Invited Plenary Talk:
System Identification Applications in Power System Stability Monitoring and Modeling

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Outline

- **Generalities**
- About Me (Luigi)
- Recruiting for ALSETLab

- **Introduction**
  - Need for monitoring and modeling in power systems
  - Power System Dynamics

- **Part 1: How to Monitor Power System Dynamics?**
  - Electromechanical Mode Estimation
  - Real-Time Application
  - Nordic Case Study
  - Forced Oscillations
  - Damping Estimate Corruption

- **Part 2: How to improve mode estimation?**
  - Covariance Matrix Computation
  - Input (probing) signal design

- **Part 3: How to validate models?**
  - Modelica
  - The OpenIPSL Library
  - The RaPId Toolbox
  - Parameter estimation
  - Model calibration

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About Me - http://ALSETLab.com - Dr. Luigi!

YOB.
1981
Guatemala

2000 – 2005.
5 year Electrical Power Engineering program @ Universidad de San Carlos de Guatemala.

Fall 2004
Intern at INDE (National Electrification Institute), Substations Engineering

Visiting Researcher @ The University of Glasgow, Scotland

2006 – 2009
MSc and PhD @ RPI

2010
Post-Doc @ RPI

2010 – 2017, KTH Royal Inst. Of Tech., Stockholm, Sweden
2010: Associate Professor
2012: Docent (Habilitation)
2013: Associate Professor ('tenured')

2011 – 2017, SmarTS Lab. Research Group

2011 -External Scientific Advisor (Consultant)

2011 – 2016
Special Advisor
R&D Division

2016 - 2017
Consultant.

All @ Statnett SF, Oslo, Norway (Power System Operator)

Rensselaer

Other facts and numbers:

- Guatemalan and Italian Citizenships.
- Speak/write Spanish (native), English, Italian (spoken, poorly written), Norwegian (Basic)
- 36 years, married (March 4th, 2017) - no kids yet… but really want a dog!
- *Lived in 4 countries, worked in 5…*

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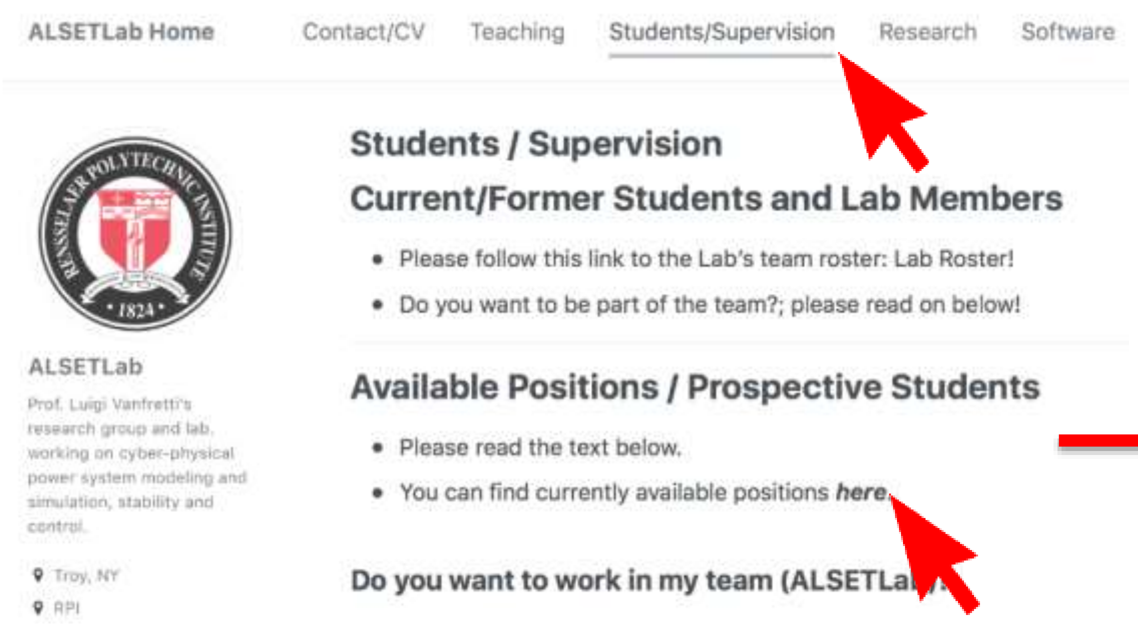
Recruiting! @ ALSETLab

- I'm looking for graduate students to join my team!
- If you know someone that would be interested, please tell them to check my website and to get in touch with me! (OR let me know after the talk!!!)
- See: http://ALSETLab.com



- Work on the development of applied system identification methods for power system model validation.
- Work on the development of a time-sensitive experimental platform and design of experiments for synchrophasor applications.

A Fundamental Question:
Why do we develop models and take measurements?

- To reduce the lifetime cost of a system
  - ***In requirements:*** trade-off studies
  - ***In test and design:*** fewer proto-types
  - ***In training:*** avoid accidents
  - ***In operation:* anticipate problems!**
    - Crucial for electrical power systems!
    - **Measurements:** monitor and control the system. Validate and calibrate models.
    - **Simulations:** anticipate!

- (1910) The prospective pilot sat in the top section of this device and was required to line up a reference bar with the horizon.
- 42% of the British pilots who died in WW1 were killed in training [Jones, Dr.]

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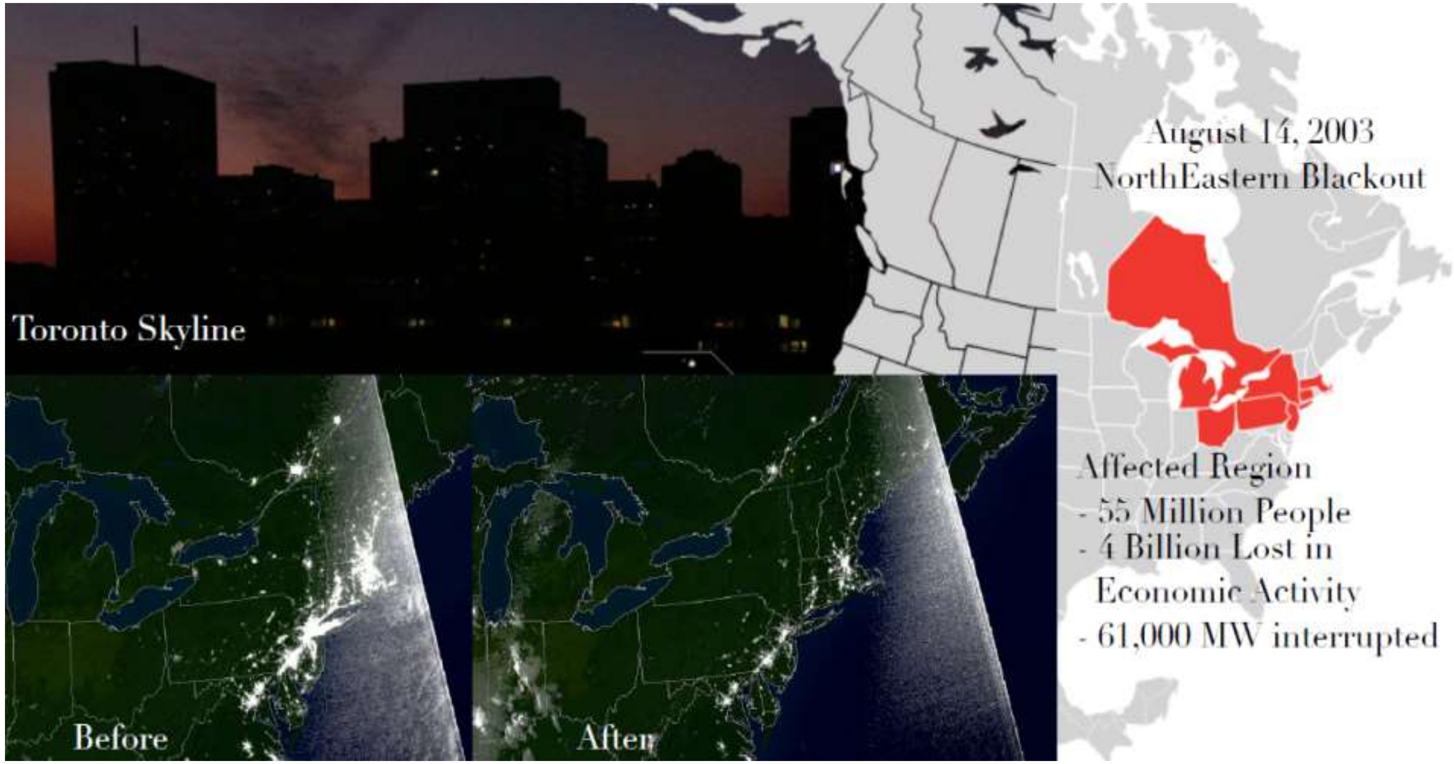
A *Failure* to Anticipate → Huge Costs!

There are many examples of failures to anticipate problems in power system operation!



Others: WECC 1996 Break-up, European Blackout (4-Nov.-2006), London (28-Aug-2003), Italy (28-Sep.-2003), Denmark/Sweden (23-Sep.-2003)

Challenges:

- Lack of ability to model (and to validate models) accurately power system phenomena
- Lack of ability to monitor and learn from measured data.
- System Identification offers a unique toolbox to deal with these challenges!
- BUT: IT **has to be applicable by domain engineers!**

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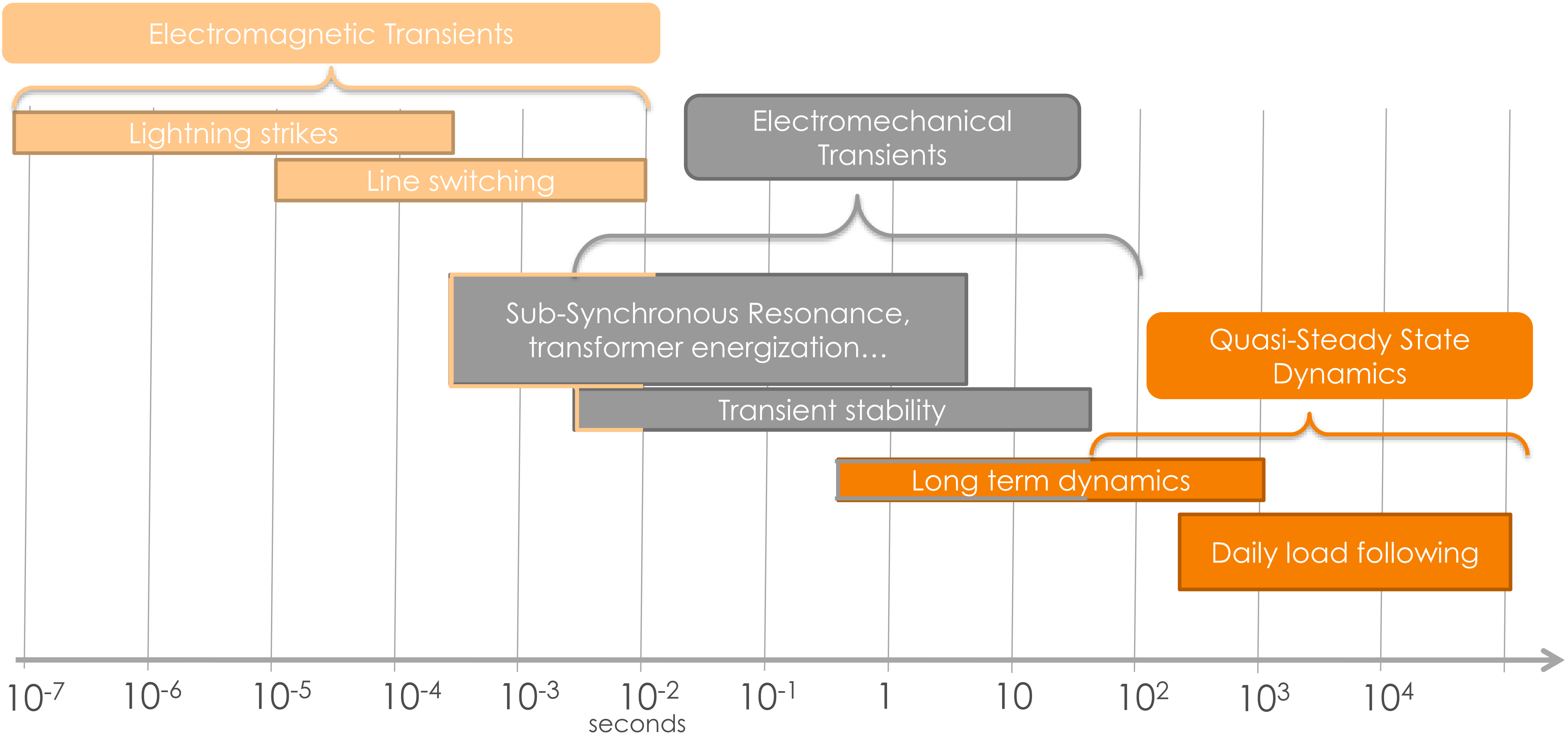
Power System Phenomena

@ different time-scales



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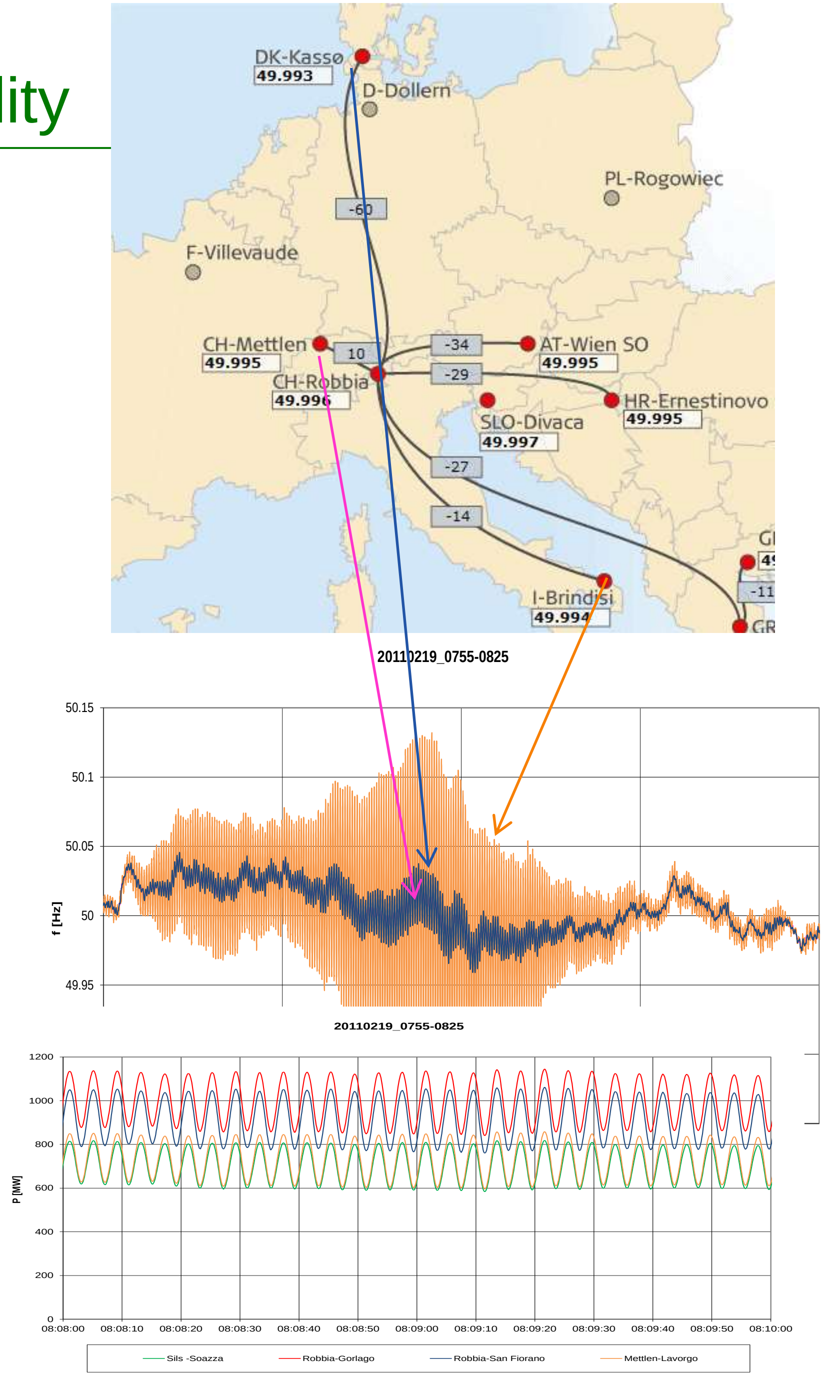
Types of Power System Phenomena:
Wide-Area Behavior – Transient and Small-Signal Stability

- **Transient (and 'dynamic') Stability**
- The ability of a power network to survive (overcome) the transition following a large disturbance and reach an acceptable operating condition is called **transient stability.**
- Transient-stability-type models are also called "power system dynamic models", and they are suitable to analyze common properties of a power system across large geographical regions.
- Such phenomena involves large energy exchanges between rotating inertias in machines across transmission lines, which are reflected in "power system oscillations'
- Methods to analyze these oscillations can exploit the power system models to a great extent.
- When the models can be linearized, eigenanalysis tools can be applied and the state-space / transfer function representation of the system (or portions of it) can be obtained, allowing the application of system identification theory and tools.



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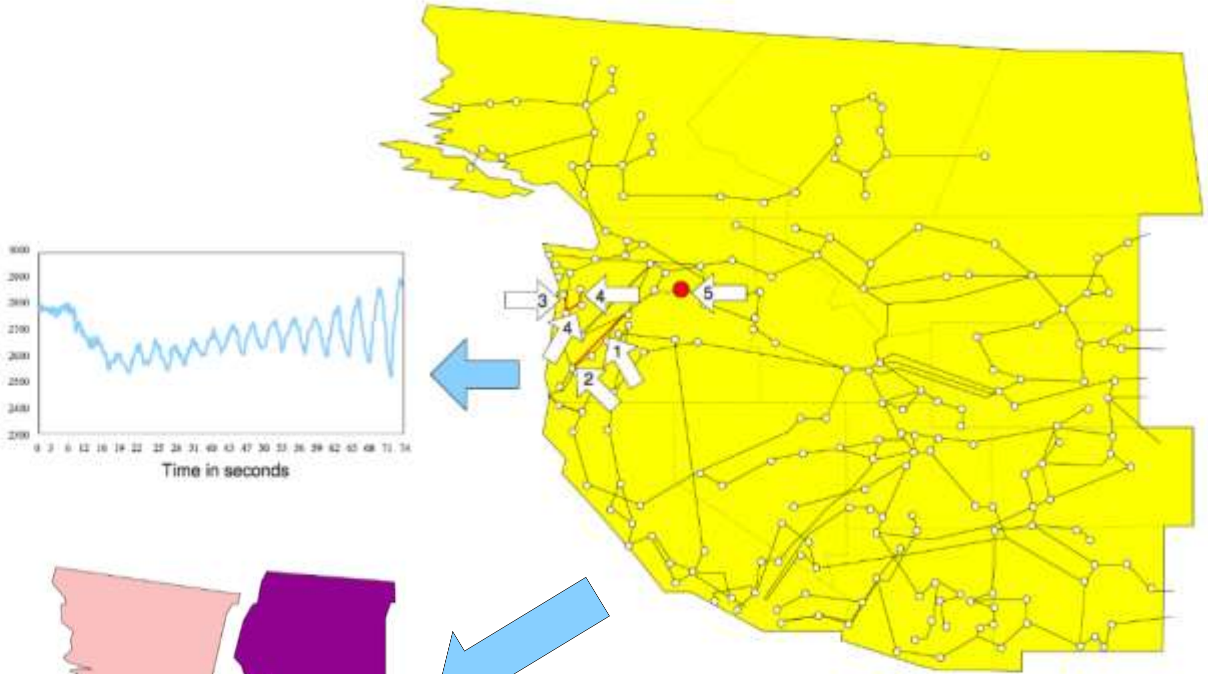
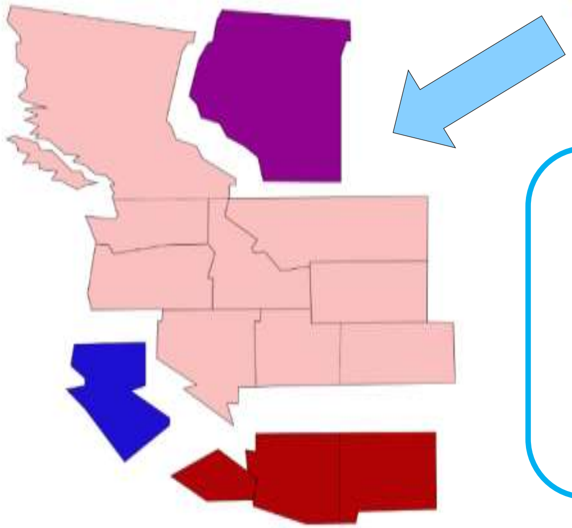
Part 1:

HOW TO MONITOR POWER SYSTEM DYNAMICS?

Need for **Monitoring *Wide-Area Behavior:***
Electromechanical Dynamics Leading to Break-up in the Western US (1996)

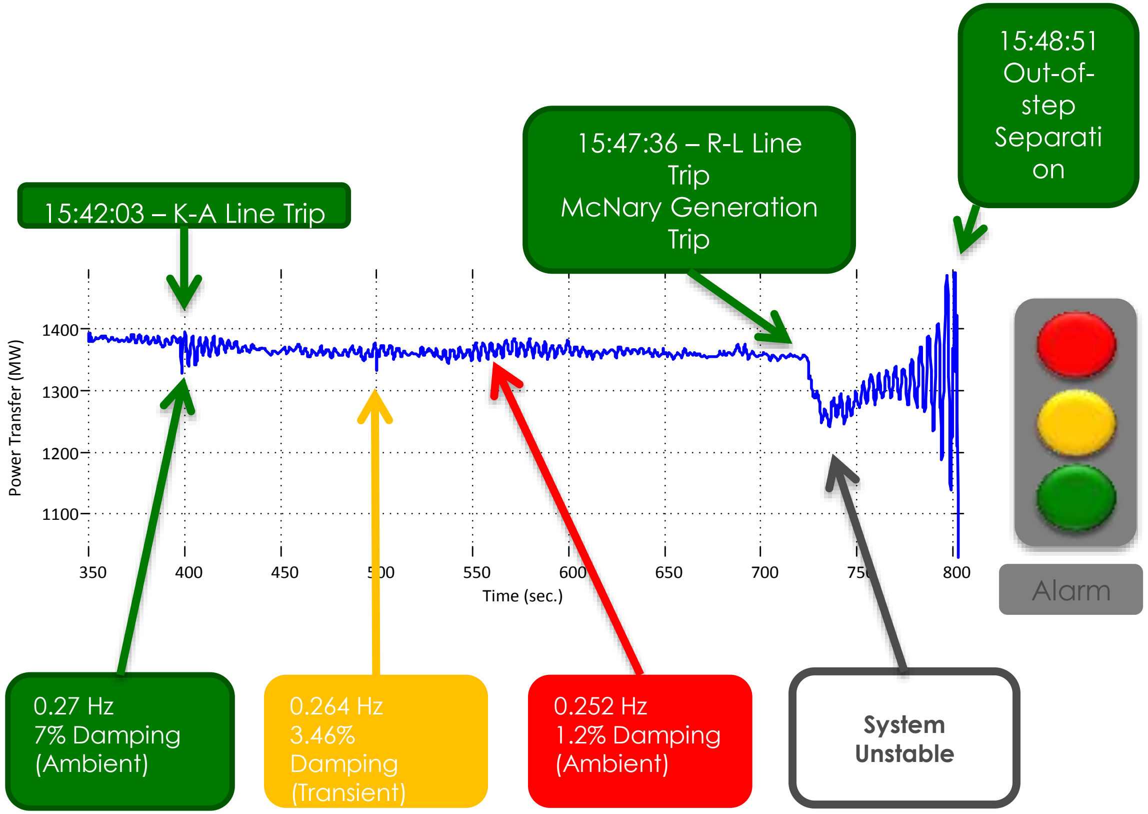
- What was measured:



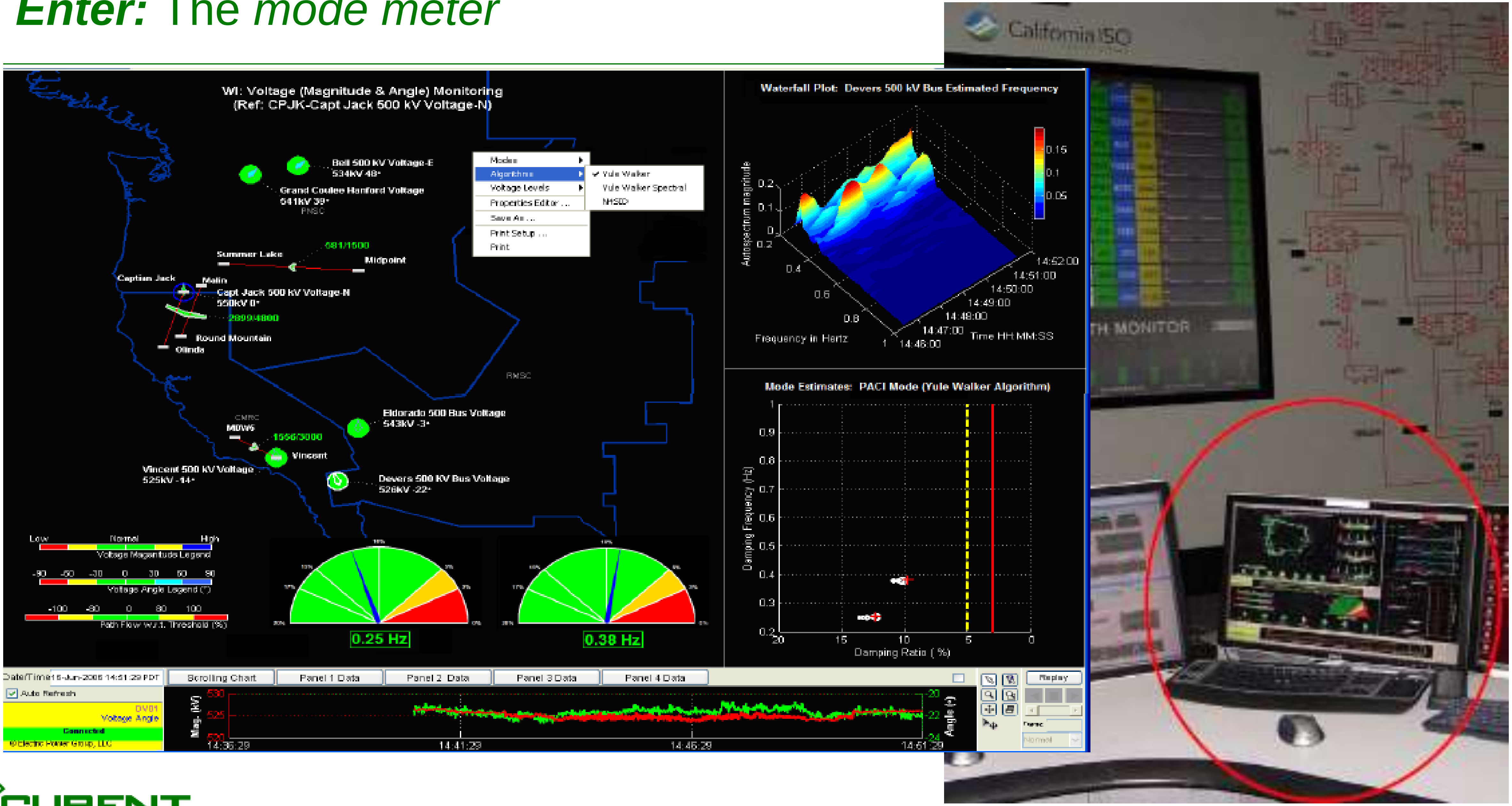


This event lead to largest effort in the world in using synchrophasor measurements for power system monitoring of power system dynamics.

- **Monitoring:** why use frequency and damping as warning indicators?
  - Lightly damped oscillations can lead to a system black-out.
  - Oscillations occupy transmission capacities, increase losses and wear & tear.



Enter: The *mode meter*



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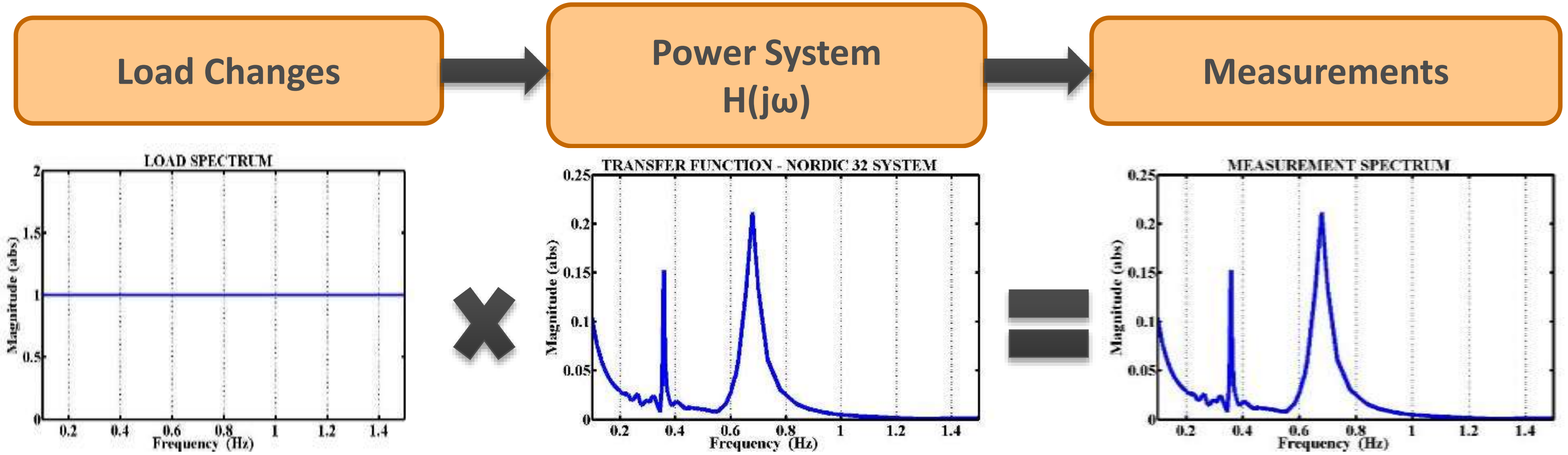
Ambient data-based mode estimation

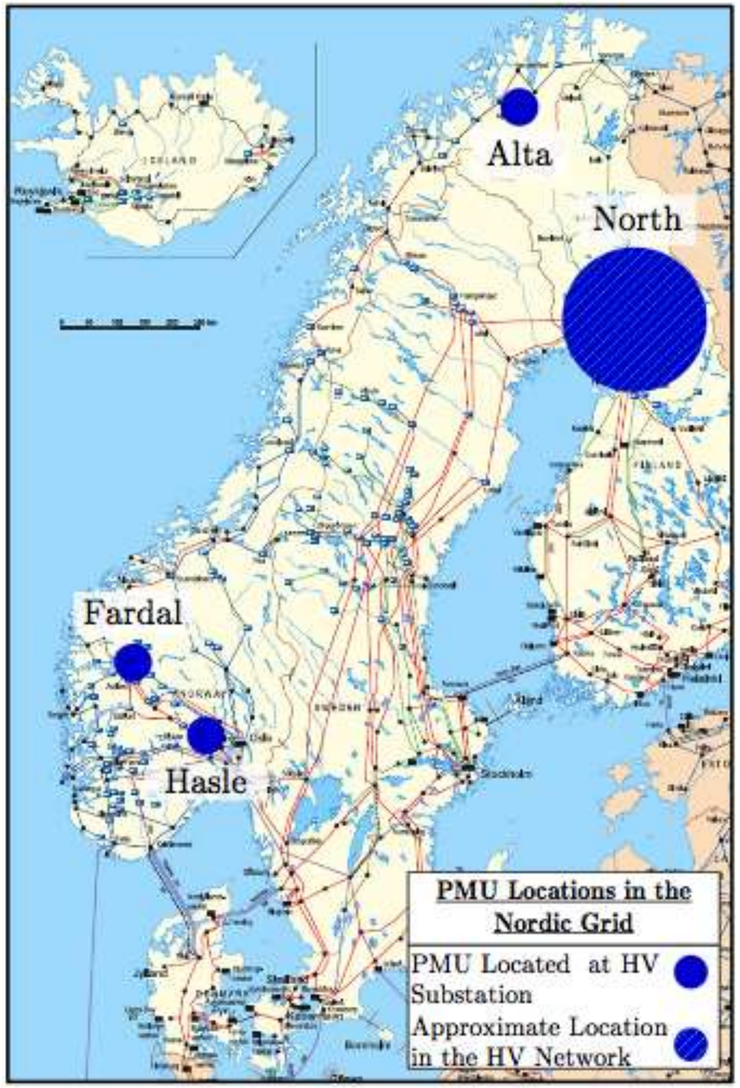
- **Assumptions:**
  - The system operates in **quasi steady state** period
  - Behavior of the system is modeled by a **linear model**
  - System is excited only by **small load changes** modeled as **white noise**



- The model of measured stochastic signal **is determined by a model set and set of parameters.**
- Most common model set is: $H(z) = \frac{B(z)}{A(z)} = \frac{\sum_{k=0}^{q} b_k z^{-k}}{1 + \sum_{k=0}^{p} a_k z^{-k}}$

Estimating Low-Frequency Oscillations in the Nordic Grid

- Previous studies carried out with data from the Nordic grid at High-Voltage Substations.
- The following results are from a continuation study.
- Data from the HV grid of the Nordic Transmission Network
  - Norway:
    - Alta, Fardal, Hasle
  - Finland:
    - “North”
- 72 hrs of data (3 days) for each unit – heavy processing for a standard computer…
- Non-disclosure agreement took a while to sign with grid operators, and was impossible to get data from some of them.



Non-Parametric Mode Estimation – The Periodogram

- Establishing the relation between the autocovariance sequence and the PSD:

$$S(f) = \Delta t \sum_{\tau=-\infty}^{\infty} s_{\tau} e^{-i2\pi f \tau \Delta t}$$

- And considering *N* observations of a stationary process $X_1, X_2, .., X_N$, the autocovariance sequence for $\tau = 0, \pm 1, ..., \pm(N-1)$ can be used to determine The Periodogram:

$$\hat{s}_{\tau} = \frac{1}{N} \sum_{t=1}^{N-|\tau|} X_t X_{t+|\tau|} \quad \longrightarrow \quad \hat{S}(f) = \frac{\Delta t}{N} \left| \sum_{t=1}^{N} X_t e^{-i2\, pif \tau \Delta t} \right|^2$$

- *Drawbacks: spectral leakage and high variance.*

- ***Welch spectral estimator***
  - Split the original N observations into N_B overlaping blocks with Ns samples each.
  - Applies a taper to each block.
  - Obtains a periodogram for each block – averages the individual periodograms together.
  - Very little leakage – good frequency estimates.

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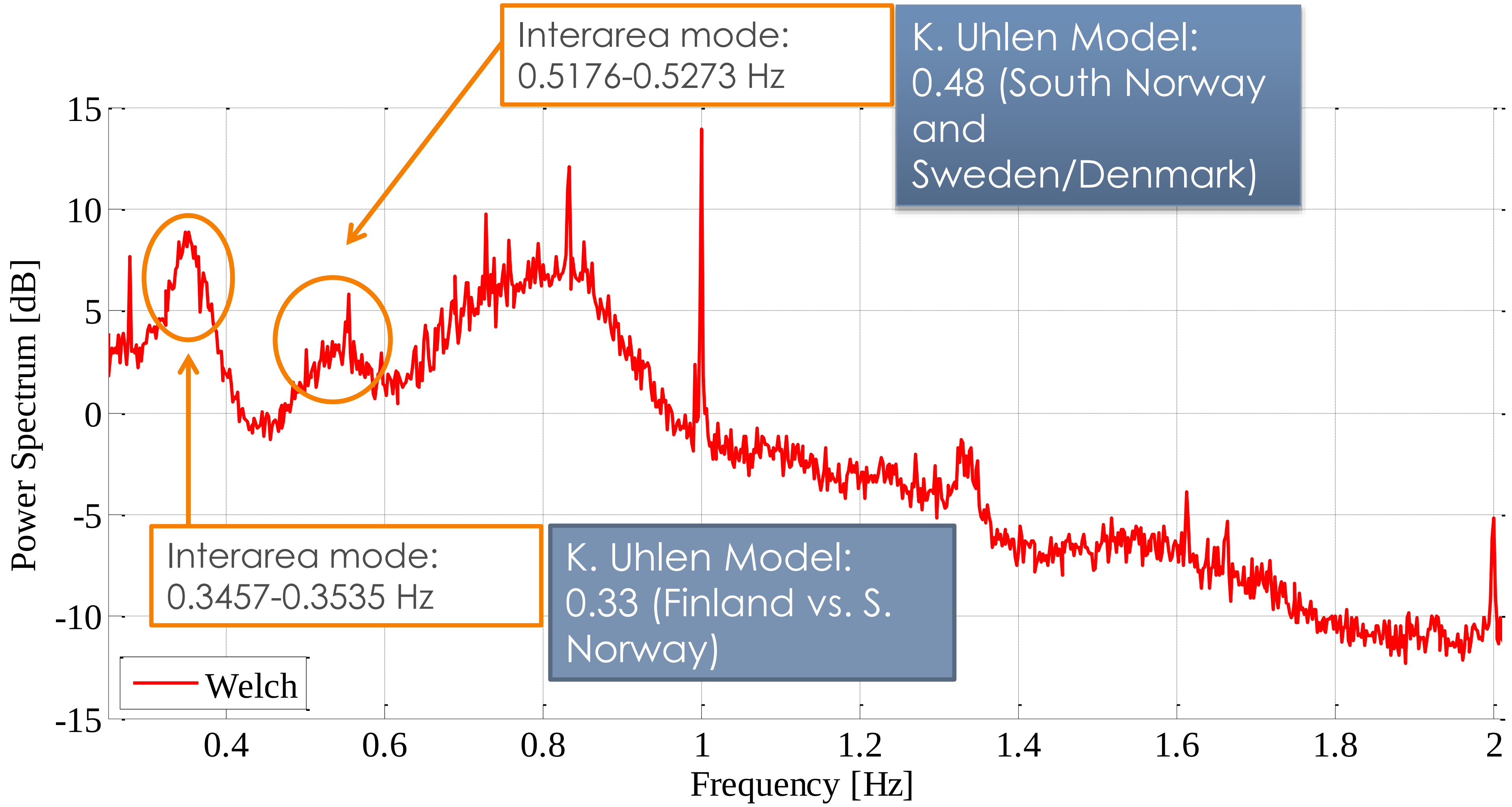
Mode ***Frequency*** Estimation - PSD, 24hrs, Alta, *f* signal – Welch's Method



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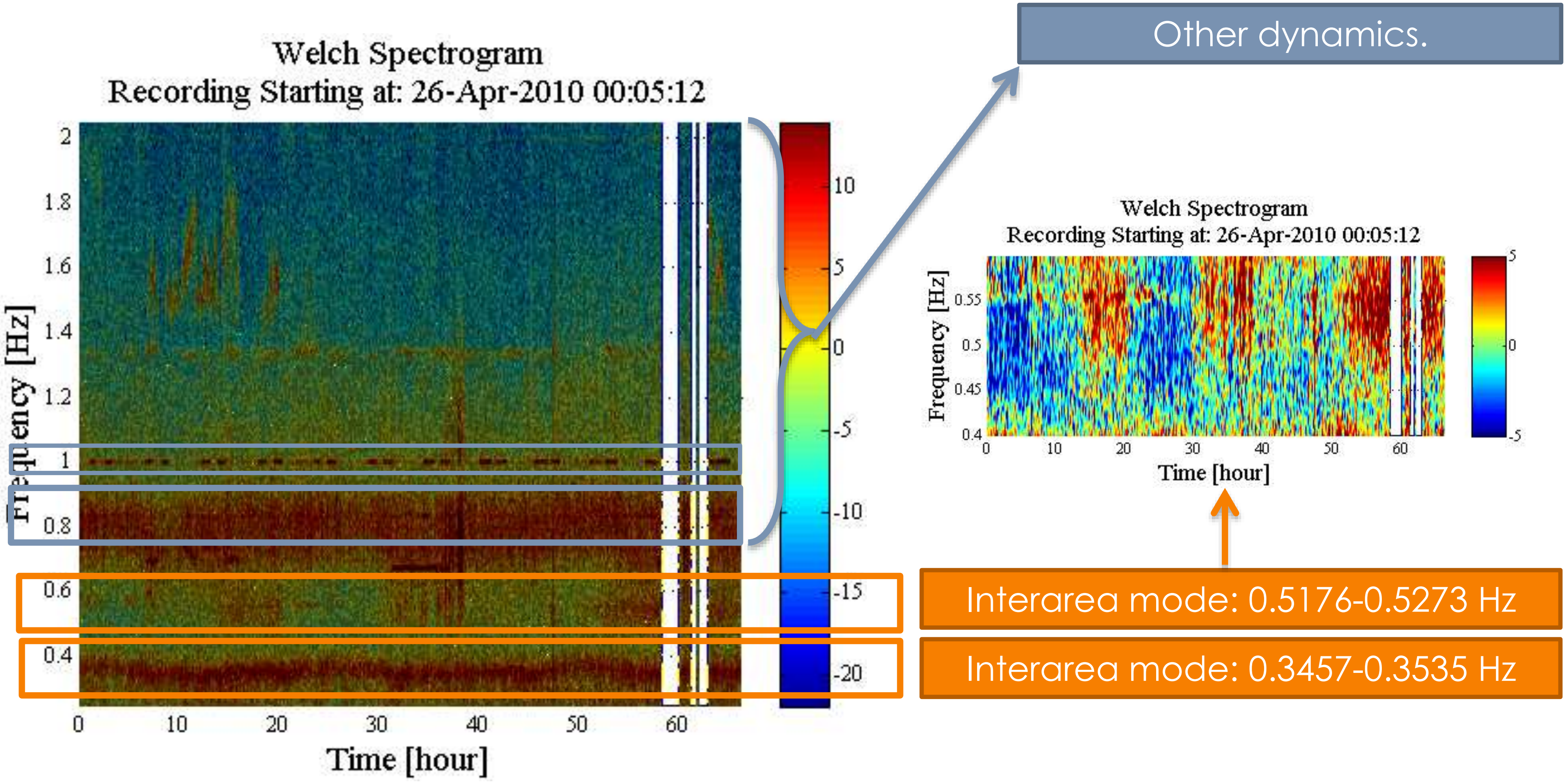
Spectral Estimator:
Alta (*f*), 70 hrs, Welch, 700 block size, 10 min parcels, 9 min overlap



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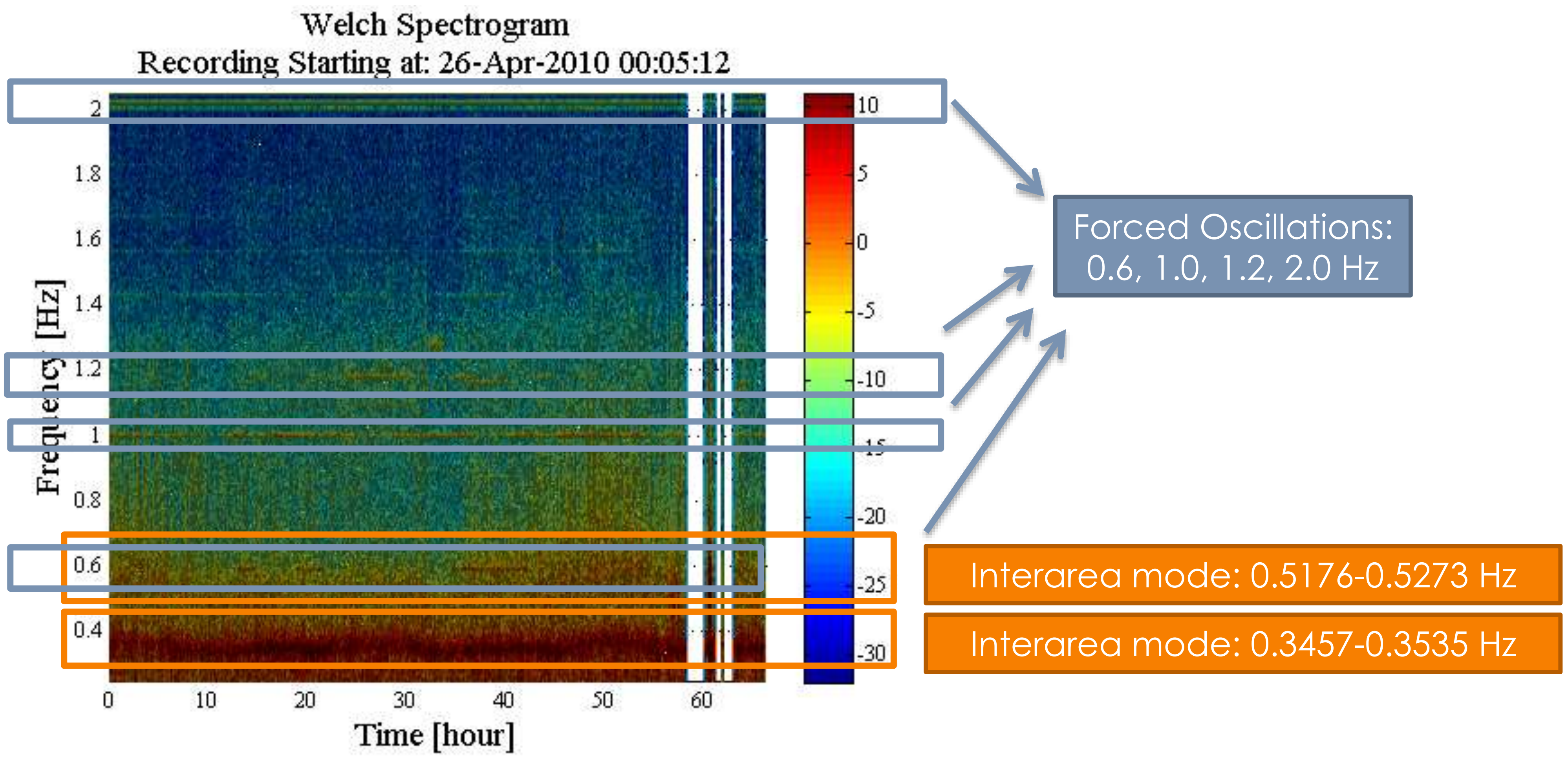
Spectral Estimator:
Hasle (*f*), 72 hrs, Welch, 700 block size, 10 min parcels, 9 min overlap



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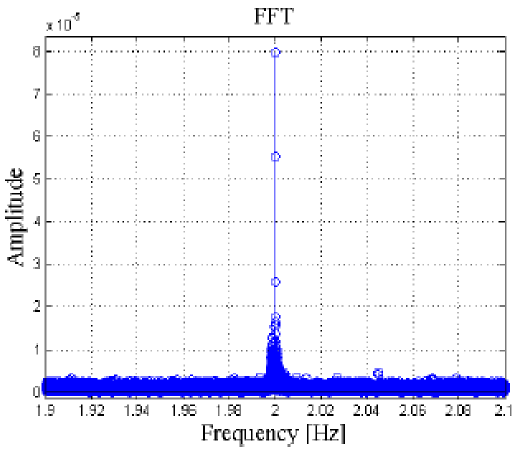
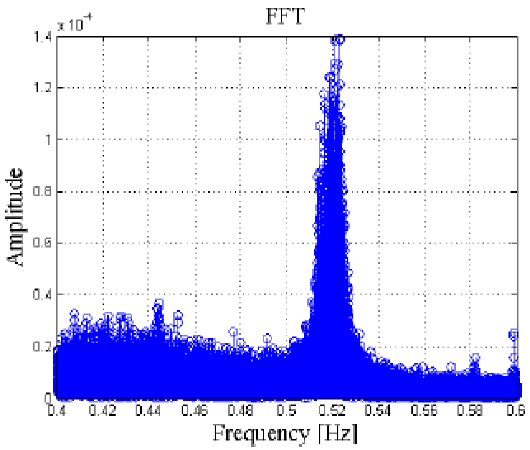
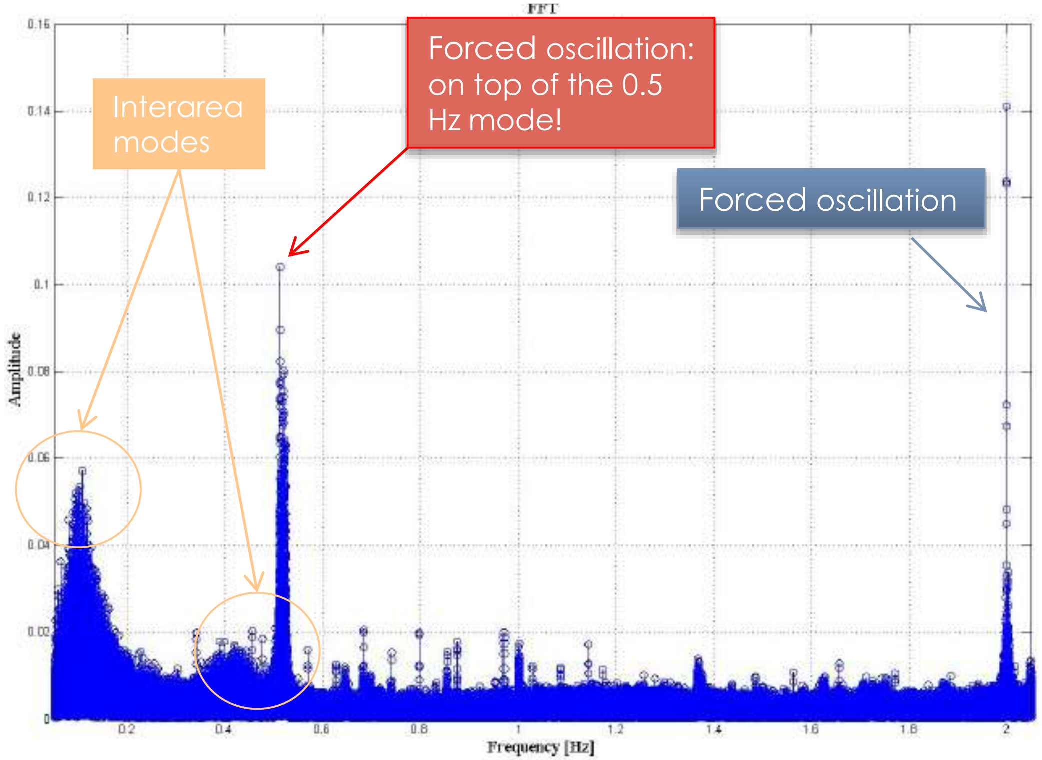
Enter: "Forced Oscillations"

- Forced oscillations are narrow-band spectral components:
  - All spectral content is concentrated in one small frequency bin
  - Think about a 0% damping sinusoid at a single frequency.
- **Actual system modes are spread around a main peak.**

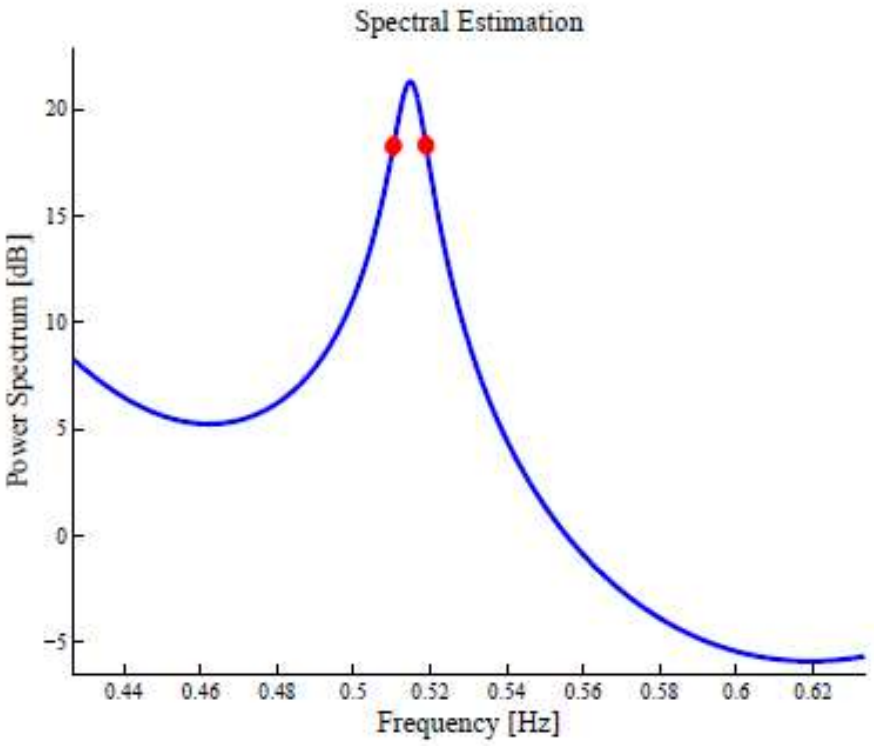
- Forced oscillations ***can corrupt damping*** estimates if they are "close to" or "on top" of a low-frequency oscillation.
- Concern not only for inter-area, but also local modes.







Mode *Damping* Estimation



- Different methodologies:
  - Applied the Yule-Walker autoregressive model, and developed a new method

- ***The Welch Half Power Point method:***
  1. PSD is computed with Welch's method
  2. By examining the peak width of a mode the damping is computed
     - *A narrow peak means a low damped mode, while a wide peak means that the mode is well damped.*
  3. The distance between the two half-power points surrounding the peak center is roughly proportional to mode damping

$$|H(\omega)| = \frac{1}{\sqrt{(1-(\frac{\omega}{\omega_n})^2)^2 + (2\zeta\frac{\omega}{\omega_n})^2}} \longrightarrow \zeta = \frac{\omega_2 - \omega_1}{2\omega_n}$$

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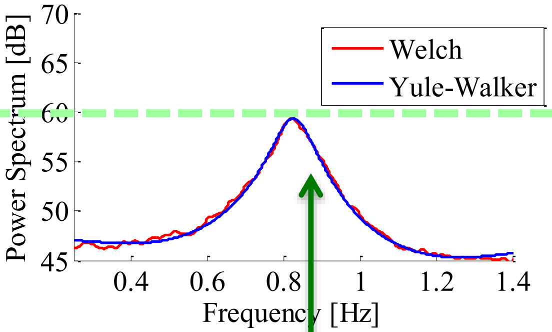
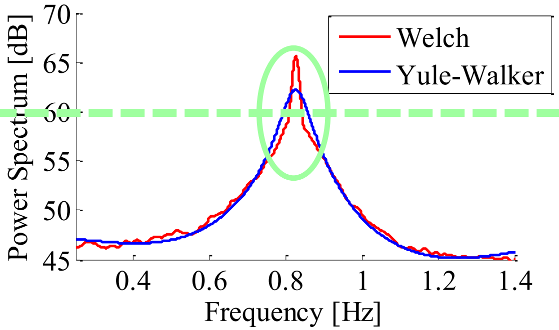
Effect of Forced Oscillations in **Synthetic Data**
Yule-Walker Autoregressive Method

- Introducing a forced oscillation in the data (0.83 Hz, and 1 Hz)

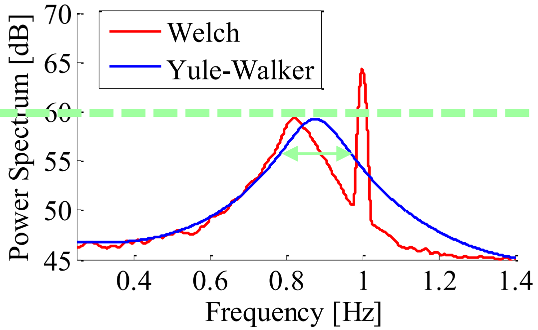
No F.O.



Sumperimposed F.O.

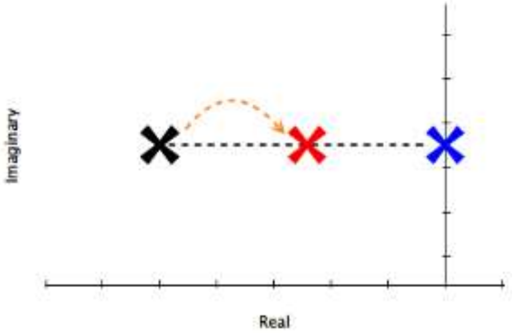


F.O. Close to the *real* Mode



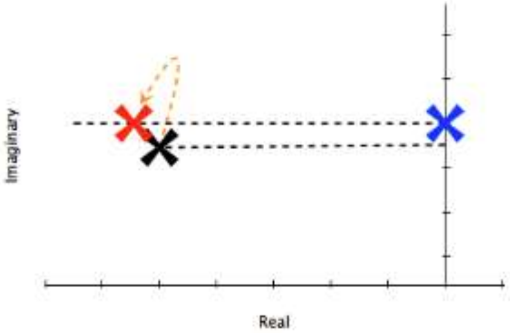
Notice the Yule-Walker PSD (Blue Line)

$$\zeta_j = \frac{-\sigma_j}{\sqrt{\sigma_j^2 + \omega_j^2}} = \frac{-\Re\ \lambda_{j,p}}{\sqrt{\Re\ \lambda_{j,p}^{\ \ 2} + \Im\ \lambda_{j,p}^{\ \ 2}}}$$



$\Re\ \lambda_{j,p}\ \downarrow\rightarrow\zeta\downarrow$

Decrease in Real Part of the Eigenvalues.



$\Re\ \lambda_{j,p}\ \uparrow\rightarrow\zeta\uparrow$

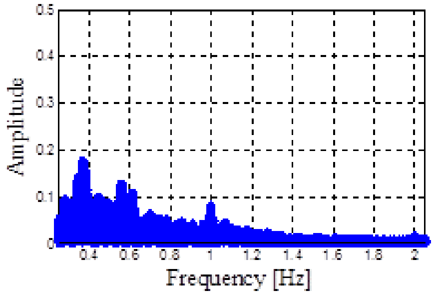
Increase in real part of Eigenvalues.

Effects

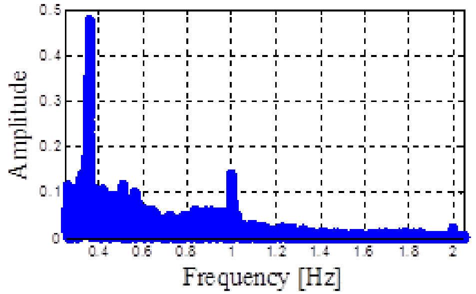
Method	Without F.O.	Superimposed F.O.	F.O. Close to the *real* Mode
Yule-Walker	---	Moves real part to the right	Moves real part to the left
Results	Correct	Lower Damping	Higher Damping

Effects of Forced Oscillations in ***Real*** PMU Data

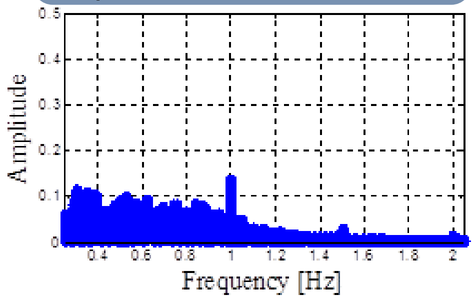
Well-behaved Spectral Content



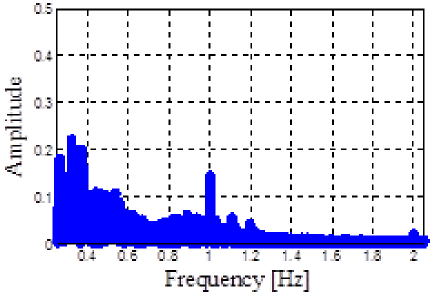
Super-imposed F.O.



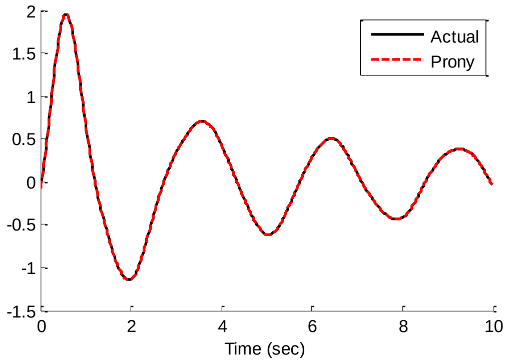
Insufficient Spectral Content



F.O. Close to Mode



- Reference Mode Damping from Transient Data:



Frequency: 0.3561
Damping: 6.0481 %

- ***Well-behaved Spectral Content:***
  - HPPM[%]: 6.0860, YW[%]: 5.9714
- ***Superimposed F.O.:***
  - HPPM[%]: 3.8037, YW[%]: 3.8117
- ***F.O. Close to Mode:***
  - HPPM[%]: 9.6009, YW[%]: 9.522
- ***Insufficient Spectral Content:***
  - HPPM[%]: 15.7967, YW[%]: 15.63

Well-behaved Spectral Content:
Both methods are close to reference value.

Correct Estimates!

Super-imposed F.O.:
Increase in peak height causes methods to yield ***lower damping!***

False alarm!

F.O. Close to Mode:
Increase in peak width will cause that methods yield ***higher damping!***

Lack of alarm!

Insufficient Spectral Content:
Spectral est. degraded, mode peak missing results in ***too high damping!***

Lack of alarm!

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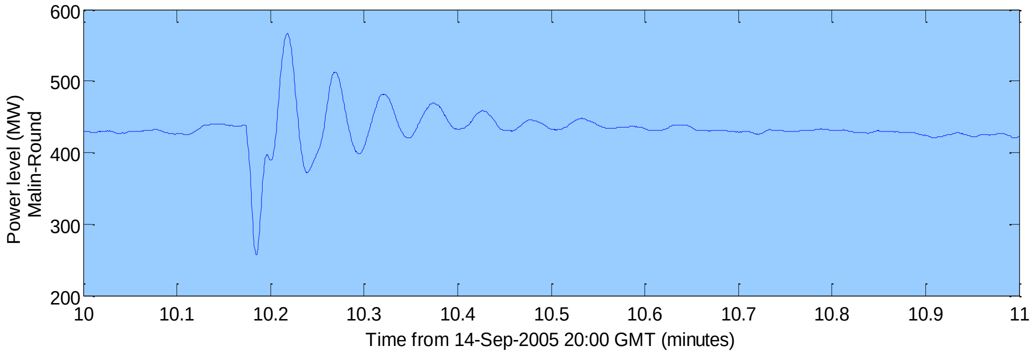
Part 2:

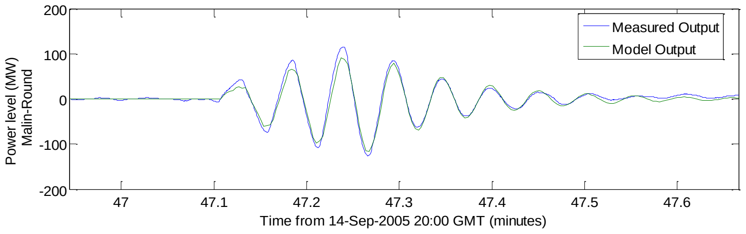
HOW TO IMPROVE THE ESTIMATION OF FREQUENCY AND DAMPING FOR MONITORING APPLICATIONS?

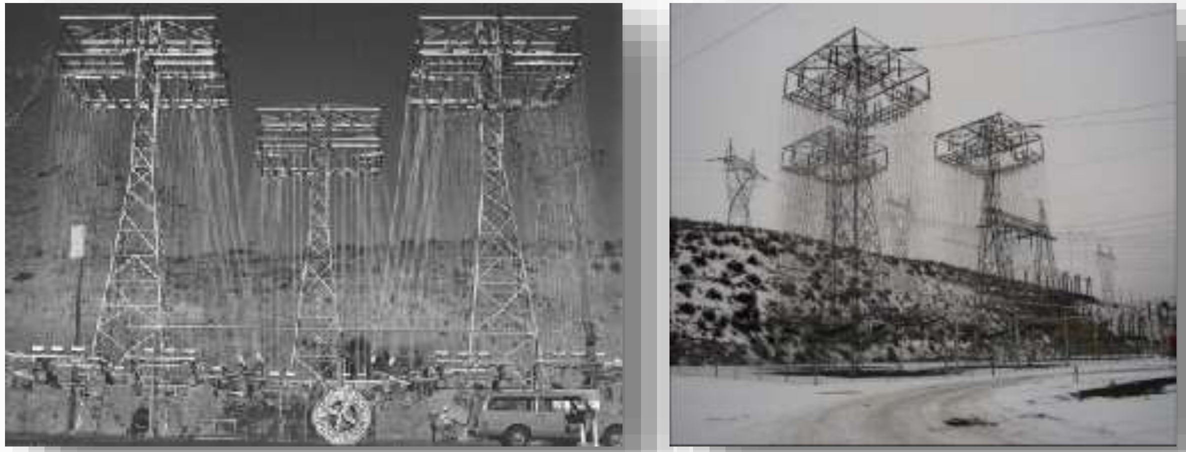
Enter: The Toaster!

- Experiments at the **system** scale are very rare in electrical power networks.
- “The Toaster” is a unique facility in the world that allows to make a **“breaker insertion”** capable of producing a large transient in the system (see top plot).
- One of its uses has been in providing reference values to tune mode meters and model validation (more later).



0.3 Hz Validation





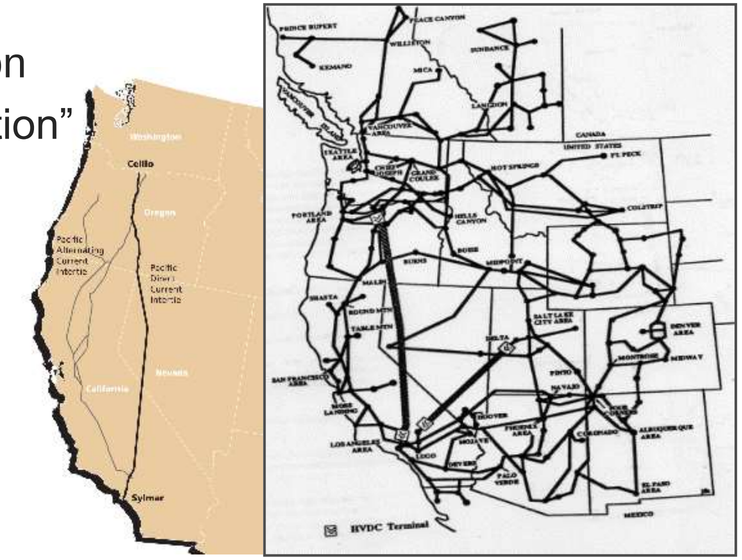
Chief Joseph Dynamic Breaker – “The Toaster”

[BPA] “It can consume 1,440 MW - more than the output of Bonneville Dam. It's only capable of staying on for 3 seconds - beyond that, it would destroy itself.”

History of the DC Pacific intertie: link

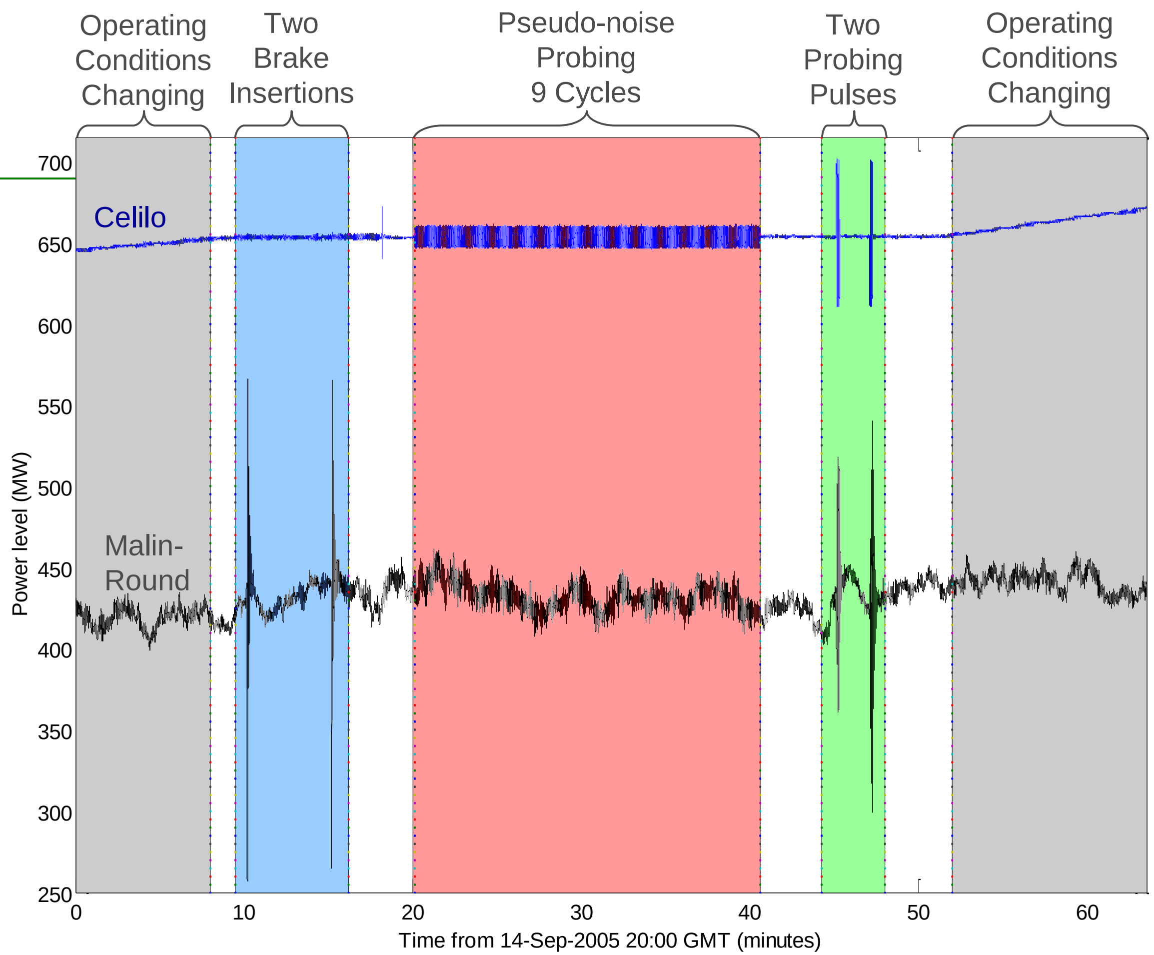
Probing Experiments:

- The WECC conducts unique experiments for extracting power system properties.
- They include:
  - Breaker insertion
  - HVDC “Modulation”

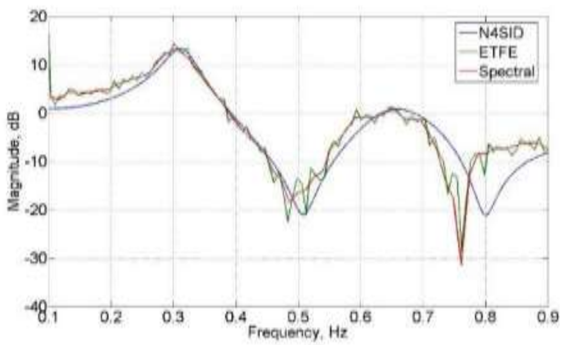


- Test Dates:
  - September 2005
  - June 2006
  - August 2006
  - August 2008
  - Weekly Summer 2009
  - Weekly Summer 2011
  - Weekly Summer 201

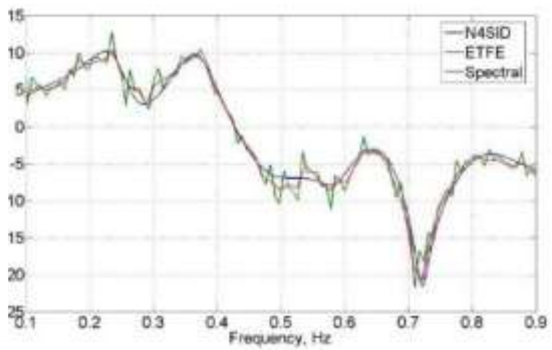
File Name	Test	Type	Band Width or Frequency
MSF/1/2/6/100	A,B	Multi-sine fitted	1 Hz 6th order filter, stop at 2 Hz
MSF/1/5/1/100	C	Multi-sine fitted	1 Hz 1st order filter, stop at 5 Hz
MSF/1/5/2/100*	D	Multi-sine fitted	1 Hz 2nd order filter, stop at 5 Hz
MSF/0.1/4x	A	Single Freq Sine	Four sine wave cycles
MSF/0.3/4x	A	Single Freq Sine	Four sine wave cycles
MSF/0.7/4x	A	Single Freq Sine	Four sine wave cycles
MSF/1.0/4x	A	Single Freq Sine	Four sine wave cycles



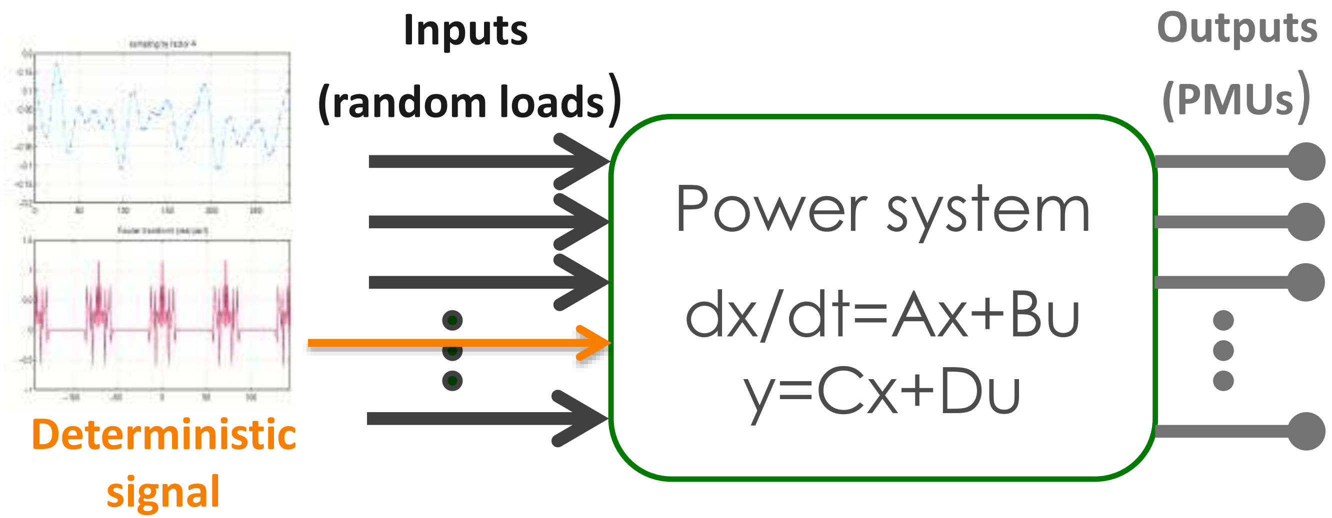
2005 Test



2006 Test

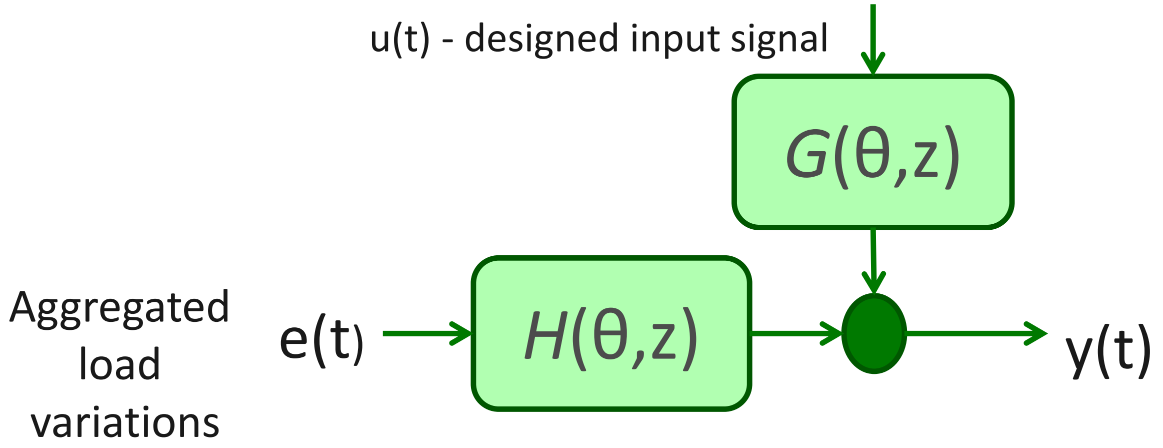


Input Signal Design: probing-based mode estimation



By designing the excitation (input/probing signal) new information that can be used for improved mode identification can be obtained!

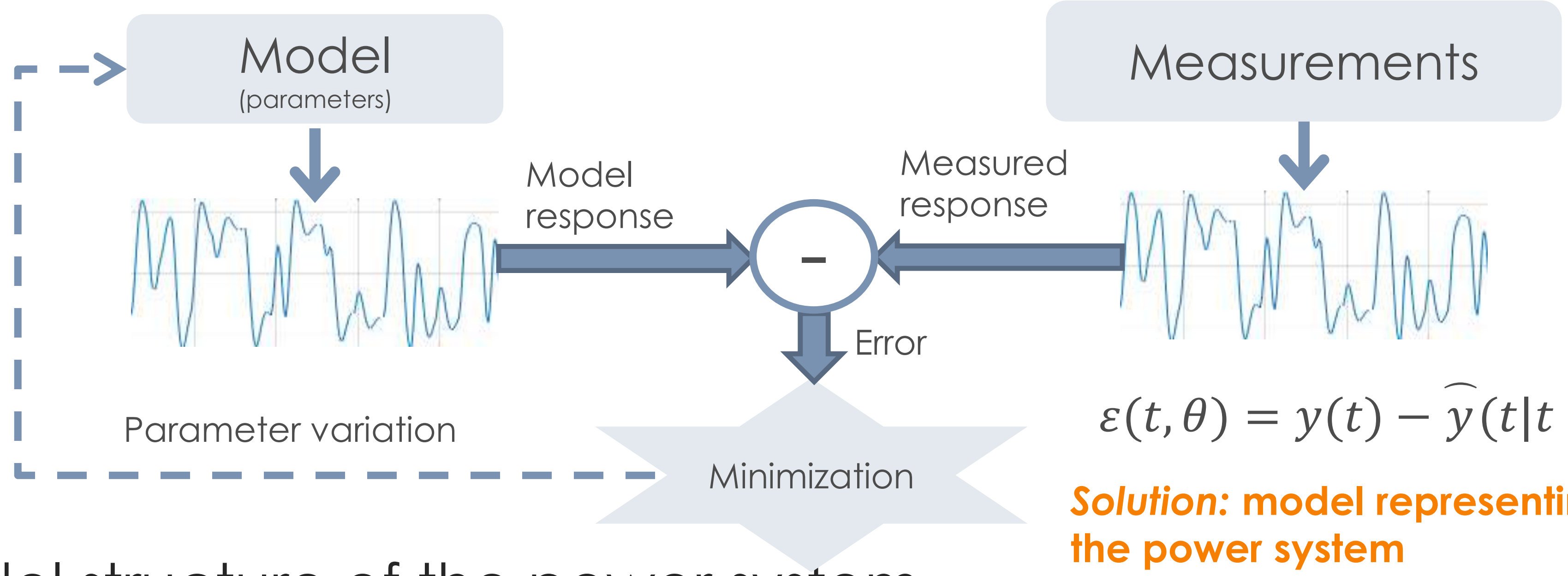
Single Output Model



Mathematical formulation
and problem solution sketch

X. Bombois, G. Scorletti, M. Gevers, P.M.J. Van den Hof and R. Hildebrand, "Least costly identification experiment for control", Automatica, vol.42, no.10, pp.1651-1662, Oct. 2006.

- Optimization problem: $\min_{\theta} \frac{1}{N} \sum_{t=1}^{N} \varepsilon(t,\theta)^2$



$$\varepsilon(t,\theta) = y(t) - \widehat{y}(t|t-1)$$

***Solution:* model representing the power system**

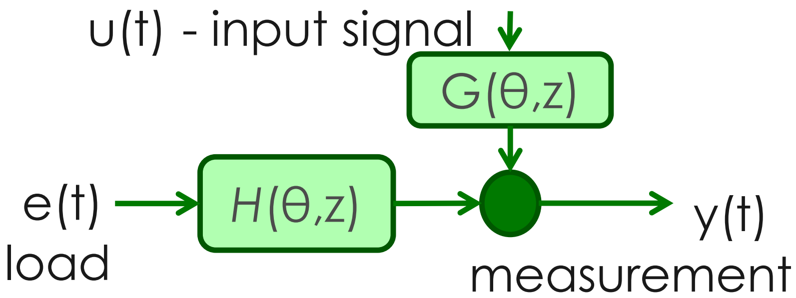
- Model structure of the power system
  - ARMAX

$$y(t) = \frac{B(z,\theta)}{A(z,\theta)} u(t) + \frac{C(z,\theta)}{D(z,\theta)} e(t)$$

Contains information about the critical modes/poles

Optimal probing: problem formulation

- **Objective:** Identify the critical damping ratio of G(z)



P_θ^{-1} ↑ ⟹ **Good estimate** $\Phi_u(\omega)$ ↑

P_θ^{-1} ↓ ⟹ **Bad estimate** $\Phi_u(\omega)$ ↓

$$P_\theta^{-1} = \overbrace{\left(\frac{N}{\sigma^2} \frac{1}{2\pi} \int_{-\pi}^{\pi} F_u(\omega,\theta_0) F_u^*(\omega,\theta_0) \Phi_u(\omega) d\omega \right)}^{Probing} + \overbrace{\left(\frac{N}{2\pi} \int_{-\pi}^{\pi} F_e(\omega,\theta_0) F_e^*(\omega,\theta_0) d\omega \right)}^{Ambient}$$

How should the probing (input) signal look like?

Spectrum influences accuracy

Stronger probing provides better accuracy

There is a limit how strong probing can be

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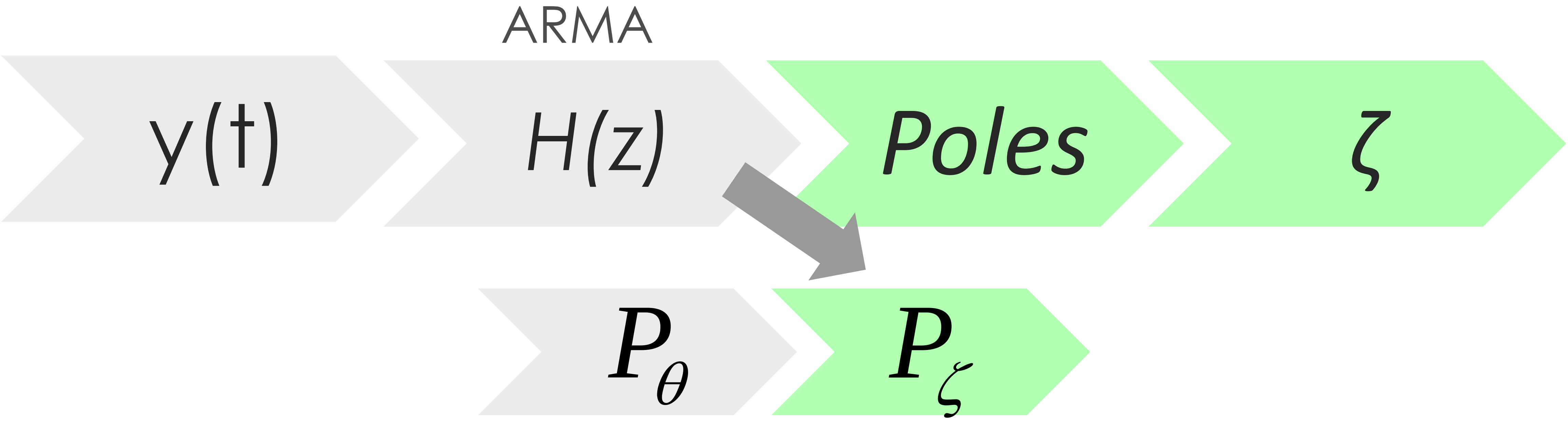
Computing the Covariance Matrix of the
Critical Damping Ratio Parameter

V. S. Perić, X. Bombois and L. Vanfretti, "Optimal Signal Selection for Power System Ambient Mode Estimation Using a Prediction Error Criterion," in IEEE Transactions on Power Systems, vol. 31, no. 4, pp. 2621-2633, July 2016.doi: 10.1109/TPWRS.2015.2477490

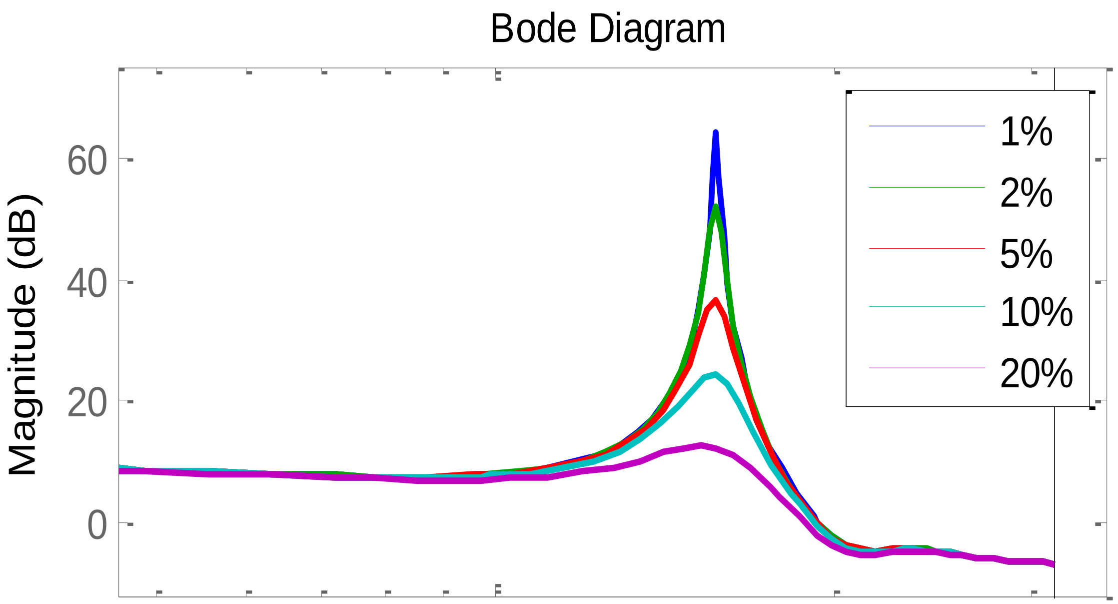


Important!

The covariance matrix depends directly on the estimated mode H(z)!

Relationship:
damping ratio variance and transfer function

$$P_\theta = \left[\frac{1}{2\pi} \int_{-\pi}^{\pi} \frac{1}{\left|H_0\right|^2} \left(\frac{dH}{d\xi} \right)^T \frac{dH}{d\xi} d\omega \right]^{-1}$$



- The given function depends only on the estimated parameter, because of cancellationS
- The larger peak means smaller variance

Spectrum calculation of the probing signal

Requirements:

1) Control effort 2) System pertubation 3) Accuracy

Objective function $$\min_{u(t)} J = \left(\frac{k_1}{2\pi} \int_{-\pi}^{\pi} \Phi_u(\omega) d\omega \right) + \left(\frac{k_2}{2\pi} \int_{-\pi}^{\pi} \left| G(s) \right|^2 \Phi_u(\omega) d\omega \right)$$

Input power *Output power*

Constraint: *Accuracy constraints* $$\mathrm{var}(\zeta_i) = e_i^T P_\theta e_i < r$$, *r* - tolerance

Optimization problem in a form of LMIs

The solution is the power spectrum of the probing signal

Accuracy:
damping ratio estimates
variances!

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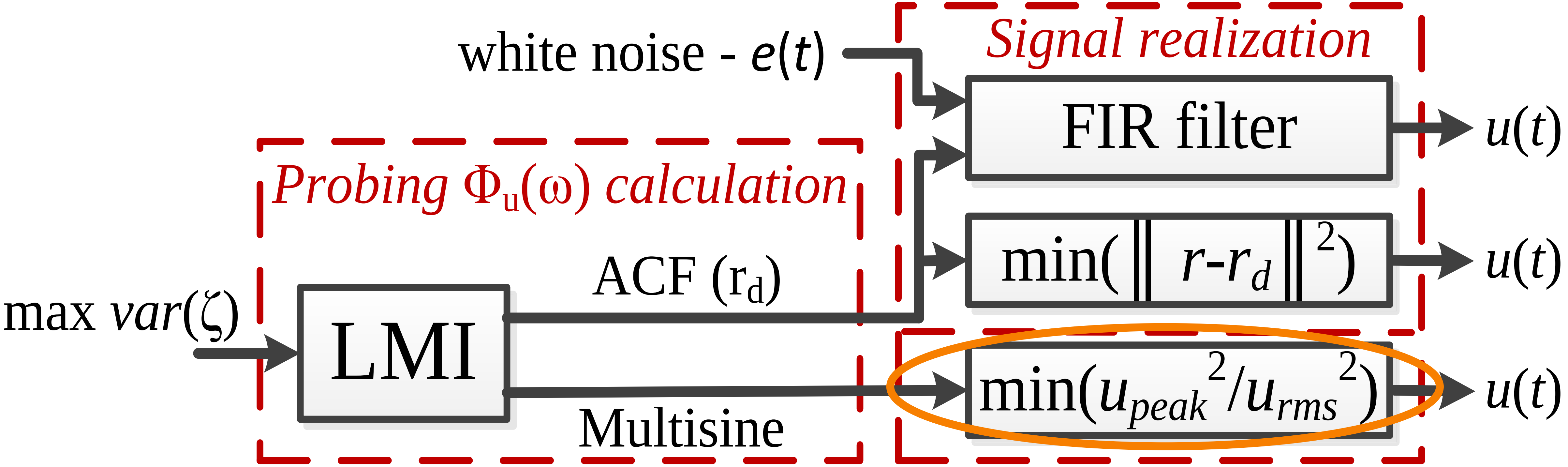
Time domain probing signal realization

- Spectrum calculation (solved)
- Time domain signal realization



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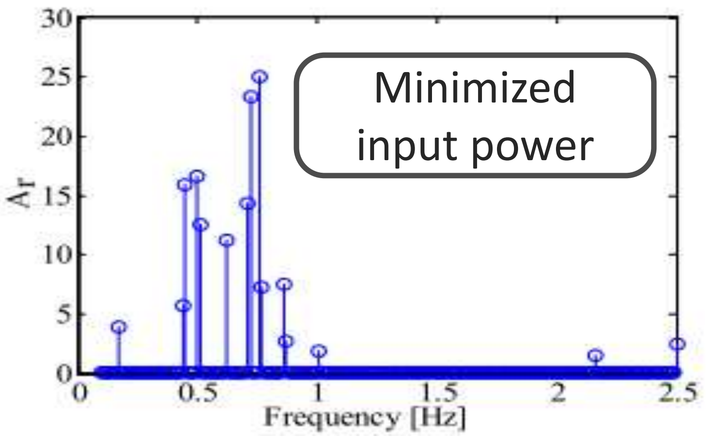
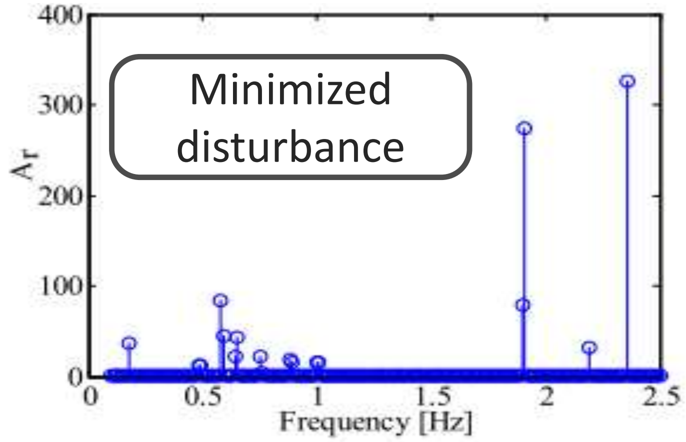
Optimal probing (input) signal design results



2 critical modes 0.5Hz & 0.76Hz

Reactive power probing

Damping variance < 10^{-5}



	White noise	Minimized function		
		var{u(t)}	var{y(t)}	var{uy(t)}
var{u(t)}	10410	1179.8	101850	1441.6
var{y(t)}	1.6761	2.0915	1.2425	1.5980
var{uy(t)}	6881.1	7981.4	52167	2318.8

Benefits of the proposed method

- The same accuracy obtained with the 5-7 times weaker excitation
- The same input power provides 4-5 times better accuracy ($0.25*10^{-5}$)

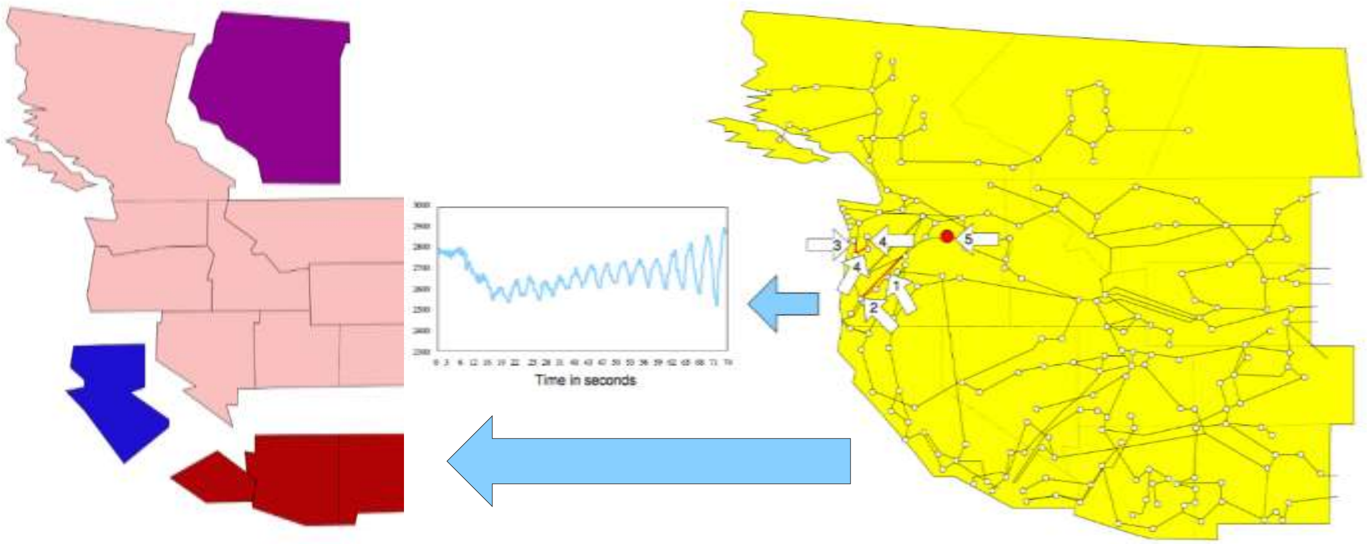
The spectrum and not time domain probing signal determines accuracy of the mode estimation procedure

Part 3:

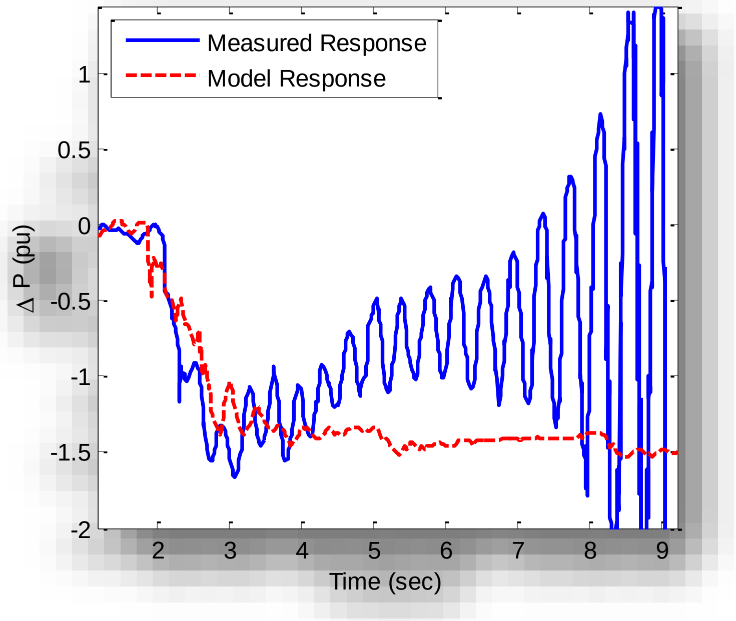
HOW TO VALIDATE POWER SYSTEM MODELS?

Why validate power system Models?

- What was measured:



- What was simulated:



The quality of the models used by off-line and on-line tools will affect the result of any computations

- Good model: approximates the simulated response as "close" to the "measured response" as possible
- Validating models helps in having a model with "good sanity" and "reasonable accuracy"

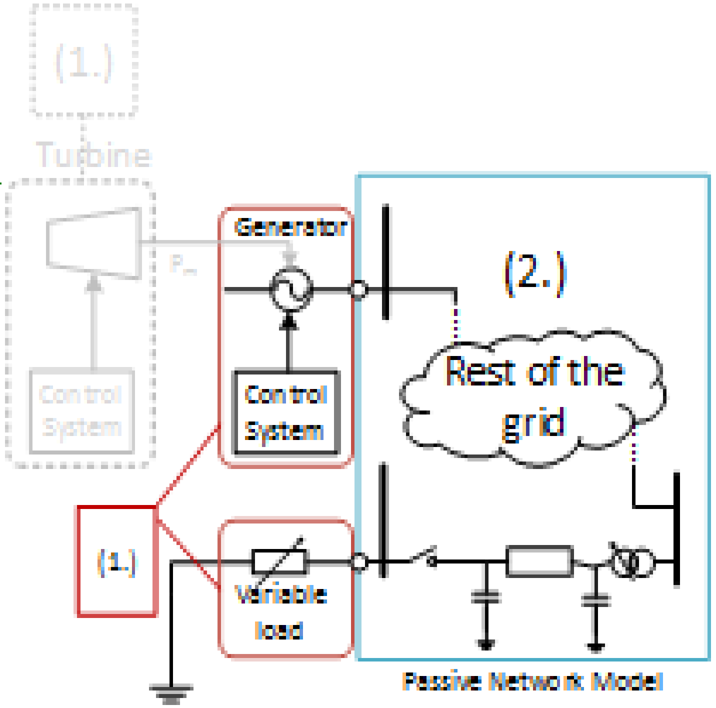
Increasing the capability of reproducing actual power system behavior (better predictions)

Power System Modeling and Simulation Approach

- Equation set ***g*** is separated in two sets of algebraic equations:

$$\left.\begin{aligned}\dot{\mathbf{x}} &= f\left(\mathbf{x},\mathbf{y},\boldsymbol{\eta},\tilde{\mathbf{u}}\right),\\ \mathbf{0} &= g_1\left(\mathbf{x},\mathbf{y},\boldsymbol{\eta},\tilde{\mathbf{u}}\right),\end{aligned}\right\}\quad (1.)$$

$$\mathbf{0} = g_2\left(\mathbf{y},\boldsymbol{\eta},\tilde{\mathbf{u}}\right)\}\quad (2.)$$



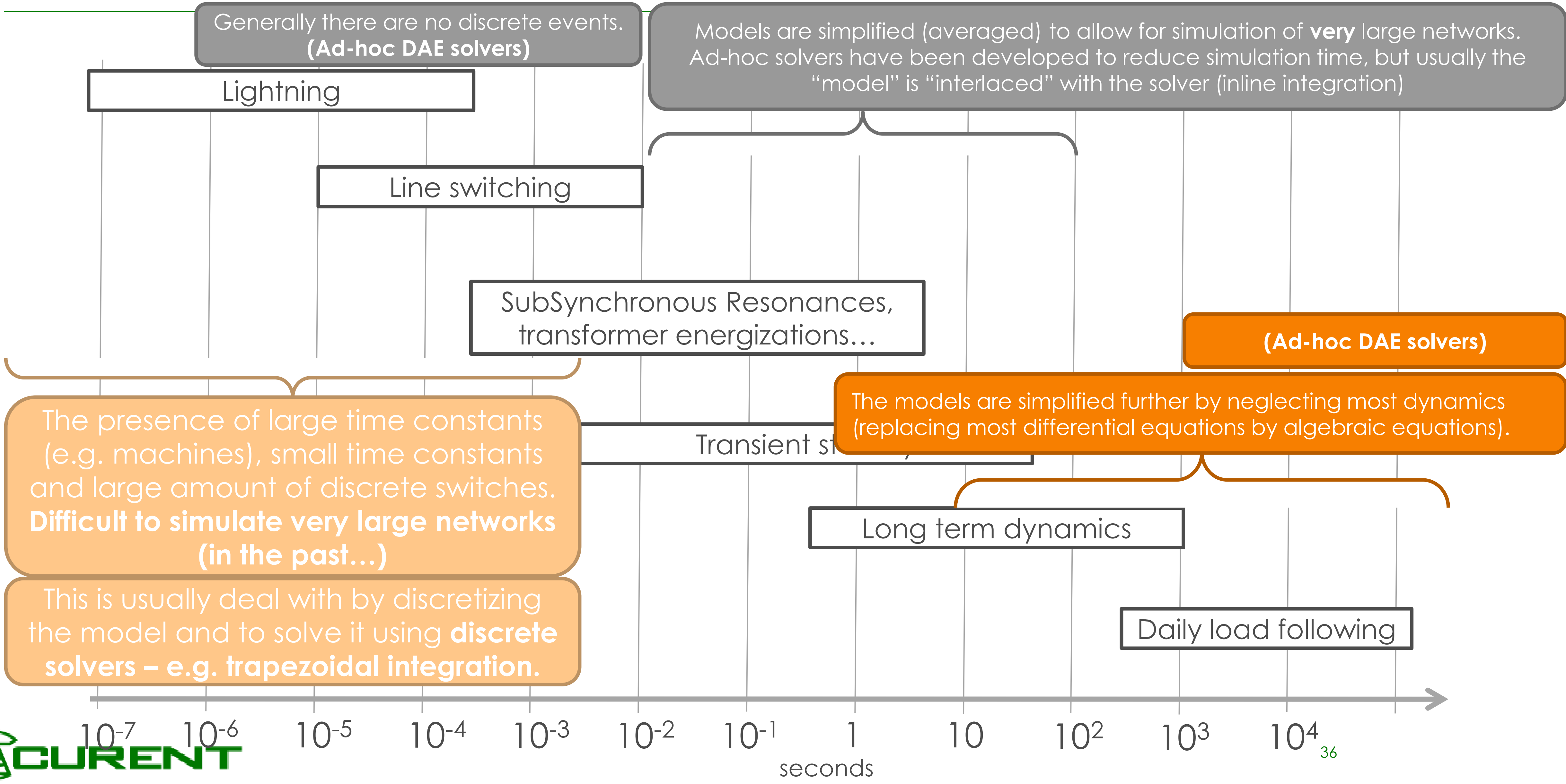
(1) Is the part which governs how dynamic models will evolve, since they depend on both **x** and **y** , e.g. generators and their control systems.

(2) Is the network model, consisting of transmission lines and other passive components which only depends on algebraic variables, **y**.

Simulation: Starting from a solution of (2) **only**, equations (1) are solved at equilibrium **individually;** to compute the starting guess of an ad-hoc DAE solver that iterates for (1)-(2) at each time step.

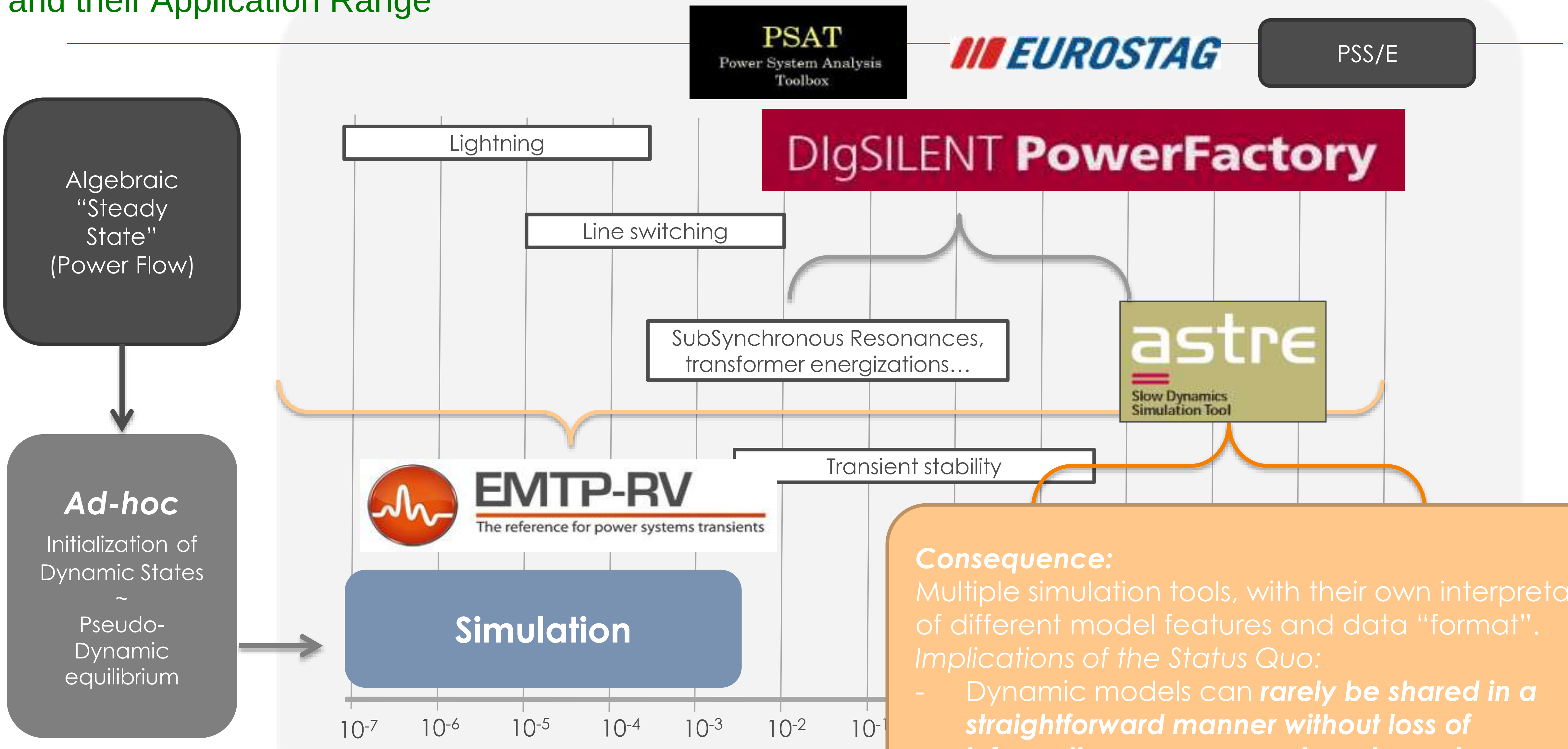
Power System Modeling and Simulation Approaches

to deal with Time-Scale Complexities



Power System Simulation Tools

and their Application Range

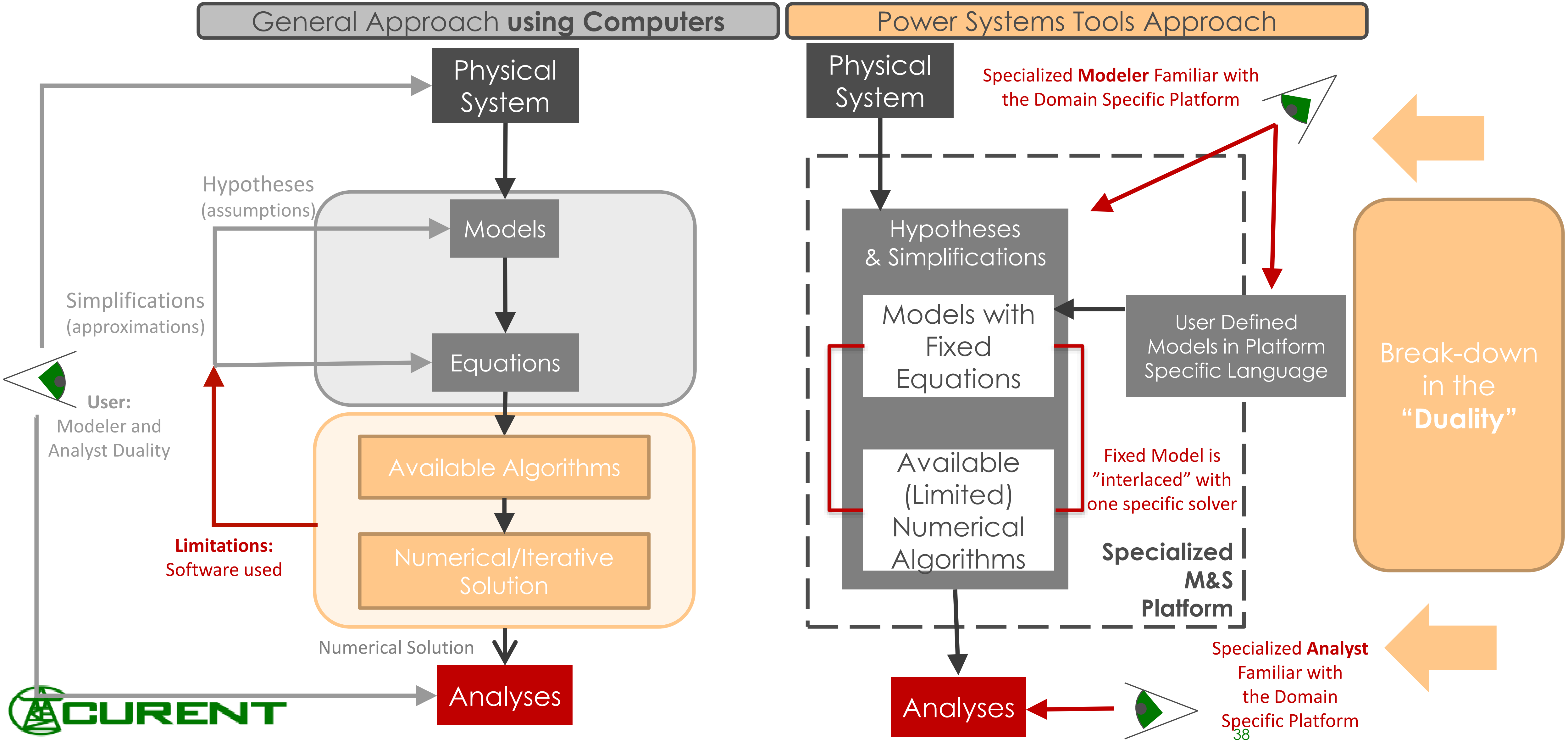


Broad range of time constants results in specific domain tools for simulation.
Non-exhaustive list. There exists other proprietary and few OSS tools.

Consequence:
Multiple simulation tools, with their own interpretation of different model features and data "format".
Implications of the Status Quo:

- Dynamic models can ***rarely be shared in a straightforward manner without loss of information on power system dynamics.***
- ***Simulations are inconsistent without drastic and specialized human intervention.***

General Approach vs Power System Approach for Modeling and Simulation



MODELICA is a (computer) modeling language, *it is* ***not*** *a tool!*

- Modelica is a free/*libre* object-oriented modeling language with a textual definition to describe physical systems using differential, algebraic and discrete equations.
- A Modelica modeling environment is needed to edit or to browse a Modelica model graphically in form of a composition diagram (= schematic).
- A Modelica translator is needed to transform a Modelica model into a form (usually C-code) which can be simulated by standard tools.
- A Modelica modeling and simulation environment provides both of the functionalities above, in addition to auxiliary features (e.g. plotting)

MODELICA

Modelica® - A Unified Object-Oriented Language for Systems Modeling

Language Specification

Version 3.3 Revision 1

July 11, 2014

http://modelica.readthedocs.io/en/latest/#

Key: standardized and open language specification

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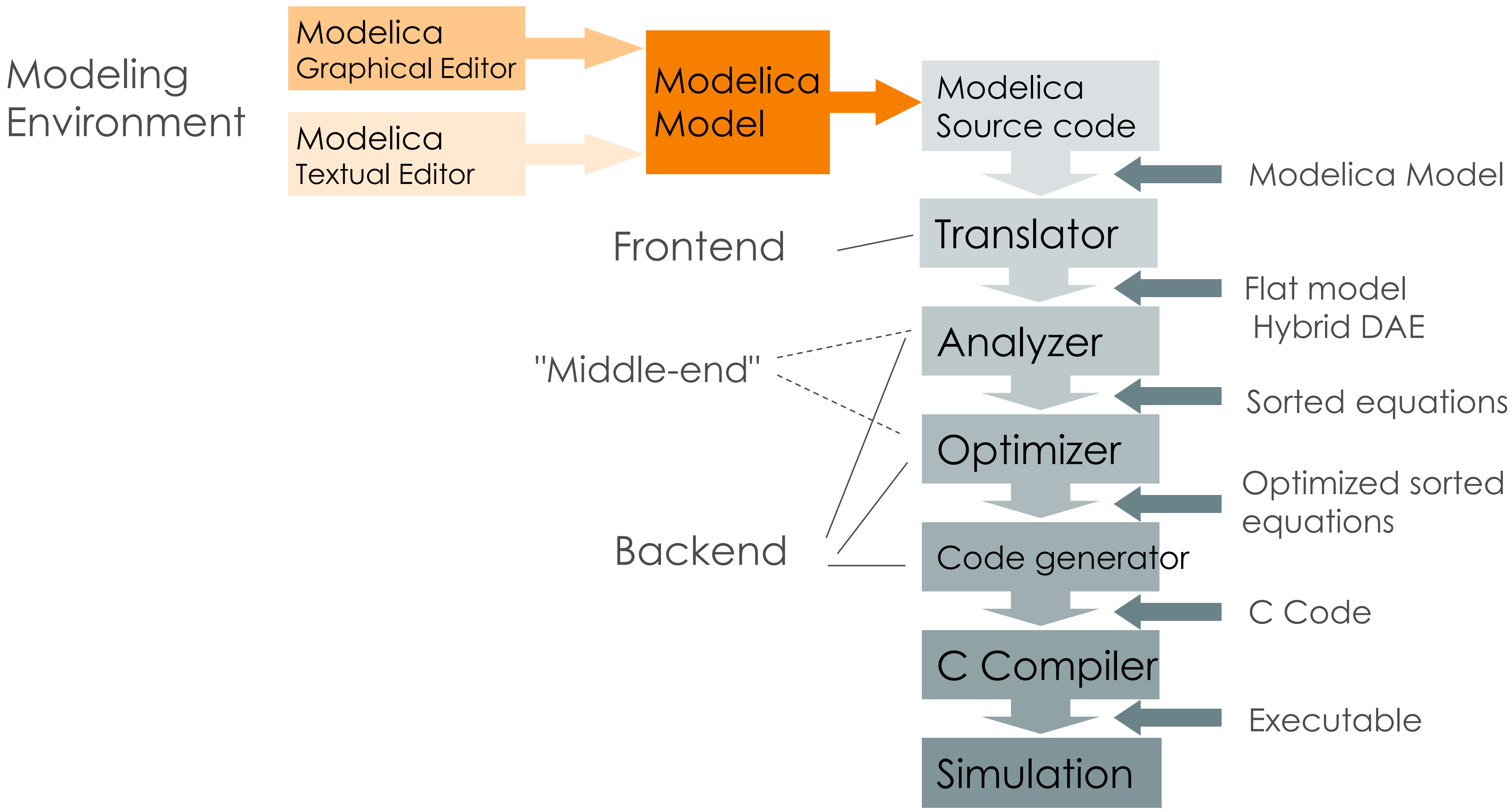
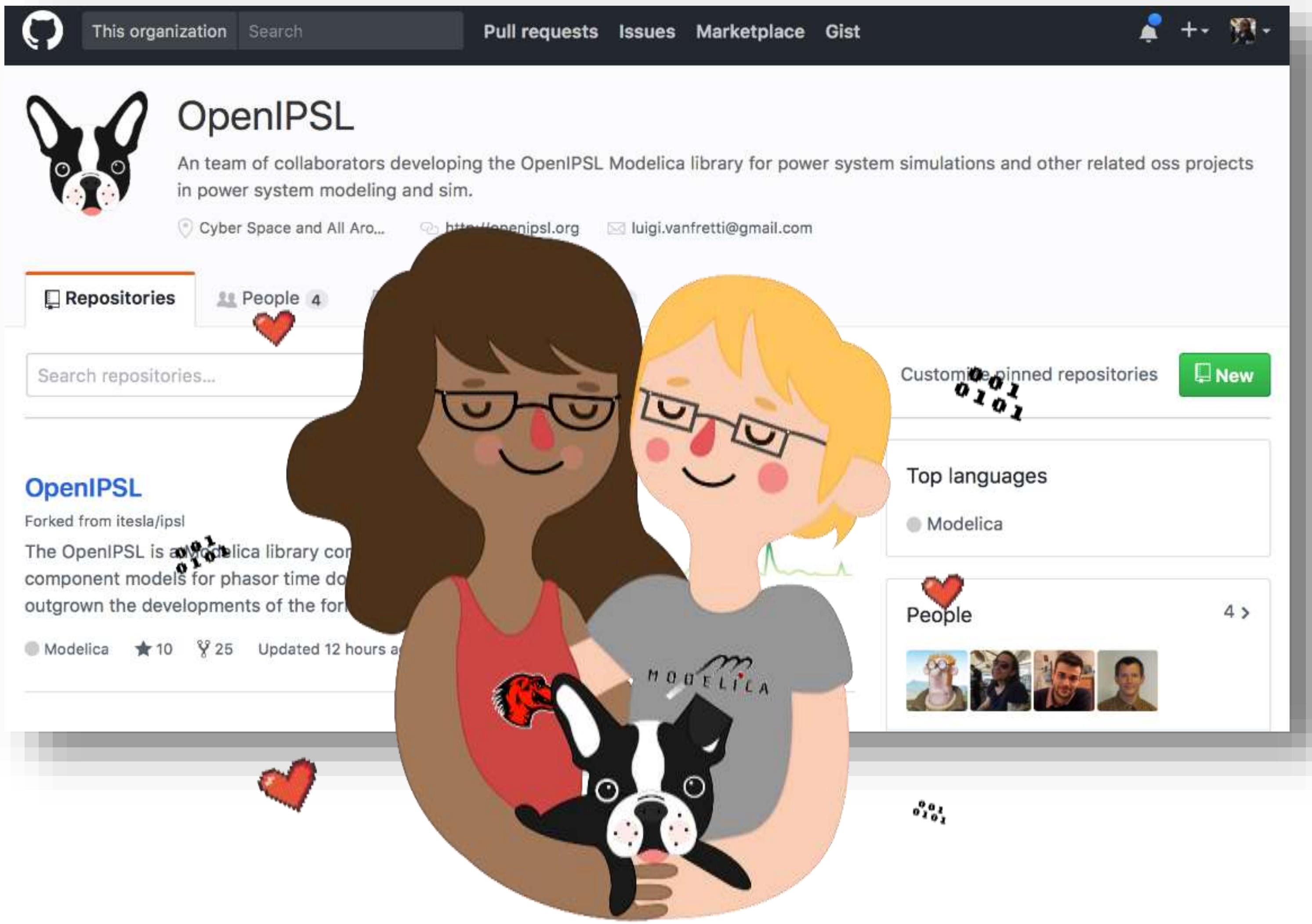
modeling and simulation environment (tool) tasks



Enter: The *OpenIPSL* Project

- http://openipsl.org
- Built using the Modelica language:

- Distributed with the MPL2 license:



Free as in Puppy!
Needs a lot of **your** love and care to grow and be happy!

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The *OpenIPSL* Library – Key Feautures

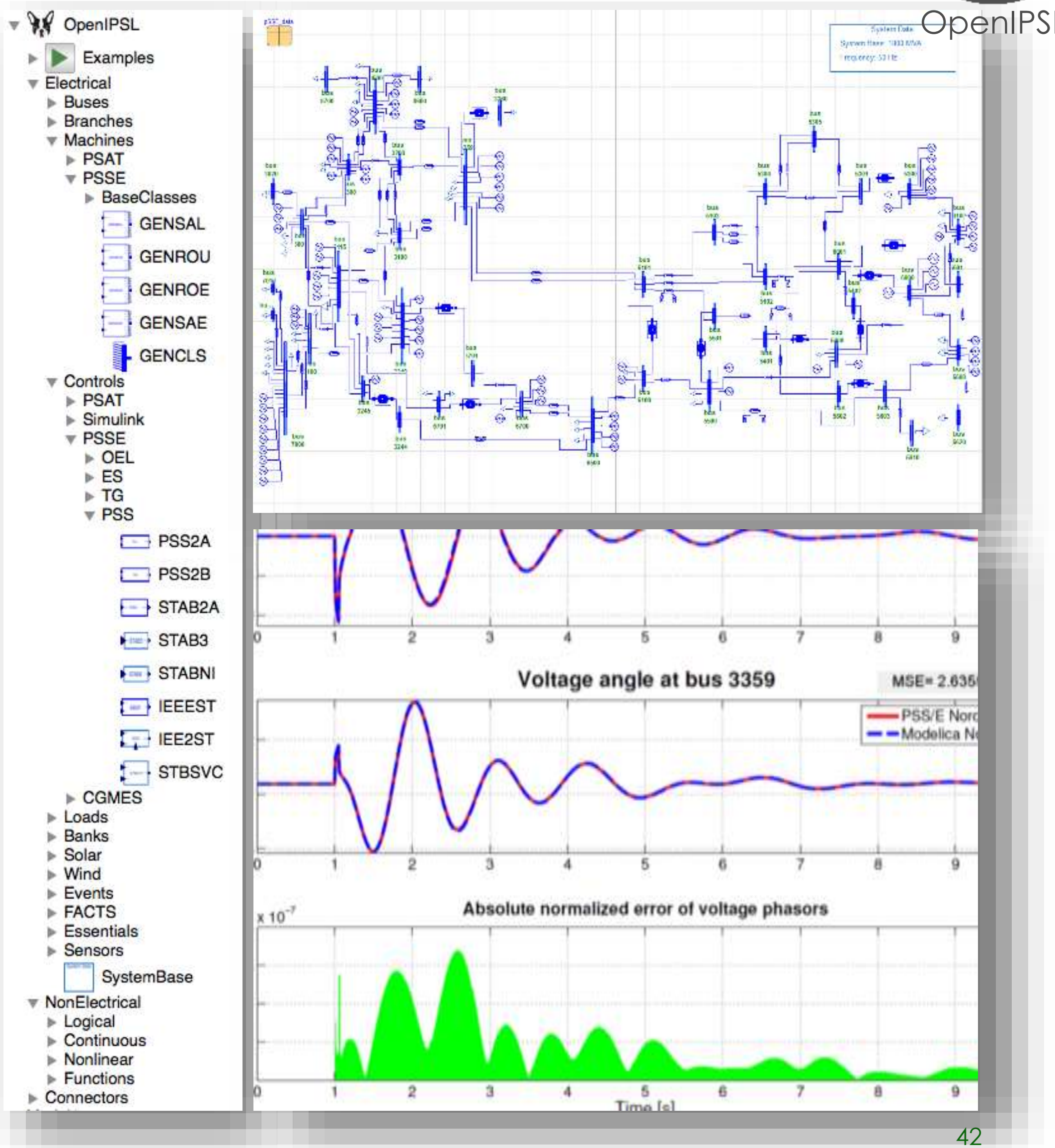
OpenIPSL

OpenIPSL is an open-source Modelica library for power systems

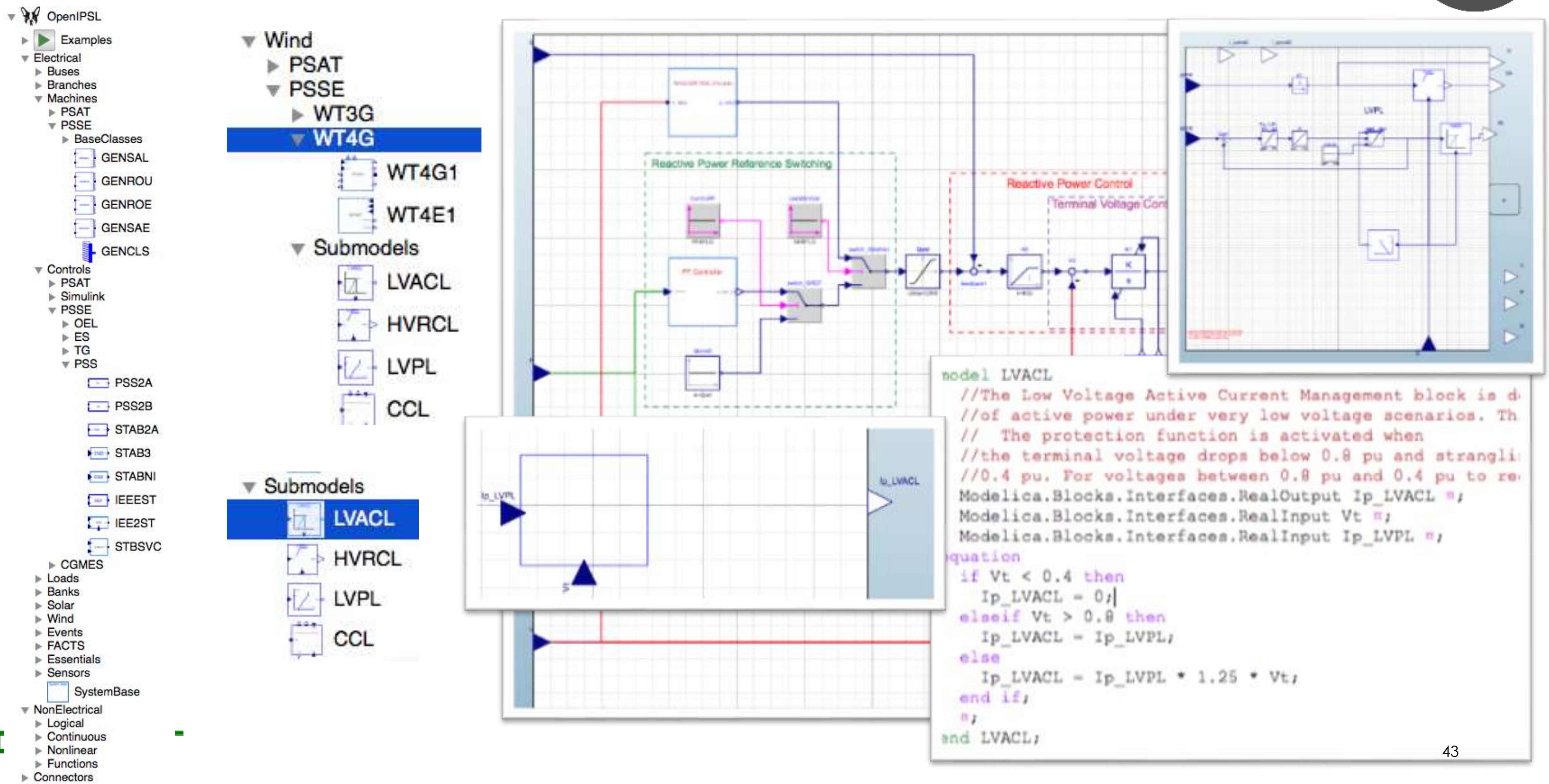
- It contains a set of **power system components** for **phasor time domain** modeling and simulation
- Models have been **validated** against a number of reference tools (mainly PSS/E)

OpenIPSL enables:

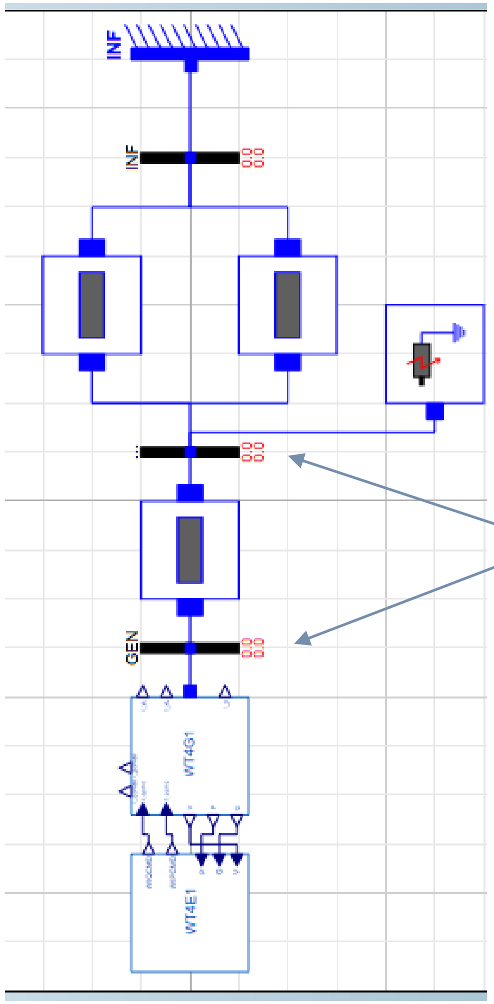
- **Unambiguous** model exchange
- Formal **mathematical description** of models
- **Separation** of **models** from tools/IDEs and **solvers**
- Use of **object-oriented** paradigms



The *OpenIPSL* Library – WT Example



The *OpenIPSL* Library – Network Example



- OpenIPSL
  - Examples
    - Machines
  - Wind
    - PSSE
      - WT4G
        - WT4G1_WT4E1
        - WT4G1

Class Connections

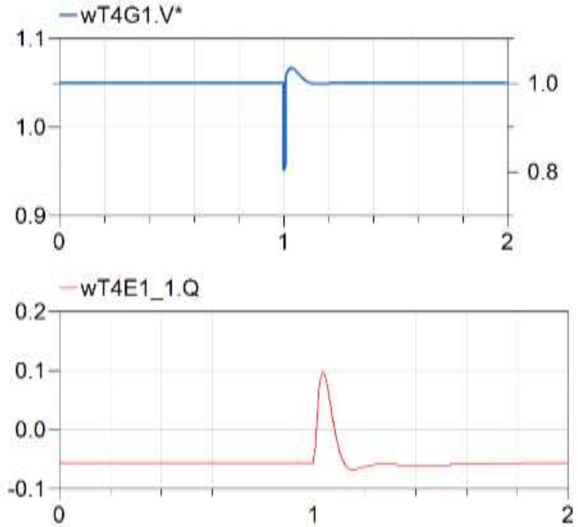
```
equation
  connect(wT4G1.p, GEN.p) ;
  connect(GEN.p, pwLine2.p) ;
  connect(pwLine2.n, BUS1.p) ;
  connect(BUS1.p, pwLine.p) ;
  connect(pwLine1.p, pwLine.p) ;
  connect(pwFault.p, BUS1.p) ;
  connect(pwLine.n, INF.p) ;
  connect(pwLine1.n, INF.p) ;
  connect(INF.p, gENCLS2_1.p) ;
  connect(wT4E1_1.WIQCMD, wT4G1.I_qcmd)
  connect(wT4E1_1.WIPCMD, wT4G1.I_pcmd)
  connect(wT4G1.P, wT4E1_1.P) ;
  connect(wT4G1.V, wT4E1_1.V) ;
  connect(wT4G1.Q, wT4E1_1.Q) ;

end WT4G1_WT4E1;
```

Resulting Parameter Declaration

```
model WT4G1_WT4E1
  extends Modelica.Icons.Example;
  constant Real pi=Modelica.Constants.pi;
  parameter Real V1=1.00000;
  parameter Real A1=-1.570655e-005;
```

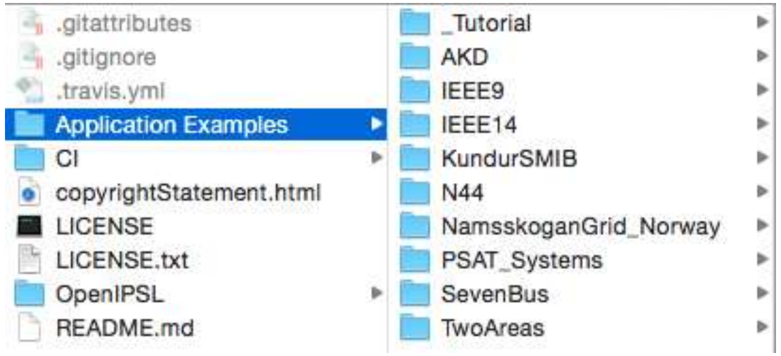
Resulting Class Instantiation

```
OpenIPSL.Electrical.Branches.PwLine pwLine2(
  G=0,
  B=0,
  R=2.50000E-3,
  X=2.50000E-3) ;
OpenIPSL.Electrical.Wind.PSSE.WT4G.WT4G1 wT4G1(
  V_0=V3,
  angle_0=A3,
  M_b=100,
  P_0=P3,
  Q_0=Q3,
  T_IQCmd=0.02,
  T_IPCmd=0.02,
  V_LVPL1=0.4,
  V_LVPL2=0.9,
  G_LVPL=1.11,
  V_HVRCR=1.2,
  CUR_HVRCR=2,
  RIp_LVPL=2,
  T_LVPL=0.02) ;
```

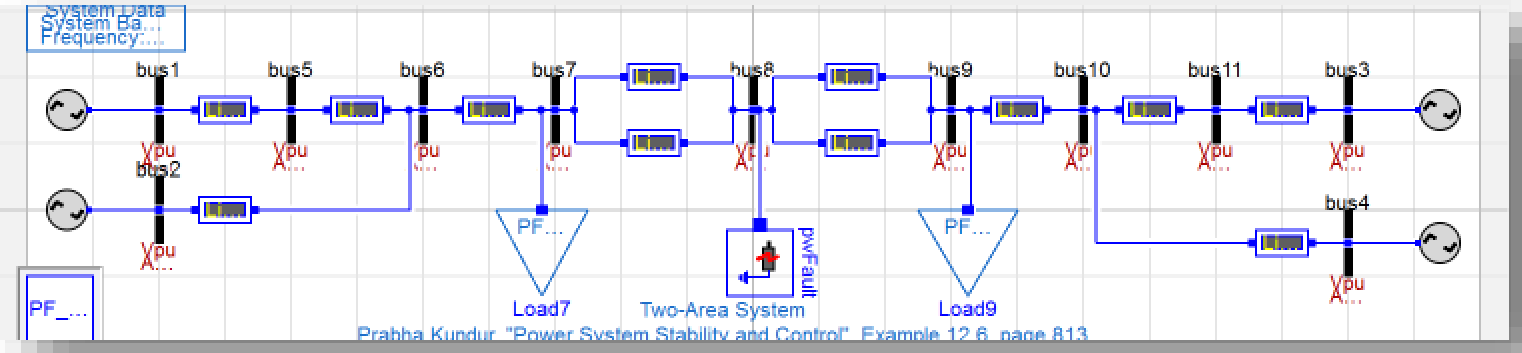


The *OpenIPSL* Library – Application Examples

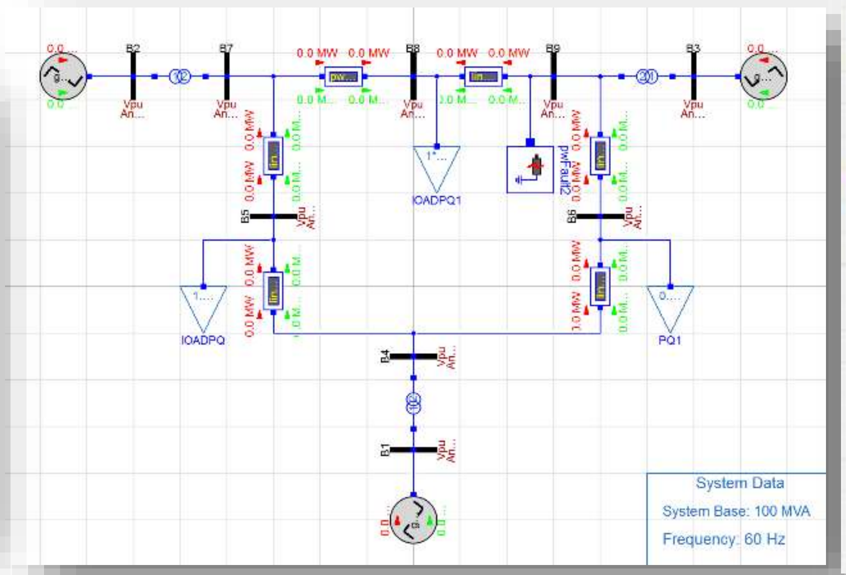
Many Application Examples Developed!!!



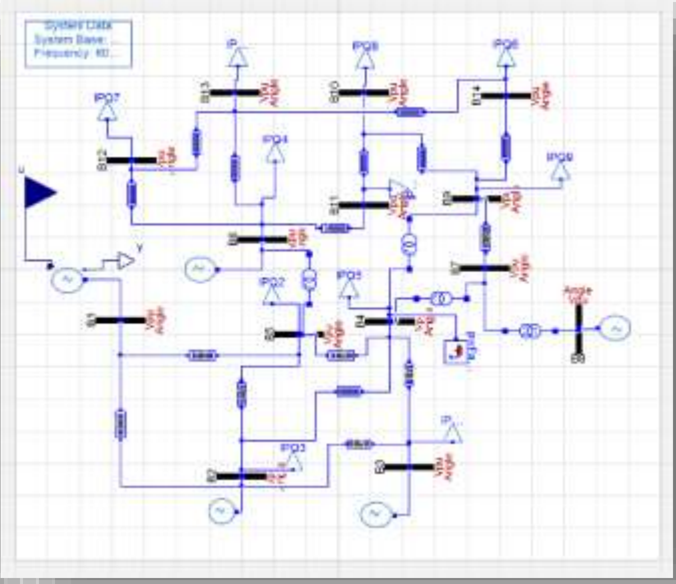
Klein-Rogers-Kundur 2-Area 4-Machine System



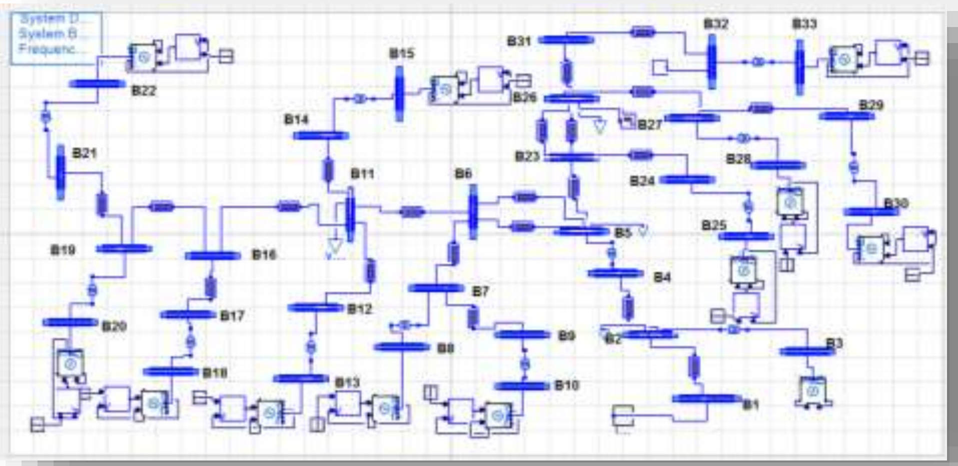
IEEE 9 Bus



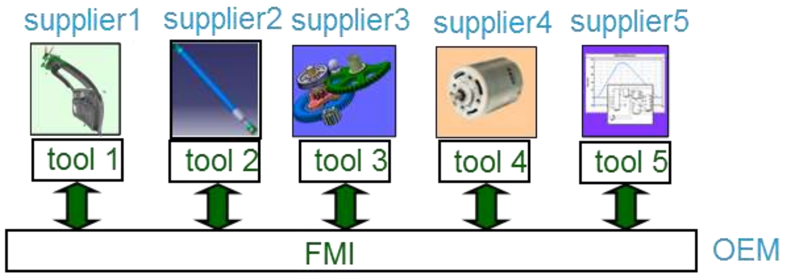
IEEE 14 Bus

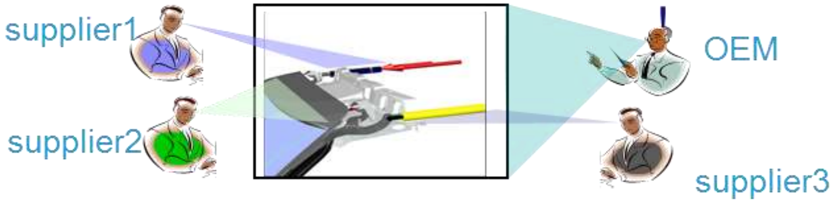


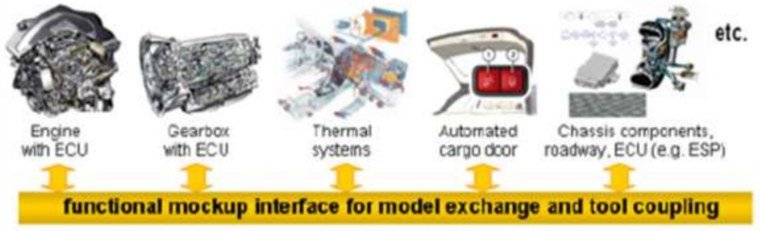
Namsskogan Distribution Network



Open-Standarized Model Exchange and Simulation: **FMI and FMUs**







- **FMI** stands for **F**unctional **M**ock-up **I**nterface:
  - *FMI is* ***a tool independent standard*** to support both model exchange and co-simulation of dynamic models using a combination of xml-files and C-code, originating from the automotive industry

The FMI Standard is now supported by more than 40 different simulation tools.

- A **F**unctional **M**ock-up **U**nit (**FMU**) is a model which has been compiled using the FMI standard definition

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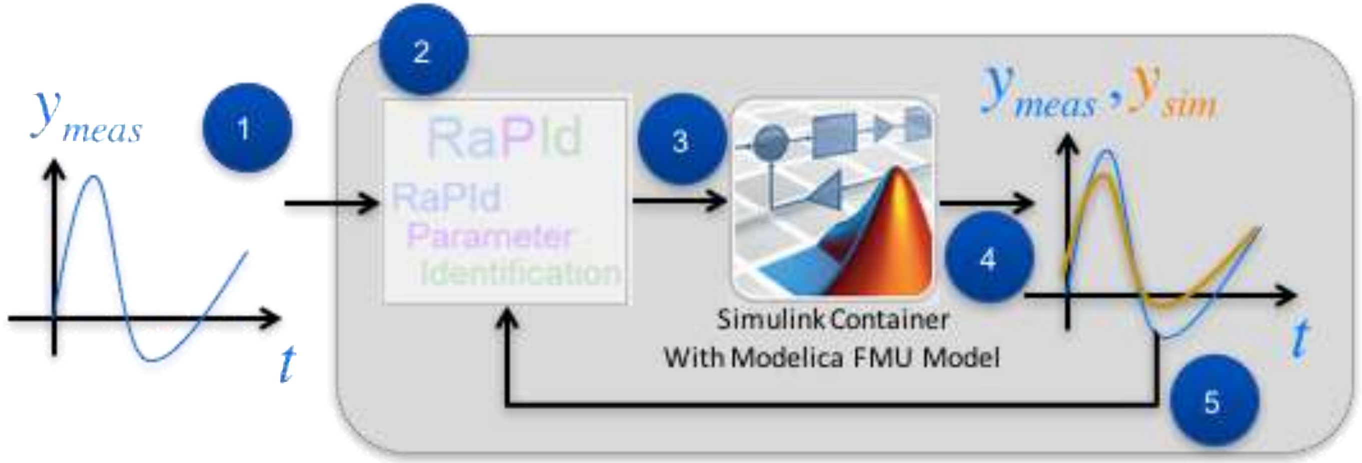
Model Validation:

Methods and Tooling for Validating Power System Models

- **RaPId** is a toolbox providing **a general framework to solve system identification problems.**
- The SW is modular and extensible, with a plug-in SW architecture allowing to use different optimization, simulation and signal processing techniques.
- **A common application of RaPId** is to attempt to **tune the parameters** of the model so as to satisfy the user-defined fitness function



Model Validation:

Methods and Tooling for Validating Power System Models

- **RaPId** was developed in **MATLAB**.
  - The MATLAB code acts as ***wrapper*** to provide interaction with several other programs (which may not need to be coded in MATLAB).

- Optimization process can be set up and ran from the **GUI** or more advanced users can simply use **MATLAB scripts** for the same purpose

- **Plug-in Architecture:**

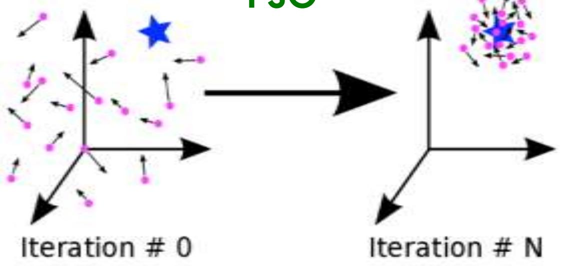
Completely extensible and open architecture allows advanced users to add:

- Identification methods
- Optimization methods
- Specific objective functions
- Solvers (numerical integration routines)

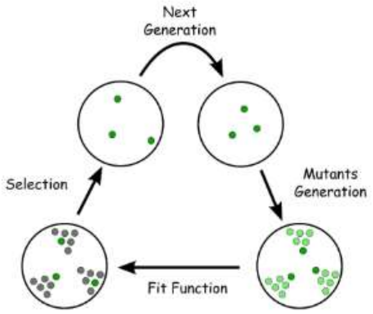
Optimization method agnostic: a number of optimization algorithms are available, and any method with MATLAB interfaced can be used:

- Particle Swarm Algorithm (PSO)
- Genetic Algorithm (GA)
- Naïve method
- Knitro Algorithms

PSO



GA

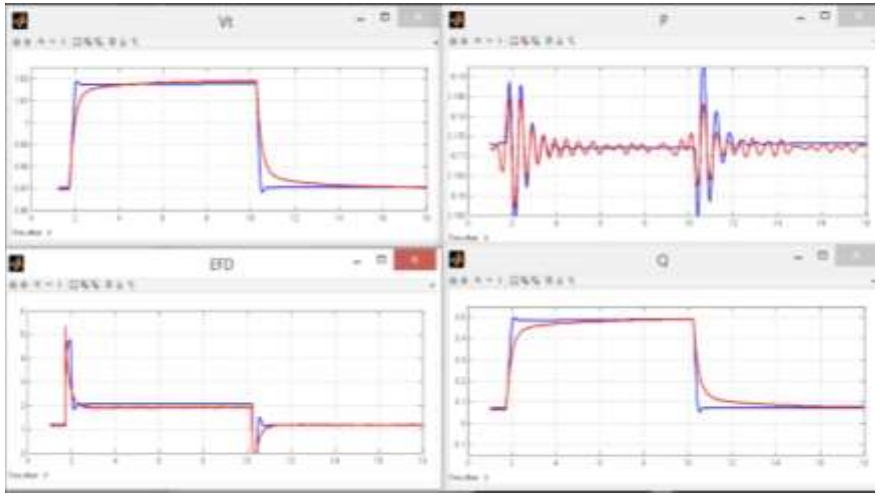


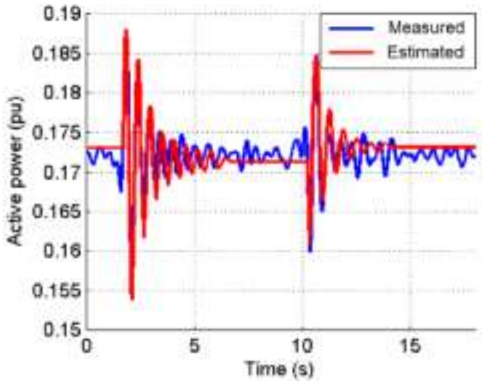
Model Validation:
Methods and Tooling for Validating Power System Models

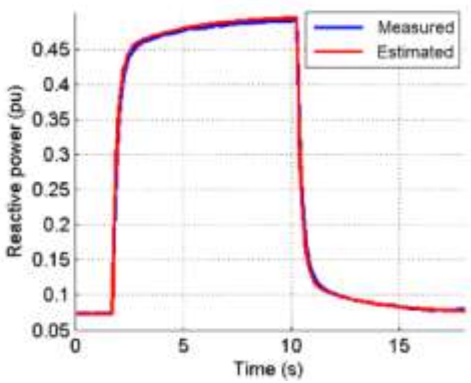
Video!

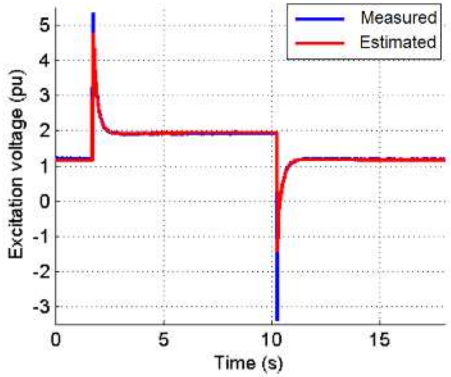
Excitation System Parameter Estimation for the MOSTAR Generator

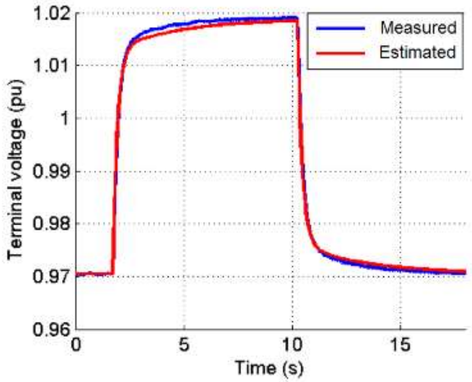
https://www.youtube.com/watch?v=X8X89I1HBjo











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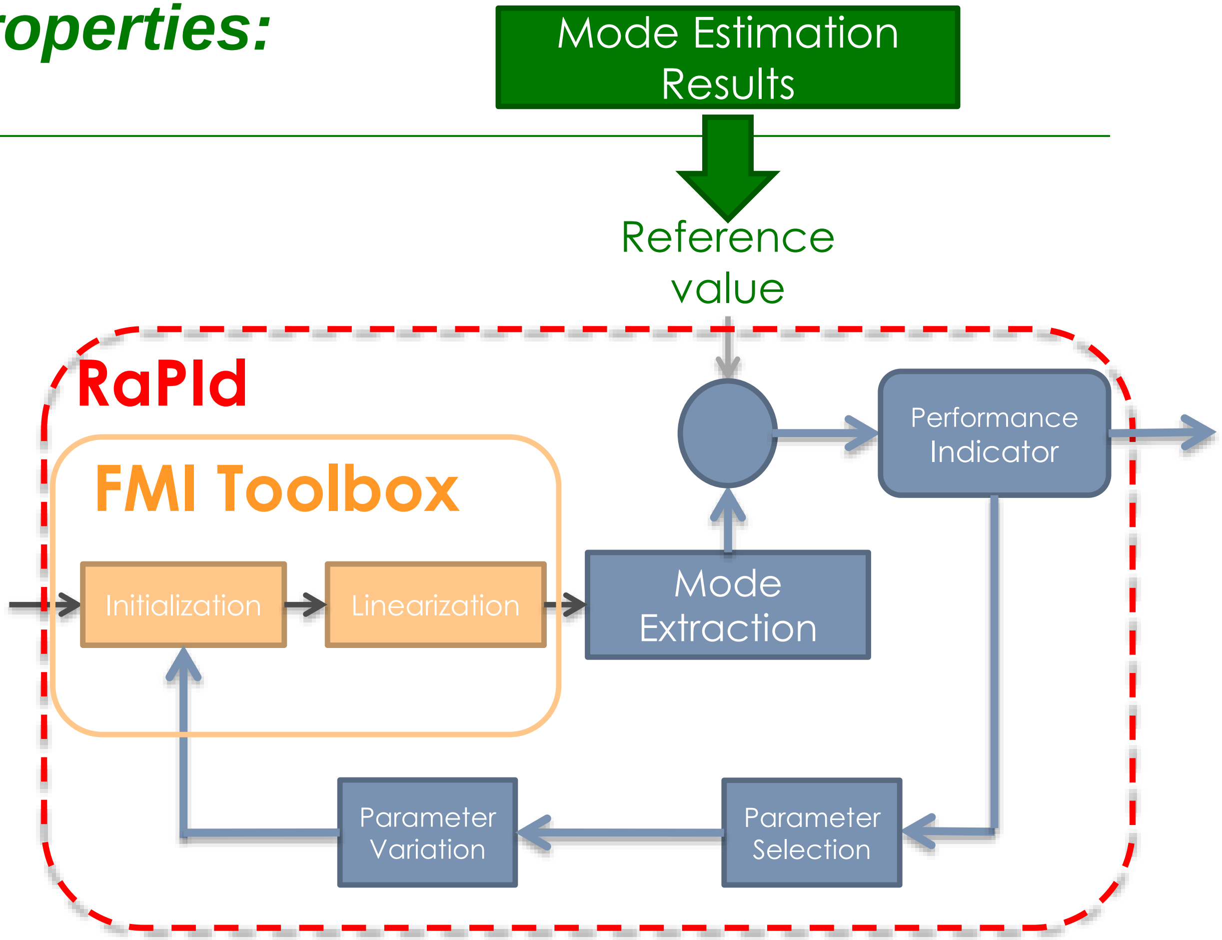
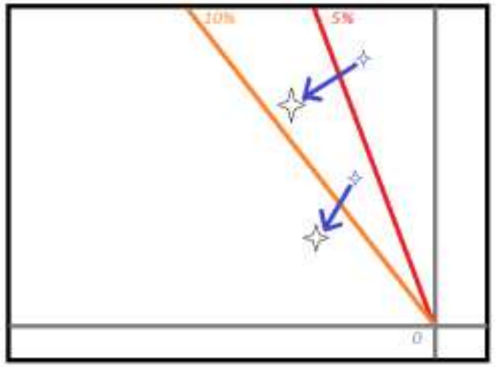
https://github.com/ALSETLab/RaPId

Validating Wide-Area Power System Properties:
Mode Estimates are a Reference

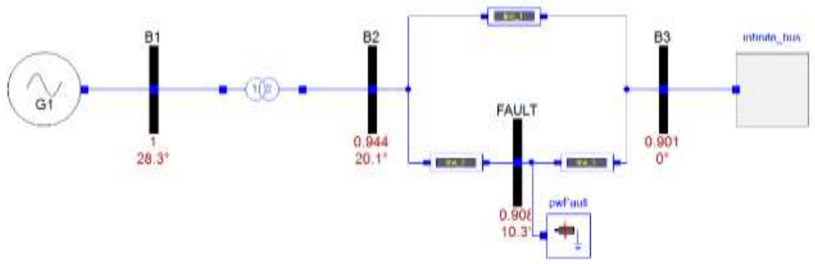


- The RaPId code was extended to include calibration based on the model linearization.
- The implementation utilize FMI technologies to extract the eigenvalues of the non-linear model.
- **Mode extraction**
  - Frequency closest to the reference modes
- **Performance indicator**
- Weighted objective function with
  - ***Small signal*** : Euclidian distance between modes
  - ***Time domain*** : Time domain fitness criterion
- **Parameter selection**
  - Defined in RaPId options
- **Parameter variation**
  - RaPId optimization methods
- Optimization problem: $\text{Min } PI = w_1 PI_{\substack{small\\signal}} + w_2 PI_{\substack{time\\domain}}$

$$PI_{\substack{small\\signal}} = \|s_{model} - s_{ref}\| = \sqrt{\left(re(s_{model}) - re(s_{ref})\right)^2 + \left(\omega_{model} - \omega_{ref}\right)^2}$$

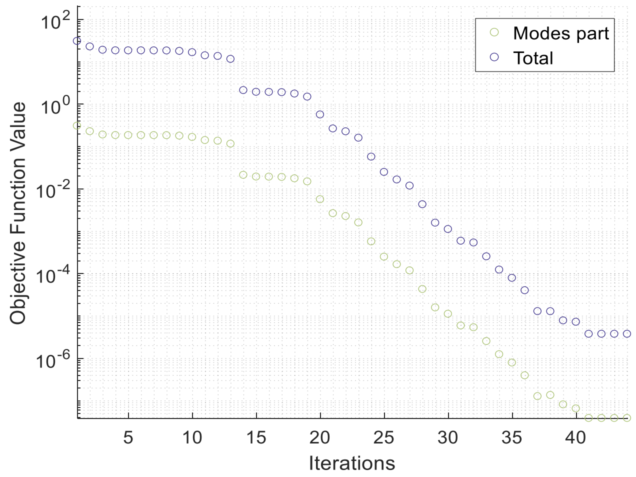


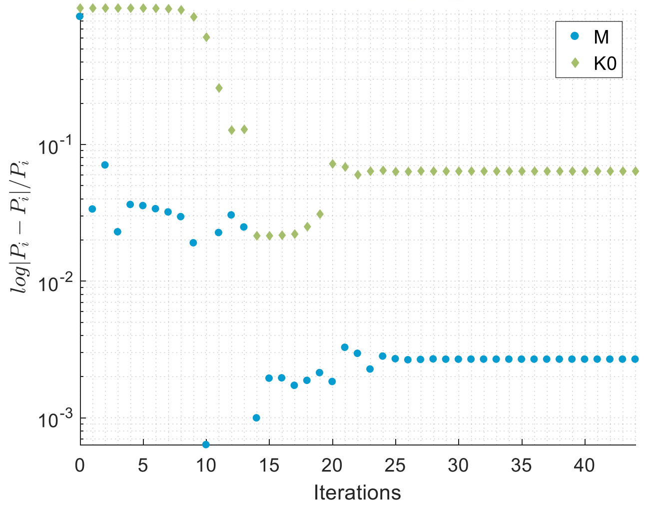
Single Machine Infinite Bus Example



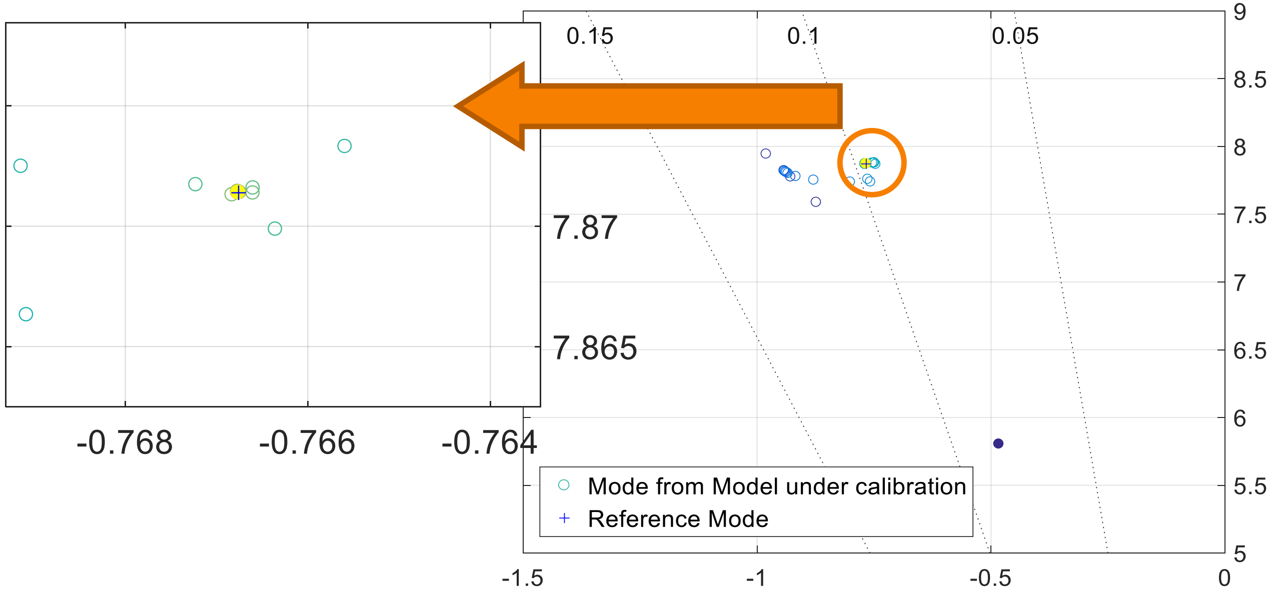
- In this example, a simple Single Machine – Infinite Bus (SMIB) is set up in for calibration:
  - The selected parameters:
    - AVR Gain K0
    - Generator's Inertia M
  - The mode(s) of the system were estimated with the Mode Estimator

→ Successful Calibration !





Parameter	M	K0
Result	6.98	212.74
"True Value"	7	200



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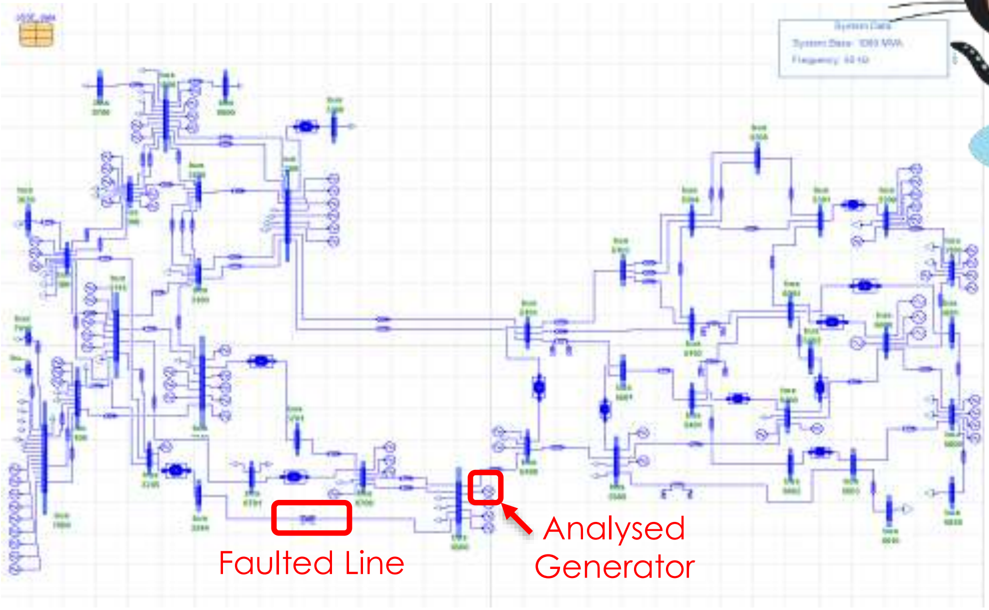
Nordic44 – Small Signal Model Calibration

https://github.com/ALSETLab/Nordic44-Nordpool

- The **calibration of the generator inertia** in the N44 system has been carried out on the marked generator
- The **disturbance** is introduced to the system in form of **line opening** between buses 3244 and 6500
- **Three signals** are used for parameter estimation:
  - Terminal voltage magnitude
  - Terminal voltage angle
  - Active power transfer over the faulted line

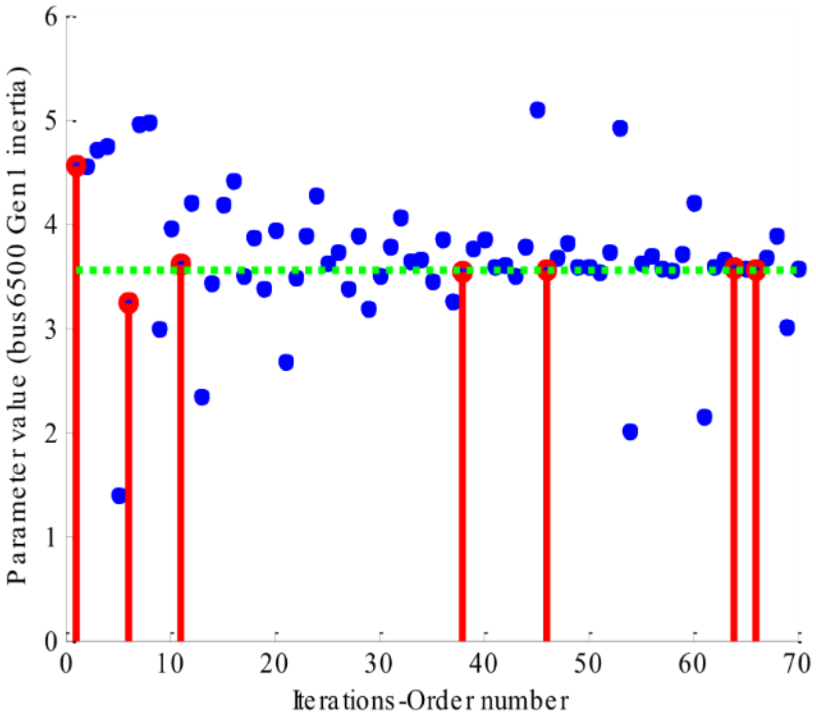


- The calibration is carried out with the following setting of performance indicator:

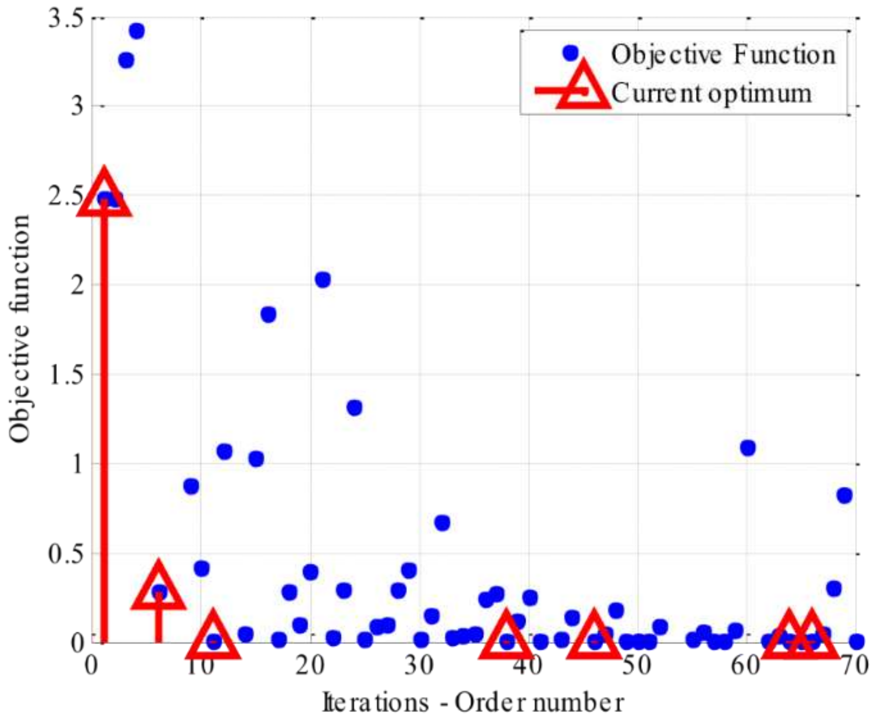
$$PI = w_1 PI_{\substack{small\\signal}} + w_2 PI_{\substack{time\\domain}}, \qquad w_1 = 1000, \qquad w_2 = 1$$

- The large difference between two weighing factors is due to the numerical difference between the two performance indicators (small signal and time domain)
- The true value of the estimated generator inertia is 3.556 and the starting guess is 4.556

Nordic44 – Small Signal Model Calibration

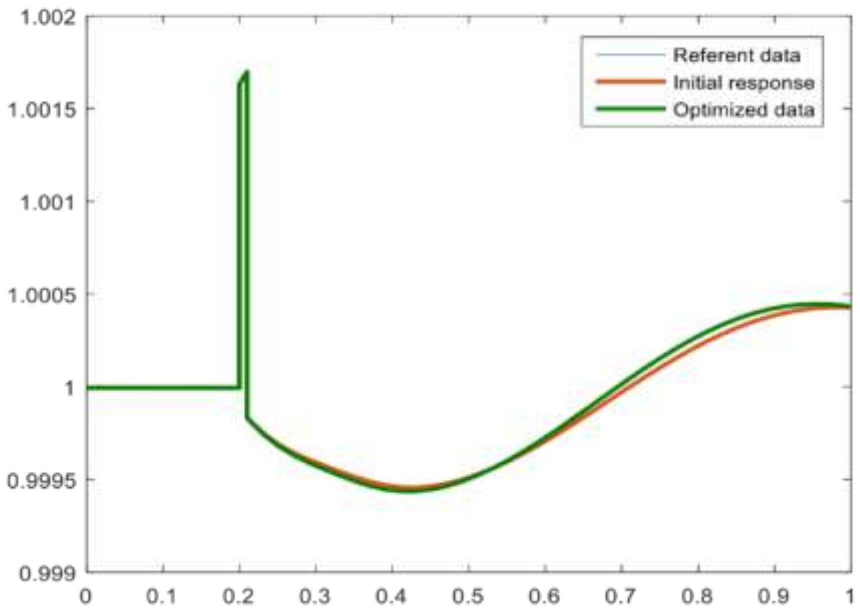


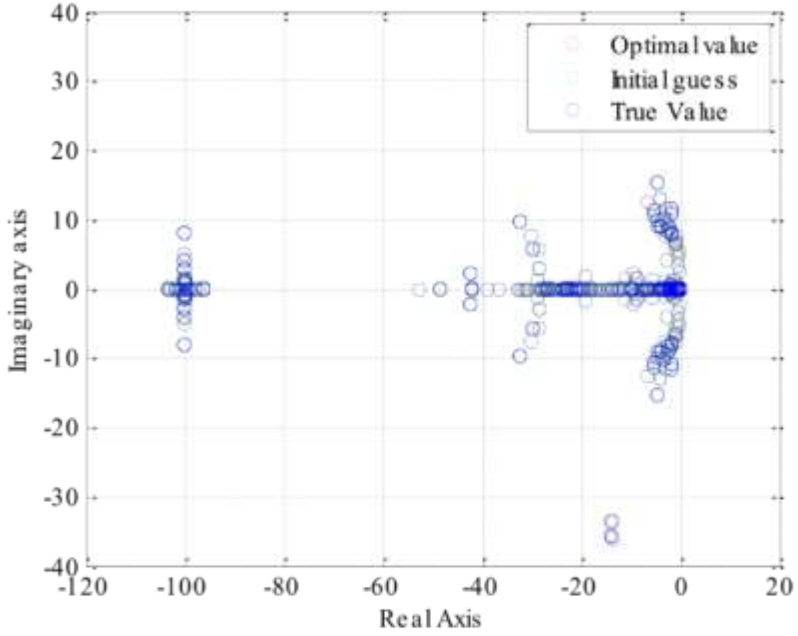
- The figure (left) shows evolution of parameter value with respect to number of iterations being carried out
- The total number of iterations is 70 and the estimated parameter value is 3.5546 which is very close to the true value of 3.556
- The dots marked in red are parameter values currently giving optimum and the ones in blue are just attempts by the algorithm

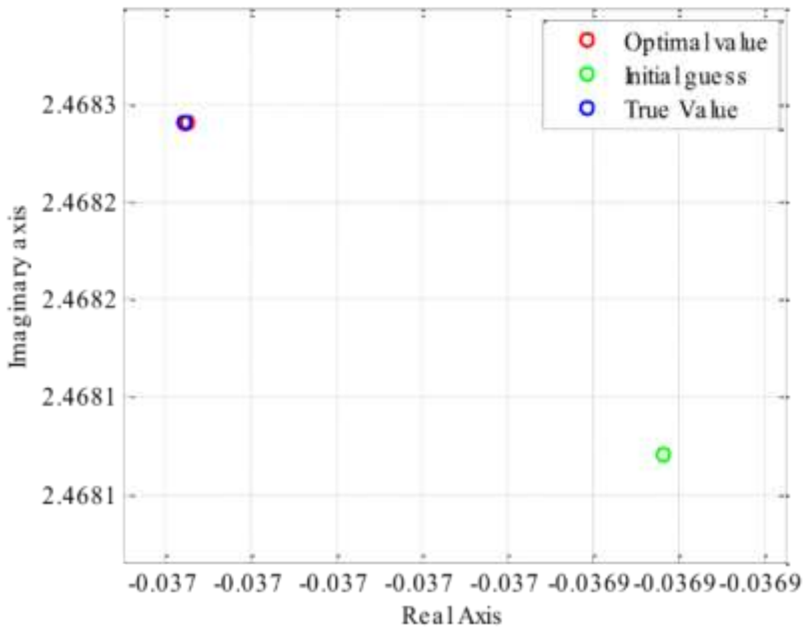


- Objective function evolution shows the same behaviour of the estimation process, only from a different perspective
- Convergence of the estimation is reached in a definite time and the objective function is close to the value of 0

Nordic44 – Small Signal Model Calibration







- Time domain results show a very good fit of data
- However, since the small signal analysis was used in parameter estimation, one should also look at the changes in the stability plane

- This figure shows all of the modes of the system
- The position of true poles, poles with the parameter set to the initial value and poles with the estimated value of the parameter

- However, the estimated process was focused only one mode of oscillations shown on this figure
- We can now conclude that the estimation procedure was successful since both time domain results and the small signal analysis of system with optimal and true value give show close match of the two systems

Conclusions

- Measurement-based identification methods offer power system operators another tool for power system situational awareness.
- Use of probing signals leads to more accurate mode estimates, complete system models, and provides validation data.
- Model validation depends as much in the tooling and modeling language as in the methods.

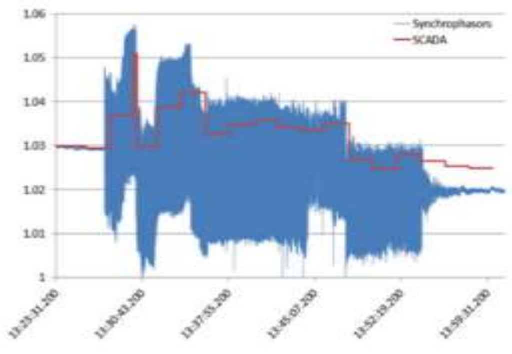


FIGURE 1. Comparison example between PMU measurements and SCADA data during a fast dynamic event; grid voltage is in p.u.

Real-time monitoring and model-validation is crucial to anticipate power system problems and for planning, **this is crucial as we integrate more renewables and power electronics into the grid.**

And for the system identification community:
"My fellow researchers: **ask** not what **your power system can do** for **you—ask what you can do for your power system**" Dr. Luigi

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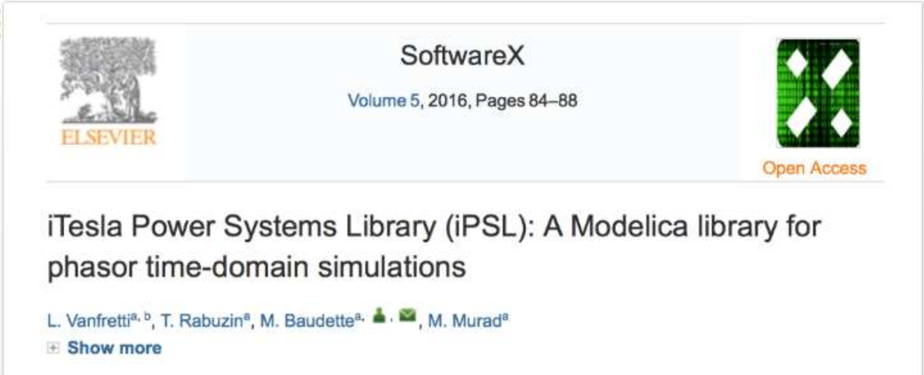
The **OpenIPSL** can be found online

- http://openipsl.org

Our work on **OpenIPSL** has been published in the SoftwareX Journal:

- http://dx.doi.org/10.1016/j.softx.2016.05.001



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iTesla Power Systems Library (iPSL): A Modelica library for phasor time-domain simulations

L. Vanfretti[a, b], T. Rabuzin[a], M. Baudette[a], M. Murad[a]
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RaPId: A modular and extensible toolbox for parameter estimation of Modelica and FMI compliant models

RaPId, a **system identification** software that uses OpenIPSL can be found at:

- https://github.com/ALSETLab/RaPId
- http://dx.doi.org/10.1016/j.softx.2016.07.004


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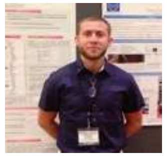
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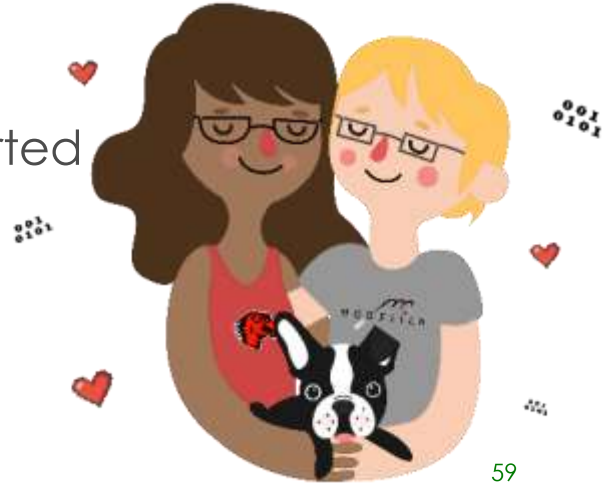

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