Panel session on “Experiences and insights on the use of the generic Distributed Energy Resource model (DER) in transient stability simulations” - Ref. 19PESGM2979

Dynamic model of an active distribution network derived from multiple large-disturbance simulations

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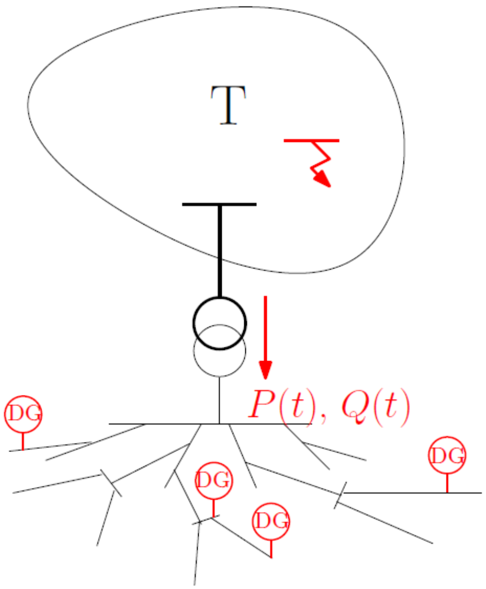
Context

- 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 ?

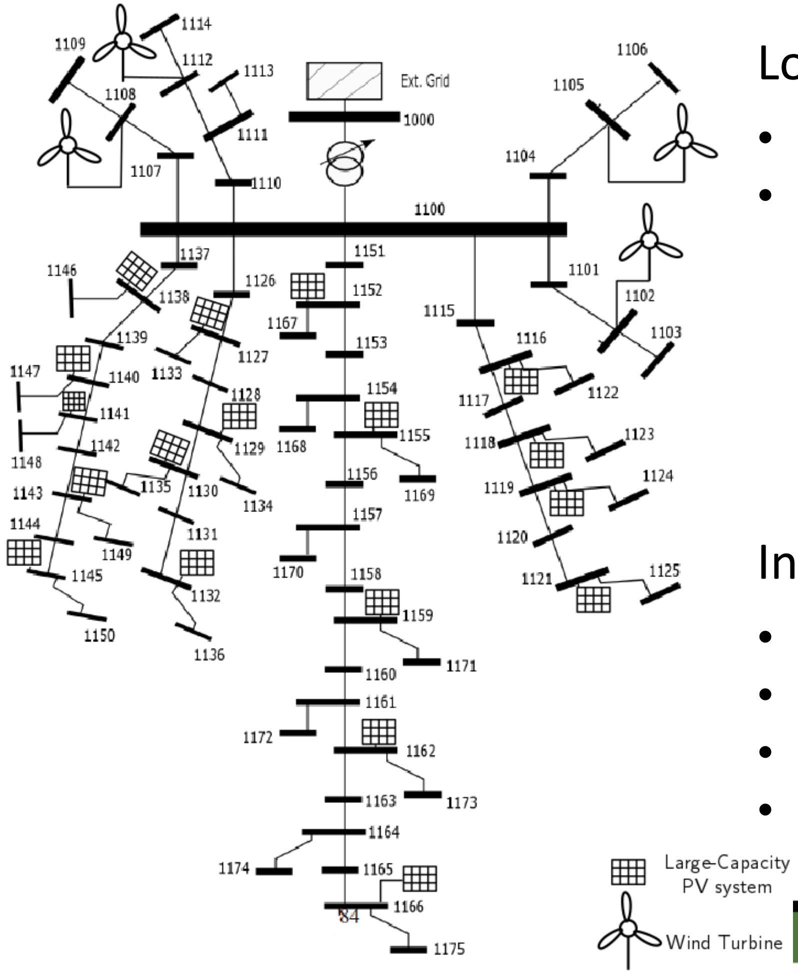
- Dynamic simulations of combined Transmission – Distribution system are impractical
  - large computing times
  - heavy model maintenance
  - confidentiality issue
- DSOs process their own data and transmit to the TSO simplified, reduced-order models of their distribution systems : dynamic equivalents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

Desired features of ADN equivalent



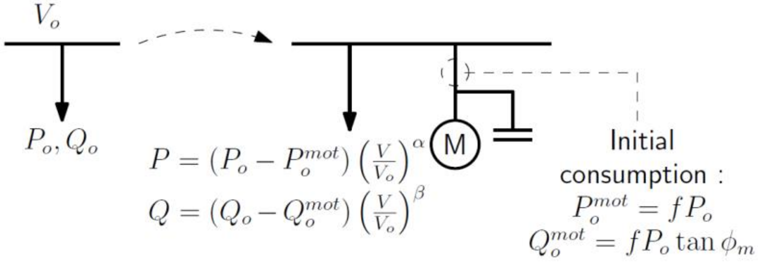
- For use in simulation of large disturbances in the transmission system
- accurate in terms of *P(t)* and *Q(t)* power flows in the distribution transformer
- accounting for discrete controls of dispersed units
  - dynamic voltage support, undervoltage tripping, etc.
- compatible with TSO dynamic simulation software
- physically intuitive $\rightarrow$ “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



$$P = (P_o - P_o^{mot}) \left(\frac{V}{V_o}\right)^{\alpha}$$

$$Q = (Q_o - Q_o^{mot}) \left(\frac{V}{V_o}\right)^{\beta}$$

$$P_o^{mot} = f P_o$$

$$Q_o^{mot} = f P_o \tan \phi_m$$

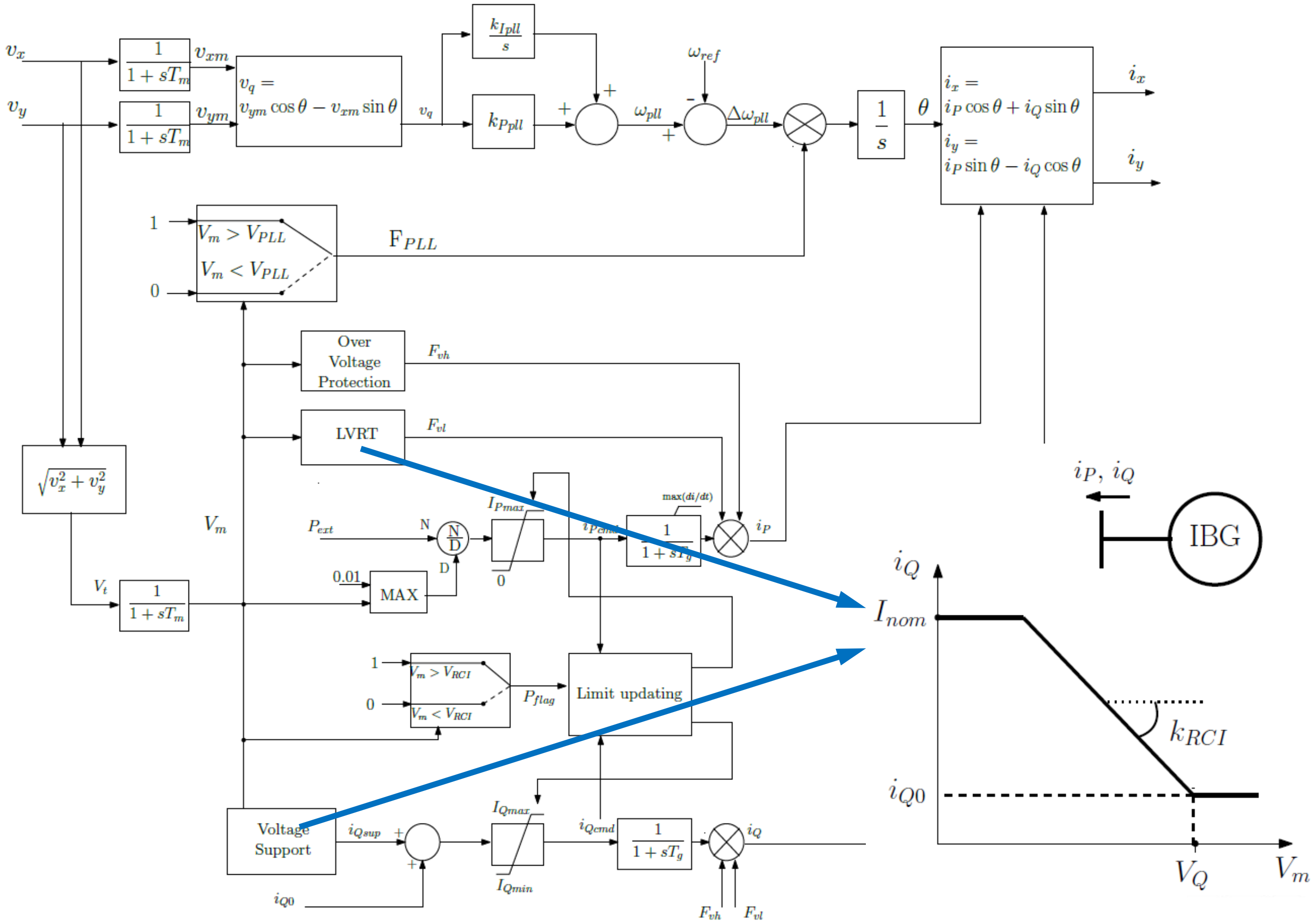
Inverter-Based Generators (IBGs) :

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

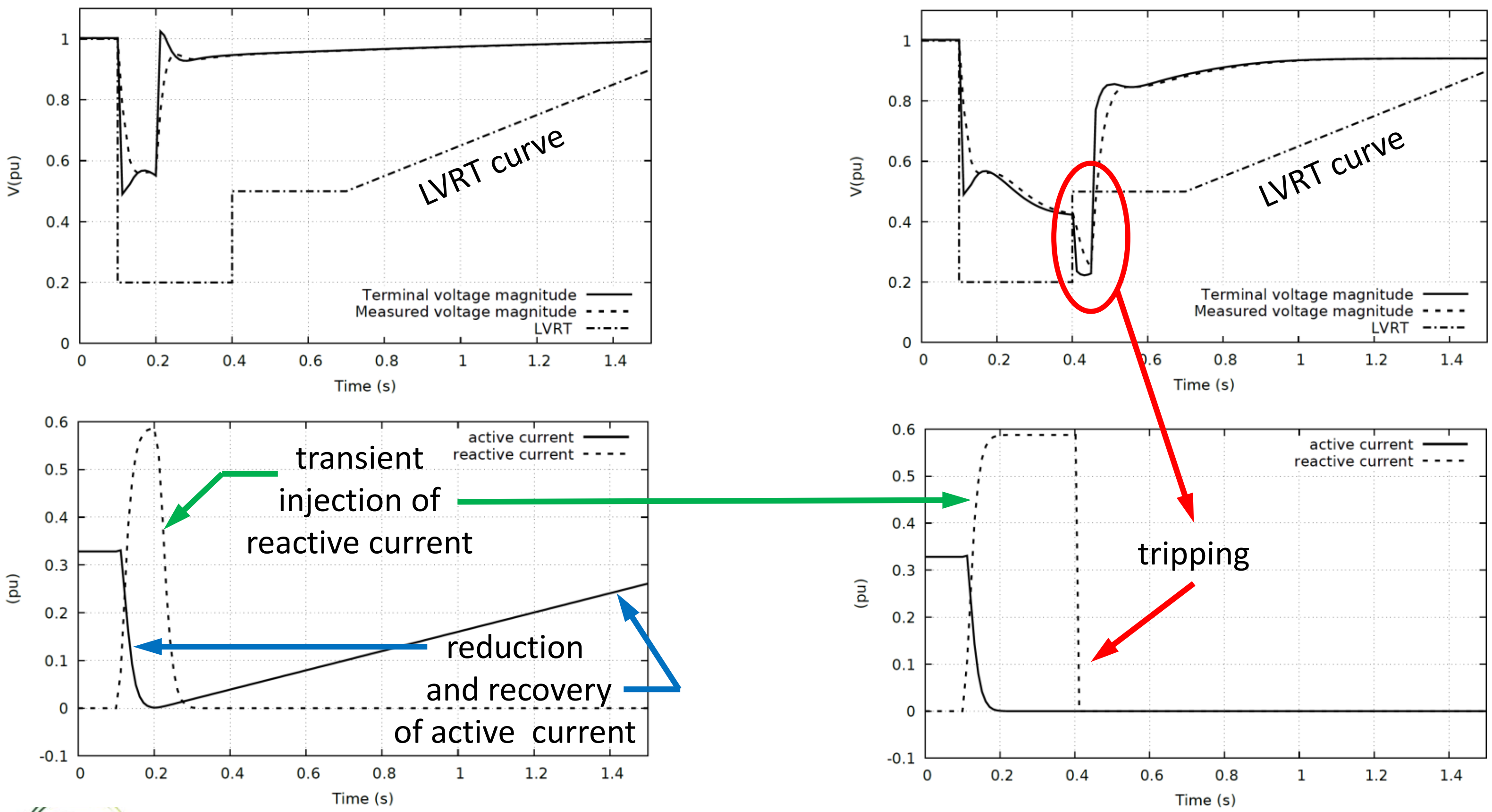
IBG modeling

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

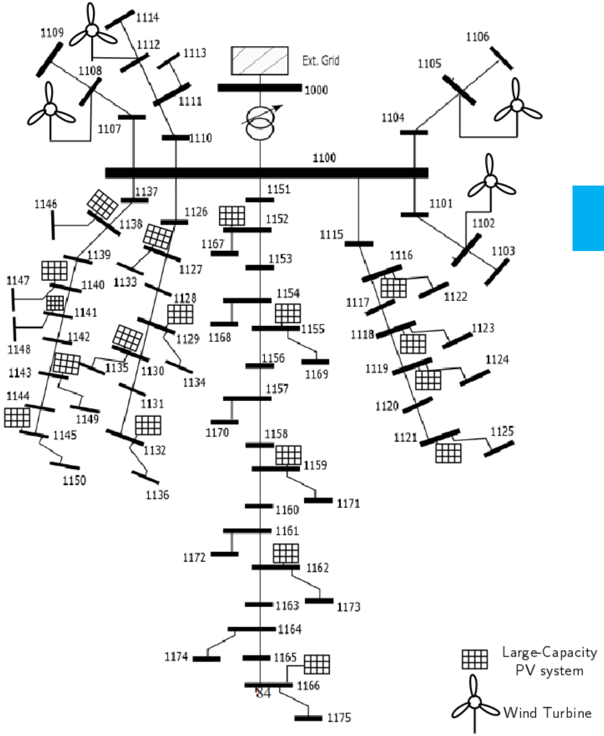
- NC RfG (ENTSO-e)
- VDE AR N 4105/ BDEW MV (Germany)
- IEEE 1547
- etc.



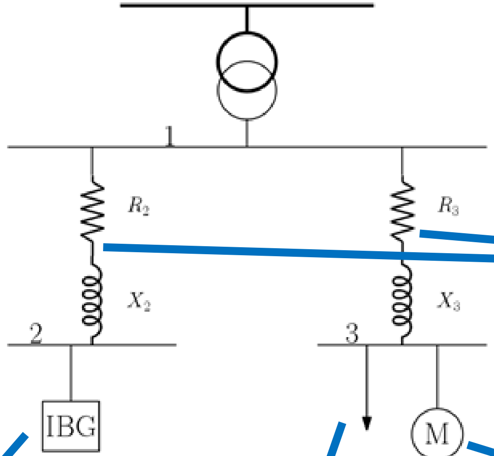
Example of IBG response to voltage dips



ADN dynamic equivalent : grey-box model



model reduction



equivalent impedances

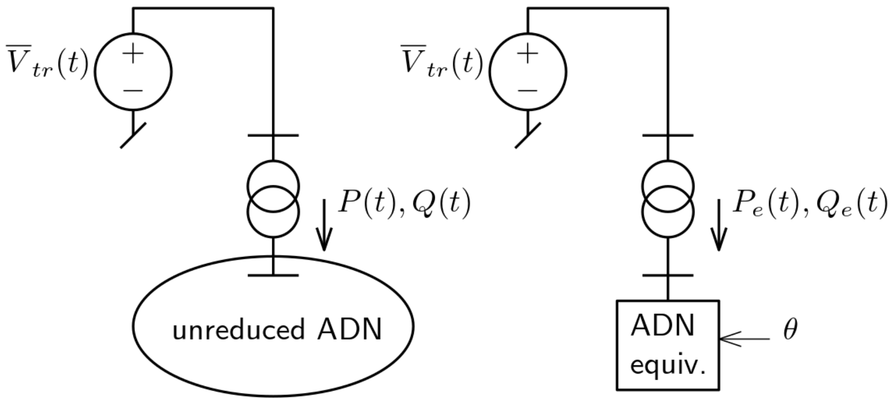
equivalent IBG : similar to generic model used in unreduced system

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

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Weighted Least Square (WLS) identification of θ

derivative-free, metaheuristic optimization :

Differential Evolution algorithm

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

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

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

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

response of equivalent fitted to reference (from unreduced model)

varying weights

d : number of "training" disturbances

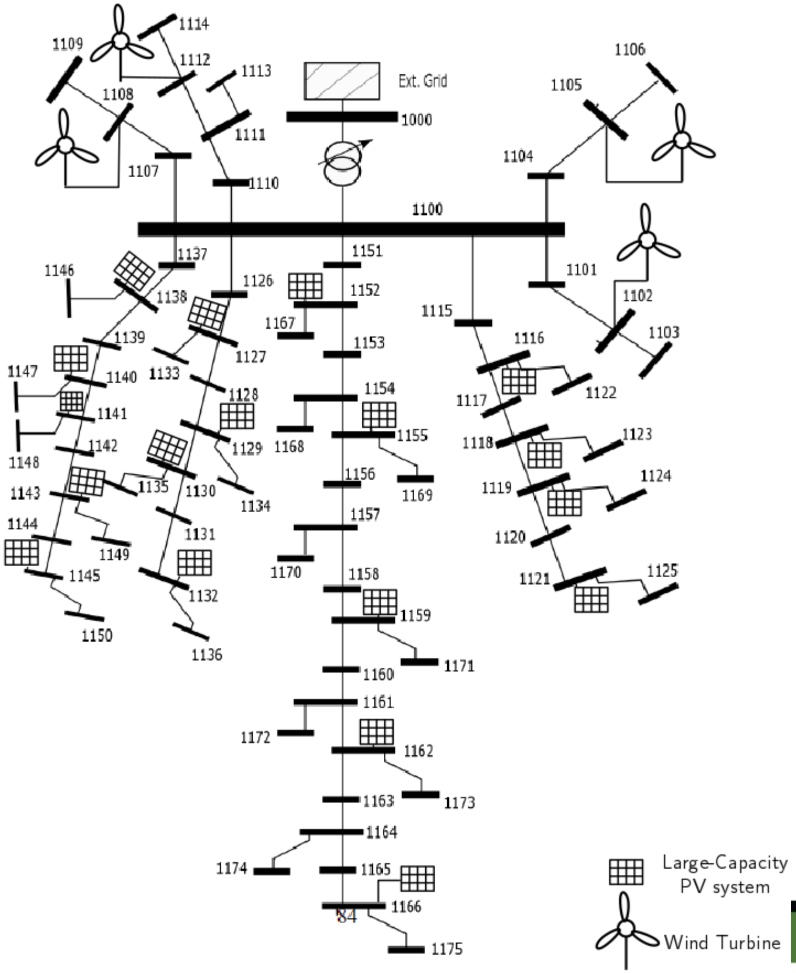
N : number of discrete times of simulation

$\mu_P(j,k)$: 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 : 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

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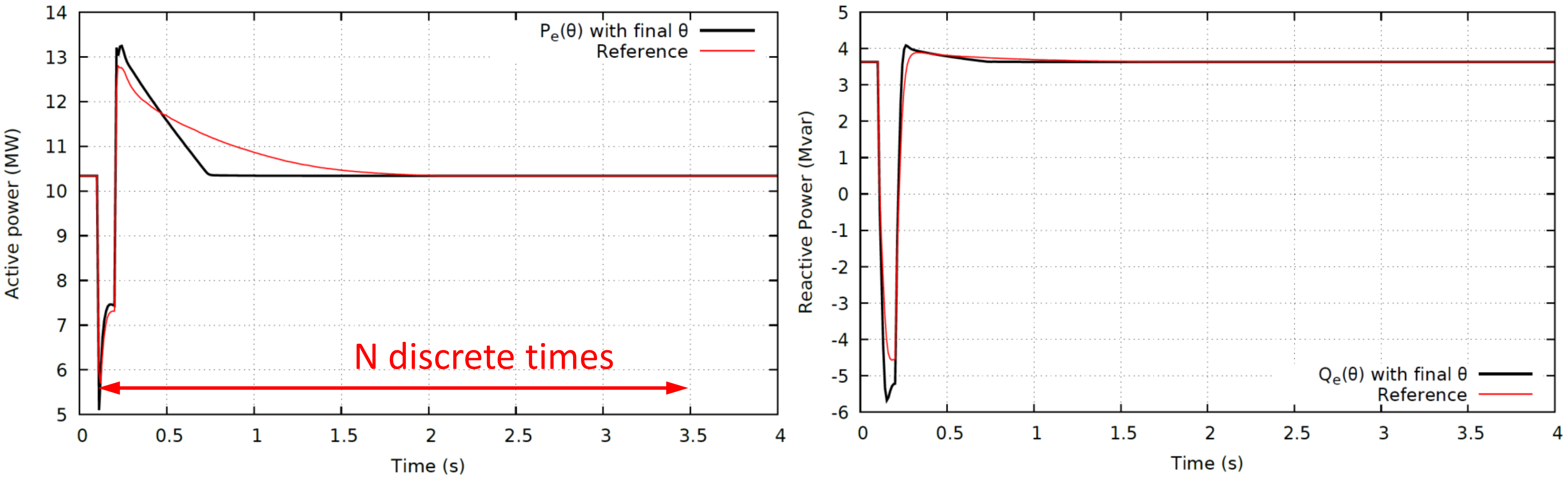
Simulation results : fitting of equivalent

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



Training the equivalent with multiple disturbances

- Make the equivalent valid for multiple disturbances – don't *overfit* one of them
- starting from a set of candidate disturbances
    - include them progressively in the *training set* (i.e. add them in WLS objective *F*)
    - stop as soon as the obtained equivalent is accurate for the *non-trained* disturbances

Recursive procedure

1. Select a small subset of d_o training disturbances; $d := d_o$
2. Obtain $\widehat{\boldsymbol{\theta}}$
3. Compute $F_P(\widehat{\boldsymbol{\theta}}, i) + F_Q(\widehat{\boldsymbol{\theta}}, i)$ for each non-trained disturbance i
4. **If** $\max_i F_P(\widehat{\boldsymbol{\theta}}, i) + F_Q(\widehat{\boldsymbol{\theta}}, i) < F_{max}$

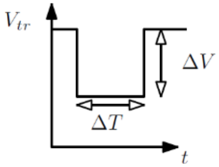
    then stop

    else add the disturbance with the largest $F_P(\widehat{\boldsymbol{\theta}}, i) + F_Q(\widehat{\boldsymbol{\theta}}, i)$ to the training set;

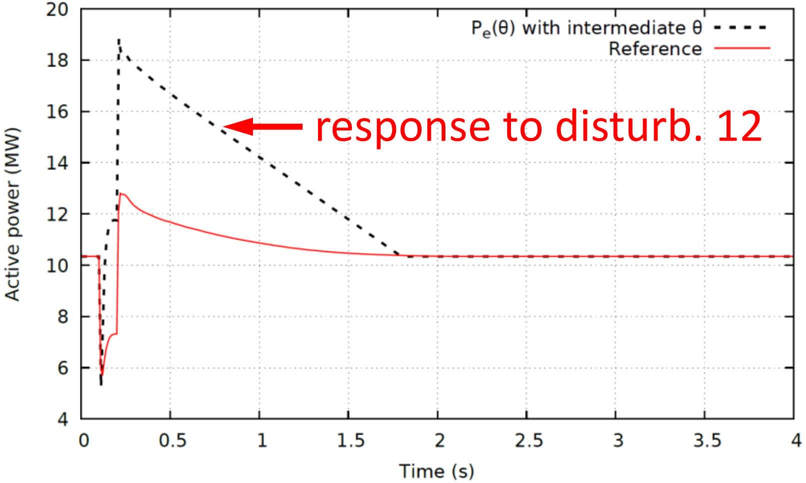
    $d := d + 1$; **go to** Step 2.

Simulation results : recursive training

Candidate disturbances



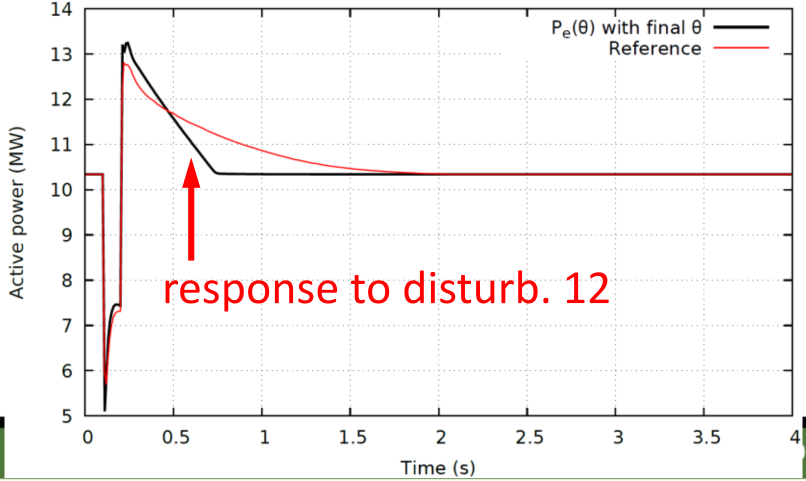
disturb. No	ΔV (pu)	ΔT (s)
1	0.2	0.10
2	0.2	0.25
3	0.3	0.10
4	0.3	0.25
5	0.4	0.10
6	0.4	0.25
7	0.5	0.10
8	0.5	0.25
9	0.6	0.10
10	0.6	0.25
11	0.7	0.10
12	0.7	0.25
13	0.8	0.1
14	0.8	0.25



Intermediate $\widehat{\boldsymbol{\theta}}$:

trained on disturbances

7, 8 and 4

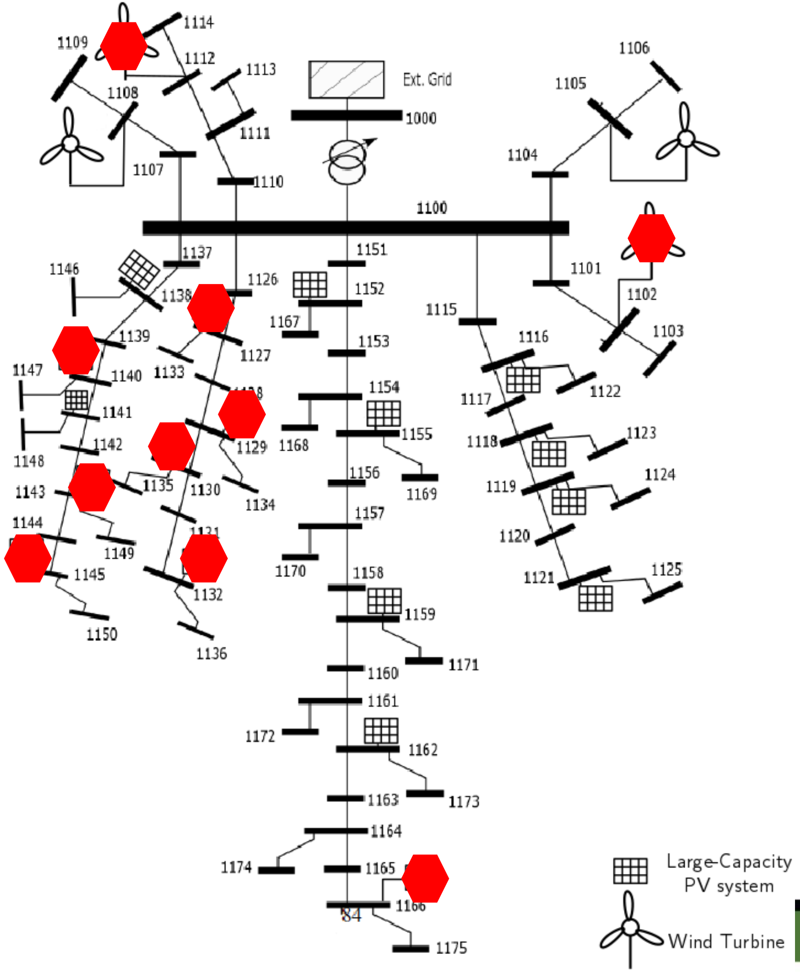


Final $\widehat{\boldsymbol{\theta}}$:

trained on disturbances

7, 8, 4, 12, 11 and 9

Undervoltage tripping of IBGs

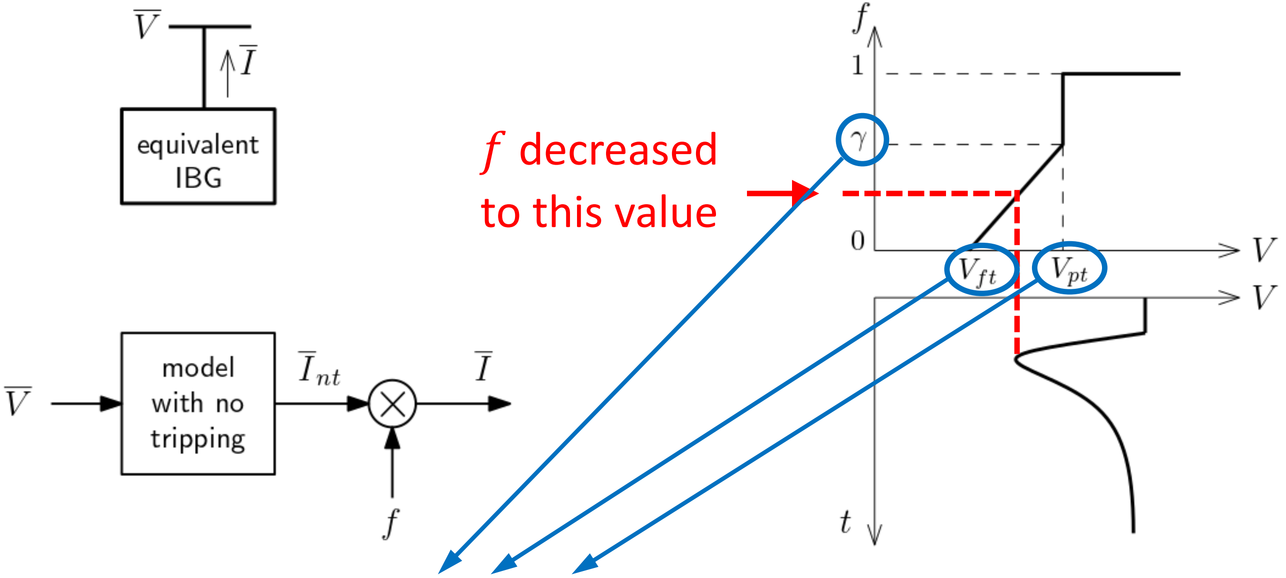


- If the transmission voltage drop is deep enough, some IBGs may disconnect
  - voltage falls below LVRT curve

- Example : transmission voltage drop of 0.8 pu lasting 250 ms

Tripping accounted in the equivalent

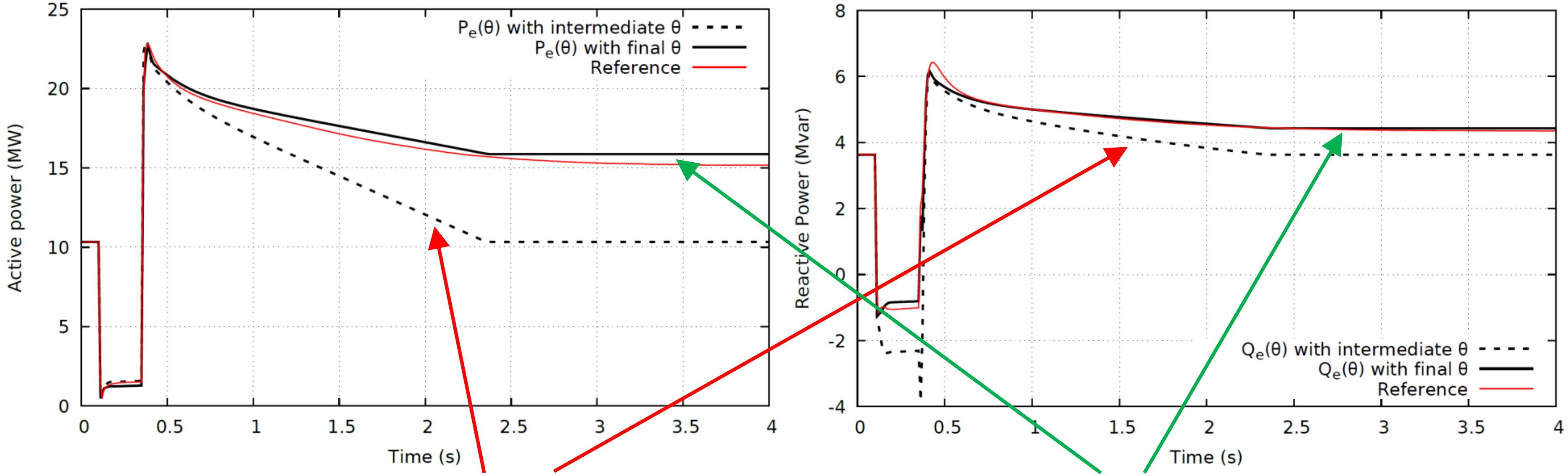
- by reducing the current injected by the equivalent IBG



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

Training on disturbances with tripping

Responses to a transmission voltage dip of 0.8 pu during 250 ms
(some IBGs trip)



Intermediate $\widehat{\boldsymbol{\theta}}$
no disturbance with IBG tripping
in training set

final $\widehat{\boldsymbol{\theta}}$
some disturbances with IBG tripping
in training set

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
  - fitting an reference response + weighting factors
- equivalent trained with multiple disturbances
  - including partial tripping of IBGs
  - recursive procedure to reduce computational effort
- good results on a test system with high penetration of renewable energy sources.