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Determination of equivalent circuit models for the aggregated representation of downstream HV networks

Academia-Industry Workshop

Challenges of harmonic studies in modern transmission systems

TUD Dresden University of Technology

November 8, 2023

Agenda

- Motivation
- Downstream HV networks
- Equivalent circuit models
  - Circuit parameters
  - Circuit topologies
  - Application results
- Challenges

Motivation

- 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**

Measurements | **Simulations**

- **Implementation** of frequency-dependent impedances of **in simulations**

➢ **Determination of equivalent circuit models**
for the aggregated representation of downstream HV networks

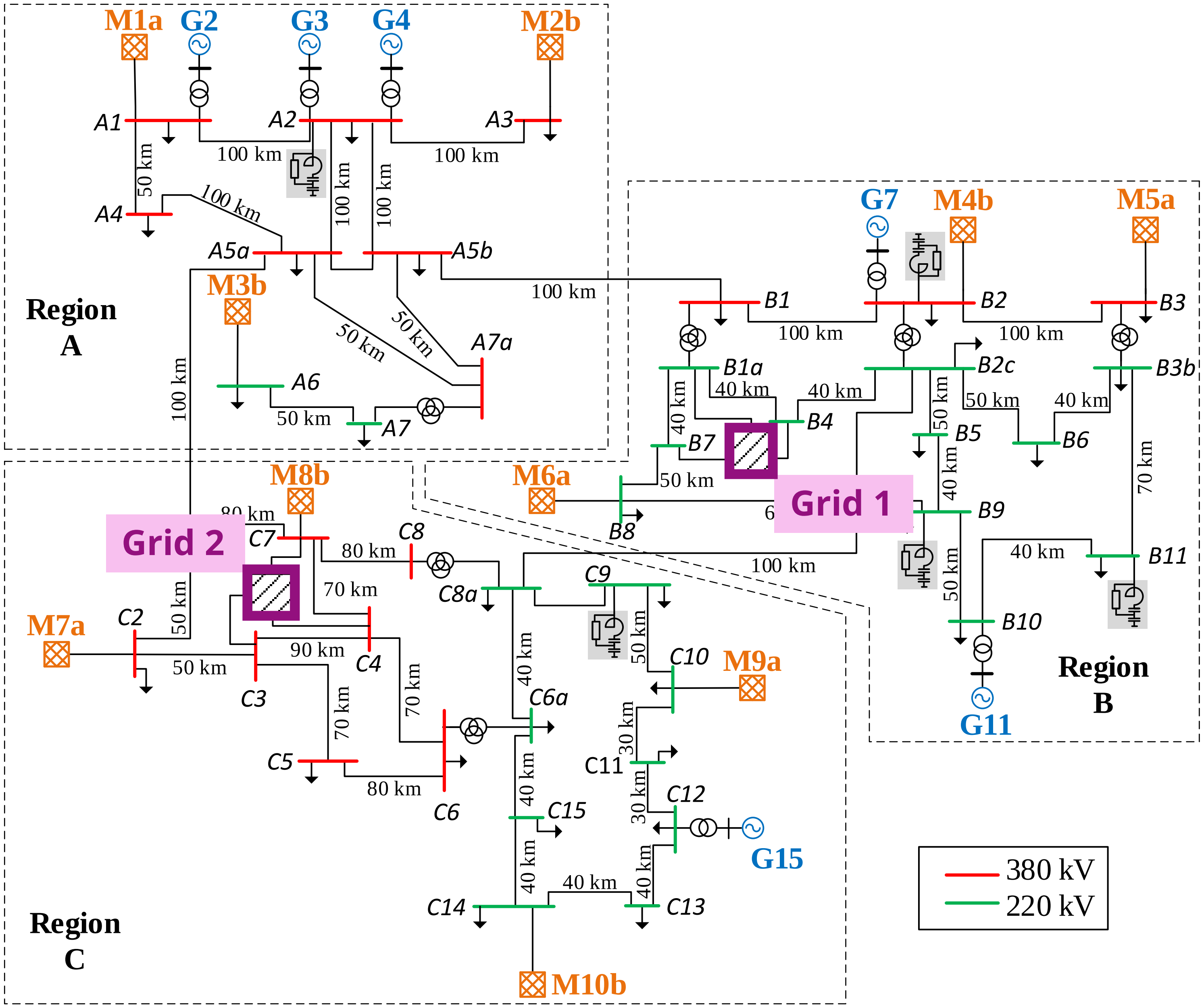
Downstream HV networks
Test network

Transmission system

- 17 Nodes in 380 kV
- 22 Nodes in 220 kV
- 16 Generators (60% MMCs)
- 5 compensation devices

Distribution system

- 39 Nodes in 110 kV
  - 37 aggregated networks
  - **2 detailed networks (with 3 in-feeds)**



Downstream HV networks
Detailed 110-kV-model

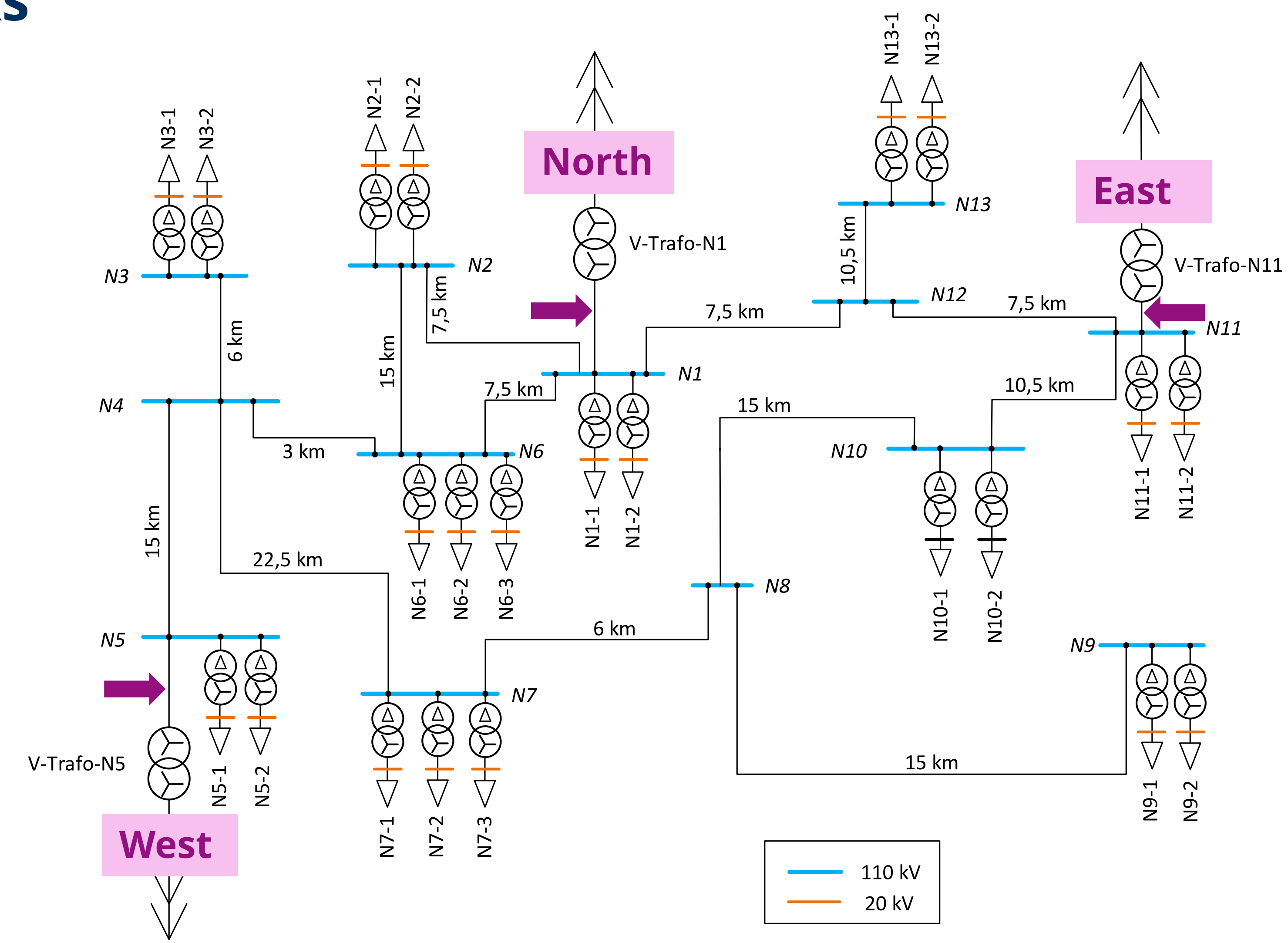
Model details

- 13 Nodes in 110 kV
- 22 Nodes in 20 kV
- Aggregated 20-kV-load models

- All overhead lines

- 3 in-feeds from EHV:
  - 220 kV for Grid 1
  - 380 kV for Grid 2

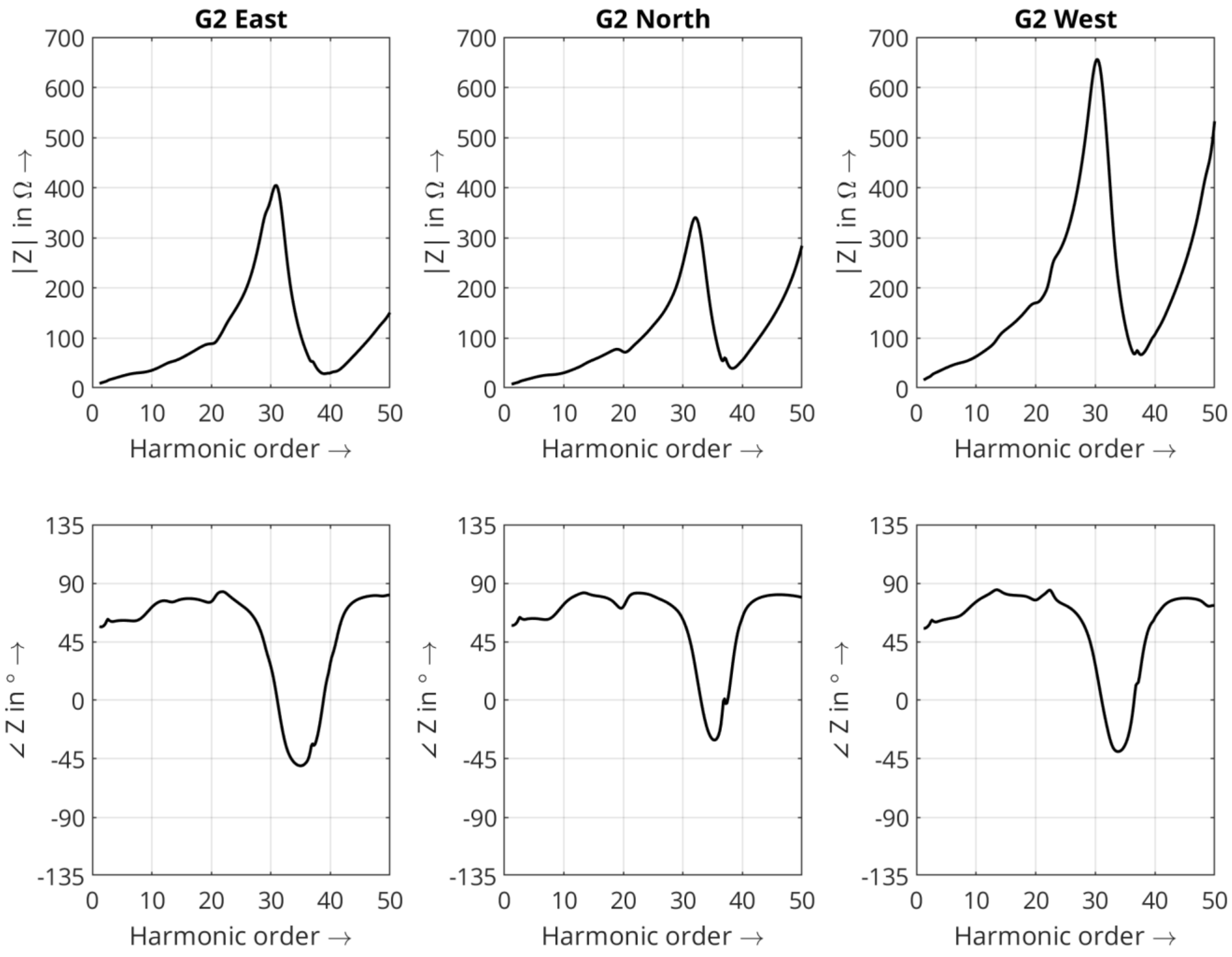
➢ **Determination of frequency-dependent downstream impedances of HV networks**



Downstream HV networks
Impedance characteristics (1)

- Focus on **positive sequence** impedances
- Multiple resonances for downstream impedance of detailed 110-kV-model
- Similar resonance frequencies at in-feeds

Downstream HV impedance (at 110-kV-side of Grid 2)

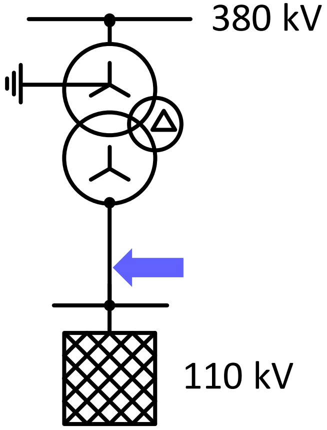


Downstream HV networks
Impedance characteristics (2)

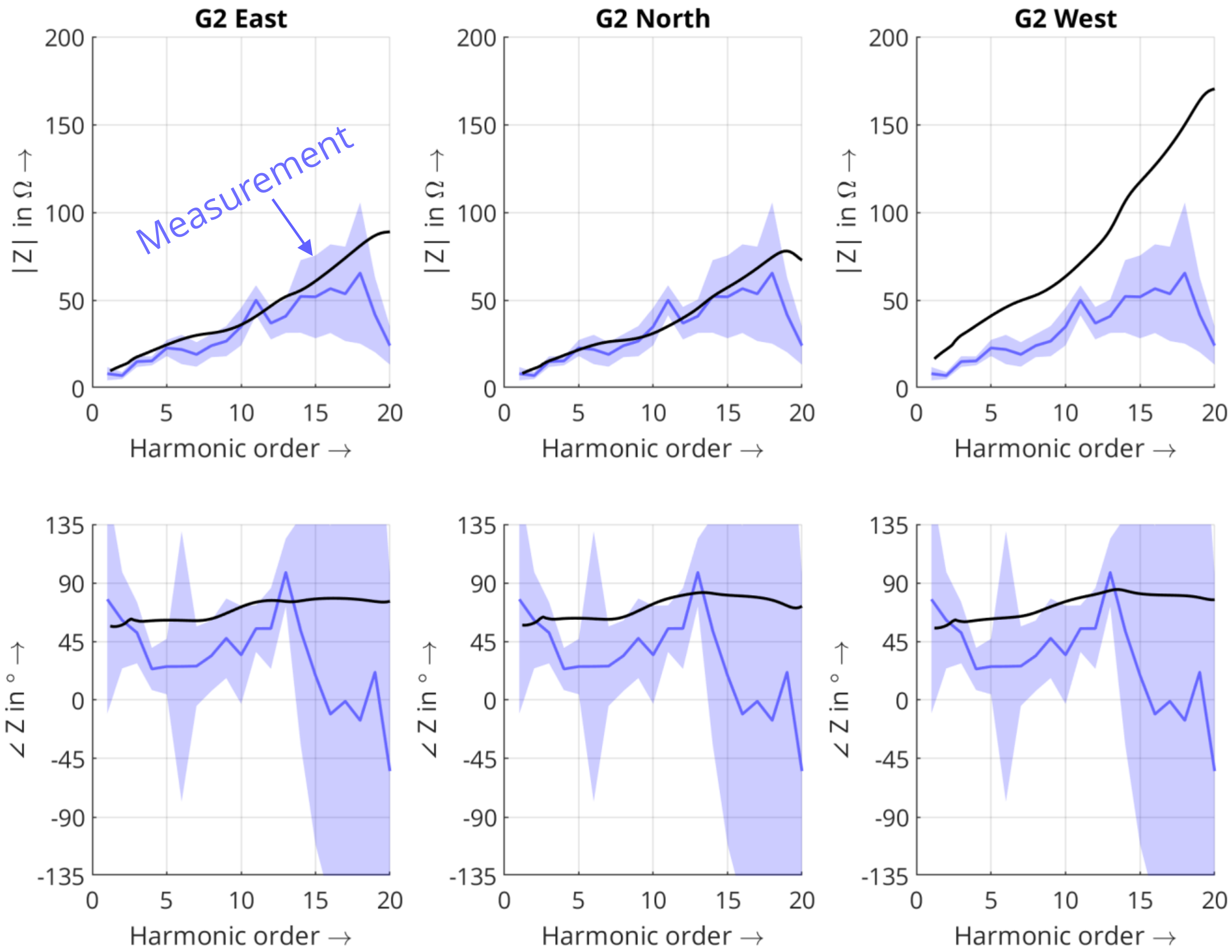
- Focus on **positive sequence** impedances
- Multiple resonances for downstream impedance of detailed 110-kV-model
- Similar resonance frequencies at in-feeds

Field measurement:

- Different network topology
- Excititation using transformer in-rush currents at 380 kV
- Comparable impedances



Downstream HV impedance (at 110-kV-side of Grid 2)



Equivalent circuit models

Frequency-dependent downstream impedance obtained from:
- impedance measurements or
- detailed network simulations

Model fitting

Circuit parameters

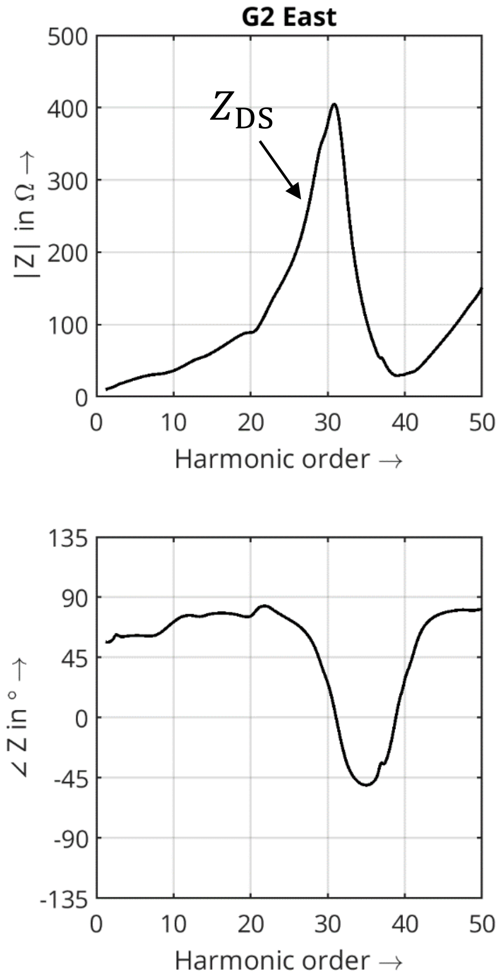
Circuit topology

Equivalent circuit models
- increased sample size
- representative variety

Equivalent circuit models
Circuit parameters (1)

Estimation of circuit parameters

- Finding parameter values for defined circuit topology to fit downstream impedance $\underline{Z}_{\mathrm{DS}}$
- Typical optimization problem for:
  - Nonlinear least squares
  - Constrained nonlinear multivariate functions
  - Particle swarm optimization
  - …
- Limit search space for meaningful results (lower and upper boundaries for parameters e.g. R = [0, 200] Ω)
- May require initial parameters values (e.g. middle of search space R_0 = 100 Ω)



Equivalent circuit models
Circuit parameters (2)

Estimation of circuit parameters

- Finding parameter values for defined circuit topology to fit downstream impedance $\underline{Z}_{DS}$
- Typical optimization problem for:
  - Nonlinear least squares
  - Constrained nonlinear multivariate functions
  - Particle swarm optimization
  - …
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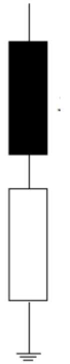


RL series (IEEE Model 1)

$$\underline{Z}_{EC}(s) = R + s \cdot L$$

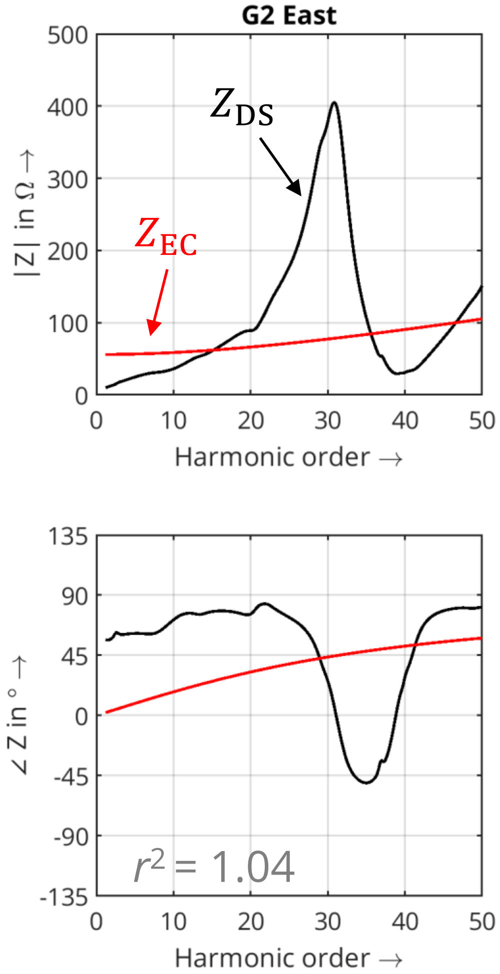
with $s = j\omega = j2\pi f$

Optimization function

$$\min f(s) \coloneqq \sum \left|\underline{Z}_{DS}(s) - \underline{Z}_{EC}(s)\right|^2$$

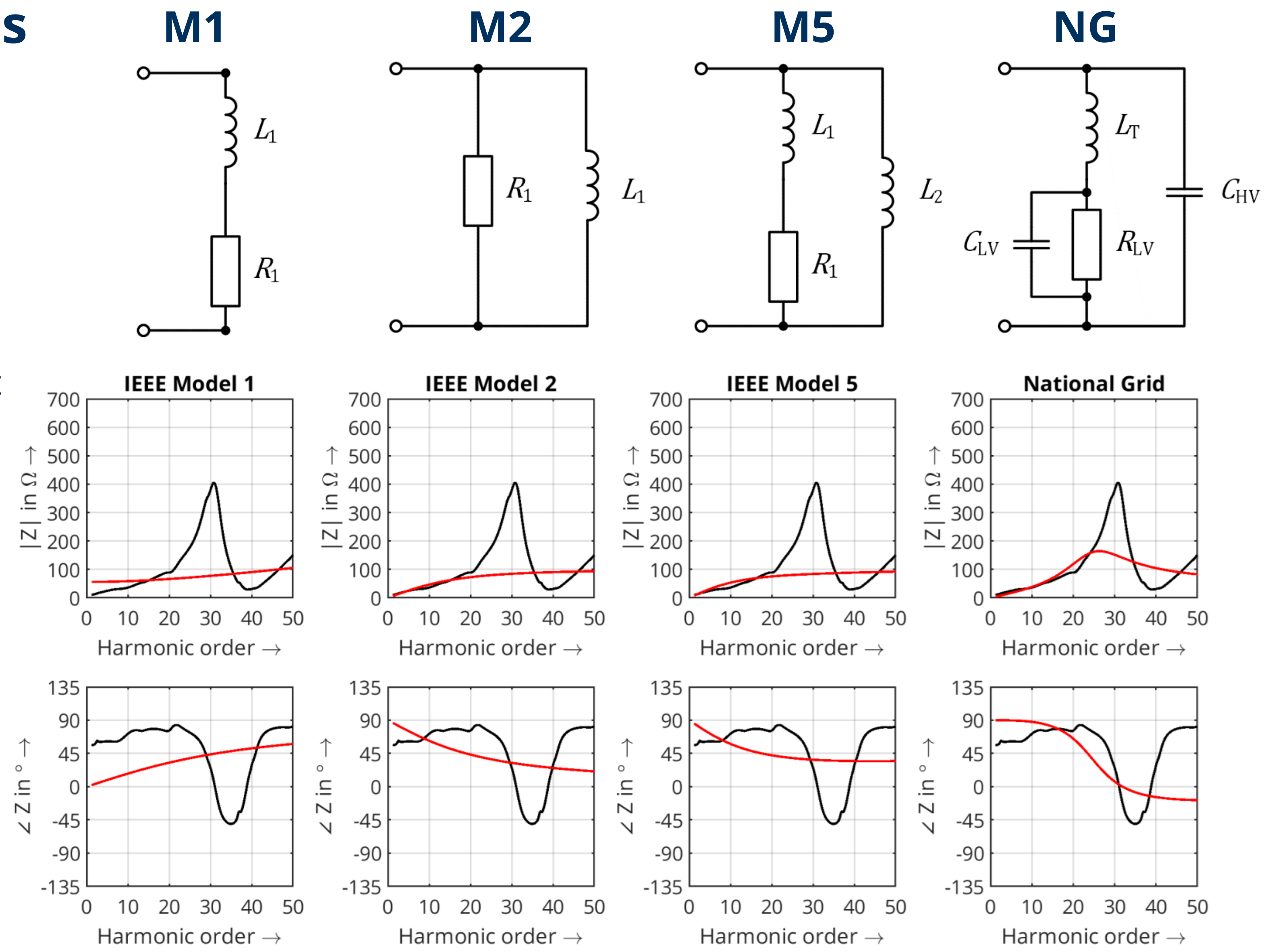
Measure of fit
("normalized" R-squared)

$$r^2 \approx \frac{\sum \left|\underline{Z}_{DS} - \underline{Z}_{EC}\right|^2}{\sum \left|\underline{Z}_{DS} - \overline{\underline{Z}}_{DS}\right|^2}$$



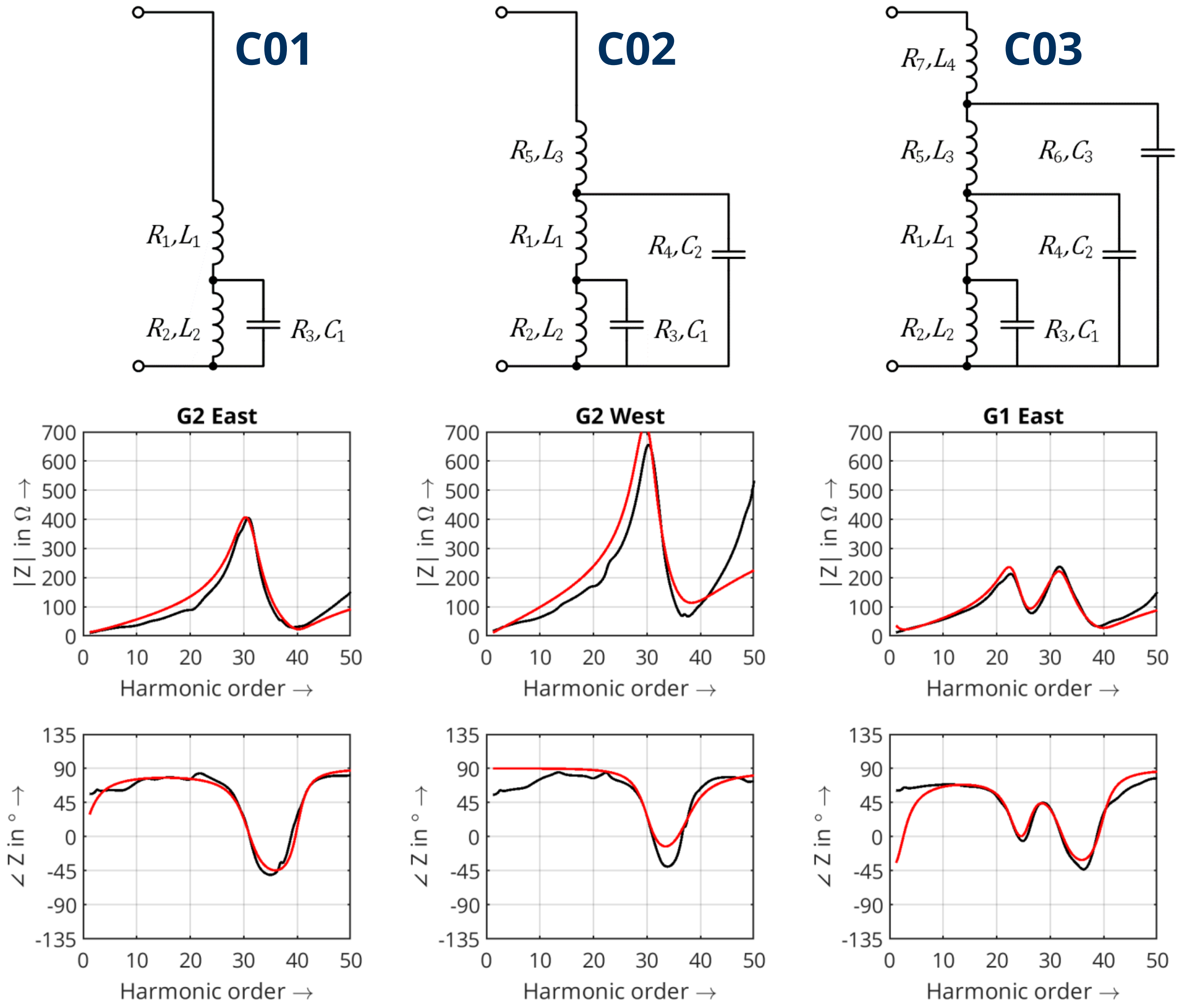
Equivalent circuit models
Circuit topologies (1)

- Defining circuit topologies essential for the aggregated representation
- Conventional load models alone not suitable for (multiple) resonances



Equivalent circuit models
Circuit topologies (2)

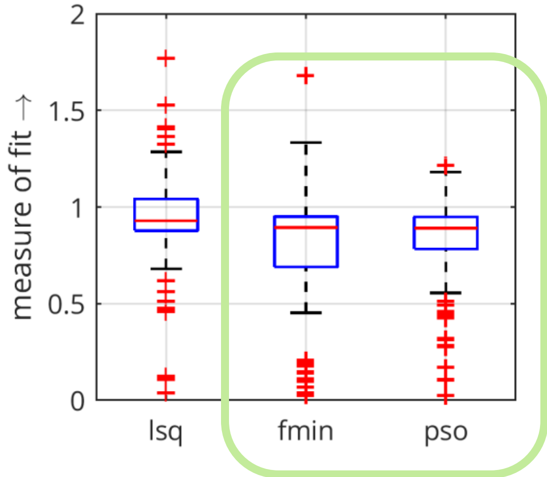
- Defining circuit topologies essential for the aggregated representation
- Conventional load models alone not suitable for (multiple) resonances
- Requires parallel and series resonant circuits:
  - C01 = 1x parallel/series resonances
  - C02 = 2x parallel/series resonances
  - C03 = 3x parallel/series resonances



Equivalent circuit models
Application results (1)

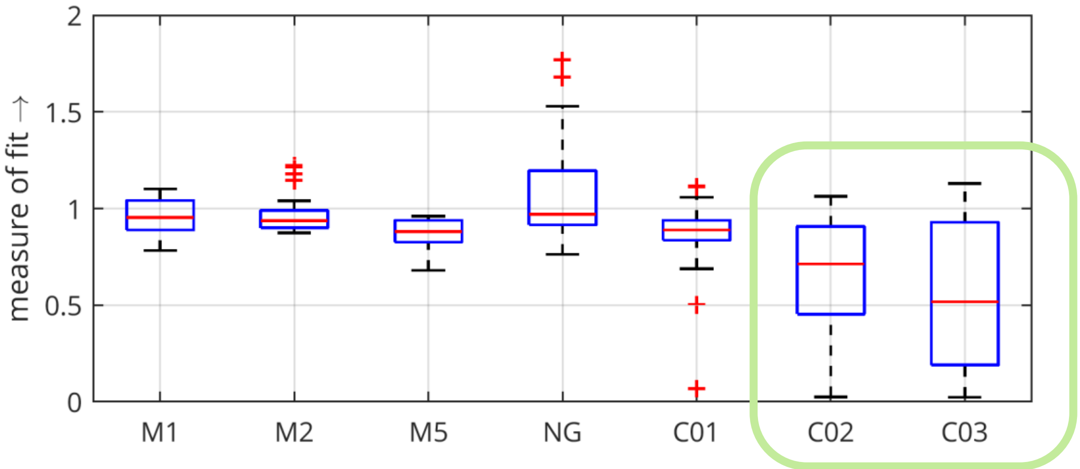
- Estimation of circuit parameters for different:
  - Fitting methods
  - Circuit topologies
  - Downstream impedances
  - Parameter search spaces
  - Initial parameter values

Fitting methods



lsq ... Nonlinear least squares
fmin ... Constrained nonlinear multivariate functions
pso ... Particle swarm optimization

Circuit topologies

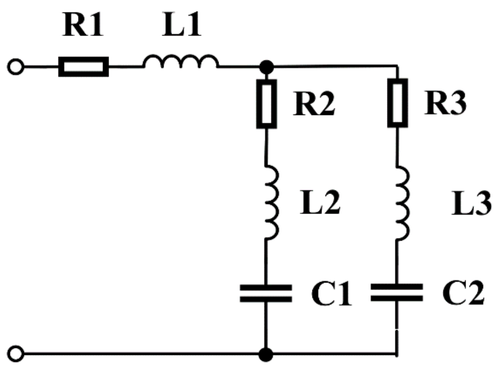


Equivalent circuit models
Application results (2)

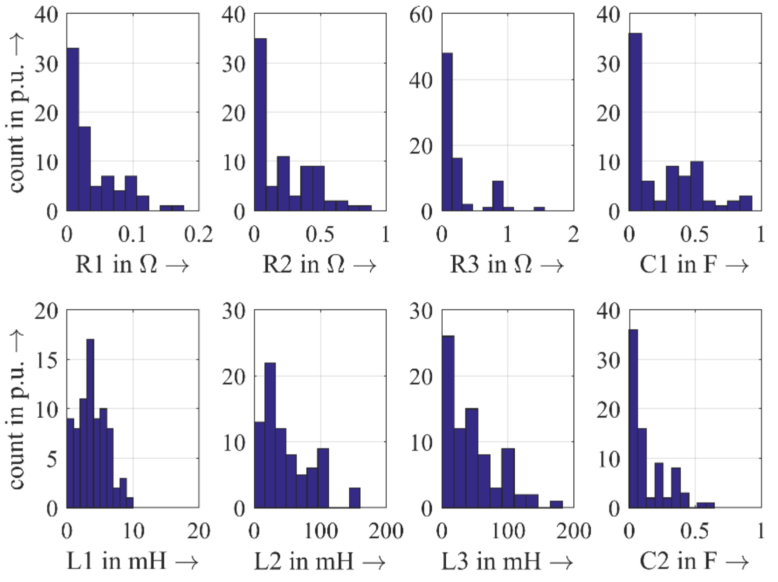
Example application

- Fitting of **measured downstream LV impedances**
- Implementation for MV simulations
- Artificial increase of sample size by averaging parameters for combinations of fitted circuits

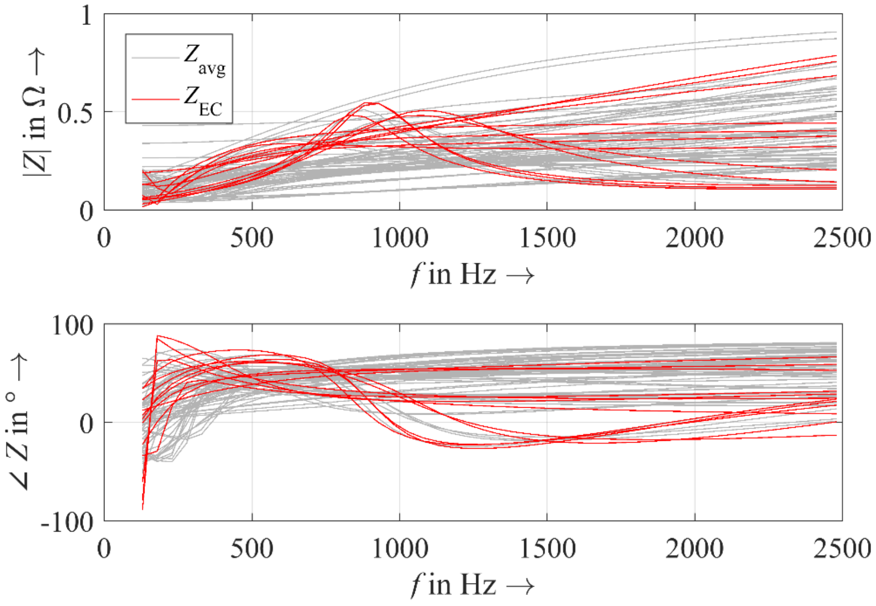
Optimal circuit topology



Range of parameter values

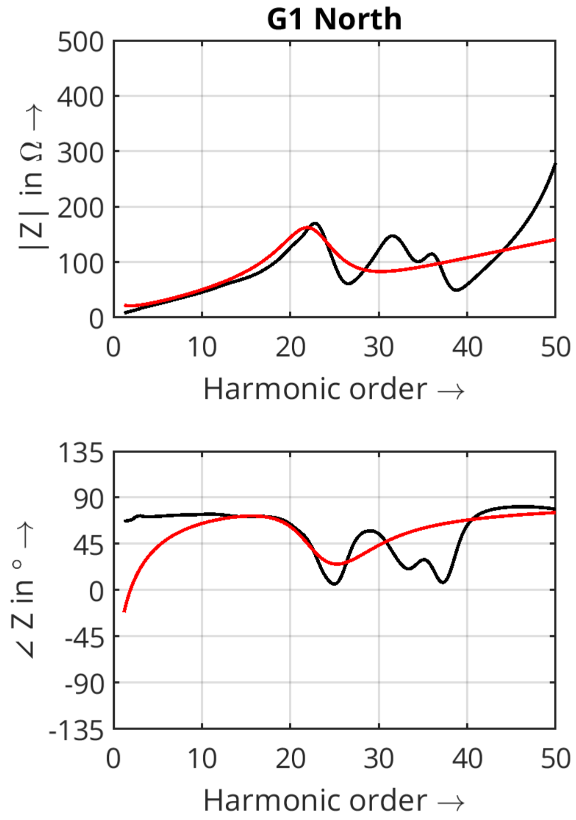


12 measured and 66 artificial impedances



Challenges
Model fitting

Suboptimal fitting for multiple resonances



Selection of circuit topologies

- Modified load models
- Combinations of multiple load models

Estimation of circuit parameters

- Parameter selective search spaces
- Additional constraints

Alternative approaches

- Deduct circuit topologies from vector fitting results
  (e.g. number of poles → resonances)

Challenges
Model implementation

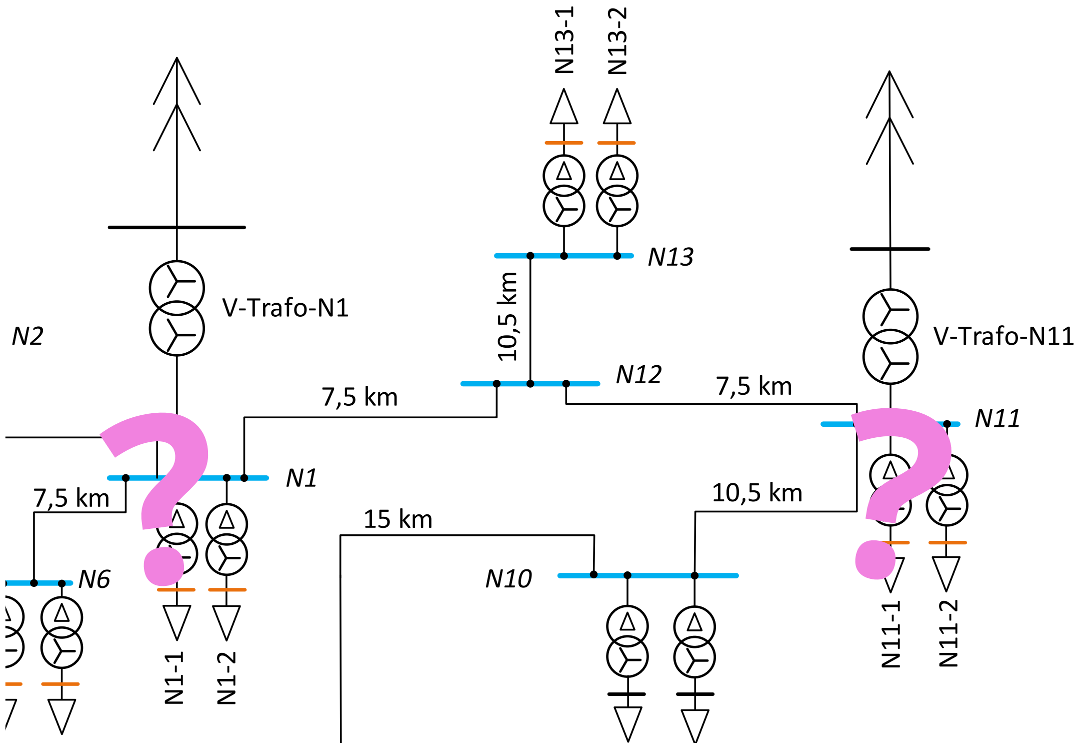
Multiple in-feeds

- Individual equivalents per in-feed
- Determination of “meshed” equivalents

Sequence systems

- Individual equivalents per sequence
  (positive, negative and zero sequence)
- Equivalents for coupled sequence systems
  (e.g. unbalanced conditions)

Distribution network with multiple in-feeds



Thank you for your attention!

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