TECHNISCHE UNIVERSITÄT DRESDEN

DRESDEN concept

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Analysis of the Converter-Driven Stability of Q(V)-Characteristic Control in Distribution Grids

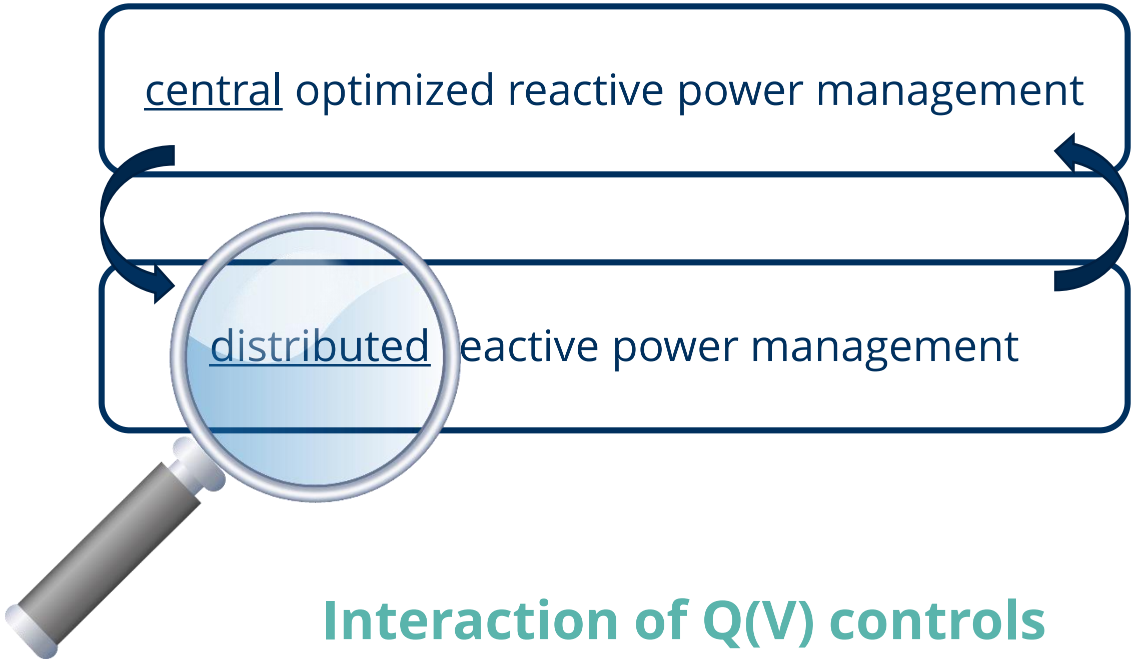
SEST 2022

Eindhoven // 05.-07. Sept. 2022

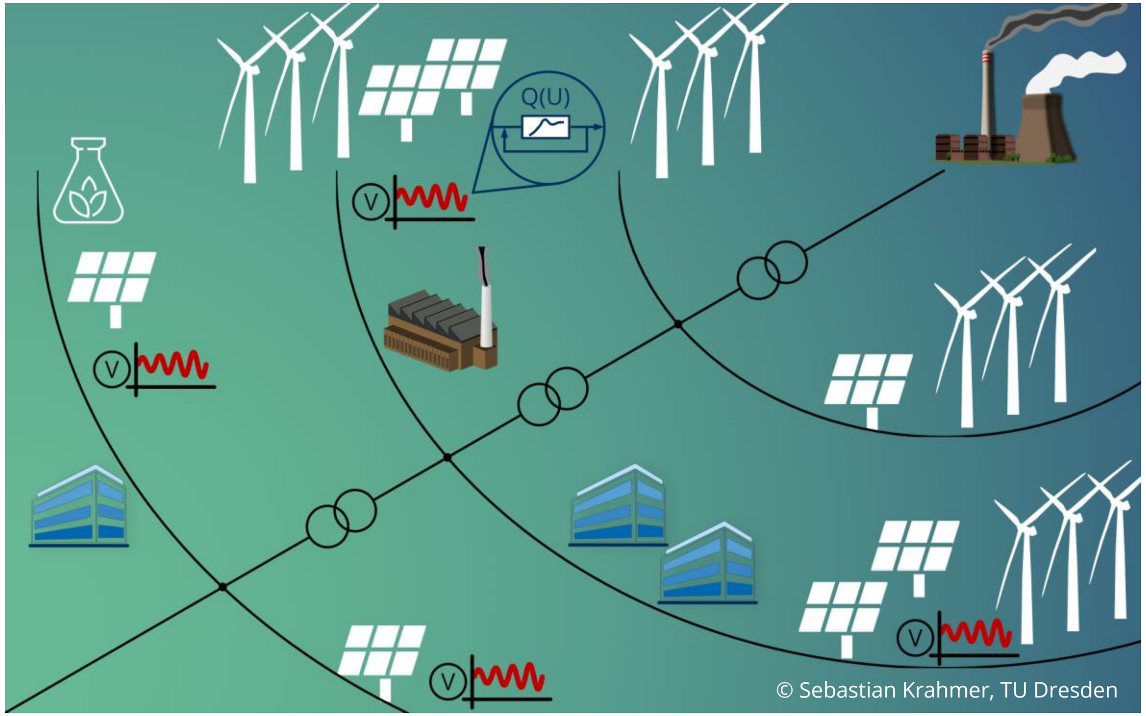
Paper 207

This contribution was funded within the project STABEEL by the German Research Foundation (DFG) – 442893506.

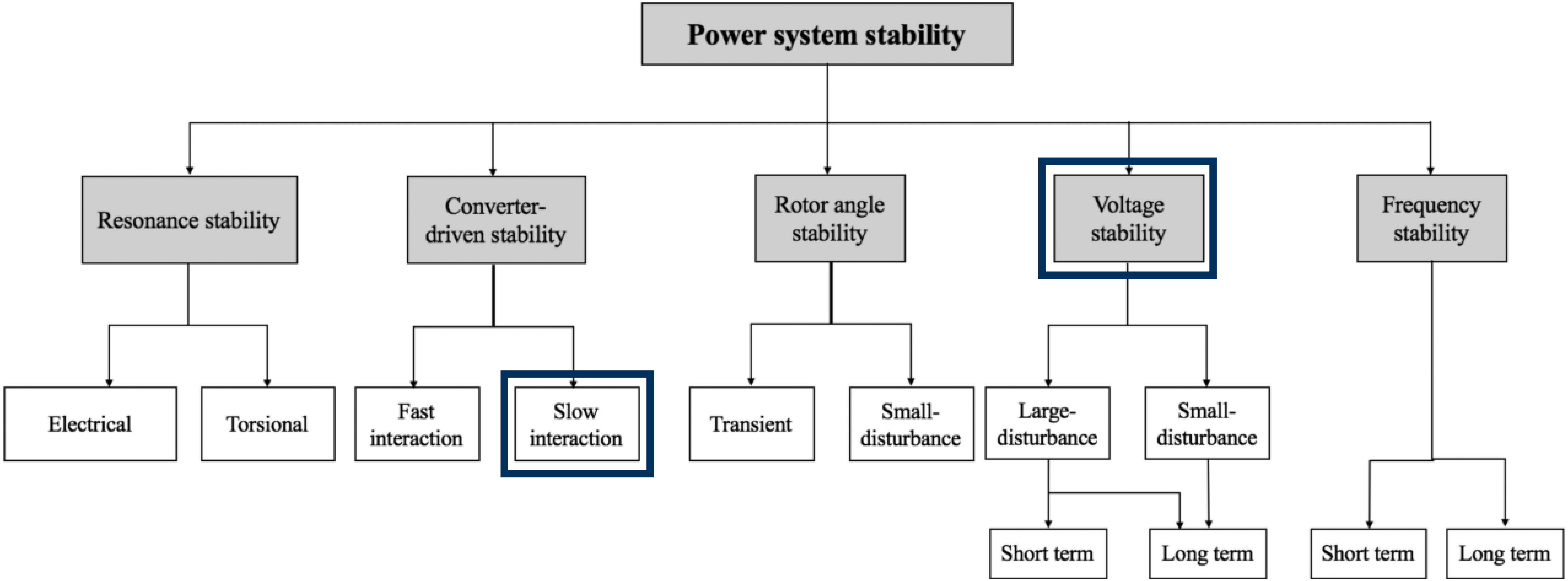
How will voltage and reactive power management work in distribution grids with high penetration of distributed energy resources?



Interaction of Q(V) controls



Stability Terms in Power Systems



[Hat2021] Hatziargyriou, Nikos et al.: „Definition and Classification of Power System Stability - Revisited & Extended," IEEE Transactions on Power Systems vol. 35 issue 4, 2021.

Related Literature

Low Voltage Level

- PV generation
- controller dead times [And15]
- damping time constants [Mar18, Lin18]

→ **No practically relevant limitations on the penetration rate for Q(V)-controlled PV-generators. [Lin18]**

Medium and High Voltage Level

- wind generation
- centralized / decentralized plant controls [Chi15, Asa20]
- consideration of communicaton delay [Hau17]
- control interactions [Qia16, Egg21]

→ **Stability is term of local controller setting and grid interaction. How to assess?**

Outline

1 MOTIVATION

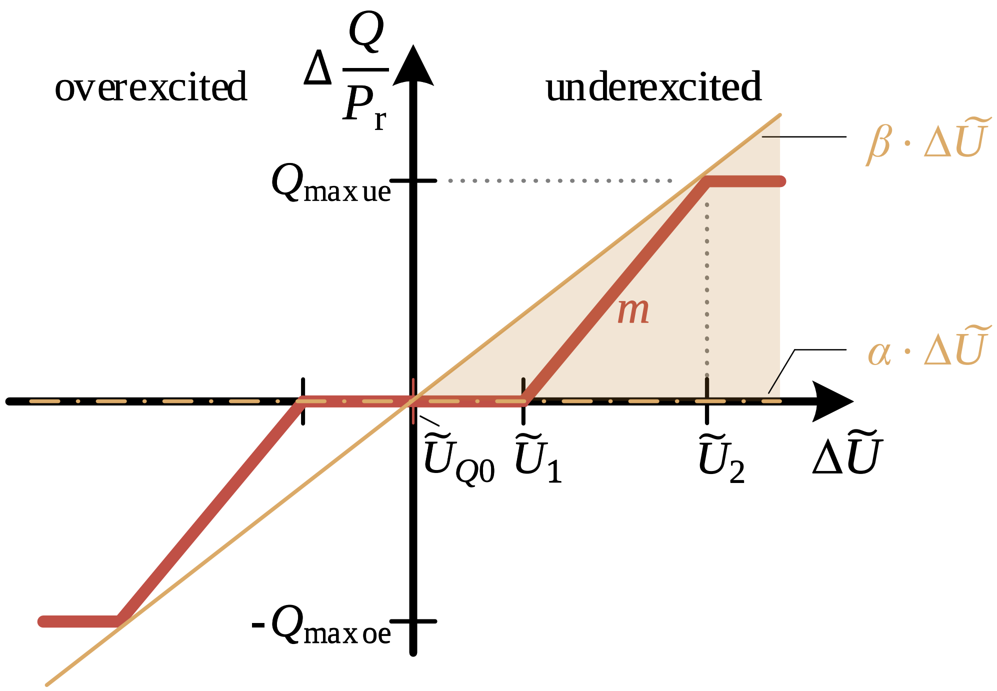
2 MODELS FOR DISTRIBUTED ENERGY RESOURCES

3 CIRCLE CRITERION

4 SIMULATION BASED VERIFICATION

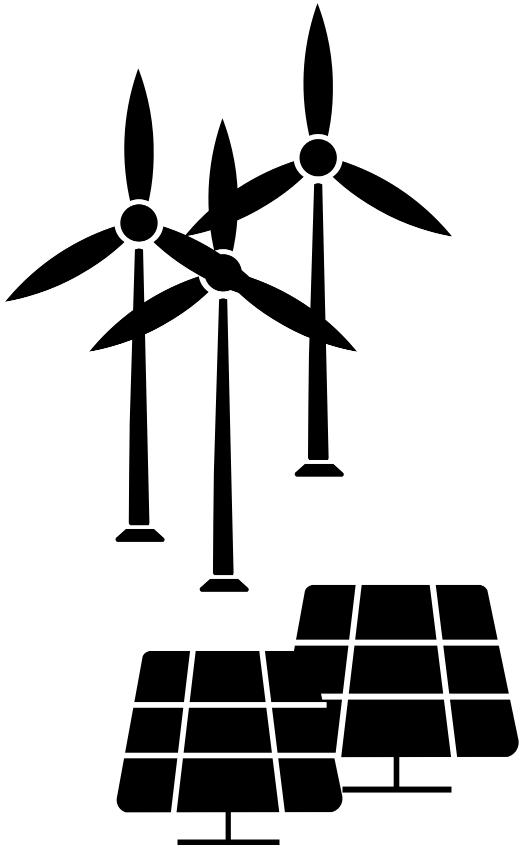
5 CONCLUSION & OUTLOOK

Models for Distributed Energy Resources (DER)



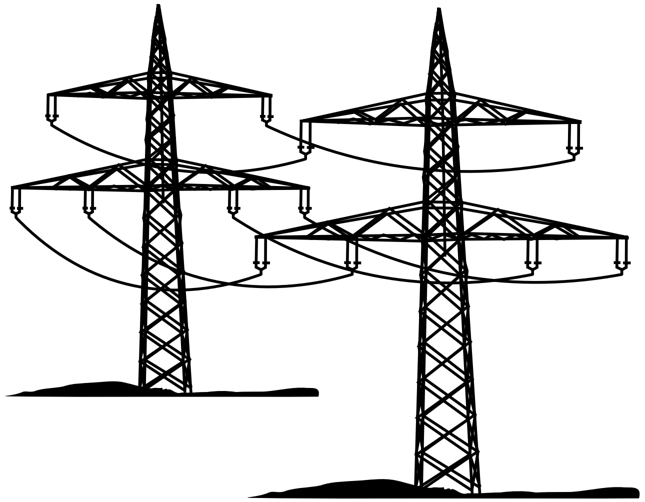
Q(*V*)-characteristic

+



DER control loops

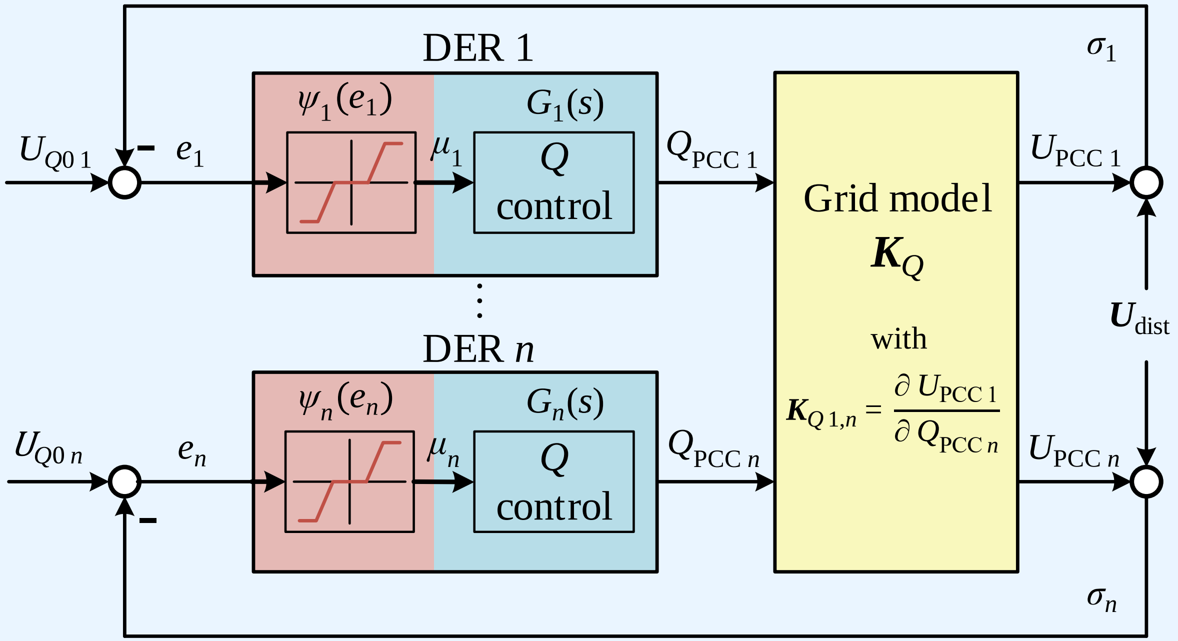
+



Nodal admittance matrix of grid

Models for Distributed Energy Resources

Detailed control loop



DER approximation using PT2-fitting

$$\mathrm{PT2}(s) = \frac{\kappa}{1 + 2 \cdot D \cdot T \cdot s + T^2 \cdot s^2}$$

PT2-DER
- fit based on known DER model
- fit quality evaluated via frequency response

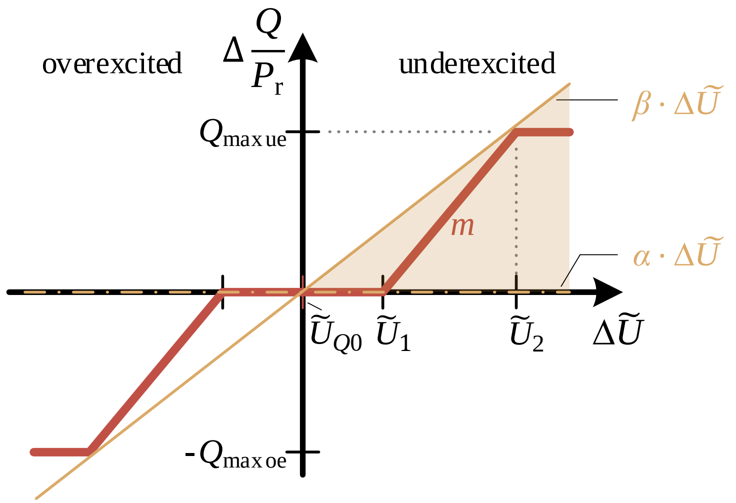
PT2-TAR
- fit based on admissible generic control response in grid codes (e.g. German TAR)
- fit quality evaluated via step response

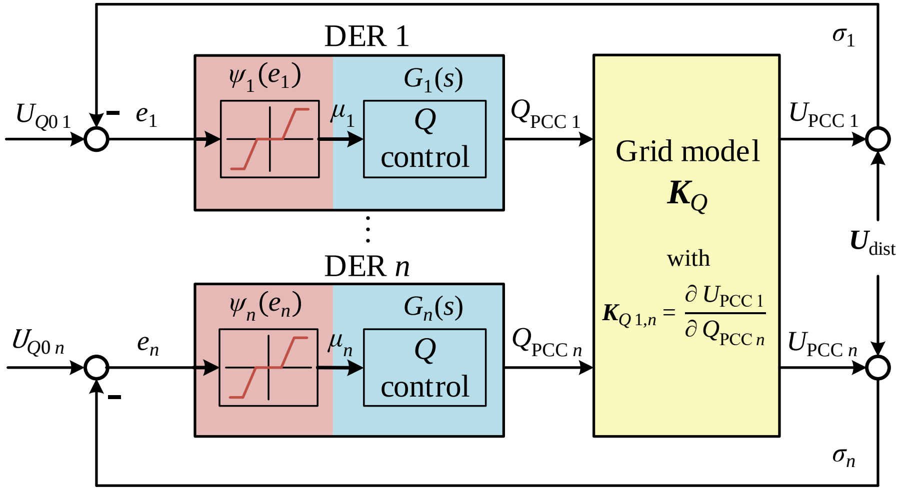
Stability Assessment via Circle Criterion
Multiple-Input Multiple-Output (MIMO)

Circle Criterion

$\boldsymbol{\Omega}(s) = \boldsymbol{I} + \boldsymbol{M}_\beta\, \tilde{\boldsymbol{G}}(s)$ must be strict positive real

- $\boldsymbol{I}$: identity matrix
- $\boldsymbol{M}_\beta$: diag $(\beta_1, \ldots, \beta_n)$
- $\tilde{\boldsymbol{G}}(s)$: remaining linear system





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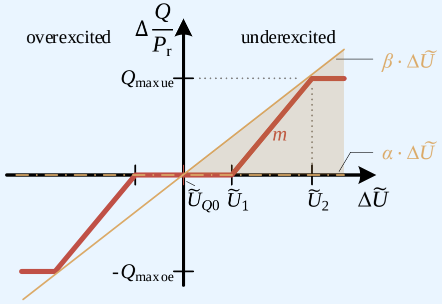
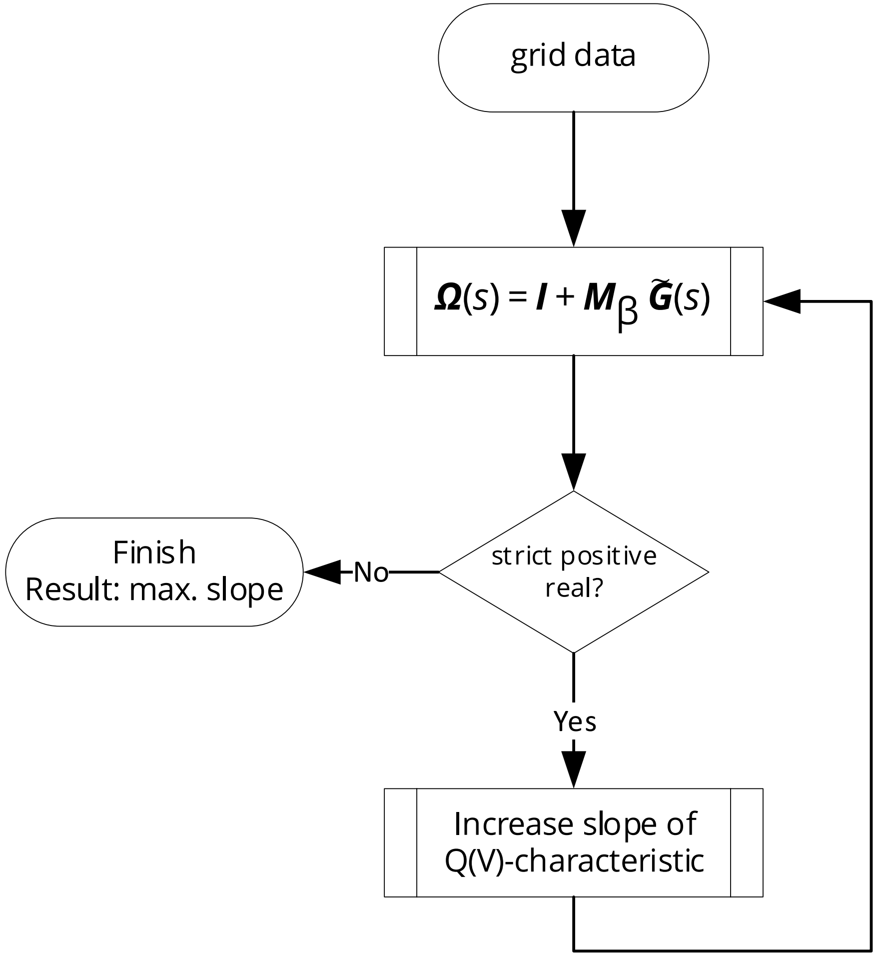
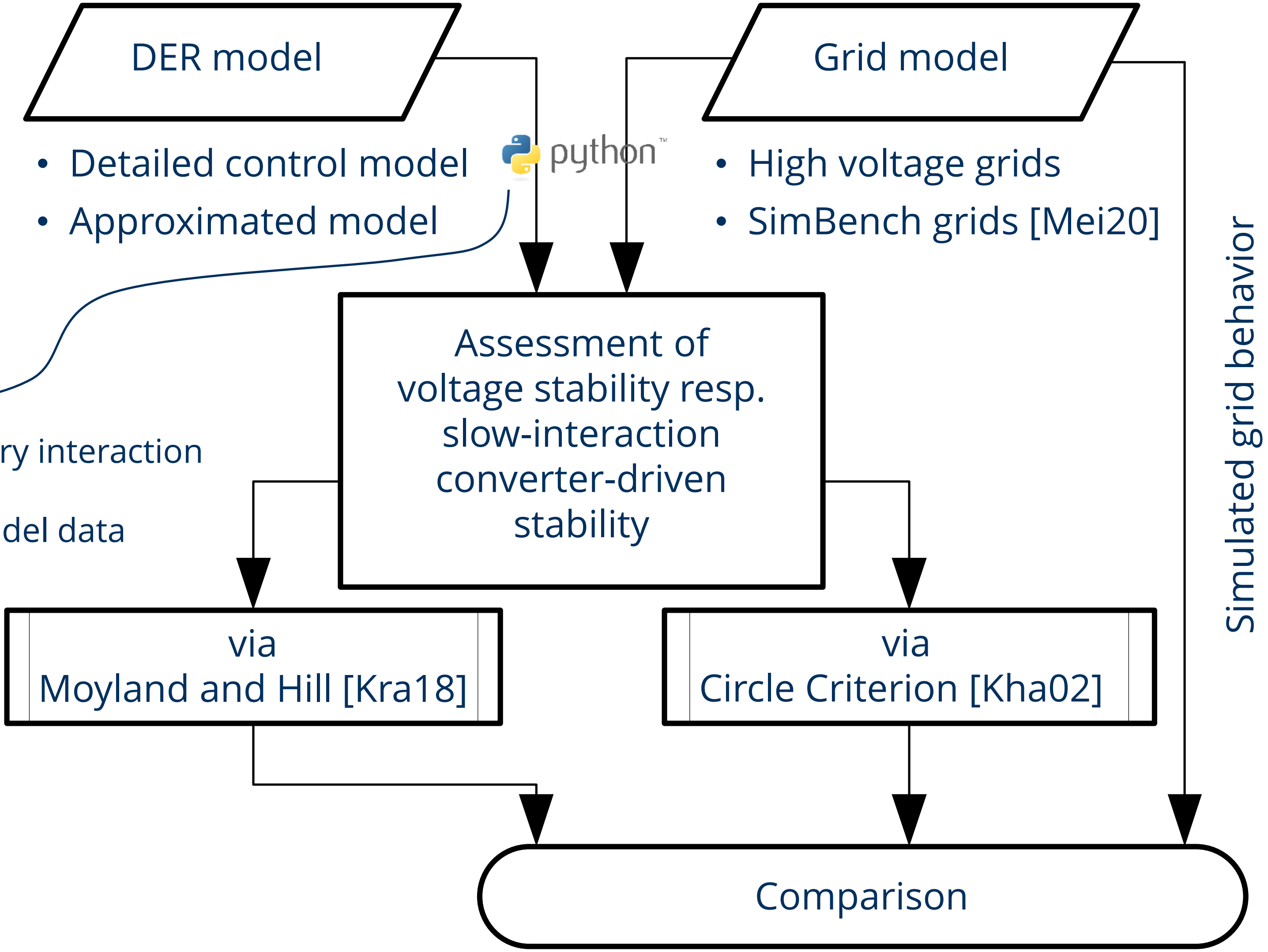


→ Strict Positive Realness can be checked with the criterion of [Sho08]



Verification and Comparison of Stability Assessment



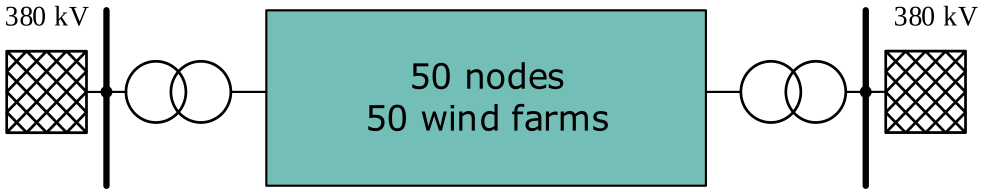
powerfactory-utils

- Toolbox for easy powerfactory interaction
- Python based
- Export of structured grid model data

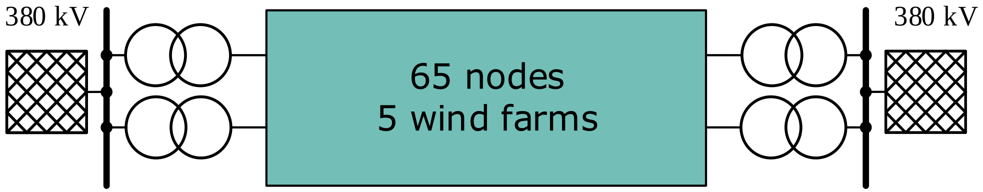
Verification and Comparison of Stability Assessment

Models for High Voltage Distribution Grid (DG)

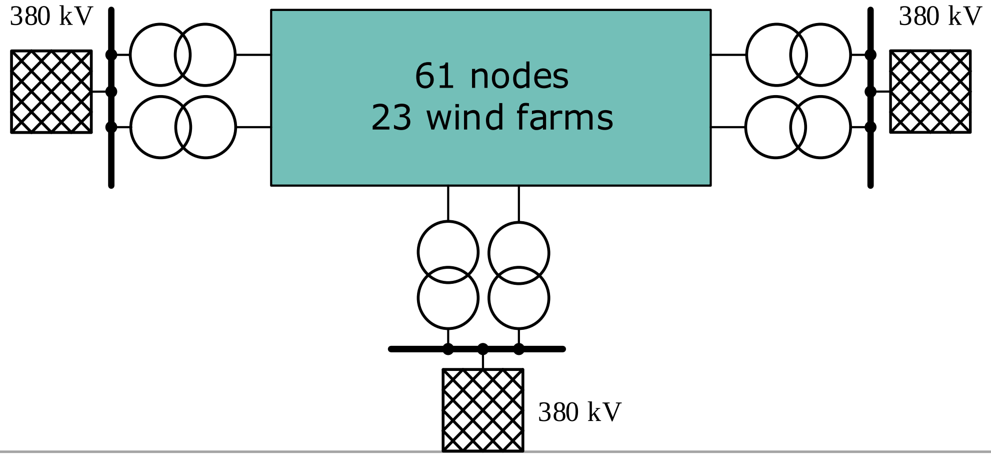
synthetic distribution grid
sDG 1



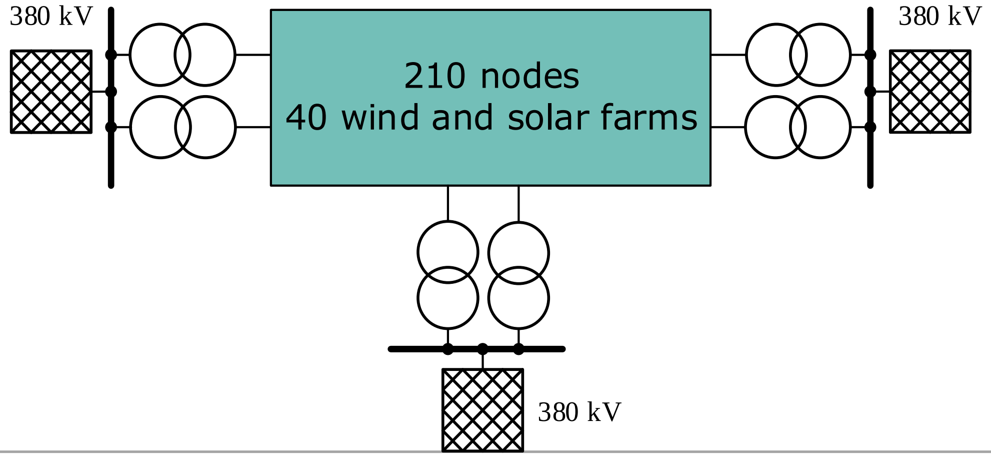
realistic distribution grid
rDG 1



synthetic distribution grid
sDG 2



realistic distribution grid
rDG 2

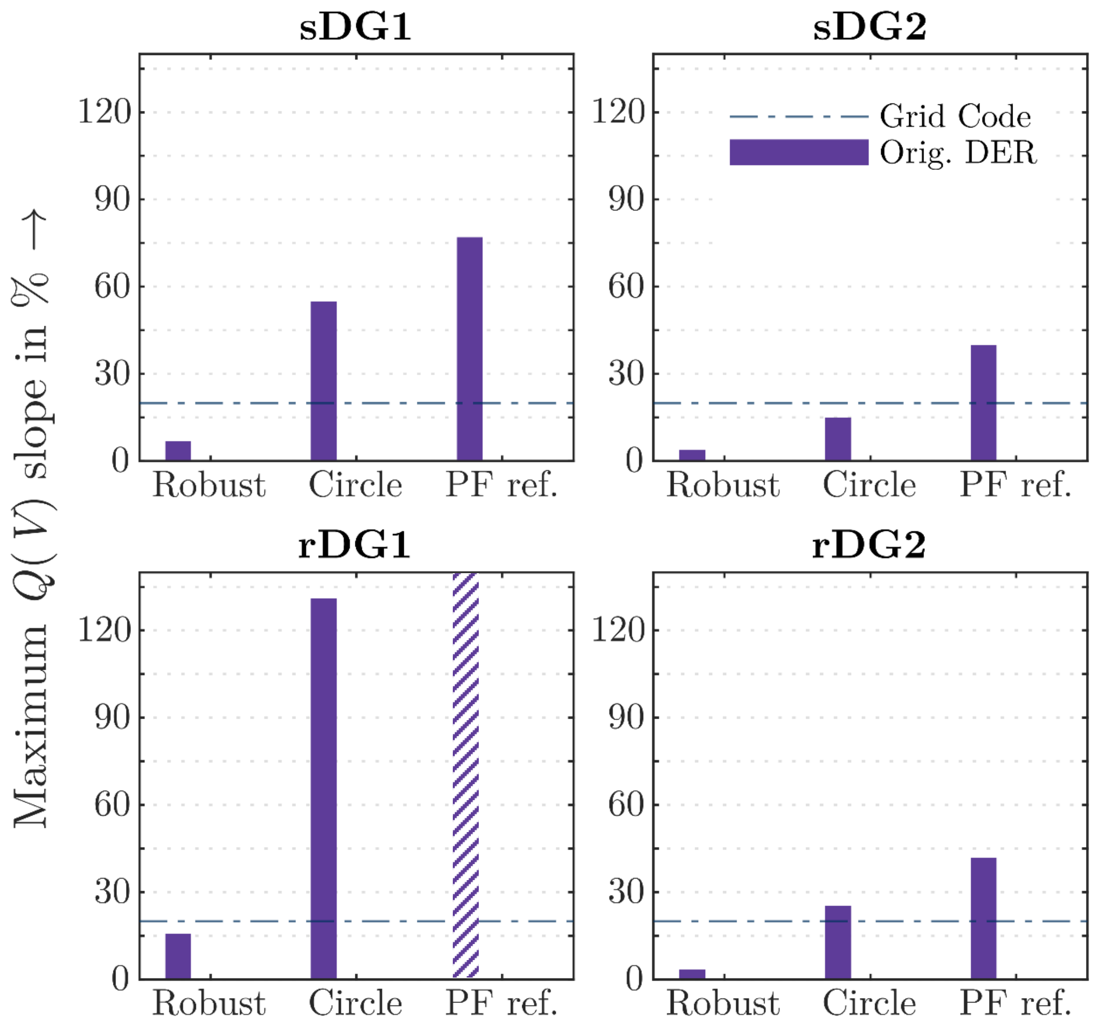


Verification and Comparison of Stability Assessment

Simulation based Verification

Constraints
- DER models are based on FRC wind farm type
- each DER has the same parameterization (e.g. β)

Results
- Circle criterion allows for much higher Q(V) slopes than the Robust Criterion
- Circle criterion is validated as it is below the PowerFactory reference



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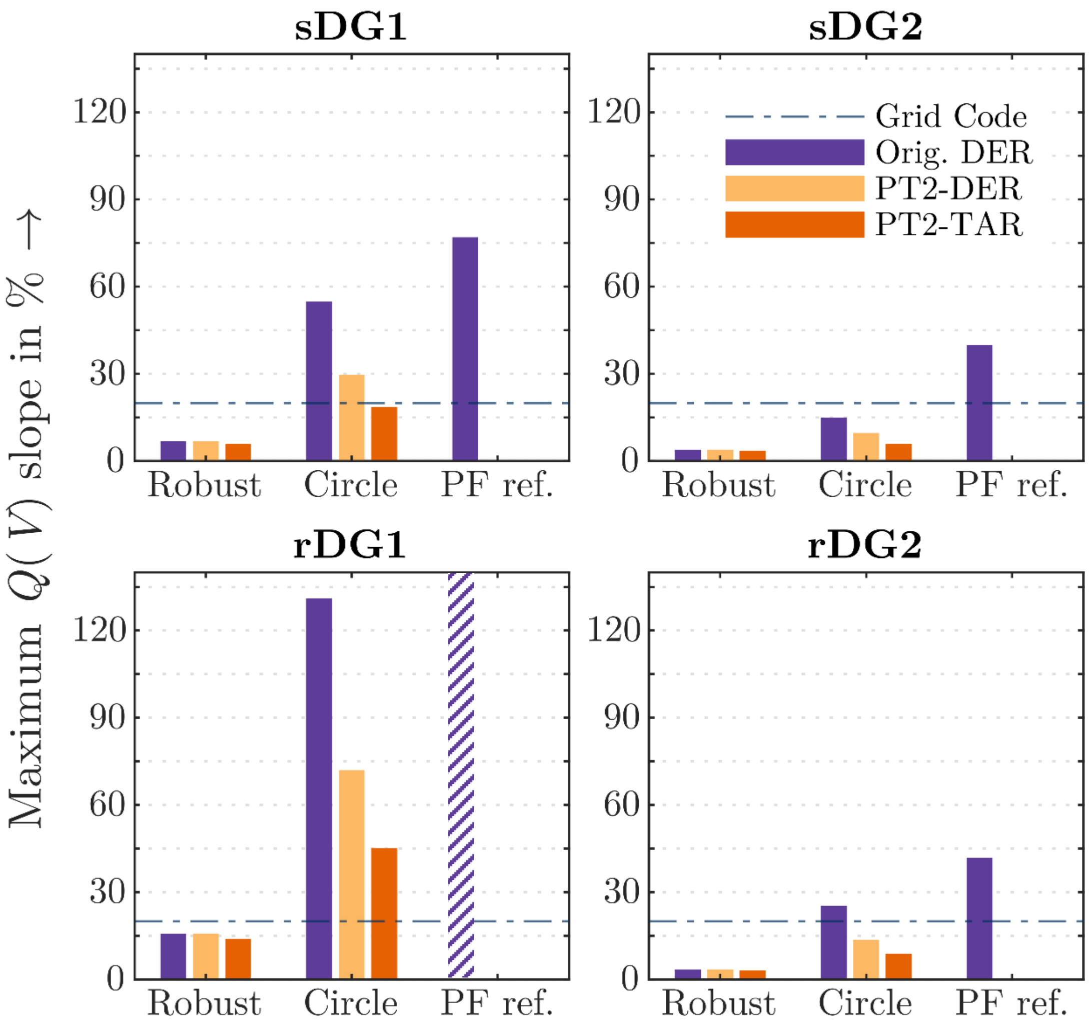
- **Benefits for optional PT2-models**
  - PT2-models are more conservative then detailed DER model
  - PT2-models offer a shorter computing time



Conclusion

Stability Assessment of Q(V) Controlled DERs

- Introduction of Circle Criterion
  - Application to MIMO systems to assess small-signal stability
  - Results are much less conservative compared to previous work
  - Analytic method is much faster than time-domain analysis
- DER model approximation
  - Complexity reduction of DER models via PT2 fits
  - Compromise between accuracy and complexity possible
- Open Source Python toolbox *PowerFactory Utils* to export grid data from PowerFactory

Thank you for your attention!

This contribution was funded within the project STABEEL by the German Research Foundation (DFG) – 442893506.

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Publications: www.fis.tu-dresden.de

Project info: www.researchgate.net #STABEEL

PowerFactory Utils

- Python toolbox for interaction with DIgSILENT PowerFactory
- Purpose: automation and interoperability
- www.github.com/ieeh-tu-dresden

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[Hau17] M. Hau and M. Shan, "Stability of Fast Q(U) Voltage Droop Control of Wind Parks in High Voltage Distribution Grids," in Conference on Sustainable Energy Supply and Energy Storage Systems (NEIS 2017), Hamburg, 2017

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[Moy78] P. Moylan und D. Hill, "Stability criteria for large-scale systems", *IEEE Transactions on Automatic Control 23.2*, pp. 143–149, 1978.

[Ras22] S. J. Rasti, S. Krahmer and M. Schmidt, powerfactory-utils - A toolbox for Python based control of PowerFactory, https://github.com/ieeh-tudresden, 2022.

[Sho08] R. N. Shorten, P. Curran, K. Wulff and E. Zeheb, "A Note on Spectral Conditions for Positive Realness of Transfer Function Matrices," IEEE Trans. Automat. Contr., vol. 53, no. 5, pp. 1258 - 1261, Jun. 2008.

[Qia16] Y. Qian, X. Yuan and M. Zhao, "Analysis of Voltage Control Interactions and Dynamic Voltage Stability in Multiple Wind Farms," in IEEE Power and Energy Society General Meeting, Boston, 2016.

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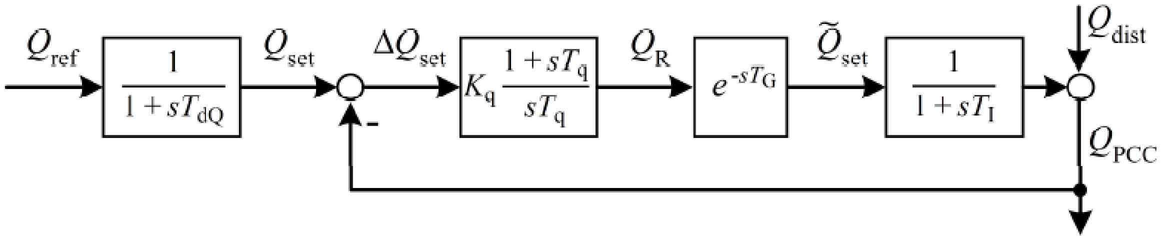
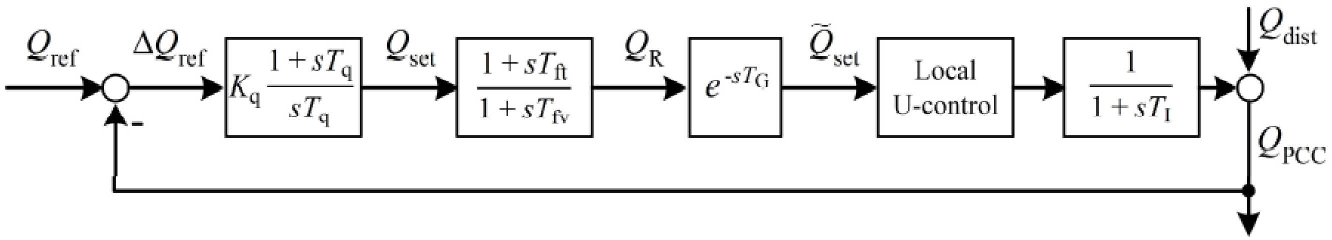
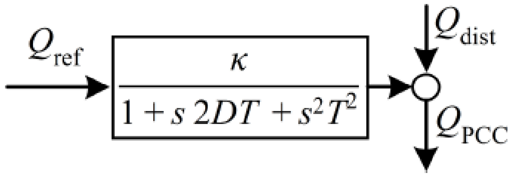
Models for Distributed Energy Resources

TABLE II. PROPOSED MODEL CONFIGURATION OF DIFFERENT DER TYPES AND RELATED PT2 APPROXIMATIONS

DER type	Control loop $G(s)$			Ref.
	Voltage averaging	*Reactive power control loop*		
(i) WF-FRC	$\frac{1}{1+sT_U}$ $T_U = 0.02$ s	 $T_{dQ} = 2$ s, $K_q = 0.5$, $T_q = 0.2$ s, $T_I = 0.1$ s, $T_g = 0.2$ s		[12, 18, 30]
(ii) WF-DFIG				[17, 18, 30]
(iii) PVF	$\frac{1}{(1+sT_U)^3}$ $T_U \approx 0.004$ s	A PV inverter with fast power control T_I according to [19] can be extended by a farm control. The emerging control loop can be established analogously to (i). $T_{dQ} = 2$ s, $K_q = 0.5$, $T_q = 0.2$ s, $T_I = 0.0033$ s, $T_g = 0.1$ s		[19]
(iv) PT2-TAR	Not explicit necessary.		Based on the generic step response given in TAR [24]. $\kappa = 1$, $D = 0.517$, $T = 2.335$ s	
(v) PT2-DER			Based on the frequency response of detailed DER model (i). $\kappa = 1$, $D = 0.747$, $T = 1.028$ s	

Stability Assessment via Circle Criterion
Multiple-Input Multiple-Output (MIMO)

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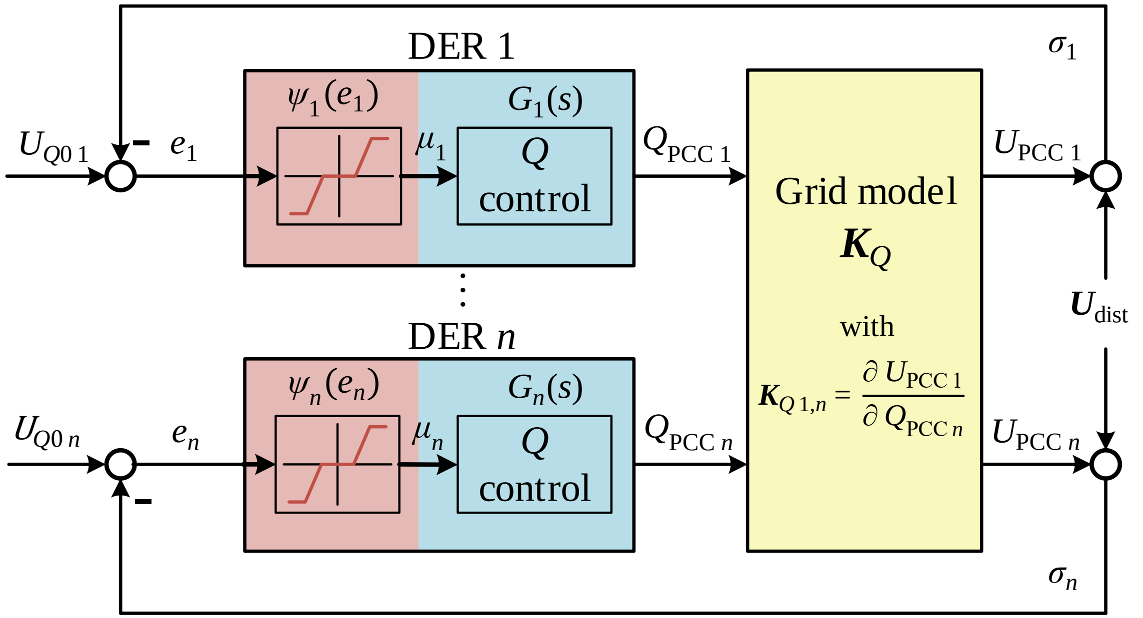
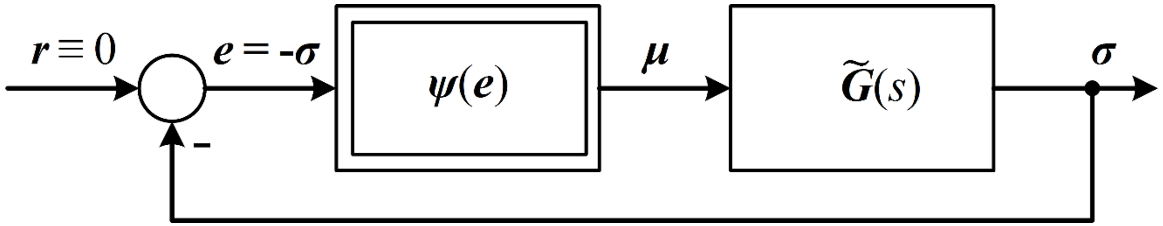
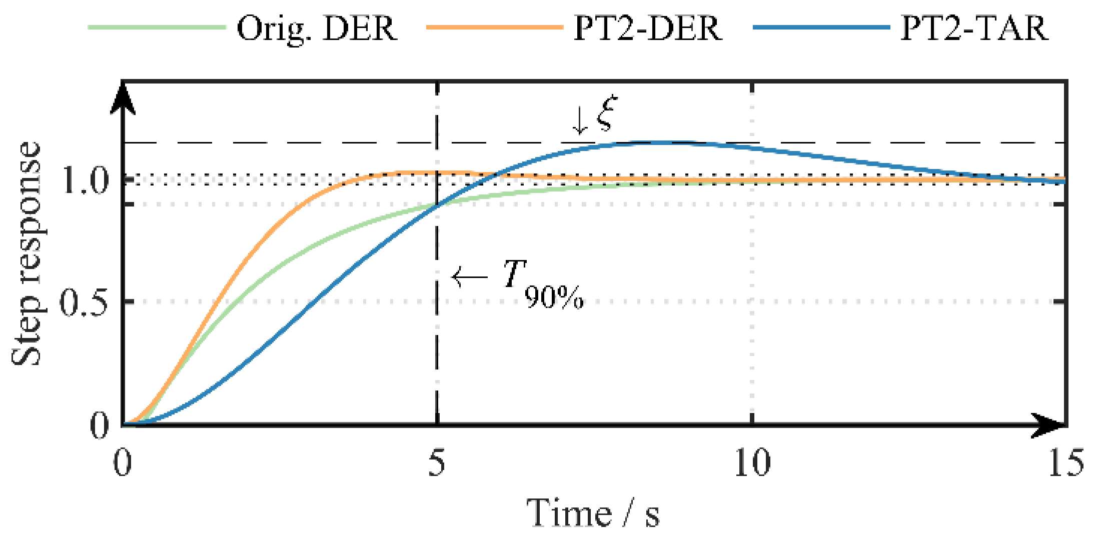
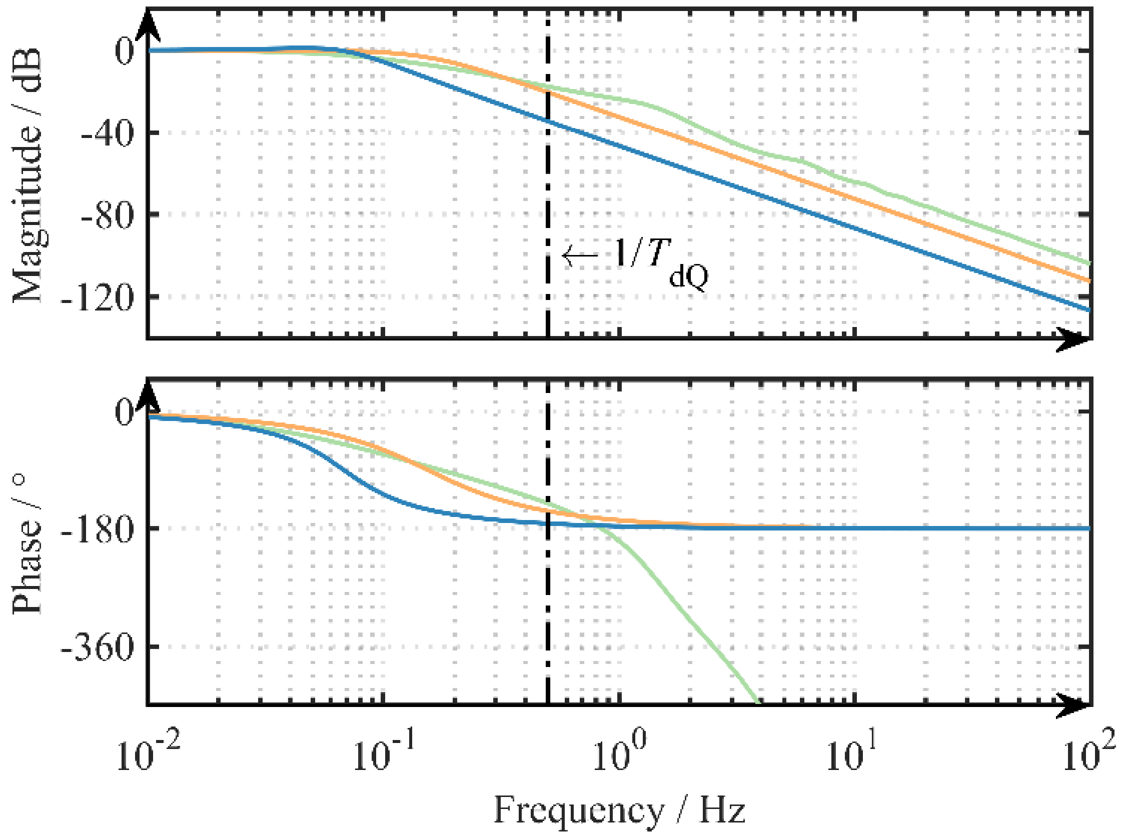




Comparison of DER models





PT2-TAR

- hits an overshoot of 15 % and a rise time of 5 s

→ Intention: a very bad, but still allowed DER control

PT2-DER

- fits the frequency response of orig. DER very good

→ valid model reduction for relevant input frequencies

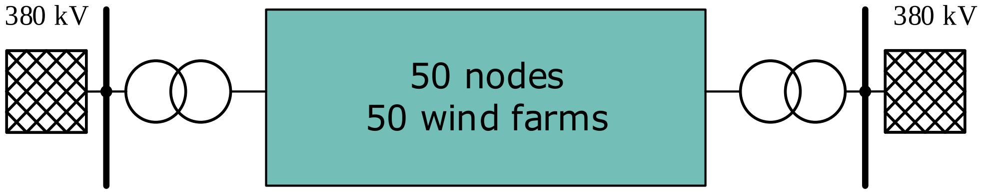
Verification and Comparison of Stability Assessment
Grid Models for Verification

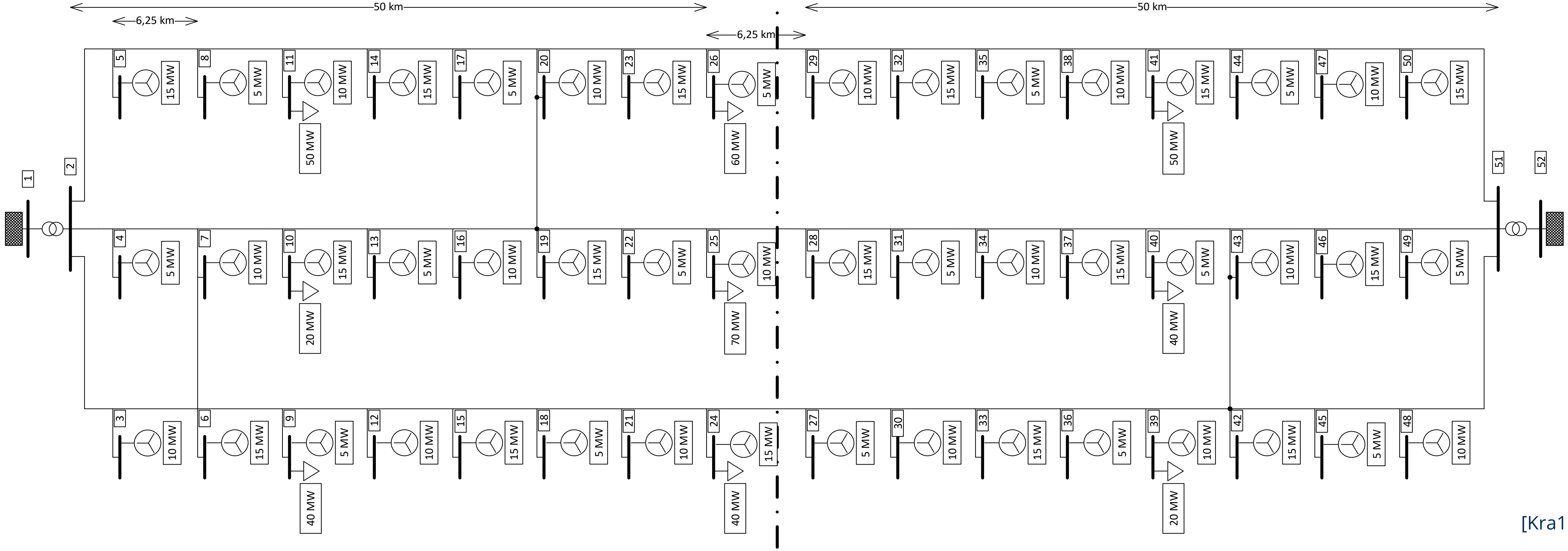
DER penetration rate: $\rho = \frac{\sum P_{\text{DER inst}}}{\ell_{\text{grid}}}.$

grid	connection points 110/380 kV	number of nodes	$\sum P_{\text{DER}}$ in MW	ρ in kW/km
sDG1	2	50	480	1400
sDG2	3	61	1560	1440
rDG1	2	65	135	≈ 200[a]
rDG2	3	210	840	≈ 600[a]

a As concrete branch length of grid is unavailable, ρ of related DSO grid area is presented instead.

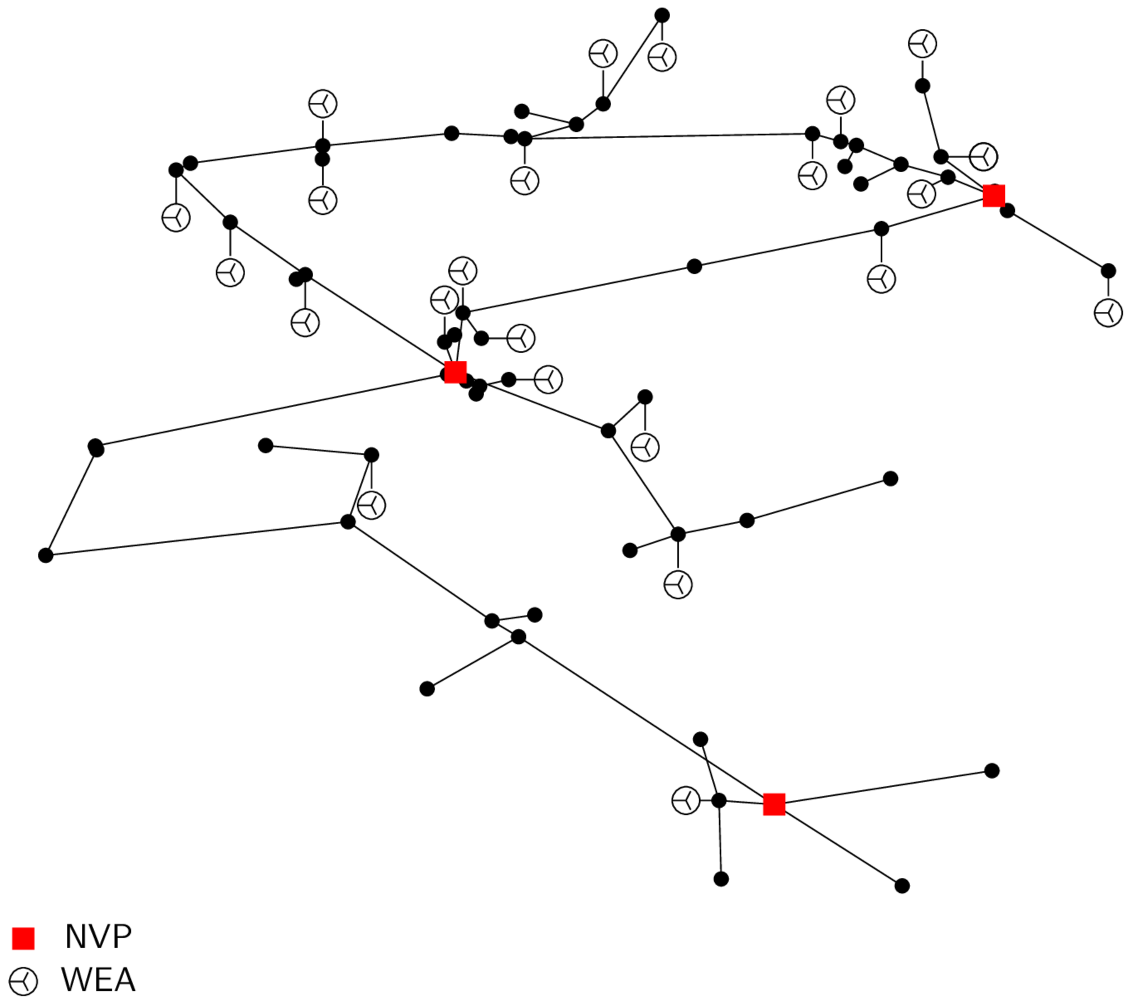
Backup
Grid Model sDG1

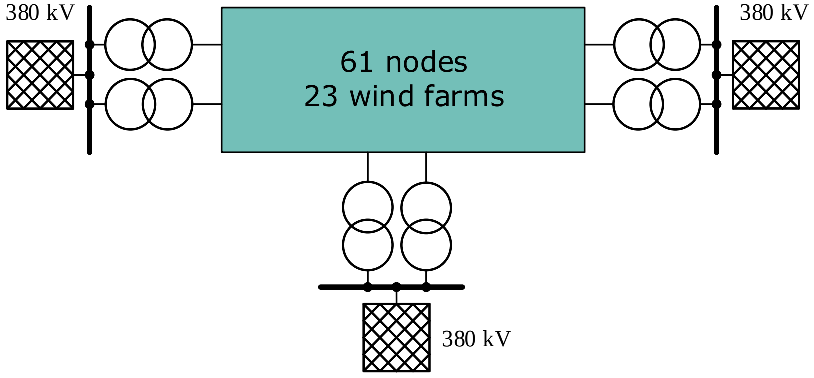




[Kra18]

Backup
Grid Model sDG2 - SimBench





[Mei18]