PEGASE

PAN EUROPEAN GRID ADVANCED SIMULATION AND STATE ESTIMATION

SIMPLIFIED DYNAMIC SIMULATION

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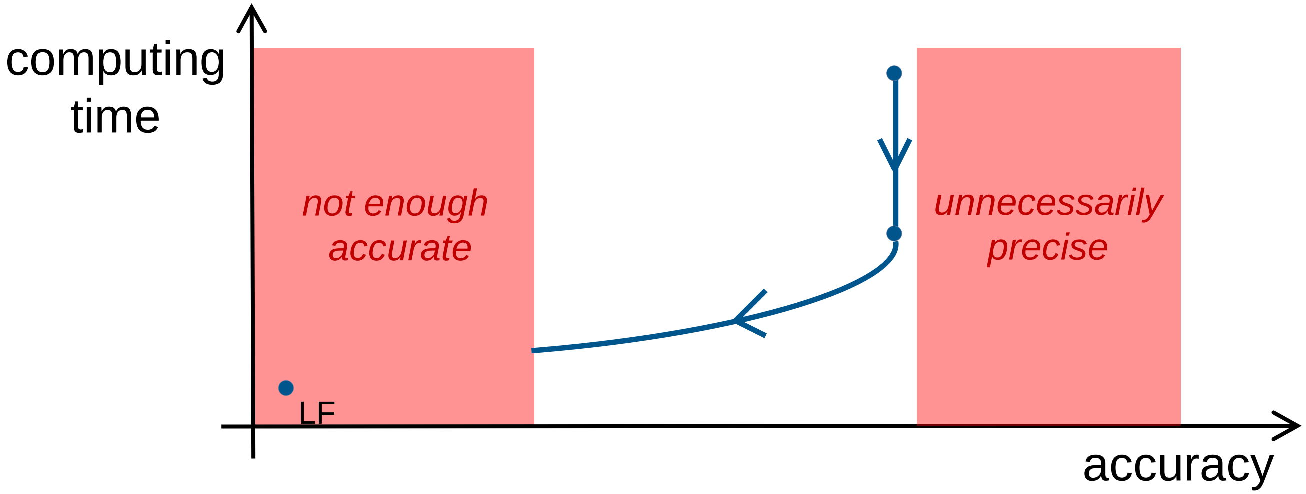
PEGASE

Purpose

- Dynamic Security Assessment (simulating responses to contingencies)
- Why time-domain simulation for security analysis ?
  - operation closer to stability limits, under the pressure of the market
  - unexpected power flow patterns, due to renewables
  - etc.
- Why not just power flow calculation ?
  - a static calculation that seeks a post-disturbance operating point; does not consider system evolution that may (or may not) lead to this point
  - secure operation will rely more and more on corrective (post-disturbance) controls $\Rightarrow$ need to consider the time sequence of events
  - may diverge, leaving no information

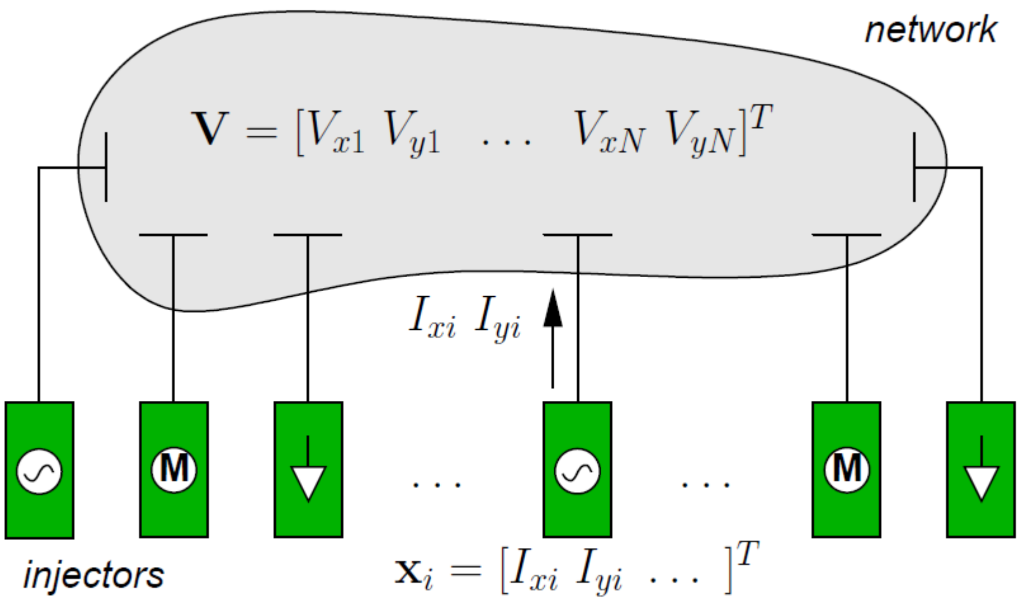
Challenge & overall approach

- Differential-Algebraic (DA) models are nonlinear, stiff and hybrid
- Time simulation of large-scale systems computationally heavy for DSA
  - even more since DSA requires simulating long-term dynamics (e.g. 5 to 10 min. of post-disturbance system evolution)
- Approach in PEGASE :
  - use the same model as for detailed simulation
  - develop a solver that speeds up computation and allows relaxing accuracy



Structure of model

$$\boxed{\mathbf{D}\,\mathbf{V} - \sum_{i=1}^{n} \mathbf{C}_i \mathbf{x}_i = \mathbf{g}(\mathbf{x}_1, \ldots, \mathbf{x}_n, \mathbf{V}) = \mathbf{0}}$$



to be solved

at each time step

by Newton method

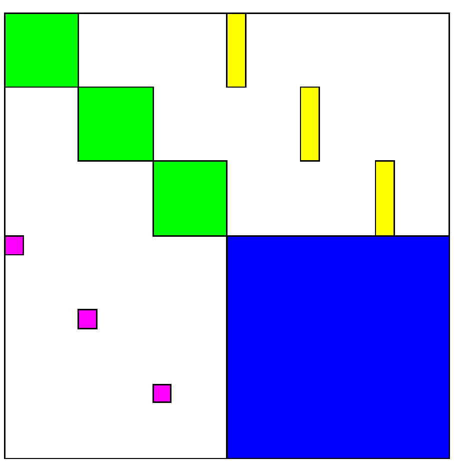
Each injector (i=1,…,n) : $\boldsymbol{\Gamma}_i\, \dot{\mathbf{x}}_i = \boldsymbol{\varphi}_i(\mathbf{x}_i, \mathbf{V})$

numerical integration over discrete time steps $\rightarrow$ $\boxed{\mathbf{f}_i(\mathbf{x}_i, \mathbf{V}) = \mathbf{0}}$

Newton iterations and structure of Jacobian

At k-th iteration, solve :

$$\underbrace{\begin{bmatrix} \mathbf{A}_1 & & & & \mathbf{B}_1 \\ & \mathbf{A}_2 & & & \mathbf{B}_2 \\ & & \ddots & & \vdots \\ & & & \mathbf{A}_n & \mathbf{B}_n \\ -\mathbf{C}_1 & -\mathbf{C}_2 & \dots & -\mathbf{C}_n & \mathbf{D} \end{bmatrix}}_{\mathbf{J}} \begin{bmatrix} \Delta\mathbf{x}_1 \\ \Delta\mathbf{x}_2 \\ \vdots \\ \Delta\mathbf{x}_n \\ \Delta\mathbf{V} \end{bmatrix} = - \begin{bmatrix} \mathbf{f}_1(\mathbf{x}_1^{k-1}, \mathbf{V}^{k-1}) \\ \mathbf{f}_2(\mathbf{x}_2^{k-1}, \mathbf{V}^{k-1}) \\ \vdots \\ \mathbf{f}_n(\mathbf{x}_n^{k-1}, \mathbf{V}^{k-1}) \\ \mathbf{g}(\mathbf{x}_1^{k-1} \dots \mathbf{x}_n^{k-1}, \mathbf{V}^{k-1}) \end{bmatrix}$$



bordered
block diagonal
structure

Decomposed Newton scheme

update and re-factorize (sub-)Jacobians as rarely as possible

and independently of each other !

network:

solve

$$\boxed{\left(\mathbf{D} + \sum \tilde{\mathbf{C}}_i \mathbf{B}_i\right)} \Delta \mathbf{V}^k = \mathbf{g}(\mathbf{x}_i^{k-1}, \ldots, \mathbf{x}_n^{k-1}, \mathbf{V}^{k-1}) - \sum \tilde{\mathbf{C}}_i \mathbf{f}_i(\mathbf{x}_i^{k-1}, \mathbf{V}^{k-1})$$

$$\mathbf{V}^k := \mathbf{V}^{k-1} + \Delta \mathbf{V}^k$$

skip injectors which have already converged

solve

$$\boxed{\mathbf{A}_i} \Delta \mathbf{x}_i^k = -\mathbf{f}_i(\mathbf{x}_i^{k-1}, \mathbf{V}^{k-1}) - \mathbf{B}_i \Delta \mathbf{V}^k$$

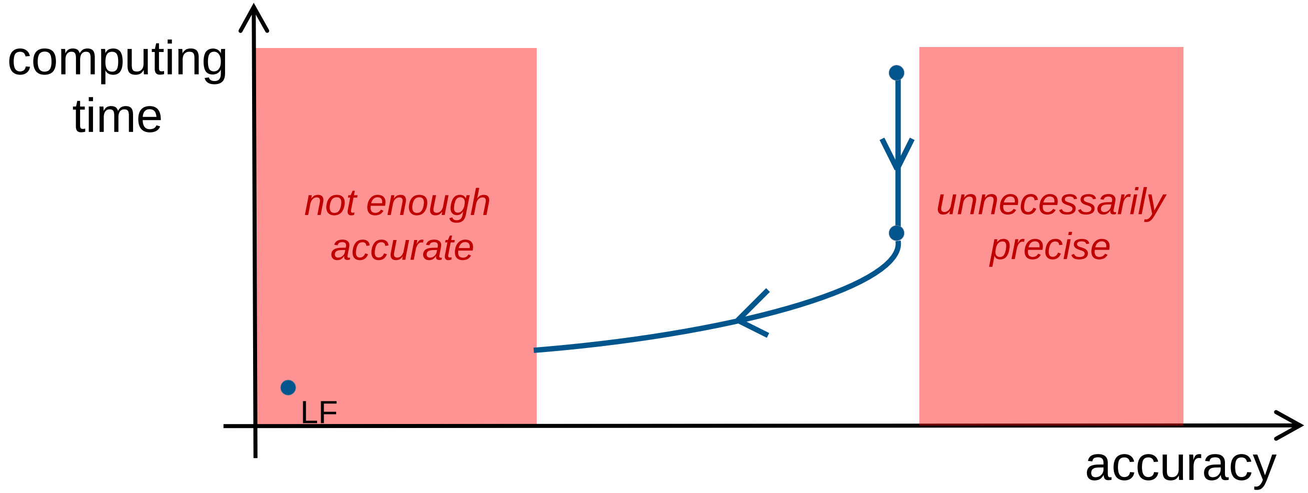
$$\mathbf{x}_i^k := \mathbf{x}_i^{k-1} + \Delta \mathbf{x}_i^k$$

convergence criteria satisfied?

Y → stop

N → $k := k + 1$

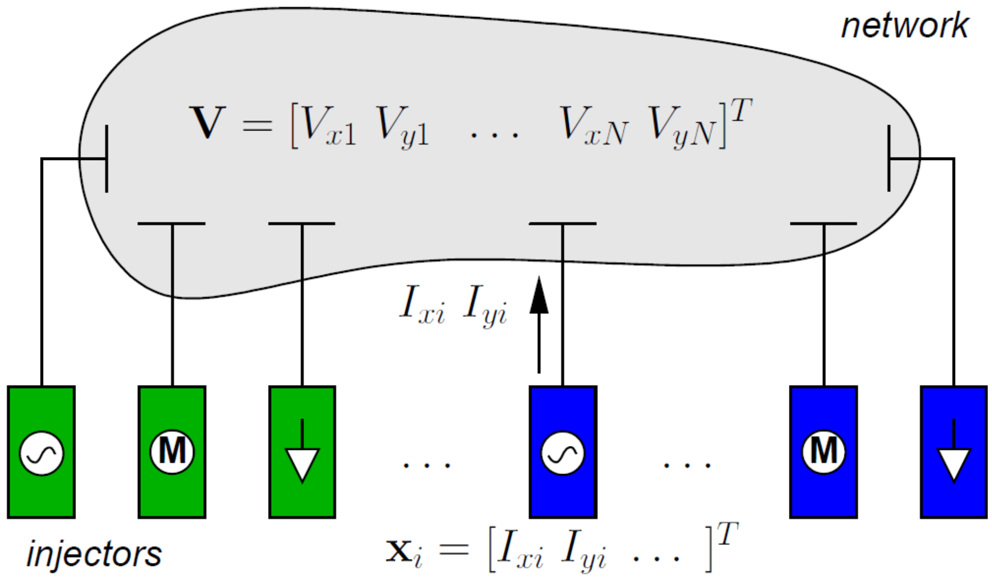
Relaxing accuracy of simulation



Relaxing accuracy

- in space → *localizing* the simulated system response
- in time → *time-averaging* the simulated system response

Localizing the simulated system response



active injectors

solved as in detailed simulation

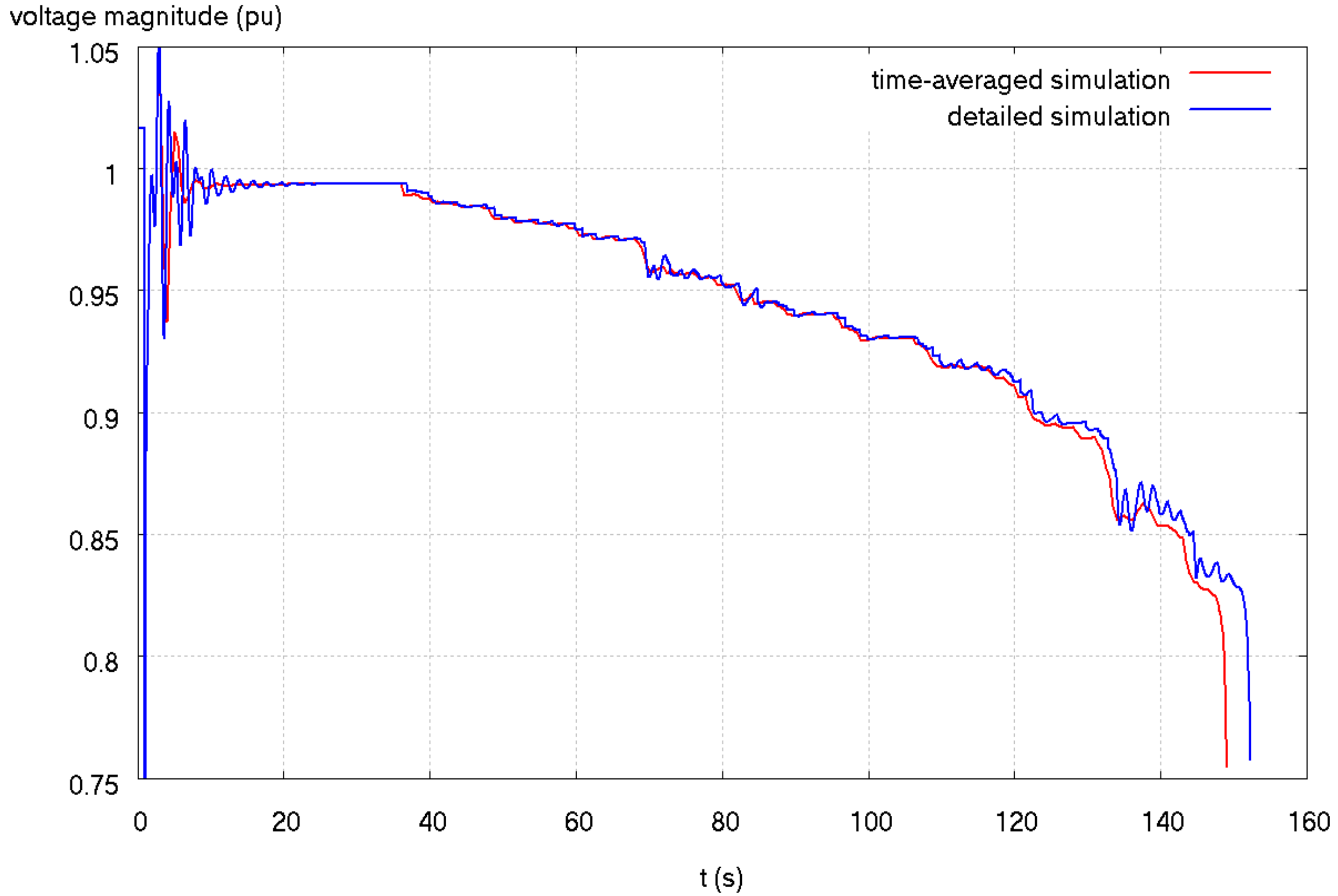
$$\mathbf{f}_i(\mathbf{x}_i, \mathbf{V}) = \mathbf{0}$$

latent injectors with lower participation in dynamic response

replaced by volt. dep. current source

$$\begin{bmatrix} I_x \\ I_y \end{bmatrix} = \begin{bmatrix} I_x^* \\ I_y^* \end{bmatrix} + \mathbf{S} \begin{bmatrix} V_x - V_x^* \\ V_y - V_y^* \end{bmatrix}$$

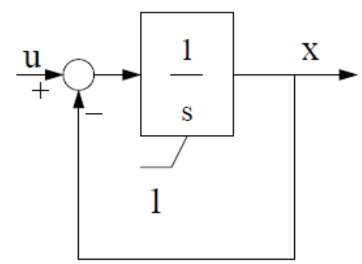
Time-averaging the simulated system response

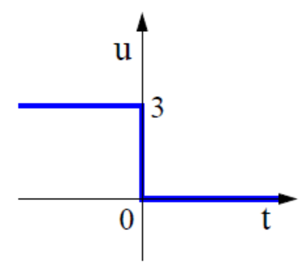


Integration with large step size "filters out" fast dynamics of lower interest

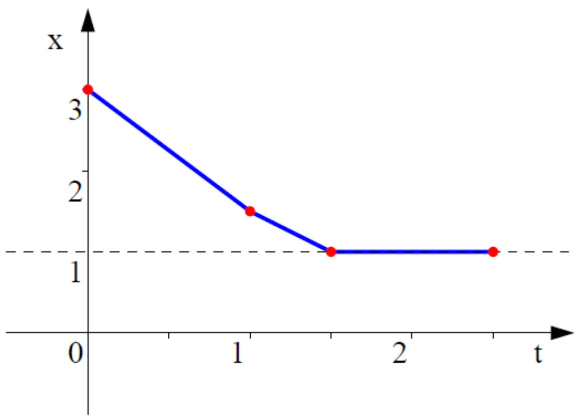
Implementation of time-averaging

- Integration method must have “stiff-decay” property (being implicit is not sufficient)
  - e.g. backward differentiation formulae of order 1 (backward Euler) or 2
  - hyper-stable numerical integration $\Rightarrow$ cannot detect oscillatory instability of filtered dynamics
- Proper handling of discrete (state) events

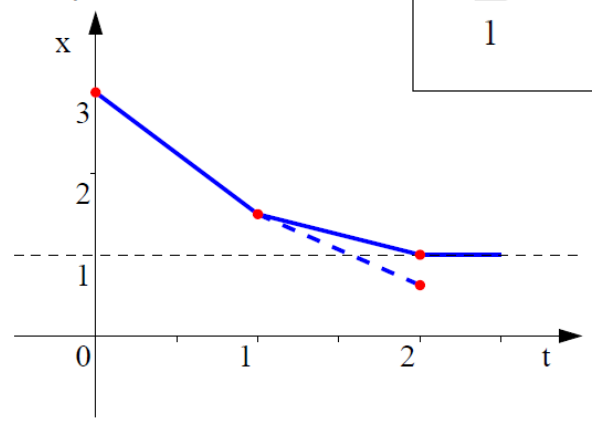




detailed



simplified



Example of results

PEGASE test system: **15226** buses **62293** differ. + **63946** algeb. variables

Response to double-line tripping simulated over 300 s

number of times	A	B	C	D	E
factorizing $\tilde{\mathbf{D}}$	1,255	18	16	25	29
solving for $\mathbf{\Delta V}$	14,259	14,465	6,109	823	774
evaluating $\mathbf{g}$	20,299	20,505	20,384	2,039	2,015
factorizing $\mathbf{A}_i$	7,145,970	193,604	203,453	67,125	54,357
solving for $\mathbf{\Delta x}_i$	81,190,746	82,363,710	37,710,892	4,856,017	714,194
evaluating $\mathbf{f}_i$	196,773,252	199,119,180	106,887,298	12,998,437	1,831,232
CPU time (s)	717	548	348	37	18

A detailed simulation - reference

B same as A with (sub-)Jacobians updated independently

C same as B with solutions of converged injectors skipped

D same as C with time steps of 0.5 s

E same as D with localization of response.

Conclusion

- Speed up of simulation with preserved accuracy
  - Decomposing the linear system to solve at each Newton iteration
  - Keeping the (sub-)Jacobians as constant as possible
  - Skipping iterations on already converged components
- Adjustable relaxation of accuracy
  - Localizing the simulated system response
  - Integrating with larger time steps + handling of discrete events

- Validation on large-scale model typical of pan-European grid
- In terms of efficiency, DSA comes closer to static security analysis
- Implemented in a prototype based on Eurostag.

Thank you for your attention !

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