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Uncertainty in the Assessment of Harmonic Voltages and Currents in Sequence Domain

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Agenda

Motivation

Uncertainty Propagation

- Uncertainty in Phase Domain
- Simulation of Uncertainty Propagation
- Uncertainty in Sequence Domain

Application Example

Conclusion

Motivation

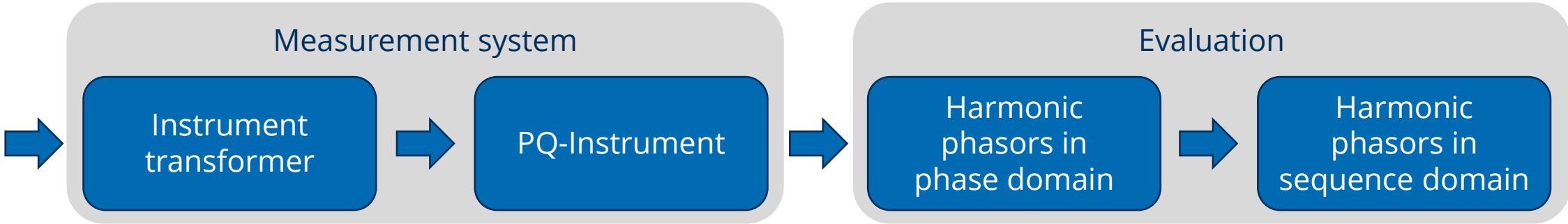
- **Modern power systems: more complex**
  - Large scale renewable integration (wind, solar)
  - Proliferation of non-linear loads and power-electronics

- **Harmonic distortion: rising concern**
  - Requires simulations to coordinate and limit harmonic emissions
  - Depends on accurate measurement data and simulation models
  - Often analyzed via symmetrical components (sequence domain)

- **Measurement uncertainty: critical factor**
  - PQ instruments must meet accuracy requirements
    (IEC 61000-4-30 Class A and IEC 61000-4-7 Class I)
  - Uncertainty from sensors, A/D converters and algorithms
  - Inaccurate data → flawed planning or compliance risks

Uncertainty Propagation
Uncertainty in Phase Domain

Measurement chain for harmonic phasors:



Accuracy requirements:
- Only limited to fundamental frequency (most VTs were designed accordingly)

Accuracy requirements:
- IEC 61000-4-30
- IEC 61000-4-7 (harmonics)

Resulting uncertainty:
- Magnitude ≤ 10 %
- Phase angle ≤ 5 °

Resulting uncertainty:
???

Uncertainty Propagation
Simulation of Uncertainty Propagation

Phase domain

Reference phasors

$$\underline{\boldsymbol{U}}_{\mathrm{abc}} = [\underline{U}_{\mathrm{a}} \quad \underline{U}_{\mathrm{b}} \quad \underline{U}_{\mathrm{c}}]^T$$

Uncertainty phasors

$$\underline{\boldsymbol{\epsilon}}_{\mathrm{abc}} = [\underline{\epsilon}_{\mathrm{a}} \quad \underline{\epsilon}_{\mathrm{b}} \quad \underline{\epsilon}_{\mathrm{c}}]^T$$

Phasors with uncertainty

$$\underline{\tilde{\boldsymbol{U}}}_{\mathrm{abc}} = (\boldsymbol{E} + \mathrm{diag}(\underline{\epsilon}_{\mathrm{a}}, \underline{\epsilon}_{\mathrm{b}}, \underline{\epsilon}_{\mathrm{c}})) \cdot \underline{\boldsymbol{U}}_{\mathrm{abc}}$$

Sequence domain

$$\underbrace{\frac{1}{3}\begin{bmatrix} 1 & \underline{a} & \underline{a^2} \\ 1 & \underline{a^2} & \underline{a} \\ 1 & 1 & 1 \end{bmatrix}}_{\underline{\boldsymbol{S}}} \cdot \underline{\boldsymbol{U}}_{\mathrm{abc}} = \underline{\boldsymbol{U}}_{120}$$

$$\underline{\boldsymbol{S}} \cdot \underline{\tilde{\boldsymbol{U}}}_{\mathrm{abc}} = \underline{\tilde{\boldsymbol{U}}}_{120}$$

$$\left|\underline{\tilde{\boldsymbol{U}}}_{120}\right| - \left|\underline{\boldsymbol{U}}_{120}\right| = \left|\underline{\boldsymbol{\epsilon}}_{120}\right|$$

$$\angle\underline{\tilde{\boldsymbol{U}}}_{120} - \angle\underline{\boldsymbol{U}}_{120} = \angle\underline{\boldsymbol{\epsilon}}_{120}$$

Sampling of uncertainties in phase domain:

- Monte Carlo method with **100.000 samples**
- Distribution as **uniform** and **normal** (3σ covering 99.7%)
- Magnitude uncertainty of **±10 %** and phase angle uncertainty of **±5 °**

Uncertainty Propagation
Simulation of Uncertainty Propagation

Combination of sequence components (reference phasors):

Characteristic sequence components of harmonics

h	2	3	4	5	6	7	8	9	…
Pos.			X			X			
Neg.	X			X			X		
Zero		X			X			X	

Relative Unbalance Level (RUL)

$$RUL_s^{(h)} = \frac{U_s^{(h)}}{U_1^{(h)} + U_2^{(h)} + U_0^{(h)}} \text{ for } s \in \{1,2,0\}$$

Balanced 7th harmonic → RUL = 100% / 0% / 0% (pure positive seq.)

Unbalanced 7th harmonic → RUL = 70% / 20% / 10% (mixed seq. comp.)

Combinations of sequence components

	RUL in %		
Comb.	**Pos.**	**Neg.**	**Zero**
1	100	0	0
2	90	0	10
3	80	10	10
…	…	…	…
67	33.3	33.3	33.3

67 unique combinations of sequence components

Uncertainty Propagation
Uncertainty in Sequence Domain

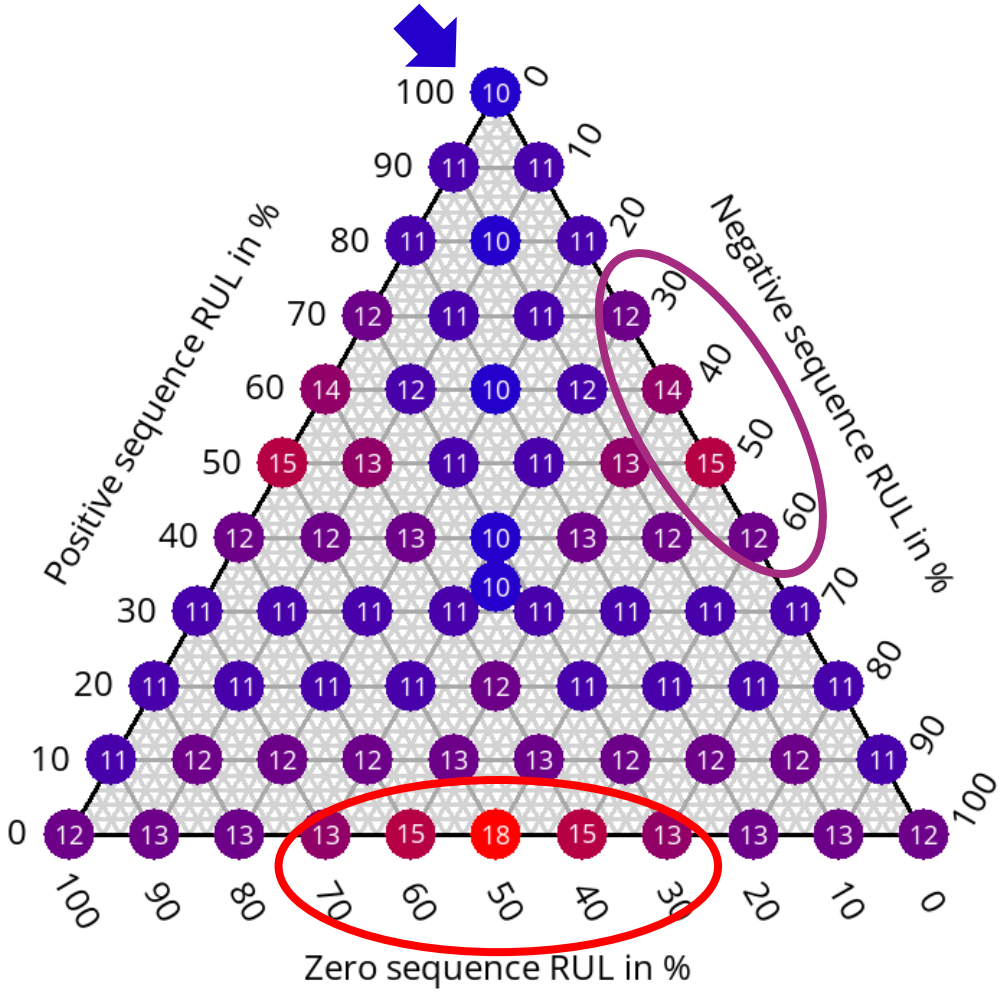
Resulting uncertainty for positive sequence:

- **Lowest absolute uncertainty**
  - Pure positive sequence (100% / 0% / 0%) and
  - Balanced seq. comp. (33.3% / 33.3% / 33.3%)
- **Higher absolute uncertainty**
  - Only two dominant components (e.g. 40% / 60% / 0%)
- **Highest absolute uncertainty**
  - No positive sequence (e.g. 0% / 50% / 50%)

➢ Similar uncertainties for other sequence components
(e.g. zero seq. with lowest uncertainty → pure zero seq.)

➢ Similar behaviour of phase angle uncertainty

Maximum magnitude uncertainty (in V) of positive seq. (references phasors of 100 V)



Uncertainty Propagation
Uncertainty in Sequence Domain

Resulting uncertainty:

- Uniform and normal distributions
- Uncertainties of 10 % / 5 ° and 0.1 % / 0.05 °

Magnitude uncertainty

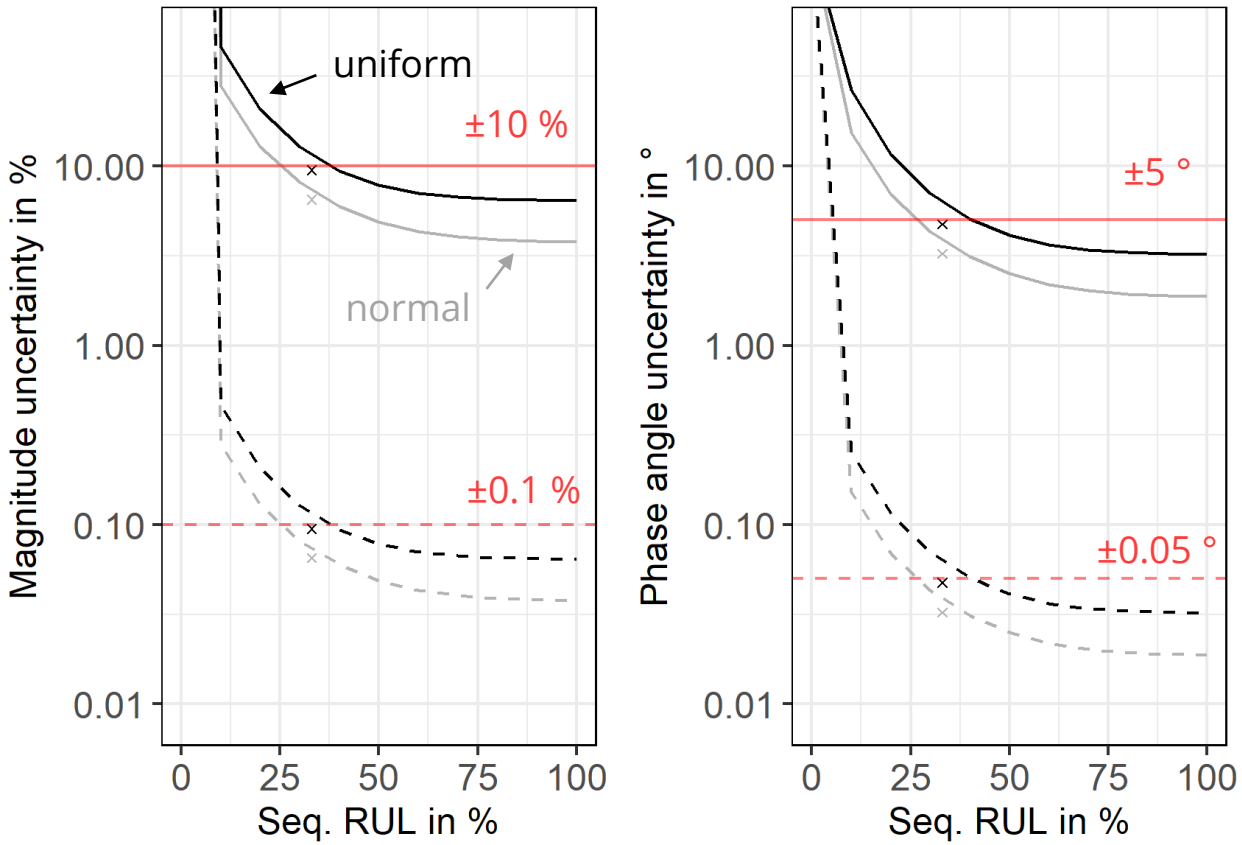
➢ Absolute magnitude uncertainty consistent across different magnitudes

➢ Relative magnitude uncertainty vastly higher for lower sequence magnitudes

Phase angle uncertainty

➢ Phase angle uncertainty vastly higher for lower sequence magnitudes

95th percentile values of uncertainty in sequence domain



Exceedance of uncertainty in phase domain: smallest sequence component with **RUL < 37 %**

Application Example

Measurement data

- 5 German TSO sites (2×220 kV, 3×400 kV) over 45 to 72 days
- 10-min values from PQ instruments (IEC 61000-4-30 Class A)

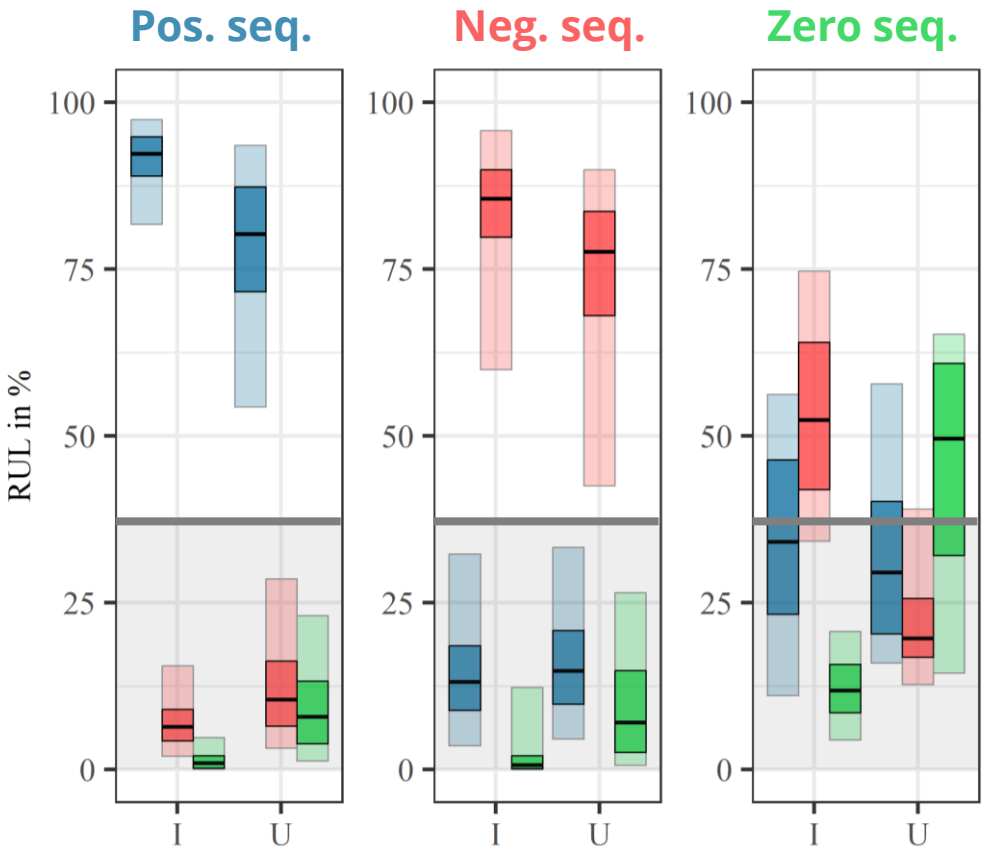
Data pre-processing

- Harmonic phasors for voltage and current
- Filtering to ensure uncertainty in phase domain below ±10 % and ± 5 °
  - Retained: odd harmonics e.g. 3, 5, 7, 11, 13 (≥80 % data)
  - Excluded: even harmonics & order >17

Uncertainty assessment in sequence domain

- ➢ Most non-characteristic components with RUL ≤ 37 %
- ➢ Characteristic pos./neg. sequence harmonics reliable with RUL ≈ 80%
- ➢ Zero-sequence results show mixed reliability

RUL by characteristic sequence aggregated over 5 sites for current and voltage harmonics



Conclusion

- Propagation of uncertainty from the **phase domain** to the **sequence domain** can significantly reduce harmonic phasor accuracy in sequence domain
- **Small, non-characteristic sequence components** are particularly affected, exhibiting high relative uncertainties, which makes them unreliable for further analysis
- A **37 % RUL threshold** is applied to ensure that only reliable harmonic voltage/current data are used

Thank you for your attention!

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