Study Committee C4

Power System Technical Performance

Paper 1103

Measurement and Simulation of Harmonic Propagation in Transmission Systems

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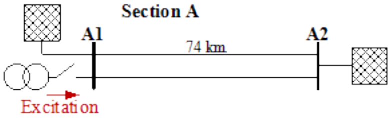
Motivation

- Growing number of harmonic sources (e.g. wind and solar plants, HVDC stations, FACTS, ...)
- Harmonic emissions have to be coordinated and limited
- Harmonic propagation is required for calculation of emission limits according to IEC 61000-3-6
- Harmonic propagation based on simulations can contain uncertainties due to complexity of harmonic models: *How do simulations compare with reality?*

Aim: **Measurement based identification of harmonic propagation**

Method

- Measurements in three network sections (A, B, C) in the German 380-kV-network in cooperation with two TSO's
- Dedicated and significant source of harmonics necessary
  - Section A and B: Intentional switching of transformer (inrush current)



  - Section C: Emission of arc furnace
- Measurement of relevant voltage harmonics with GPS-synchronized transient recorders
- Prior characterization of used voltage transformers confirms suitability up to 25th harmonic order

Analysis procedure

- Definition of influence coefficient:

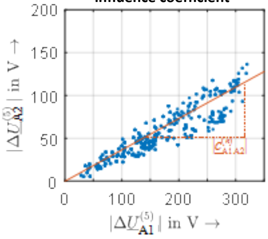
$$\underline{c}_{XY}^{(h)} = \frac{\Delta \underline{U}_Y^{(h)}}{\Delta \underline{U}_X^{(h)}}$$

  - $\underline{c}_{XY}^{(h)}$: influence of harmonic h at node X (source node) on harmonic h at node Y (influenced node)

Calculation steps:

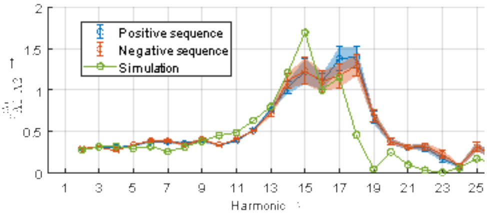
- DFT on synchronous 10-cycle-intervals
- Transfer in symmetrical components
- Calculation of difference spectra to remove constant background harmonics present in network
- Calculation of influence coefficient with regression

Regression example: magnitude of influence coefficient



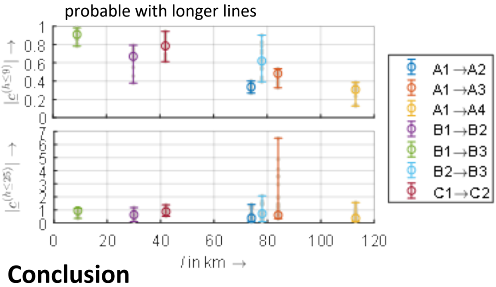
Comparison with simulation

- Large-scale network model for section A was developed in standard power flow calculation package
- Improved harmonic models have been implemented in area around section of measurements:
  - Geometrically modelled lines
  - Transformer stray capacitances
  - Harmonic impedance equivalents for downstream networks and customer installations
- Good match of results for low order harmonics (damping)
- Slightly shifted range of amplification (resonance) between measurement and simulation
  - ➢ High differences for individual harmonics
  - ➢ Approximate prediction of frequency and amplification range of resonance



Influence coefficient depending on distance

- Aggregated representation of all measurement results: influence coefficient depending on line length
- Low order harmonics ($h \leq 9$):
  - Damping dependent on line length
  - Damping not monotonous → influence of customers
- Higher order harmonics:
  - Significant resonance amplifications
  - No clear tendency but resonances are more probable with longer lines



Conclusion

- Influence coefficients can be determined by measurements with distinct harmonic source
- High resonance amplification may occur at higher orders
- Accurate harmonic simulations can give a reasonable estimate of influence coefficients (especially at $h \leq 9$)
- Continuous measurements recommended (consider impact of different load conditions)

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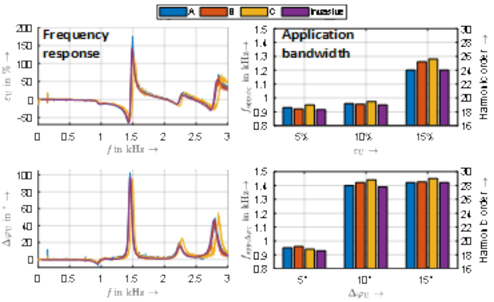
continued

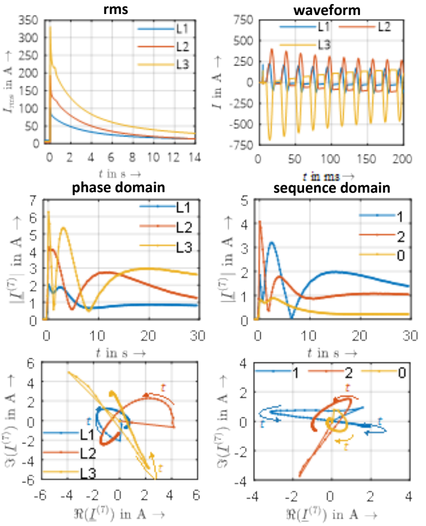
Voltage transformer accuracy

- Inductive voltage transformer can have high inaccuracy in harmonic range
- In all three network sections same type of voltage transformer were installed
  →Characterization of four samples of transducer type
  →Three measured noninvasively under realistic conditions (in-situ), one invasively in the lab
- Up to 18th harmonic results are reliable ($\varepsilon_U < 5\%$), up to 25th harmonic results are indicative ($\varepsilon_U < 15\%$)



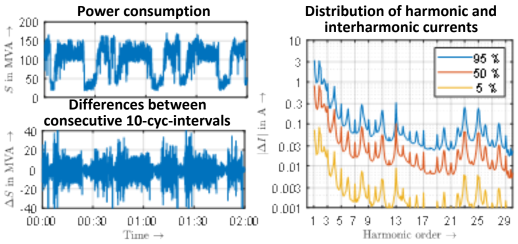
Characterization of excitation: transformer switching

- **Section A and B**: switch-on process of a 380 kV / 110 kV, 300 MVA transformer
- Inrush current depends strongly on switching moment
  → 14 resp. 15 switch-on's in each network section
- Broad spectrum of long-lasting harmonic currents
- Unbalanced harmonic currents: excitation of positive-, negative- and zero-sequence



Characterization of excitation: arc furnace

- **Section C**: normal operation of arc furnace over 18 hours
- In melting phases (S ≈ 100 MVA … 150 MVA) high dynamics with $\Delta S \approx$ 5 MVA … 10 MVA between consecutive 10-cycle-intervals
- Arc furnace is emitting significant and highly varying harmonics and interharmonics
- No zero-sequence components at EHV side due to delta winding of transformer



Regression of influencing coefficient

Magnitude:

- Absolute value of influencing coefficient is determined as slope of a linear function:

$$\left|\Delta \underline{U}_Y^{(h)}\right| = \left|\underline{c}_{XY}^{(h)}\right| \cdot \left|\Delta \underline{U}_X^{(h)}\right|$$

Phase angle:

- Phase angle is determined by separate regressions for real and imaginary part
  - Rotation of individual 10-cycle-spectrum differences so that voltage phasors at node X become real:

$$\Delta \underline{U}_X^{(h)\prime} = \Delta \underline{U}_X^{(h)} \cdot \frac{\Delta \underline{U}_X^{(h)*}}{\left|\Delta \underline{U}_X^{(h)}\right|}$$

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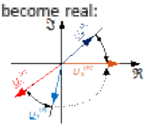

  - Individual regressions for real and imaginary part:

$$\Re\left(\Delta \underline{U}_Y^{(h)\prime}\right) = \Re\left(\underline{c}_{XY}^{(h)}\right) \cdot \Delta U_X^{(h)\prime}$$

$$\Im\left(\Delta \underline{U}_Y^{(h)\prime}\right) = \Im\left(\underline{c}_{XY}^{(h)}\right) \cdot \Delta U_X^{(h)\prime}$$

  - Calculation of phase angle:

$$\angle \underline{c}_{XY}^{(h)} = \operatorname{atan}\left(\frac{\Im\left(\underline{c}_{XY}^{(h)}\right)}{\Re\left(\underline{c}_{XY}^{(h)}\right)}\right)$$

- Due to absolute synchronous measurement, propagation time on the line must be considered
  - Example: line length of 100 km and $c_0 = 3 \cdot 10^8$ m/s corresponds to a delay of 0.33 ms
    → phase shift of 60° for the 10th harmonic
  - Correction of phase angle of influencing coefficient:

$$\Delta\angle \underline{c}_{XY}^{(h)} = \frac{l_{XY}}{c_0} \cdot \frac{360°}{20\ \text{ms}} \cdot h$$

Consideration of uncertainty:

- For each regression the 95% confidence interval is determined to consider uncertainty of results

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Detailed results

- Regression value as circle, confidence interval as whiskers
  → true value is with 95 % probability inside the colored area

- Influence coefficient for positive- (1) and negative-sequence (2) component is similar, coefficient for zero-sequence (0) is different
  → influence of sequence component impedance
- True value of influence coefficient for positive- and negative-sequence component is most probable in overlapping area of confidence intervals
- Change of phase angle confirms existence of resonances