Probabilistic Transient Stability Assessment of Power Systems with High Penetration of Renewable Generation

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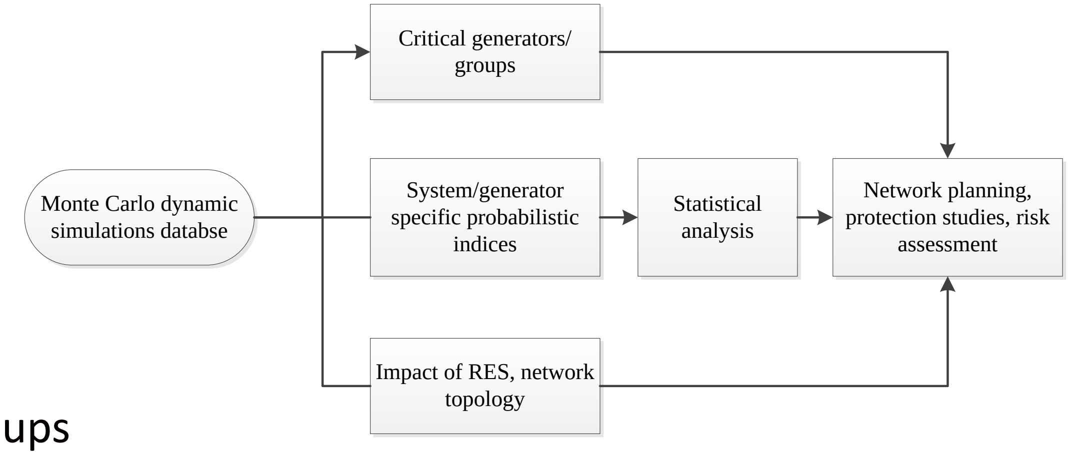
Probabilistic Transient Stability Assessment

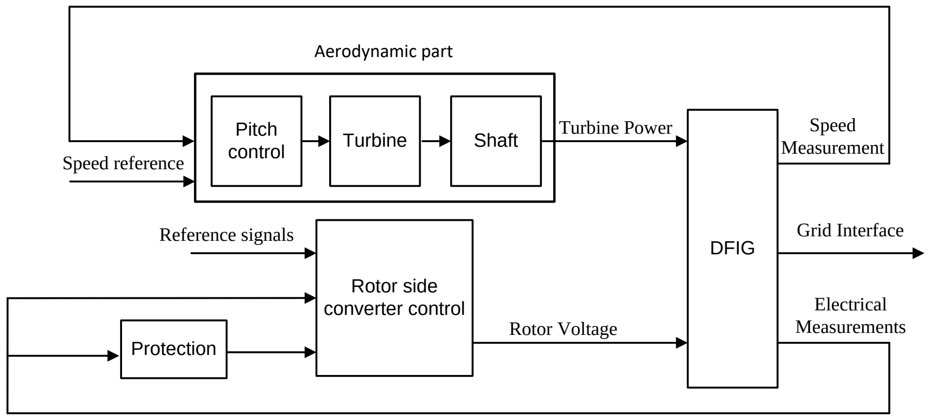
- Probabilistic stability assessment
  - Increasing uncertainty and complexity
  - Transmission but also Distribution level (Active Distribution Networks, EV, etc.)
- Particular challenge for transient stability assessment
  - Detailed dynamics are important
  - Not straightforward impact (improvement and deterioration)
  - Important and challenging to quantify overall impact over a range of possible operating conditions and disturbances
- Important to quantify risk of instability
  - With adequate detail to be informative
  - Inform planning or operational decisions for secure and cost-effective operation
- Particularly useful for data-driven, machine learning applications

Probabilistic transient stability assessment

Key points

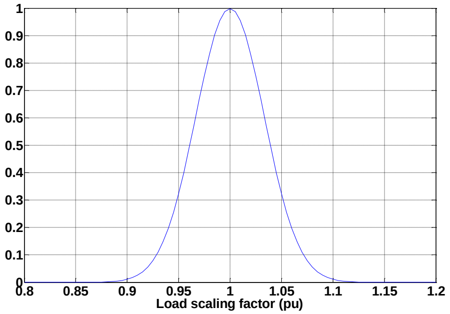
- Account for multiple operating conditions while capturing detailed dynamic behaviour (uncertainty and complexity)
  - Effect of initial operating conditions - intermittent renewables, economic dispatch, generation disconnection
  - Dynamic behaviour of renewables in RMS framework (e.g. FRT)
  - Impact of location changes
- More informative: Quantify behaviour of individual generators and groups of unstable generators
  - Which generators, in what groups and in what order
  - Supervised machine learning - hierarchical clustering to define groups
  - Useful information in defining probabilistic behaviour or instability risk in more detail (investigation of indices for individual generators and groups)
  - Aperiodic and oscillatory

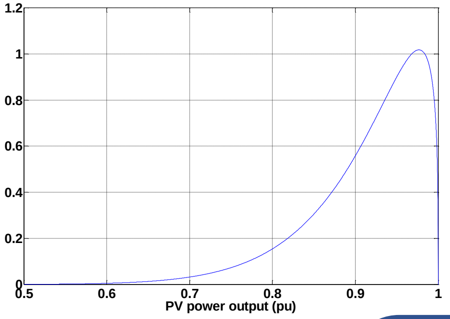




Probabilistic framework for transient stability assessment with high share of renewables

- Fault location (uniform)
- Fault duration (normal)
- System loading (normal)
- PV (beta)
- Wind farms (Weibull)





- RMS time domain simulations
- Large disturbances – 3ph faults

SG disconnection (inertia reduction)

$$SC_{ig}=1-\frac{P_{SG,ig}}{S_{SG,ig}\cdot pf_{SG,ig}}$$

Power system dynamic model

Sampling of uncertainties

Run OPF

Conventional generation disconnection → Effect of conventional generation spare capacity

Monte Carlo simulations (N_s cases)

Obtain rotor angles → Hierarchical clustering → Critical generators/groups

Calculate Transient Stability Indices

Statistical analysis

Output of Probabilistic TSA

$$TSI_i=100\cdot\frac{360-\delta_{max,i}}{360+\delta_{max,i}}$$

$$\Delta\delta_{ig}^{max}=\max\left(\left|\delta_{ig}-\delta_{ig}^{0}\right|\right)$$

$$\Delta\omega_{ig}^{max}=\max\left(\left|\Delta\omega_{ig}(t)\right|\right)=\max\left(\left|\frac{\delta_{ig}(t)-\delta_{ig}(t-\Delta t)}{2\pi f\Delta t}\right|\right)$$

$$a_{ig}^{max}=\max\left(\left|a_{ig}(t)\right|\right)=\max\left(\left|\frac{\omega_{ig}(t)-\omega_{ig}(t-\Delta t)}{\Delta t}\right|\right)$$

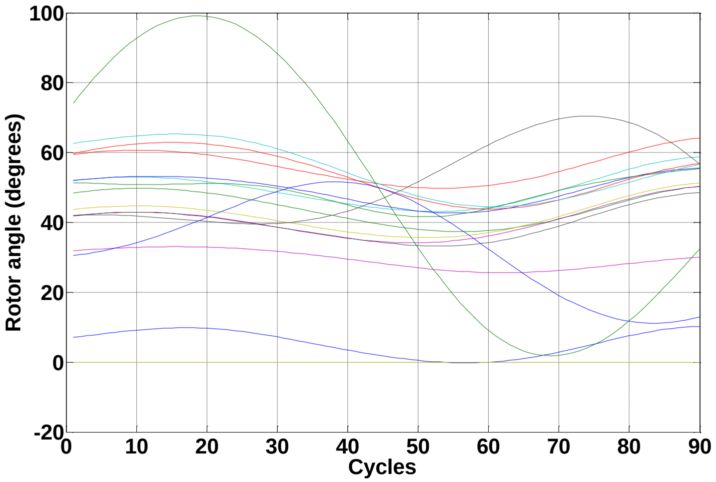
N_s simulations (error <5%)

$$e_{\bar{X}_N}=\frac{\Phi^{-1}\left(1-\frac{\delta}{2}\right)\sqrt{\frac{\sigma^2(X_N)}{N}}}{\bar{X}_N}$$

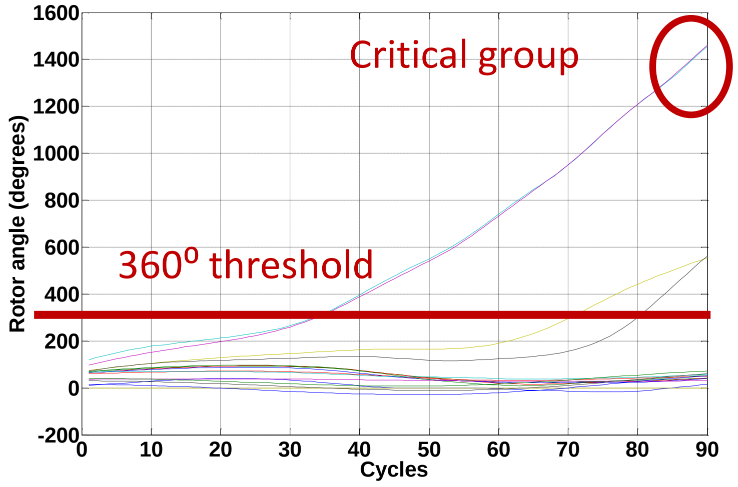
P. N. Papadopoulos, J. V. Milanović, "Probabilistic Framework for Transient Stability Assessment of Power Systems With High Penetration of Renewable Generation," IEEE Transactions on Power Systems, vol. 32, no. 4, pp. 3078-3088, July 2017.

Unstable generator groups – hierarchical clustering

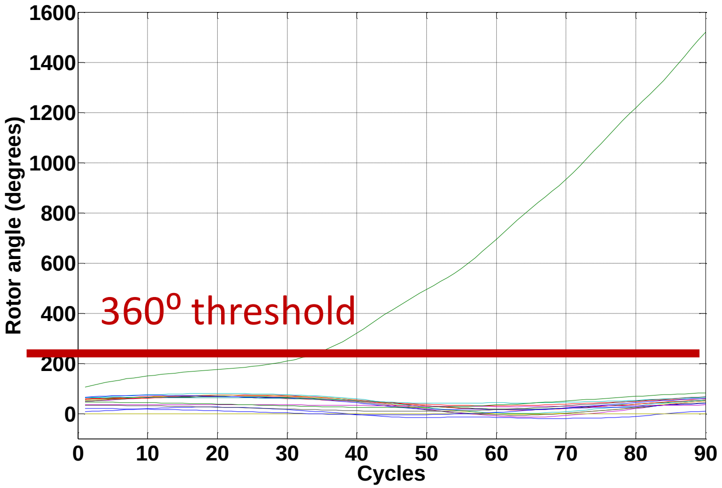
(G1-G16) – stable case



(G4-G5)/(G6-G7) /(G1-G3,G10-G16)



(G9)/(G1-G8,G10-G16)



Test cases description

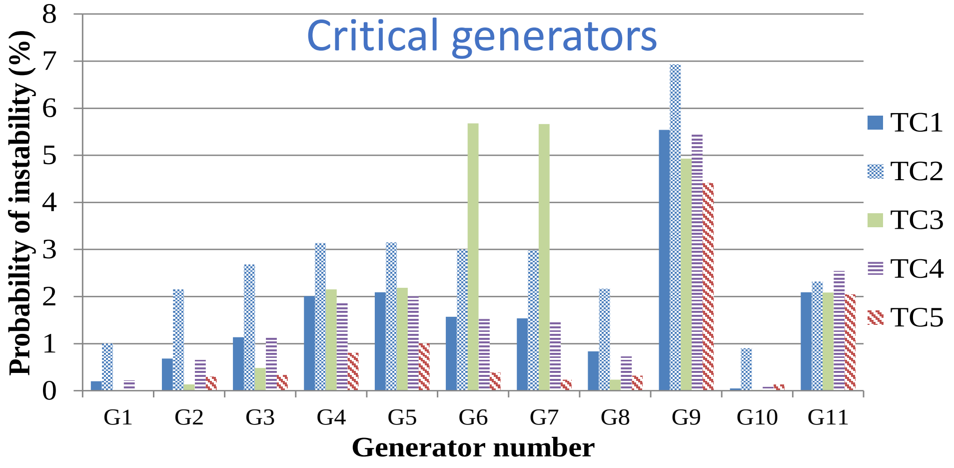
TCs	RES installed capacity (% of system nominal capacity)	Lines out of service
TC1	20%	-
TC2	-	-
TC3	20%	Line 1
TC4	20%	Line 2
TC5	60%	-

Impact of RES and topology changes on unstable generator groups

	Unstable generator groups	Frequency of appearance (%)		
		TC1	TC2	TC5
1	(G9)	49.38	42.96	51.39
2	(G11)	22.12	19.91	10.24
3	(G2-G9)	2.65	7.63	0.01
4	(G4-G5)/(G6-G7)	1.95	1.35	-
5	(G3)	3.01	4.04	3.39
6	(G4-G7,G9)/(G3)	0.88	-	-
7	(G4-G7)	4.78	5.69	1.2
8	(G4-G5)	4.60	1.20	5.78
9	(G1-G9)	1.59	2.40	-
10	(G8)	2.12	1.80	3.19
11	(G5)	0.88	0.15	2.19
12	(G1-G10)	0.35	2.69	-
13	(G10)	0.18	2.25	1.59
14	(G1-G9)/(G10)	-	2.25	-

Probabilistic transient stability assessment focusing on individual generator behaviour

- Locational impact – detailed impact/changes on transient stability
- Additional information for system dynamic behaviour
- Quantile plots: highlight detailed changes in individual generator behaviour



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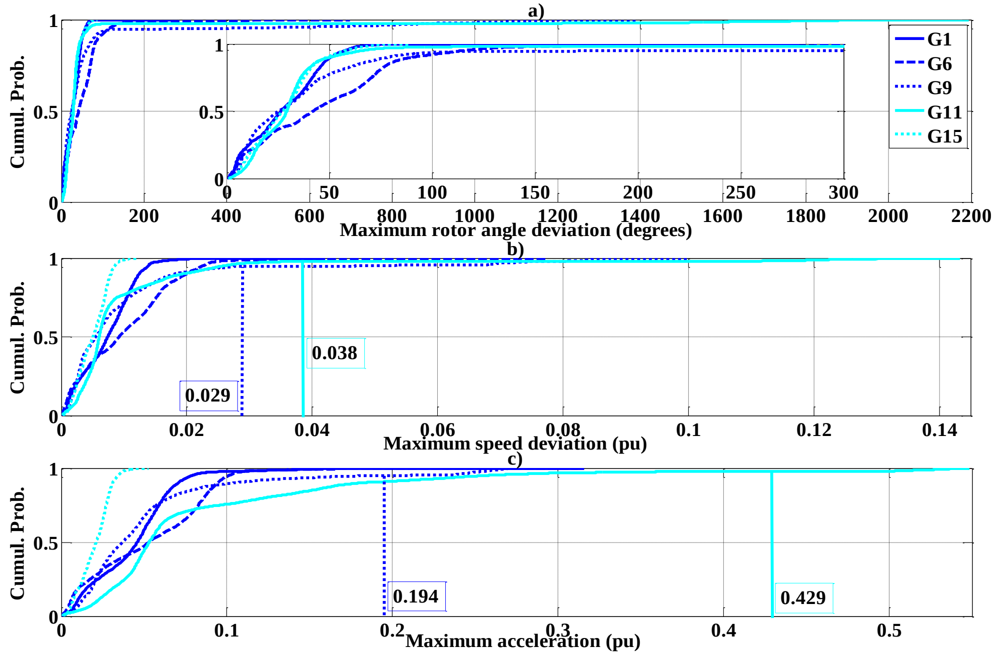
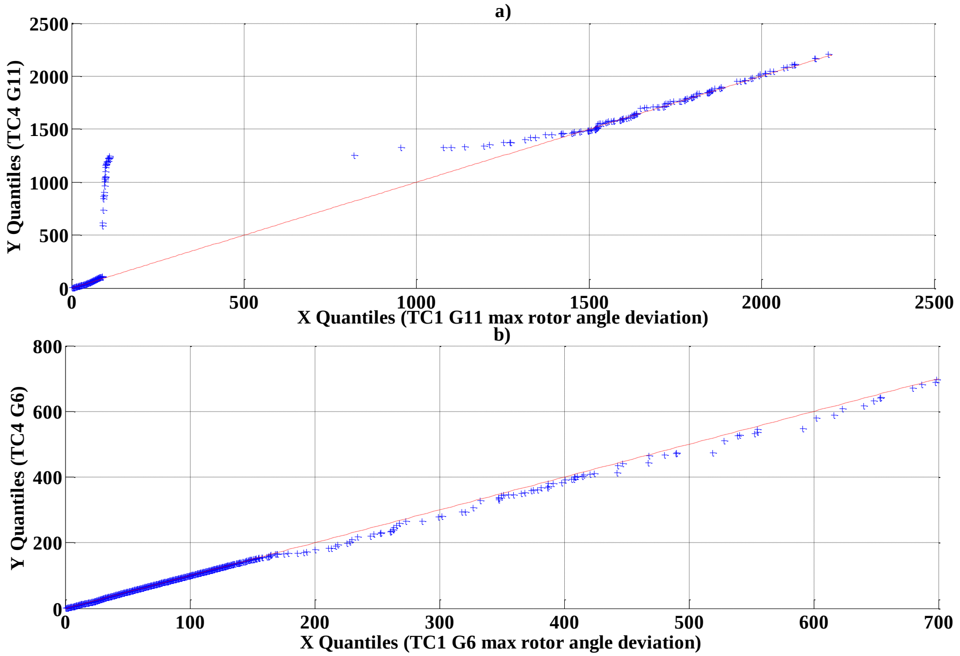
Transient stability Indices



Quantile plots highlighting probabilistic behaviour



Impact of synchronous generation disconnection

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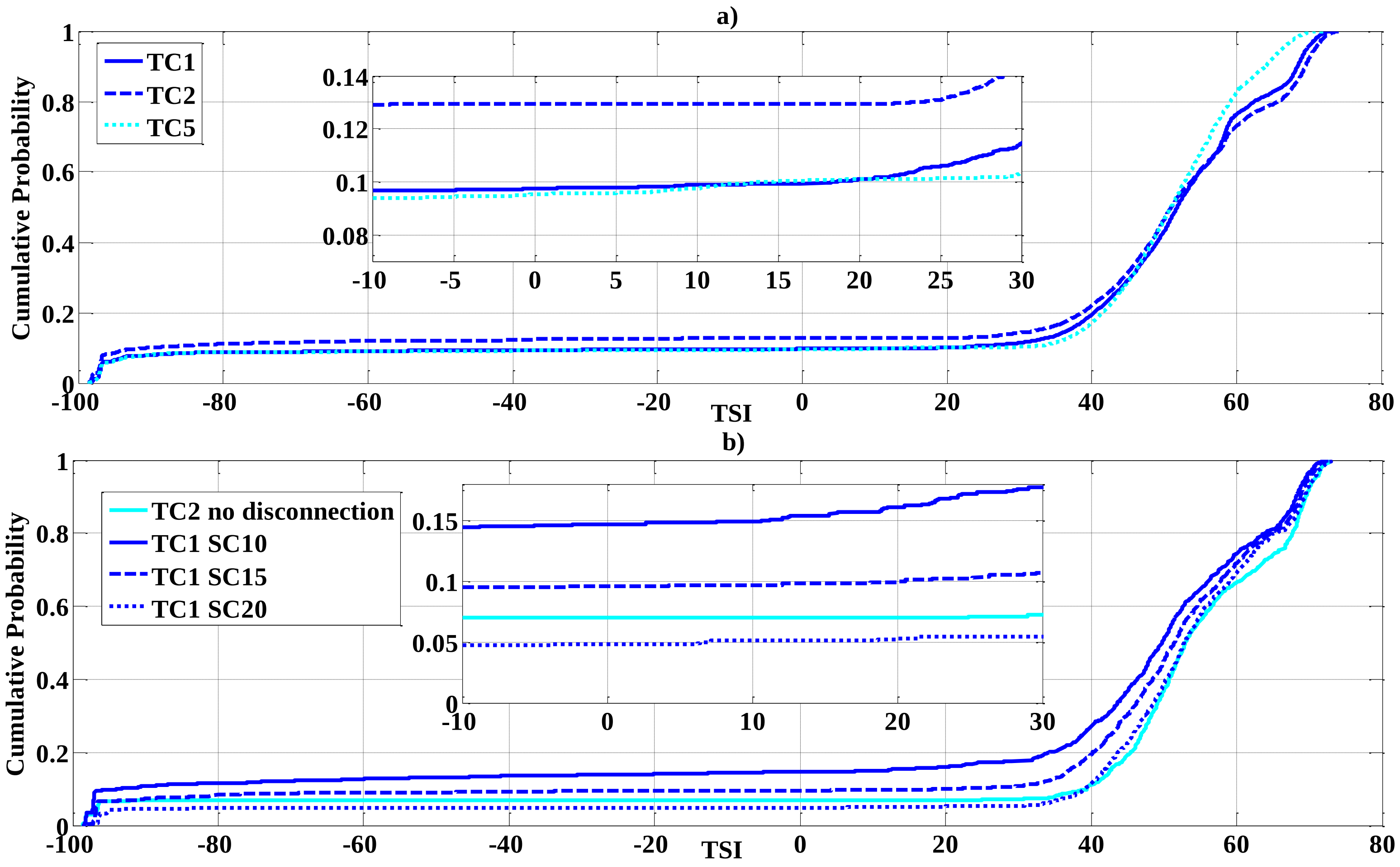
- Overall transient stability assessment (detail over TSI range)
- Amount and location of disconnection is important
- Critical headroom identification

Transient stability Index



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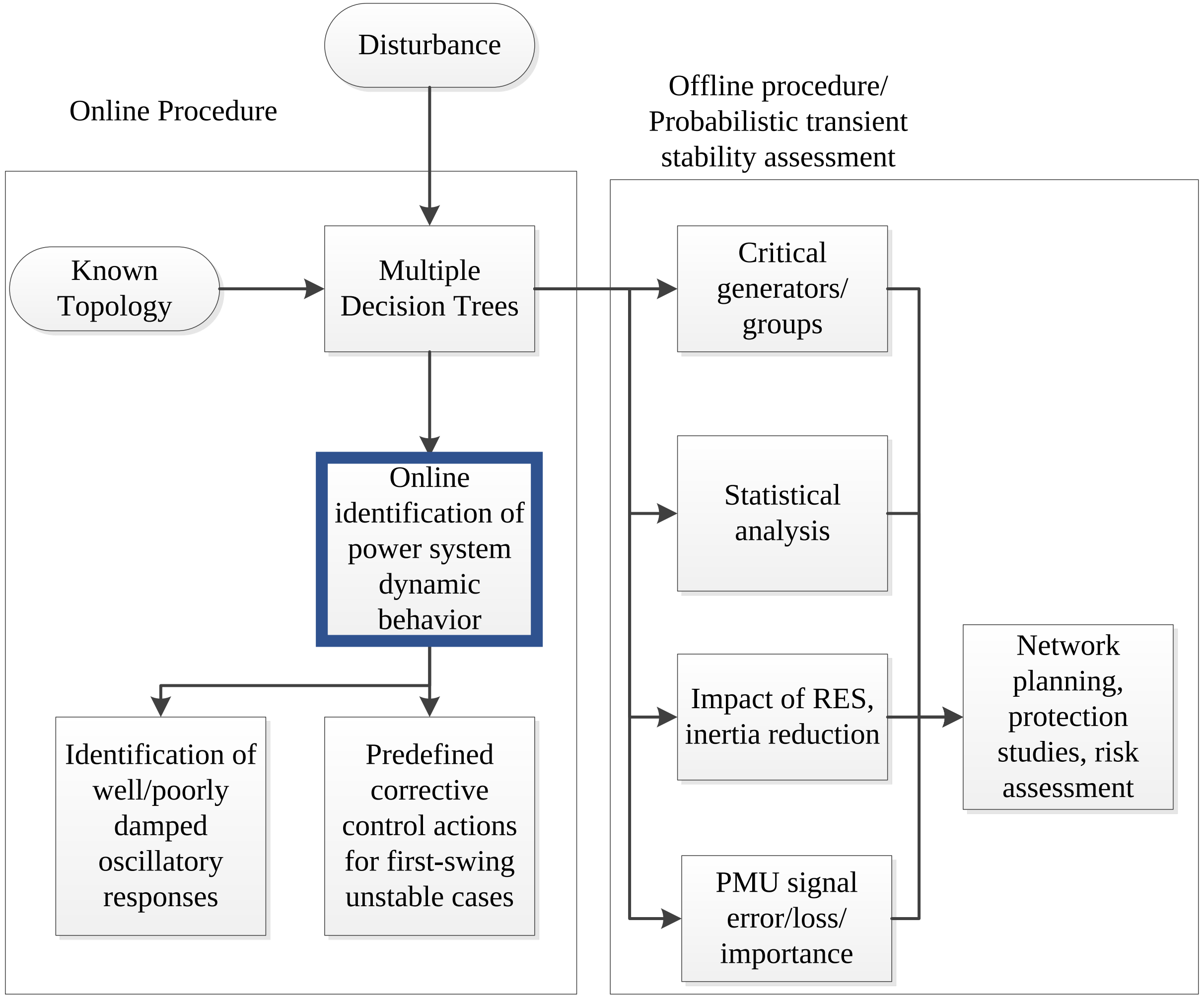
Probabilistic framework for online transient stability assessment



Probabilistic framework for online transient stability assessment

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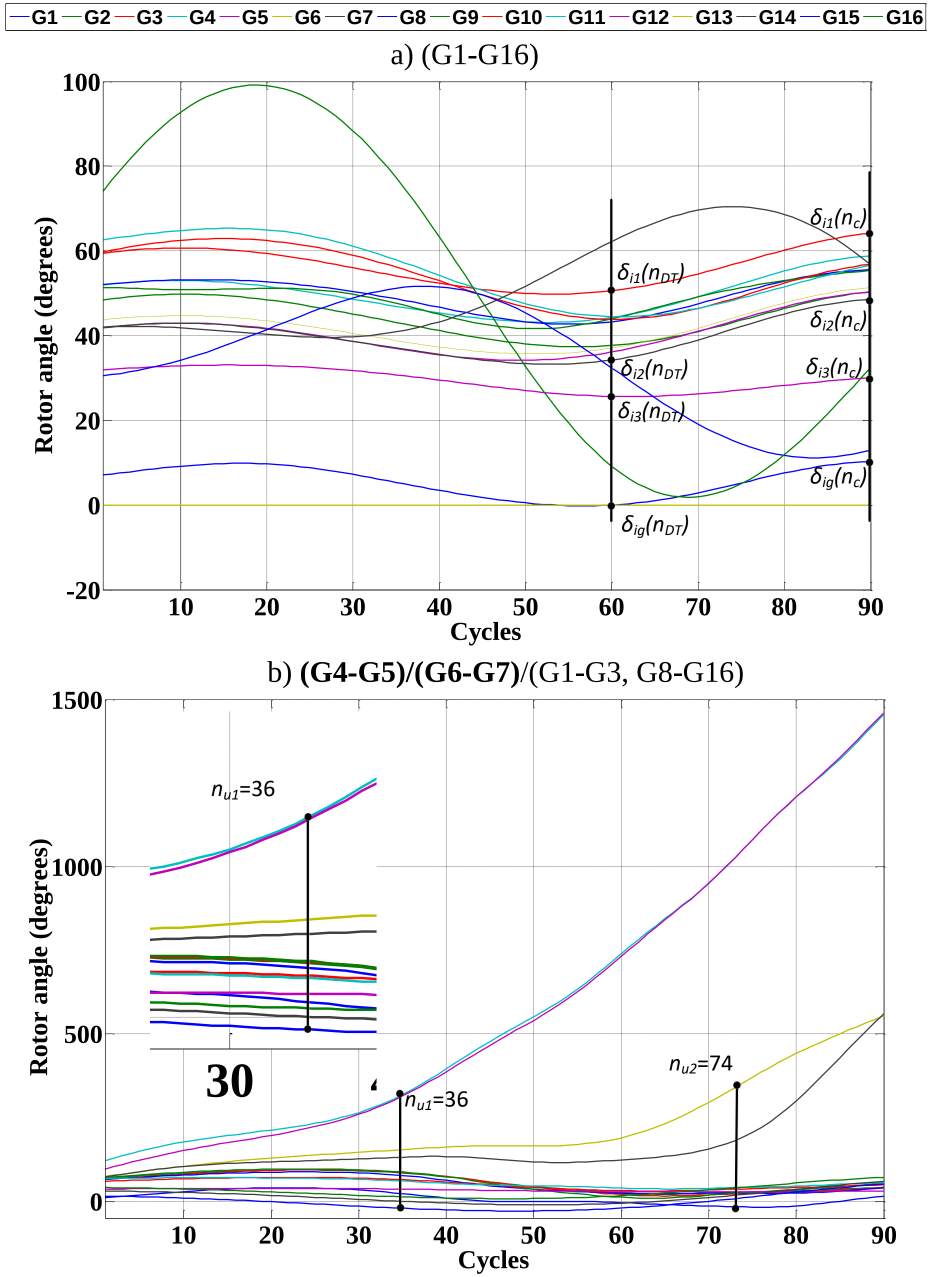

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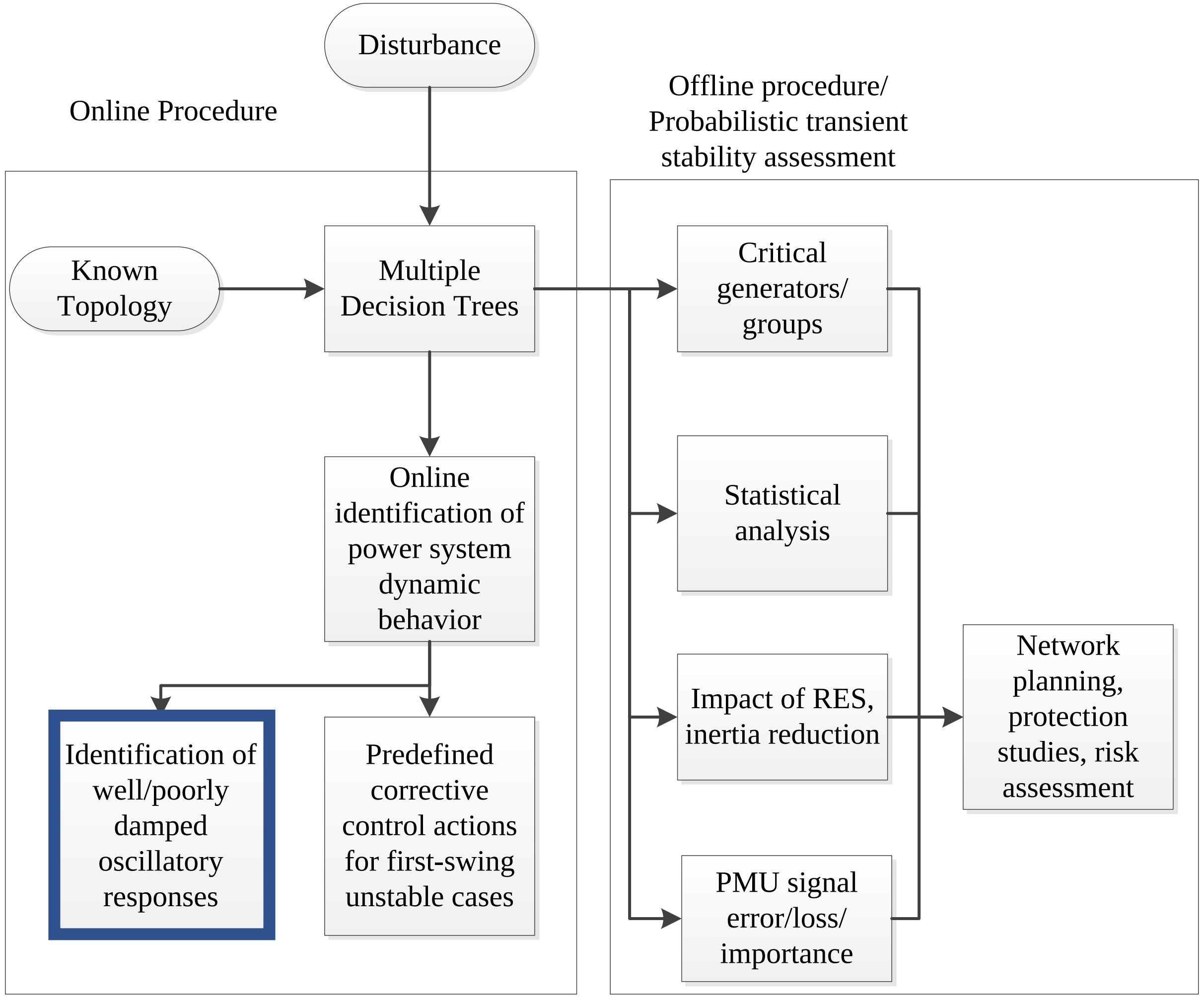

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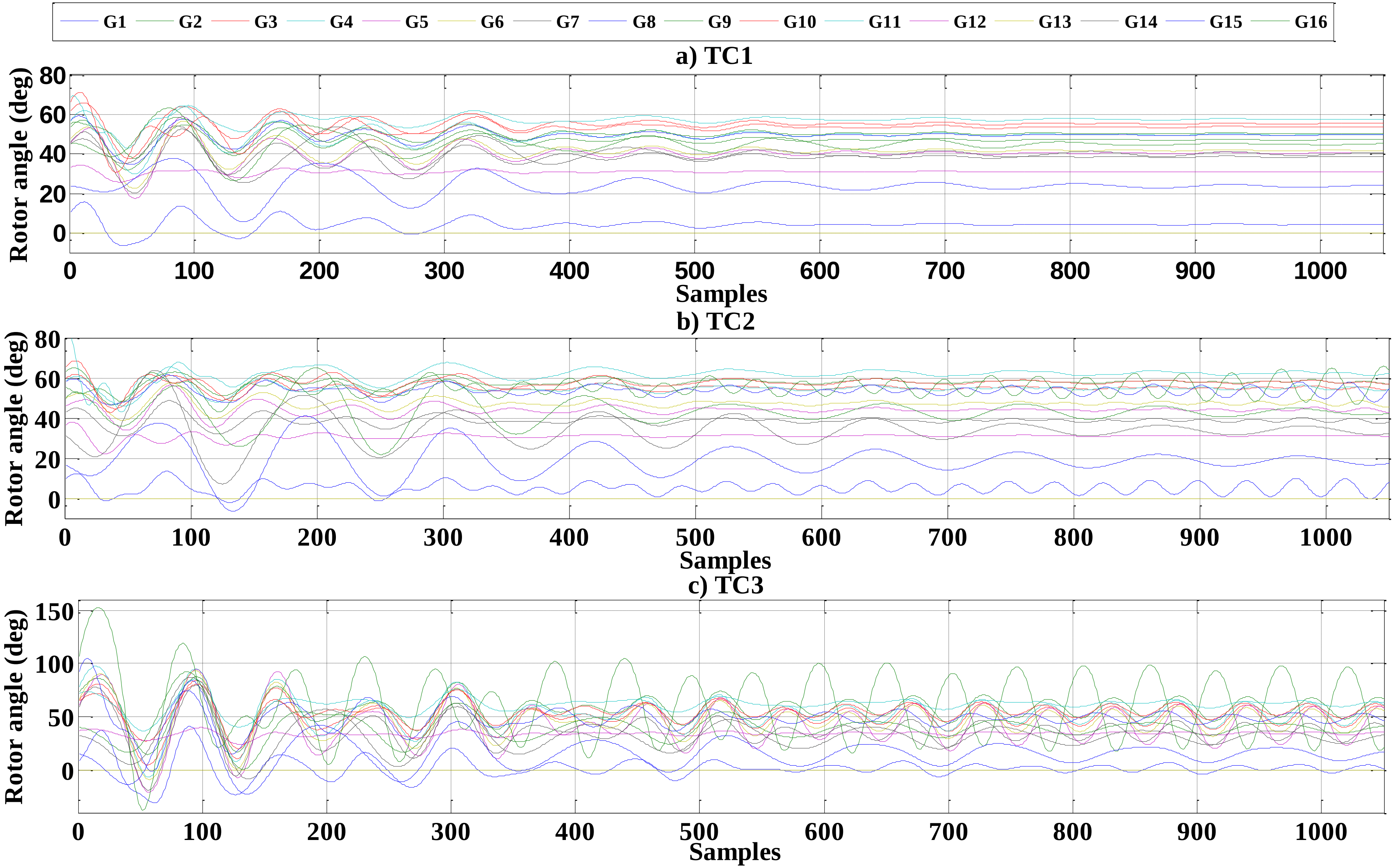
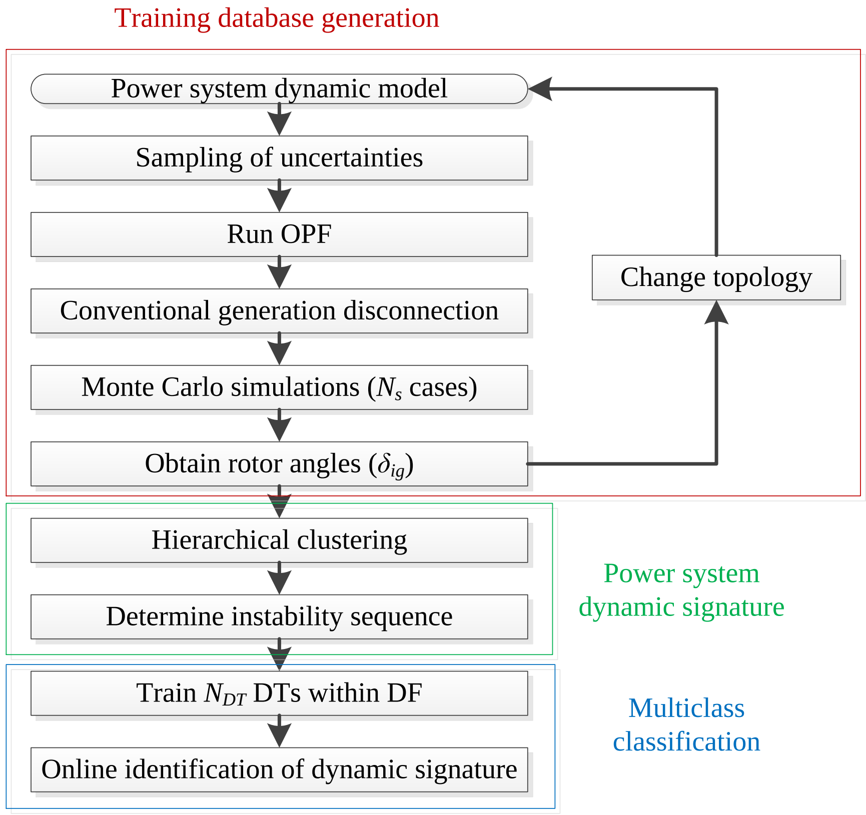


Prediction of impending transient instability close to real time using machine learning

Main contributions

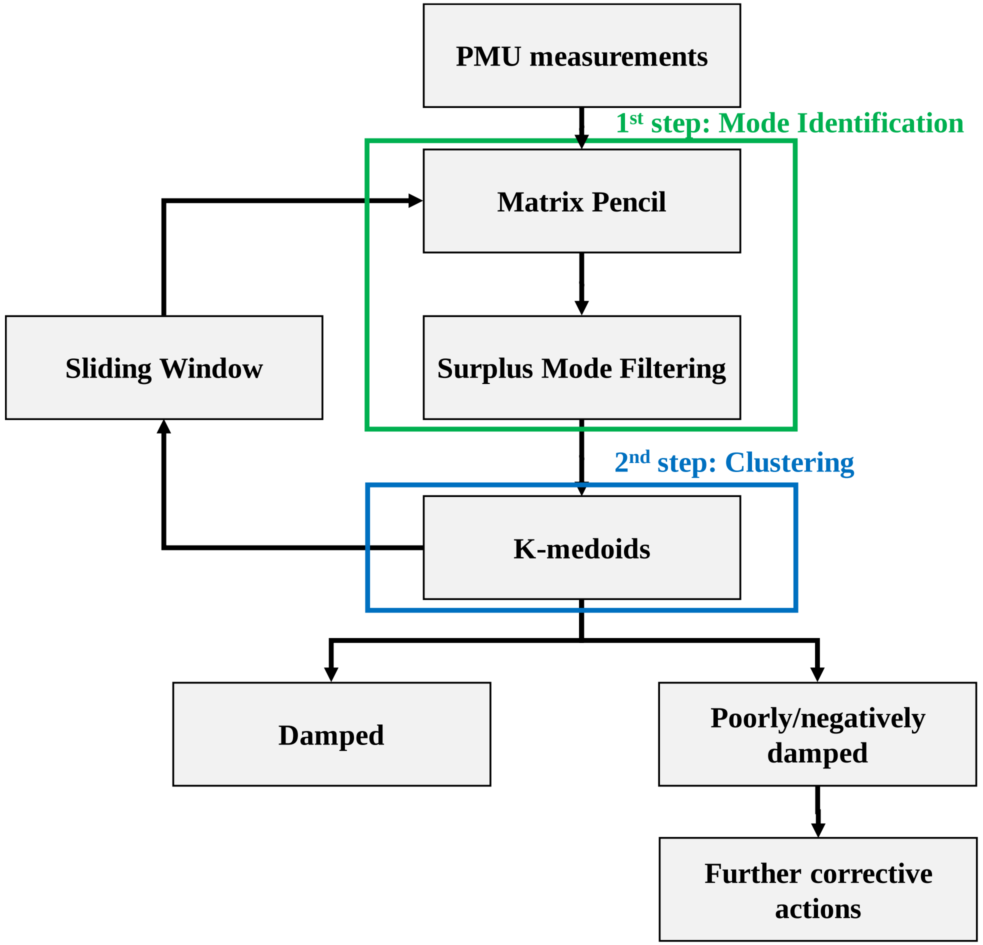
- Impact of renewables and topology changes investigated
  - Decision trees with boosting
- Uncertainty and detailed dynamic behaviour (RMS simulations) considered
- More information for corrective control: Which generators, in what groups and in what order
- We have shown:
  - Detection of exact unstable groups and order of loss of synchronism with >93% accuracy while accounting for renewables and topology changes
  - Detection of instability >97% accuracy
  - Performance drops for faster predictions



P. N. Papadopoulos, T. Guo, J. V. Milanovic, "Probabilistic Framework for Online Identification of Dynamic Behavior of Power Systems with Renewable Generation", IEEE Transactions on Power Systems, vol. 33, no. 1, pp. 45-54, Jan. 2018.

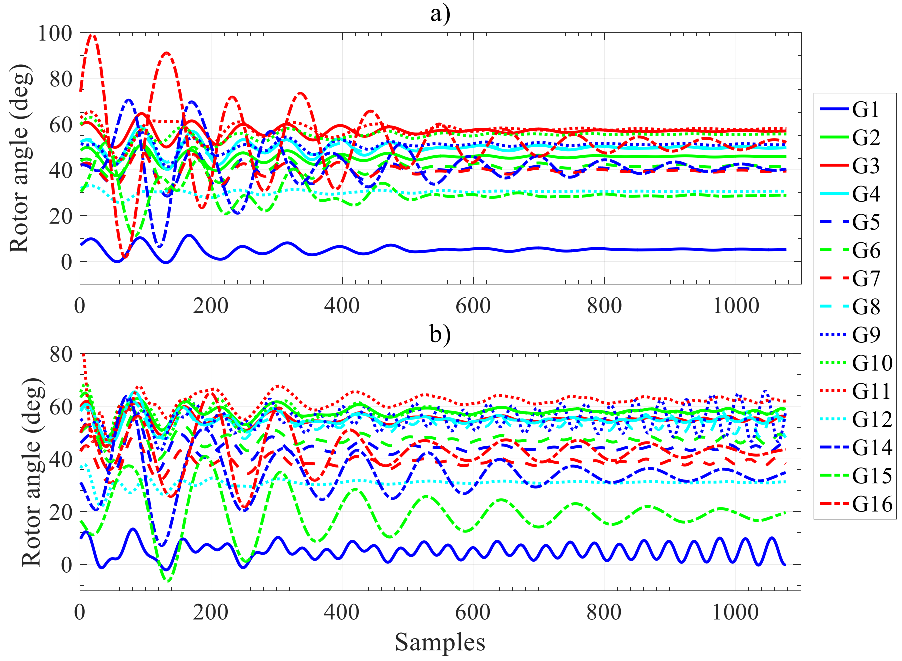
Measurement based oscillatory instability identification

- Measurement based identification of low damped and unstable oscillatory modes
  - Mode identification (matrix – pencil method) and unsupervised machine learning (k-medoids clustering)
- Identify generators that participate in critical or unstable modes
  - Additional information for corrective control
- Practical considerations for real world applications
  - Filtering of “artificial” modes based on energy, moving window
- Probabilistic investigation accounting for large variation in operating conditions

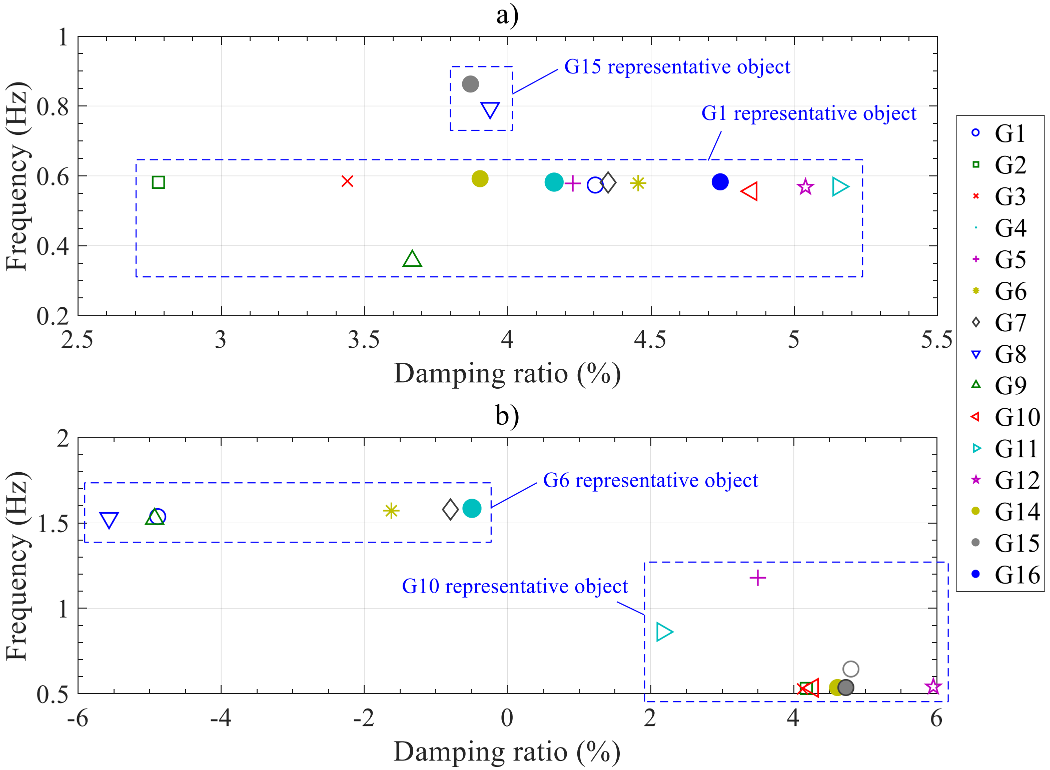


P. N. Papadopoulos, T. A. Papadopoulos, A. I. Chrysochos and J. V. Milanovic, "Measurement based method for online characterization of generator dynamic behaviour in systems with renewable generation," IEEE Transactions on Power Systems, vol. 33, no. 6, pp. 6466-6475, Nov. 2018.

Oscillatory instability

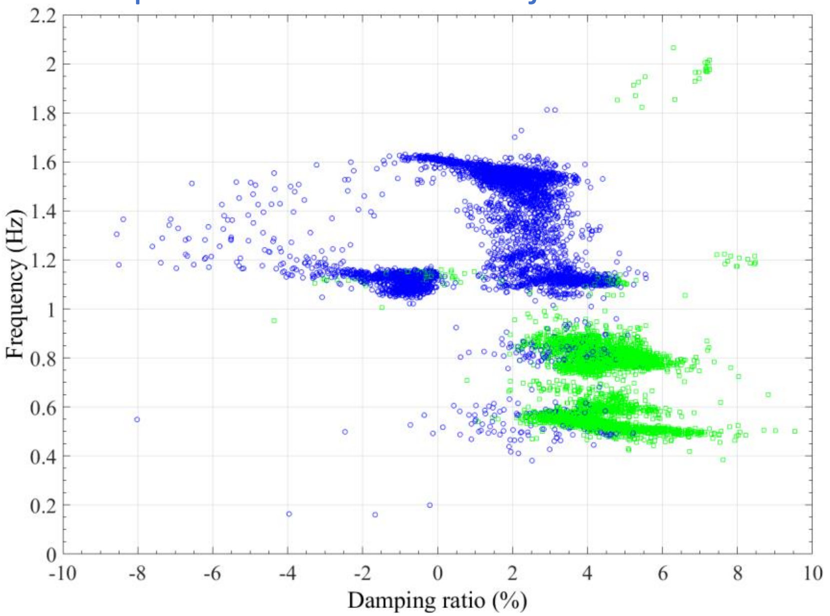


- Cluster centroid: provides representative information for oscillatory behaviour (frequency/damping)

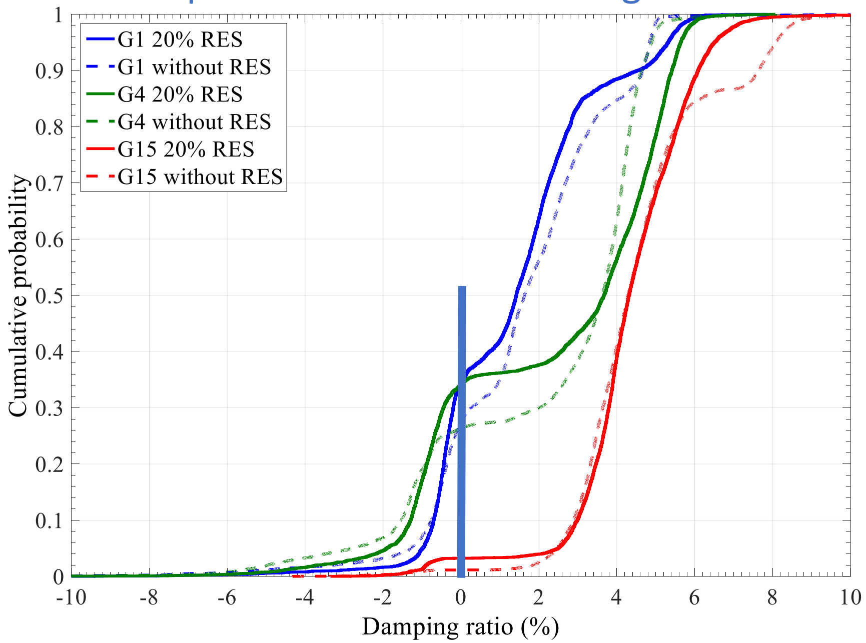


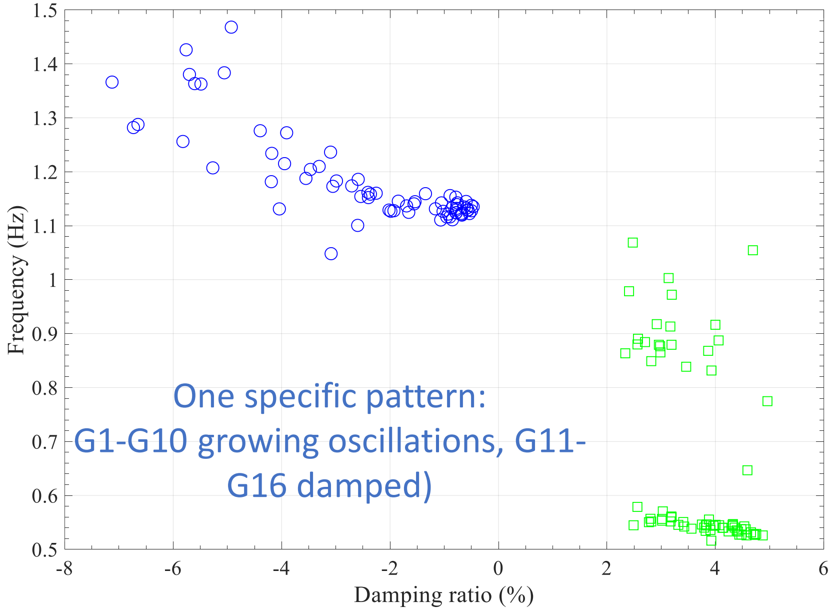
Probabilistic oscillatory stability assessment

Representative cluster objects - all cases



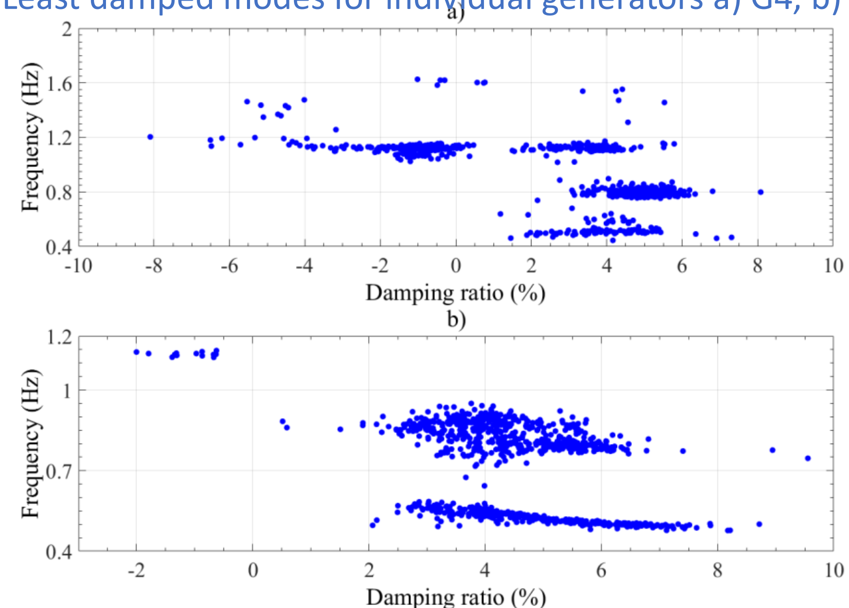
Impact of RES on individual generators





One specific pattern: G1-G10 growing oscillations, G11-G16 damped)

Least damped modes for individual generators a) G4, b) G15



Conclusions

- Probabilistic transient stability assessment important
  - Investigate the overall impact under increased uncertainty and complexity
  - Capturing the detailed dynamic behaviour
  - Capture the effect of a range of operating conditions
  - Quantify risk of instability and enable planning/operational interventions
- Aperiodic and oscillatory stability heavily affected
  - Effect of initial operating conditions, SG disconnection, converter dynamics
  - Implication on security and cost-effective operation
- Use of machine learning for impending instability prediction

Contact details

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Some relevant publications

1. P. N. Papadopoulos, T. Guo, J. V. Milanovic, “Probabilistic Framework for Online Identification of Dynamic Behavior of Power Systems with Renewable Generation”, IEEE Transactions on Power Systems, vol. 33, no. 1, pp. 45-54, Jan. 2018.
2. P. N. Papadopoulos, J. V. Milanović, "Probabilistic Framework for Transient Stability Assessment of Power Systems With High Penetration of Renewable Generation," IEEE Transactions on Power Systems, vol. 32, no. 4, pp. 3078-3088, July 2017.
3. P. N. Papadopoulos, J. V. Milanović, "Methodology for online identification of dynamic behavior of power systems with an increased amount of power electronics interface units," CSEE Journal of Power and Energy Systems, vol. 5, no. 2, pp. 171-180, June 2019.
4. P. N. Papadopoulos, T. Guo, J. V. Milanovic, “Probabilistic Framework for Online Identification of Dynamic Behavior of Power Systems with Renewable Generation”, IEEE Transactions on Power Systems, vol. 33, no. 1, pp. 45-54, Jan. 2018.