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

\[ Z_0 = 31.6 \, \Omega, f_{\text{res}} \approx 5 \, kHz \]
\[ Z_0 = 1581 \, \Omega, f_{\text{res}} \approx 5 \, kHz \]
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 mm²**
  - 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 reflectic

\[ f = \frac{1}{4\tau}, \quad f = \frac{2n-1}{4l\sqrt{LC}} = \frac{2n-1}{4l} \cdot \nu = \frac{2n-1}{4\tau} \]

![Graph showing admittance and voltage over frequency and time](image)

- 290 Hz
- 174.2 kHz
- 26.2 kHz
Example of resonance excitation in OWF

- Voltage oscillations visible at terminals of all wind turbines
- The same frequency at all turbines
- Driving-point admittance 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 discontinuity = 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 mismatch
- 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 mm²)
- 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!

![Graph showing voltage ratio and admittance variations](image-url)
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.