Transient interaction between wind turbine transformers and the collection grid of offshore wind farms

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Outline

- Project description
- Interaction between components
- Electrical resonance
- Resonance overvoltages
- Example: Energization of a radial
- Summary

PhD project

- This presentation is mostly based on results from Ph.D. project:
  - Technical University of Denmark
  - PhD project title: Compatibility of Electrical Main Components in Wind Turbines, EMC Wind
  - Duration: 2010:2013
  - PhD thesis: Interaction between components in wind farms.

What is transient interaction?

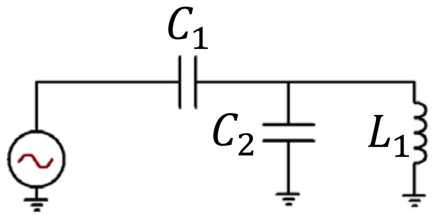
- In 1979, WG 12-07 (Transformers): “Resonance Behavior of High-Voltage Transformers”
  - resonance phenomenon is not a matter of a passive structure (transformer) alone
  - an active structure providing various sources of oscillating voltages needed
  - transformer resonance very difficult to occur and needs:
    - its winding’s natural frequency and excitation frequency coincide
    - amplitude of excitation voltage is sufficiently large and of appropriate duration
- 2013: Cigré Working Group A2/C4.39: Electrical Transient Interaction between Transformers and the Power System
  - ‘Transformers suffer dielectric failure even with good insulation coordination studies and well-accepted insulation design practices’.
- Investigation in OWF still needed

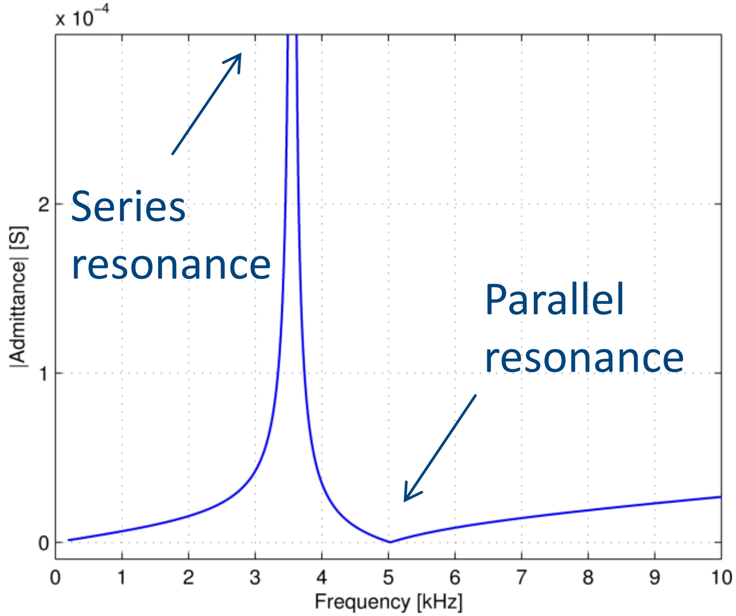
Electrical resonance

- Excitation of an electric system containing inductances and capacitances results in oscillations -> natural frequency

$$f = \frac{1}{2 \cdot \pi \cdot \sqrt{L \cdot C}}$$

- Resonance when periodic source has frequency similar to the circuit's natural frequency
- High amplification of voltage/current due to energy exchange between electric and magnetic field
- Depending on connection: series or parallel resonances





Resonance overvoltages

- Stationary resonance – stationary source of excitation

- Transient resonance – aperiodic excitation:
  - Two or more natural frequencies need to be present, i.e. network must contain at least two adjacent parts having similar resonance frequency:

$$\frac{1}{\sqrt{L_1 \cdot C_1}} = \frac{1}{\sqrt{L_2 \cdot C_2}}$$

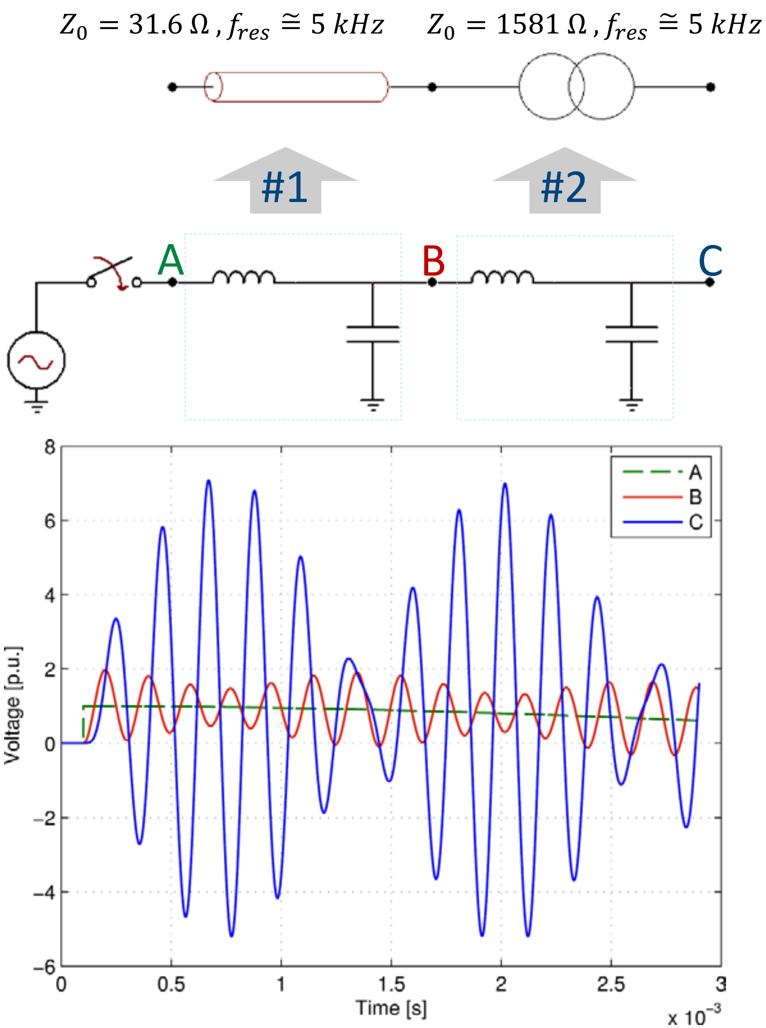
  - The two network parts have large difference in characteristic impedance, $Z_0 = \sqrt{\frac{L}{C}}$

$$\sqrt{\frac{L_1}{C_1}} \ll \sqrt{\frac{L_2}{C_2}}$$

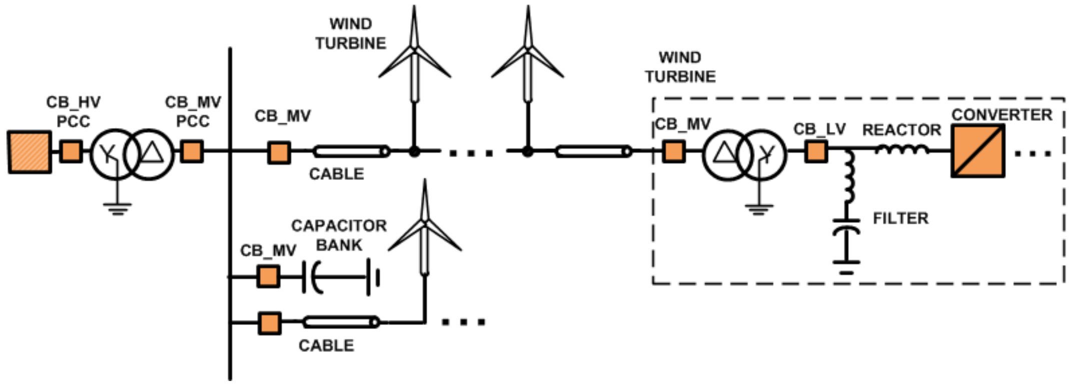
  - The source of the oscillation must come from the part of network characterized by the low characteristic impedance

Resonance overvoltage example

- The conditions might fulfilled for cable-transformer system
- Cable resonance frequency depends on length
- High overvoltages might occur on transformer terminals
- Important for Offshore Wind Farms, which contain large amount of cables and transformers
- Example might resemble energization of a radial



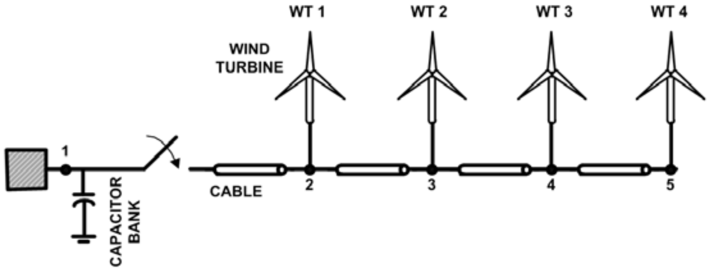
Sources of oscillations in OWF

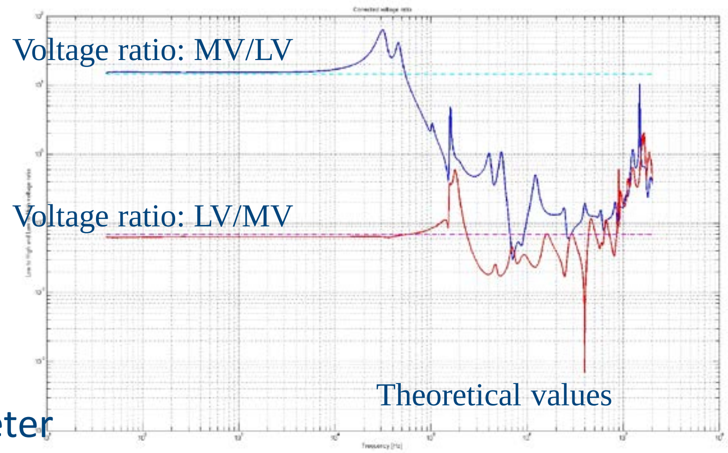


- Main sources of oscillations
  - External grid
  - Circuit breakers (HV, MV, LV) -> switching
  - Converter
  - Faults

Example: energization of a radial

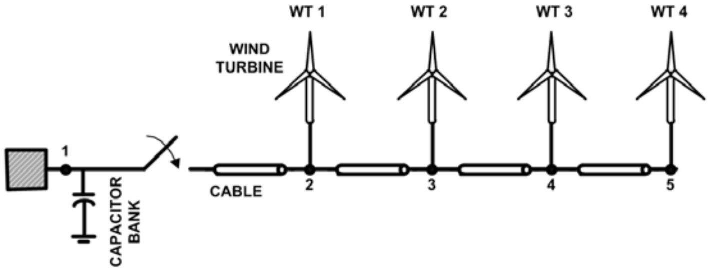
- External grid / park transformer -> X/R
- 3-phase submarine cable: 50 mm^2
  - 4 sections of 400 m
  - J.Marti models in ATP
- Wind turbines
  - 100 kVA transformer
    - Wide band model
    - Admittance matrix measurements
    - sFRA commercial device
    - Admittance matrix approximated with VF
    - Passivity enforced
    - Included in ATP-EMTP as a lumped parameter network
    - LV terminals left open

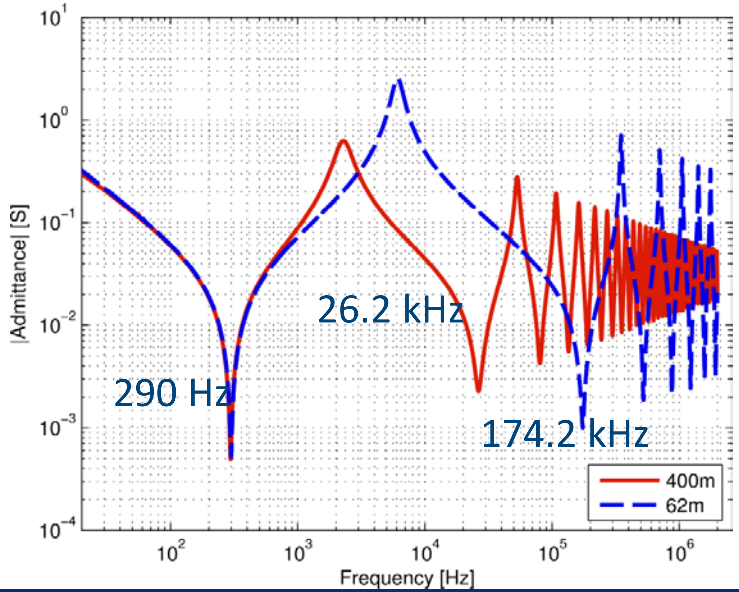


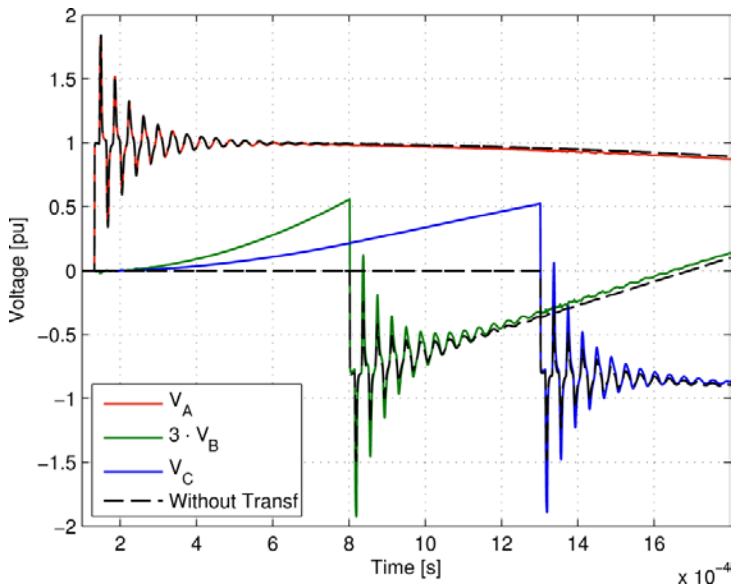


Example: energization of a radial

- Close breaker poles
- Voltage oscillation due to wave reflectio
- $f = \frac{1}{4\tau}, f = \frac{2n-1}{4l\sqrt{LC}} = \frac{2n-1}{4l} \cdot v = \frac{2n-1}{4\tau}$

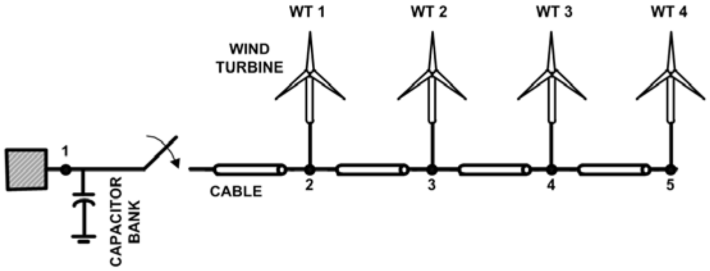




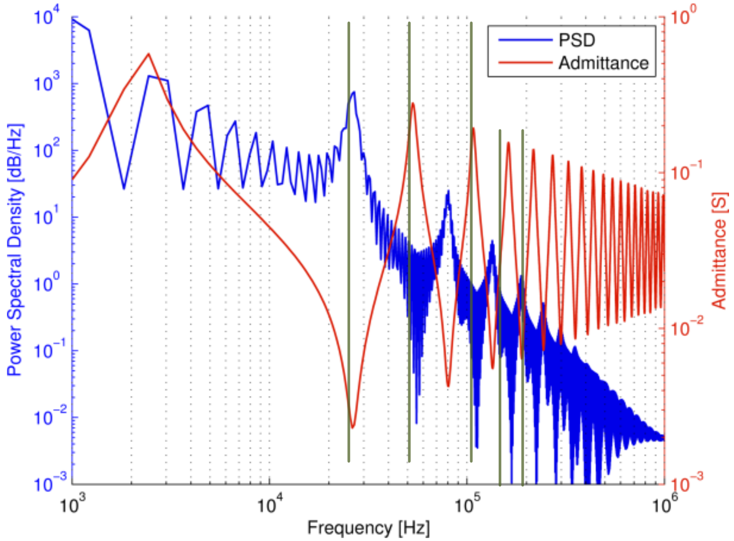


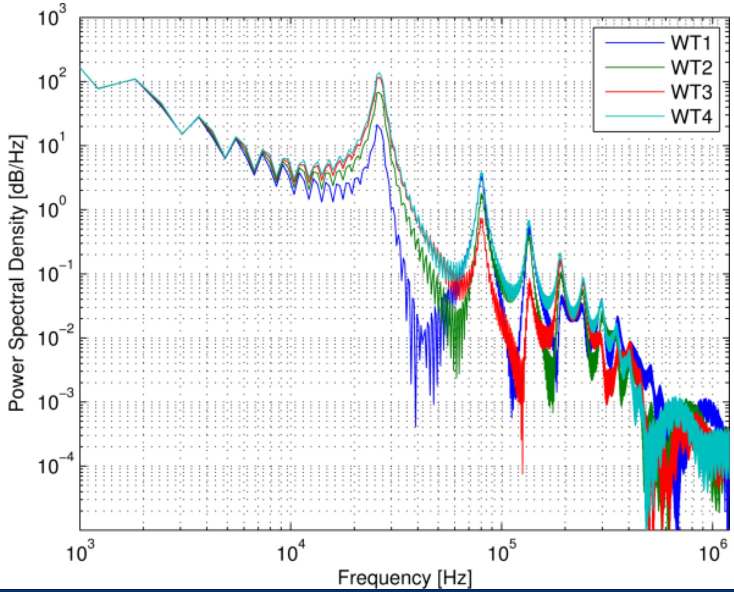
Example of resonance excitation in OWF

- Voltage oscillations visible at terminals of all wind turbines
- The same frequency at all turbines



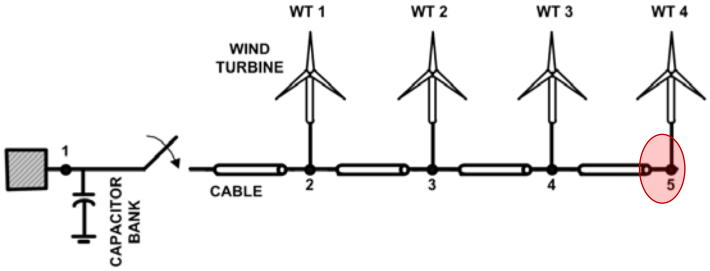
- Driving-point admittace at WT 4 and PSD of a surge waveforms at phase A

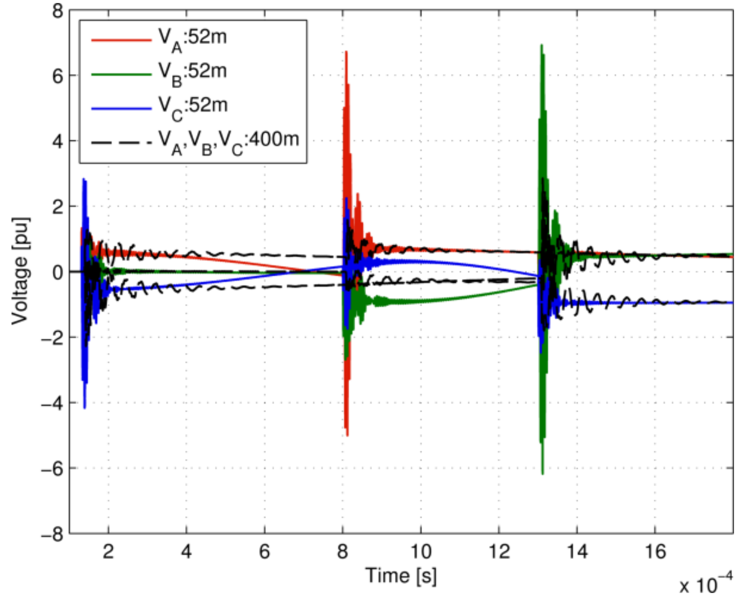


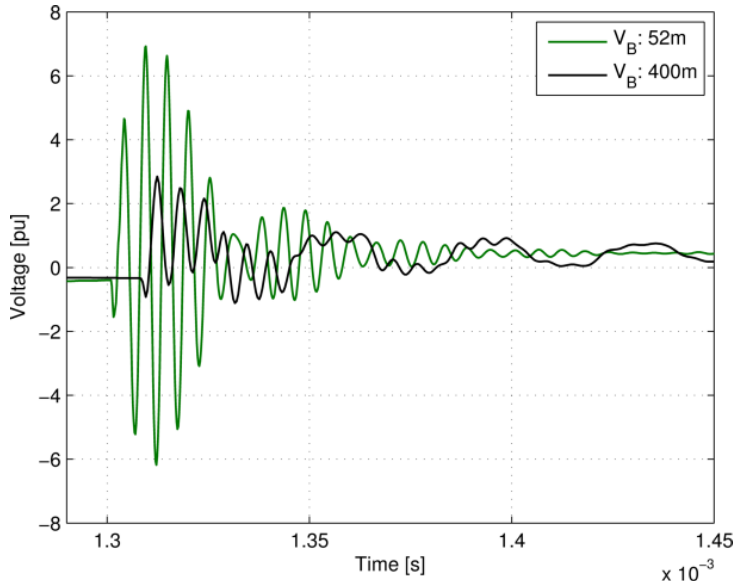


Example: resonance overvoltages

- Oscillation frequency matches resonance frequency of transformer
- Large overvoltage at LV terminals of transformer
- Magnitude depends also on loading

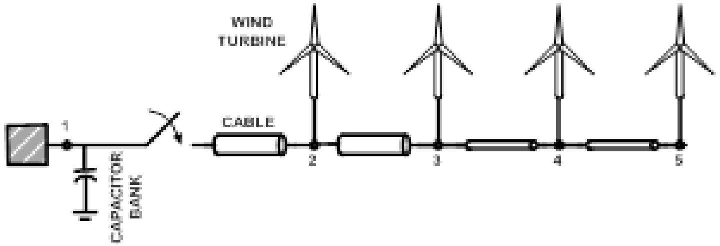


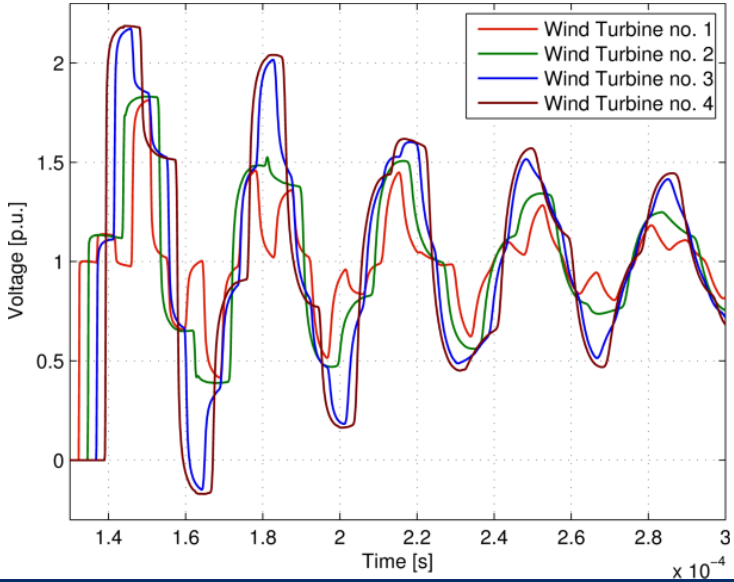


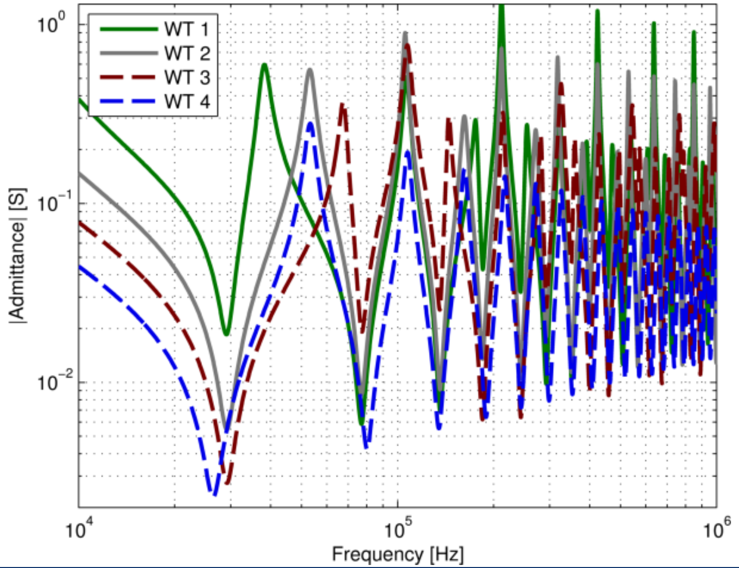


Influence of point of discontinuity for wave

- Cables of different cross sections
- Different cross-sections = different characteristic impedance Z_0
- Point of discontinuity = additional reflections
- Short cable lengths between point of dicontinuity = higher frequencies
- Might increase maximum overvoltage above 2 p.u.

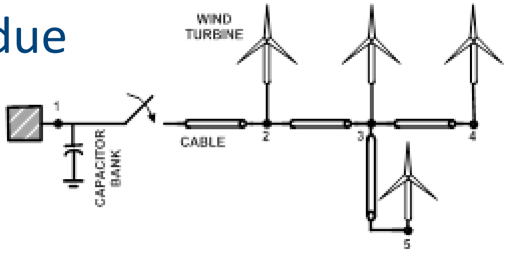


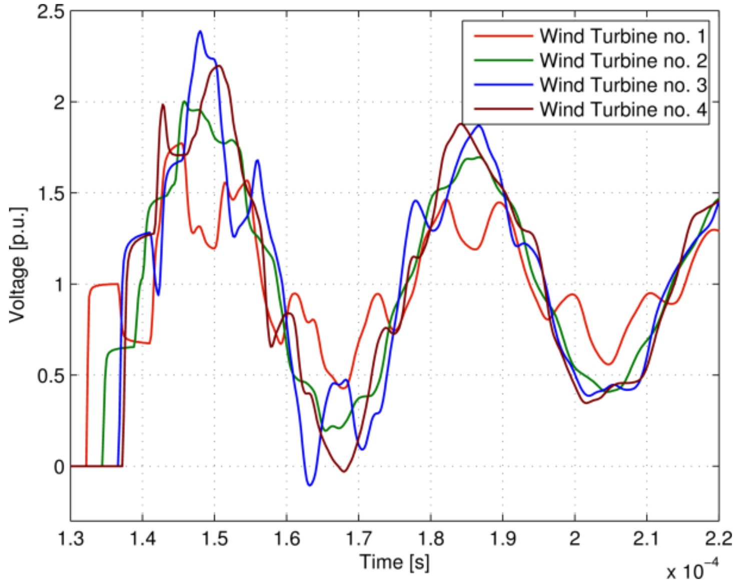


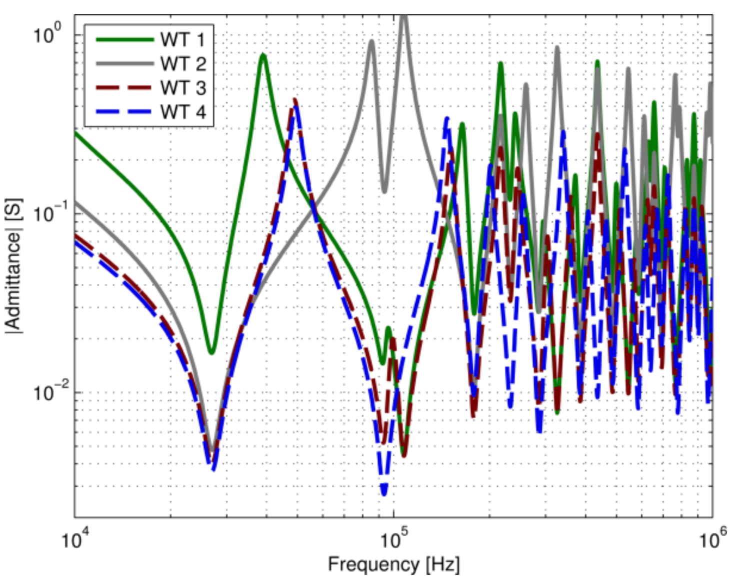


Influence of line bifurcation

- Subsections (branches) of strings often in large OWF
- Line bifurcation introduces additional reflections due to characteristic impedance missmatch
- Increases number of higher frequency oscillations
- Might cause maximum overvoltages > 2 p.u.

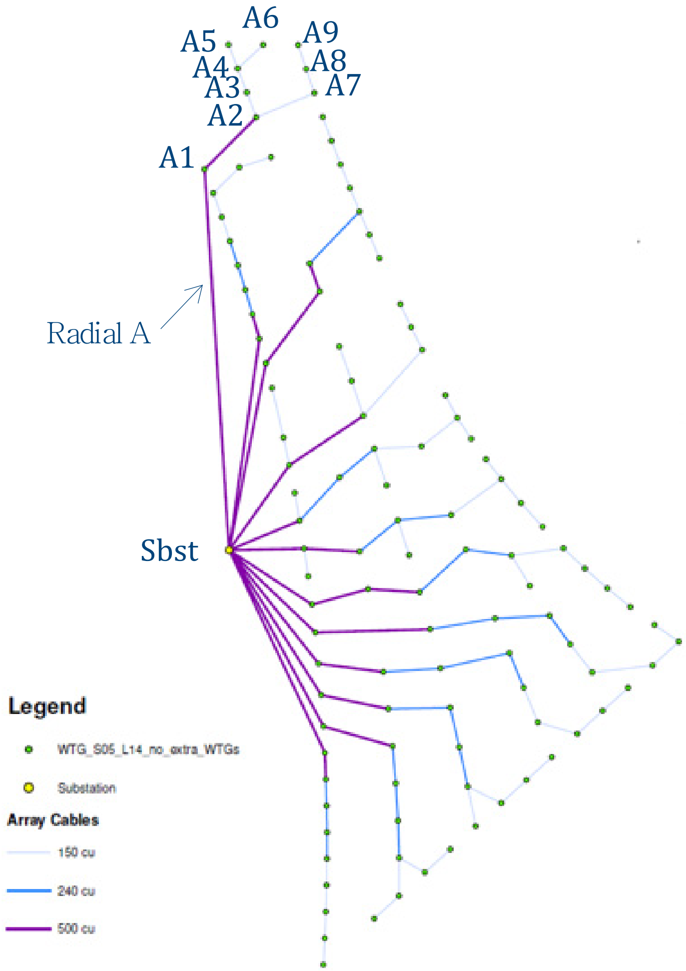






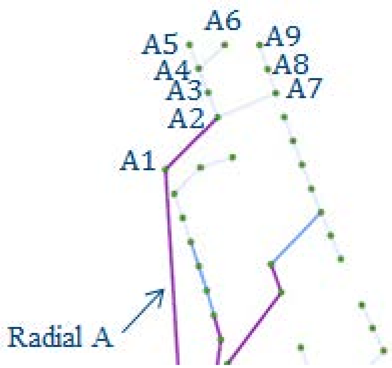
Example of OWF with complex topology

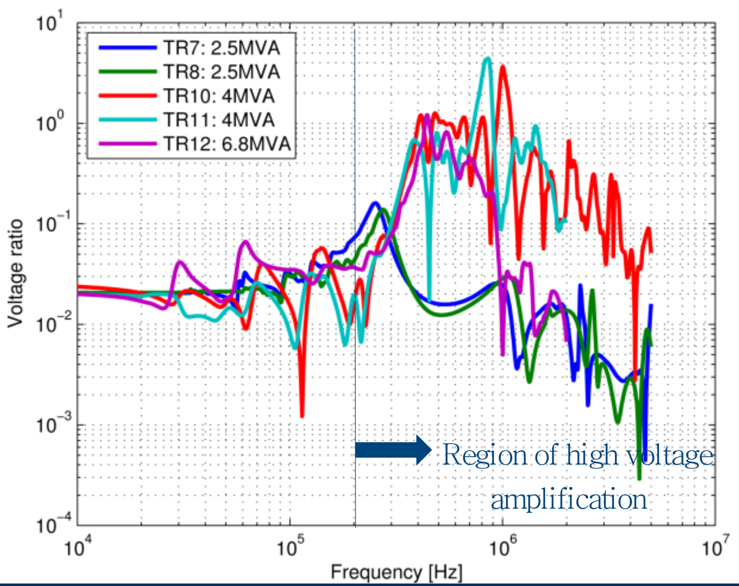
- Modern large OWF
- 111 x 3.6 MW wind turbines
- 12 strings
- 400 MW
- Cable cross-sections: (500, 240, 150 mm^2)
- Model:
  - ATP-EMTP
  - Frequency dependent cable model
  - Transformers based on SC and OC tests with additional capacitances

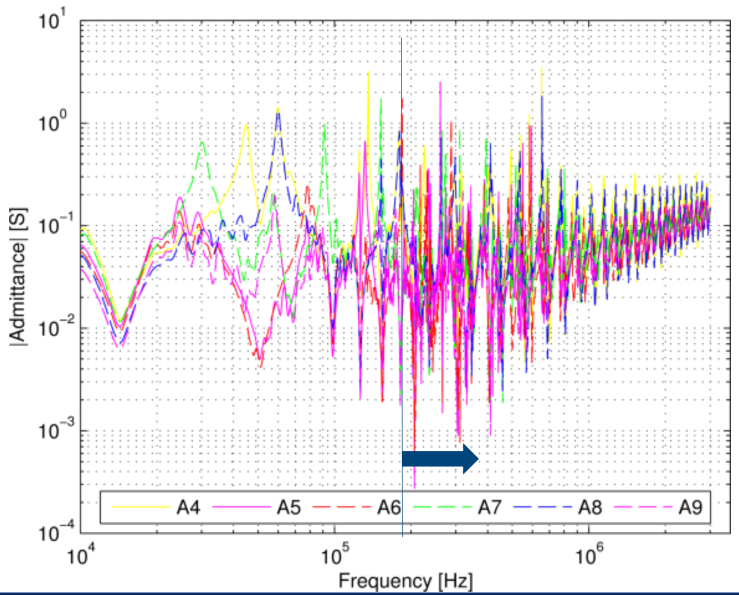


Reflections vs. transformer voltage ratio

- Voltage ratio (high to low) of several wind turbine transformers
  - Calculated from short circuit measurements
  - TR7 and TR8 -> dry type
  - TR10 – TR12 -> liquid insulated
  - High voltage amplification above approx. 200kHz
- Oscillations in string corresponding!







Summary

- Voltage oscillations of appropriate frequency and duration might excite transformer resonance
- Transient interaction important in OWF due to large amount of cables and transformers
- Line bifurcation and point of discontinuity for voltage wave introduce high frequency oscillations
- These oscillations are in the region of high amplification in voltage transfer of liquid insulated wind turbine transformers
- This might lead to resonant overvoltages at LV side of WT transformers
- This phenomenon depends on specific design of an OWF

The end

- Thank you for your attention.