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Innovations for Grid-Integration of Wind- and Solar Power systems

Grid-Integration of Wind and Solar
Agenda

1. **Introduction**
2. **Grid Forming Inverter**
3. **Power System Studies**
4. **Conclusions and Next Steps**

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Introduction

Overview of distribution of installed capacities per energy source in Germany

German Grid Development Plan: Scenario A

Total renewable generation:

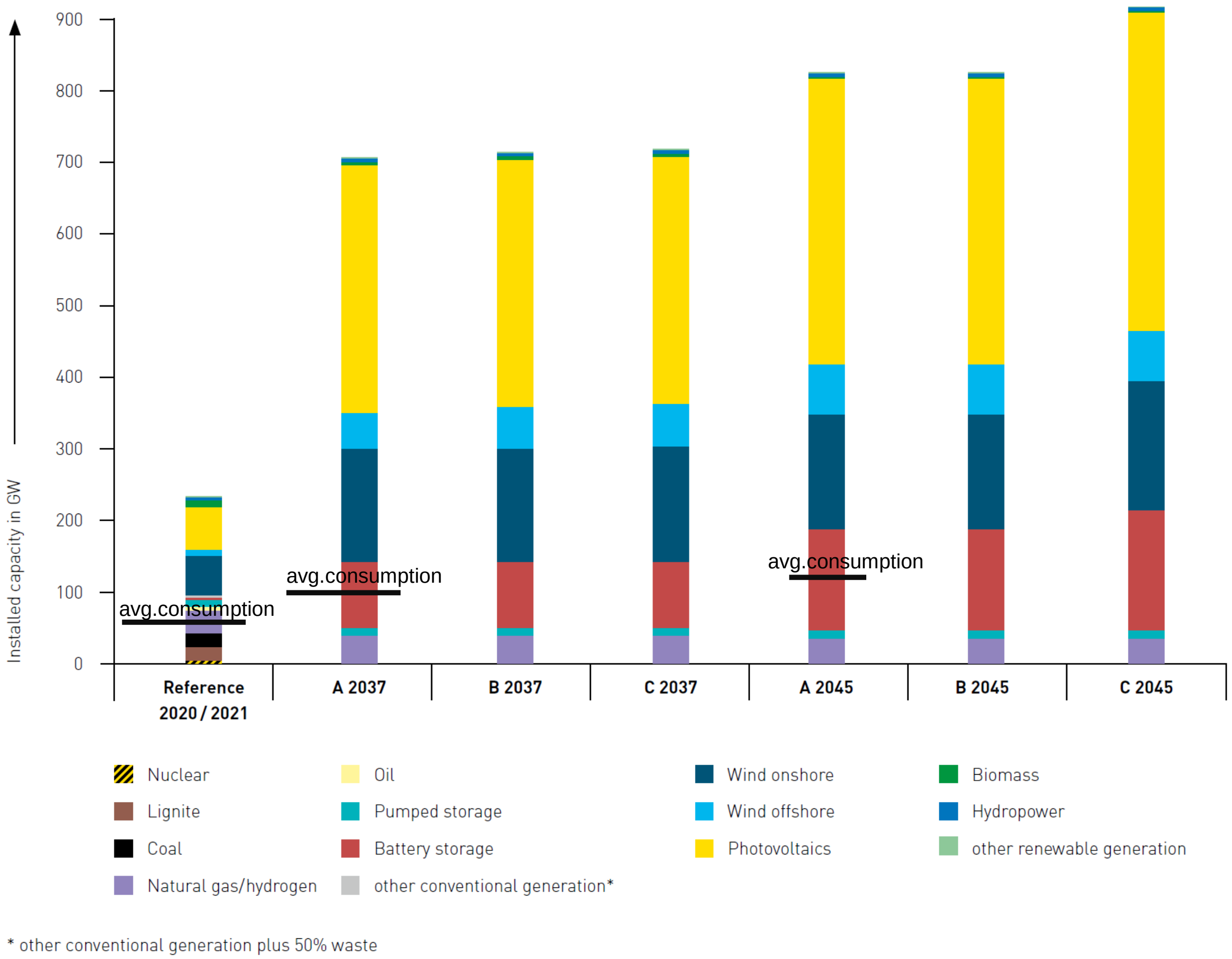
- 2021/22: 139 GW
- 2037: 565 GW
- 2045: 638 GW

Total generation:

- 2021/22: 232 GW
- 2037: 617 GW
- 2045: 686 GW

Gross power consumption:

- 2021/22: 533 TWh (61 GW avg.)
- 2037: 899 TWh (103 GW avg.)
- 2045: 1079 TWh (123 GW avg.)



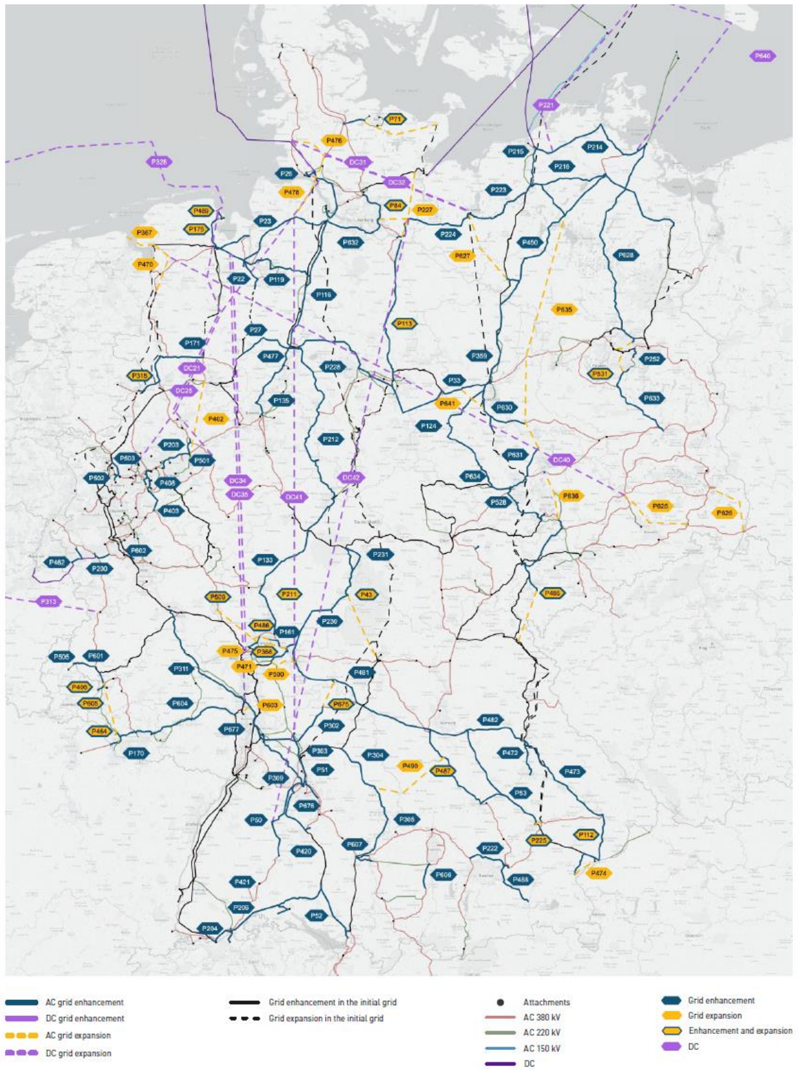
Source: Grid Development Plan Electricity 2037 / 2045, (2023), second draft | Transmission system operator CC-BY-4.0

Introduction

Changes to the energy supply system

- Shutdown of conventional power plants with synchronous generators
- Large generation capacities in the distribution grid
- High penetration of power converter-based generation systems
- Integration of HVDC corridors
- Increasing use of active network components
- Limited and delayed expansion of transmission and distribution grids

Onshore grid expansion scenarios A / B / C 2037, A / B / C 2045, only power line construction projects*



*The presentation of the new construction projects shows the starting and end points, but no specific routes. They will only be determined in downstream approval procedures.

Introduction

Changes (continued)

Changed system properties:

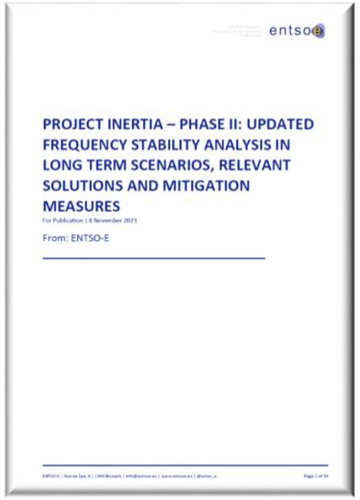
- Reduction of physically coupled inertia and short-circuit power
- Relevance of power converter control and operating point-dependent system perturbations
- New network usage scenarios

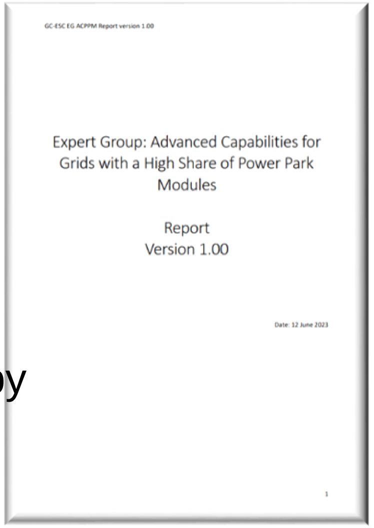
New challenges:

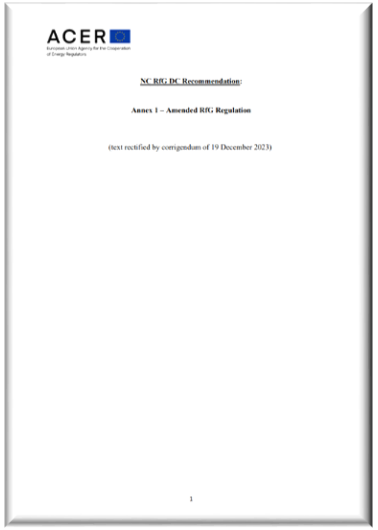
- Operating the system closer to stability limits
- New power converter-induced stability aspects
- Operation of low-inertia interconnected grids
- Complex analysis of power converter-dominated networks in the appropriate level of detail

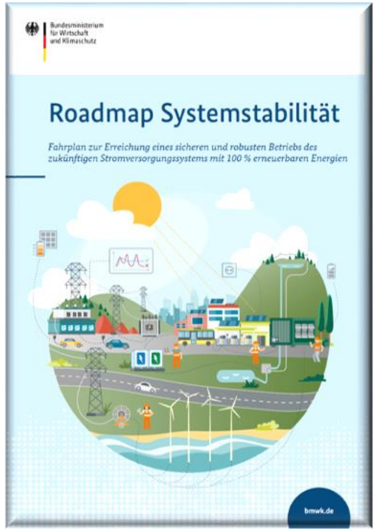
Aim: Safe System Operation with Distributed Energy Resources

- System services from conventional power have to be taken over by other generation units
- One approach: **grid forming inverter control**









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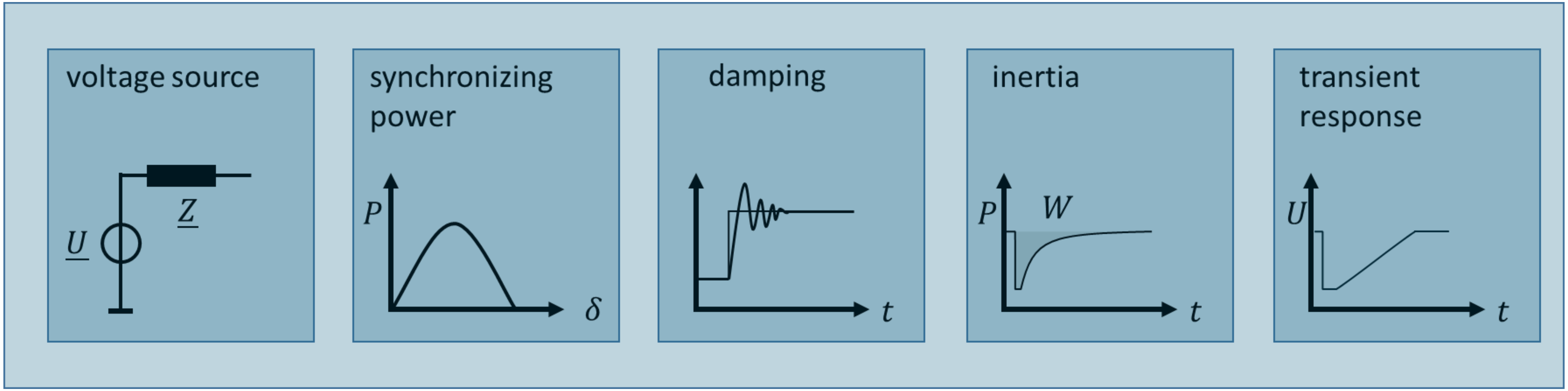
Grid-Forming Inverters

Overview of properties



Source: Fraunhofer IEE in “Netzregelung 2.0 – Regelung und Stabilität im stromrichter-dominierten Verbundnetz“, Final Public Report, 2023. Philipp Strauß, Thomas Degner (Editors), https://publica.fraunhofer.de/entities/publication/2c7f5fcd-4b4d-429d-a288-

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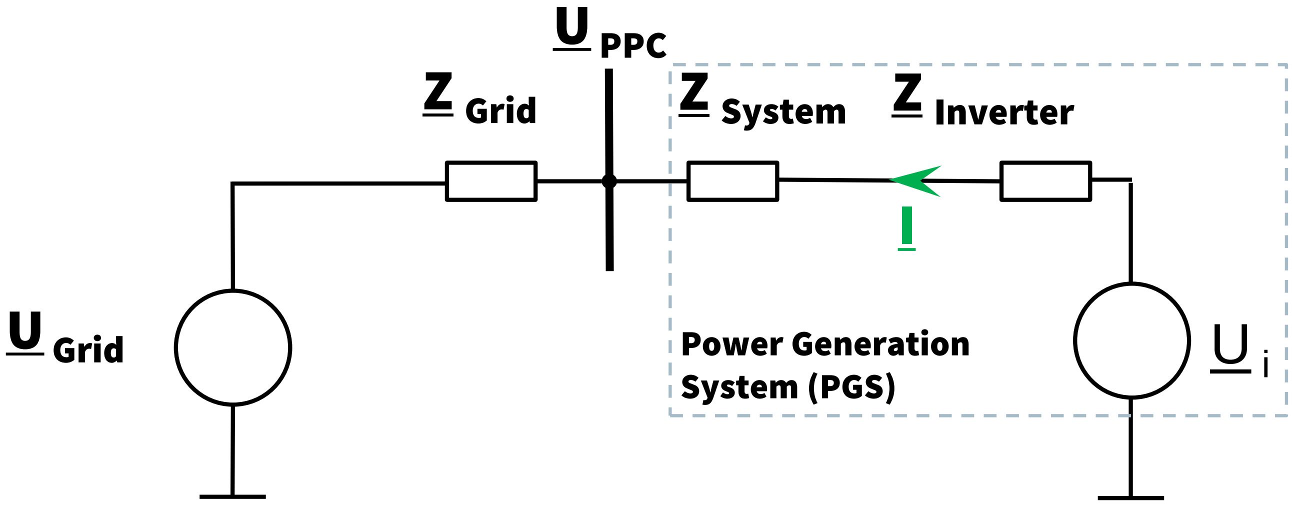
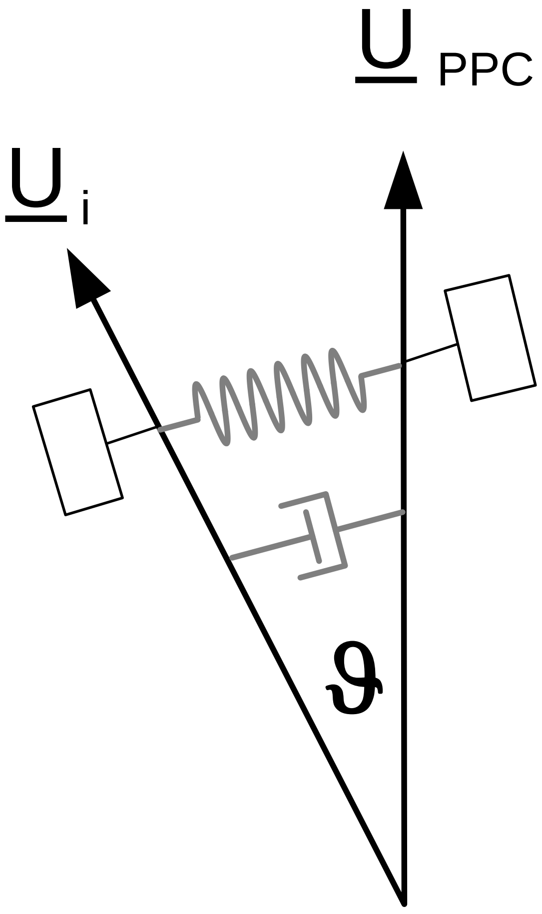
Grid-Forming Inverters

Definition of voltage controlled, grid forming inverter operation





- In voltage-controlled, grid-forming operation, the power converter provides a grid-synchronous sinusoidal voltage
- During transient voltage changes at the network connection point, the power converter voltage follows the grid voltage delayed and with damping
- If current limitation is necessary to avoid damage of semiconductors, grid-forming control must be modified (several solutions are available)

Source: Fraunhofer IEE in "Netzregelung 2.0 – Regelung und Stabilität im stromrichter-dominierten Verbundnetz", Final Public Report, 2023. Philipp Strauß, Thomas Degner (Editors), https://publica.fraunhofer.de/entities/publication/2c7f5fcd-4b4d-429d-a288-

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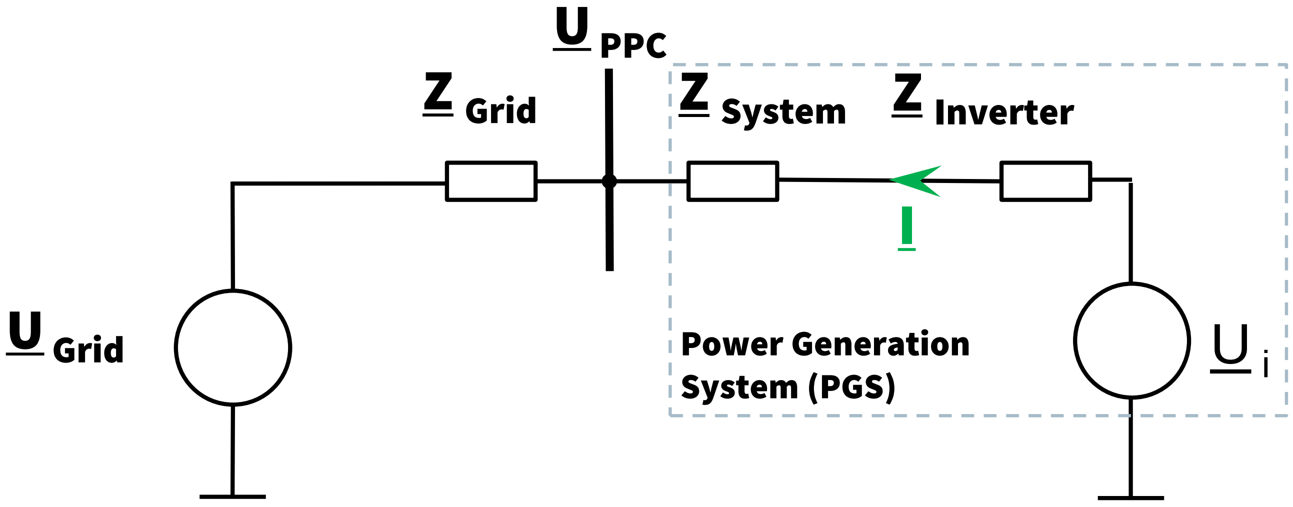

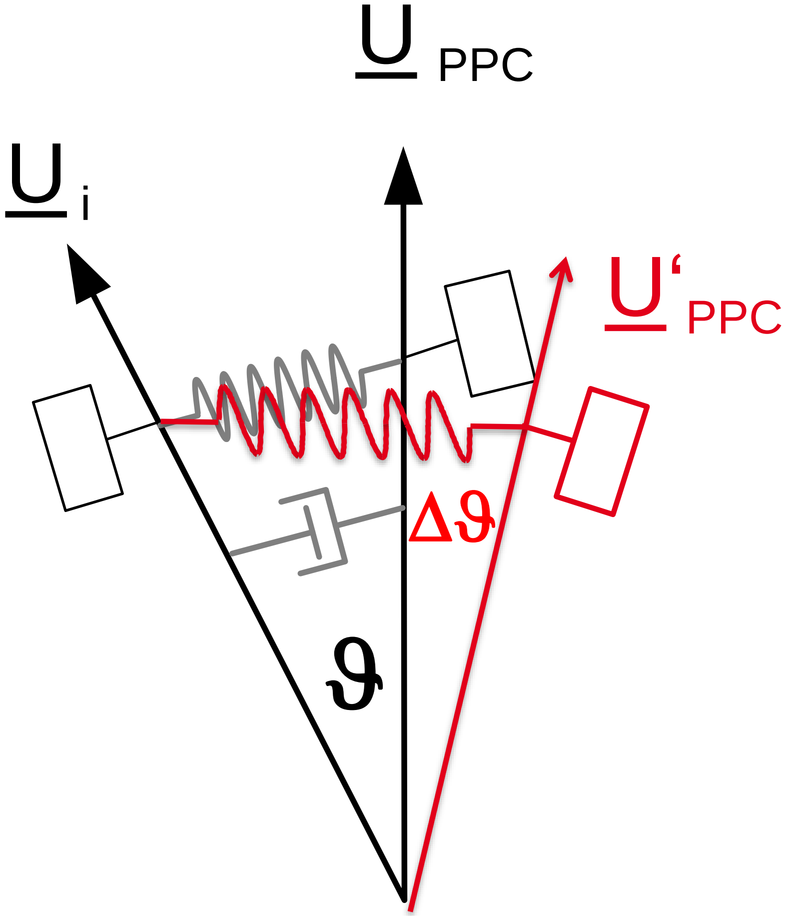

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Power System Studies

Frequency stability

Ability of an energy system to achieve and maintain a steady operating point after a disturbance with active power imbalance, while complying with steady-state and transient limits.

Steady State Limits*:

f_{max} = 50,2 Hz

f_{min} = 49,8 Hz

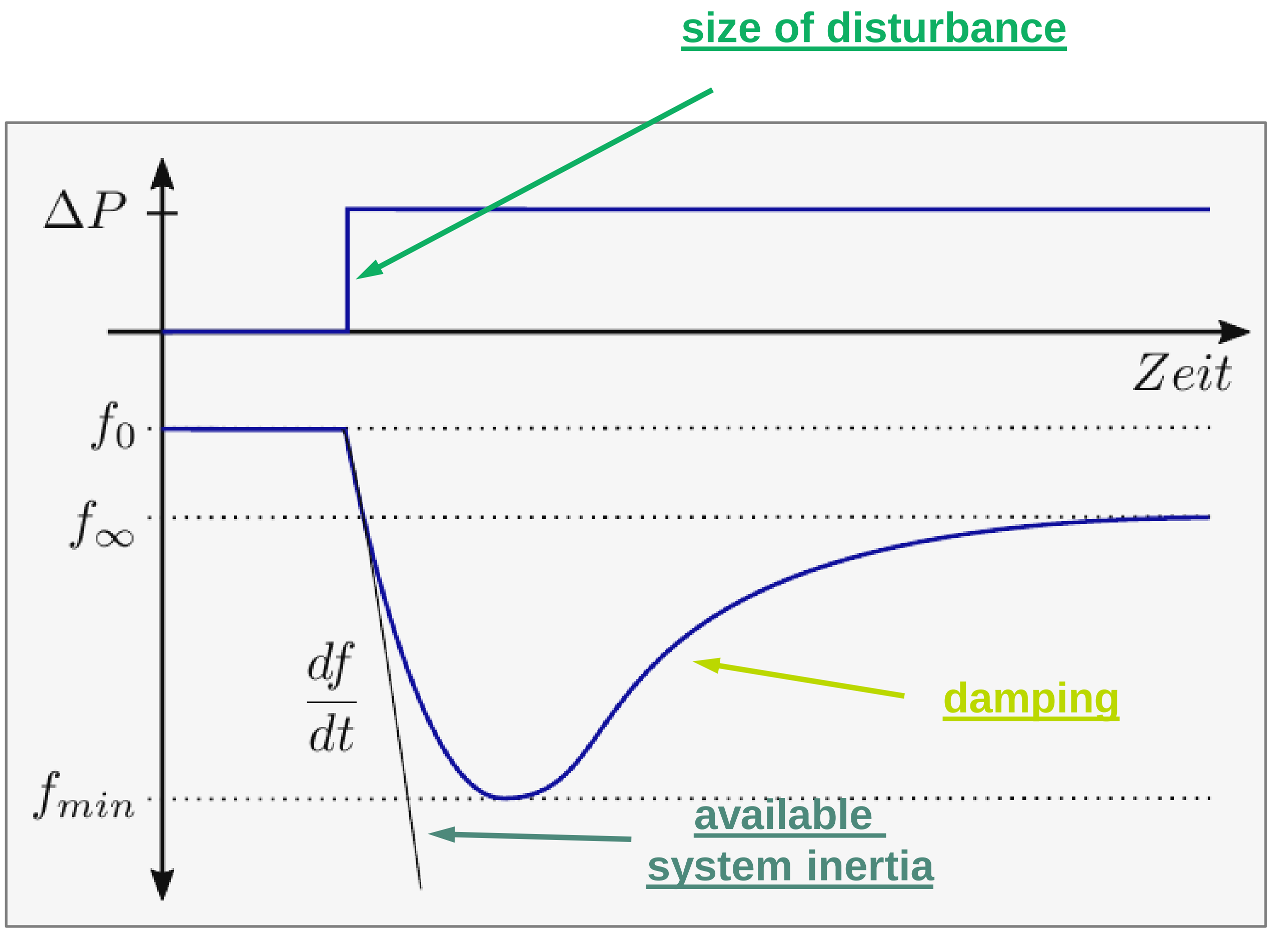
Transient Limits*

f_{max} = 51,5 Hz

f_{min} = 47,5 Hz

df/dt = 2 Hz/s

In case of violations, generation plants may disconnect. Due to the loss of generation the power system may collapse.



Frequency deviation after loss of power plant

[*] ENTSO-E, “P5 – Policy 5: Emergency Operations: Document Control”

Power System Studies

System split simulations

Frequency stability analysis in system split scenarios

- Test system for investigations of system split situation with large scale inverter shares designed by German TSOs[1,2].
- System split resulting in an over-frequency situation (power surplus with 40% Export)
- Decreasing share of synchronous generation
- Power reduction due to overfrequency (LFSM-O)
- Consideration of grid-forming and grid-supporting inverters[3]. With respect to frequency stability:
  - … limited allowable share of grid-supporting inverters.
  - … 100% inverters with utilization grid-forming units.

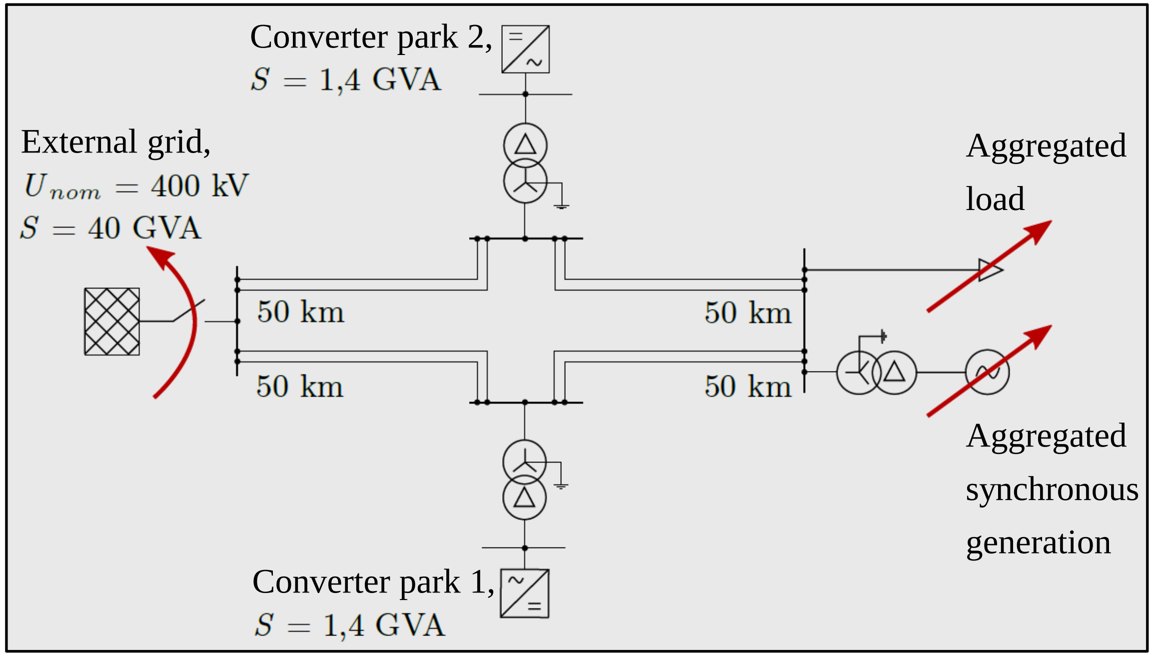


Fig.: Test system for investigations of system split situation

[1] K. Vennemann et al., "Systemic Issues of Converter-based Generation and Transmission Equipment in Power Systems", Wind Integration Workshop, vol.17., Stockholm, Sweden, 2017
[2] M. Nuschke, B. O. Winter, D. Strauß-Mincu, B. Engel, "Power system stability analysis for system-split situations with increasing shares of inverter based generation", NEIS 2019, Hamburg.
[3] M. Nuschke, "Frequenzstabilität im umrichterdominierten Verbundnetz", Dissertation TU Braunschweig, Fraunhofer Verlag, June 2022.

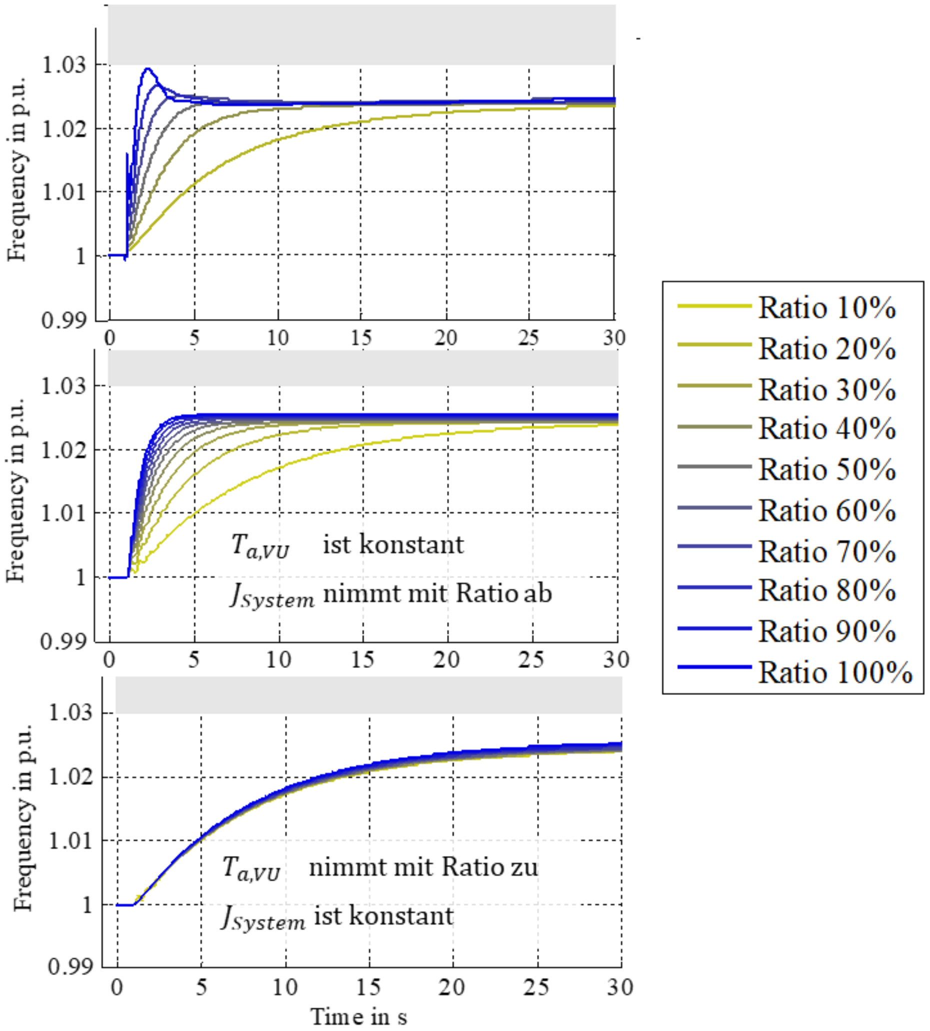
Power System Studies

Grid forming inverter control vs current control

Current controlled inverter — Maximum penetration with current controlled inverter depends on parametrization between 20-60%.

Grid forming inverter control — Voltage controlled inverter limit frequency gradients.
Considering frequency stability, a 100% inverter share is possible in the test system

Grid forming inverter control — Compensation of missing mechanical inertia realized by adaptation of parameters in the inverter control.
Overall system inertia is kept constant for all considered cases



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Power System Studies

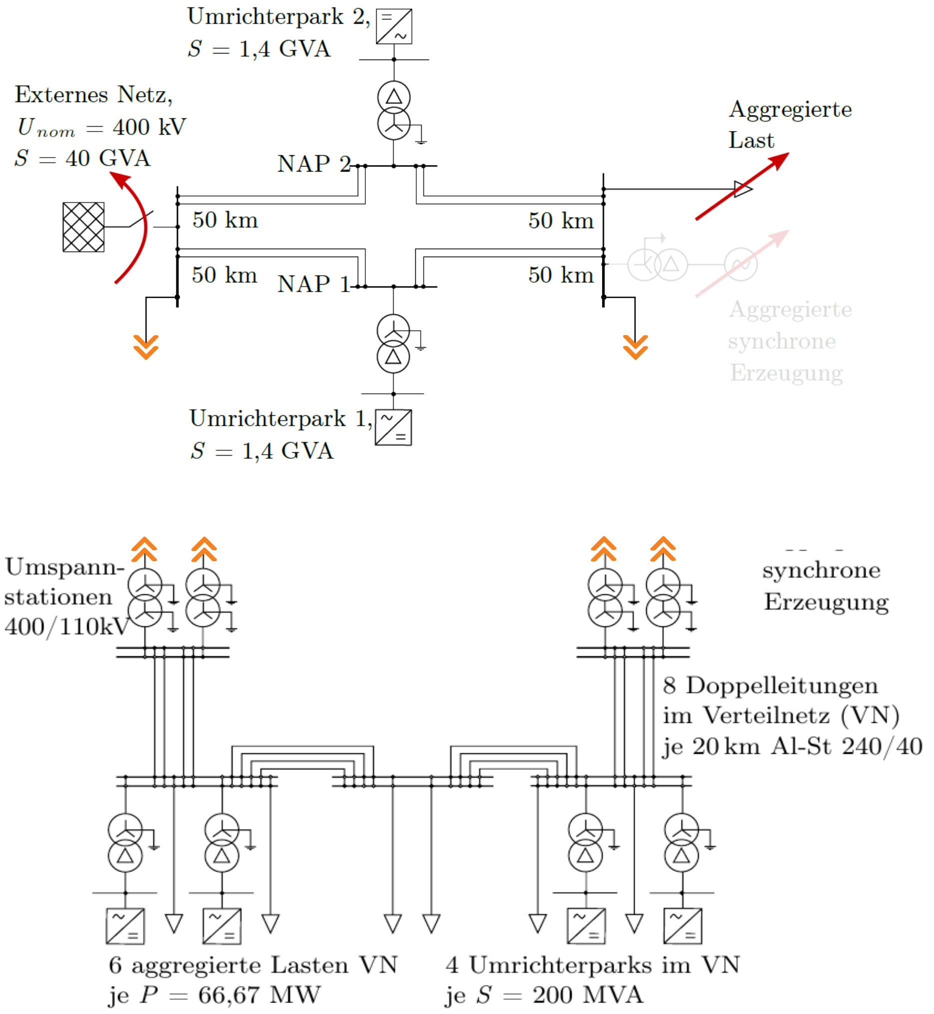
Inertia from Distribution Grids

Why:

A significant share of power electronic coupled powerplants (esp. photovoltaic systems, storage systems und loads) will be connected to the distribution grids.

Case study:

- Grid model
  - Extended transmission grid model with distribution grid model (110kV)
  - Several grid forming inverter in the distribution grid, in total 800 MW (same magnitude as distortion)
  - Current controlled inverter in the transmission grid
- Scenario
  - System split resulting in an over-frequency situation (power surplus 40% Export)
  - Power reduction due to overfrequency (LFSM-O)



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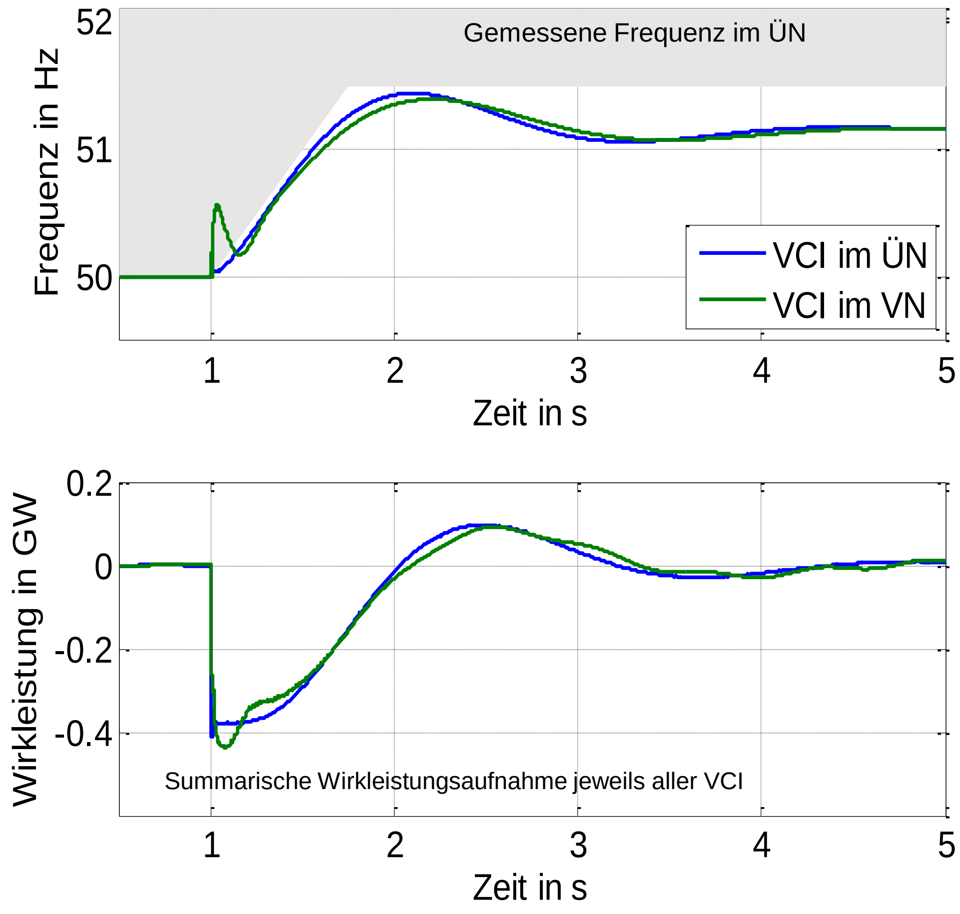
Power System Studies

Inertia from Distribution Grids

- Simulation results of system split
  - Only grid forming inverters (VCI) in transmission grid (ÜN)
  - Only grid forming inverters in distribution grid (VN)
  - In both cases: Current controlled inverter in transmission grid (ÜN)
- Result
  - Provision of inertia from distribution grids works
  - Several voltage controlled inverter may interact



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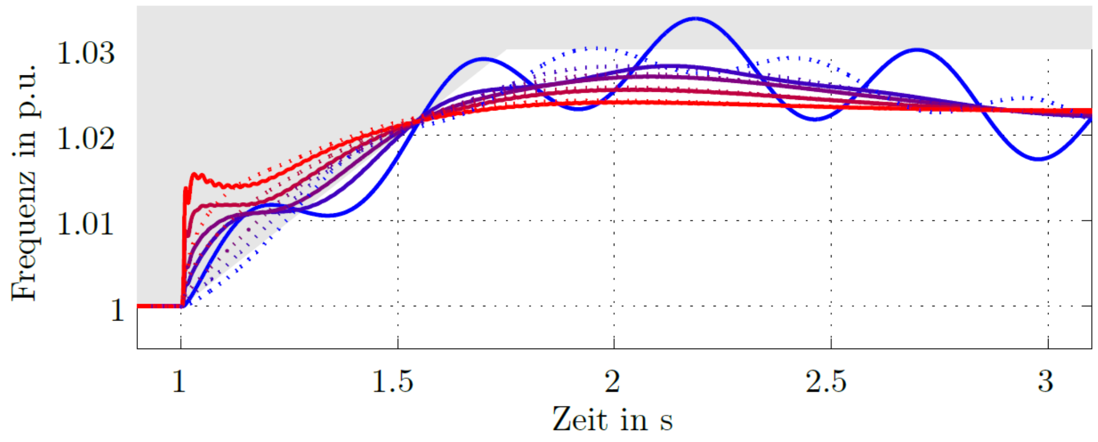
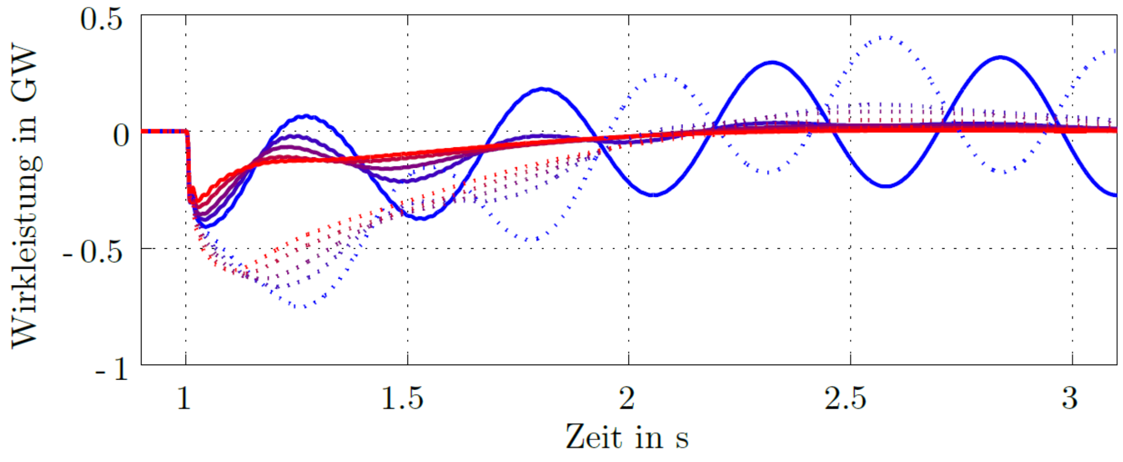
Power System Studies

Inertia from Distribution Grids

- Simulation results of system split
  - Frequency and active power at GFI terminal of GFIs in the distribution grid
  - Solid lines: GFI with smaller rated power, dotted lines GFI with higher rated power
  - Red to blue: variation of damping constant
- Result
  - Power oscillations between GFI in the distribution system
  - These oscillations should be avoided





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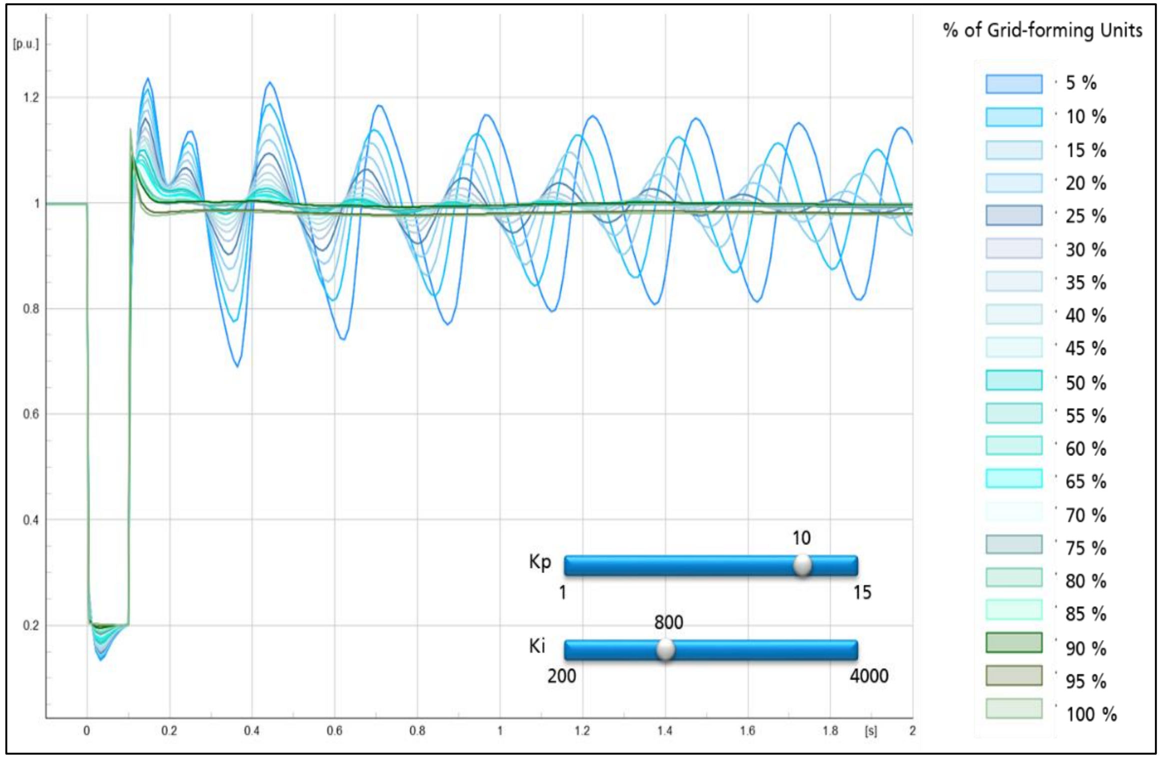
Power System Studies

Converter Driven Instability

- After a loss of line PLL instabilities may occur due to changed network impedance
- Grid forming inverters may help to damp oscillations



Example of a PLL instability. The parameters of the PLL are Kp=10 and Ki=800. The oscillations can be damped by grid-forming units. With a share of 25% grid-forming units, the occurring oscillations are strongly damped in less than 2 seconds.

Ref: Luis Pabon, Daniel Pabon, Valeria Usuga (Fraunhofer IEE), “Plausibility and implications of converter-driven oscillations induced by unstable long-term dynamics”. In IEEE Transactions on Power Systems, Volume: 38, Issue: 6, November 2023.

Conclusions

- To achieve carbon-neutrality in Germany until 2045 and to get more independent in terms of energy supply Germany plans to increase the installed capacity of renewable energies significantly.

- Essential conditions for maintaining a secure energy supply include:
  - Balance of generation and consumption at any time
  - Voltage and loading of network assets must stay within permissible limits
  - Power system stability must be ensured to be robust against disturbances

- Grid forming inverters are a key technology to enable systems pre-dominantly powered by renewables

- In Germany, a significant proportion of renewable energy generation and storage will be connected to distribution grids. The potential of grid-forming technology should also be utilized in the distribution grid. However, several issues need to be thoroughly researched and addressed before a widespread deployment can occur.

Next Steps

- Development of methods and metrics to quantify system needs
- Definition of requirements to enable qualification of generation systems, storage systems and loads
- Development of systems with grid forming control for different technologies
(e.g. STATCOMs, wind turbines, photovoltaic systems, battery storage systems, loads, .).
- Advanced standard models for grid forming and grid-following inverter to enable grid studies
- Demonstration and pilot projects in distribution grids
- International exchange of development and experience

Thank you for your attention!

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