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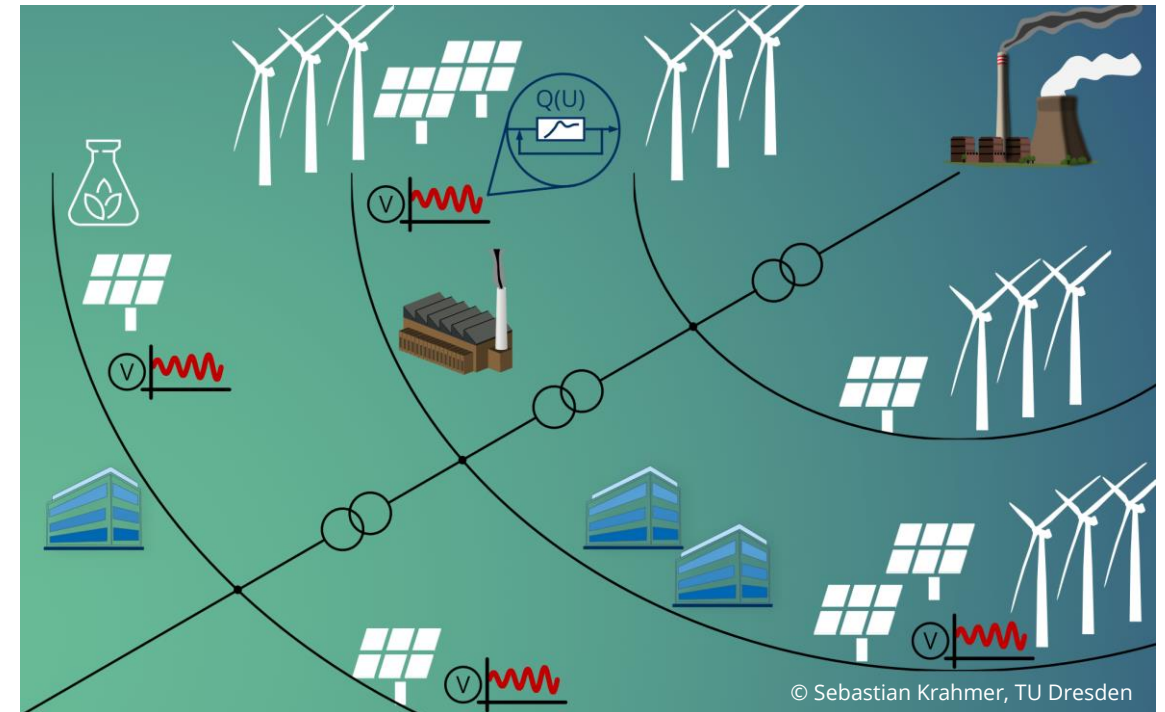
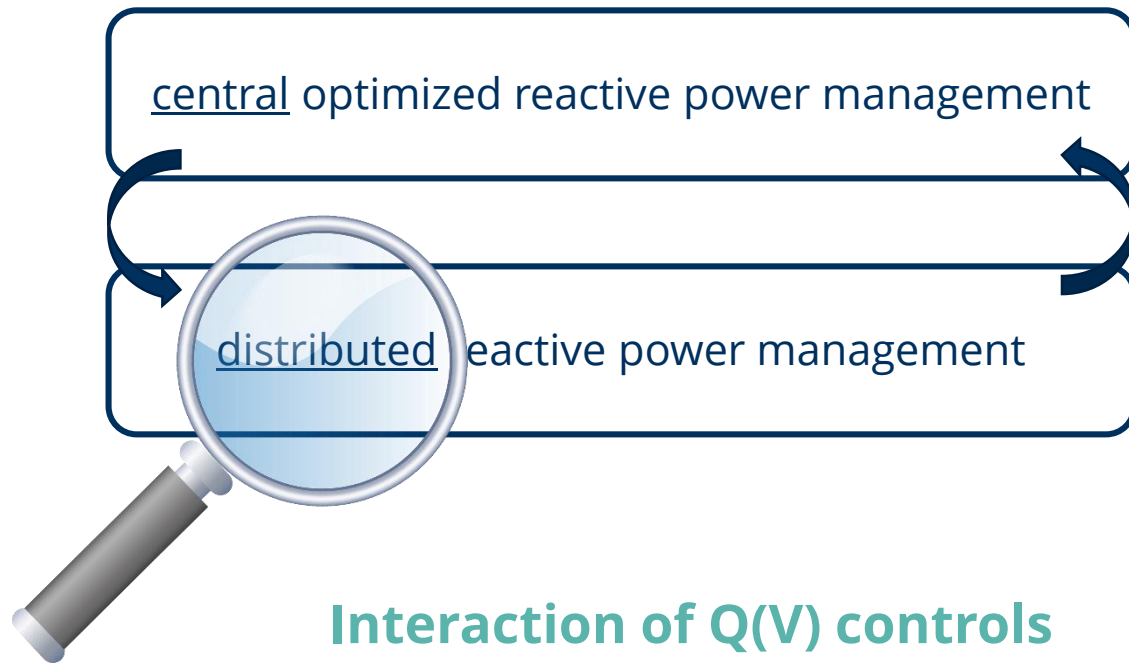
Analysis of the Converter-Driven Stability of Q(V)-Characteristic Control in Distribution Grids

SEST 2022

Eindhoven // 05.-07. Sept. 2022

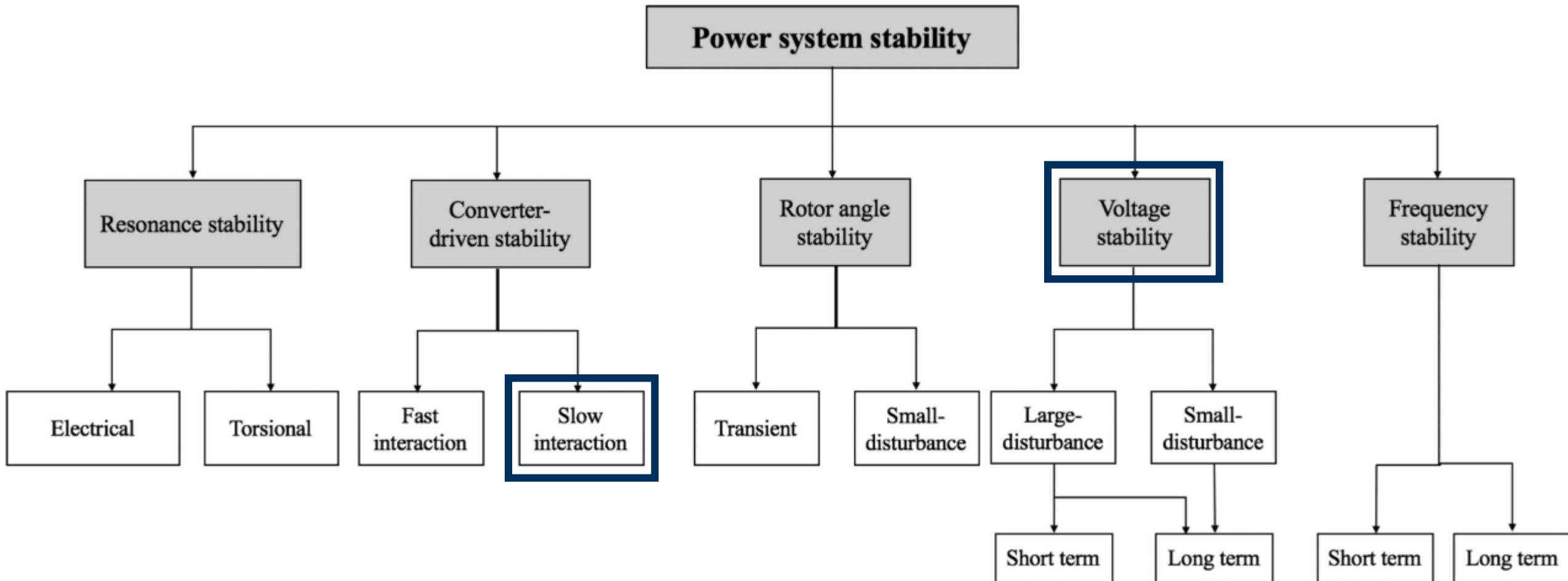
Paper 207

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



Stability Terms in Power Systems

1 2 3 4 5



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

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 communication 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

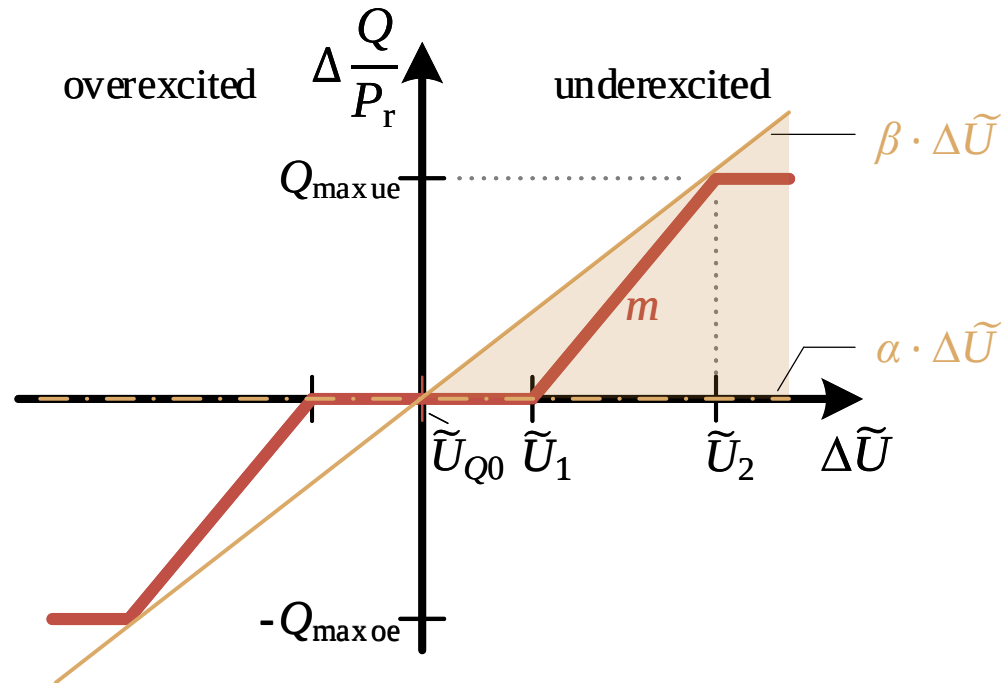
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CONCLUSION & OUTLOOK

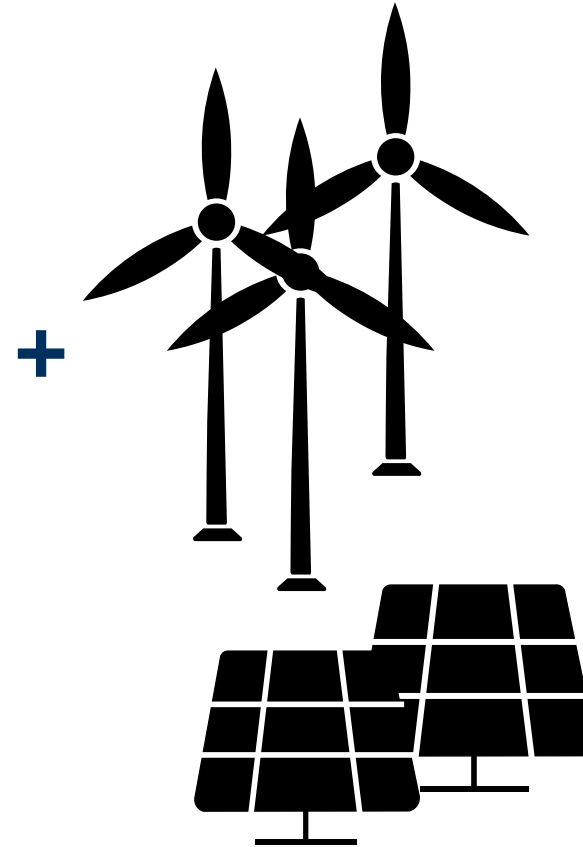
Photo by RawFilm on Unsplash

Models for Distributed Energy Resources (DER)

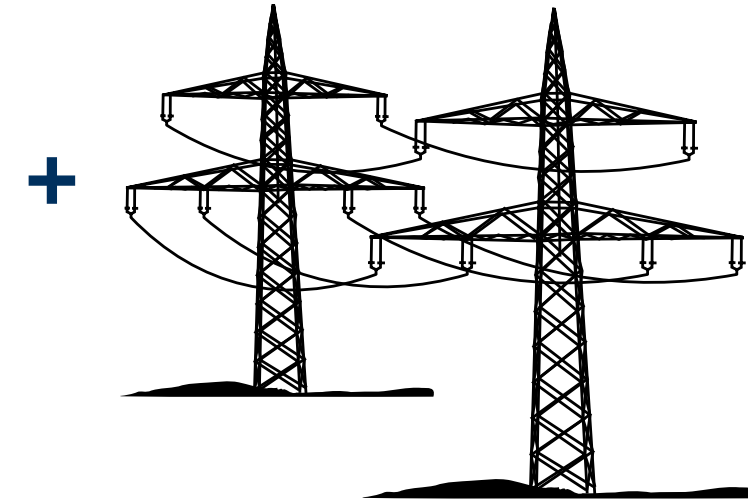
1 2 3 4 5



Q(V)-characteristic



DER control loops

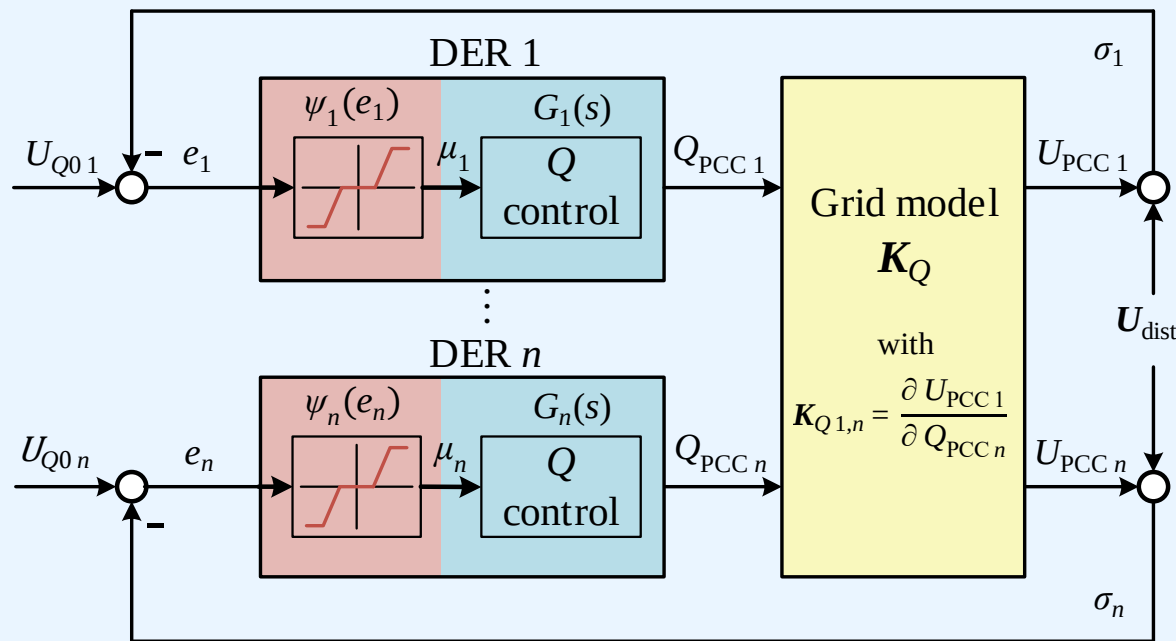


Nodal admittance matrix
of grid

Models for Distributed Energy Resources

1 2 3 4 5

Detailed control loop



DER approximation using PT2-fitting

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

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

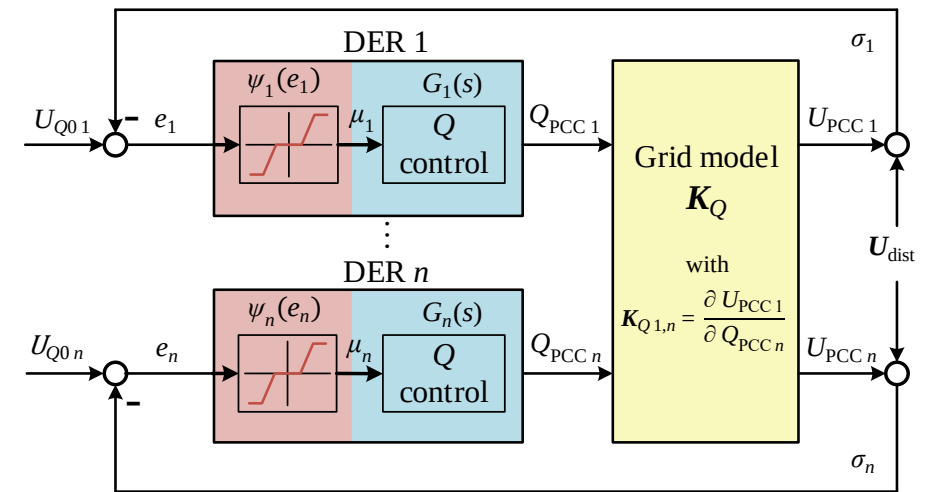
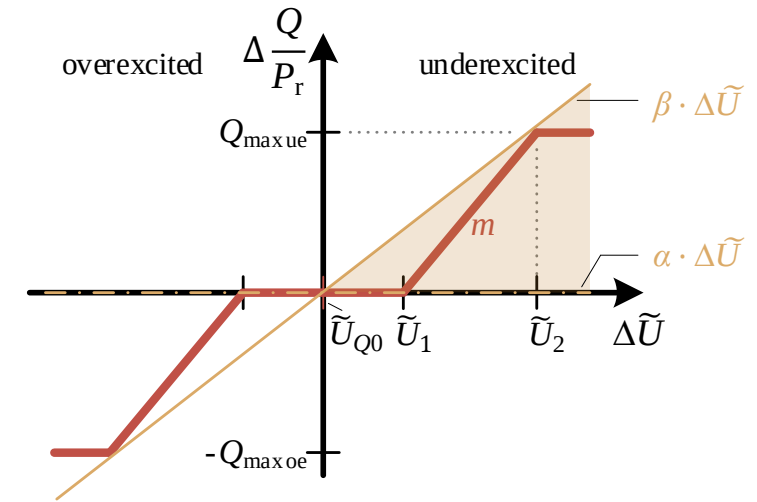
Stability Assessment via Circle Criterion

Multiple-Input Multiple-Output (MIMO)

Circle Criterion

$\Omega(s) = I + M_\beta \tilde{G}(s)$ must be strict positive real

- I : identity matrix
- M_β : $\text{diag}(\beta_1, \dots, \beta_n)$
- $\tilde{G}(s)$: remaining linear system



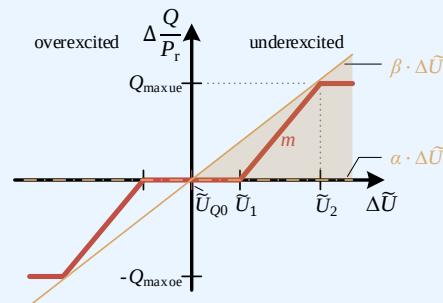
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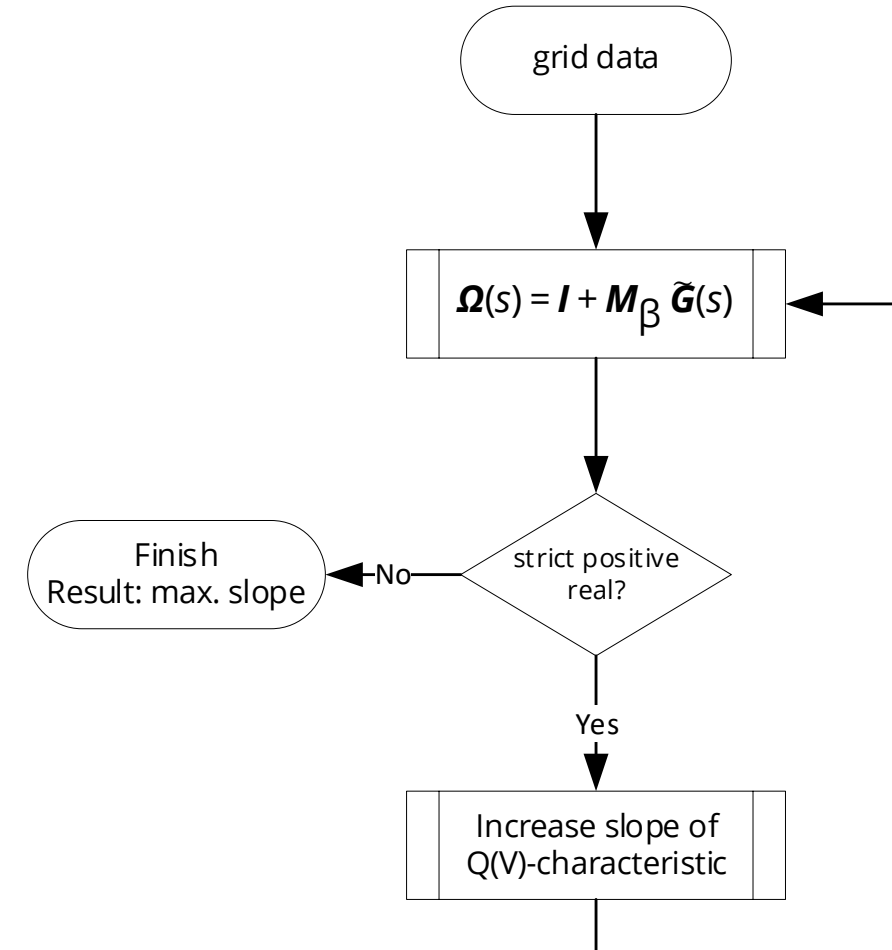
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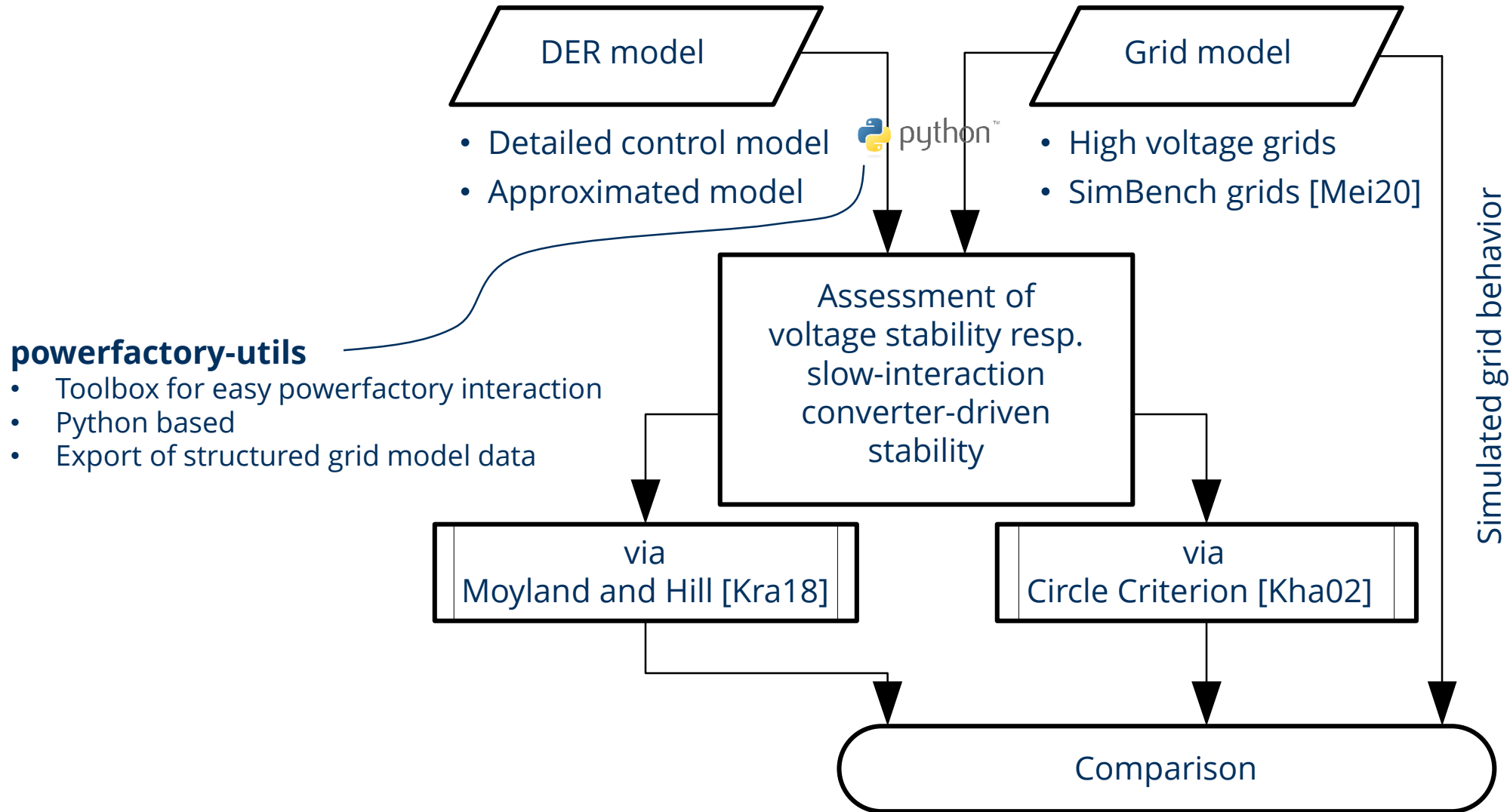


→ Strict Positive Realness can be checked with the criterion of [Sho08]



Verification and Comparison of Stability Assessment

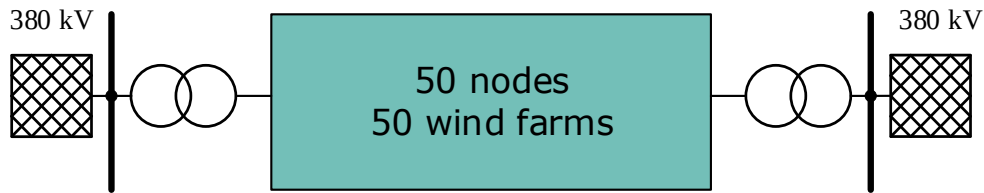
1 2 3 4 5



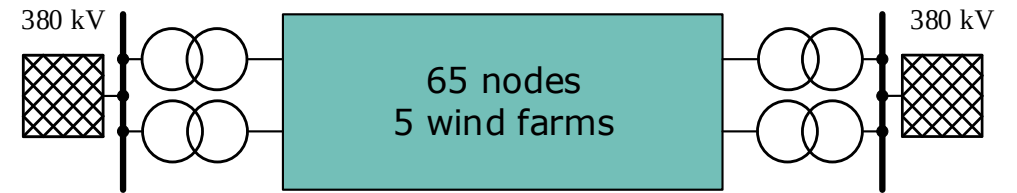
Verification and Comparison of Stability Assessment Models for High Voltage Distribution Grid (DG)

1 2 3 4 5

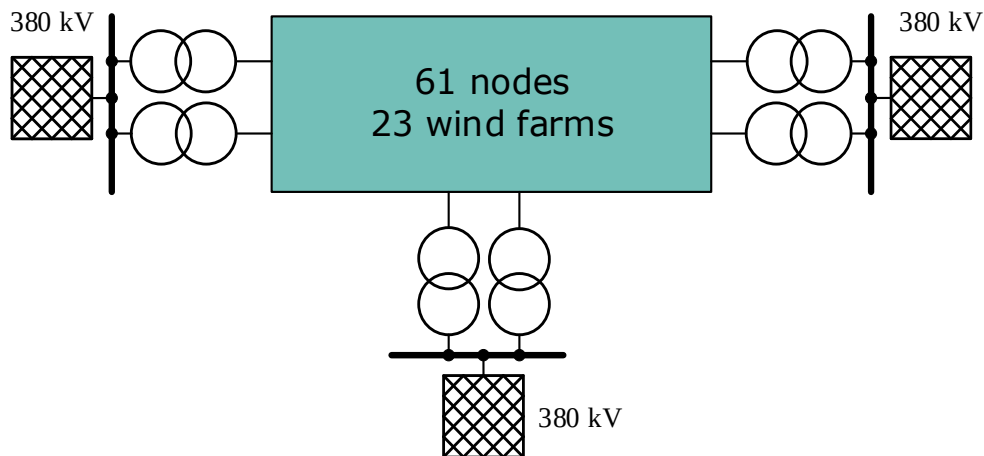
synthetic distribution grid
sDG 1



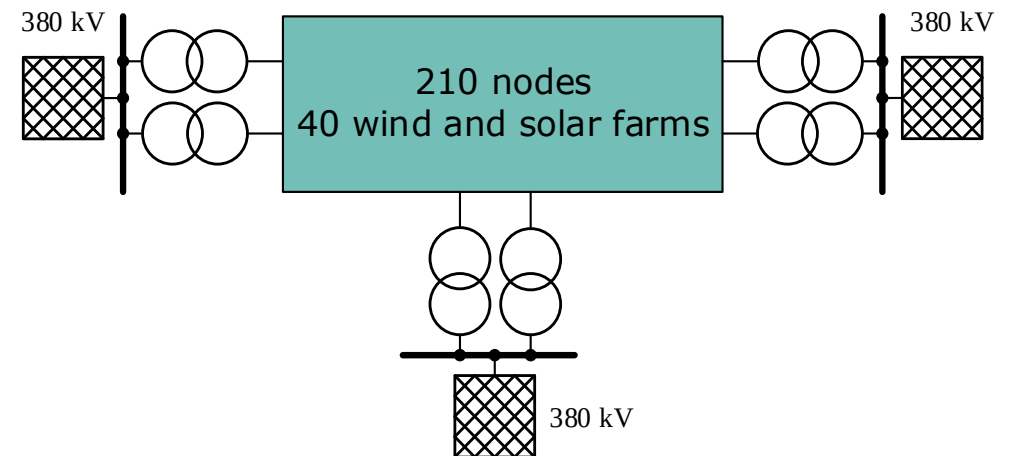
realistic distribution grid
rDG 1



synthetic distribution grid
sDG 2



realistic distribution grid
rDG 2



Verification and Comparison of Stability Assessment

1 2 3 4 5

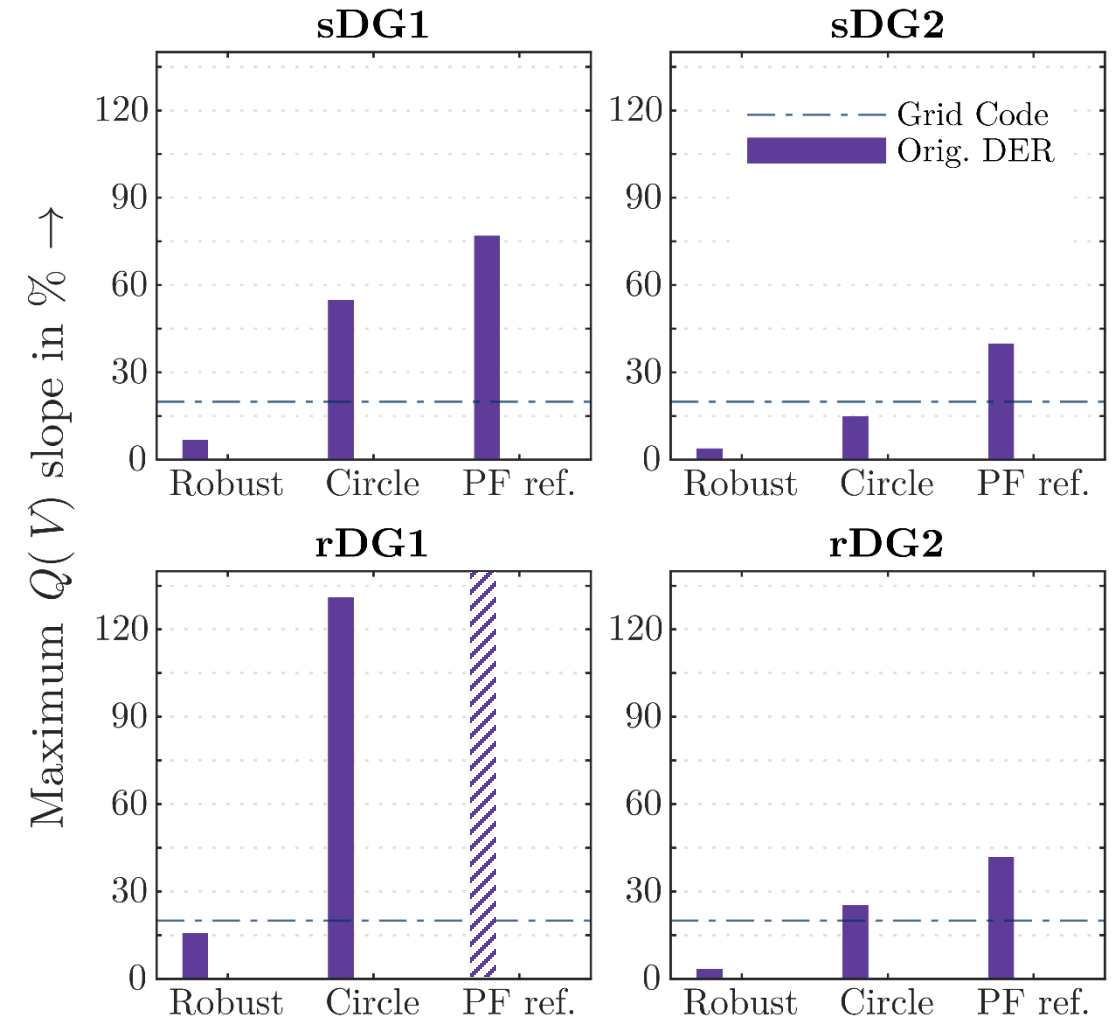
Simulation based Verification

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



Verification and Comparison of Stability Assessment

1 2 3 4 5

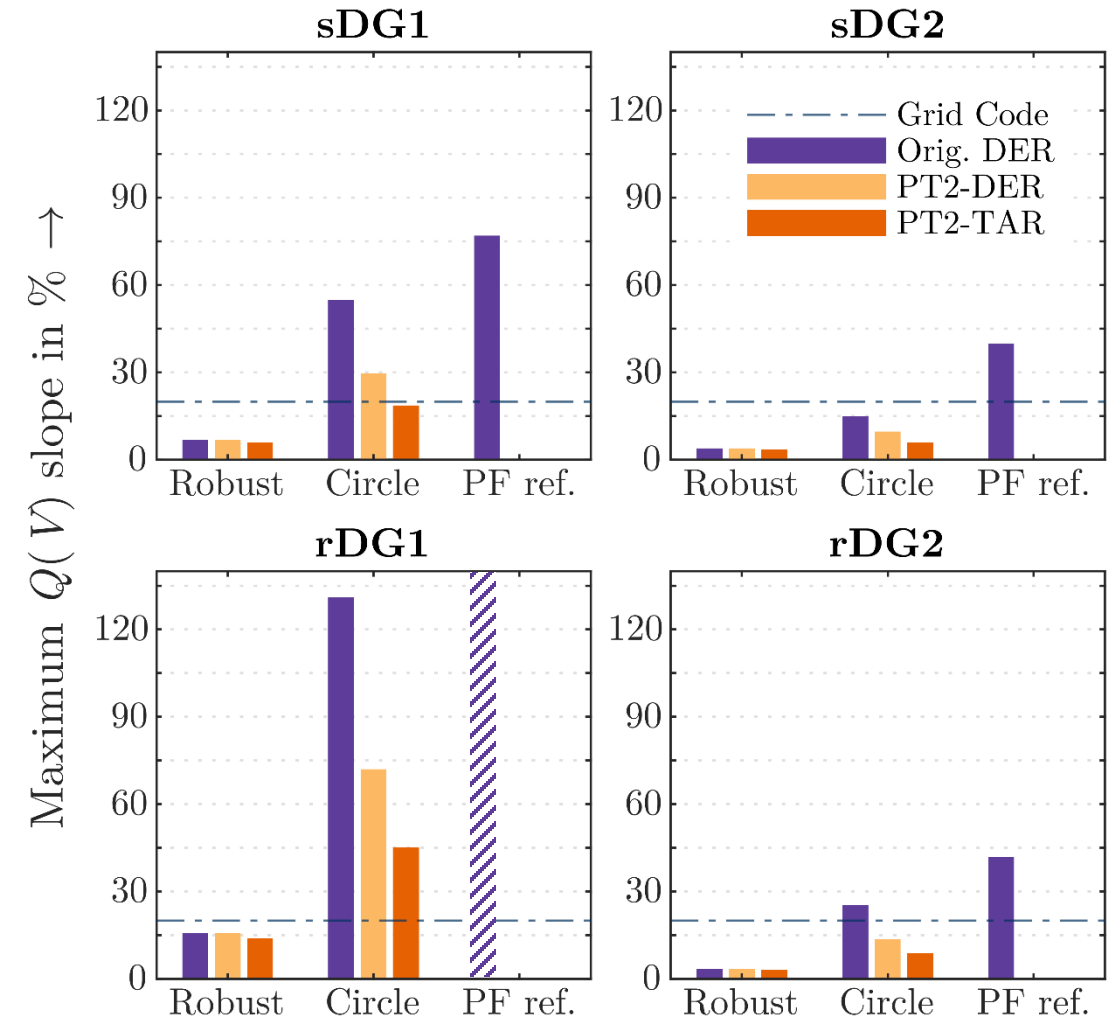
Simulation based Verification

Constraints

- DER models are based on FRC wind farm type
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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
- **Benefits for optional PT2-models**
 - PT2-models are more conservative than detailed DER model
 - PT2-models offer a shorter computing time



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!



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Publications: www.fis.tu-dresden.de

Project info: www.researchgate.net #STABEEL

PowerFactory Utils

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



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Models for Distributed Energy Resources

1 2 3 4 5

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	$\frac{1}{1 + sT_U}$ $T_U = 0.02 \text{ s}$	$T_{dQ} = 2 \text{ s}, K_q = 0.5, T_q = 0.2 \text{ s}, T_I = 0.1 \text{ s}, T_g = 0.2 \text{ s}$	[12, 18, 30]
(ii) WF-DFIG			[17, 18, 30]
(iii) PVF	$\frac{1}{(1 + sT_U)^3}$ $T_U \approx 0.004 \text{ s}$	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). $T_{dQ} = 2 \text{ s}, K_q = 0.5, T_q = 0.2 \text{ s}, T_I = 0.0033 \text{ s}, T_g = 0.1 \text{ s}$	[19]
(iv) PT2-TAR	Not explicit necessary.	Based on the generic step response given in TAR [24]. $\kappa = 1, D = 0.517, T = 2.335 \text{ s}$	
(v) PT2-DER		Based on the frequency response of detailed DER model (i). $\kappa = 1, D = 0.747, T = 1.028 \text{ s}$	

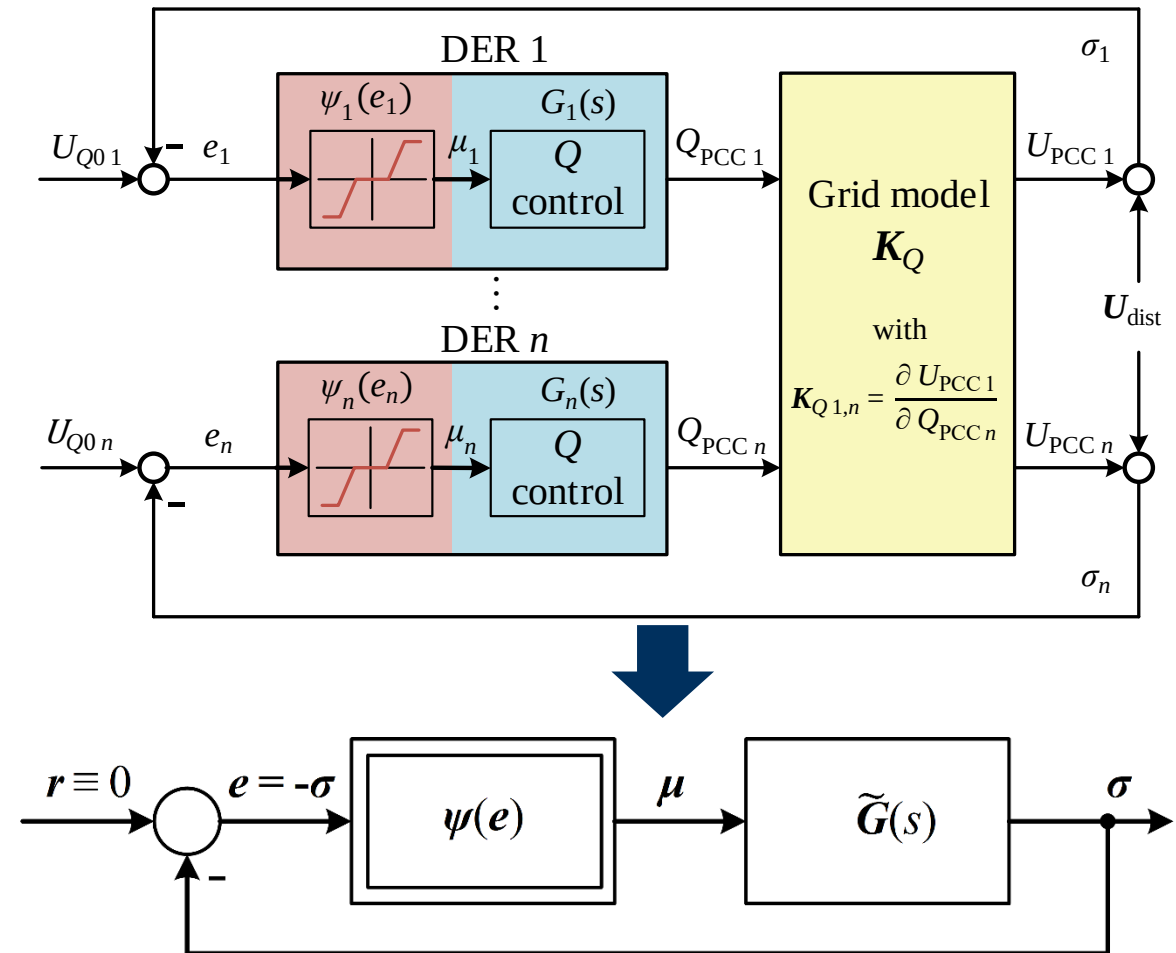
Stability Assessment via Circle Criterion

Multiple-Input Multiple-Output (MIMO)

Circle Criterion

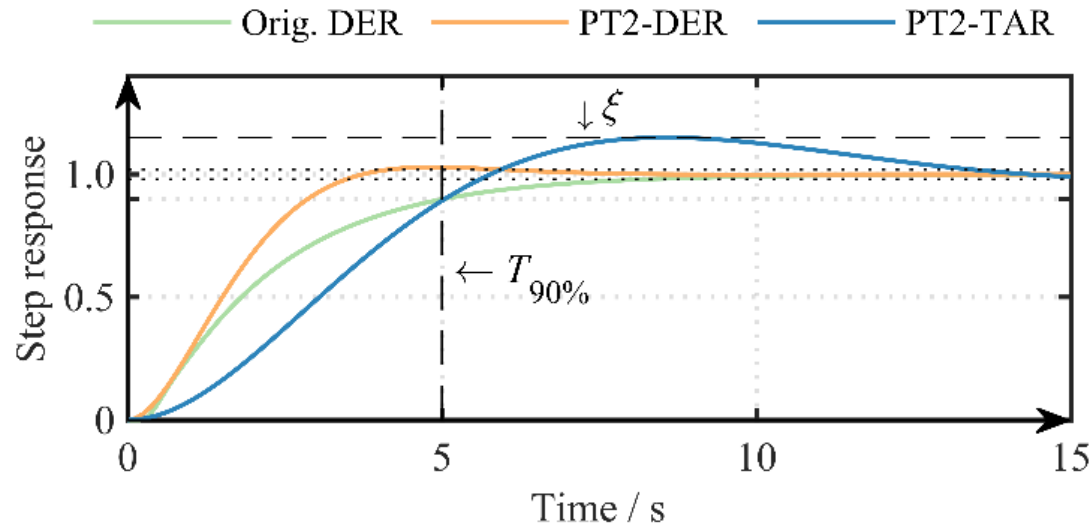
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Comparison of DER models

1 2 3 4 5

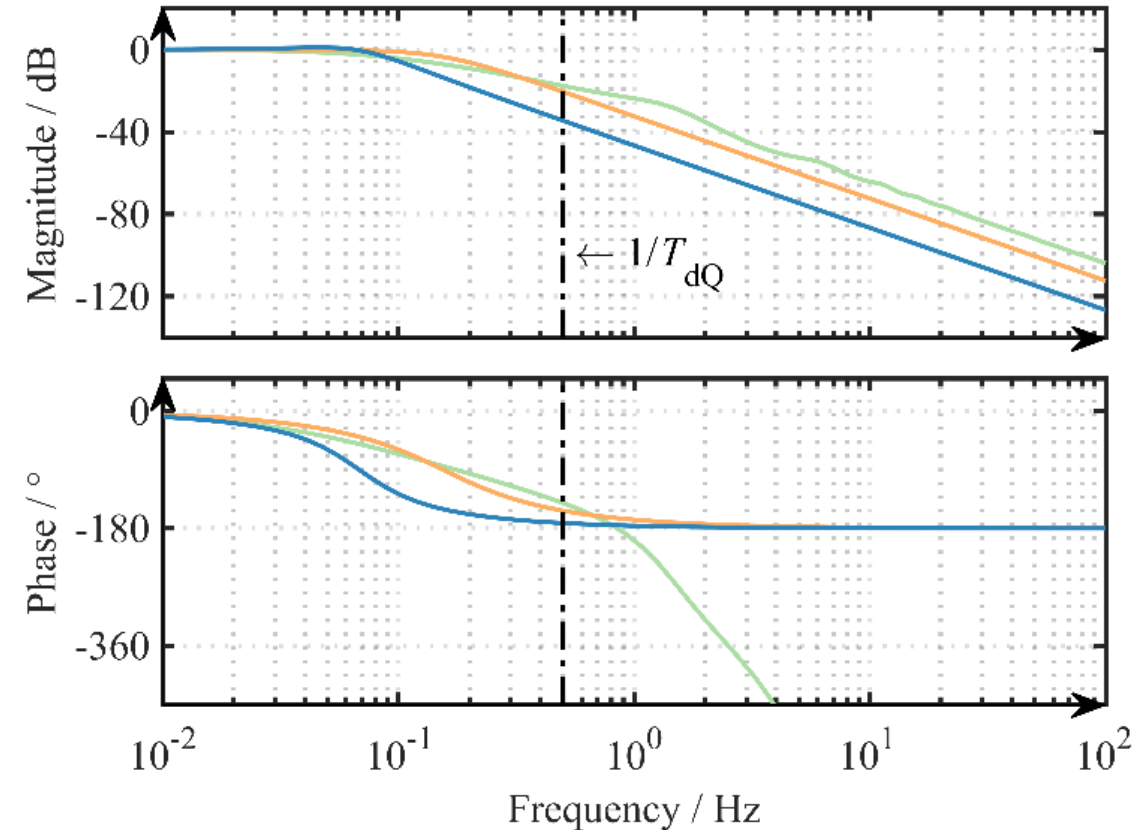


PT2-TAR

- 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

1 2 3 4 5

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

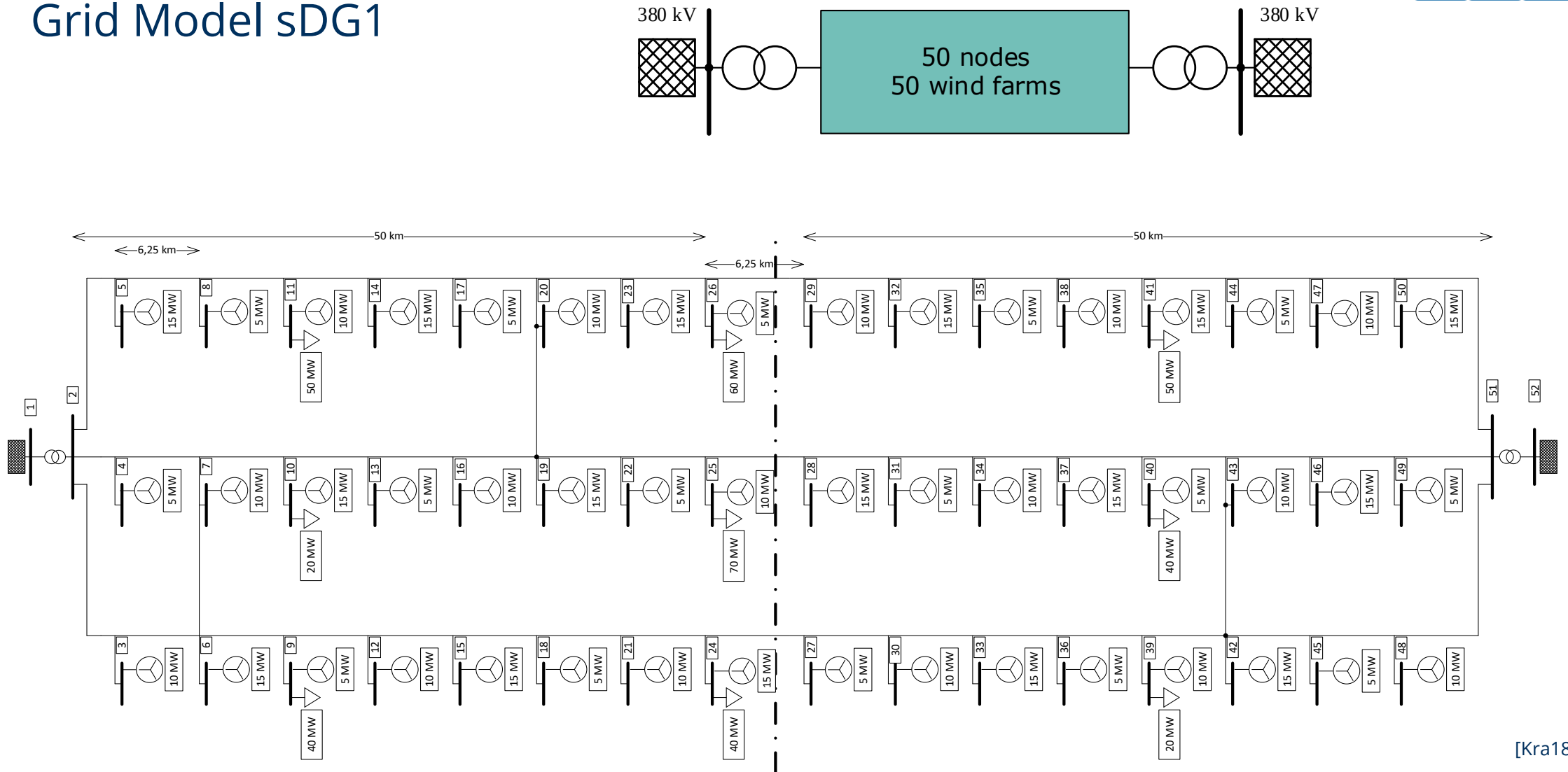
grid	connection points 110/380 kV	number of nodes	$\sum P_{\text{DER}}$ in MW	ρ in kW/km
sDG1	2	50	480	1400
sDG2	3	61	1560	1440
rDG1	2	65	135	$\approx 200^a$
rDG2	3	210	840	$\approx 600^a$

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

Backup

Grid Model sDG1

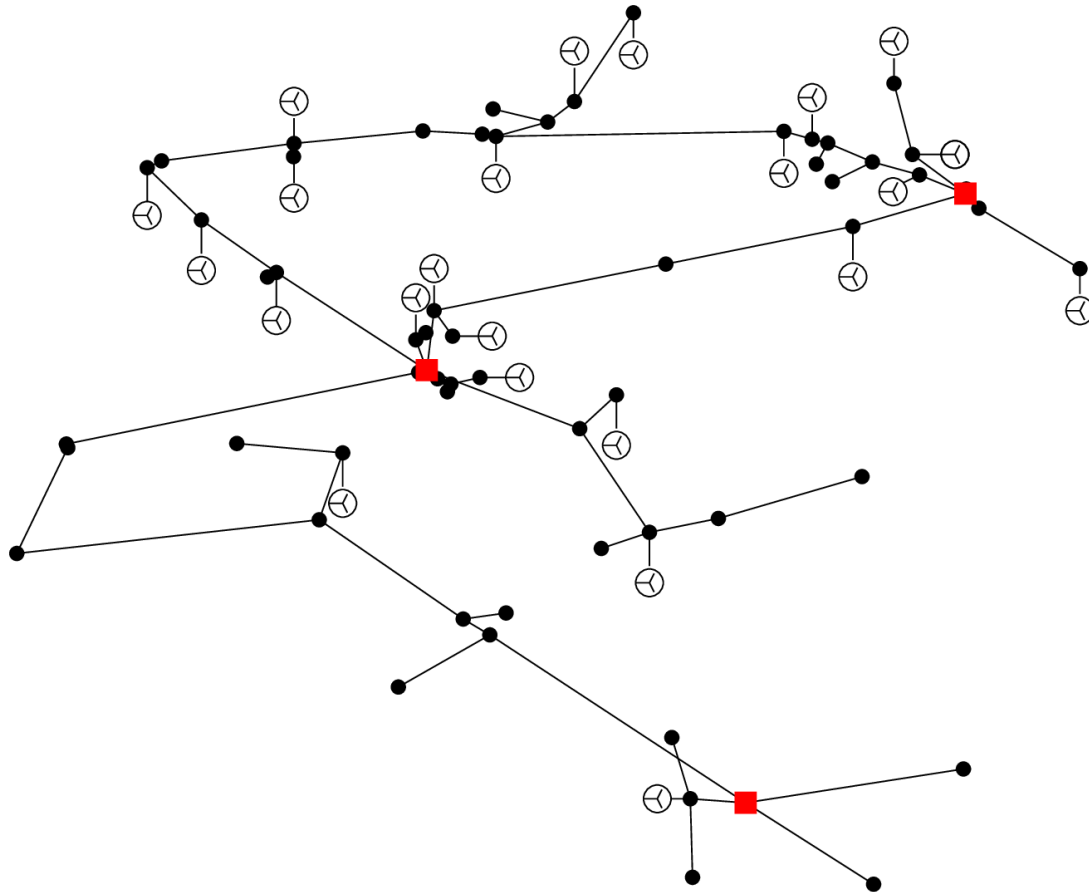
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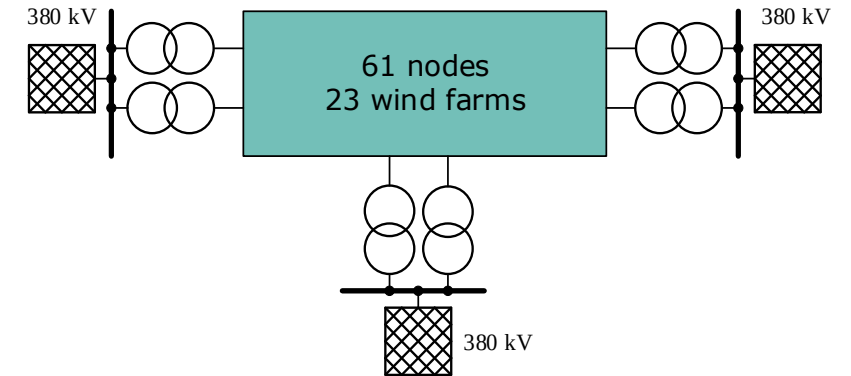
[Kra18]

Backup

Grid Model sDG2 - SimBench



■ NVP
⊗ WEA



[Mei18]