grid stability
renewable energy and their turbulent dynamics

grid stability renewable energy and their turbulent dynamics

Katrin Schmietendorf, Hauke Hähne, Joachim Peinke,

Detlev Heinemann, Lüder von Bremen

U Oldenburg / ForWind

Mehrnaz Anavri MPI Dresden

Oliver Kamps U Münster

Research Alliance Wind Energy

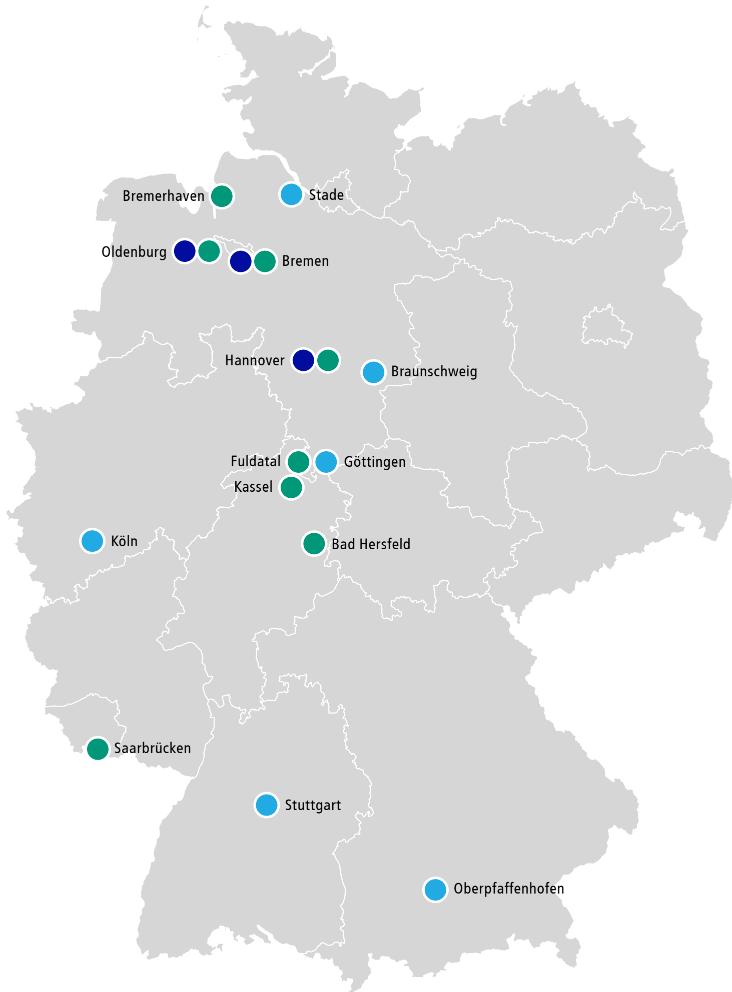
ForWind Center for Wind Energy Research Bremen Hannover Oldenburg

Research Alliance
Wind Energy

Deutsches Zentrum
für Luft- und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft
DLR

ForWind
Zentrum für Windenergieforschung

Fraunhofer
IWES



grid stability
renewable energy and their turbulent dynamics

PV and Wind energy are **renewable energies** -

fabrication sustainable?

Three reasons for these renewable energies:

- **Cost** - cheapest way to get electric power
- **environmental** - no CO_2
- **resources** - no fossil energy

There has never been so much wind power in Europe!

2128 GWh

were generated by wind in Europe on 2018-01-03, covering 22.7% of EU's electricity demand

- France 14.6% wind
- Germany 60.1% wind

content

transition of the grid

wind power forecast

high frequency power fluctuations

grid stability

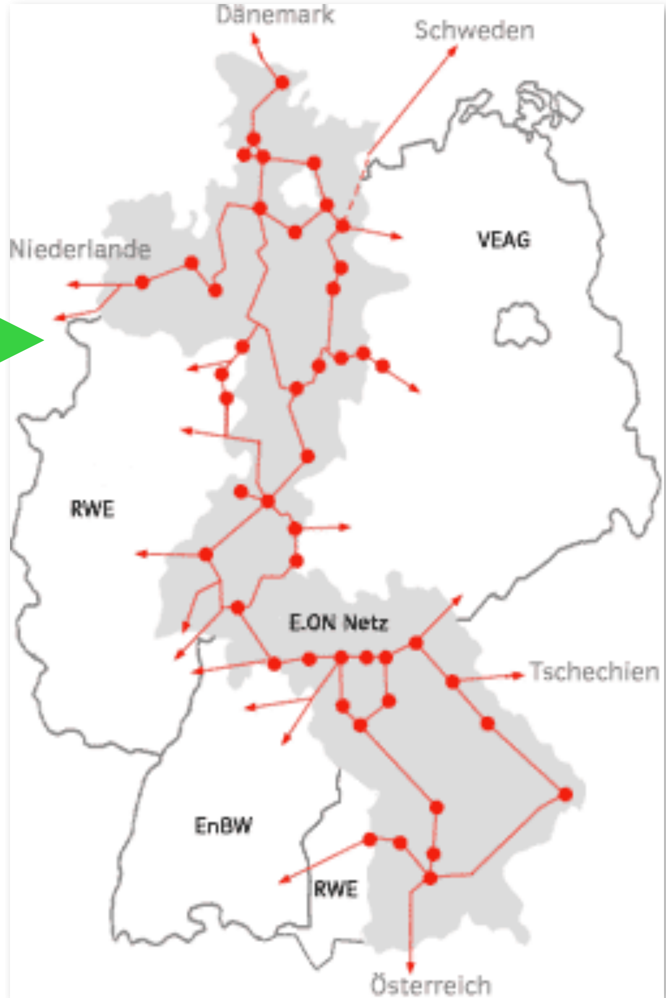
transition of the grid
to renewable energies

transition of the grid

concept for grid development

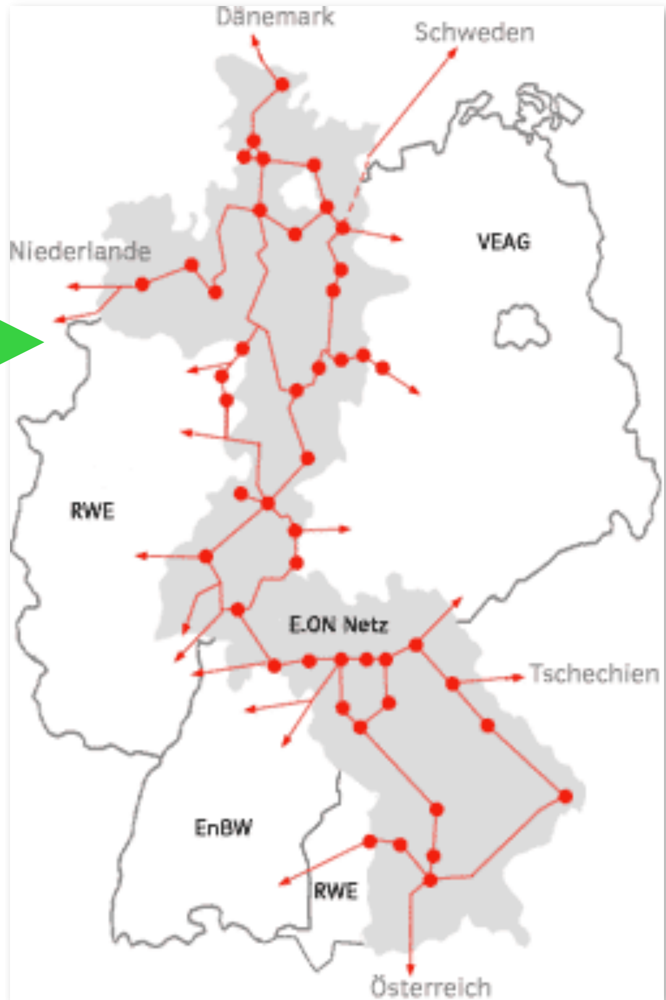
few big power stations provide about 100GW

top down structure

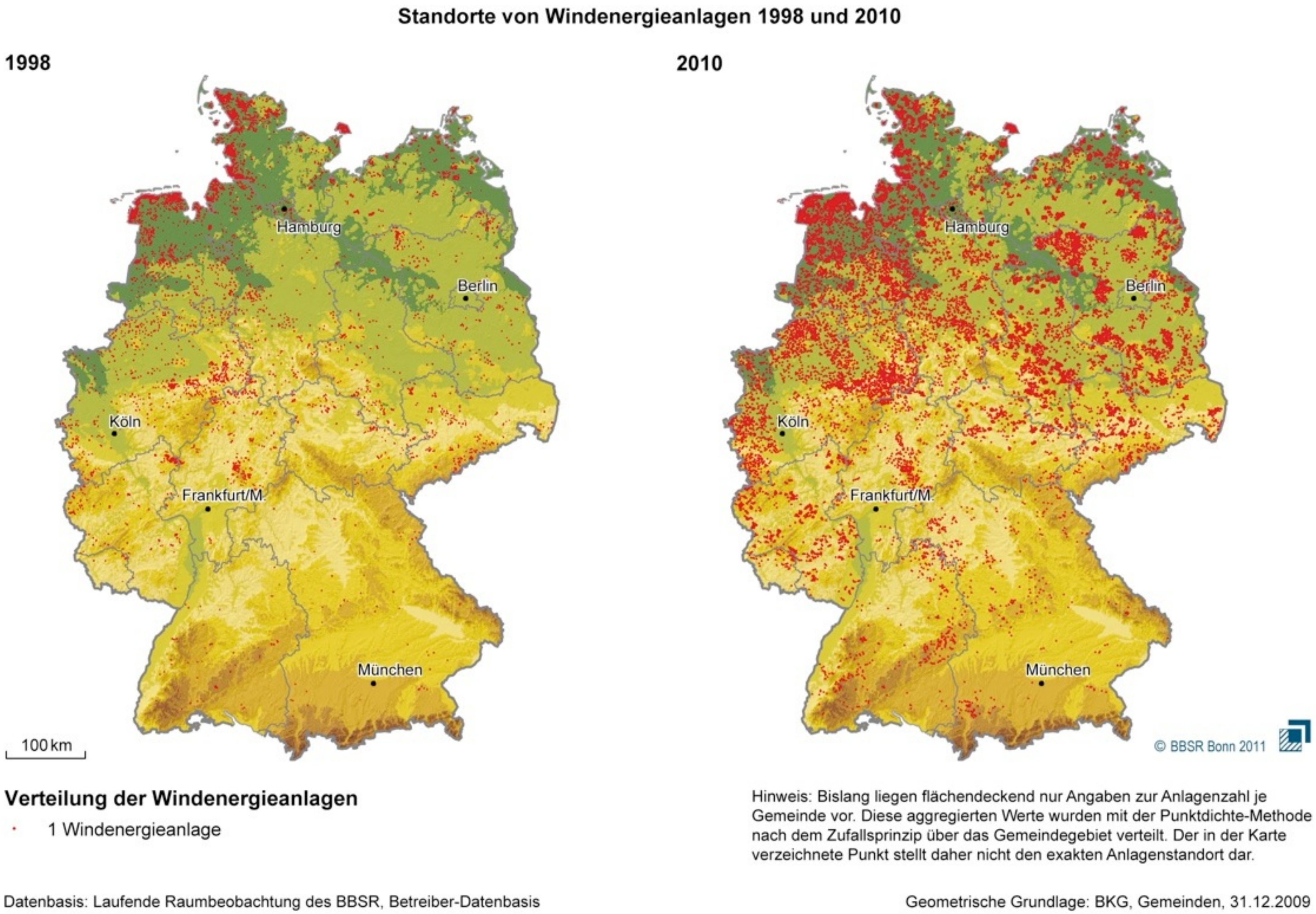


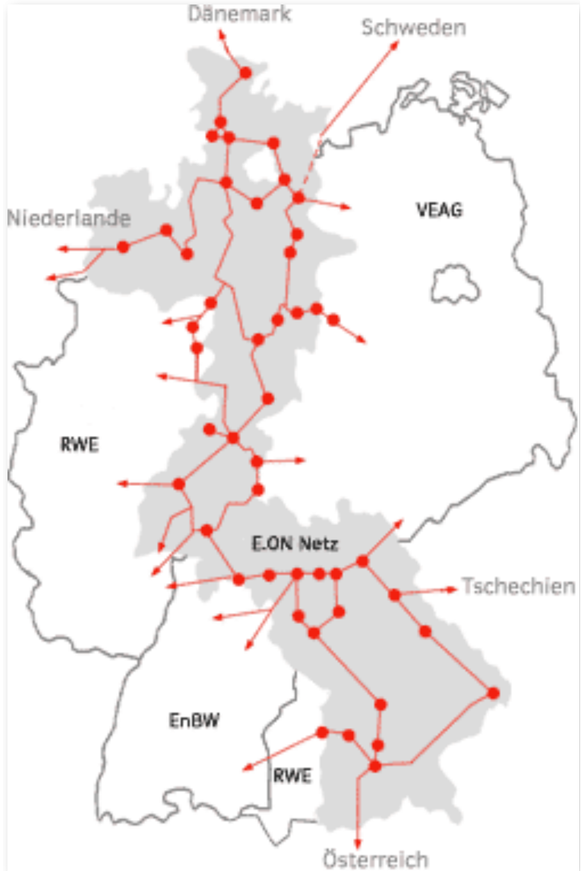
transition of the grid

actual many small renewable units feed power in at low voltage level



transition of the grid





transition of the grid

Stability of the grid

different aspects - sometimes called the intermittency problem of renewable energies

voltage stability ⟷ **frequency stability** ⟷ **rotor angle stability**

voltage stability
constant voltages
(+/- 10%)

- **power balance**

frequency stability
constant system frequency
(tolerance $O(10^{-1}$ Hz)

- **short time fluctuation**

rotor angle stability
machines remain
synchronized

- **state of each node**

transition of the grid

Stability of the grid

different aspects

voltage stability ↔ **frequency stability** ↔ **rotor angle stability**

voltage stability
constant voltages
(+/- 10%)

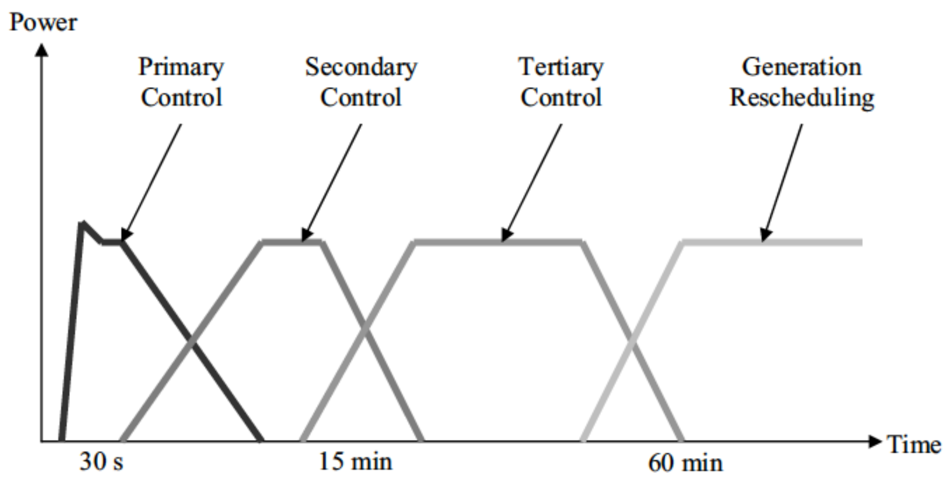
frequency stability
constant system frequency
(tolerance $O(10^{-1}$ Hz)

rotor angle stability
machines remain
synchronized

- power balance

- short time fluctuation

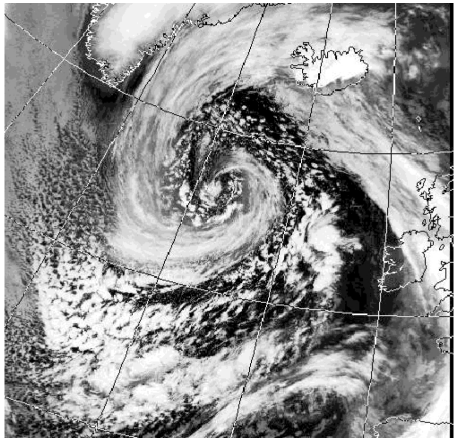
- state of each node

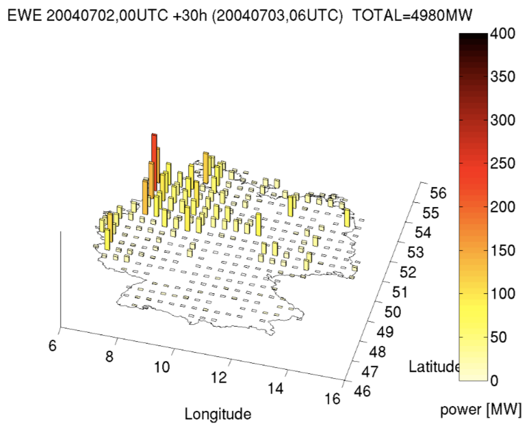


Wind Power Forecasting

important issue for power balance
production — consumption

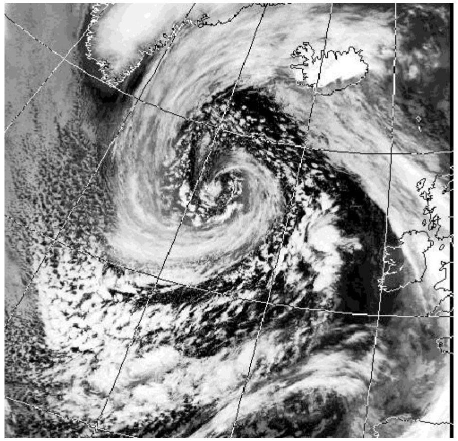
weather forecast used to predict expected wind power

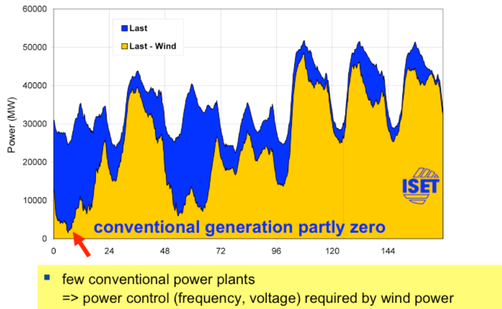




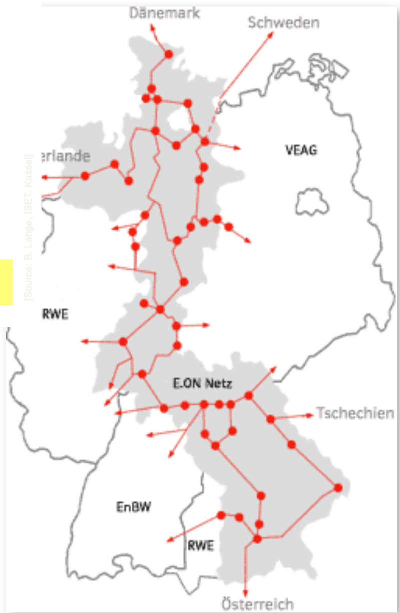
used to plan to power production of other units

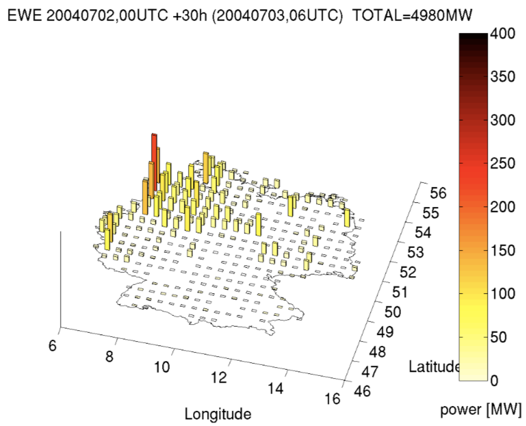
weather forecast used to predict expected wind power



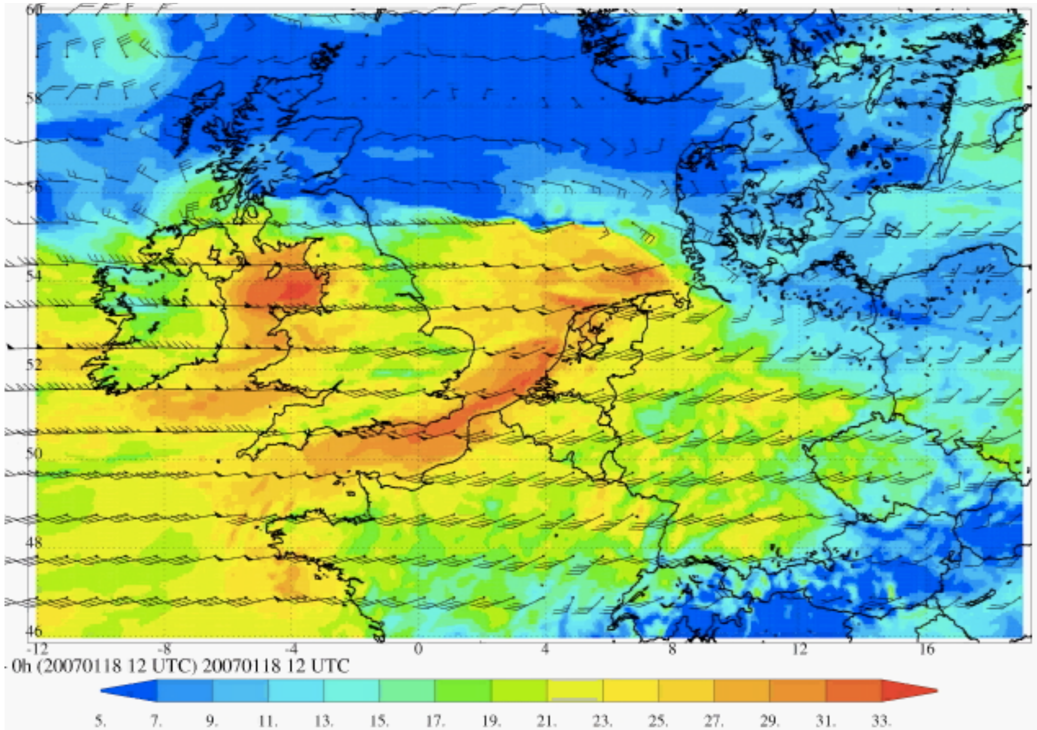


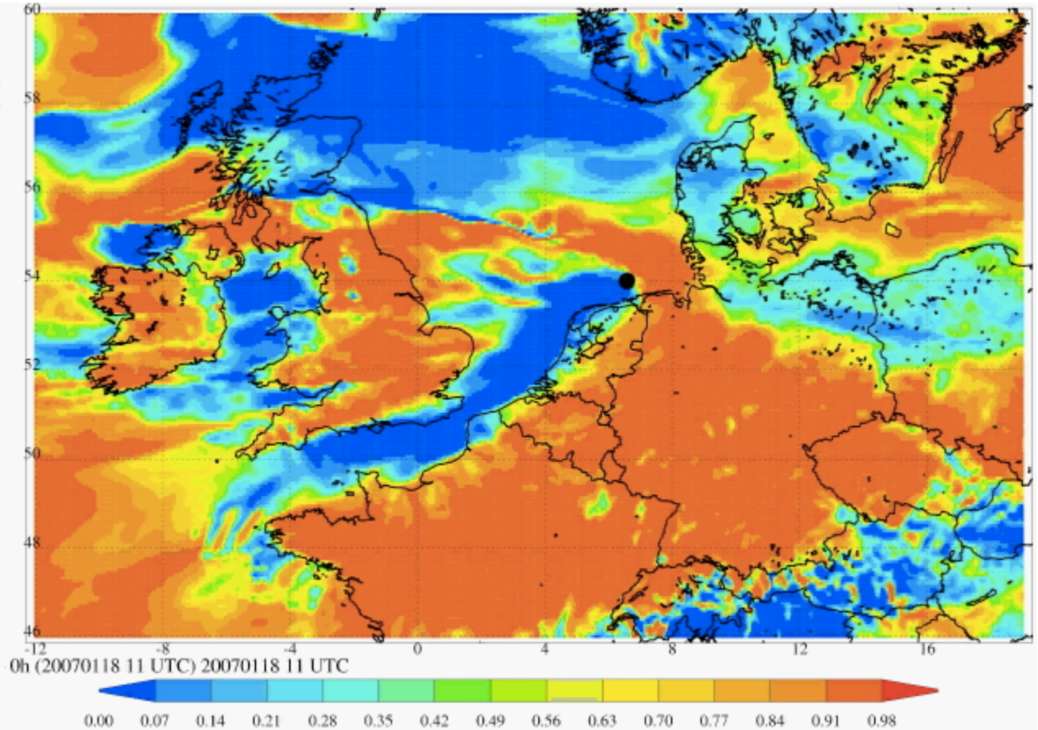
- few conventional power plants
  => power control (frequency, voltage) required by wind power





used to plan to power production of other units

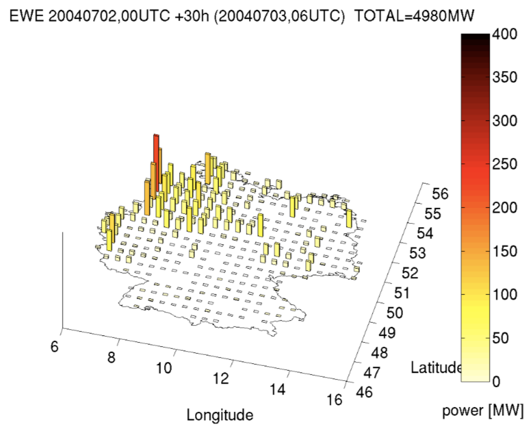




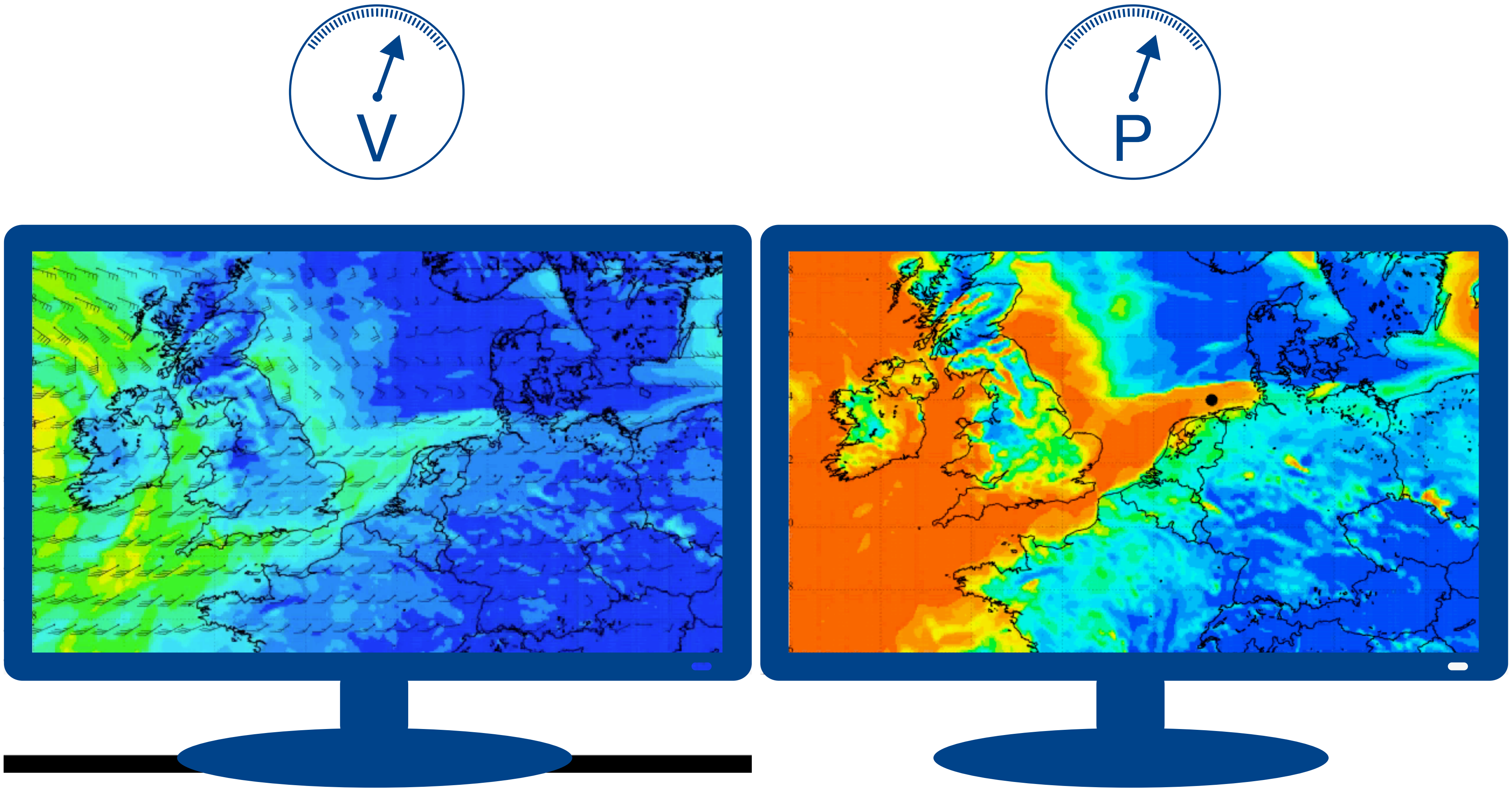
from wind prediction

to

power prediction



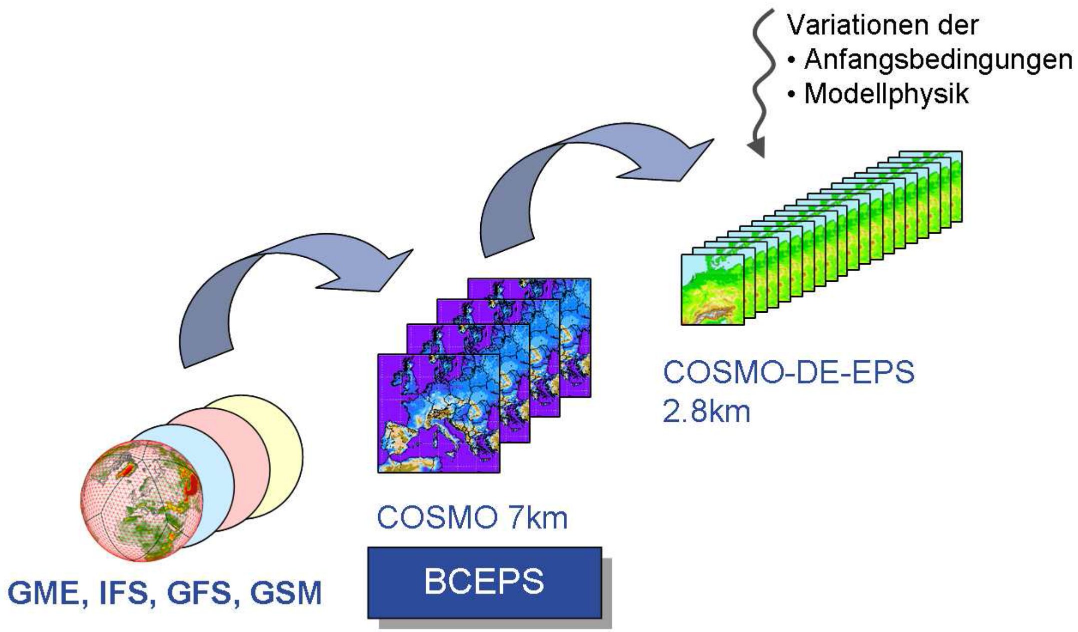
wind and power forecast

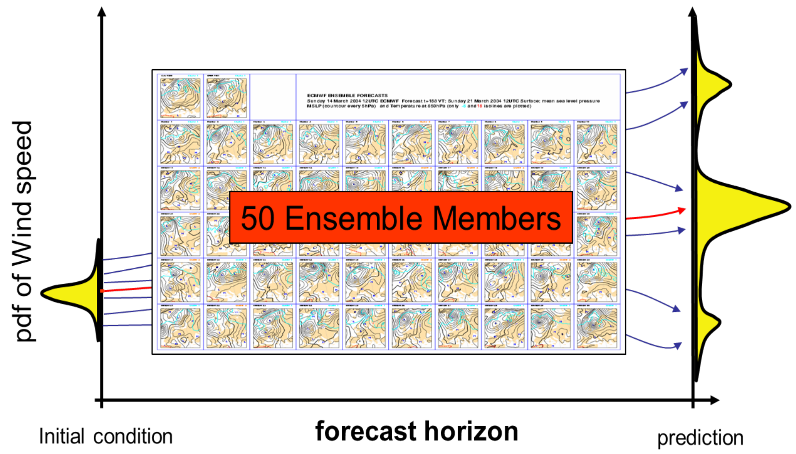


Probabilistic Wind Power Forecasting

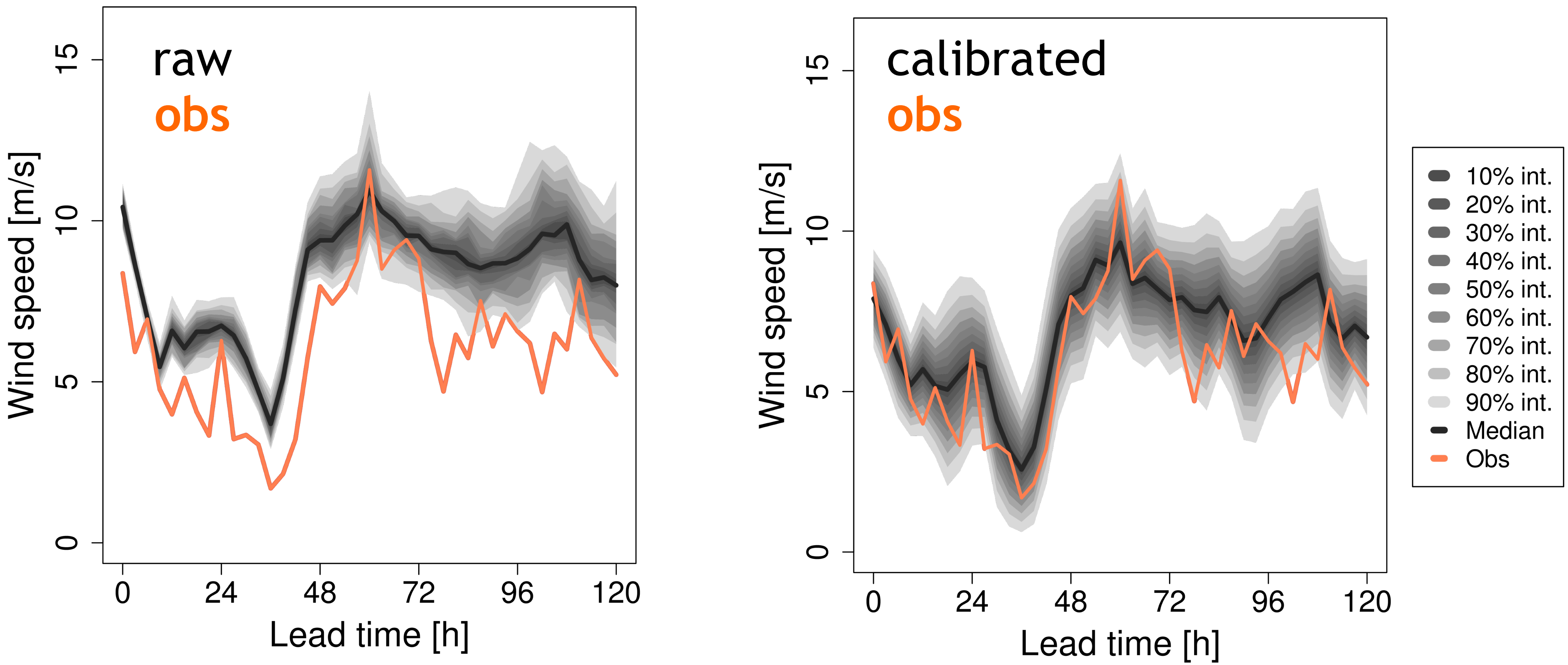
- Weather forecast is initial value problem
- Model physics is not perfect
- Weather forecast show inherent uncertainty
- Need to quantify forecast uncertainty

Ensemble Forecasting





Probabilistic wind power forecasts (2)



- Raw forecasts have too little spread
- Pre-processing (calibration) of ensemble forecasts and their combination
- Various calibration techniques are available for wind/power forecasts

wind (Solar) power forecasting

Stability of the grid:

on **time scales of hours and more** quite well know system, manageable

voltage stability
constant voltages
(+/- 10%)

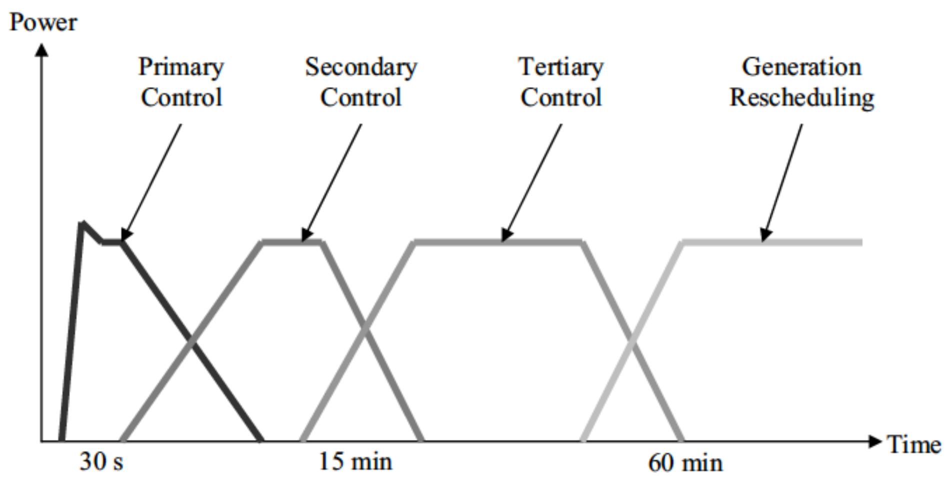
- power balance

frequency stability
constant system frequency
(tolerance $O(10^{-1}$ Hz)

- short time fluctuation

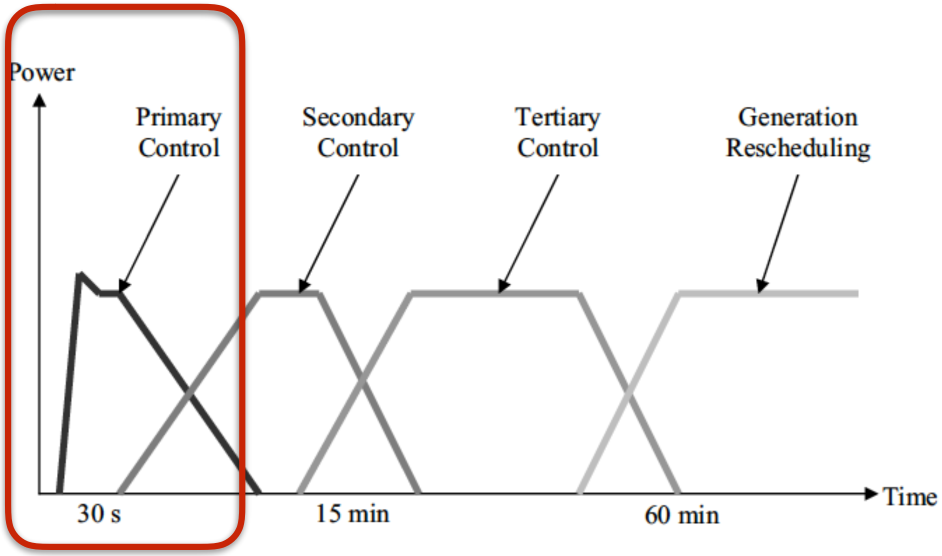
rotor angle stability
machines remain
synchronized

- state of each node

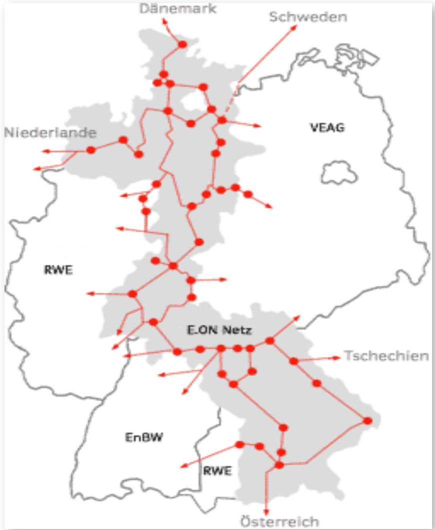


handling high frequency

short time power fluctuations



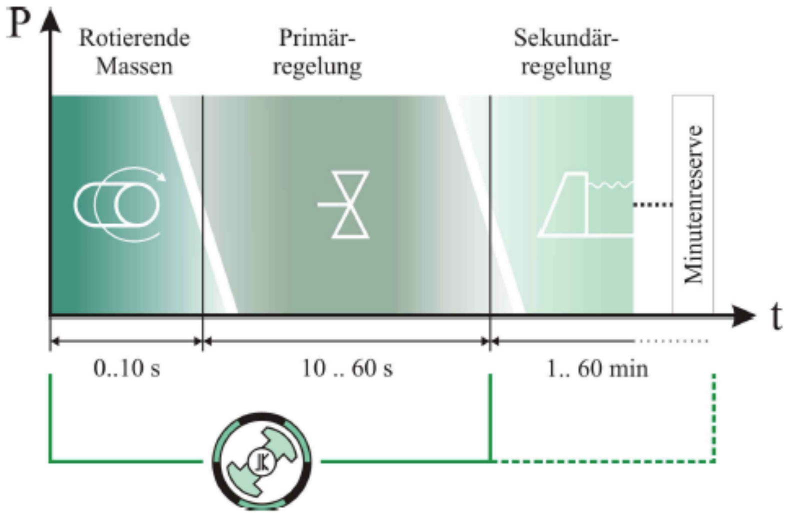
handling high frequency



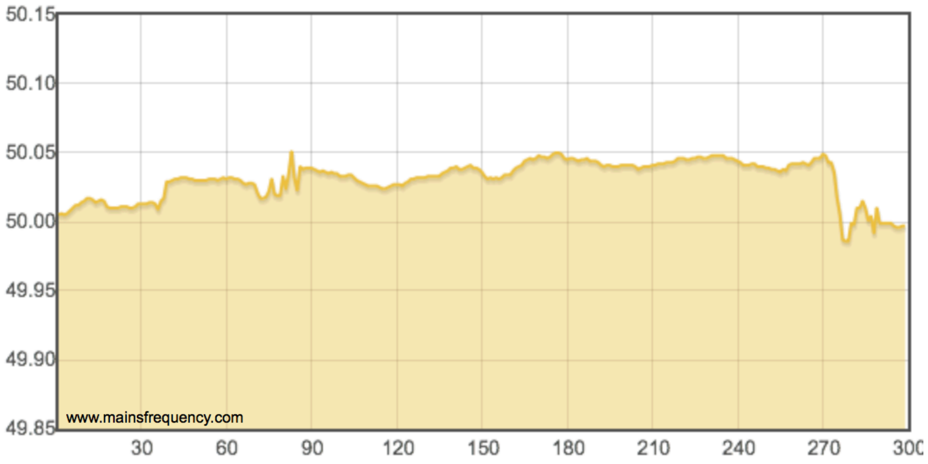
short time grid frequency

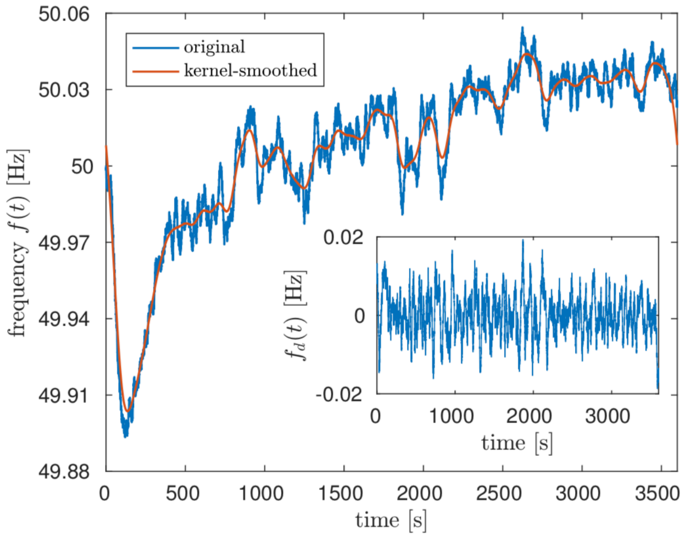
stabilisation by rotating mass of synchronous generators — grid frequency changes in the range of mHz

www.netzfrequenzmessung.de



http://www.mainsfrequency.com/verlauf_en.htm





handling high frequency
- what is the nature of the fluctuations - solar and wind

typical resource 1kW / m^2 (solar - nice sunny sky; wind - 12m/s)

electric power = resource X efficiency (solar 0.2 ; Wind 0.5)

5MW wind turbine

latest prototype

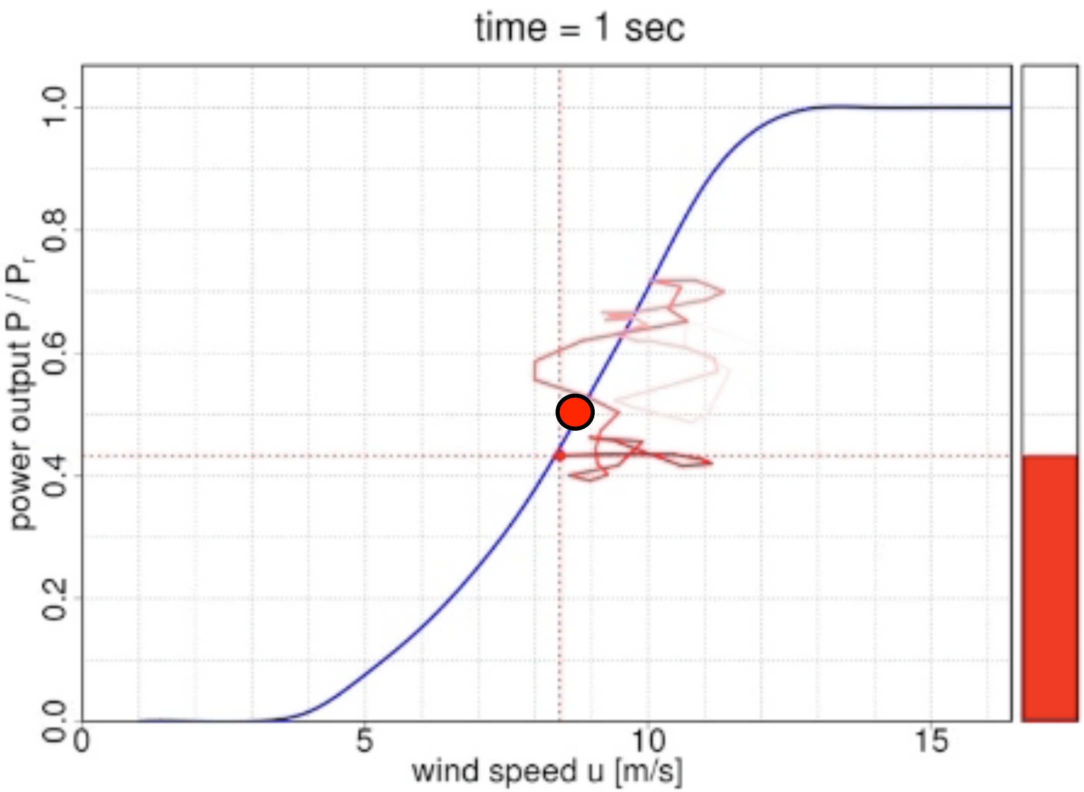
12MW (GE February 2018)

blade 107m

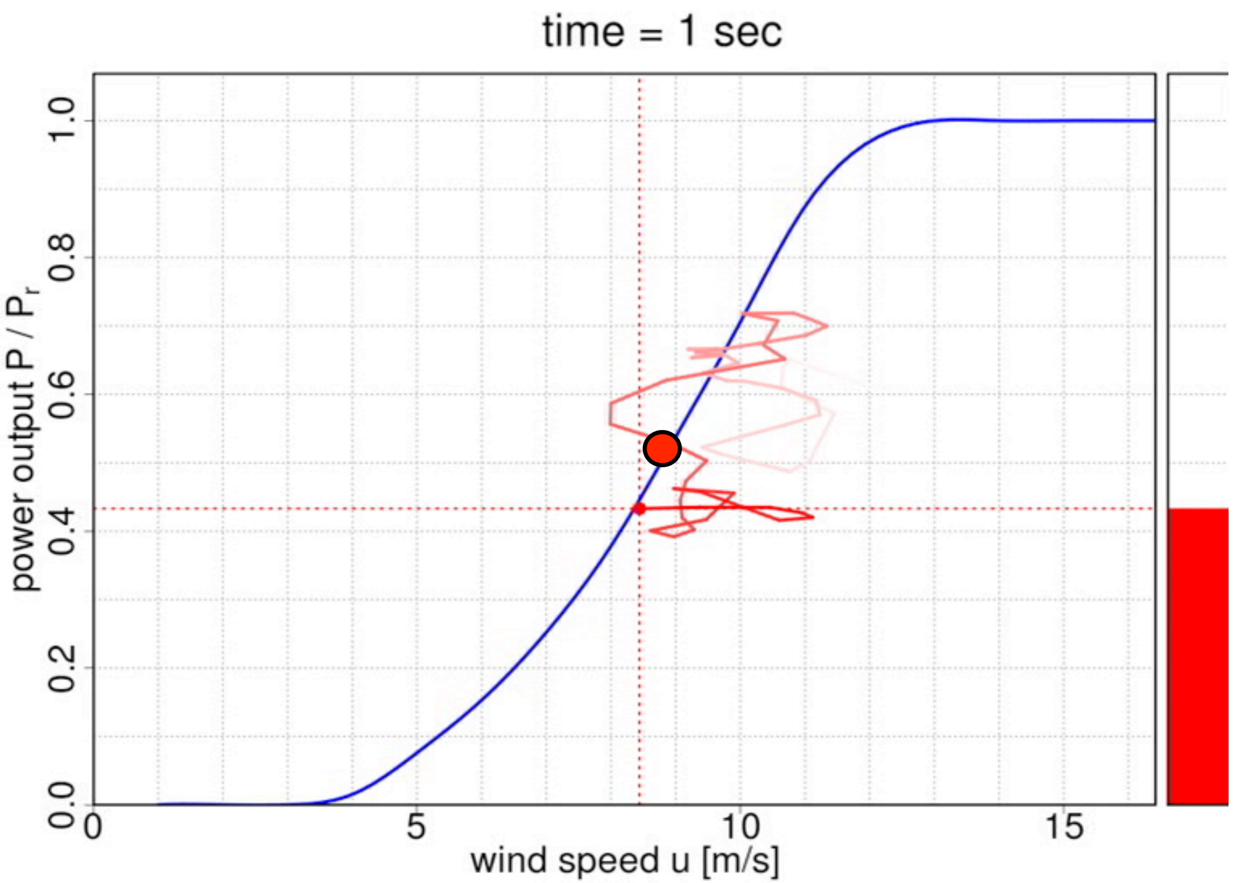
ForWind Zentrum für Windenergieforschung Bremen Hannover Oldenburg

dynamics of wind power

$$P_{WT} = \frac{1}{2} c_p(\lambda)\, \rho\, u_{wind}^3 \cdot A$$



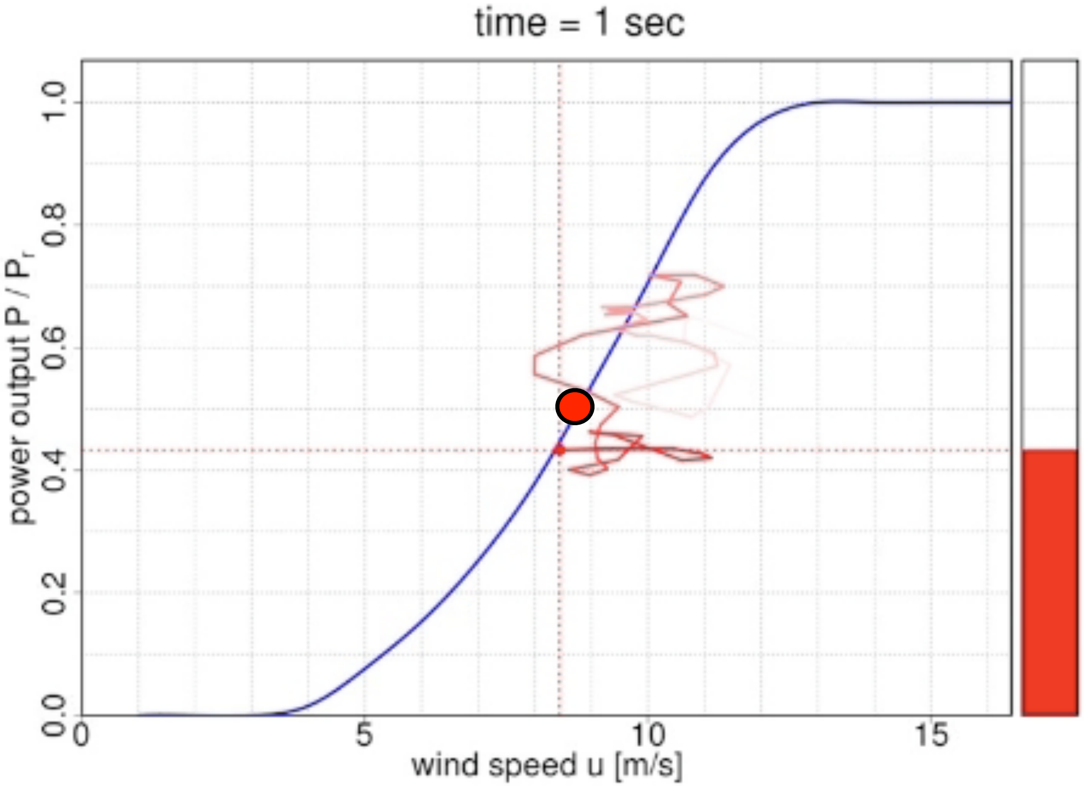
dynamics of wind power



http://phys.org/news/2013-04-turbines-great-turbulence-consequences-grid.html

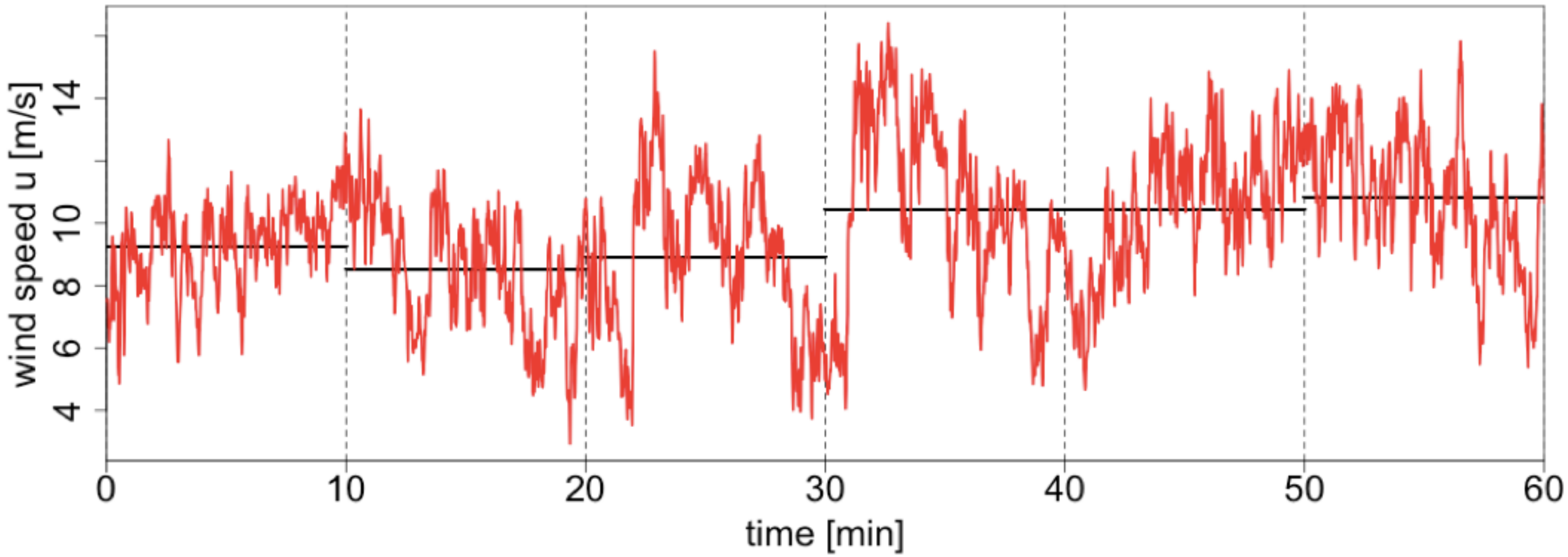
dynamics of wind power

$$P_{WT} = \frac{1}{2} c_p(\lambda)\, \rho\, u_{wind}^3 \cdot A$$



http://phys.org/news/2013-04-turbines-great-turbulence-consequences-grid.html

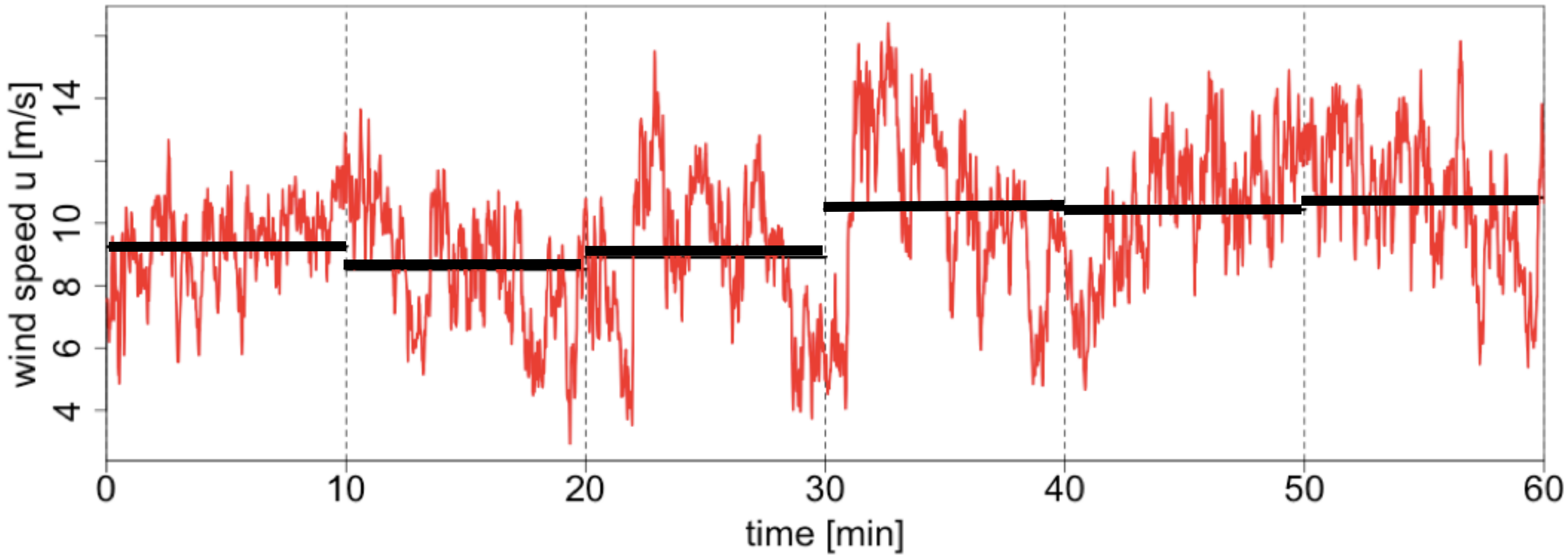
data analysis (here wind data are used)



wind measurements and data analysis

- common characterization

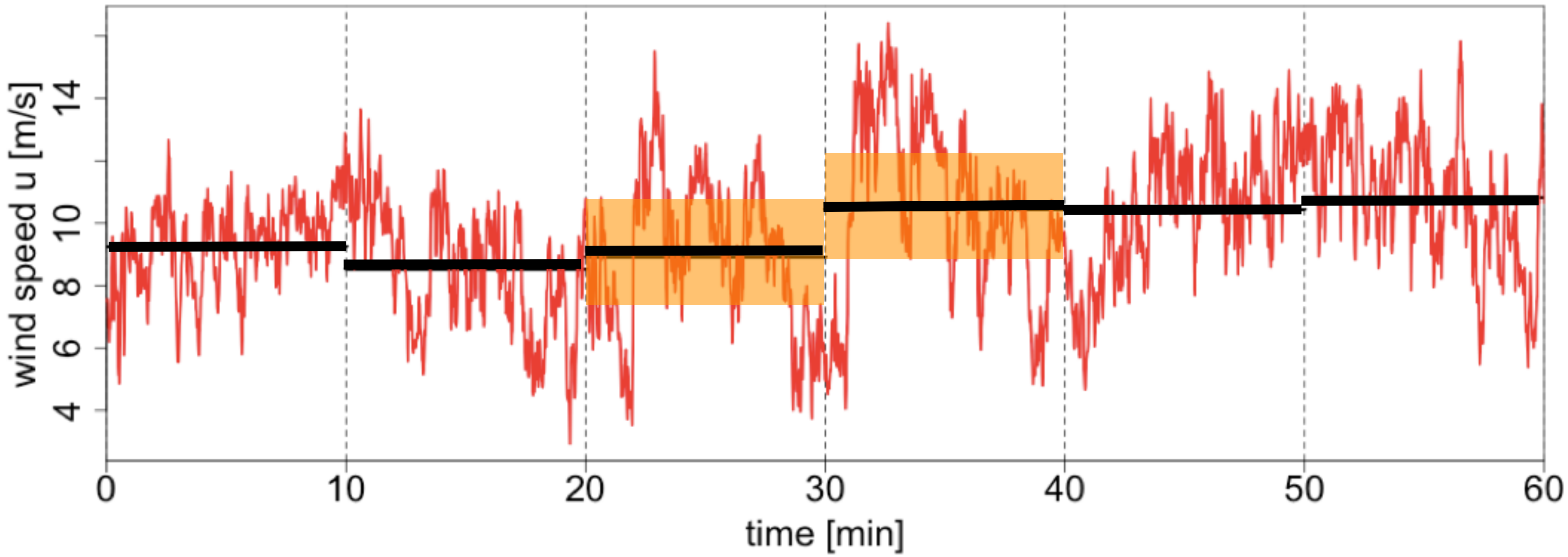
- 10 min mean values



wind measurements and data analysis

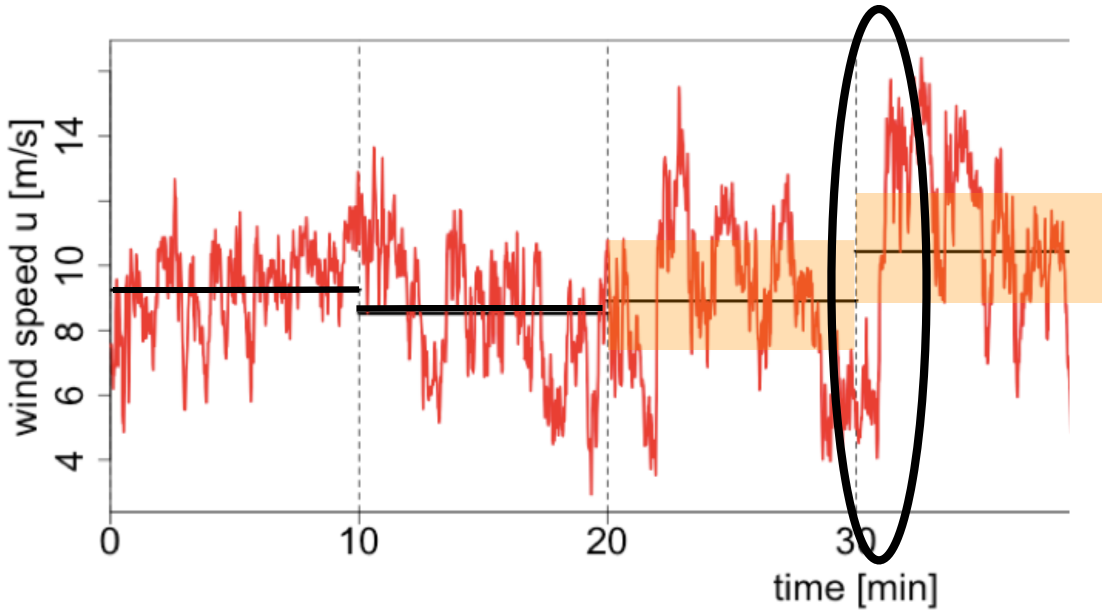
- common characterization

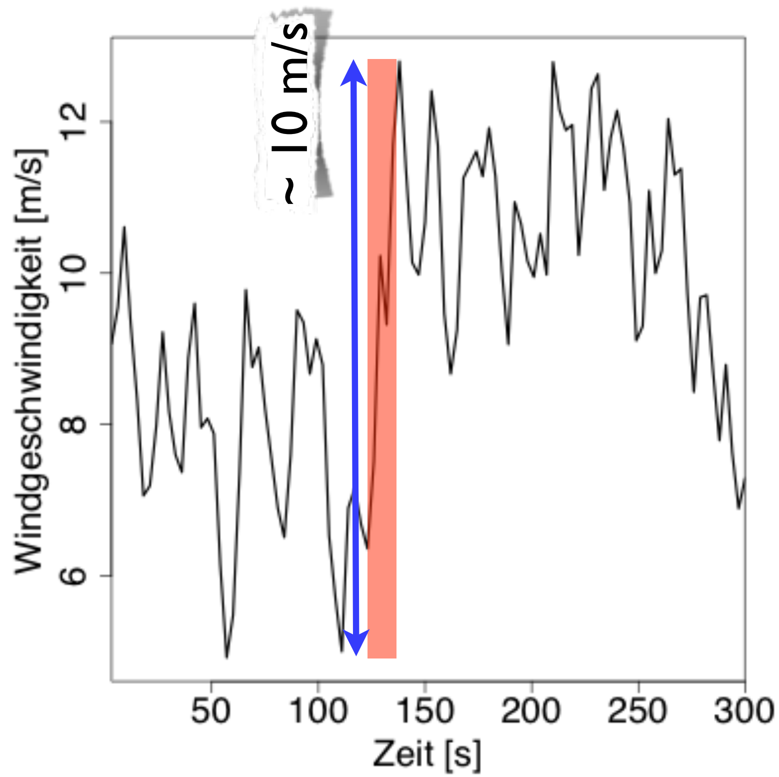
- 10 min mean value
- turbulence intensity



wind measurements and data analysis

- common characterization

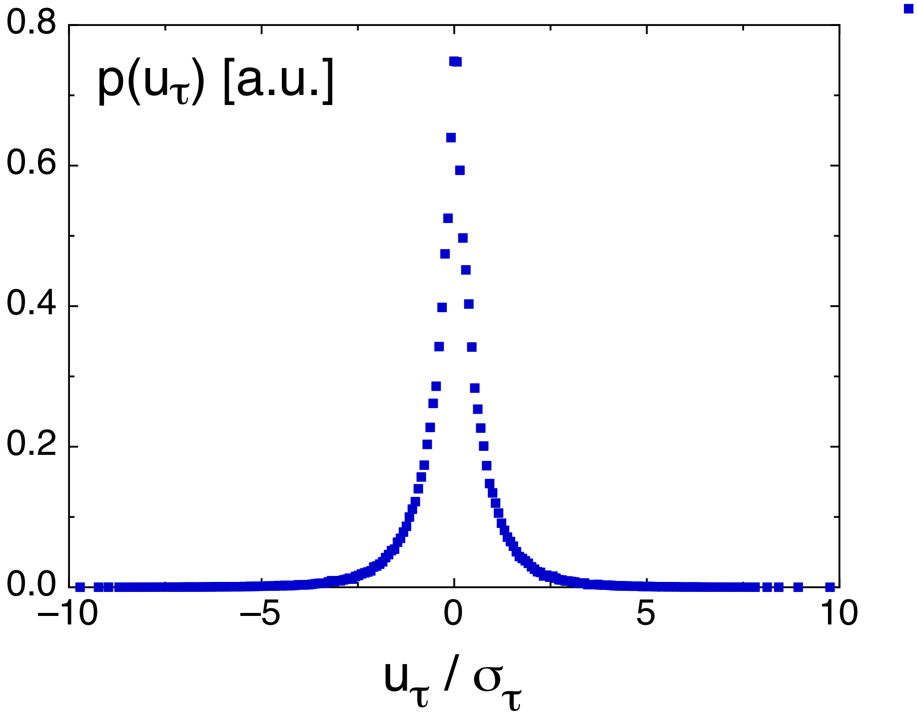


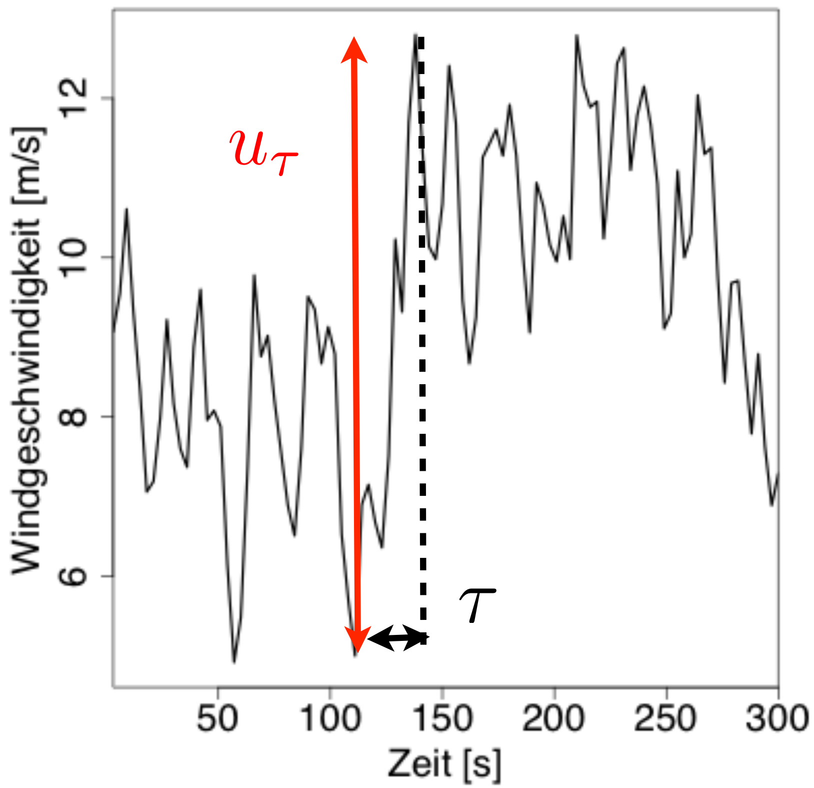


wind data analysis

- wind fluctuations can be measured by velocity increments

$$u_\tau = u(t+\tau) - u(t)$$

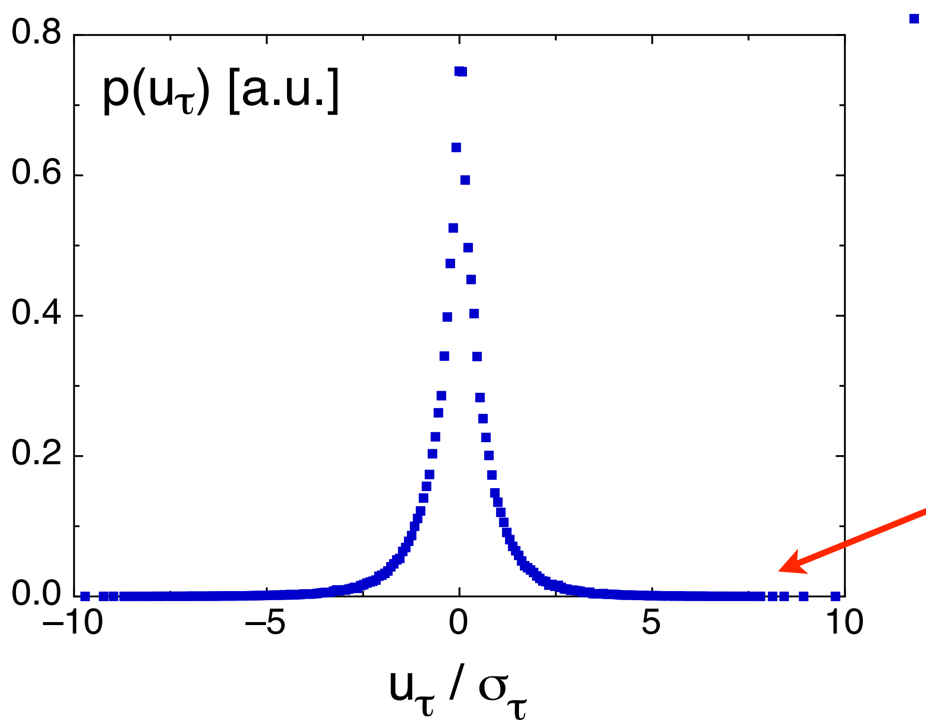


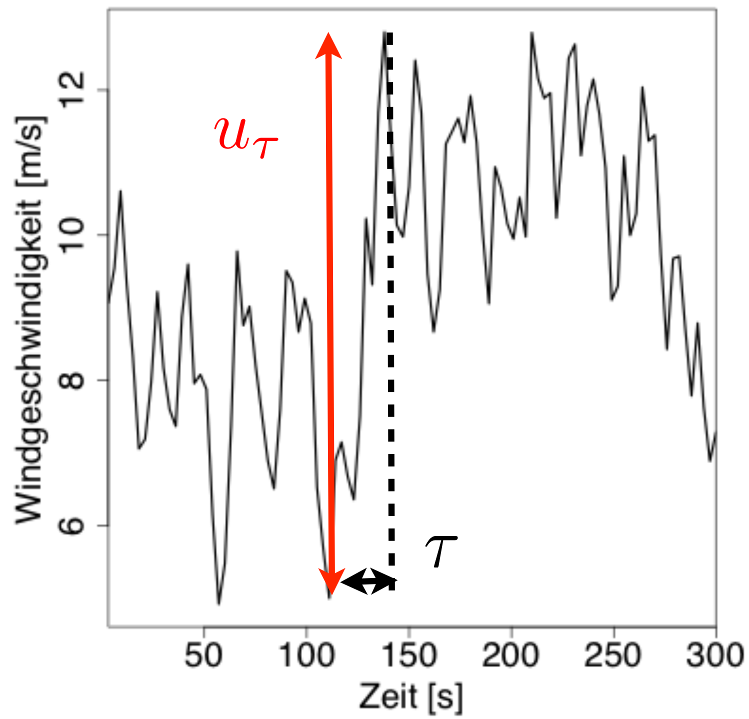


wind data analysis

- wind fluctuations can be measured by velocity increments

$$u_\tau = u(t+\tau) - u(t)$$



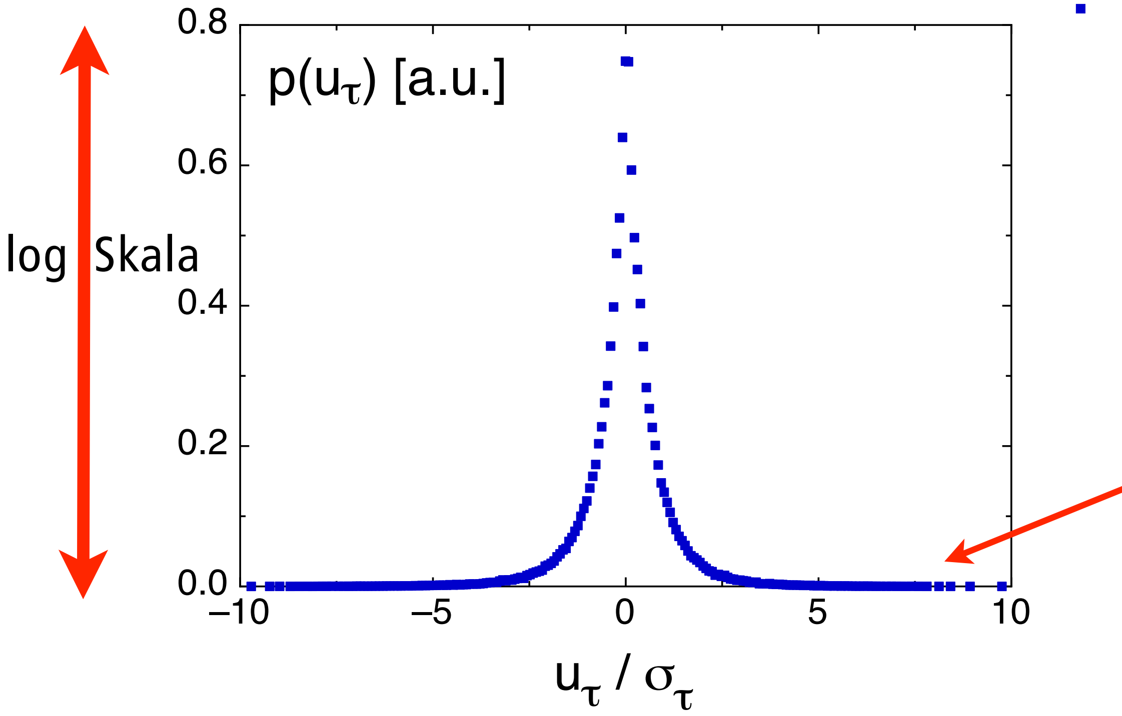


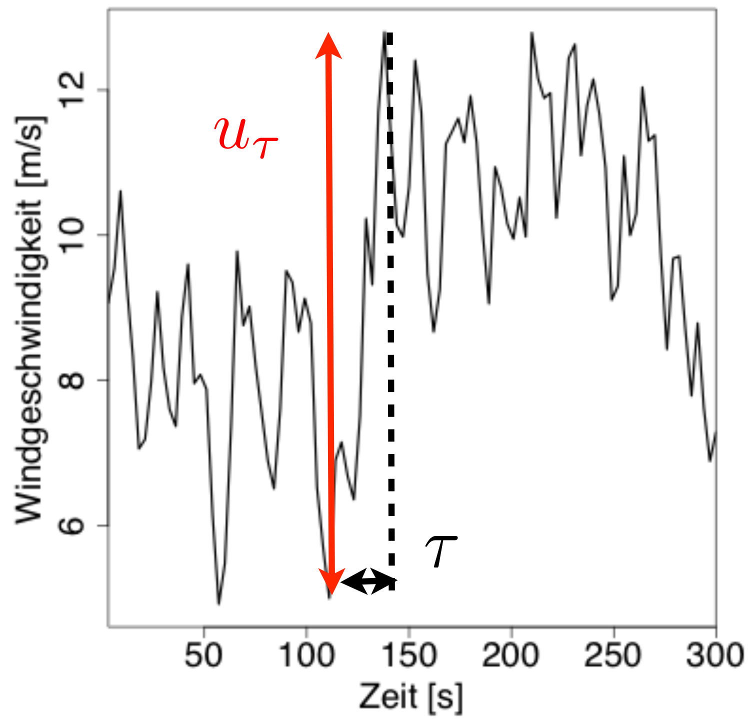
big events with small probability

wind data analysis

- wind fluctuations can be measured by velocity increments

$$u_\tau = u(t+\tau) - u(t)$$



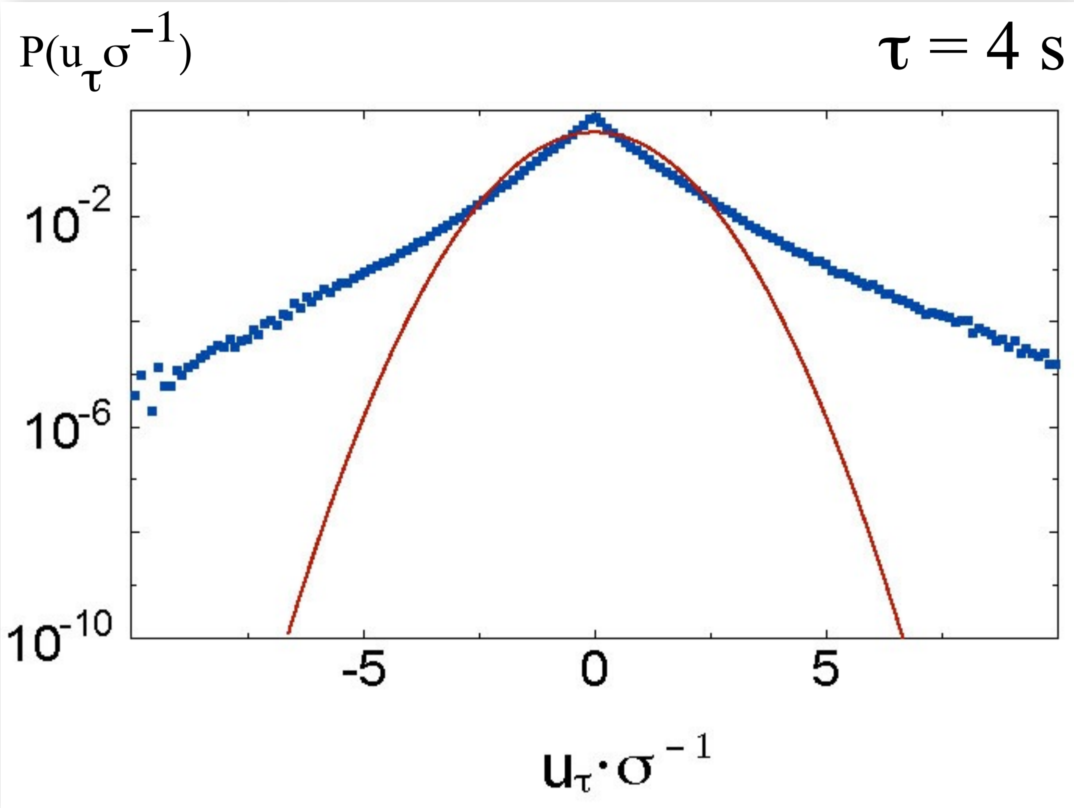


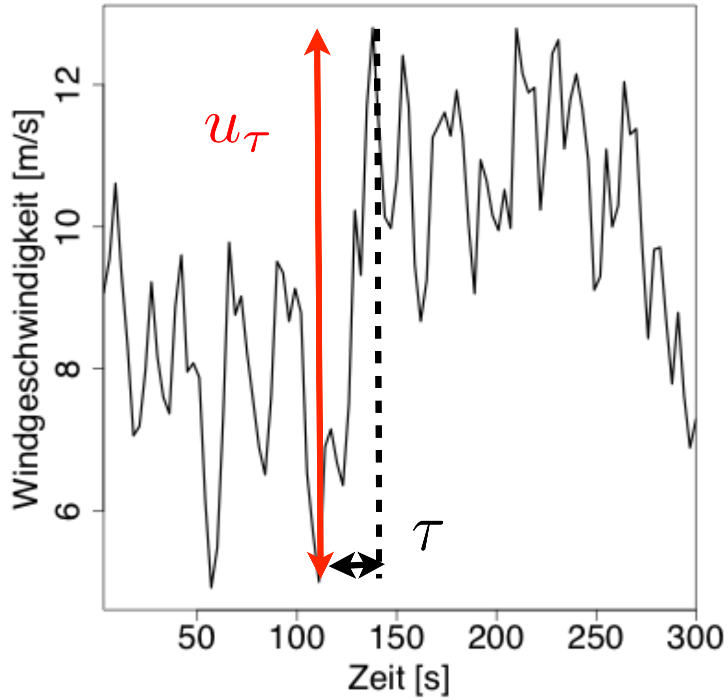
big events with small probability

wind data analysis

- wind fluctuations can be measured by velocity increments

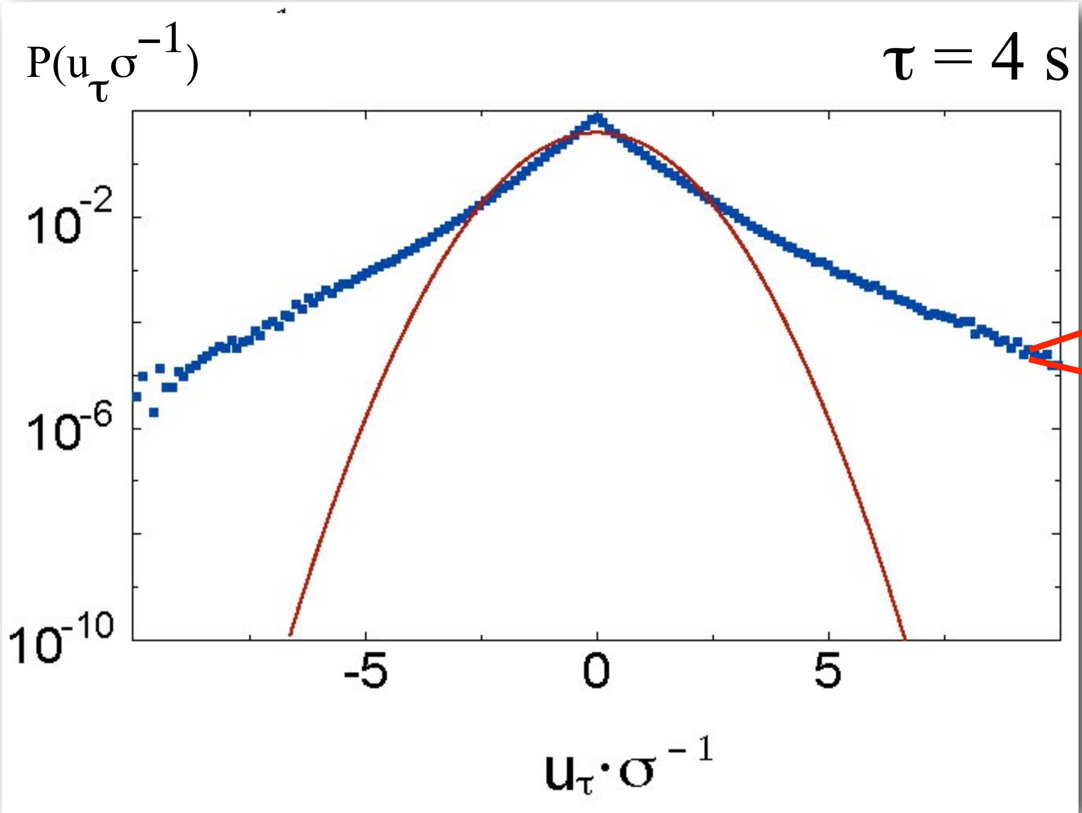
$$u_\tau = u(t+\tau) - u(t)$$

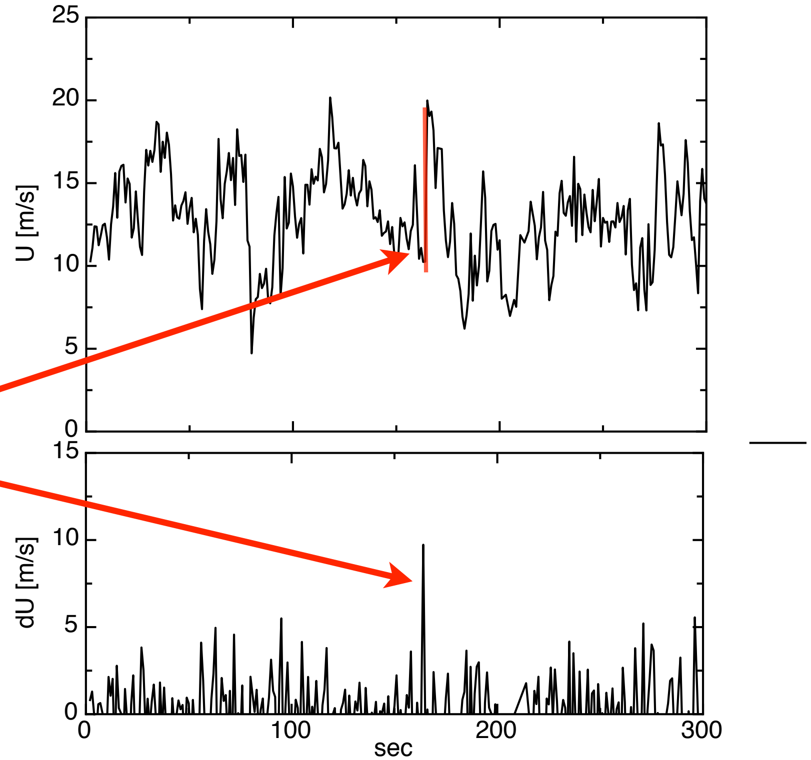




Boundary-Layer Meteorology **108** (2003)

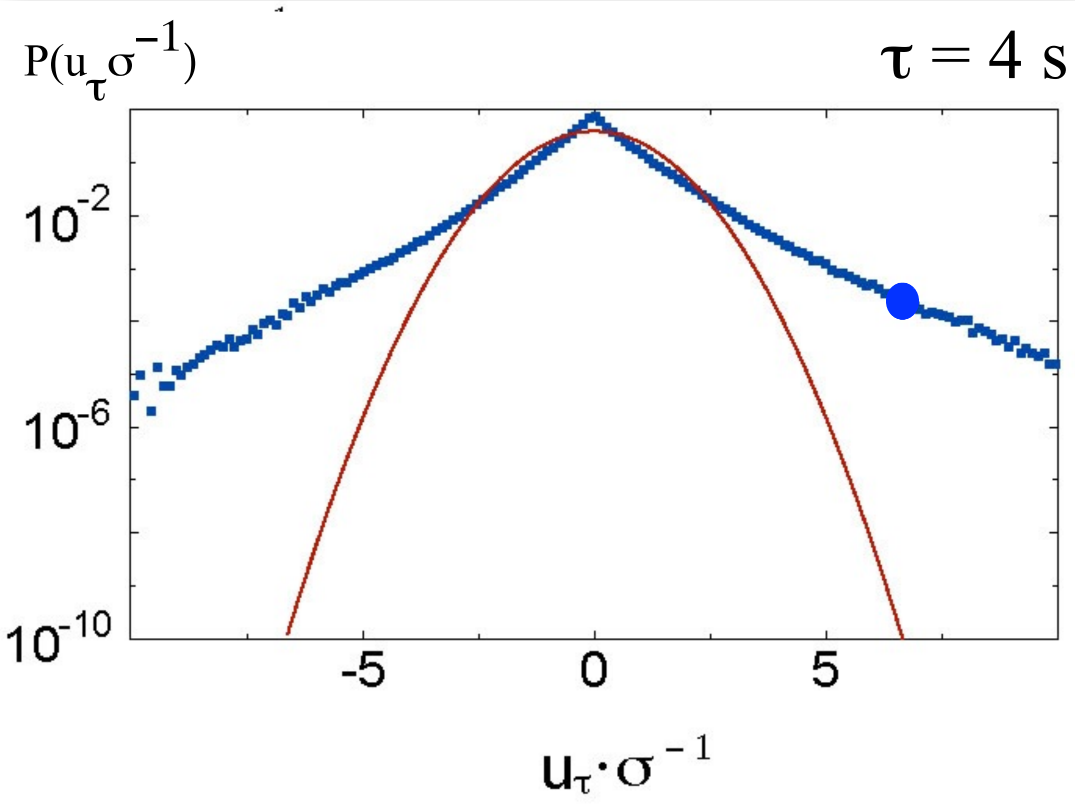
wind data analysis





Boundary-Layer Meteorology **108** (2003)

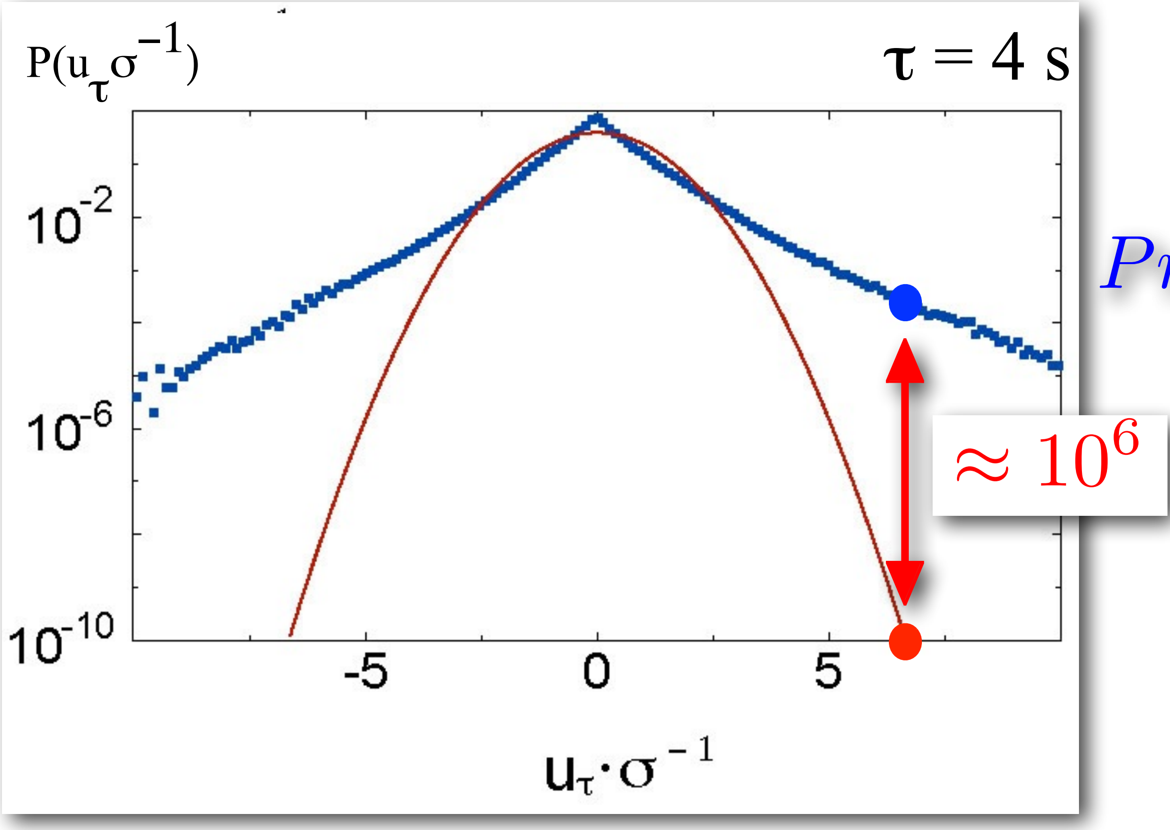
wind data analysis



$$Prob(u_\tau > 6\sigma) \approx 10^{-4}$$

1/Tag

wind data analysis
— this is intermittency in the sense of turbulence



$$Prob(u_\tau > 6\sigma) \approx 10^{-4}$$

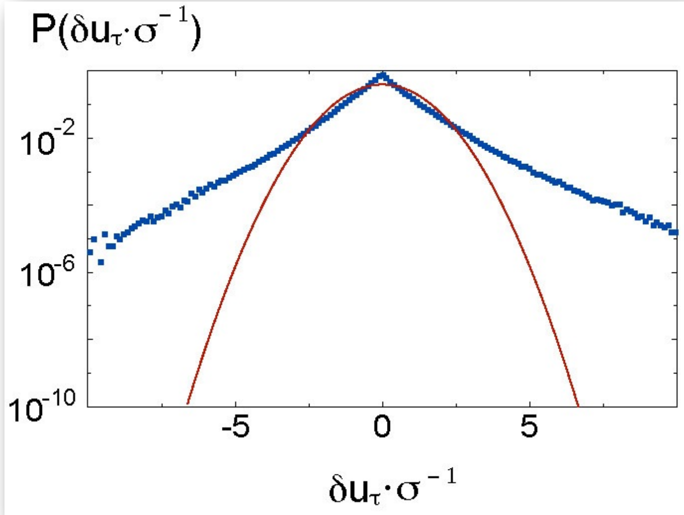
1/Tag

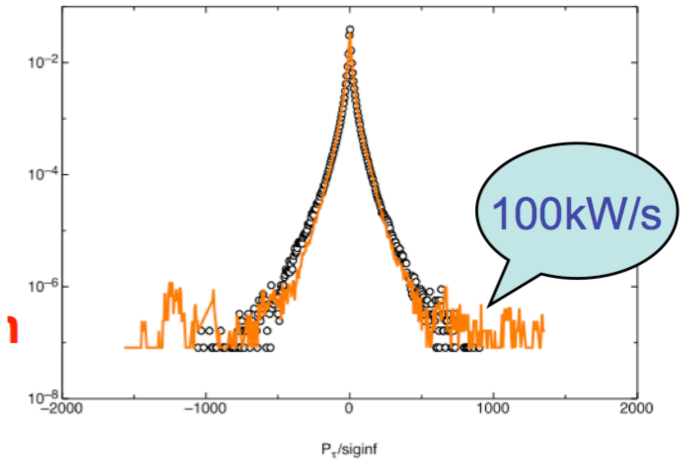
Boundary-Layer Meteorology **108** (2003)

$$Prob(u_\tau > 6\sigma) \approx 10^{-10}$$

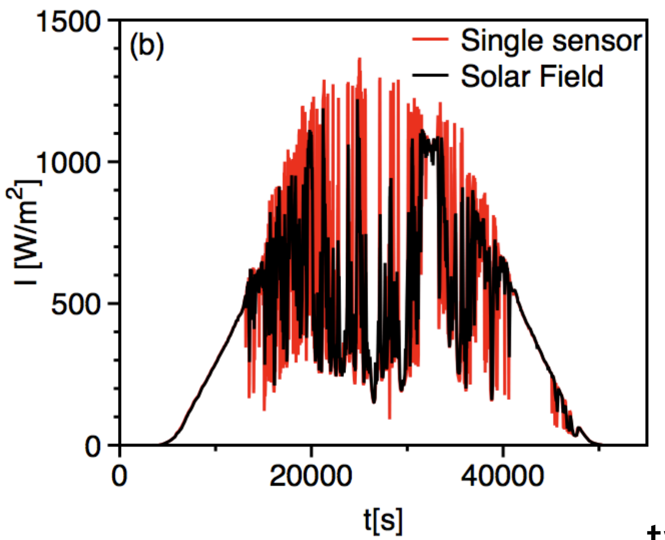
1/3000 Jahre

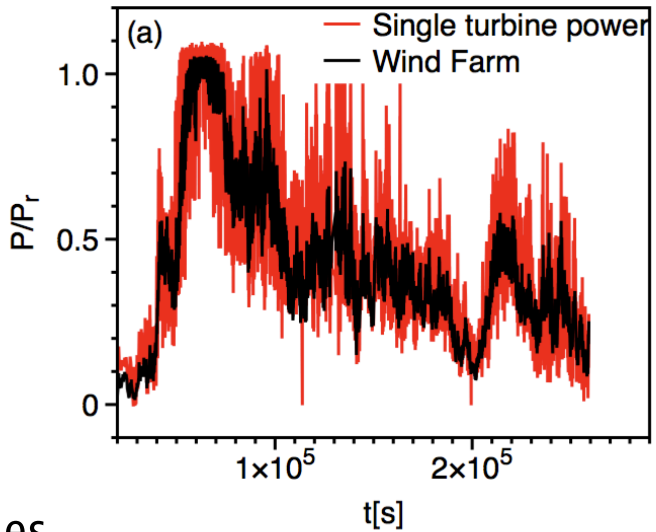
handling high frequency
- what is the nature of the fluctuations - solar and wind





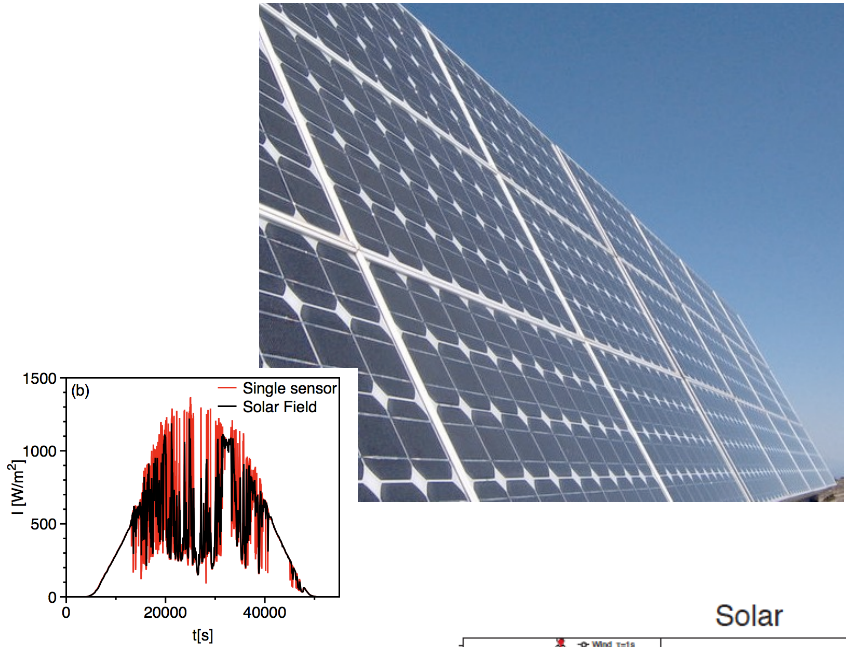
nature of solar and wind power

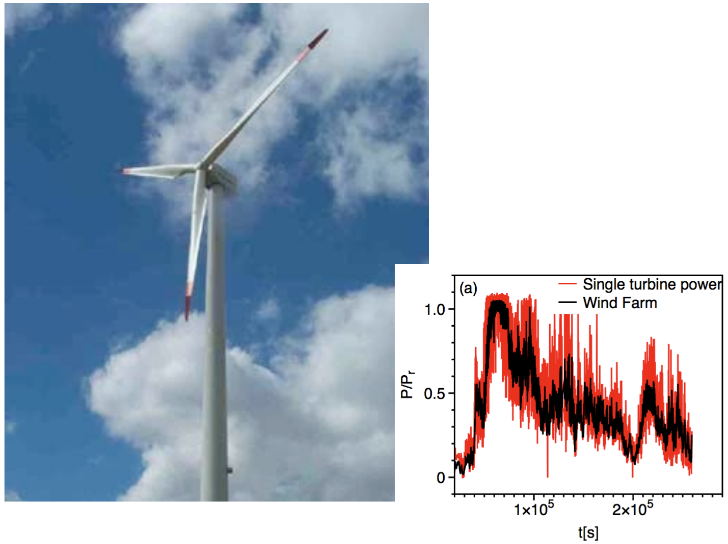


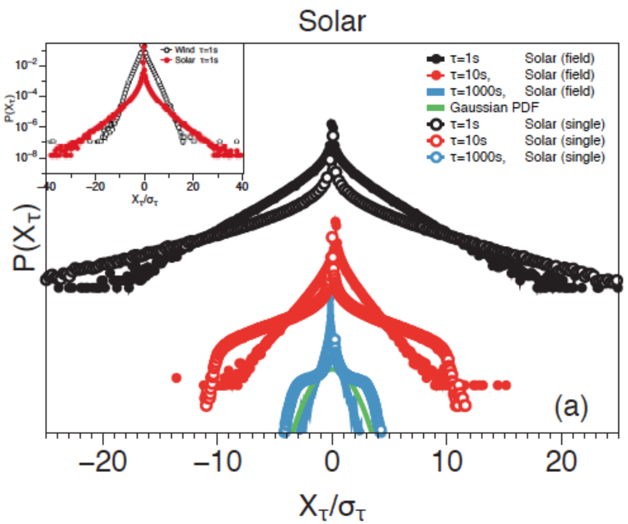


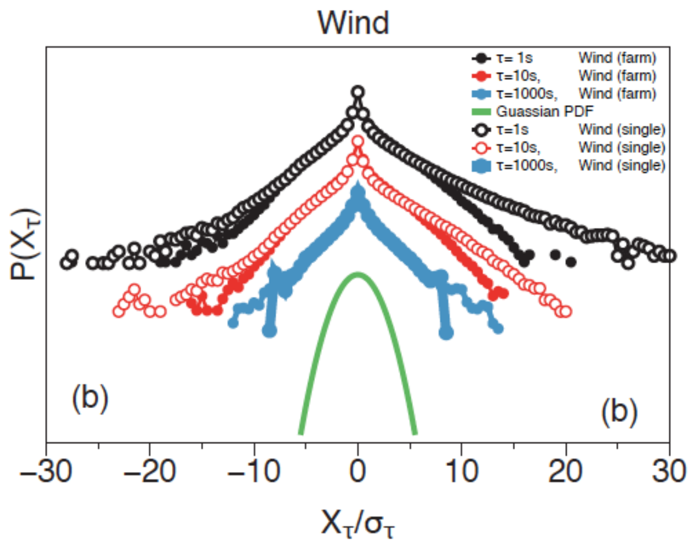
typical time series

nature of solar and wind power

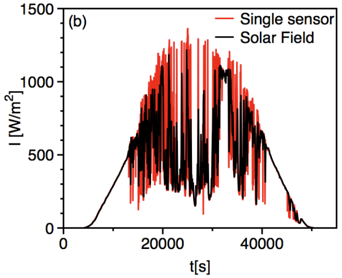


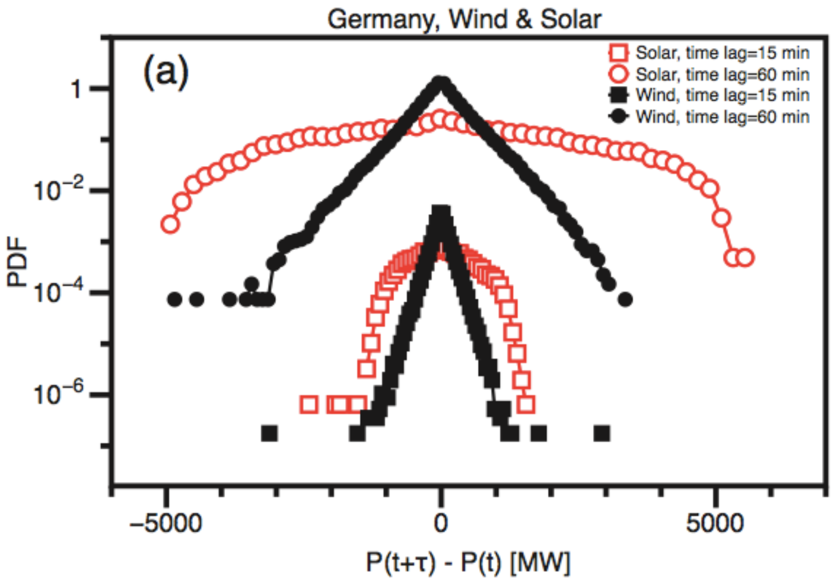


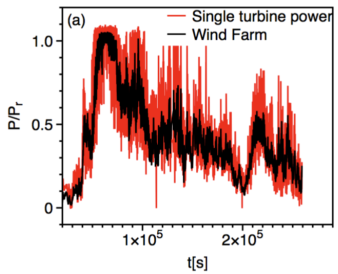




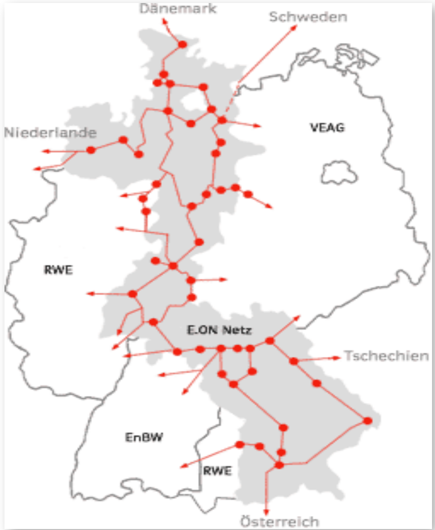
nature of solar and wind power

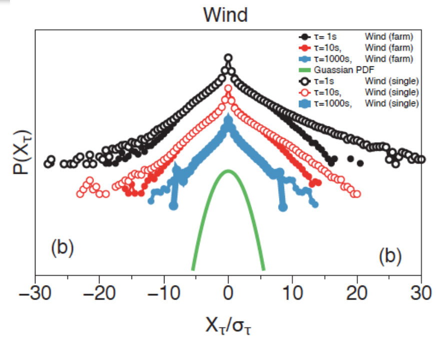






handling high frequency - heavy tailed statistics

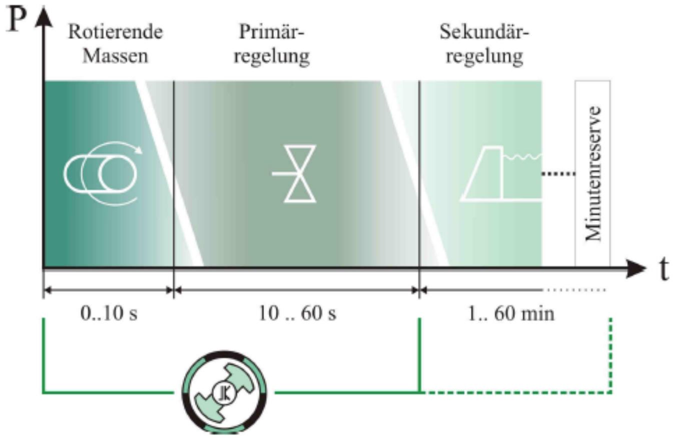




short time grid frequency

stabilisation by rotating mass of synchronous generators — grid frequency changes in the range of mHz

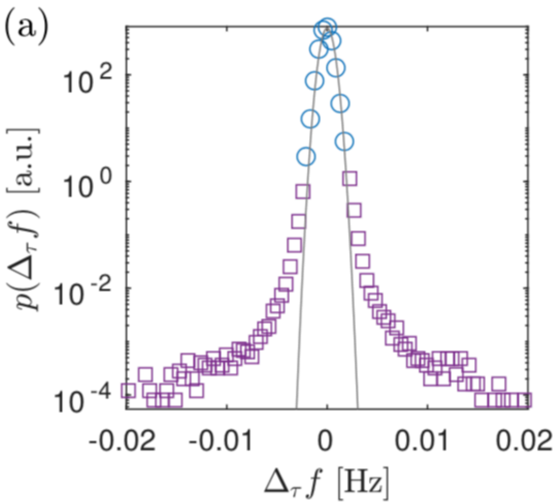
www.netzfrequenzmessung.de

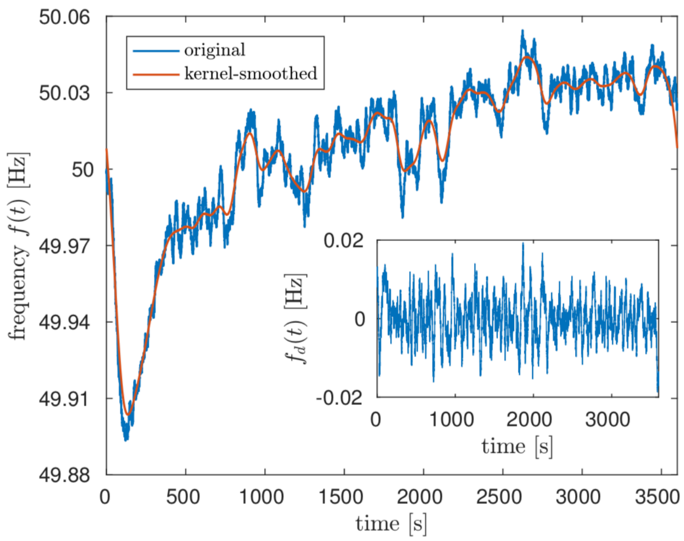


ForWind Zentrum für Windenergieforschung Bremen Hannover Oldenburg analysis of the grid frequency

- frequency increments

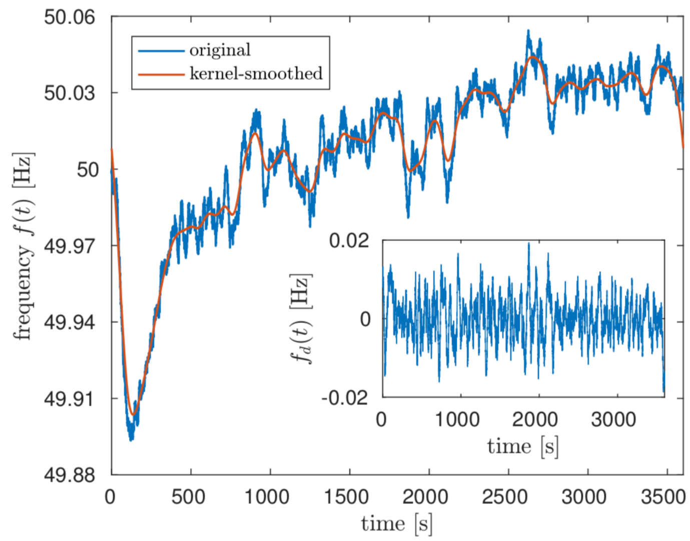
$$\tau < 1sec$$

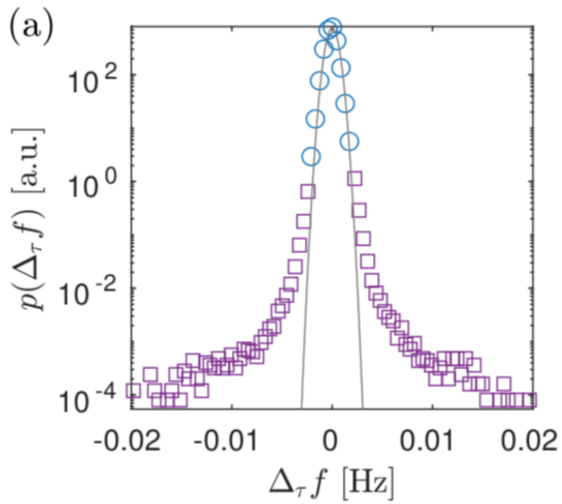


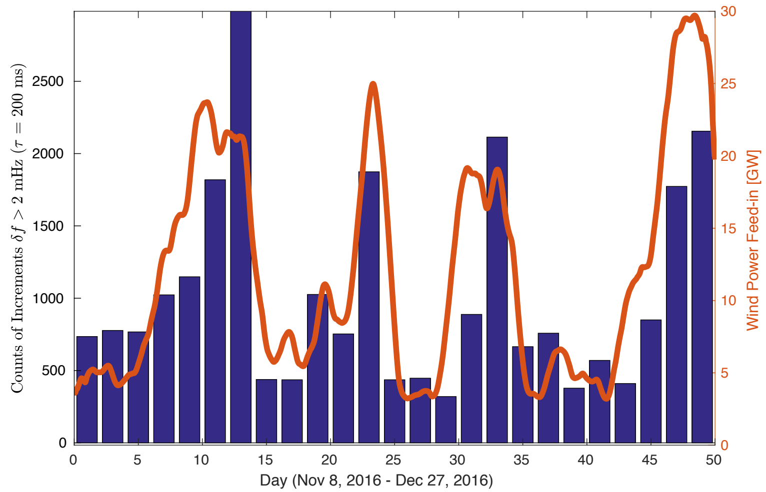


analysis of the gird frequency

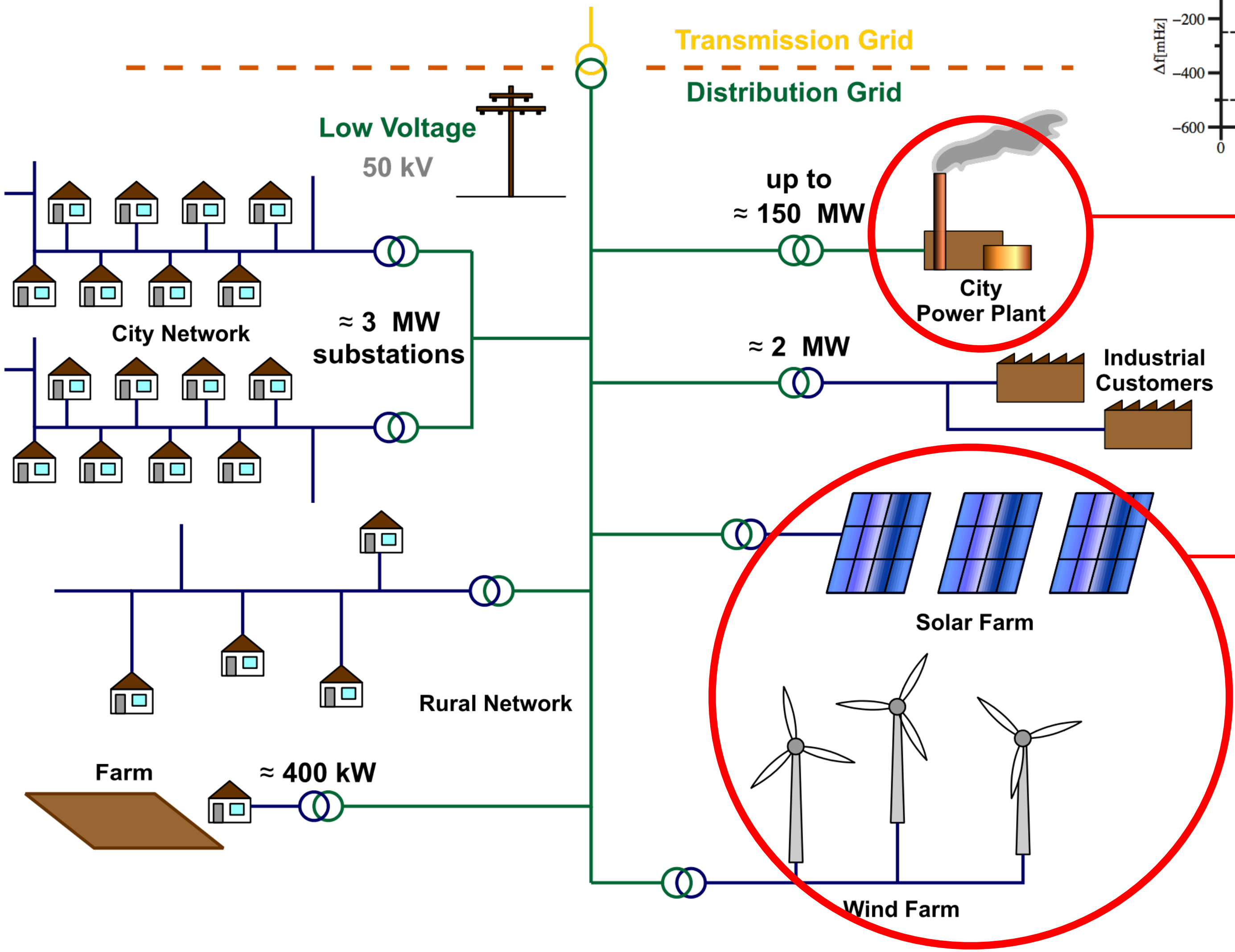
— clear fingerprint of renewable energies

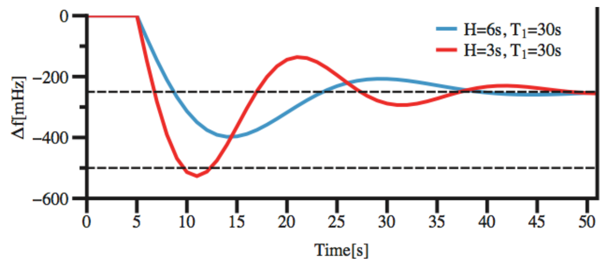






http://arxiv.org/abs/1802.00628





Traditional Generators with rotational inertia

Renewable sources with no rotational inertia

Wikipedia

wind (Solar) power forecasting

Stability of the grid:

on time scales of hours quite well know system, manageable

on short time scales

- need proper understanding of fluctuations
- need efficient methods - batteries?? self-adaption …..

voltage stability
constant voltages
(+/- 10%)

- **power balance**

↔

frequency stability
constant system frequency
(tolerance $O(10^{-1}$ Hz)

- **short time fluctuation**

↔

rotor angle stability
machines remain
synchronized

- **state of each node**

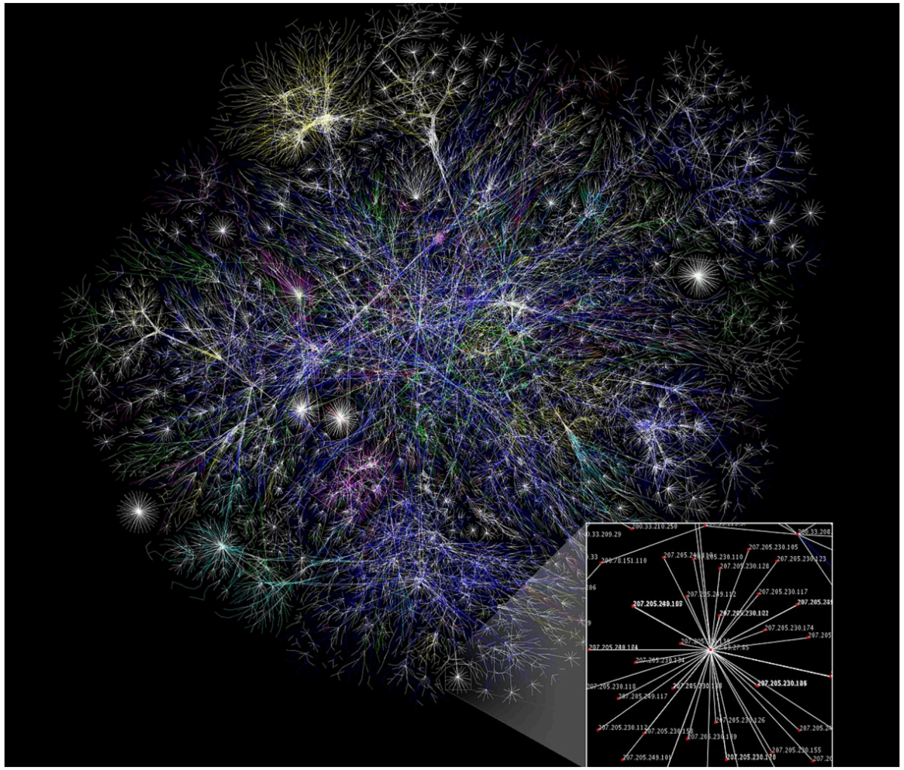
grid stability

grid stability

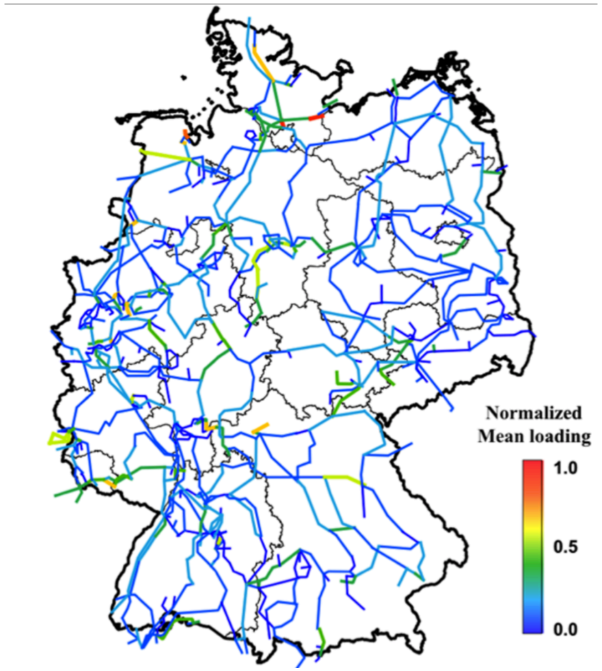
Complex networks

modern field of statistical physics

- internet, travel system, social interaction, brain ….. to - power grid

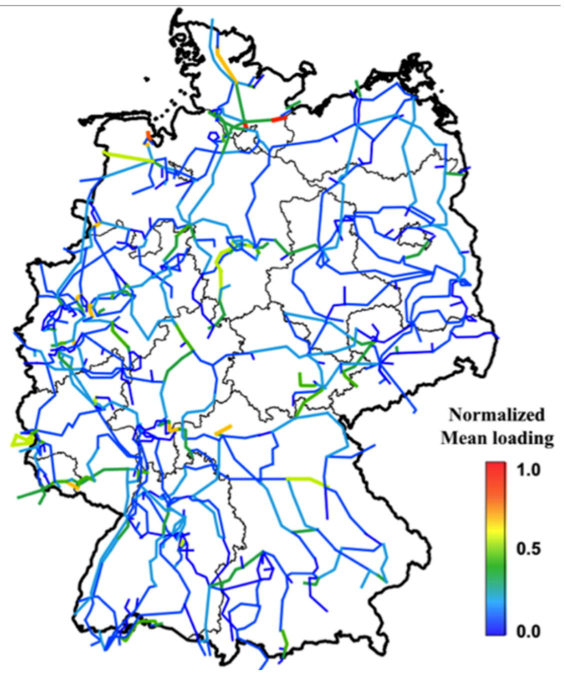


internet Wikipedia



power grid lower order nodes

grid stability



two aspects -

static one — (DC model) capacity of power lines

dynamics one — stability of phase synchronization

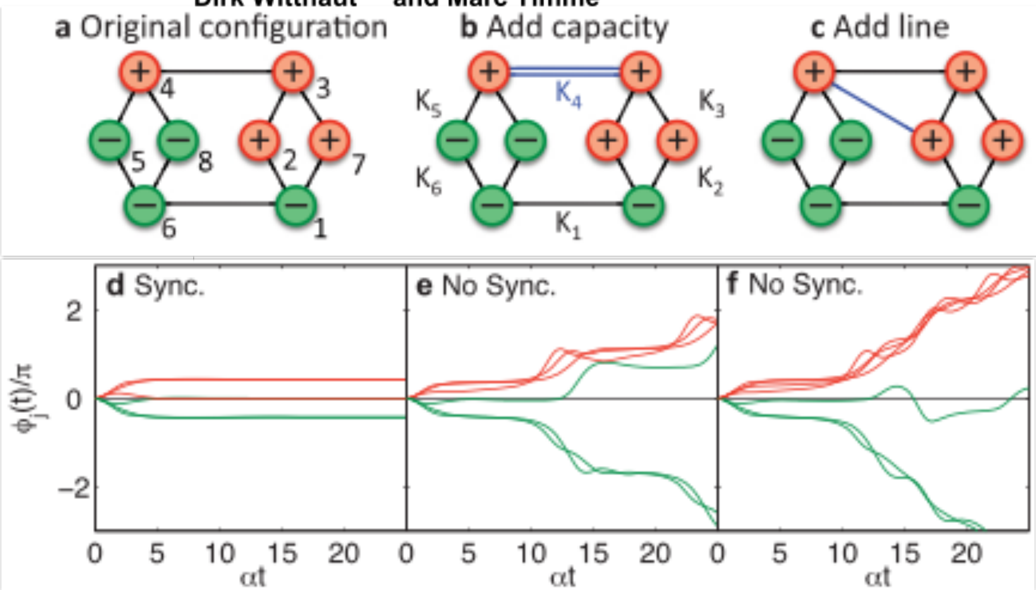
grid stability - static example

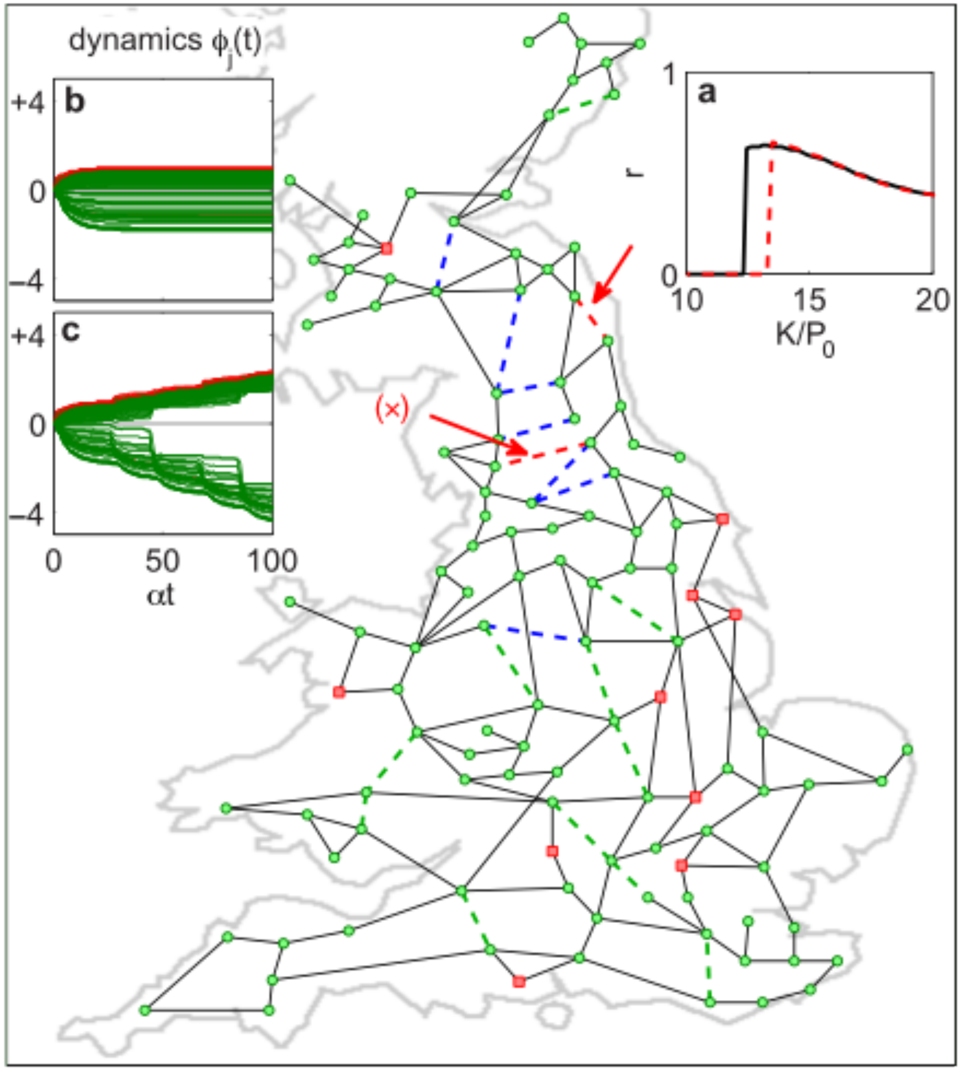
New Journal of Physics
The open-access journal for physics

Vol.14 (2012)

Braess's paradox in oscillator networks, desynchronization and power outage

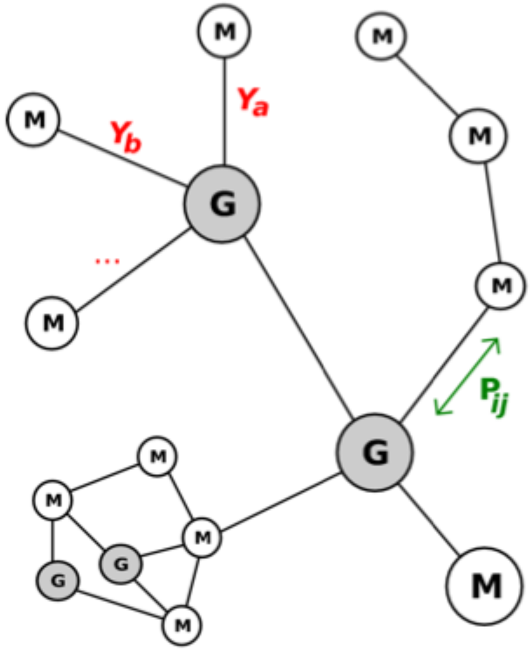
Dirk Witthaut[1,3] and Marc Timme[1,2]



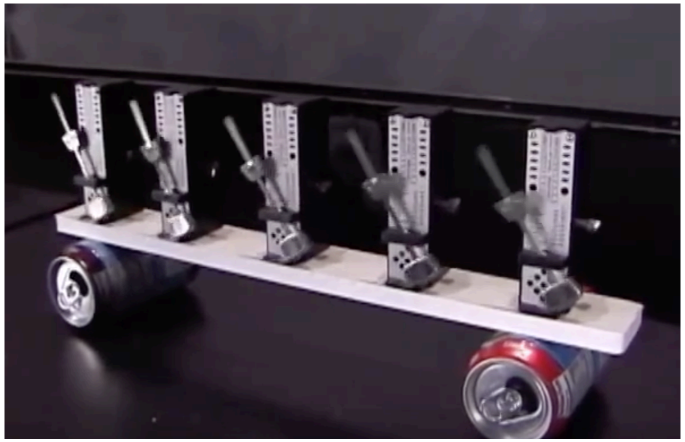


grid stability - dynamic examples
power grid basic features

alle nodes are nearly synchronised



https://www.youtube.com/watch?v=Aaxw4zbULMs

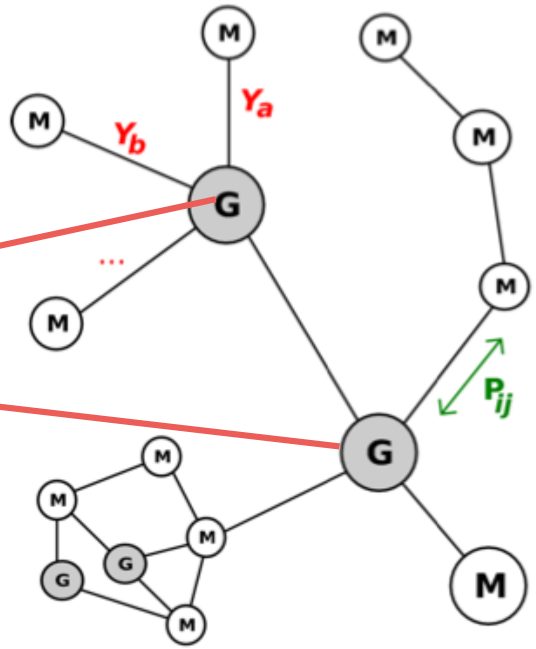


grid stability - dynamic examples
power grid basic features

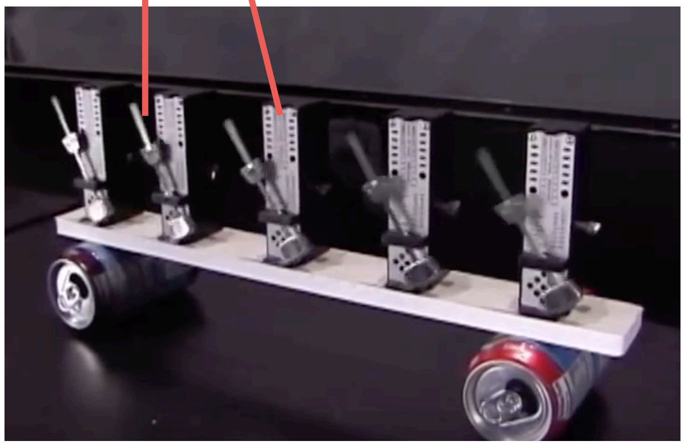
alle nodes are nearly synchronised

power flow is given by phase differences

$$P_{ij} = V_i V_j \left[B_{ij} \sin(\delta_i - \delta_j) + G_{ij} \cos(\delta_i - \delta_j) \right]$$



https://www.youtube.com/watch?v=Aaxw4zbULMs



grid stability - dynamic examples
power grid basic features

alle nodes are nearly synchronised

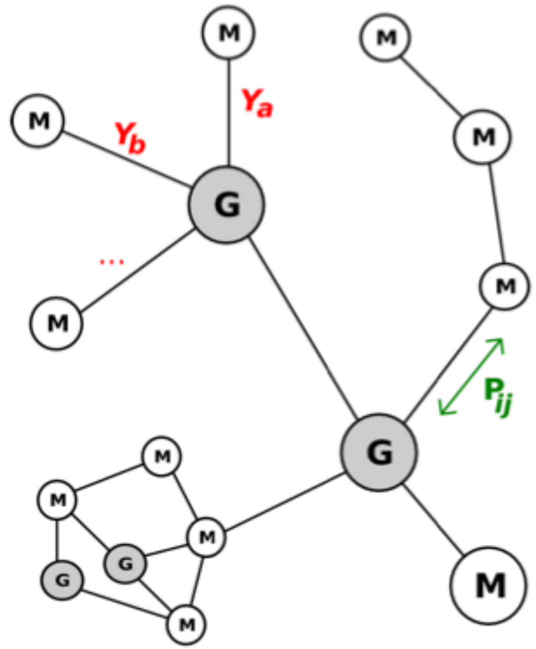
power flow is given by phase differences

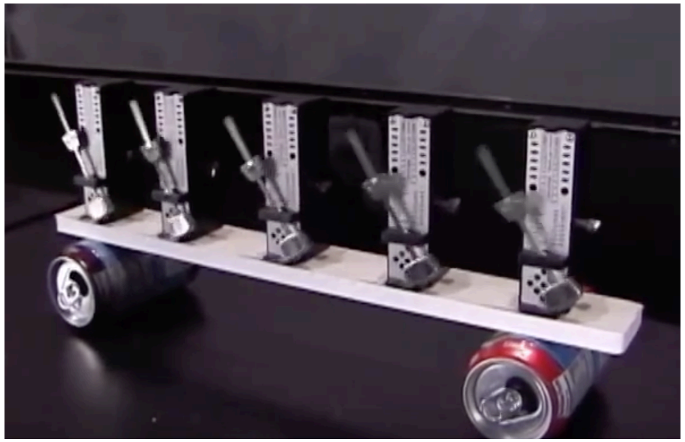
$$P_{ij} = V_i V_j \left[B_{ij} \sin(\delta_i - \delta_j) + \cancel{G_{ij} \cos(\delta_i - \delta_j)} \right]$$

!

-> KM

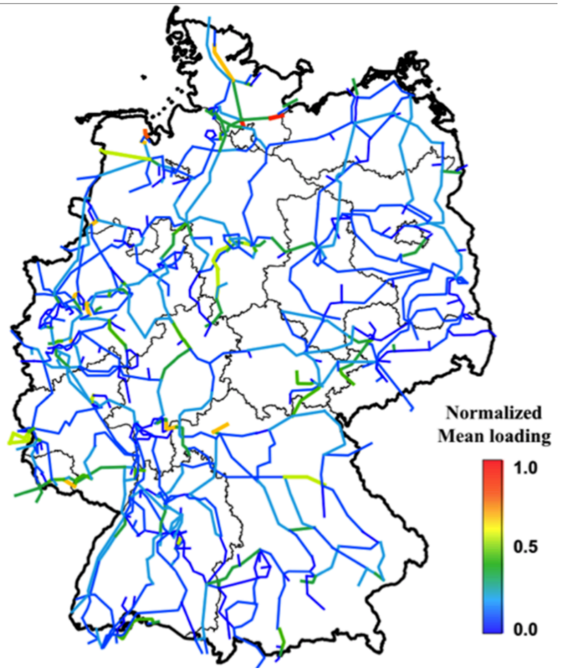
lossless grids:
$G_{ij} = 0$





grid stability

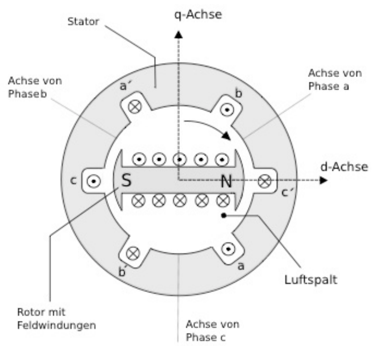
modelling of gird dynamics

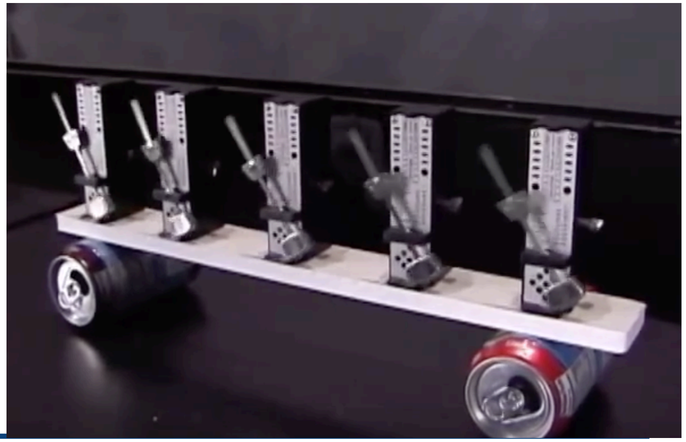


coupled oscillators

Kuramoto equation

synchron generators



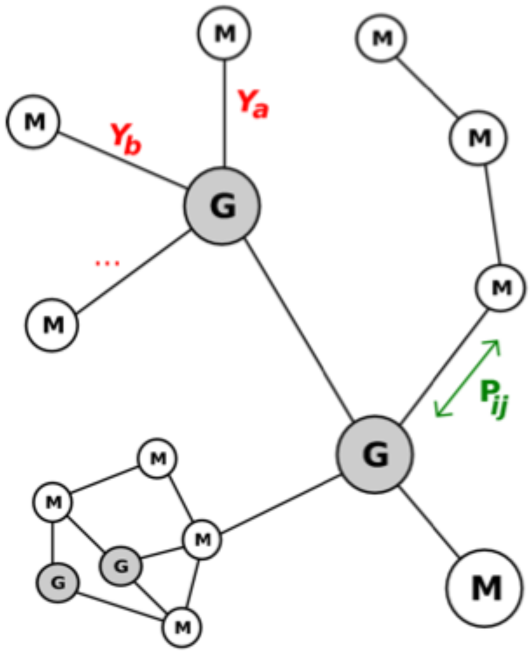


grid stability

power grid basic features

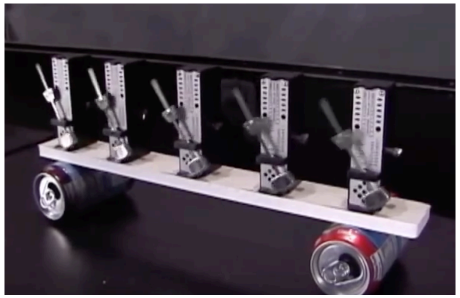
alle nodes are nearly synchronised

- interaction over phase difference



$$\ddot{\delta}_i = -\gamma_i \dot{\delta}_i + P_{\mathrm{m},i} - \sum_{j=1}^{N} E_i(t) E_j(t) B_{ij} \sin(\delta_i - \delta_j)$$

$$\alpha_i \dot{E}_i = C_i - \Gamma_i E_i + \chi_i \sum_{j=1, i \neq j}^{N} E_j(t) B_{ij} \cos(\delta_i - \delta_j)$$

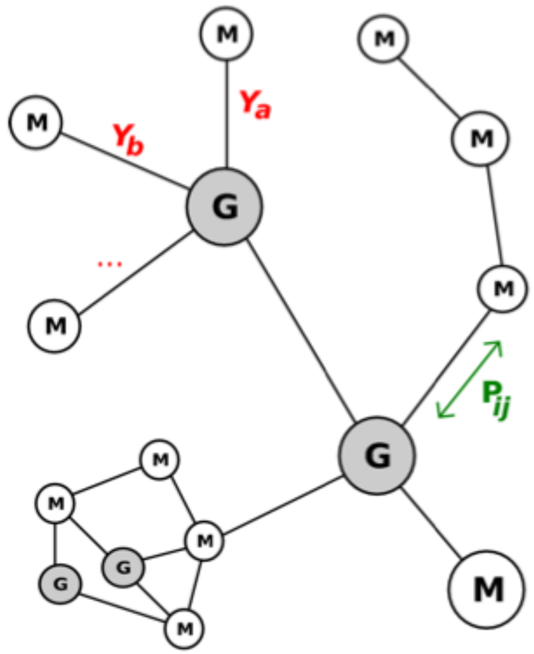


grid stability

power grid basic features

alle nodes are nearly synchronised

- interaction over phase difference



$$\ddot{\delta}_i = -\gamma_i \dot{\delta}_i + P_{\mathrm{m},i} - \sum_{j=1}^{N} E_i(t) E_j(t) B_{ij} \sin(\delta_i - \delta_j)$$

$$\alpha_i \dot{E}_i = C_i - \Gamma_i E_i + \chi_i \sum_{j=1, i\neq j}^{N} E_j(t) B_{ij} \cos(\delta_i - \delta_j)$$

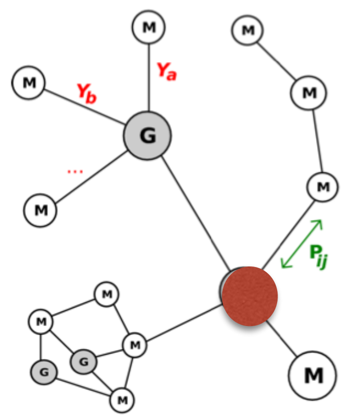
Kuramoto Model

$$\dot{\theta}_i = \omega_i + \sum_{j=1}^{N} K_{ij} \sin(\theta_j - \theta_i)$$

grid stability

power grid basic features

dynamics of one node



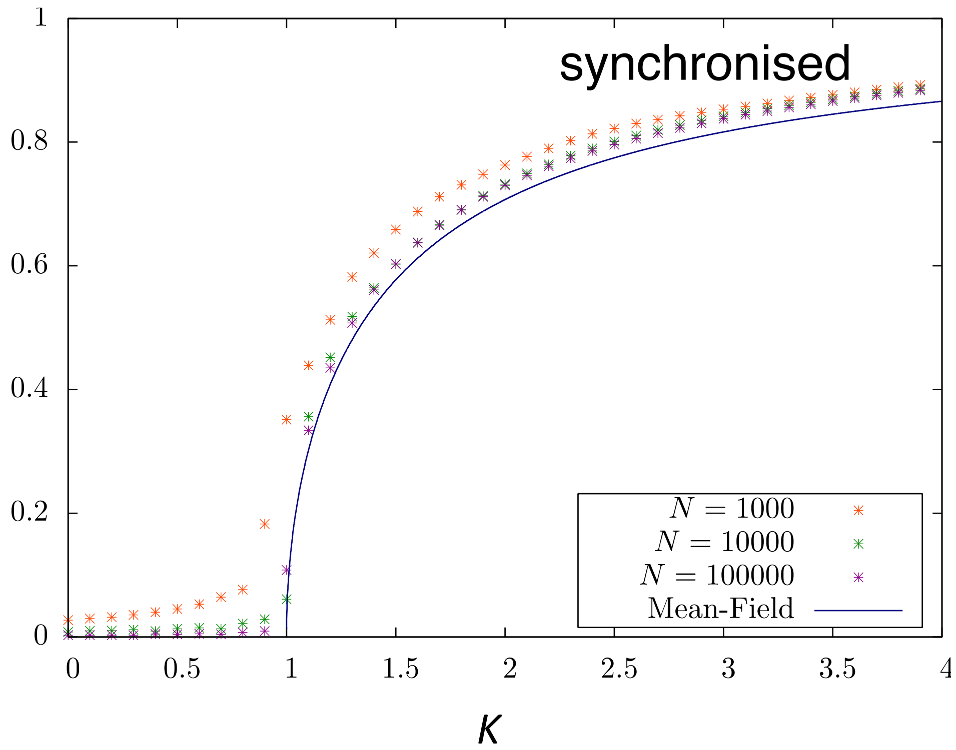
mean field:

- global all-to-all coupling $K_{ij}=K/N$
- infinite number of oscillators

$$\dot{\theta}_i = \omega_i + K r \sin(\Psi - \theta_i)$$

r : measure of phase coherence
ψ: average phase

phase transition from incoherence to partially synchronized states at critical coupling K_c



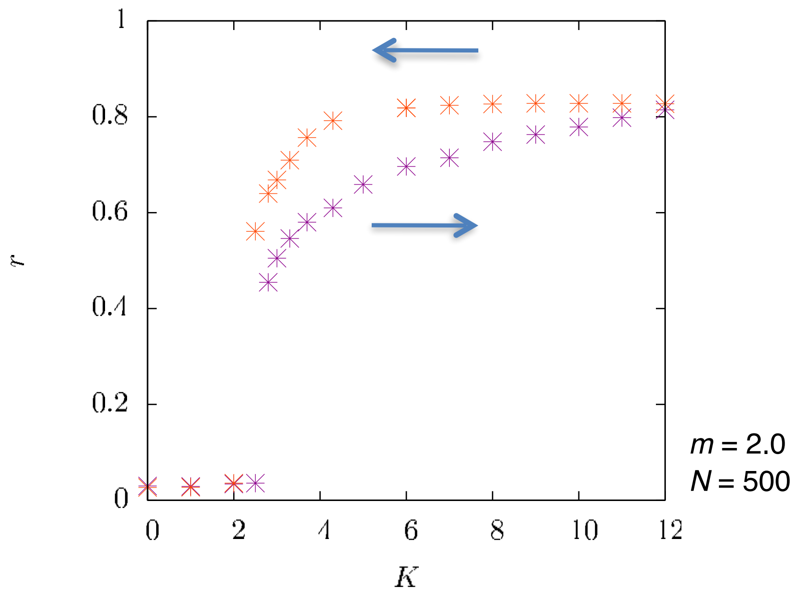
Research Alliance Wind Energy

ForWind Center for Wind Energy Research Bremen Hannover Oldenburg

KM Modifications

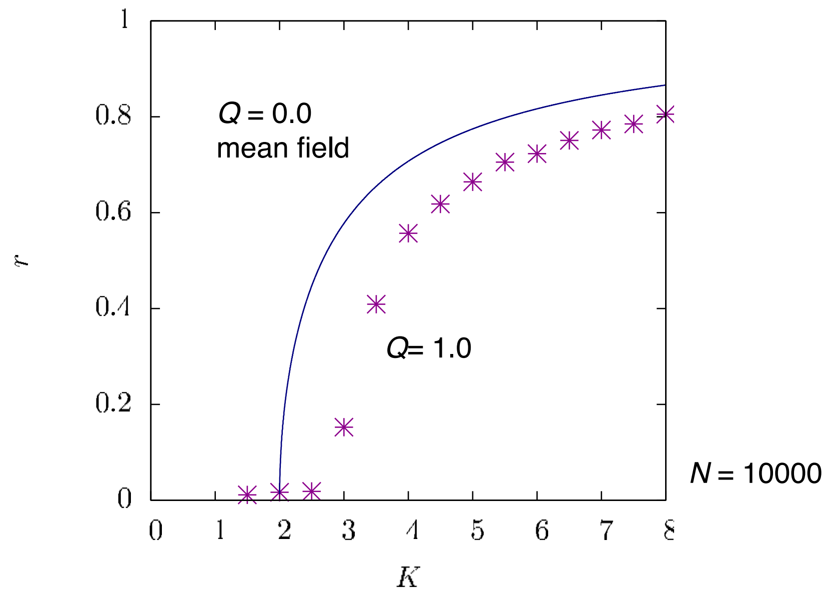
- inertia: -> hysteresis [Tanaka et al., PRL 97]

$$m\ddot{\theta}_i + \dot{\theta}_i = \Omega_i + Kr\sin(\Psi - \theta_i)$$



- noise [Bag et al. PRE 07], e.g. white noise

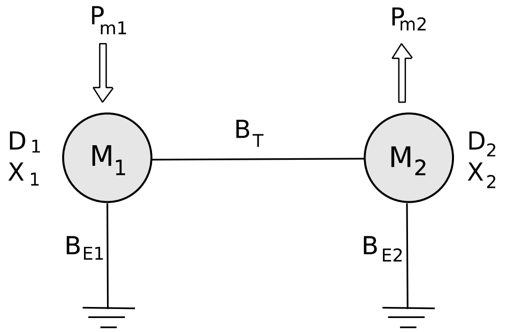
$$\dot{\theta}_i = \omega_i + Kr\sin(\Psi - \theta_i) + \xi_i(t)$$

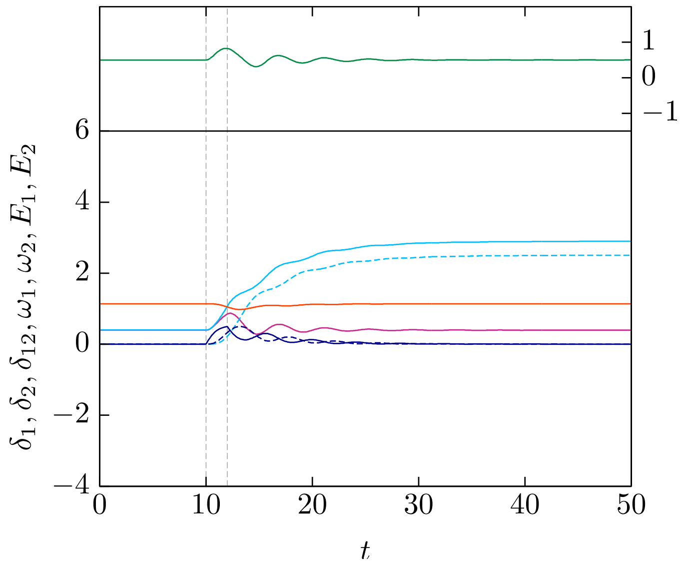


- various coupling topologies, different distributions of natural frequencies, delay, external fields [Acebron et al. 05]

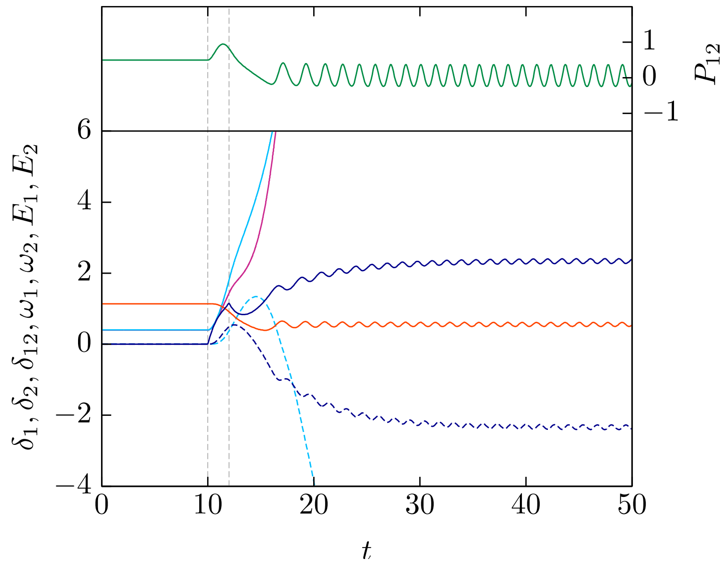
Basic Component: Two-machine system

perturbation scenario: temporal increase of mechanical input





stable



unstable

- power flow
- voltages
- phase angles
- frequencies
- phase angle difference

- operates in a coexistence region
- displays typical power system behaviour: after a disturbance the system either
  - returns to stationary operation (-> fixed point) or
  - transitions to unstationary operation (-> limit cycle)

- problem how to quantify the stability of the grid system

Stability of the fixed point

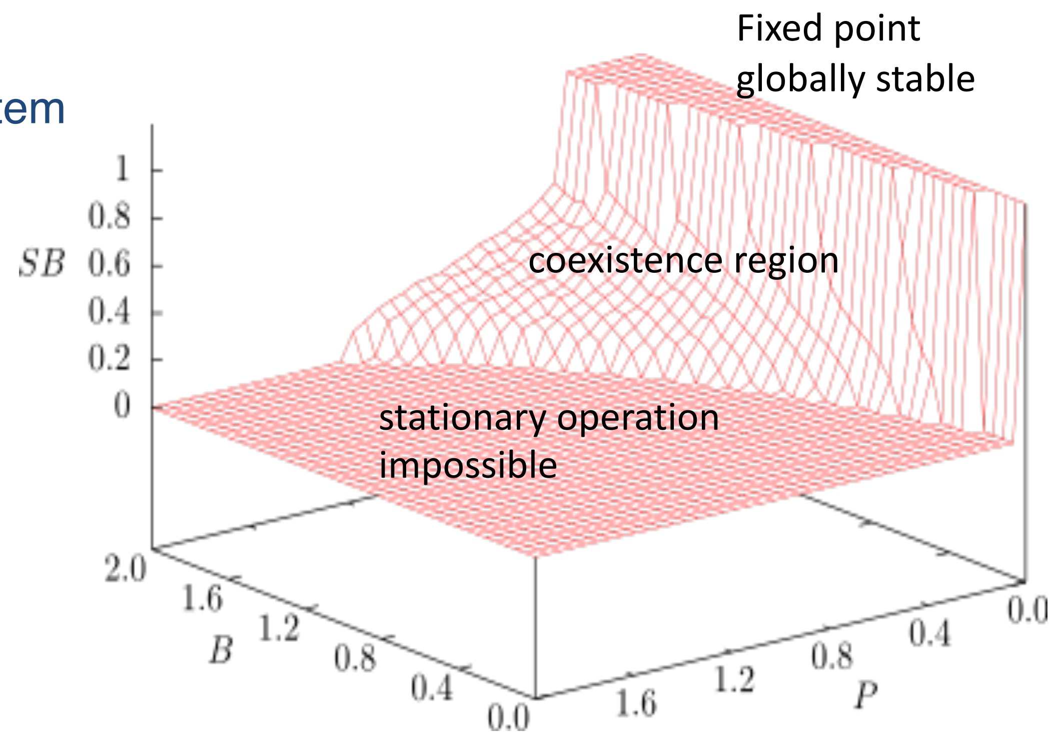
system is unstable in the sense of power system stability: it has left the fixed points' basin of attraction

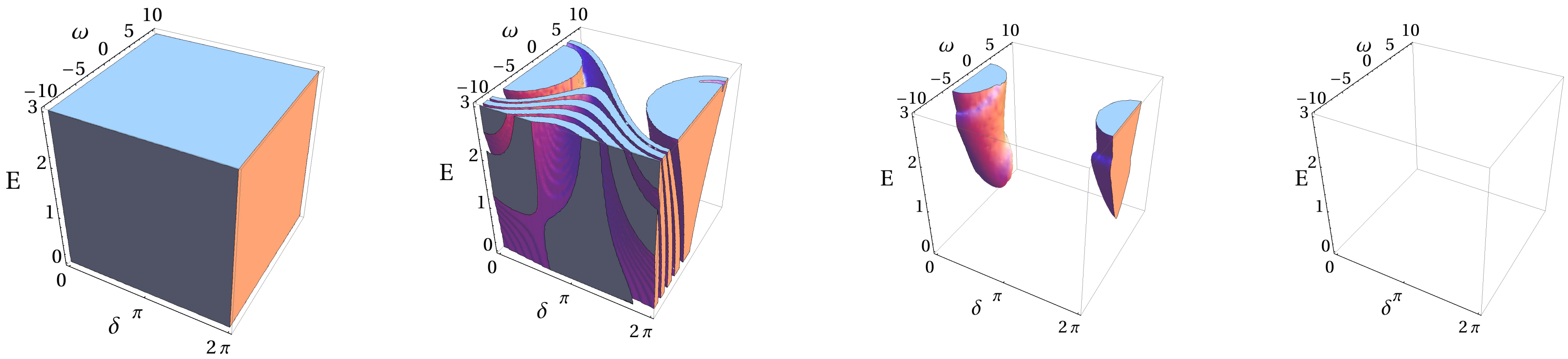
Basin Stability concept [Menck et al.]:

Nat. Commun. 5, 3969 (2014)

- M random initial conditions
- $$SB = \frac{M_{fp}}{M} \in [0, 1]$$

-> volume of the stability basin

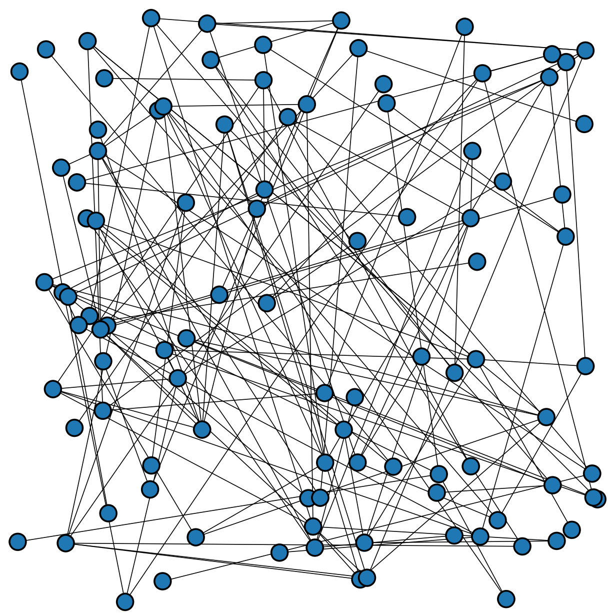




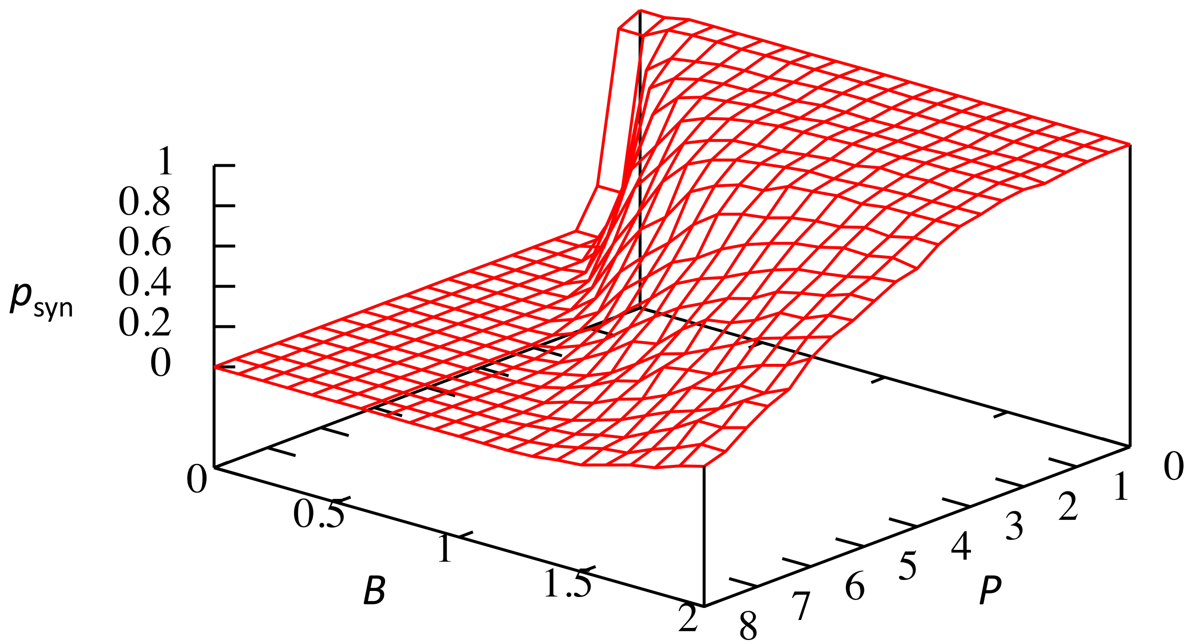
On a complex network topology

random network of $N = 100$ nodes,
50 generators and 50 motors

average degree 2.7



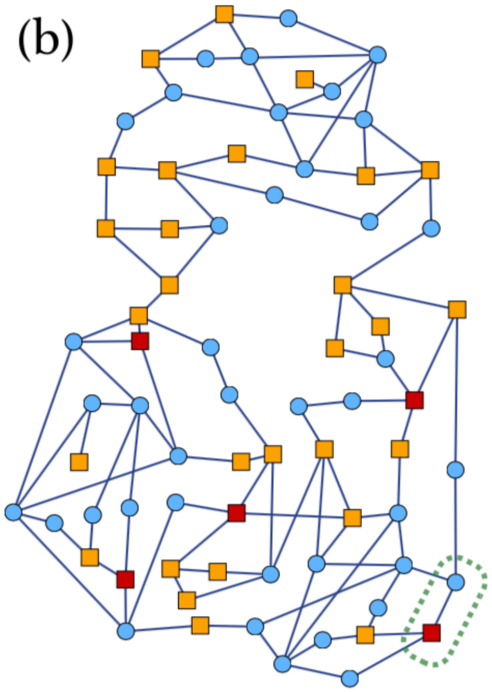
ensemble of 100 networks,
different initial conditions
-> synchronization probability p_{syn}



grid stability — impact of nonGaussian noise

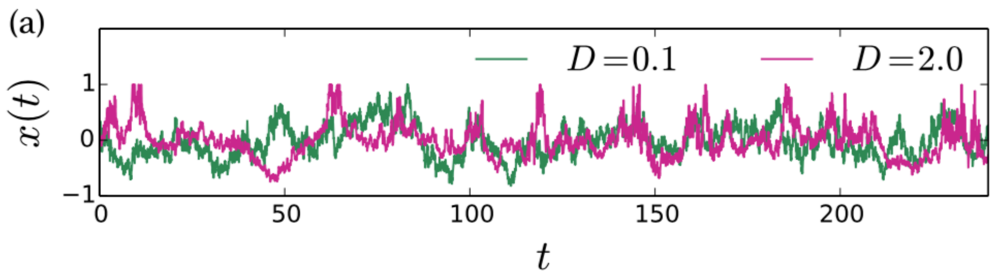
THE EUROPEAN PHYSICAL JOURNAL B

Schmiedender et. al.
Eur. Phys. J. B (2017) 90: 222
DOI: 10.1140/epjb/e2017-80352-8



IEEE Grid

frequency variation due to different intermittency

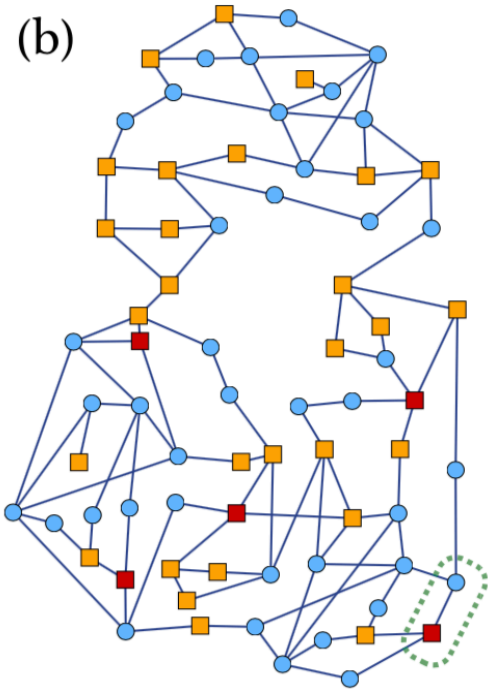


grid stability — impact of nonGaussian noise

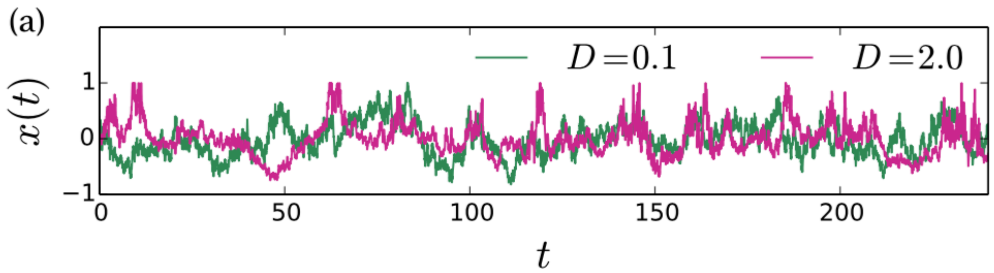
THE EUROPEAN PHYSICAL JOURNAL B

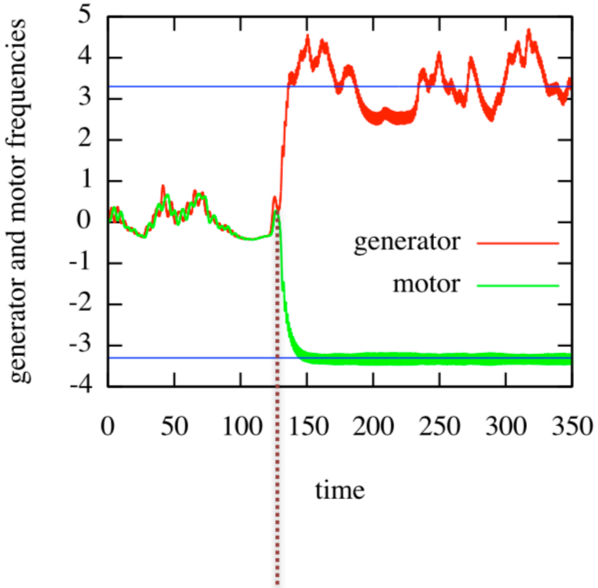
Schmiedender et. al.
Eur. Phys. J. B (2017) 90: 222
DOI: 10.1140/epjb/e2017-80352-8

frequency variation due to different intermittency



IEEE Grid





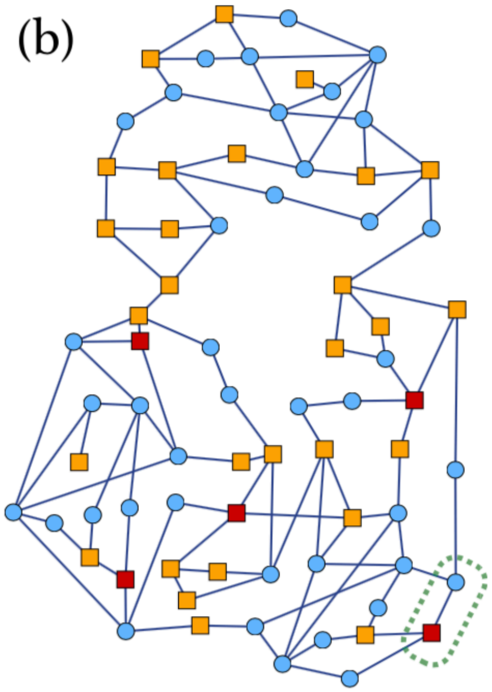
events of instability

escape time t=130

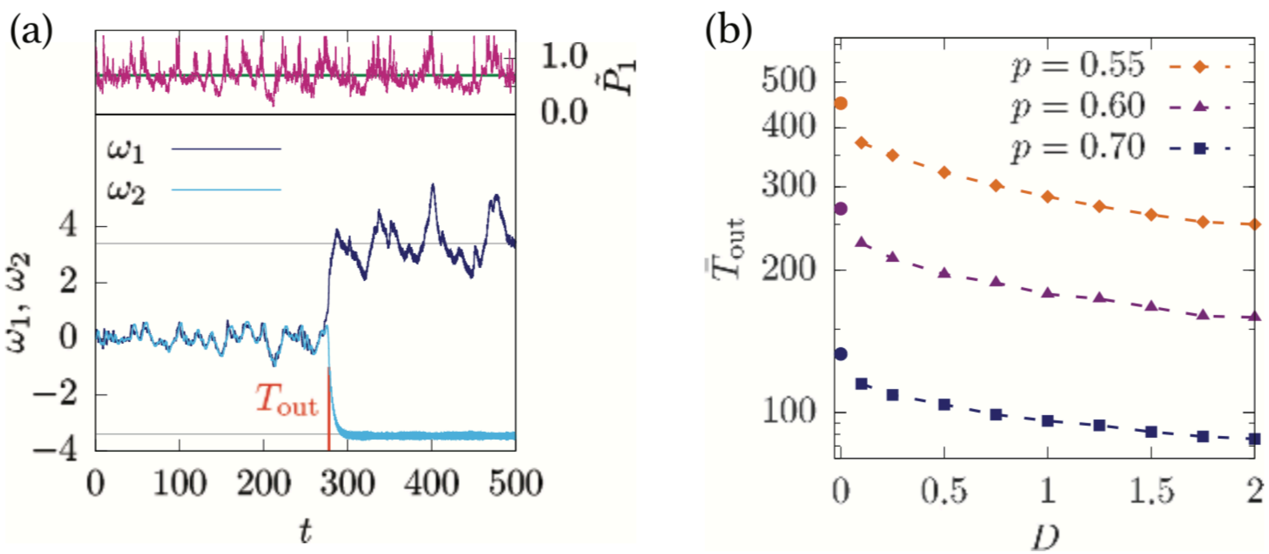
grid stability — impact of nonGaussian noise

THE EUROPEAN PHYSICAL JOURNAL B

Schmiedender et. al.
Eur. Phys. J. B (2017) 90: 222
DOI: 10.1140/epjb/e2017-80352-8



IEEE Grid



different stability due to different intermittency

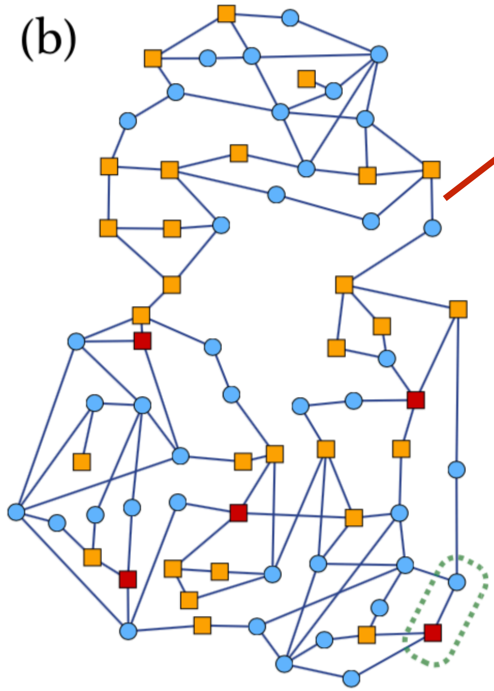
the higher D (intermittency the shorter the escape times)

Research Alliance Wind Energy

ForWind Center for Wind Energy Research Bremen Hannover Oldenburg

grid stability — summary

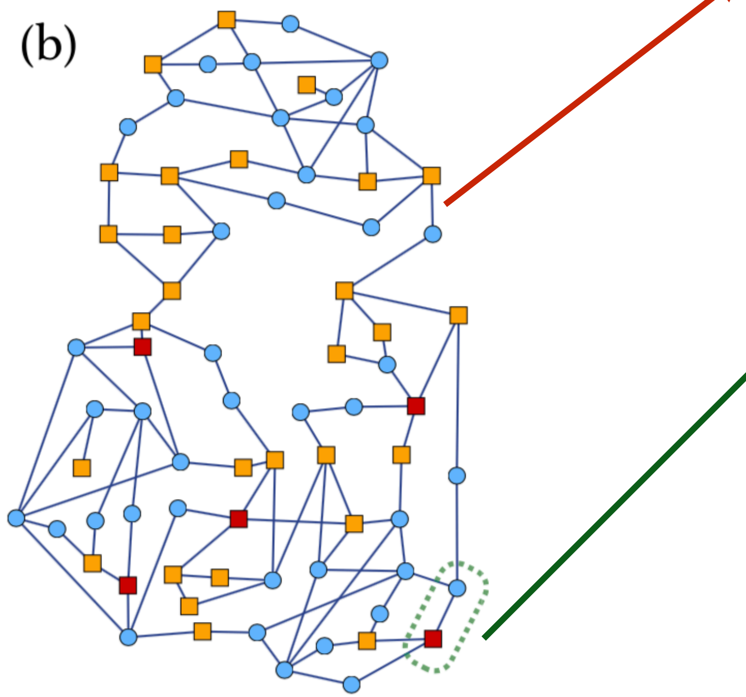
(b)



overloads of lines - black out

domino effect?

grid stability — summary



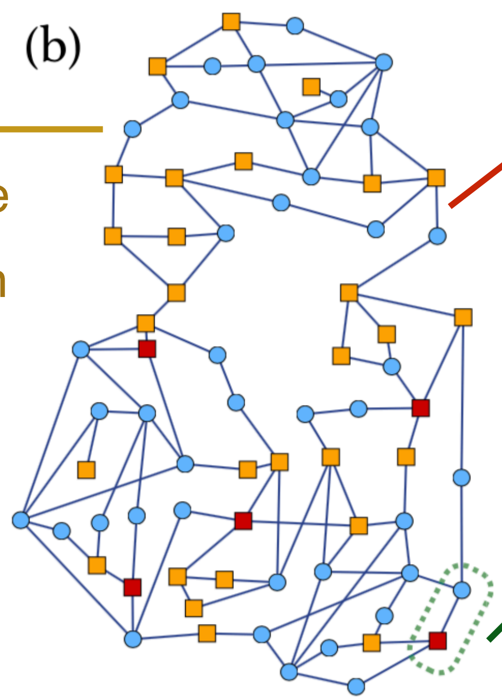
overloads of lines - black out

domino effect?

phase oscillation between two nodes - oscill. reactive power reduces line capacity

grid stability — summary

single node
- different frequency due
to two regions mismatch



overloads of lines - black out
domino effect?

phase oscillation between two
nodes - oscill. reactive power
reduces line capacity

grid stability — summary

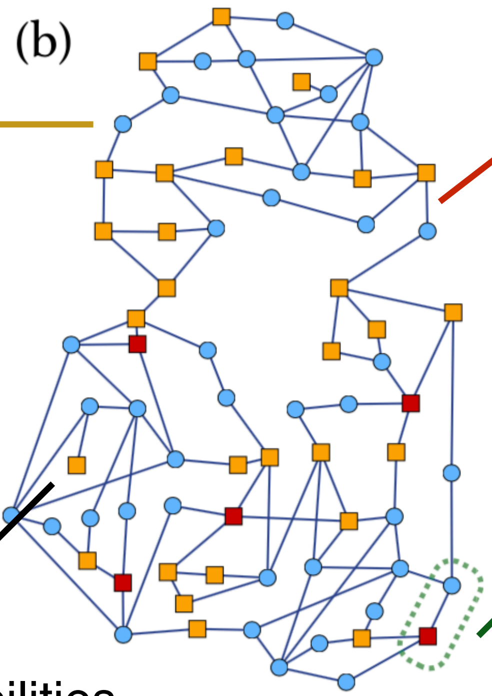
overloads of lines - black out

domino effect?

single node

- different frequency due

to two regions mismatch



phase oscillation between two

nodes - oscill. reactive power

reduces line capacity

sensitive node to instabilities

— end position

grid stability — summary

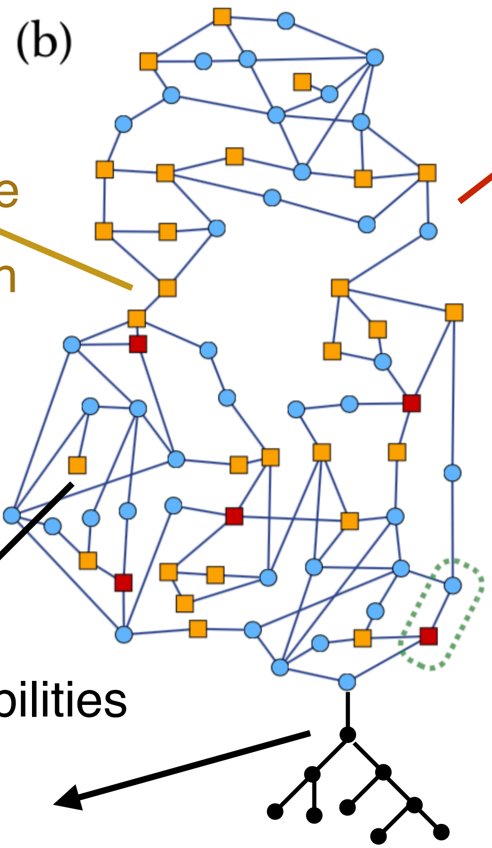
overloads of lines - black out

domino effect?

single node

- different frequency due

to two regions mismatch



phase oscillation between two

nodes - oscill. reactive power

reduces line capacity

sensitive node to instabilities

— end position

— root of a tree structure

grid stability — summary

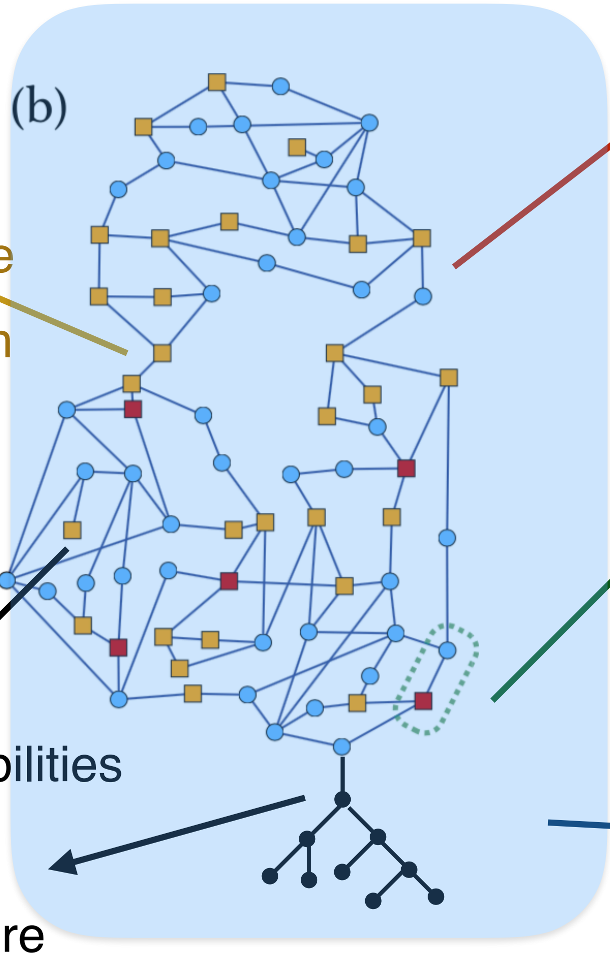
overloads of lines - black out

domino effect?

single node

- different frequency due

to two regions mismatch



phase oscillation between two

nodes - oscill. reactive power

reduces line capacity

sensitive node to instabilities

— end position

— root of a tree structure

all operating on a noisy

background

grid stability — summary

challenge to understand and predict these effects.

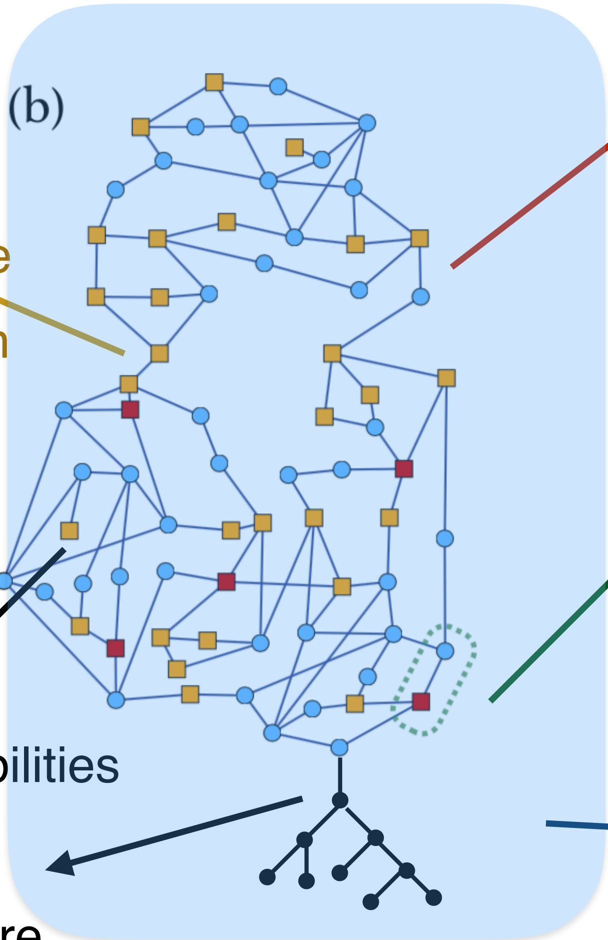
overloads of lines - black out

domino effect?

single node

- different frequency due

to two regions mismatch



phase oscillation between two

nodes - oscill. reactive power

reduces line capacity

sensitive node to instabilities

— end position

— root of a tree structure

all operating on a noisy

background

END — transition of the grid

Stability of the grid

different aspects (- forecasting - intermittency - dynamics of complex systems)

voltage stability
constant voltages (+/- 10%)

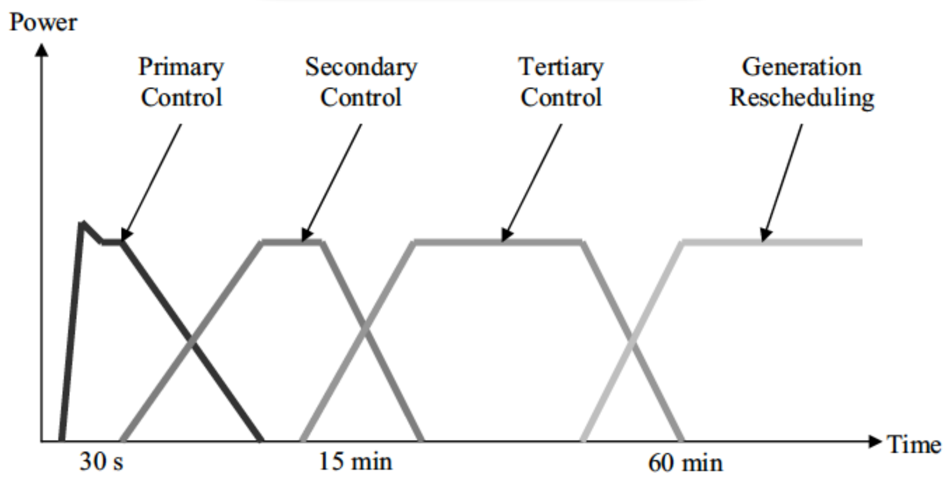
- power balance

frequency stability
constant system frequency (tolerance $O(10^{-1}$ Hz)

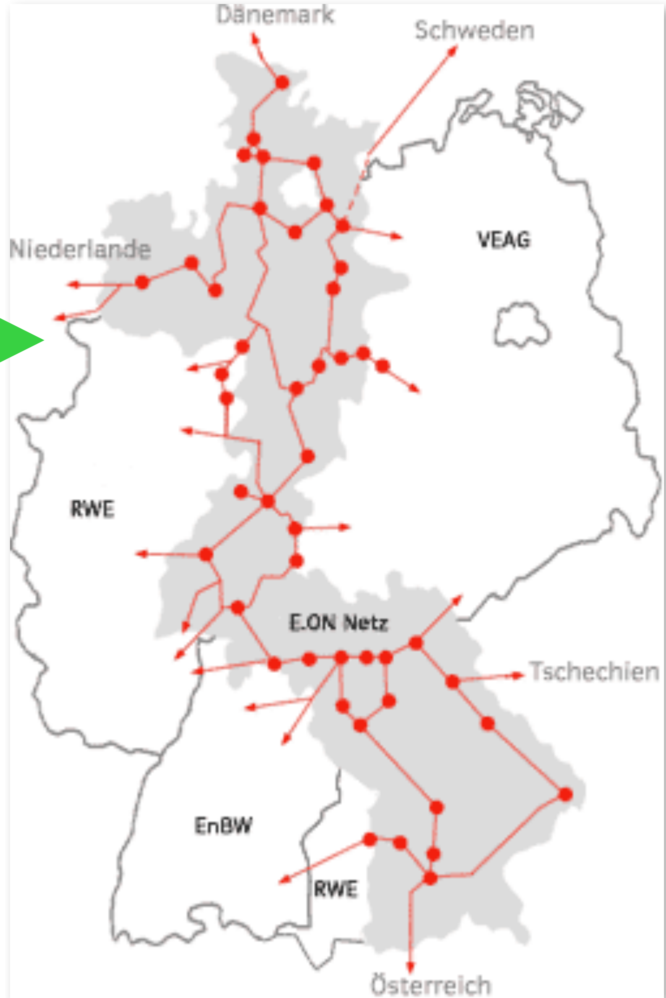
- short time fluctuation

rotor angle stability
machines remain synchronized

- state of each node



transition of the grid is more than adding only renewable sources to the grid - there are challenges:
- smart solution are necessary
- concept of physics of use



references

grid:

P.J. Menck, J. Heitzig, J. Kurths, H.J. Schellnhuber, Nat. Commun. 5, 3969 (2014)

D. Witthaut, M. Timme, New J. Phys. 14, 083036 (2012)

P. Menck, J. Heitzig, N. Marwan, J. Kurths, Nat. Phys. 9, 89 (2013)

K. Schmietendorf, J. Peinke, O. Kamps, R. Friedrich, Eur. Phys. J. Special Topics 223, 2577 (2014)

K. Schmietendorf, J. Peinke, O. Kamps, Eur. Phys. J. B 222, 90 (2017)

intermittency

M. Anvari, et al: New J. Phys. 18, 063027 (2016)

P.Milan,M.Wächter,J.Peinke,Phys.Rev.Lett.110, 138701 (2013)

R. Calif, F.G. Schmitt, Nonlinear Process. Geophys. 21, 379 (2014)

H. Hähne, et.al, The footprint of atmospheric turbulence in power grid frequency measurements http://arxiv.org/abs/1802.00628

wind power forecasts

St. Späth, L. von Bremen, C. Junk, D. Heinemann, Meteorologische Zeitschrift **24,** 381 (2015),

C. Junk, S. Spath, L. von Bremen, and L. Delle Monache, Weather and Forecasting, **30**, 1234 (2015)

https://www.youtube.com/watch?v=Aaxw4zbULMs

http://www.mainsfrequency.com/verlauf_en.htm