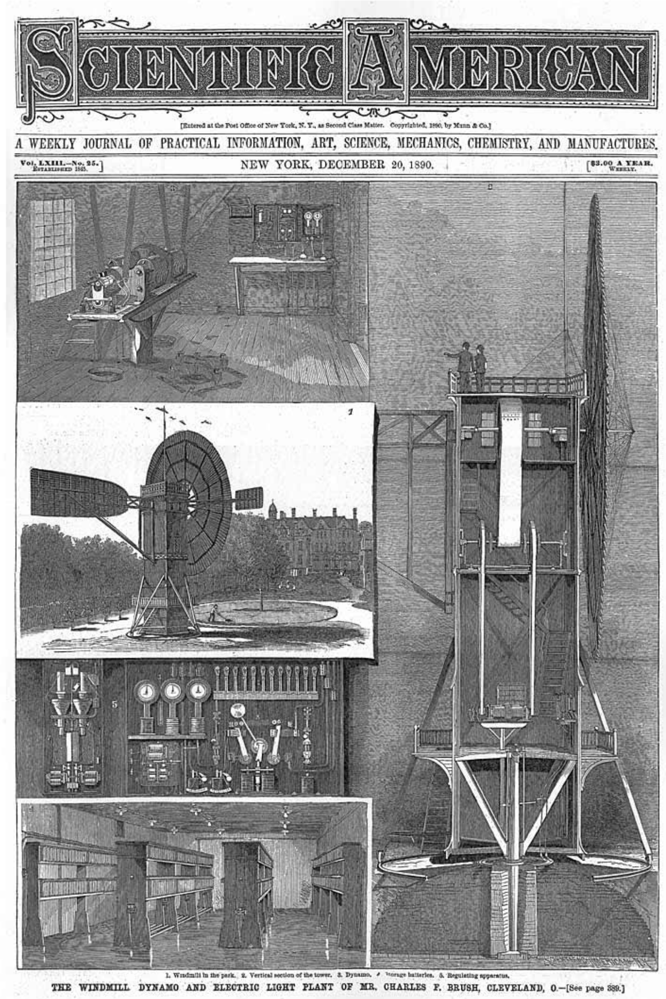


- Inventor, Poul La Cour
- Installed, Askov, Denmark



Electric Wind Turbines, 1887, Cleveland, USA

- Inventor, Charles Francis Brush
- Manufactured, Cleveland USA
- Turbine Dia 17m
- 144 blades
- 10 rev/min, variable speed
- DC generator
- Power Output, 12kW



1980, California, USA

- Result of Californian environmental laws
- Small turbines <100kW
- Many synchronous generators
- Turbine diameters, 10-15m
- 70-80 rev/min, depending on turbine design, fixed speed
- Poorly sited
- Blade failures common
- Disastrous reliability

2003, Modern Product

- Manufacturer, DeWind
- Manufactured, Loughborough, UK
- Turbine Dia 70m
- 3 blades
- 17 rev/min, variable speed
- Doubly fed induction generator
- Power Output, 2 MW

Basic Wind Power

Variation of Wind-Speed with time

Wind is turbulent

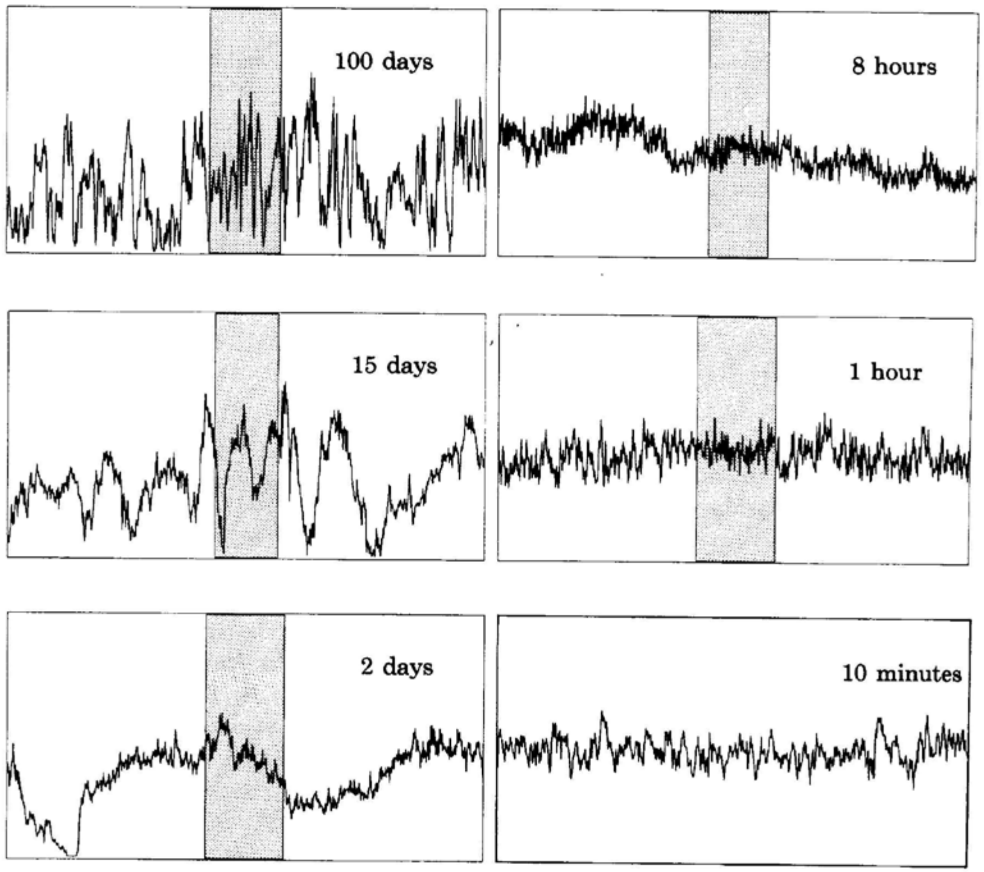


Figure 8.3: Wind speed measured 30 m above flat homogeneous terrain in Denmark (Courtney, 1988). Each graph shows the measured wind speed over the time period indicated. The number of data points in each graph is 1200, each data point corresponding to the speed averaged over 1/1200 of the period. Vertical axis is wind speed, 0-20 m s^{-1}.

Data provided by
Prof N Jenkins,
Univ of Manchester

Variation of Wind-Speed with height
Turbines located in turbulent boundary layer

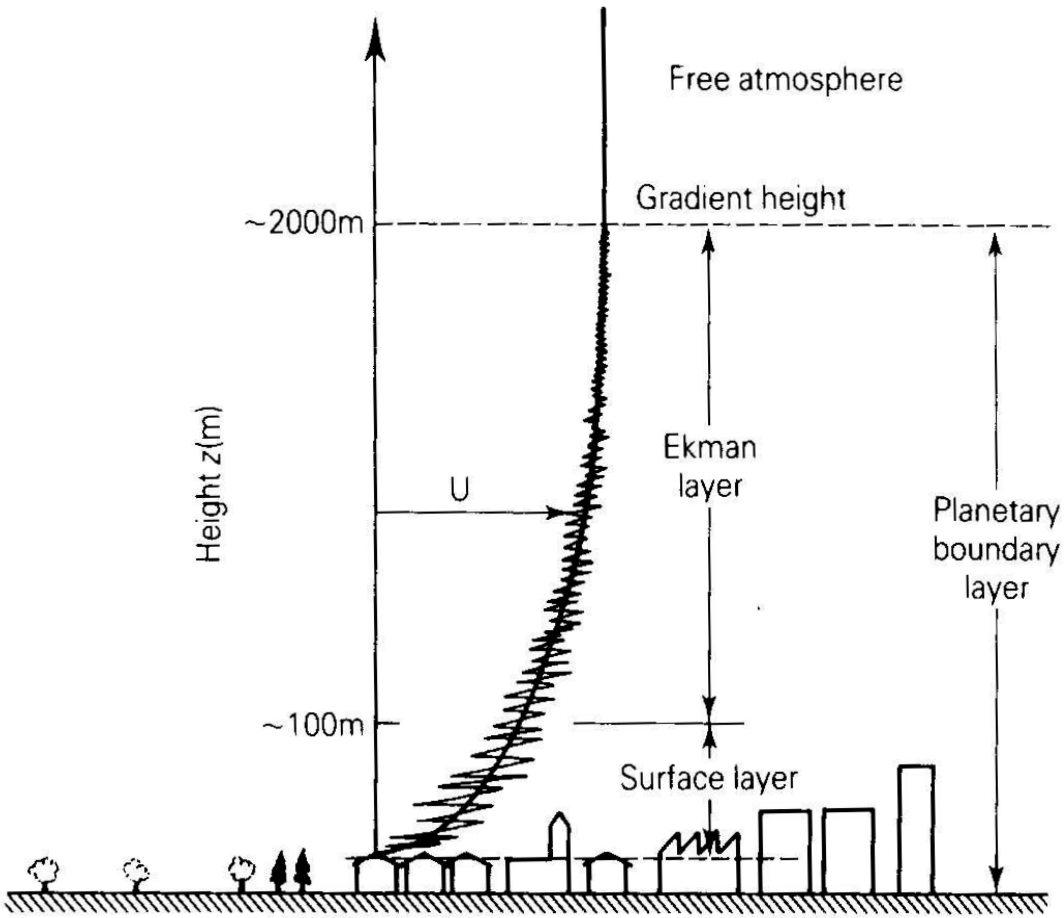
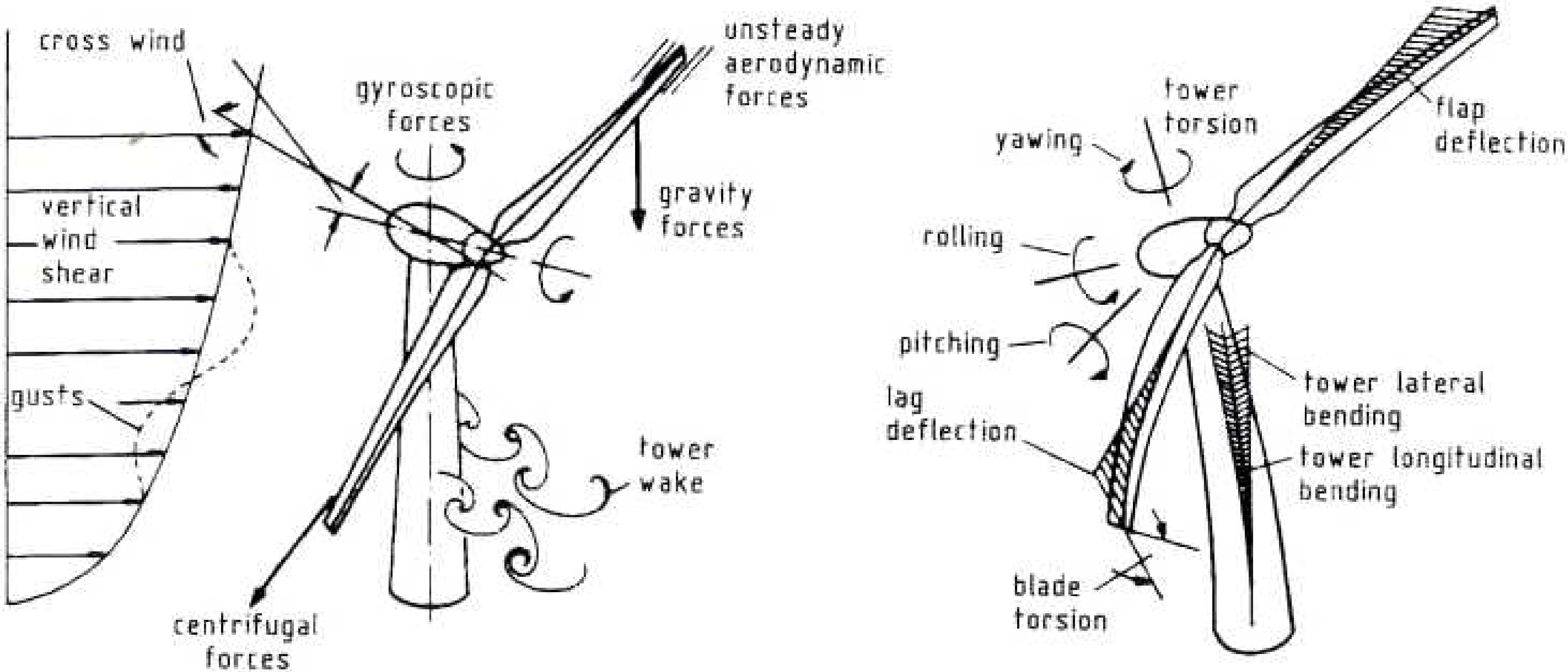


Figure 2.3 **Atmospheric boundary layer**

Data provided by
Prof N Jenkins,
Univ of Manchester

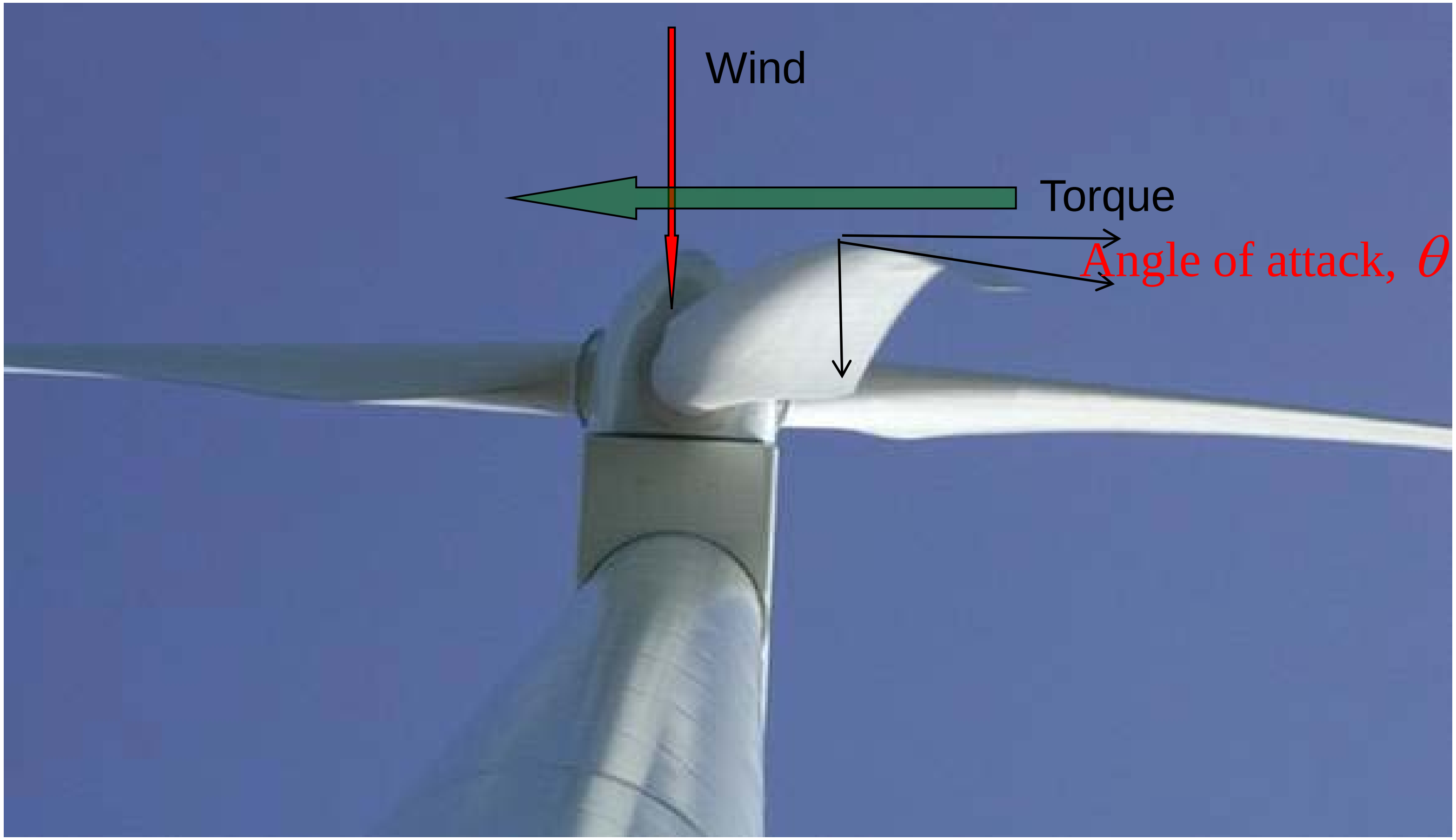
Variation of turbine forces, time & space
Turbulent forces



Power Generation

- The blades sweep circular area, $A\ m^2$ & the wind velocity is $u\ m/s$
- *Kinetic Energy* incident on turbine, per s, is of a cylindrical volume of air, cross sectional area A, length u
- Density of air $1.2\ kg/m^3$, so for a 2 MW turbine of *70m* dia (Area 3850m^2) in a wind speed u of *10 m/s*, the mass of air passing in a second is 46 *tonnes*
- That kinetic energy/s is $1/2 \rho A\, u^3$
- Wind turbine is extracting KE from wind injected by solar heating.

Turbine Blade or Wing



Function of the Blade in a Turbine Disc

- Divert streamline in the incident tube of air from axial to circumferential flow, Accelerate the streamline, Develop **Lift** on the blade and imparting **Torque** to the turbine
- Ideal wind power incident on a wind turbine

  $$P_{wind} = 1/2 \rho A\, u^3$$

- In 1928 Albert Betz showed that 59.3% is the maximum %ge that can theoretically be extracted from wind

  $$P_{Mech\ Max} = 1/2 \text{x} 0.593 \text{x} \rho A\, u^3$$

- C_p Coefficient for how close we are to Betz = Energy extracted/Ideal kinetic energy
- C_p Function of blade tip velocity/wind speed = λ and blade angle of attack= θ
- So energy extracted depends on blade aerodynamics, redefine mechanical power

  $$P_{mech} = 1/2 C_p \rho A\, u^3$$

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How C_p Varies

Betz 59.3%

48%

At $\theta=0$
C_p-λ curve collapses to zero

$\lambda=$ blade tip speed/ wind speed

Angle of attack, θ

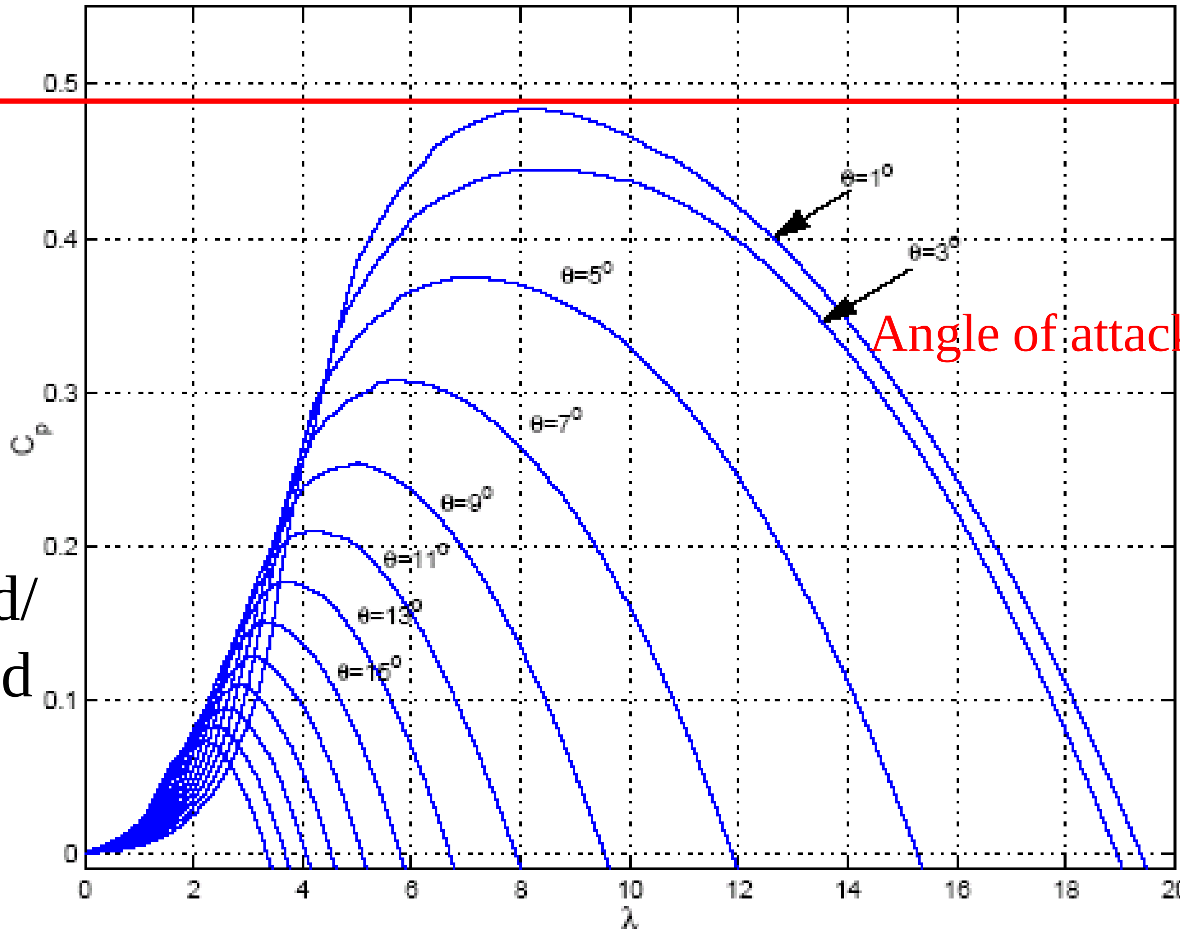
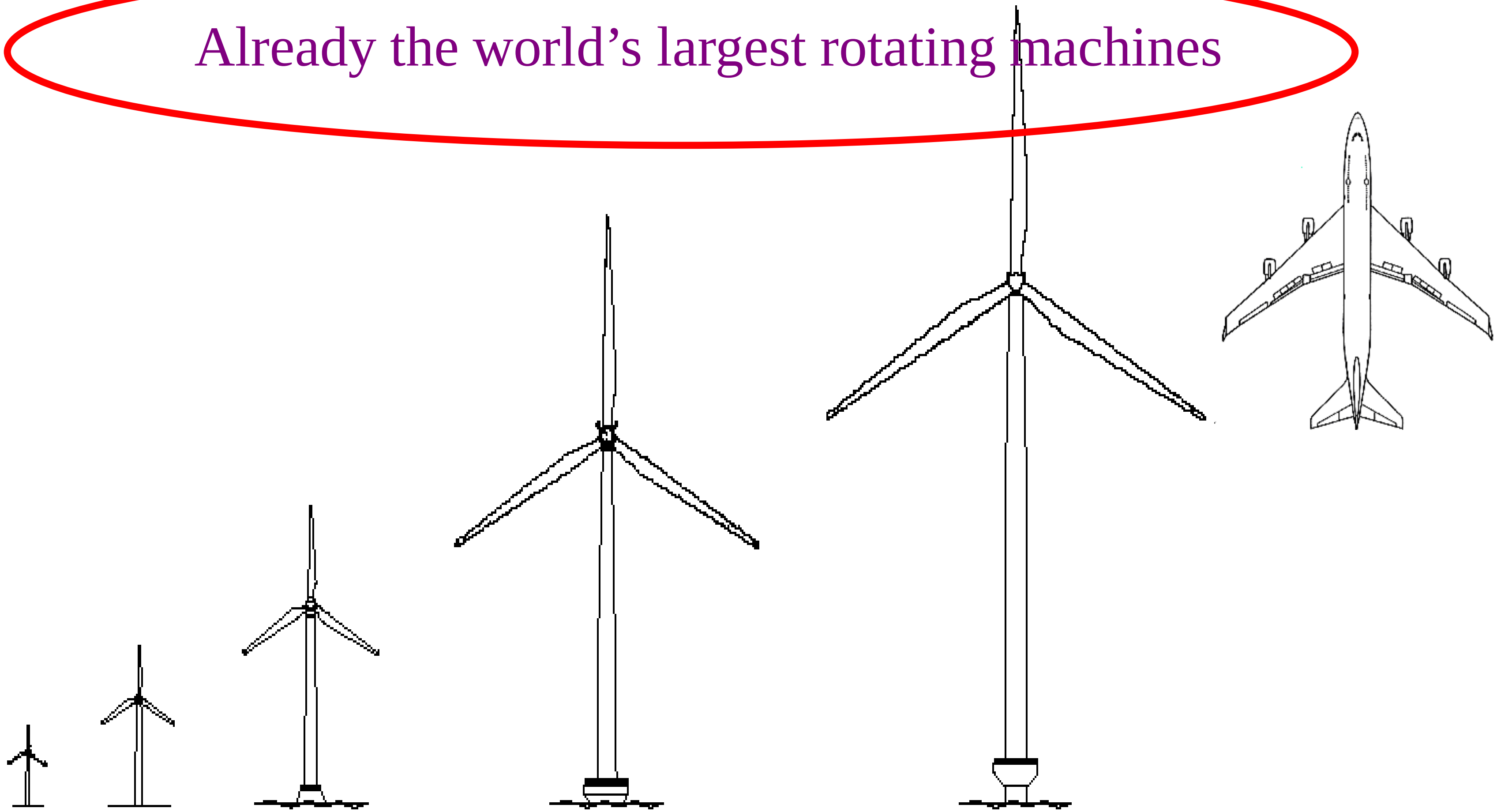


Figure 4-7. Wind Power C_p Curves

Scale

Already the world's largest rotating machines



Taxonomy of Wind Turbines

Types of Turbine & their Control

Speed Control	Pitch Control	Power Control
Fixed speed/Dual speed	None	Passive stall regulation geared drive train with asynchronous generator
Fixed speed	Yes, pitch to stall	Active stall regulation geared drive train with asynchronous generator
Limited variable speed	Yes	Geared drive train with asynchronous generator control using variable rotor resistance
Variable speed	Yes	Geared drive train with slip ring asynchronous generator control using a partly rated converter
Variable speed	Yes	Direct drive with synchronous generator control using a fully rated converter

Fixed Speed (rows 1–2)

Variable Speed (rows 3–5)

Geared Drive (rows 1–4)

Direct Drive (row 5)

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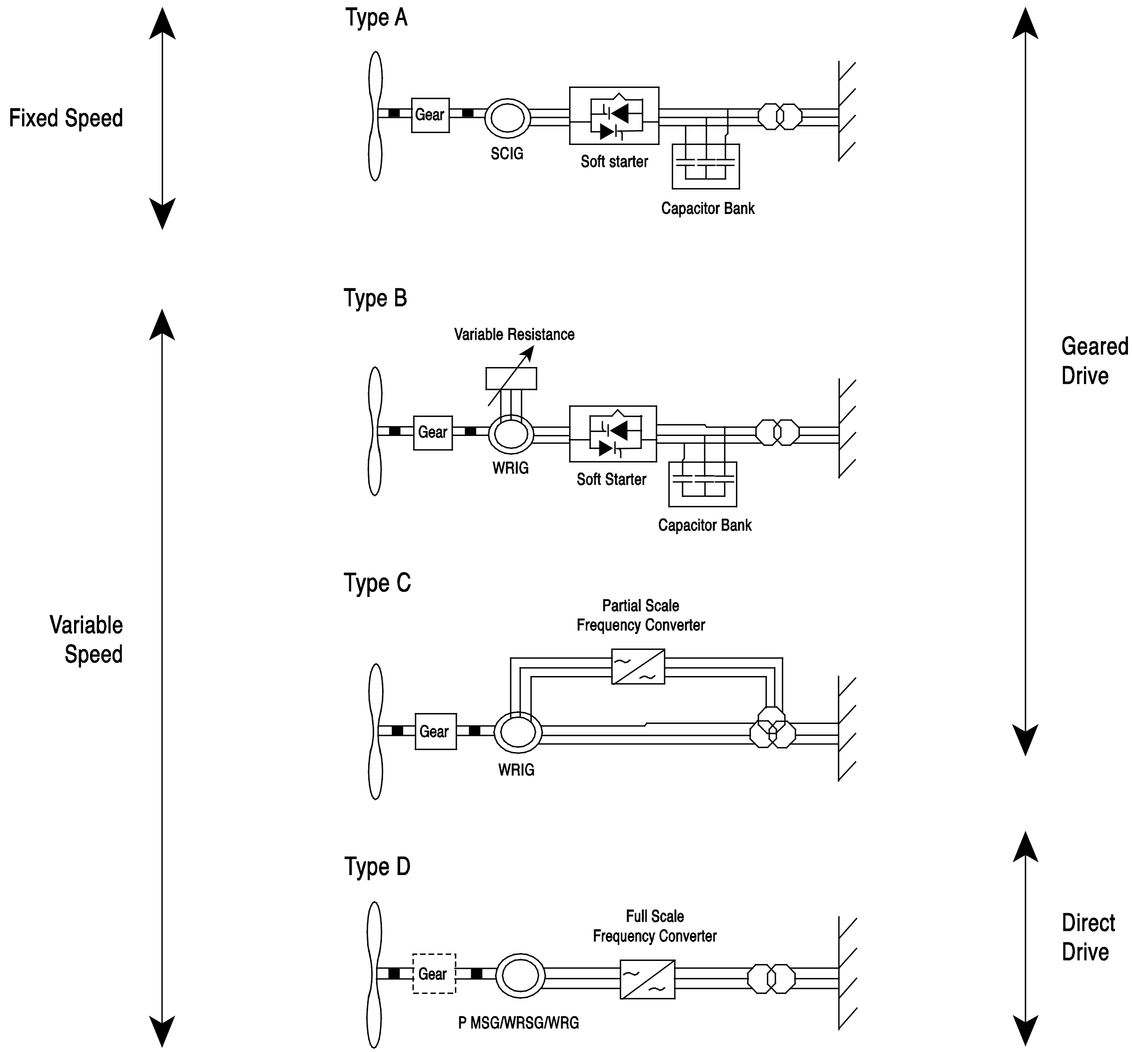
Types of Turbine & their Generators



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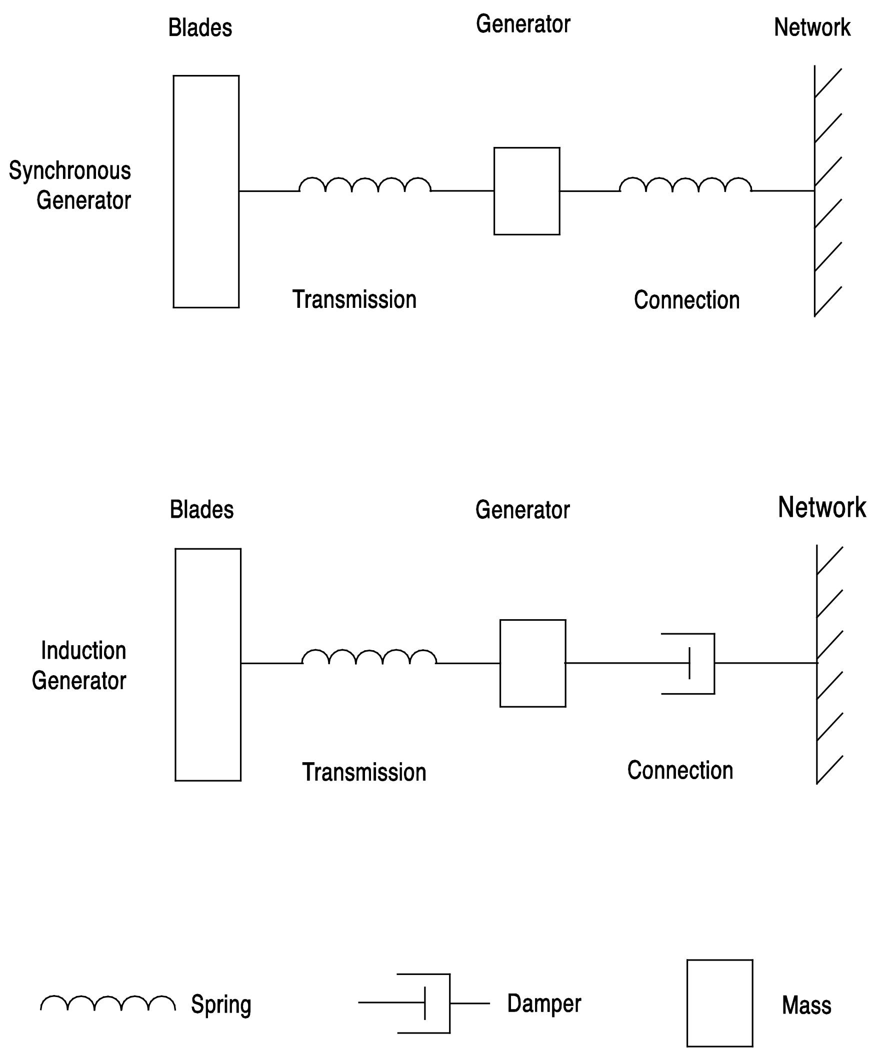
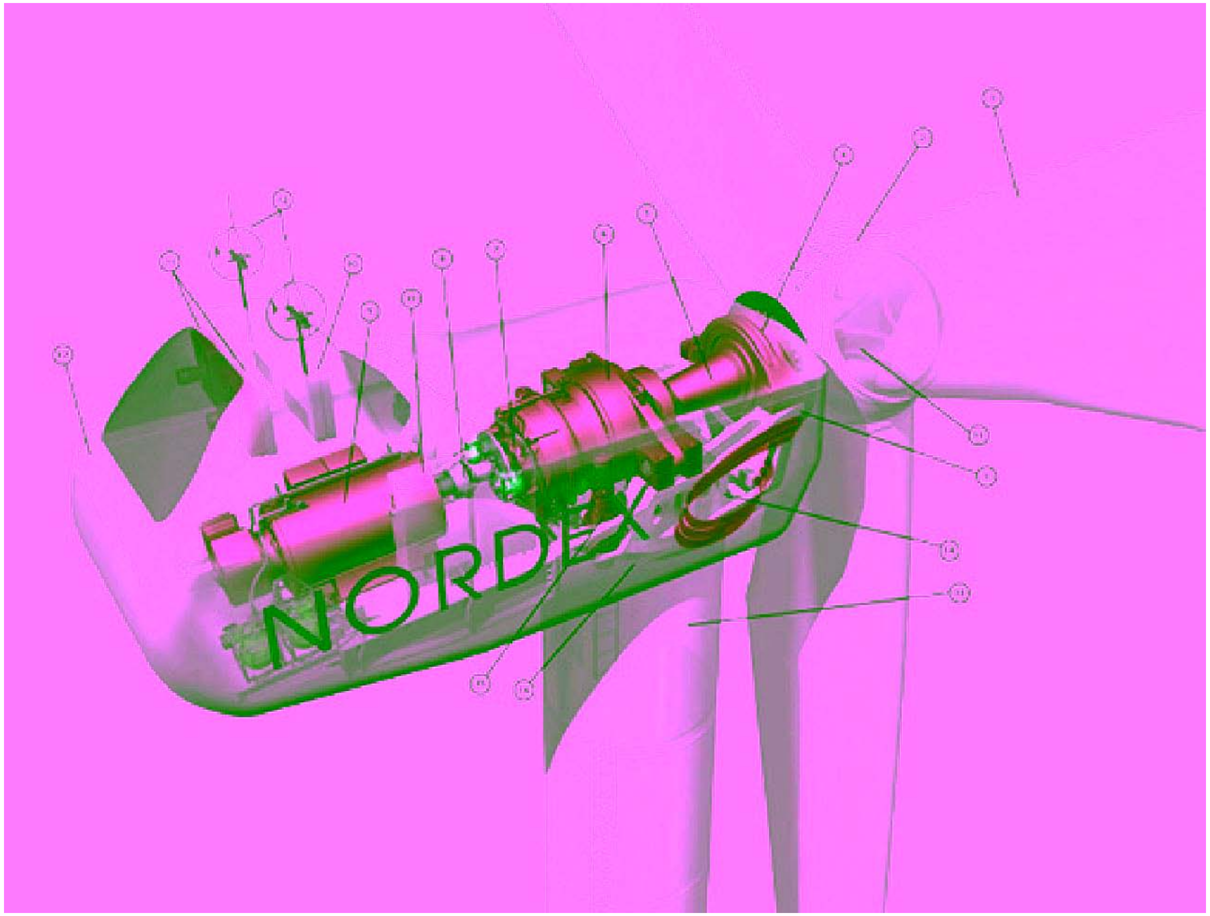
Changing Technology

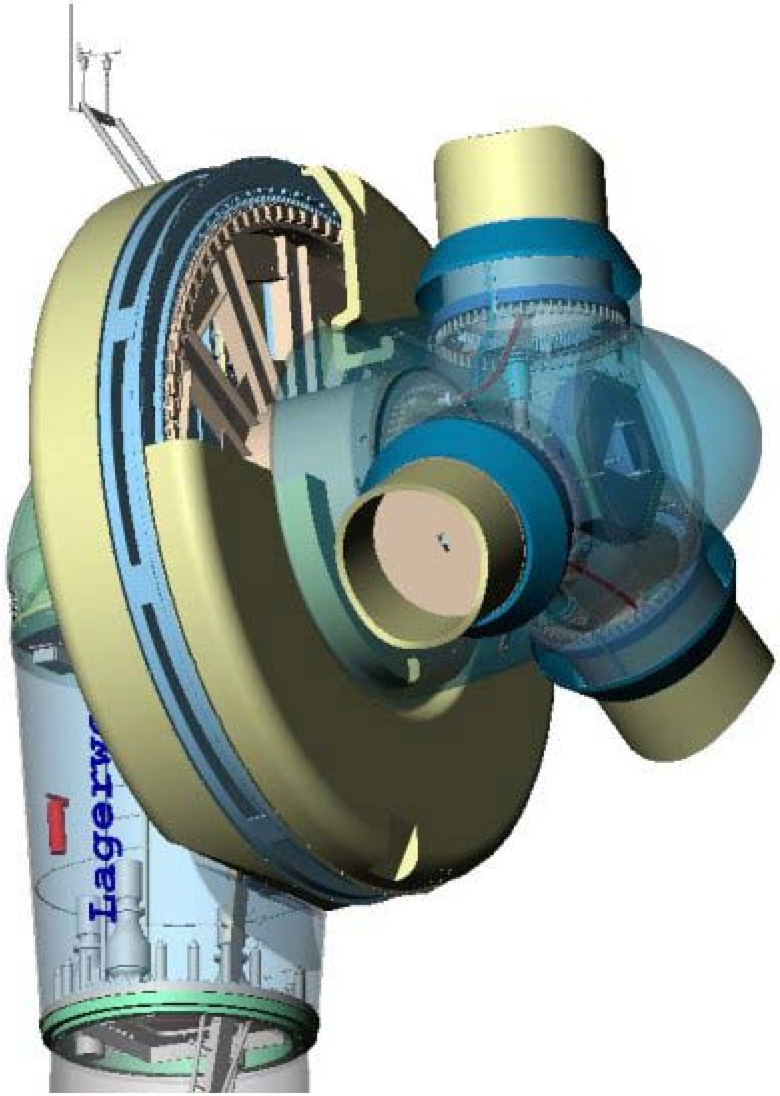


Geared Wind Turbine
Two Speed Induction Machine

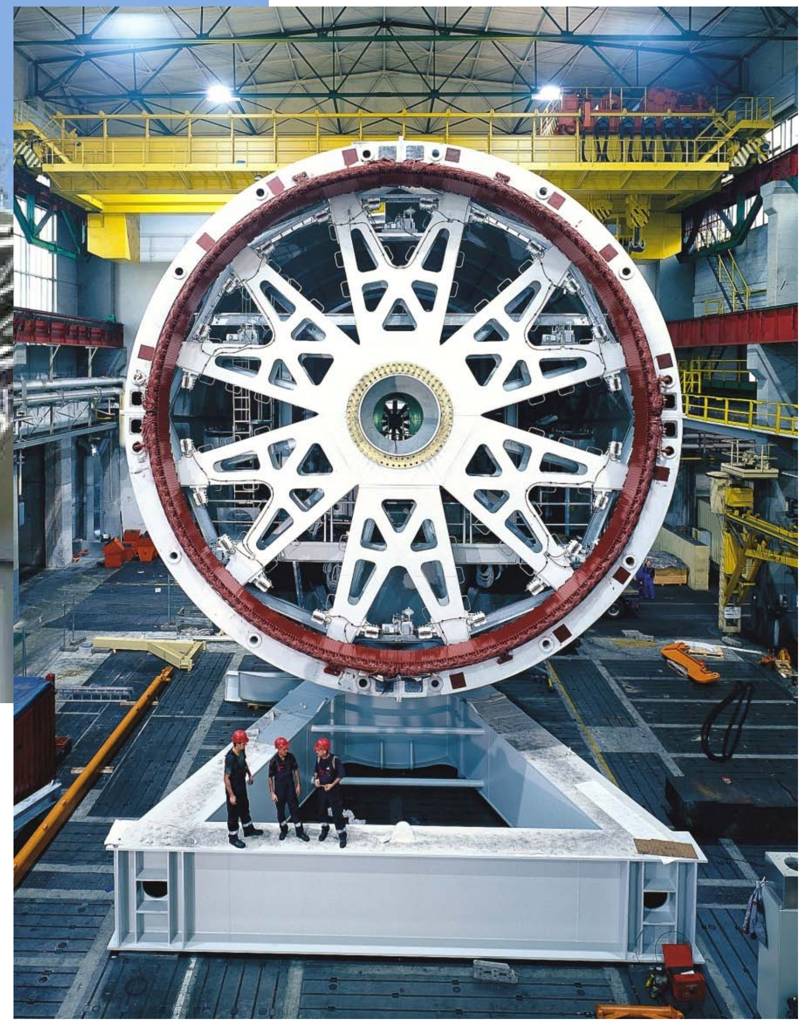
Geared Wind Turbine
Doubly Fed Induction Machine



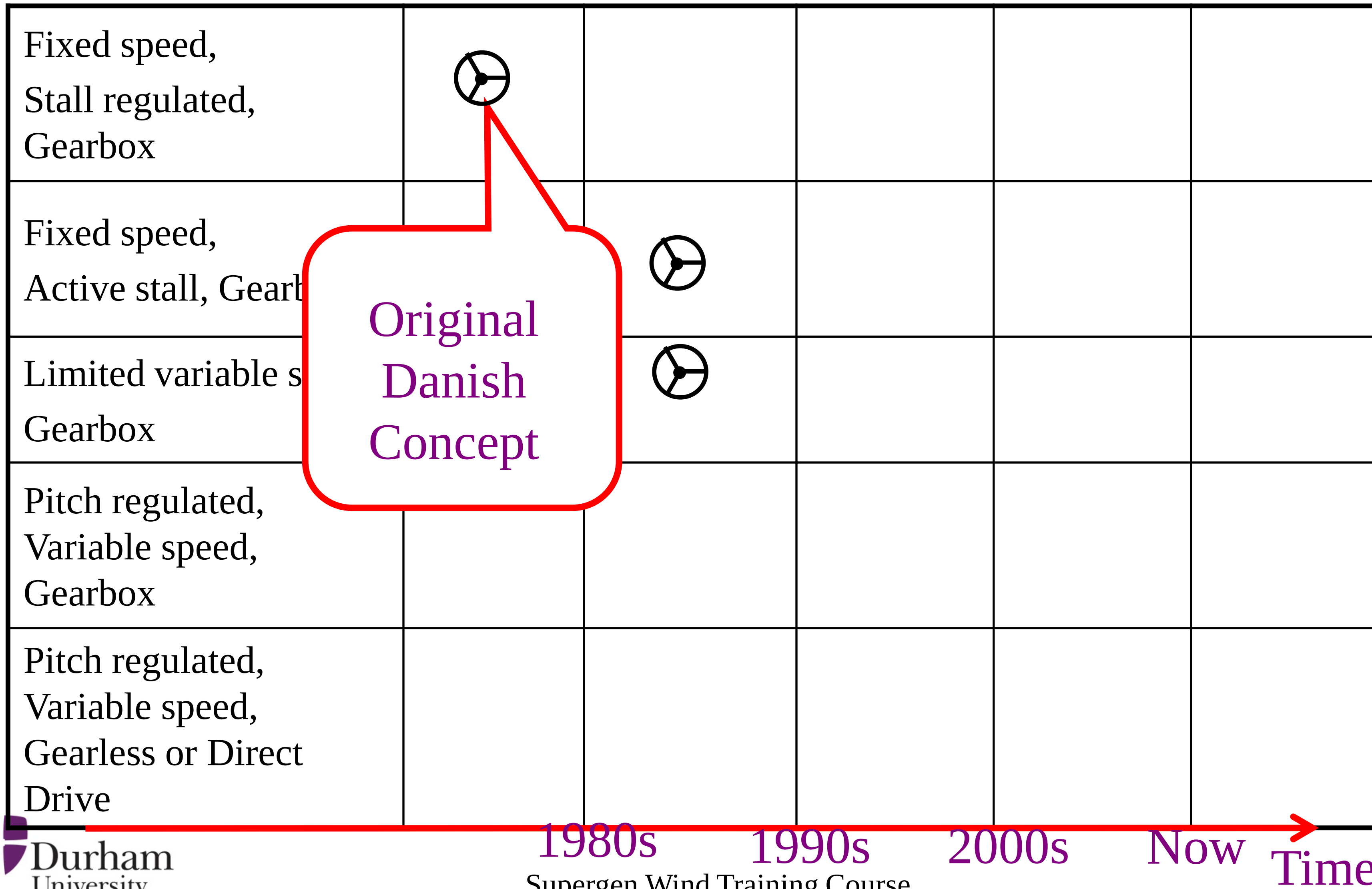
Direct Drive Wind Turbine
Permanent [illegible] Generator



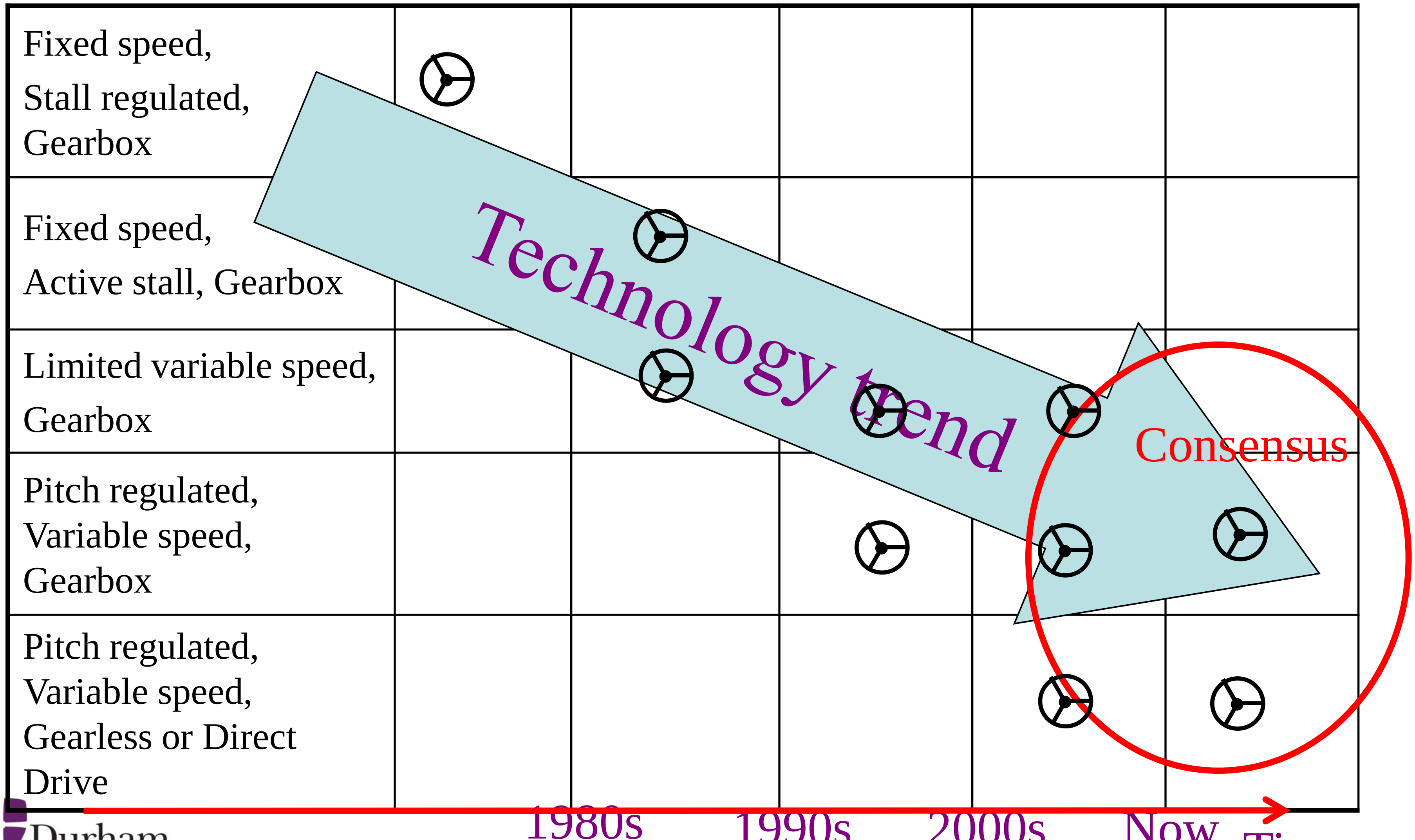
Direct Drive Wind Turbine Wound Synchronous Generator



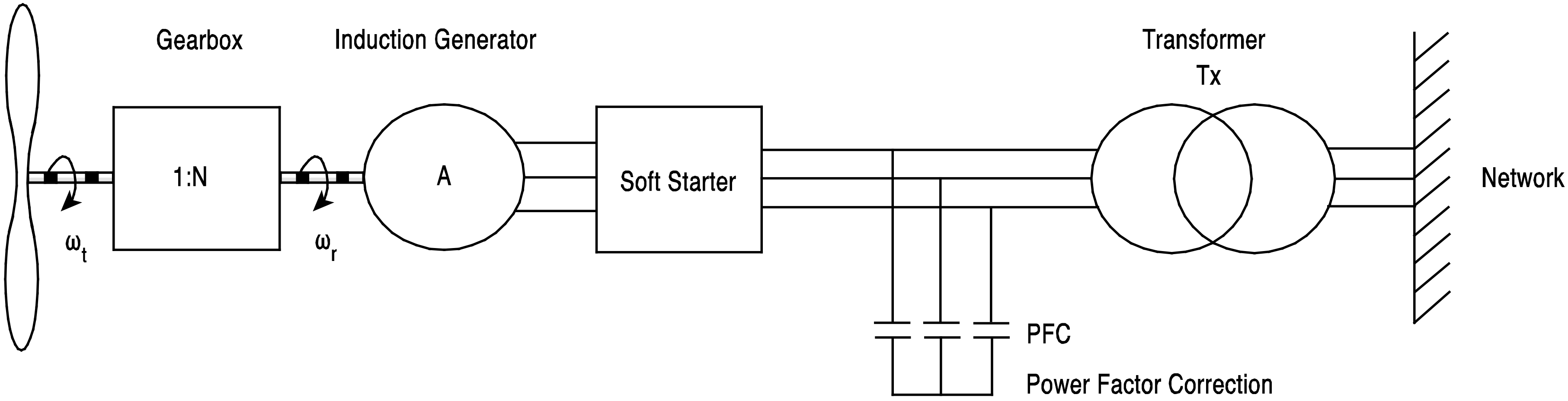
Technology spectrum



Technology spectrum

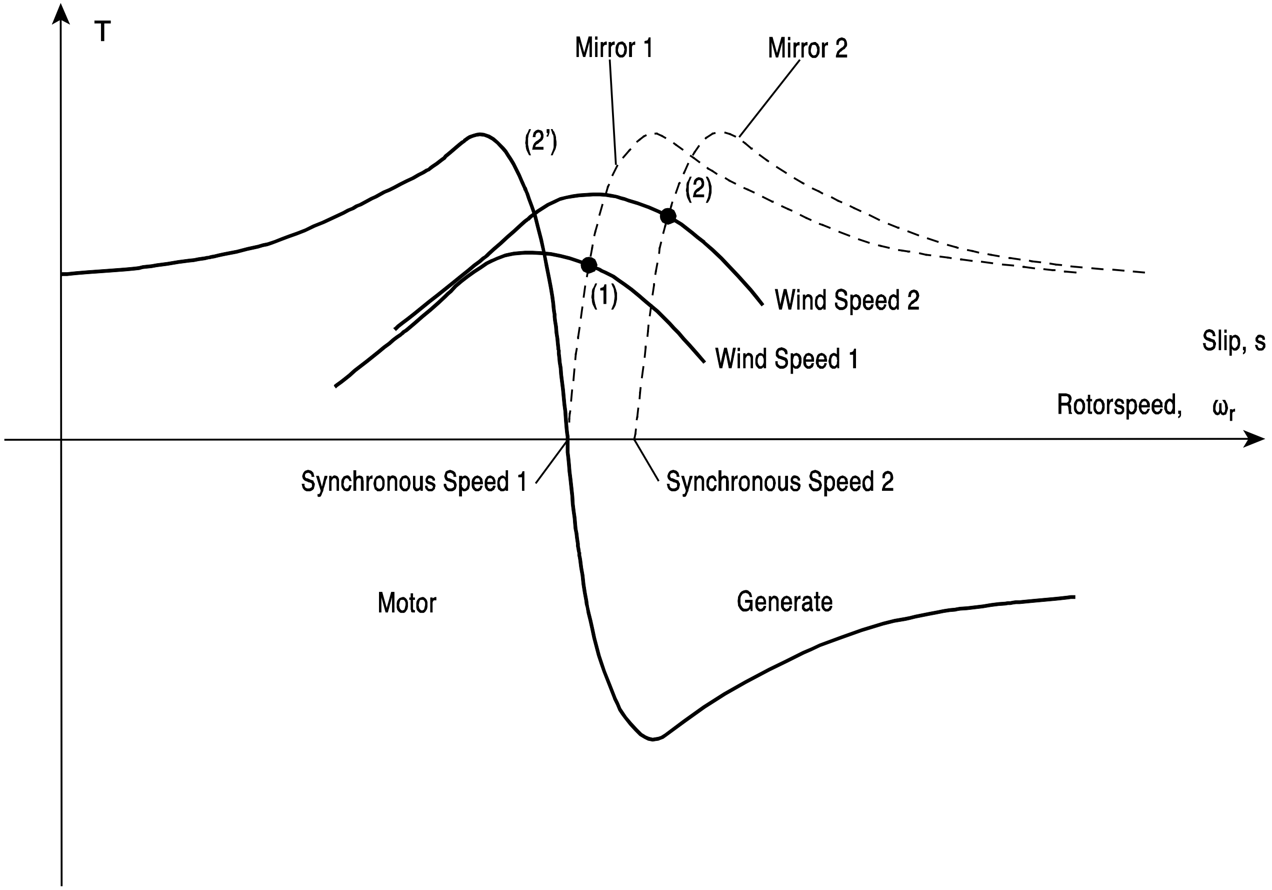


Fixed Speed Turbine Induction Generator

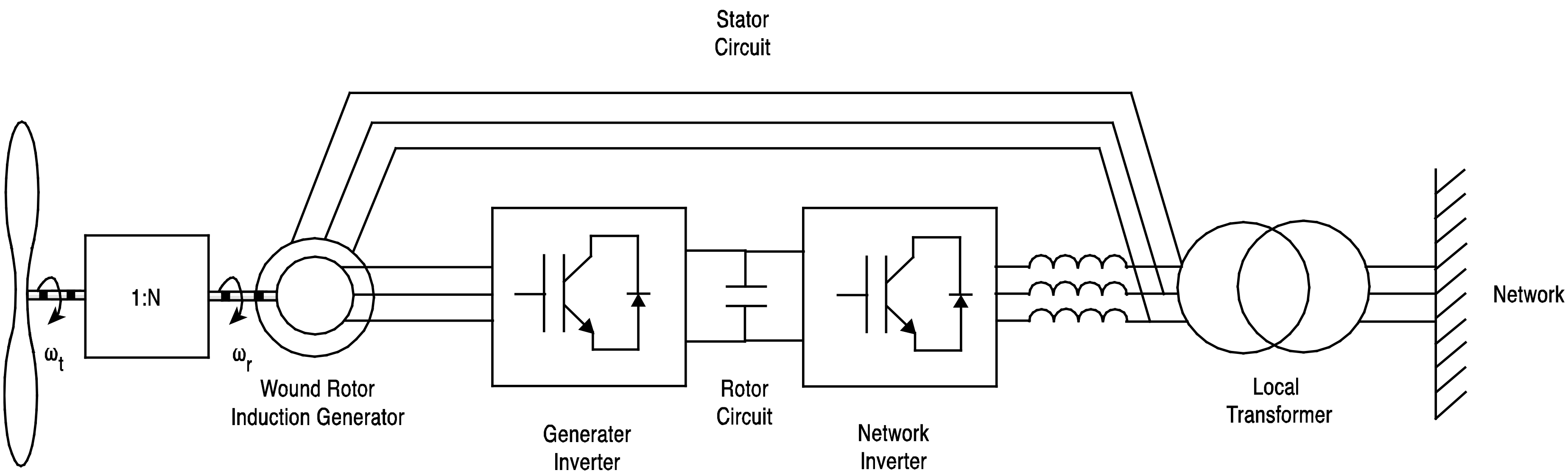


Geared Wind Turbine Induction Machine

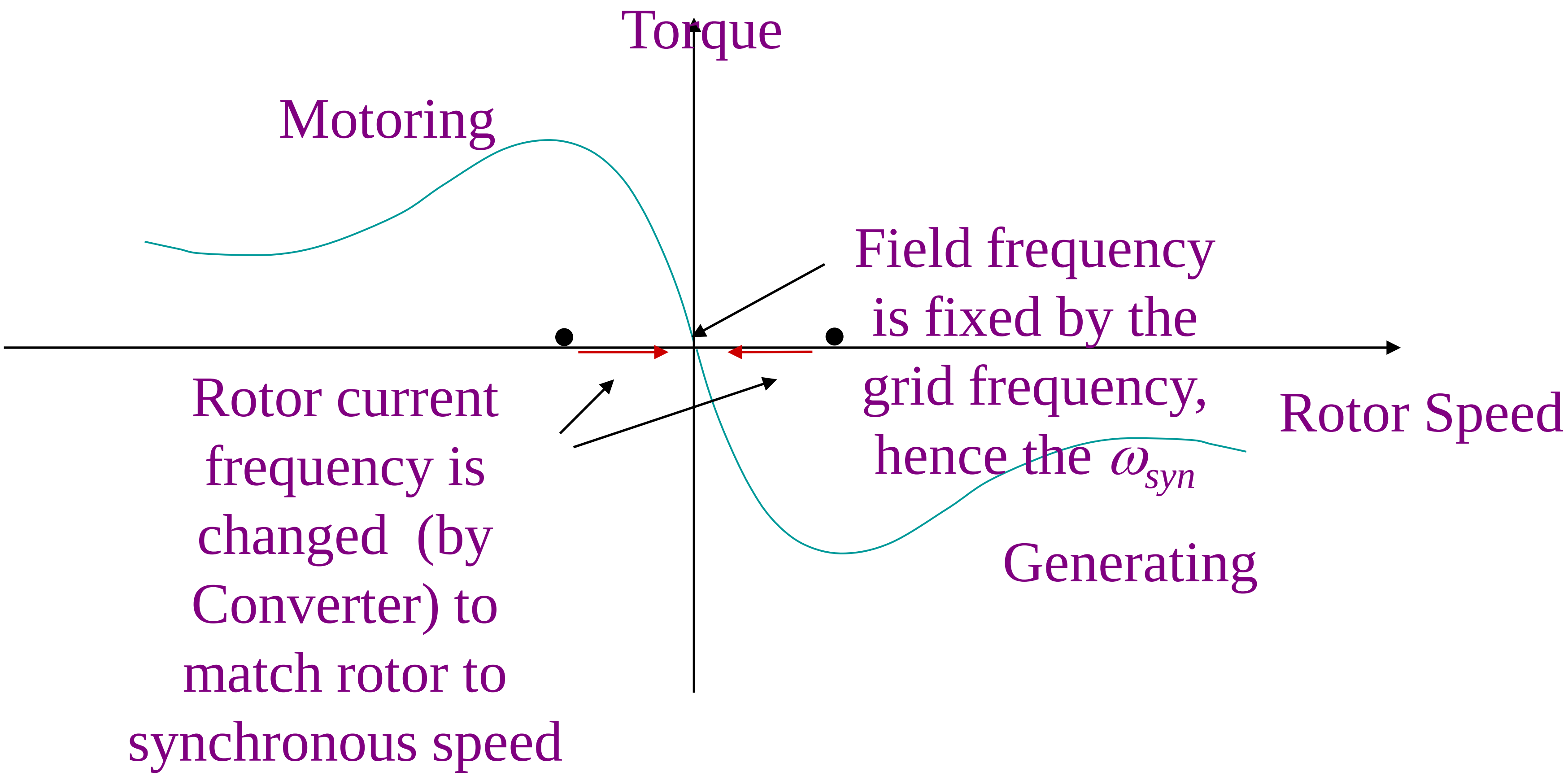
Variable Speed Turbine Induction Generator



DFIG with partially rated converter, Narrow speed range



DFIG with partially rated converter



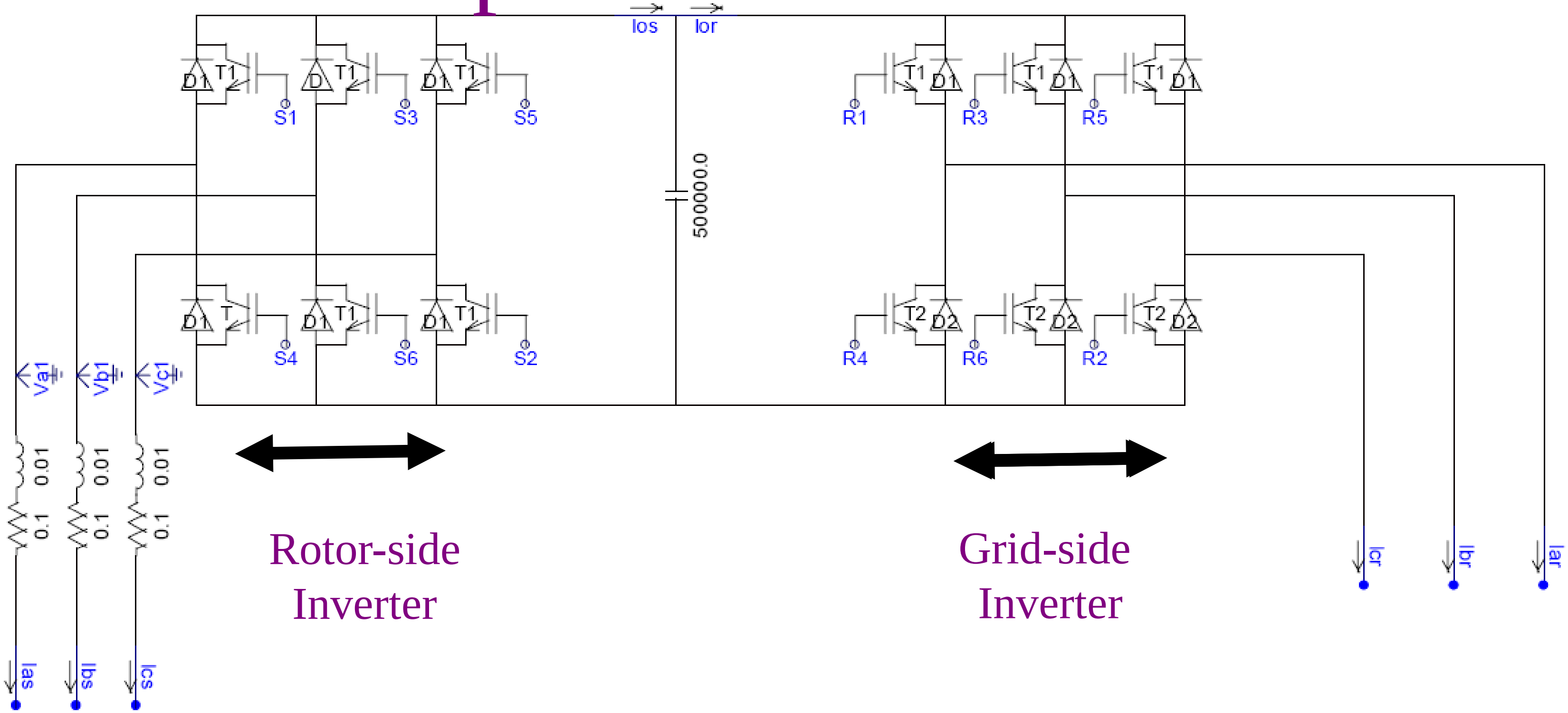
Variable Speed Turbine Converter

Converter

Rotor-side Inverter

Grid-side Inverter

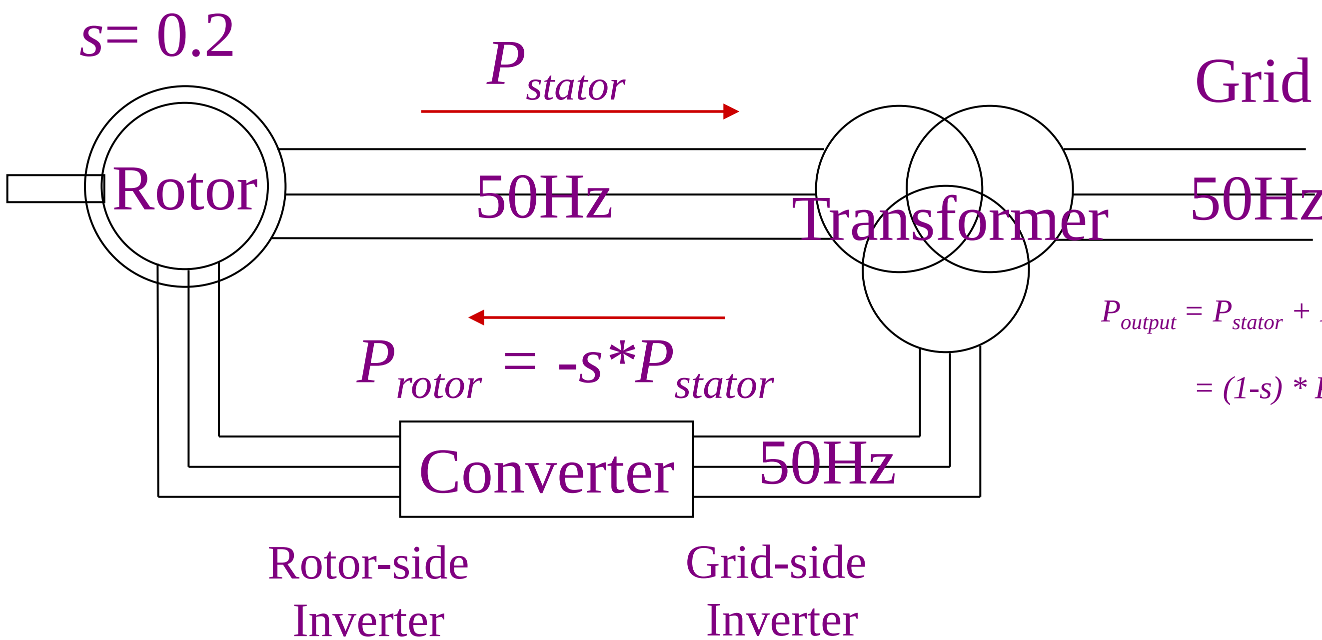
Variable Speed Turbine Converter



Back to back PWM converter

DFIG-Generating mode: Sub-Synchronous

Rotor at Sub-Synchronous speed, i.e. 1200 rev/min (40Hz)



$P_{output} = P_{stator} + P_{rotor}$

$= (1\text{-}s) * P_{stator}$

For Example,

If P_{output} = 2 MW, s= 0.2; P_{stator} = 2.5MW, P_{rotor} = -0.5MW

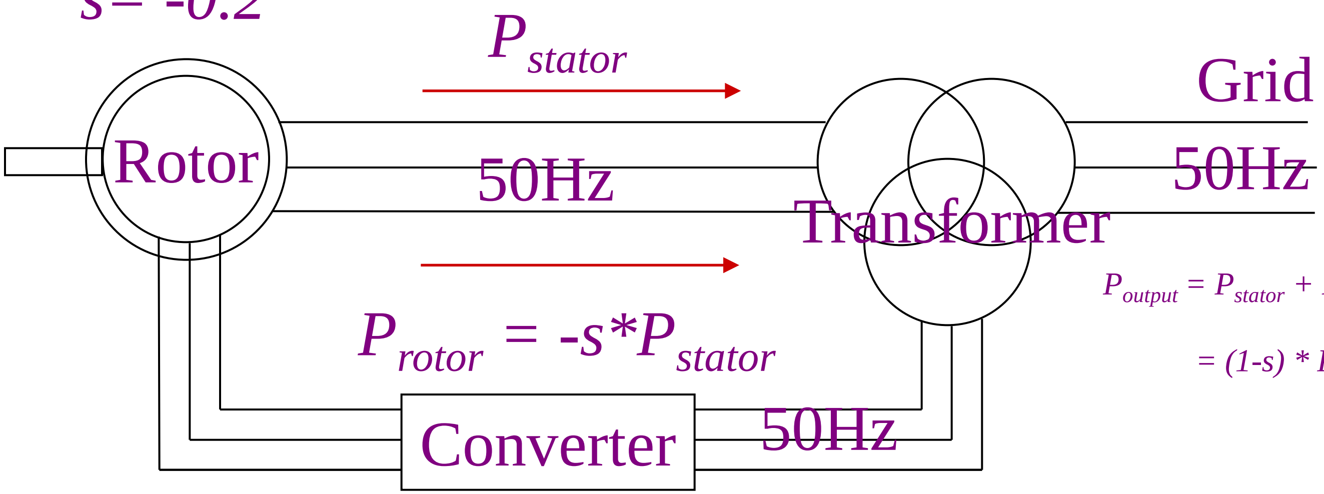
Hence, the rating of the converter required ≈ 25% of the total rating of the generator

DFIG-Generating mode: Super-Synchronous

$s = -0.2$

Rotor at Sub-Synchronous speed, i.e. 1800 rev/min

(60Hz)



$P_{output} = P_{stator} + P_{rotor}$

$= (1-s) * P_{stator}$

Rotor-side Inverter

Grid-side Inverter

For Example,

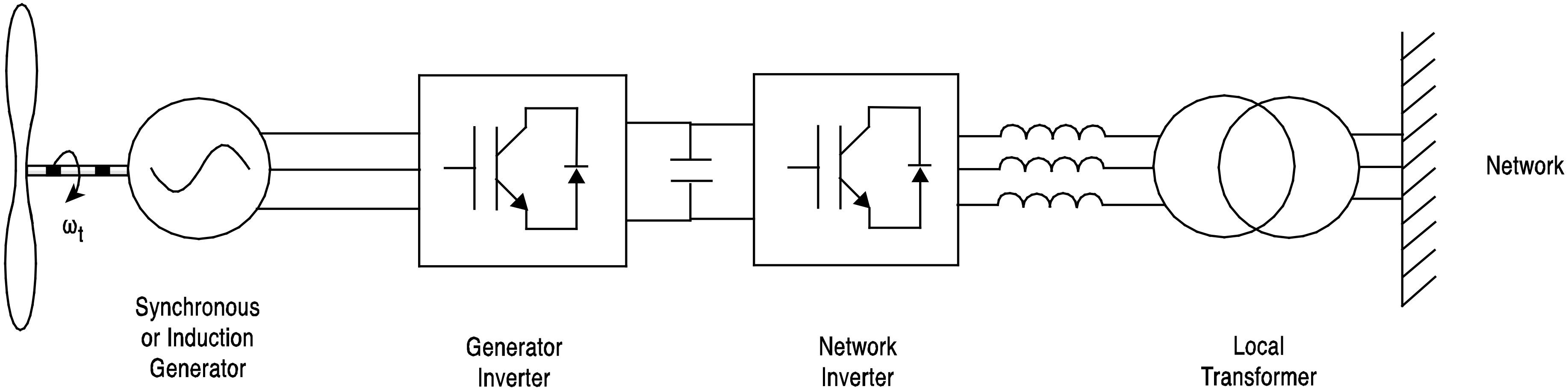
If $P_{output} = 2\ MW,\ s = -0.2;\ P_{stator} = 1.6\ MW,\ P_{rotor} = 0.4\ MW$

Hence, the rating of the converter required ≈ 20% of the total rating of the generator

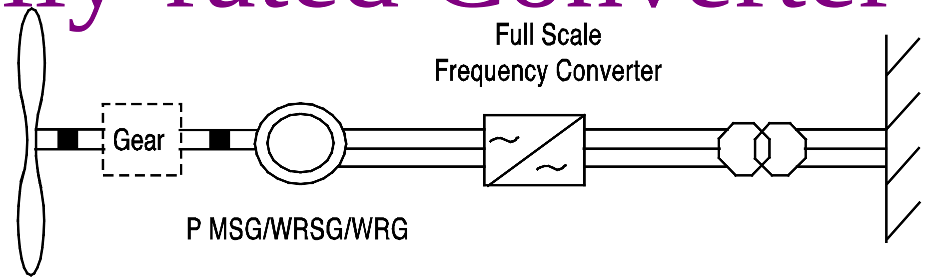
DFIG Four operating modes

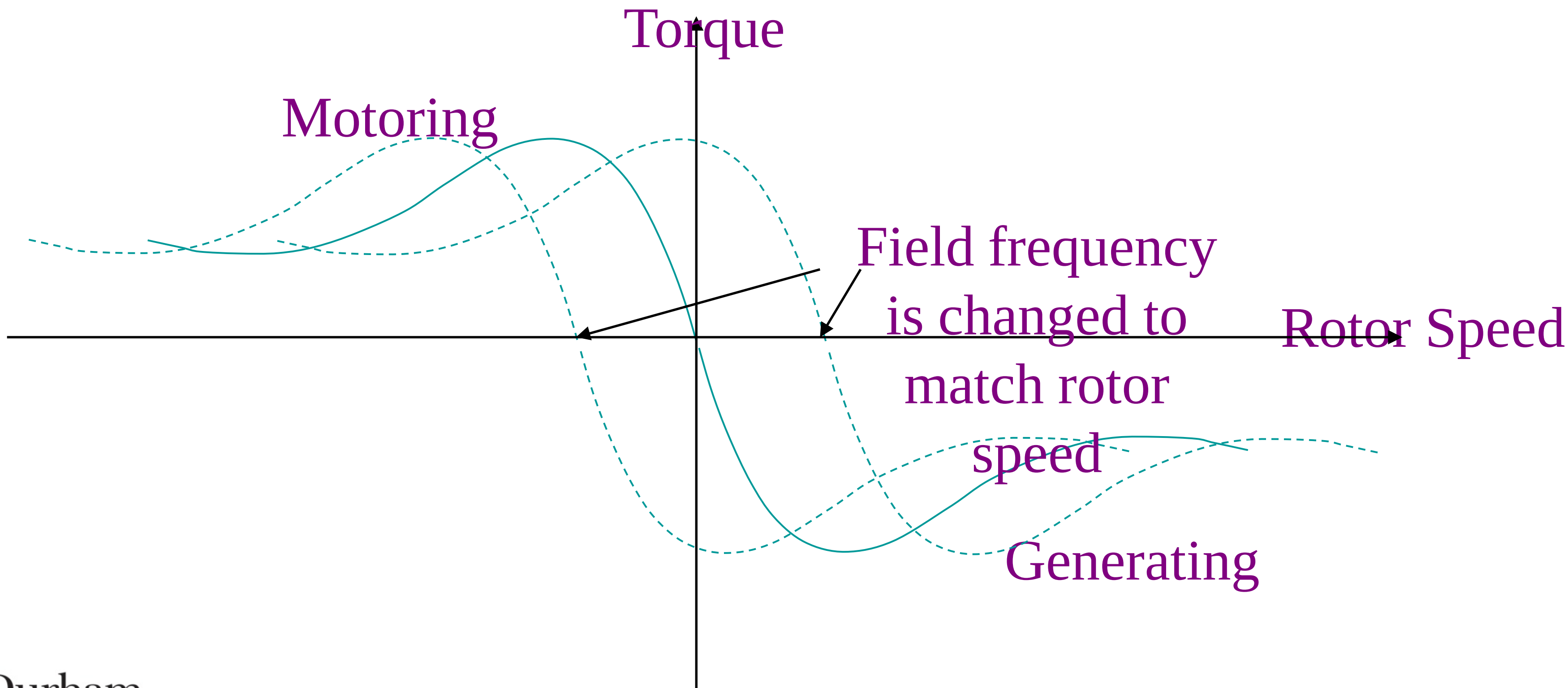
Mode	Rotor Speed	Slip power/ rotor power	Grid-side Inverter	Rotor-side Inverter
Generating	Super-synchronous	Rotor to Grid	Rectifier	Inverter
	Sub-synchronous	Grid to Rotor	Inverter	Rectifier

Variable Speed Broad Speed Range- SG, PMSG or IG with fully-rated Converter



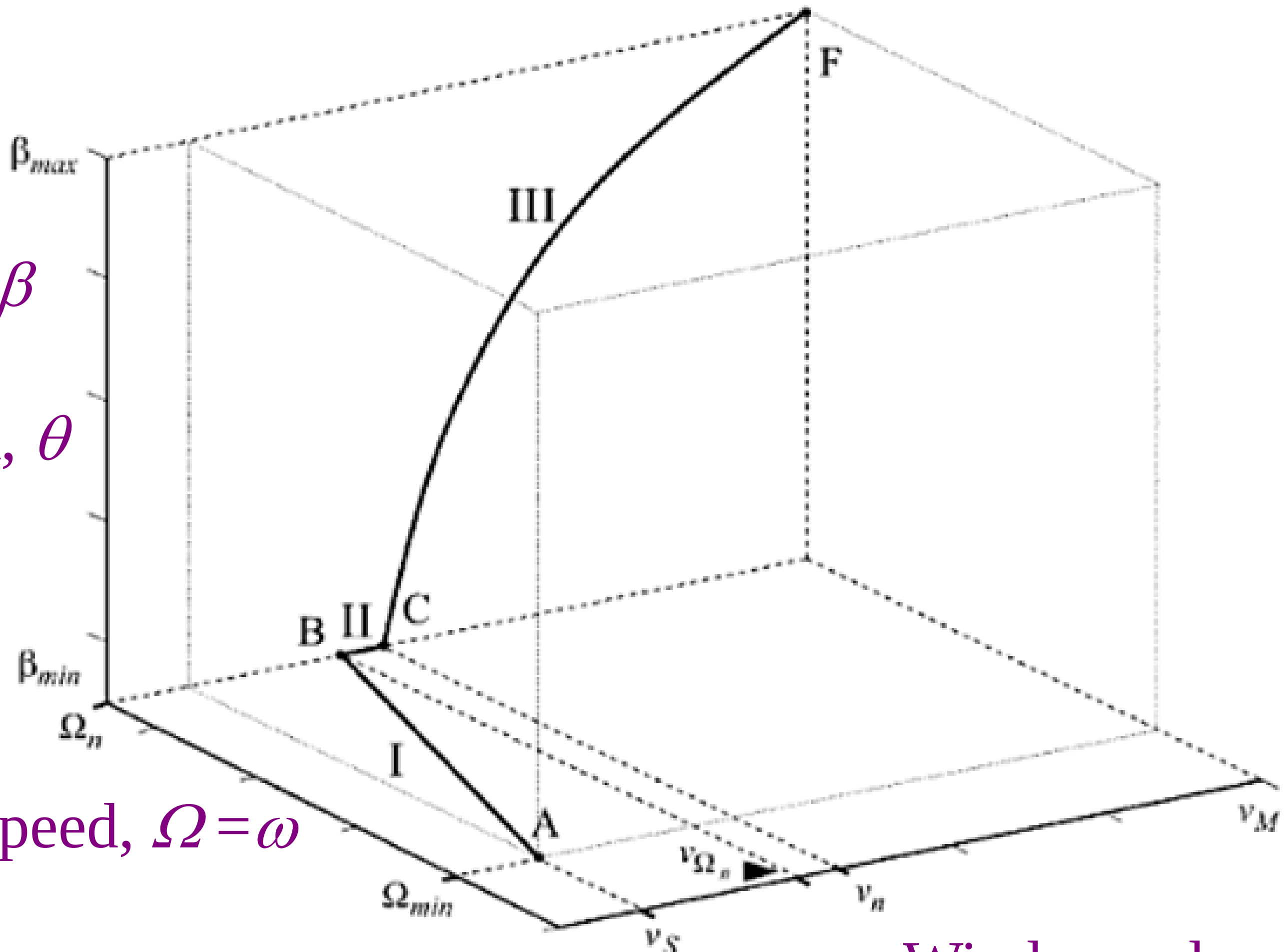
SG, PMSG or IG with fully-rated Converter





Variable Speed Turbine Control

Blade angle, β
Related to
angle of attack, θ



Turbine speed, $\Omega = \omega$

Wind speed, v

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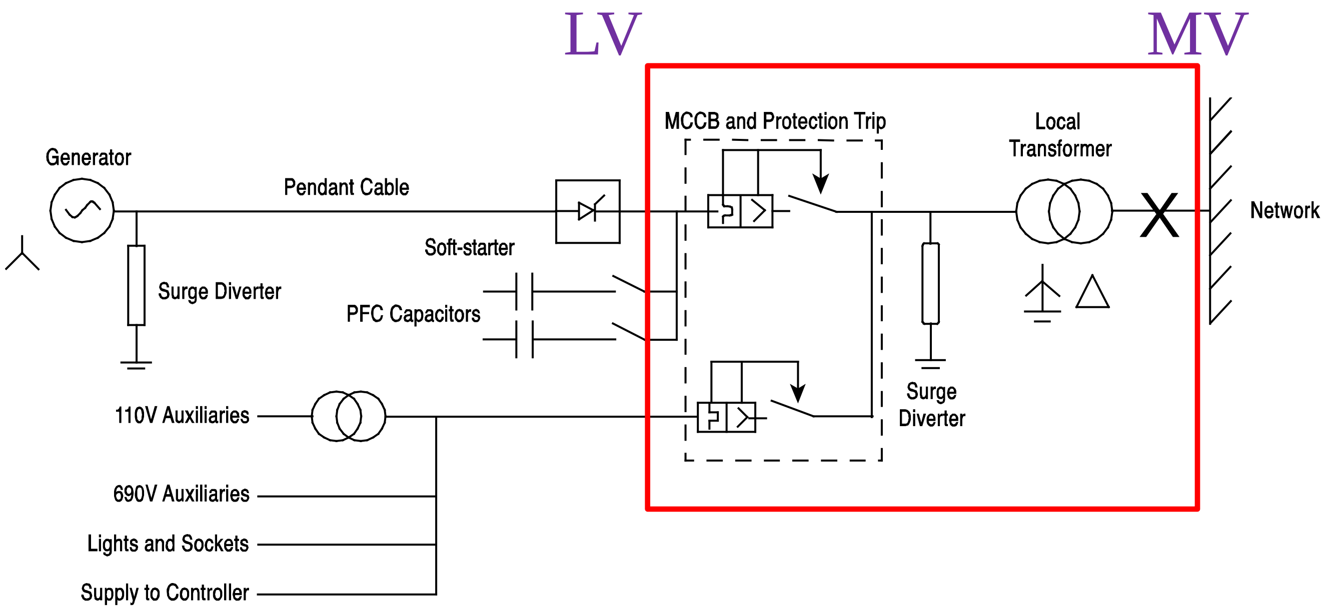
Grid Connection Issues

- Voltage levels, LV (<1 kV),
  MV (1-66 kV),
  HV (110-220 kV),
  EHV (>220 kV)
- Line impedances relate to voltage levels,
  (>voltage, <line impedance)
- Fault levels, inversely proportional to line impedance and therefore depend on voltage levels
- Cable versus overhead line
- Redundancy of circuits to ensure security
- AC or HVDC cable connection for offshore
- Ridethrough
- Lightning
- Impact of harmonics

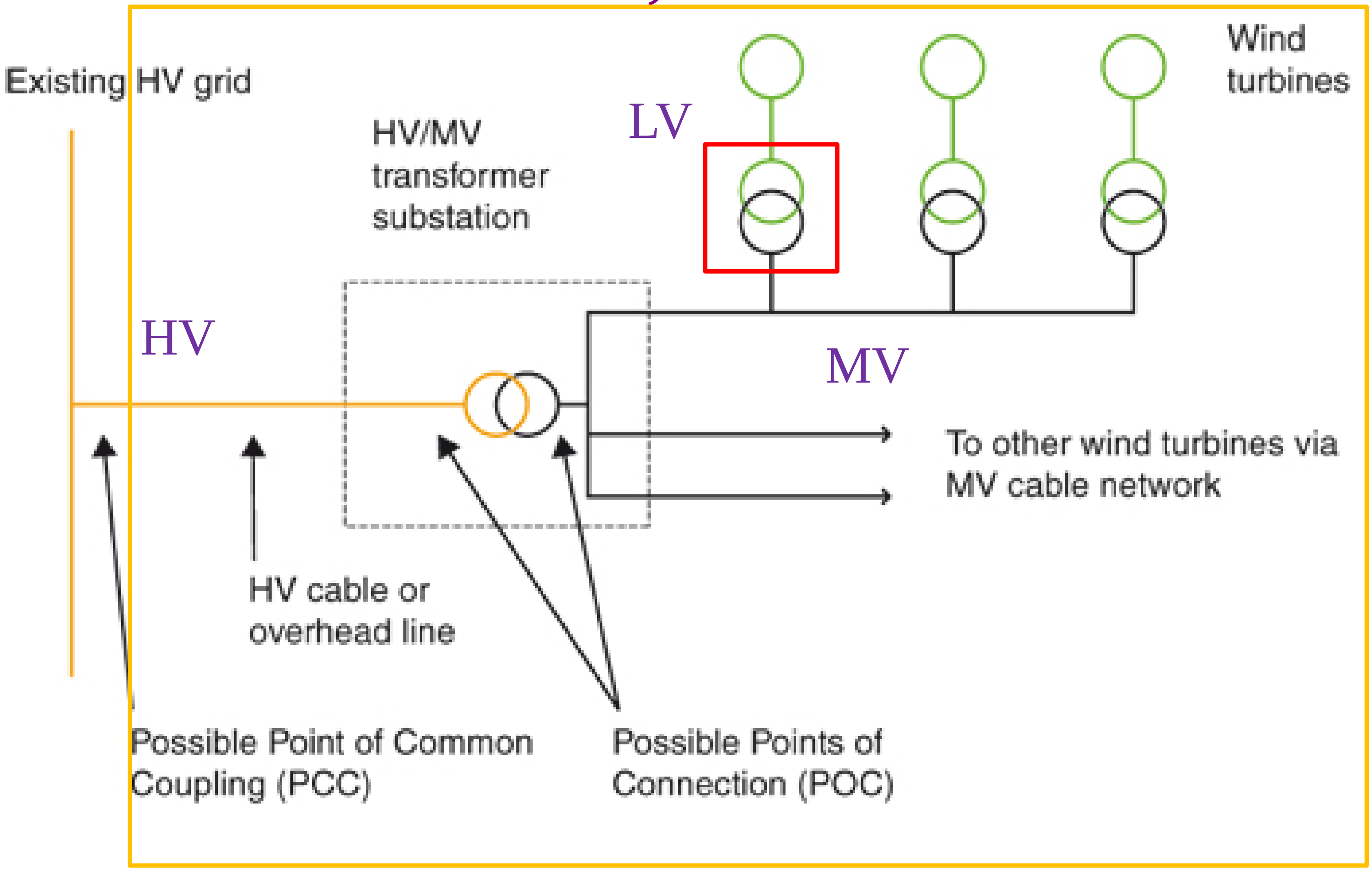
Power Collection, Single Wind Turbine



Power Collection, Single Wind Turbine

Figure 10.2 Transformer and Switchgear of 1.5 MW Wind Turbine, MV Switchgear on right, LV Switchgear on left (Reproduced by permission of NEG MICON; www.neg-micon.dk)

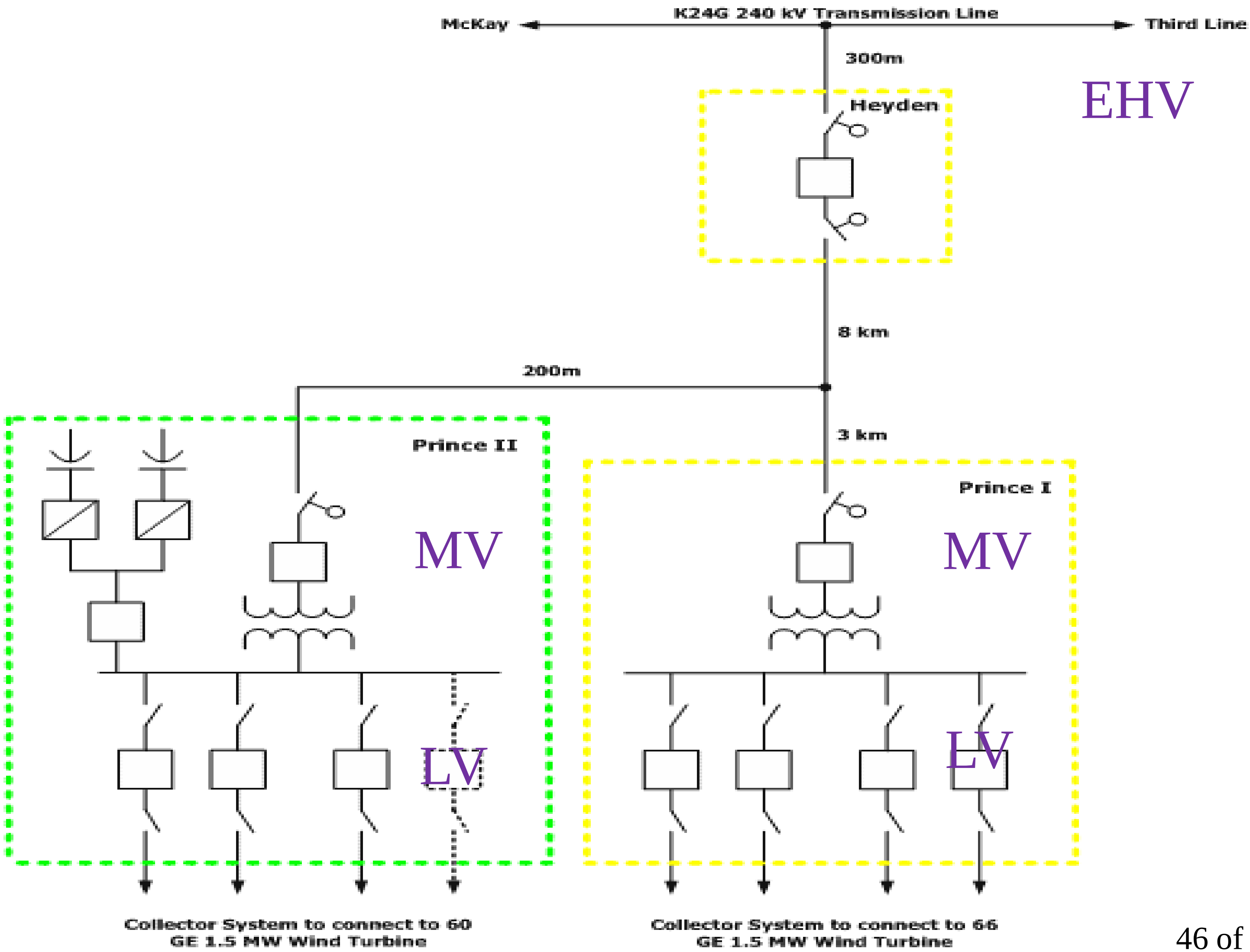
Power Collection, Small Wind Farm



Summary of Cable or Overhead Line for MV & HV

- Cable is buried so less visual impact but more expensive & requires special care:
  - Wayleaves
  - Onshore trenching to promote cable cooling
  - Offshore armouring and trenching to ensure protection
  - Cable *C*
  - Line *L/R* ratio
- Overhead line has more visual impact but is less expensive & also requires special care:
  - Wayleaves
  - Line *L/R* ratio

Power Collection, Multiple Wind Farms



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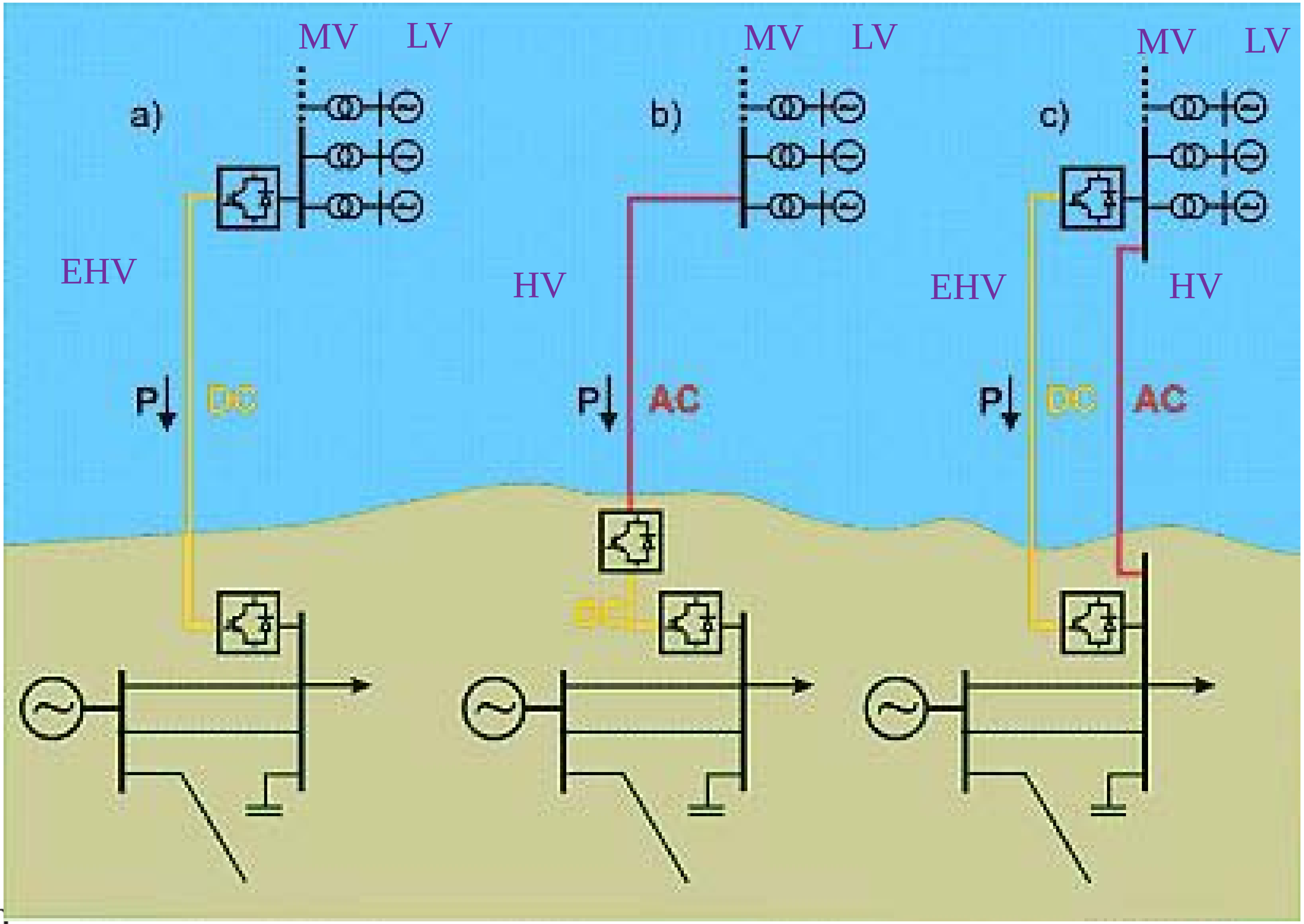
Power Collection, Wind Farm Offshore, HVDC Light



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Power Collection Offshore, Horns Rev 1

Substation, Horns Rev 2

Grid Problems

- Ridethrough
  - Grid voltage reductions, caused by lightning or switching activity, can damage DFIG converters or trip WTs
  - Solution is Crowbar operation of Converter
  - Voltage reductions damage Line-side Inverter
  - Crowbar operations damage Generator-side Inverter
- Harmonics
  - WT Converters impose harmonics on the Grid
  - Can be mitigated by choice of Converter and use of Phase Shift Transformers
- Voltage Transients
  - Grid voltage reductions, caused by lightning or switching activity, can damage WT drivetrain by imposing transient torques
  - WT generator speed changes can cause damaging torque transients on WT drivetrain

Grid Codes

B. Frequency Range and Control

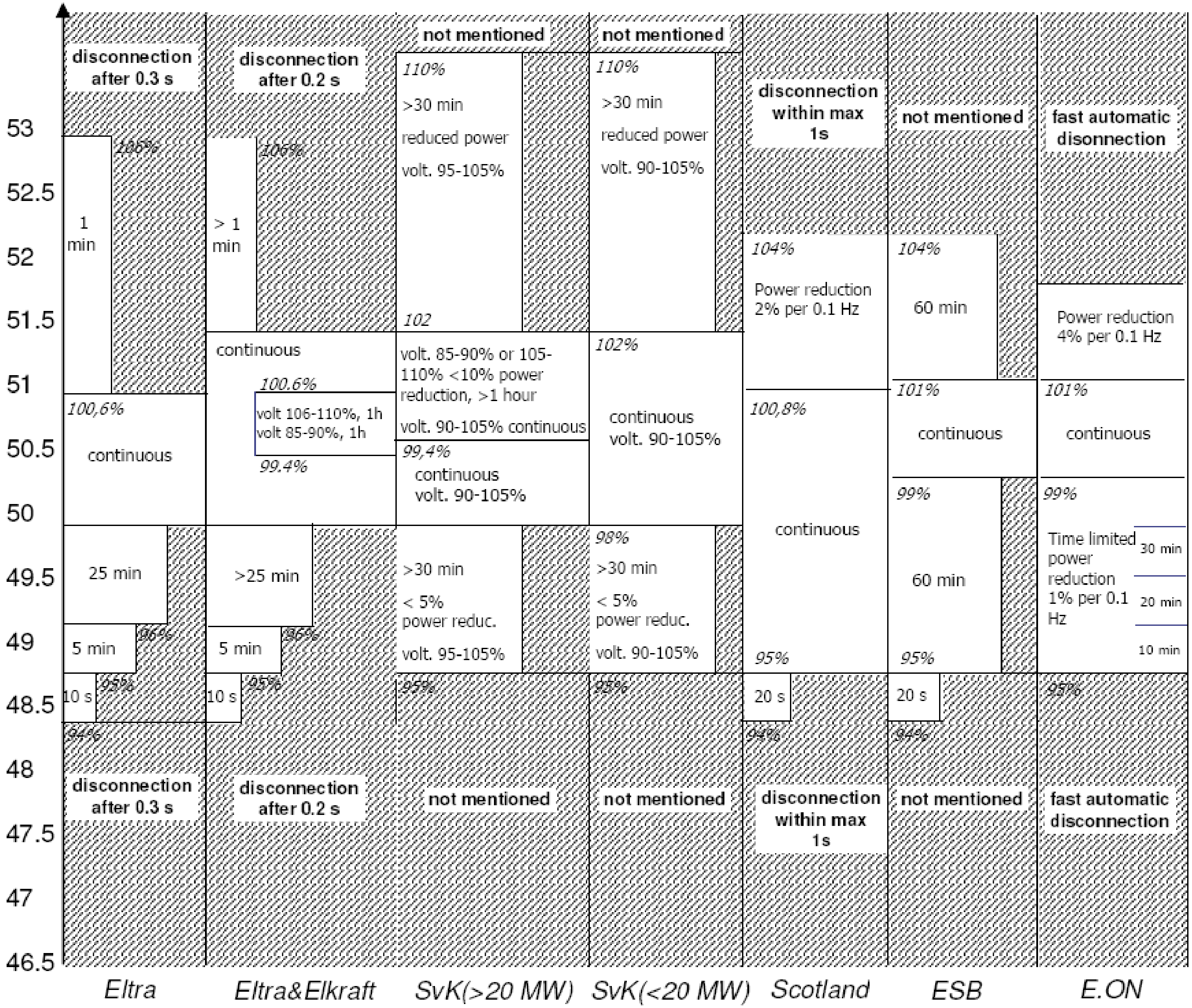

Fig. 2. Requirements to frequency range and frequency control

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Ridethrough, Typical Requirement

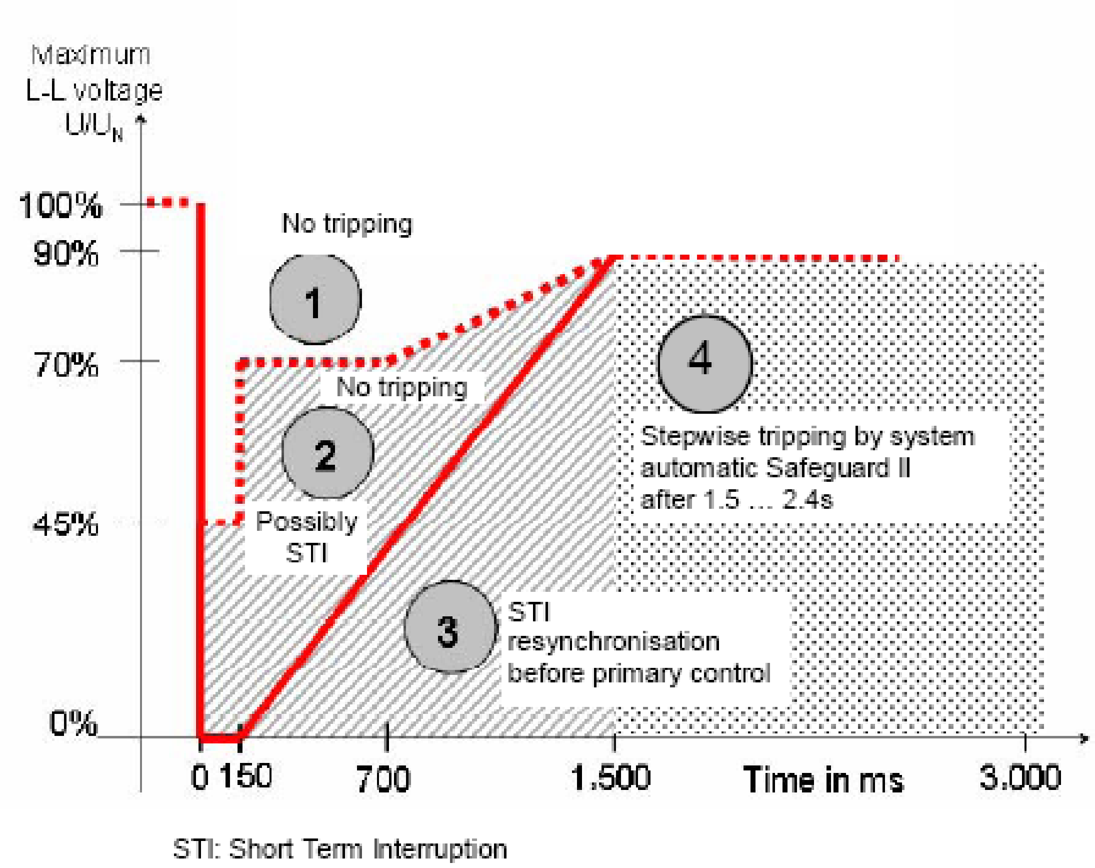
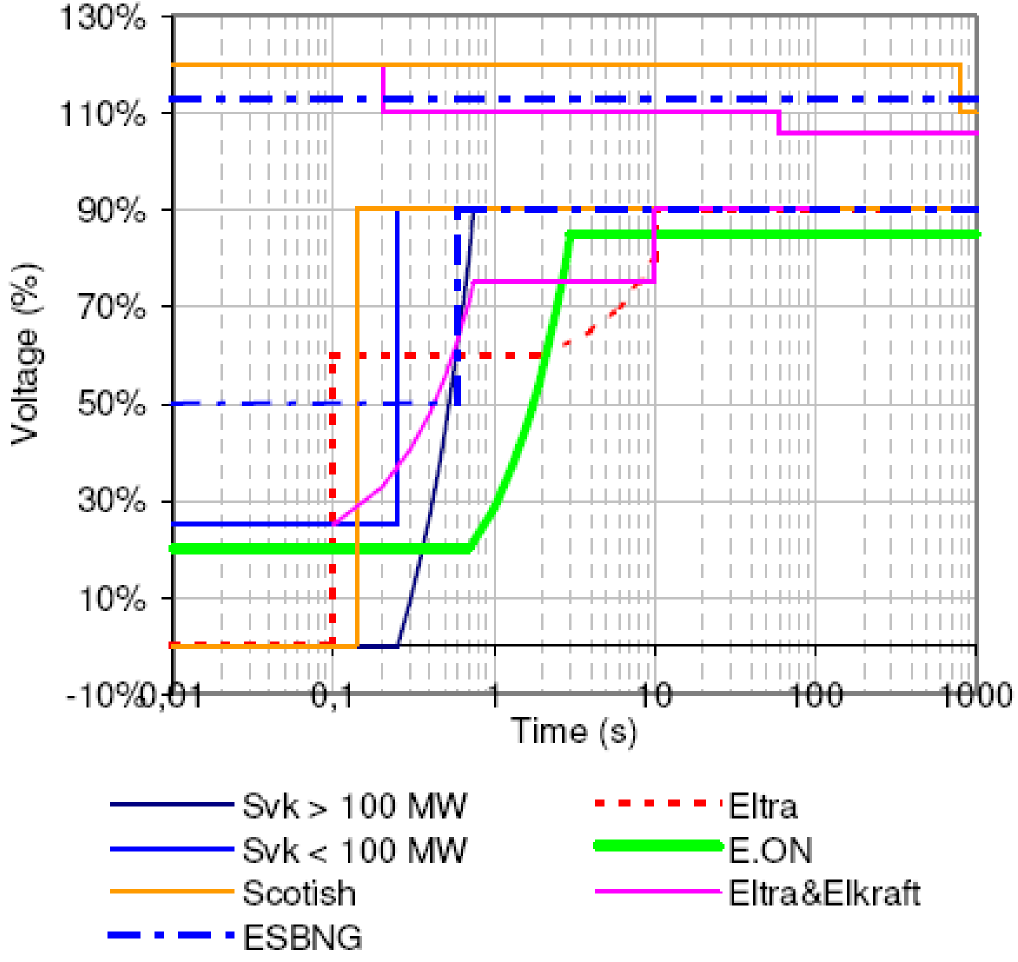


Fig. 1. Fault-ride through requirements

Ridethrough, Different Requirements



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Thank you

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