Faculty of Electrical Power Systems and High Voltage Engineering
Chair of Electrical Power Supply

Measurement-based black-box harmonic stability analysis of commercially available single-phase photovoltaic inverter in public low voltage networks

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1st Conference 2022, Interessenverband Netzimpedanz
7th April 2022

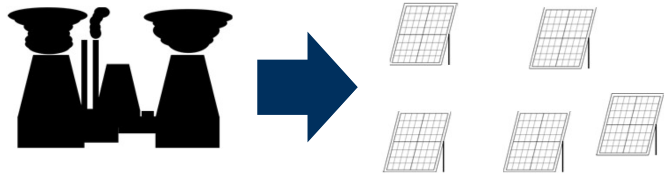
Agenda
Structure

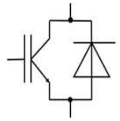
1. **Introduction**
2. **Black-box stability analysis**
3. **Probabilistic stability assessment**
4. **Conclusion**

1. Introduction
Motivation

Trends

- Pursuing climate goals
  - Replacement of traditional, central energy generation
- Growth of share..
  - of photovoltaics
  - of power electronic devices



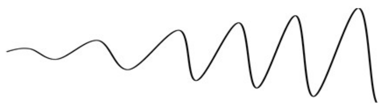


Challenges

Use of power electronic devices:
  - Reduction of damping loads
  - Increase of nonlinearities
- High penetration of inverters in the grid
  - Unwanted shut down of photovoltaic inverters
- Large diversity of inverters
  - Different behavior due to different design
  - Complex, usually unknown design of circuit and controls
  - Interactions with other inverters/devices

Aim

Prediction of instable inverter conditions



2. Black-box stability analysis

Impedance-based analysis

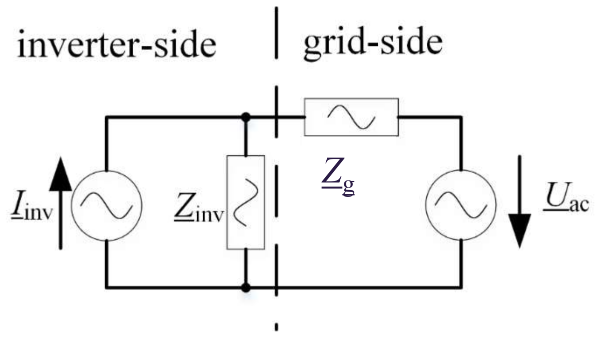
Black-box analysis

- No knowledge about internal structure and parameters required
- Measurement-based parameter identification

Impedance-based analysis

- Considers electric impedances
- Suitable for small-signal analyses

Small signal model



$\underline{Z}_g$… Grid impedance

$\underline{Z}_{inv}$… Inverter impedance

Nyquist criterion

Gain margin	*Phase margin*
Ratio of grid impedance and inverter impedance → Detect intersection	Stable if: $180^\circ - \phi_g + \phi_{inv} > 0$

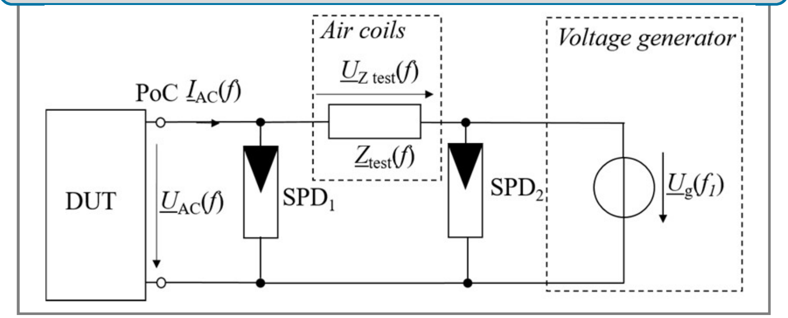
2. Black-box stability analysis
Laboratory validation – set up

Measurement set up

$$\underline{U}_{AC}(f) = \underline{Z}_{test}(f)\underline{I}_{AC}(f) + \underline{U}_{g}(f)$$

Voltage at PoC is affected by $\underline{Z}_{test}(f)$

Test stand set up



Network representation

Use of two air coils

- Air gap defines the resulting inductance

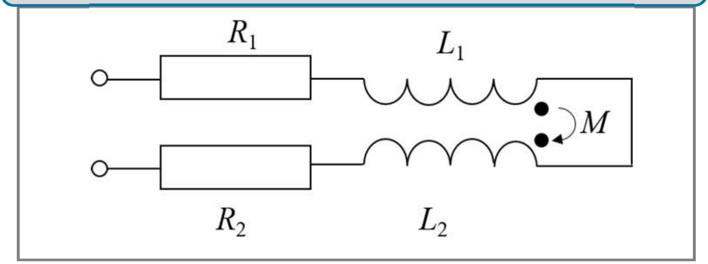
$$\underline{Z}_{test}(f) = R_{test} + 2\pi f\ L_{test}$$

$$L_{test} = L_1 + 2M + L_2$$

$$R_{test} = R_1 + R_2$$

→ Flexible and cost-efficient design

Equivalent circuit of air coils



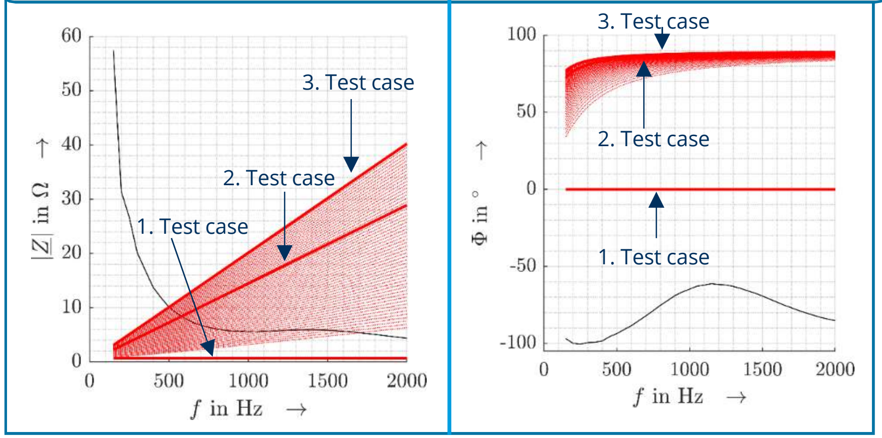
2. Black-box stability analysis

Laboratory validation – test cases

Test cases		
Test cases	**Applied inductances**	**Expectations**
Test case I	0 mH	Stable, Little distortion
Test case II	2.3 mH	Stable, Noticeable distortion
Test case III	3.2 mH	Instable, Shutdown

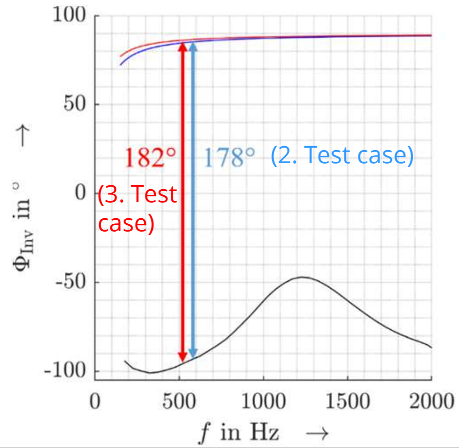
Impedance characteristic of $\underline{Z}_{test}$

Magnitude	Phase angle



$$180° - \Phi_g + \Phi_{PE} > 0$$

182°



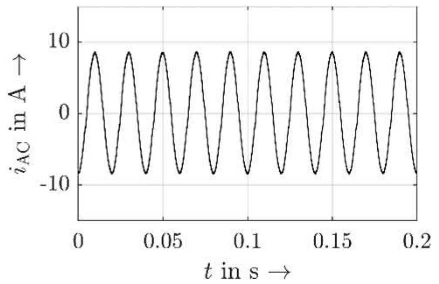
2. Black-box stability analysis

Laboratory validation

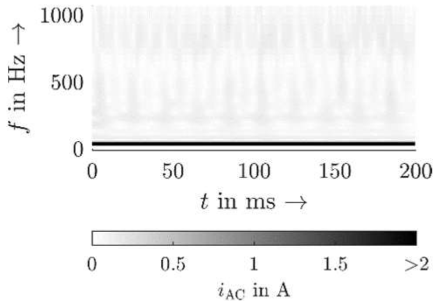
Grid-side current measurements

Test case I: 0 mH

Time domain



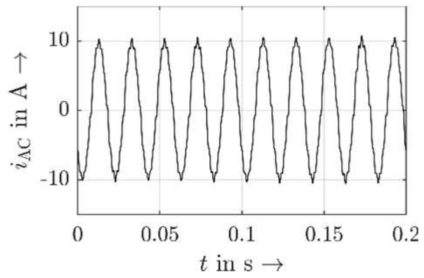
Wavelet domain



Stable:
Low distortion

Test case II: 2.3 mH

Time domain



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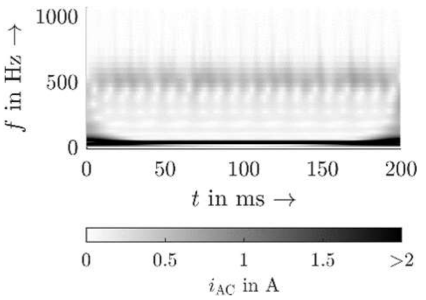
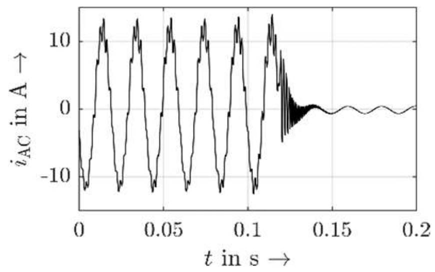


Stable:
Noticeable distortion

Test case III: 3.2 mH

Time domain



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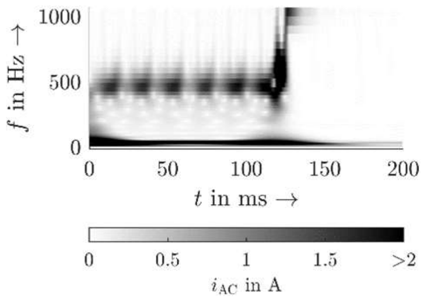
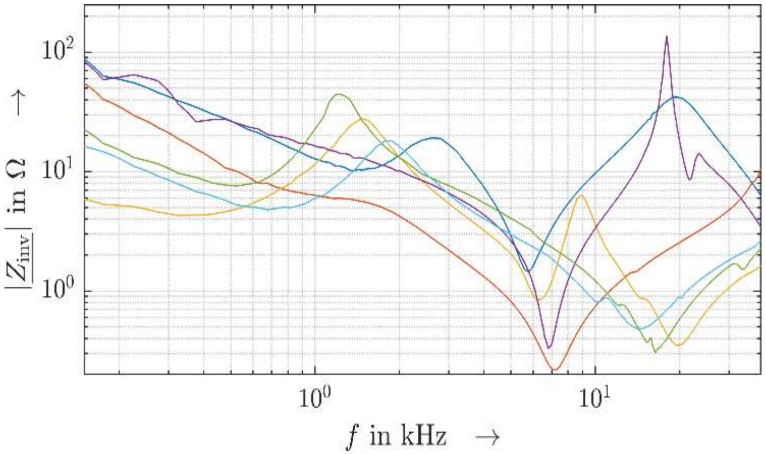


Instable:
Shutdown

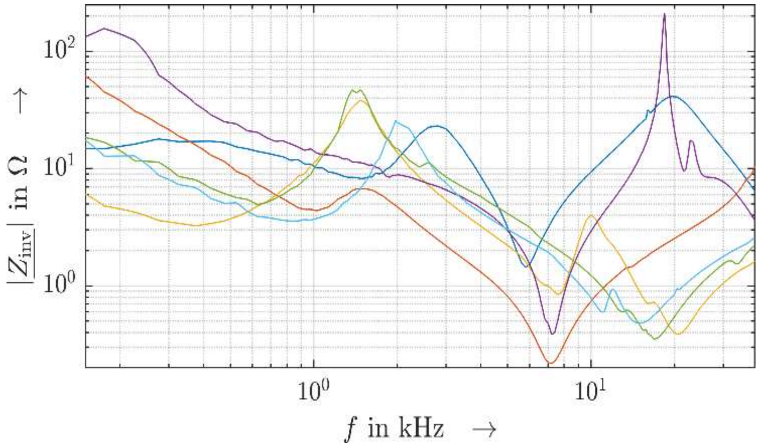
3. Probabilistic stability assessment
Inverter impedance amplitudes

- 6 commercially available low-power inverters for rooftop PV applications
- Laboratory measurements up to 39 kHz
- Dependency of impedances on power level

10 % rated power



100 % rated power

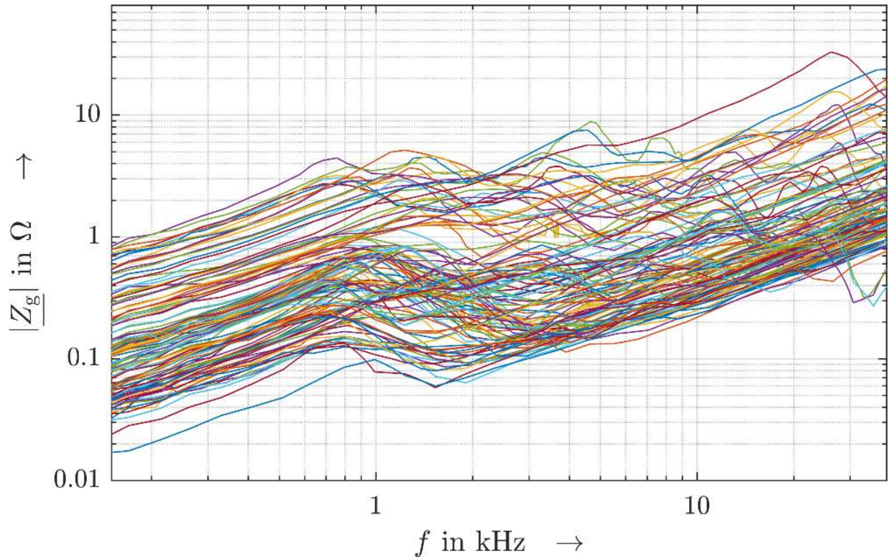


3. Probabilisitc stability assessment
Grid impedance measurements

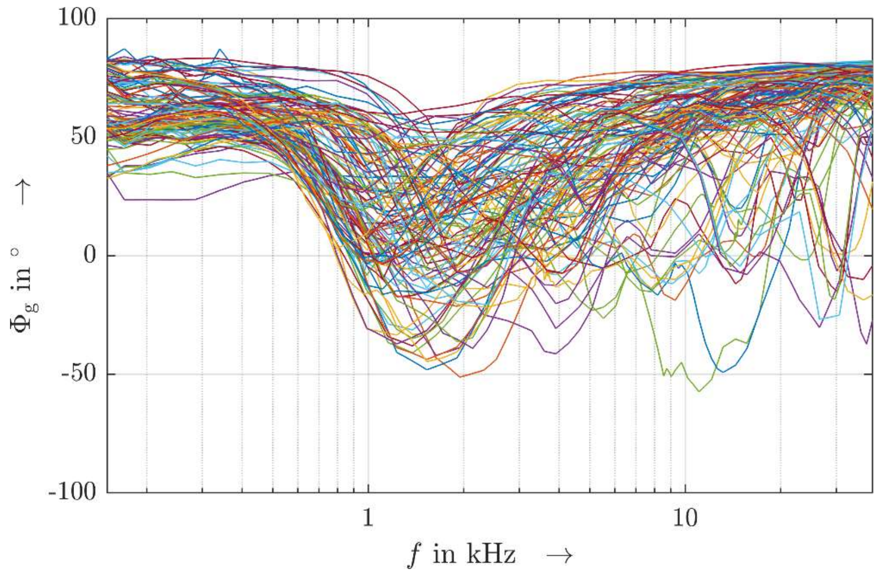
Data from measurement campaign [1]

- About 200 loop impedance measurements in public low-voltage grids
- Measurement sites in Germany, Austria, Switzerland, Czech Republic
- 75 % at junction boxes, 25 % at LV busbars in MV/LV substations
- About 80 %: first resonance peak between 600 Hz and 1.8 kHz

Amplitudes



Phase angles



[1] Stiegler, R.; Meyer, J. Schori, S. ; Höckel, M. : Survey of network impedance in the frequency range 2-9 kHz in public low voltage networks in AT/CH/CZ/GE. In *25th International Conference on Electricity Distribution*, 2019, S.3-6

3. Probabilistic stability assessment
Probabilistic considerations

Application of Nyquist criterion

- *no critical grid – inverter combination found*

However:
1. Grid measurements not taken directly at customer terminals, where PV-inverters are usually connected
(Grid impedance can be different)
2. Grid-connected devices at Point of Connection of inverter might dominate the impedance behavior (more capacitive character)
3. Change of impedance seen by inverter, dependent on daytime

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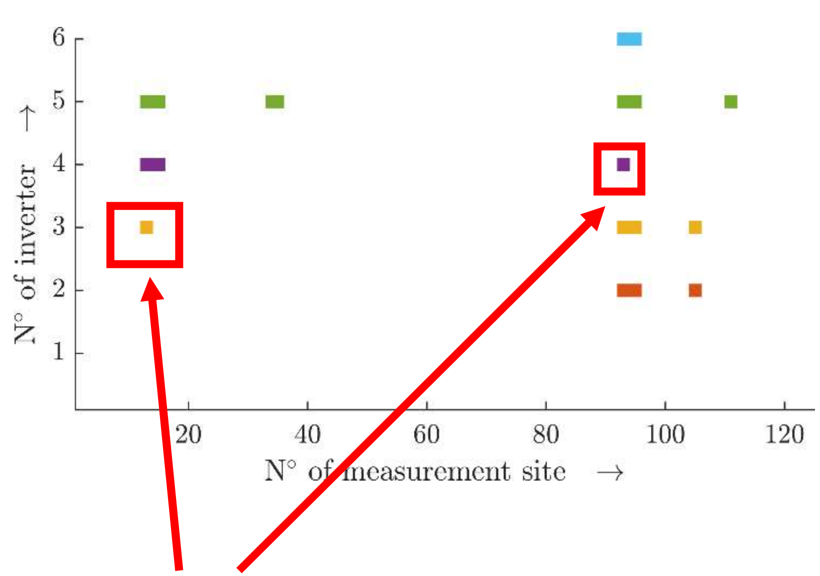
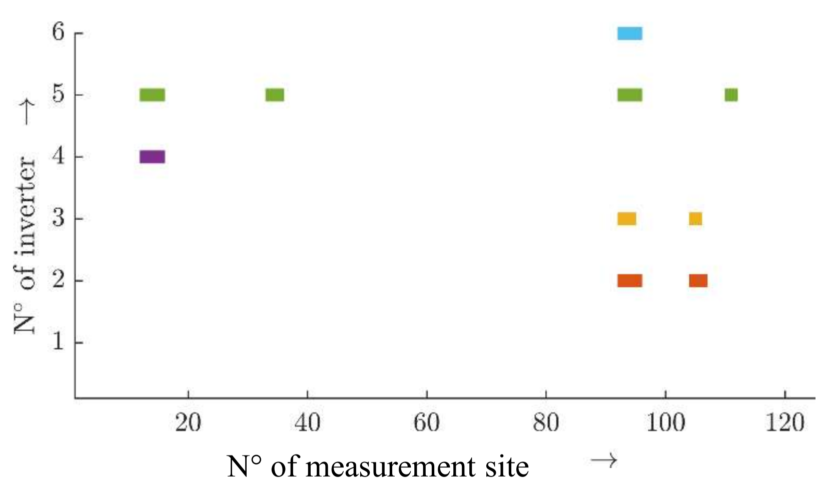
Consideration of an additional phase margin of 30°

3. Probabilistic stability assessment
Critical Measurement sites

Results with adjusted phase margin criterion

10 % rated inverter power	100 % rated inverter power





More critical sites, if operated at 10 % of rated power

4. Probabilistic stability assessment
Grid compatibility index

Grid compatibility index

Index to assess the robustness of inverters with regard to grid integration

n_c… number of critical measurement sites
n_{tot}… number of all considered measurement sites

$$\text{gci} = 1 - \frac{n_c}{n_{tot}}$$

N° of inverter	grid-compatibility index gci
1	1
2	0.9669
3	0.9587
4	0.9669
5	0.9256
6	0.9835

5. Conclusion
Summary and future work

- Harmonic stability assessment of commercially available photovoltaic inverters
- Laboratory validation of the theory
- Probabilistic approach for assessment of robustness of inverters for public LV grids
  - Diversity of public low voltage grids considered by extensive measurements
  - Grid operators can estimate grid robustness with respect to their specific grid
- Assessment index provided for grid compatibility (gci)

Future Work

- Expand Database
  - Grid-measurements
  - Inverters
- Study on nonlinearities of inverters

Thank you for your attention

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