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Challenges of measurement-based determination of frequency-dependent impedance characteristics

TransCampus project workshop

Modelling of distribution systems for harmonic studies in transmission systems

King's College London, Strand Campus

May 31, 2023

Agenda

Motivation

Frequency-dependent impedance

- Methodology
- Characterisation of excitation
- Measurement results

Challenges

Motivation

- Power Quality aspects, like **harmonic distortion**, become more important in **transmission systems** (growing number of disturbing sources like wind/solar power plants, HVDC stations, FACTS, …)
- Harmonic levels need to be managed to ensure planning levels are not exceeded
- Coordination and limitation of harmonic emissions for installations require **harmonic simulations** (to determine harmonic propagation (influence coefficients) and summation in transmission systems)
- Simulations based on **reliable models** of all relevant components, incl. **downstream distribution networks**
- Models of component require realistic **frequency-dependent impedances**

➢ **Challenges of measurement-based determination** of frequency-based impedance characteristics for downstream distribution networks

Measurement-based determination
Methodology

Determination of frequency-dependent impedance characteristics

- Based on harmonic current and harmonic voltage variations
- Requires significant excitation / dedicated source of harmonics

$$\underline{Z}^{(h)} = \frac{\Delta \underline{U}^{(h)}}{\Delta \underline{I}^{(h)}}$$

Invasive approach

- **Injection of harmonic currents**
  e.g. by power electronic frontends, like STATCOM with active filtering
- **Switching of impedances**
  e.g. by pseudo random binary switching (PRBS)

Non-invasive approach

- **Continuous measurements**
  e.g. by permanent analysis of events
- **Active switching**
  e.g. by intentional component switching (transformer inrush)

Measurement-based determination
Methodology

Switching of transformer TR1:

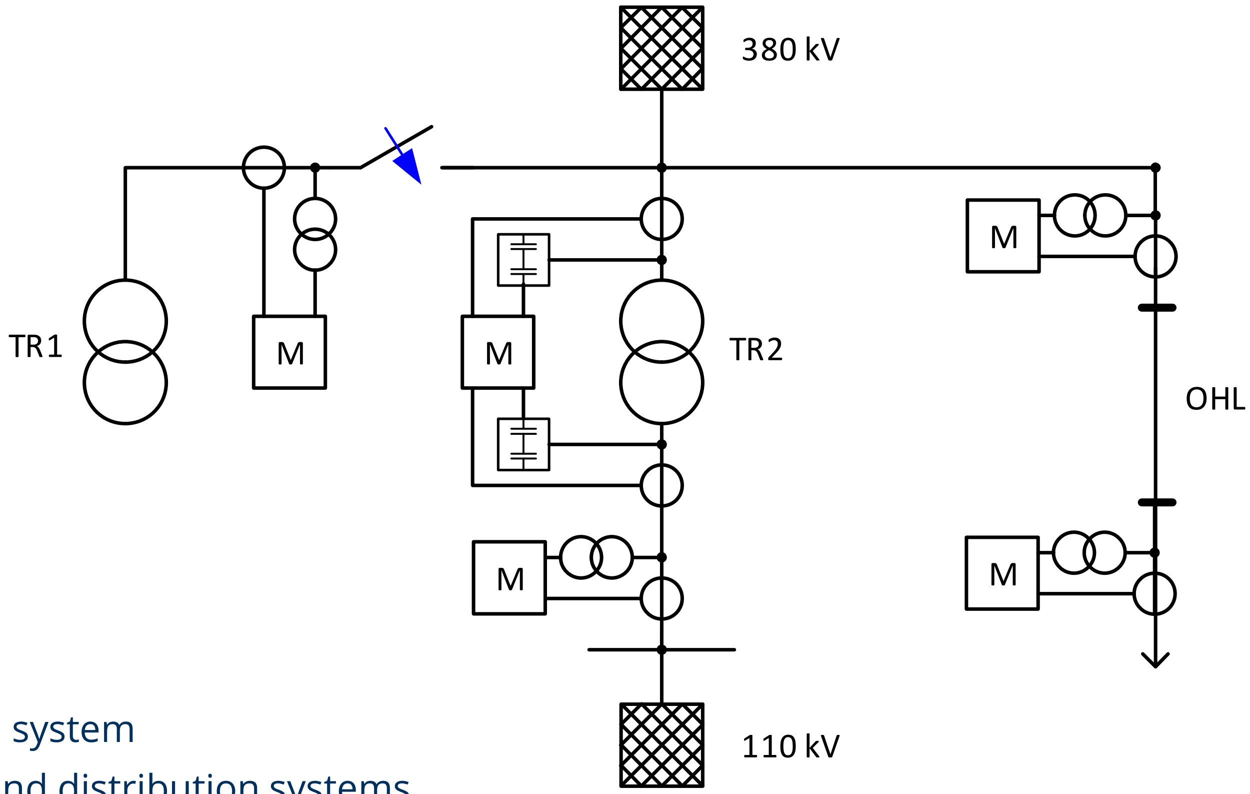
- Switched on 380-kV-side
- Open 110-kV-side
- Excitation due to inrush current

Measuring (M) with transient recorders:

- Voltage & current waveforms with up to 500 kS/s
- GPS synchronized

Measurement-based determination of:

- Harmonic propagation within transmission system
- Harmonic transfer between transmission and distribution systems
- Frequency-dependent impedance characteristics
- …

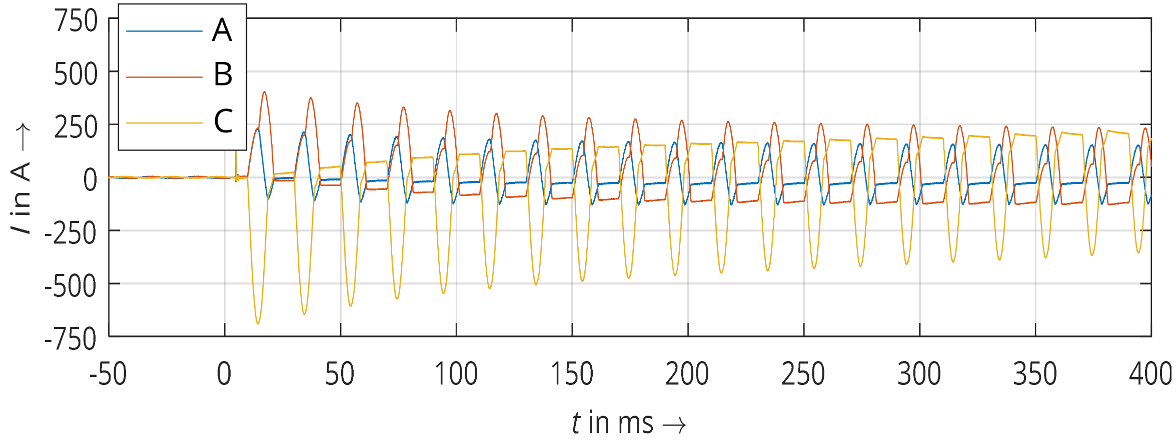


Measurement-based determination
Characterisation of excitation

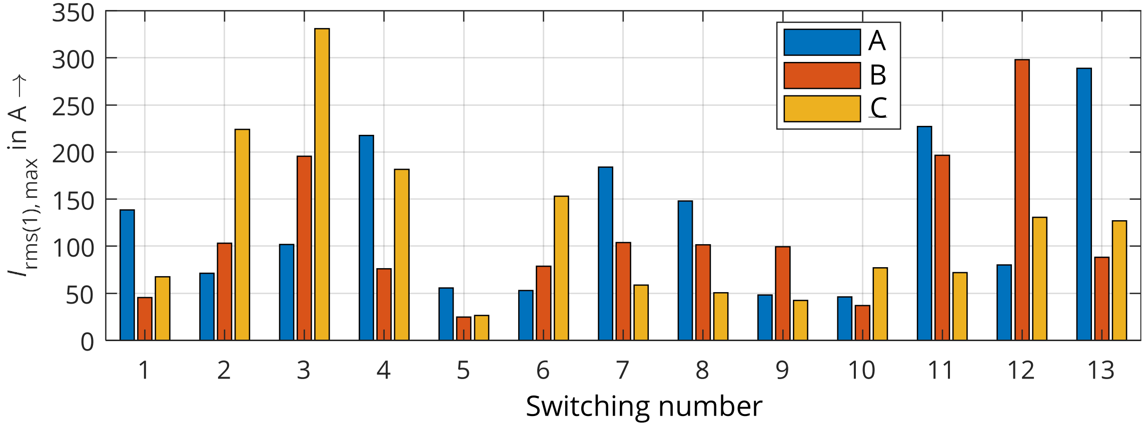
Transformer inrush current:

- Strong saturation resulting in significant excitation of harmonics
- Characteristic of current significantly influenced by switch-on time (varies between a few Amps and up to 300 A)
- Switching of transformer multiple times (e.g. 10 to 15 times)

Waveform of inrush current



Maximum 1-cycle-RMS value



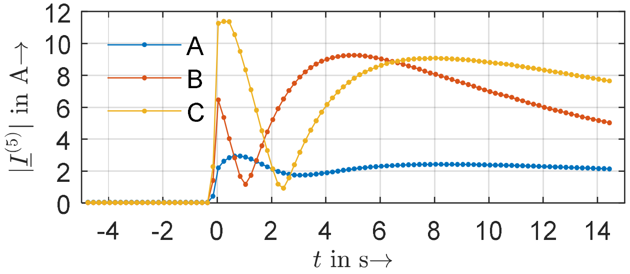
Measurement-based determination
Characterisation of excitation

Example of the 5th harmonic current of one transformer switching

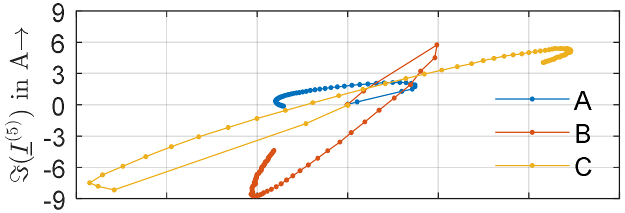
Phase components (ABC):

- Switching of transformer at $t = 0$
- Three phases unbalanced and highly variable over time

Time characteristic



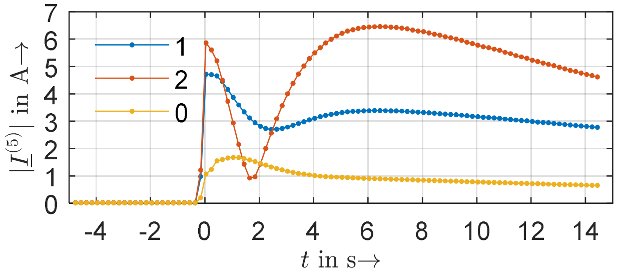
Loci over time



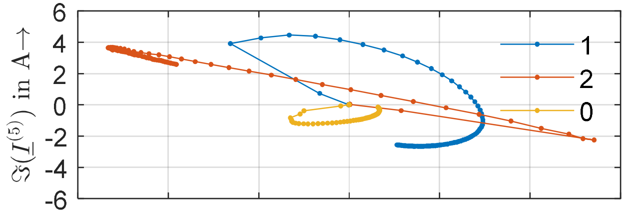
Sequence components (120):

- Balanced 5th harmonic only results in negative sequence component
- Due to unbalance all sequence components are excited

Time characteristic



Loci over time

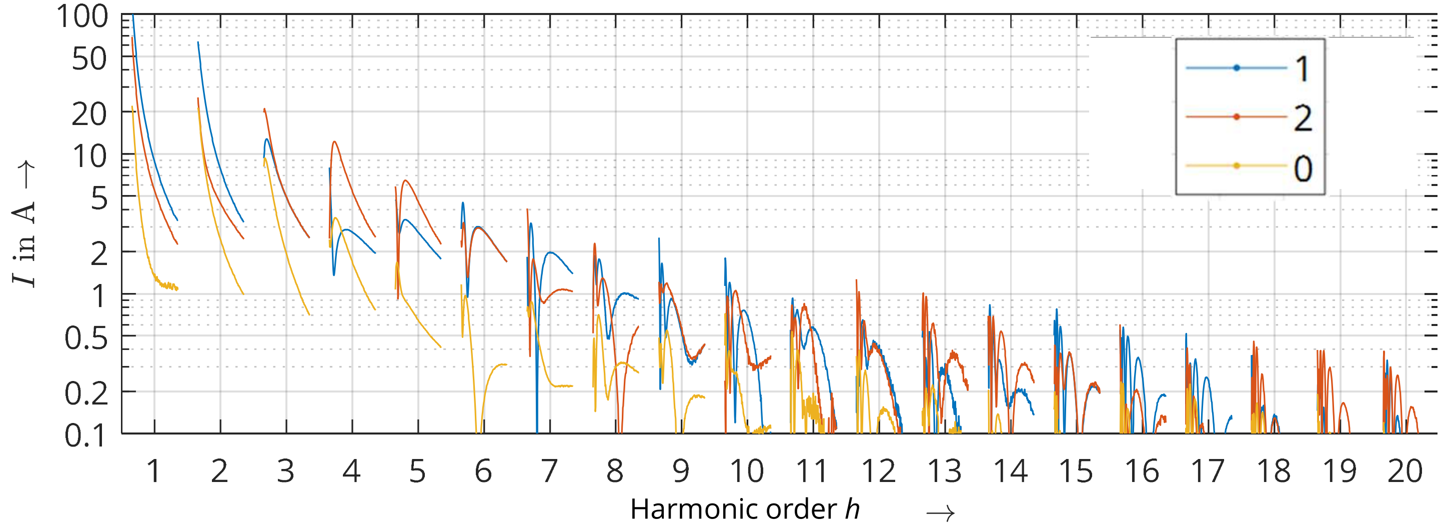


Measurement-based determination
Characterisation of excitation

Harmonic currents of inrush:

- Rich spectrum including odd and even harmonics
- Emitted current inversely proportional to harmonic order ($I^{(h)} \sim 1/h$)
- Excitation at higher harmonics quite low (e.g. *h* > 20)

Time characteristics of harmonic currents (one transformer switching)



➢ Good source of low order harmonics for measurement-based determination

➢ Limitations for higher order harmonics

Measurement-based determination

Measurement results

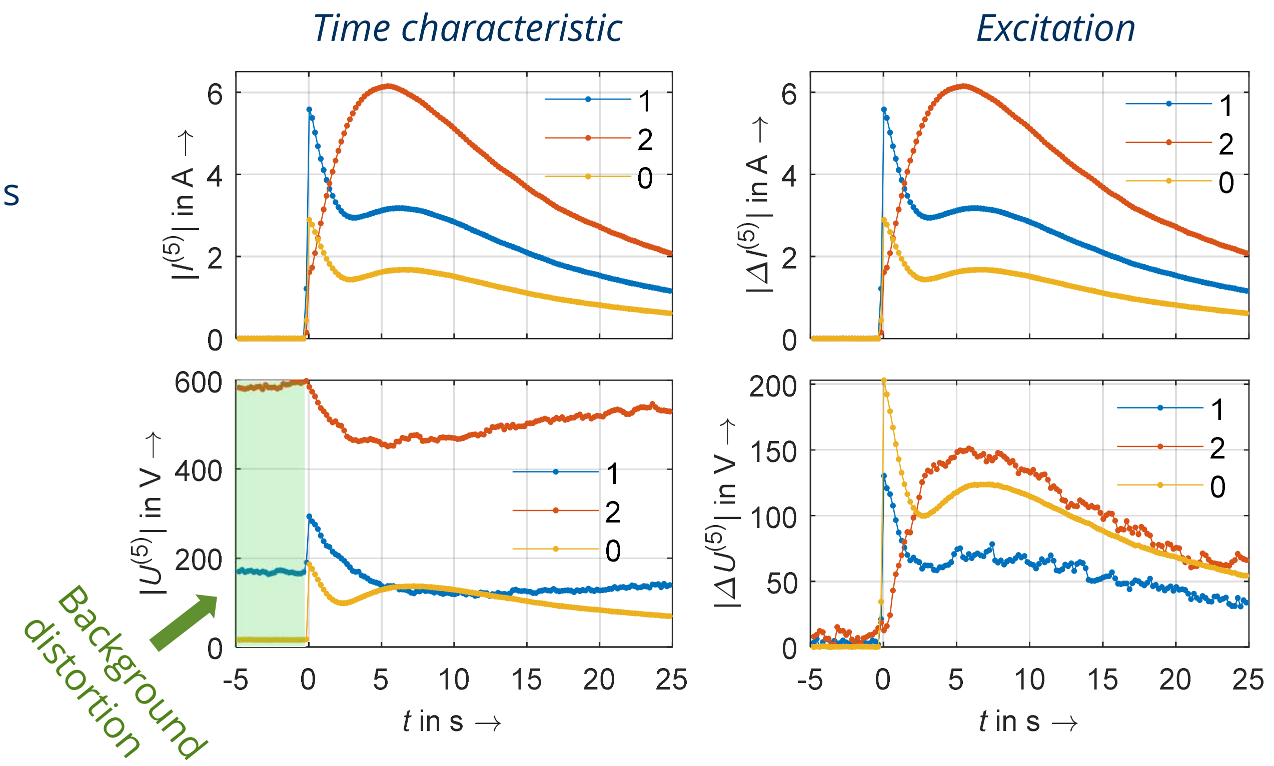
Estimation of impedances:

- Differences between background distortion and voltage harmonics due to inrush significant enough for $t < 15$ s
- Subtraction of background distortion prior to switching to get voltage changes

$$\underline{Z}^{(h)} = \frac{\Delta \underline{U}^{(h)}}{\Delta \underline{I}^{(h)}}$$

- Estimation of impedance using linear regression:
  - Magnitude (absolute voltages/currents)
  - Phase angle (real and imaginary parts)

Example of the 5th harmonic



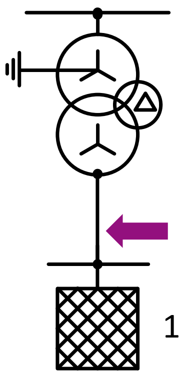
Measurement-based determination
Measurement results

Resulting impedance characteristics:

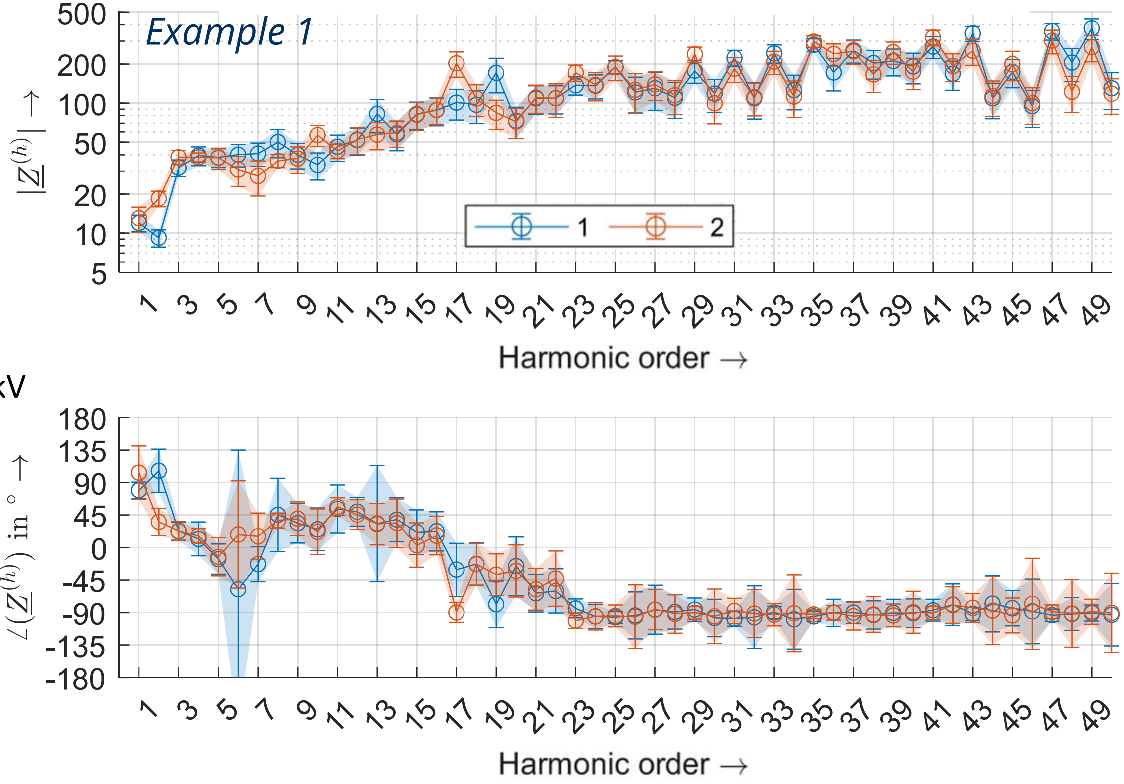
- Estimation based on all transformer switching operations
- Resulting average impedance with 95-%-confidence interval of regression
- Excitation for $h > 20$ possibly too small for accurate results

Downstream impedance:

- Measured at 110-kV-side of transformer
- Zero sequence not evaluable (e.g. due to isolated star point)



Downstream impedance of 110 kV



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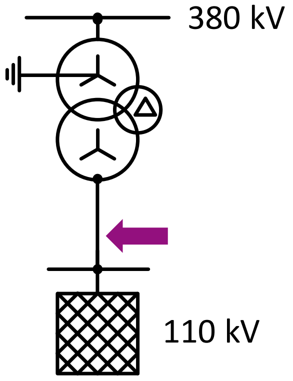
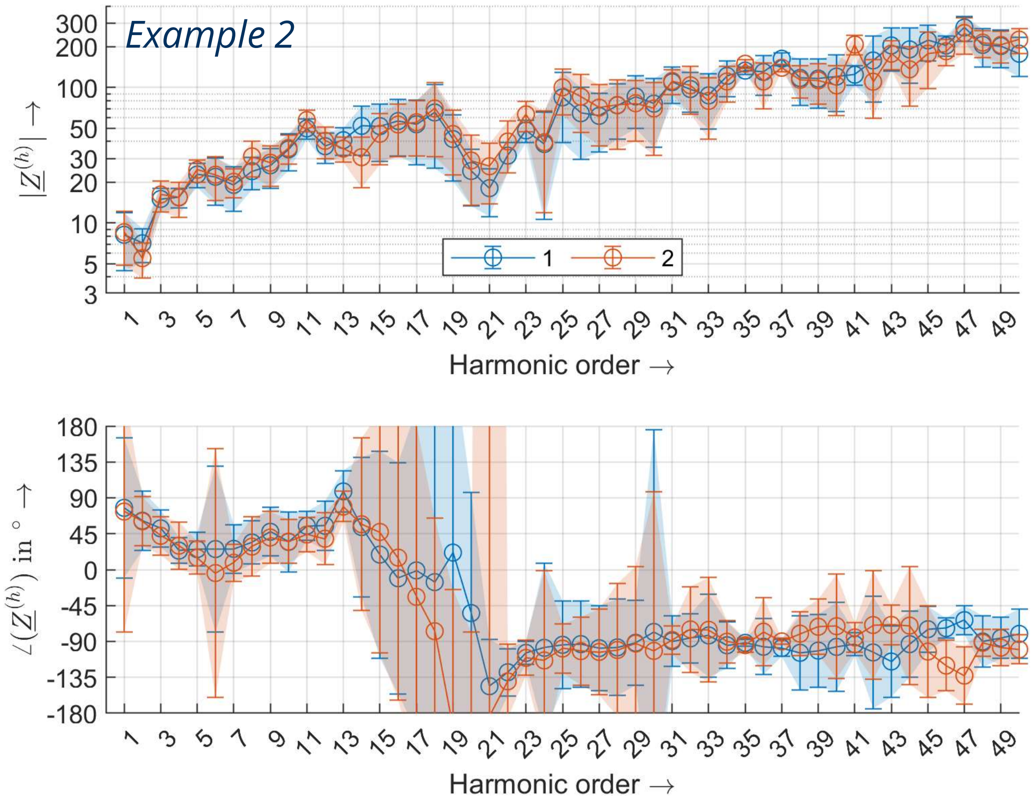


Downstream impedance of 110 kV



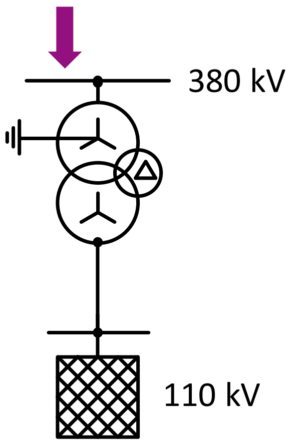
Measurement-based determination
Measurement results

Resulting impedance characteristics:

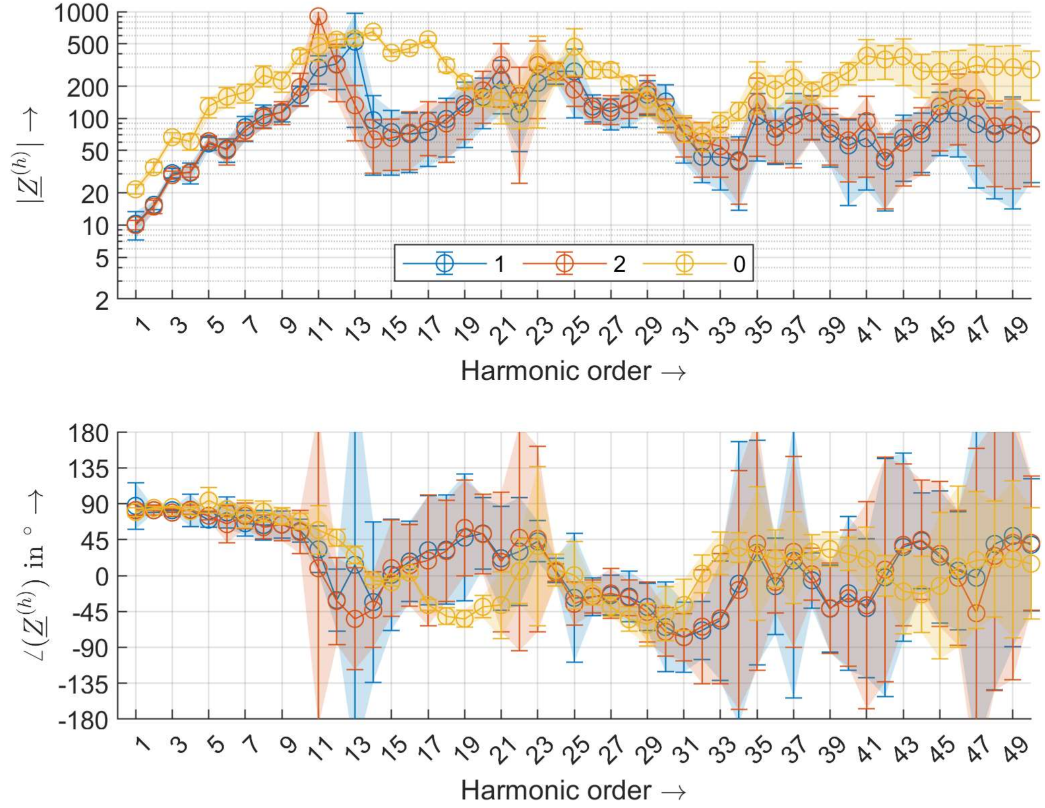
- Estimation based on all transformer switching operations
- Resulting average impedance with 95-%-confidence interval of regression
- Excitation for *h* > 20 possibly too small for accurate results

Node impedance 380 kV:

- Measured at point of excitation in 380 kV
- High uncertainty for *h* > 9

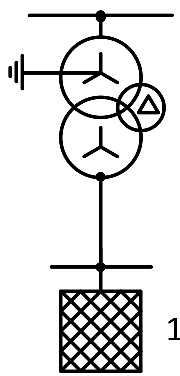


Node impedance at 380 kV

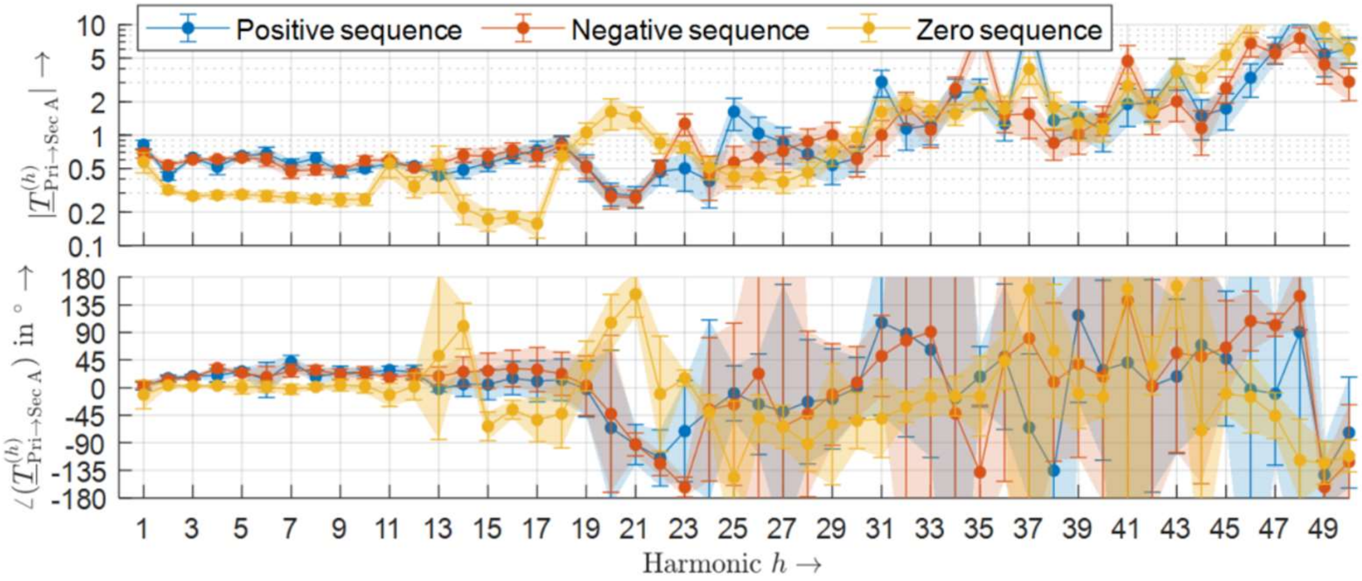


Measurement-based determination
Measurement results

Resulting transfer coefficients:



Transfer coefficient from primary side to secondary side



- Excitation for *h* > 20 possibly too small for accurate results
- Harmonic transfer coefficient < 1 for low order harmonics ($h \leq 18$) (harmonics tend to be damped when transferred downstream from EHV to HV)

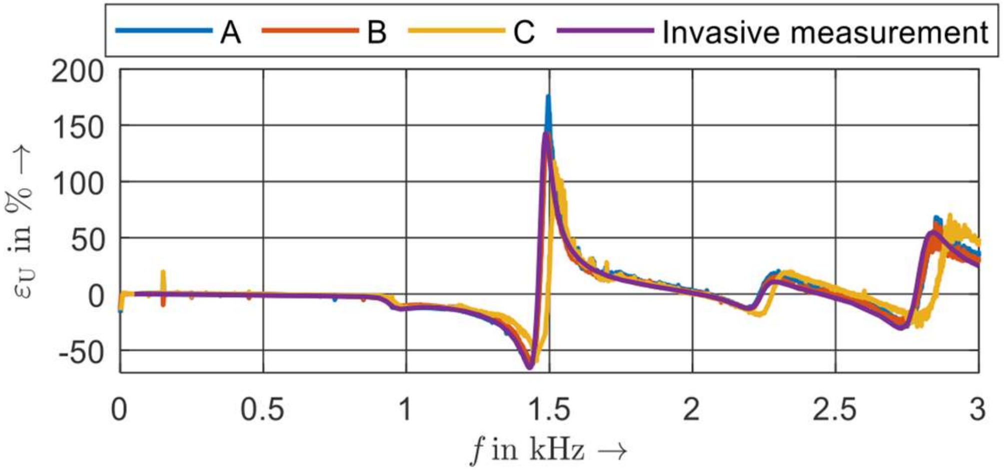
Challenges
Measurement

Uncertainty of measurement chain

- Inductive voltage transformers (IVTs)
  - Measurement errors due to resonances

- Transformer bushings
  - Capacitive divider with good linearity but temperature drift
  - Divider ratio temperature dependent
    (e.g. fundamental voltage of IVT as reference)

Transfer characteristic of sample 4 IVTs
(same type, RC dividers used as reference)



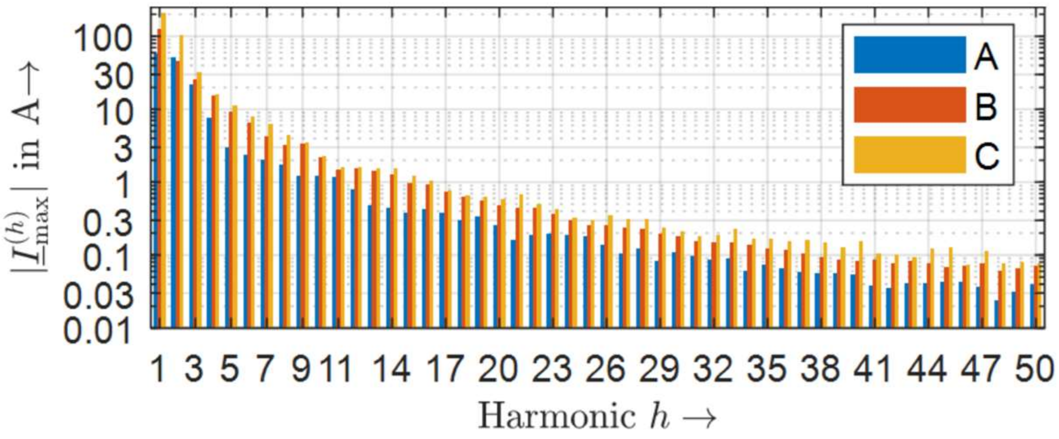
Improvements in signal processing

Challenges
Excitation

Magnitude of excitation

- Low magnitudes or small bandwidths for non-invasive approaches
- Feasibility of invasive approaches

Maximum harmonic currents of inrush



Impact of excitation

- Dynamic vs. steady-state response of the system (e.g. STATCOM with active filtering at specific frequencies)
- Non-typical switching states (e.g. one transformer out of order for measurement of transfer coefficients)

Challenges
Impedance characteristics

Determination of impedances

- Possibility to measure impedances (e.g. zero sequence impedances due to isolated star points)

Time dependency of impedances

- Different switching states of networks
- Connection of new installations or expansions of network
- Possible seasonal effects due to different usage behaviour (e.g. summer vs. winter months)

Thank you for your attention!

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