KTH ROYAL INSTITUTE
OF TECHNOLOGY

Real-Time Simulation @ KTH SmarTS-Lab for *MBSE of Synchrophasor Systems*

A journey of 7 years in development of PMU applications and end-to-end testing…

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This work was supported in part by:

openCPS

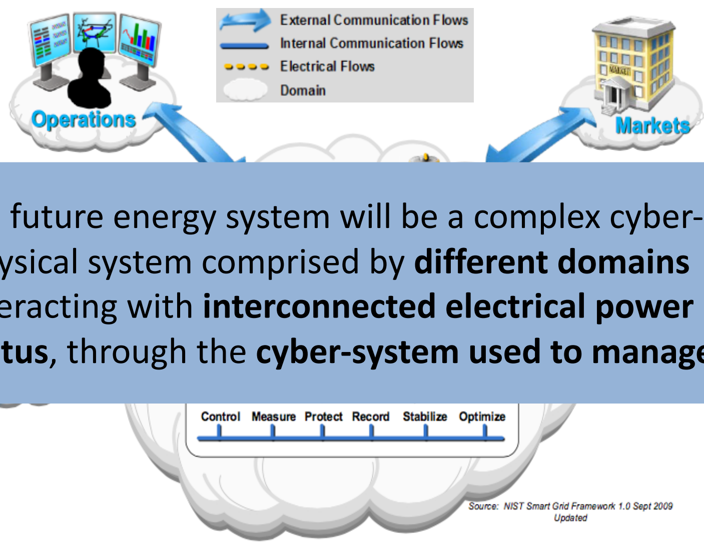
ITEA 3 EUREKA innovation across borders

STandUP for ENERGY

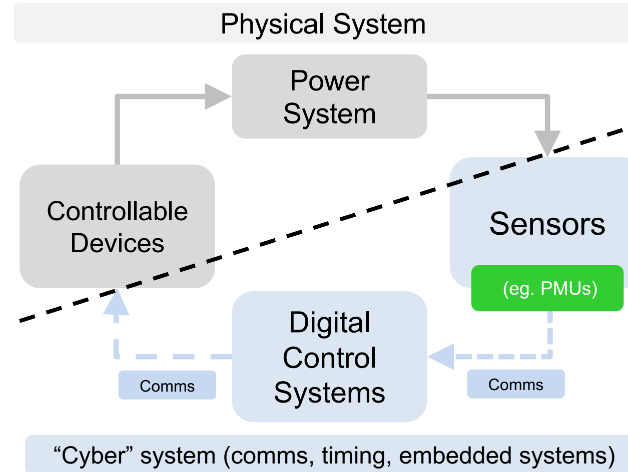
2ND WORKSHOP ON DYNAMIC SYSTEM MODELLING

March 23rd, 2017
Dublin, Ireland

Smart Grids = **Cyber-Physical Power Systems**



The future energy system will be a complex cyber-physical system comprised by **different domains** interacting with **interconnected electrical power apparatus**, through the **cyber-system used to manage it.**



A Specific Example - Wide-area control systems (WACS):
WACS include an ICT platform that merges the input measurement data and transforms it to a useful input signal for controllable devices to perform a given function.

WACS *consists of:* (A) a number of synchronized phasor measurements units (PMUs – a sort of GPS **time-syncronized distributed sensor**) from geographically spread locations, *sending data through (B) a communication network* (C) a *computer system* termed phasor data concentrator (aggregates and time-aligns data from different sensors), (D) a real-time computer system where control functions are implemented, (E) a physical component that varies electrical quantities following the control function, and (F) using the GPS system for timing.

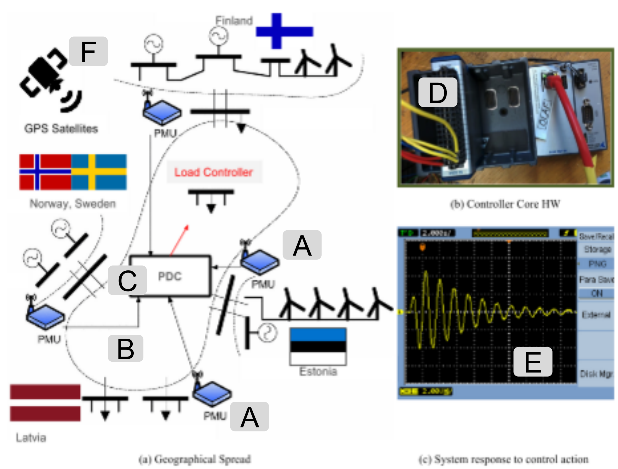


Fig. 1. A hypothetical WACS system in the Nordic-Baltic Region

WACS represent a true cyber-physical system that requires, **at a minimum:**
Tools for design,
Tools for simulation and
Tools for hardware and firmware deployment

These kind of tools don't really exist today for a joint "cyber" & "physical" system.

What *technologies* will be needed for smart grids?

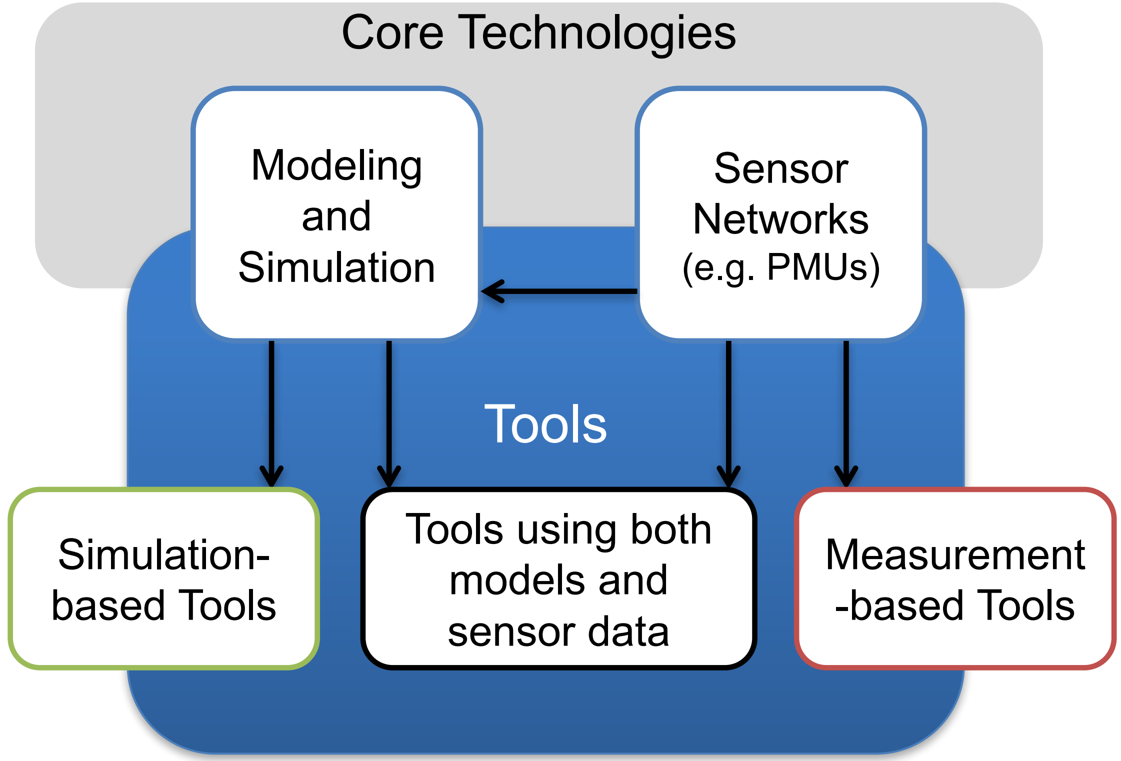
In general, we have two types of “data” that can be used to take decisions: **measurements** and/or **simulations**

- These tools should aim at answering critical questions:
  - What can be learned from the past?

Learning from measurement data

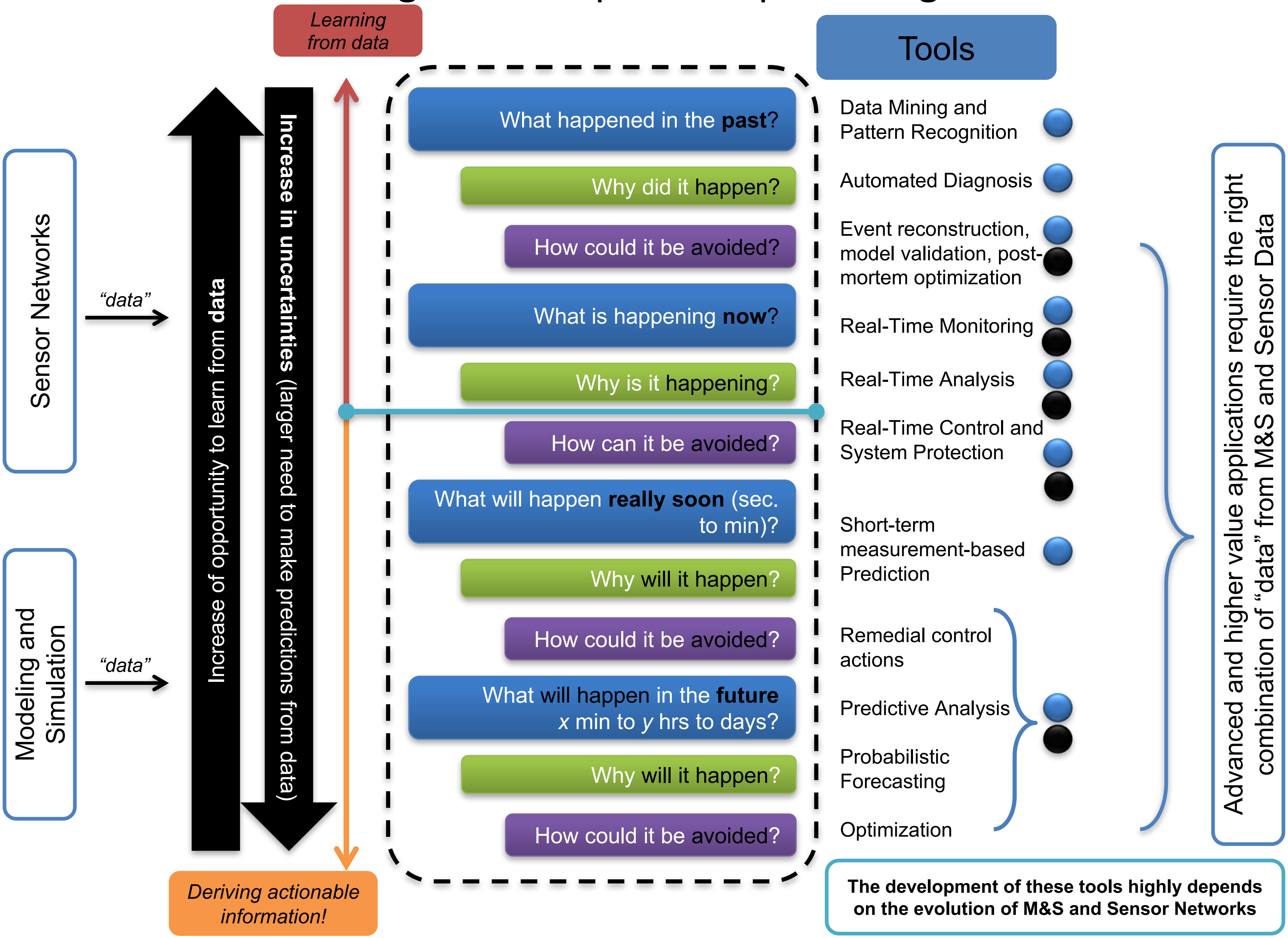
- What actions can be taken now?
- What actions can be taken in the future?

Deriving actionable information from ***measurement and simulation data***



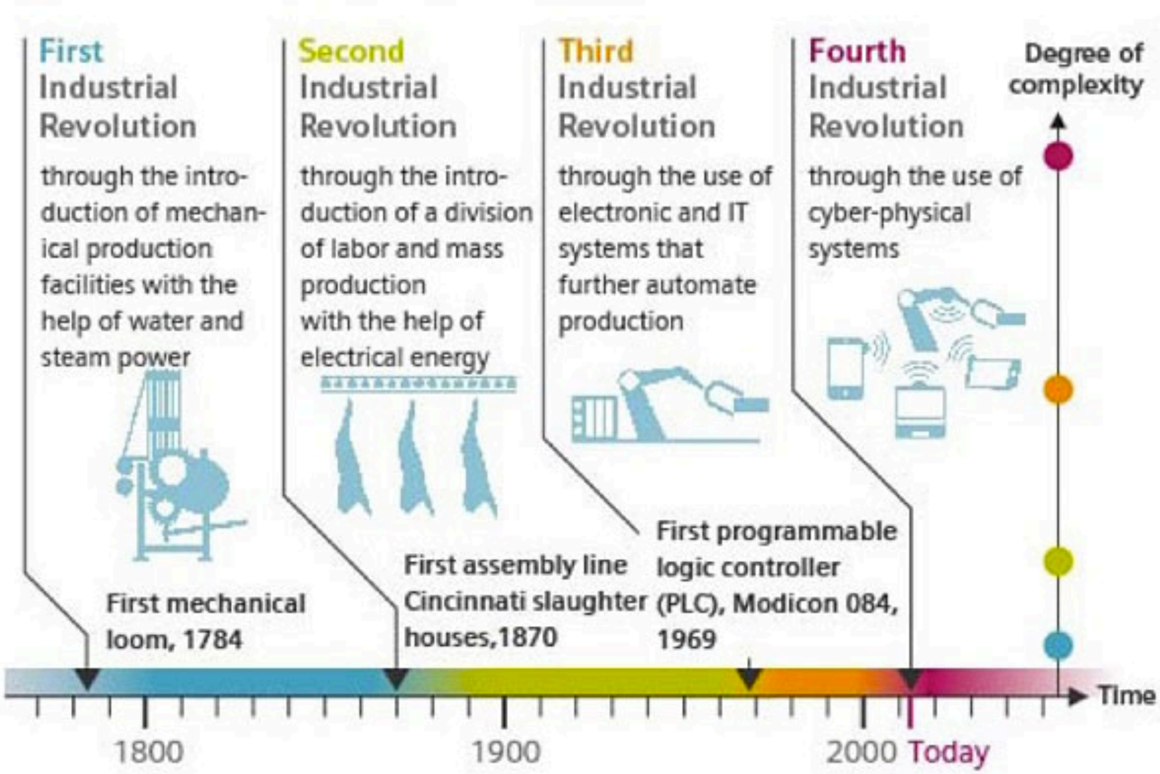
The development of these tools highly depends on the **evolution** of M&S Technologies and Sensor Networks Data (e.g. PMU)

Future Tools: learning from the past and predicting the future



"Smart Grids"

Is our technology in power systems evolving towards a 4th Industrial revolution?



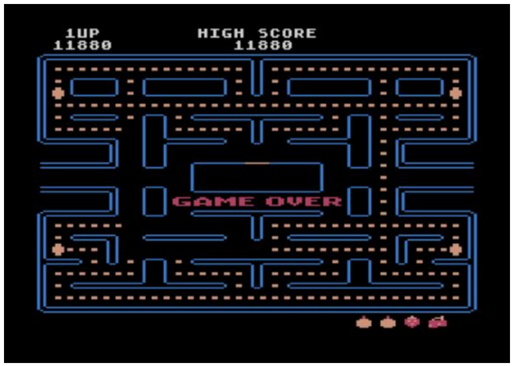
- Has the sensor networks evolved sufficiently to enable the fourth industrial revolution?
- Are our Modeling and Simulation (M&S) tools prepared to fulfill the needs of cyber-physical systems?

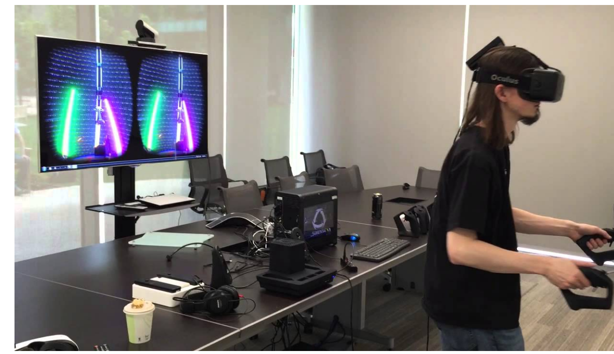
Is Model Systems-Based Engineering a framework for this evolution?

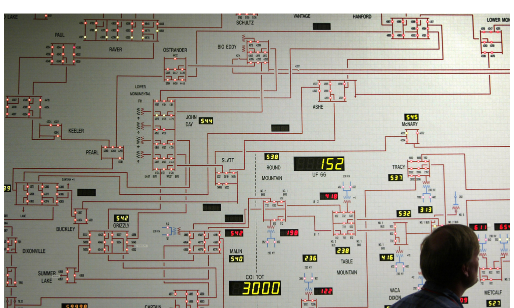
Evidence: what can we learn from multiple historical timelines?

Comparing technology development in three different engineering fields

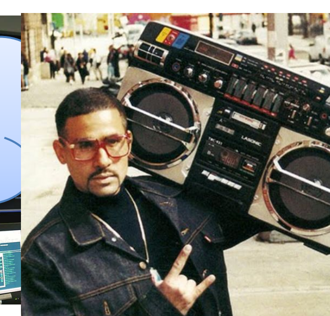
1980s	1990s-2000s	Today







… looks like
we are stuck
in 80s-90s



Evidence: what can we learn from 'smart grid' development?

Two Examples Highlighting "unspoken" Truths

The Royal Sea Port's 'Active House'

NyTeknik

Smart fiasco for prestige building in Stockholm Royal Seaport

2015-02-14 06:00 Av: Helen Ahlbom

Were technically the ... but there was ... required an ins...

- And it became p... because valuable ... spent trying to reso... the problem with anot... communications solution, remember Carin T...

Although the product was never ready to test in ... apartment, so ABB delivered the functionality p... the form of software and a PC.

Motion sensors would extinguis... ts in rooms where no one was. Appliances sh... automatically when the price of ele... tal emissions were lowest. E... electricity consump...

According Carin Torstensson was great companies unaccustomed to working together in a development project.

...ons have been spent

...ects in Stockholm Royal Seaport

...otal budget (million) which support from the Swedish Energy Agency / VINNOVA		
Preliminary study Smart grids	33.8	13.4
Conscious energy consumption	6.2	2.5
Active House in the sustainable city	20:10	
Smart power grids in urban	121.2	29.5
Total	181.2	55.4

Source: Energy Agency

Smart Meters

Smart meters: Hacking fear ahead of nationwide roll-out

25 May 2013 Last updated at 12:07 BST

Smart meters have helped many people take control of their energy use by showing how much gas or electricity they are using, there and then.

Over the next few years the plan is for every household to get one, at a cost of £11bn - but technology experts say some of the meters can be hacked.

Structural Weaknesses in the Open Smart Grid Protocol

SMART METER COSTS

DCC cost £2.47bn

Total roll-ou...

To...

...£6.2bn

...urce: Government/DECC 2014 impact assessment

"By contrast, they use the NIST-approved digest functions known as HMAC-SHA256 and AES-GMAC which are currently considered 'strong authentication,'" Crain said. "The No. 1 rule of cryptography is 'Don't invent your own.'"

Will smart m... ...e money?

By Lesley Curwe... BBC Radio 4...

Mil... ...rs in Britain are about to get a ... ...g system - smart meters - techn... ...which has been rejected by Germany and found not to be cost-effective by other nations.

Smart meter IT system delayed until autumn

By John Moylan
Industry correspondent, BBC News

17 August 2016 Business

The government wants every home and business to be offered a smart meter by the end of 2020. That requires 53 million meters to be fitted in over 30 million premises over the next four years.

From the technical perspective: Why were these failures not identified and avoided from an early stage?

New kind of integration of tech and user needs:

- Inadequate understanding of user requirements.
- Lack of a cohesive approach for 'system-of-system' design – different suppliers **NOT able to speak the same *language* and working in the same framework**
- Product integration and deployment w/o testing and verification.

Two domains, previously loosely related, & release 'to the wild':

- Cyber-security requirements and metering requirements should have been **jointly** defined, designed and assessed.
- Meter experts perhaps are not security experts
- **Both domain experts NOT working in the same framework.**
- Lack of joint integration testing, verification and validation

Is it really that hard to develop a "systems-of-systems"/cyber-physical system requiring experts of two or more domains?

Model and Simulation-Based Systems Engineering

megaprojects

flight test. The 5-hour, 48-minute program included flying the plane at low altitude, to evaluate how it would handle when the ground was close enough to affect the airflow around the aircraft. Also tested was the "configuration deviation list," to ensure that the plane would perform as expected should key electronic units fail. Less than a year later, on June 7, 1995, the first production unit started revenue service by flying from London to Washington, D.C.

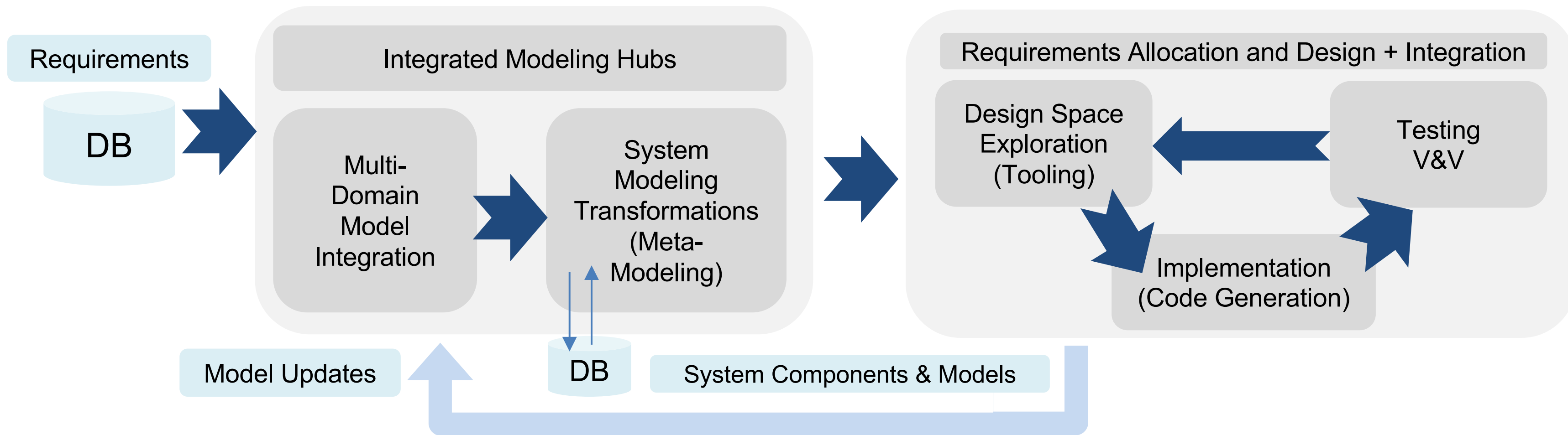
Fresh start

The answers are in the new technology used in the 777 itself, and in the design-engineering revolution that stormed through Boeing, based in Everett, Wash., during the creation of its first all-new jetliner since the early 1980s. Advances in electronics and in computer-aided design, manufacture and simulation provided the foundation for the new technology. Using these tools and systems to an unprecedented extent, Boeing was able to start afresh with the 777, changing the way in which the company builds aircraft. The results have been so dramatic that practically every new Boeing flight product—from the new generation of the venerable 737 family and F-22 air superiority fighter to International Space Station and the proposed X-33 reusable launch vehicle—is adopting some part of the program pioneered by the 777.

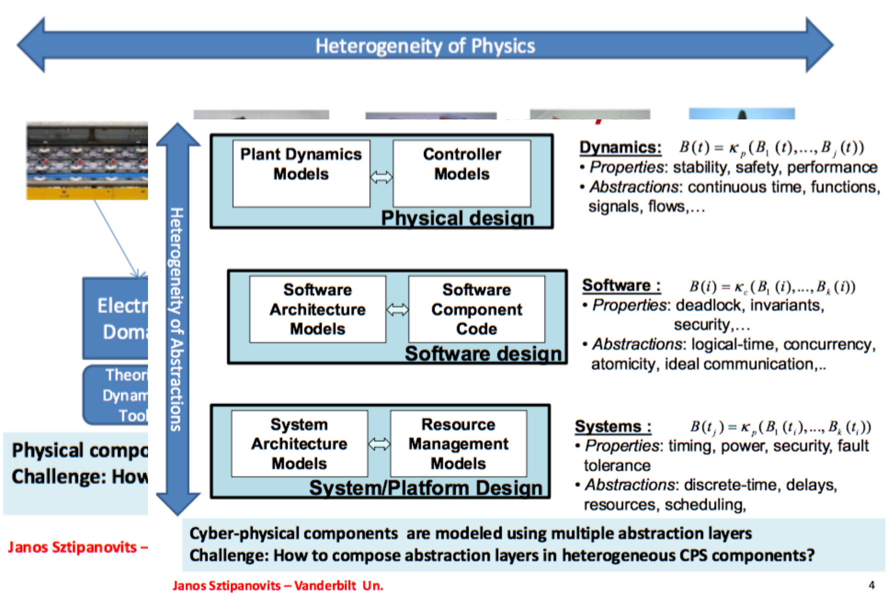
BOEING’S SEVENTH WONDER

Model and Simulation-Based Systems Engineering

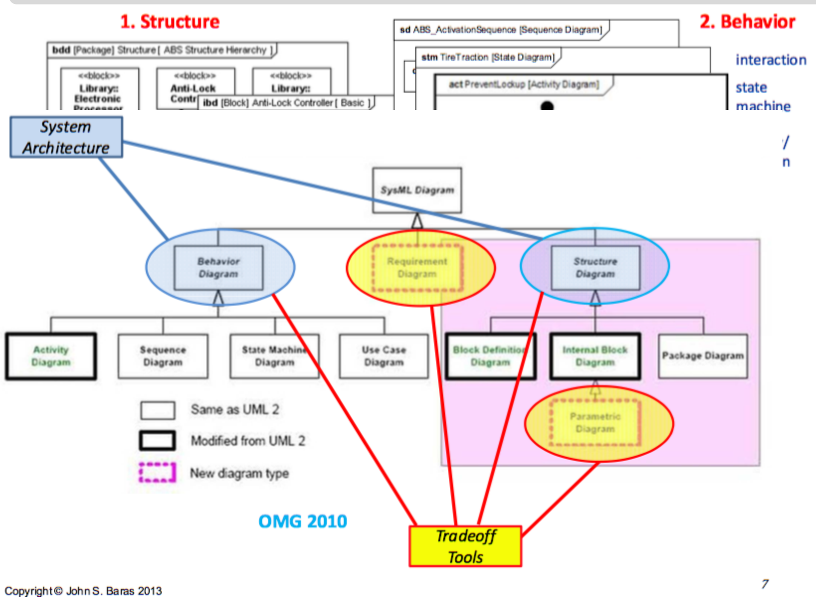
an evolving framework for multi-domain multi-physics system design, manufacturing and operation



Multi-Domain Model Integration

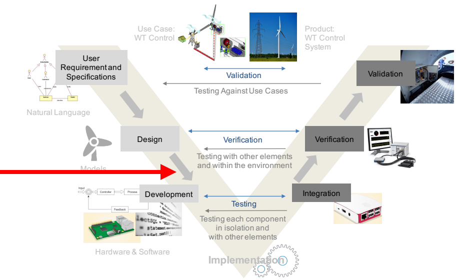


Abstraction Layers, Behavior and Transformations



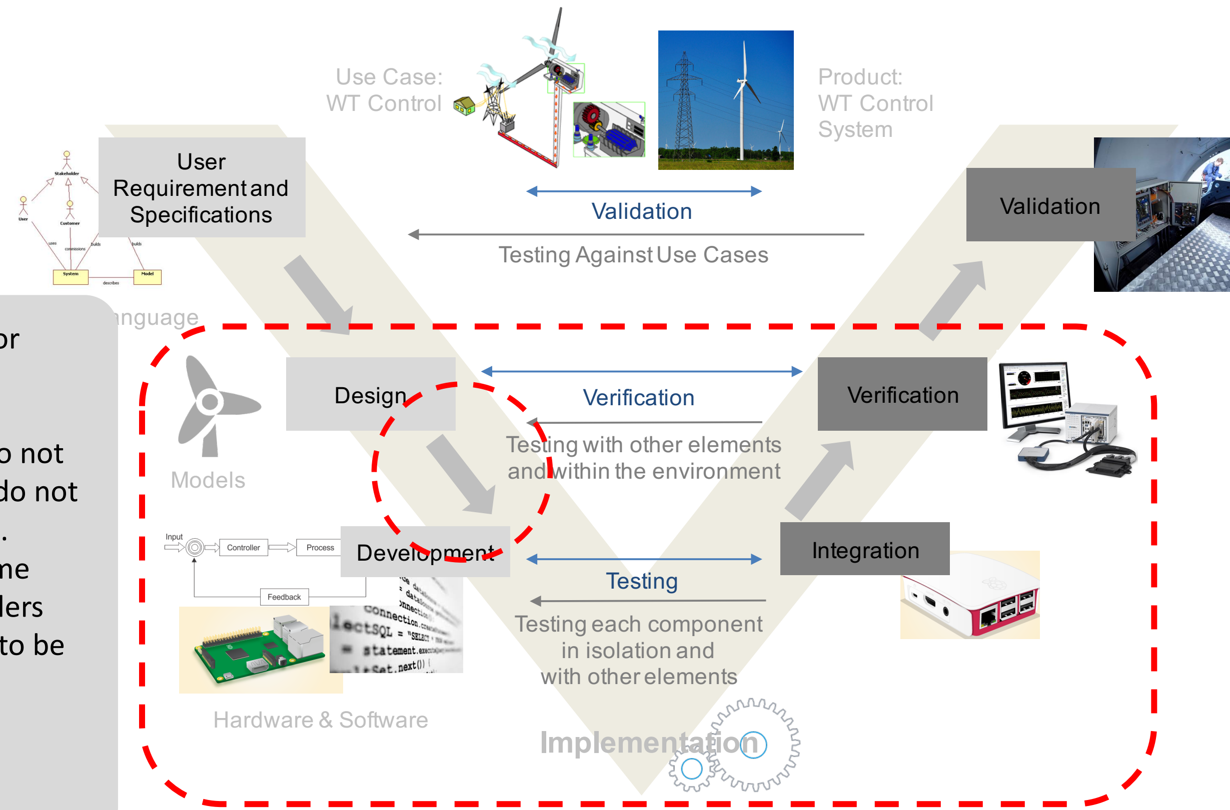
Beyond System Level Design and Analysis:

Model Transformation Advances and **Challenges**



Challenge: Bottleneck in Model Transformation

- CIM does not consider the requirement for support in model transformation for component-level design.
- Power system analysis and design tools do not support means for model exchange, and do not model/capture low-level device functions.
- There are still limitations for using real-time code generated by some Modelica compilers (need for special parallelization methods to be supported in large network simulation.
- FMI support for real-time?
- Etc., etc.,…



For the reminder of the work, we thus use a the typical Mathworks-based workflow for Modeling-Code Generation and Real-Time HIL simulation using a proprietary solution.

Research Infrastructure (Lab.) Dev. (1/3)

A Laboratory for Testing, V&V of PMU Applications

SmarTS Lab
Smart Transmission Systems Laboratory

2010:

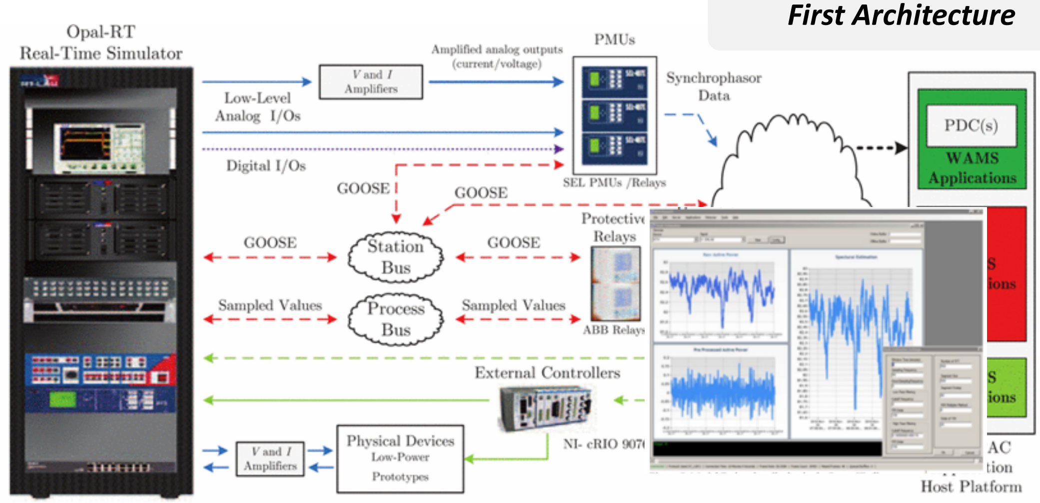
- I started working on the development of a lab. around August/September 2010.
- Not a lot of people where doing this back then (for power systems), it was also seen as "unnecessary" or "useless" by many of the 'experts'.
- I prepared a white paper for negotiations internally in the university on the potential use of RT-HIL technology: http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-63372
- Procurement process for the simulator was carried out in 2010 / RT Target arrived somewhere in March/April 2011.

2011 - 2012

- We carried out the first implementation of the lab through 2011, mostly by MSc student (Almas), myself and a little help from technicians.
- First implementation was fully operational around Dec. 2011.
- A paper with the implementation done in 2011 was presented in the IEEE PES General Meeting → **Experience as basis for next implementation.**
- A proof of concept application built using openPDC → Experience was basis for **defining the needs for the environment to develop prototype apps.**

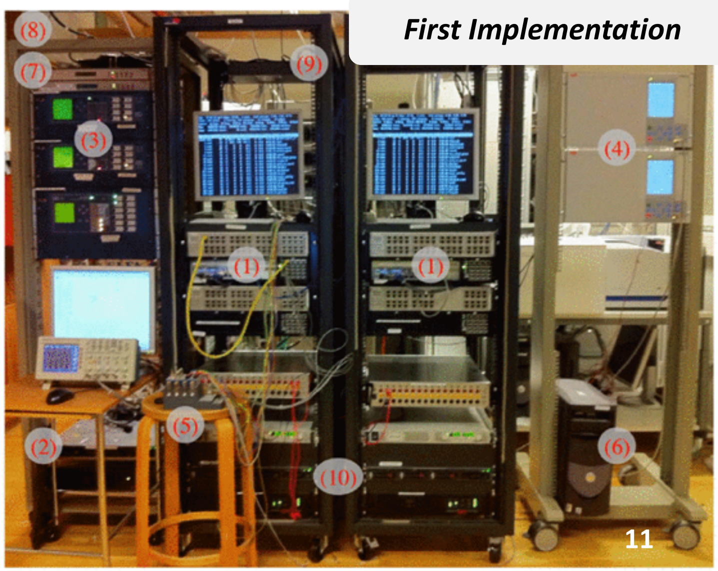
- L. Vanfretti, et al, "SmarTS Lab – A laboratory for developing applications for WAMPAC Systems," *2012 IEEE Power and Energy Society General Meeting*, San Diego, CA, 2012, pp. 1-8. doi: 10.1109/PESGM.2012.6344839
- M. Chenine, L. Vanfretti, et al, "Implementation of an experimental wide-area monitoring platform for development of synchronized phasor measurement applications," *2011 IEEE Power and Energy Society General Meeting*, San Diego, CA, 2011, pp. 1-8. doi: 10.1109/PES.2011.6039672

First Architecture



(a) Conceptual Architecture of SmarTS Lab. Measurement and data streams are indicated, non-exclusively, as follows: blue for WAMS, red for WAPS, and green for WACS applications. Solid lines indicate measurement streams, while dotted lines indicate digital data streams over IP.

First Implementation

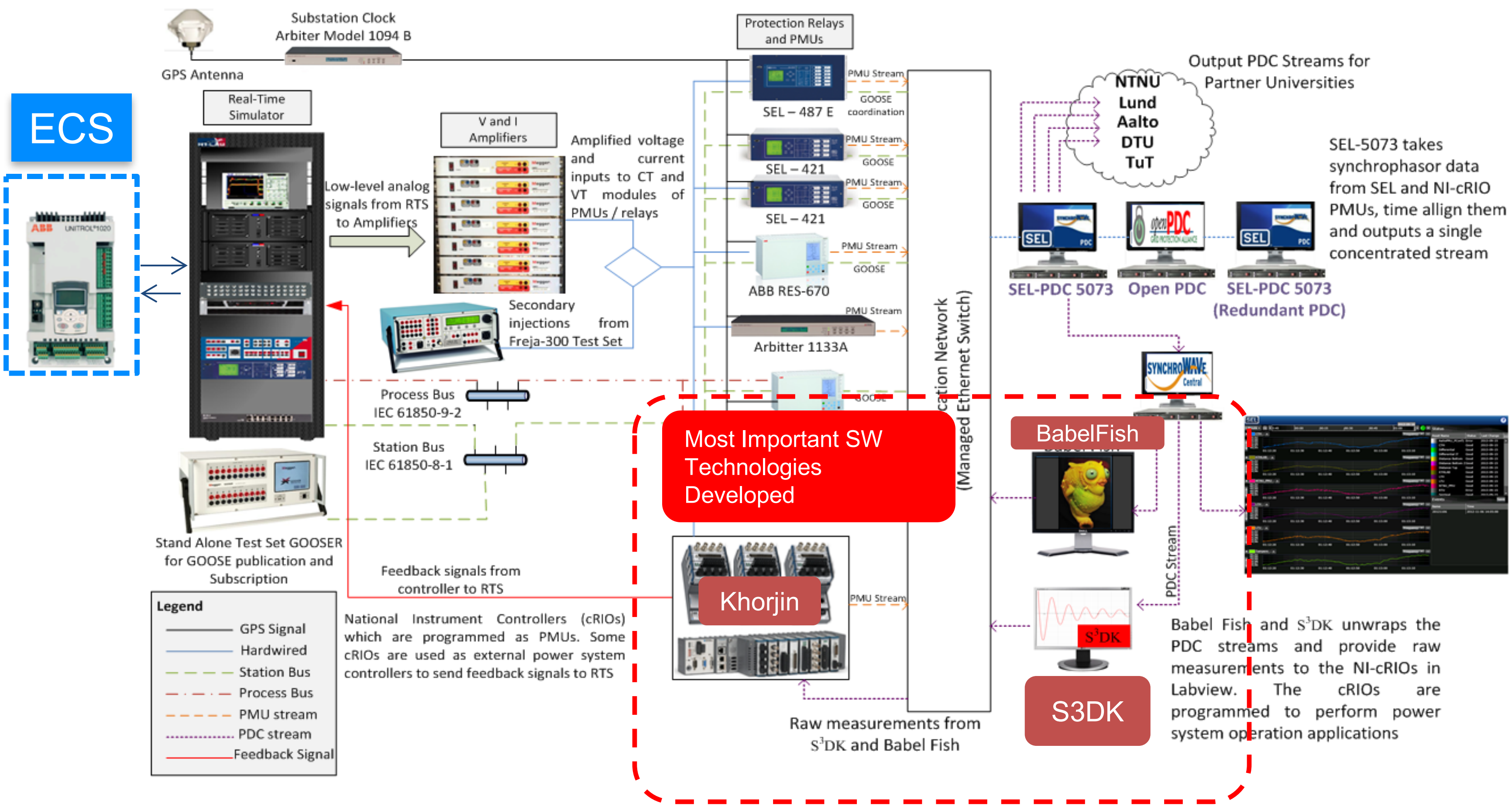


(b) Hardware Implementation of SmarTS Lab as of Dec. 2011.

Research Infrastructure (Lab.) Dev. (2/3)

A Laboratory for Testing, V&V of PMU Applications

SmarTS Lab
Smart Transmission Systems Laboratory



M. S. Almas, M. Baudette, L. Vanfretti, S. Løvlund and J. O. Gjerde, "Synchrophasor network, laboratory and software applications developed in the STRONg2rid project," 2014 IEEE PES General Meeting | Conference & Exposition, National Harbor, MD, 2014, pp. 1-5. doi: 10.1109/PESGM.2014.6938835

Research Infrastructure (Lab.) Dev. (3/3)

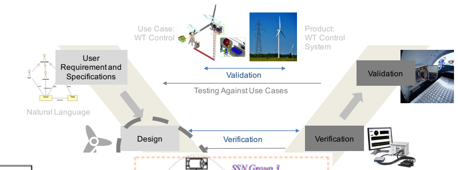
A Laboratory for Testing, V&V of PMU Applications

SmarTS Lab
Smart Transmission Systems Laboratory

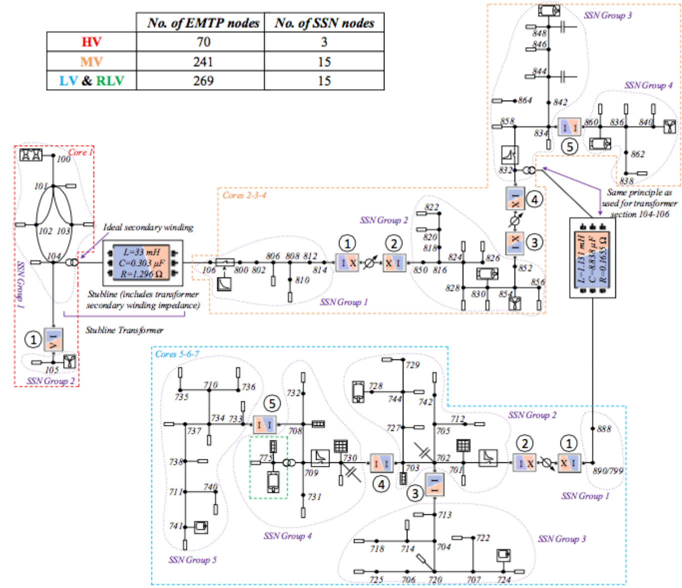
Contribution towards the MBSE **Foundations** in Cyber-Physical Power Systems

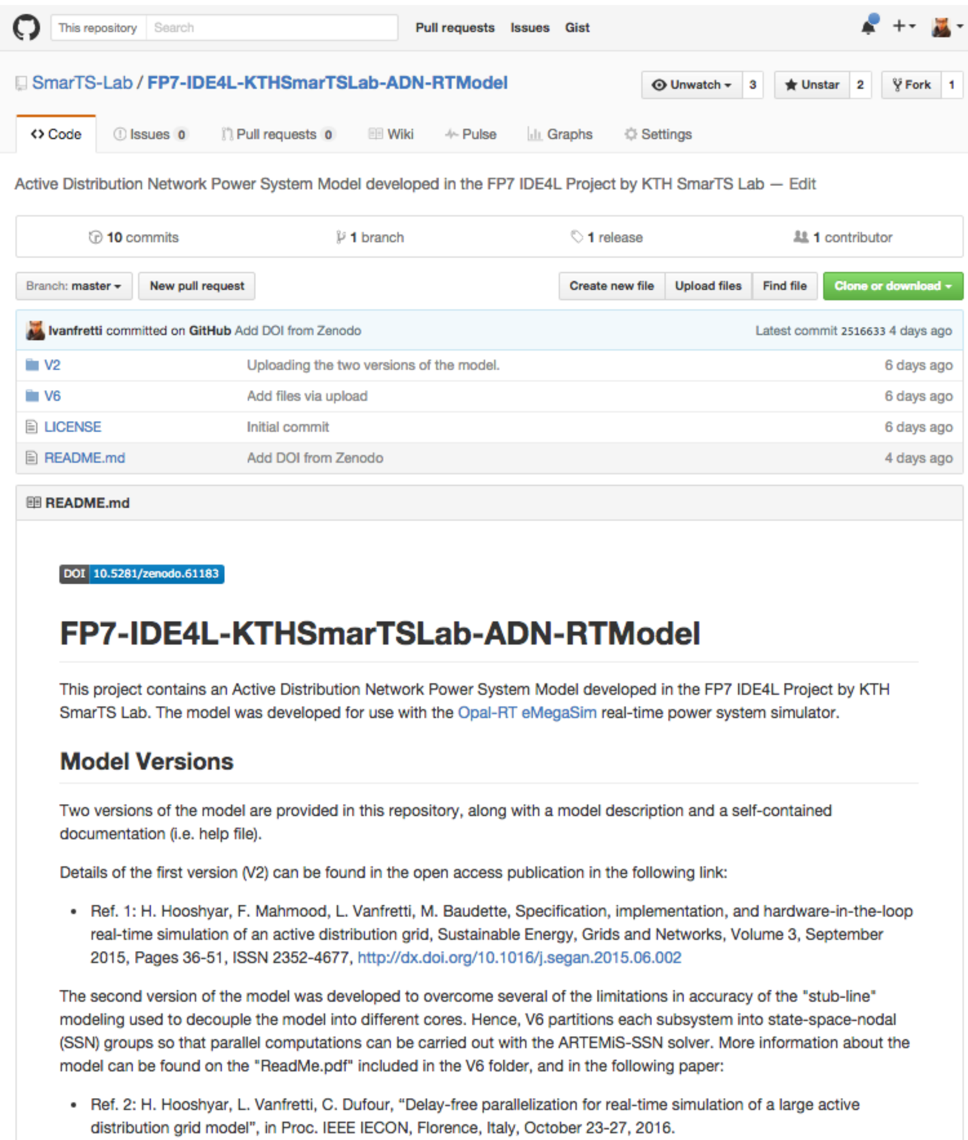
Modeling for Real-Time Simulation

for Synchrophasor Applications



	No. of EMTP nodes	No. of SSN nodes
HV	70	3
MV	241	15
LV & RLV	269	15





First Version published in SEGAN:

H. Hooshyar, F. Mahmood, L. Vanfretti, M. Baudette, Specification, implementation, and hardware-in-the-loop real-time simulation of an active distribution grid, Sustainable Energy, Grids and Networks, Volume 3, September 2015, Pages 36-51, ISSN 2352-4677, http://dx.doi.org/10.1016/j.segan.2015.06.002

Second version published in IECON:

H. Hooshyar, L. Vanfretti, C. Dufour, "Delay-free parallelization for real-time simulation of a large active distribution grid model", in Proc. IEEE IECON, Florence, Italy, October 23-27, 2016.

Soon in release of RT-Lab and ARTEMiS (ask Christian Dufour @Opal-RT).

All source files available in Github!

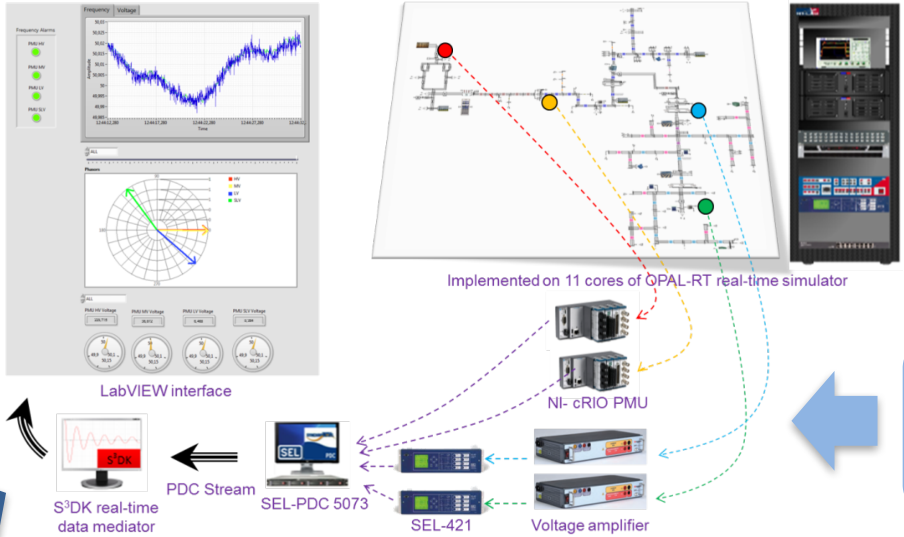
https://github.com/SmarTS-Lab/FP7-IDE4L-KTHSmarTSLab-ADN-RTModel

Testing, V&V: **Experimental** Work in the

Development, Implementation and Testing of PMU Apps using RT-HIL Simulation

(5) During development, implementation and testing, the application is fine-tuned through multiple HIL experiments.

(1) A real-time simulation model of active distribution networks is developed to test the PMU application.

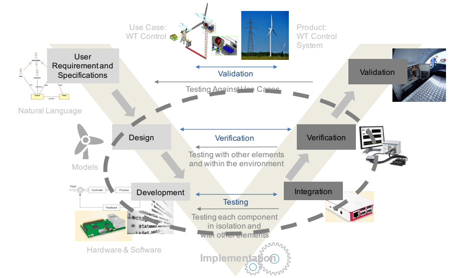


(2) The real-time simulation model is interfaced with phasor measurement units

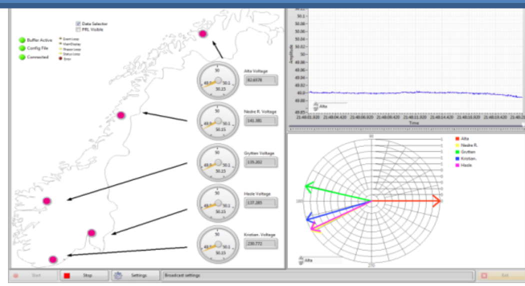
(4) A computer with development tools within the LabVIEW environment receives the PMU data.
All data acquisition is carried out using the corresponding standards (i.e. IEEE C37, IEC 61850).

(3) PMU data is streamed into a PDC, and the concentrated output stream is forwarded to an application development computer

PMU-Based Real-Time Monitoring Applications

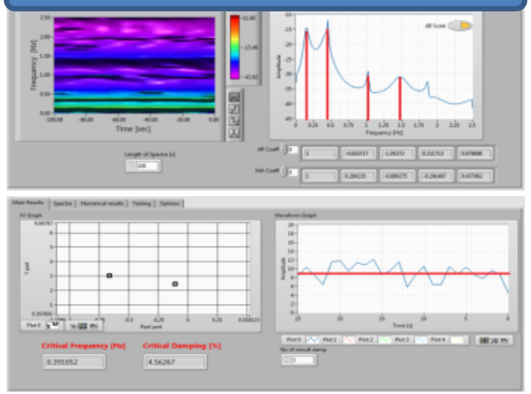


(1) Monitoring & Visualization

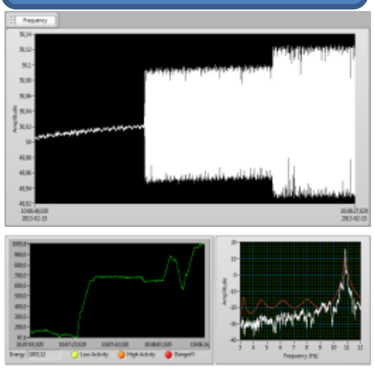


(2) Mobile Apps

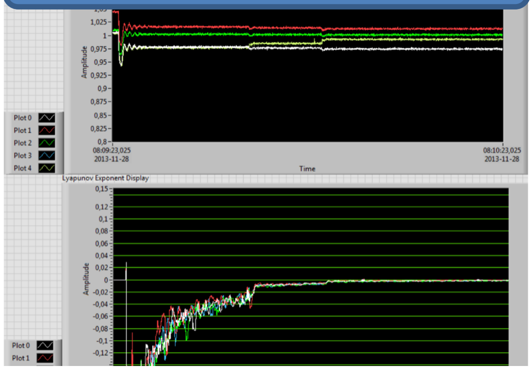
(3) Inter-Area Oscillation Assessment



(4) Forced Oscillation Detection



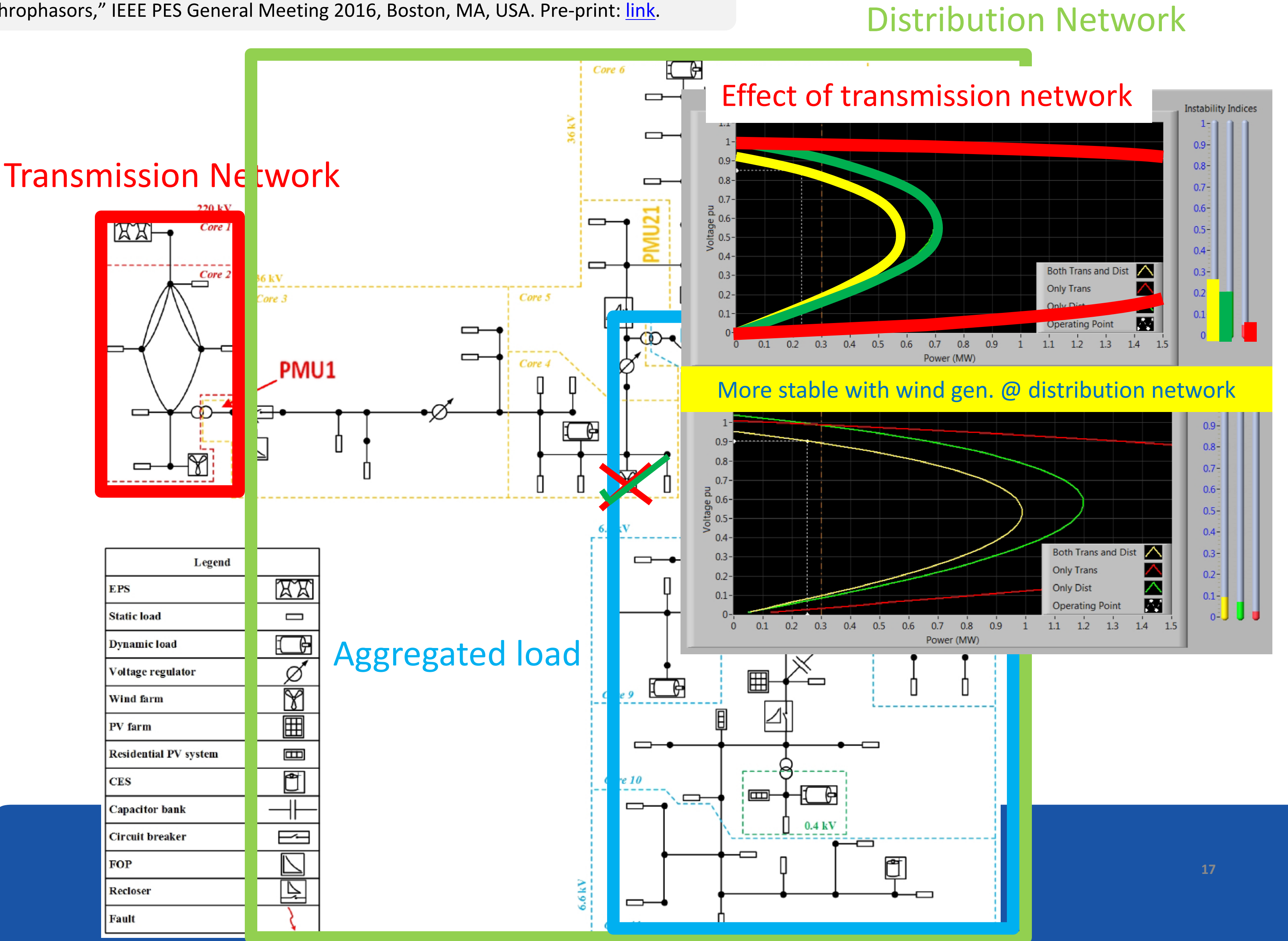
(5) Real-Time Voltage Stability Assessment



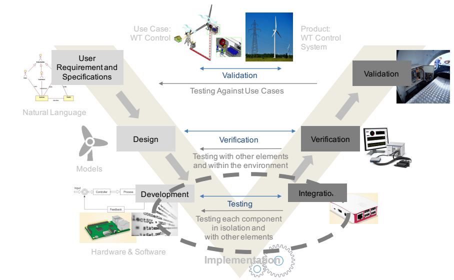
(1)-(2) M. S. Almas, et al, "Synchrophasor network, laboratory and software applications developed in the STRONg2rid project," 2014 IEEE PES General Meeting | Conference & Exposition, National Harbor, MD, 2014, pp. 1-5. doi: 10.1109/PESGM.2014.6938835
(3) V. S. Perić, M. Baudette, L. Vanfretti, J. O. Gjerde and S. Løvlund, "Implementation and testing of a real-time mode estimation algorithm using ambient PMU data,"*Power Systems Conference (PSC), 2014 Clemson University*, Clemson, SC, 2014, pp. 1-5.
doi: 10.1109/PSC.2014.6808116
(4) M. Baudette *et al.*, "Validating a real-time PMU-based application for monitoring of sub-synchronous wind farm oscillations," *Innovative Smart Grid Technologies Conference (ISGT), 2014 IEEE PES*, Washington, DC, 2014, pp. 1-5.
doi: 10.1109/ISGT.2014.6816444
(5) J. Lavenius and L. Vanfretti, "Real-Time Voltage Stability Monitoring using PMUs", Workshop on Resiliency for Power Networks of the Future, May 8th 2015. Online: http://www.eps.ee.kth.se/personal/vanfretti/events/stint-capes-resiliency-2015/07_JanLav_Statnett.pdf

Decoupled Voltage Stability Assessment of Distribution & Transmission Networks

A. Bidadfar, H. Hooshyar, M. Monadi, L. Vanfretti, Decoupled Voltage Stability Assessment of Distribution Networks using Synchrophasors," IEEE PES General Meeting 2016, Boston, MA, USA. Pre-print: link.

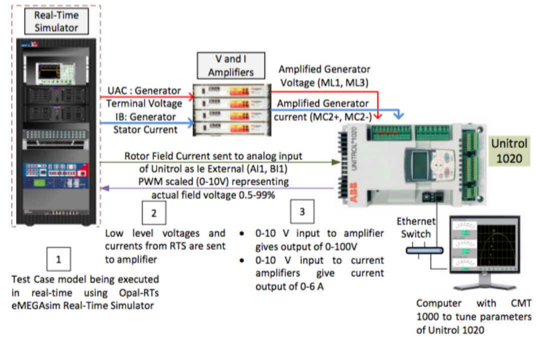


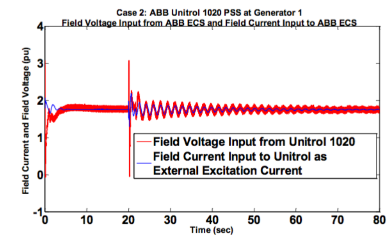
Component Design
for Wide-Area Control Systems



(1) RT-HIL Assessment of ECS

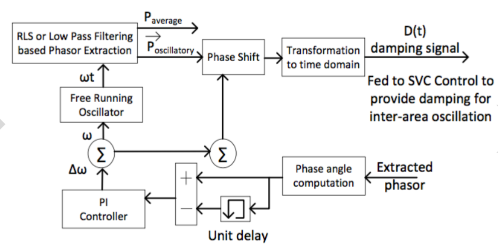
- Auto Mode: (Voltage regulation)
- Manual Mode: Field (Current Regulation)
- *PSS Functionality (Multi-Band PSS)*

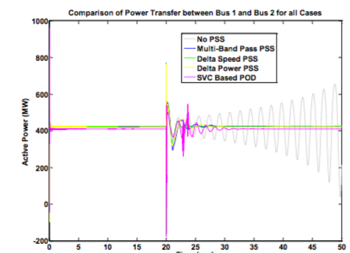




(2) Development of Damping Control Models (PSS) for RT-SIL

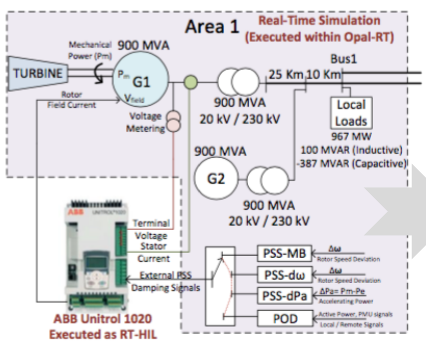
Stabilizers Δω, ΔPa, MB-PSS, and the **Phasor POD** where developed for SIL testing.

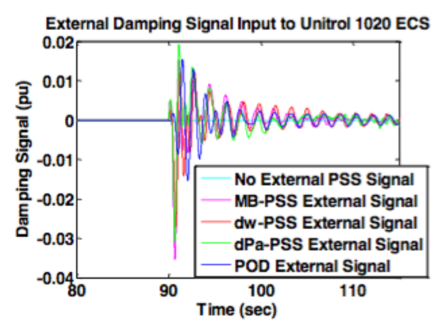


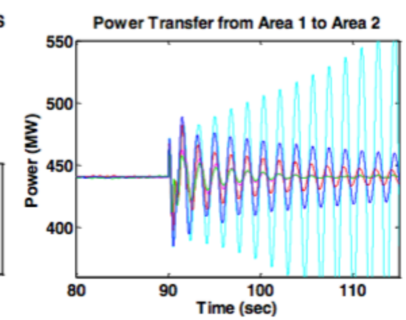


(3) Interfacing Control Models with ECS System

Stabilizers models where testing both for the MB-PSS and our target control (Phasor Oscillation Damper) with the ECS in the loop.





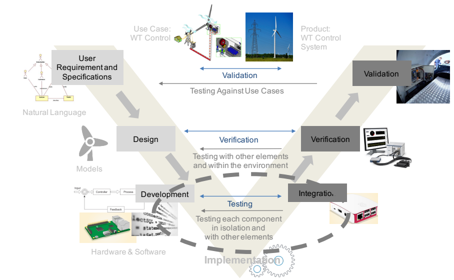


(1) M. S. Almas and L. Vanfretti, "Experimental performance assessment of a generator's excitation control system using real-time hardware-in-the-loop simulation," *IECON 2014 - 40th Annual Conference of the IEEE Industrial Electronics Society*, Dallas, TX, 2014, pp. 3756-3762. doi: 10.1109/IECON.2014.7049059

(2) M. S. Almas and L. Vanfretti, "Implementation of conventional and phasor based power system stabilizing controls for real-time simulation," *IECON 2014 - 40th Annual Conference of the IEEE Industrial Electronics Society*, Dallas, TX, 2014, pp. 3770-3776. doi: 10.1109/IECON.2014.7049061

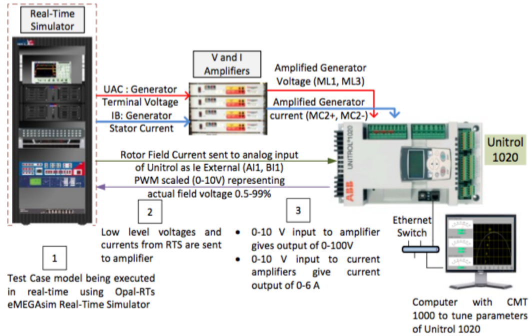
(3) M. S. Almas and L. Vanfretti, "RT-HIL testing of an excitation control system for oscillation damping using external stabilizing signals," *2015 IEEE Power & Energy Society General Meeting*, Denver, CO, 2015, pp. 1-5. doi: 10.1109/PESGM.2015.7286100

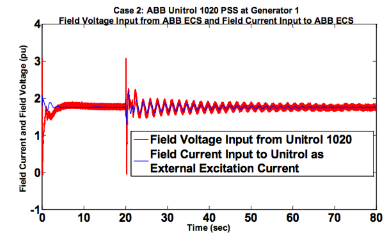
Component Design
for Wide-Area Control Systems



(1) RT-HIL Assessment of ECS

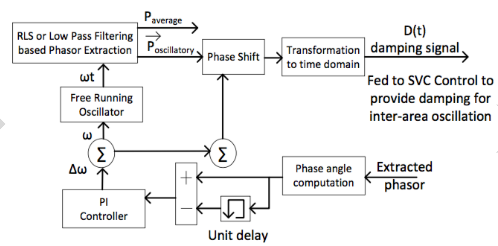
- Auto Mode: (Voltage regulation)
- Manual Mode: Field (Current Regulation)
- *PSS Functionality (Multi-Band PSS)*

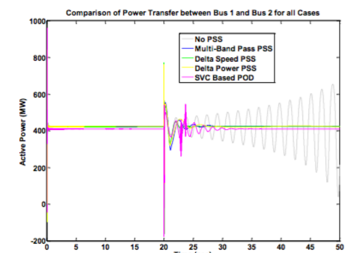




(2) Development of Damping Control Models (PSS) for RT-SIL

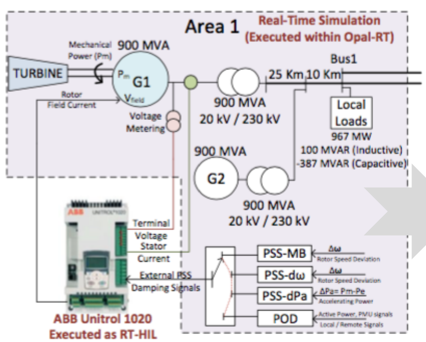
Stabilizers Δω, ΔPa, MB-PSS, and the **Phasor POD** where developed for SIL testing.

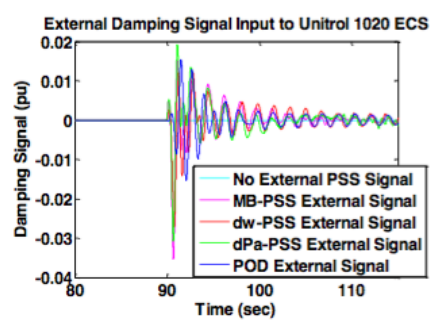


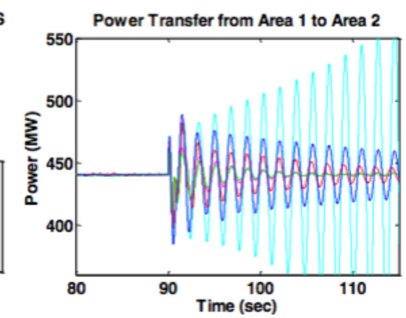


(3) Interfacing Control Models with ECS System

Stabilizers models where testing both for the MB-PSS and our target control (Phasor Oscillation Damper) with the ECS in the loop.







(1) M. S. Almas and L. Vanfretti, "Experimental performance assessment of a generator's excitation control system using real-time hardware-in-the-loop simulation," *IECON 2014 - 40th Annual Conference of the IEEE Industrial Electronics Society*, Dallas, TX, 2014, pp. 3756-3762. doi: 10.1109/IECON.2014.7049059

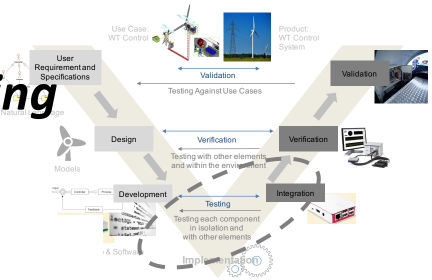
(2) M. S. Almas and L. Vanfretti, "Implementation of conventional and phasor based power system stabilizing controls for real-time simulation," *IECON 2014 - 40th Annual Conference of the IEEE Industrial Electronics Society*, Dallas, TX, 2014, pp. 3770-3776. doi: 10.1109/IECON.2014.7049061

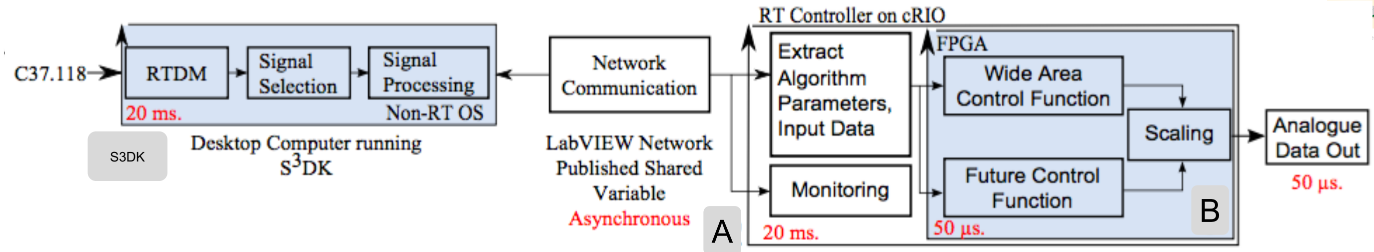
(3) M. S. Almas and L. Vanfretti, "RT-HIL testing of an excitation control system for oscillation damping using external stabilizing signals," *2015 IEEE Power & Energy Society General Meeting*, Denver, CO, 2015, pp. 1-5. doi: 10.1109/PESGM.2015.7286100

Contribution towards the MBSE **Foundations** in Cyber-Physical Power Systems

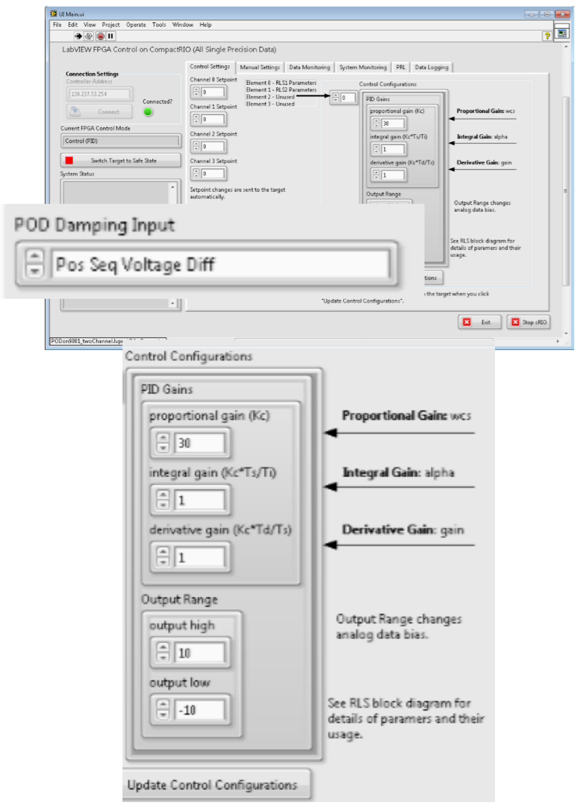
Component Implementation, Rapid Prototyping and Testing

for Wide-Area Control Systems

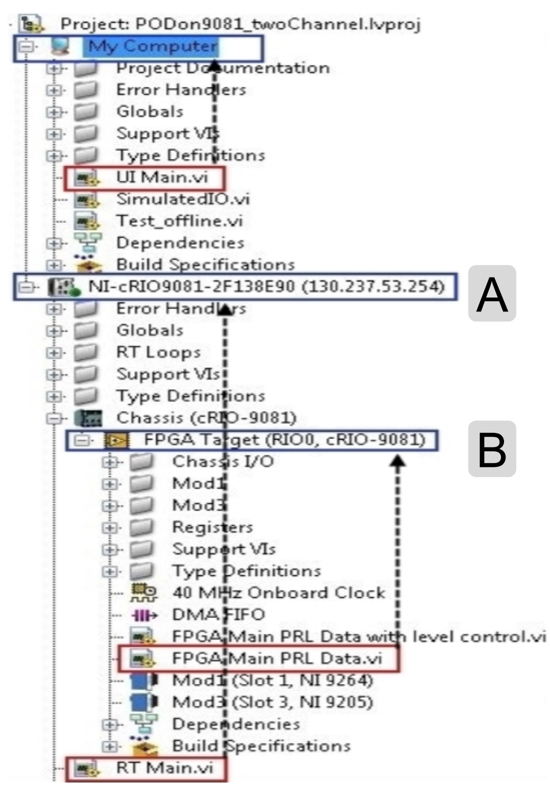




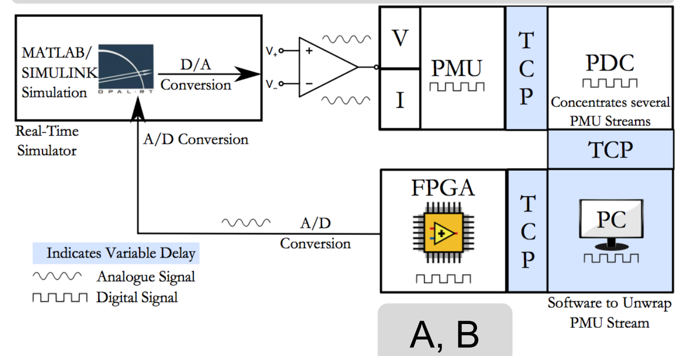
Controller Configuration Interface

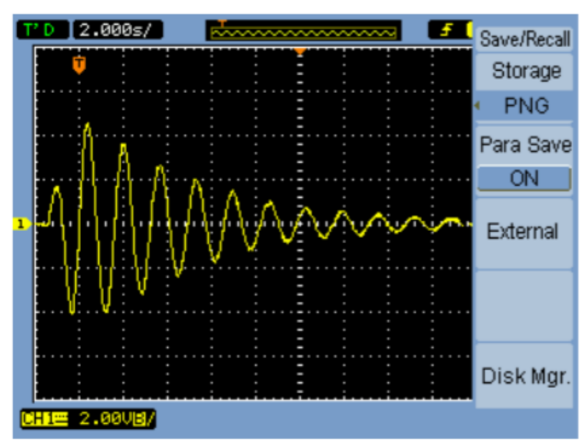


Software-Hardware Layers



Testing



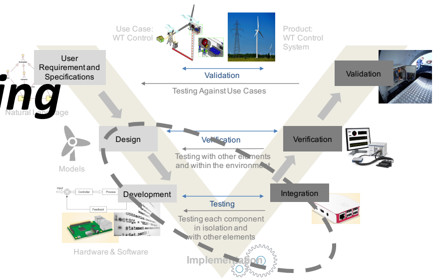


E. Rebello, M. S. Almas and L. Vanfretti, "An experimental setup for testing synchrophasor-based Damping control systems," *Environment and Electrical Engineering (EEEIC), 2015 IEEE 15th International Conference on*, Rome, 2015, pp. 1945-1950. doi: 10.1109/EEEIC.2015.7165470
E. Rebello, L. Vanfretti and M. Shoaib Almas, "Software architecture development and implementation of a synchrophasor-based real-time oscillation damping control system," *PowerTech, 2015 IEEE Eindhoven*, Eindhoven, 2015, pp. 1-6. doi: 10.1109/PTC.2015.7232288
E. Rebello, L. Vanfretti and M. Shoaib Almas, "PMU-based real-time damping control system software and hardware architecture synthesis and evaluation," *2015 IEEE Power & Energy Society General Meeting*, Denver, CO, 2015, pp. 1-5. doi: 10.1109/PESGM.2015.7285812

Contribution towards the MBSE **Foundations** in Cyber-Physical Power Systems

Component Implementation, Rapid Prototyping and Testing

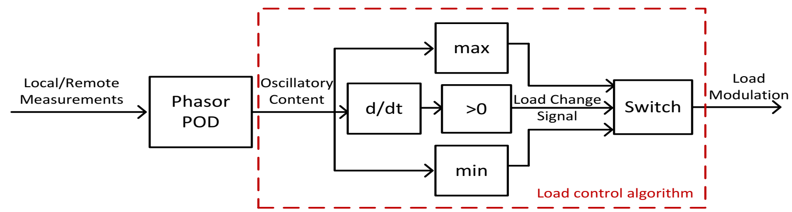
exploiting the availability of models for **new applications**

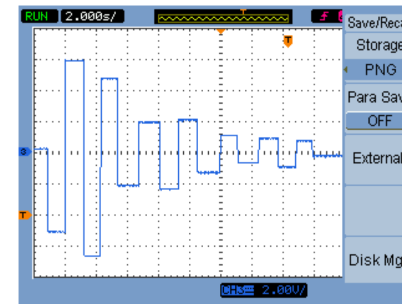


Idea:

Develop an algorithm to control industrial load, in particular aluminium smelters for damping of inter-area oscillations.

The load control algorithm developed



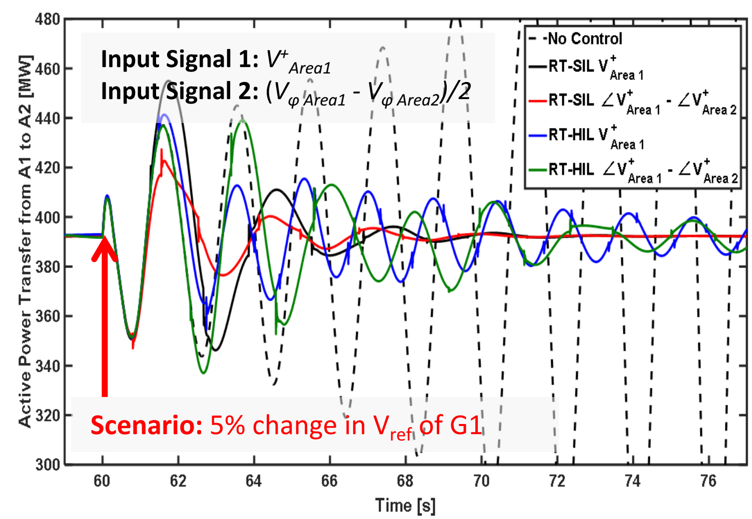


Testing:

- Using the 2-Area Four machine Klein-Roger-Kundur power system model.
- In RT-SIL and RT-HIL.

Results:

- Several local and remote synchrophasor input signals tested
- There is a big difference in the perfromance of the controller in RT-SIL and RT-HIL.
- **These results highlight the importance of considering the effect of the hardware implementation when looking at software simulation results.**

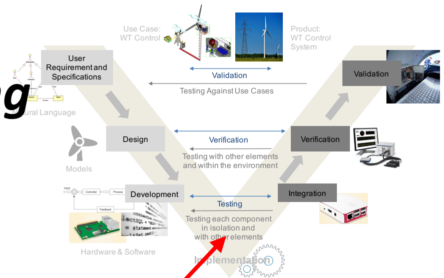


G. M. Jonsdottir, M. S. Almas, M. Baudette, M. P. Palsson and L. Vanfretti, "RT-SIL performance analysis of synchrophasor-and-active load-based power system damping controllers," *2015 IEEE Power & Energy Society General Meeting*, Denver, CO, 2015, pp. 1-5. doi: 10.1109/PESGM.2015.7286372

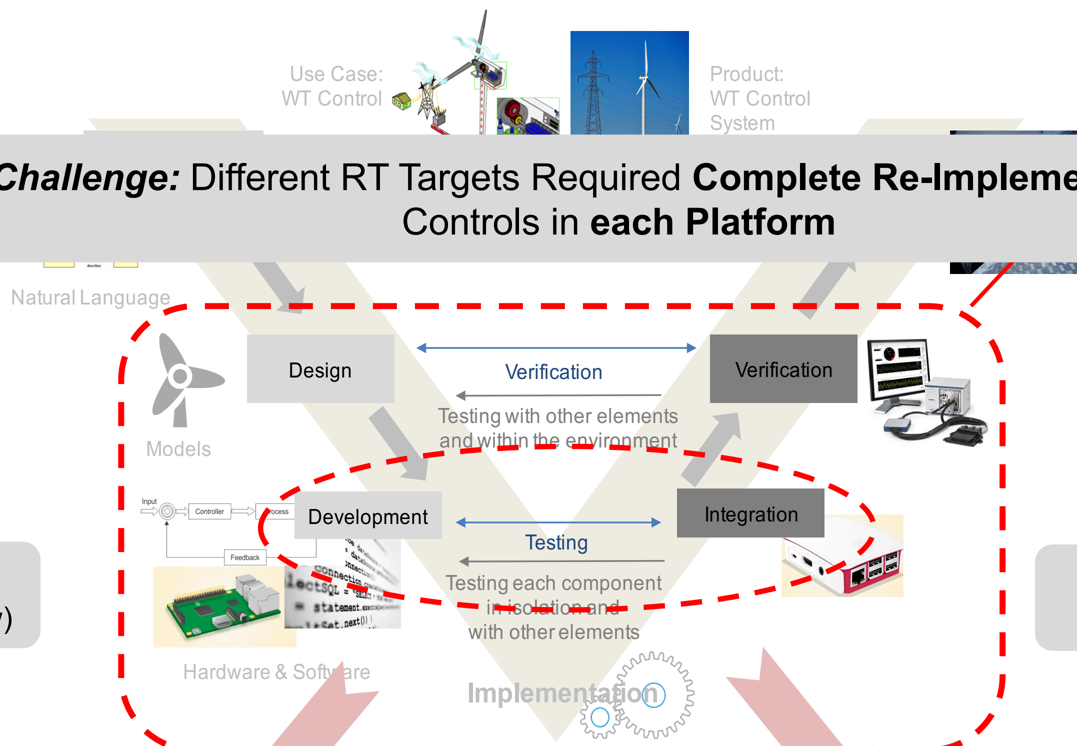
G. M. Jonsdottir, M. S. Almas, M. Baudette, L. Vanfretti, and M. P. Palsson, “Hardware Prototyping of Synchrophasor and Active Load-Based Oscillation Damping Controllers using RT-HIL Approach”, IEEE PES GM 2016, July 17-21, Boston, Massachusetts, USA

Challenge in Component Implementation and Prototyping

Component Level Functionality also Requires Portability



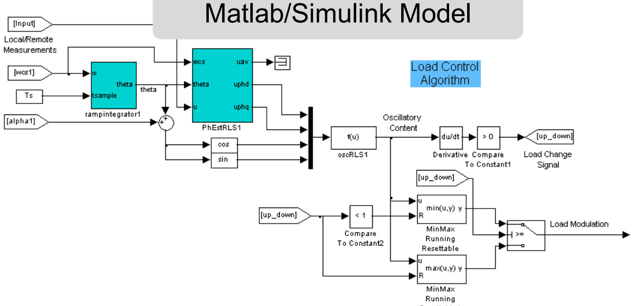
Challenge: Different RT Targets Required **Complete Re-Implementation** of Controls in **each Platform**



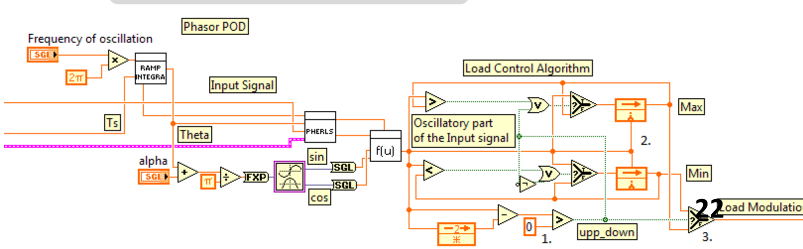
Opal-RT Target
(Mathworks-Based Workflow)

NI-cRIO Target
(LabView Workflow)

Matlab/Simulink Model

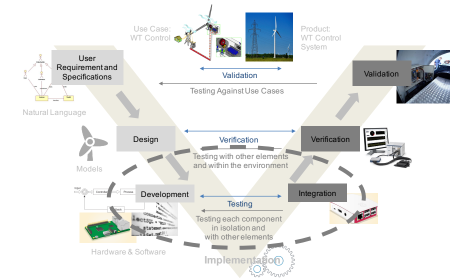


LabView FPGA Model



Networking Protocol Tools and Source Code

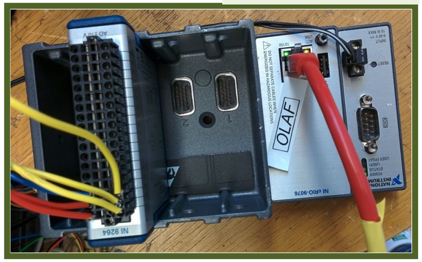
for Synchrophasor Applications – Real-Time Control Example



S3DK
Khorjin

S3DK is executed on a PC with a non real-time operating system **=> Non-deterministic delay**

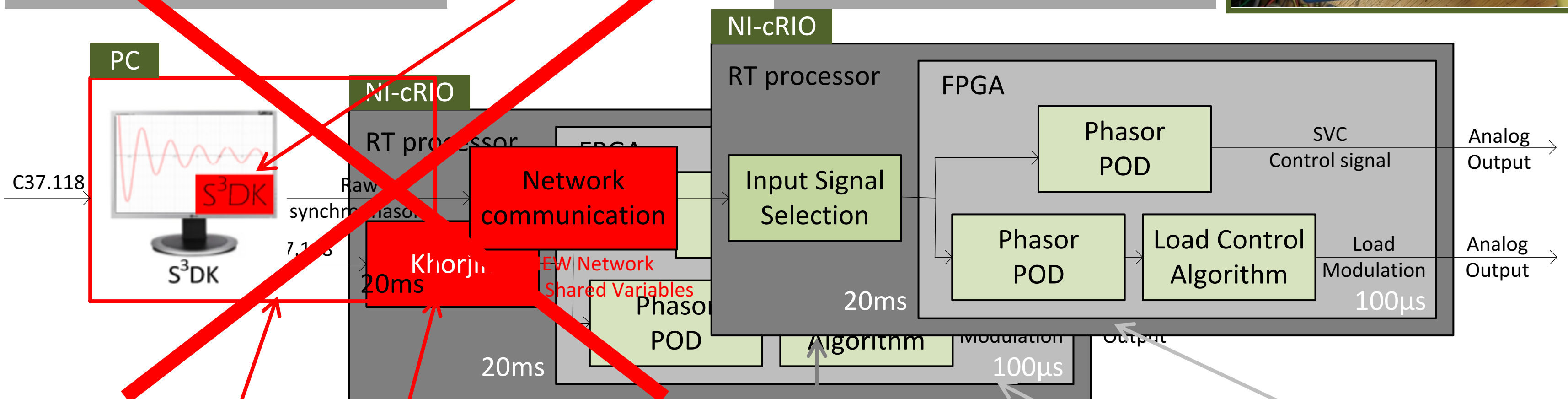
NI-cRIO



The hardware prototype controller design

Three level design

Two level design



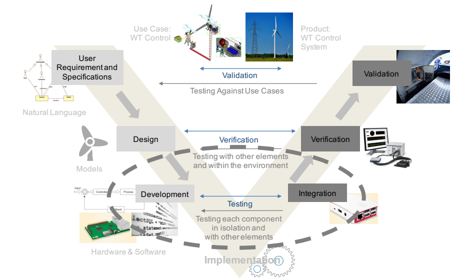
Real-Time Software VI
- Runs on the real-time processor of the cRIO.
- Khorjin used to unwrap PDC stream.
- Input signal selected

Core FPGA Software VI
- Runs on the FPGA
- The load control and SVC control implemented.

Contribution towards the MBSE **Foundations** in Cyber-Physical Power Systems

Networking Protocol Tools and Source Code

for Synchrophasor Applications – Real-Time Control Example



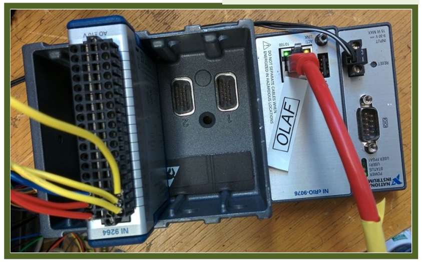
S3DK

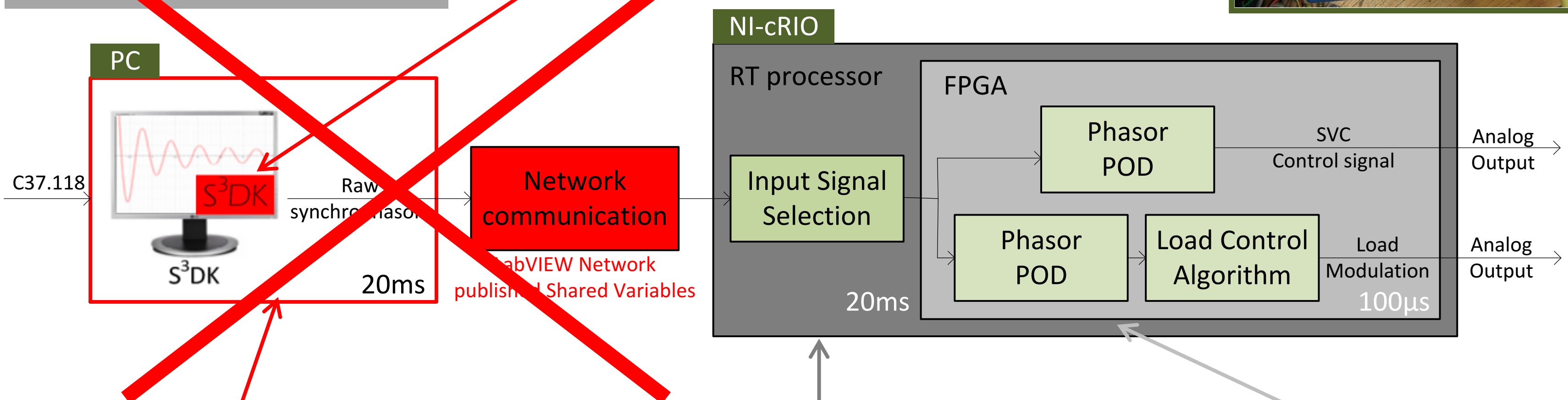
S3DK is executed on a PC with a non real-time operating system **=> Non-deterministic delay**

The hardware prototype controller design

Three level design

NI-cRIO





Remotely run VI

- Runs on a PC.
- S3DK used to unwrap PDC stream.

Real-Time Software VI

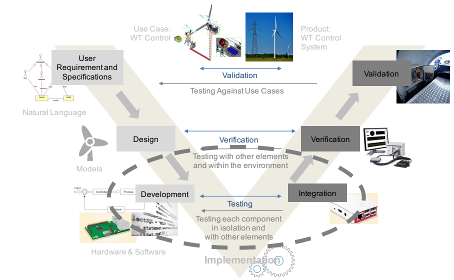
- Runs on the real-time processor of the cRIO.
- Manages the signal selection

Core FPGA Software VI

- Runs on the FPGA
- The load control and SVC control implemented.

Networking Protocol Tools and Source Code

for Synchrophasor Applications – Real-Time Control Example

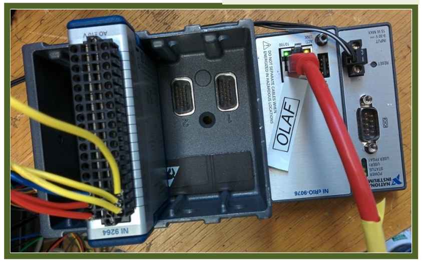


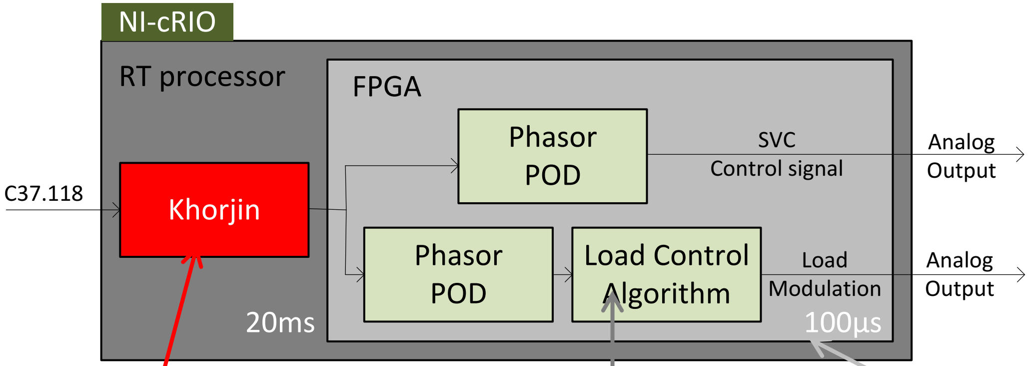
Khorjin

The hardware prototype controller design

Two level design

NI-cRIO





Real-Time Software VI

- Runs on the real-time processor of the cRIO.
- Khorjin used to unwrap PDC stream.
- Input signal selected

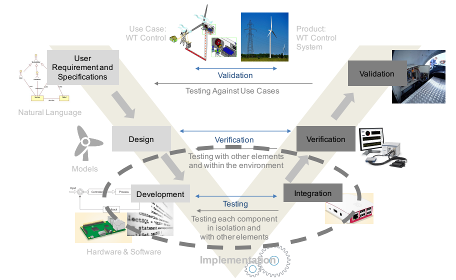
Core FPGA Software VI

- Runs on the FPGA
- The load control and SVC control implemented.

Contribution towards the MBSE **Foundations** in Cyber-Physical Power Systems

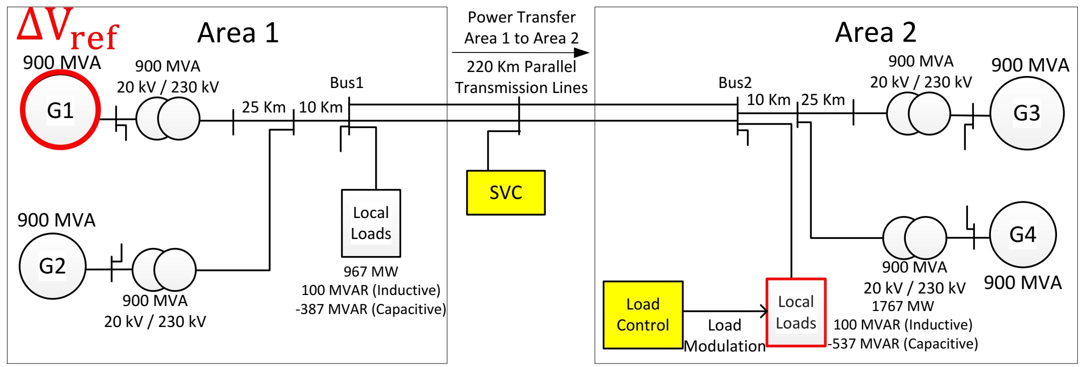
Networking Protocol Tools and Source Code

for Synchrophasor Applications – Real-Time Control Example



Hardware prototype controllers **tested:**

- In RT-SIL and RT-HIL.
- In RT-HIL using **S3DK** and **Khorjin.**



Total delay in RT-HIL setup:

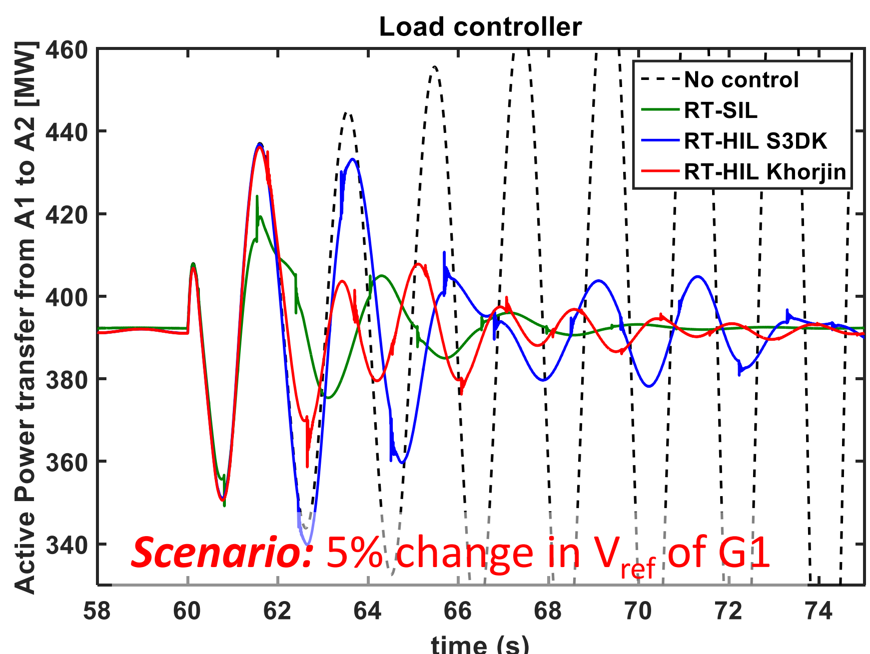
S3DK: *200-500 ms* **Khorjin:** *50-76 ms*

In RT-HIL using **S3DK**

- ○ *Blue line far from green line.*
- ○ Larger delay (S3DK) can only run in a non-deterministic computer (... under windows).
- ○ PDC adds to latency.

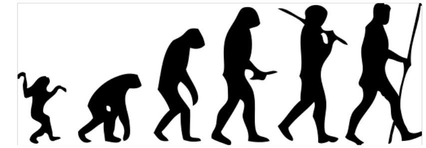
In RT-HIL using **Khorjin.**

- ○ **Protocol client runs in RT-Target** avoiding delays from: PDC and parser in PC.

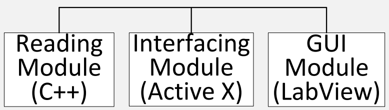


Contribution towards the MBSE **Foundations** in Cyber-Physical Power Systems

SmarTS Lab OSS Tools Evolution

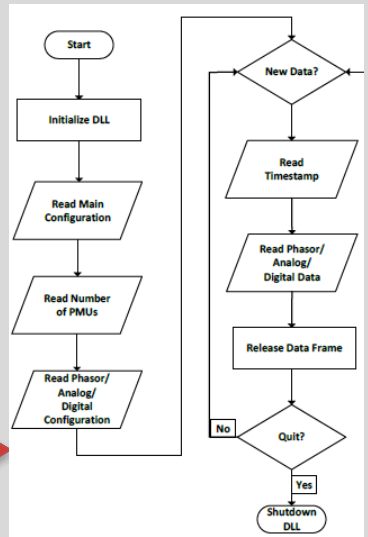


BabelFishV1 (LabView & C++)



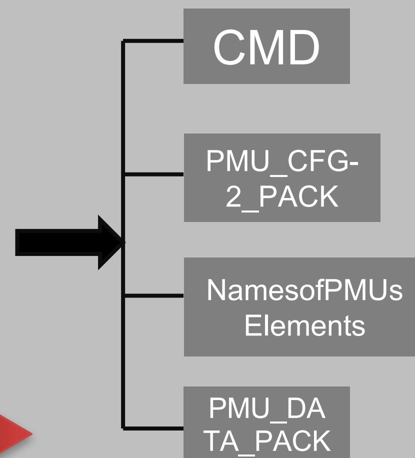
- Real-time reading from PMU/PDC (DLL)
- Interfacing with LabView via ActiveX (minimum delay)
- LabView presentation layer

S3DK (LabView & C++)



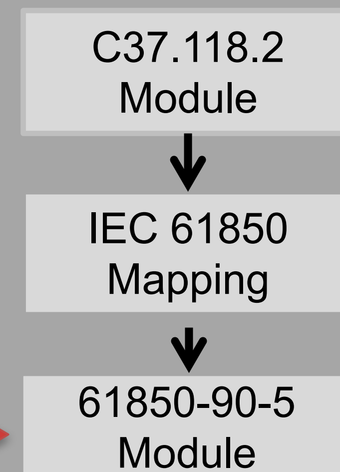
- Client/Server Architecture
- Multi-Threading
- LabView VI/API
  - Calls C++ Methods
  - Toolbox-like functions

BabelFish Engine (LabView Only)



- Developed entirely in LabView.
- Only requires IP address, Port number and Device ID of the PMU/PDC stream

Khorjin (C++)



- Focus on Performance
- Not necessary to be user friendly
- Gateway for IEC transition
- Executes on embedded systems with low requirements

Why only Labview?

Derive Requirements for Embedded Computers

Why Khorjin?

Support for COTS Embedded Computers

Development: 2011 - 2013

Development: 2014 – 2016 …

Repositories Currently Available at GitHub

S3DK: https://github.com/SmarTS-Lab-Parapluie/S3DK

BabelFish: https://github.com/SmarTS-Lab-Parapluie/BabelFish

Audur: https://github.com/SmarTS-Lab-Parapluie/Audur

Khorjin: Will be available at GitHub…

L. Vanfretti, V. H. Aarstrand, M. S. Almas, V. S. Perić and J. O. Gjerde, "A software development toolkit for real-time synchrophasor applications," *PowerTech (POWERTECH), 2013 IEEE Grenoble*, Grenoble, 2013, pp. 1-6.
doi: 10.1109/PTC.2013.6652191

L. Vanfretti, I. A. Khatib and M. S. Almas, "Real-time data mediation for synchrophasor application development compliant with IEEE C37.118.2," *Innovative Smart Grid Technologies Conference (ISGT), 2015 IEEE Power & Energy Society*, Washington, DC, 2015, pp. 1-5.
doi: 10.1109/ISGT.2015.7131910

L. Vanfretti, M.S. Almas and M. Baudette, "BabelFish – Tools for IEEE C37.118.2-compliant Real-Time Synchrophasor Data Mediation," SoftwareX, submitted, June 2016.

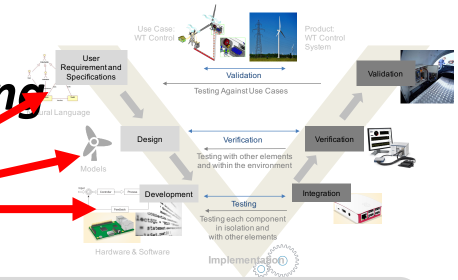
S.R. Firouzi, L. Vanfretti, A. Ruiz-Alvarez, F. Mahmood, H. Hooshyar, I. Cairo, "An IEC 61850-90-5 Gateway for IEEE C37.118.2 Synchrophasor Data Transfer," IEEE PES General Meeting 2016, Boston, MA, USA. Pre-print: link.

S.R. Firouzi, L. Vanfretti, A. Ruiz-Alvarez, H. Hooshyar and F. Mahmood, "Interpretation and Implementation of IEC 61850-90-5 Routed-Sampled Value and Routed-GOOSE Protocols for IEEE C37.118.2 Compliant Wide-Area Synchrophasor Data Transfer," Electric Power Systems Research. March 2016. Submitted. August 2016. First Revision.

L. Vanfretti, G.M. Jonsdottir, M.S. Almas, E. Rebello, S.R. Firouzi and M. Baudette, "Audur – A platform for Synchrophasor-Based Power System Wide-Area Control System Implementation," submitted for review, Software X, February 28, 2017.

Challenge in Component Implementation and Prototyping

Networking & Protocol **Models** and **Software** (Libs. / Source)



Challenge: Joint (integrated) modeling of networking, IT and power grid physics through the whole Model & Simulation - Based Systems Engineering Framework.

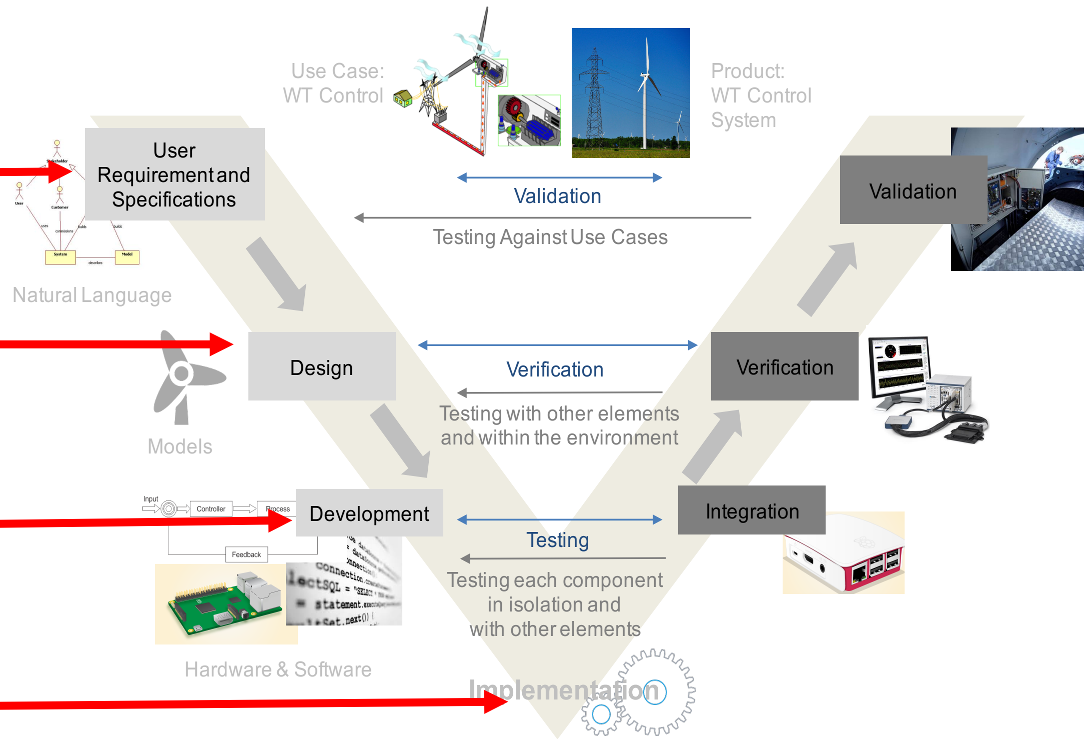
Through SGAM, but need to *create* CIM profile

Potential for use of Modelica Synchronous – library of components is needed…

Software Models with ICT Behavior

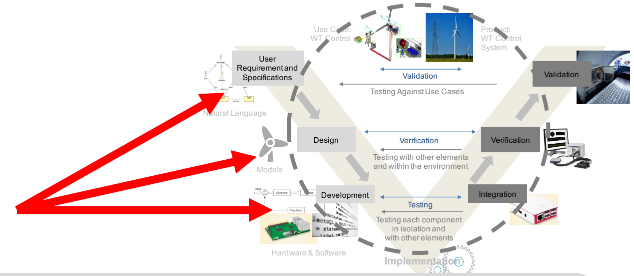
Network Protocol Client/Server Source

(with some help from Khorjin, maybe!)



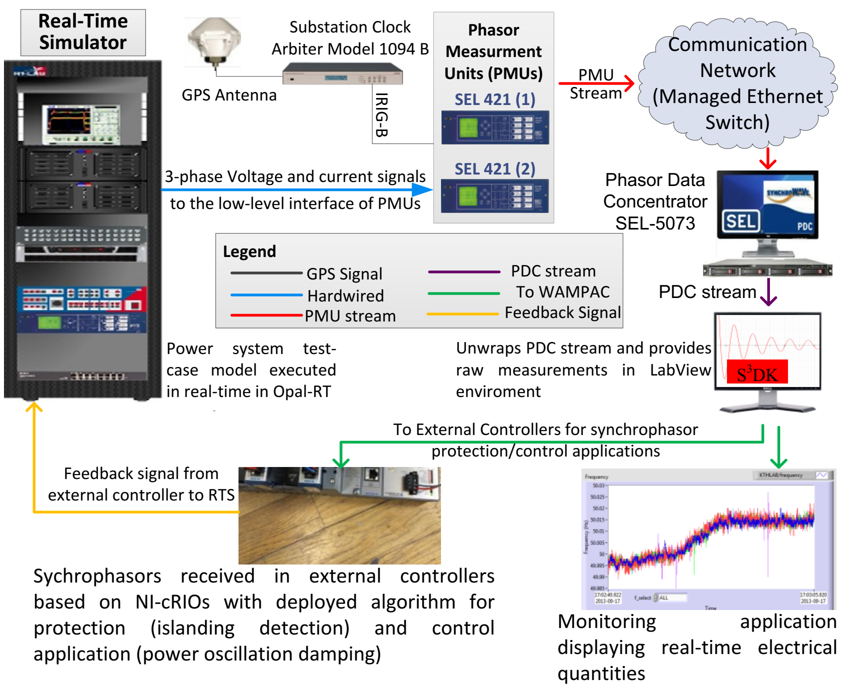
Verification and Validation

for Timing System-Dependent Applications

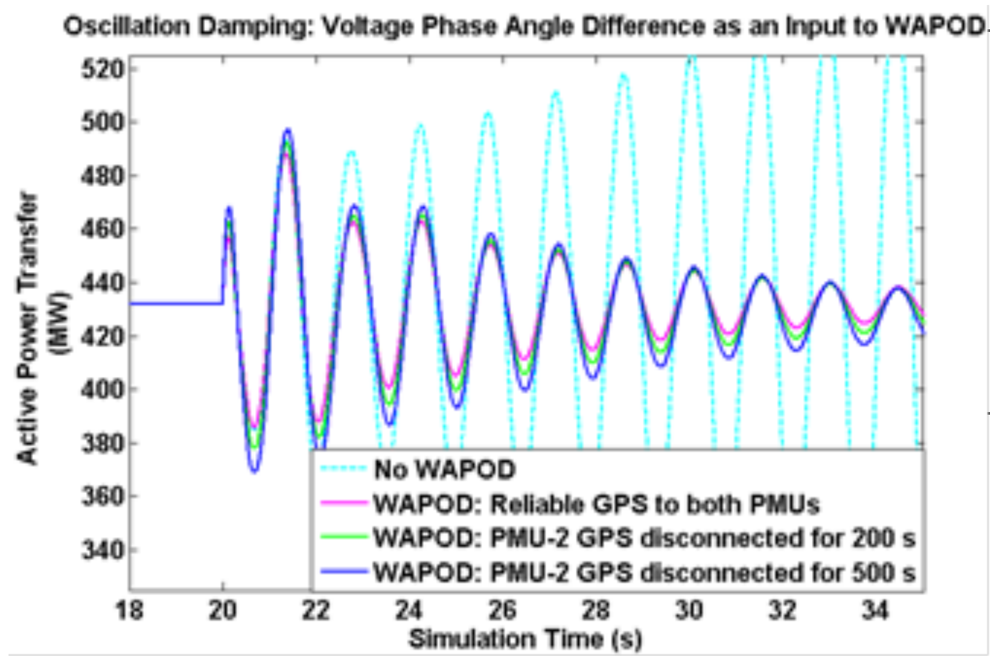


Challenge: Joint (integrated) modeling, simulation and TV&V including ***Timing Systems*** through the whole Model & Simulation - Based Systems Engineering Framework.

Case Study: GPS Vulnerability and Impact on Synchrophasor Applications



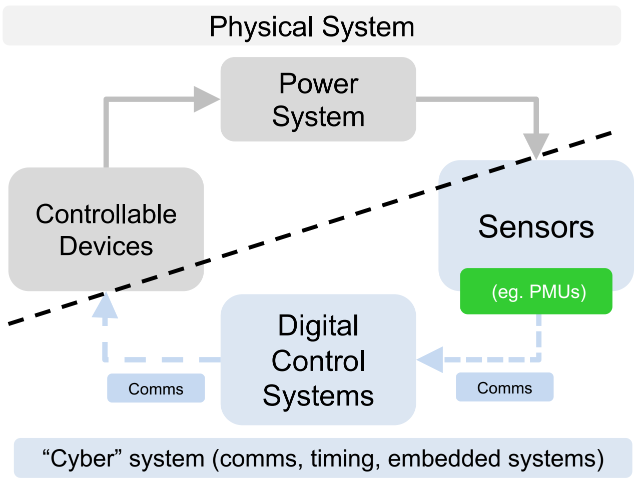
Impact on Real-Time Control



M.S. Almas and **L. Vanfretti,** "Impact of Time-Synchronization Signal Loss on PMU-based WAMPAC Applications," IEEE PES General Meeting 2016, Boston, MA, USA. Pre-print: link.

Conclusions: The Cyber-Physical Future… *is in our hands!*

- We need to spend significant efforts to face the challenges of the cyber-physical future of power systems!
- Model & Simulation-Based Systems Engineering (**MBSE)** **gives a proven foundation** for developing complex cyber-physical systems from design to manufacturing to operation.



- We need to focus in the development of
  - **Tools** for multi-domain and multi-physics modeling
  - **Tools** and **models for design**,
  - **Tools** for simulation and
  - **Tools** for hardware implementation
- Capable of taking into account interactions (ICT, cyber and physical security, etc) from different parts of the "cyber-physical" system while managing the basic functions of the grid.
- **We have only began to develop these foundations – we can't do it alone: Systems View is key.**
- **We also need to think about the socio/economical/phylosophical implications of software pervasiveness.**
- **The cyborg-world is upon us! Let's be prepared!**