Modelling and impact of distributed generation on system dynamics

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- 6 MSc students

Some of them and many (140+) other researchers who worked with me in the past contributed to different extent and at different stages of research to the results presented on the following slides

Overview of the presentation

- New approach to modelling of distributed RES
- The impact of RES on system dynamics
- Examples of
  - probabilistic modelling of RES
  - probabilistic stability studies of power systems with RES
- Summary

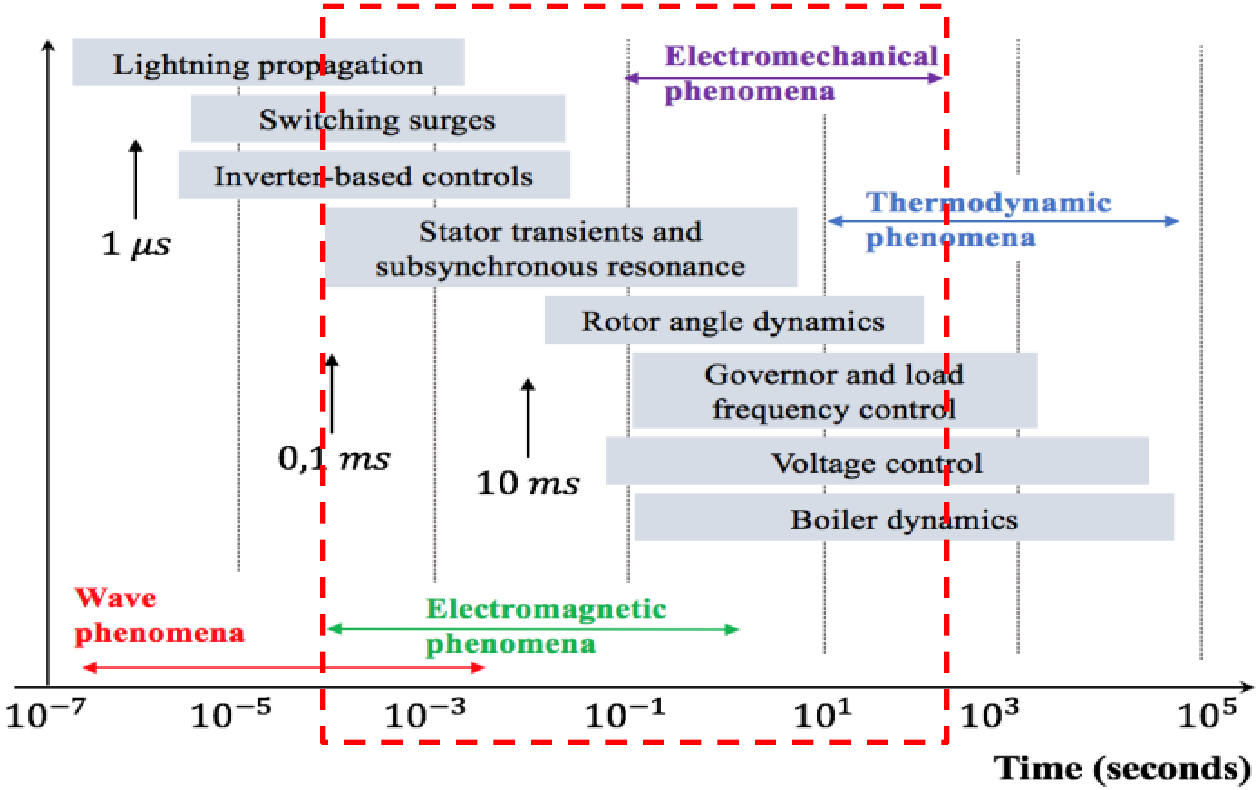
New approach to modelling of distributed RES

The existing power systems are already, and the future ones will be even more, characterised by integration of wide range of integrated, widely distributed generation (majority of which are renewable), storage and demand technologies resulting in

- Reduced/variable inertia leading to different dynamic behaviour following small and large disturbances
- Increased uncertainties in system parameters and operation

Both of these are to a large extent contributed to by increasing penetration of RES

Power system dynamics times scales



N. Hatziargyriou, J. V. Milanović, C. Rahmann,V. Ajjarapu, C. Cañizares, I. Erlich, D. Hill, I. Hiskens, I. Kamwa, B. Pal, P. Pourbeik, J. J. Sanchez- Gasca, A. Stanković, T. Van Cutsem, V. Vittal, C. Vournas, "Definition and Classification of Power System Stability – Revisited & Extended", IEEE Transactions on Power Systems, TPWRS-00907-2020,

IEEE PSDP Task Force Report on "Stability definitions and characterization of dynamic behavior in systems with high penetration of power electronic interfaced technologies", Nikos Hatziargyriou (chair), J. V. Milanović (co-chair), C. Rahmann, V. Ajjarapu, C. Cañizares, I. Erlich, D. J. Hill, I. A. Hiskens, I. Kamwa, B. Pal, P. Pourbeik, J. J. Sanchez- Gasca, A. Stanković, T. Van Cutsem, V. Vittal, C. Vournas, IEEE PES, PES-TR77, April 2020, https://resourcecenter.ieee-pes.org/technical-publications/technical-reports/PES_TP_TR77_PSDP_stability_051320.html ***2021 PSDP Committee WG/TF Award for the report***

Abundance of, and increasing uncertainties

- Network
  - topology, parameters & settings (e.g., tap settings, temperature dependent line ratings)
  - observability & controlability
- *Generation*
  - *pattern (size, output of generators, types and location of generators, i.e., conventional, renewable, storage, RES at distribution level)*
  - *parameters (conventional and renewable generation and storage)*
- Load (time and spatial variation in load, load composition (mix), models and parameters)
- Controls
  - parameters of generator controllers (AVRs, Governors, PSSs, PE interface), network controllers (secondary voltage controller), FACTS devices and HVDC line controllers
- Contractual power flow (consequence of different market mechanisms and price)
- Faults (type, location, duration, frequency, distribution, impedance)
- ICT related uncertainties (noise, measurement errors, time delays, loss of signals, bandwidth)
- Weather/climate related uncertainties (wind speed, wind direction, temperature, solar irradiation, tidal/wave conditions)

Too many uncertainties to justify conventional deterministic modelling

Causes of reduction of “system” inertia

- Proliferation of power electronics interfaced generation technologies both, generators (e.g., wind, PV, fuel cells, micro-turbines) and storage
  - Participation of directly connected synchronous generators (SG) in power/energy production is variable and reducing (on overall annual scale)
  - SGs get disconnected or de-loaded to accommodate RES
  - SGs may continue to remain disconnected for a period of time and replaced by storage (e.g., during the night when PVs get replaced by storage)
- Proliferation of HVDC power lines which (may) decouple AC interconnected system in synchronous islands with reduced inertia
- Proliferation of power electronics interfaced load devices (variable/adjustable speed drives in particular)
  - The inertia of electric motors, though of significantly lower influence than inertia of SG, for system frequency (and dynamic response in general) becomes “invisible” to the system

What is system inertia ?

Inertia is a property or natural tendency of an object to remain at rest or in motion at a constant speed.

The rotational kinetic energy (*KE*) stored in synchronous generators (SG) provides an indication of the "inertia" of a power system. A large rotating mass of SG connected to the grid has stored *KE* given by

$$\boxed{\boldsymbol{KE_{gen}[Ws] = \frac{1}{2} J_{gen}[kgm^2\,](2\pi f_m[mech.rad/s])^2}}$$

The inertia constant of a SG

$$\boxed{H_{gen} = \frac{KE_{gen}}{S_{gen}} \left[\frac{\mathrm{MW\cdot s}}{\mathrm{MVA}}\right]}$$

corresponds to the *KE* of its mass rotating at synchronous speed, and effectively represents the time in seconds the generator could continue to provide the rated power to the network if it gets disconnected from the prime mover.

The question therefore is

Considering evolving power/energy system with increased uncertainties and increased reliance on non-conventional power electronics connected generation technologies are the deterministic tools currently in use for system analysis adequate, and if not, how should we modify them, or what other tools should we be using?

The impact of RES on system dynamics

Key attributes of converter interfaced generation (CIG) affecting system dynamics

- CIGs can provide limited short-circuit current contributions (often ranging from 0 as converter blocks for close in bolted 3-phase faults, to $1.5\ p.u.$ for a fully converter interfaced resource)

- The PLL and inner-current control loop play a major role in the dynamic recovery after a fault. For connection points with low-short circuit ratio, the response of the inner current- control loop and PLL can become oscillatory. (This is due to the PLL not being able to quickly synchronize with the network voltage, and also due to high gains in the inner-current control loop and PLL. This can potentially be mitigated by reducing the gains of these controllers. The exact value of the short circuit strength at which this may occur will vary depending on the equipment vendor and network configuration. A typical range of short-circuit ratios below which this may occur is 1.5 to 2.)

Key attributes of converter interfaced generation (CIG) affecting system dynamics

- The overall dynamic performance of CIGs is largely determined by the dynamic characteristics of the PLL, the inner-current control loop, and the high-level control loops and their design.

With the switching frequency of the power electronic switches typically in the kHz range, and the high-level control loops typically in the range of **1 to 10 Hz**, similar to most other controllers in power systems, CIGs can impact a wide range of dynamic phenomena, ranging from electromagnetic transients to voltage stability, and across both small- and large-disturbance stability.

Effects of CIGs on Rotor Angle Stability

- Changing the flows on major tie-lines, which may in turn affect damping of inter-area modes and transient stability margins

- Displacing large synchronous generators, which may in turn affect the mode shape, modal frequency, and damping of electromechanical modes of rotor oscillations

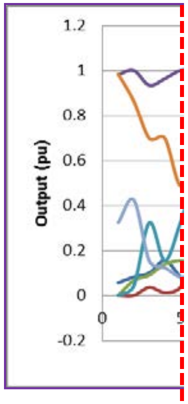
- Influencing/affecting the damping torque of nearby synchronous generators, similar to the manner in which flexible ac transmission (FACTS) devices influence damping .This is reflected in changes in the damping of modes that involve those synchronous generators.

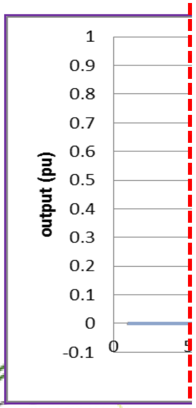
- Displacing synchronous generators that have crucial power system stabilizers.

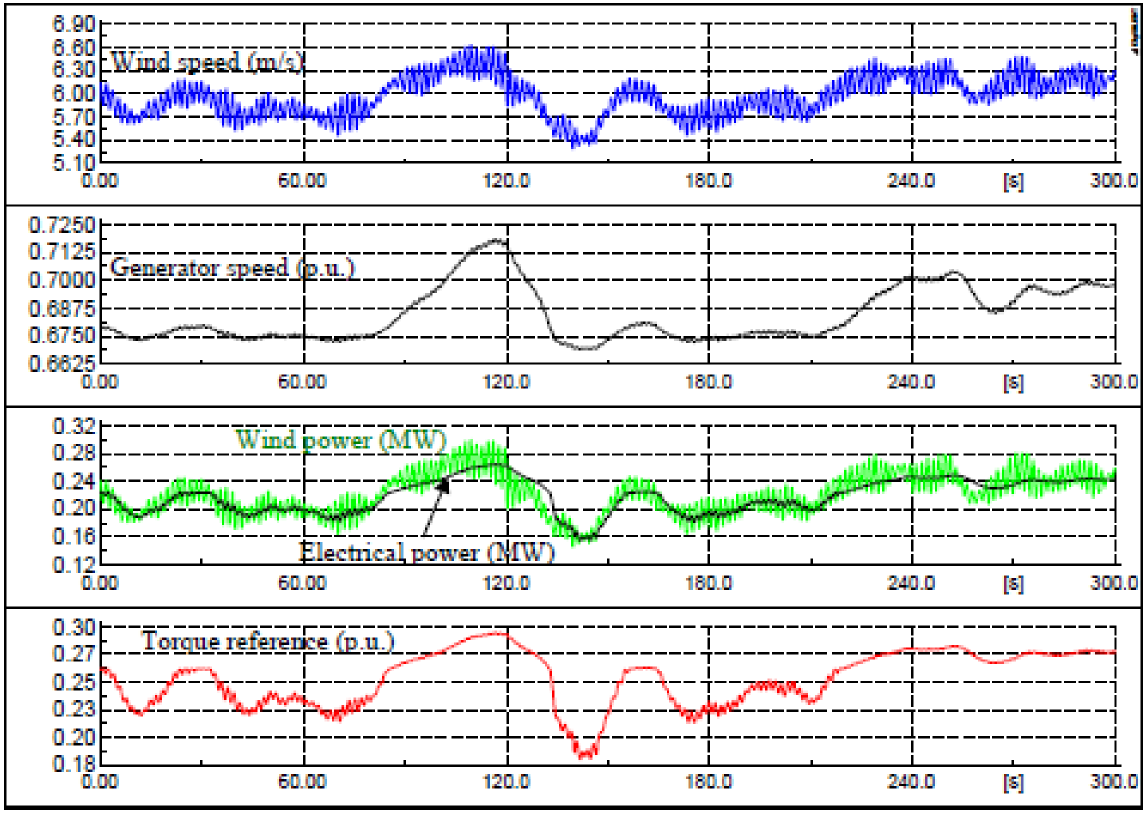
- Different dynamic behavior of RES changes the system dynamic behavior

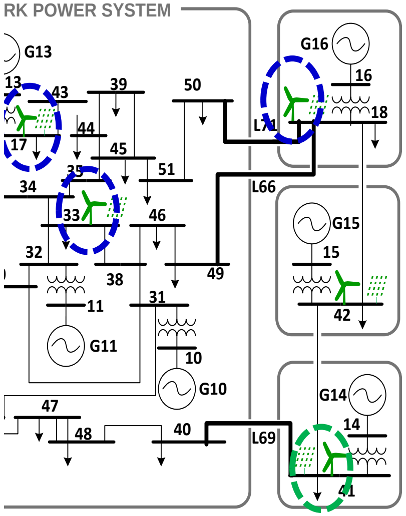
The impact of RES on system dynamics

- Increased uncertainty in the pre-fault operating conditions due to the intermittent behavior of RES and their availability, both temporal and spatial

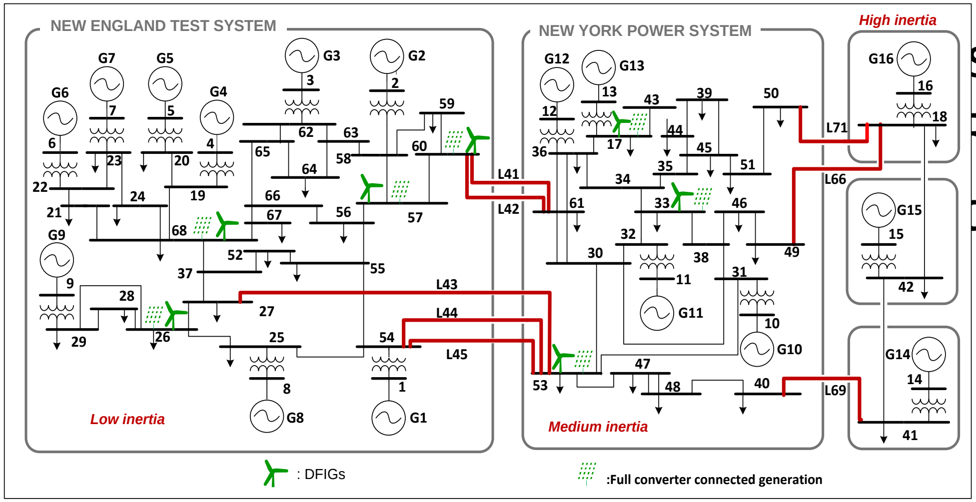








The impact of RES on system dynamics



	NPL NET & NYPS	Average 'H' sec			
		H_{NETS}	H_{NYPS}	H_{Eq}	H_{Sys}
100% loading	0	3.9	7.9	11.1	7.95
100% loading	30%	2.7	5.5	11.1	6.8
60% loading	45%	1.64	3.32	7.8	4.1
40% loading	52%	1.28	2.26	6.6	2.86

$$H_{sys} = \frac{\Sigma_{i=1}^{n} S_i H_i}{\Sigma_{i=1}^{n} S_i}$$

$$PL_a = \frac{\Sigma_{n=1}^{d} P_{RES,in}^{0}}{\Sigma_{m=1}^{g} S_{SG,im} + \Sigma_{n=1}^{d} P_{RES,in}^{0}}$$

Penetration level

$$NPL_a = \frac{\Sigma_{n=1}^{d} P_{RES,n}^{0}}{\Sigma_{m=1}^{g} S_{SG,m} \cdot pf_{SG,m} + \Sigma_{n=1}^{d} P_{RES,n}^{0}}$$

Nominal penetration level

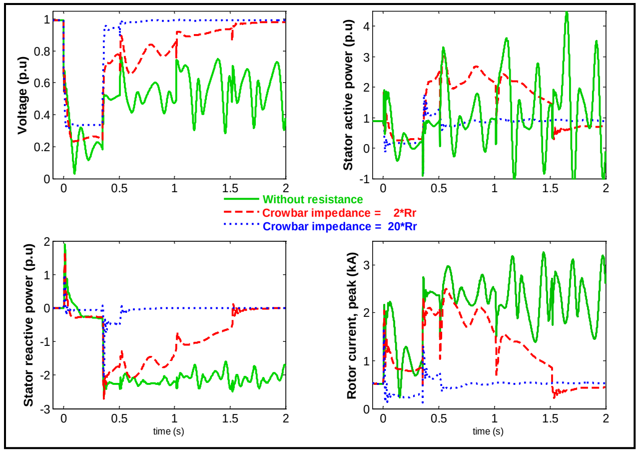
How should be H calculated or estimated considering different definitions of "penetration level"

$$INPL_a = \frac{\Sigma_{n=1}^{d} P_{RES,in}^{0}}{\Sigma_{m=1}^{g} P_{SG,im} + \Sigma_{n=1}^{d} P_{RES,in}^{0}}$$

Instantaneous penetration level

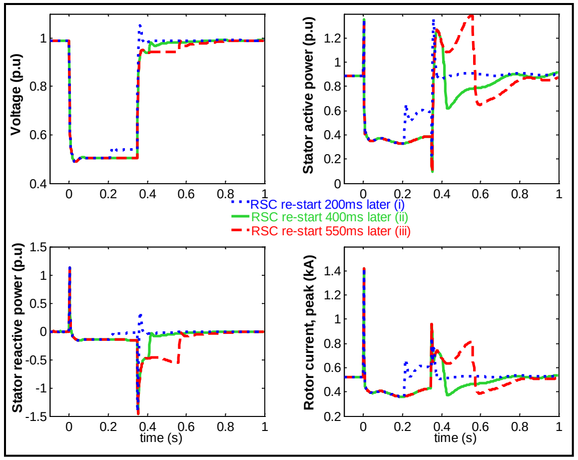
The impact of RES on system dynamics

- Different dynamic behavior of RES changes the system dynamic behavior



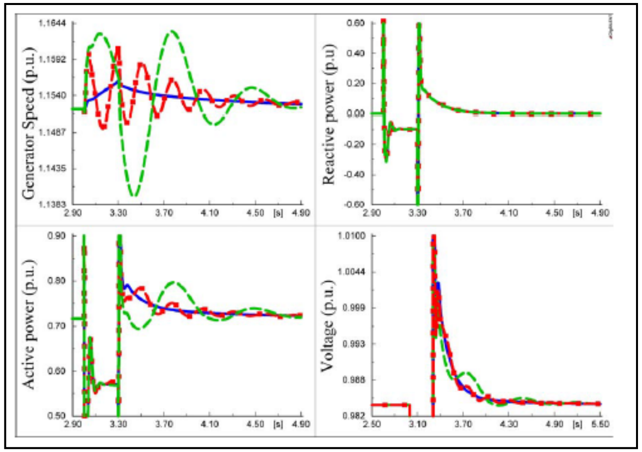
DFIG response to a short-circuit for different crowbar impedances

(Solid – no crowbar impedance, Dashed – 2Rr, Dotted – 20Rr)



DFIG response to a 350ms short-circuit for different RSC restart times.

(RSC is re-started; Dotted – 200ms, Solid – 400ms, Dashed – 550ms after the fault clearance.)

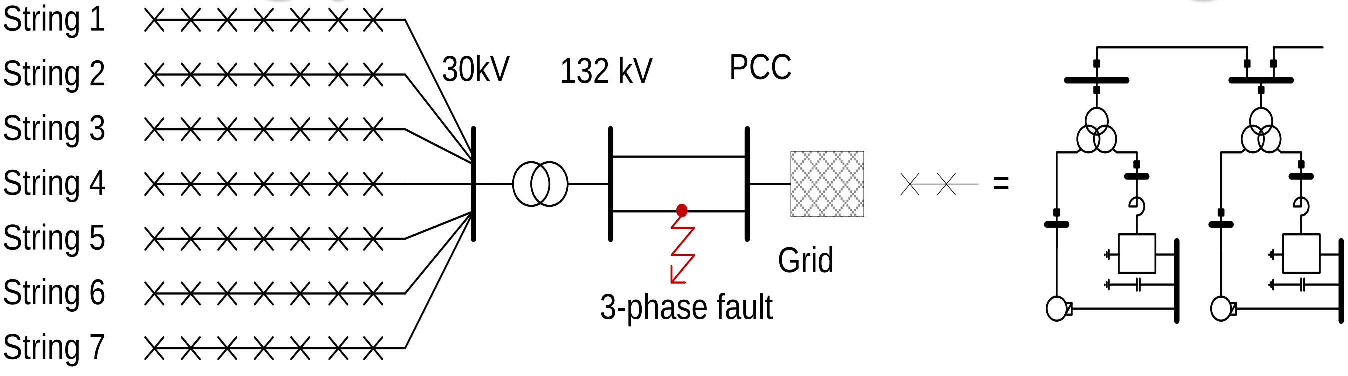


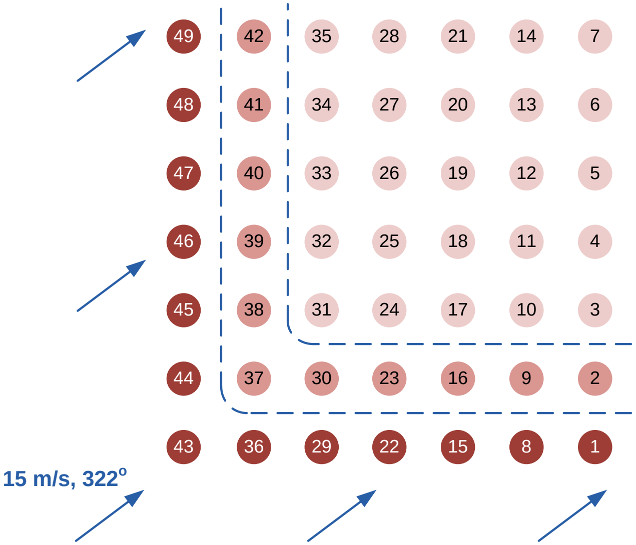
Influence of shaft stiffness on DFIG responses to a 3-phase fault.

(Dash-dot – Original case (K_s = 2.1 p.u/rad), Dashed – Soft shaft (K_s = 0.3 p.u/rad), Solid – Lumped mass)

Examples of probabilistic modelling of RES

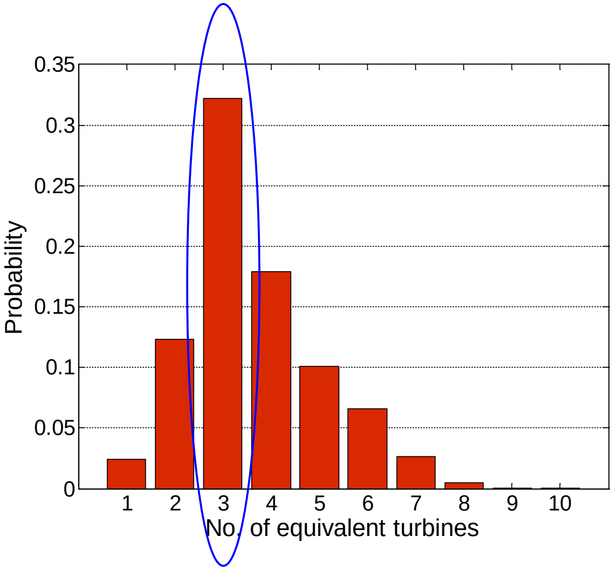
Dynamic equivalent models of Wind farm using probabilistic clustering





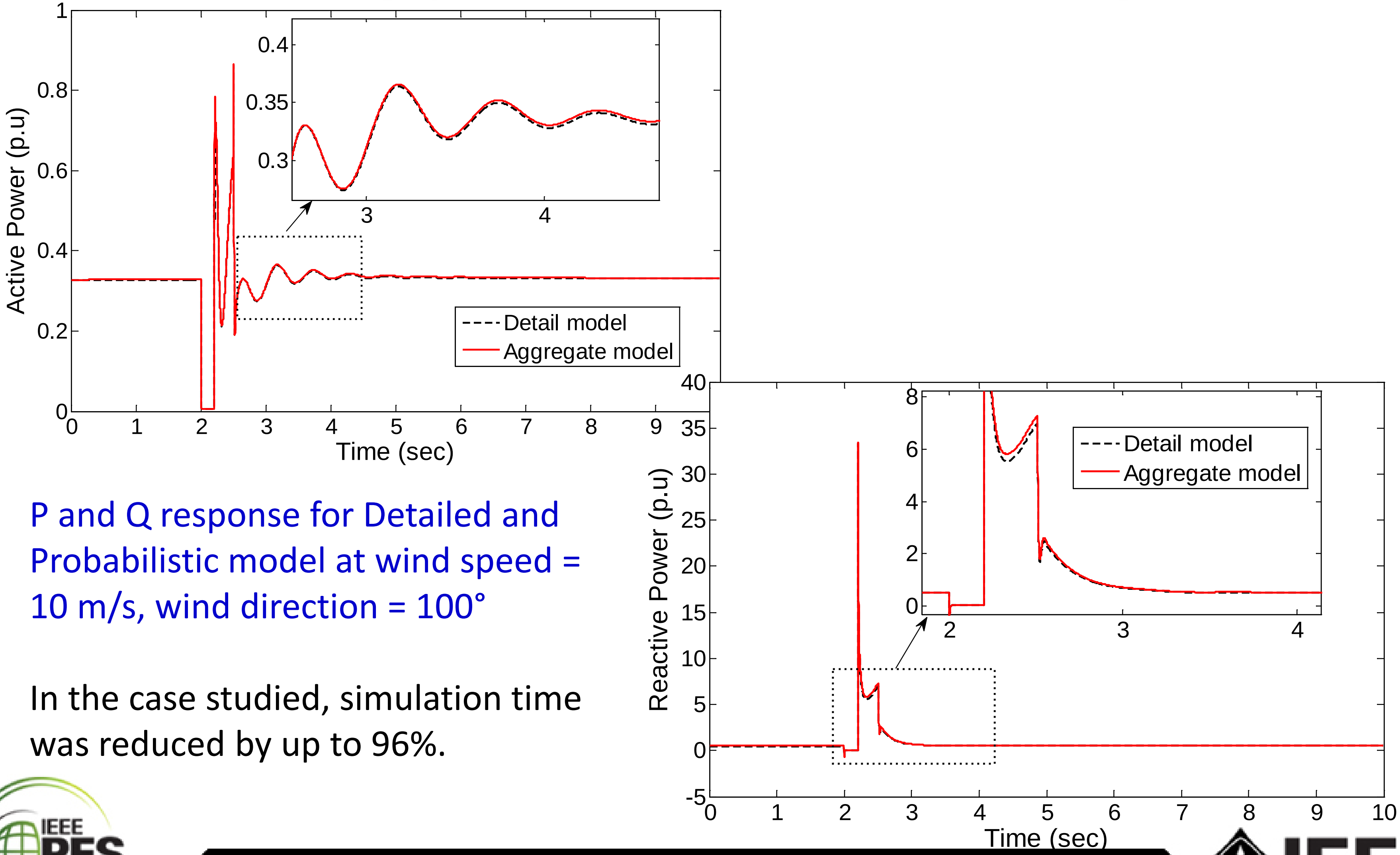
Wind speed variation inside a wind farm at 15 m/s, 322°

Support Vector Machine (SVM) based clustering



Probability of equivalent turbines needed to represent the WF

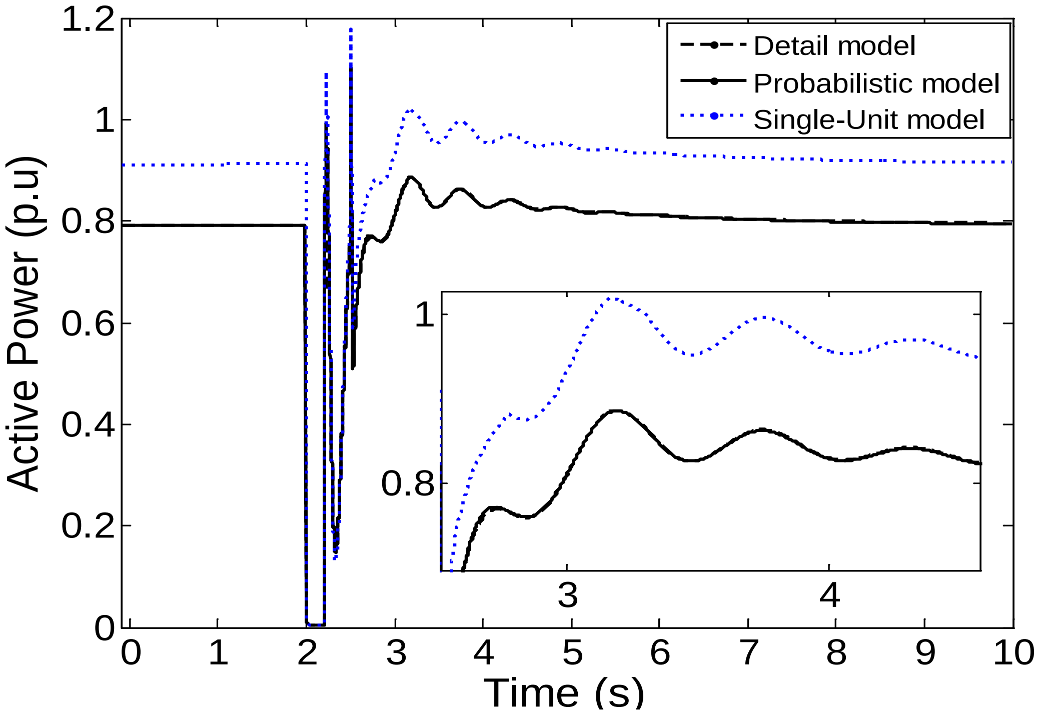
Dynamic equivalent models of Wind farm using probabilistic clustering



P and Q response for Detailed and Probabilistic model at wind speed = 10 m/s, wind direction = 100°

In the case studied, simulation time was reduced by up to 96%.

Dynamic equivalent model of Wind farm using probabilistic clustering



P and Q response for Detailed , Probabilistic and single unit model at wind speed WS = 12 m/s, WD = 349°

Both P and Q are **over-estimated** by the single-unit model as it ignores variation in wind speed (received by individual turbines)due to wake effects (pre-disturbance operating point is the major cause of difference in responses)

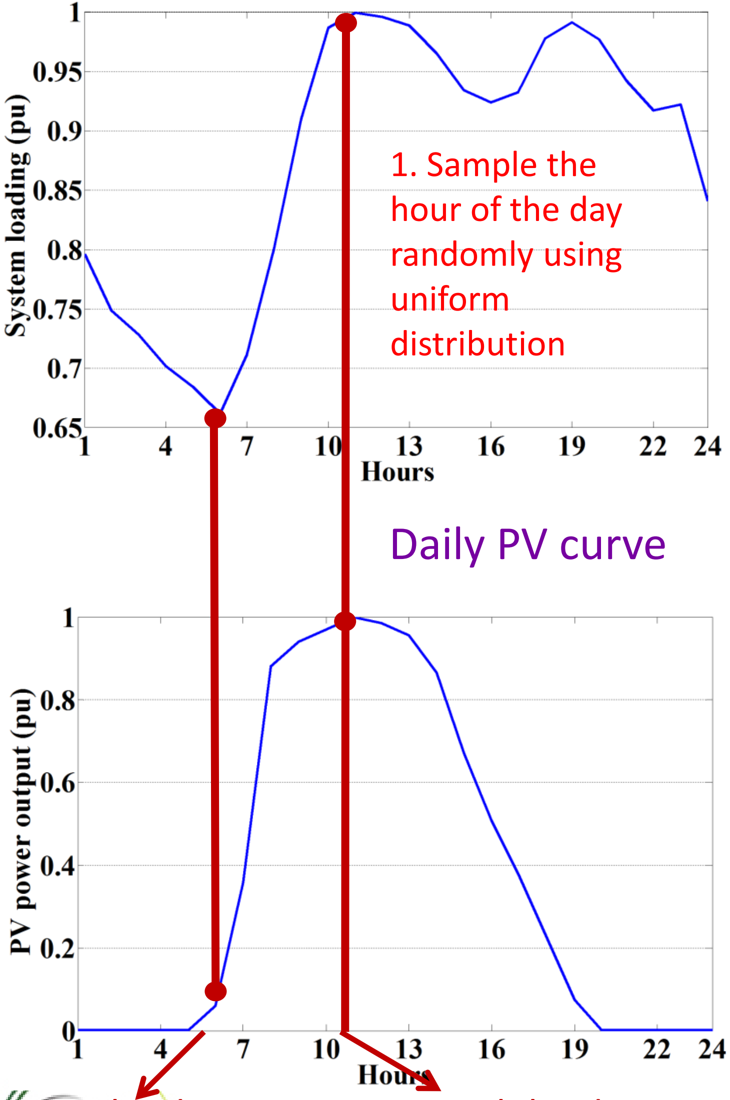
Single-unit equivalent model is generally most suitable for simulating wind farm behavior at **full wind speed only.**

This modelling approach **does not require** changes in equivalent model every time the wind speed or direction changes.

Modelling RES uncertainty

Daily load curve

Daily PV curve



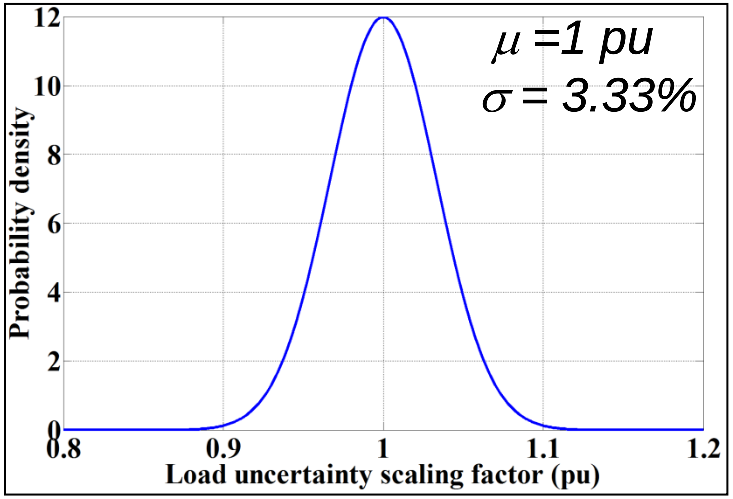
1. Sample the hour of the day randomly using uniform distribution

Low loading

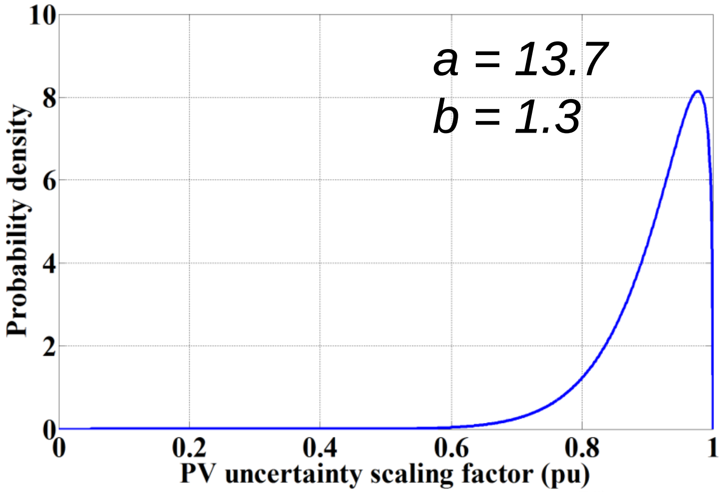
High loading

2. Model associated uncertainties using corresponding distribution

Load scaling factor – normal distribution



Beta distribution – PV power output



Modelling RES uncertainty –

when uncertainty within a day is considered

- Wind Generation
  - the mean value of the wind speed within one day is considered constant,
  - the uncertainty of the wind speed is modelled using a Weibull distribution (φ =11.1, k=2.2)
  - After considering the wind speed uncertainty, the power curve of a typical wind generator is used to derive the power output.
- All distributions are sampled separately for each load and RES unit in the system. Therefore, independent random variables are used for each specific load and RES.
- After considering the uncertainties, OPF is solved to determine the conventional generators dispatch for the specific test network.
  - The disconnection of conventional generation due to both load variations and RES penetration is considered by adjusting the nominal apparent power of each generator. (Since the generators are considered equivalent generators, reducing the nominal apparent power, is equivalent to a reduction in the moment of inertia of the power plant and an increase in the generator reactance.)

Modelling RES uncertainty –
for a specific mean loading level (e.g. within 1 hour)

- When studies are performed for a specific mean value of loading level (e.g. 1pu, 0.6 pu, 0.5 pu) the daily loading and PV curves are not used.
- The load uncertainty is still considered to follow a normal distribution
- The PV uncertainty is considered to follow a beta distribution (assumption is that there is nominal PV production for this time of the day but this can be scaled accordingly for different scenarios).
- For wind generation a normal distribution is used instead of a Weibull distribution assuming generation for this time of the day derived from Weibull distribution

Examples of probabilistic stability studies of power systems with RES

Required number of Monte Carlo simulations

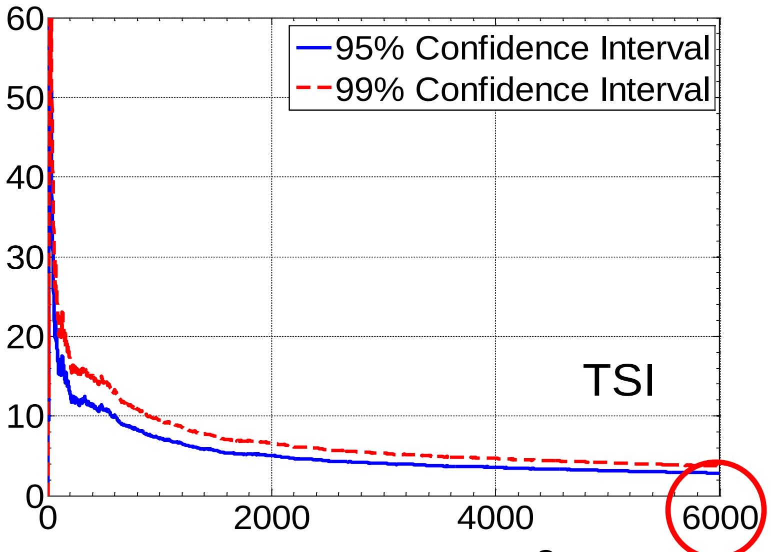
The number of simulations should be chosen to ensure **that the error of the sample mean is below certain threshold,** e.g., 5% (or 1%) , for 99% confidence interval, considering the sampled random variable. The higher the standard deviation of the generated outputs with respect to its mean value, the larger the number of simulations will be required to meet a specific level of error.

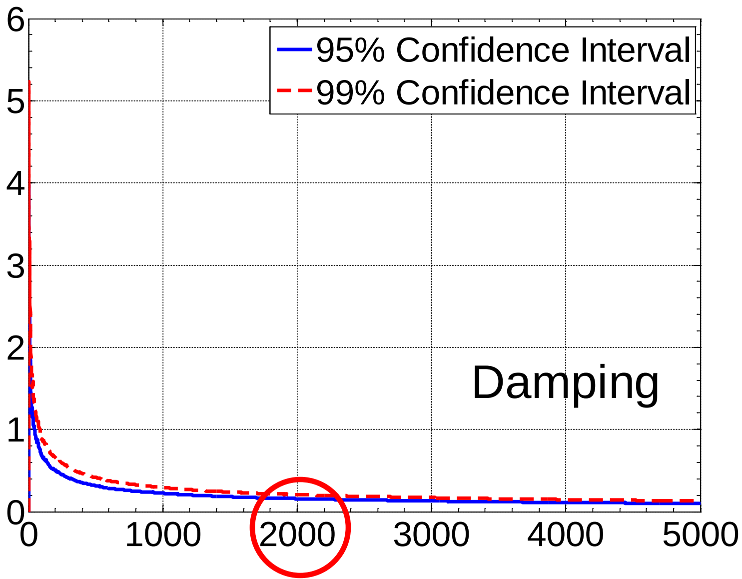
$$e_{\bar{X}_N} = \frac{\Phi^{-1}\left(1-\frac{\delta}{2}\right)\sqrt{\frac{\sigma^2(X_N)}{N}}}{X_N}$$

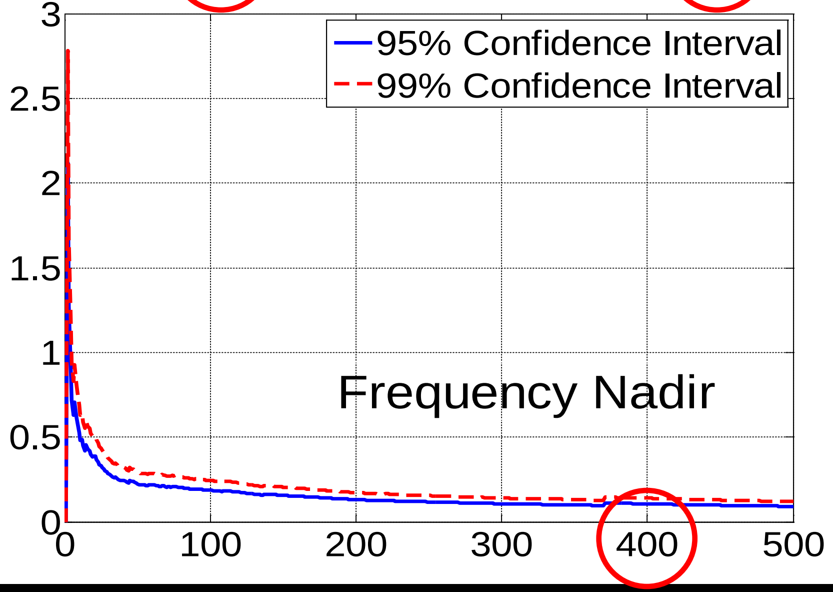
Φ^{-1} - the inverse Gaussian CDF with a mean of zero and standard deviation one,
σ^2 - the variance of the sampled random variable,
δ - the confidence level
X_N - the sampled random variable
N - number of samples

A confidence interval (CI) of a confidence level of 99% indicates the range of values calculated from the data set, which includes the true value of estimation of the data set with the highest probability. It indicates the precision of estimation/prediction of a certain method, and the measure of precision is described as the margin of error.

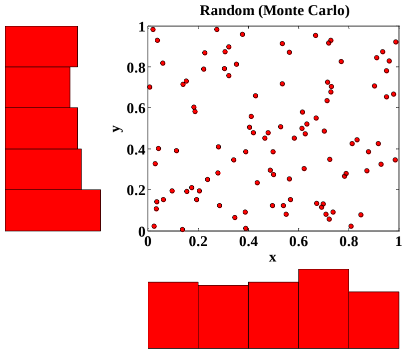
Required number of Monte Carlo simulations

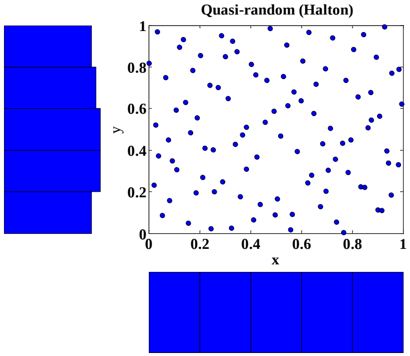




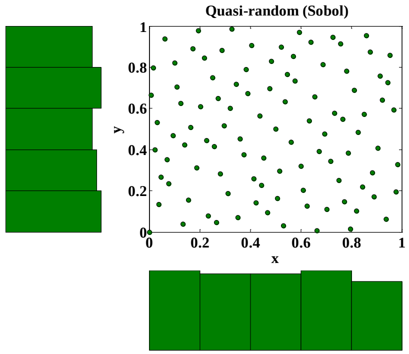


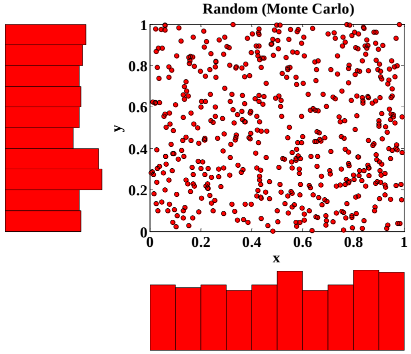
Random and Quasi-random sampling

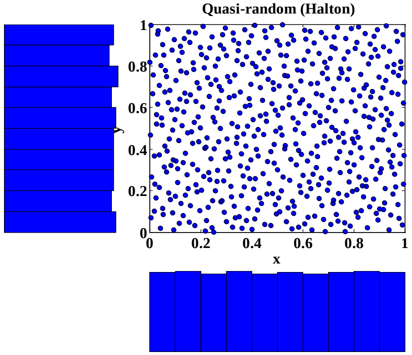

Random (Monte Carlo)


Quasi-random (Halton)

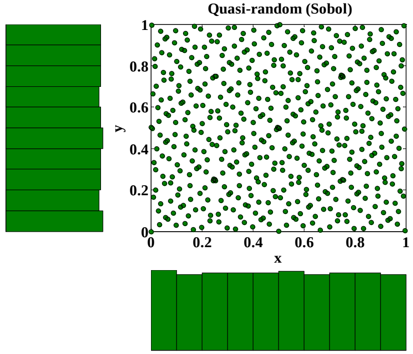
100 samples

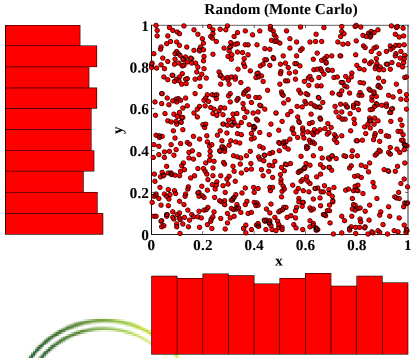

Quasi-random (Sobol)

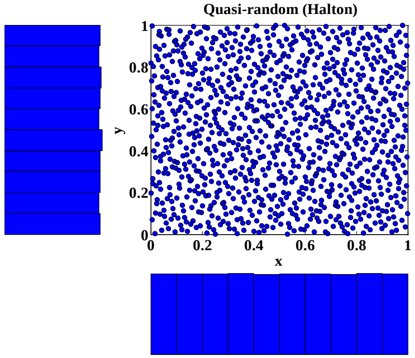

Random (Monte Carlo)


Quasi-random (Halton)

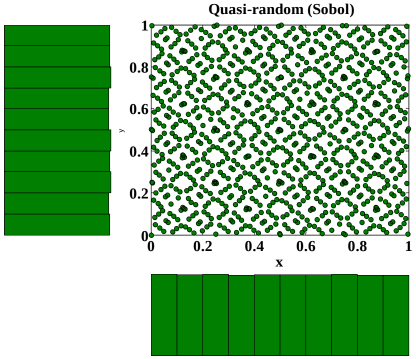
500 samples


Quasi-random (Sobol)


Random (Monte Carlo)


Quasi-random (Halton)

1000 samples


Quasi-random (Sobol)

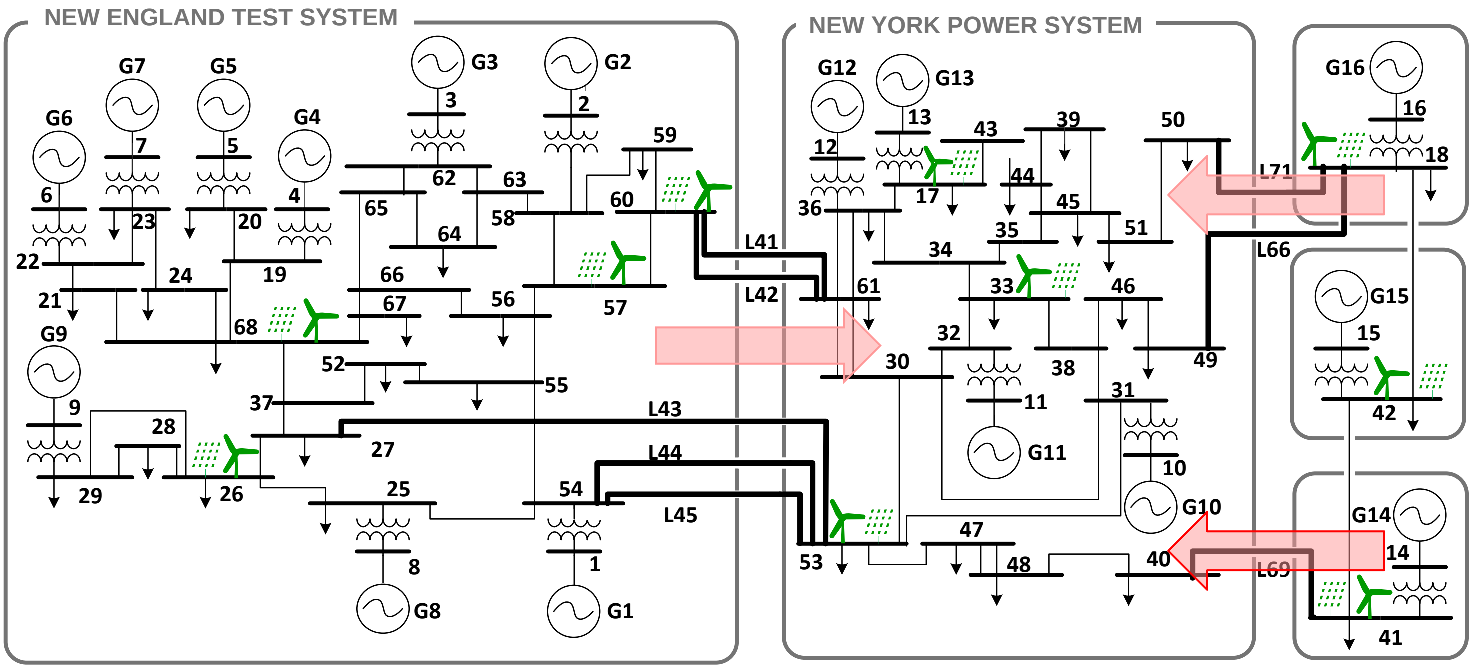
Random (Monte Carlo)

and

Quasi-random (Halton and Sobol)

samples with corresponding histograms

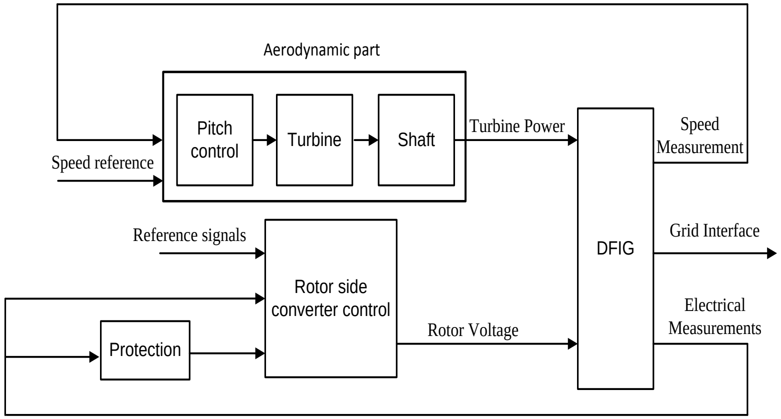
Probabilistic Stability Assessment with RES



The number of simulations (6000) is chosen by keeping the error of the sample mean up to 5%, for 99% confidence interval, considering the TSI as the random variable.

Modelling of DFIG

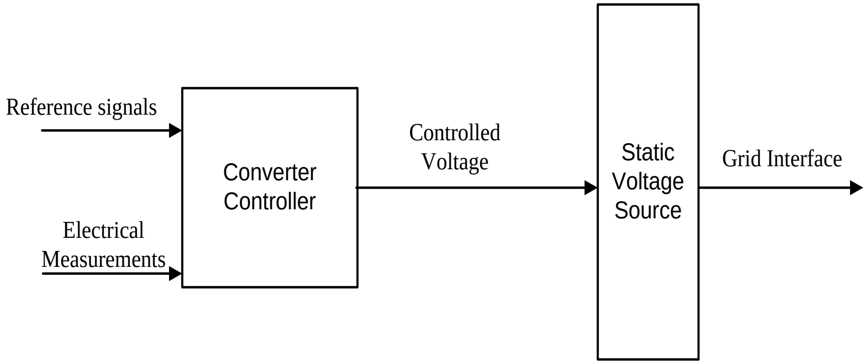
A Generic Type 3 model, suitable for large scale stability studies is used.



- The model has a structure proposed by WECC and IEC , as and is available in DIgSILENT-PowerFactory *(WECC Wind Power Plant Dynamic Modeling Guide, WECC Renewable Energy Modeling Task Force, January 2014.; Wind turbines - Part 27-1: Electrical simulation models - Wind turbines, IEC 61400-27-1, 2015.)*
- It takes into consideration the aerodynamic part and the shaft of the wind turbine/generator as well as the pitch control of the blades.
- The rotor side converter controller is also modeled including relevant limitations, ramp rates and protection mechanisms, such as the crowbar.
- The DFIG is represented by a typical 2nd order model of an induction machine neglecting the stator transients and including the mechanical equation.
- The rotor side converter is controlling the voltage in the rotor.

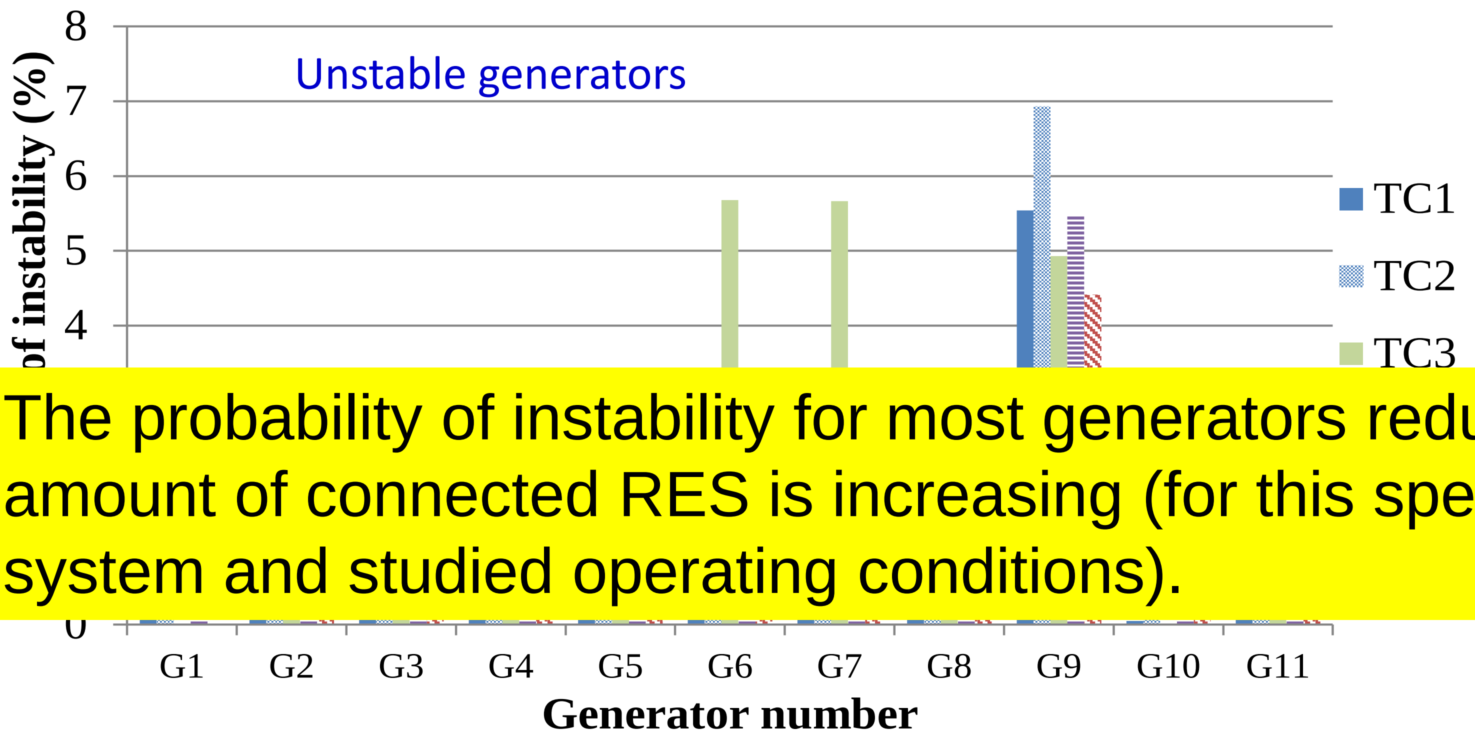
Modelling of full converter connected CIGs

A generic Type 4 wind generator model is used to represent all FCC units. Both wind generators and PV units can be represented by a type 4 model in stability studies, since the converter can be considered to decouple the dynamics of the source on the dc part. This is also suggested by the WECC Renewable Energy Modeling Task Force which develops a PV model by slightly modifying the Type 4 wind generator model. (WECC PV Power Plant Dynamic Modeling Guide, WECC Renewable Energy Modeling Task Force, May 2014.)



The FCC model has a similar structure to WECC model and is available in the DIgSILENT – PowerFactory software. *(WECC Wind Power Plant Dynamic Modeling Guide, WECC Renewable Energy Modeling Task Force, January 2014.; Wind turbines - Part 27-1: Electrical simulation models - Wind turbines, IEC 61400-27-1, 2015.)*

Probabilistic Transient Stability Assessment



The probability of instability for most generators reduces as the amount of connected RES is increasing (for this specific system and studied operating conditions).

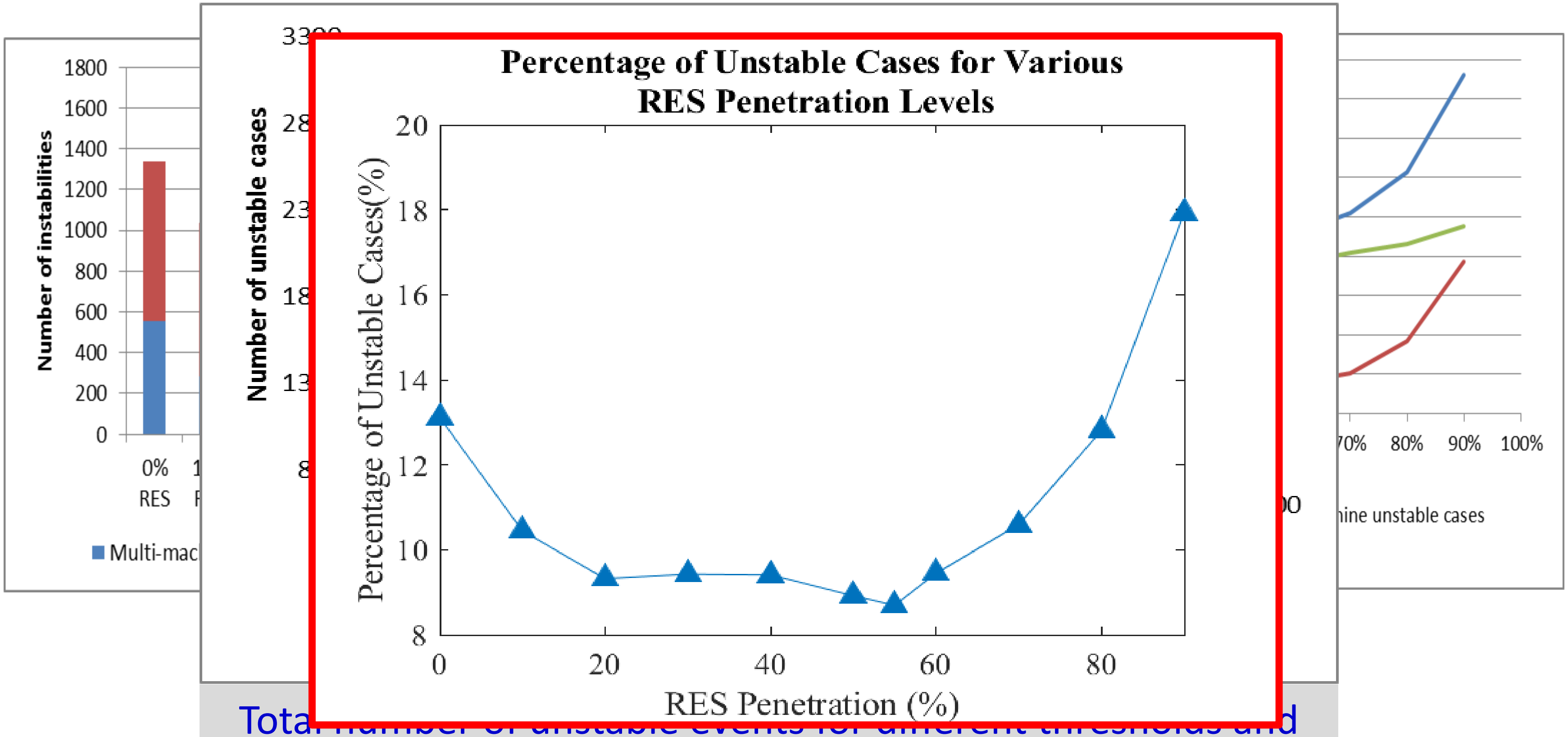
TC1 – all lines in service and low RES penetration

TC2 - all RES units are disconnected

TC3 & TC4 - low RES penetration but lines 1 (between bus 21 and 68) and 2 (between bus 33 and 38) of NETS and NYPS are disconnected, respectively

TC5 - high RES penetration

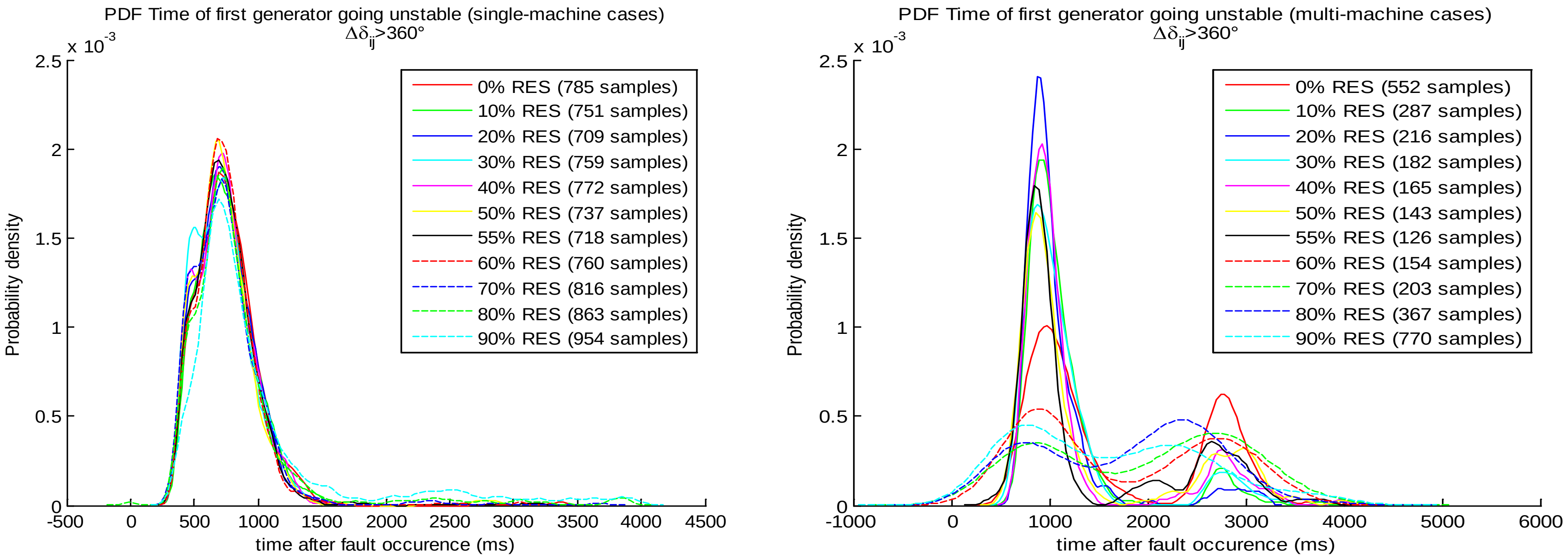
Probabilistic Transient Stability Assessment



Total number of unstable events for different thresholds and RES penetration levels

Number of unstable cases out of 10 000 MC simulations for different penetration levels.

Probabilistic Transient Stability Assessment



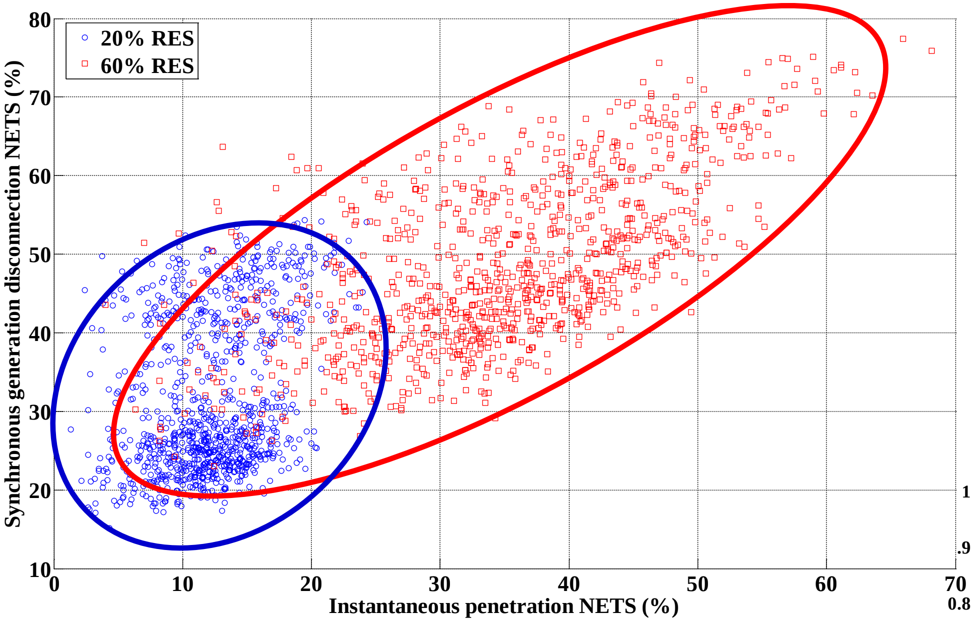
PDF Time of first generator going unstable (single-machine cases) $\Delta\delta_{ij}>360°$

PDF Time of first generator going unstable (multi-machine cases) $\Delta\delta_{ij}>360°$

PDFs of the time to instability of the first generator losing synchronism, single-machine unstable and multi-machine unstable cases, all %RES scenarios

Conventional generation disconnection

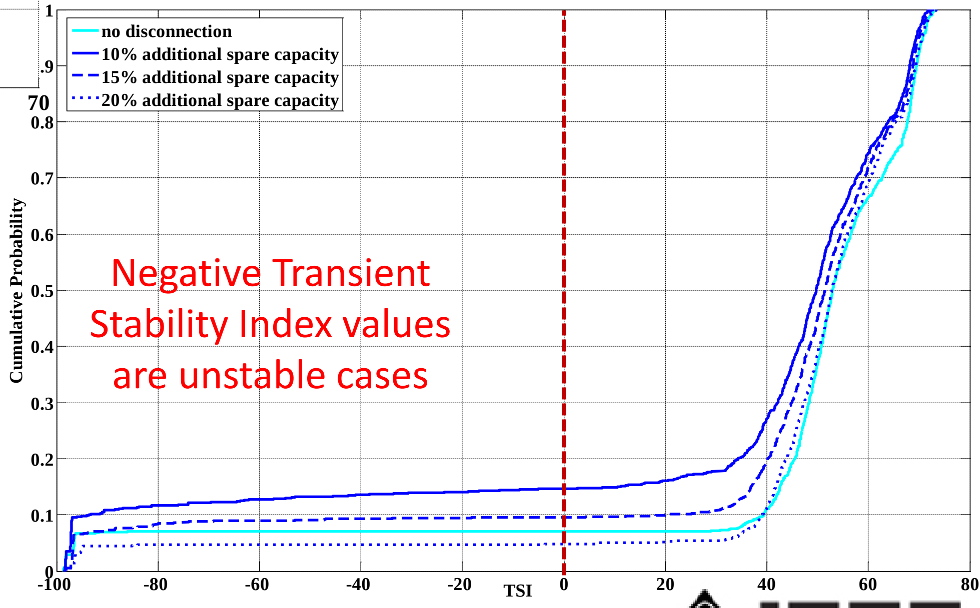
Penetration level and syn. gen. disconnection



- Larger penetration (60% vs. 40%) leads to larger variation in syn. gen. disconnection

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

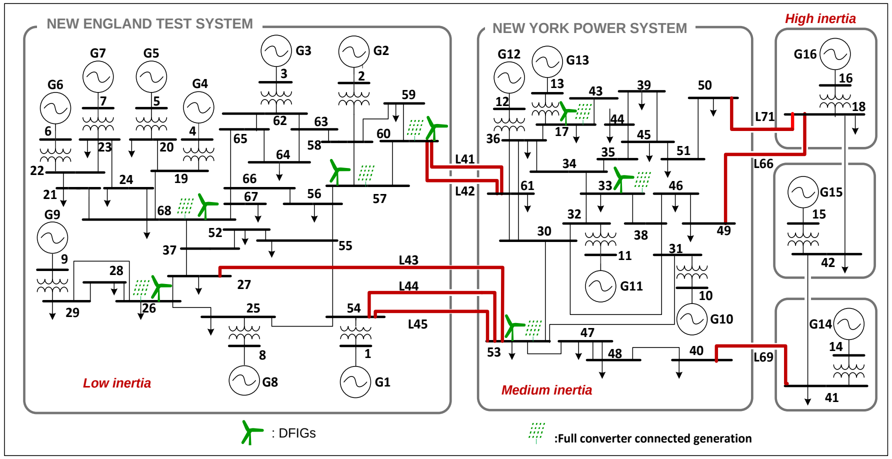
Effect of syn. Gen. disconnection on TSI



Negative Transient Stability Index values are unstable cases

Additional spare capacity of SG important for maintaining transient stability - The probability of instability increases with reduction in spare capacity from approximately 4.8% to 14.7% for spare capacity 20%, and 10%, respectively

Probabilistic frequency stability response of reduced inertia systems



	NPL	Average 'H' sec			
	NET & NYPS	H_{NETS}	H_{NYPS}	H_{Eq}	H_{Sys}
Study case i	**0**	**3.9**	**7.9**	**11.1**	**7.95**
Study case ii (nominal loading)	**30%**	**2.7**	**5.5**	**11.1**	**6.8**
Study Case iii (60% loading)	**45%**	**1.64**	**3.32**	**7.8**	**4.1**
Study Case iv (40% loading)	**52%**	**1.28**	**2.26**	**6.6**	**2.86**

OC1 - The nominal loading of the network

OC2 - 60% loading of the network

OC3 - 40% loading of the network

$$H_{sys} = \frac{\Sigma_{i=1}^{n} S_i H_i}{\Sigma_{i=1}^{n} S_i}$$

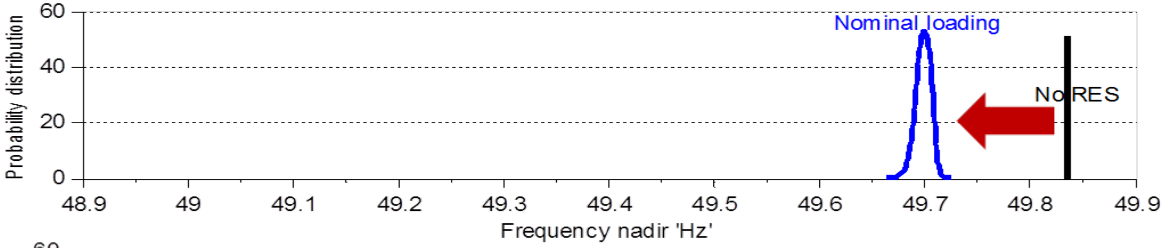
$$NPL_a = \frac{\Sigma_{n=1}^{d} P_{RES,n}^{0}}{\Sigma_{m=1}^{g} S_{SG,m} \cdot pf_{SG,m} + \Sigma_{n=1}^{d} P_{RES,n}^{0}}$$

nominal penetration level

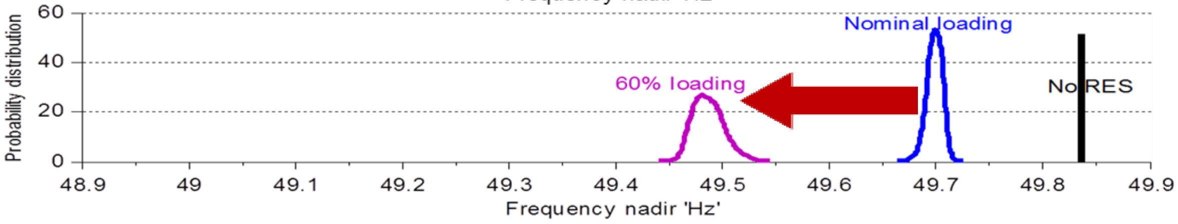
Effect of reduction in inertia

No RES in the network	**System inertia:** 7.95
30% RES in the network	**System inertia:** 6.83 s (-14%)
46% RES in the network	**System inertia:** 4.14 s (-48%)
52% RES in the network	**System inertia:** 2.83 s (-64%)

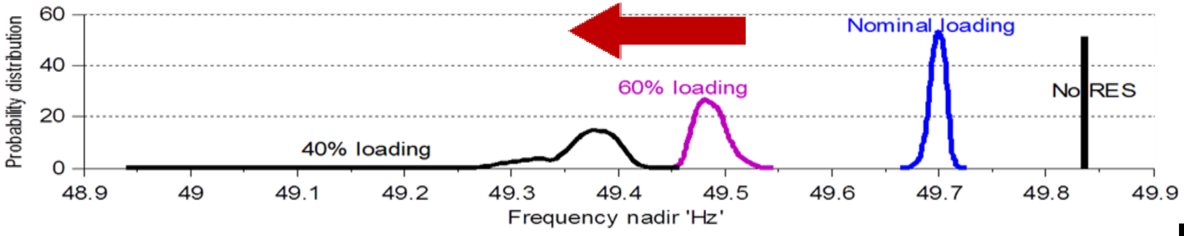
Active power disturbance: simultaneous outage of G2, G7 and G10



Frequency nadir drops from 49.84 Hz to 49.7 Hz (0.14 Hz)



Most probable value drops from 49.7 Hz to 49.47 (0.23 Hz)



Most probable value drops from 49.48 Hz to 49.38 (0.1 Hz)

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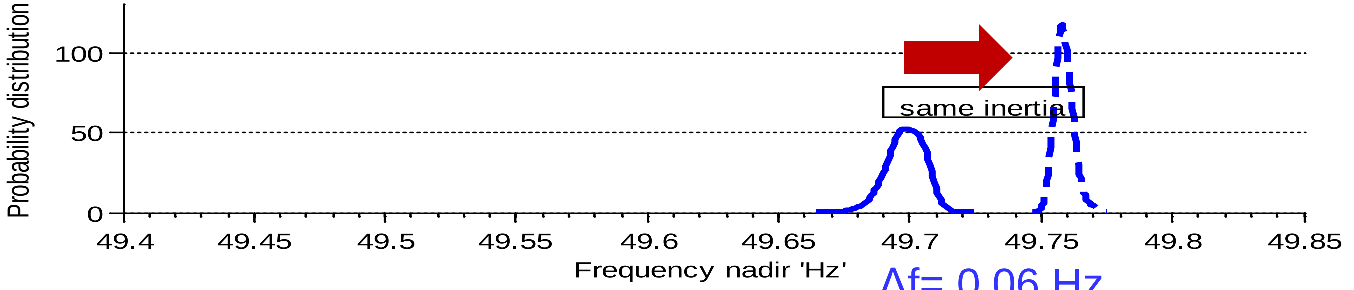
Effect of spinning reserves

30% RES Nominal loading **H=**6.83 s

30% RES 60% loading **H=**6.83 s Spinning reserve increases by 1500 MW (200%)

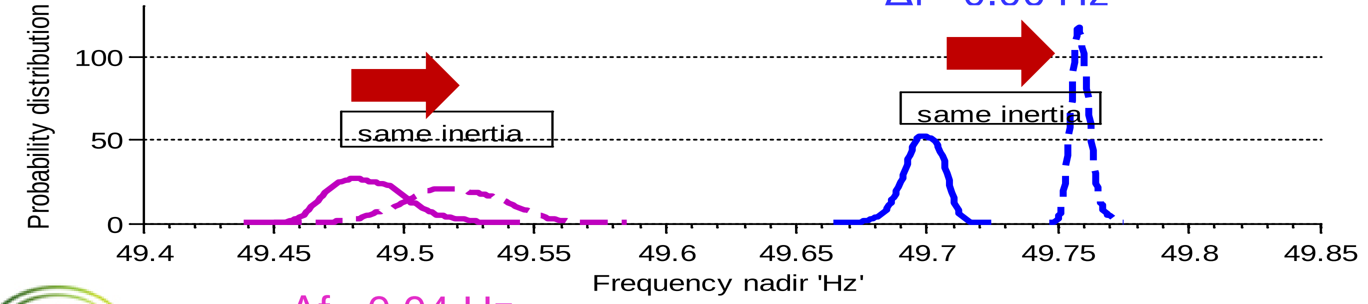
46% RES 60% loading **H=**4.13 s

46% RES 40% loading **H=**4.13 s Spinning reserve increases by 1700MW (325%)



Δf= 0.06 Hz

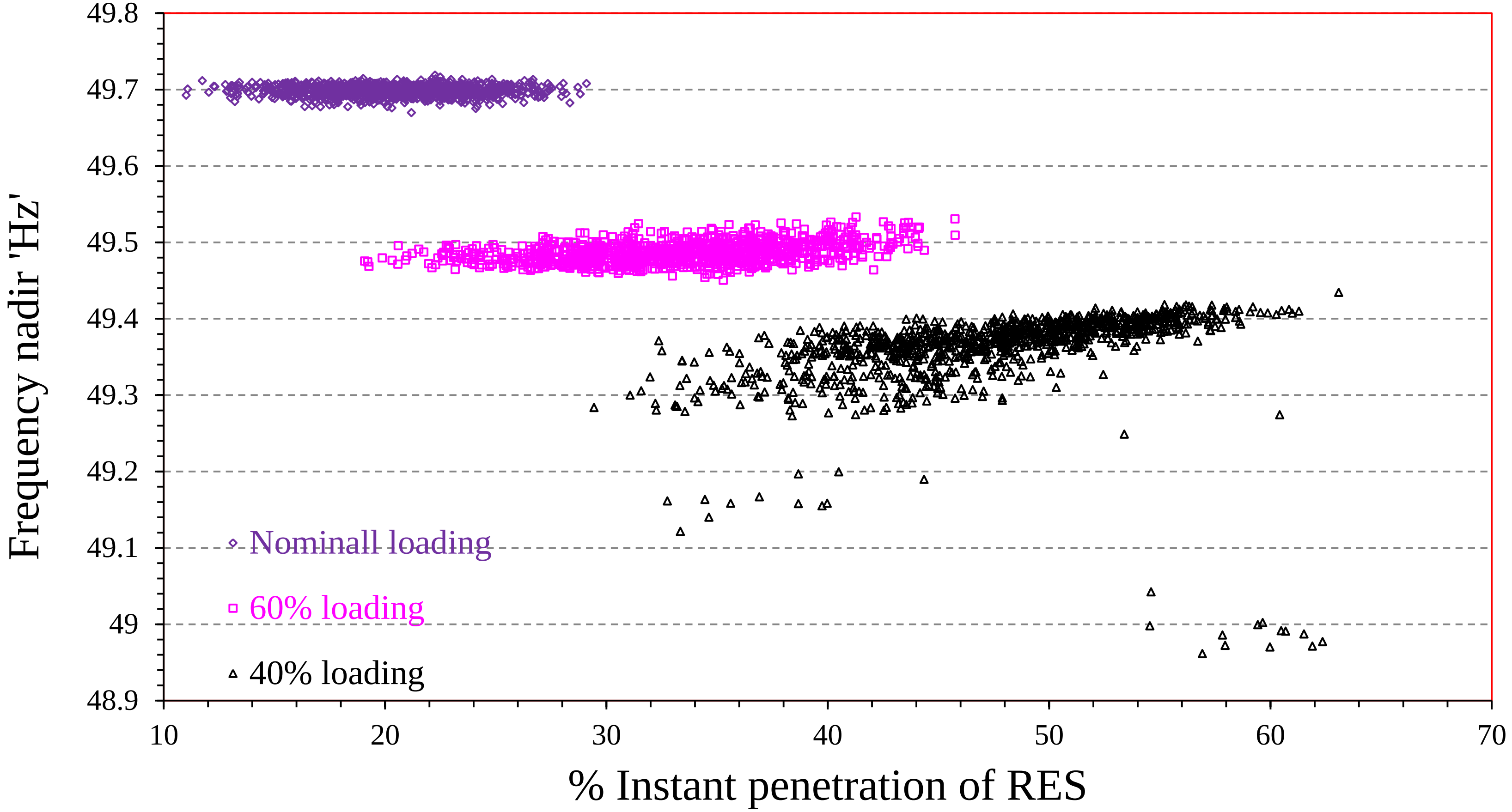
Frequency nadir improves from 49.7 Hz to 49.76 Hz



Δf= 0.04 Hz

Frequency nadir improves from 49.48 Hz to 49.52 Hz

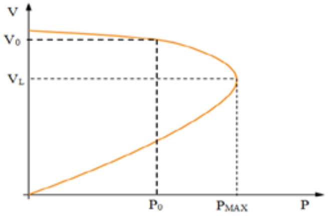
Probabilistic frequency stability response in low inertia systems



Frequency nadir for different operating conditions and penetration levels of RES

How accurate the model needs to be?

- Power system stability indices applied:
  - Voltage stability: PV margin, (L-indicator, impedance ratio index, voltage collapse index, channel components transform index, diagonal element dependent index)
  - Small disturbance stability: damping of critical mode (damping factor of critical mode)
  - Transient stability: transient stability index, (transient angle severity index, rotor acceleration index, rotor angle deviation, critical clearing time, generator specific indices
  - stability: frequency nadir, rate of change of frequency



$$PV_{margin} = P_{MAX} - P_0$$

$$\lambda = \sigma \pm j\omega$$

$$f = \frac{\omega}{2\pi}$$

$$\zeta = \frac{-\sigma}{\sqrt{\sigma^2 + \omega^2}}$$

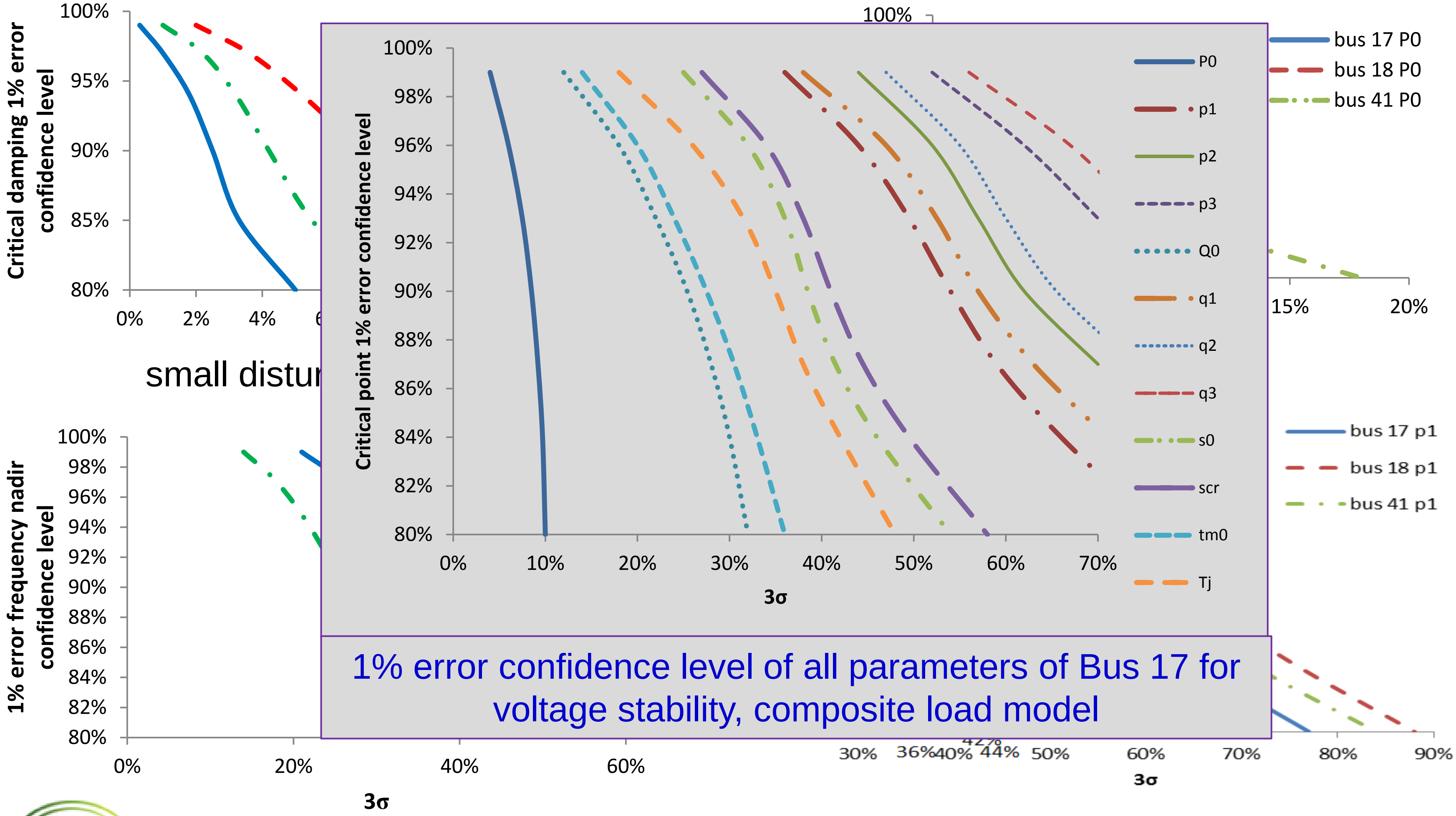
$$\lambda = -\zeta\omega_n \pm j\omega_n\sqrt{1-\zeta^2}$$

$$TSI = 100\,\frac{\delta_T - \delta_{max}}{\delta_T + \delta_{max}}$$

$$\delta_T < \delta_{max} = \max(|\delta_i - \delta_j|)$$

$$f_N = f_0\text{-}\Delta f \qquad RoCoF=\frac{df}{dt}$$

Example : 1% error confidence levels of Critical Load Model Parameter



1% error confidence level of all parameters of Bus 17 for voltage stability, composite load model

frequency stability

voltage stability

Summary

- Due to inherent variability and stochasticity the RES “contribution” to power system should be modelled using probabilistic approaches
- “Probabilistic” input of the equivalent generator is likely to be sufficient for large system studies

- Probabilistic studies offer more insight (a range of “options”) in potential stability issues
- Combined with “consequences” (financial) can lead to risk based assessment of system stability
- Suitable for studies of low probability high impact events

- A range of mathematical tools is available but still not widely accepted or understood by industry (and academia)
- Can be computationally demanding for large system applications
  - If efficient sampling techniques are not used
  - If key parameters to study have not been selected in advance (e.g., through priority ranking of key uncertainties using sensitivity analysis)

The models need to be “accurate enough”!

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