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# Probabilistic study of propagation and summation of harmonics in transmission systems

PMAPS 2022 // M2C: Probabilistic Analysis of Power Quality

# Motivation
## Standardization framework

**EMC coordination** shall ensure a low probability that the compatibility level is exceeded at any point in the network in case the network is fully utilized with devices/installations

**Emission limits** < **Compatibility level** < **Immunity test level**

Determination of emission limits based on “cake concept”

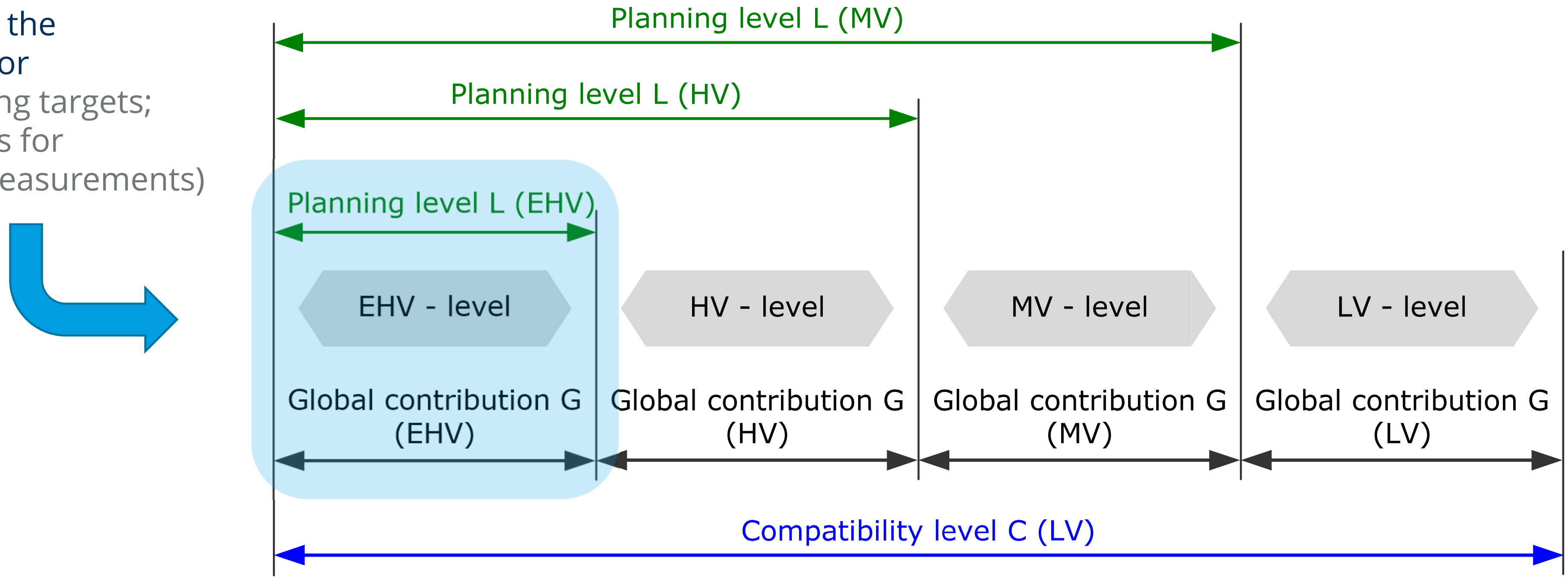
1. Share compatibility level between voltage levels (global contribution)
2. Share global contribution between installations and devices connected within voltage level

# Motivation
## Share between voltage levels

1. Share compatibility level between voltage levels → global contribution ( = planning level for EHV)

*Planning level:*

Specification by the network operator
(internal planning targets; indicative values for evaluation of measurements)



# Motivation
## Share within EHV level

1. Share compatibility level between voltage levels → global contribution ( = planning level for EHV)
2. Distribution of **planning level ($L_{EHV}$)** among nodes within EHV network → **nodal contribution ($G_h$)**
3. Share nodal contribution between customers/installation at node → Emission limits

# Motivation
## Share within EHV level

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3. Share nodal contribution between customers/installation at node → Emission limits

**IEC 61000-3-6**

$$G_{h\,m} \leq \sqrt[\alpha]{\frac{S_{t\,m}}{K^{\alpha}_{h\,1-m} \cdot S_{t\,1} + \cdots + S_{t\,m} + \cdots}} \cdot L_{h\,\mathrm{EHV}}$$

- Detailed approach considers all nodes of network
- Requires detailed knowledge
  - Maximum total capacity $S_t$ for all nodes
  - Influence coefficients $K$ between nodes

**AR-N 4130** (technical requirements for Germany)

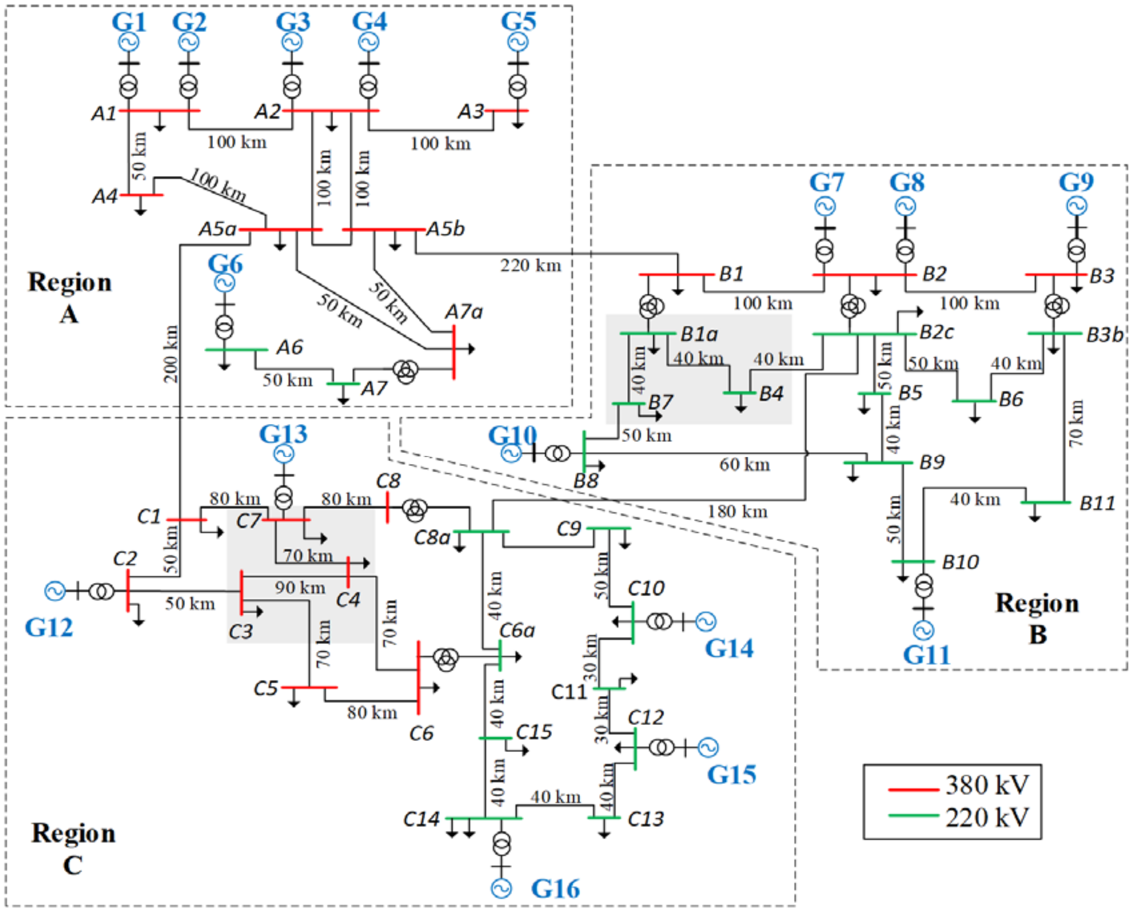
$$G_h = \sqrt[\alpha]{k_{\mathrm{red}\,h}} \cdot L_{h\,\mathrm{EHV}}$$

- Simplified approach considers each node separately
- Reduction factor $k_{red\,h}$ to take other nodes into account

→ **Verification of reduction factor and better understanding of influence between nodes**

# Simulation framework
## Network model

- **18 nodes – 380 kV**
- **22 nodes – 220 kV**
- 39 nodes – 110 kV
- 16 generators
- Generic (German) transmission system with symmetric impedances and emissions
- Model validation
  (load flow, voltage band, short-circuit currents)
- Qualitative comparison of frequency-dependent network impedance with existing simulations and measurements
  (only available for 380 kV and 110 kV level)
- Validation of frequency-dependent impedances necessary especially of the zero-sequence system impedances necessary
  (further measurements, detailed simulations)



# Simulation framework
## General procedure

1) Determination of **nodal contribution**
   for each node and harmonic order according to AR-N 4130

$$G_h = \sqrt[\alpha]{k_{\text{red } h}} \cdot L_{h \text{ EHV}}$$

Conservative assumption:
Full expansion of network with connected customers/installations up to maximum total capacity $S_t$ at every node

2) Sampling of **actual emission**
   for each node and harmonic order

3) Sampling of **phase angles** for actual emission
   taking into account the summation exponent according to IEC 61000-3-6 (α = 1, 1.4, 2)

4) Calculation of **resulting harmonic voltages** at all nodes

5) Determination of the **utilization of planning levels**
   (ratio between maximum resulting voltage of all nodes and planning level for each harmonic order)

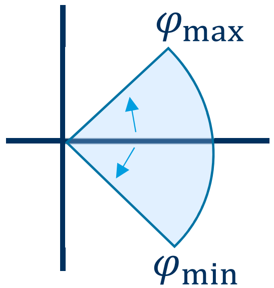
# Simulation framework
## Sampling methodology for emission

### Magnitude

- For reduced concurrencies (e.g. $g = 0.8$)
- Sampling from normal distribution ($\mu = g$ and $\sigma = 0.2$) for all nodes
- Limitation of value range to [0, 1]
- Repeated until $\overline{g_s} \approx g$ with $|\overline{g_s} - g| \leq 0.01$ → actual emission $U_1, U_2, \dots, U_N = g_1 \cdot G, g_2 \cdot G, \dots, g_N \cdot G$

### Phase angles

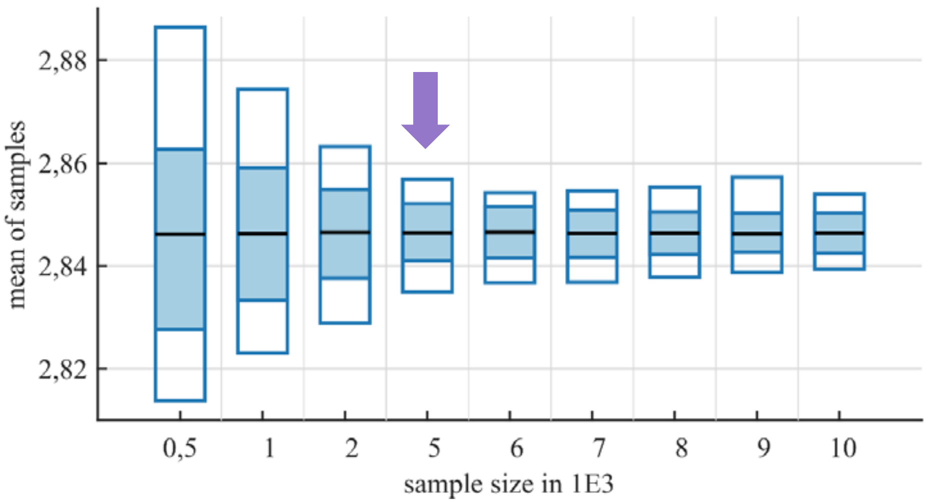
- Given $U_1, U_2, \dots, U_N$ and $\alpha$
- Summation exponent : $U_\mathrm{A} = \sqrt[\alpha]{U_1^\alpha + U_2^\alpha + \cdots + U_N^\alpha}$
- Vector sum: $U_\mathrm{V} = |\underline{U_1} + \underline{U_2} + \cdots + \underline{U_N}|$
- Repeated sampling until $e = |(U_\mathrm{V} - U_\mathrm{A})|/U_\mathrm{A} \leq 0.01$

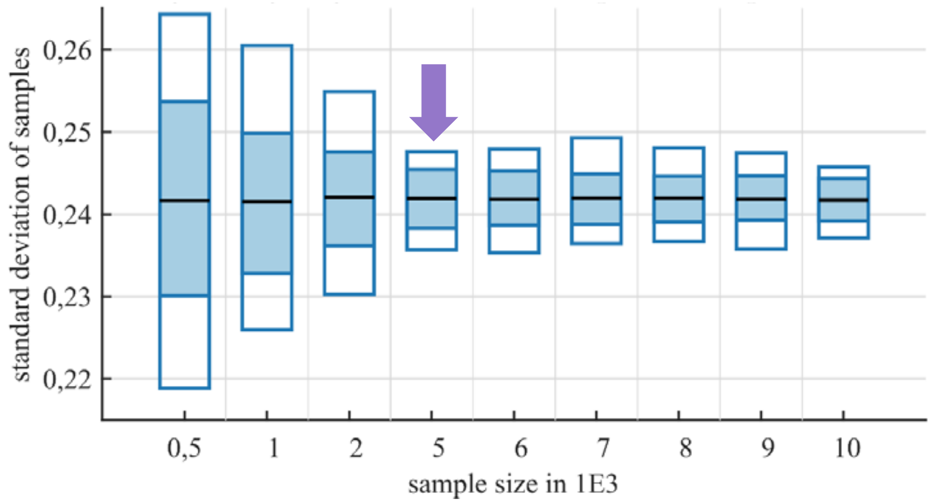



→ phase angles $\varphi_1, \varphi_2, \dots, \varphi_N$

# Simulation framework
## Estimation of required simulation runs

- Utilization of planning level for each simulation
- Mean and standard deviation for different number of simulations {500, 1.000, 2.000, ...,10.000}
- 1.000 samples for each number of simulations



# Simulation framework

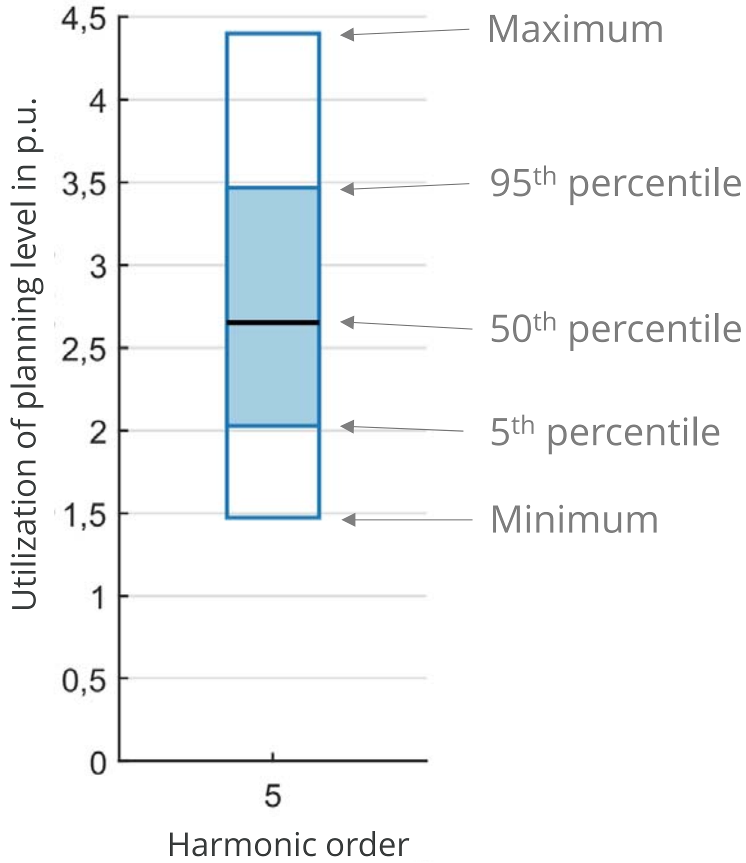
## Example for 5th harmonic

$$G_h = \sqrt[\alpha]{k_{\text{red } h}} \cdot L_{h \text{ EHV}}$$

- $h = 5$, $\alpha = 1.4$
- Planning level → $L_{5 \text{ EHV}}$ = 1.57 %
- Reduction factor → $k_{red\ 5}$ = 0.33^(1/1.4) = 0.453
- Nodal contribution $G_5$ = 0.72 %

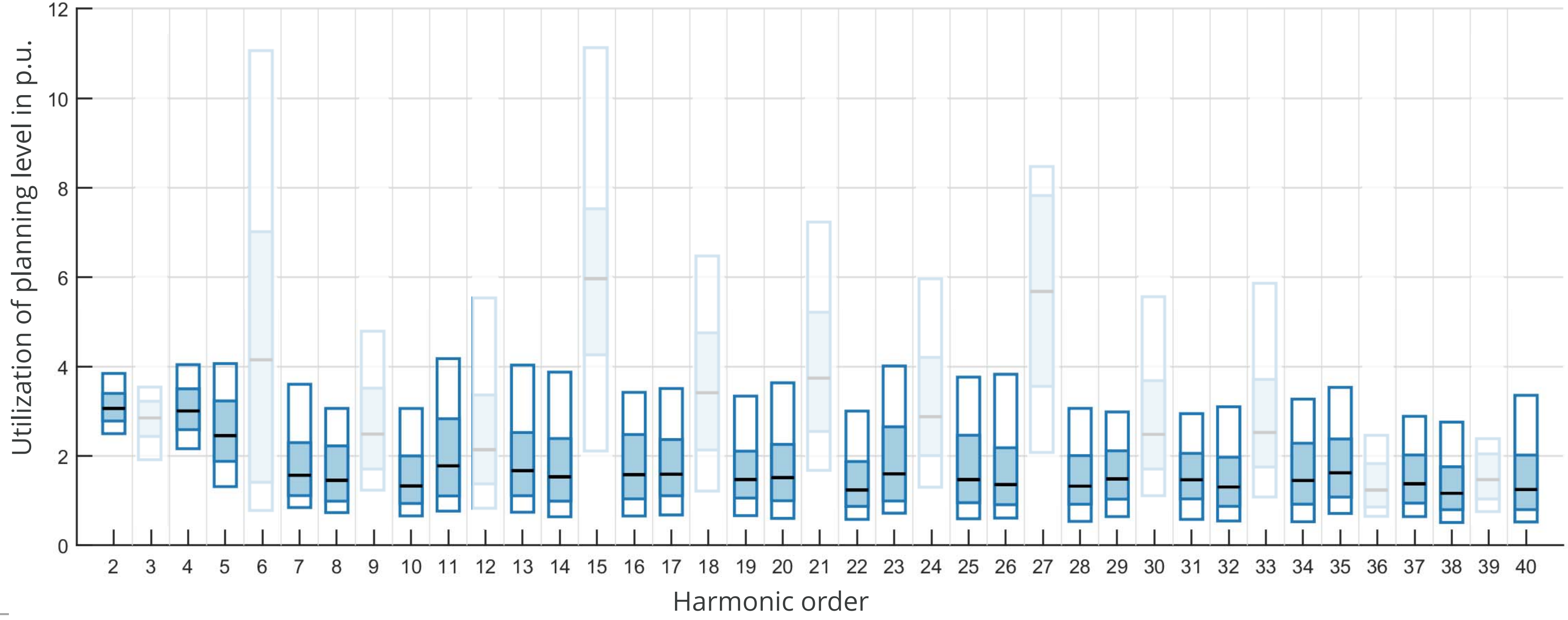
*Evaluation for 5.000 simulation runs*

- „Worst case“ with full emission at all nodes (concurrency $g$ = 1)
- Actual emission = nodal contribution → 0.72 % at each node
- Random phase angles with $\alpha$ = 1.4
- Calculation of resulting voltages at each node to determine utilization of planning level



# Results
## Realistic scenario

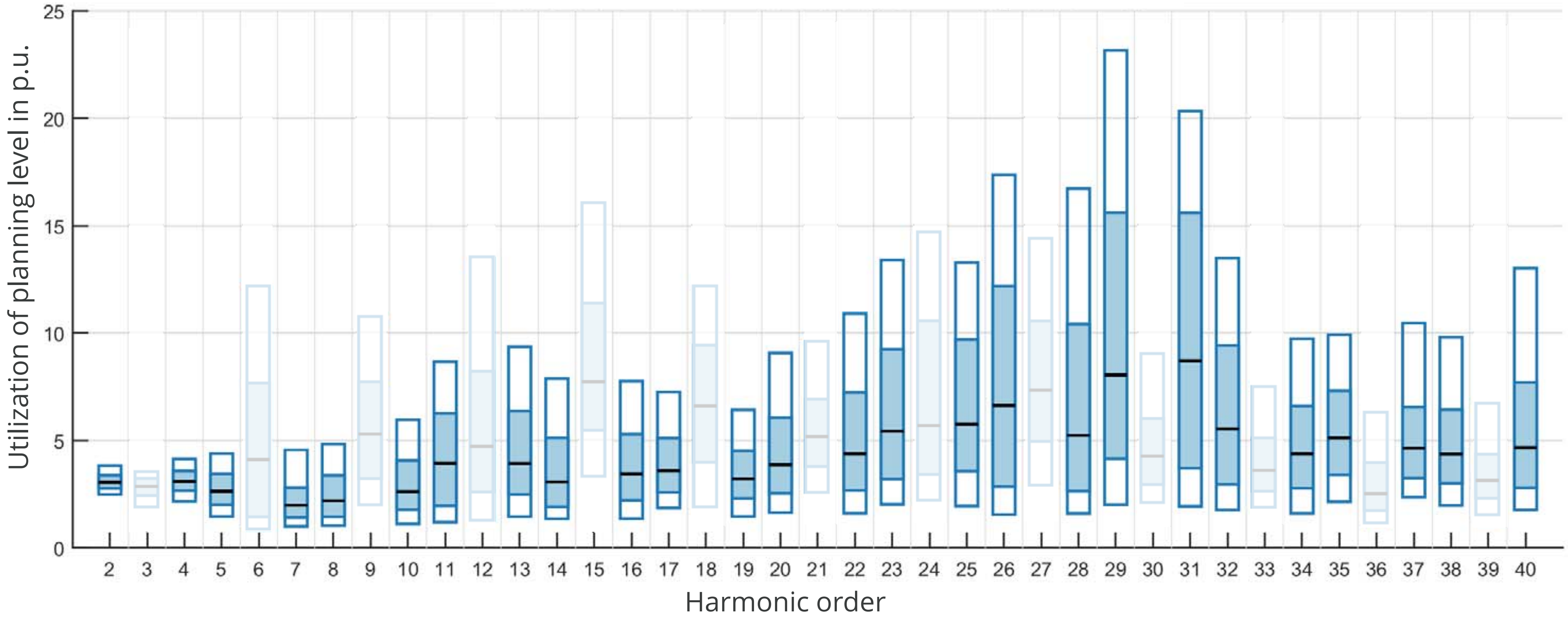
- Reduced concurrencies (actual emission at nodes < allowed nodal contribution)
- Limitation of actual emission in case of resonances (requires frequency-dependent network impedance at nodes)



# Results

## No consideration of local resonance amplifications

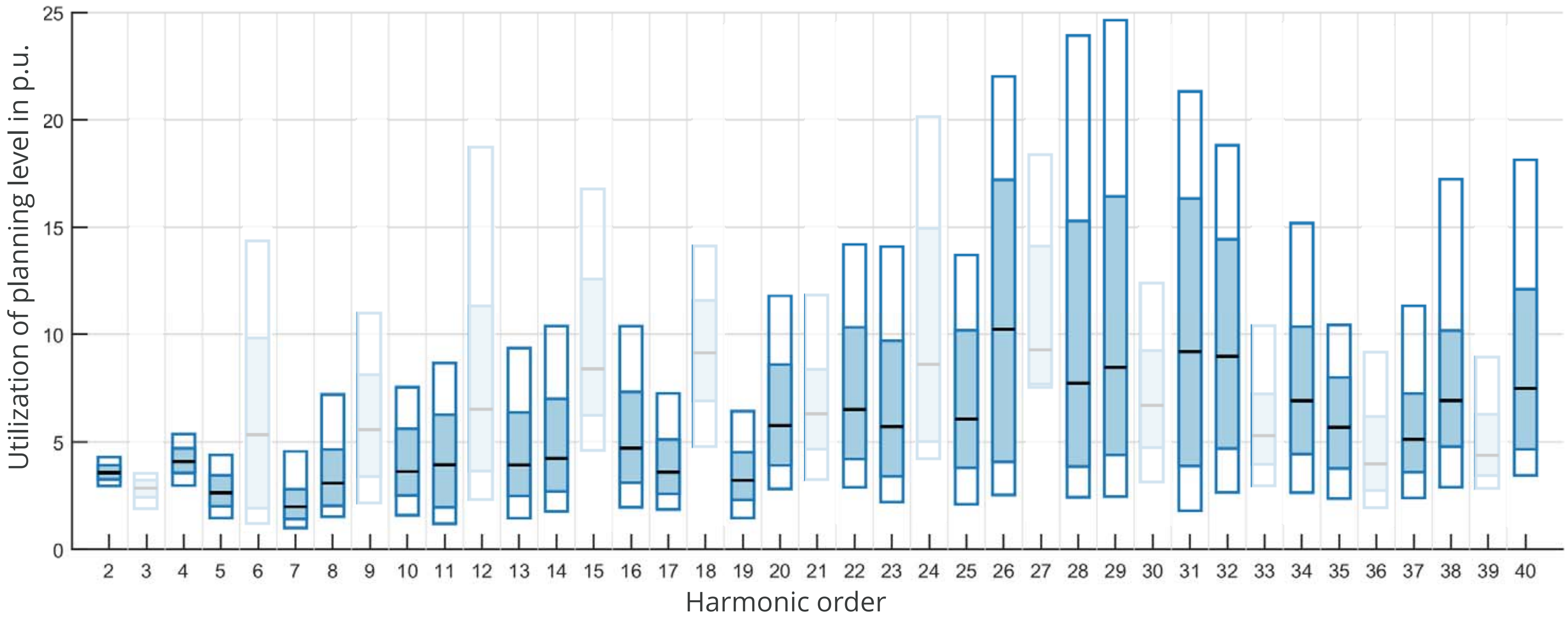
- Reduced concurrencies (actual emission at nodes < allowed nodal contribution)
- Without limitation of actual emission (amplifications due to resonances)



# Results

## No consideration of concurrency and local resonance amplifications

- Full utilization of nodal contribution at all nodes (*g* = 1)
- Without limitation of actual emission (amplifications due to resonances)



# Conclusion

- Influence between nodes in meshed EHV networks cannot be neglected → application of reduction factor justified
- Large number of resonances whose frequency and magnitude depend on location and vary greatly (minor changes in the network topology or in the impedance of connected customer installations can significantly shift or change resonances)
- Without limitation of emissions → impermissibly high harmonic levels at other nodes due to resonances
- Application of AR-N 4130 results in harmonic levels that can exceed the planning level for the simulation (95$^{th}$ percentile reaches 2 to 3 times the planning level)
- Due to conservative assumptions for the simulation (full expansion of network with max. capacity at all nodes) → no immediate need to change simplified approach in AR-N 4130

*Future work*

- Improvement of modelling and validation of zero-sequence impedances necessary (measurements, simulations)
- Analysis of the influence of asymmetric impedances (equipment and customer installations) as well as for emissions (symmetrical conditions often insufficient, e.g. for long cable lengths with asymmetrical installation)

## Thank you for your attention!

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