Panel session on “Handling Uncertainties and Use of Equivalents in Dynamic Security Assessment”
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Model Reduction of Active Distribution Networks under Uncertainty

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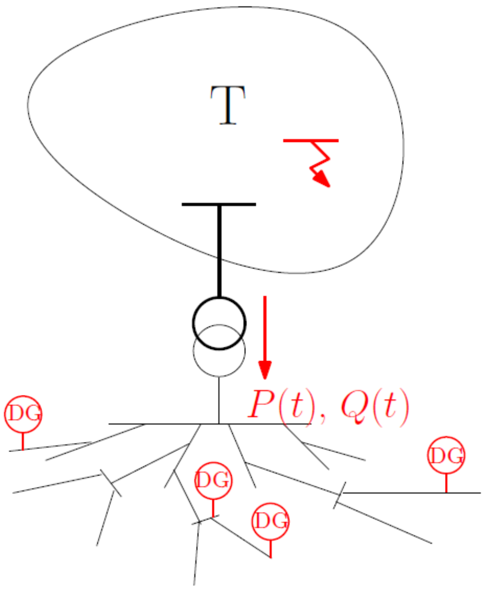
Context

- More and more Inverter-Based Generators connected to distribution grids
- distribution networks become active
- their influence on the whole power system dynamics increases
- it is increasingly important for TSOs to model those Active Distribution Networks (ADNs) in their dynamic simulations

Why model reduction ?

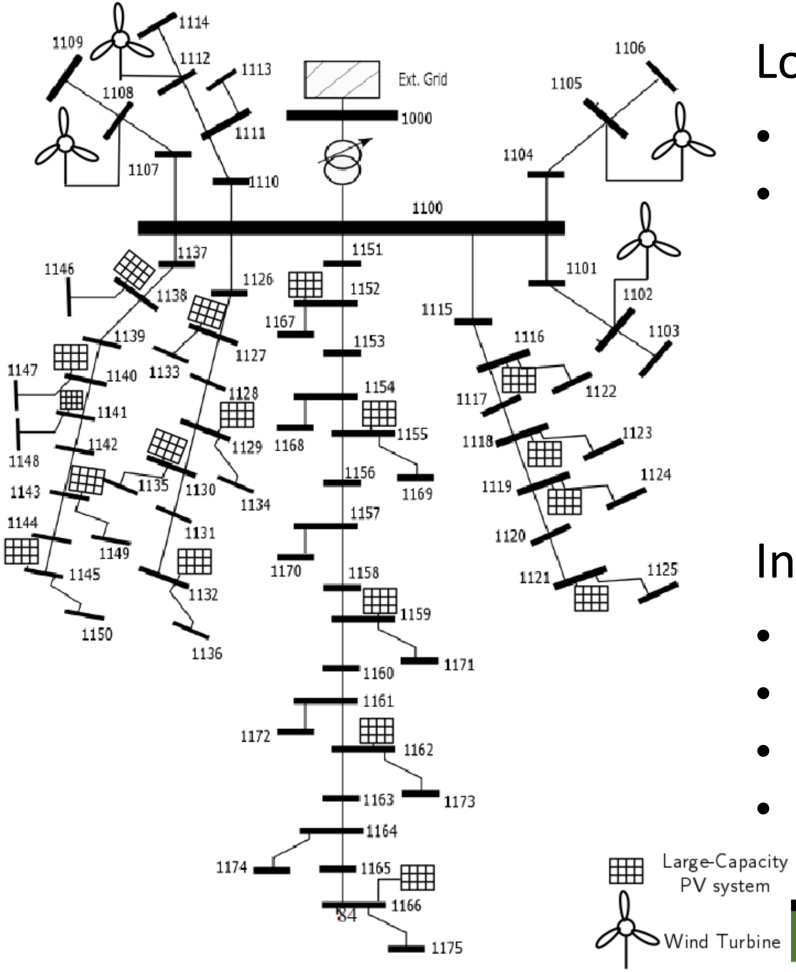
- Dynamic simulations of combined Transmission – Distribution system are impractical
  - large computing times
  - heavy model maintenance
  - confidentiality issue
- DSOs process their own data and transmit to the TSO simplified, reduced-order models of their distribution systems : dynamic equivalents
  - to be attached to the transmission system model
  - no confidentiality issue

Desired features of ADN equivalent



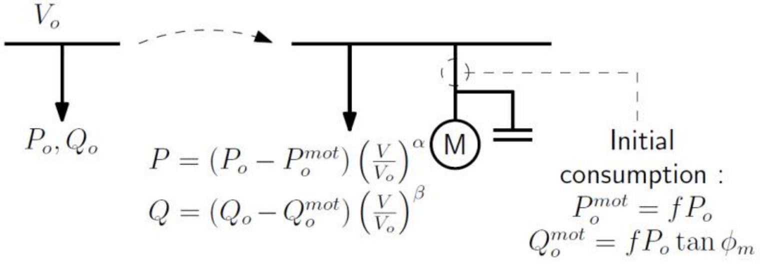
- For use in simulation of large disturbances in the transmission system
- accurate in terms of *P(t)* and *Q(t)* power flows in the distribution transformer
- accounting for discrete controls of dispersed units
  - dynamic voltage support, undervoltage tripping, etc.
- compatible with TSO dynamic simulation software
- physically intuitive → "grey-box" model
  - includes "physical" components with known models
  - but unknown parameters
- easily updated when operating point changes.

Unreduced system modeling



Loads :

- static part : exponential model
- dynamic part : 3rd-order induction motor model



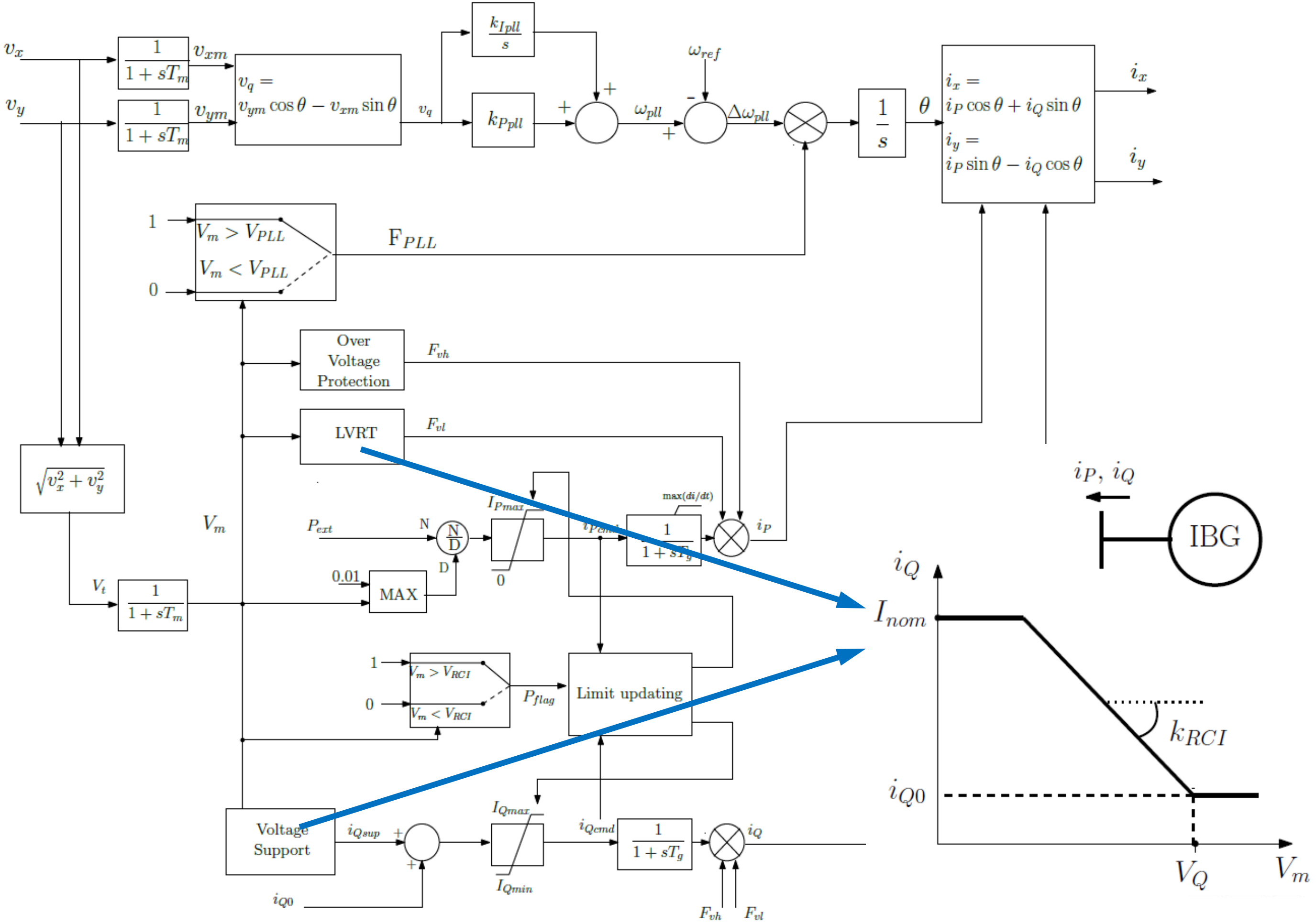
Inverter-Based Generators (IBGs) :

- Phase Locked-Loop (PLL)
- Low Voltage Ride-Through (LVRT)
- dynamic volt. support by reactive current injection
- limited rate of active current recovery after limitation

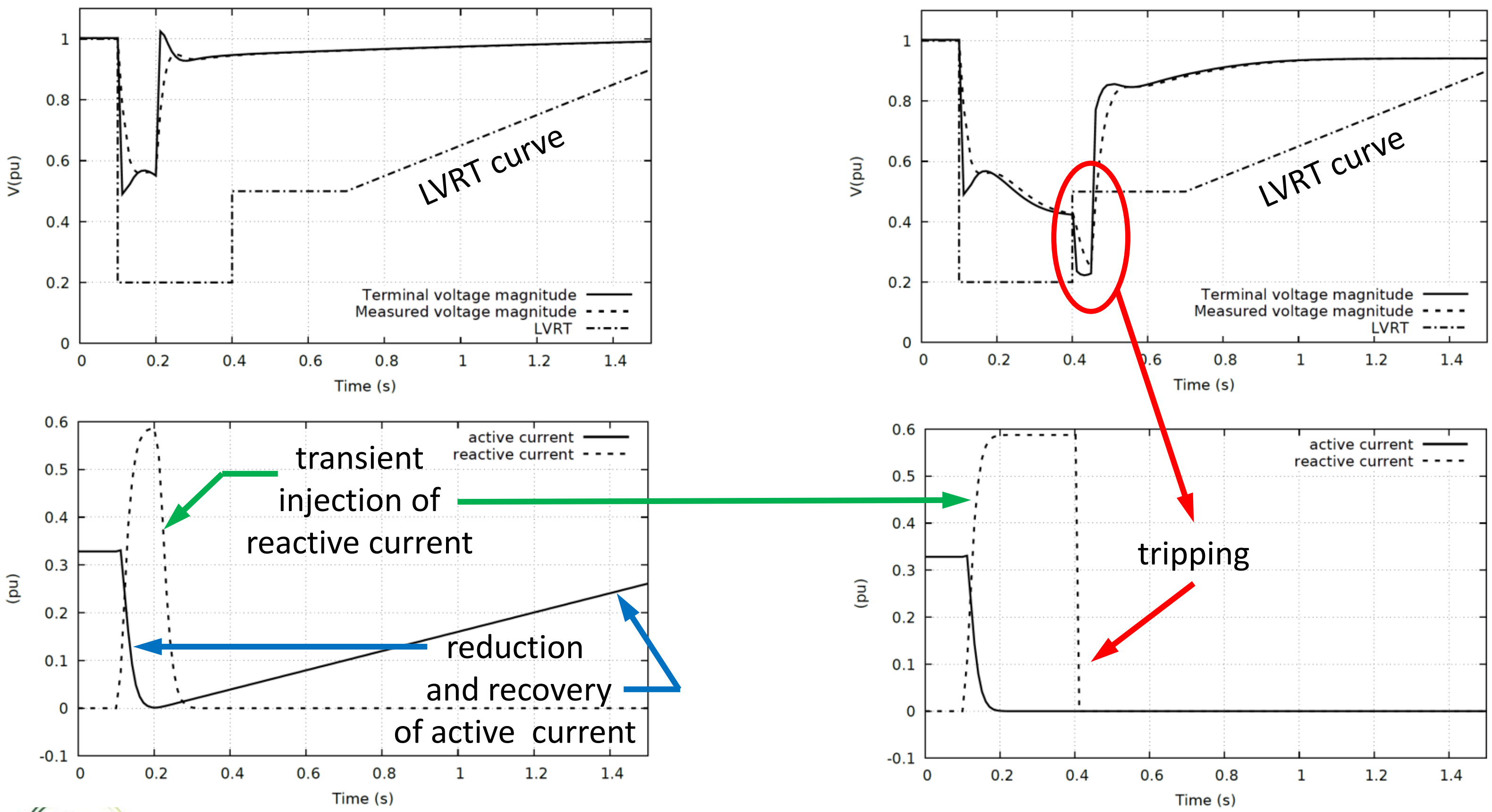
IBG modeling

IBG generic model reproducing the response to voltage variations required by most grid codes

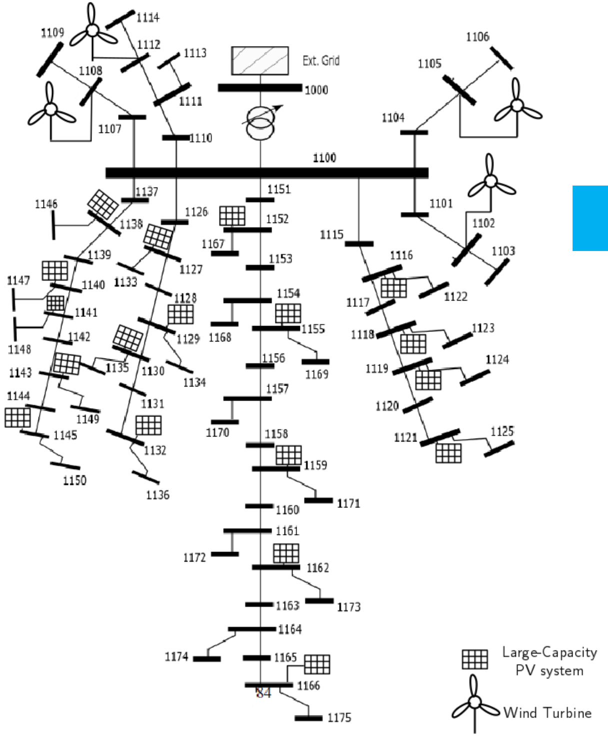
- NC RfG (ENTSO-e)
- VDE AR N 4105/ BDEW MV (Germany)
- IEEE 1547
- etc.



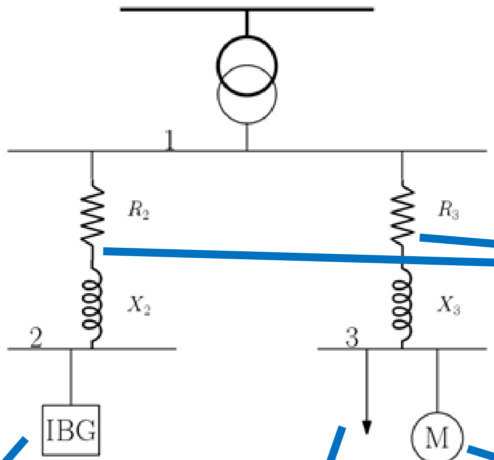
Example of IBG response to voltage dips



ADN dynamic equivalent : grey-box model



model reduction



equivalent impedances

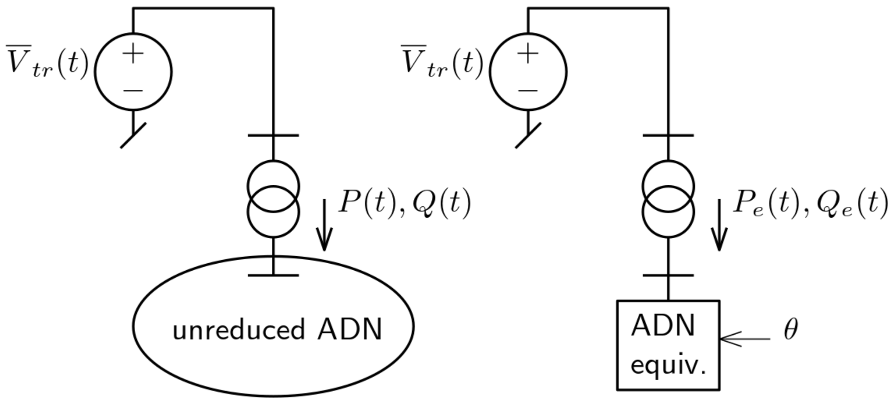
equivalent IBG : similar to generic model used in unreduced system

equivalent load - static part : exponential model

equivalent load - dynamic part : 3rd-order model of induction motor

parameters θ to be identified

Identifying the ADN equivalent from simulations

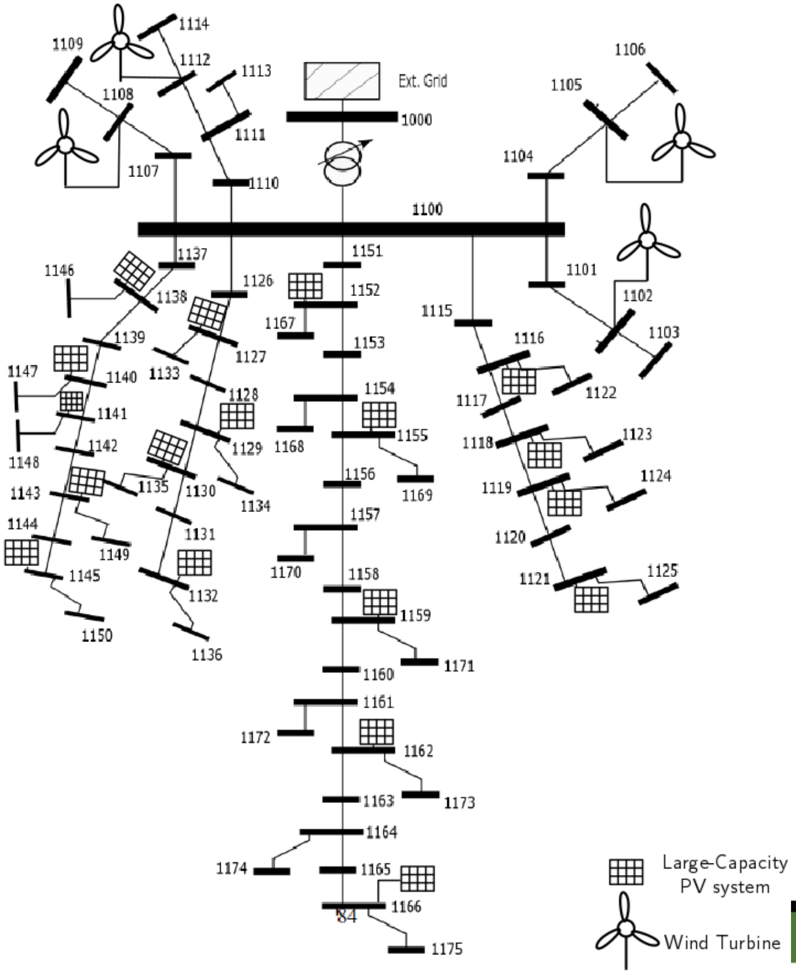


- Measurements not available…
- transmission system replaced by voltage source $\bar{V}_{tr}(t)$ imposing various disturbances
  - voltage magnitude, phase angle, frequency
- parameters $\boldsymbol{\theta}$ of the ADN equivalent tuned so that $(P_e\,, Q_e)$ approaches (P, Q) of unreduced system

Dealing with parameter uncertainty

- Dynamic models involve parameters not known accurately
  - loads : models are already simplified equivalents
  - IBGs : grid codes leave freedom on some parameters
- Impact assessed through Monte-Carlo simulations
  - at a given initial operating point, a disturbance is simulated for s instances of the same model corresponding to randomly drawn parameter vectors $\boldsymbol{p}_1, \ldots, \boldsymbol{p}_S$.
  - s randomized dynamic responses to the disturbance
  - statistics computed at each point in time

Simulation results : test system



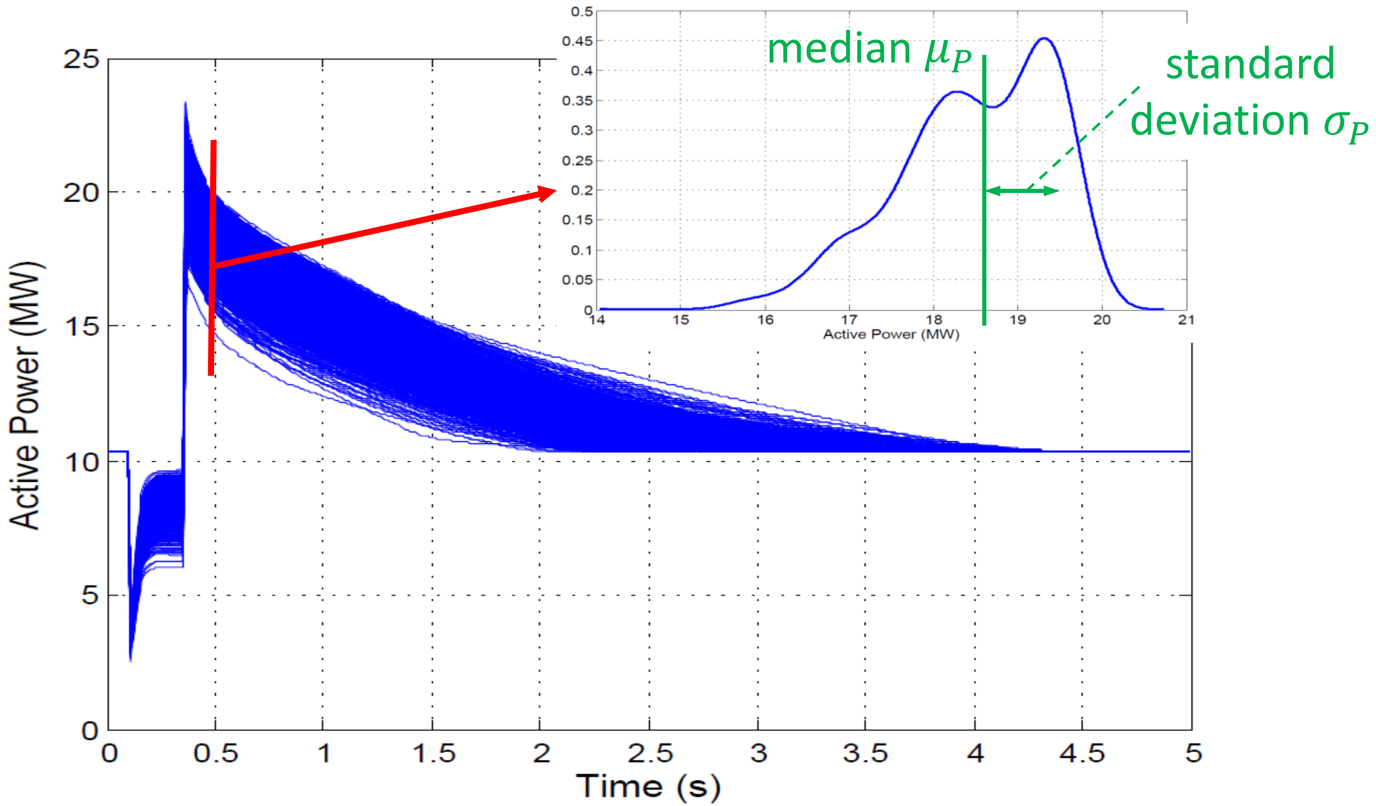
- 75 buses 53 loads 22 IBGs

	MW	Mvar
Consumption of loads	19.95	2.83
Production of IBGs	9.80	0
Power flow in transformer	10.33	2.96

- Nb of differential-algebraic equations :
  - unreduced model : 3297
  - equivalent : 117
- Nb of components in θ :
  - 17 initially tested
  - 7 removed : negligible impact identified

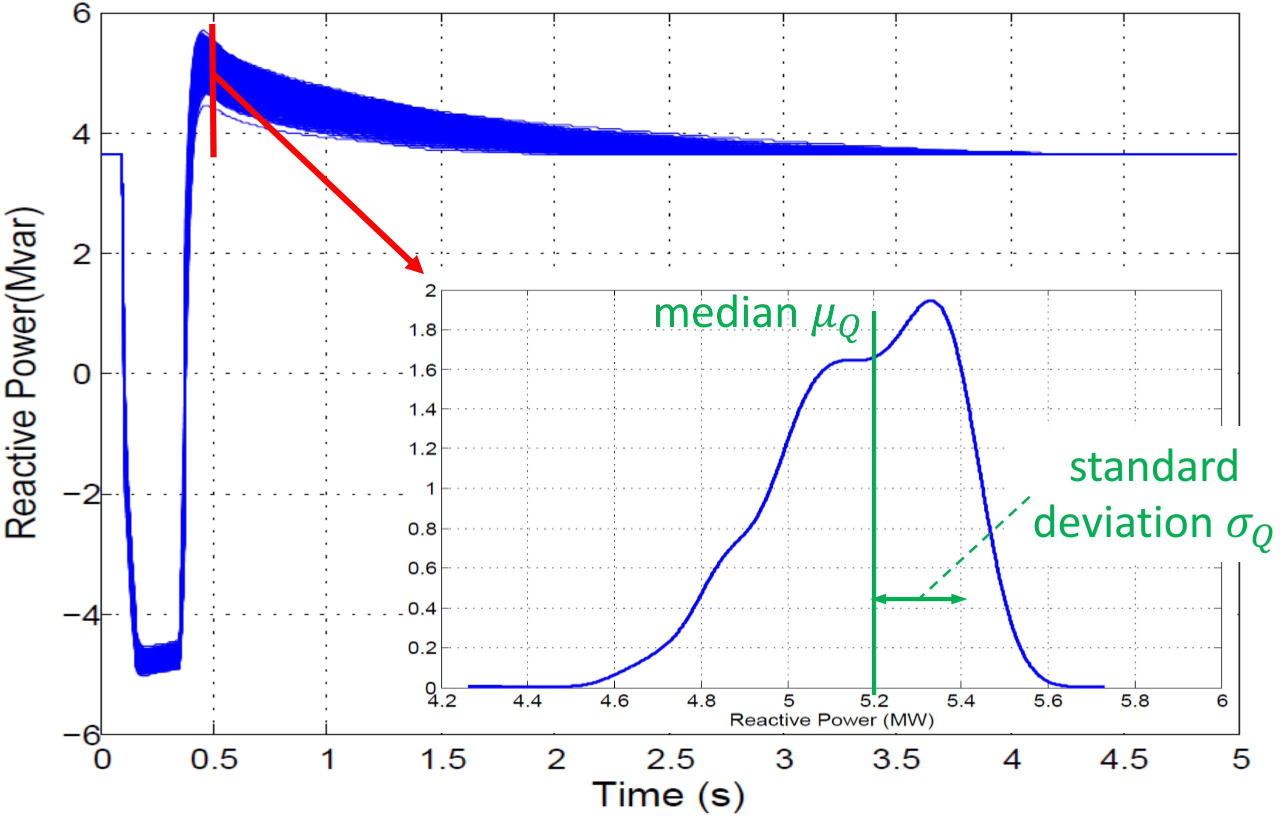
Example of Monte-Carlo simulations

Responses of active power to a transmission voltage dip of 0.5 pu during 250 ms



Example of Monte-Carlo simulations

Responses of reactive power to a transmission voltage dip of 0.5 pu during 250 ms



Weighted Least Square (WLS) identification of θ

derivative-free, metaheuristic optimization :

Differential Evolution algorithm

$$\min_{\boldsymbol{\theta}} \quad F(\boldsymbol{\theta}) = \frac{1}{d}\sum_{j=1}^{d}[F_P(\boldsymbol{\theta},j) + F_Q(\boldsymbol{\theta},j)]$$

$$\text{with} \quad F_P(\boldsymbol{\theta},j) = \frac{1}{N}\sum_{k=1}^{N}\left[\frac{P_e(\boldsymbol{\theta},j,k) - \mu_P(j,k)}{\sigma_P(j,k)}\right]^2$$

$$F_Q(\boldsymbol{\theta},j) = \frac{1}{N}\sum_{k=1}^{N}\left[\frac{Q_e(\boldsymbol{\theta},j,k) - \mu_Q(j,k)}{\sigma_Q(j,k)}\right]^2$$

$$\boldsymbol{\theta}^L \leq \boldsymbol{\theta} \leq \boldsymbol{\theta}^U$$

response of equivalent fitted to the median

lower weight if larger dispersion

d : number of "training" disturbances

N : number of discrete times of simulation

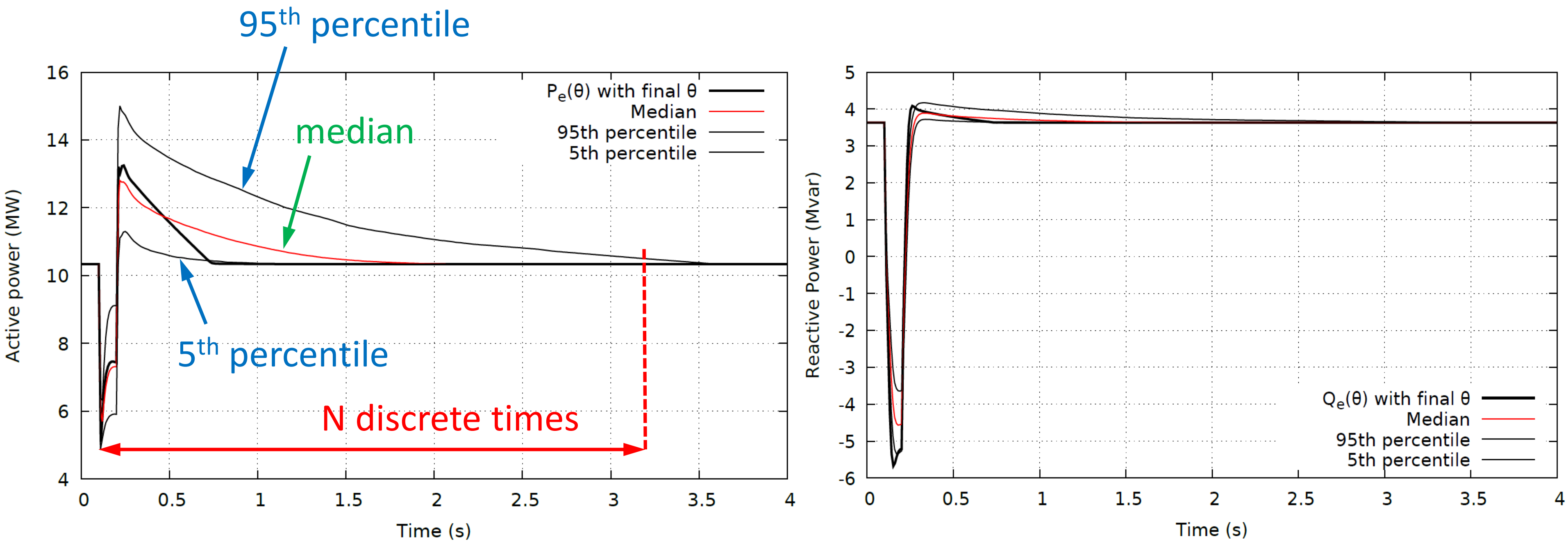
$\mu_P(j,k)$: median of distribution of P at time k for the j-th disturbance

$\sigma_P(j,k)$: corresponding standard deviation

$\mu_Q(j,k)$ and $\sigma_Q(j,k)$: same for Q

Simulation results : fitting of equivalent

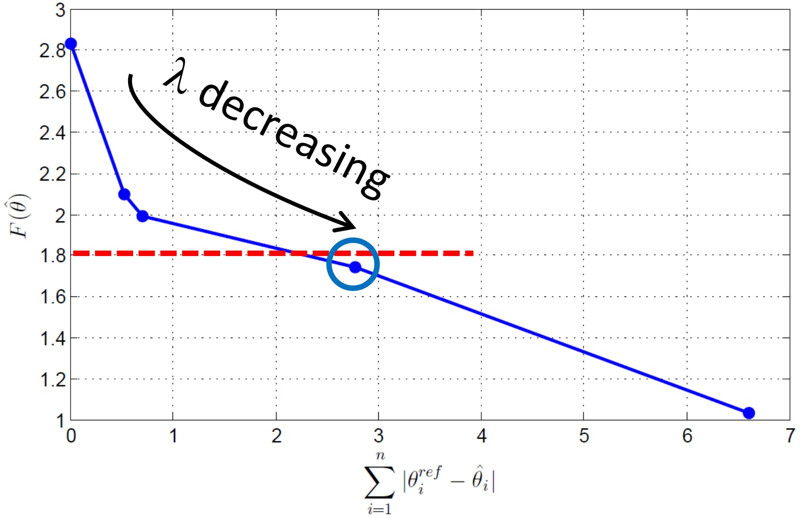
Responses to a transmission voltage dip of 0.3 pu during 100 ms

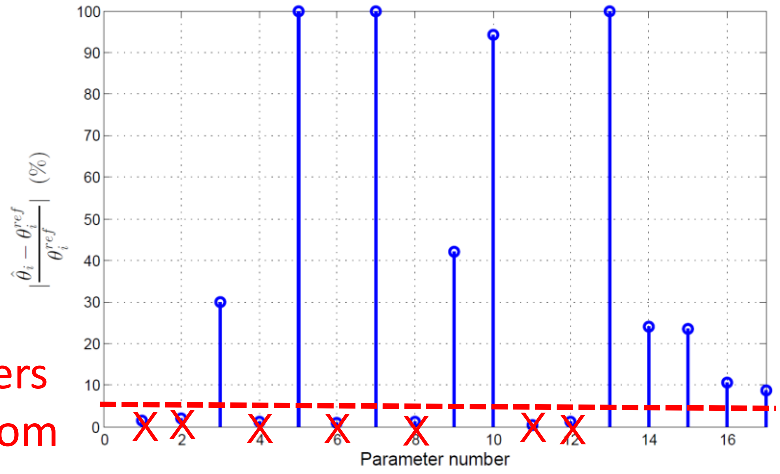


Keeping the dimension of θ as small as possible

- To make the reduced model :
  - easier to optimize (faster convergence of DE)
  - more consistent from one case to another
  - easier to interpret
- variant of *Least Absolute Shrinkage and Selection Operator* (LASSO) method

$$\min_{\boldsymbol{\theta}} \quad F(\boldsymbol{\theta}) + \lambda \sum_{i=1}^{n} |\boldsymbol{\theta}_i^{ref} - \hat{\boldsymbol{\theta}}_i|$$

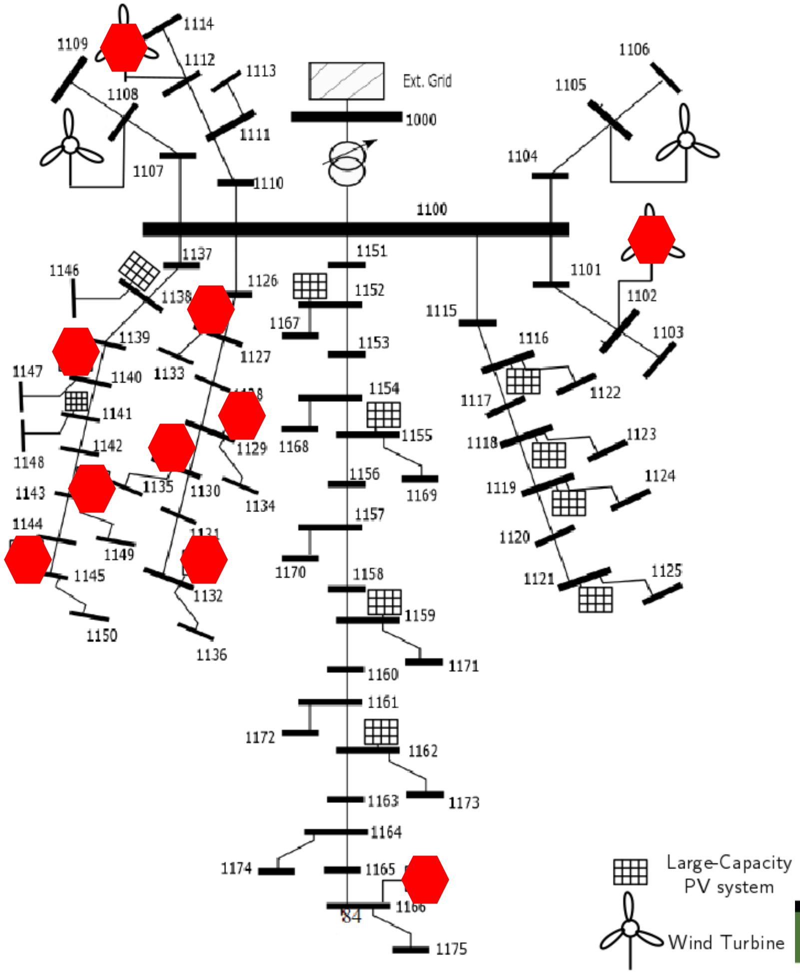




7 parameters removed from final $\boldsymbol{\theta}$

IEEE

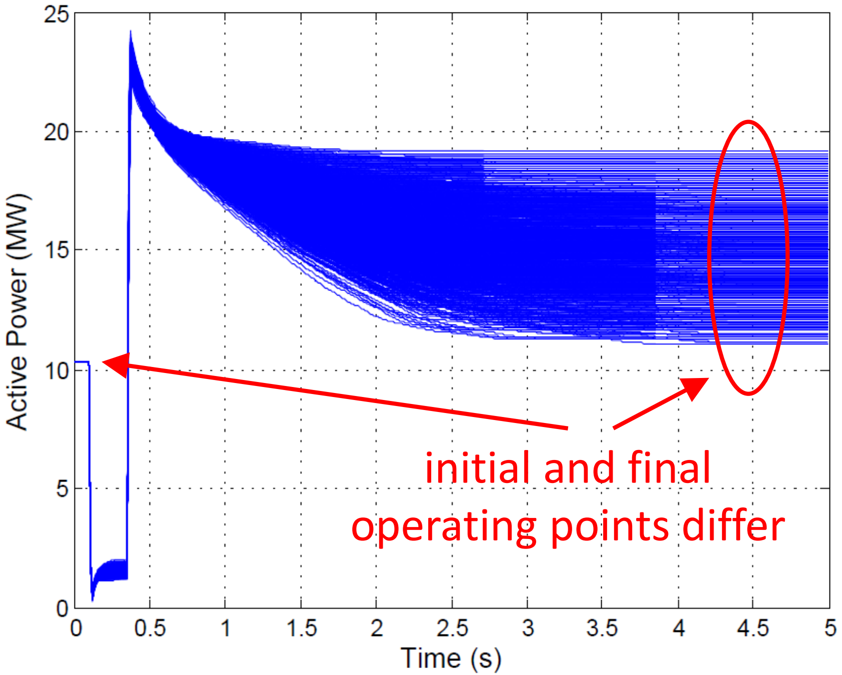
Undervoltage tripping of IBGs

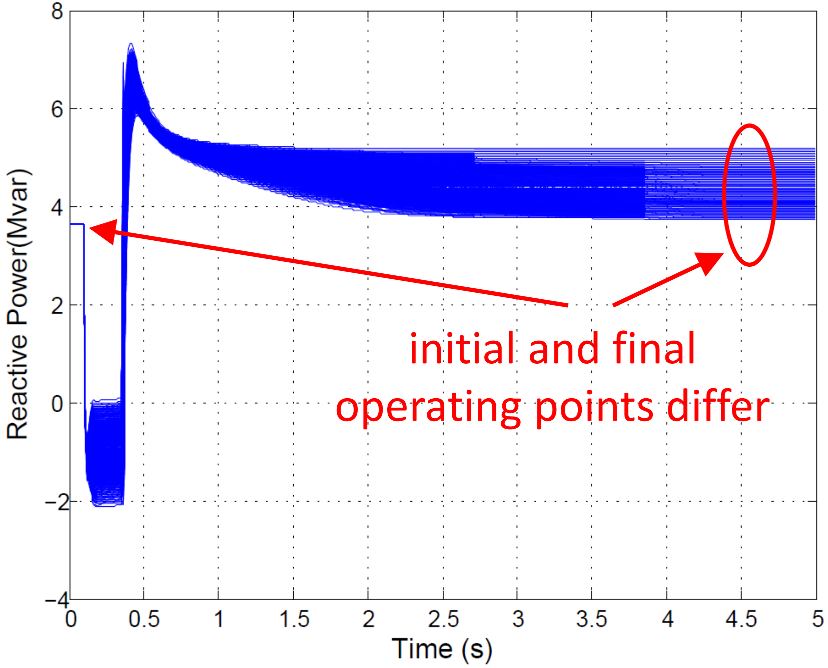


- If the transmission voltage drop is deep enough, some IBGs may disconnect
  - voltage falls below LVRT curve
- Example : transmission voltage drop of 0.8 pu lasting 250 ms

Monte-Carlo simulations with randomized tripping

Responses to a transmission voltage dip of 0.8 pu during 250 ms

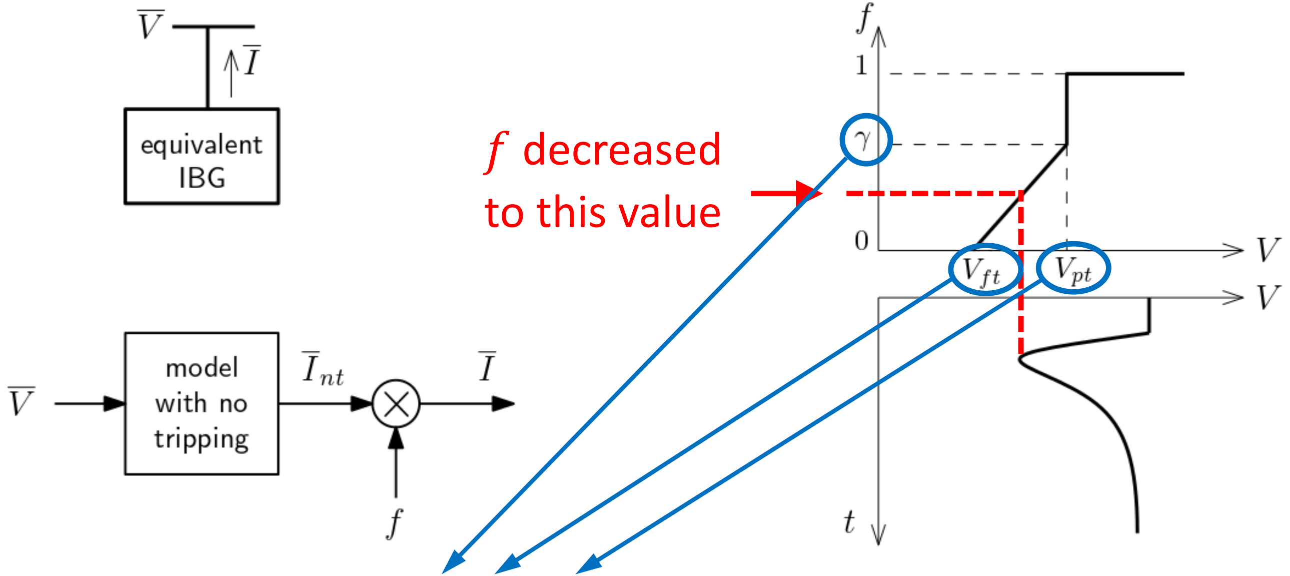




- IBGs with voltage falling below the LVRT curve <u>may</u> trip
  - responses with tripping randomized, together with other parameters

Tripping accounted in the equivalent

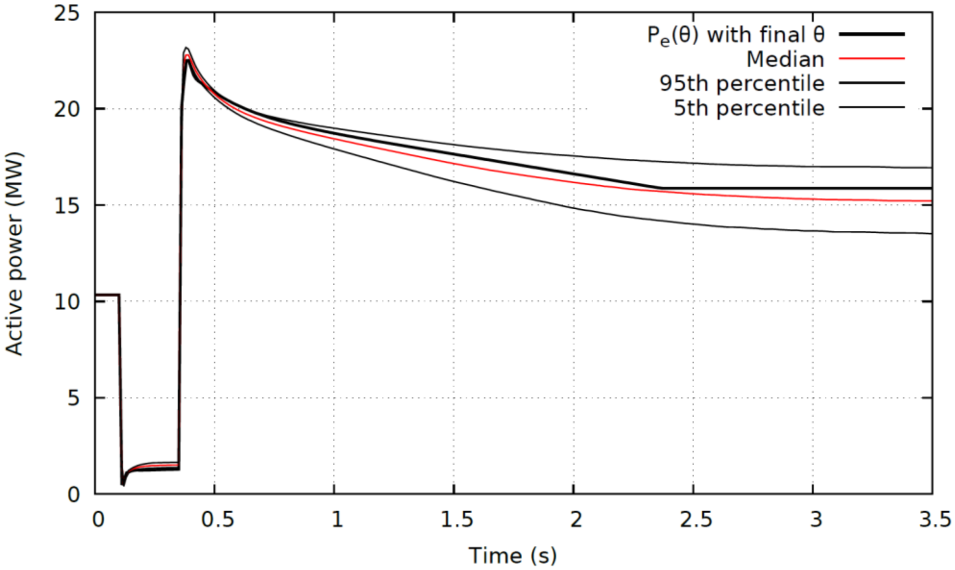
- by reducing the current injected by the equivalent IBG

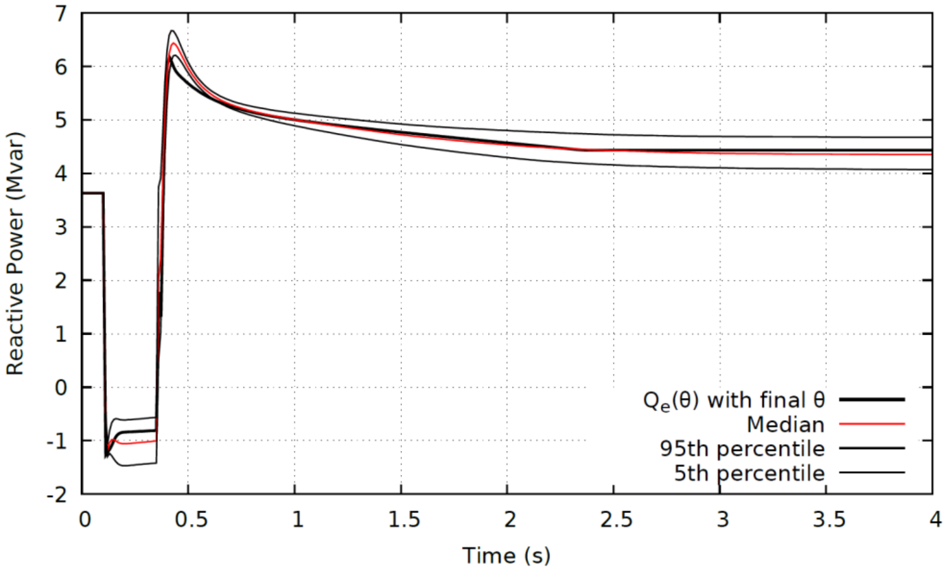


- V_{pt}, V_{ft}, γ are adjusted by weighted least squares
  - after dealing with the other components of $\boldsymbol{\theta}$

Response of equivalent with tripping of some IBGs

Responses to a transmission voltage dip of 0.8 pu during 250 ms





Summary

- ADN equivalent for simulation of large disturbances at transmission level
- grey-box model
- equivalent significantly smaller than unreduced system
- strong nonlinearities and discontinuities considered
    - in particular, partial tripping of IBGs
- weighted-least square identification
    - number of parameters to identify : as small as possible (LASSO)
- impact of model uncertainties identified from Monte-Carlo simulations
    - fitting the “average” response + weighting factors to reflect dispersion
- equivalent trained with multiple disturbances
- good results on a test system with high penetration of renewable energy sources.