On real-time predictive voltage stability monitoring

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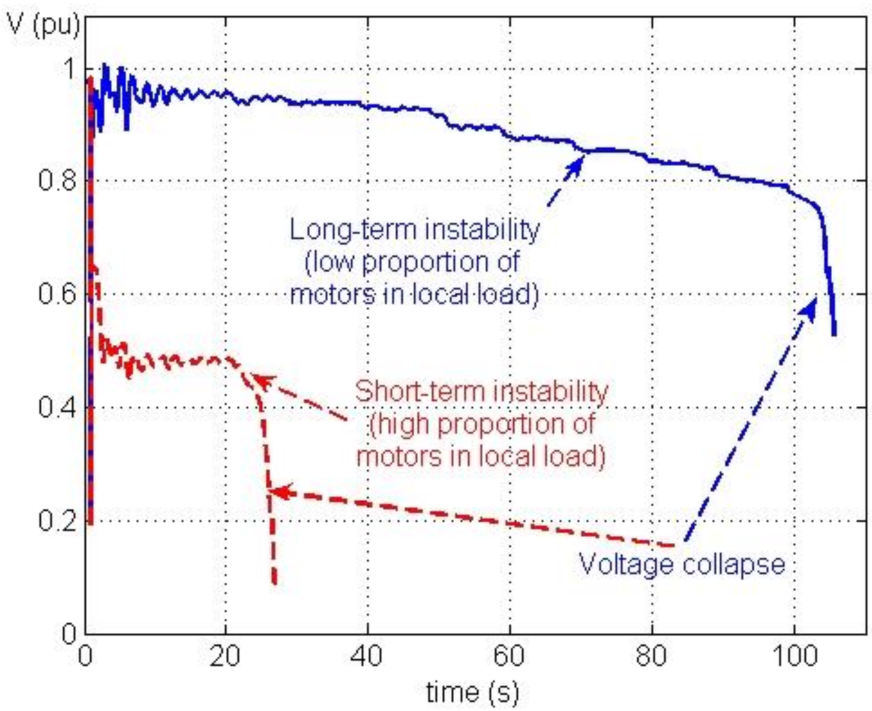
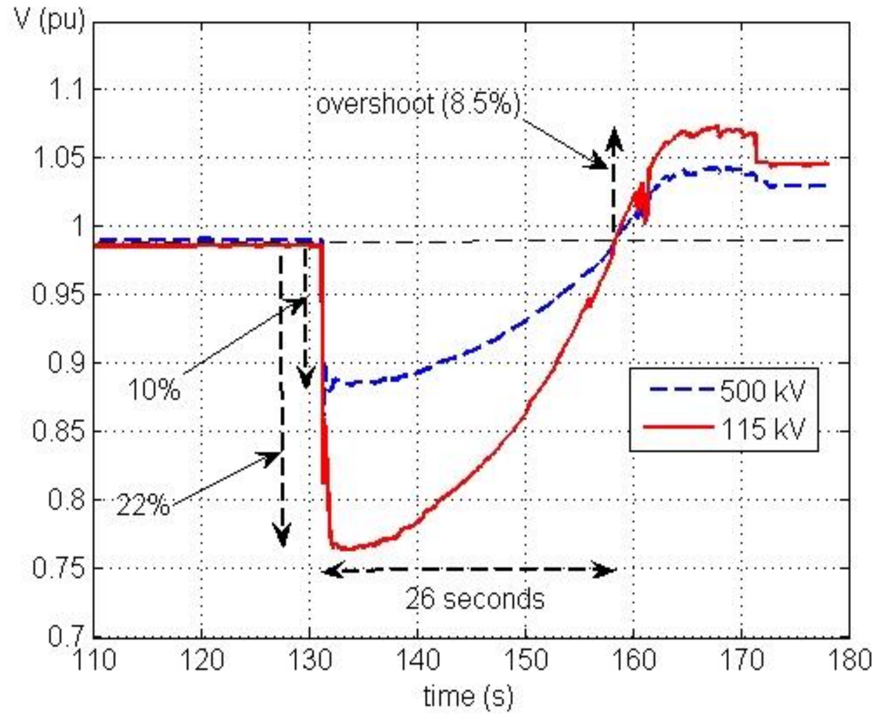
DTU, Lyngby, DENMARK
April 8, 2015

In this presentation:

- Review of R&D approaches for voltage stability monitoring (model-free or measurement-based),
- Identify those with potential to provide predictive capability,
- Hybrid voltage stability monitoring (model-free + contingency analysis),
- Faster tracking of network states and uses for predictive voltage stability monitoring,
- Identify some research opportunities.

Reminder: problems, definitions





- **Voltage stability refers to the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating conditions.**
- **FIDVR is the phenomenon whereby system voltage remains at significantly reduced level for anywhere between several seconds to several tens of seconds after a transmission, sub-transmission, or distribution fault has been cleared.**

Is voltage (in)stability still important?

- **YES, more than ever:**

  - this phenomenon has contributed to a number of recent major blackouts/brownouts,

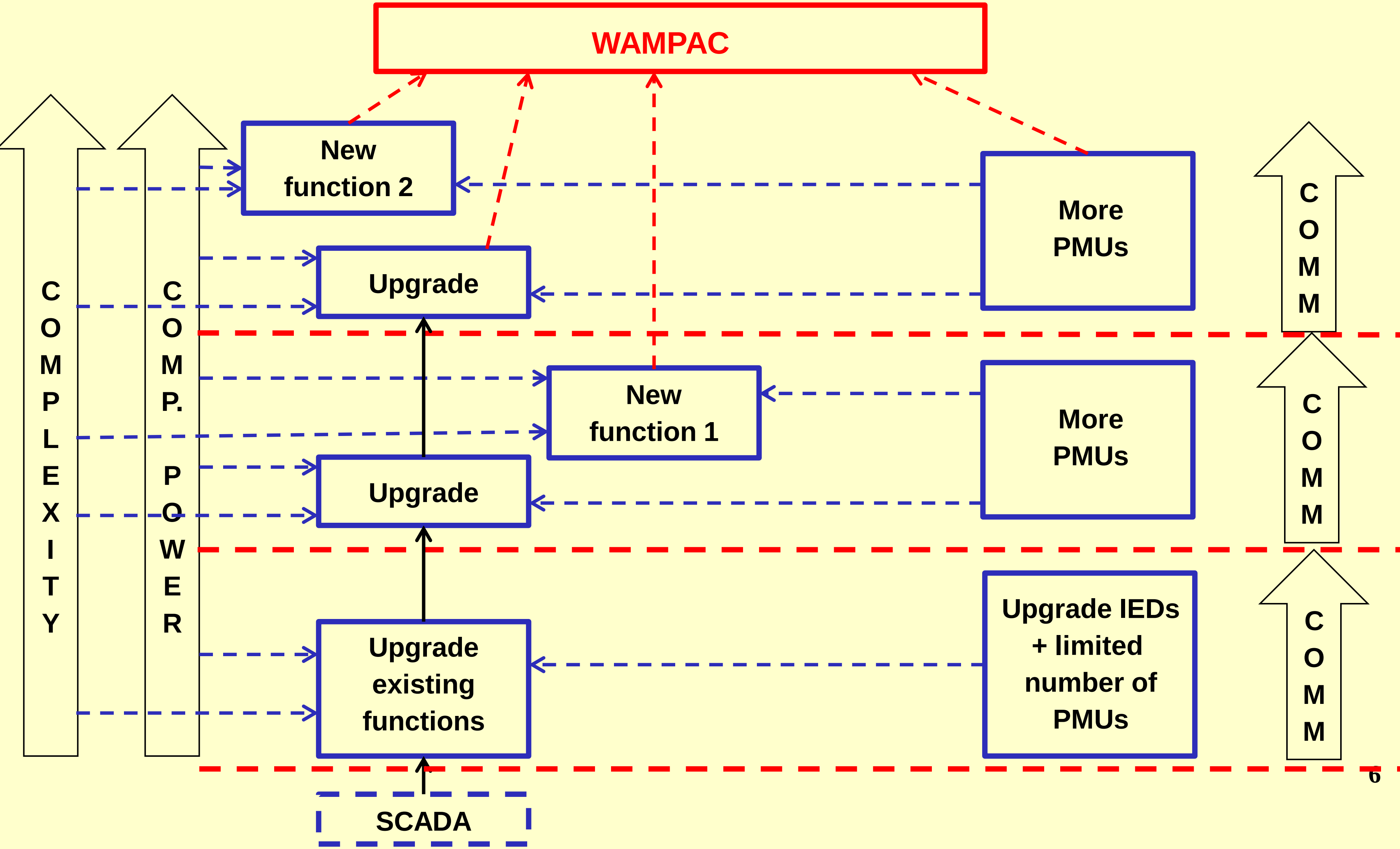
  - growing interest from industry for real applications (accelerated partly by more and more presence of PMUs),

  - industry interests focused on: predictive capability, ease to implement and interpret,…

Industry: known and expected problems

- Western France (voltage instability, known for decades),
- Region of Marseille (low voltages, voltage instability),
- Germany (heavy transfer over long distances),
- The Netherlands (heavy transfer over long distances),
- BPA (USA): voltage instability and FIDVR,
- PG&E (USA): voltage instability (heavy transfers over corridors),
- SCE (USA): FIDVR,
- SDG&E (USA): voltage instability, FIDVR,
- Hydro-Quebec: voltage instability.

Likely development

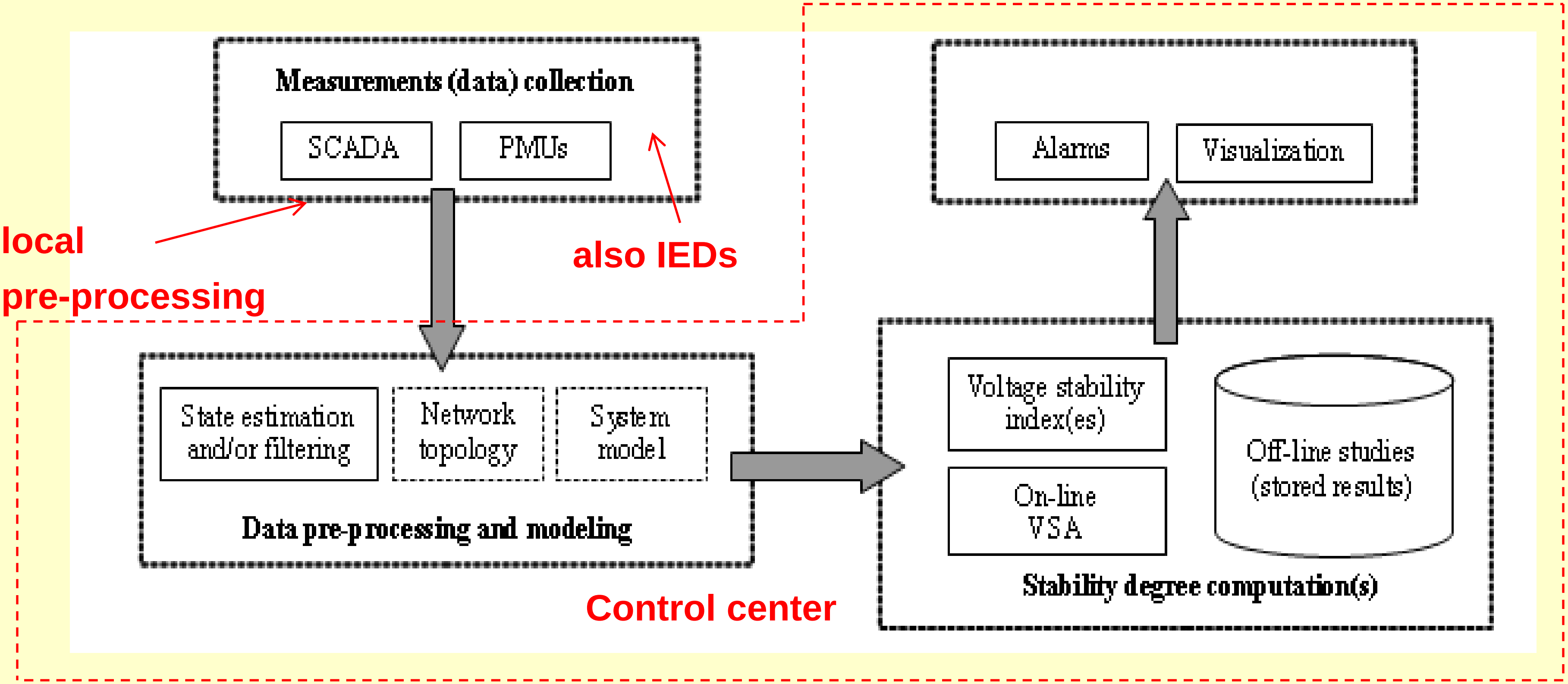


Challenges in voltage stability monitoring

- **Do better than simple monitoring of voltage magnitudes:**
  - **some methods detect instability when voltages are obviously very low.**

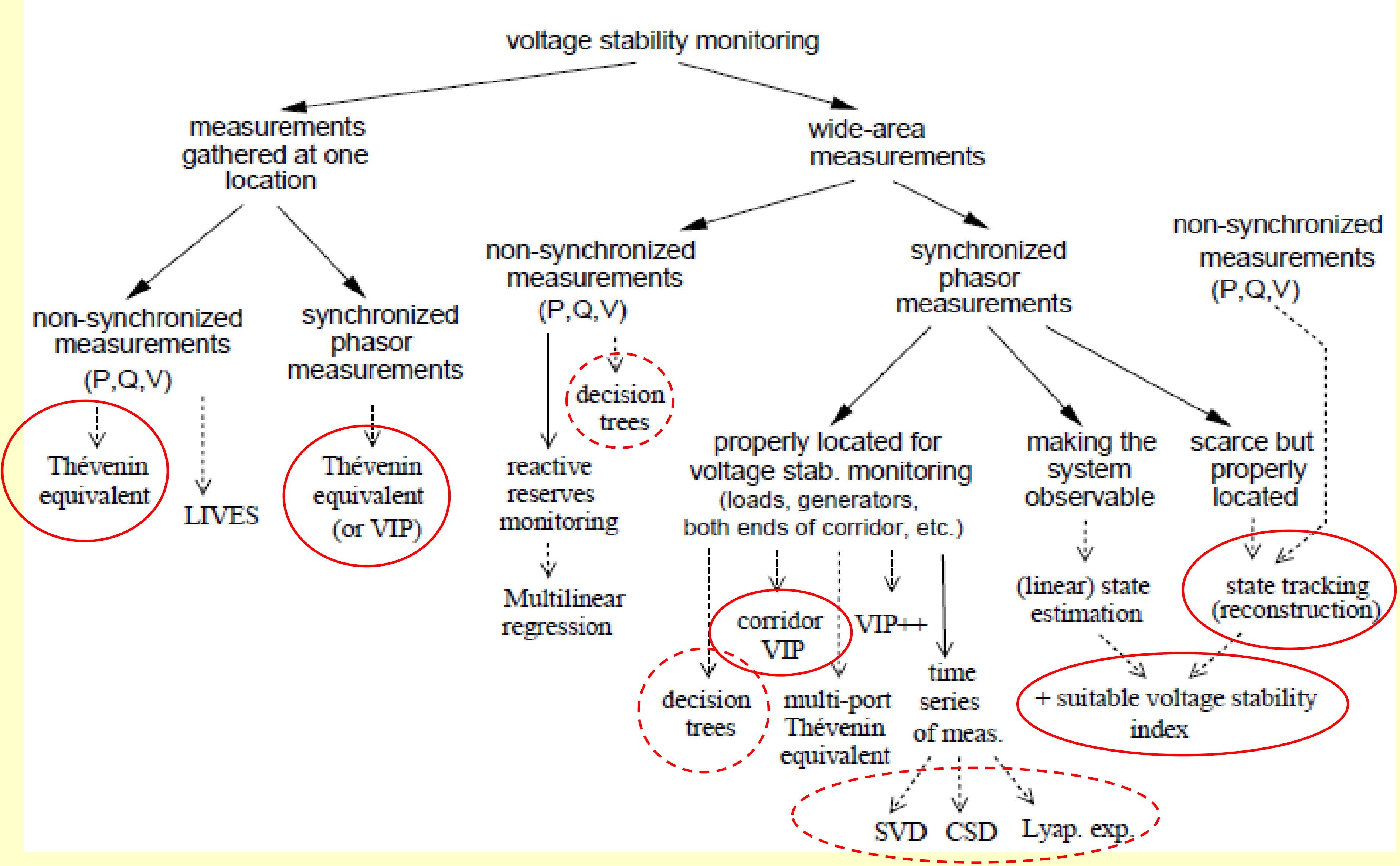
- **Deal with the system evolution after a large disturbance:**
  - **a majority of voltage instability incidents caused by sever outages,**
  - **smooth load increase can be dealt with preventive VSA.**

Real-time VS monitoring: general



- **Measurement configuration:** should be able to capture all relevant changes (does not necessarily mean huge number of measurements?).
- **Do we have enough measurements: YES** but they offer different spatial and temporal view of the system (SCADA good spatial – limited temporal, while IEDs and PMUs offer better temporal but local view of the system).

A review of existing VS monitoring approaches (model-free)



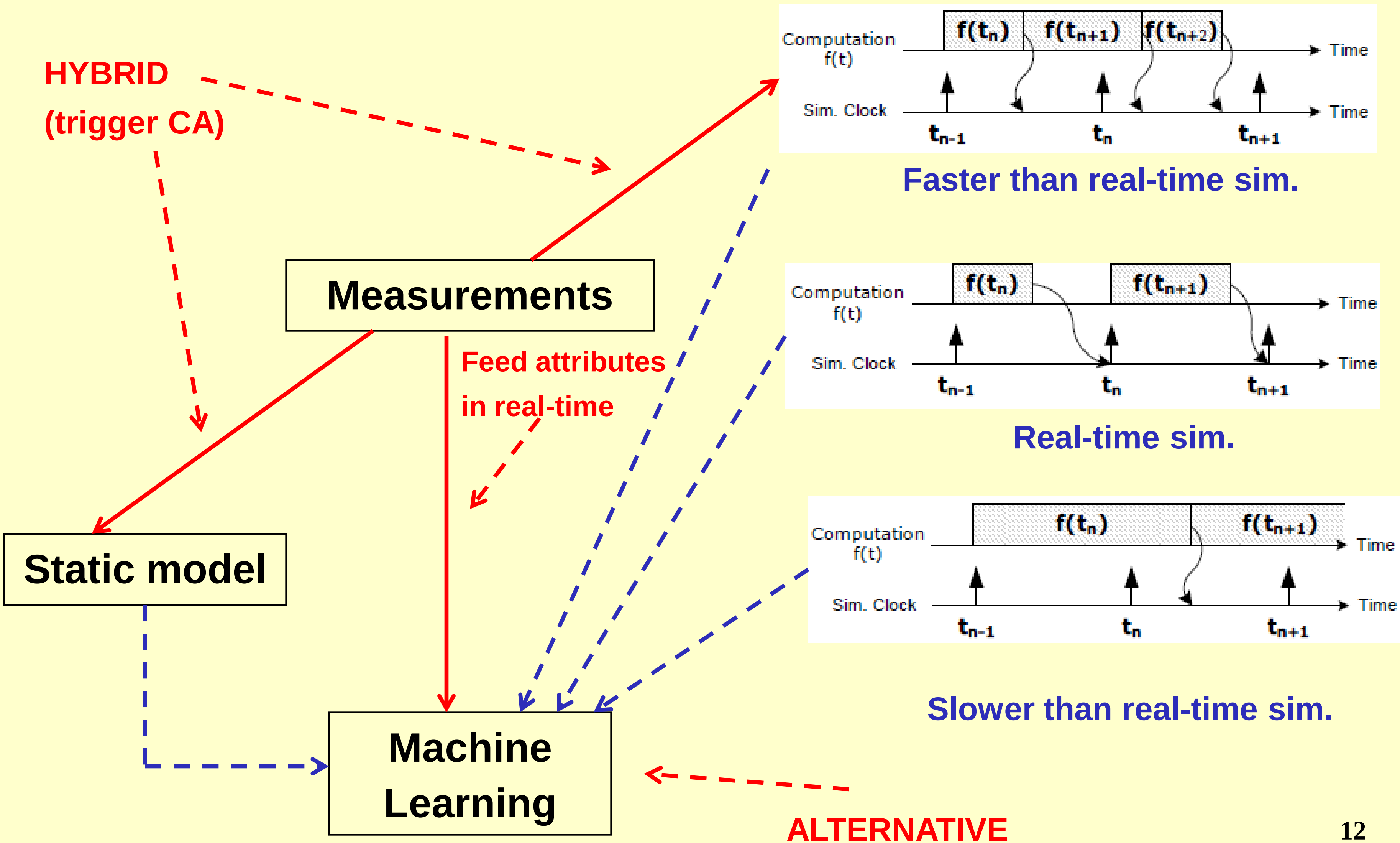
Some observations on model-free methods

- Most of them useful when limited number of measurements is available,
- Measurement devices should be placed at right location(s),
- Sort of prediction: early warning signal (as with Critical Slowing Down (CSD)) or extrapolation (Thevenin equivalent),
- What is missing with some of methods (CSD, SVD of measurement matrix, Lyapunov exponents) is demonstration on larger and real-life systems.

Which type of prediction - 1?

- Most adopted notion of prediction in power systems is contingency analysis.
- Consequently, combining a model-free monitoring scheme with contingency analysis is promising.
- Core idea: use a model-free approach for continuous monitoring and if a pre-defined threshold is reached trigger contingency analysis.
- On the use of CA and an alternative (next slide)…

What type of prediction - 2?



About the use of Machine Learning -1

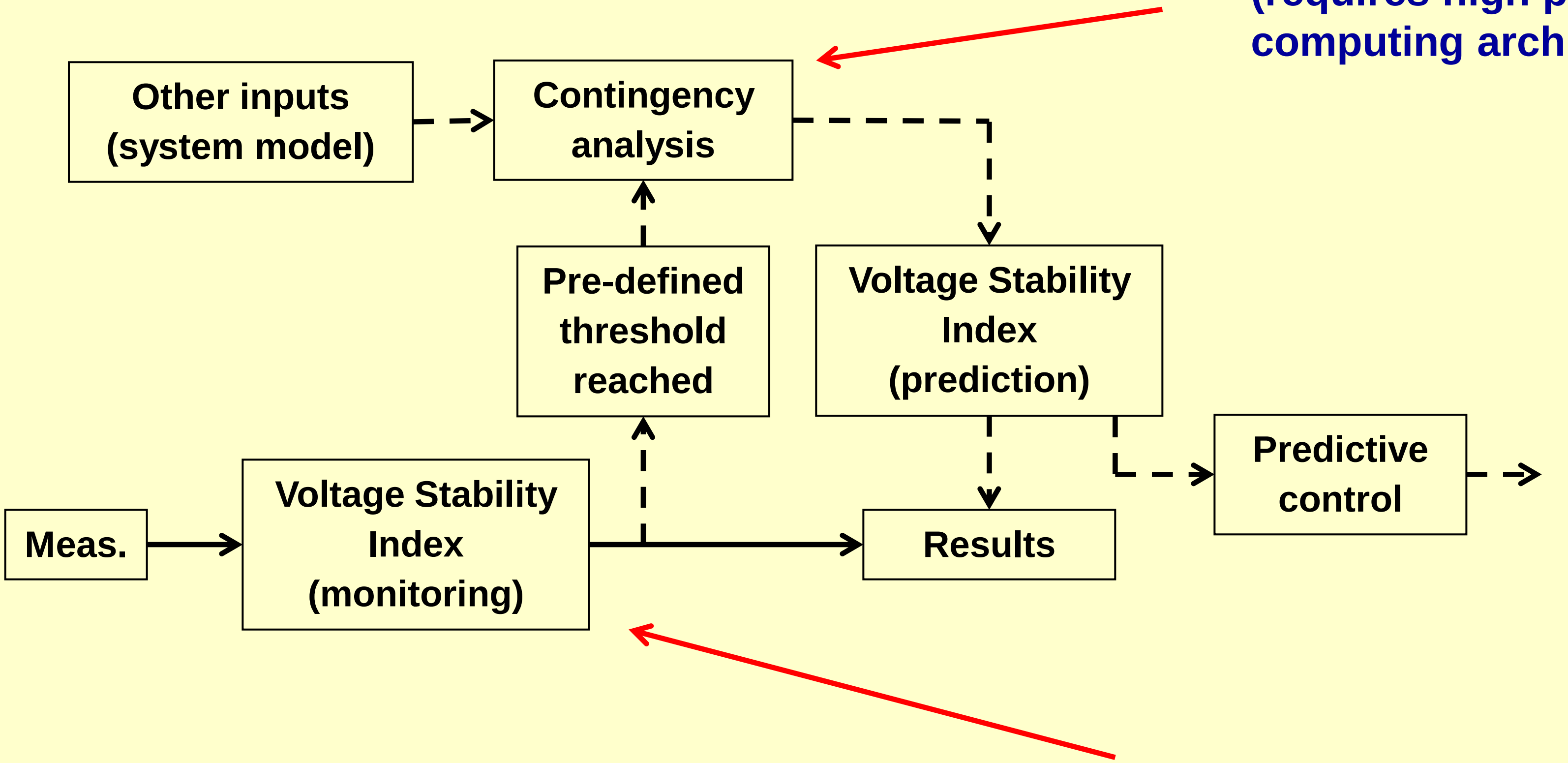
- Obvious “winner”: Decision Trees (research considerations exist, evidence with real-life systems exists, real-life applications ongoing),
- Few considerations (only research) of ANNs,
- DTs do not necessarily require good temporal view measurements but indeed make use of them,
- A major practical issues: the choice of attributes and setting up representative learning set…

About the use of Machine Learning -2

- **Suggested attributes (with PMUs):**
  - squares of bus voltages,
  - reactive power flows in lines,
  - current in lines,
  - generator reactive powers,
  - combinations of above, …

- **Predictions based on all nodes of the related path of the DTs (not only on the terminal nodes)**

Predictive VSM: hybrid approach (with dynamic model)



- Full dynamic model (requires high performances computing architectures).

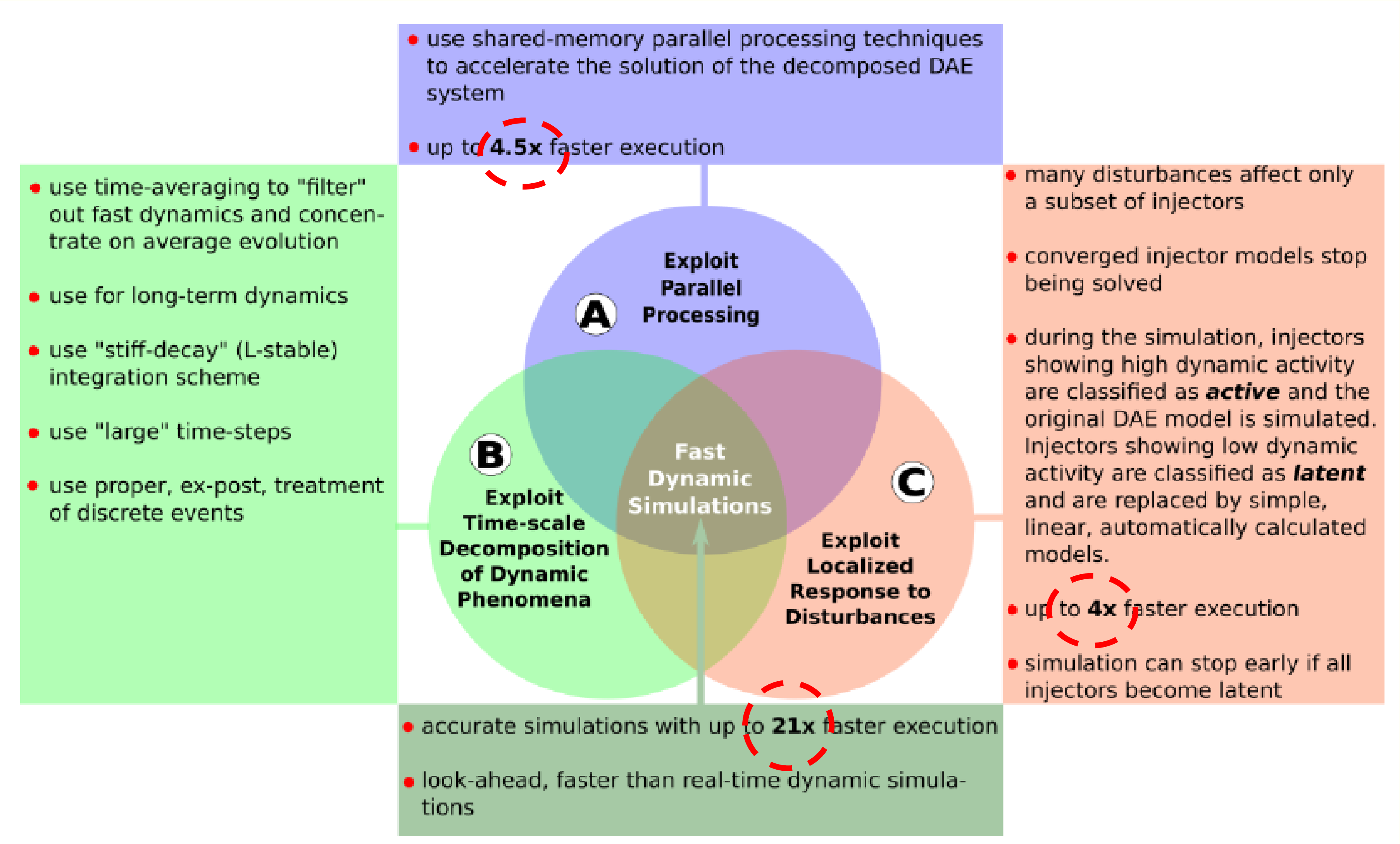
- Any appropriate index can be used. However the preferences go with:
  - Simplicity,
  - Easiness to implement and interpret.

Faster than real-time dynamic simulation

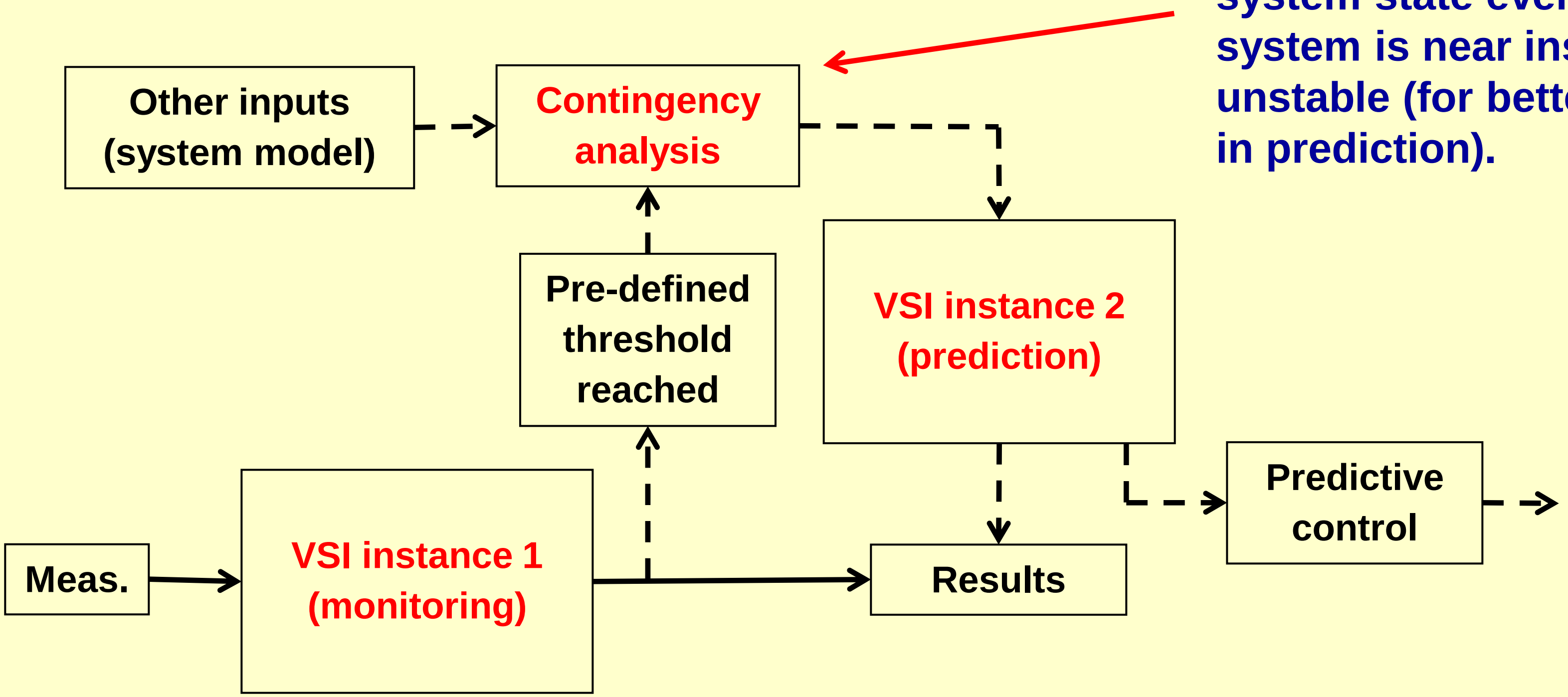
- **Use of stronger computational architectures (multi-cores, multi-processors, clusters,…),**
- **Parallelization (CA is easy to parallelize),**
- **Many existing tolls upgraded for taking advantage of stronger computational power,**
- **Some figures about faster simulations from ULg follow (next slide).**

Faster than real-time dynamic simulations (ULg)

Thierry Van Cutsem and Petros Aristidou



Predictive VSM: hybrid approach with static models



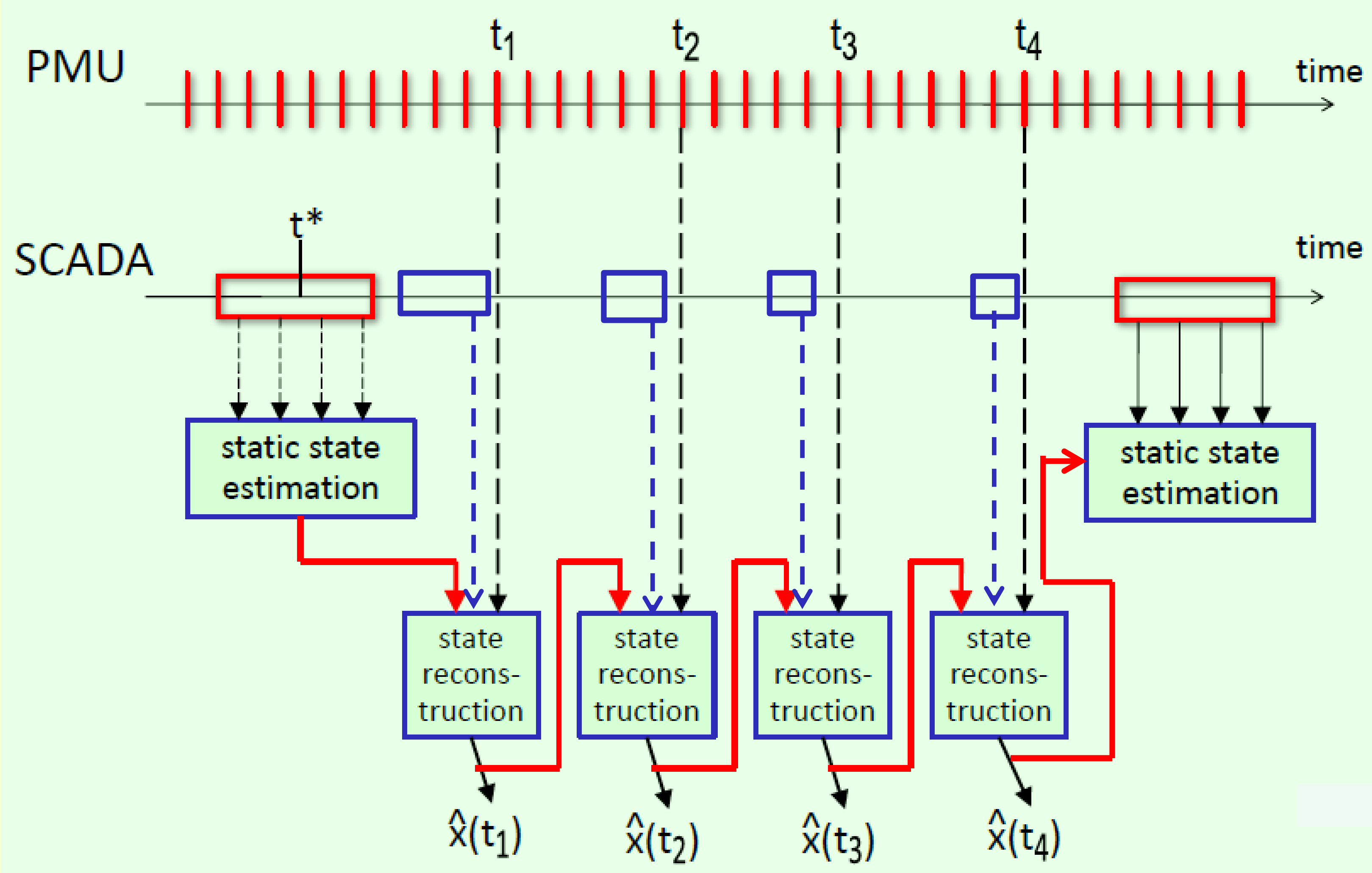
- Static model able to compute system state even when the system is near instability or unstable (for better accuracy in prediction).

- Target applications:
  - long-term voltage stability,
  - FIDVR,
  - promises to use it even for short-term stability.

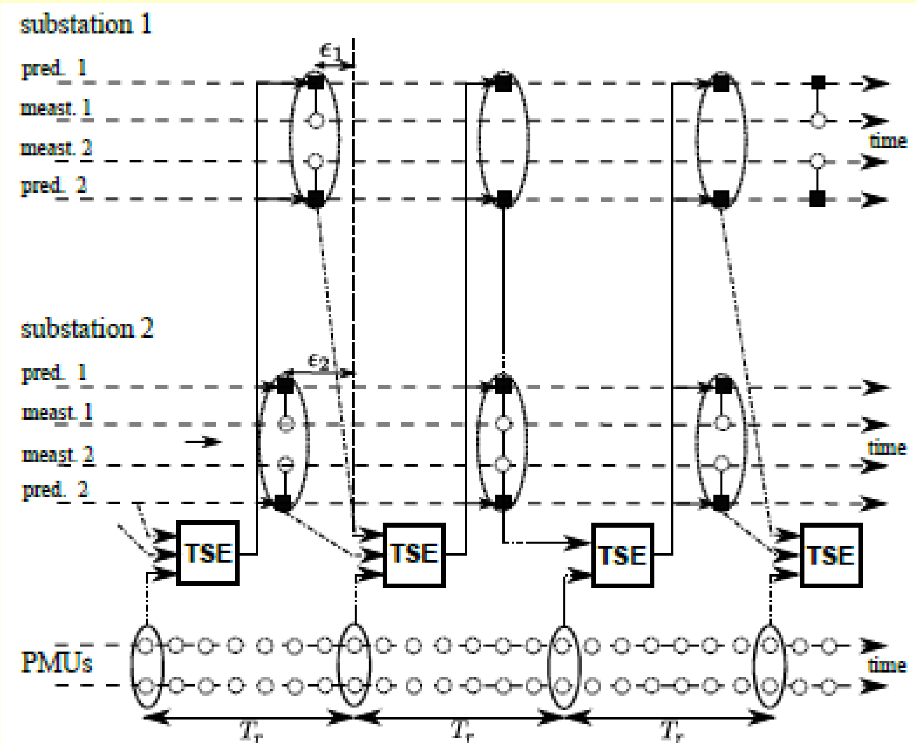
Static models for CA

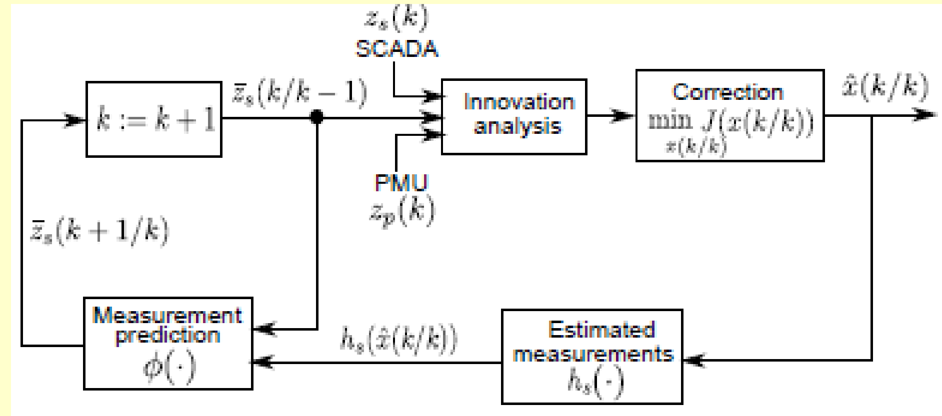
- As with dynamic simulations, use of stronger computational architectures,
- Parallelization (CA is easy to parallelize),
- Static models able to find solution even for unstable conditions,
  - Power flow with AQ bus type (to avoid Jacobian singularity at voltage instability point),
  - Efficient continuation power flow + boundary orbiting to compute VS boundary (PNNL),
  - …

State reconstruction, tracking SE - 1



State reconstruction, tracking SE -2





Analogy with (extended) Kalman filter

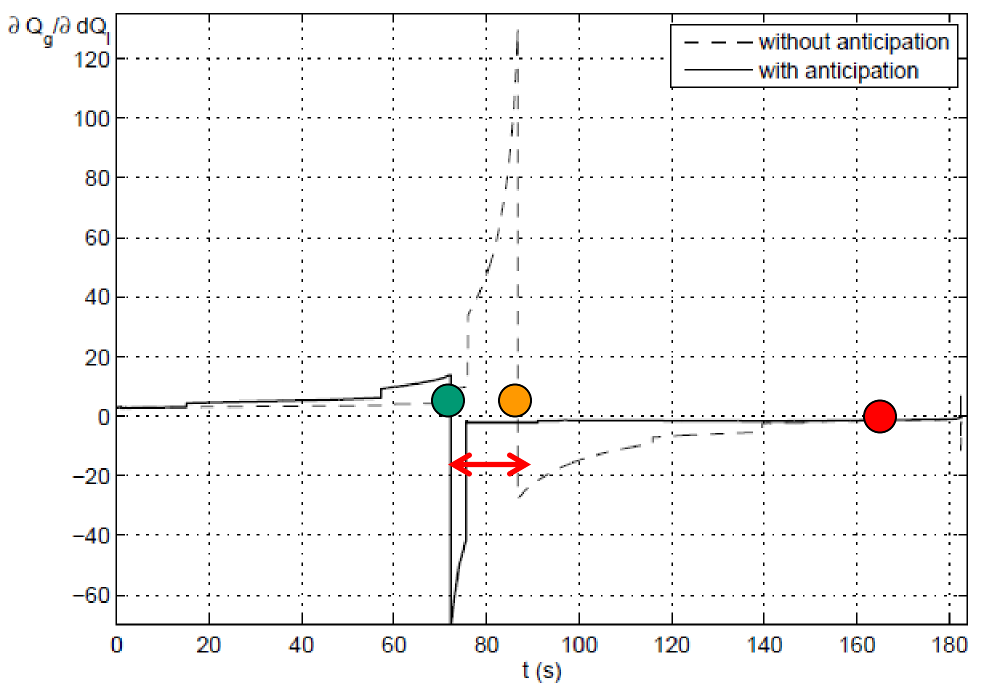
$$
\begin{aligned}
J(\boldsymbol{x}(k/k)) = \; & \frac{1}{2}\underbrace{[\boldsymbol{z}_s(k) - \boldsymbol{D}_k\boldsymbol{h}_s(\boldsymbol{x}(k/k))]^T \boldsymbol{D}_k \boldsymbol{R}^{-1} \boldsymbol{D}_k^T [\boldsymbol{z}_s(k) - \boldsymbol{D}_k\boldsymbol{h}_s(\boldsymbol{x}(k/k))]}_{\text{SCADA measurements}} \\
+ \; & \frac{1}{2}\underbrace{[\boldsymbol{z}_p(k) - \boldsymbol{h}_p(\boldsymbol{x}(k/k))]^T \boldsymbol{U}^{-1} [\boldsymbol{z}_p(k) - \boldsymbol{h}_p(\boldsymbol{x}(k/k))]}_{\text{PMU measurements}} \\
+ \; & \frac{1}{2}\underbrace{[\bar{\boldsymbol{z}}_s(k/k-1) - \boldsymbol{h}_s(\boldsymbol{x}(k/k))]^T \boldsymbol{M}^{-1} [\bar{\boldsymbol{z}}_s(k/k-1) - \boldsymbol{h}_s(\boldsymbol{x}(k/k))]}_{\text{predicted SCADA measurements}}
\end{aligned}
$$

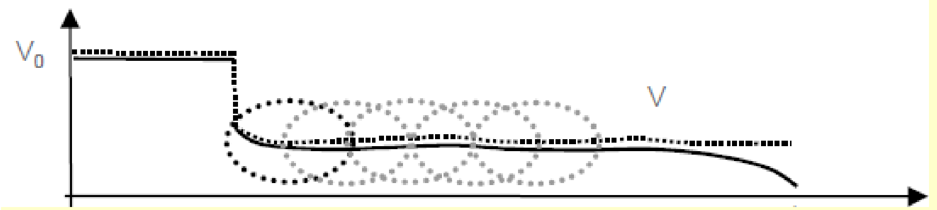
Hachtel's augmented matrix method used to solve TSE

What we can do with TSE -1 ?

- Provide a CA tool with initial snapshot,
- Provide a CA tool with updated load parameters,
- Provide a good initial guess for traditional SE called upon request, and further a snapshot for a CA tool,
- Anticipate generation limitations (OXL limits),
- Anticipate load response,
- …

What we can do with TSE -2 ?





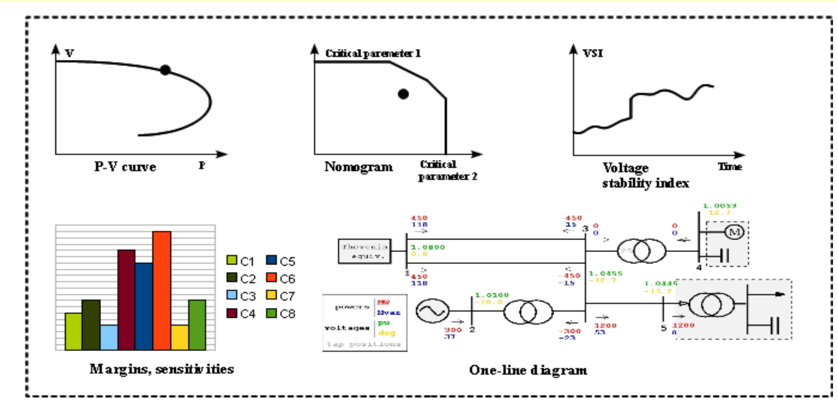
$$S_{Q_g\mathbf{q}} = -\varphi_{\mathbf{q}}^T \left(\varphi_{\mathbf{z}}^T\right)^{-1} \nabla_{\mathbf{z}} Q_g$$

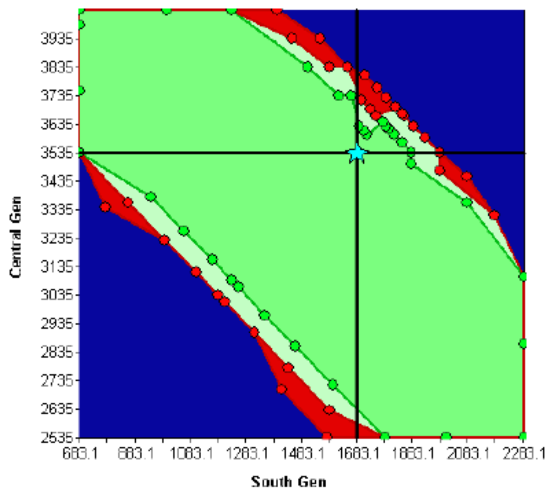
Anticipation of load response (pending)

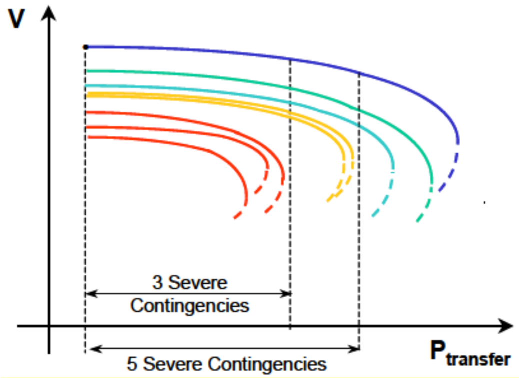
Anticipation of OXL limit (finished)

Also pending: investigate how the model used for sensitivity computation can be extended to be useful for fast CA.

On visualization

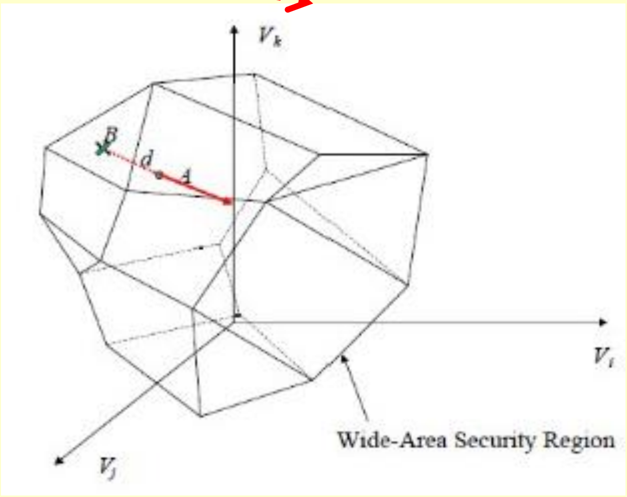


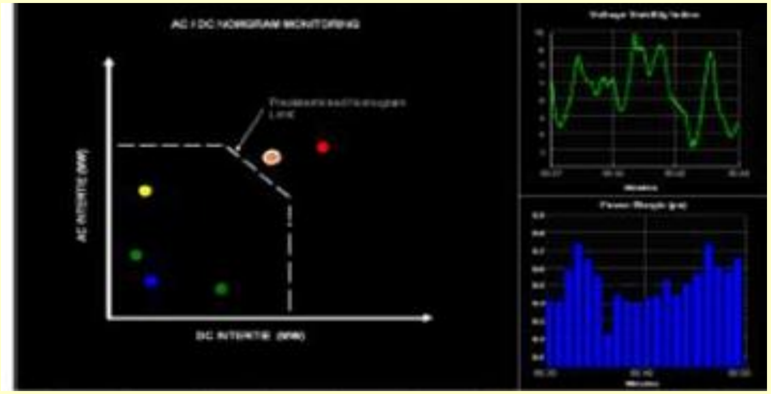




Sources:

- **PowerTech Labs,**
- **PNNL**





Some research questions (personal view)

- How about the use of Statistical Process Control techniques for monitoring and prediction?
- Why not further check some success stories in other engineering fields (Online Failure Prediction Methods)?
- How about some other early warnings of system transitions methods (again some other fields might offer good ideas)?
- Why not using temporal DTs (some work done at ULg some time ago but never completed)?
- …

Some useful links

- www.pserc.wisc.edu
- www.dsatools.com (PowerTech Labs),
- ei.pnnl.gov (Pacific Northwest National Laboratory),
- curent.utk.edu (Center for Ultra-wide-area Resilient ENergy Transmission networks),
- www.naspi.org (North American Synchrophasor Initiative),
- orbi.ulg.ac.be
- …

Thank you for your attention!

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