CHALMERS

DAT460 Förnyelsebar elproduktion och eltransporter lp2 HT20 (3,5 hp)

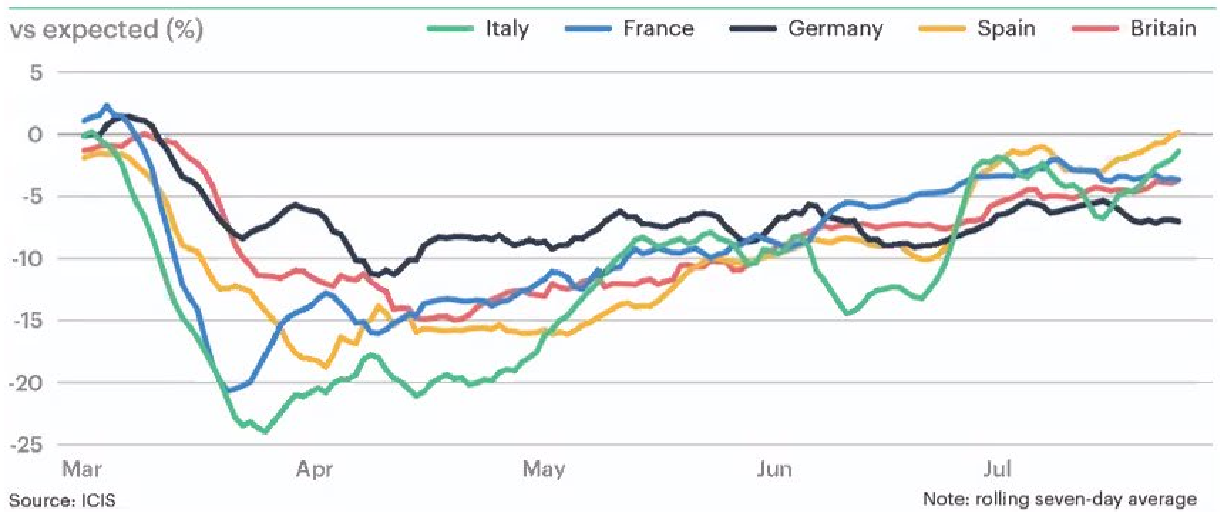
Vindkraft elsystem

Ola Carlson

Chalmers

20201111

Global electricity consumption went down due to pandemic



Source: Independent Commodity Inteligence Services (ICIS)

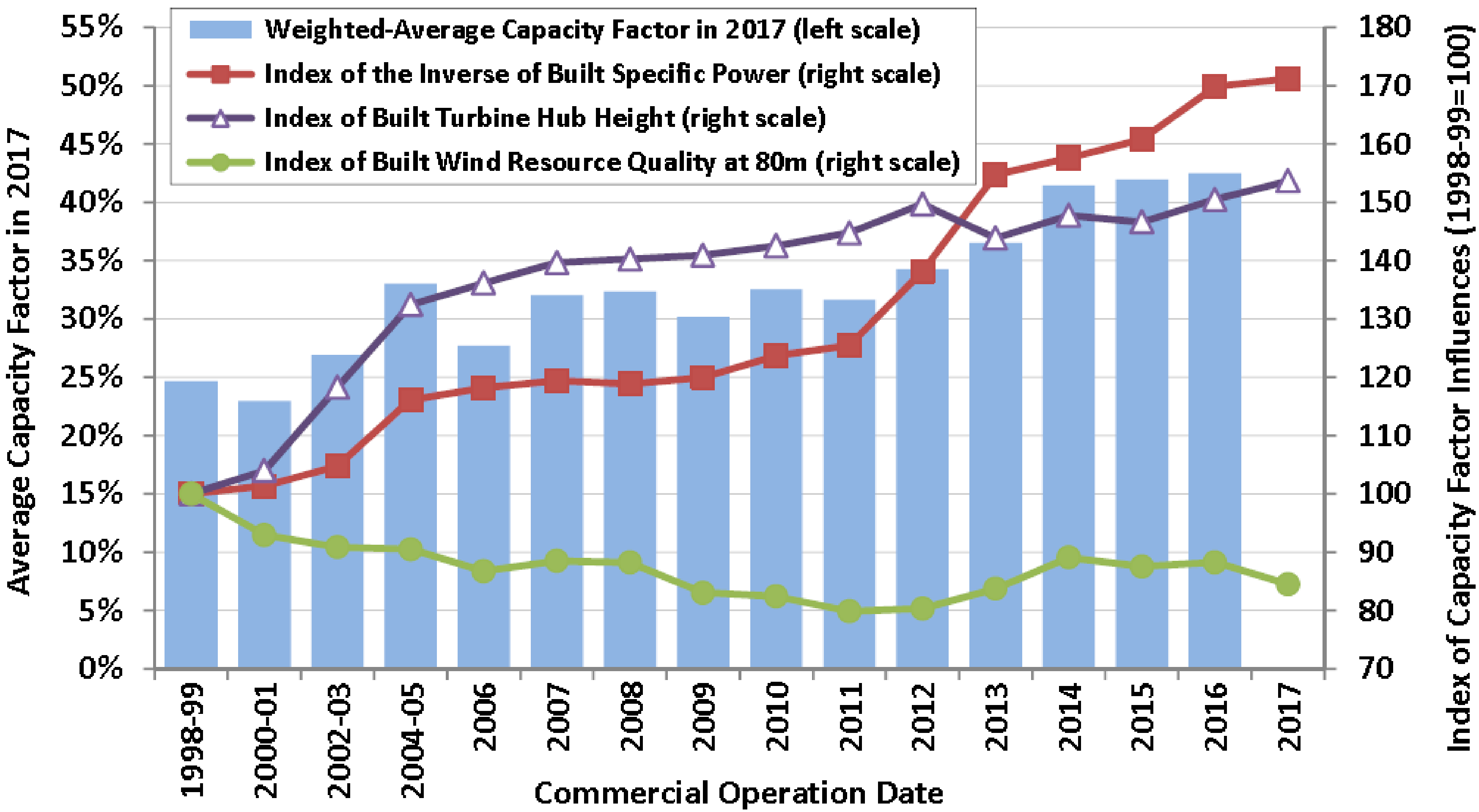
Hurricane Maria, Puerto Rico, 2017

energynautics
solutions for sustainable development

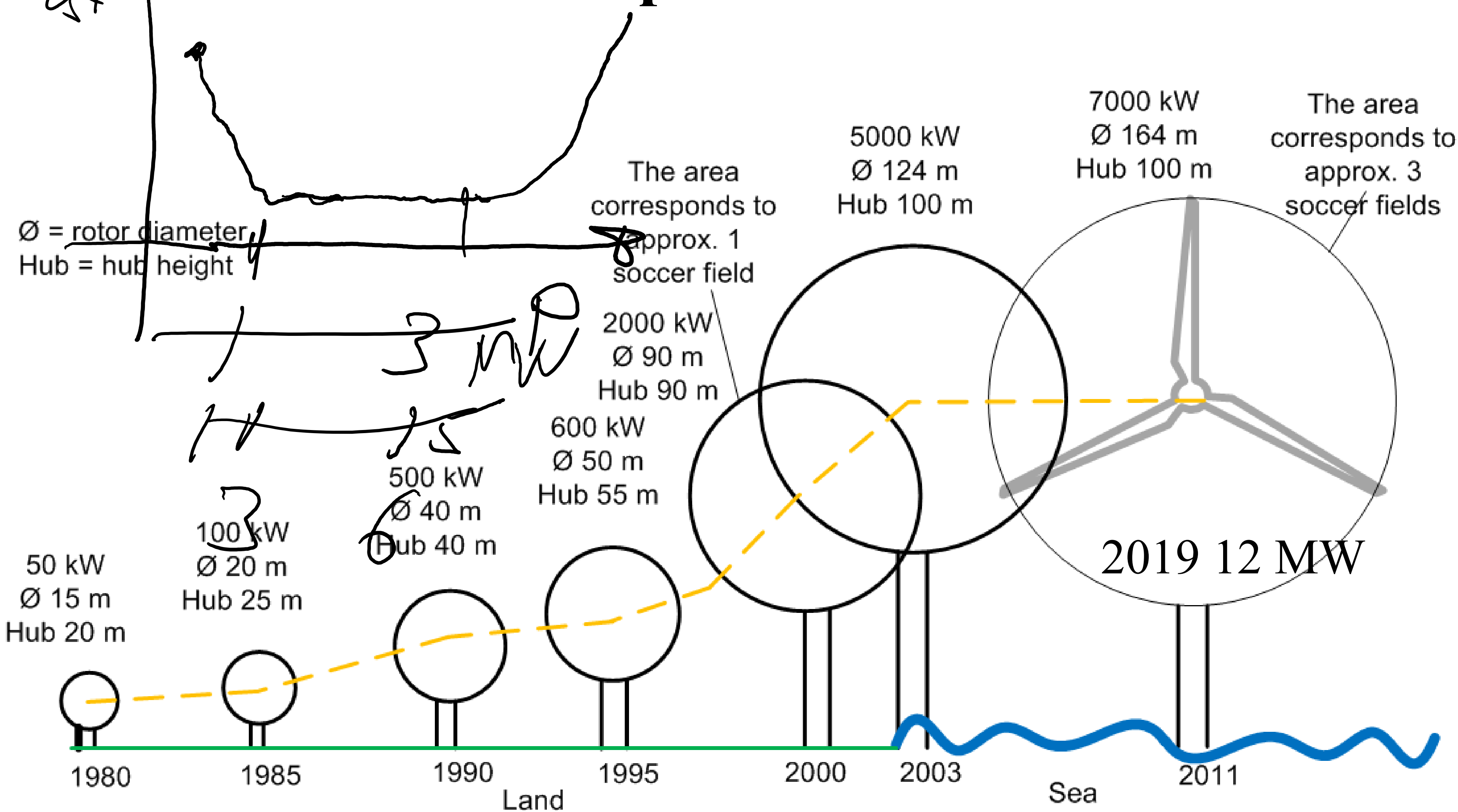
- 1,248 Million customer hours of lost electricity service

- Extensive damage to RE. Are Renewables **Resilient**?

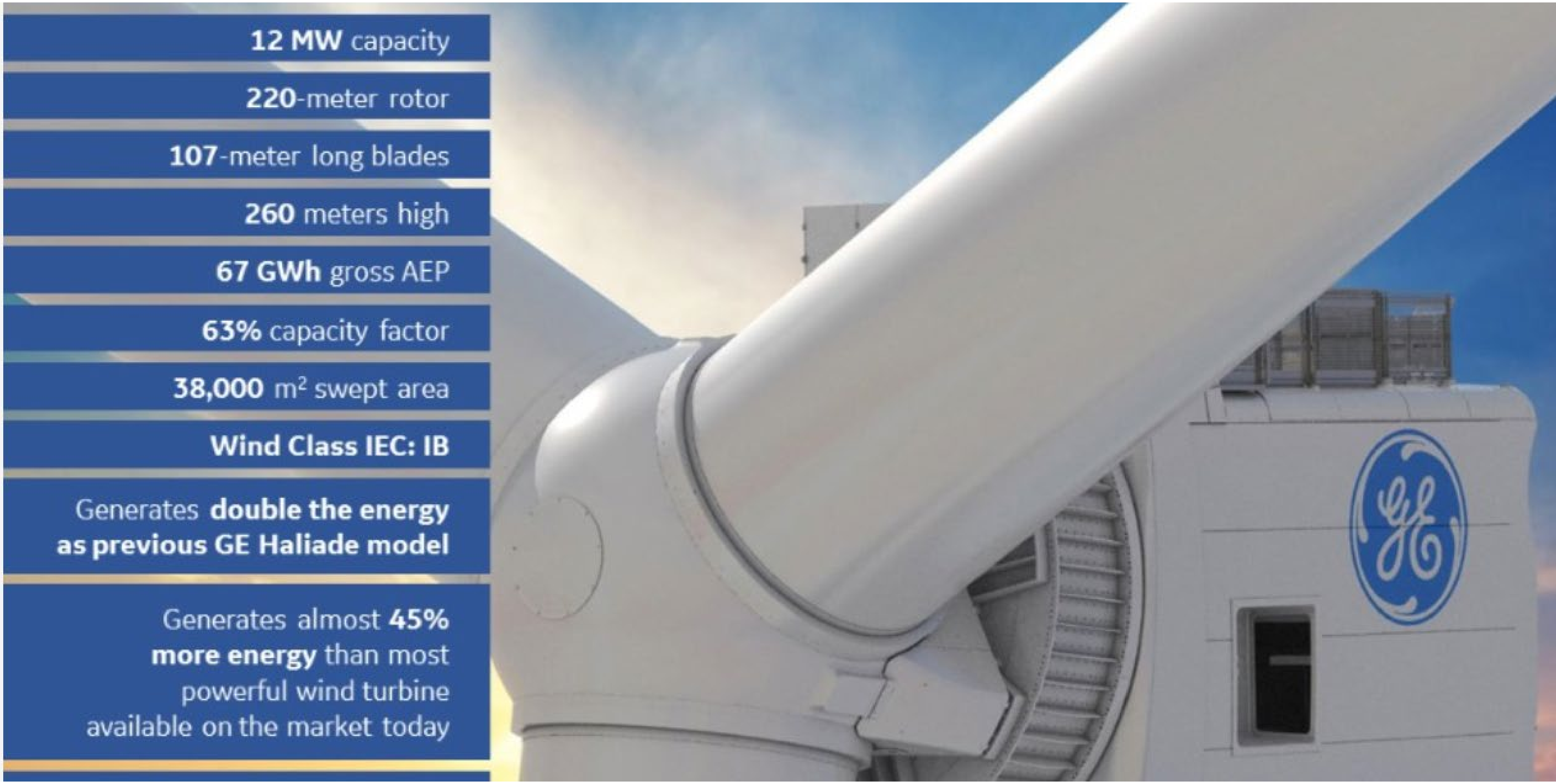
Trends Explained by Competing Influences of Lower Specific Power, Higher Hub Heights, Varying Quality Wind Resource Sites



Technical development of wind turbines



The larges design today, to demonstration in 2019



https://en.wikipedia.org/wiki/List_of_most_powerful_wind_turbines

Manufacturer	Model	Power rating (MW)	Type	Deployment status	Deployment date	Wind farms	Notes
Enercon	E-126 7.580	7.5	Onshore	No longer offered for sale[1]		Magdeburg-Rothensee, Germany Ellern, Germany Estinnes, Wallonia, Belgium	
MHI-Vestas	V164-9.5	9.5	Offshore	Commercially	December 2019	Northwester 2 Wind Farm, Belgium	
Siemens Gamesa	SG 8.0-167 DD	8	Offshore	Commercially	April 2020	Borssele, The Nederlands Dieppe-Le Tréport, France Yeu-Noirmoutier, France Saint Brieuc, France	SWT also available in 6, 7 MW variants Asia-Pacific version of SG 8 announced September 2018
GE Wind Energy	Haliade-X	12	Offshore	Prototype		Ocean Wind, US Skipjack, US Dogger Bank Wind Farms, UK	Prototype deployed October 2019. Rotor diameter 220m. Upgrade to 13MW considered
Dongfang Electric	D10000-185	10	Offshore	Prototype		Xinghua Bay, China	Prototype deployed July 2020. Rotor diameter of 185 meters.
Siemens Gamesa	SG 11.0-193 DD Flex	11	Offshore	Prototype		Hollandse Kust Zuid, The Netherlands	
MHI-Vestas	V164-10.0	10	Offshore	Upgrade of current model			Also available in 9.5 MW variant. Incremental upgrade from currently deployed V164 model
Mingyang Wind Power	MySE 11-203	11	Offshore	Prototype			Prototype planned in 2021 with commercial availability in 2022.
Siemens Gamesa	SG 14-222 DD	14	Offshore	Concept			Prototype planned for fall 2021 in Denmark
MHI-Vestas	V174-9.5	9.5	Offshore	Prototype			

Production

Mini turbine
ca 2 kW
ca 10 m height
ca 3 m i diameter

8000 kWh/year
1,6 house*

Farm turbine
10-30 kW
30-40 m height
7-15 m i diameter
20 000-75 000 kWh
4-15 house*

Medium turbine
2 MW
90-120 m height
90-100 m diam.

5 500 000 kWh
ca 1 100 house*

Big
5 MW
90-120 m height
ca 125 m diam.

18 000 000 kWh
ca 3 600 house*

* A house needs 5000 kWh per year for use of electricity

Wind turbine pays back energy

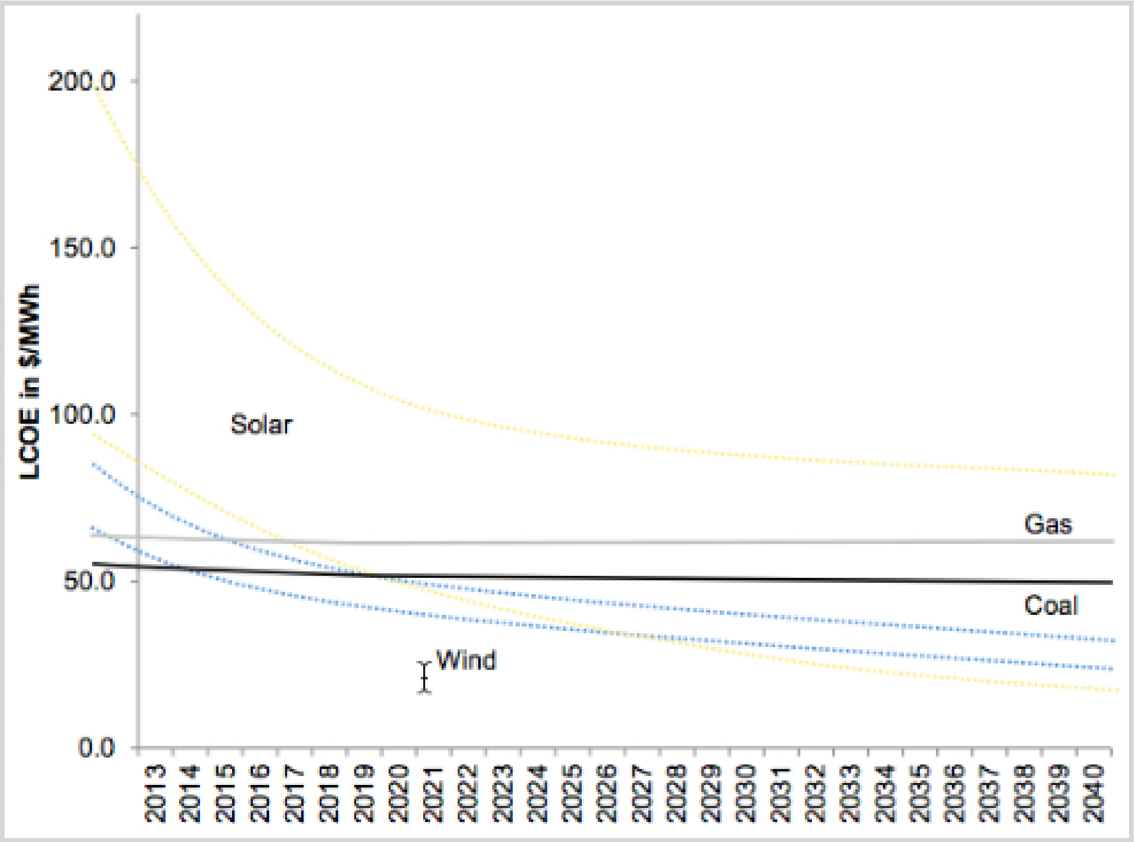
A wind turbine in a windy place has after
4 to 6 months produced, as much energy as was
needed for the production of the wind turbine

There after will the turbine be in operation 20-25 years

When the life time of the wind turbine is ended it is just to take down the turbine and use the land for something else

Why wind — and soon solar — are already cheaper than fossil fuels

August 24, 2015



Global levelized cost of energy (LCOE) by various fuel types in $/megawatt-hours (credit: Citigroup)

Citigroup has published an analysis of the costs of various energy sources called "Energy Darwinism II." It concludes that if all the costs of generation are included (known as the levelized cost of energy), renewables turn out to be cheaper than fossil fuels and a "benefit rather than a cost to society," *RenewEconomy* reports.

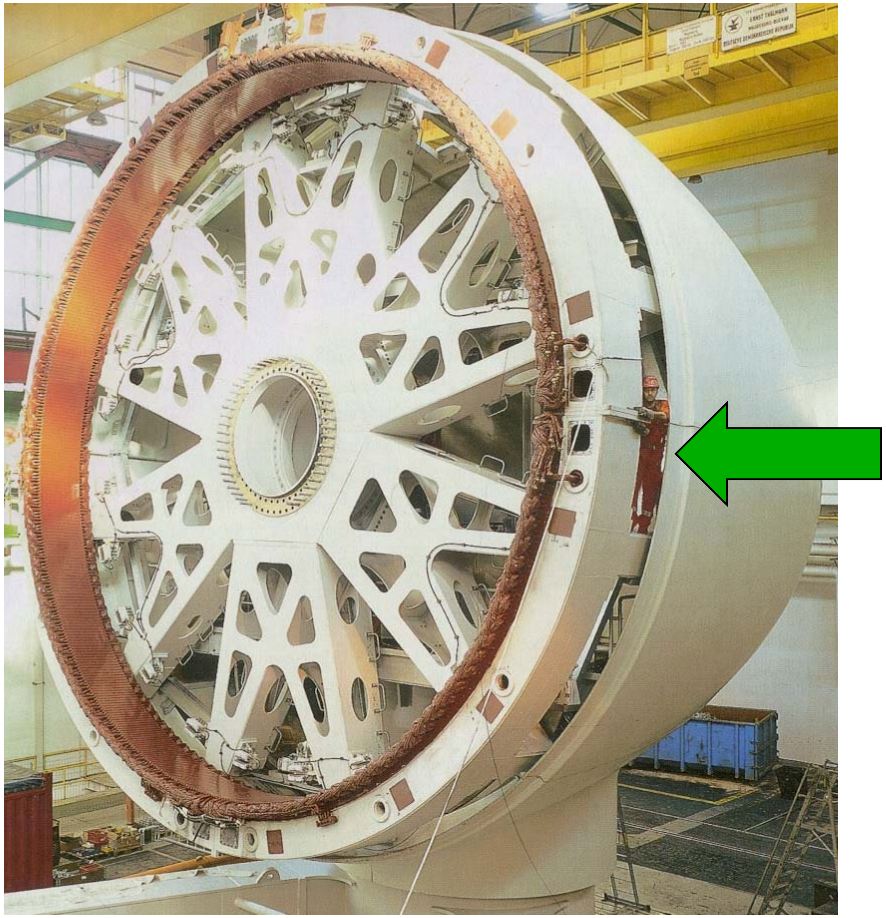
Vestas

- 3 MW,
- Diameter 90 m

Direct driven generator– Enercon

- Extreme high weight due to small air gap
- Generator weight 220 ton

  (4,5 MW)
- Look at the man!

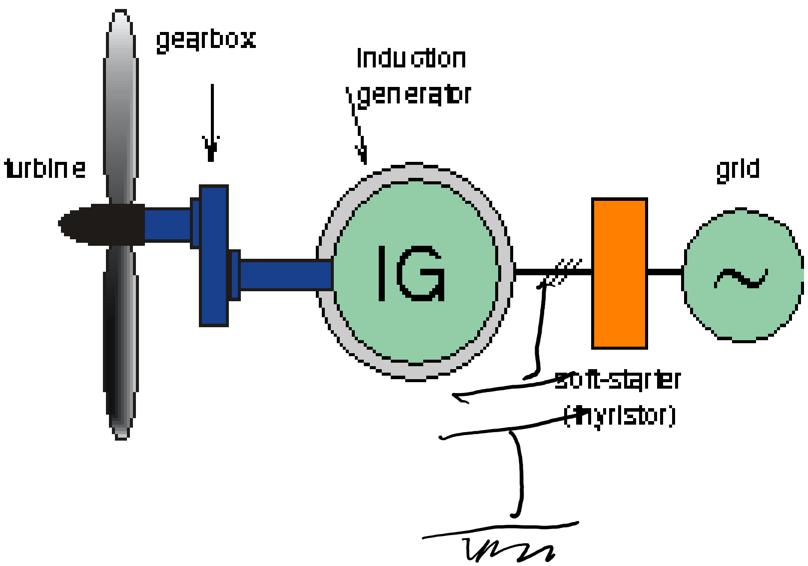


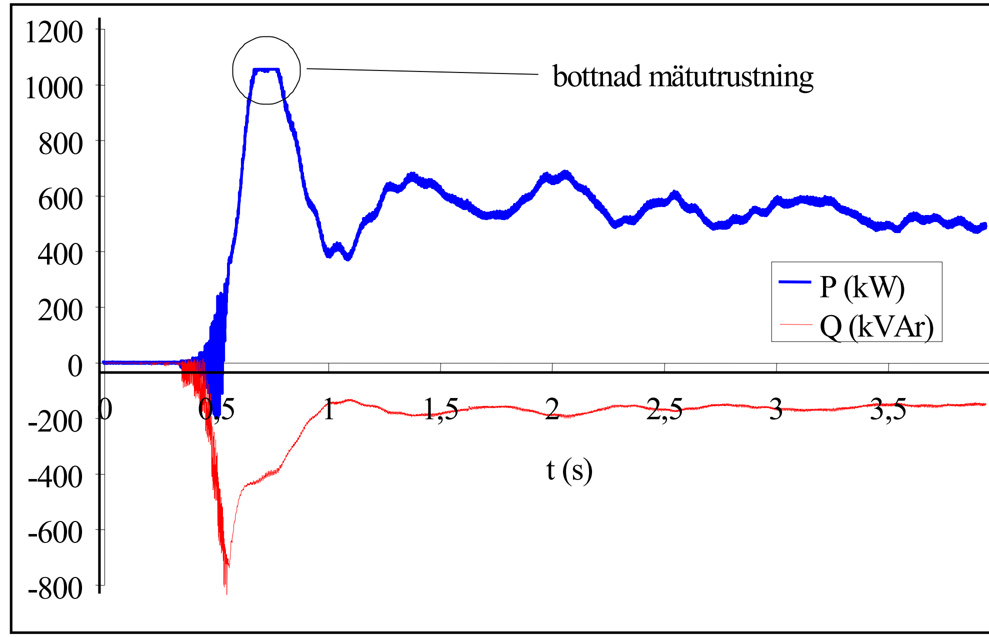
Enercon

- Power 2,0 MW
- Diameter 82m
- Tower 58-113 m

CHALMERS

Induction generator with soft-starter (thyristor)



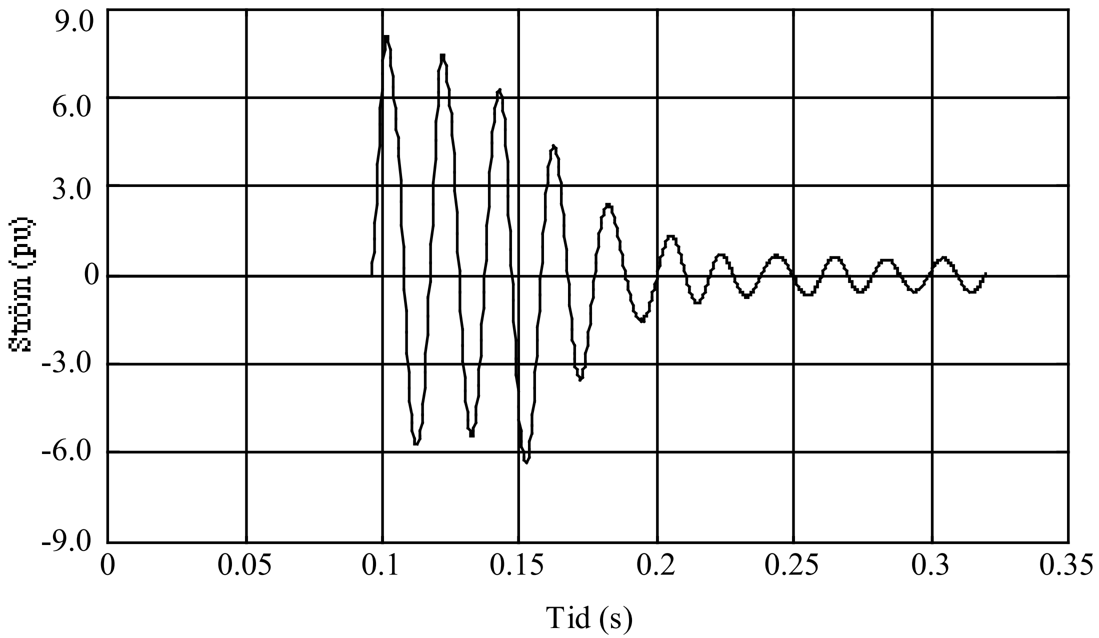


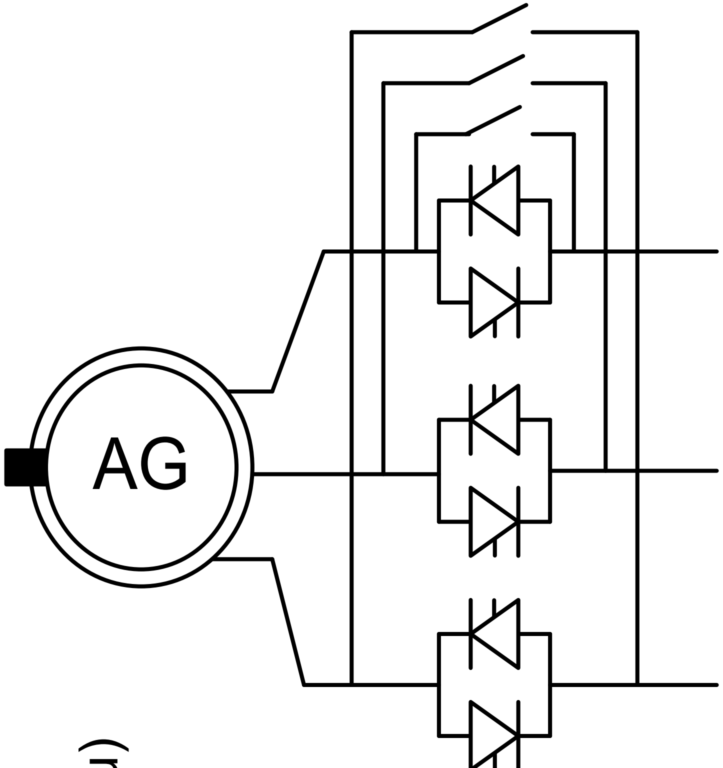
Grid connection of stall controlled wind turbine

- Robust generator
- Low maintenace
- Simpel system
- High mechanical forces
- Dominating system på 1980- 1990
- Not so common on large machines> 1.5 MW

Chalmers 1978, industry1980

Inrush current from a directly connected induction generator

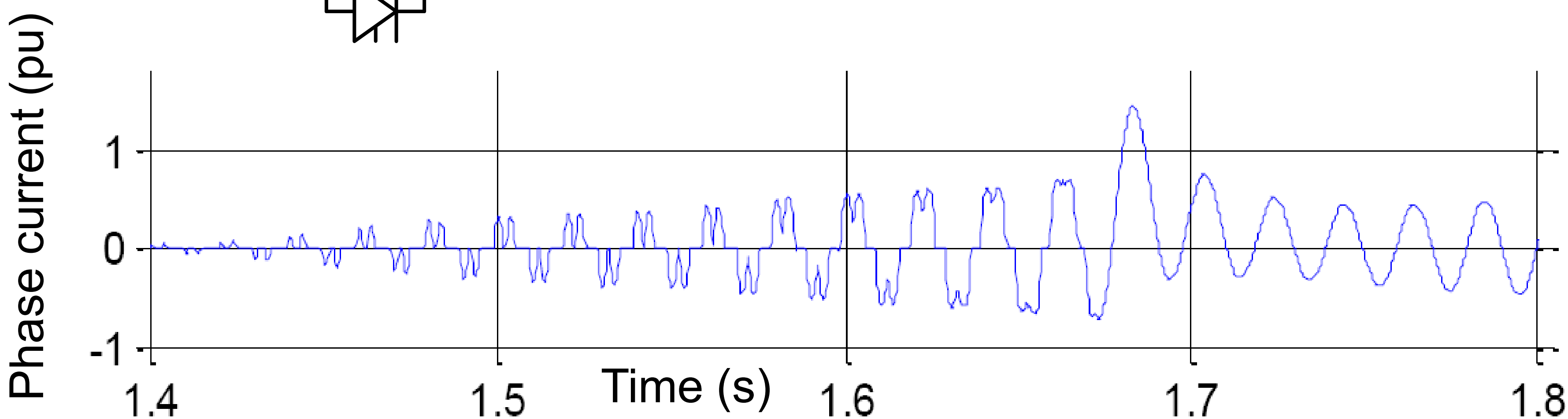




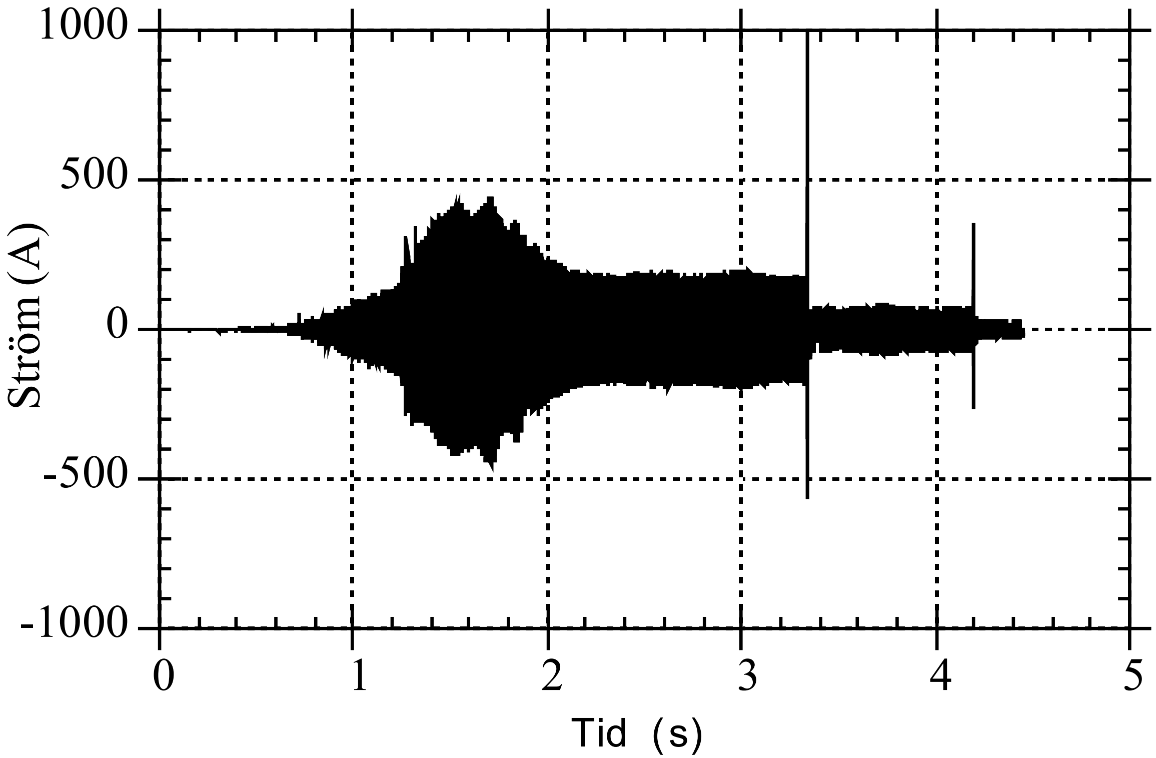
Soft starter

Active during starting/connection of induction generator.

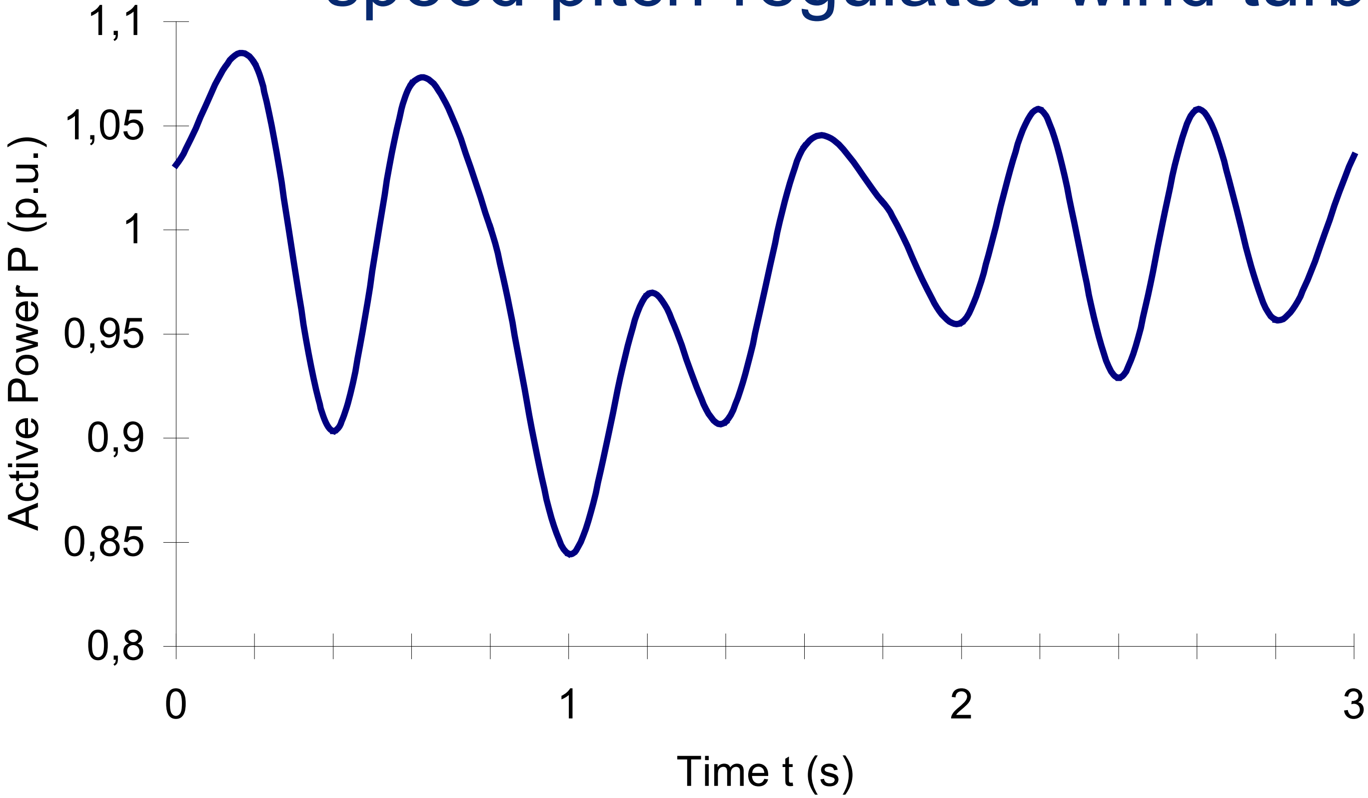
Short circuit after connection

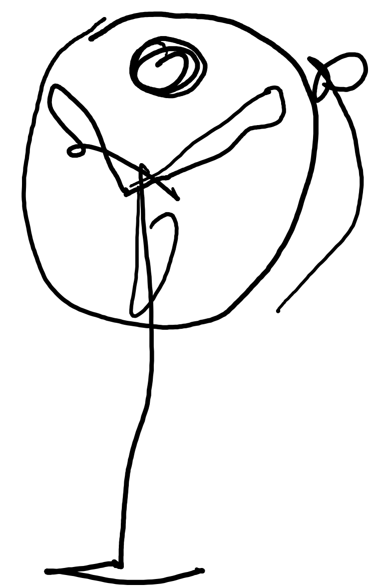


Inrush current for an induction generator with soft starter and two step capacitor connections

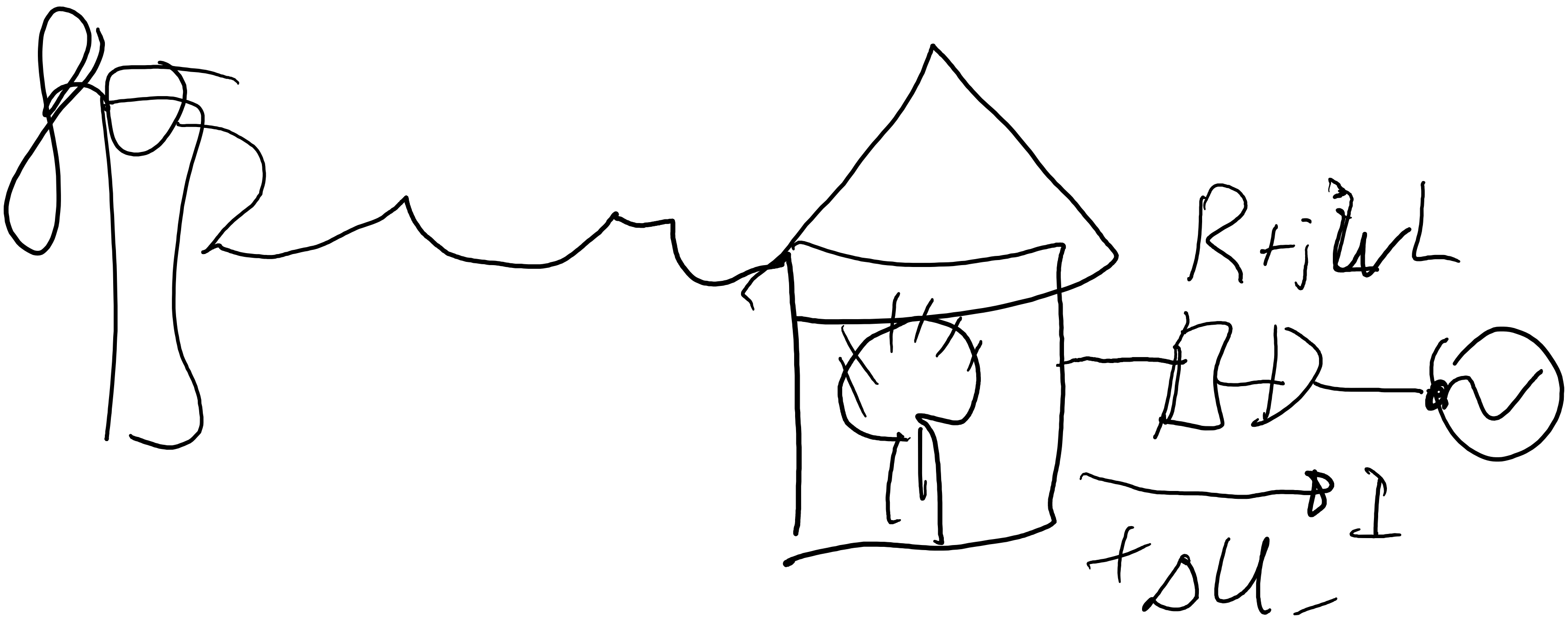


Measured power fluctuations from a fixed-speed pitch-regulated wind turbine

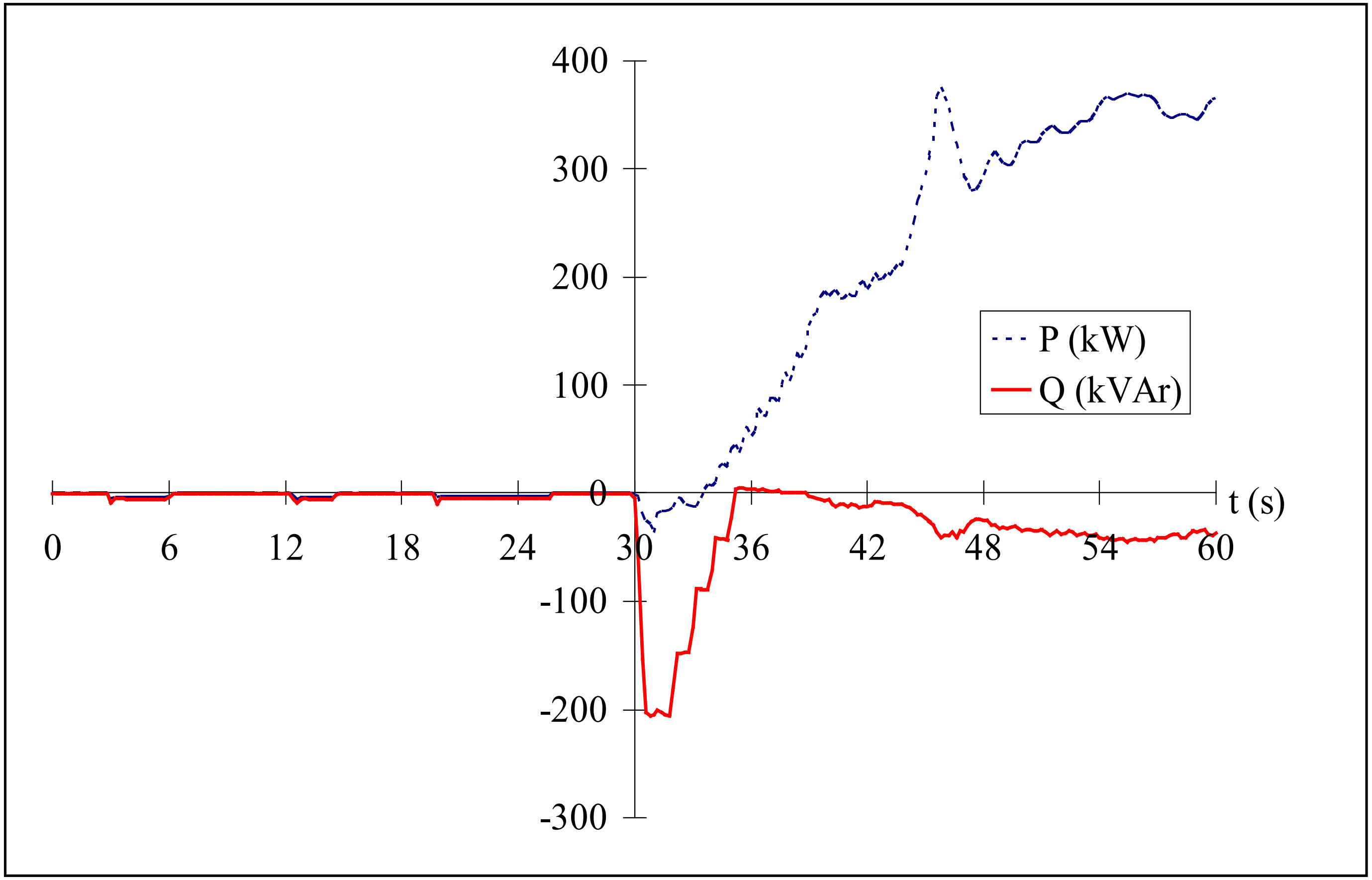




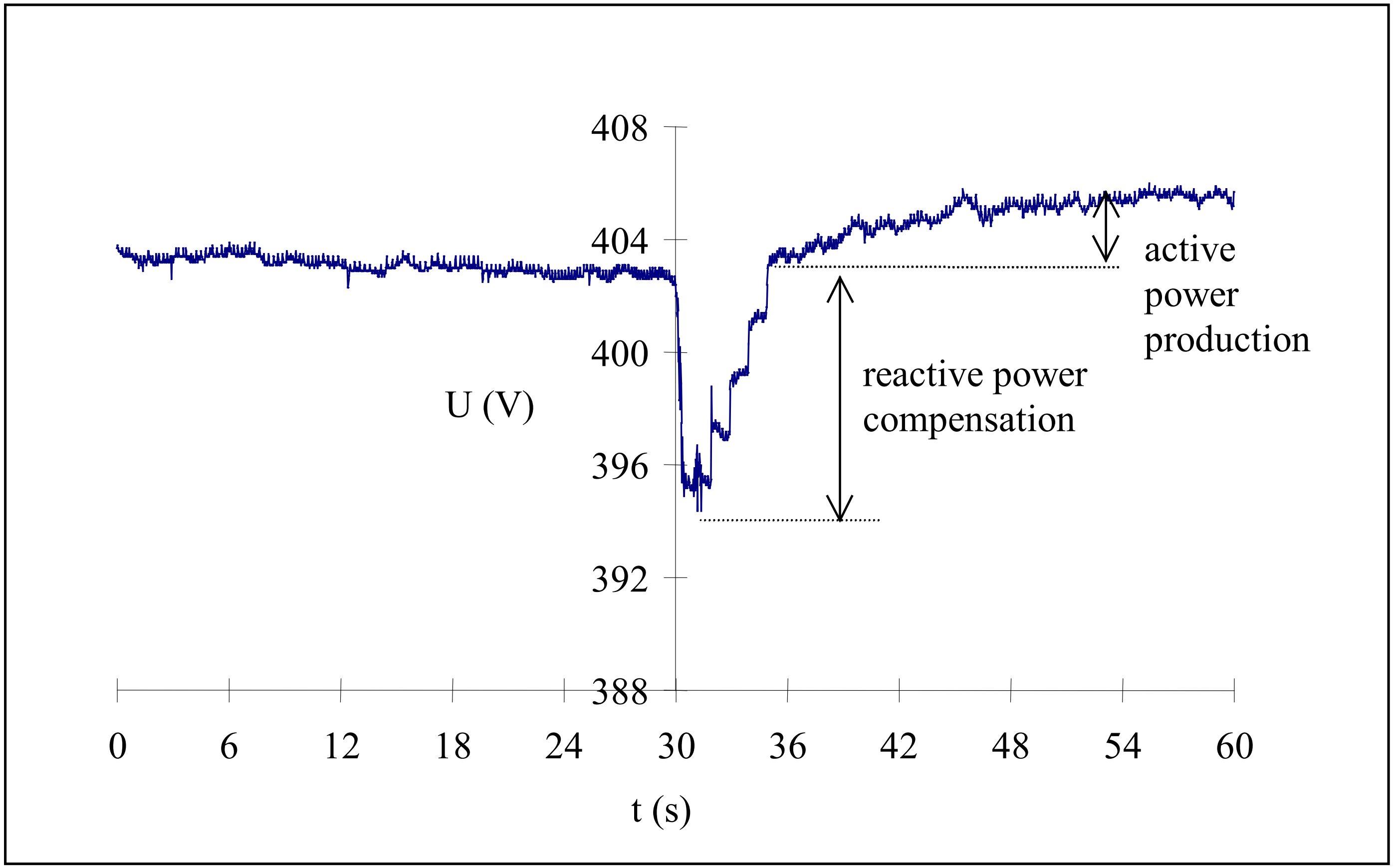
Rotational speed= 40 rpm=40/60 rps,
3 blade gives: 3*4/6=2 blade pass the tower every secunde=2Hz


R+jωL
I
+ΔU−

Grid connection with constant speed and pitch-control

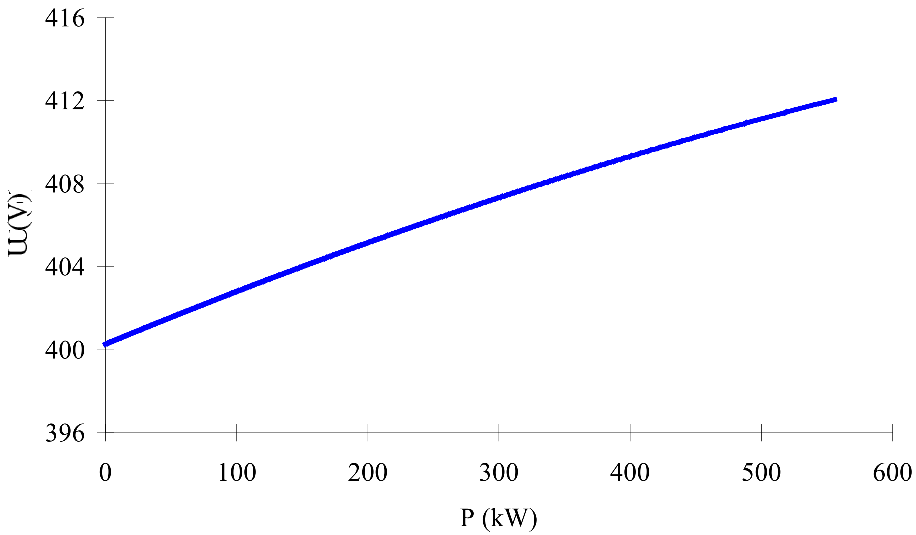


Grid voltage during connection constant speed and pitch-control

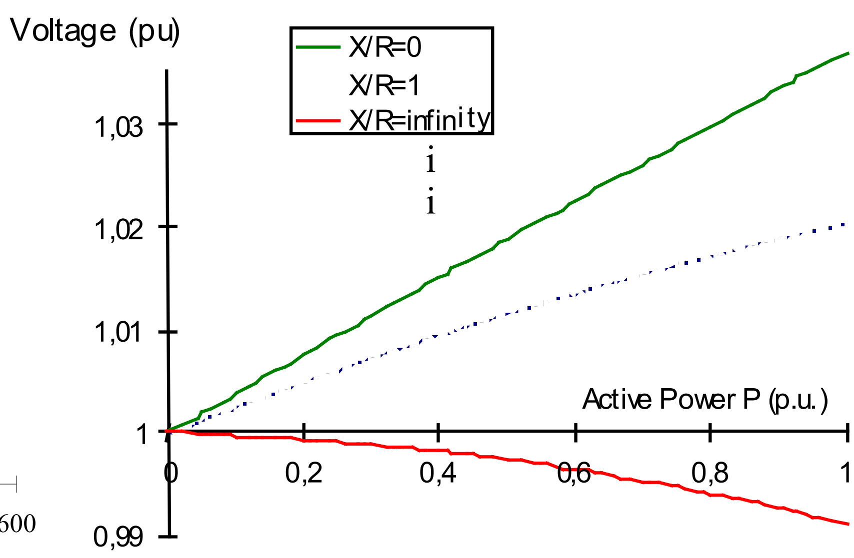


Voltage variations from a 600 kW induction generator wind turbine

Measurements in Göteborg



Calculations for different grids



Development of power electronics

- Transistor was born 1947
- Thyristor as valve for high power 1967 (HVDC) {grid-commuted}
- GTO-thyristor (switch off) ca 80-talet {switch on and off}
- MOSFET ca 90-talet low voltages
- IGBT ca 90-talet high currents {high development potential}
- Single IGBT 6500 V, 600 A or 1700 V, 3600A
- HVDC-Light 900 MW
- Research on new material, silicon carbide transistor => higher voltages and current low losses and can withstand high temperature
- **Conclusion: high potential of development**

Wind power with variable speed

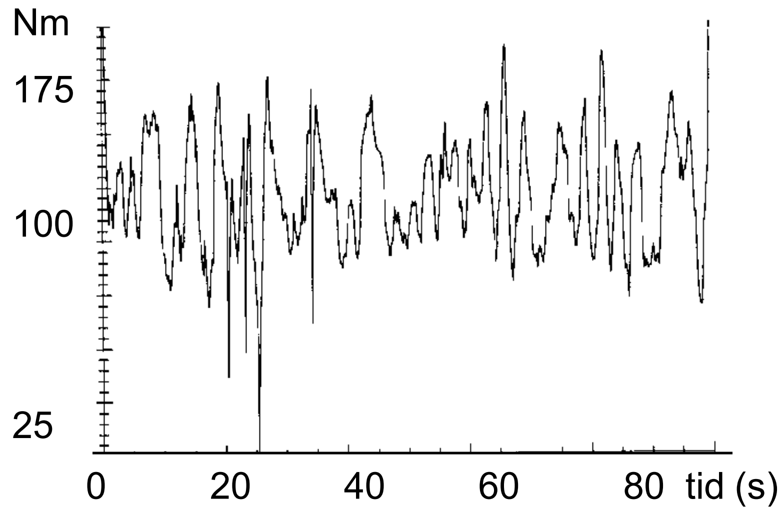
Way use variable speed?

mechanical	+	Less noise
	+	structural constitution
electric	+	Less power pulsations
	+	Possible to connect to a weak grid
	−	More expensive electric system
	•	About the same efficiency

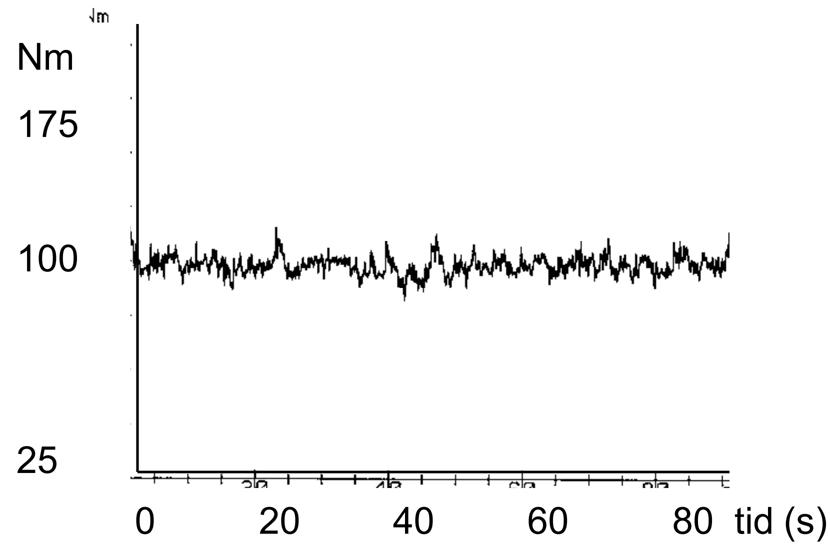
Torque measurements with constant and variabel speed

Measurements from Chalmers test wind turbine 1986

Constant speed



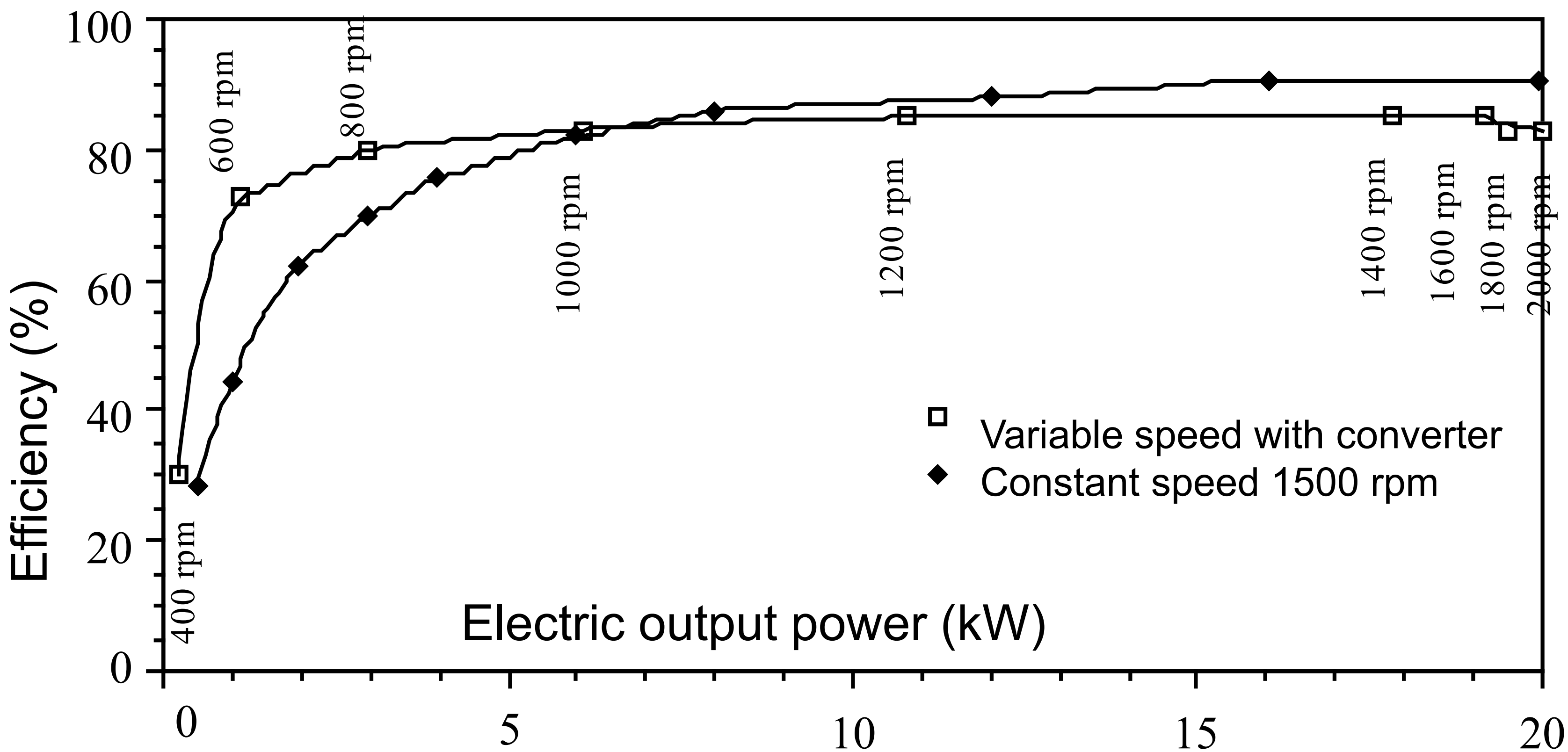
Variabel speed



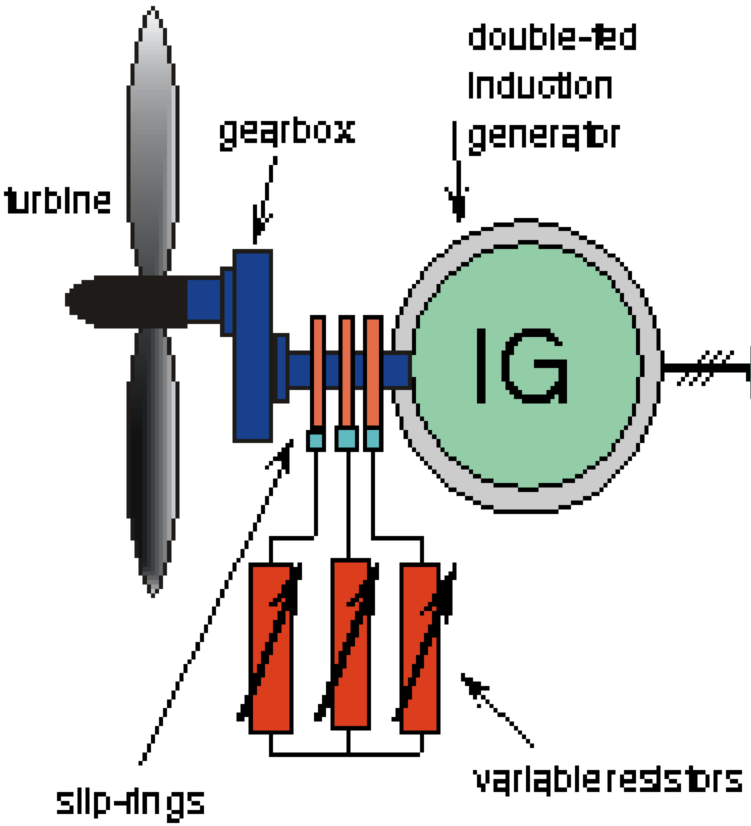
- Large torque rippel
- High mechanical forces

- Long lifetime of gearbox
- Small influence on power quality

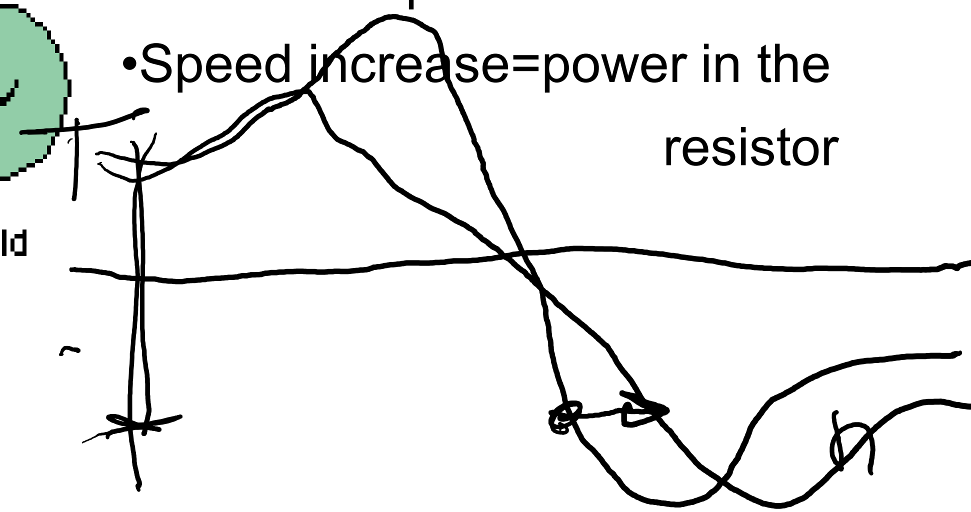
Comparison variable and constant speed operation



Induction generator with controlled rotor resistances

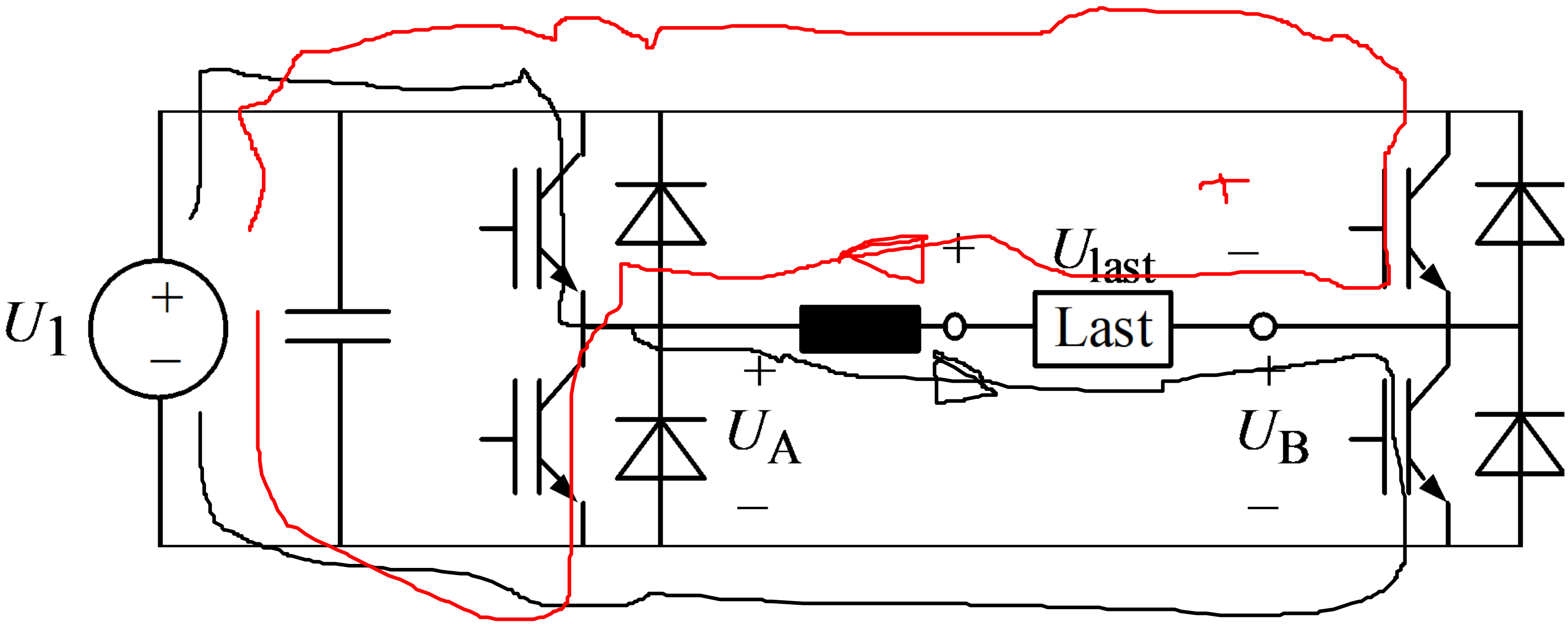


- optislip (name by Vestas)
- Small speed variations
- Limited torque control
- Speed increase=power in the resistor

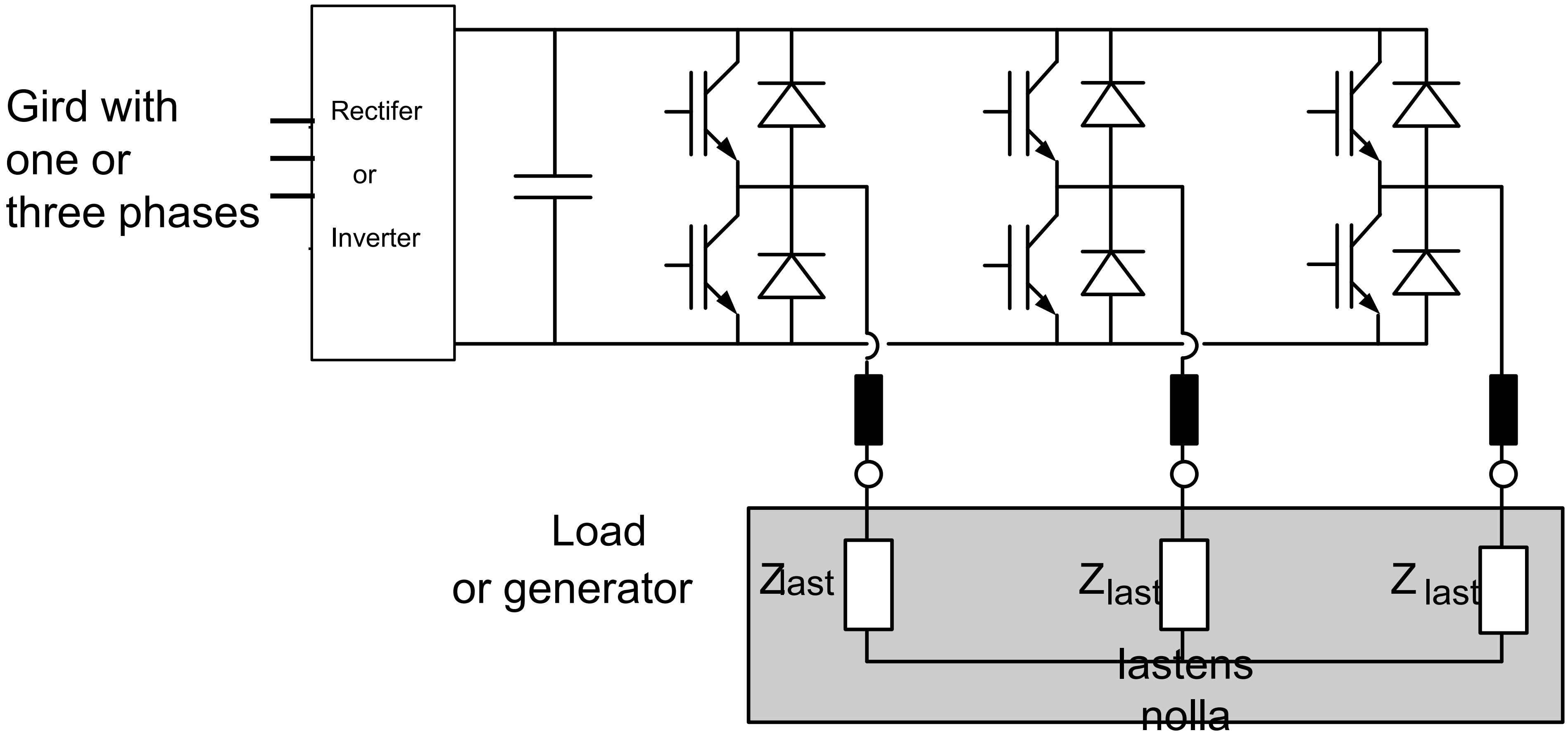


Chalmers 1984, industrin 1994

From dc- to ac-voltage

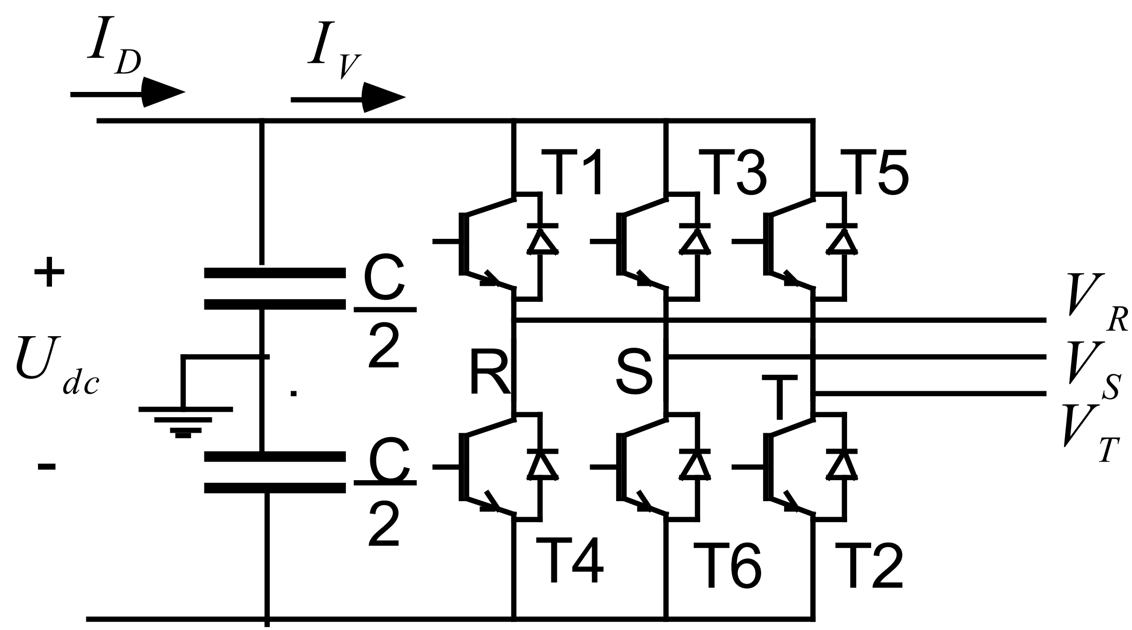


Three phase inverter

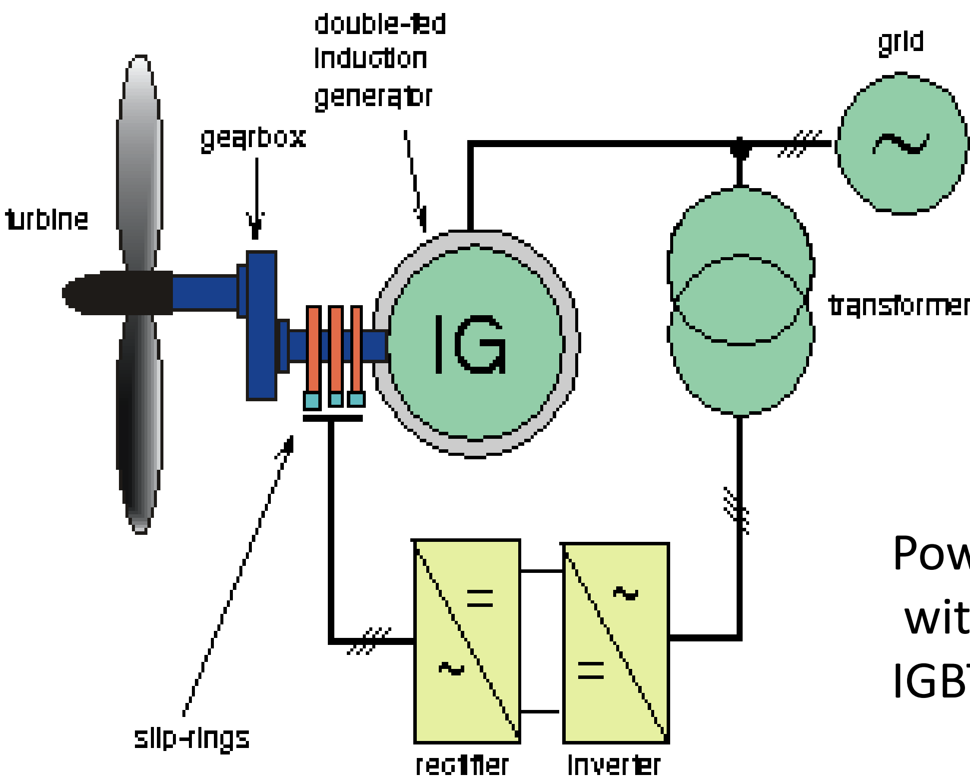


Frequency converter

IGBT-transistors
Can switch on and off the current
AC/DC or DC/AC converter
Control of active and reactive power



Double fed induction generator, DFIG



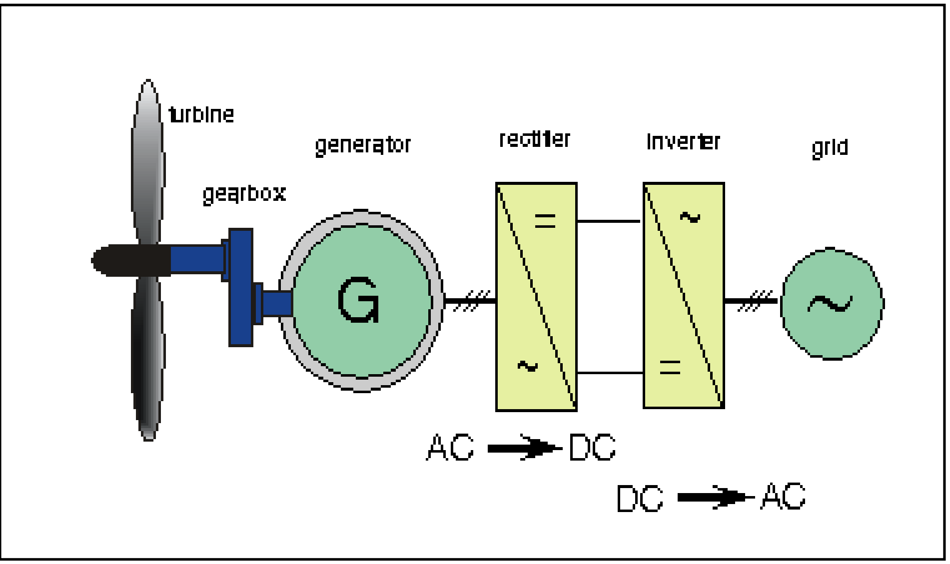
- Limited speed variation
- Limited power of the converter
- Good efficiency
- Good control of P, Q
- Slip rings=maintenance

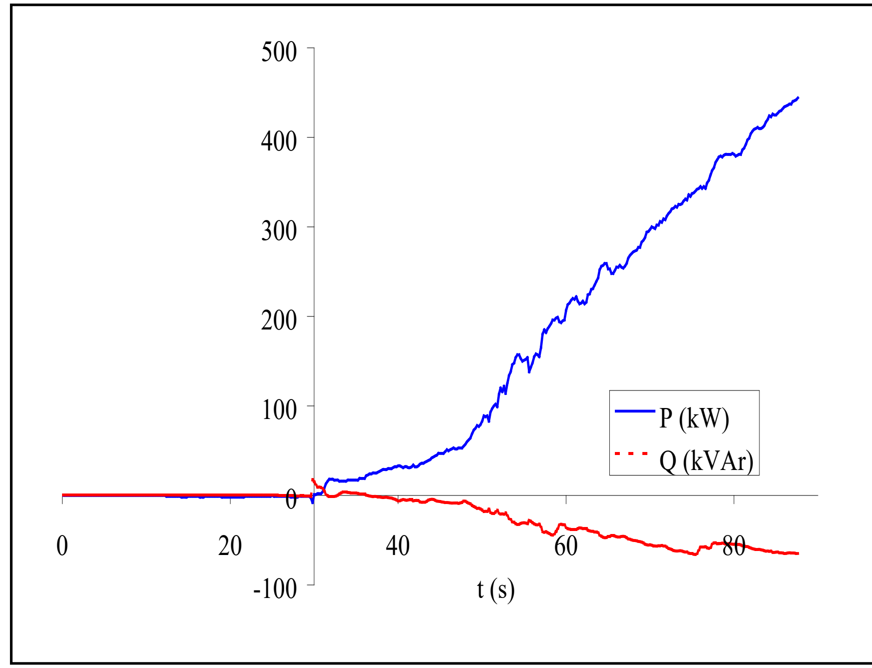
Power package with 6 IGBT-transistor

50 cm

Chalmers 1986,2002, industry 1995

Full Power Converter



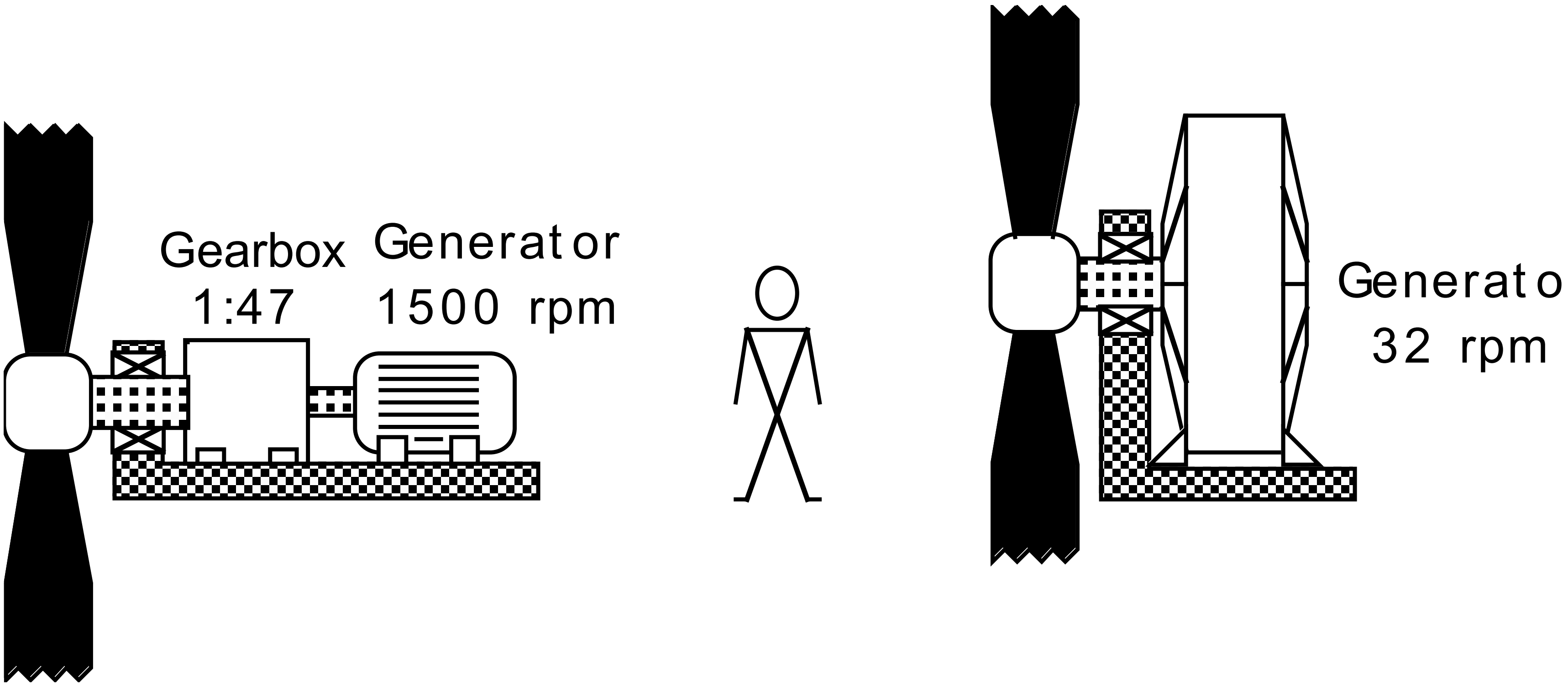


- Full control of P & Q
- All power trough the converter
- Higher losses
- Generator AG, SG, PM

Start up with variabel speed

Chalmers 1984, industry 1990

Generator with and without gearbox, 500 kW



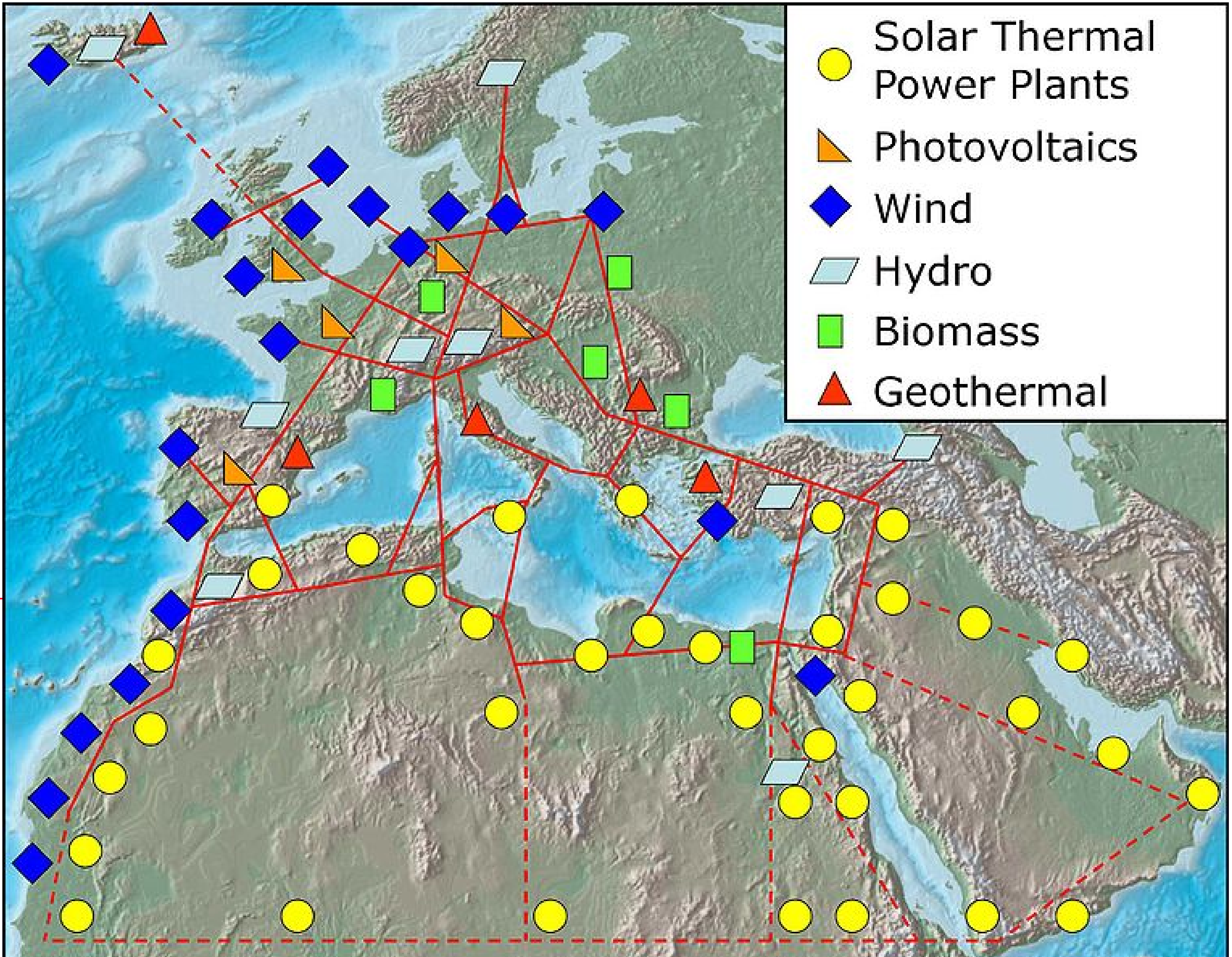
- Lower the costs for the drive line
- Lower the losses in the energy conversion from mechanical rotation to electric power
- Increase the availability for the wind turbine, there by higher energy production

DC-grid for wind farms

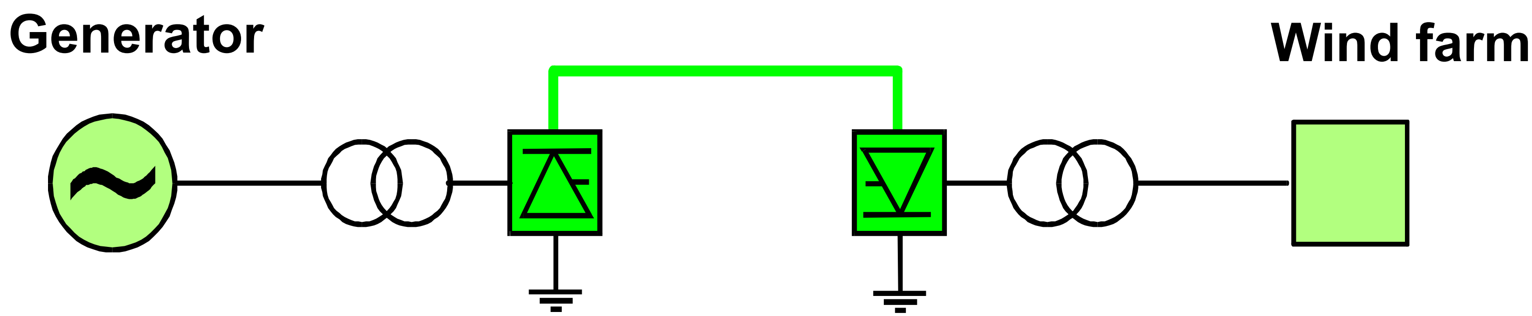
Wind farms connections

To day: point to point connections

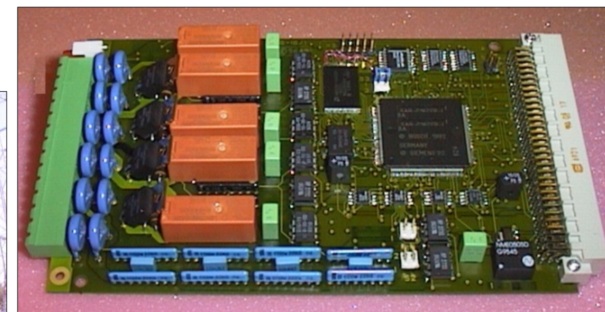
To morrow: meshed grids


Solar Thermal Power Plants
Photovoltaics
Wind
Hydro
Biomass
Geothermal

HVDC-Light transmissions system



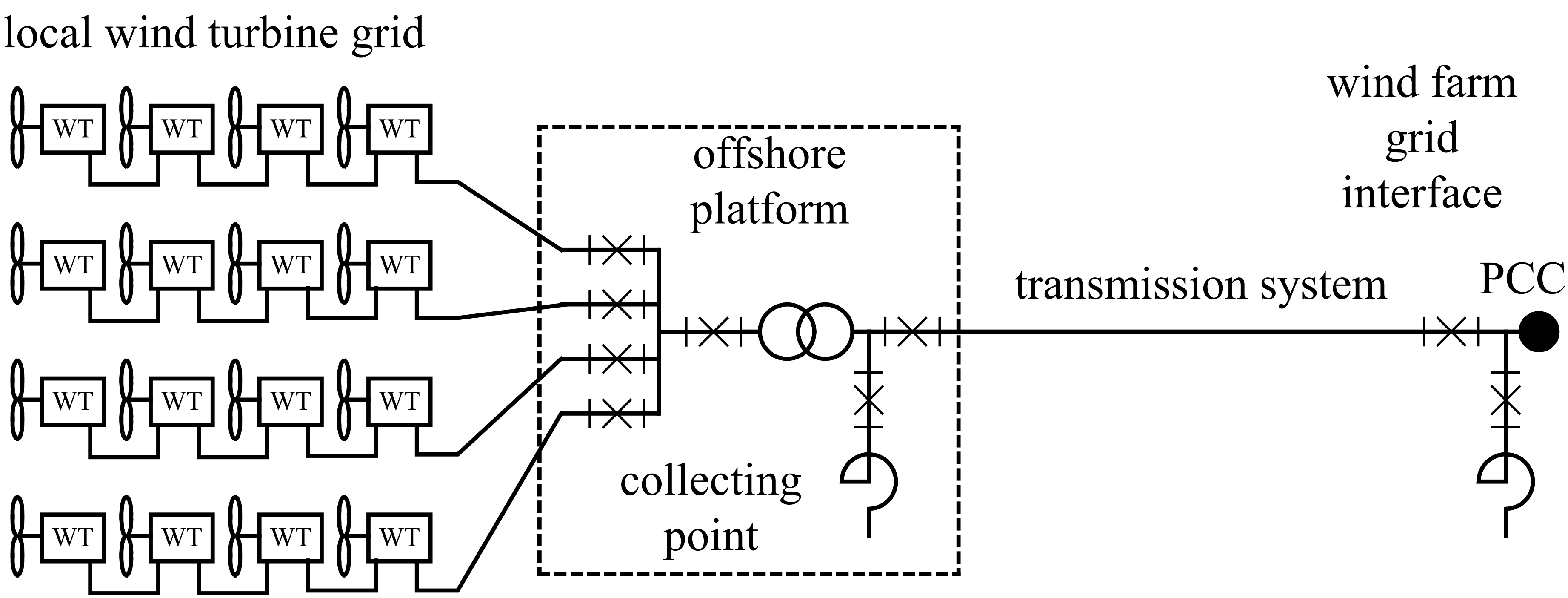
- Electric Power
- Control Eng.
- Electronic Des.
- Soft wear
- Sale
- Production



For transmission

AC	vs	DC
+	Well known	
–	”Limited” transmission distance	
	Lower transmission losses	+
	Easy to connect to the grid	+
	More control is needed	+
	Cost ?	

AC based wind farm
Used in todays wind farms



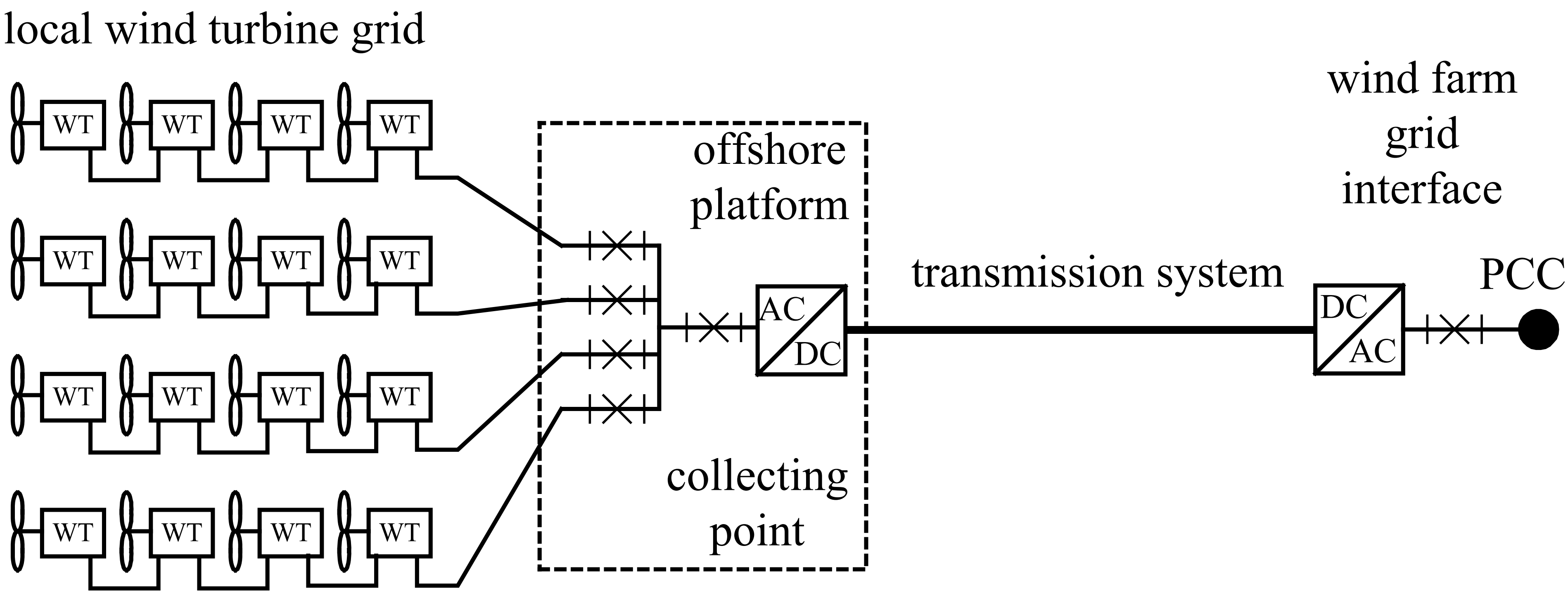
Lillgrund wind farm – Technical data

- 48 wind turbines
- 2.3 MW/turbine
- Transformer plattform 30/130 kV
- ca 330 GWh yearly production
- Mean wind speed ca 8.5 m/s (65m)
- Rotor diameter: 80 meter

Produced 110 MW

AC/DC wind farm

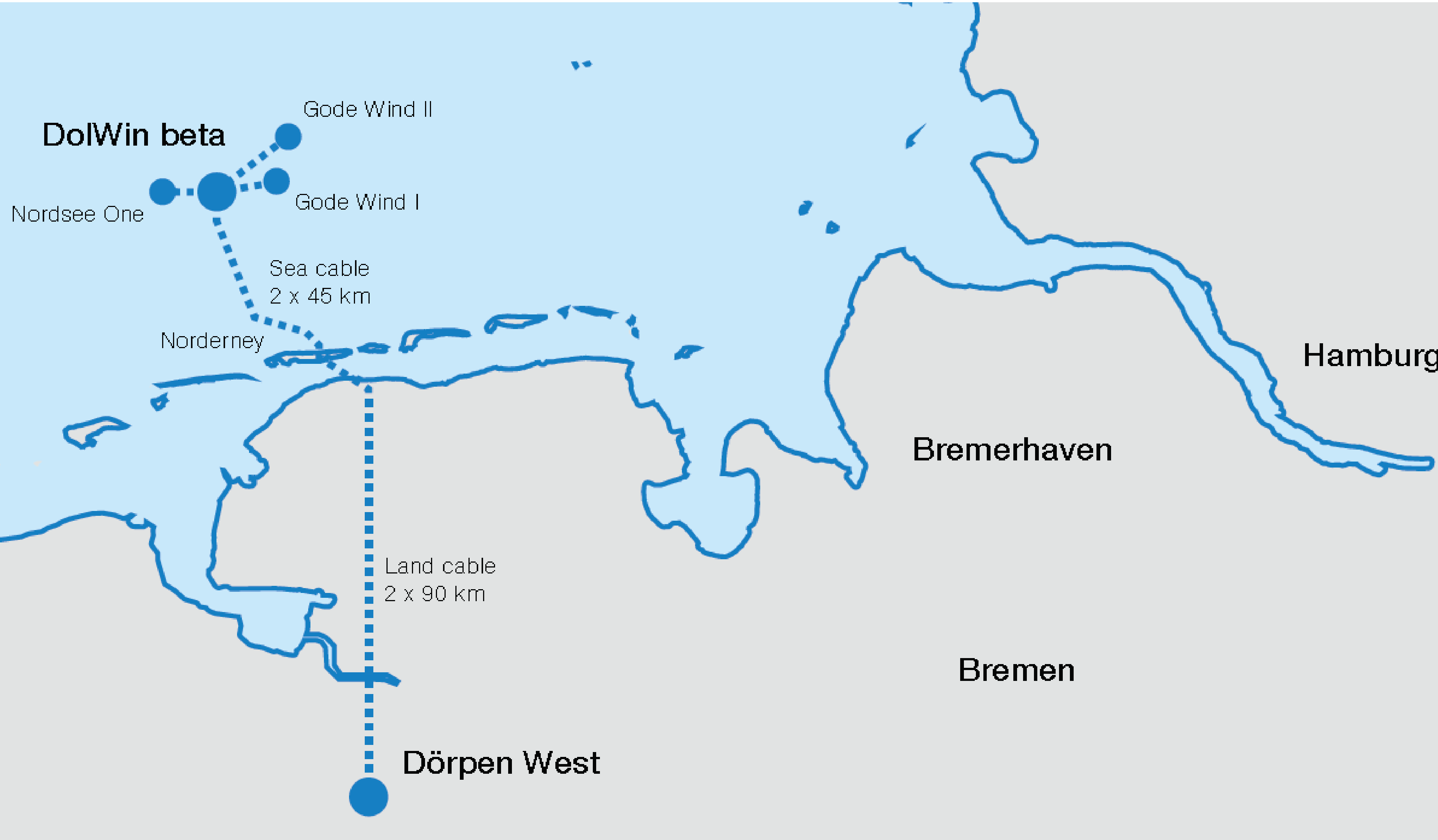
AC grid with HVDC transmission operation has recently started



DolWin2 ABB order - Windfarm in North Sea

- This is the largest power transmission order in ABB's history.
- It will deploy the world’s largest offshore HVDC (high-voltage direct current) system with a rating of over 900 megawatts (MW), keeping electrical losses to less than 1 percent per converter station.
- The completed link will be capable of supplying more than 1.5 million households with clean wind-generated electricity.

CHALMERS



DolWin beta
Gode Wind II
Gode Wind I
Nordsee One
Sea cable
2 x 45 km
Norderney
Land cable
2 x 90 km
Dörpen West
Hamburg
Bremerhaven
Bremen


Boskalis

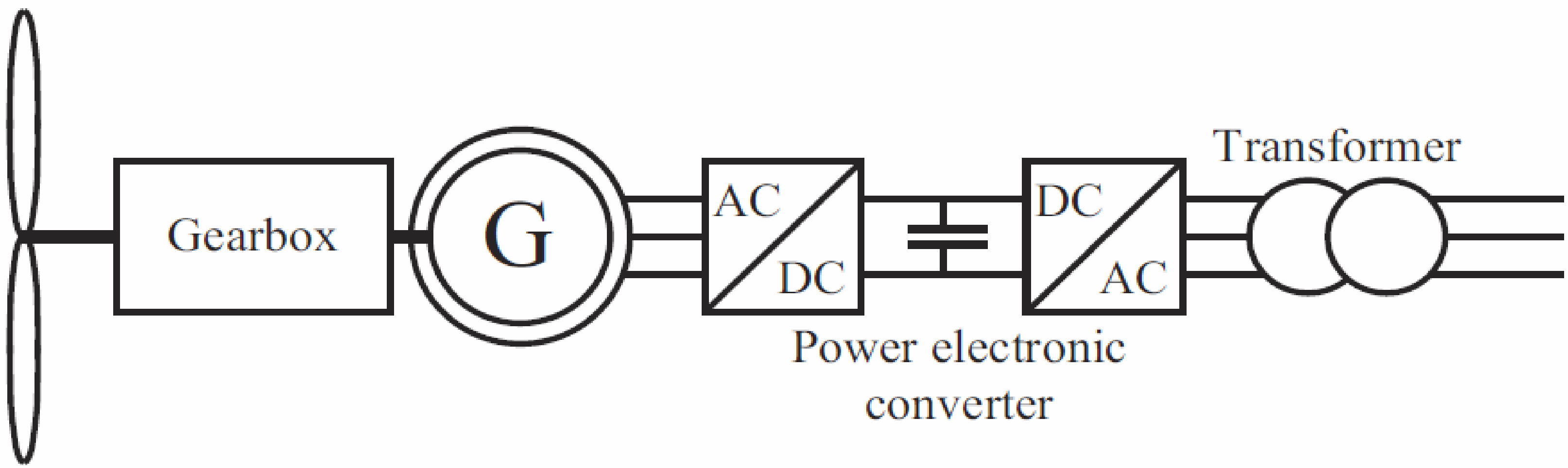
Important components in a DC-grid

- DC cable
- DC/AC inverter
- DC/DC transformers
- DC breaker

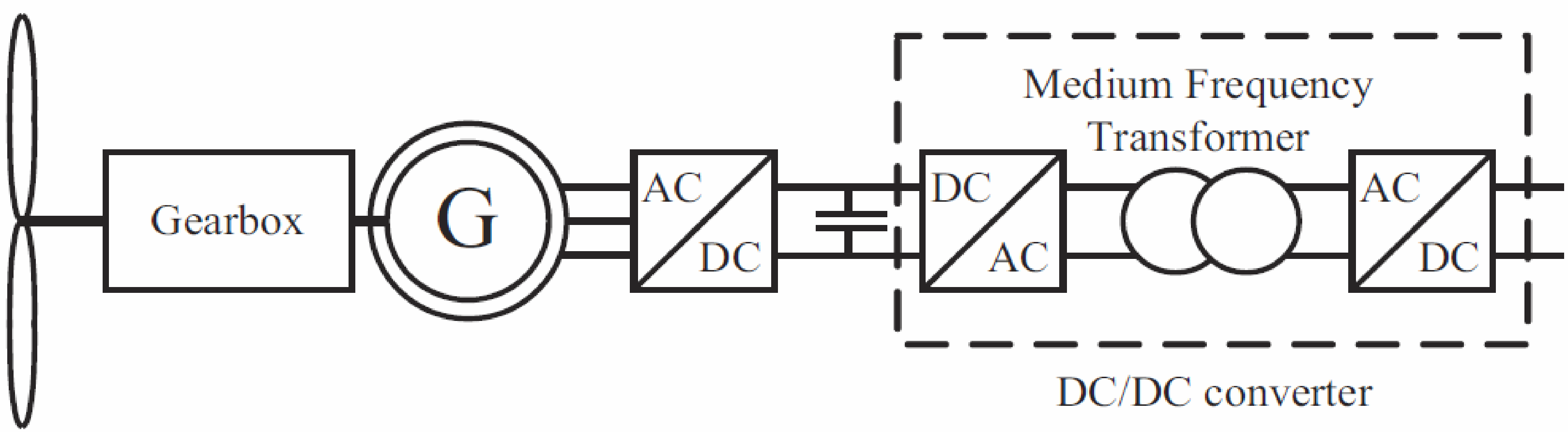
DC cable, DC/AC inverter ← Existing today

DC/DC transformers, DC breaker ← Needs further development

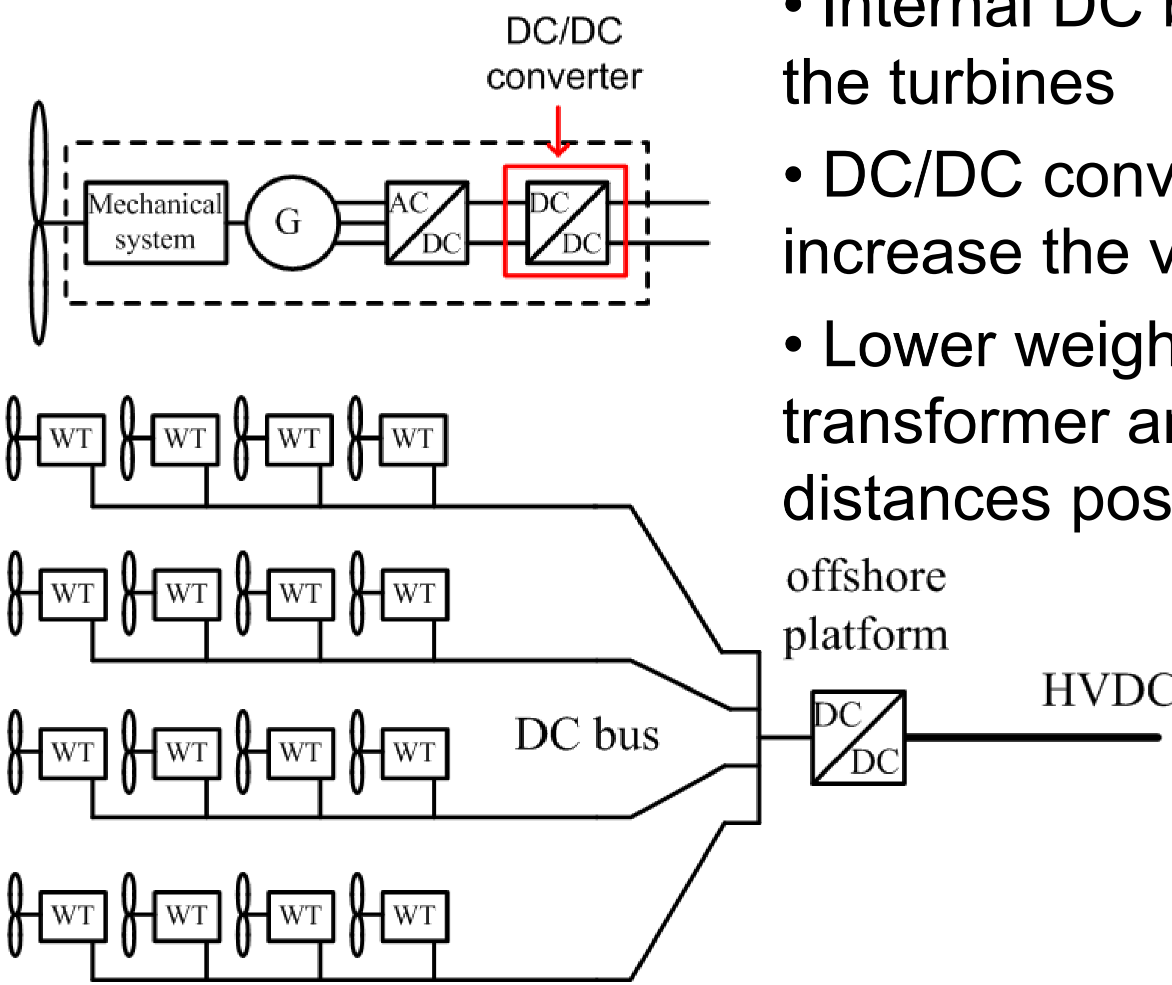
Variable speed wind turbine with AC-output



Variable speed wind turbine with DC-output



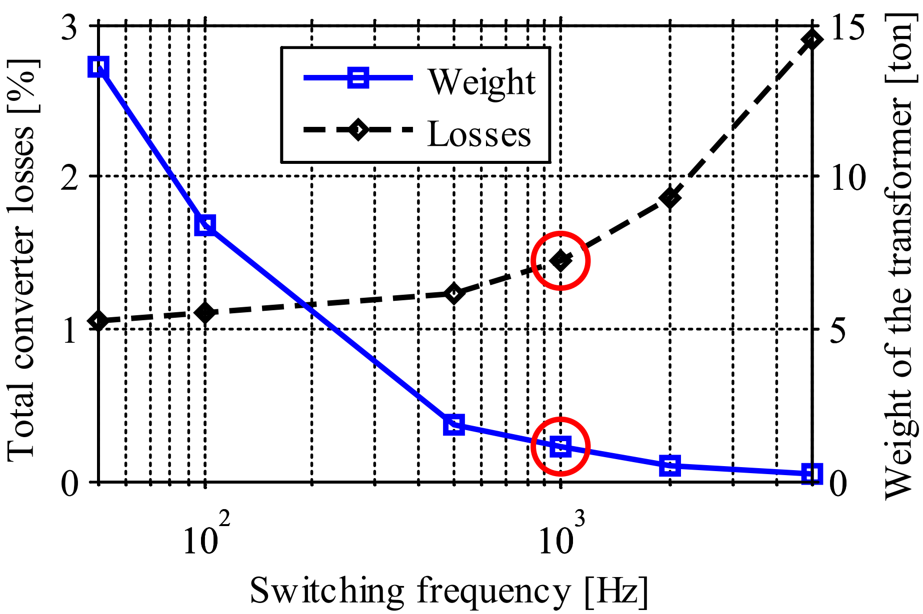
The DC-based wind farm



- Internal DC bus connecting the turbines
- DC/DC converters to increase the voltage levels
- Lower weight for the transformer and longer cable distances possible

Design of the fullbridge converter

Choice of switching frequency
A trade off between low weight and low losses



- 1 kHz is a suitable switching frequency.

- Weight of 1 kHz transformer is ~10% of the weight of a 50 Hz transformer.

- METGLAS core.

Power flow in Europe

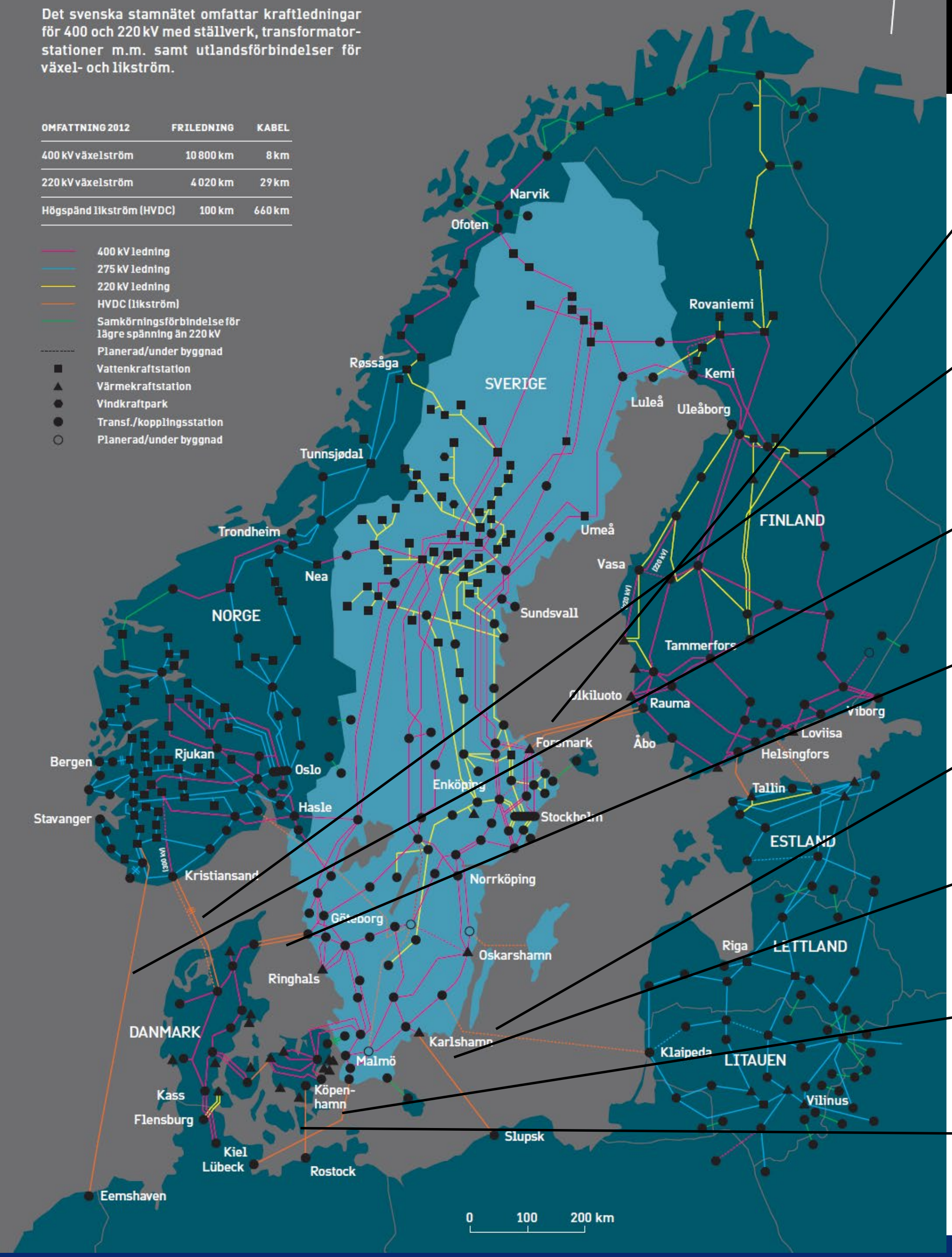
Lots of power flow,

but more
transmission power
is needed

What to do when there is no wind?

Easy in the Nordic system, but it has also a value for the EU-grid

Let the hydropower produce more and when the wind is there save the water in the lakes



Power: 550 MW, 800 MW
Energy: 11,5 TWh

Power: 250, 440, 700 MW,
Energy: 12 TWh

Power: 700 MW,
Energy: 6 TWh

Power: 600 MW,
Energy: 5 TWh

Power: 700 MW,
Energy: 6 TWh

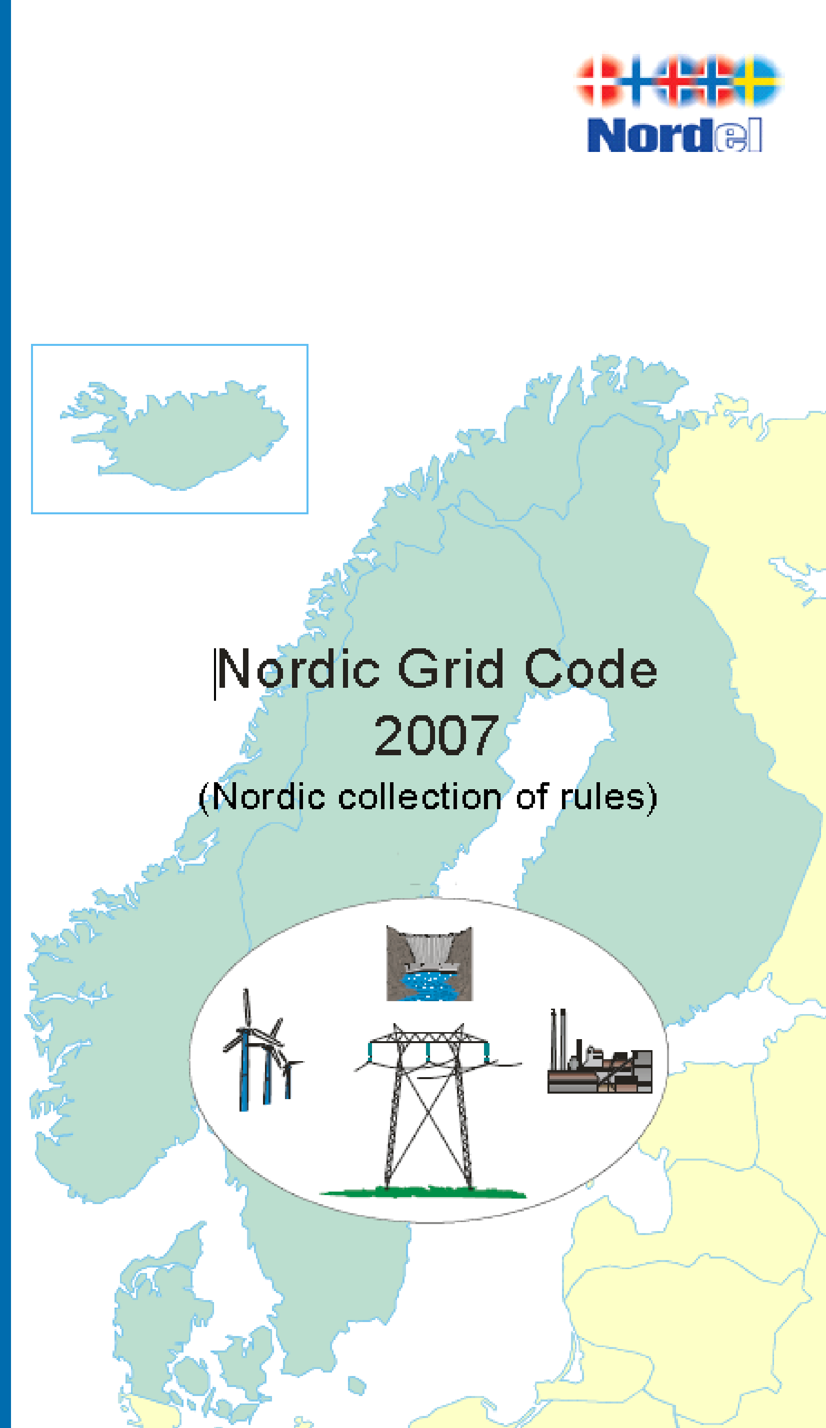
Power: 600 MW,
Energy: 5 TWh

Power: 600 MW,
Energy: 5 TWh

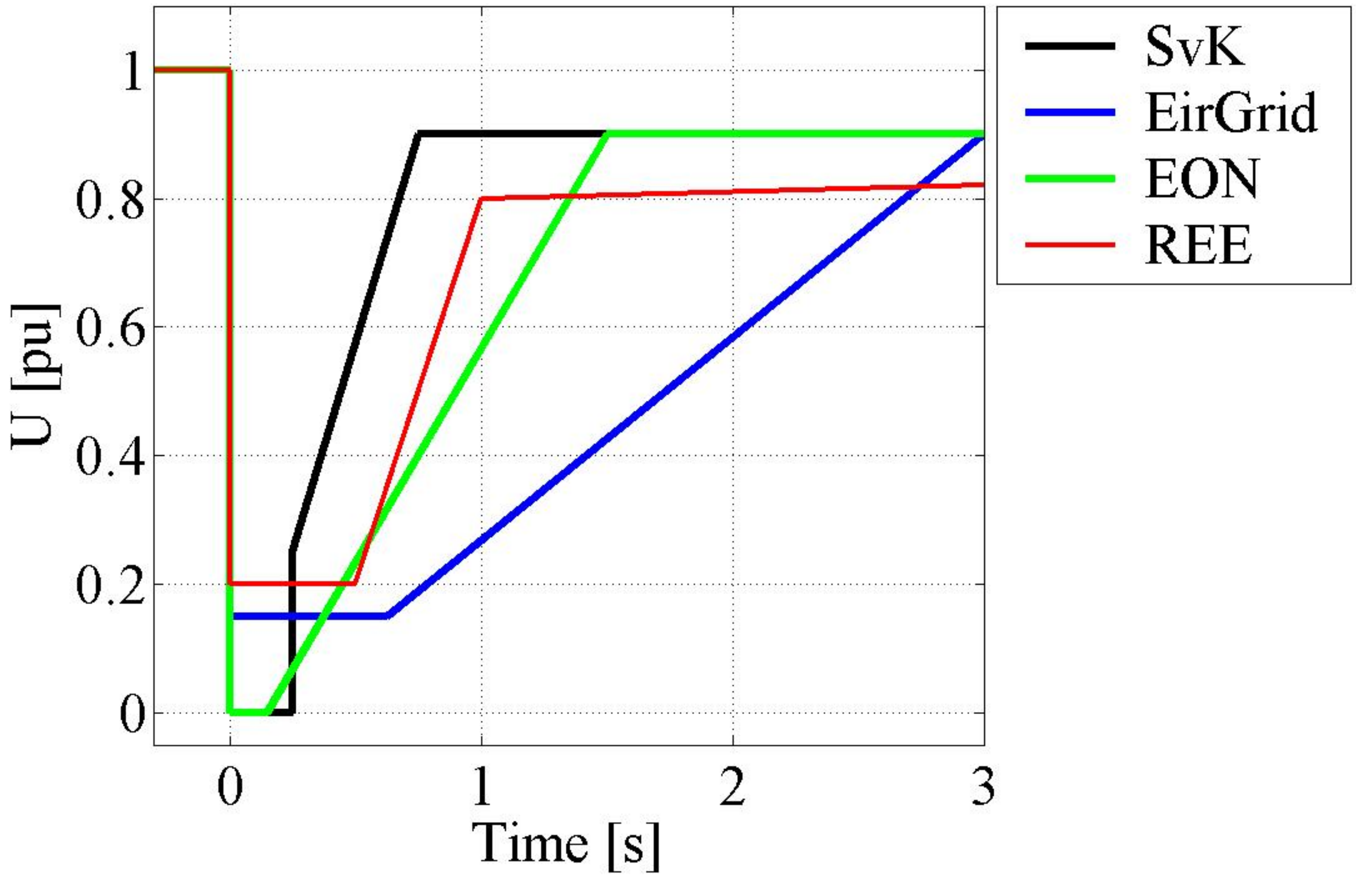
Power: 600 MW,
Energy: 5 TWh

Σ=51 TWh

Σ =6500 MW


Nordel
Nordic Grid Code
2007
(Nordic collection of rules)

Grid Code Under-voltage immunity limit, Ride-Through,



Wind turbines have to be resistant towards disturbance in the electrical grid

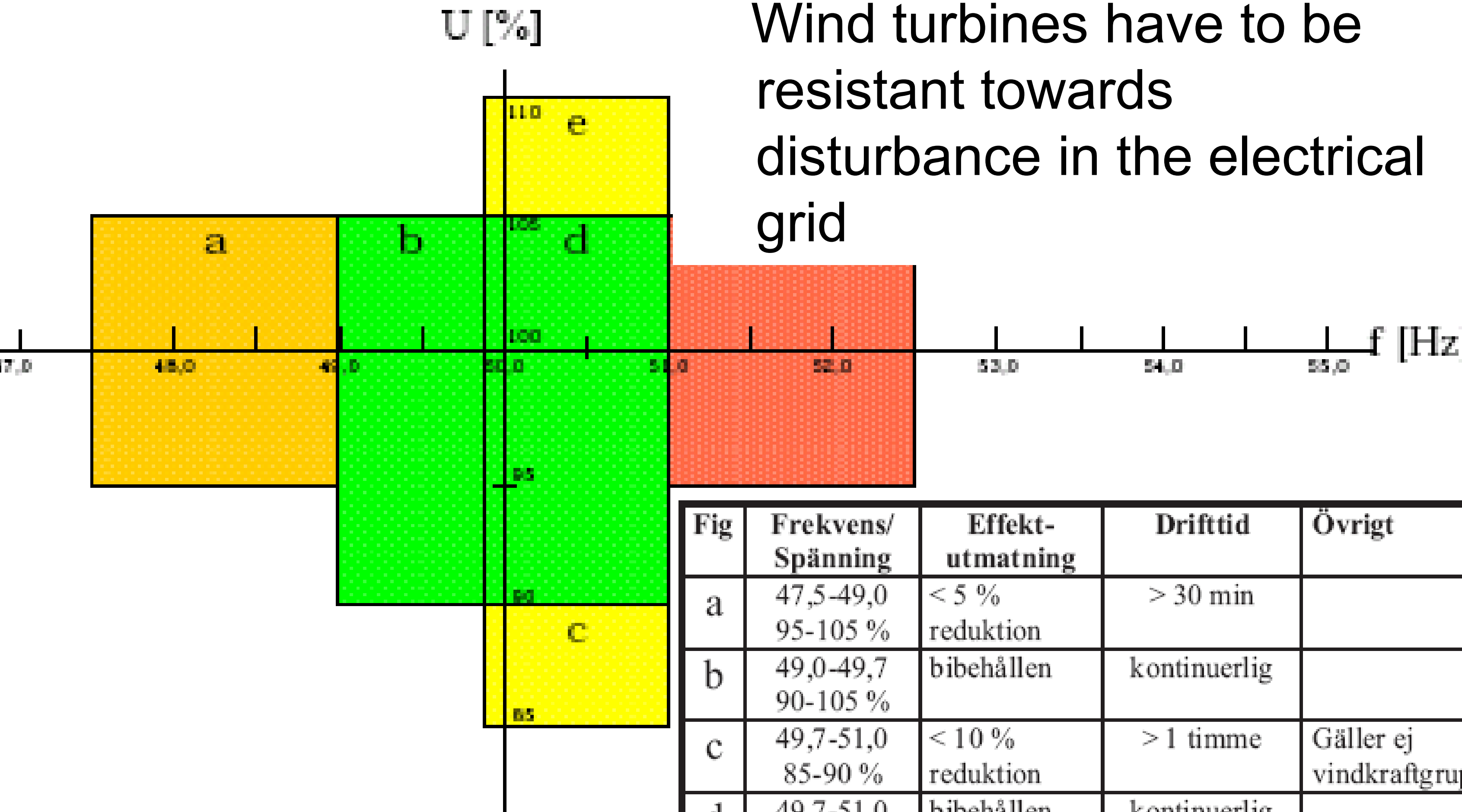
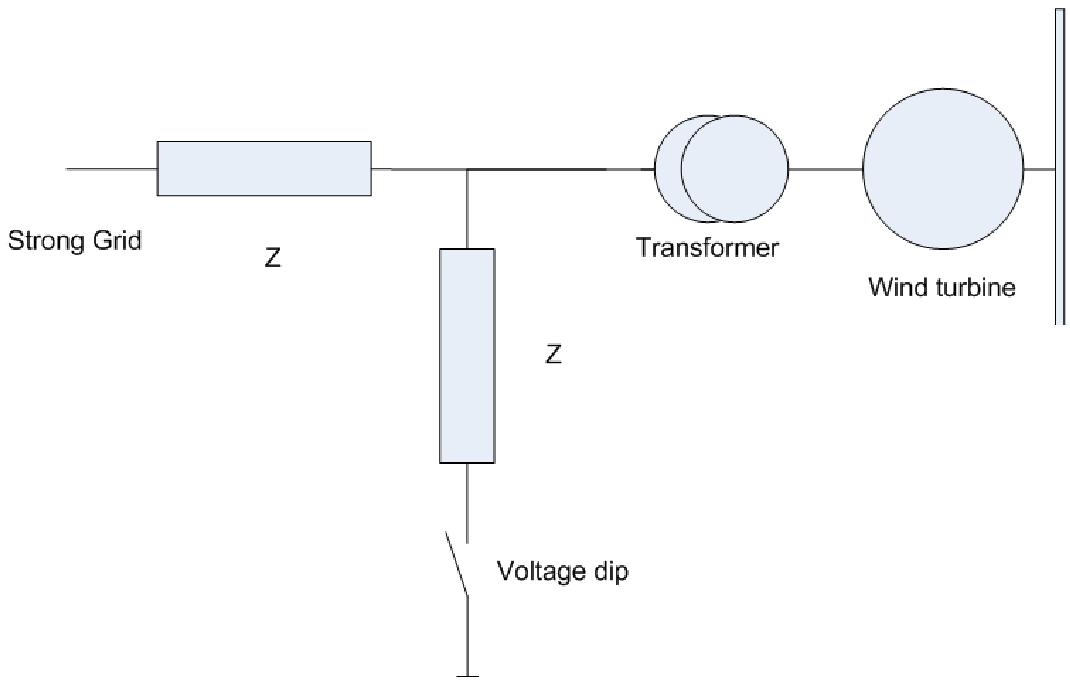
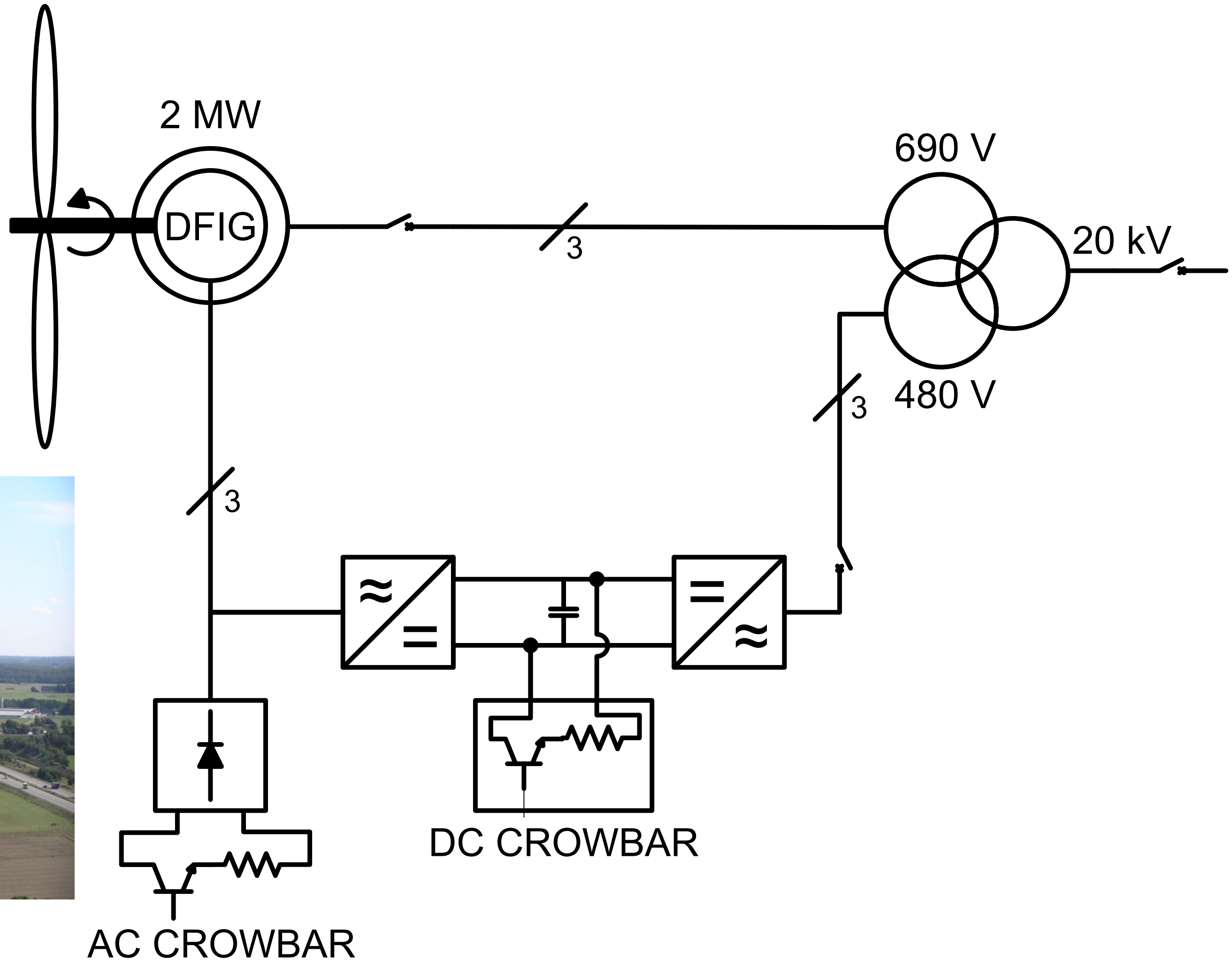


Fig	Frekvens/ Spänning	Effekt-utmatning	Drifttid	Övrigt
a	47,5-49,0 95-105 %	< 5 % reduktion	> 30 min	
b	49,0-49,7 90-105 %	bibehållen	kontinuerlig	
c	49,7-51,0 85-90 %	< 10 % reduktion	> 1 timme	Gäller ej vindkraftgrupper
d	49,7-51,0 90-105 %	bibehållen	kontinuerlig	
e	49,7-51,0 105-110%	< 10 % reduktion	> 1 timme	
f	51,0-52,5 95-105 %	Reducerad	> 30 min	Återgång till normal produktion inom 1 min då f<50,1 Hz. För vindkraftgrupper gäller frekvensintervallet 51,0-52,0 Hz

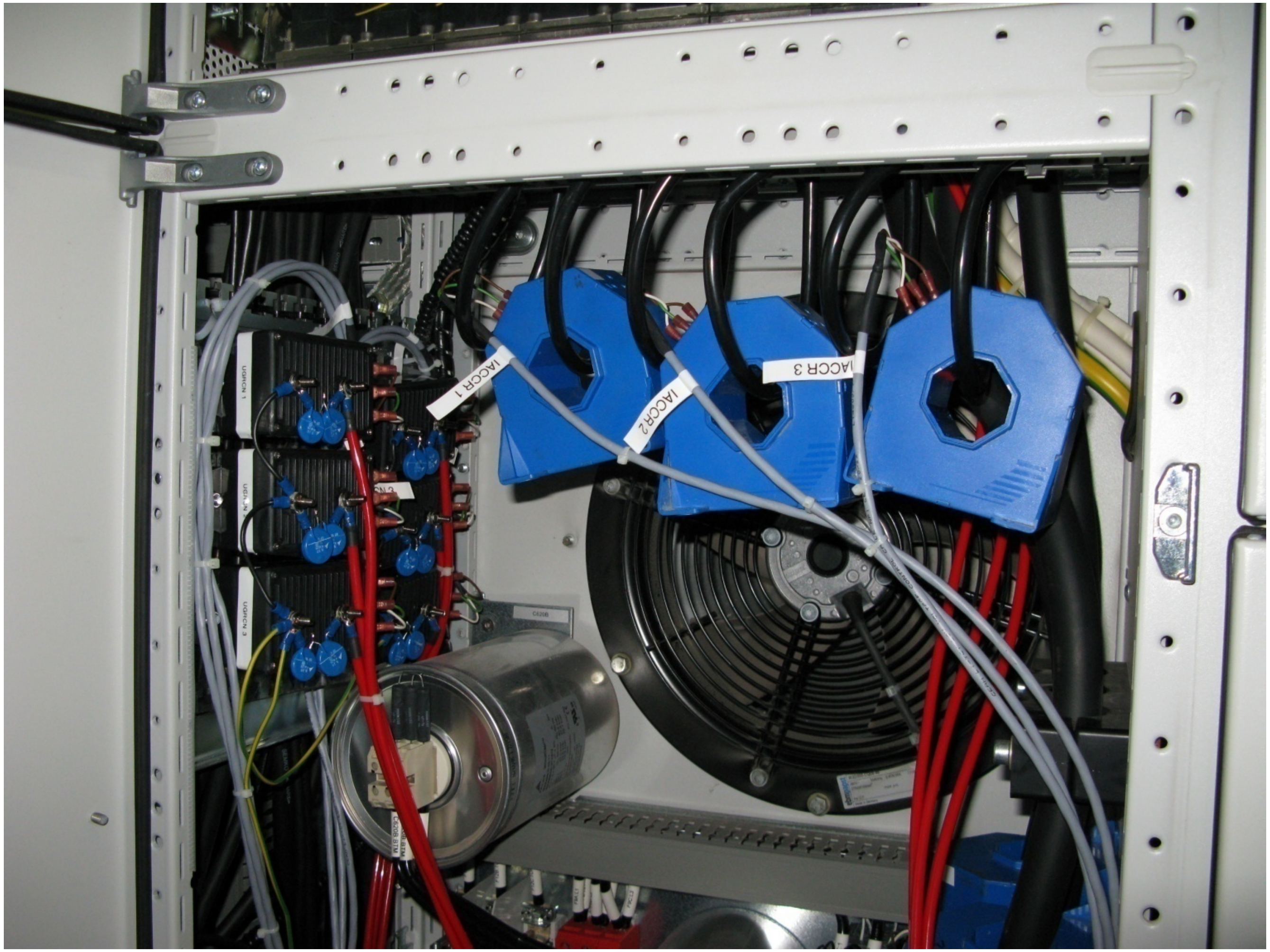
Voltage dip tester



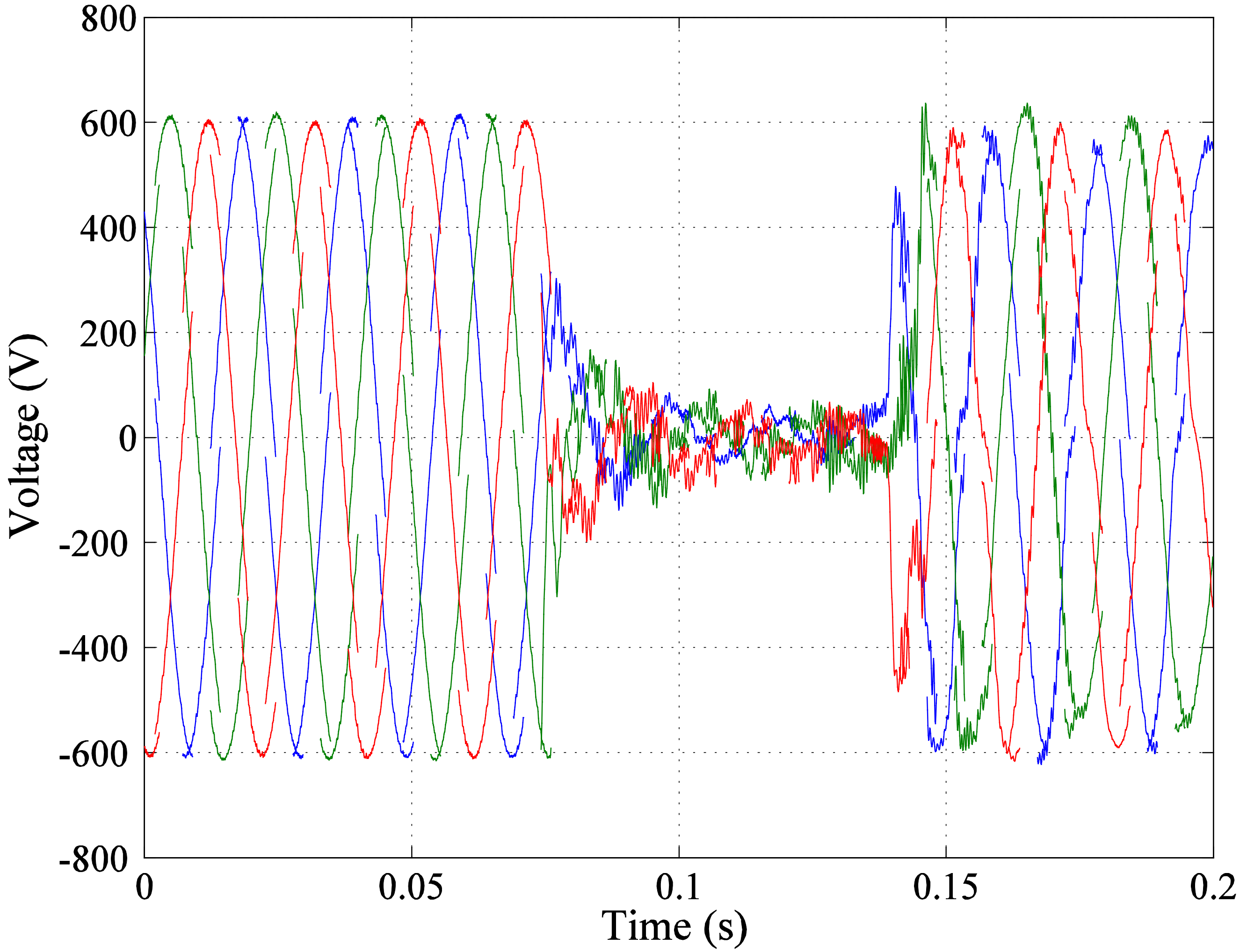
DFIG-system with ”Ride-through” Tvååker



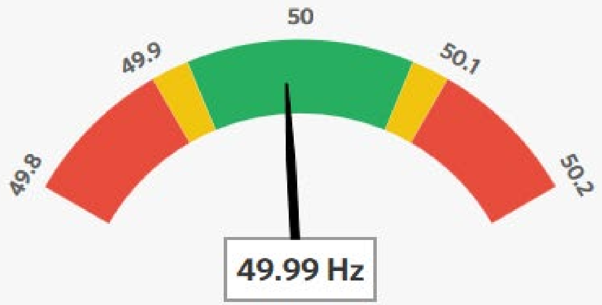
Current measurement AC crowbar

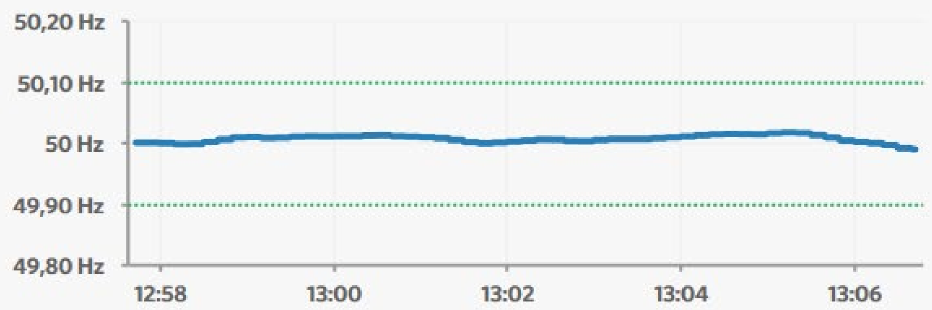


Voltages, 12th of July 2008, 16 o'clock

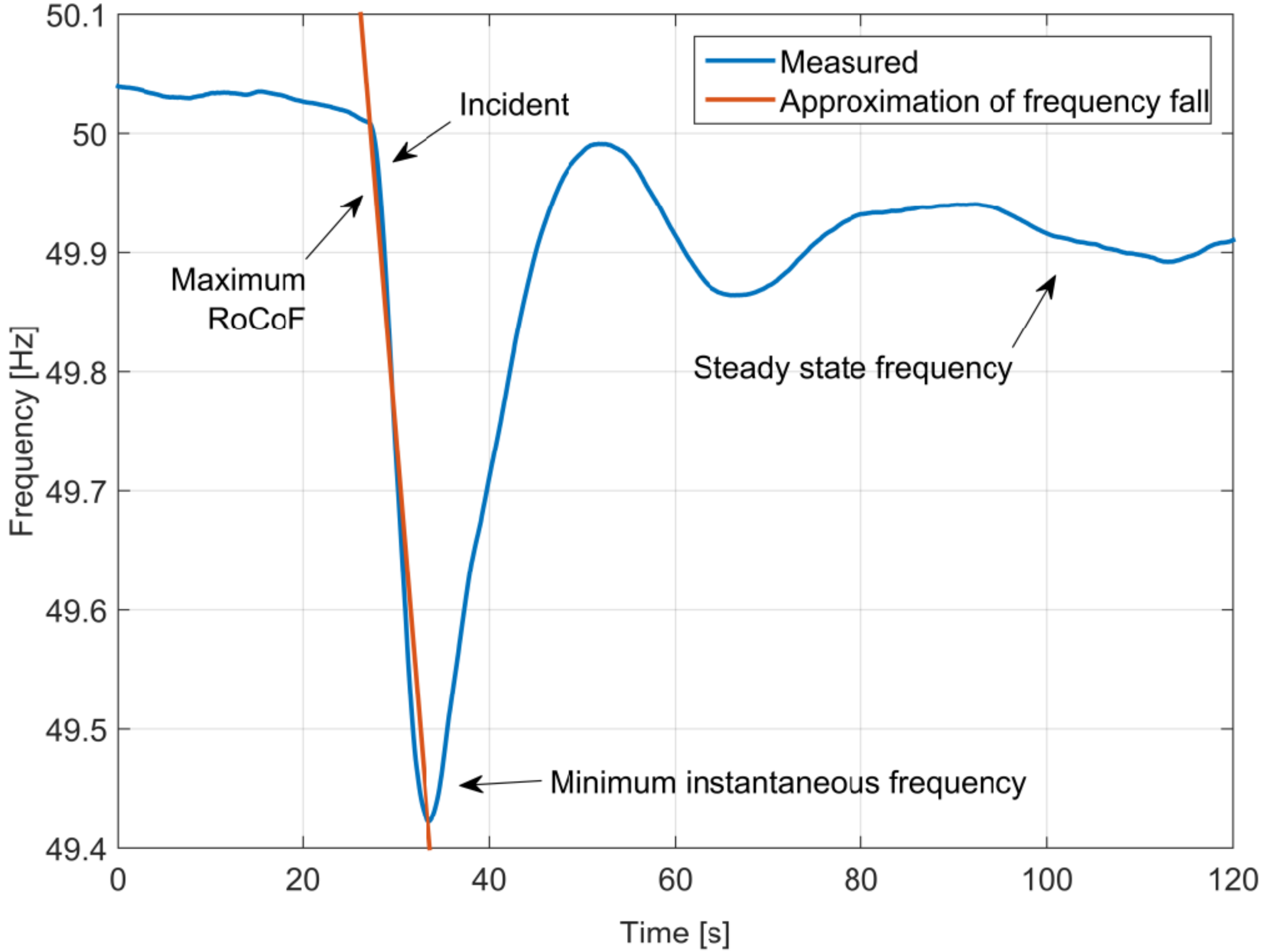


From SVK.se, 190911, 13:07





The frequency fall



Source:

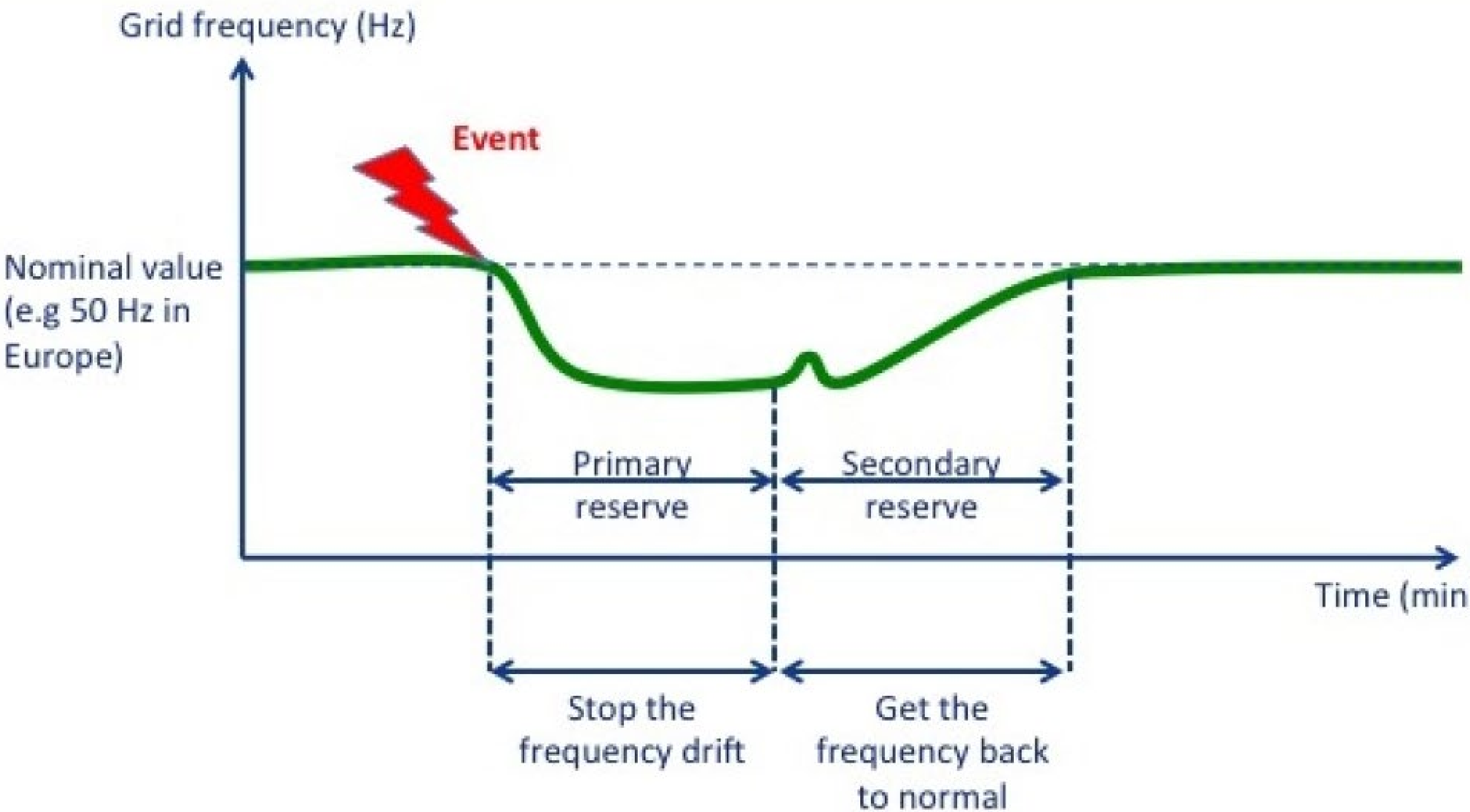
FCR-D design of requirements VERSION 1 – 5 JULY 2017 , SVK.se

Power balance

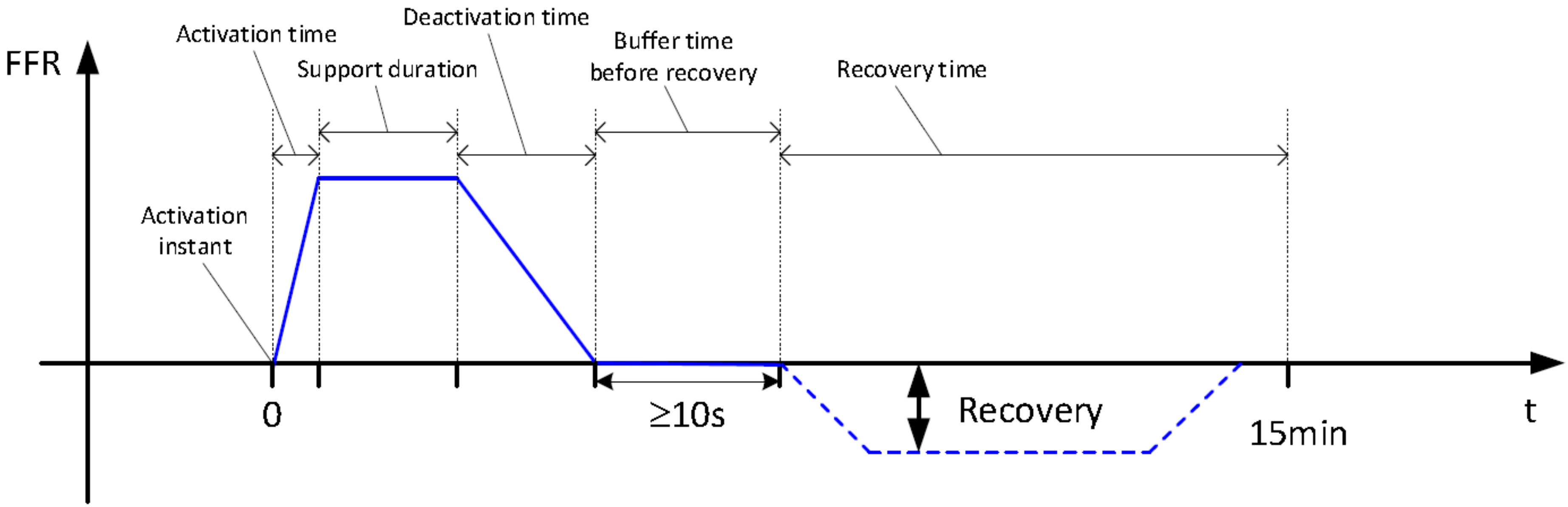
$$T_{mec} - T_{el} = J \frac{\partial \omega}{\partial t}$$

T_{mec} = mechanical torque from the turbine,
T_{el} = electric torque from the generator
J = inertial from rotating electrical machines
w = rotation speed of the generator
= frequency of the voltage

Frequency regulation with primary and secondary reserves



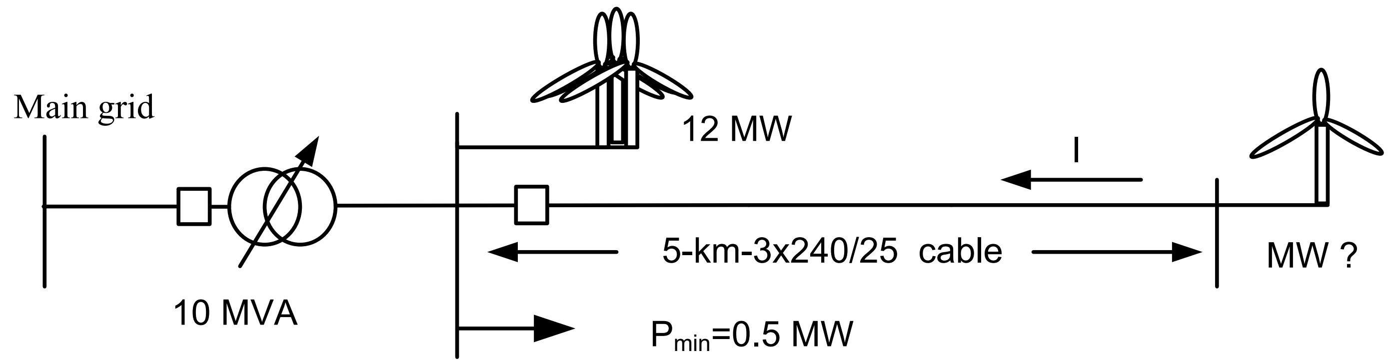
FFR recovery requirement; activation time at t=0



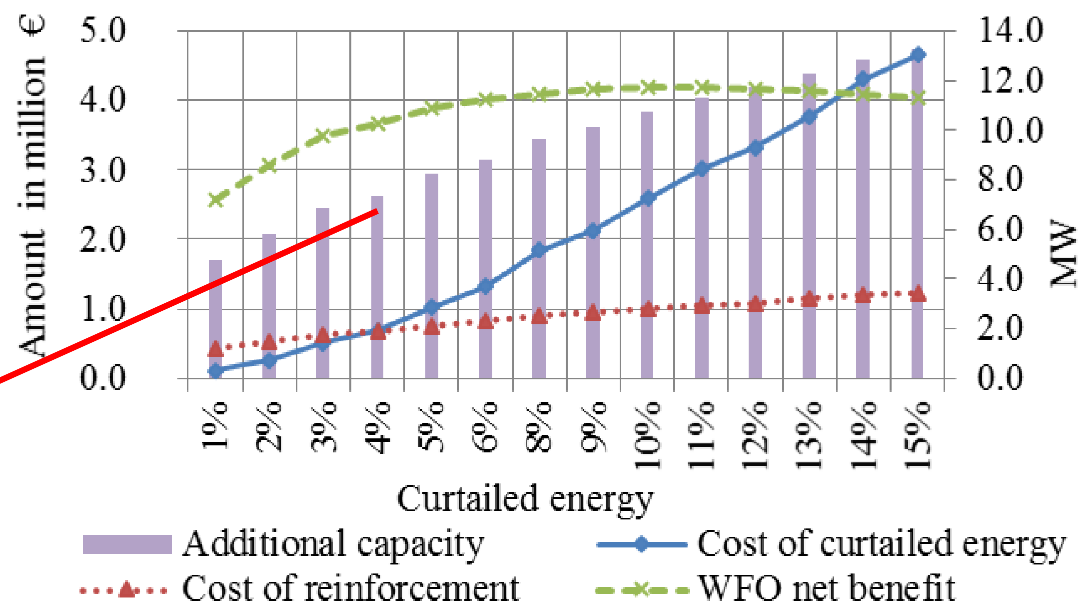
Source: Technical Requirements for Fast Frequency Reserve Provision in the Nordic Synchronous Area , svk.se

Active management strategies for increasing the hosting capacity – Shemsedin Nursebo

Based on worst case consideration= 10.5 MW



4% curtailment
Additional Capacity= 7.5 MW
Percentile increase due to Managements Systems
=(12+7.5-10.5)/10.5
= 86% increase



CHALME

Integration Aspects of Full Converter Wind Turbines and the Impact on Long-term Voltage Stability

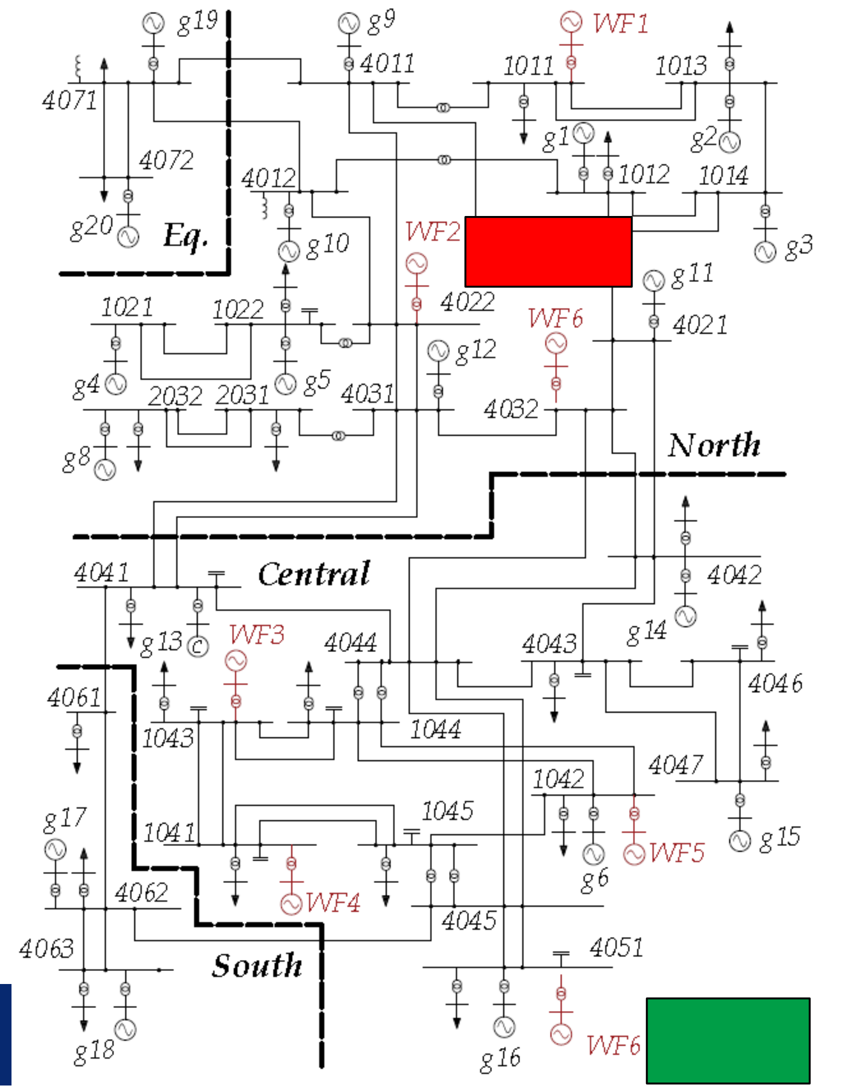
Hannes Hagmar, Le Anh Tuan, Ola Carlson
Department of Electrical Engineering
Chalmers University of Technology

Robert Eriksson
Market and System Development
Svenska Kraftnät

Placement of larger Wind farms is found to have the largest impact on the Long Term Voltage Stability of a power system,

and the closer larger WFs are located to load centers, the more they contribute to the system stability.

Thus, if ancillary services would take into account the actual improvement that the FC-WFs is providing, such aspects should be included in the design of those.

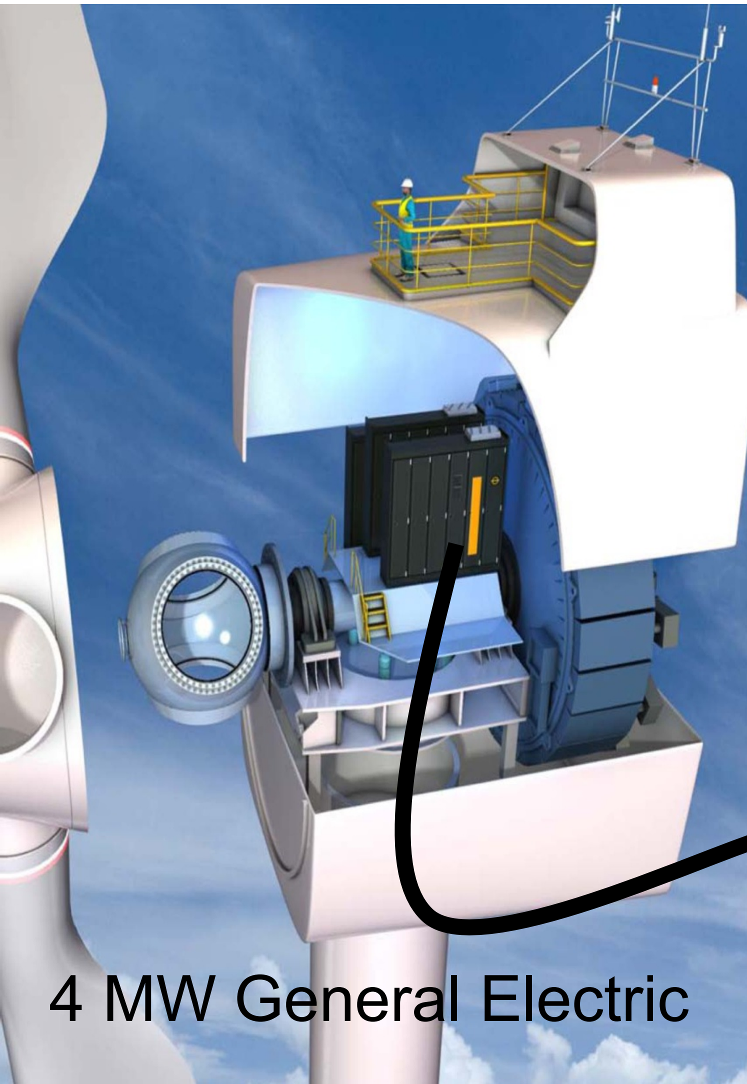


Project in Göteborg

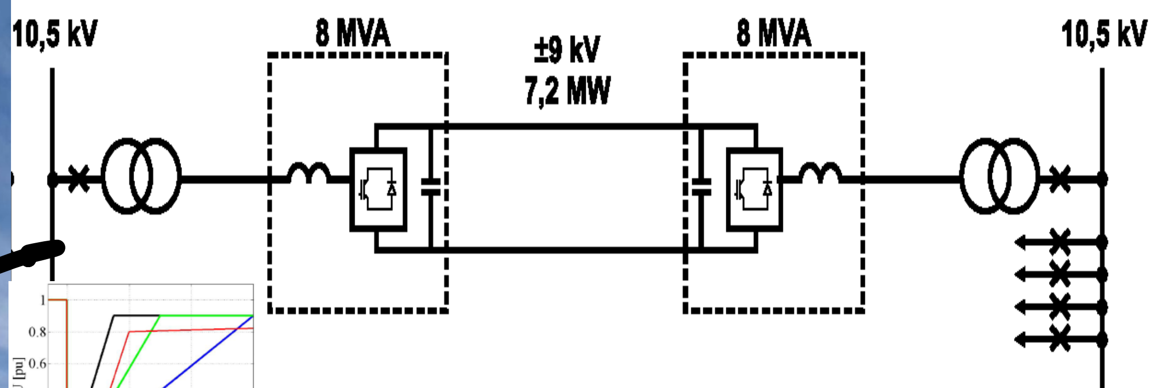
General Electric design and install, Göteborg Energi operate:

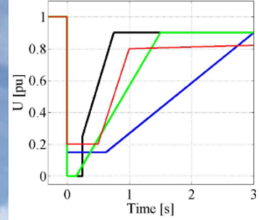
Chalmers cooperation:

- Validation of models for mechanical and electrical systems
- New control with LiDAR
- Grid code tests for the wind turbine



4 MW General Electric





8 MW HVDC-light converter

HVDC Göteborg

- **System**

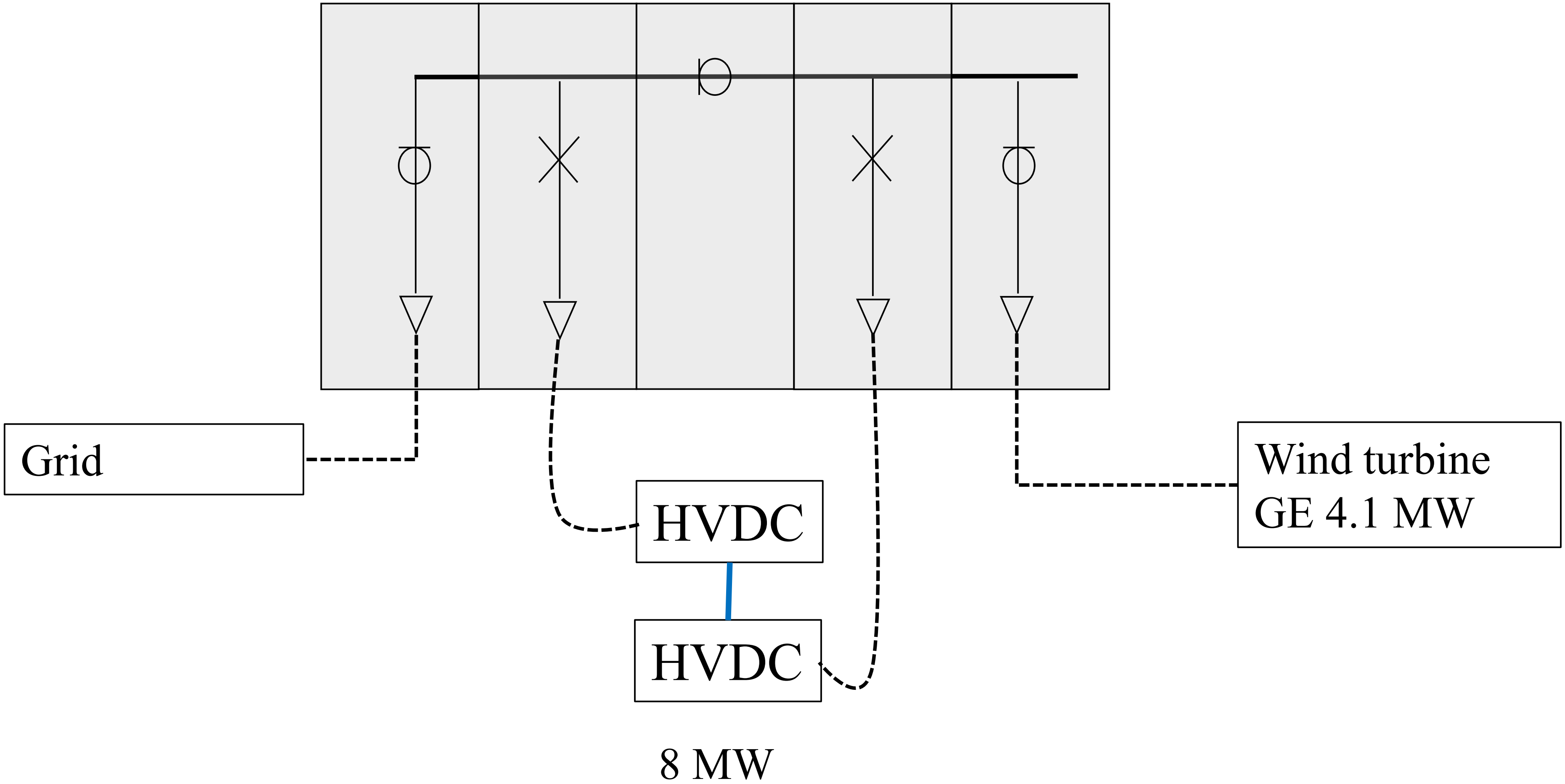



ABB
RESIBLOC
by ABB Trafo-BB
TUNGA LYFT

Wind Turbine Characterization by VSC-based testing equipment

Nicolás Espinoza, PhD student

SWPTC monthly meeting, 2016-12-05

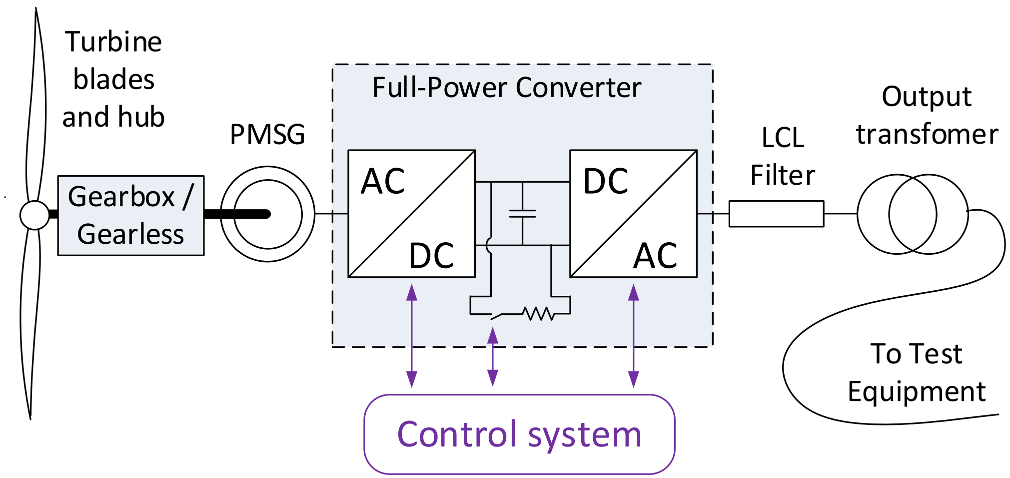
SWEDISH WIND POWER TECHNOLOGY CENTRE

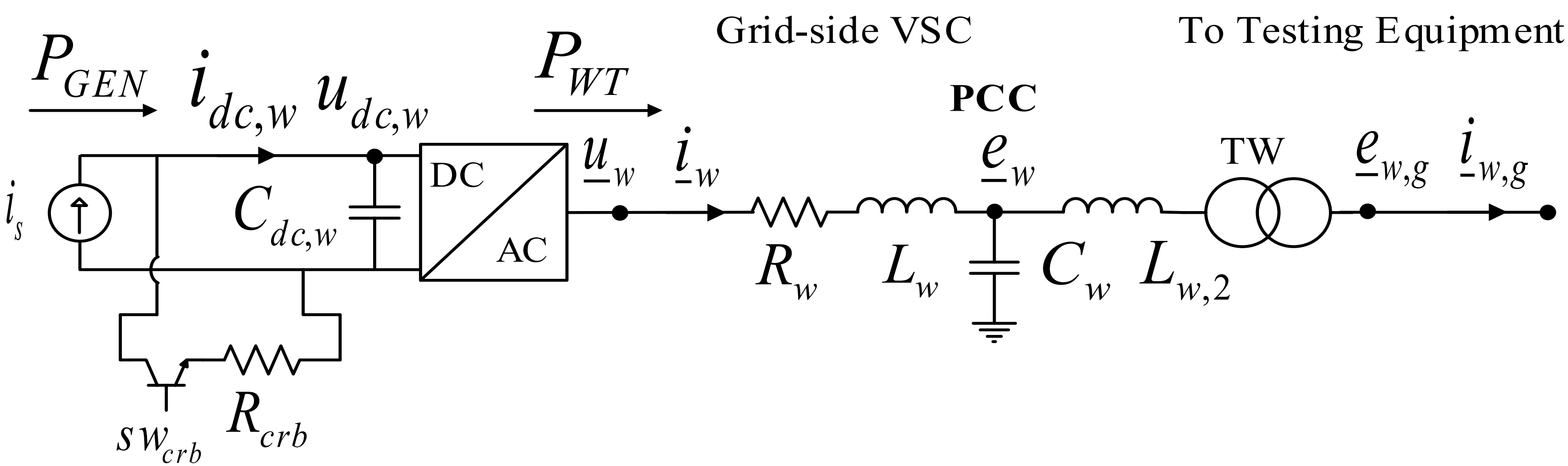
Problem Identification

- **Research questions**
  - How can we best use a fully-rated WT testing equipment?
  - What information can we obtain from the wind turbine system.
- **Aim of the project**
  - To develop methods for testing and characterizing wind turbines systems using VSC-based test system
- **Activities**
  - **Grid code analysis** for interconnection of wind parks.
  - **Control theory** of WT and VSC testing device
  - **Mathematical model** for stability analysis.
  - **Time-domain simulation** of the WT and the VSC-based TE
  - **Laboratory experiment** at Power System Lab in Chalmers.
  - **Field test** of full power 4 MW WT with 8 MW HVDC system in Göteborg harbor has started!

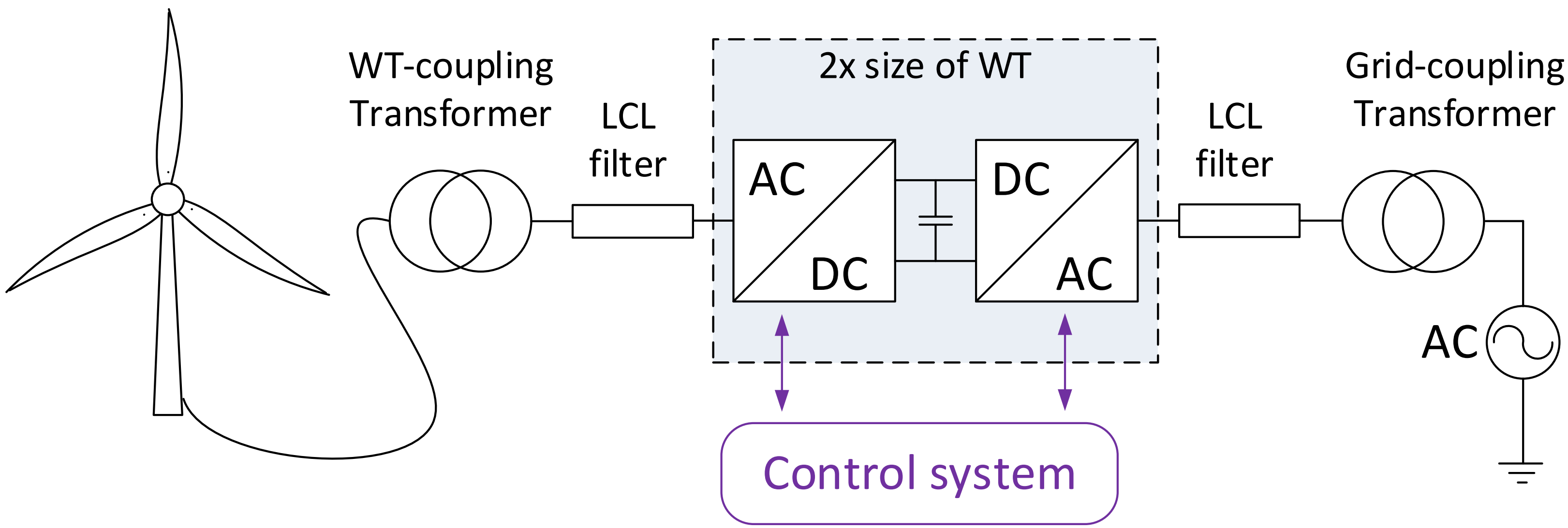
Modelling of the WT

- Grid-side VSC
  - Grid synchronization
  - DC voltage control
  - Current control
  - LVRT control



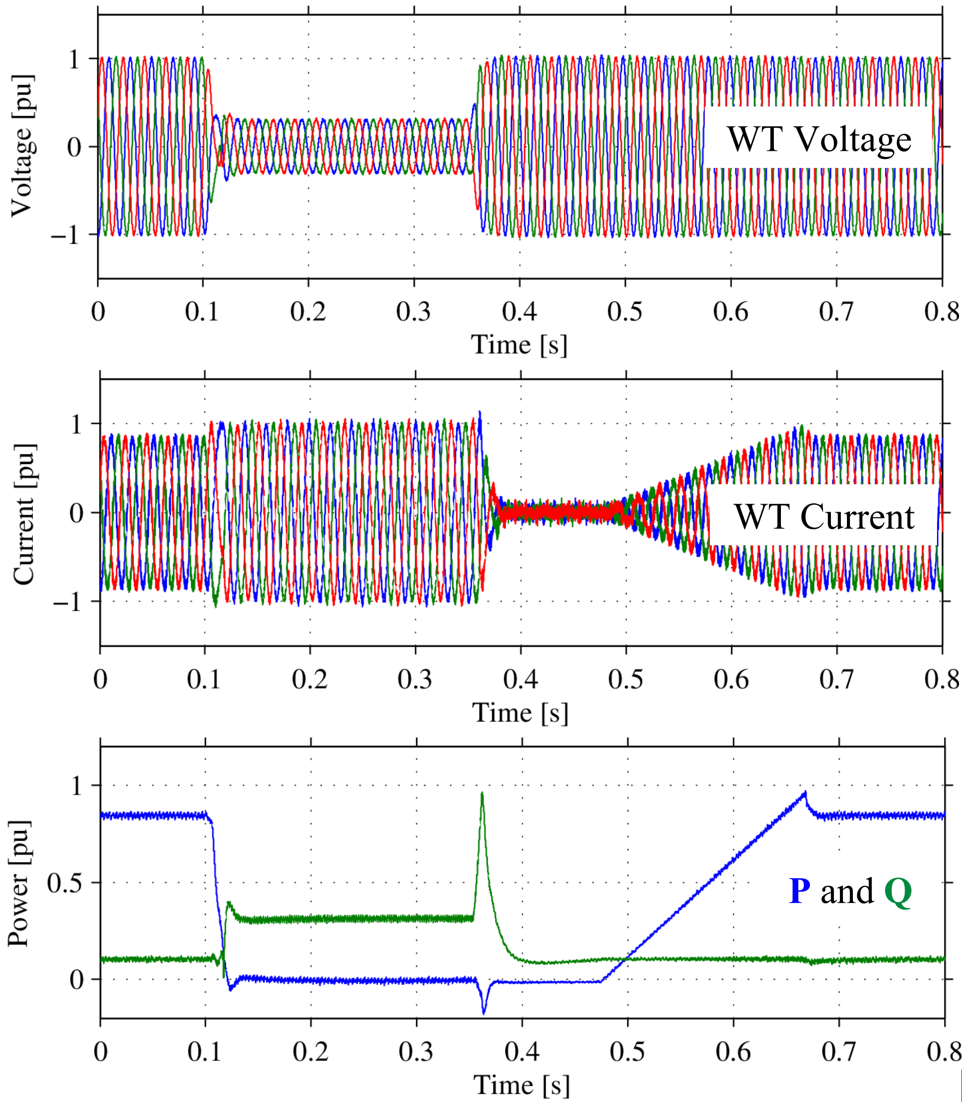


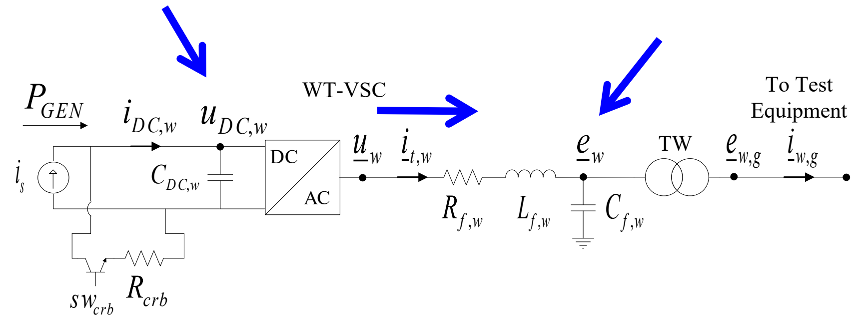
Modelling of the Test Equipment



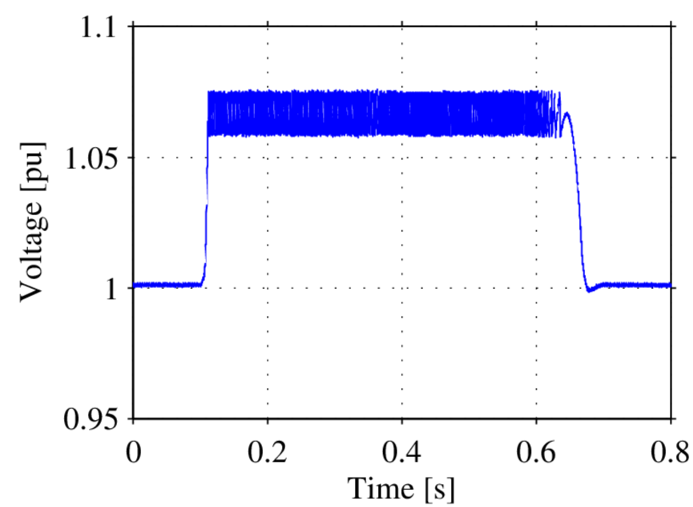
- Full control of applied voltage
  - Creates the grid for the WT
- Test performed on Big Glenn
  - Frequency scan
  - Frequency Variation
  - Voltage dips

Voltage dip test (PI ctrl) – Wind turbine



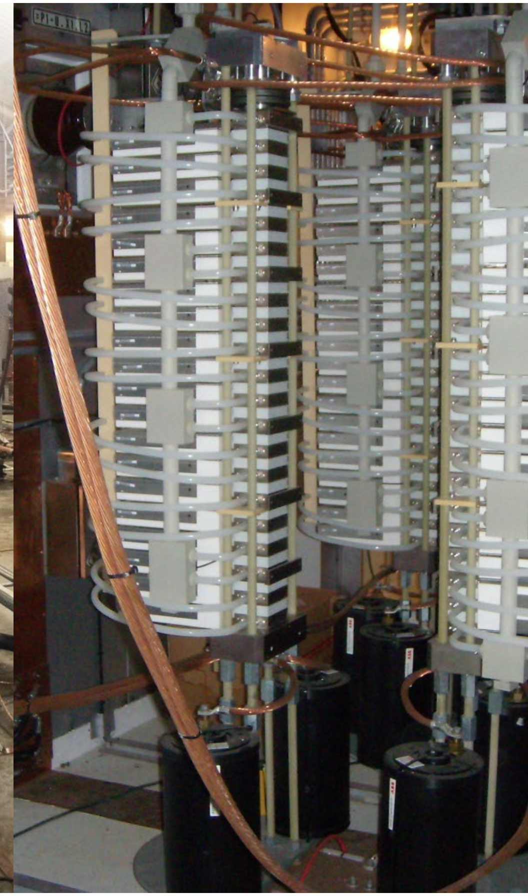


Wind turbine DC voltage

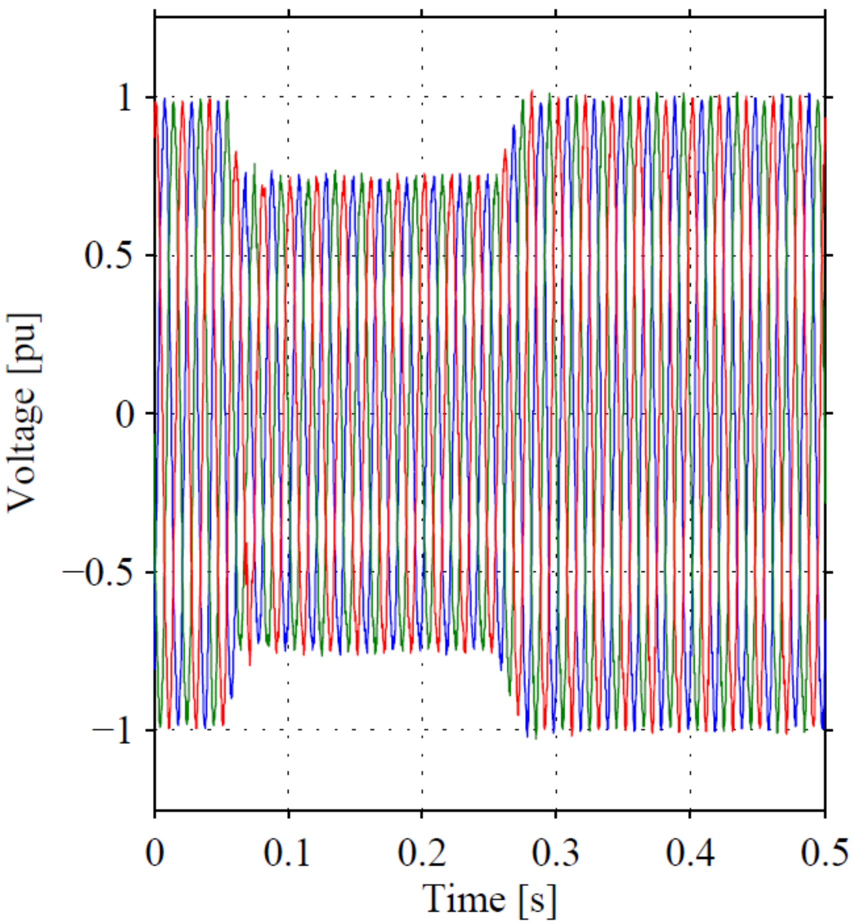


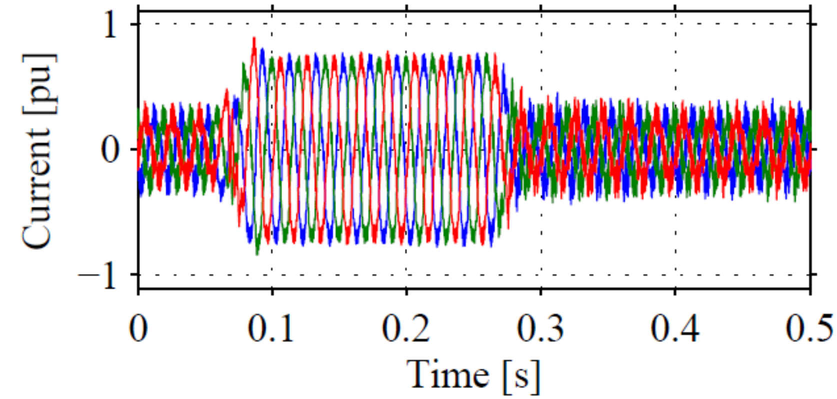
Field Test Results



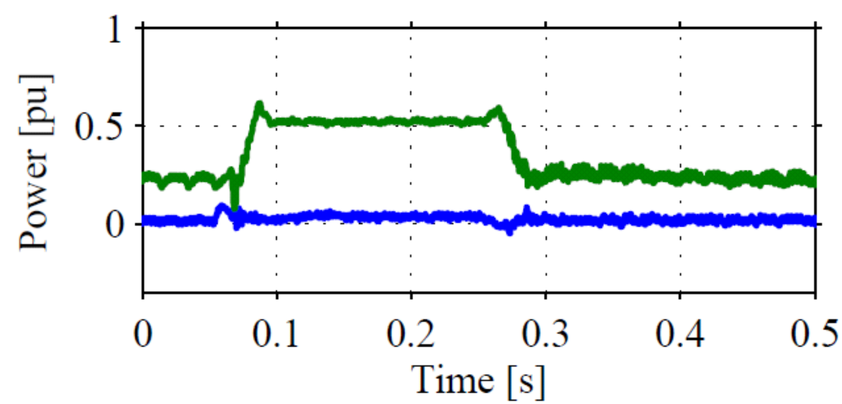



Voltage dip test of the 4 MW wind turbine





(b)



<u>WT power output:</u> **Active (blue)**, Reactive (green)

Grid side VSC during test

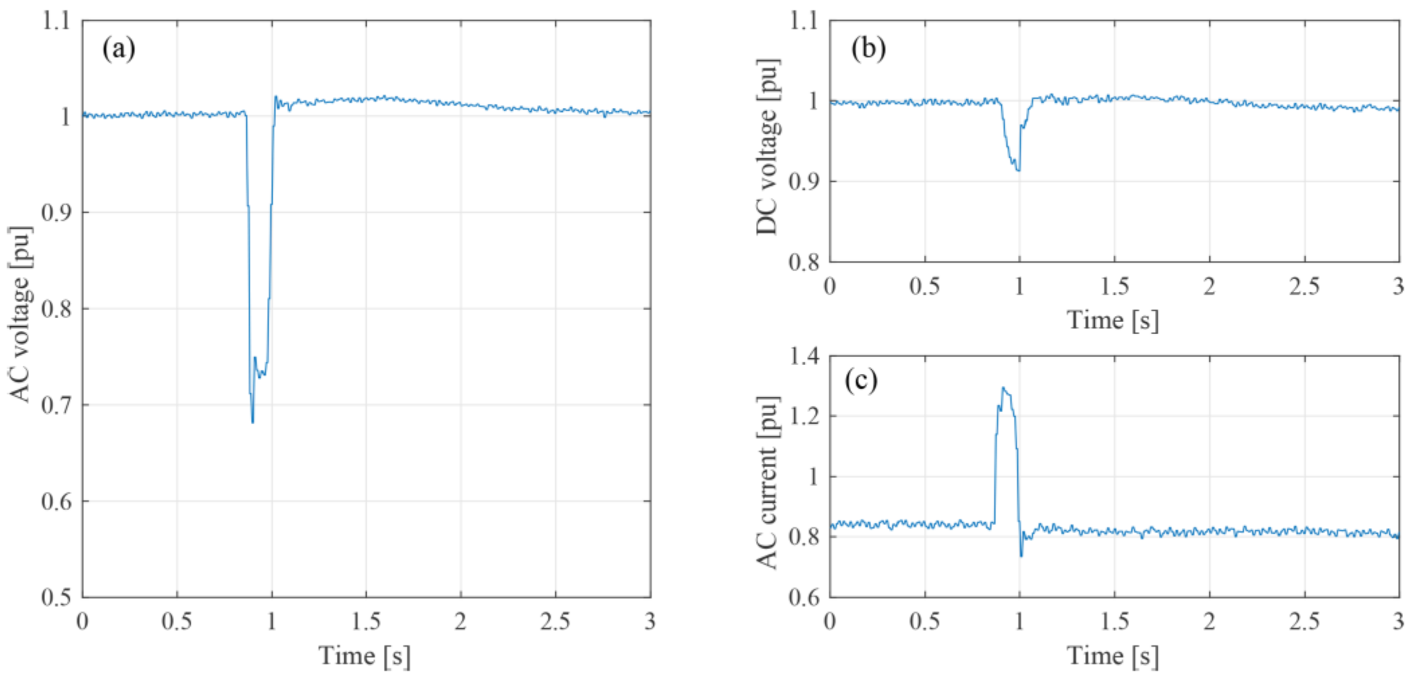


Figure 9. Wind turbine VSC under a voltage dip: AC voltage resulting at the LV side of the wind turbine transformer (**a**), and DC voltage (**b**) and AC current magnitude measured at the grid-side VSC (**c**).

Generator during test

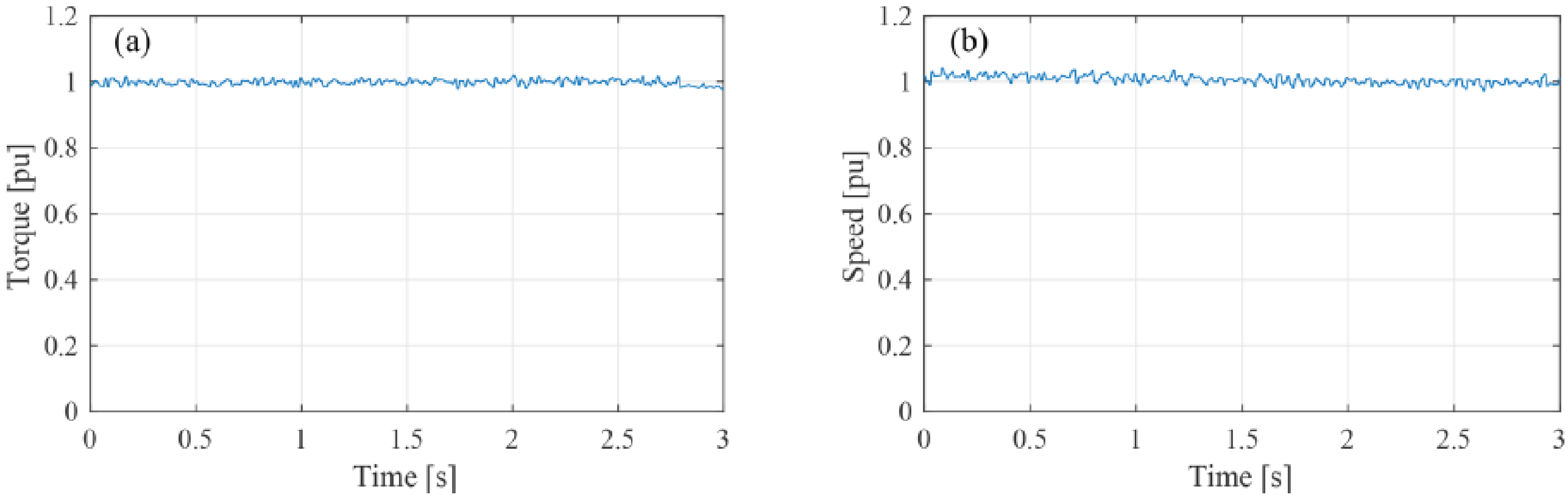
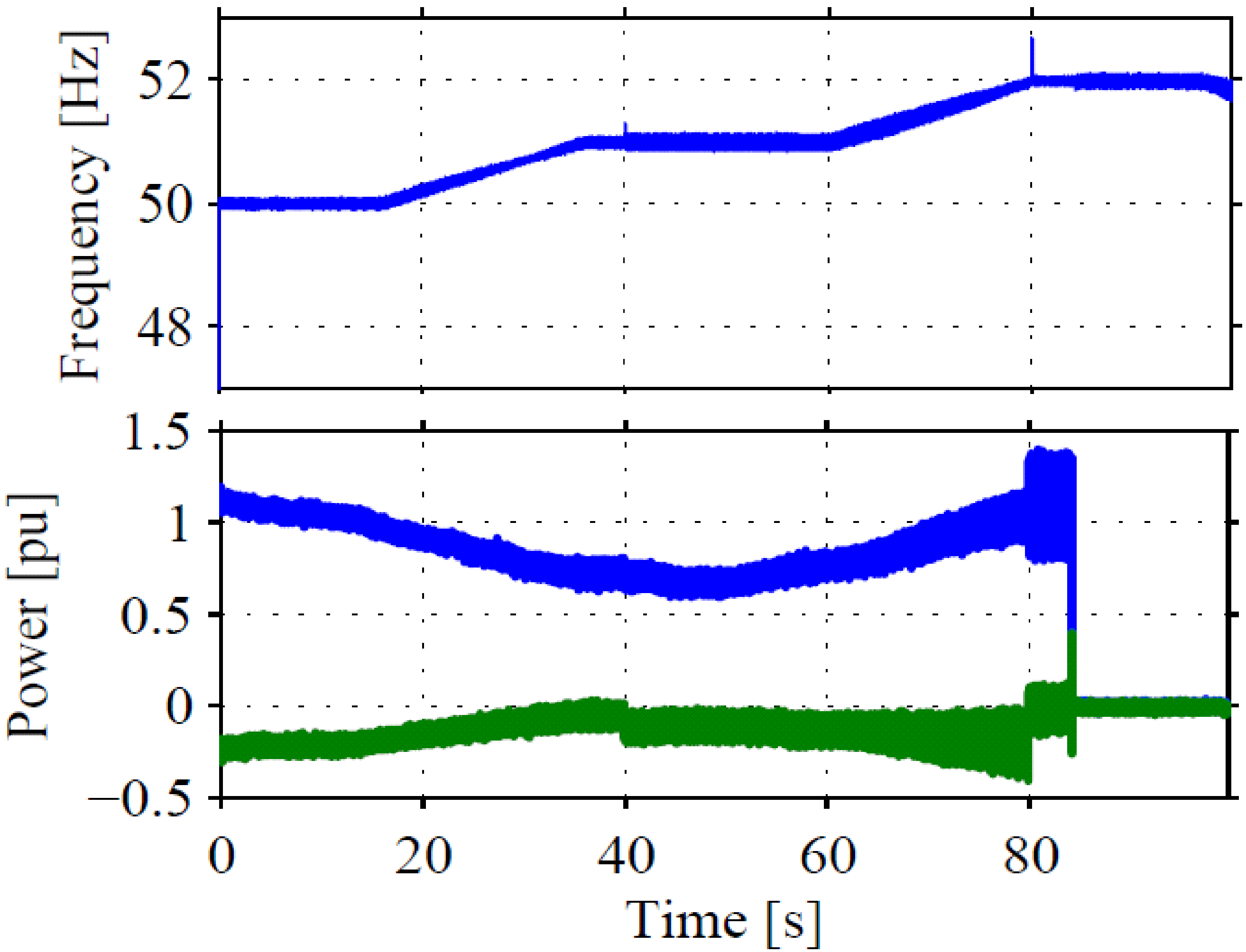


Figure 10. Wind turbine VSC under a voltage dip: generator torque (**a**) and speed (**b**).

Frequency variation during test



WT Power output:
Active (blue),
Reactive (green)

WIND-HYBRID SYSTEMS WITH VARIABLE SPEED AND DC-LINK

Ola Carlson

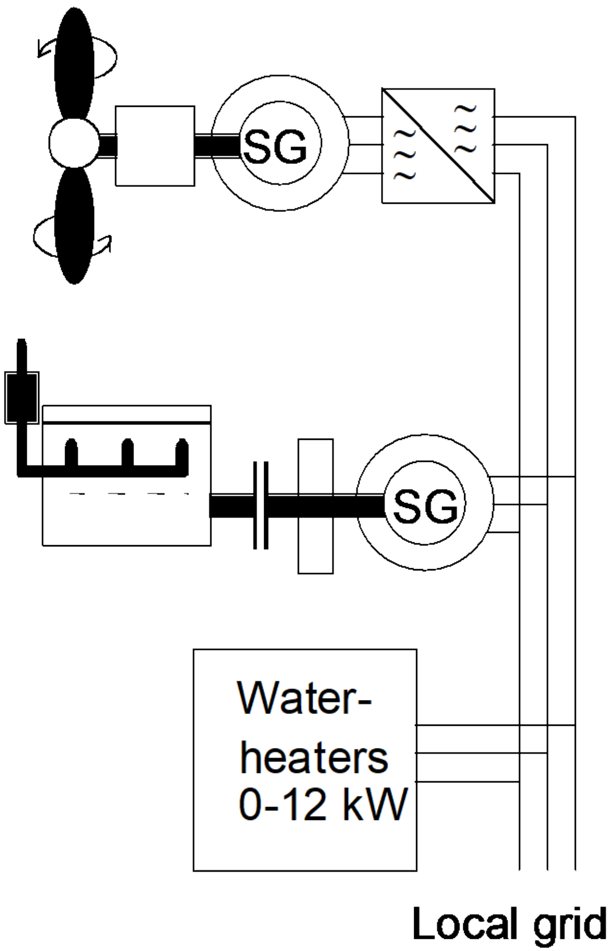
Chalmers University of Technology

Svenska högarna

Power demand: 5-7-12 kW
Heat load: 0-10 kW

Designer: Sven Svenning
Power: 20 kW
Passive balde pitch control
Variable speed operation

Wind-Diesel System on Svenska Högarna

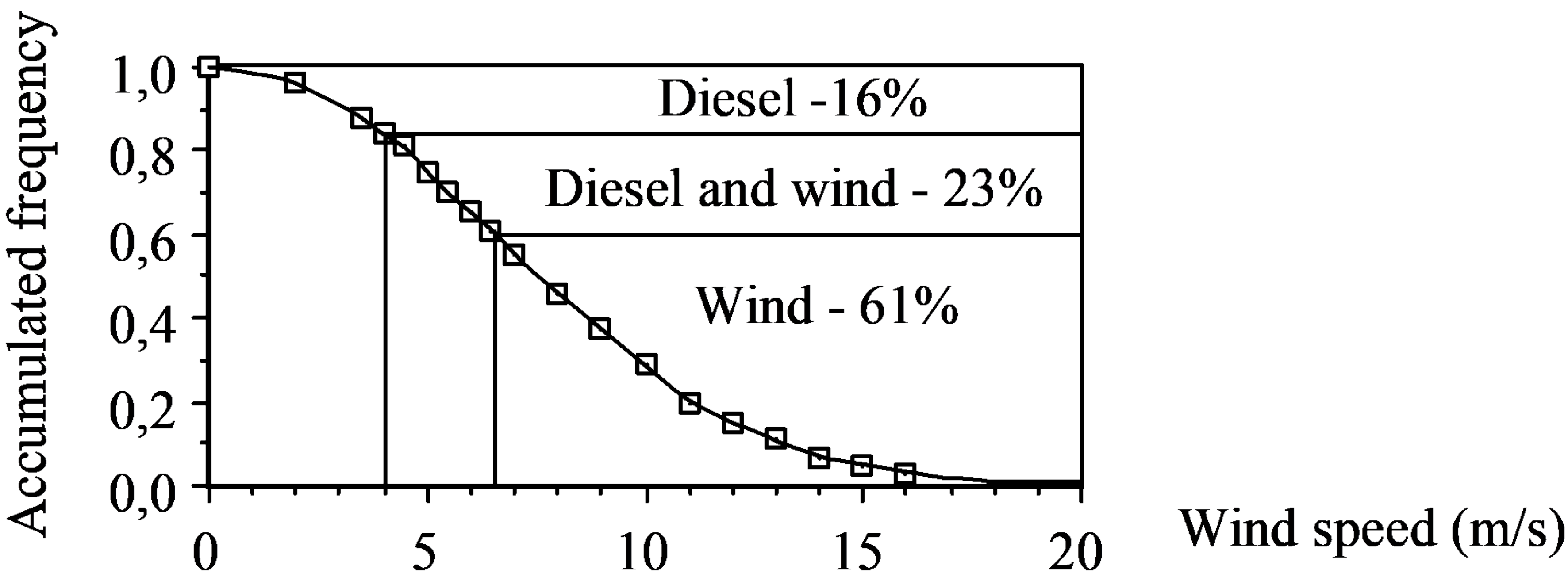


20 kW wind turbine with variable speed and passive pitch control
Large turbine diameter, 17 m.

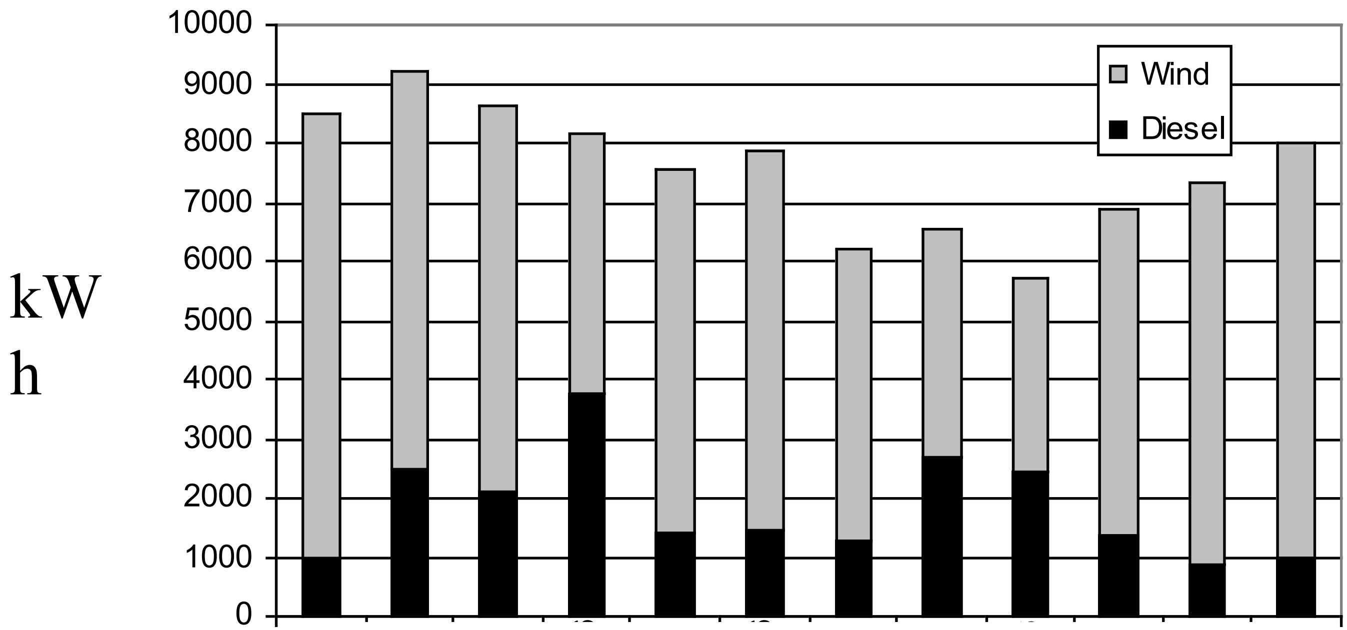
Diesel genset, 18 kW with clutch and flywheel on the generator

Controllable water heaters for using surplus power from the wind turbine (Not used for grid control)

Wind distribution and different modes of operation



Electricity production during one year on Svenska Högarna



December -95 to November -96

- wind turbine produced 76% of the electric energy
- 66% savings of diesel

Chalmers test wind turbine

- Different research projects since 1986
- Education
- Information to society

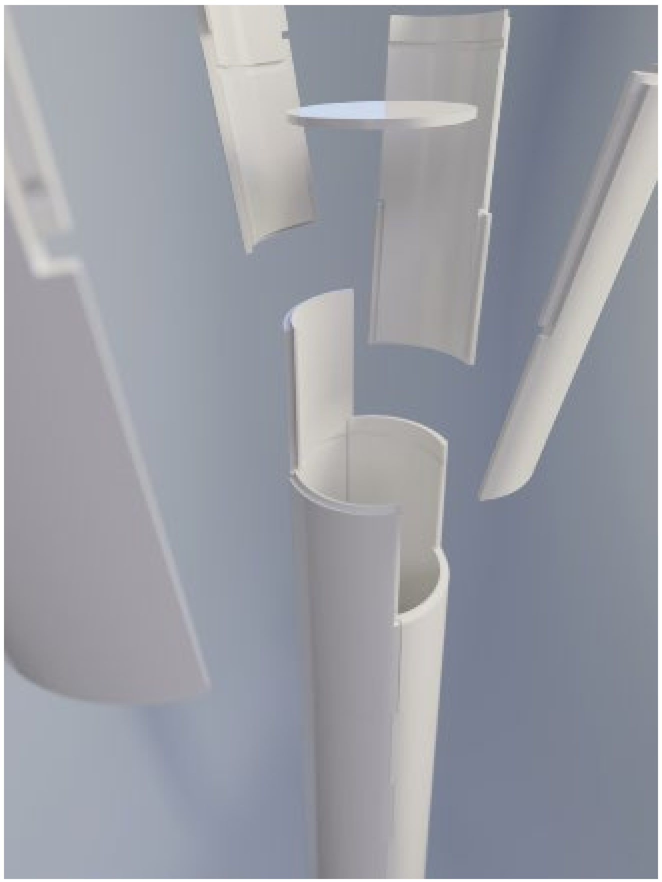

3 JINERT
JÖNKÖPING
036-35 35 00

Coming research projects: Improve wind turbine operation and fatigue life time assessment

- Developing methods for fatigue lifetime assessment
- Aerodynamic modelling – evaluation of blade profile, evaluation of analysis tools, access to full 3D geometry of a blade
- Blade sensors to improve turbine operation and fatigue life assessment
- Sensors in tower and nacelle for dynamic behavior analysis
- Assessment of sensor technology for structural health monitoring of concrete foundation and load transfer from turbine to ground
- Operation with fast frequency support, i.e. the provision of inertia from the wind turbine to the power grid

- Open for international cooperation

Wooden tower from Modvion AB

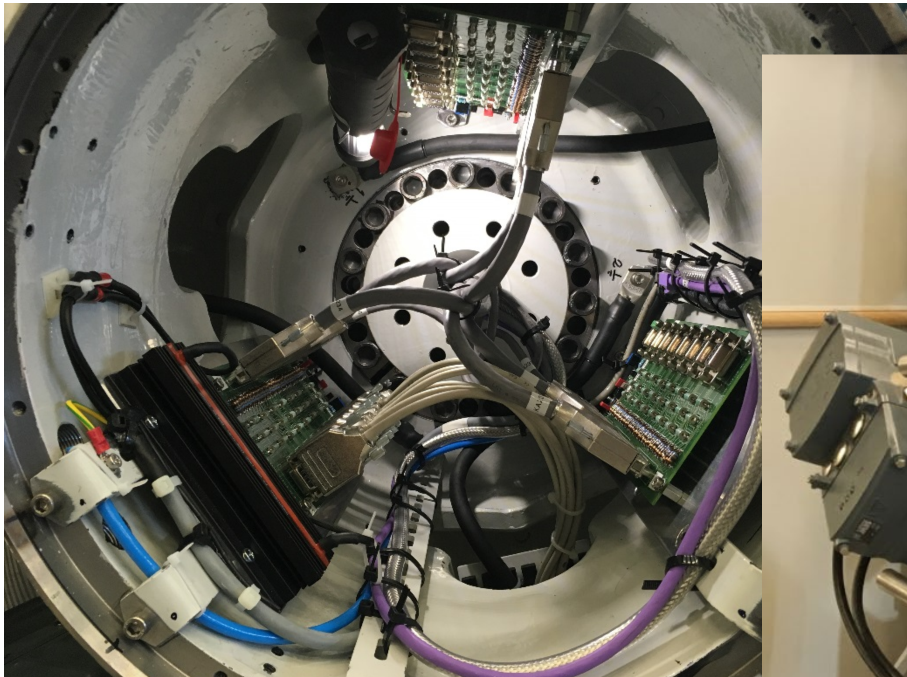


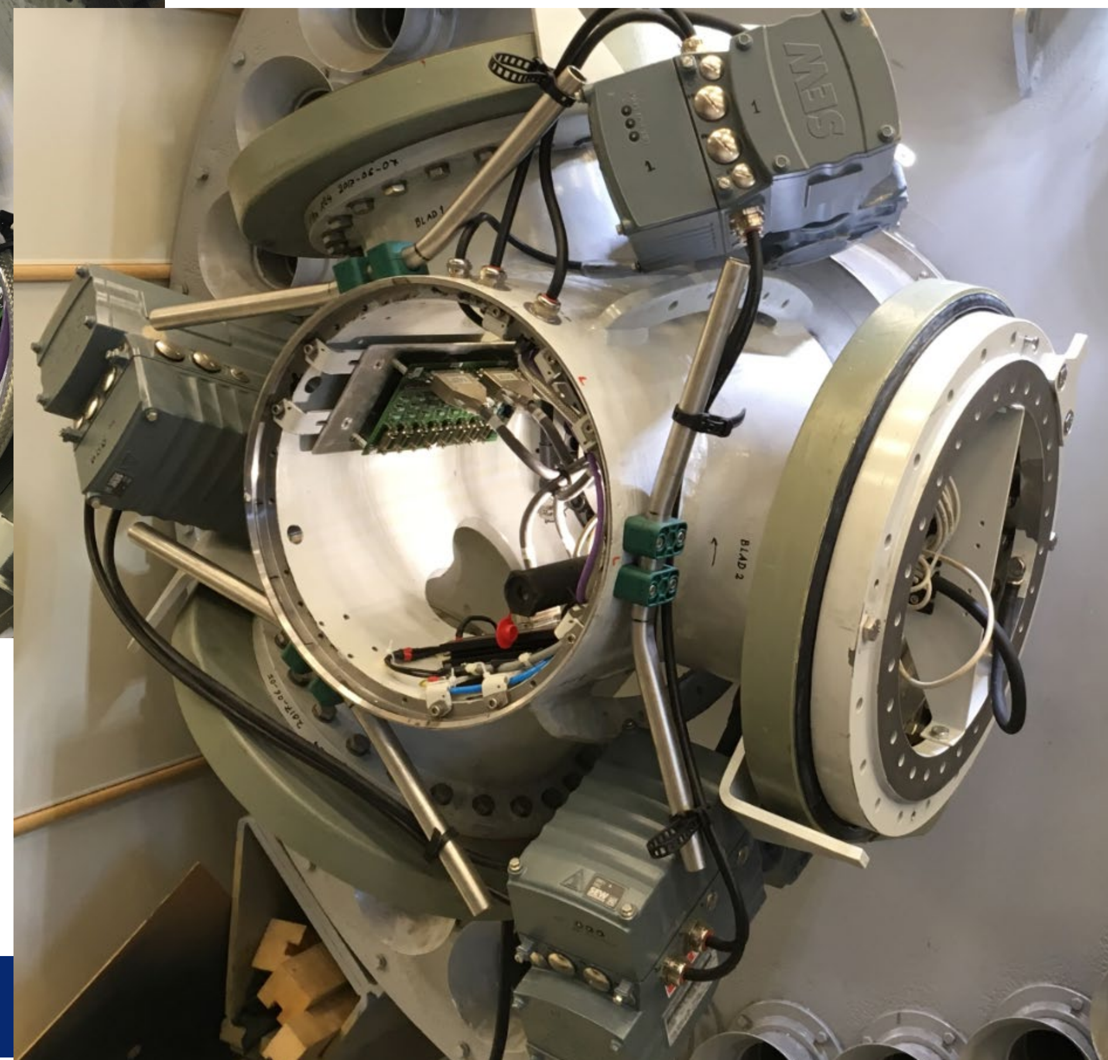
30 m wooden tower
design and manufacturing

Test with Chalmers wind turbine
Design verification,
Weather protection and climatization

Next step for Modvion:
100 m tower
Transportation in modules and
joining at site

Hub with pitch control





Connection of blade sensors and lightning (high voltage) protection

Carbon fibre blades. Sensor installation

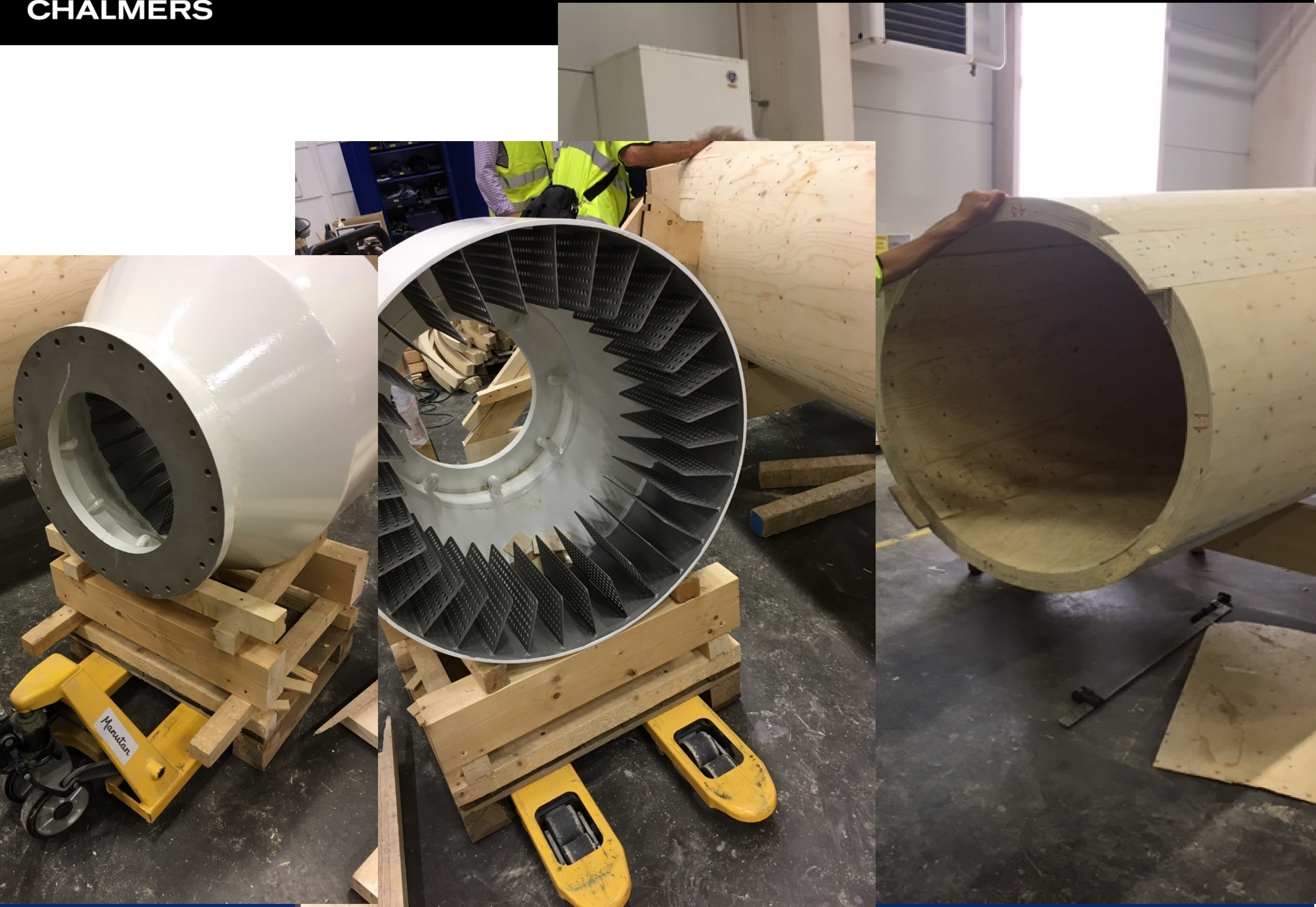
Eight strain gauges per blade

Sensor calibration

Wooden tower

from Modvion and Moelven for Chalmers wind turbine

- 30 m height,
- bottom diameter 2,3 m
- top diameter 0,8 m
- weight 8 ton.


Manutan

Offshore wind power

Wind turbine on ship

Save 16 % of fuel for e trip from Rotterdam to New-York

Rationale: urgent need for qualified workforce!

EWEA “Wind at Work” 2009

Some 400,000 jobs in 2030

~ 200,000 **new** jobs in offshore wind!!

New figures from 2018: 569.000 jobs 2030

Conclusions about education from Power Cluster

- Wind energy needs promotion as attractive professional area
- More and more intensive Wind Energy educational programmes/courses needed on all levels

Recommendations

- Increase training capacities
- Agree upon one common education standard
- Industry: share more technologies to optimize education
- Development of part-time education and dual education
- Expand courses for professionals
- Ramp up MSc programmes in Wind Energy
- Initiate international and cooperative programmes

Hywind concept

120m below surface

Moring in 3 directions

Designed for deep water 100-700 m

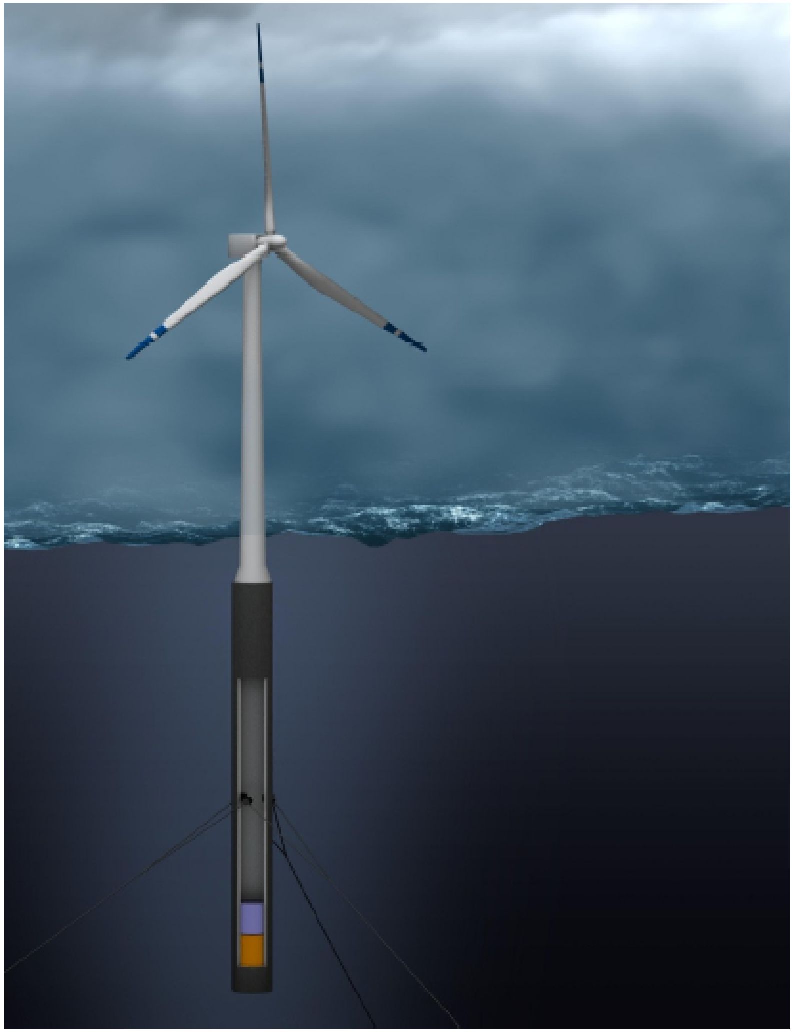
80 m tower above surface

Power of 2.3 MW

Rotor diameter 80 m

Weight 6500 ton

In operation since 2011



Hywind at 25 m/s

The world's first floating offshore wind park, 5 x 6 MW outside Scotland

https://www.sintef.no/globalassets/project/deepwind-2013/deepwind-presentations-2013/opening-session/nielsen-f.g_statoil.pdf

Wind Power Farm

Wind Power Mills

Offshore High Voltage Station

Transport and boarding are great risks

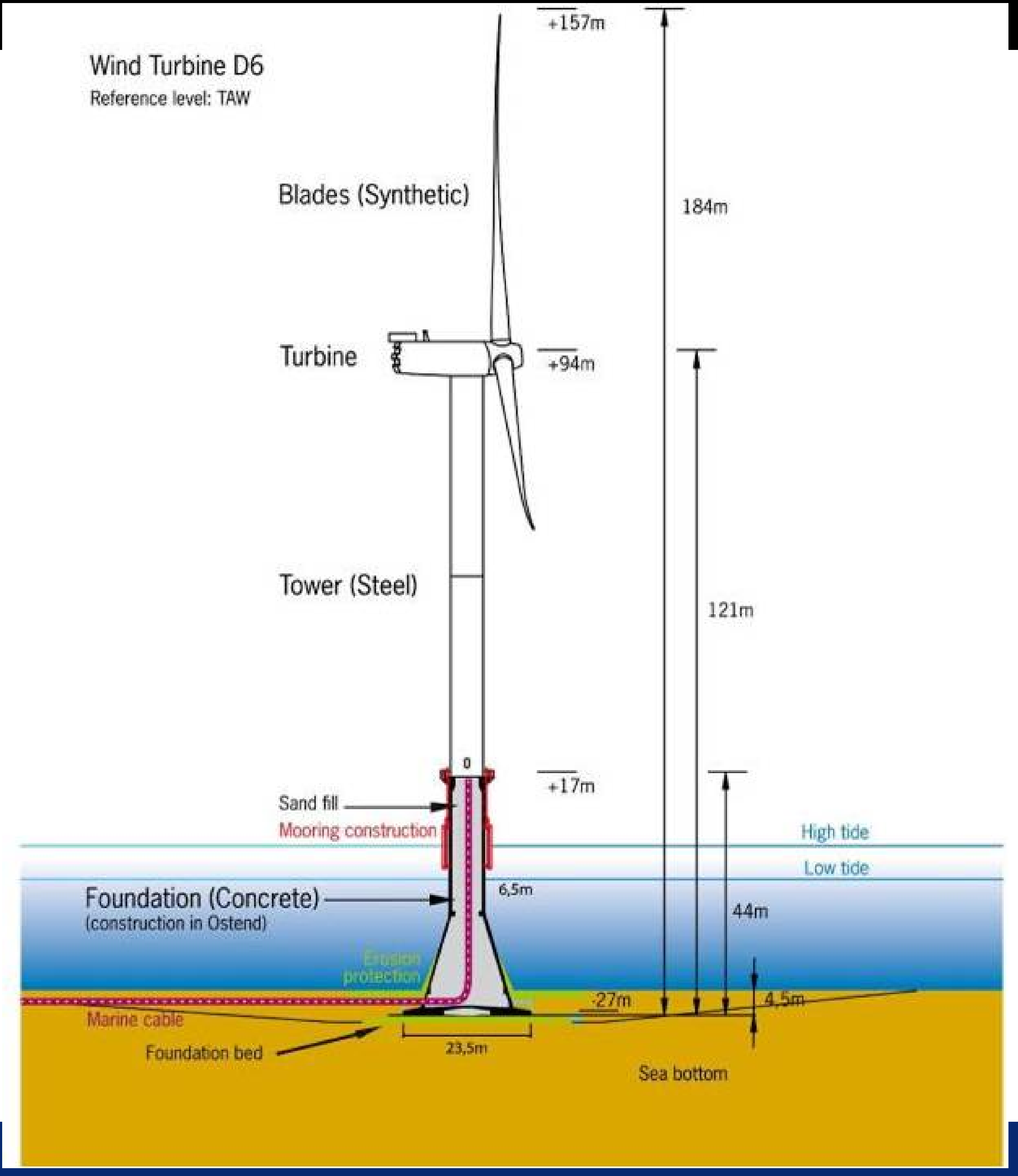
Risk can be reduced by education and training

Good routines
Good methods
Good equipment
Good attitude

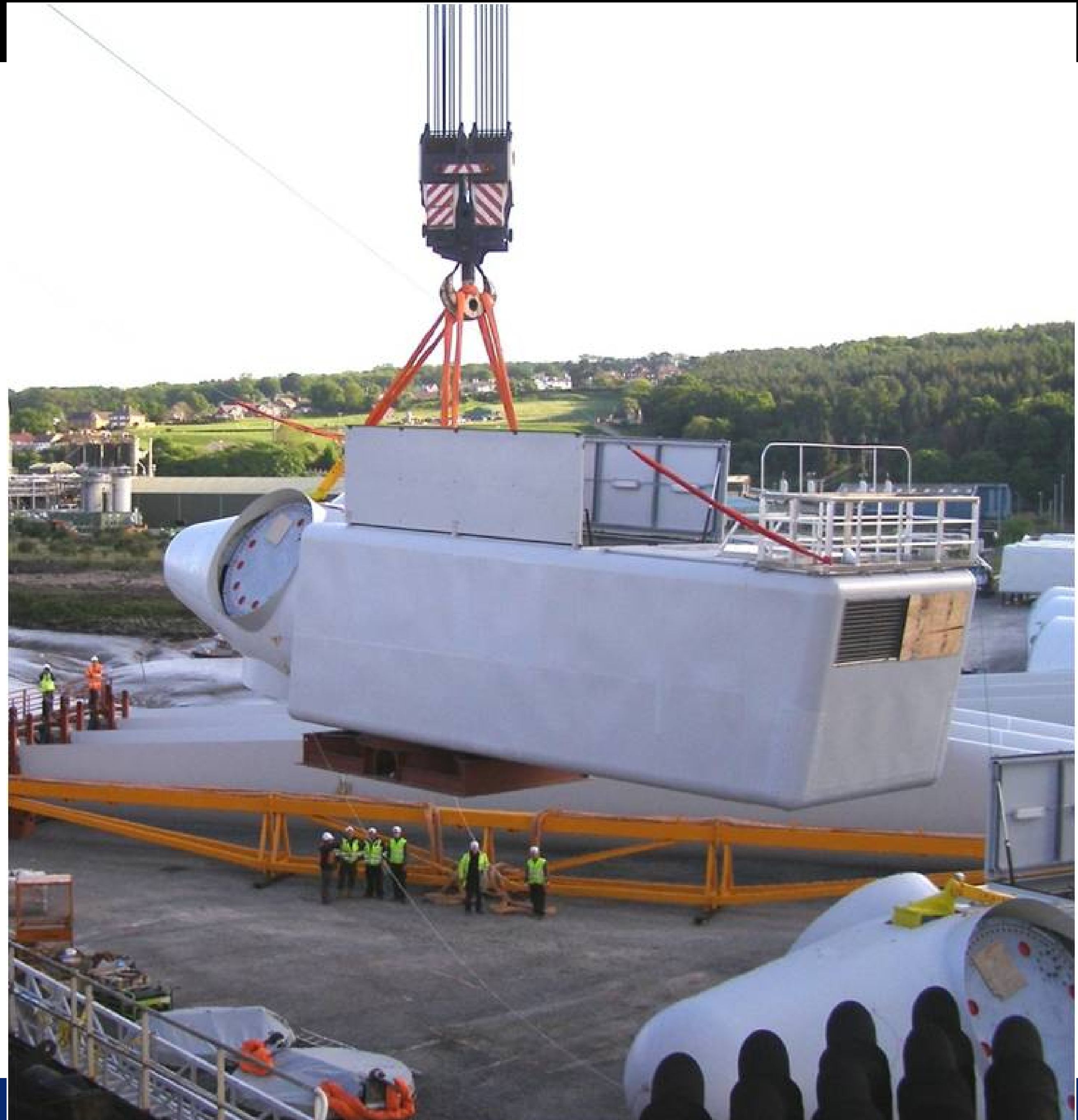
Boardning

Boarding often at harsh conditions good cooperation between boat-driver, deck man and technician going to the wind turbine

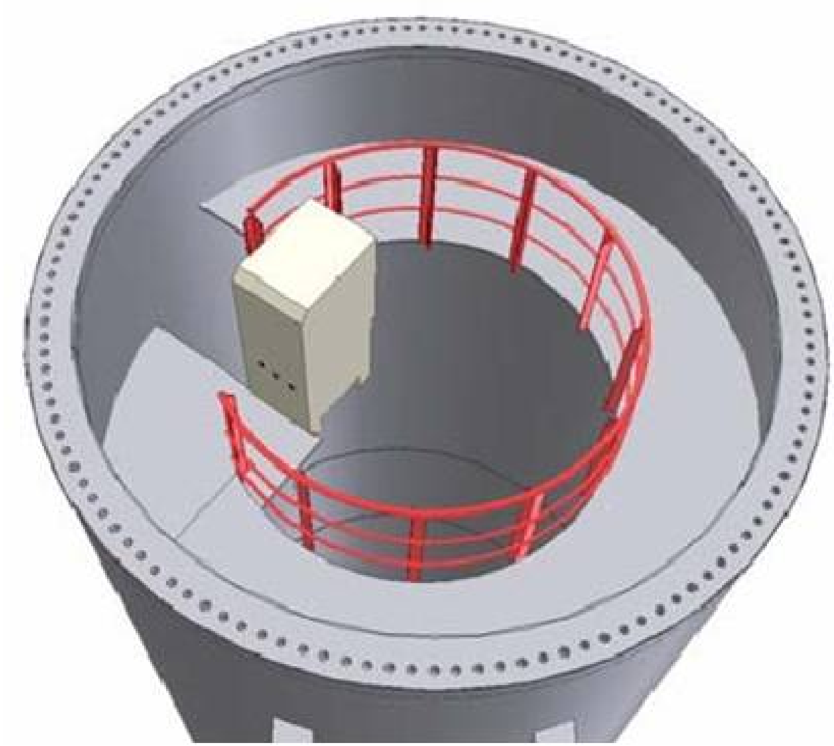
CHALMERS

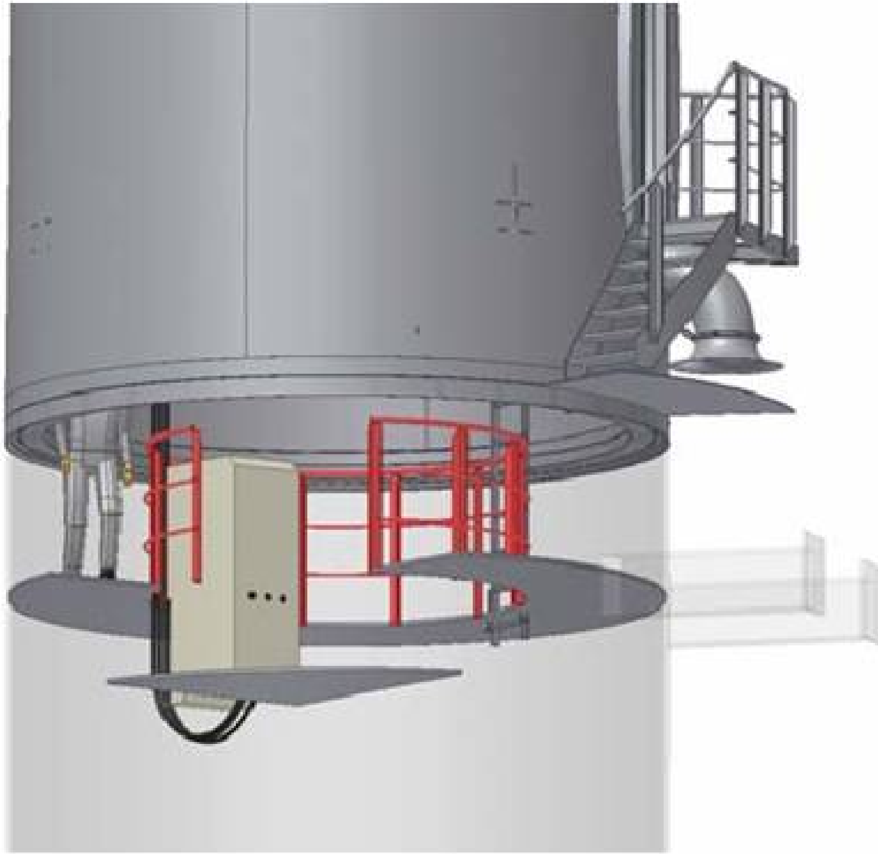


Wind Turbine D6
Reference level: TAW
Blades (Synthetic)
Turbine
Tower (Steel)
Sand fill
Mooring construction
Foundation (Concrete)
(construction in Ostend)
Erosion protection
Marine cable
Foundation bed
+157m
184m
+94m
121m
0
+17m
High tide
Low tide
6,5m
44m
-27m
4,5m
23,5m
Sea bottom

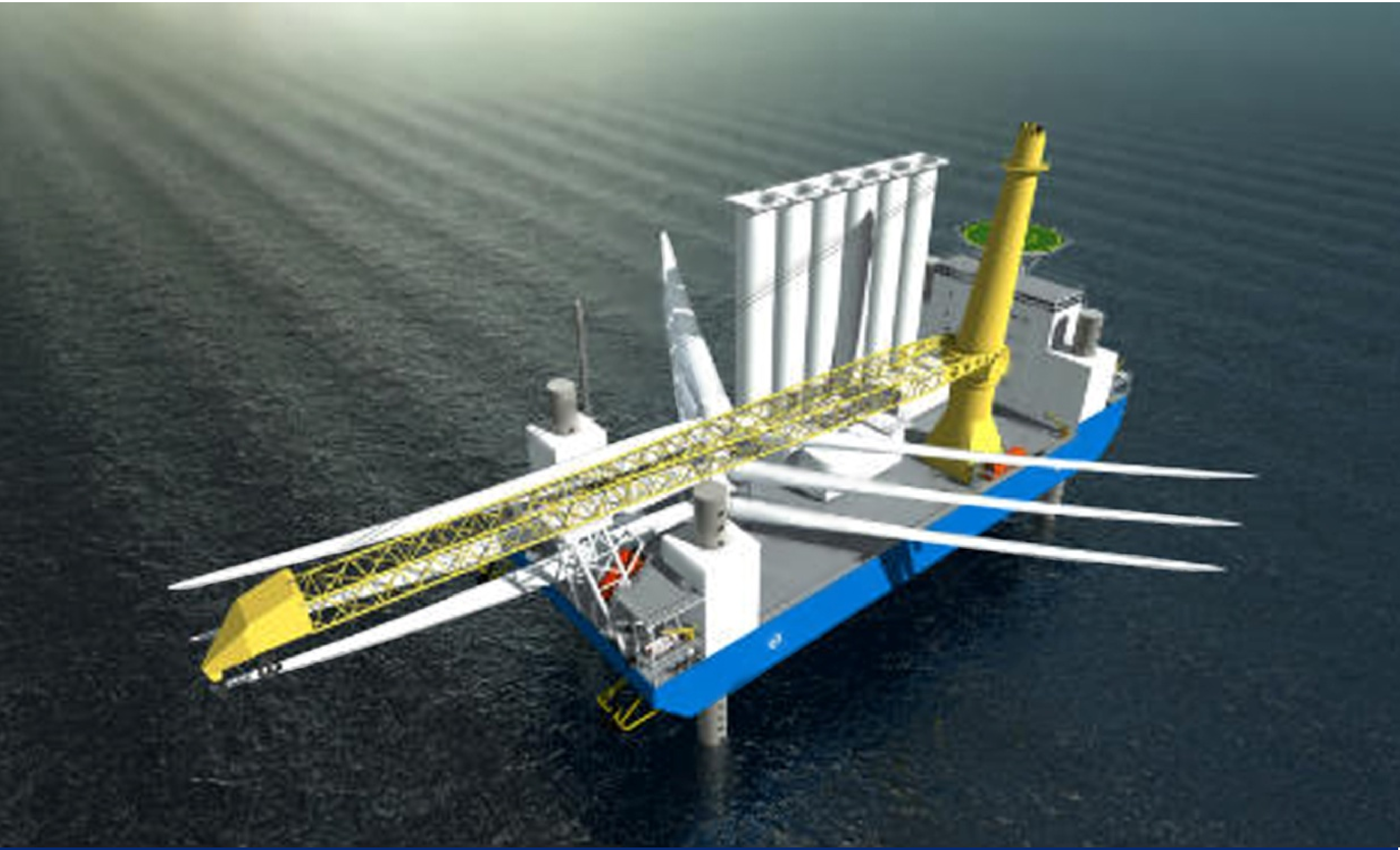



AV
11
AV
12






BBC MISSISSIPPI
B B C



Re –Power 5 MW with off-shore deep sea foundation

CHALMERS

Wenn das Testfeld steht, müssen die Servicekräfte bereit sein…

Once the test field is operational, service personnel must be ready…

Riesige Tripods als Fundamentstrukturen für Offshore-Windenergieanlagen…

Huge tripods as foundation structures for offshore wind turbines…

…hier im Stützpunkthafen…

…seen here at the port of the staging post…

CHALMERS

Rund 700 Tonnen an einem Haken auf dem Weg auf's Meer.

Roughly 700 metric tons hanging on a hook on their way out to sea.

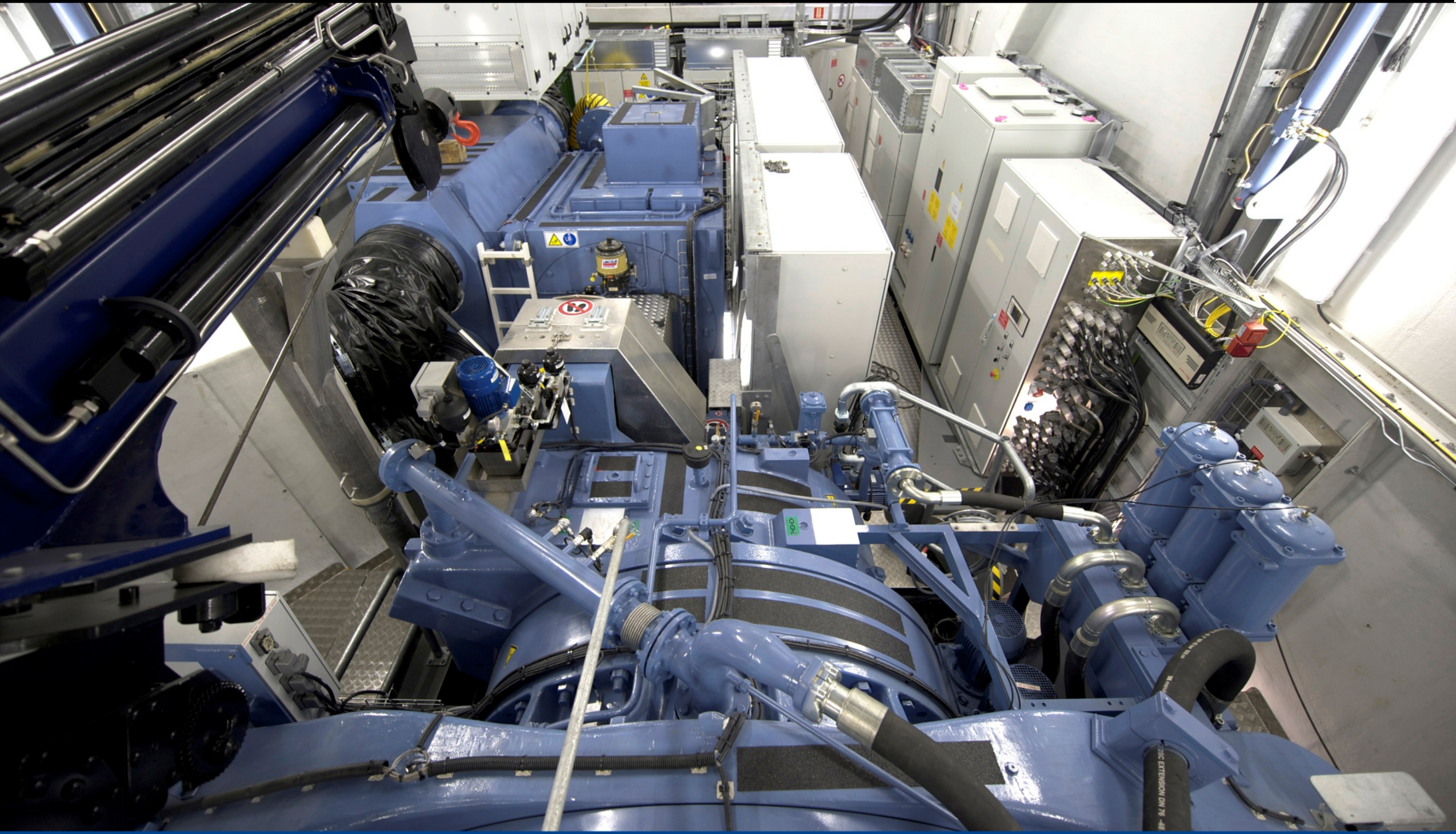
Durch Leerrohre unter Dünen und Deichen erreicht das Kabel die Insel.

The cable reaches the island through conduits under dunes and dykes.

5 MW-Anlagen von Repower, so groß wie Einfamilienhäuser…

The 5-MW turbines by REpower are as large as single-family homes…

CHALMERS



...und vollgepackt mit Technik...

...and are packed full of technology...

16. November 2009 – Geschafft!

November 16th, 2009 - Done!

Eine AREVA/Multibrid-Anlage ist errichtet.

An AREVA/Multibrid turbine is up.