LBNL EETD seminar 03/18/'04

Determining the Adequate Level of Distributed Generation Penetration in Future Grids

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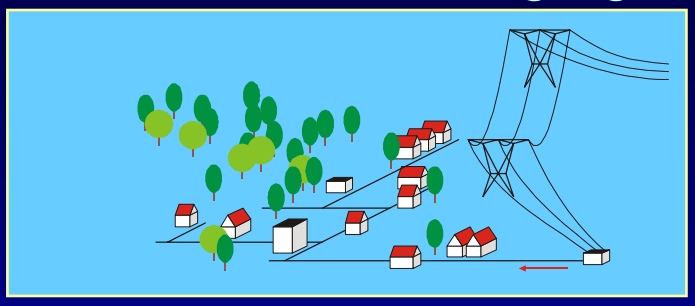
Overview

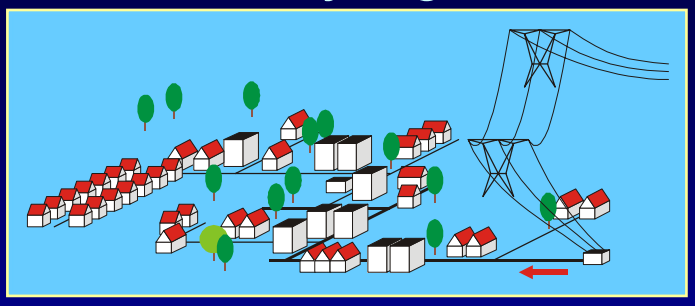
- What is understood as DG ?
- Interactions with the electrical power system
- How far can we go ?
- Specific problems of large-scale off-shore wind power

Traditional low voltage grid



- Limited number of loads
- Energy supplied top-down from central power station

Today's grid

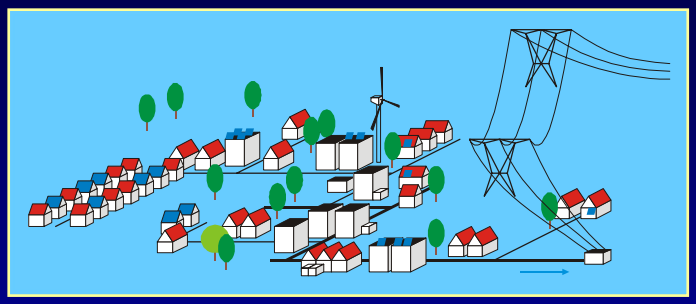


- Increased loading
- Increased distortion: due to nonlinear (power electronic) and sensitive loads power quality problems arise)

Sustain load growth ?

- The load tends to grow with 2% yearly on average
  - New generation to be build
  - Electrical power system needs expansion & upgrade
- Paradox: society consumes ever more power, but resists new power plants & power lines
- Additional: the desire to be “green” (e.g. Kyoto)
- Solution: bring (‘cleaner’) generation closer to the loads ?

Grid of tomorrow ?



- Distributed generation appears in grid, either running on traditional fuels or converting renewable energy
- Power quality and reliability is a big issue

DG: definition(s)

- International Energy Agency:
  - '**Distributed Generation**' : local electricity production in the distribution grid (in British English: 'Embedded Generation')
  - '**Dispersed Generation**' : often a synonym, but sometimes 'stand-alone' and non-connected units are included
  - '**Distributed Power**' : DG plus additional installations for energy storage
  - '**Distributed Energy Sources**' : previous + controllable loads which can be a source of 'negative power'
  - '**Decentralized Power**' : notion used to stress that these technologies are not always centrally controlled

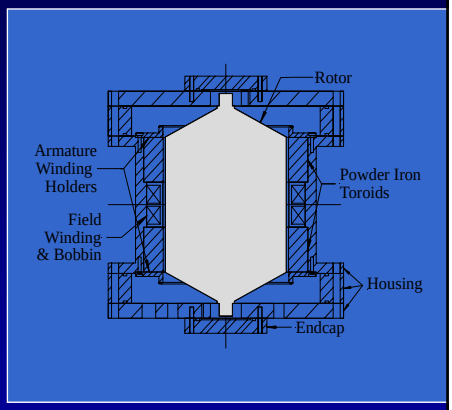
DG technologies

- Reciprocating engines
- Gas turbines
- Micro-turbines
- Fuel cells
- Photovoltaic panels
- Wind turbines

- Additional: CHP configuration

Energy storage

- Complementary technology: smooth out mismatch between production and consumption at different time scales (electricity by itself canNOT be stored!)
  - Batteries
  - Flywheels
  - Supercapacitors
  - Reversible fuel cells
  - Superconducting magnetic energy storage
  - Compressed air storage



Why use DG ?

- Interact with energy market
  - Standby capacity or peak use capacity (peak shaving)
  - Reliability and Power Quality enhancement
  - Alternative to expansion or use of the local network
  - Grid support
- Environmental concerns
  - Combined generation of heat and electricity
  - Efficient use of ‘cheap’ fuel opportunities
  - Exploit renewables

Policy issues

- High financial cost
- Less choice between more costly primary fuels: bet everything on gas?
- Economic Efficiency
- Environmental protection
- Energy Security
- Power Quality
- Connection issues

‘Energy islands’ or microgrids

- Do we need to stay connected to the grid?
  - Balancing problem
  - Provide own ancillary services: stabilize voltage and frequency
- Intentional islanding
  - for reliability reasons: back off in case of problems
  - Economic reasons: price peaks
- Theoretically possible, difficult in practice
  - Need storage, load control
  - ‘Inertia is out of system’: very dynamic (read instable)

Points of attention when introducing DG

- Power quality & reliability
- Control, or the lack of
- Safety
- Environmental issues
- Availability of transport infrastructure for primary energy sources, i.e. natural gas
- Economic aspects

Power quality & reliability

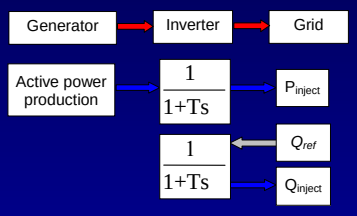
- Bidirectional power flows cannot be excluded
- Voltage profile becomes affected
- Stabilizing inertia decreases (small systems) or is zero (power electronics)
- Increasing use of power electronics (non-linear systems) cause more harmonic distortion
- Unbalance due to small single-phase PV systems
- But: power electronics may (theoretically) be configured to enhance PQ, e.g. by producing Q, filtering, …
- Some types of DG units can also be used as backup power supply

Grid study tools (1)

- Static load flow
  - Special network equations
    - Flow variables are *P* and *Q* (active/reactive power)
    - Node variables are *V* and δ (voltage amplitude and phase angle)
  - Losses along lines included
  - Loads and generators are modelled as
    - 'PV-nodes': power input + control system for *Q* to keep *V* constant (large centralised power plants)
    - 'PQ-nodes': certain power input or consumption (used for loads and DG units)
    - 'slack or infinite bus': special node that balances power (connection to HV grid)

Grid study tools (2)

- Dynamic load flow
  - Transient network equations
  - Complicated models
    - include dynamics
    - Include control system (local & global if dispatchable)
    - …
  - Some knowledge about in-house electrical system is required, e.g. the presence of induction machines



Energy Balance study

- DG units
  - produce certain amount of P, depending on various parameters
  - produce or consume a certain amount of Q, which can be controlled (e.g. inverter or synchronous machine coupled) or not (e.g. induction machine generator)
- Loads
  - Difficult to model due to irregular customer behavior
  - P and Q as a function of voltage at connection

Simplified load model

- Approximate formulae

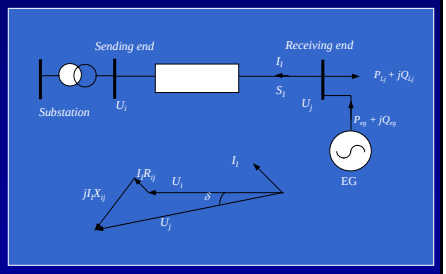
$$P_{ik} = P_{ik0}\left(\frac{U_i}{U_{i0}}\right)^{\alpha} \qquad Q_{ik} = Q_{ik0}\left(\frac{U_i}{U_{i0}}\right)^{\beta}$$

$$\alpha, \beta = 0 \ldots 2$$

- $\alpha = \beta = 0$ constant power load
- $\alpha = \beta = 1$ constant current load
- $\alpha = \beta = 2$ constant impedance load

Voltage profile along line

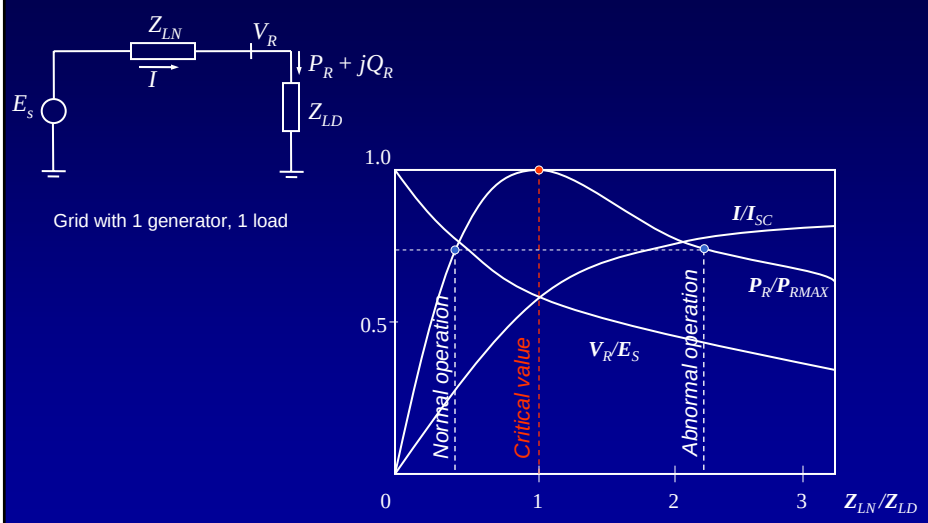
- 'Normal' situation: loads cause drop of voltage towards end of line $\frac{\Delta U}{U} = \left[\left(P_{dg} - P_{Lj}\right)R_{ij} + \left(Q_{dg} - Q_{Lj}\right)X_{ij}\right]/U^2$
- DG unit
  - inject P; rise follows
  - inject or consume Q: compensate or worsen…
- Grid characteristics (R/X) have large impact



Voltage Stability studies

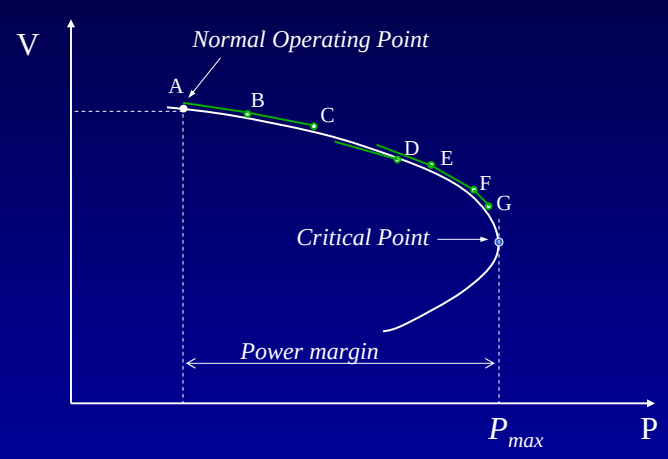
- Voltage stability problems need special attention in many systems: "weak grids", long lines, heavy loads, …
- Voltage instabilities may happen in case of reactive power shortage, large disturbance, load increasing, …
- Methods
  - Small-disturbance voltage stability: steady-state study
  - Large-disturbance voltage stability: dynamic study
- Tools
  - Static analysis is used to determine stability margin (e.g. maximum loading), identify factors influencing stability
  - Dynamic analysis is used for detail study, e.g. reaction to a fault

Illustration



Grid with 1 generator, 1 load

'Nose curve'



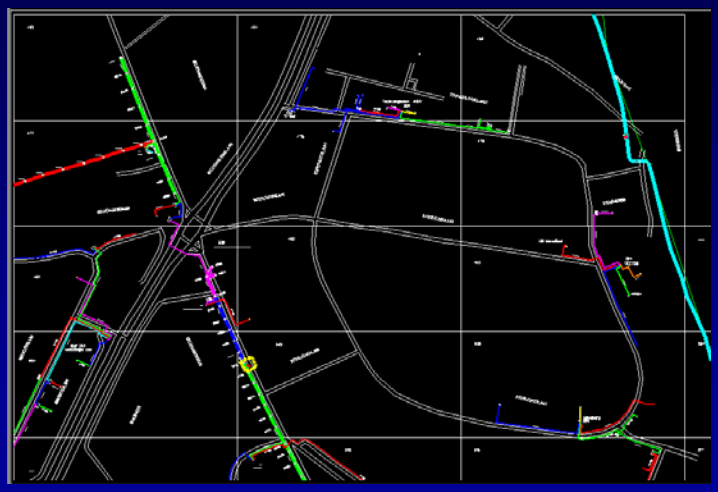
V-P curve

Test case study

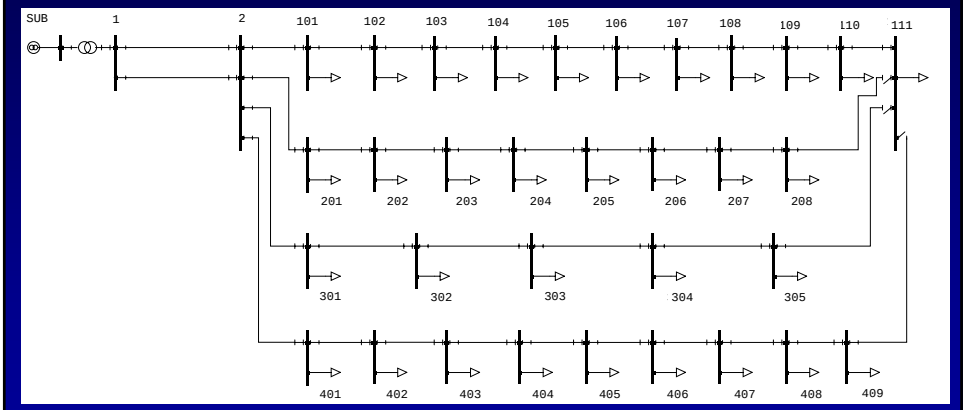
- Case: semi-industrial distribution grid
  - Some global load data (substation measurement) known
    - assume spread of load at level of 80% of rated power, with PF of 0,9
  - Assume large DG unit(s) (CHP or motor) inserted
    - with induction machine generator: consume reactive power
    - with synchronous machine generator: reactive power controllable

Industrial area: MV

Industrial area: LV

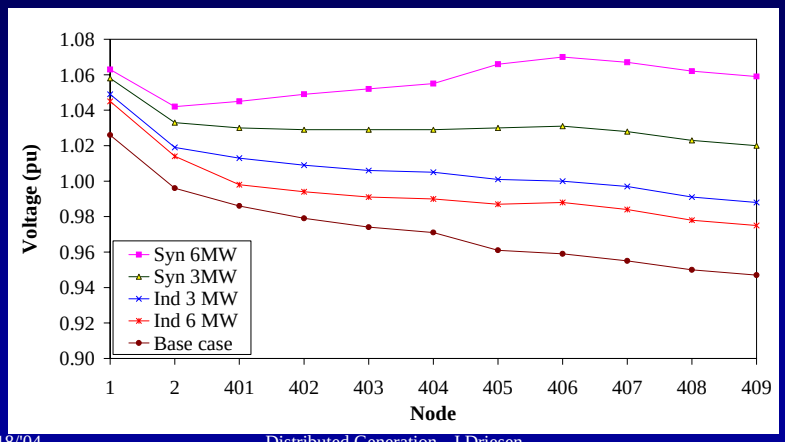


‘open-ring topology’



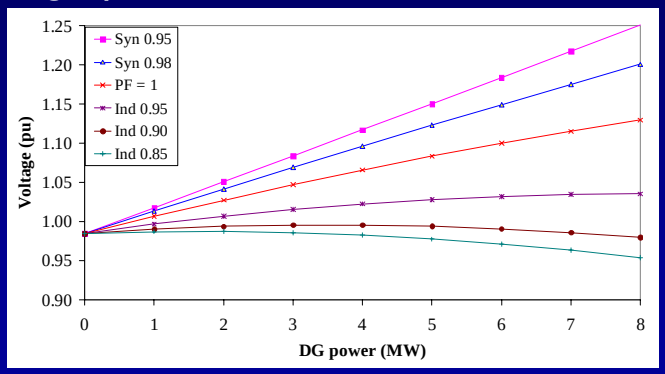
Example: voltage profile

- DG in node 406, near unity power factor
- Voltage profile for one branch



Example: power factor influence

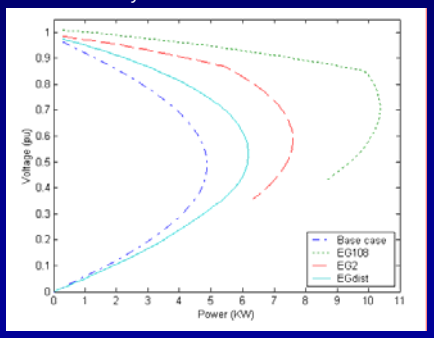
- DG in node 406, different power factors
- Voltage profile in node 406



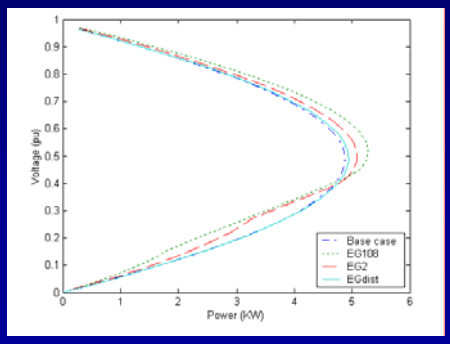
Example: steady-state voltage stability

- Voltage in certain node is ‘followed’
- Different connection points
- Difference because of generator types

Synchronous Generator

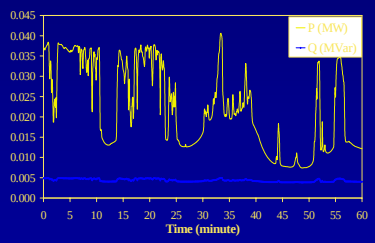


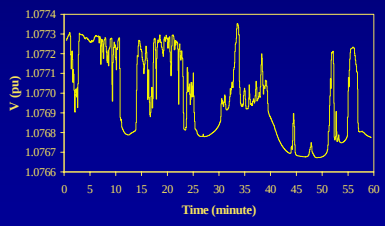
Induction Generator



Test: use of measurement data of own PV-ESAT installation

- The PV power is calculated from 5-s average irradiance data measured one year in Leuven (ESAT building)
- Extrapolation: 50 systems of 1 kWp
- Small voltage fluctuations on cloudy day

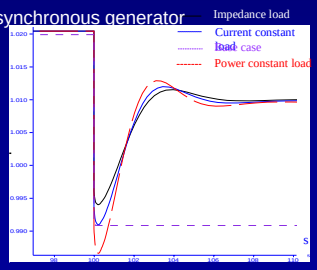




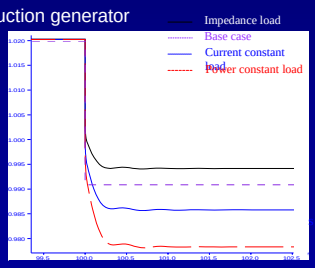
Example: dynamic voltage stability

- Opening of a branch containing a DG unit (DG units in other branches as well
  - Voltage dip arises
  - limited influence of DG unit on dip depth
  - Synchronous generators can restore voltage level

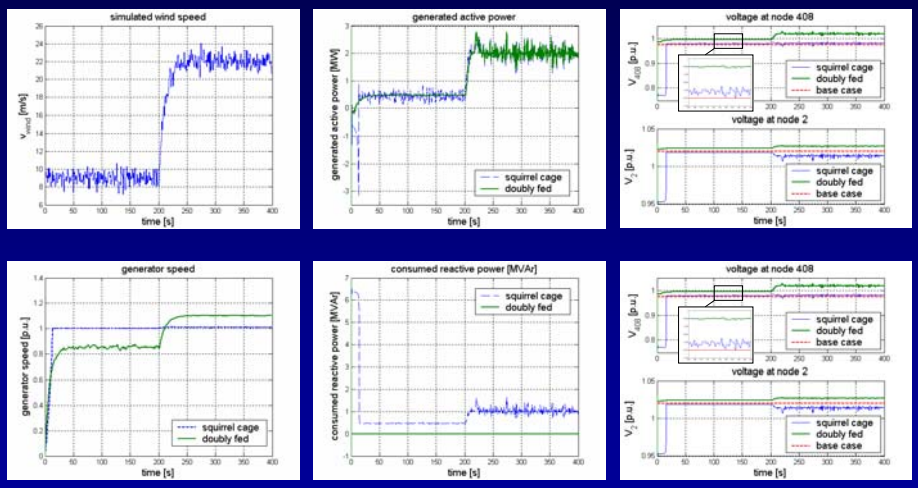
synchronous generator



Induction generator



Test: introduction of wind turbine



Control, or the lack of

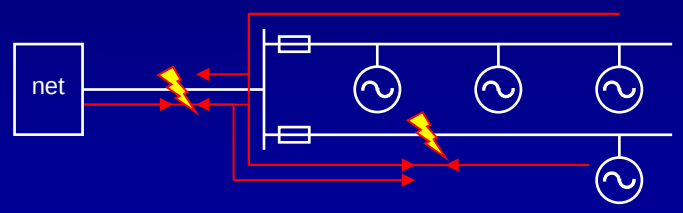
- Generators are NOT dispatched in principle
  - Weather driven
  - Heat demand driven
  - Customer has own ideas about use
- Full control necessary ? Loads are also ‘chaotic’
- Higher level of control required to coordinate balancing etc. ?
  - Need dependable communication (interdependency issue)
  - Decide about islanding and reconnection ?
    - Different control strategy: voltage source instead of current source
  - Through decentralized control: under investigation

Safety

- Problem: power system is designed for top-down power flow
- Now:
  - active power injectors in between the loads
    - contribution to the short-circuit current in case of fault
      - Fault effects more severe
      - Difficult to isolate fault location
  - bidirectional power flows
    - ‘selectivity’ principle in danger
- New active protection system necessary ?

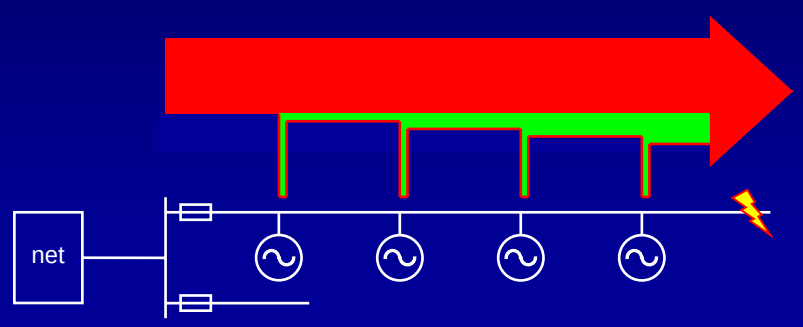
Selectivity

- Principle
  - Protection closest to the fault reacts first
  - In case of failure: next one at higher level takes over
- Short-circuit current comes from different sides: difficult to cover



Short-circuit current contribution

- Generators in a radial grid contribute to the short-circuit current
- Difficult to detect



Islanding protection

- Special protection against ‘islanding’
  - In case of close matching of load with DG: system can continue on its own
  - Protection guarantees non-energized grid after fault, to repair without risk
- Difficult to detect
- No system seems 100% effective
- Doubts about statistical chance

Adaptation of safety system ?

- Found out where the boundaries of the classical protection is
- A new active protection system may be required

- Islanding protection: too complicated for a a statistically very low chance ?

Environmental issues

- Power is produced locally, so burden is local
  - Noises
  - Chemicals (e.g. in fuel cells)
  - Emissions are local
  - Visual pollution
- Will global emission drop with more RE and same reliability level ?
  - Traditional power plant are spinning reserve for unpredictable RE
    - Less efficient mode of operation with increased losses

Visual pollution

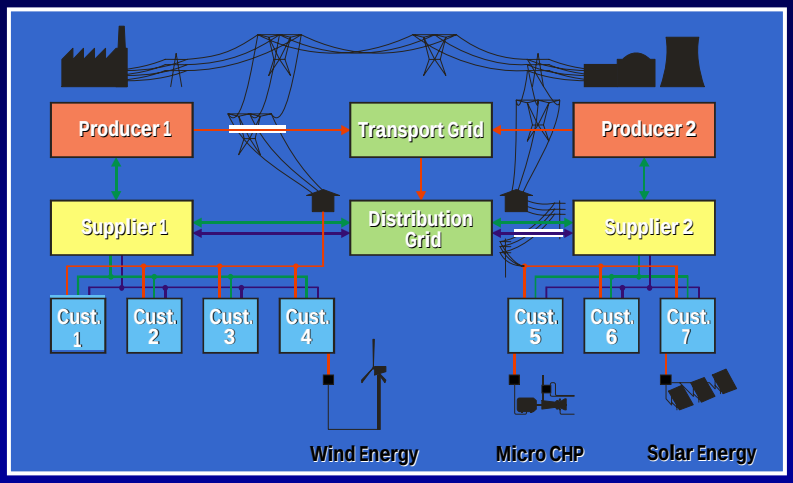
Availability primary energy sources

- Making power locally often requires transport of (more) primary energy, e.g. natural gas for CHP
  - Transport infrastructure is not allowed to be congested
  - Problem is shifted from electrical distribution grid to gas distribution grid!

Economic aspects

- Many costs in case of DG use
  - investment, operation and maintenance of DG unit
    - E.g. increased balancing cost
  - In case of large-scale introduction: cost of adapting power system control
    - How to share this cost among *all* DG units in an honest manner ?
- Pay-back uncertain in liberalized market
  - Support for 'green and efficient power'
    - Installation subsidies
    - Portfolio obligation: supplier must deliver a minimum amount of 'green power'
      - Proven by 'green certificates' obtained per MWh, for which a market is set up
  - Price for reliability enhancement difficult to estimate

Liberalized Electricity Market



Economic aspects II

- Who will finance the backbone power system ?
  - Should still be there as backup supply, so ancillary services are still necessary
  - Long-term depreciation, financed through charges included in tariffs
  - “departing fees” are sometimes charged…
- Build-in PQ mitigation can also be used as a source of extra income, e.g. offer Q

How far can we go? Questions to be addressed

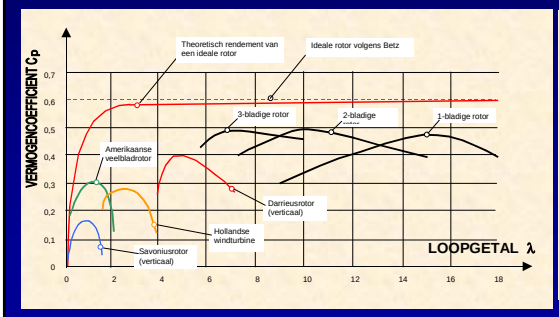
- Is there a maximum on the proliferation of not centrally dispatched generation units in local grids, and if so, what parameters determine and influence this limit ?
- Can grouping different technologies together (up to foreseeing a hybrid combination with combustion engines) mitigate the “unpredictability problem”?
- What types of problems (e.g. voltage dips) can one solve by installing storage facilities, and at what cost?
- Are there preferential combinations of embedded generation types with storage facilities?
- What are the implications for a safe and stable operation of the distribution grid?

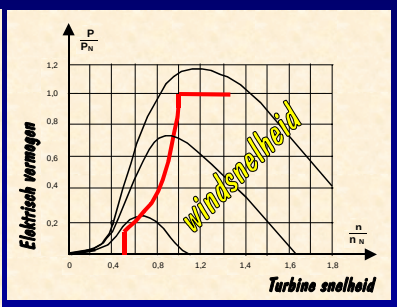
Large-scale wind power

Wind energy conversion

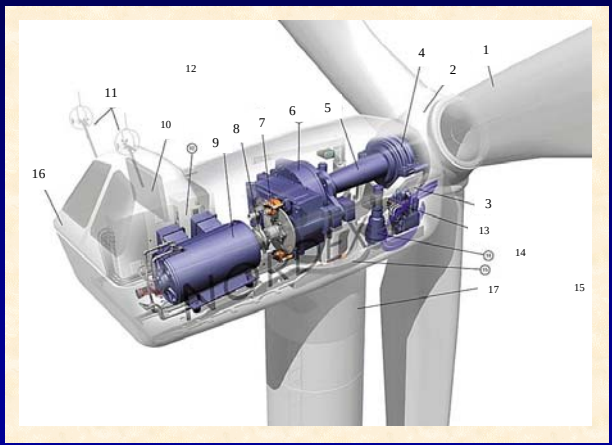
tip speed

$$\lambda = \frac{r \cdot \Omega}{v_{wind}} \qquad P_{turb} = \frac{1}{2} \rho \, C_p \, S_{rotor} \, v_{wind}^3$$





Turbine nacelle



Electrical Requirements for Off-shore Wind Turbines

- High Energy Yield
- Minimal Power Fluctuations
- Power Quality
- Controllable Behaviour during Grid Disturbances

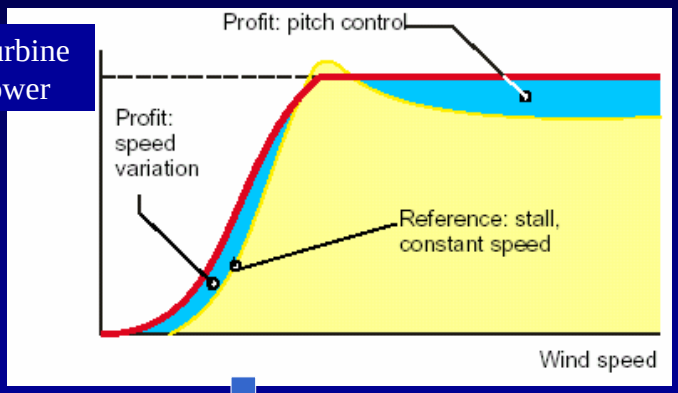
High Energy Yield

$$P_{mech} = C_p \cdot P_{wind}$$

C_p = 'wind energy capture efficiency'

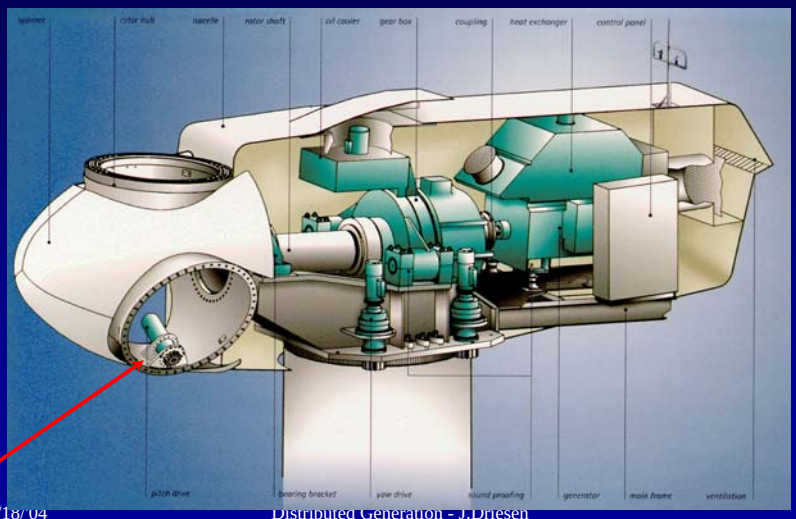
- Max. 59%
- Depends on
  - turbine design
  - blade pitch angle
  - $\frac{rpm_{turbine}}{v_{wind}}$

High Energy Yield II

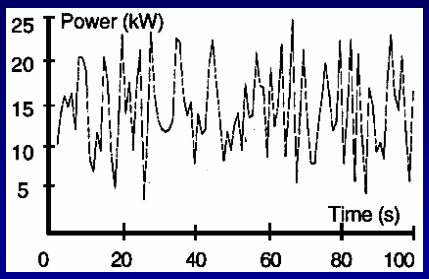


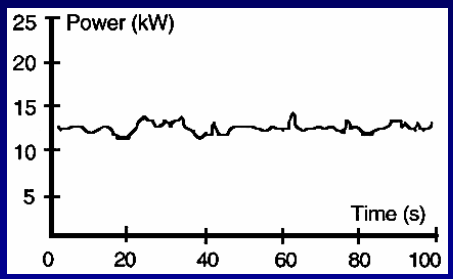
- variable speed
- pitchable blades

Pitch & stall control



Minimal Power Fluctuations

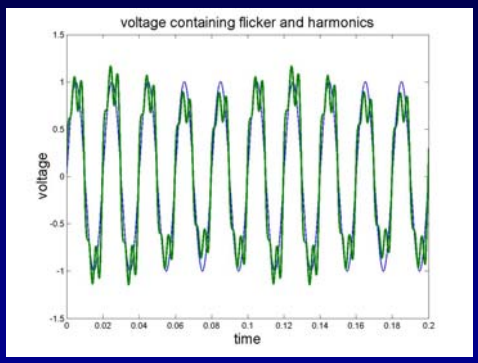




Constant speed

Variable speed

Power Quality



Power quality requirements put limits on

- frequency & voltage oscillations

- flicker, harmonics, transients…

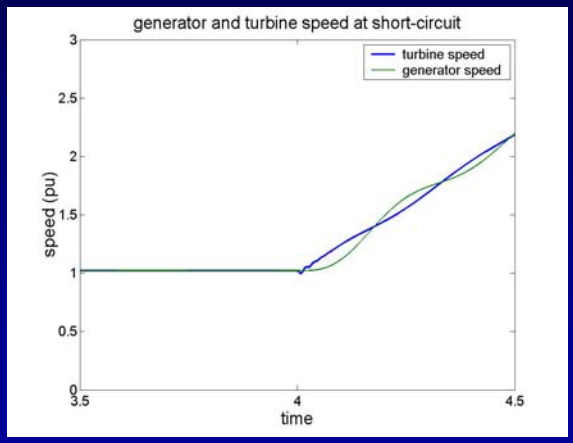
Power quality is dependent on:

Grid characteristics (*grid strength* and *X/R*)

-Generator *(reactive power)*

Must be controllable in weak grids !

Controllable Behaviour during Grid Disturbances

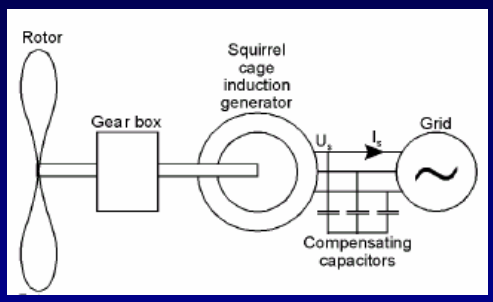


e.g. voltage dip with an asynchronous generator results in turbine acceleration and disconnection of the generator

Wind turbine generators types

- Induction Generator
- Doubly Fed Induction Generator
- Direct Drive Synchronous Generator

Induction generator with gearbox



-- Speed not controllable

-- Reactive Power not controllable

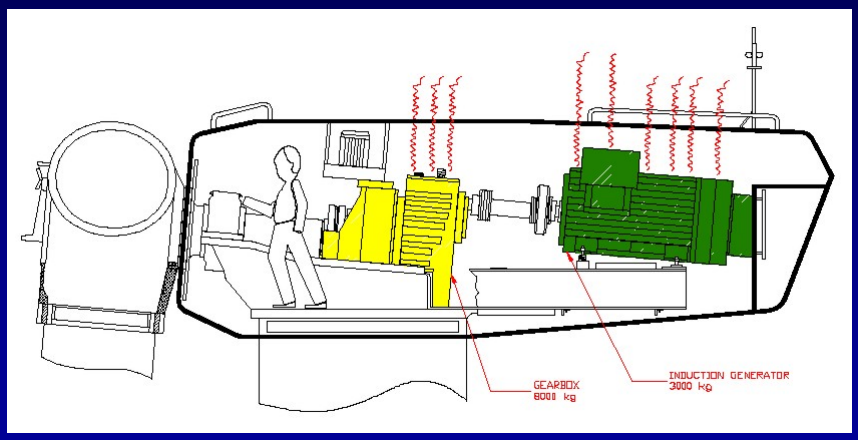
-- Gearbox requires maintenance

+ cheap

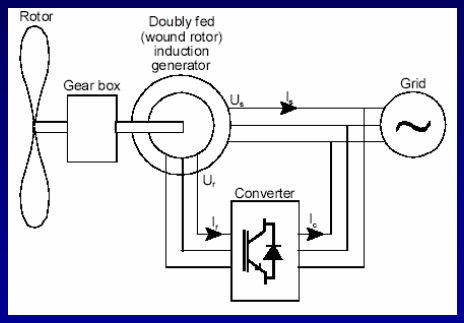
+ robust

e.g. Bonus, NEG-MICON, Turbowinds ...

Nacelle of asynchronous generator



Doubly-fed induction generator



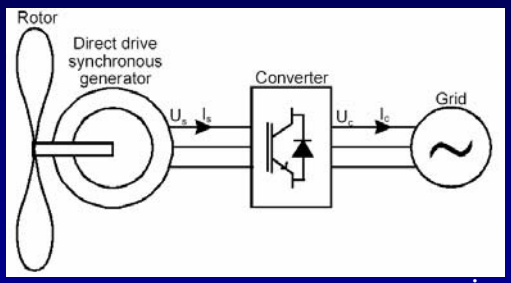
+ Speed and reactive power can be independently controlled within certain range

+ limited investment cost

- requires maintenance (gearbox, slip rings…)

vb. Vestas, GE Wind Energy, Nordex

Direct-drive synchronous generator



vb. Enercon
Lagerwey
Jeumont

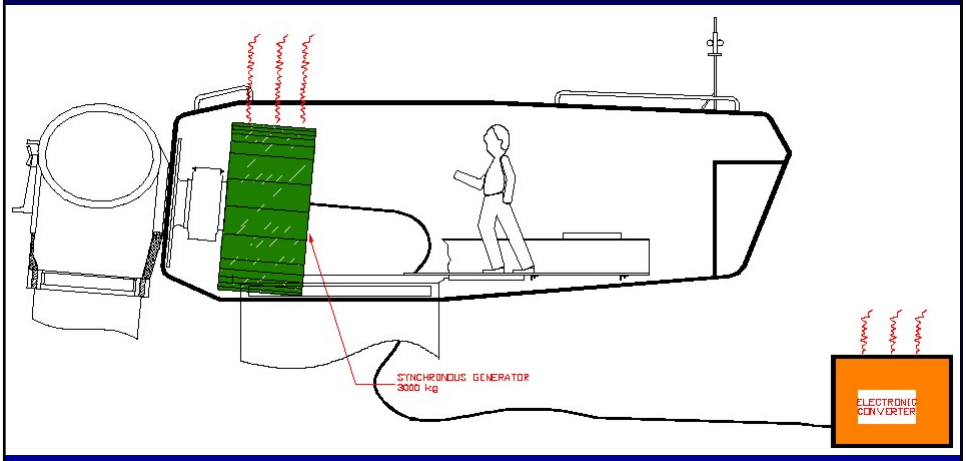
+ Speed and reactive power independently controllable

+ No gearbox

-- expensive converter

-- low generator speed requires new generator design with high torque density

Nacelle synchronous generator



Wind Turbine Generators: Trends

- Higher nominal powers (up to 5 MW)
- Variable speed and reactive power control
- Direct drive, permanent magnet rotors
- New generator designs with high power density for direct drive applications (transversal flux, axial flux, switched reluctance…)

Wind Turbine Manufacturers

fixed blades	X				
pitchable blades		X	X	X	X
fixed speed	X	X			
limited variable speed			X		
variable speed				X	X
direct drive					X
	NEG-MICON NORDEX BONUS REPOWER	BONUS NEG-MICON TURBOWINDS	VESTAS (optislip)	NORDEX REPOWER GAMESA GE POWER SYS VESTAS	ENERCON LAGERWEY JEUMONT

Multi-MW types

Conclusion on generator types

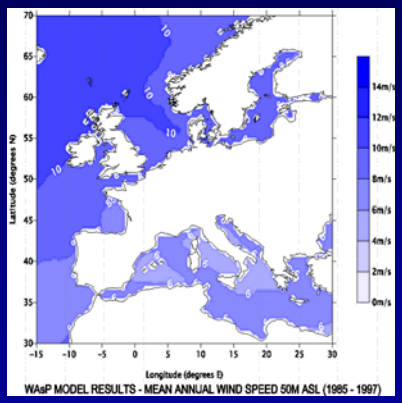
- Asynchronous generator
  - Not suited for large off-shore wind farms in a weak network
- Doubly-fed asynchronous generators:
  - Good performance in stable grid, against a reasonable cost
  - Requires maintenance (gear box, brushes)
  - Behaviour during grid distortion not well known

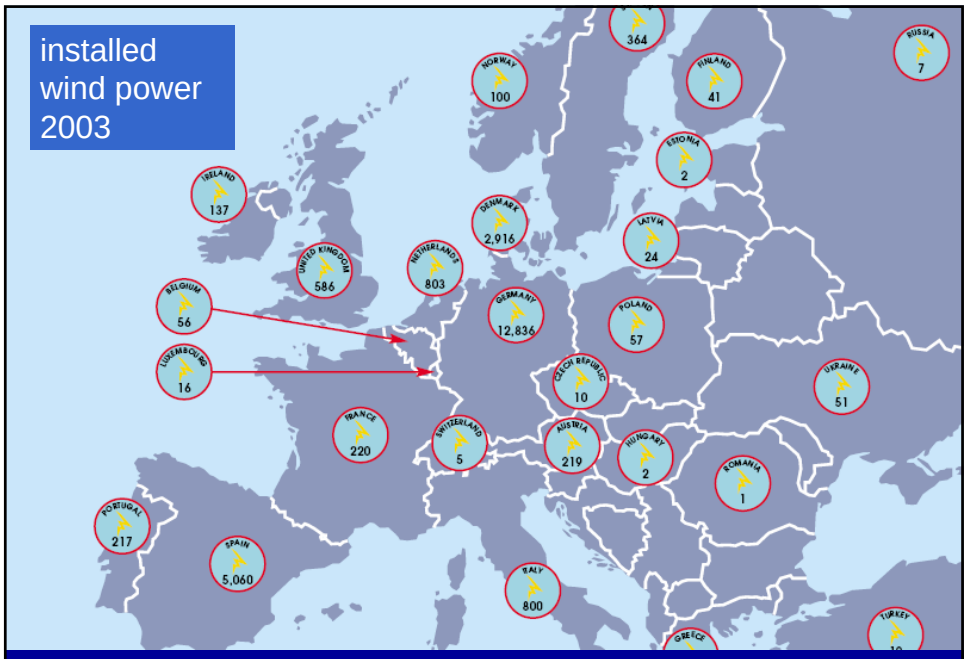
Conclusion on generator types

- Synchronous generators
  - Full control of speed and reactive power
  - Largest potential for maintaining grid stability
  - Low maintenance
  - Expensive power electronics and generator

Large off-shore wind projects

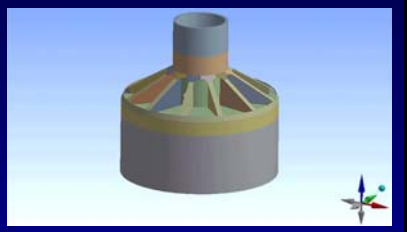
- Why off-shore?
  - equivalent full production
    - On-shore: 1000h
    - On coast/near shore: 2000h
    - Off-shore: 3000h
- Not really considered DG
  - Large accumulated power
  - Connected to transport grid
- Problem: off-shore means bad accessibility (40%/year reachable)

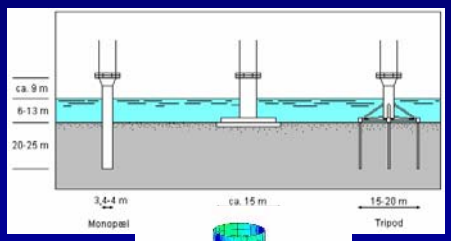


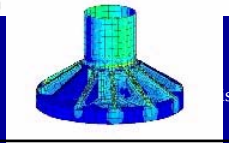


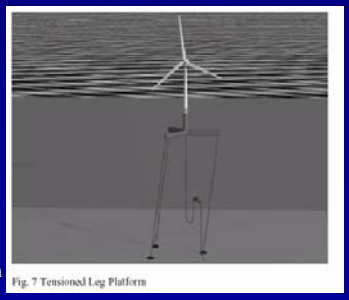
Building off-shore

- Piles: monopile - tripod
- Gravity based (GBS)
- Suction bucket
- Floating (far-offshore)





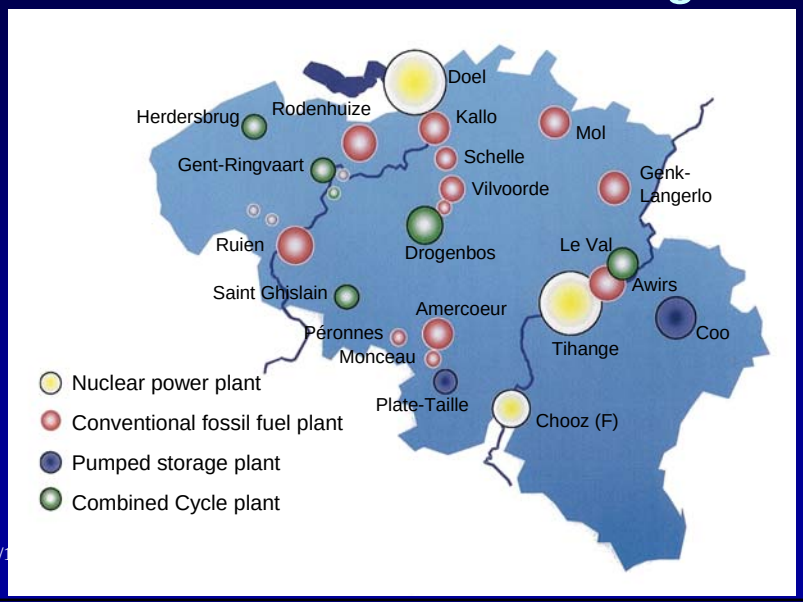




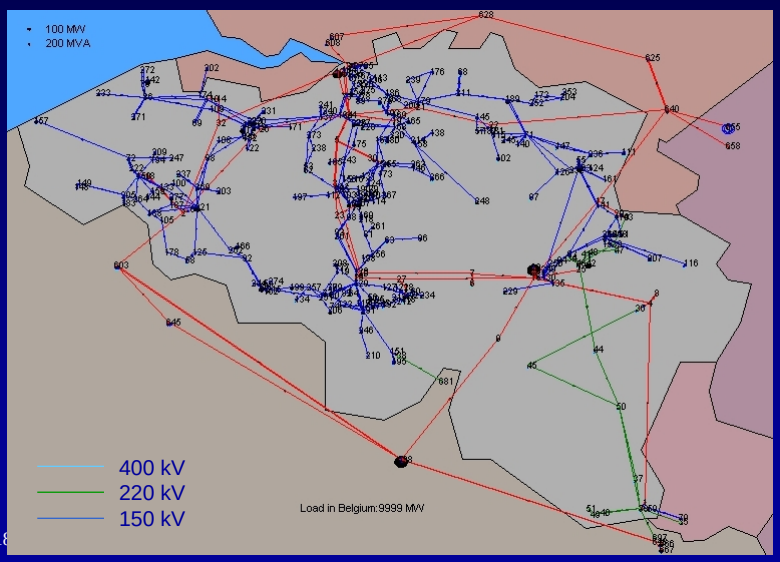
Connecting to shore

- Sub-sea cable
- AC-cable:
  - has maximum length
  - >30 km: consumes too much reactive power for internal distributed capacitance
- DC-cable:
  - only DC-resistance
  - Needs expensive rectifiers and inverters
  - No synchronization required

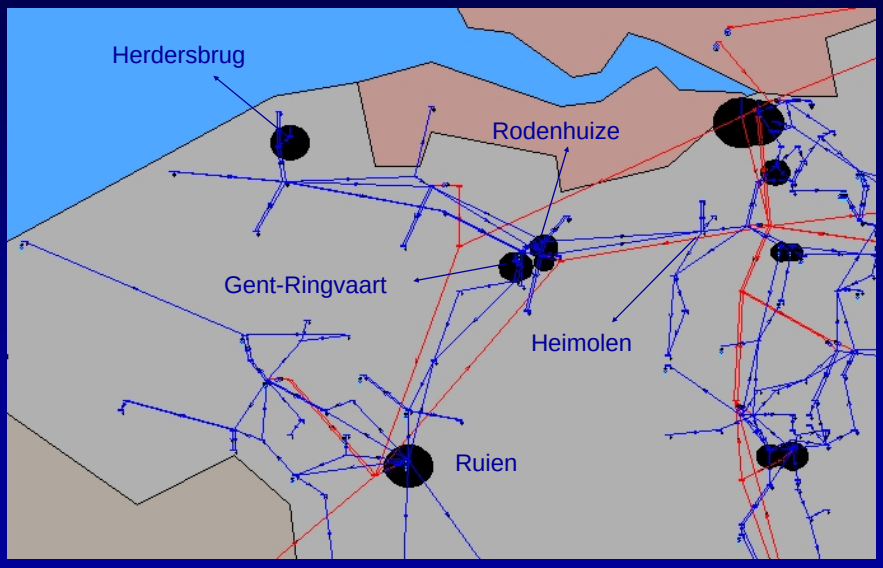
Main Power Plants in Belgium



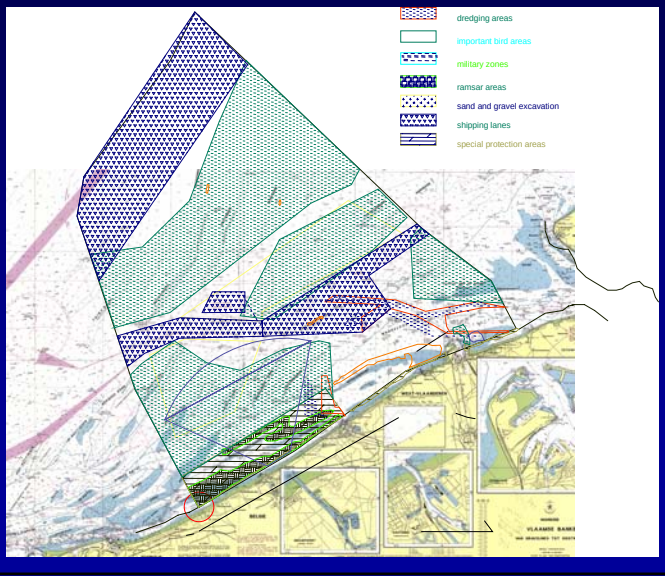
400-220-150 kV grid in Belgium



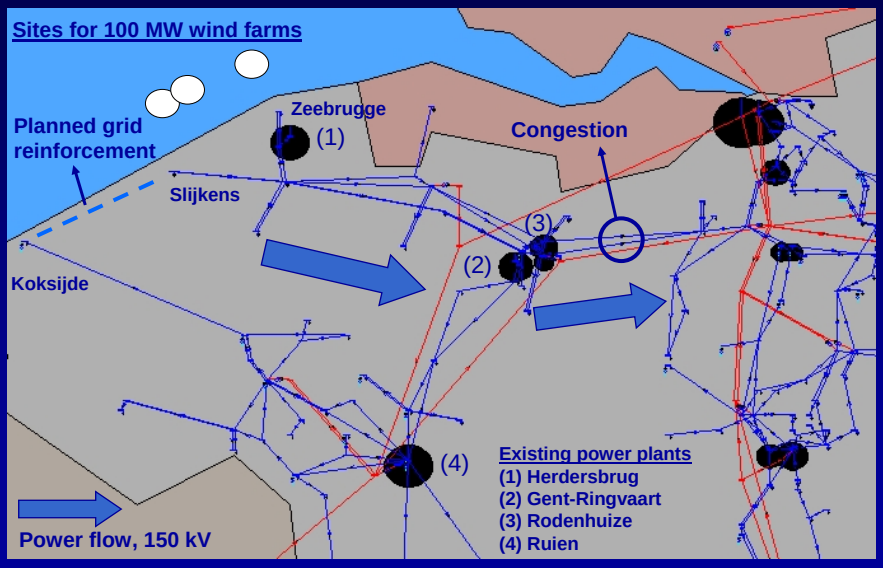
Close-up of coastal area



Exclusion zones: hard and soft



Lack of Transmission Capacity

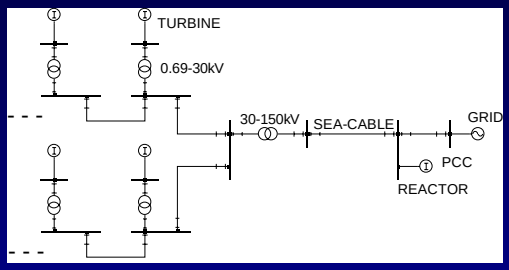


Dynamic impact

- **Assessing potential dynamic impact of wind farm of HV-grid by**
  - power system simulations
  - using a generic farm model
- **Goal:**
  - estimating grid potential to absorb amount of wind power
  - NOT: estimating accurately the impact of one specific wind farm with specific technology

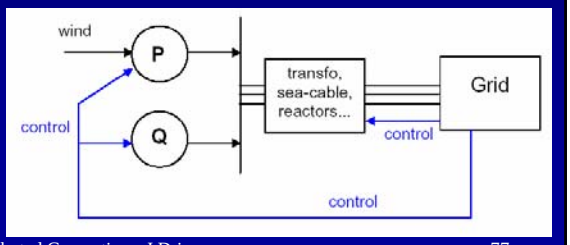
Model reduction

detailed wind farm model
(turbine type, park layout ...)



equivalent model
(active and reactive power source)

simulate impact on grid

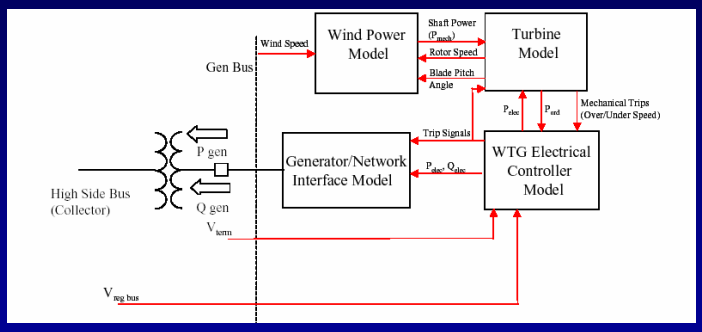


Generic Farm Model

- **Active Power Model**
  - starting from detailed turbine model from literature
- **Reactive Power and Trip Model**
  - important parameter: grid connection requirements
  - interaction reactive power control – active power control during disturbances is taken into account

Active Power Model

Starting from detailed turbine model (GE3.6) from literature

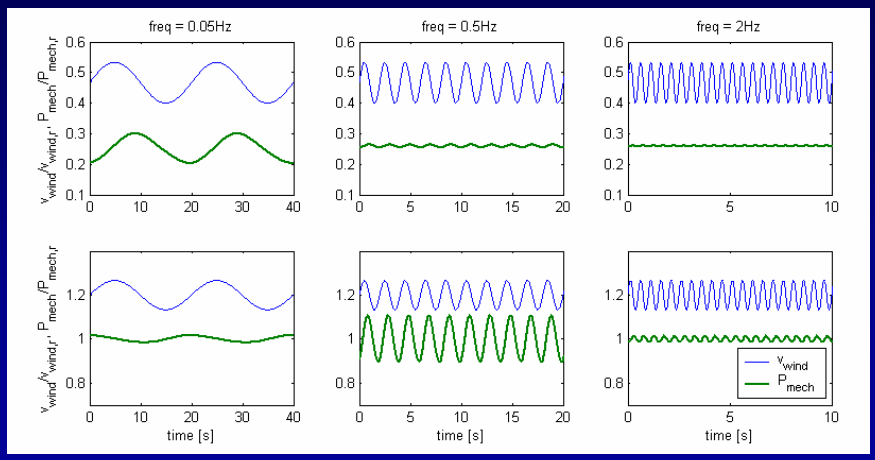


Strongly non linear !

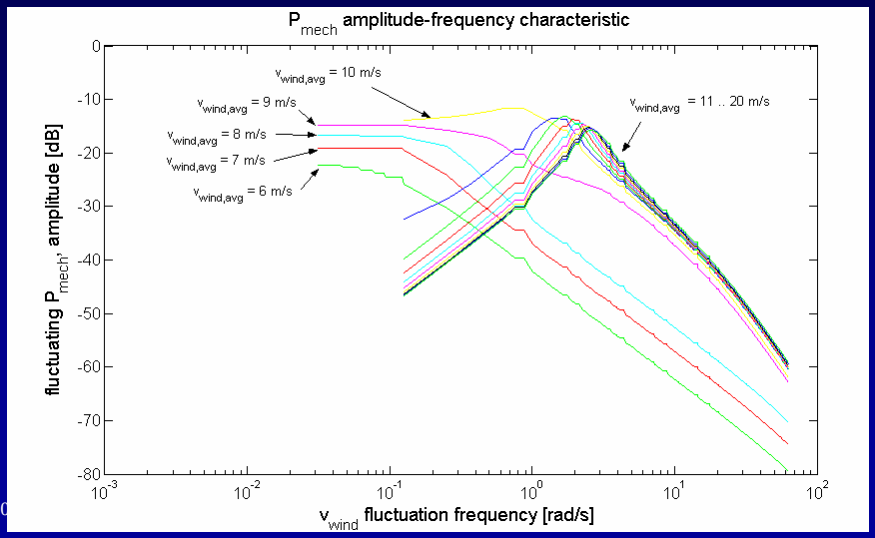
Simulations with detailed Active Power Model

- **Goal**
  - derive a frequency characteristic for the v_{wind} – power transfer function
- **Simulations**
  - with sinusoidally fluctuating wind speed superposed on average wind speed
  - frequency and average is varied
  - Evaluate the sinusoidally fluctuating output power in a Bode plot

Simulations with detailed Active Power Model



Amplitude of Fluctuating Output Power

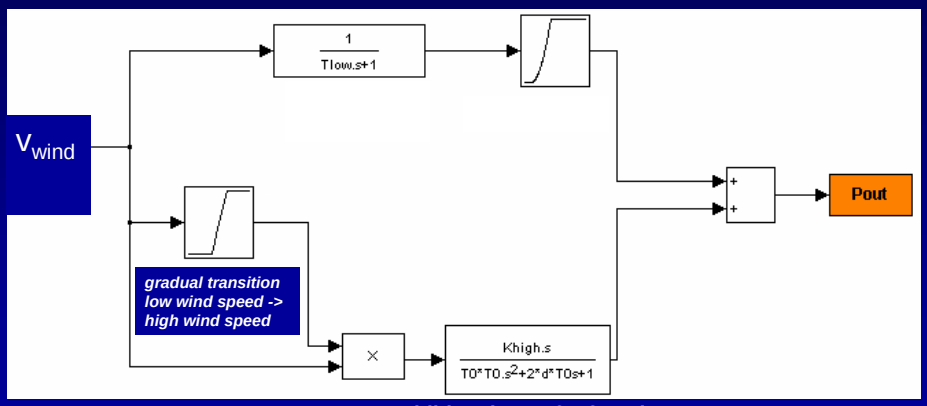


Fluctuating Output Power curves

- **low average wind speed**
  - low frequency wind speed fluctuations are transferred to power output to extract maximum power
  - high frequency wind speed fluctuations are damped by speed variation of turbine
- **high average wind speed**
  - low frequency wind speed fluctuations are annihilated by pitch control (power is continuously equal to rated power)
  - high frequency wind speed fluctuations are damped by speed variation of turbine

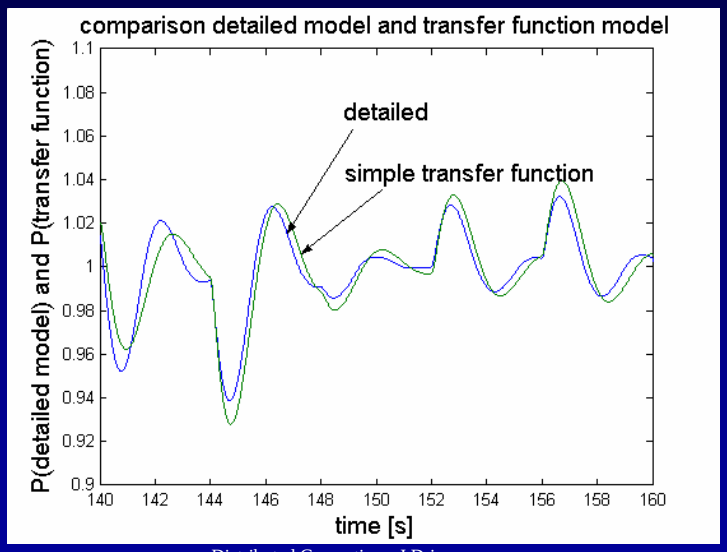
Replace detailed Model by equivalent Transfer Function

transfer function for low wind speed

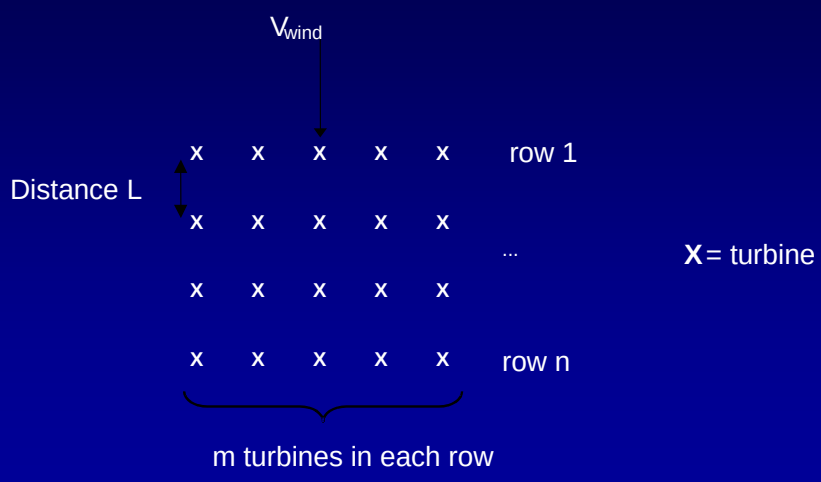


additional transfer function for high wind speed

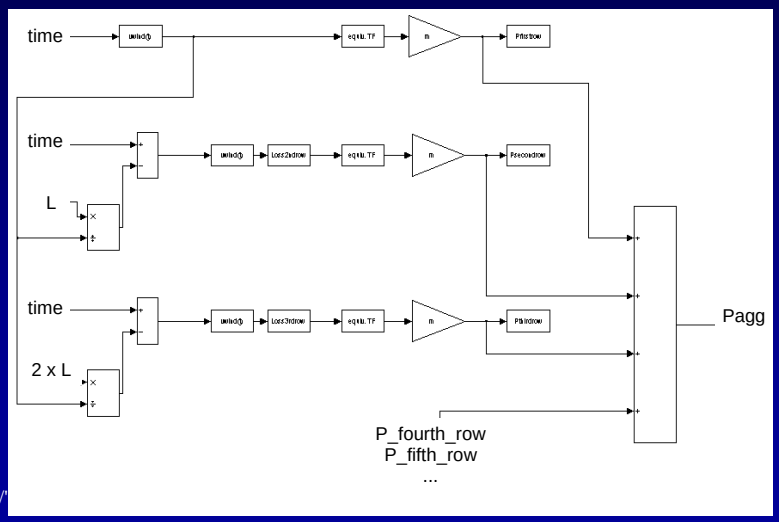
Model validation



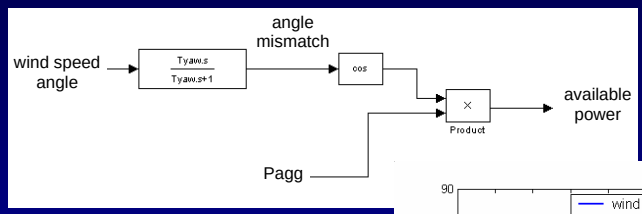
Aggregation of Turbine Model to Farm Model

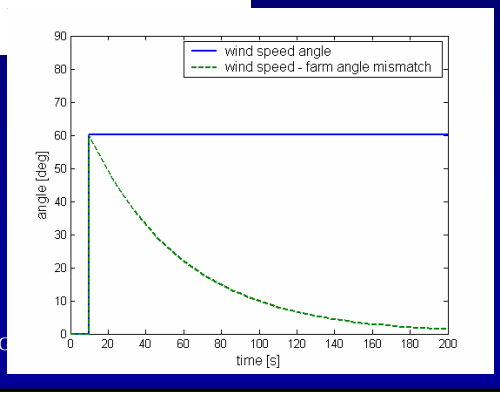


Aggregation of Turbine Model to Farm Model

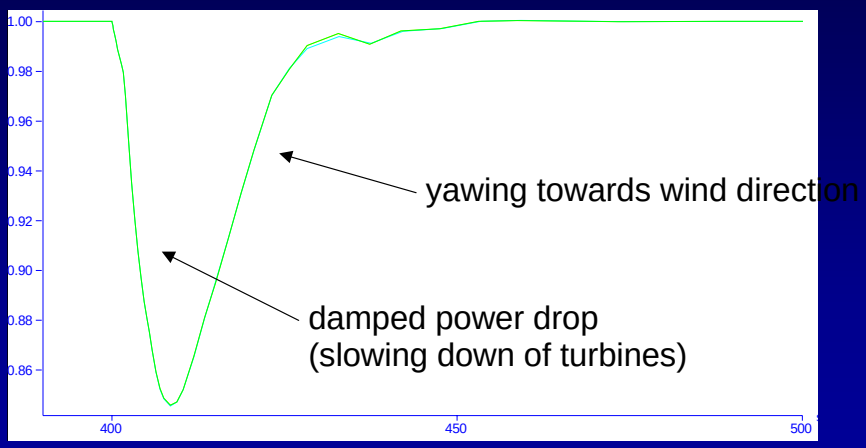


Impact of change in wind speed direction: Yawing

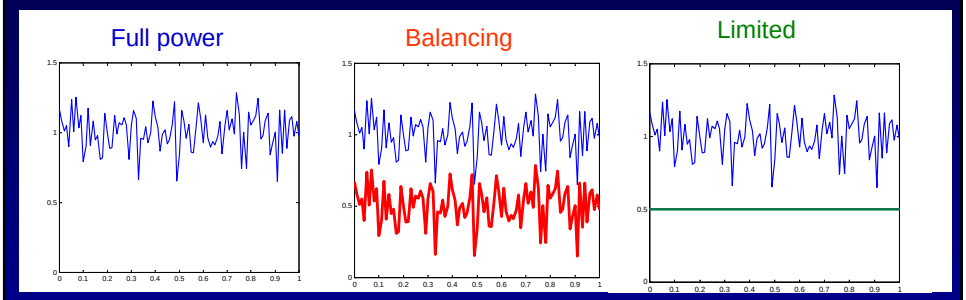




Impact of change in wind speed direction: Yawing



Active Power Operation Modes



- a specific operation mode may be demanded by grid operator, or may be chosen for economic profit (balancing power services)
- transition between modes: delay (pitch rate)

Reactive power control

- **2 options for Reactive Power Control**
  - Fixed power factor (e.g. cos[phi] = 1)
  - Dynamic Var control to control voltage at PCC
- **Reactive power in case of disturbances**
  - Parameterized tripping requirements (voltage and time thresholds)
  - Reactive power: 2 options
    - Dynamic Var Control (grid support)
    - No Dynamic Var Control
- **Control Speed:** dependent on generator or interface type
  - Doubly Fed: T ~ 0.5 – 2 s
  - Synchronous with PWM converter: T ~ 0.2 s
  - if HVDC, Statcom... used: T ~ 0.2 s

Reference: EON grid connection requirements

Voltage and reaction time

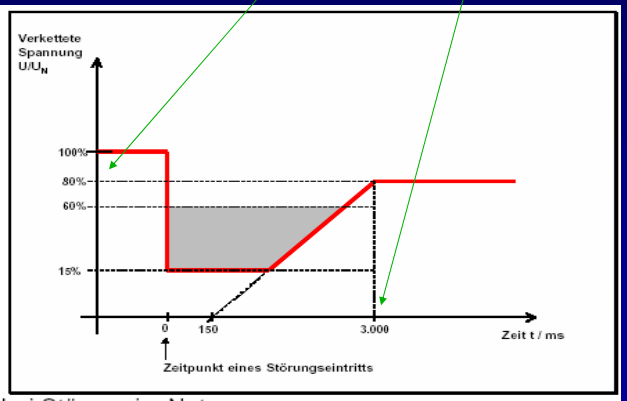


Bild 4a: Verhalten bei Störung im Netz

Conclusion

- History repeats: after 100 years idea of local supply grids is back
- Now:
  - grids are now interconnected
  - higher PQ level is wanted
- DG cannot be introduced without limits if no special measures are taken
- Determining maximum level of penetration is a difficult optimization exercise
- Finally, the customer is still the one who has to 'want' it and install it (on his premises)

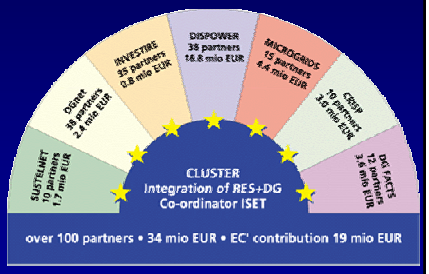
Results from study

- Congestion bottleneck in-land
  - Need extra lines…
- AC cable is possible but on the edge
  - 2*150 kV in parallel
- Reactive power support is required
  - SVC on coast
  - Q produced at turbine not much influence (due to long cable)
- Accessibility of off-shore farm is big problem
- Large legal issues remain

How will the customer react ?

Background material

- G. Pepermans, J. Driesen, D. Haeseldonckx, R. Belmans, W. D'haeseleer: "Distributed generation: definition, benefits and issues," accepted for publication in Energy Policy
- Ackermann, T., Andersson, G., S.oder, L., 2001. Distributed generation: a definition. Electric Power Systems Research 57, 195–204.
- Consortium for Electric Reliability Technology Solutions (J.Eto et al.): "White Paper on Integration of Distributed Energy Resources, The CERTS MicroGrid Concept"
- IEA, 2002. Distributed Generation in Liberalised Electricity Markets, Paris, p. 128.
- Jenkins, N., Allan, R., Crossley, P., Kirschen, D., Strbac, G., 2000., Embedded Generation. IEE, London, 245 pp.

European projects

- FP5 cluster on distributed generation: technology projects
  - http://www.clusterintegration.org/
  - http://www.dispower.org
- FP6 (recently started)
  - EU-DEEP (http://www.eu-deep.com): customer approach