Harmonic resonance and controller interactions
A brief tutorial

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2021-05-25, Mats Larsson, Hitachi ABB Power Grids Research

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Outline

The increasing importance of power electronics

Harmonic resonance and controller interactions

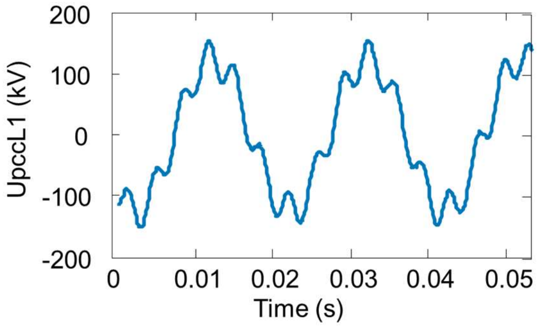
Overview of analysis techniques

System Level Analysis Example: Wind Farm with HVDC Connection

Conclusion

System Design Requirements are Changing

Example of worlds first HVDC connected wind farm



20% THD @ 290 Hz

At higher power levels than 200 MW, severe harmonic distortion occurred, typically around 290 Hz

Rätselhafter Defekt legt größten Windpark lahm

DER SPIEGEL 35/2014

DER SPIEGEL

Ökostrom

Knall auf hoher See

Störung legt Windpark BARD Offshore 1 weiter lahm

Beim Windpark BARD Offshore 1 vor der Nordseeinsel Borkum gibt es eine Panne nach der anderen. Seit März steht der Windpark still. "Die Störungen zu beheben, zieht sich länger hin, als es allen Beteiligten lieb ist", sagte Mathias Fischer, Sprecher des Netzbetreibers Tennet. Noch immer suchen Experten des Windparkbetreibers Ocean Breeze Energy, des Elektronikkonzerns ABB und von Tennet nach der Störungsursache. Erst im September können die 80 Anlagen von BARD 1 voraussichtlich wieder Strom liefern.

Seit März liefert der Windpark BARD Offshore 1 keinen Strom mehr. (Archivbild)

Schutzabschaltungen wegen "schmutzigem Strom"

- Currently no industry consensus on how studies should be made, and on requirements on equipment.

Active WGs:

1. CIGRE C4.49 “Multi-frequency stability of converter-based modern power systems”

2. CIGRE C4/B4.52 „Guidelines for Sub-synchronous Oscillation Studies in Power Electronics Dominated Power Systems”

3. IEC SC8a TR “Control interaction and power system damping (due to grid resonances)”

4. CIGRE B4.81 “Interaction between nearby VSC-HVDC converters, FACTs devices, HV power electronic devices and conventional AC equipment”

5. IEC TR 61000-2-15 “Assessment of instability/non-linear phenomena between AC-DC/DC-DC Converters and the Grid”

6. IEEE P2800 - Standard for Interconnection and Interoperability of Inverter-Based Resources Interconnecting with Associated Transmission Electric Power Systems

Harmonic Resonance

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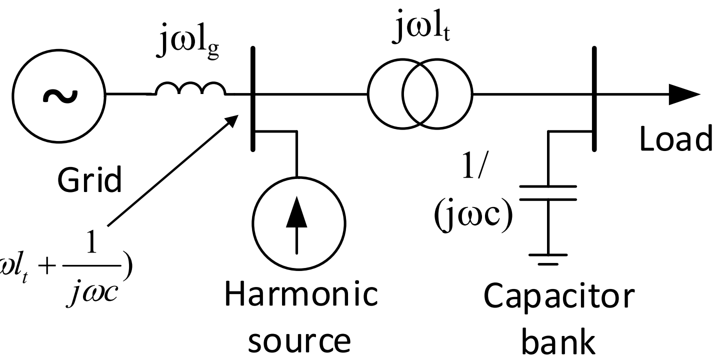
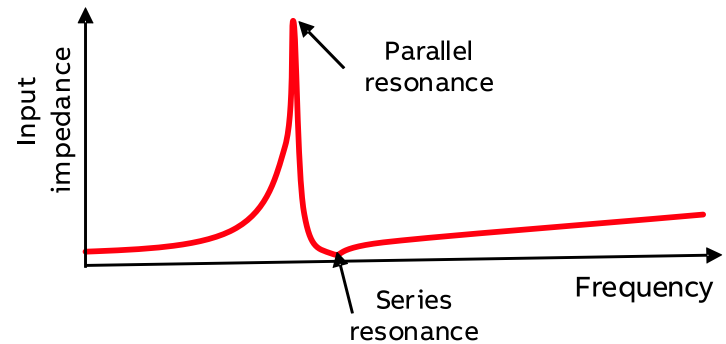


$$Z(\omega) = j\omega\, l_g \,//\, (j\omega l_t + \frac{1}{j\omega c}) = j\frac{l_g \omega(\omega^2 c\, l_t - 1)}{\omega^2 c\,(l_g + l_t) - 1}.$$



Series resonance

- A small harmonic voltage will generate a large harmonic current
- Large overvoltage on capacitor

Parallell resonance

- A small harmonic current injection will generate a large harmonic voltage
- Large overvoltage at harmonic source

Resonance can make otherwise harmless harmonic injections critical

Converter to Resonant Grid System

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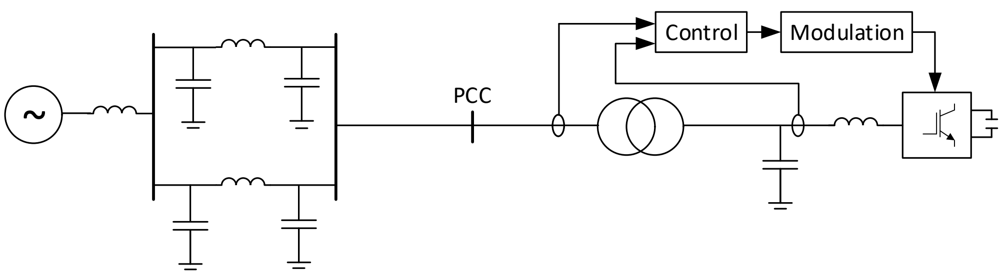
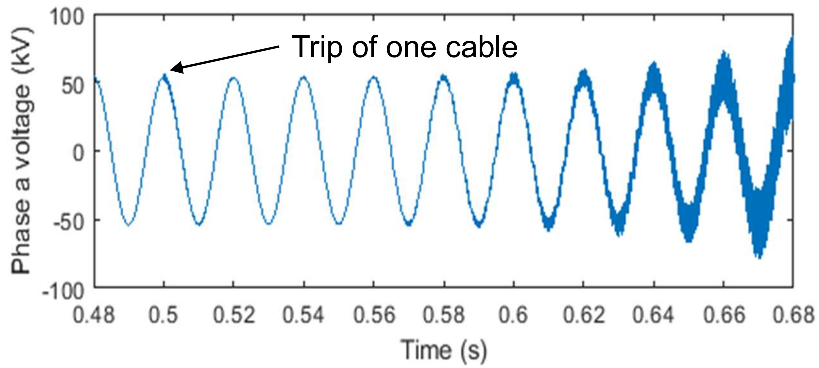
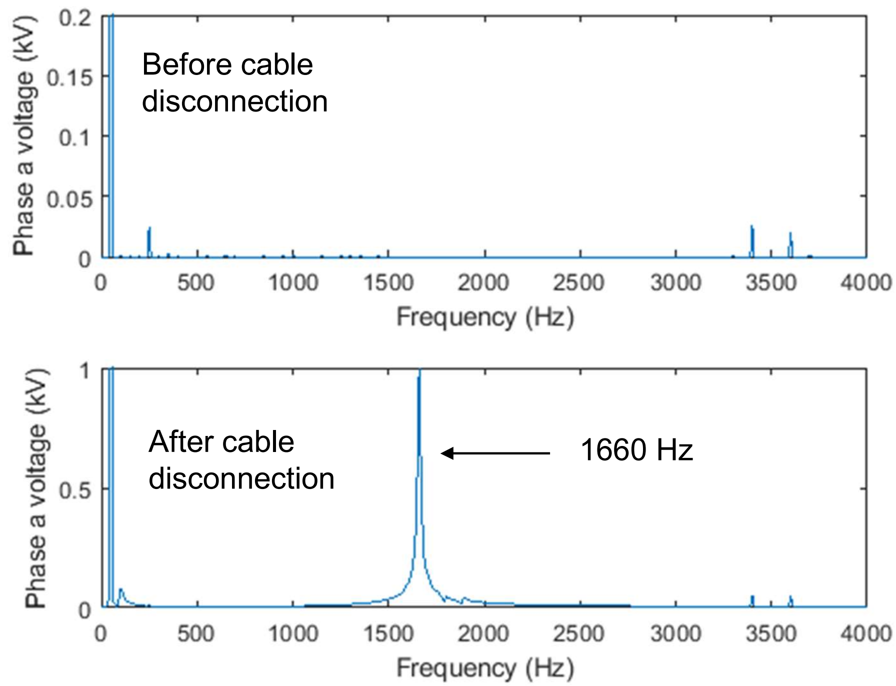
Example simulation





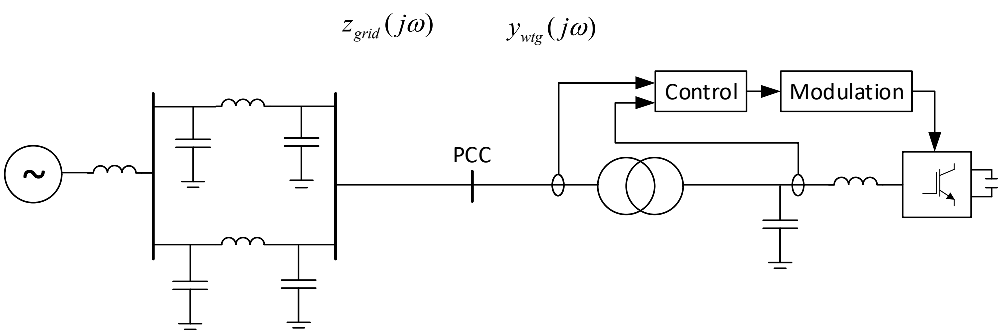
Frequency Domain Results



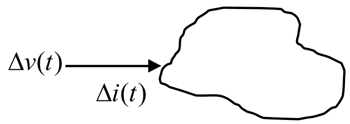
confidential

Impedance Equivalencing

Decomposition



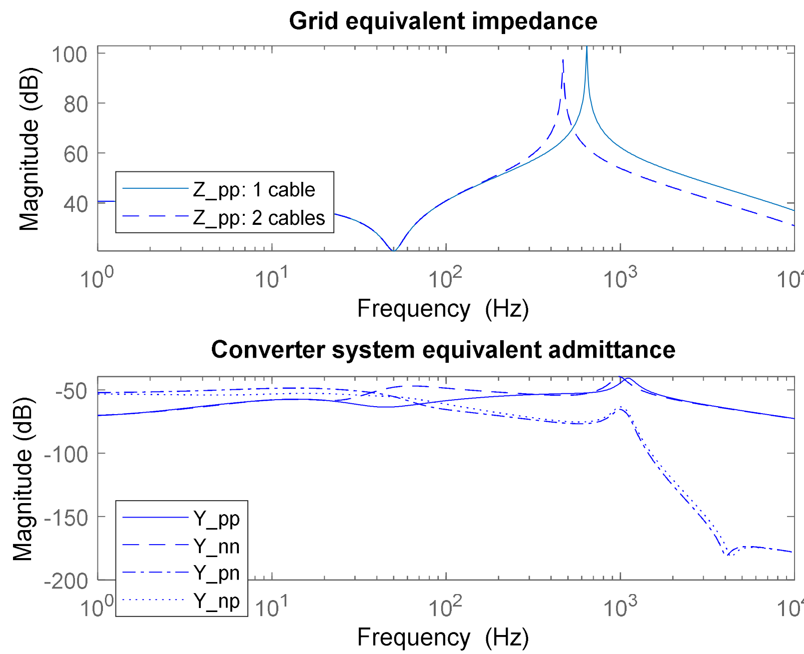
Subsystems can be represented by equivalent impedance:



$$z(j\omega) = \frac{\Delta v(j\omega)}{\Delta i(j\omega)}$$

$$y(j\omega) = \frac{\Delta i(j\omega)}{\Delta v(j\omega)}$$

Impededance matrices



Passivity Analysis

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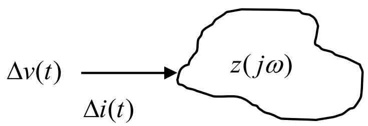
Background



Passivity is guaranteed if

$$\int_0^{T_{obs}} p(t)dt = \int_0^{T_{obs}} v^T(t)i(t)dt > 0.$$

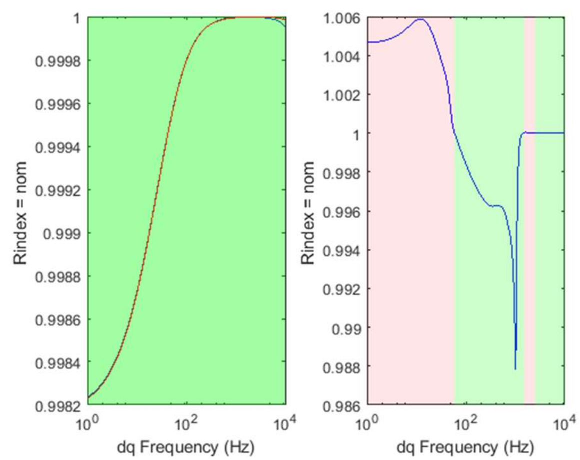
or, equivalently

$$z(j\omega) + z^H(j\omega) > 0,$$

Relative passivity index:

$$R = |(I - z(j\omega))(I + z(j\omega))^{-1}| < 1.$$

Passivity Analysis



Typical Results

Grid system

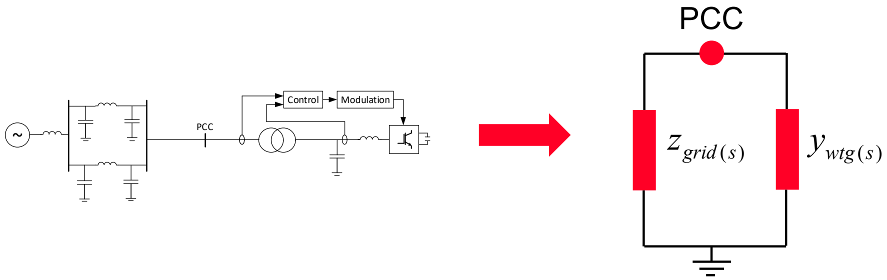
- Exhibits a small degree of passivity at all frequencies

Current controlled converter system

- Low frequency active region
  - PLL, DC link control, active damping
- High frequency passive region
  - Time delay in sampling and modulation
  - Current control

Non-passive subsystems may contribute to destabilization of grid resonances

Tracing the root cause of Instability



Form equivalent impedance

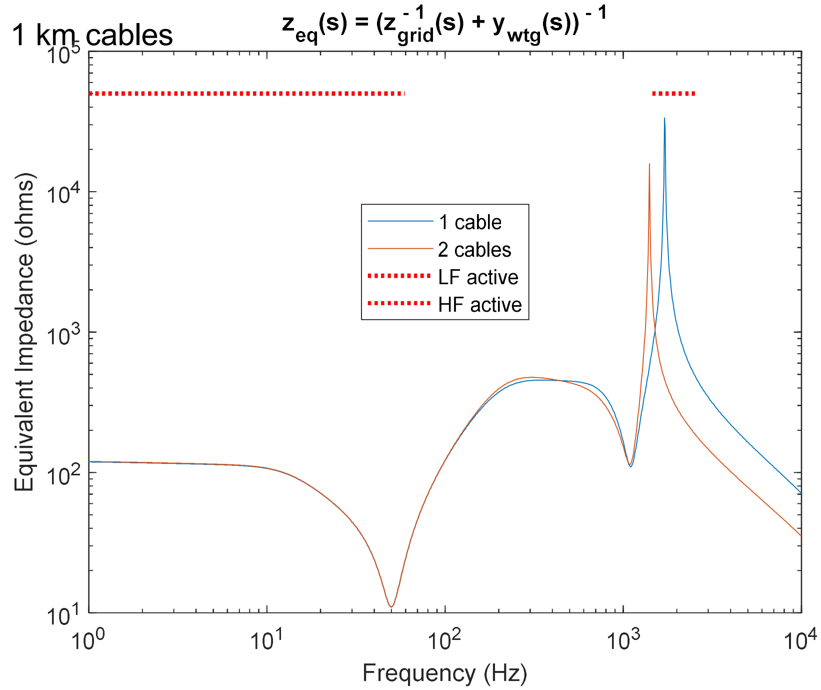
$$z_{eq}(s) = (z_{grid}^{-1}(s) + y_{wtg}(s))^{-1},$$

One cable in operation:

- Converter active region overlaps parallel resonance

Two Cables in operation

- Converter active region is above parallel resonance



System Level Analysis - Impedance Based

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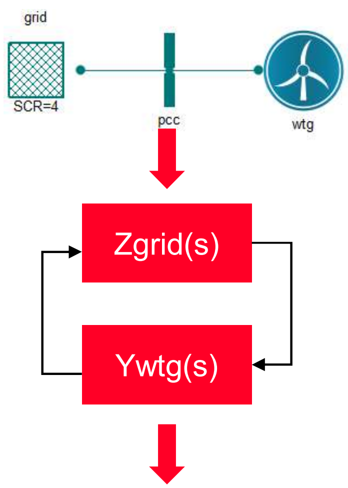
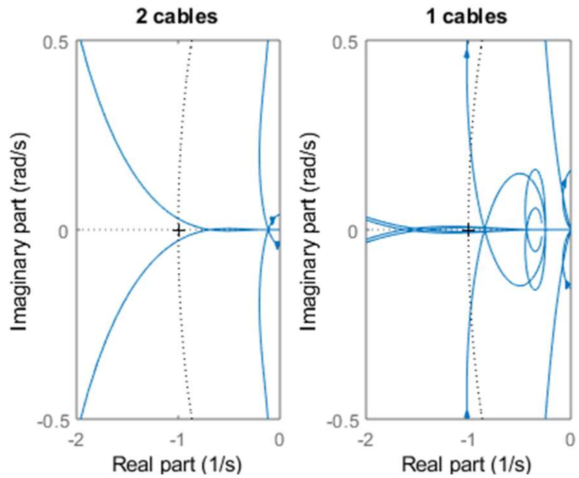
Modelling



Frequency response calculation

Eigenvalue Locus



Gain margin: 3.27 dB at 1482.60 Hz
Phase margin: 1.65 deg at 1353.47 Hz
Closed loop system is stable

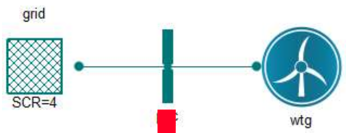
Gain margin: -4.16 dB at 1504.44 Hz
Phase margin: -0.29 deg at 1609.76 Hz
Closed loop system is unstable

Interpretation

- Visual inspection of yields amplitude and phase margin of critical mode
- Phase margin predicts dominant frequency in harmonic instability
- Partitioning introduced additional combinatorial dimension
- Difficult to apply in practical grids

System Level Analysis – Eigenvalue Based

Modelling

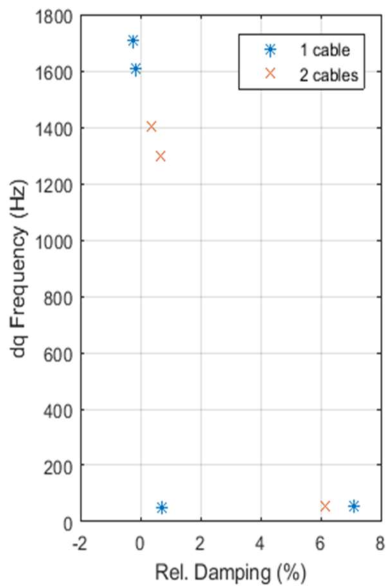


$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, \mathbf{u}, t)$$
$$\mathbf{y} = \mathbf{g}(\mathbf{x}, \mathbf{u}, t)$$

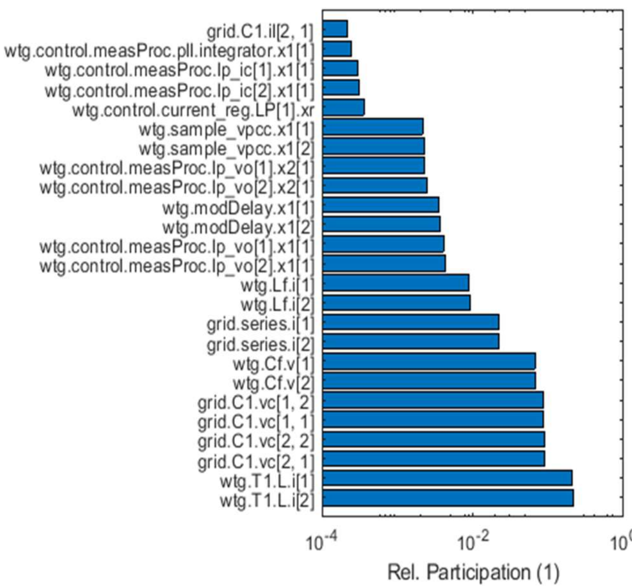
$$\Delta\dot{\mathbf{x}} = \mathbf{A}\Delta\mathbf{x} + \mathbf{B}\Delta\mathbf{u}$$
$$\Delta\mathbf{y} = \mathbf{C}\Delta\mathbf{x} + \mathbf{D}\Delta\mathbf{u}$$

Modal decomposition

Resonance Modes and Damping



Participation Factors



Conclusion

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- Grid resonances can pose a significant challenge to converter control
- Poorly damped low frequency grid resonances can be managed by converter control
- Poorly damped high frequency resonances need defensive tuning or passive filter solutions

- Modal analysis and Impedance analysis provides consistent results
- Impedance analysis hard to apply in practical cases

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