Model & Simulation-Based Systems Engineering
Of Future Cyber-Physical Electrical Power Systems
- Challenges and Foundations -

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A. JAMES CLARK SCHOOL OF ENGINEERING

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Acknowledgements

SmarTS Lab
Smart Transmission Systems Laboratory

The work presented in this seminar is product of research carried @KTH SmarTS_Lab from 2011-2013.

More than 3 Post-Docs, 10 PhD Students, many MSc students and Research Engineers have contributed in different ways towards this work. Some of them, are shown in this picture from 2015.

Almas, Maxime, Gudrun, Luigi, Francisco, Vedran

Funding & Projects:

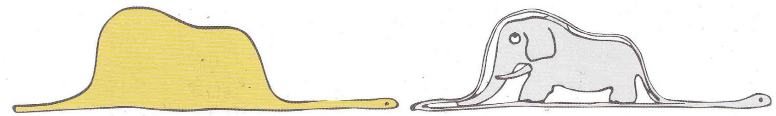
On going

ITEA3
openCPS
Statnett
STandUP for ENERGY

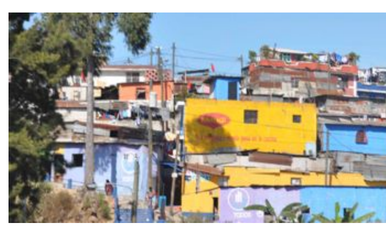
Completed

Seventh Framework Programme
European Commission
IDEAL ideal grid for all
iTesla Innovative Tools for Electrical System Security within Large Areas
norden Nordic Energy Research
STRON²grid Smart Transmission Grids Operation and Control

Context:
My Background – Different POVs



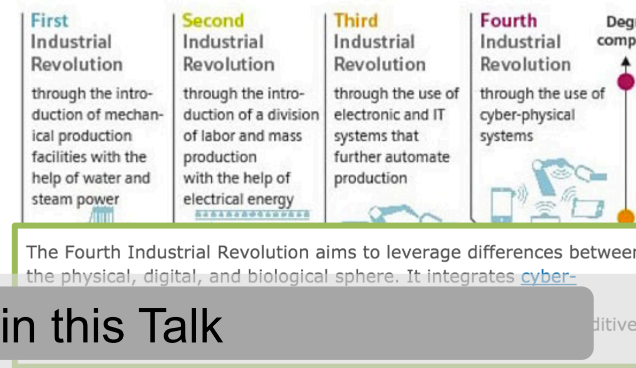
Monte María 120 kW Project



Guatemala is a country of great diversity in energy resources, and of great contrasts…

Context :

Smart Grids – Transformation of Electrical Power Networks to a Cyber-Physical Systems



Smart

Gen…
digitalization of different devices / contexts / etc.

(Micro)-Grid

Interconnected e…
(techno-and-econ…
Interconnections…
and electrical ene…

Autonomous
- Technical -

Automatic: do exa…
Autonomous: *a sy…*
influence - free wi…
Semi-autonomous: c…
and make decisions *through a pre-defined method*

Zero-Net Energy

Total amount of e…
micro-grid) is rou…
created within →

Society / Communities

Autonomous Comm…
decisions.
Autonomous Zero-N…
through their own **ir…**

Autonomy in the "cy…
interactions with the te…

Two Perspectives in this Talk

The Technical Perspective:

What **technology** is needed for
Smart and Autonomous Cyber-Physical Power Grids?

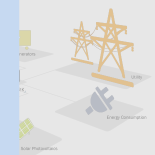
How can it be developed?

(most of the talk)

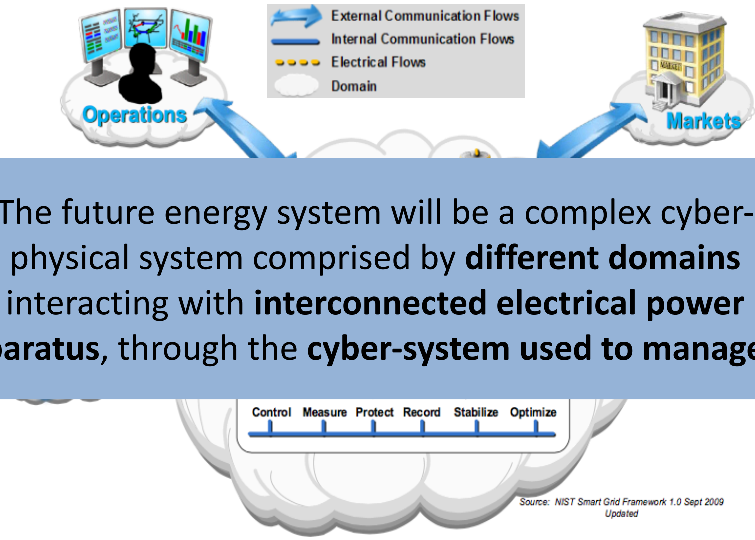
The Socio-Economical Perspective?

What do **communities** need to
autonomously harness a
Zero-Net Energy Smart Micro-Grid?

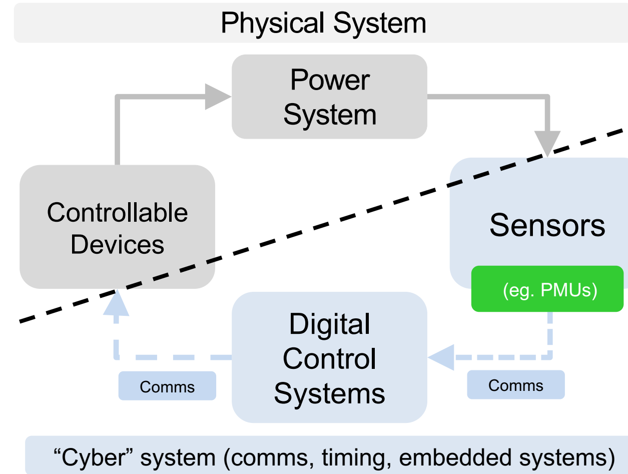
(some provocative thoughts only…)



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.

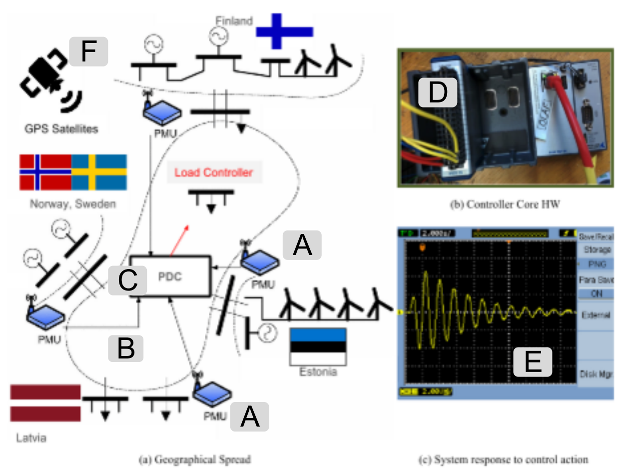


Fig. 1. A hypothetical WACS system in the Nordic-Baltic Region

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

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

What specific ***technologies*** will be needed for smart grids?

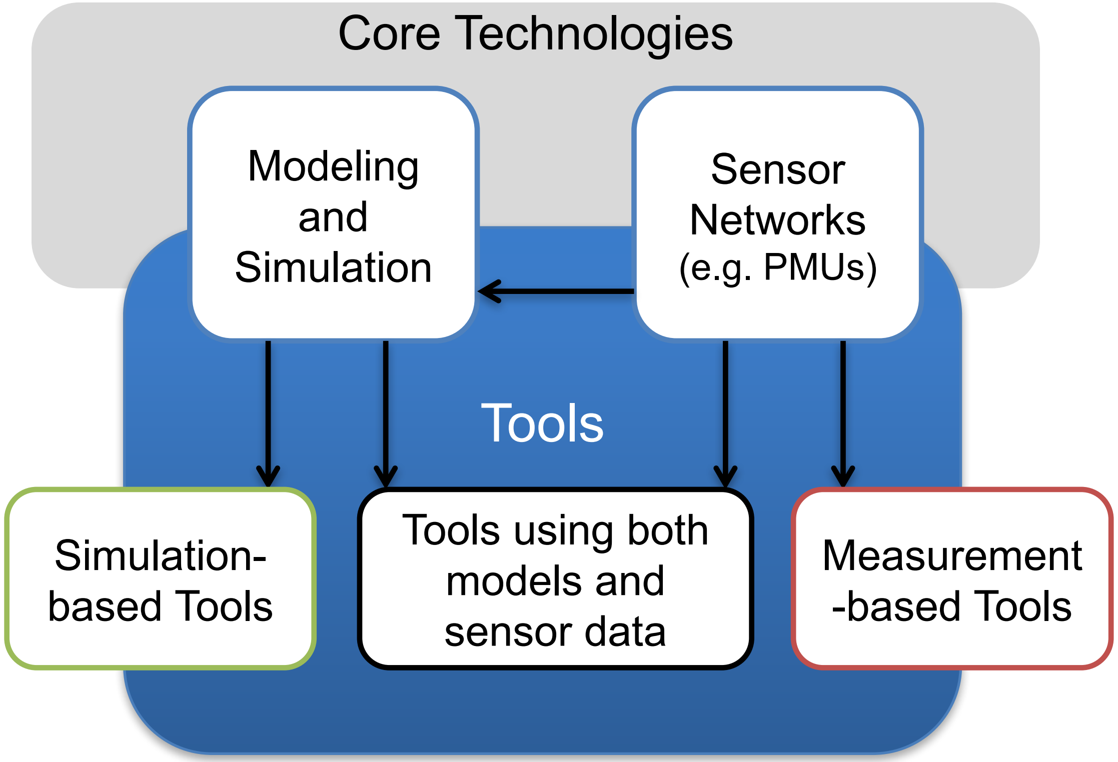
In general, we have two types of “data” that can be used to take decisions: **measurements** and/or **simulations**

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

Learning from measurement data

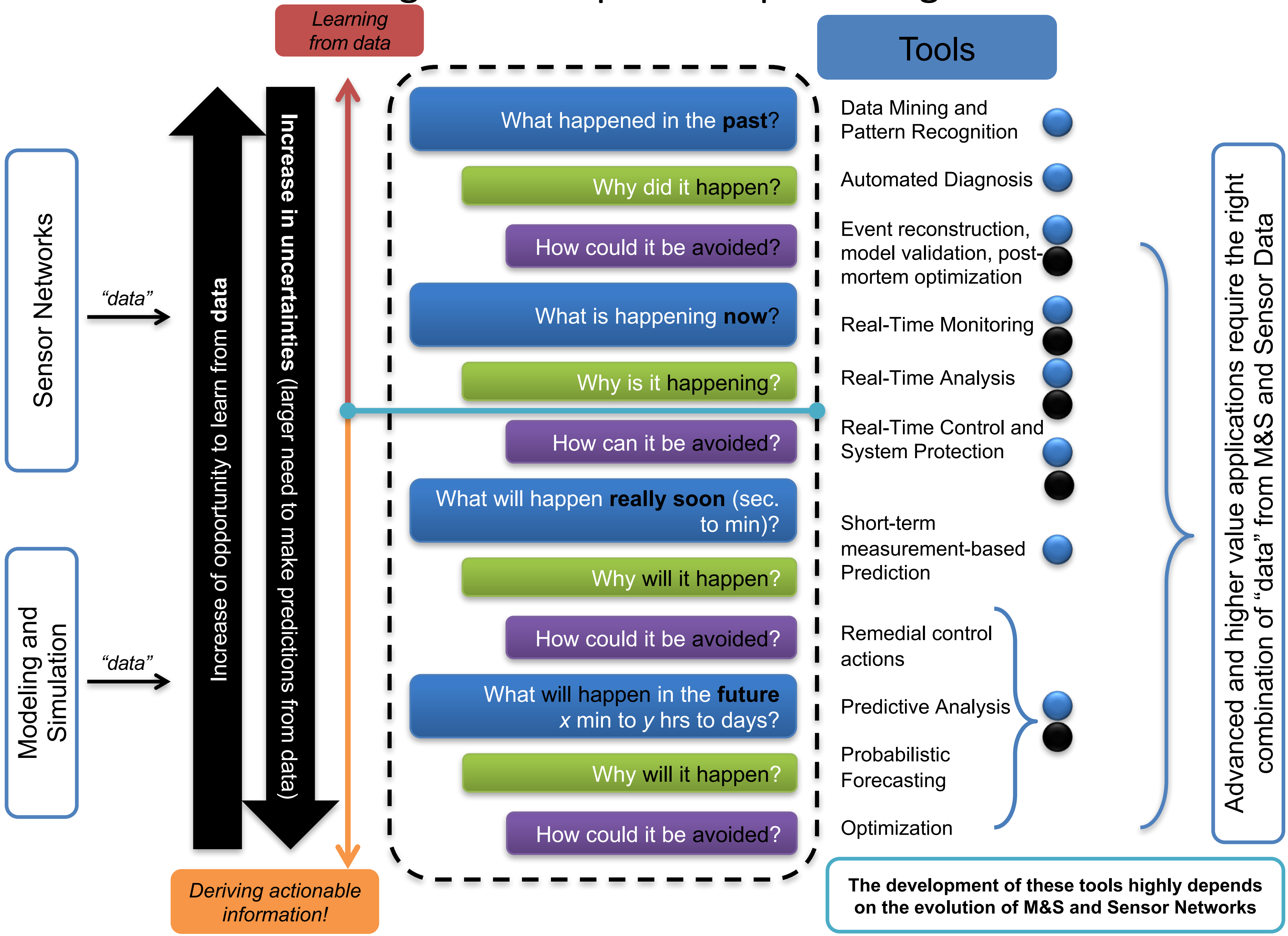
- What actions can be taken now?
- What actions can be taken in the future?

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

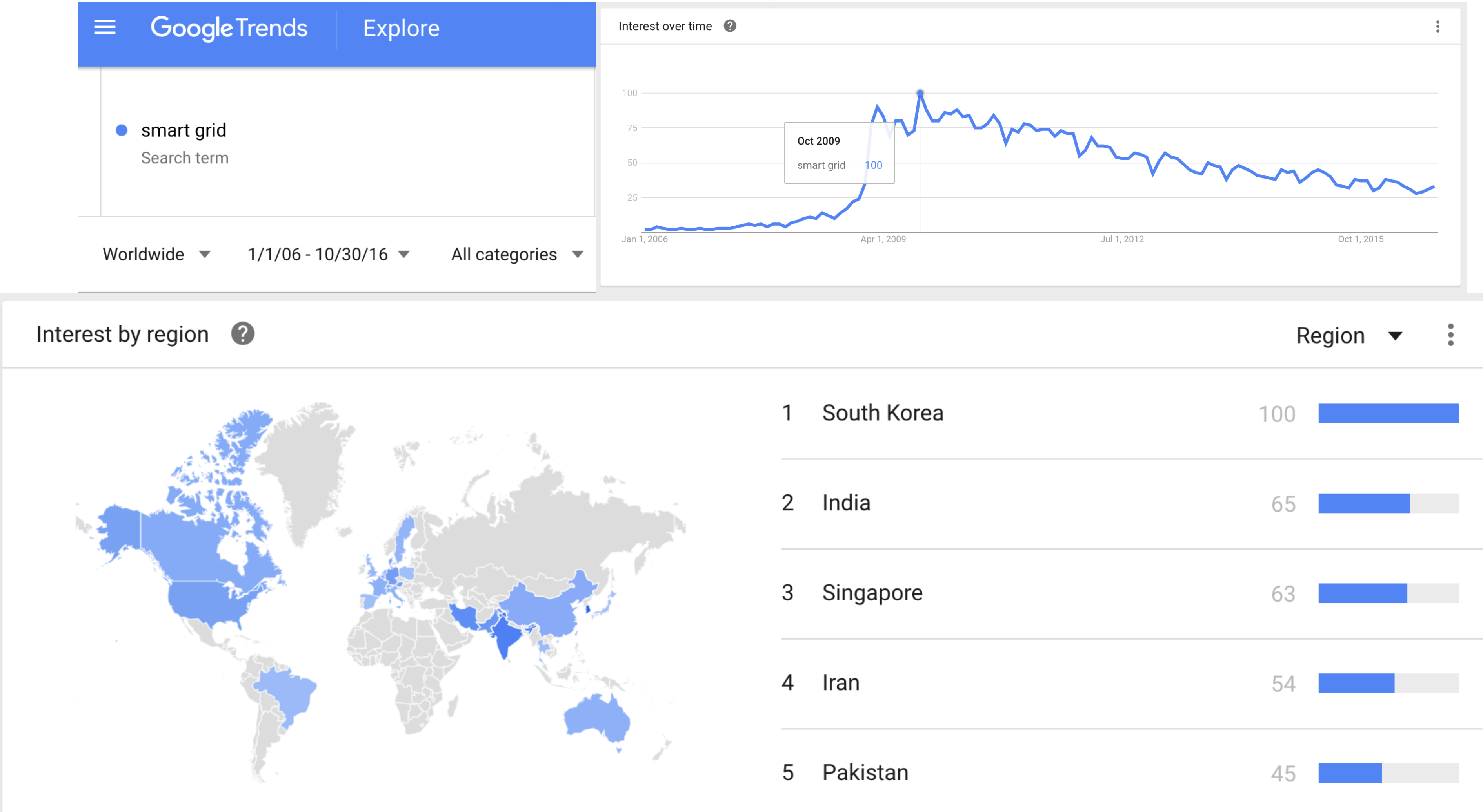


The development of these tools highly depends on the **evolution** of M&S Technologies and Sensor Networks Data (e.g. PMU)

Future Tools: learning from the past and predicting the future



*Smart Grid: **Are we evolving*** towards the 4th Industrial Revolution for the grid?



Learning from ‘smart grid’ development

Two Examples Highlighting the Main Challenges

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... ...c because valuable ... spent trying to reso... e 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 extinguish ... ts in rooms where no one was. Appliances sh... automatically when the price of ele... ...tal emissions were lowest. E... 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.

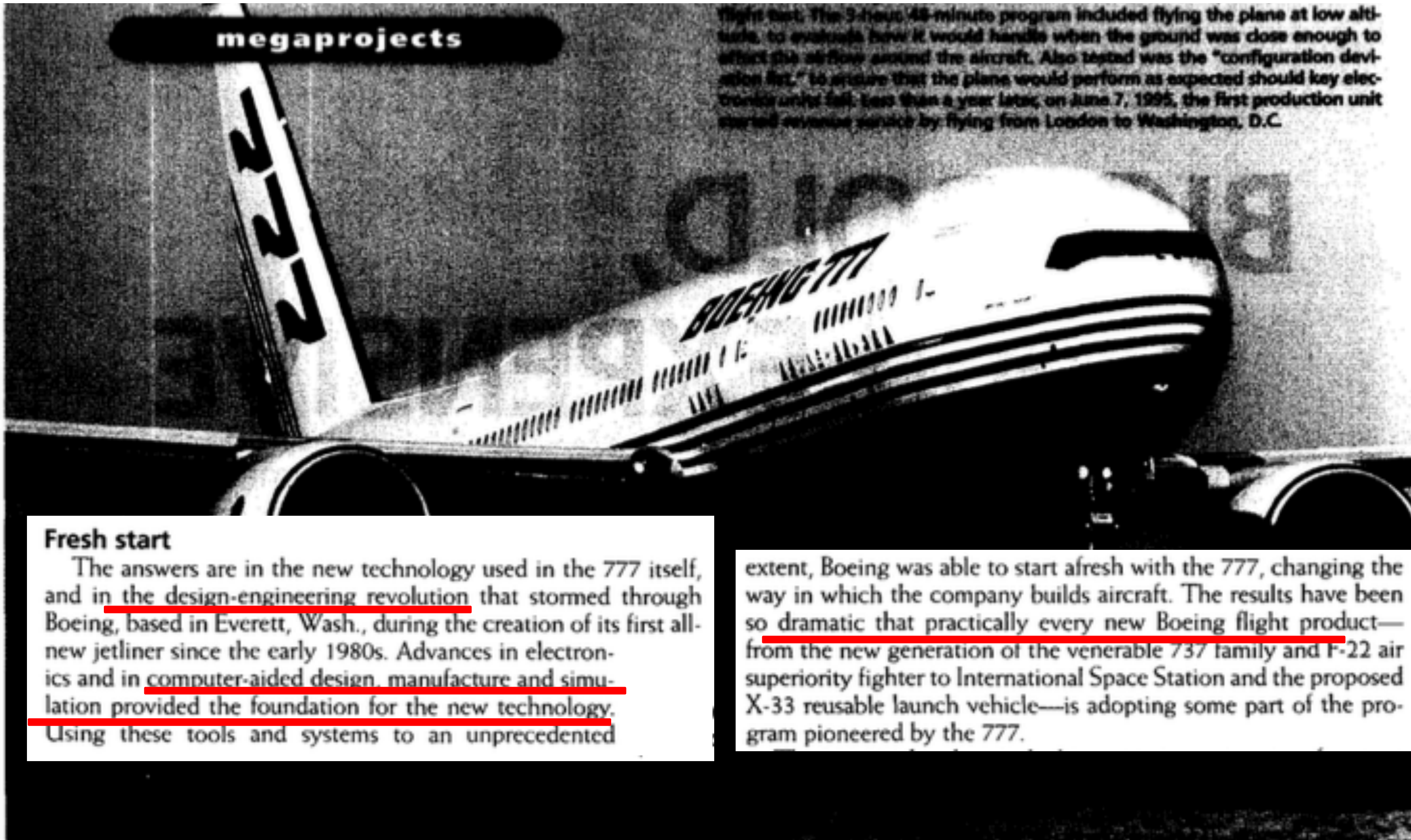
Two domains, previously loosely related, & release ’to the wild’:

- 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?

Meeting a "system-of-systems" challenge with

Model and Simulation-Based Systems Engineering



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

Meeting a “system-of-systems” challenge with

Model and Simulation-Based Systems Engineering

Simulating Success

How do modeling and simulation activities, capabilities benefit Boeing? Let us count the ways—9 of them

By Debby Arkell

Hands-on experience often can be the best way to tackle complex problems or master challenging skills. But when it comes to navigating intricate, variable-laden scenarios, or combat situations involving complex military maneuvers using expensive equipment, “on-the-job training” often is not a prudent approach.

That’s why Boeing Integrated Defense Systems, Commercial Airplanes and Phantom Works engage in a wide variety of modeling and simulation activities, designed to provide ever more realistic simulations to internal customers across the enterprise—and to external customers as well.

“There is a tremendous amount of diversity in modeling and simulation being worked on at Boeing, encompassing very complex issues within a very broad spectrum,” said Ron Fuchs, director of Modeling and Simulation for IDS. “Right now there are more than

Boeing analysts have a variety of tools available—or under development—that can demonstrate concepts and provide significant cost savings by exploring ideas, developing systems, testing and manufacturing within a virtual environment before committing to specific approaches.

4 Product or system testing

Models and simulations are used to test

M&S used to test prototypes in variety of environments.

networked computer systems in the FCS system of systems will be tested in a large-scale distributed simulation facility called the FCS System of Systems Integration Lab. The SoSIL provides a

6 Training systems and maintenance

M&S are used to *train users in the operational environment* – enhancing learning. Simulation *costs 1/10* of running actual scenarios.

Network communications

Tactical military communications networks—such as Joint

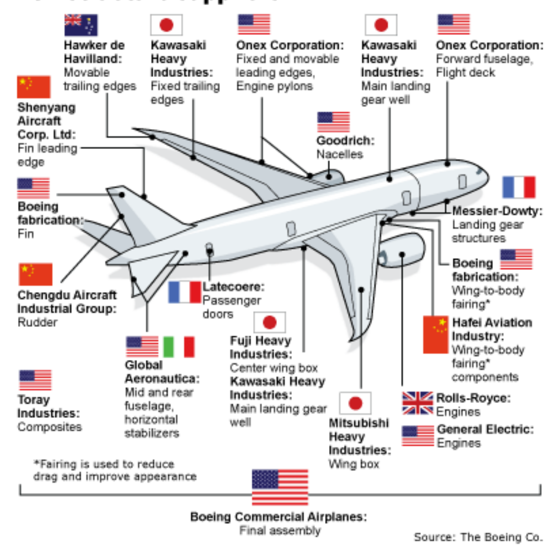
Scale of networks: cost-prohibitive or technically impossible for field tests.

M&S used to test and validate networking protocols in laboratory - environment acting as a test bed.

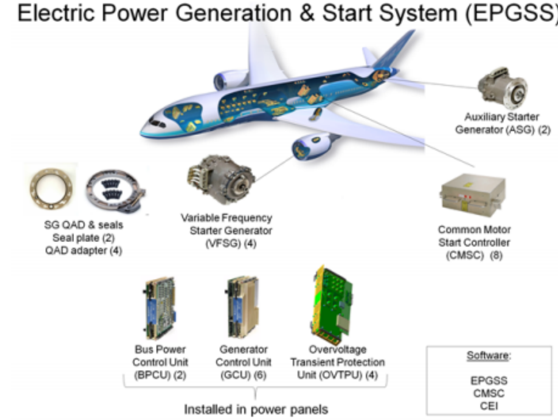
8

Calif., is an environment that acts as a distributed virtual test bed, and the Boeing Transformational Communications Laboratory in El Segundo, Calif., performs a similar function for satellite communications.

Large Number of Vendors for the Final System

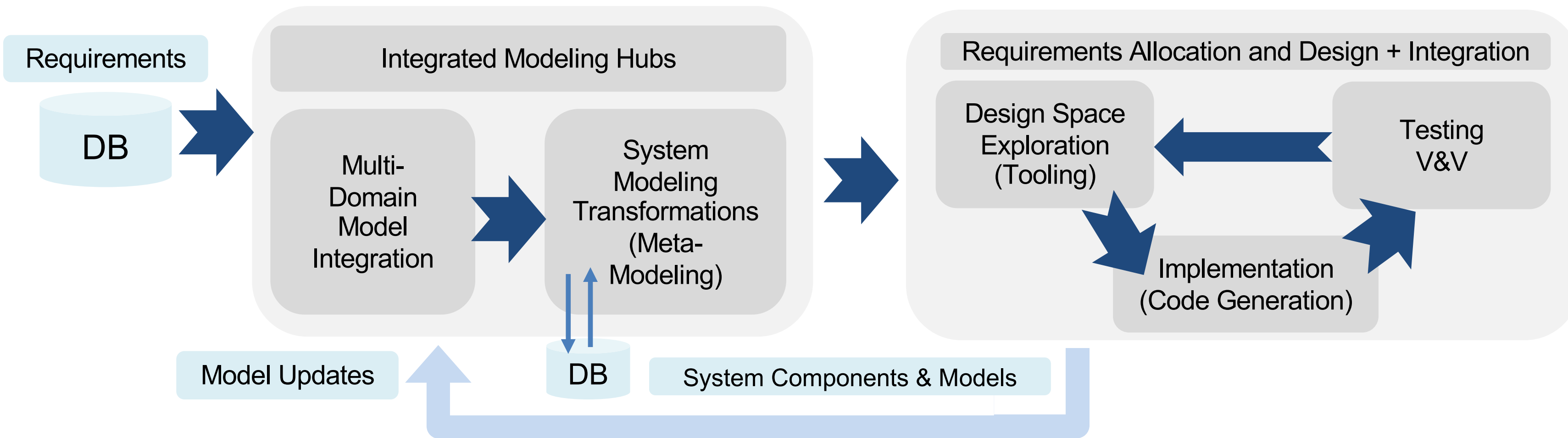


A Flying Micro-Grid!

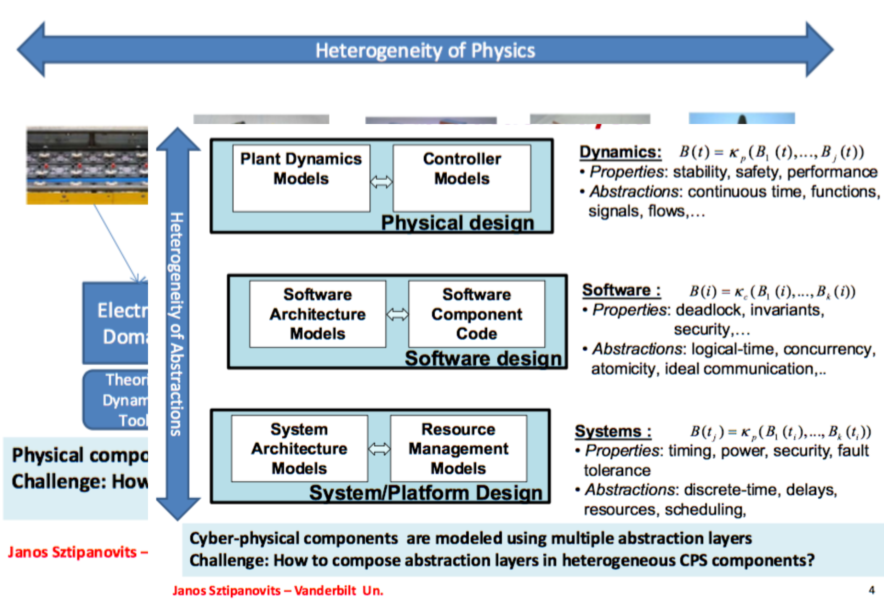


Model and Simulation-Based Systems Engineering

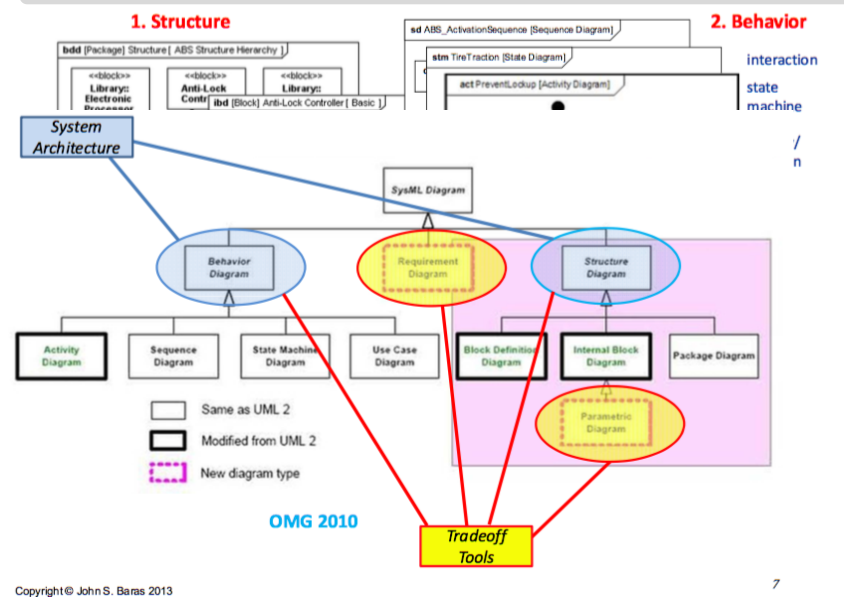
an evolving framework for multi-domain multi-physics system design, manufacturing and operation



Multi-Domain Model Integration



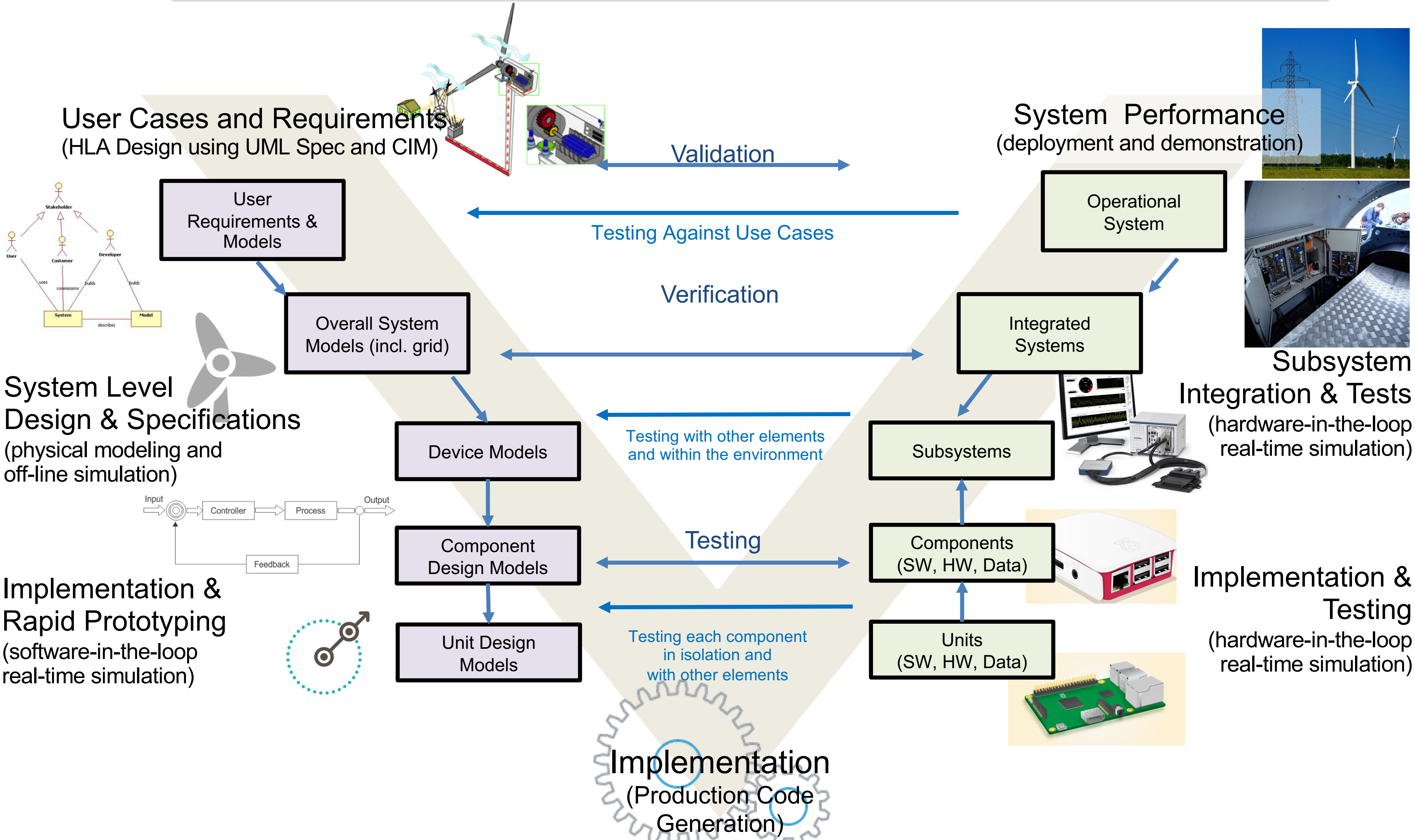
Abstraction Layers, Behavior and Transformations



Model and Simulation-Based Systems Engineering

Framework for Manufacturing to Operation **of Cyber-Physical Power Systems** components and services

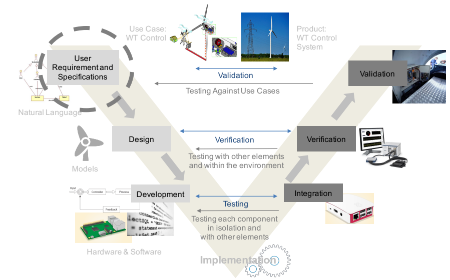
Conceptual Application for the Development of a WT Synchro phasor-Based Controller

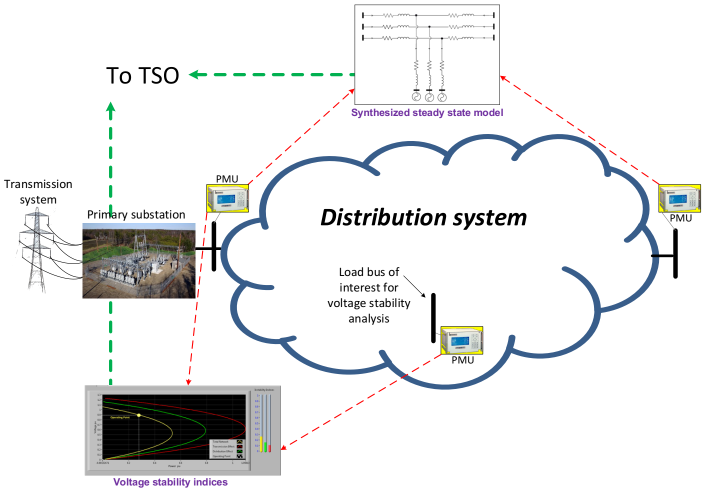


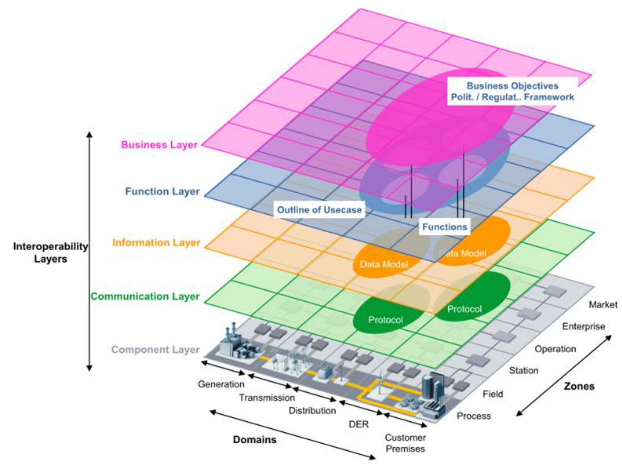
Contribution towards the MBSE **Foundations** in Cyber-Physical Power Systems

Use Cases, Behavior and Structure

Using SGAM for Synchrophasor Applications for TSO/DSO



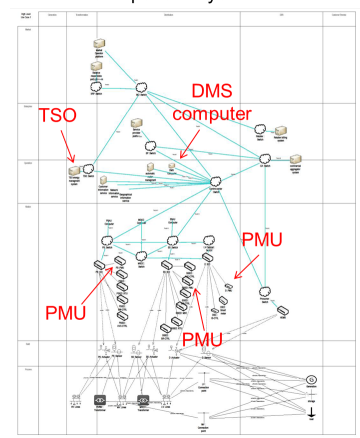




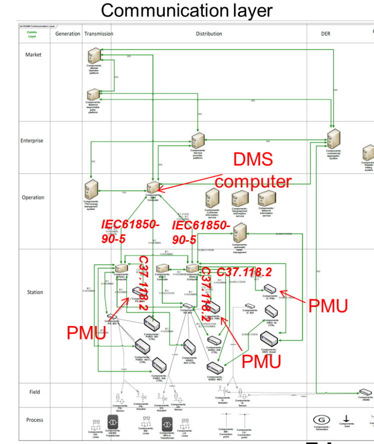
SGAM Layers

Mapping of each layer/

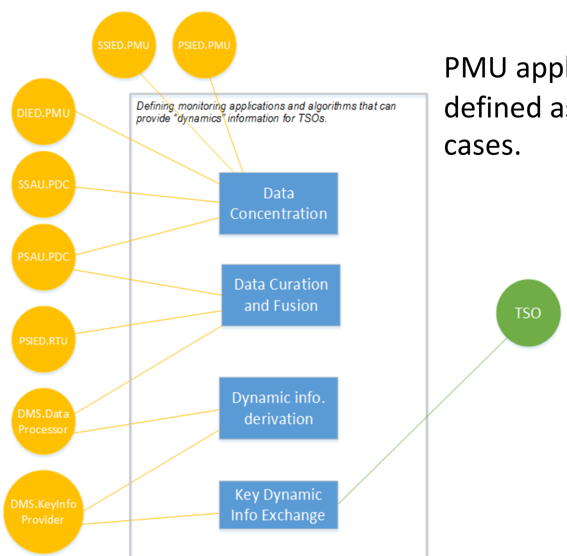
Component layer



Communication layer

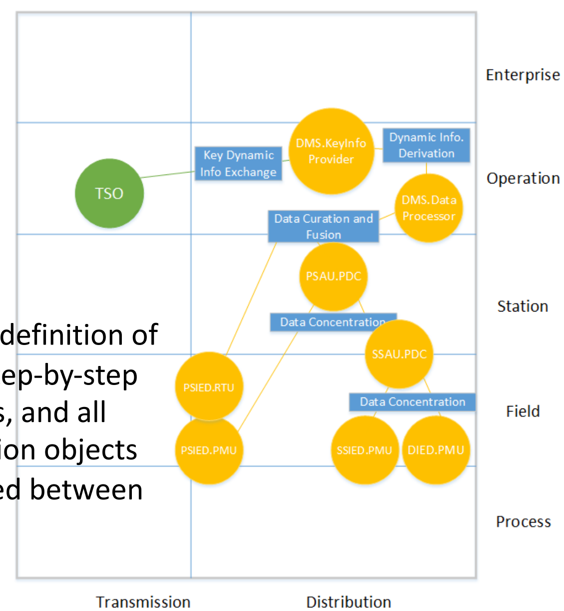


Use Case



PMU application defined as use cases.

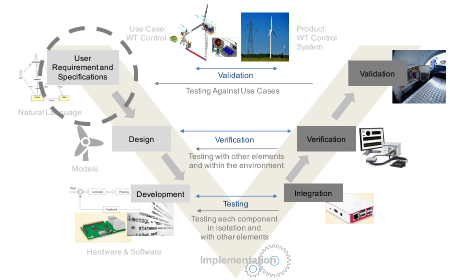
Actors and Scenarios



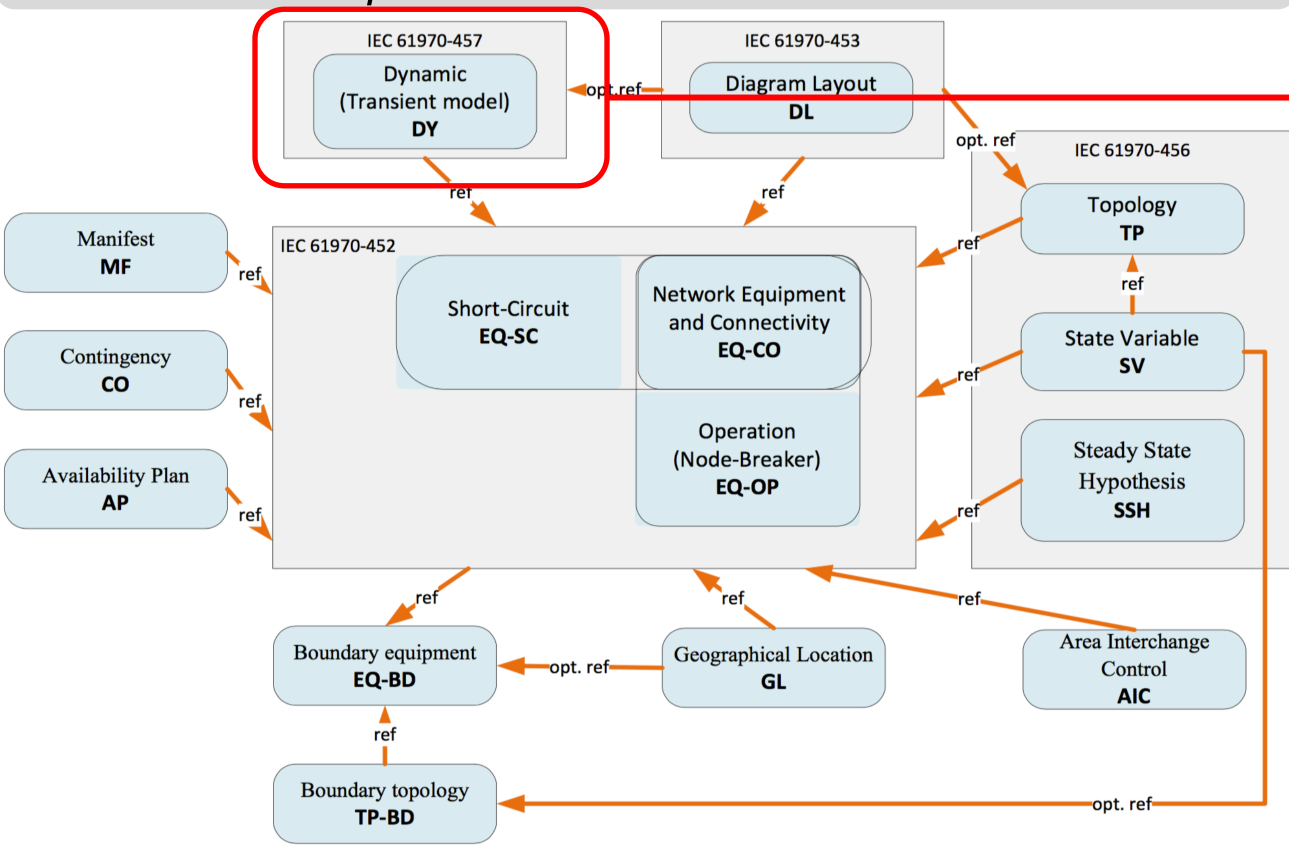
Detailed definition of actors, step-by-step scenarios, and all information objects exchanged between actors.

Information Modeling and Exchange

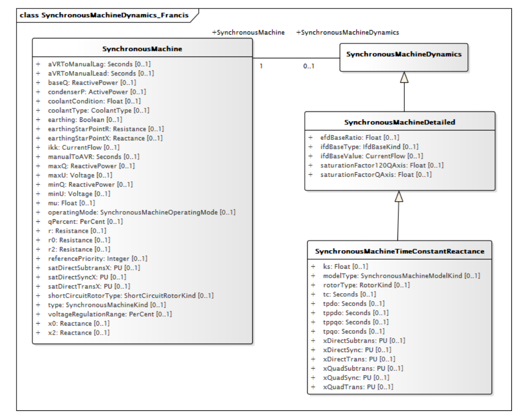
CIM as foundation for future MBSE in Power Grids



The Common Grid Modeling Standard (CGMES) V.2.5. *Dependencies Between Profiles*



UML class diagram shows set of classes represent the CIM classes and ***attributes for a Generator.***

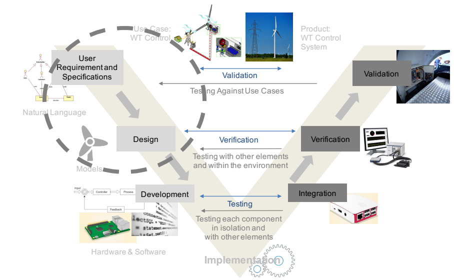


Physics not fully defined!

CIM Provides means to model Behavior, Structure, Parametrics and Requirements

Model to Model Transformation

From the CIM Model to Simulation through Transformation

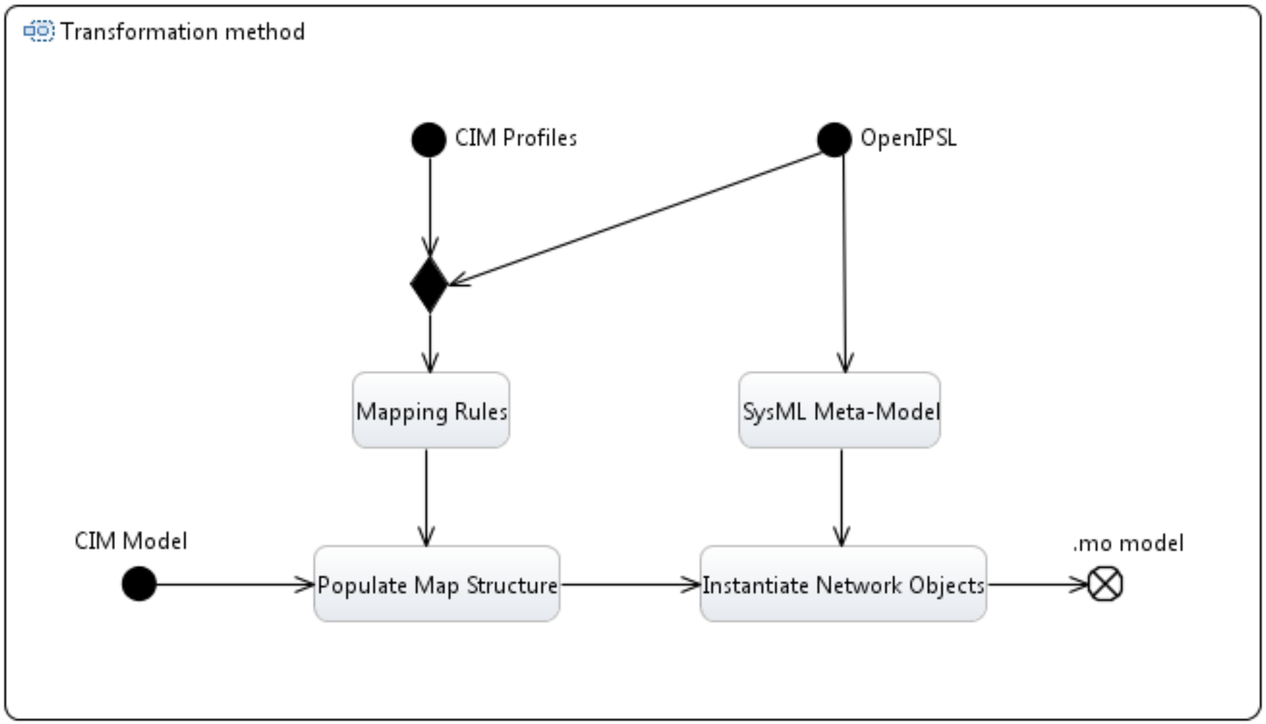


CIM Model (UML – RDF) → **Model** Transformation → Modelica Tool → Simulation Results

OpenIPSL

Add Physical Behavior!

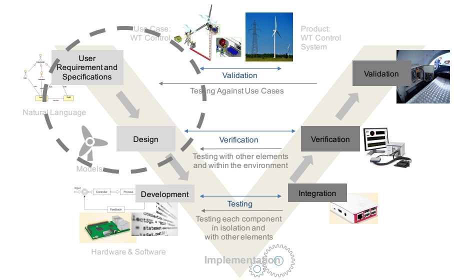
Proposed Mapping Methodology



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

Model to Model Transformation

From the CIM Model to Simulation through Transformation

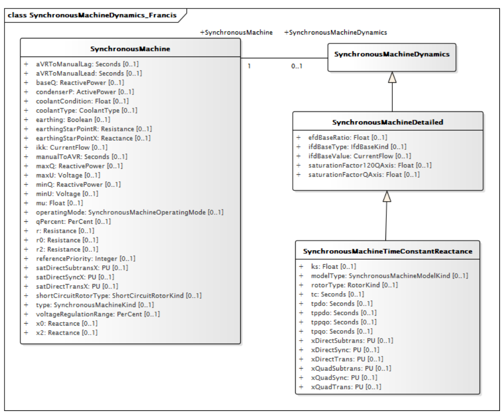


CIM Model (UML – RDF) SysML (Papyrus) → **Model** Transformation → Modelica Tool → Simulation Results

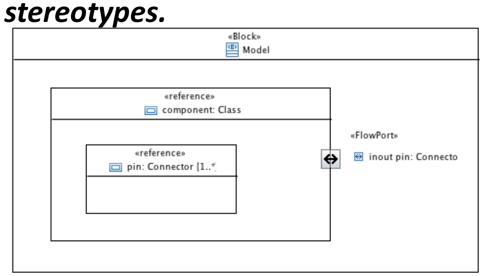
papyrus www.eclipse.org/papyrus

OpenIPSL

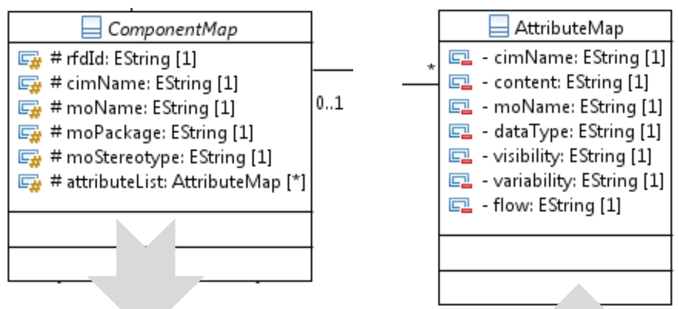
UML class diagram shows set of classes represent the CIM classes and ***attributes for a Generator.***



SysML component diagram shows the definition of ***Modelica model stereotypes.***



Model Transformation through Mapping Rules: ***Example Mappings***




```
<!DOCTYPE model SYSTEM "cim_iteslalibrary_pwpin.dtd">
<pwPinMap cim_name="Terminal" rfd_id="" package="iPSL.Electrical.Connectors" ... "PwPin"
stereotype="connector">
  <attributeMap cim_name="IdentifiedObject.name" mo_name="InstanceName" data... ring"
variability="none" visibility="none">name</attributeMap>
  <attributeMap cim_name="SvVoltage.angle" mo_name="vi" datatype="Real" vari...="none"
visibility="public" flow="0">0</attributeMap>
  <attributeMap cim_name="SvVoltage.v" mo_name="vr" datatype="Real" variability="none"
visibility="public" flow="0">0</attributeMap>
  <attributeMap cim_name="SvPowerFlow.p" mo_name="ir" datatype="Real" variability="none"
visibility="public" flow="1">0</attributeMap>
  <attributeMap cim_name="SvPowerFlow.q" mo_name="ii" datatype="Real" variability="none"
visibility="public" flow="1">0</attributeMap>
</pwPinMap>
```

This classes compose an internal structure of CIM2Modelica Factory for ***storing the values from the CIM model***

The ***mapping rules*** are used ***to read value from CIM*** model and are used to ***create instances of iPSL/OpenIPSL*** classes.

```
within iPSL.Examples.Machines.PSSE;
model GENSAL "SMIB system with one load and GENSAL model"
...
iPSL.Electrical.Machines.PSSE.GENSAL.GENSAL gen_1(
```

Class name and package name as data type, and Instance name from IdentifiedObject.name (CIM attribute)

```
iPSL.I
R=0.0
```

```
connect(gen_1.PMECH, gen_1.PMECH0);
connect(gen_1.p, gen_1.p);
connect(gen_1.p, pwLine.p);
```

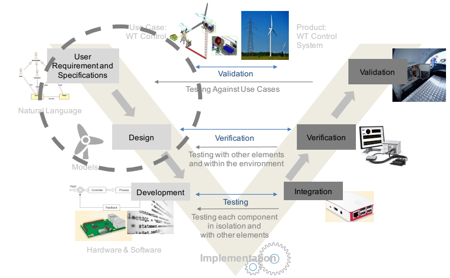
The a... rules

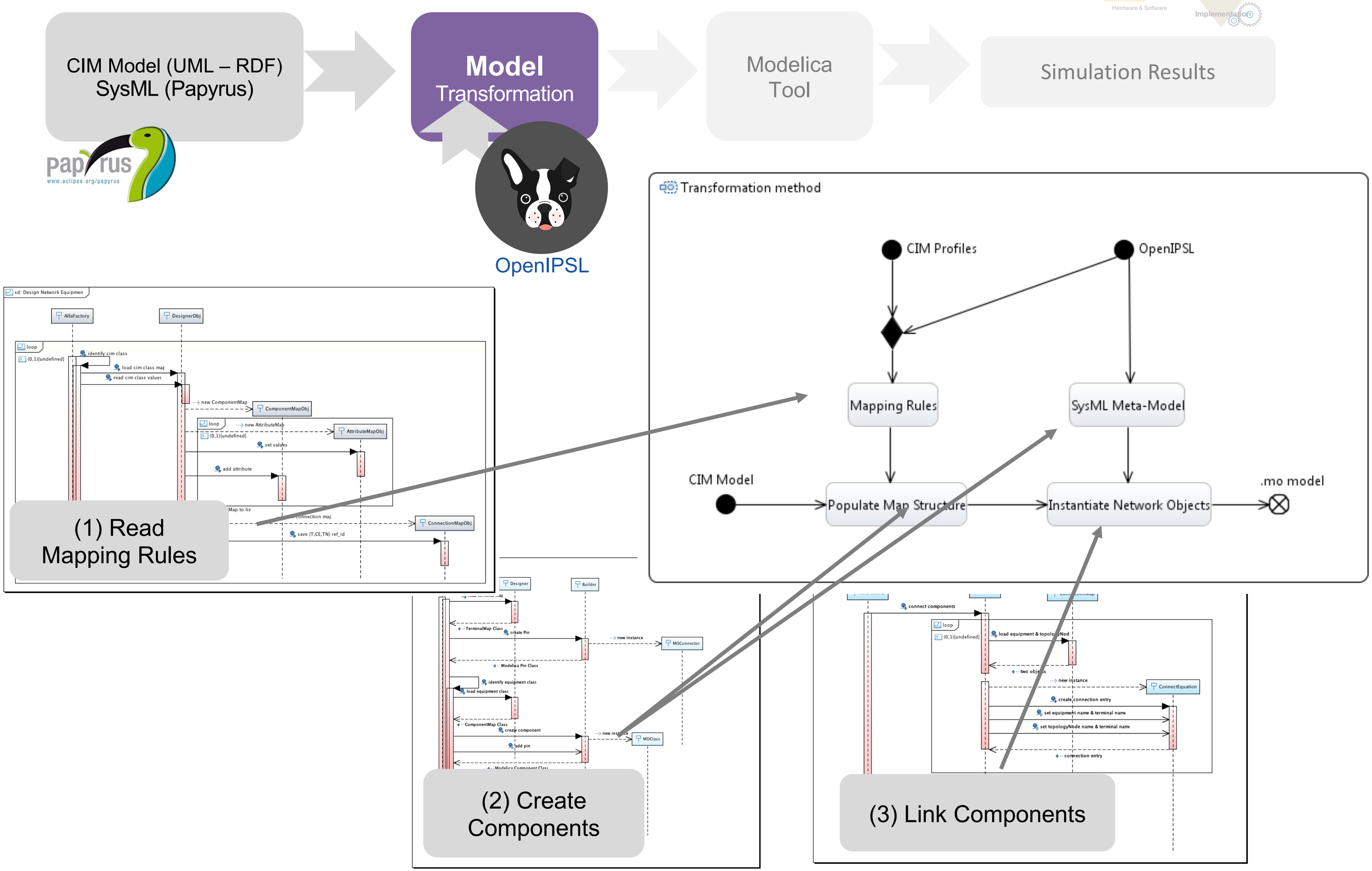
Connections are created with name and reference of Terminal, ConductingEquipment and TopologicalNode

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

Model to Model Transformation Engine

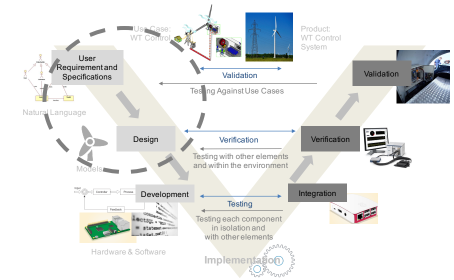
CIM2ModelicaFactory Workflow





Model to Model Transformation

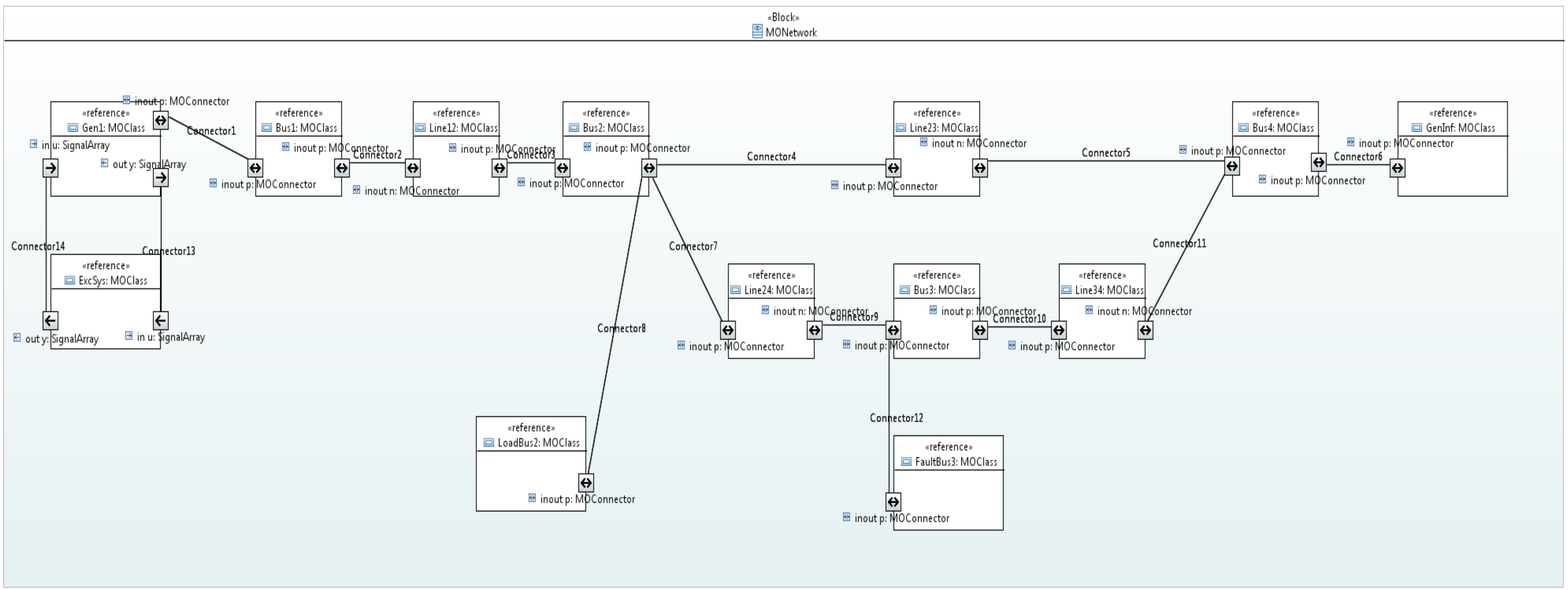
CIM2ModelicaFactory Workflow - SysML



CIM Model (UML – RDF) SysML (Papyrus) → **Model** Transformation → Modelica Tool → Simulation Results

OpenIPSL

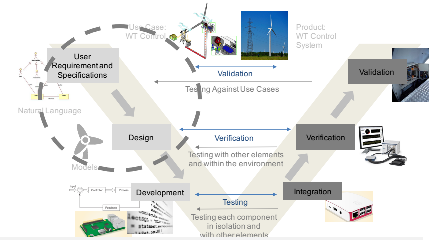
SysML Model showing the Structure, Attributes and added Physical Behavior



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

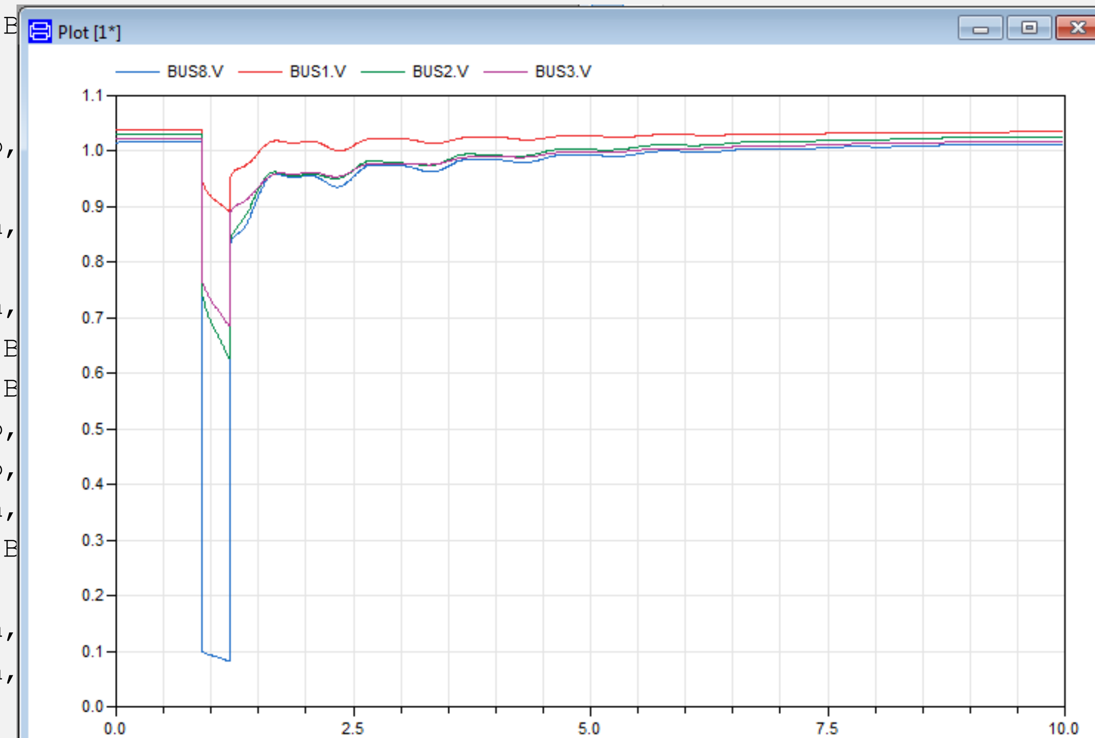
Model to Model Transformation Engine

CIM2ModelicaFactory Workflow: Output Model and Simulation



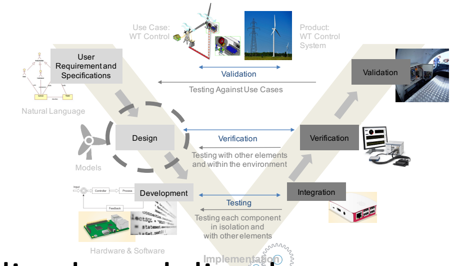

```
model IEEE_9BUS_CIM "something here"
iPSL.Electrical.Branches.PwLine Ln46(R=0.017000000923871994,X=0.09200000017881393,G=0,B=0.07900000363588333) "something here" annotation();
iPSL.Electrical.Buses.Bus BUS4 "something here" annotation();
iPSL.Electrical.Buses.Bus BUS2 "something here" annotation();
iPSL.Electrical.Buses.Bus BUS7 "something here" annotation();
iPSL.Electrical.Buses.Bus BUS6 "something here" annotation();
iPSL.Electrical.Loads.PSSE.Load Ld8(angle_0=-91.6318588256836,V_0=1.0116652250289917,P_0=1,Q_0=0) "something here" annotation();
iPSL.Electrical.Buses.Bus BUS8 "something here" annotation();
iPSL.Electrical.Machines.PSSE.GENROU.GENROU Gn2(S_b=0,M_b=320,V_b=18,V_0=1.030107021331787,angle_0=-
82.5199966430664,P_0=177.21009826660156,Q_0=12.977800369262695,R_a=0,Xl=0.10000000149011612,H=3.3299999237060547,D=0.6700000166893005,S10=1.0099999
904632568,S12=1.0199999809265137,Tpd0=6,Tpq0=0.5350000262260437,Tppd0=0.05000000074505806,Tppq0=0.05000000074505806,Xd=1.7200000286102295,Xpd=0.230
0000041723251З,Xppd=0.20999999344348907,Xq=1.659999966621399,Xpq=0.3700000047683716,Xppq=0.20999999344348907) "something here" annotation();
iPSL.Electrical.Branches.PwLine Ln57(R=0.032000000151991844,X=0.1609999984502792,G=0,B=0.1529999971389770) "something here" annotation();
iPSL.Electrical.Buses.Bus
iPSL.Electrical.Loads.PSSI
iPSL.Electrical.Branches.I
iPSL.Electrical.Loads.PSSI
iPSL.Electrical.Branches.I
iPSL.Electrical.Buses.Bus
iPSL.Electrical.Branches.I
T3(R=0,X=0.0625,G=0,B=0,AI
"something here" annotati
iPSL.Electrical.Branches.I
T1(R=0,X=0.05860000103712
"something here" annotati
iPSL.Electrical.Branches.I
T2(R=0,X=0.05759999901056
here" annotation();
iPSL.Electrical.Buses.Bus
iPSL.Electrical.Machines.I
94.33999633789062,P_0=58.
4632568,S12=1.01999998092
47858,Xppd=0.100000001490
iPSL.Electrical.Buses.Bus
iPSL.Electrical.Branches.I
iPSL.Electrical.Machines.I
12.135199546813965,R_a=0,
99866485596,Tpq0=0.600000
9344348907,Xq=1.61000001 4
iPSL.Electrical.Branches.I
// manully implemented
iPSL.Electrical.Events.PwI
```

```
equation
    connect(Ln46.p, BUS4.p);
    connect(T2.n, BUS7.p);
    connect(T2.p, B
    connect(Ld8.p,
    connect(Gn2.p,
    connect(Ln57.p,
    connect(Ld6.p,
    connect(Ln45.n,
    connect(Ld5.p,
    connect(Ln89.n,
    connect(T3.n, B
    connect(T1.n, B
    connect(Ln89.p,
    connect(Ln45.p,
    connect(Ln57.n,
    connect(T1.p, B
    connect(Gn1.p,
    connect(Ln78.n,
    connect(Ln46.n,
    connect(Gn3.p,
                                      connect(Ln69.p, BUS6.p);
                                      connect(Ln69.n, BUS9.p);
                                      connect(Ln78.p, BUS7.p);
```

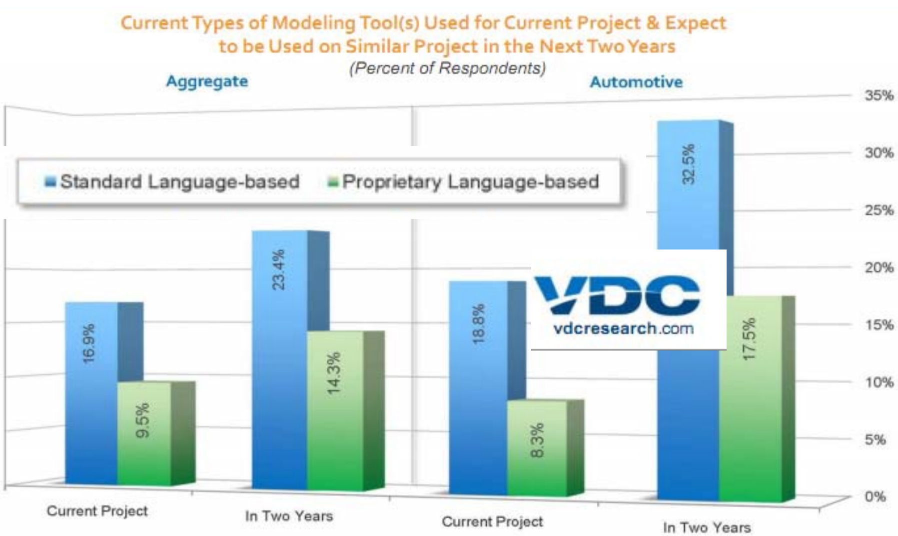


System Level Design:

using the Modelica (open) standard mathematical modeling language



Why standardized languages?



- Modeling tools first gained adoption as engineers looked for ways to simplify SW development and documentation.
- Today's mnodeling tools and their use cases have evolved.
- ***Now:*** need for addressing both system level design and SW development/construction.

MODELICA is an open standardized modeling language among all Modelica compliant IDEs

- Modelica Language Specification: https://www.modelica.org/documents/ModelicaSpec33.pdf

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

OpenIPSL allows:

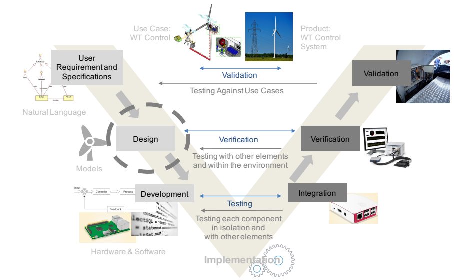
- **Unambiguous** model exchange
- Formal **mathematical description** of models
- Exploitation of **object-oriented** paradigms
- **Separation** of **models** from IDEs and **solvers**

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

System Level Design:

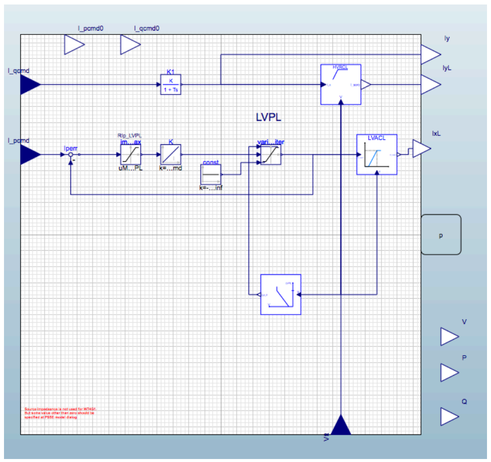
OpenIPSL Models – Wind Turbine Example

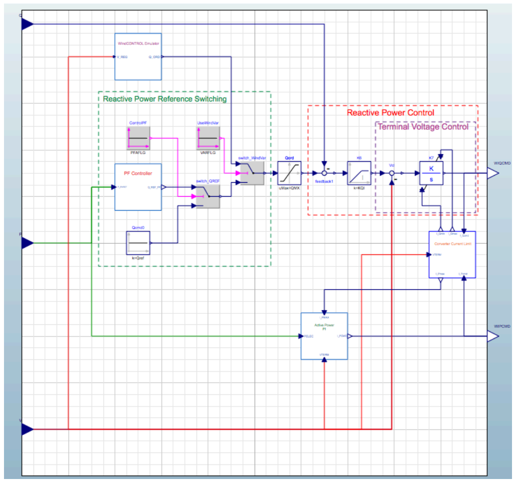
OpenIPSL



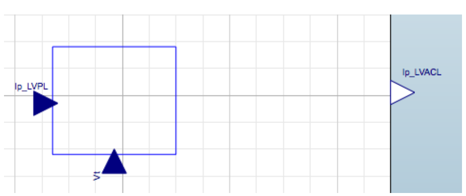
- OpenIPSL
  - Examples
  - Electrical
    - Buses
    - Branches
    - Machines
      - PSAT
      - PSSE
        - BaseClasses
        - GENSAL
        - GENROU
        - GENROE
        - GENSAE
        - GENCLS
    - Controls
      - PSAT
      - Simulink
      - PSSE
        - OEL
        - ES
        - TG
        - PSS
          - PSS2A
          - PSS2B
          - STAB2A
          - STAB3
          - STABNI
          - IEEEST
          - IEE2ST
          - STBSVC
      - CGMES
    - Loads
    - Banks
    - Solar
    - Wind
    - Events
    - FACTS
    - Essentials
    - Sensors
    - SystemBase
  - NonElectrical
    - Logical
    - Continuous
    - Nonlinear
    - Functions
  - Connectors

- Wind
  - PSAT
  - PSSE
    - WT3G
    - WT4G
      - WT4G1
      - WT4E1
      - Submodels
        - LVACL
        - HVRCL
        - LVPL
        - CCL





- Submodels
  - LVACL
  - HVRCL
  - LVPL
  - CCL

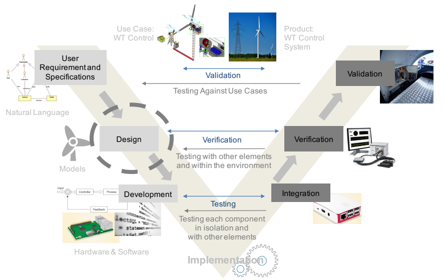


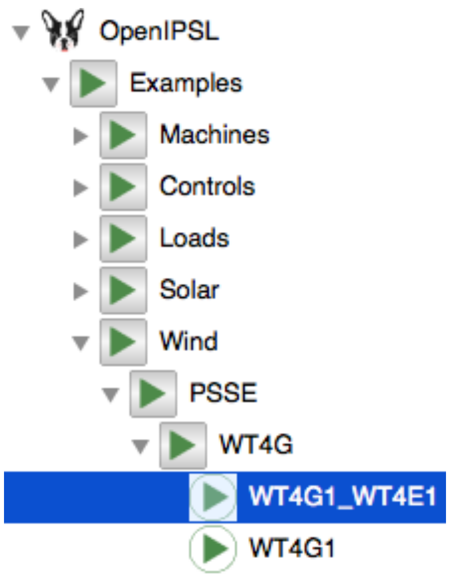

```
model LVACL
  //The Low Voltage Active Current Management block is de
  //of active power under very low voltage scenarios. Thi
  //  The protection function is activated when
  //the terminal voltage drops below 0.8 pu and stranglin
  //0.4 pu. For voltages between 0.8 pu and 0.4 pu to red
  Modelica.Blocks.Interfaces.RealOutput Ip_LVACL ;
  Modelica.Blocks.Interfaces.RealInput Vt ;
  Modelica.Blocks.Interfaces.RealInput Ip_LVPL ;
equation
  if Vt < 0.4 then
    Ip_LVACL = 0;
  elseif Vt > 0.8 then
    Ip_LVACL = Ip_LVPL;
  else
    Ip_LVACL = Ip_LVPL * 1.25 * Vt;
  end if;
  ;
end LVACL;
```

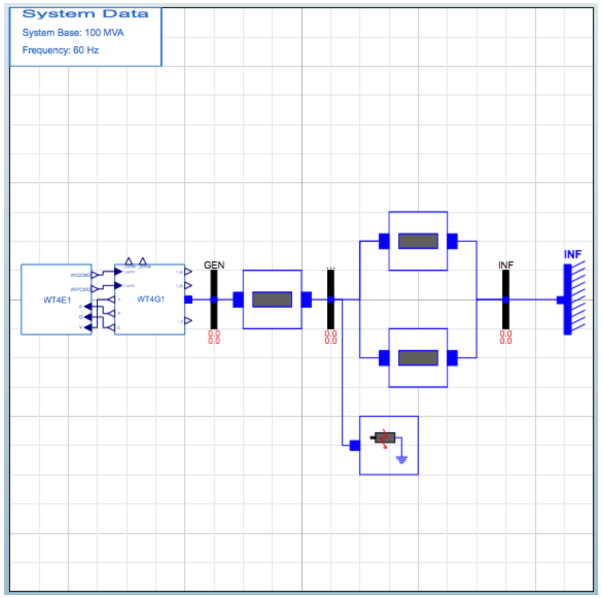
System Level Design:

OpenIPSL Models – Power System Examples

OpenIPSL

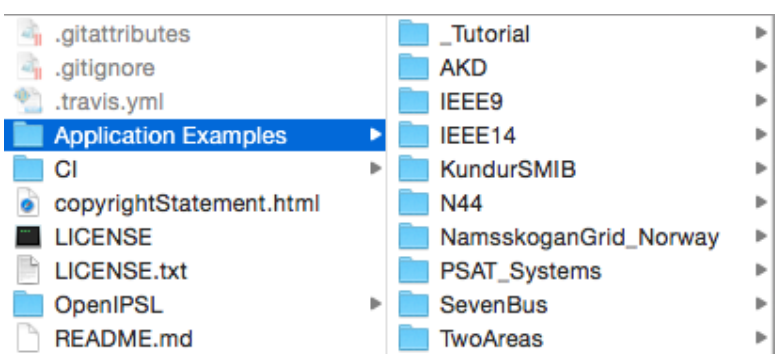







```
model WT4G1_WT4E1
  extends Modelica.Icons.Example;
  constant Real pi = Modelica.Constants.pi;
  parameter Real V1 = 1.0;
  parameter Real A1 = -1.570655e-05;
  parameter Real V3 = 0.99999990000000001;
  parameter Real A3 = 0.02574992;
  parameter Real P1 = -1.4988;
  parameter Real Q1 = -4.334;
  parameter Real Zr = 0.0;
  parameter Real Zi = 0.2;
  parameter Real P3 = 1.5;
  parameter Real Q3 = -5.6658;
  parameter Real R1 = 0.025;
  parameter Real X1 = 0.025;
  parameter Real B1 = 0.05;
  parameter Real dyrw[1, 9] = [0.02, 0.02,
  OpenIPSL.Electrical.Branches.PwLine pwLin
  OpenIPSL.Electrical.Branches.PwLine pwLin
  OpenIPSL.Electrical.Machines.PSSE.GENCLS
  OpenIPSL.Electrical.Branches.PwLine pwLin
  OpenIPSL.Electrical.Wind.PSSE.WT4G.WT4G1
  OpenIPSL.Electrical.Events.PwFault pwFaul
  OpenIPSL.Electrical.Wind.PSSE.WT4G.WT4E1
  inner OpenIPSL.Electrical.SystemBase SysD
  OpenIPSL.Electrical.Buses.Bus GEN ¤;
  OpenIPSL.Electrical.Buses.Bus BUS1 ¤;
  OpenIPSL.Electrical.Buses.Bus INF ¤;
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;
```

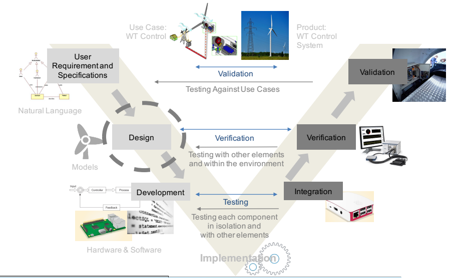
Many Application Examples Developed



System Level Design:

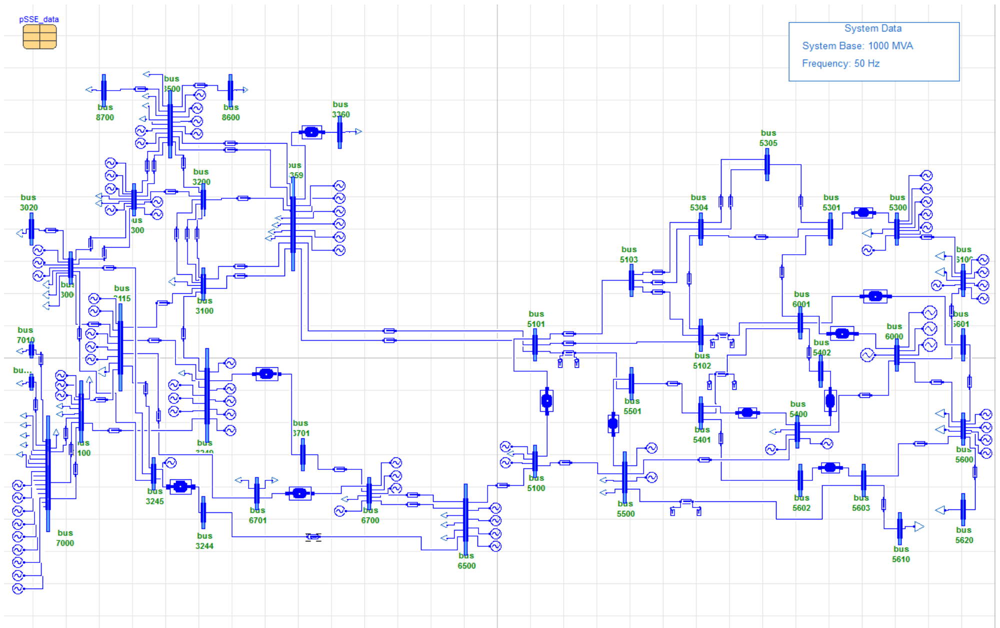
OpenIPSL Models – Big Grids? N44!

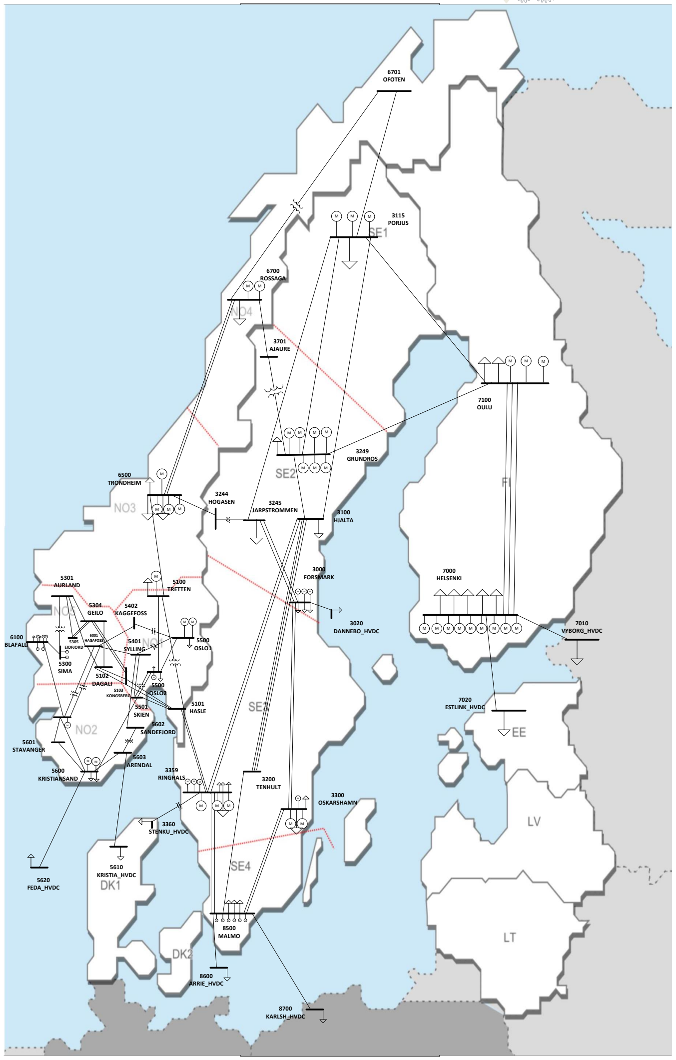
OpenIPSL



Modelica model of Nordic44 system

- Modelica can be used to build models of various sizes
- Norwegian TSO Statnett provided a PSS/E model of Nordic44 system
- The same model was implemented in Modelica and validated against a reference software, PSS/E

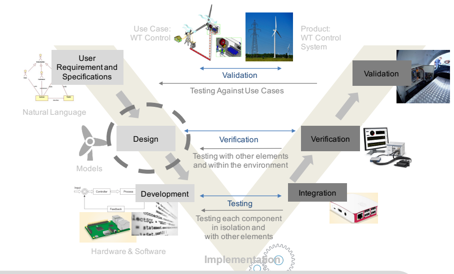




System Level Design:

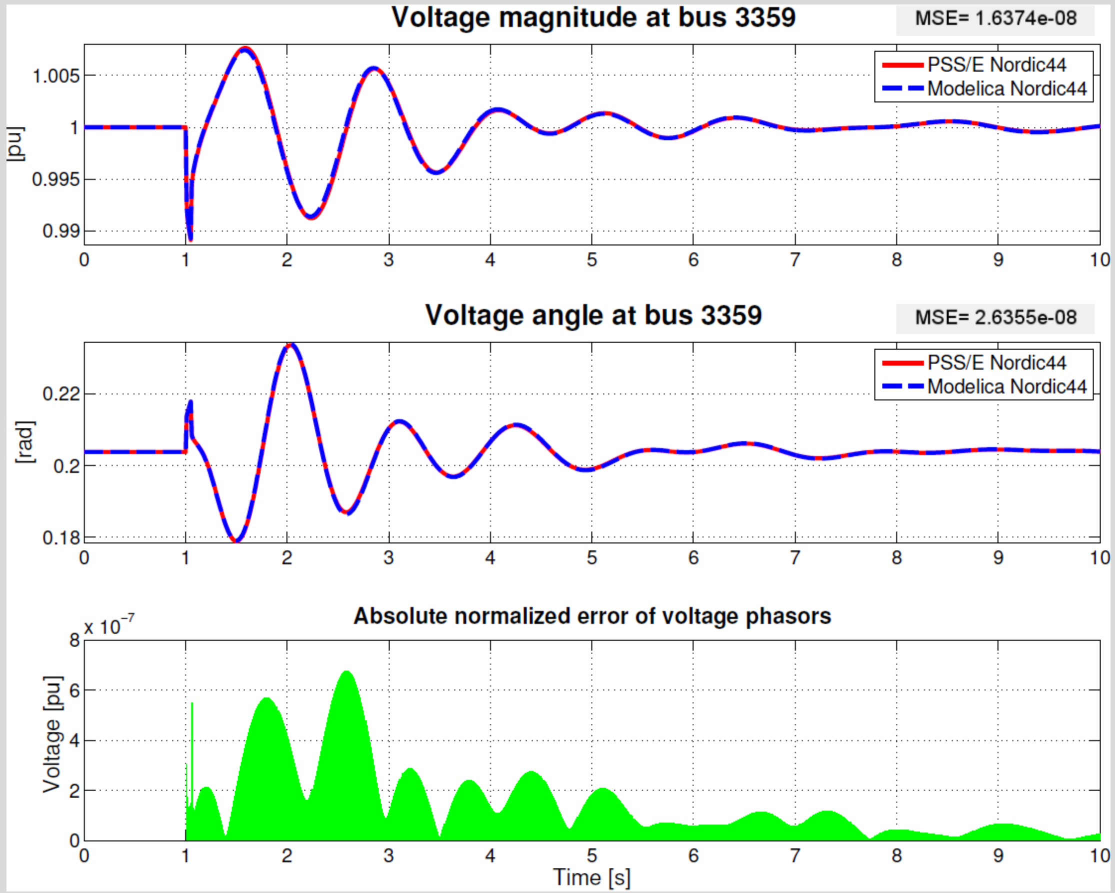
OpenIPSL Models – Big Grids? N44!

OpenIPSL



	PSS®E
Output interval length	0.01
Integration algorithm	Modified Euler
Tolerance	0.0001

	Modelica Tool (Dymola)
Output interval length	0.01
Integration algorithm	Rkfix2
Tolerance	0.0001

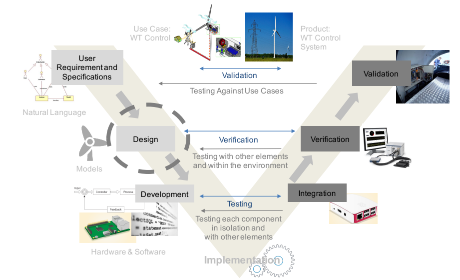


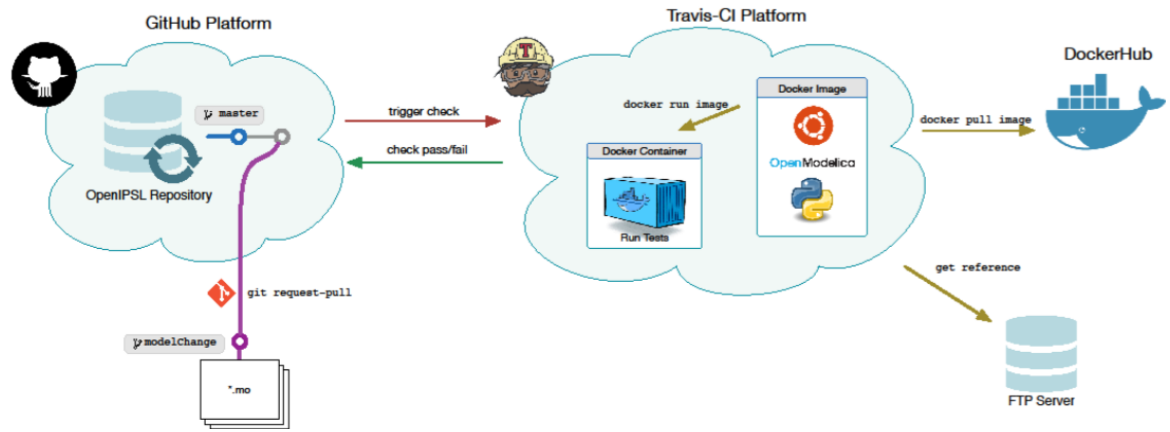
Simulation time	Fault type	Fault location	Fault impedance	Fault duration
0-10 sec	3 phase-to-ground	bus 6500	(0+j5e-10) Ω	1-1.05 sec

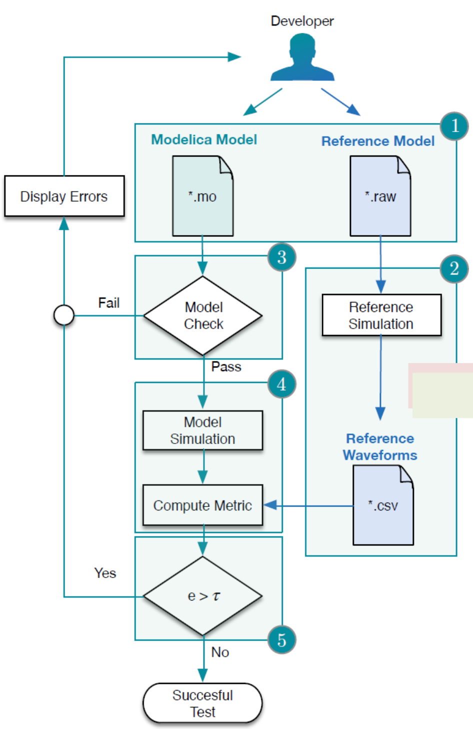
System Level Design:

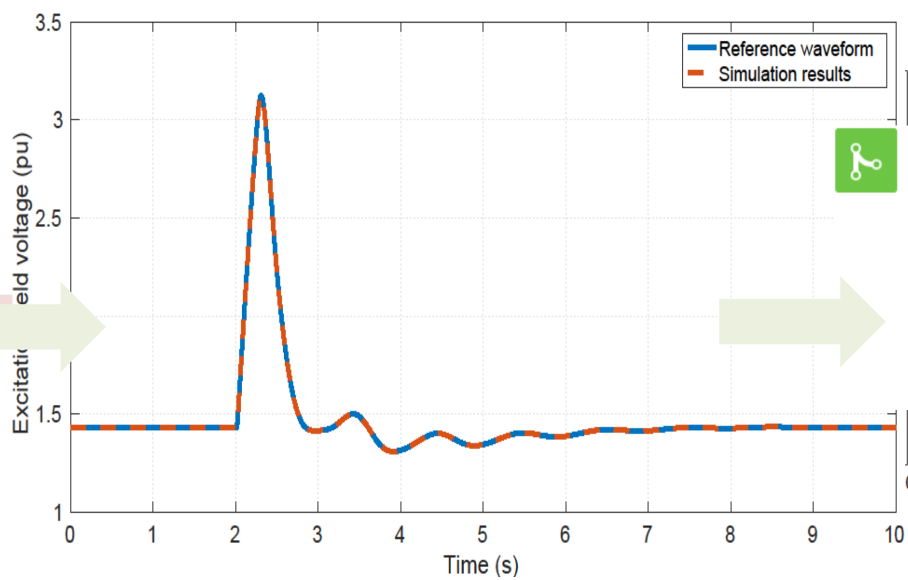
OpenIPSL – Continuous Development and Implementation Framework

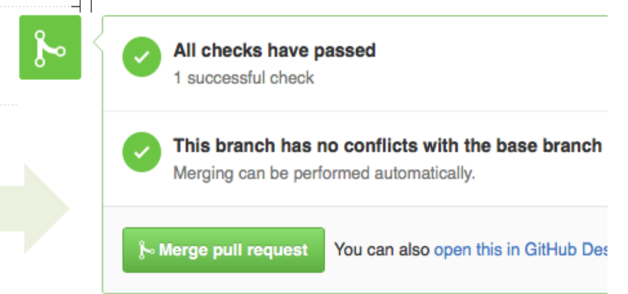
OpenIPSL





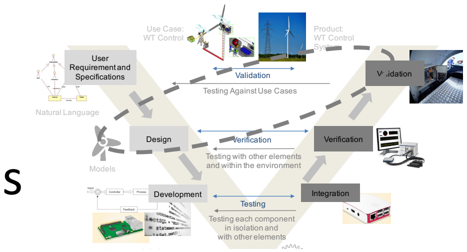




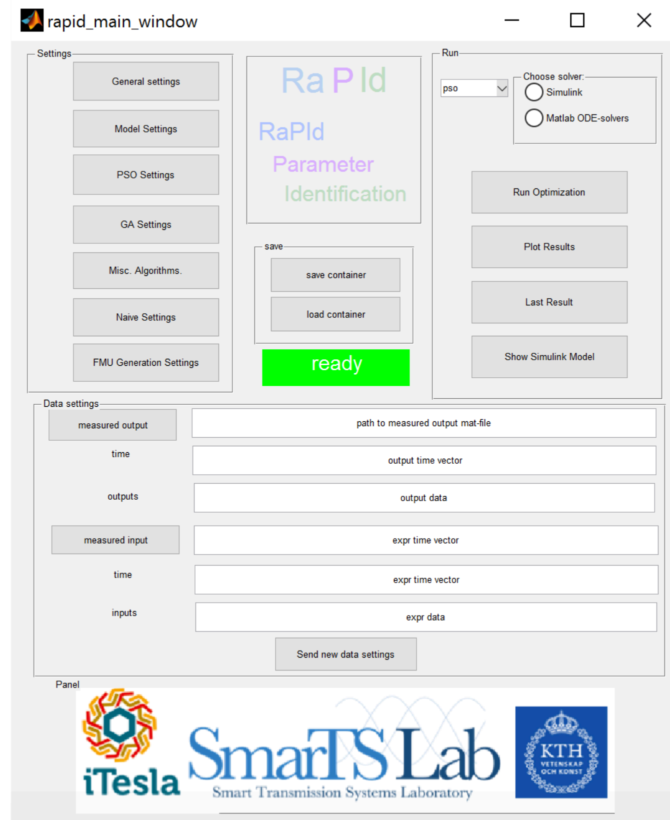


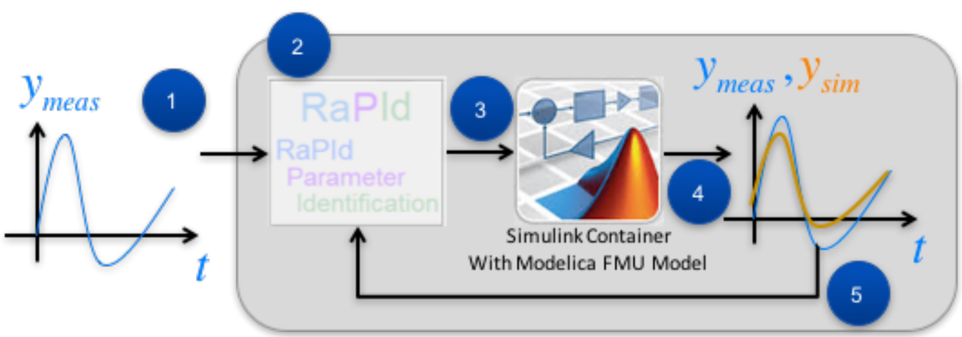
Model Validation:

Methods and Tooling for Validating Power System Models



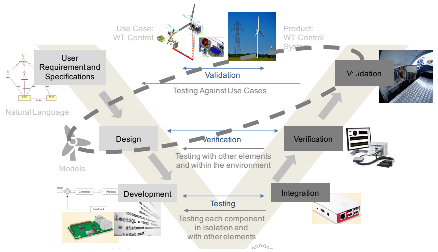
- **RaPId** is a toolbox providing **a general framework to solve system identification problems.**
- The SW is modular and extensible, with a plug-in SW architecture allowing to use different optimization, simulation and signal processing techniques.
- **A common application of RaPId** is to attempt 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



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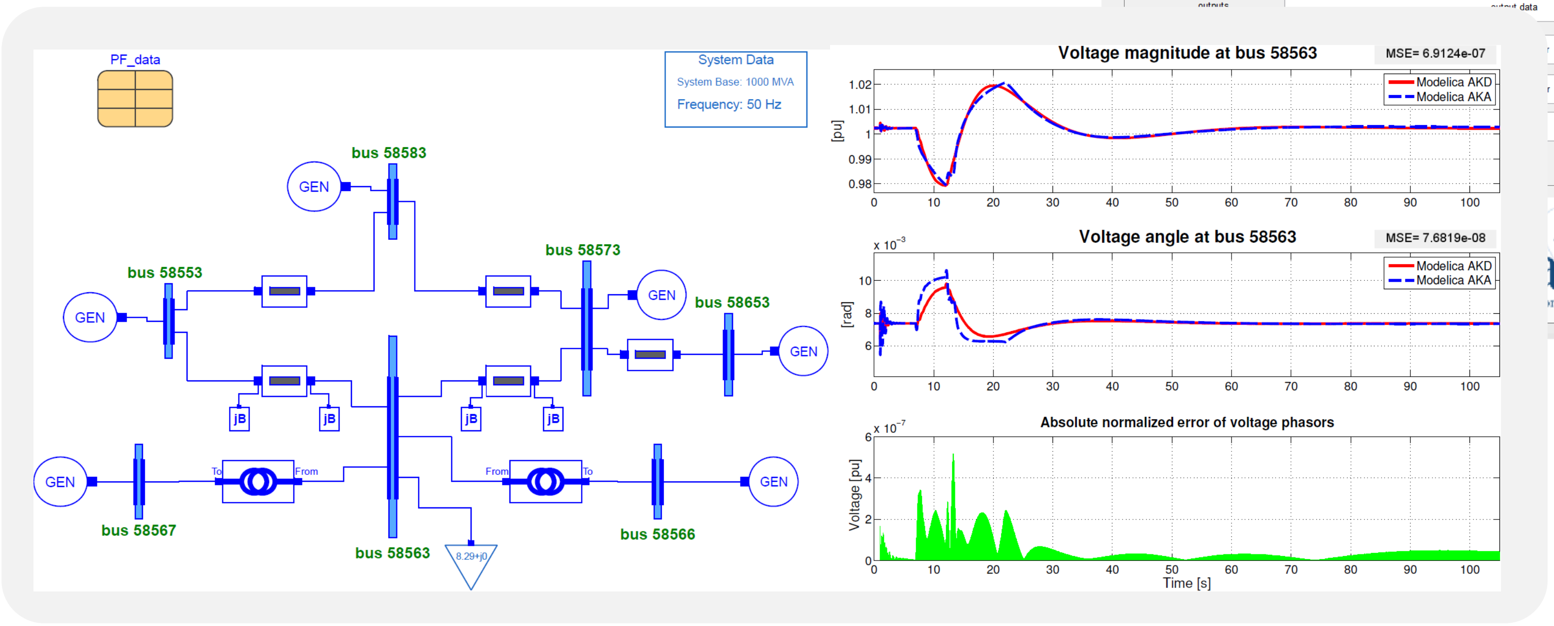
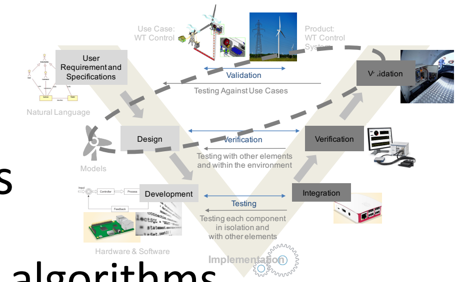


Model Validation:

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).

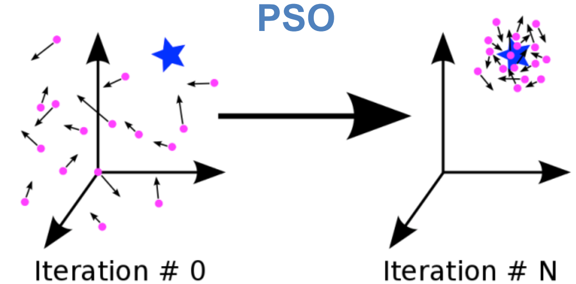
Optimization process can be set up and ran from the **GUI** or more advanced users can simply use **MATLAB scripts** for the same purpose

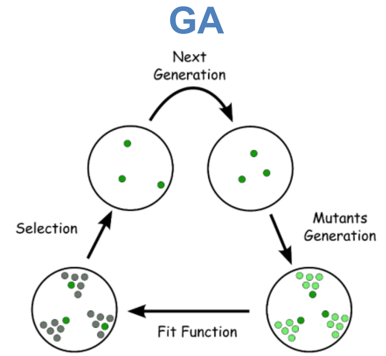
Plug-in Architecture:

- **Completely extensible and open architecture** allows advanced users to add:
  - Identification methods
  - Optimization methods
  - Specific objective functions
  - Solvers (numerical integration routines)

A number of optimization algorithms are available:

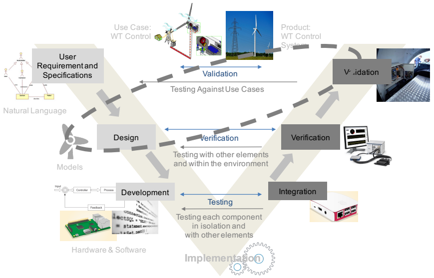
- Particle Swarm Algorithm (PSO)
- Genetic Algorithm (GA)
- Naïve method
- Knitro Algorithm





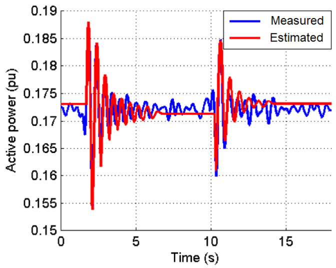
Model Validation:

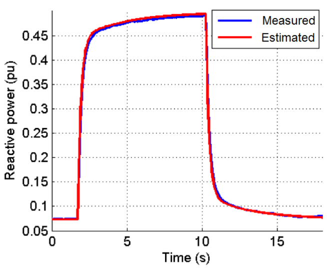
Methods and Tooling for Validating Power System Models

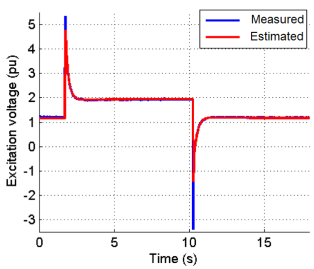


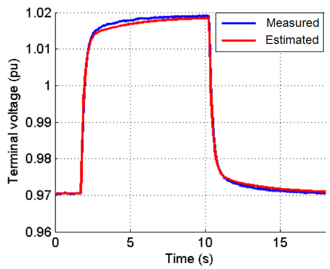
Video!

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





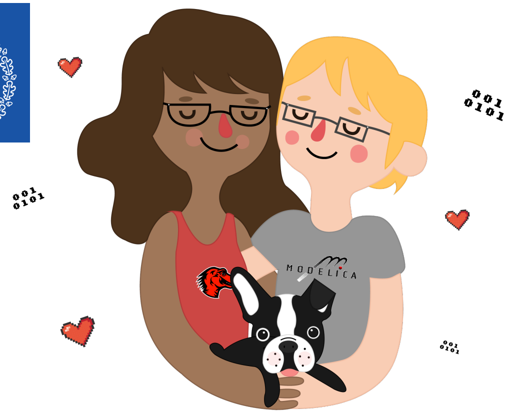


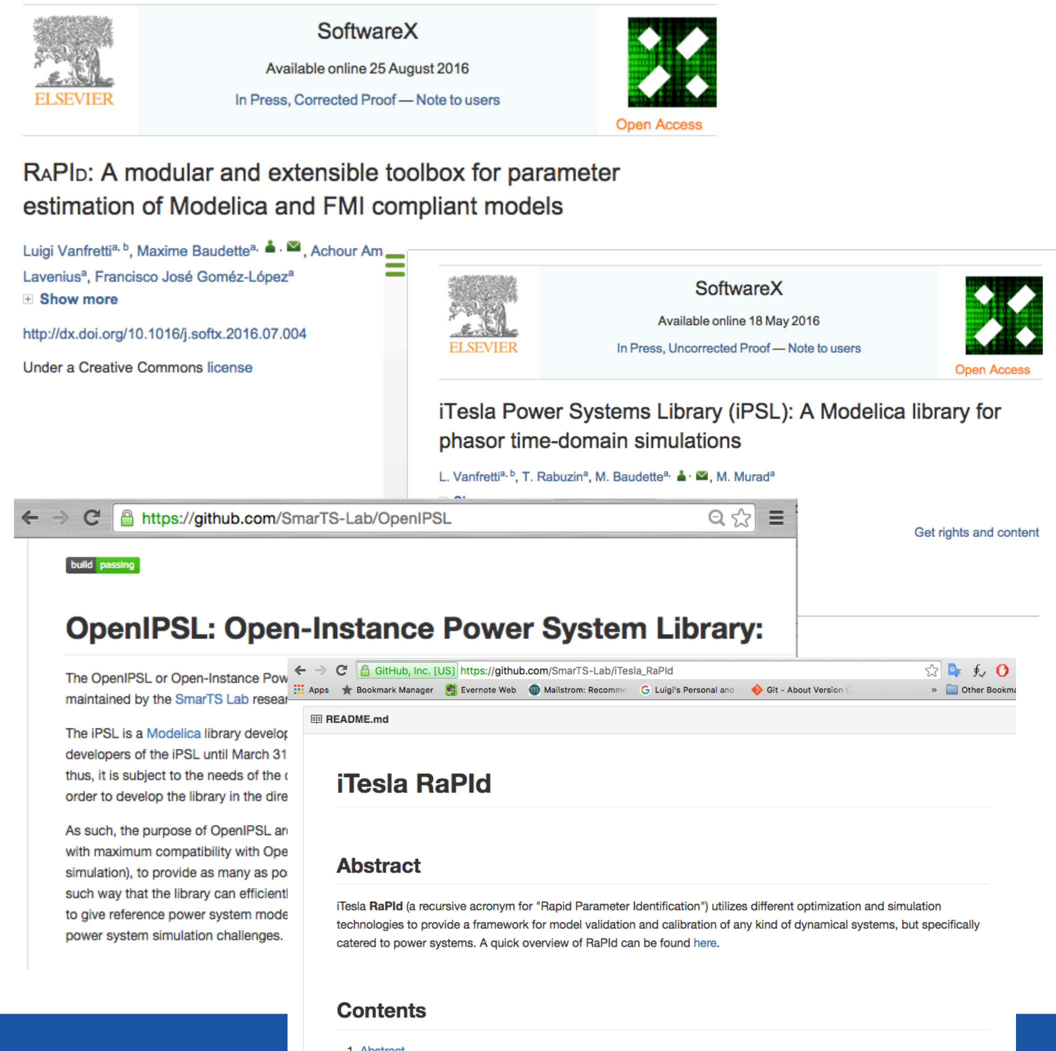


Contribution towards the MBSE **Foundations** in Cyber-Physical Power Systems

RaPId and OpenIPSL

Now Available as OSS!



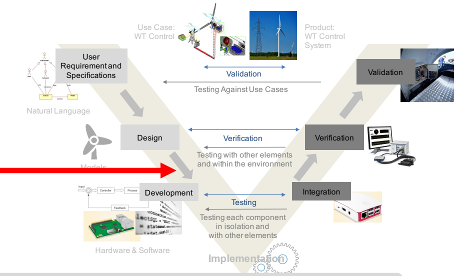


- Our work on **OpenIPSL** and **RaPId** has been published in an Open Access Journal, available on-line:
  - http://dx.doi.org/10.1016/j.softx.2016.05.001
  - http://www.sciencedirect.com/science/article/pii/S235271101630019X
- The **OpenIPSL** library can be found on-line at Github:
  - https://github.com/SmarTS-Lab/OpenIPSL
- The **RaPId** software can be found at:
  - https://github.com/SmarTS-Lab/iTesla_RaPId

… and more to come! See our Github accounts: https://github.com/SmarTS-Lab/
And coming soon with more synchrophasor-related applications: https://github.com/SmarTS-Lab-Parapluie

System Level Design:

Model Transformation **Advances** and Challenges



Advances – and our contribution to EU Standardization!

entsoe
Reliable Sustainable Connected
european network of transmission system operators for electricity

ABOUT ENTSO-E MAJOR PROJECTS PUBLICATIONS DAT

ENTSO-E WEBSITE > NEWS & EVENTS > EVENTS >
REGISTRATION FOR THE SIXTH ENTSO-E INTEROPERABILITY TEST "COMMON INFORMATION MODEL (CIM) FOR SYSTEM DEVELOPMENT

Registration for the sixth ENTSO-E Interoperability Test "Common Information Model (CIM) for System Development and System Operations" 2016 opened.

Use of Modelica in the Dynamics profile of the CGMES version 2.4

Version 2 - draft

31 January 2016

Common Grid Model Exchange Specification (CGMES)

Version 2.5

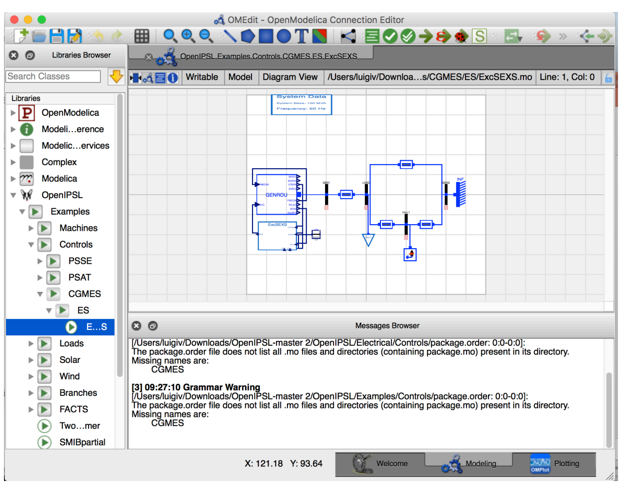
Draft IEC 61970-600 Part, Edition 2

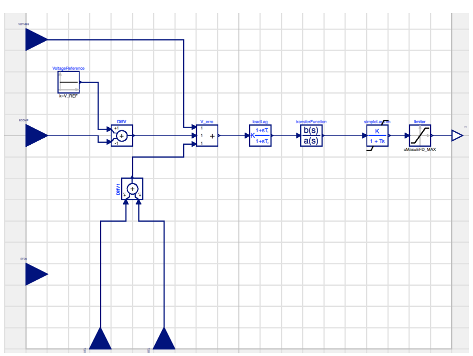
Annex F (normative)

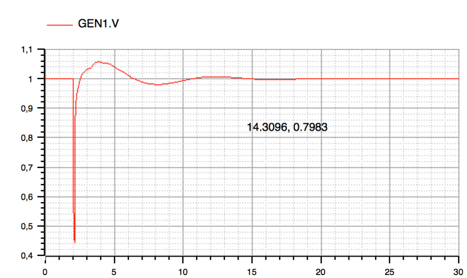
Use of Modelica in the Dynamics profile

- To demonstrate exchange of dynamics model following the implementation effort performed by a group of vendors. The use of models expressed in Modelica code will also be validated.

CGMES - ExcSEXS Model (Available in OpenIPSL)

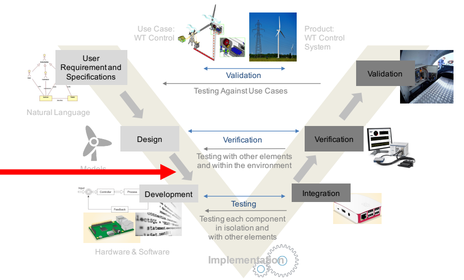




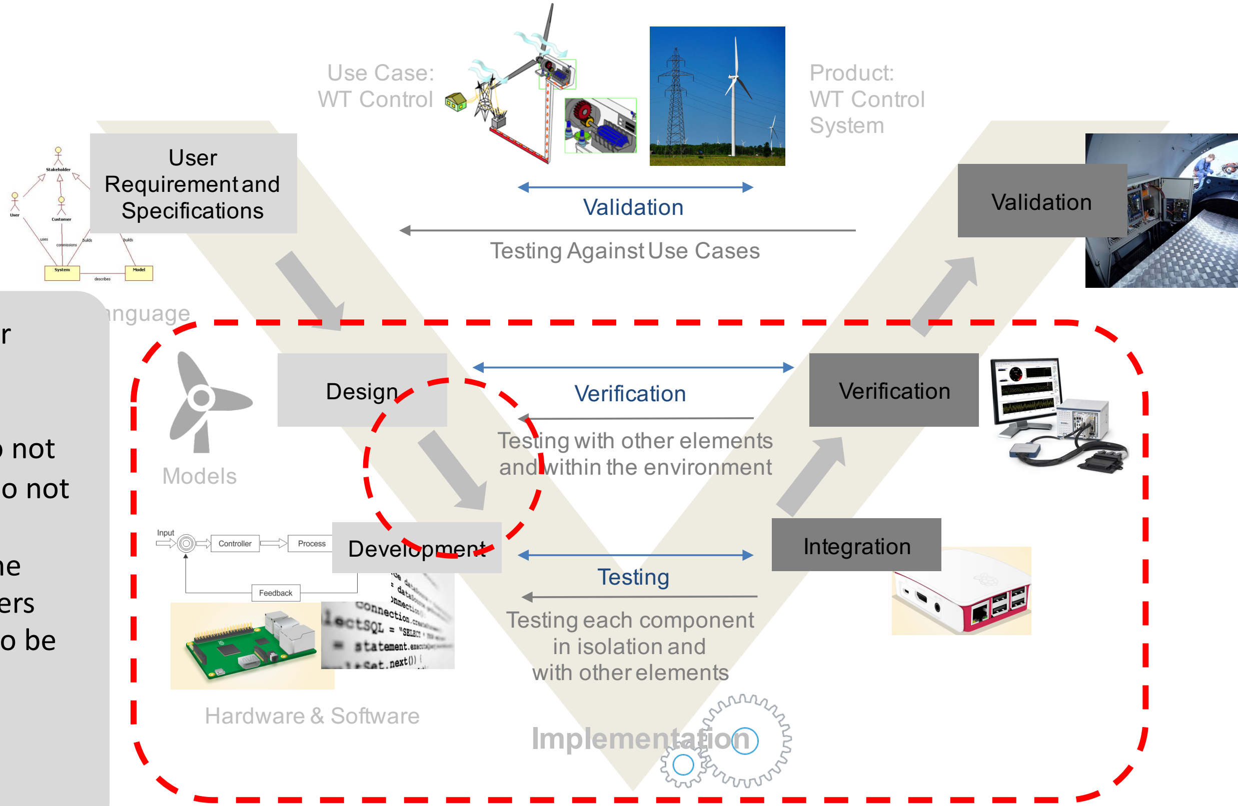


System Level Design:

Model Transformation Advances and **Challenges**



Challenge: Bottleneck in Model Transformation

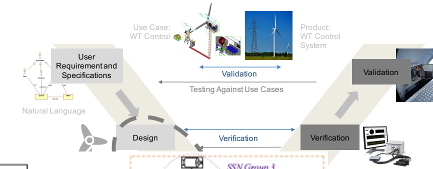


- CIM does not consider the requirement for support in model transformation for component-level design.
- Power system analysis and design tools do not support means for model exchange, and do not model/capture low-level device functions.
- There are still limitations for using real-time code generated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

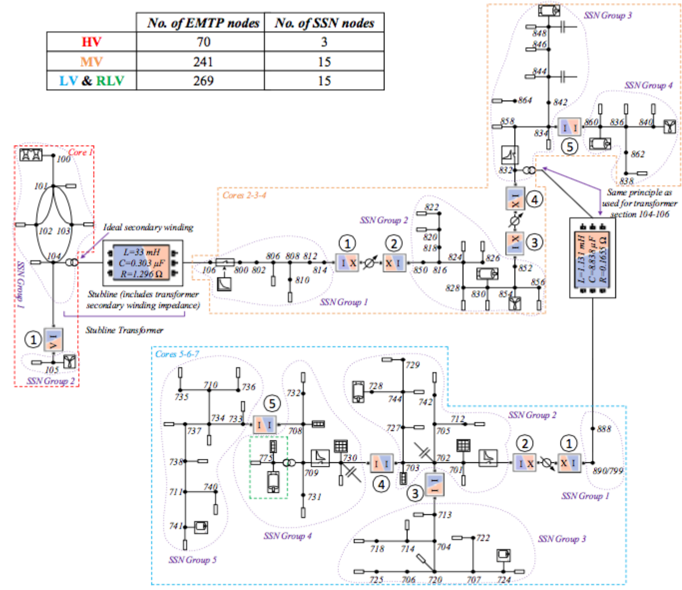
For the reminder of the work, we thus use a the typical Mathworks-based workflow for Modeling-Code Generation and Real-Time HIL simulation using a proprietary solution.

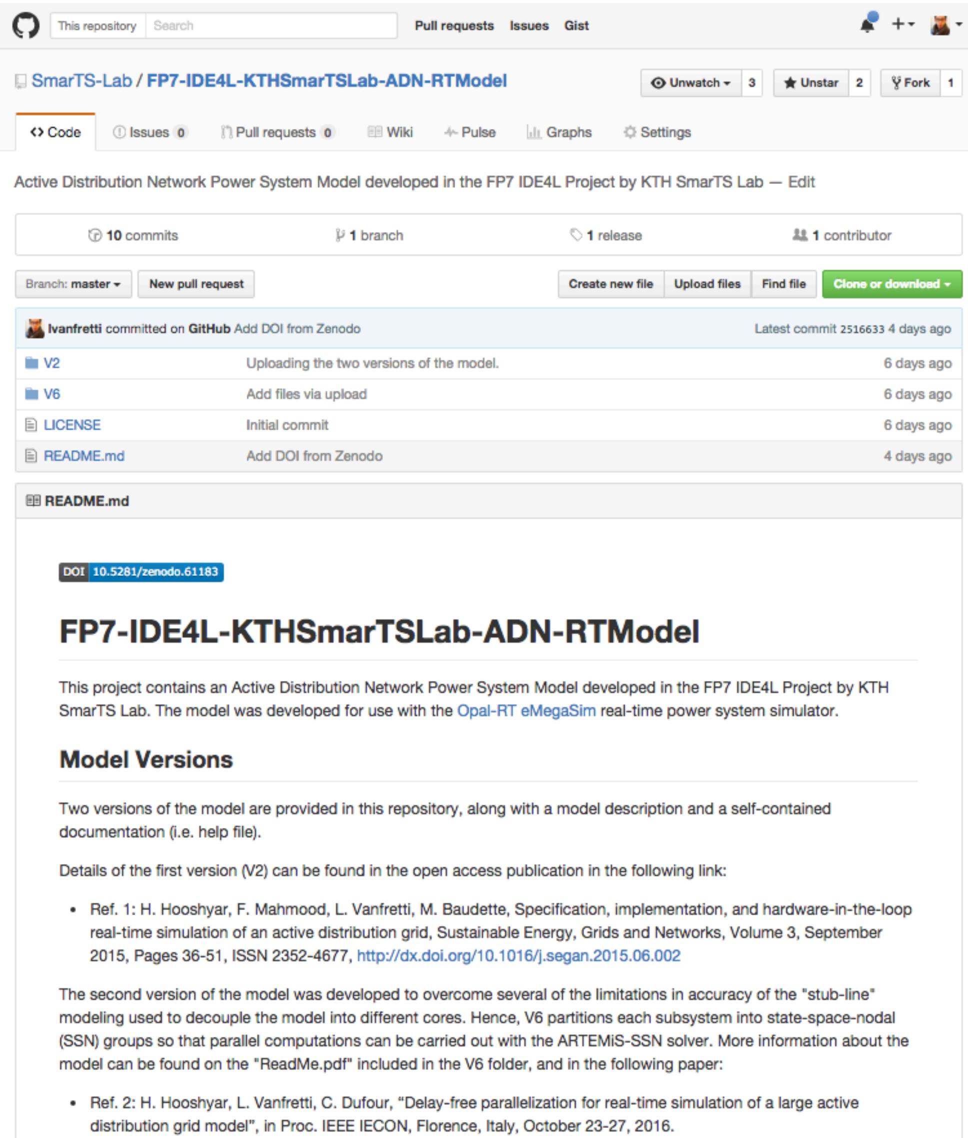
Modeling for Real-Time Simulation

for Synchrophasor Applications



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




DOI 10.5281/zenodo.61183

SmarTS-Lab / FP7-IDE4L-KTHSmarTSLab-ADN-RTModel

Active Distribution Network Power System Model developed in the FP7 IDE4L Project by KTH SmarTS Lab — Edit

10 commits | 1 branch | 1 release | 1 contributor

Ivanfretti committed on GitHub Add DOI from Zenodo — Latest commit 2516633 4 days ago

V2	Uploading the two versions of the model.	6 days ago
V6	Add files via upload	6 days ago
LICENSE	Initial commit	6 days ago
README.md	Add DOI from Zenodo	4 days ago

README.md

FP7-IDE4L-KTHSmarTSLab-ADN-RTModel

This project contains an Active Distribution Network Power System Model developed in the FP7 IDE4L Project by KTH SmarTS Lab. The model was developed for use with the Opal-RT eMegaSim real-time power system simulator.

Model Versions

Two versions of the model are provided in this repository, along with a model description and a self-contained documentation (i.e. help file).

Details of the first version (V2) can be found in the open access publication in the following link:

- Ref. 1: 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

The second version of the model was developed to overcome several of the limitations in accuracy of the "stub-line" modeling used to decouple the model into different cores. Hence, V6 partitions each subsystem into state-space-nodal (SSN) groups so that parallel computations can be carried out with the ARTEMiS-SSN solver. More information about the model can be found on the "ReadMe.pdf" included in the V6 folder, and in the following paper:

- Ref. 2: 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.

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.

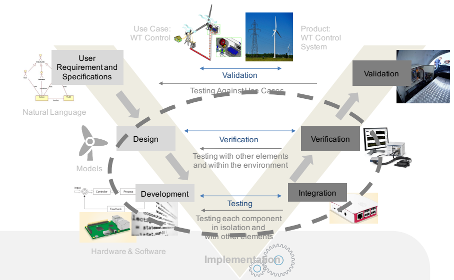
Soon in release of RT-Lab and ARTEMiS (ask Christian Dufour @Opal-RT).

All source files available in Github!

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

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

A Laboratory for Testing, V&V of for Synchrophasor Applications



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.

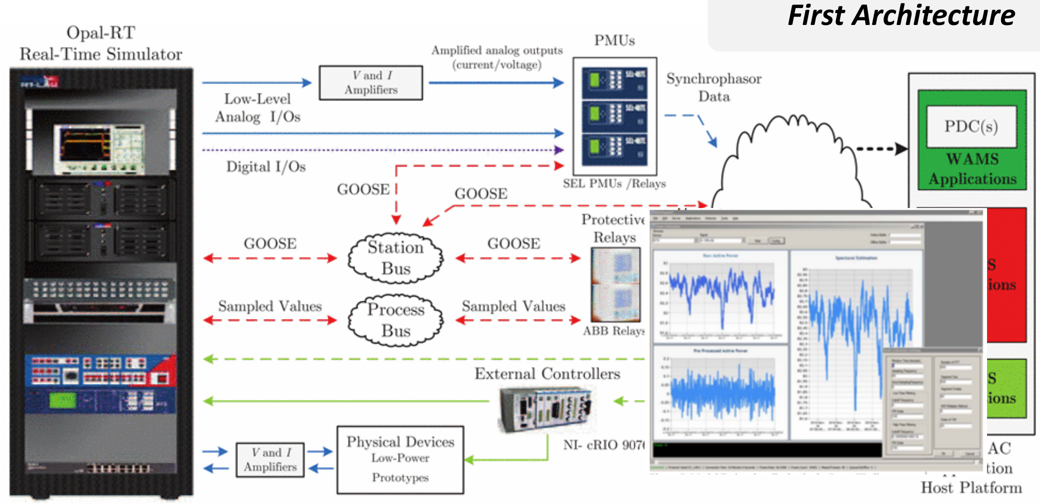
2011 - 2012

- 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

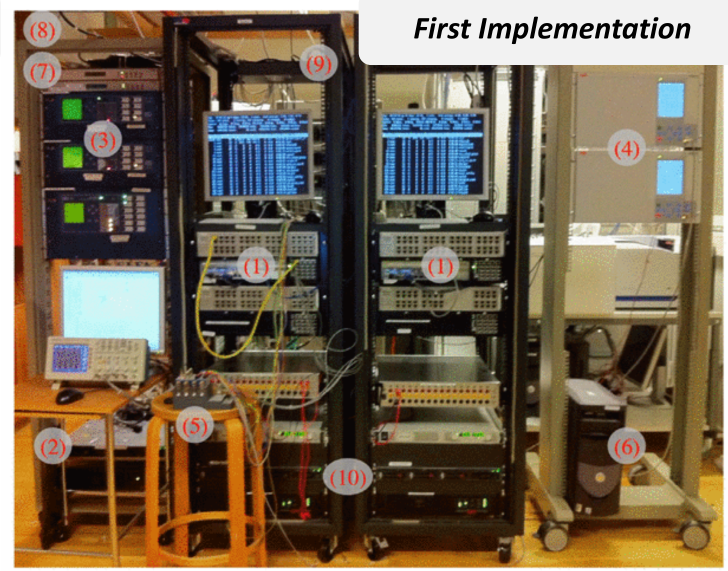
- M. Chenine, L. Vanfretti, et al, "Implementation of an experimental wide-area monitoring platform for development of synchronized phasor measurement applications," *2011 IEEE Power and Energy Society General Meeting*, San Diego, CA, 2011, pp. 1-8. doi: 10.1109/PES.2011.6039672

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.

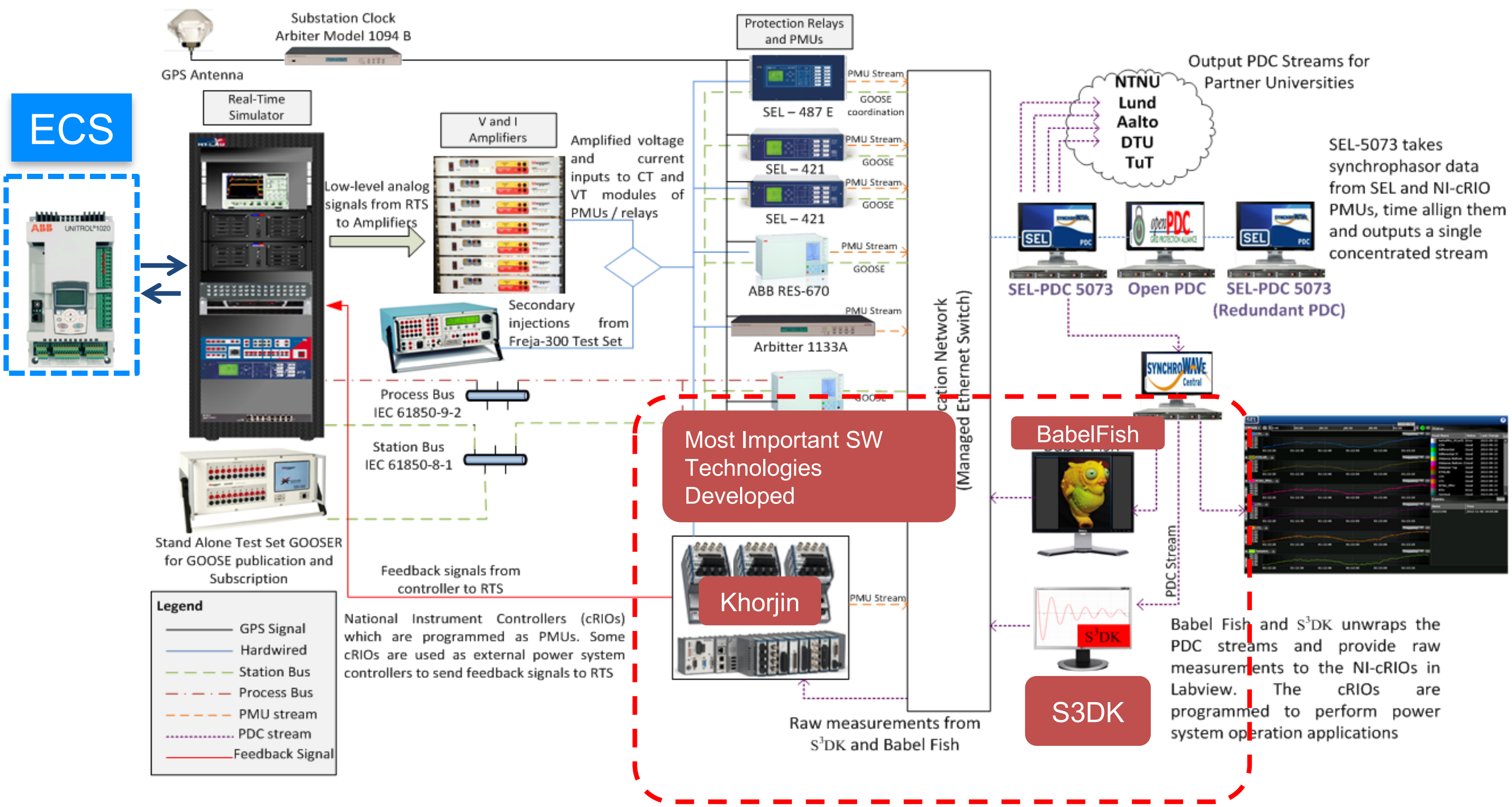
First Implementation



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

SmarTS Lab Architecture post 2012

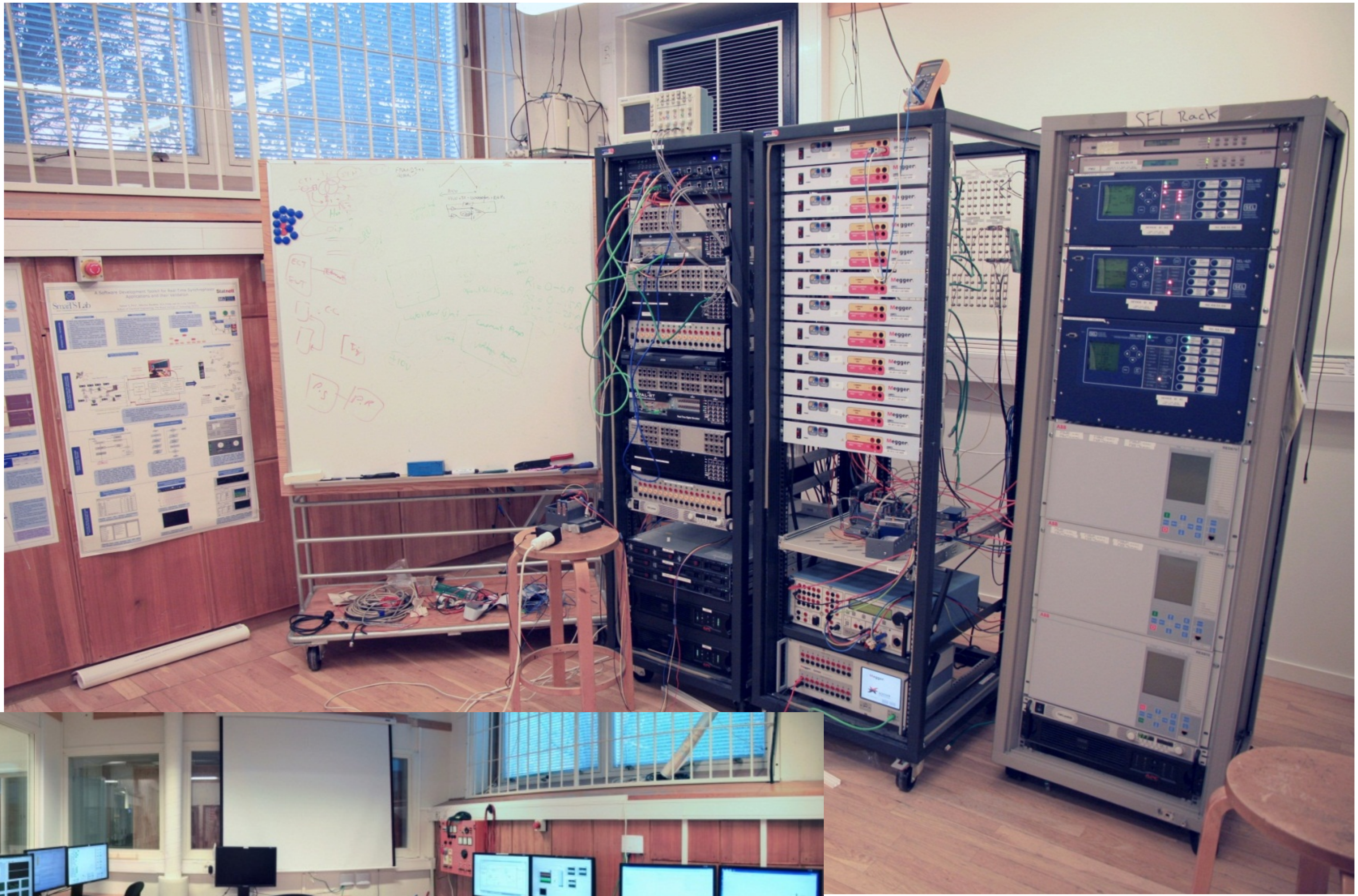
Smart Transmission Systems Laboratory



M. S. Almas, M. Baudette, L. Vanfretti, S. L⌀vlund 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

SmarTS Lab
Smart Transmission Systems Laboratory

Implementation

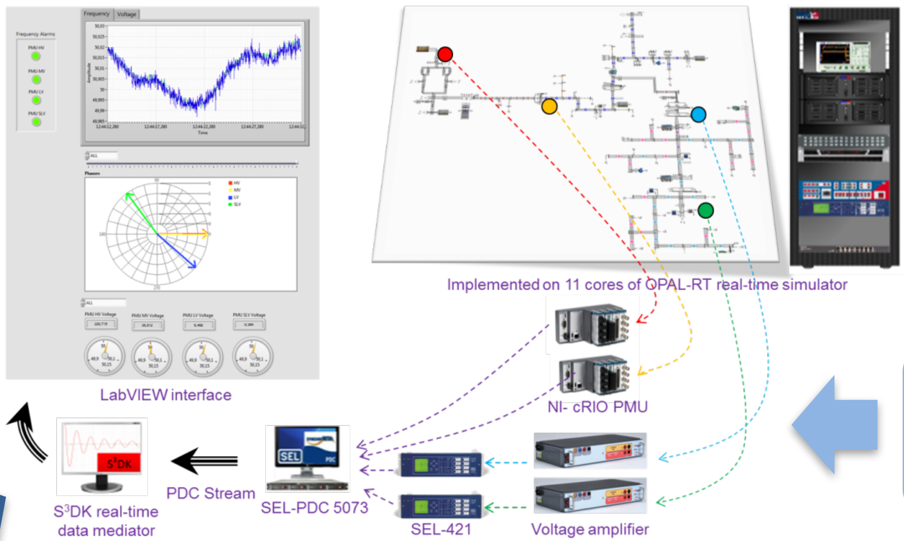


Testing, V&V: **Experimental** Work in the

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.

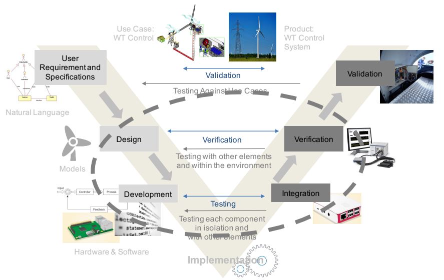


(2) The real-time simulation model is interfaced with phasor measurement units

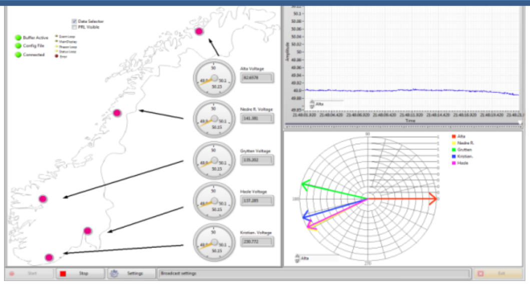
(4) A computer with development tools within the LabVIEW environment receives the PMU data.
All data acquisition is carried out using the corresponding standards (i.e. IEEE C37, IEC 61850).

(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

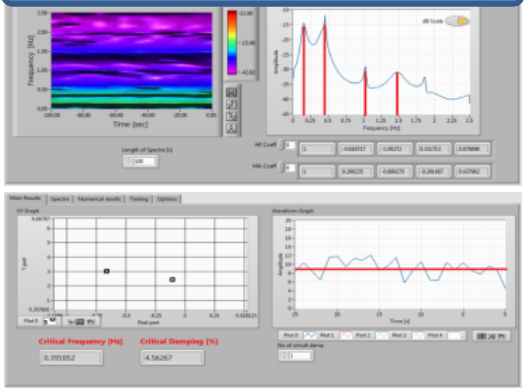


(1) Monitoring & Visualization

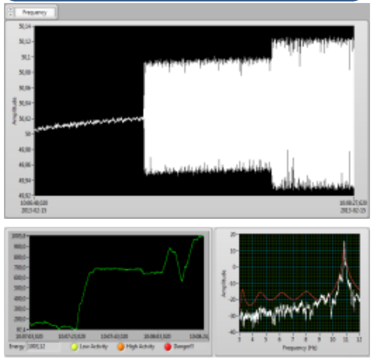


(2) Mobile Apps

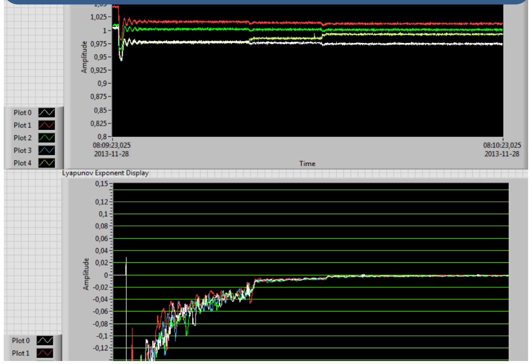
(3) Inter-Area Oscillation Assessment



(4) Forced Oscillation Detection



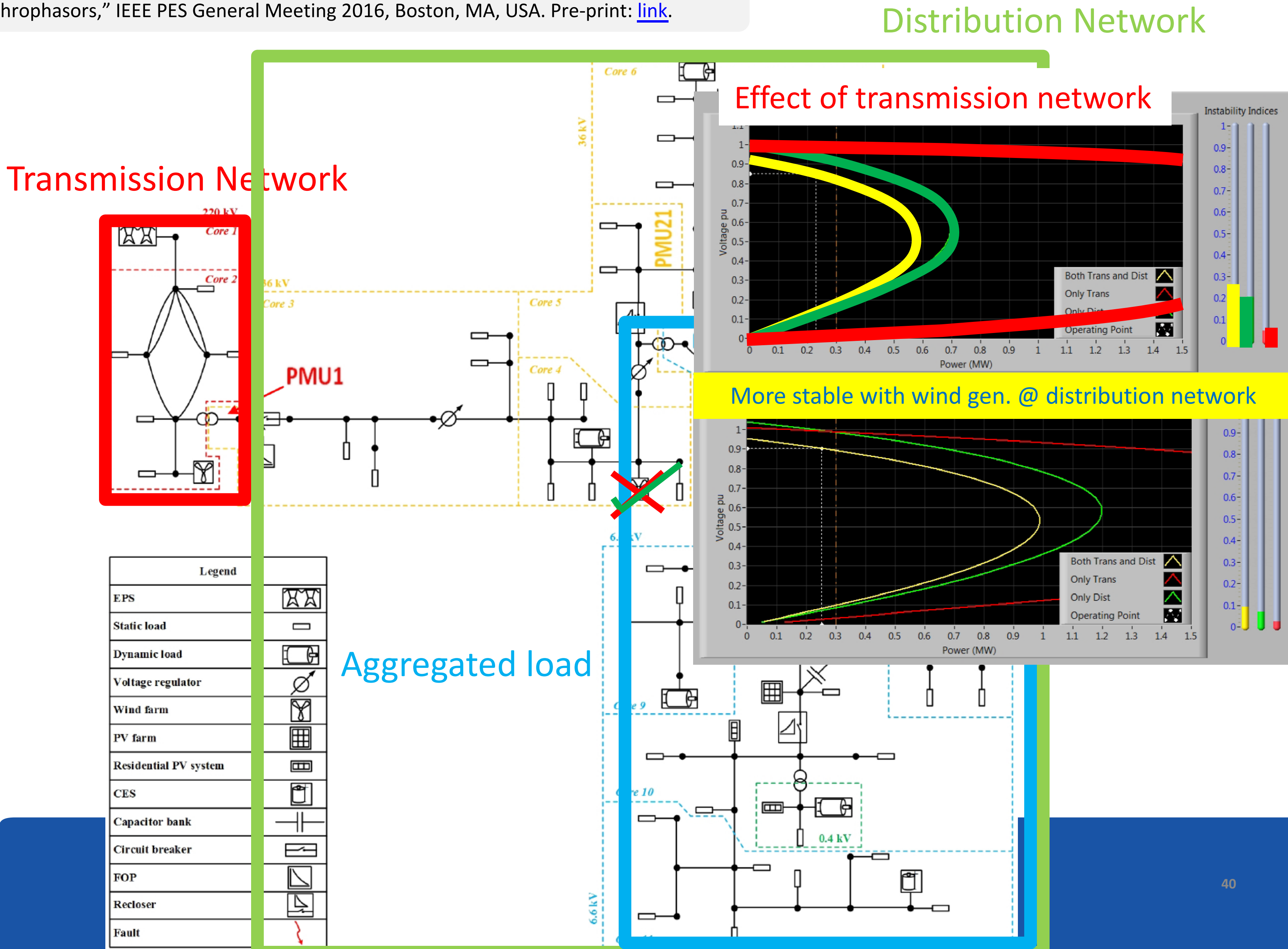
(5) Real-Time Voltage Stability Assessment



(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

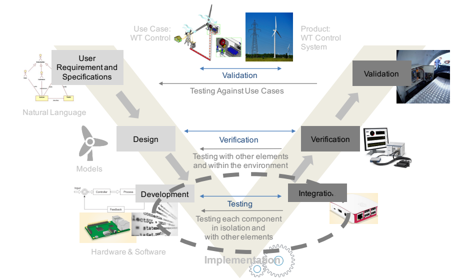
Decoupled Voltage Stability Assessment of Distribution & Transmission Networks

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.



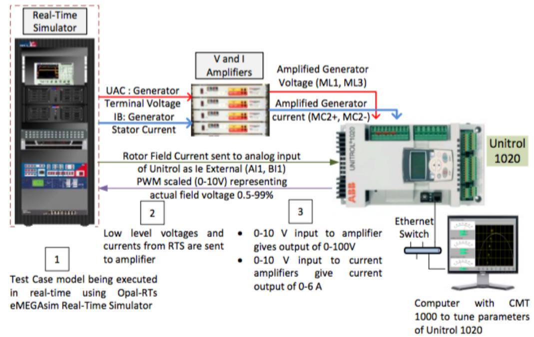
Component Design

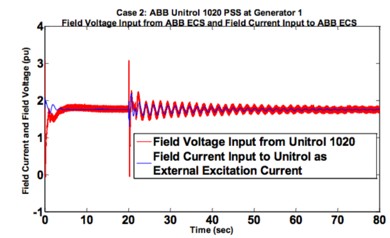
for Wide-Area Control Systems



(1) RT-HIL Assessment of ECS

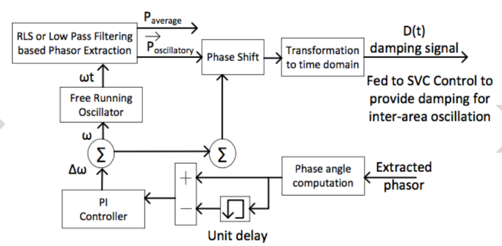
- Auto Mode: (Voltage regulation)
- Manual Mode: Field (Current Regulation)
- *PSS Functionality (Multi-Band PSS)*

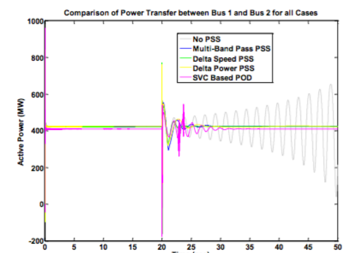




(2) Development of Damping Control Models (PSS) for RT-SIL

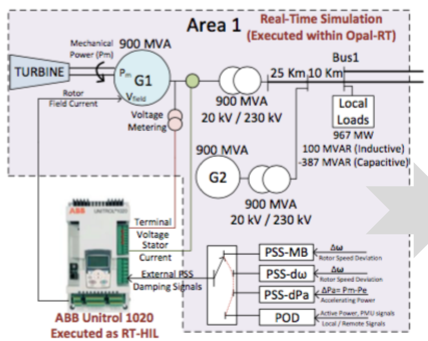
Stabilizers Δω, ΔPa, MB-PSS, and the **Phasor POD** where developed for SIL testing.

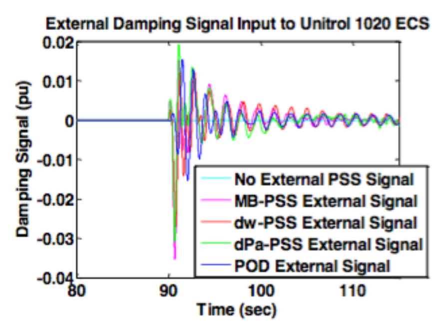


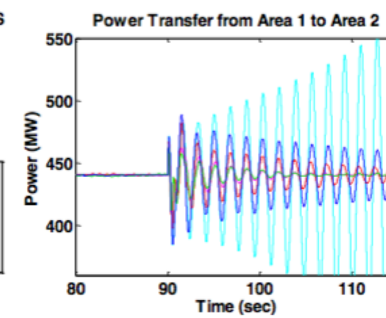


(3) Interfacing Control Models with ECS System

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







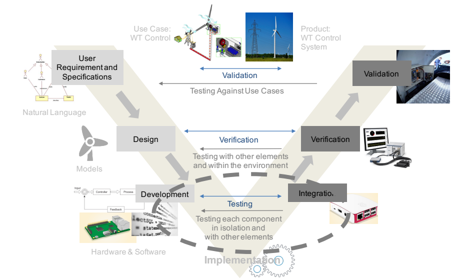
(1) M. S. Almas and L. Vanfretti, "Experimental performance assessment of a generator's excitation control system using real-time hardware-in-the-loop simulation," *IECON 2014 - 40th Annual Conference of the IEEE Industrial Electronics Society*, Dallas, TX, 2014, pp. 3756-3762. doi: 10.1109/IECON.2014.7049059

(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



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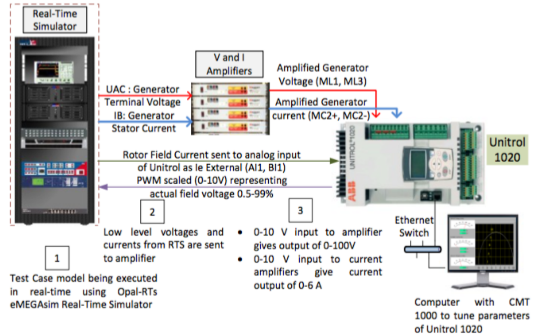

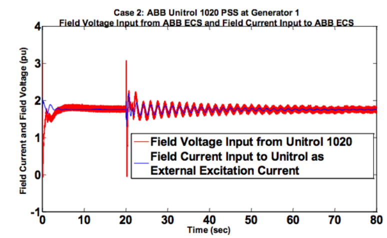

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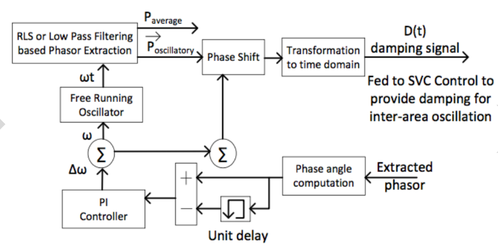

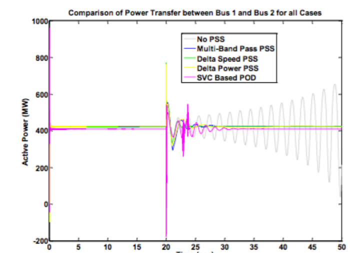

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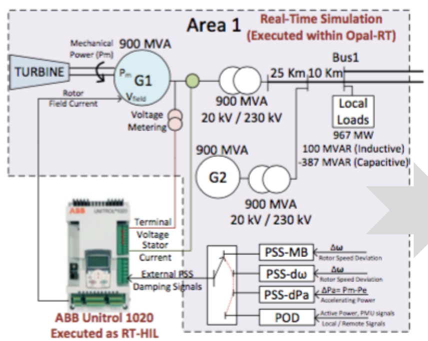

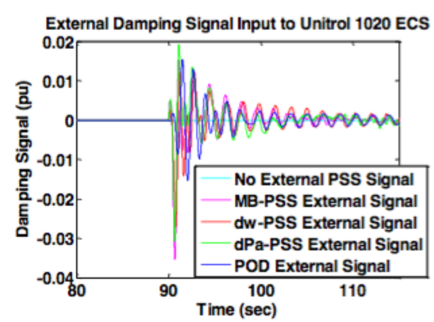

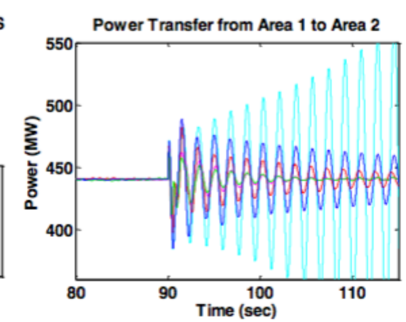

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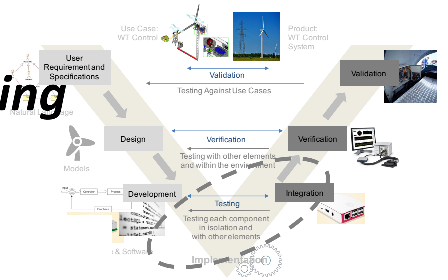
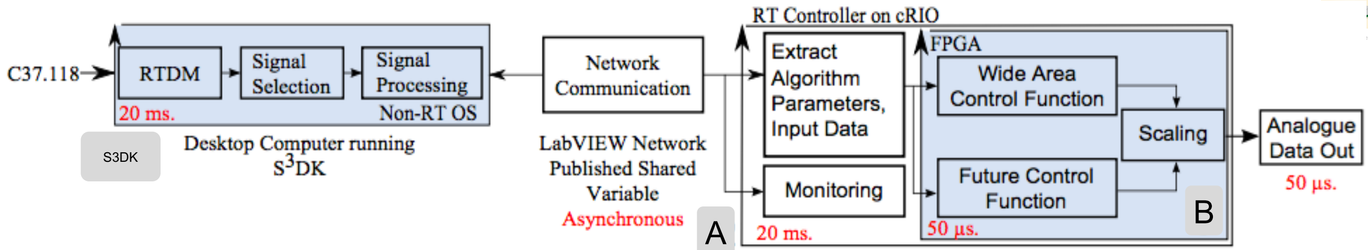
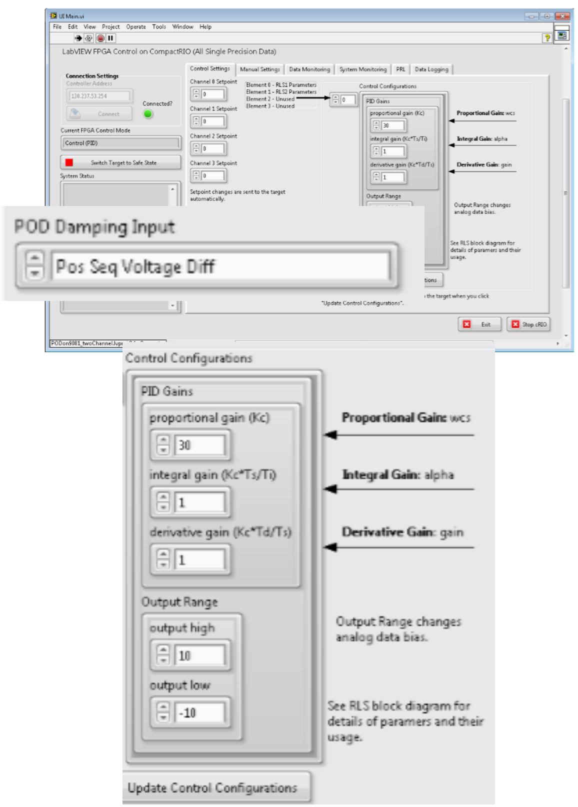
Component Implementation, Rapid Prototyping and Testing

for Wide-Area Control Systems

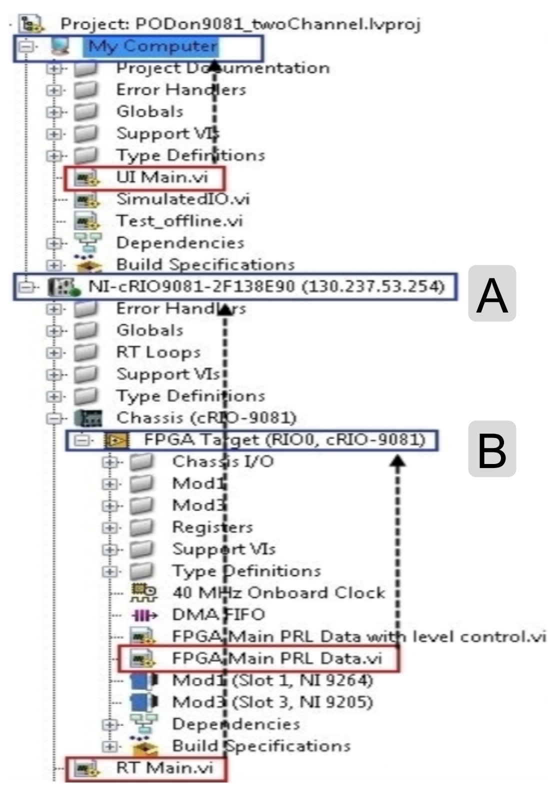




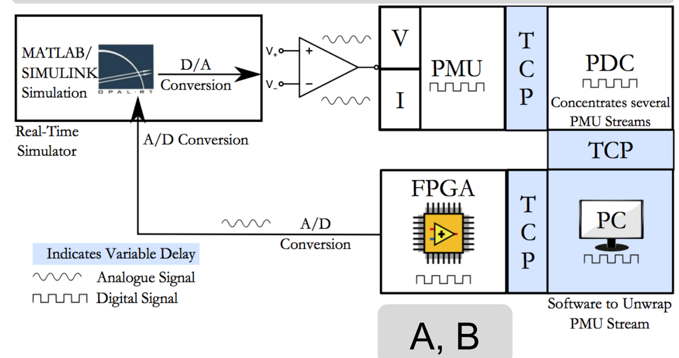
Controller Configuration Interface

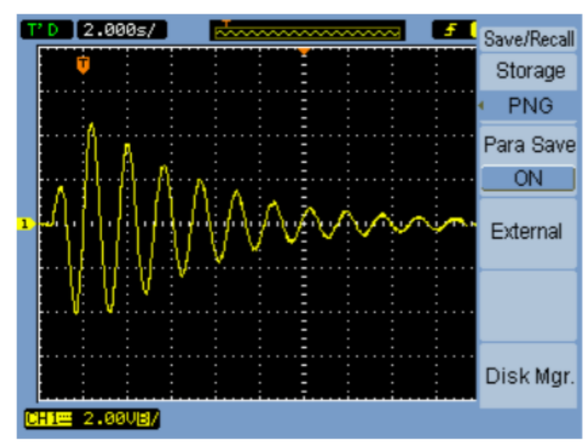


Software-Hardware Layers



Testing



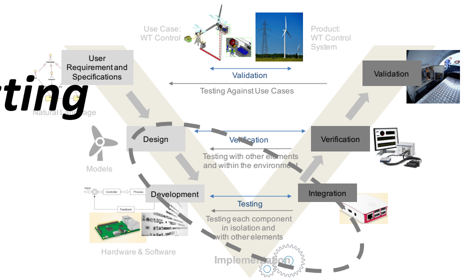


E. Rebello, M. S. Almas and L. Vanfretti, "An experimental setup for testing synchrophasor-based Damping control systems," *Environment and Electrical Engineering (EEEIC), 2015 IEEE 15th International Conference on*, Rome, 2015, pp. 1945-1950. doi: 10.1109/EEEIC.2015.7165470
E. Rebello, L. Vanfretti 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

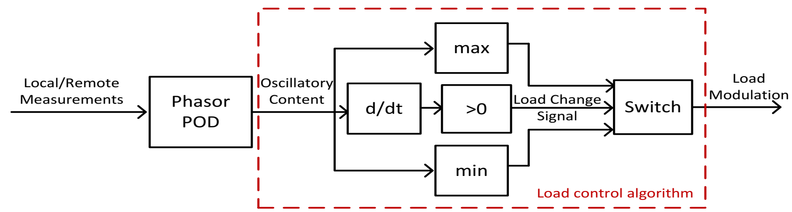
exploiting the availability of models for **new applications**

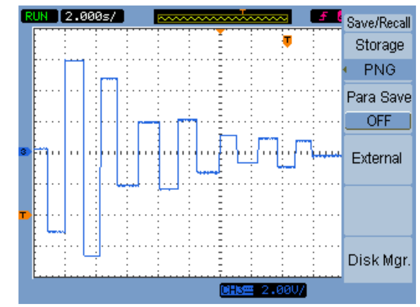


Idea:

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

The load control algorithm developed



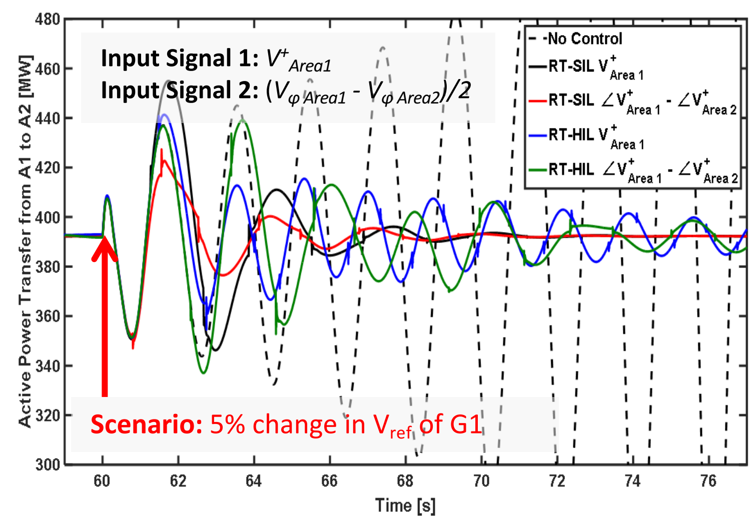


Testing:

- 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.**



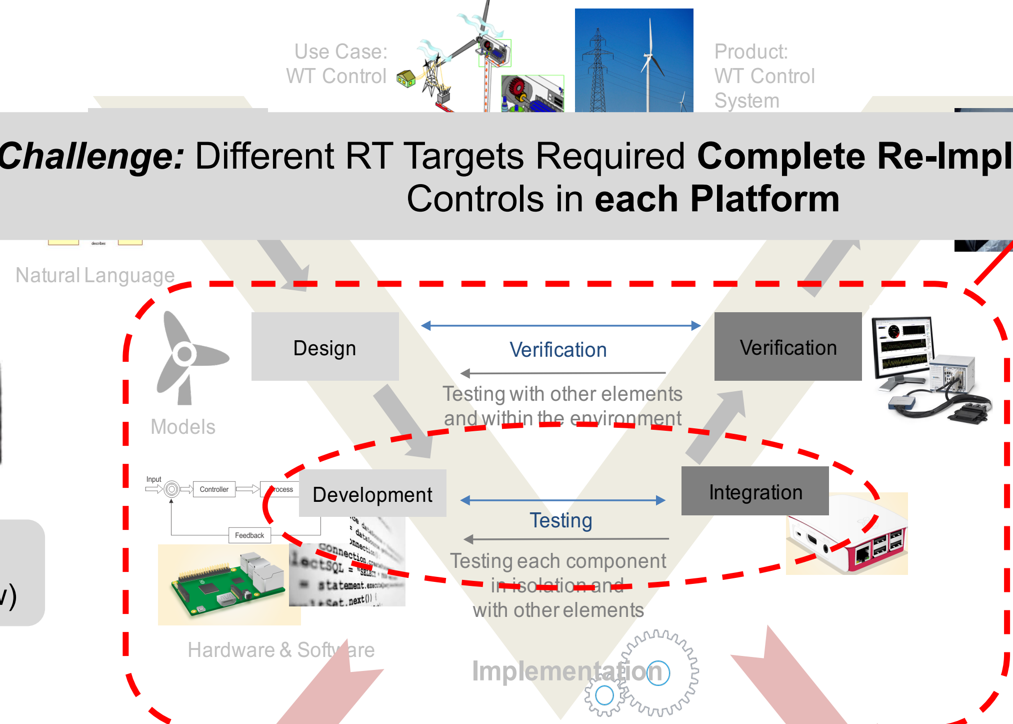
G. M. Jonsdottir, M. S. Almas, M. Baudette, M. P. Palsson and L. Vanfretti, "RT-SIL performance analysis of synchrophasor-and-active load-based power system damping controllers," *2015 IEEE Power & Energy Society General Meeting*, Denver, CO, 2015, pp. 1-5. doi: 10.1109/PESGM.2015.7286372

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

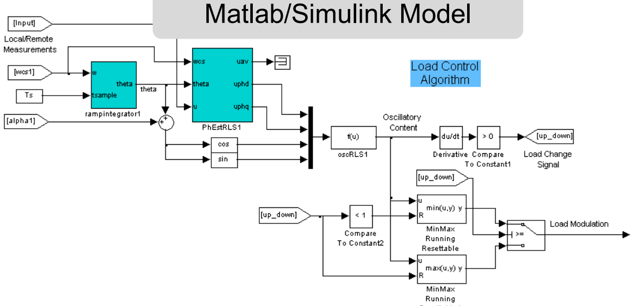
Challenge: Different RT Targets Required **Complete Re-Implementation** of Controls in **each Platform**



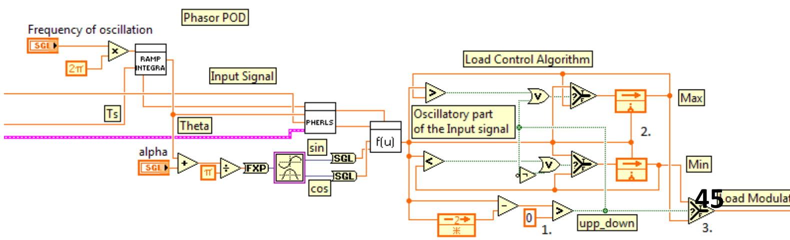
Opal-RT Target
(Mathworks-Based Workflow)

NI-cRIO Target
(LabView Workflow)

Matlab/Simulink Model

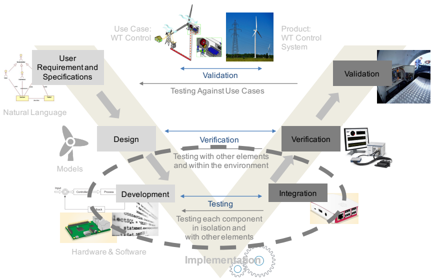


LabView FPGA Model



Networking Protocol Tools and Source Code

for Synchrophasor Applications – Real-Time Control Example

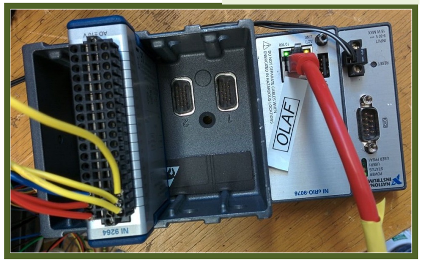


S3DK

Khorjin

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

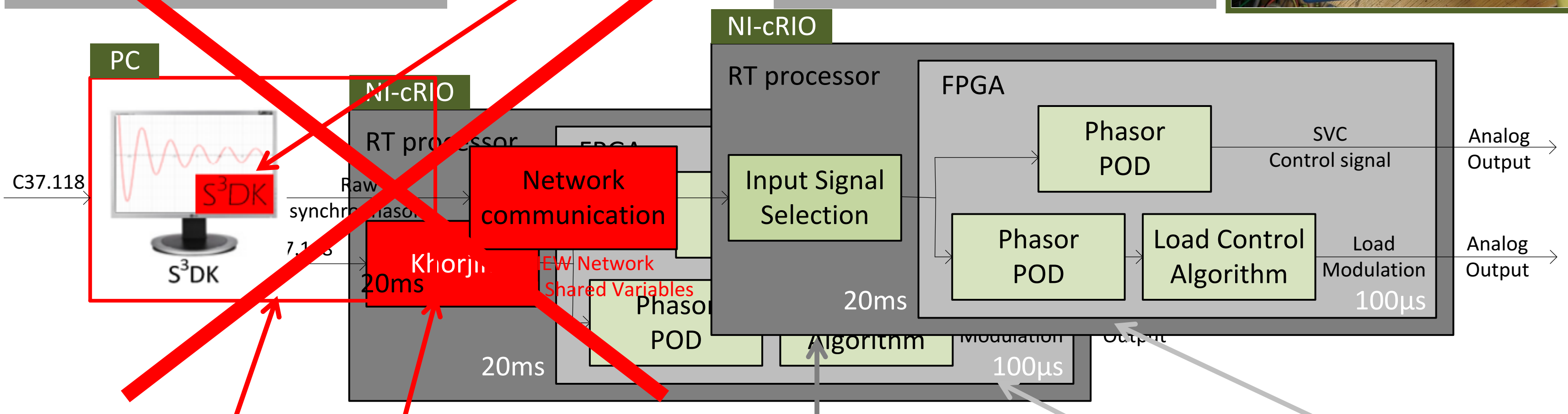
NI-cRIO



The hardware prototype controller design

Three level design

Two level design



Real-Time Software VI

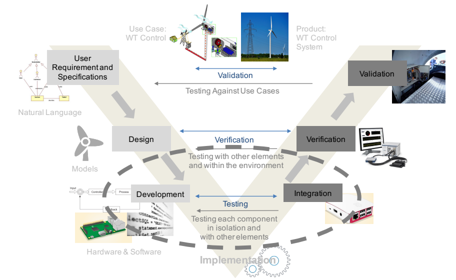
- Runs on the real-time processor of the cRIO.
- Khorjin used to unwrap PDC stream.
- Input signal selected

Core FPGA Software VI

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

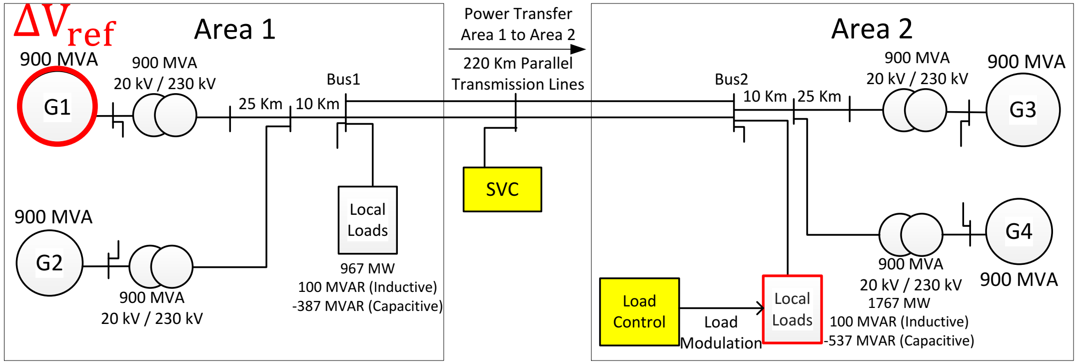
Networking Protocol Tools and Source Code

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:

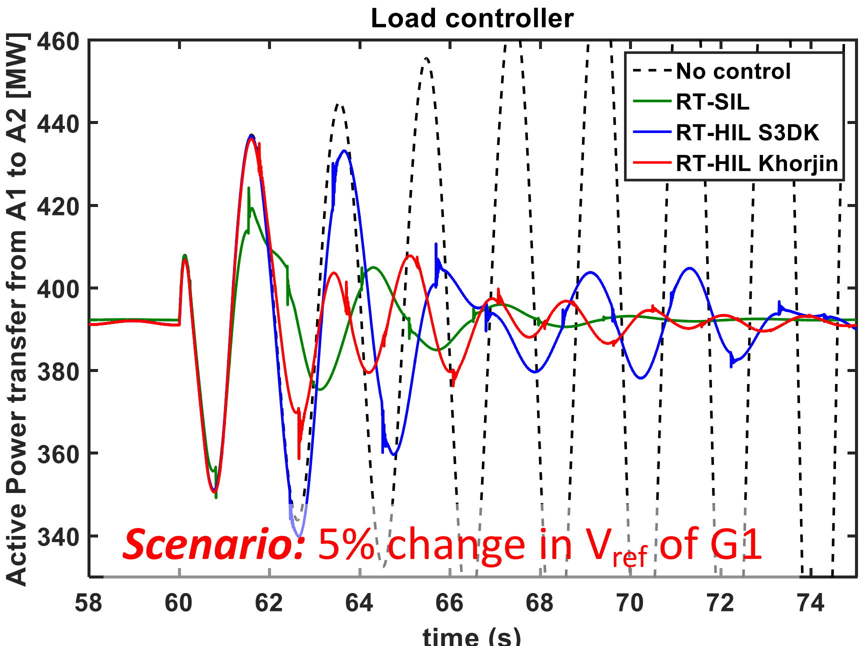
S3DK: *200-500 ms* **Khorjin:** *50-76 ms*

In RT-HIL using **S3DK**

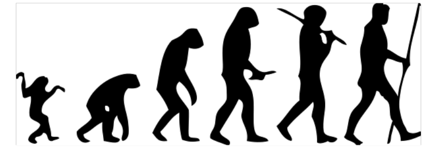
- ○ *Blue line far from green line.*
- ○ Larger delay (S3DK) can only run in a non-deterministic computer (... under windows).
- ○ PDC adds to latency.

In RT-HIL using **Khorjin.**

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



SmarTS Lab OSS Tools Evolution

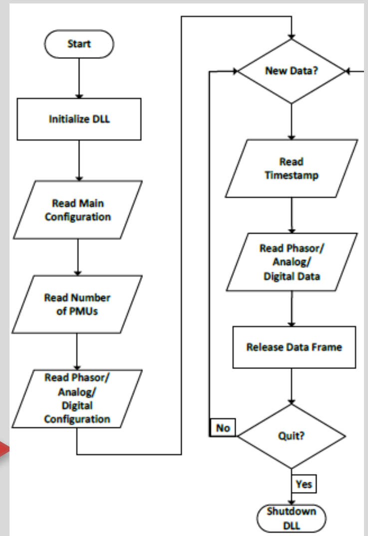


BabelFishV1 (LabView & C++)

Reading Module (C++) | Interfacing Module (Active X) | GUI Module (LabView)

- 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)

CMD
PMU_CFG-2_PACK
NamesofPMUs Elements
PMU_DATA_PACK

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

Khorjin (C++)

C37.118.2 Module
IEC 61850 Mapping
61850-90-5 Module

- 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

Khorjin: Will be available at GitHub end of 2016.

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.

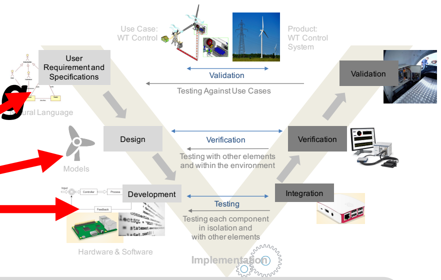
S.R. Firouzi, L. Vanfretti, A. Ruiz-Alvarez, F. Mahmood, H. Hooshyar, I. Cairo, “An IEC 61850-90-5 Gateway for IEEE C37.118.2 Synchrophasor Data Transfer,” IEEE PES General Meeting 2016, Boston, MA, USA. Pre-print: link.

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.

G.M. Jonsdottir, E. Rebello, S.R. Firouzi, M.S. Almas, M. Baudette and L. Vanfretti, “Audur – Templates for Custom Synchrophasor-Based Wide-Area Control System Implementations,” SoftwareX, in preparation, 2016.

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.

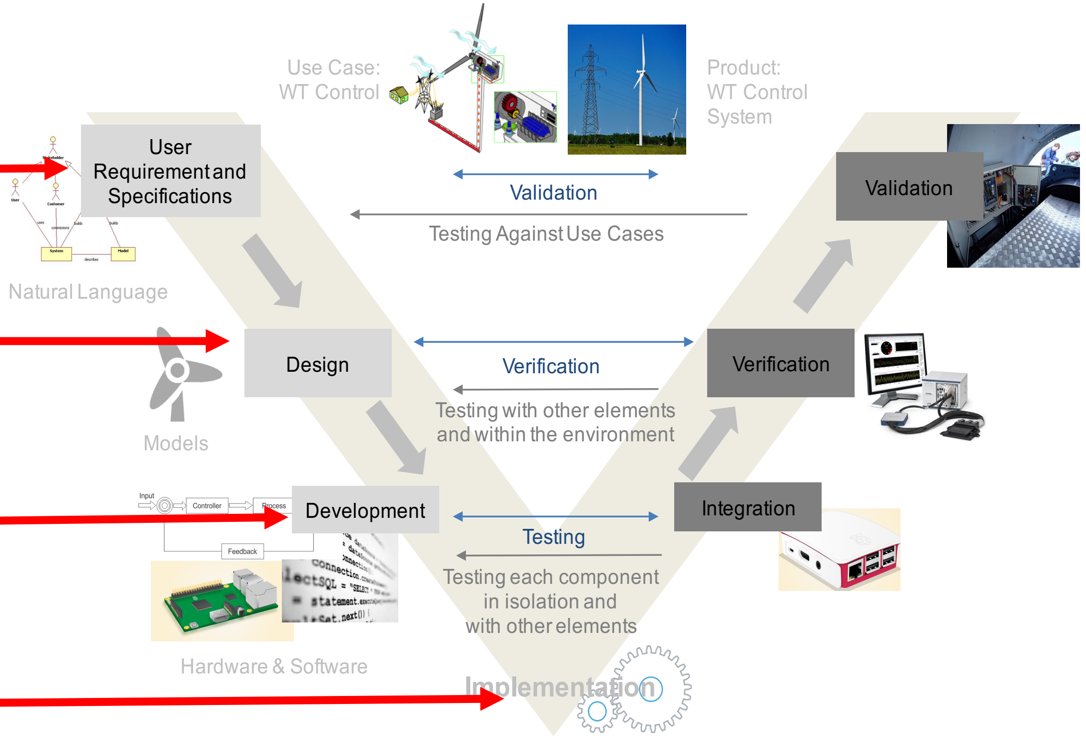
Through SGAM, but need to *create* CIM profile

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

Software Models with ICT Behavior

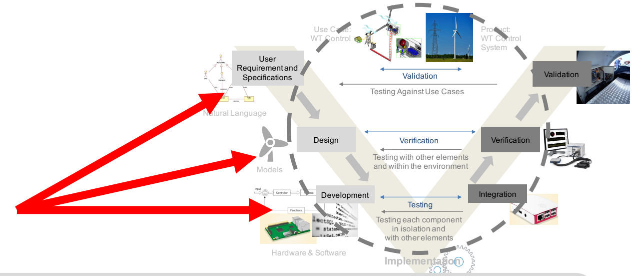
Network Protocol Client/Server Source

(with some help from Khorjin, maybe!)



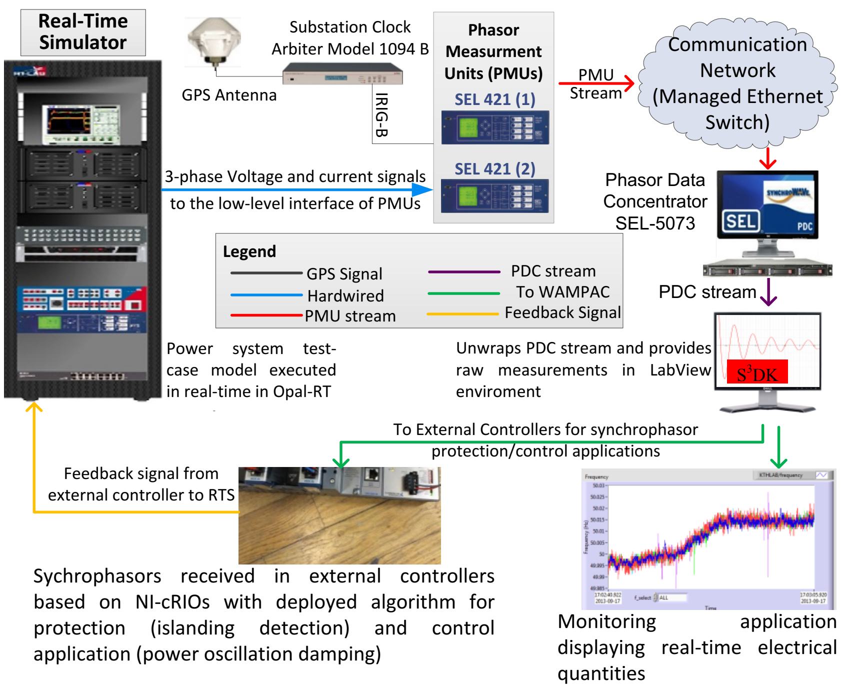
Verification and Validation

for Timing System-Dependent Applications

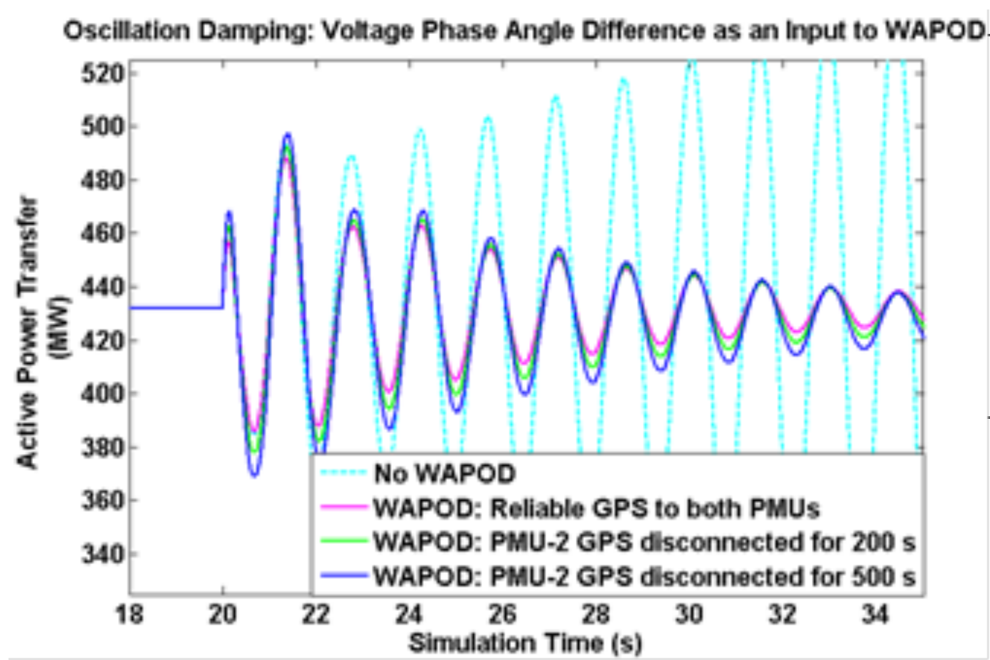


Challenge: Joint (integrated) modeling, simulation and TV&V including ***Timing Systems*** through the whole Model & Simulation - Based Systems Engineering Framework.

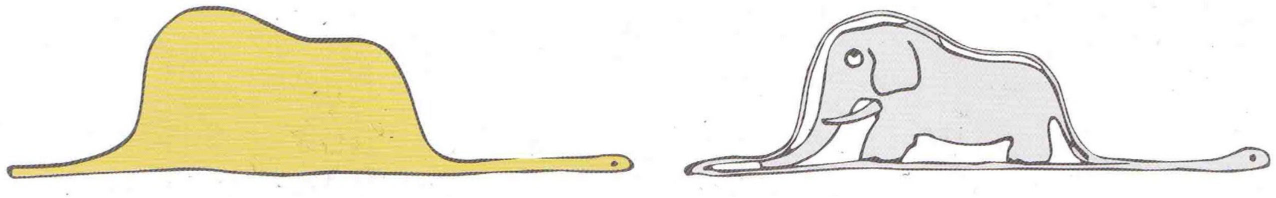
Case Study: GPS Vulnerability and Impact on Synchrophasor Applications



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.



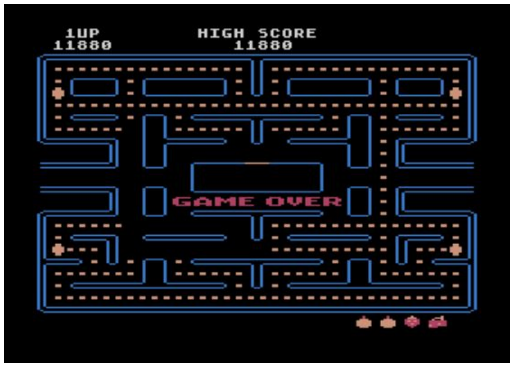
The Socio-Economical Perspective

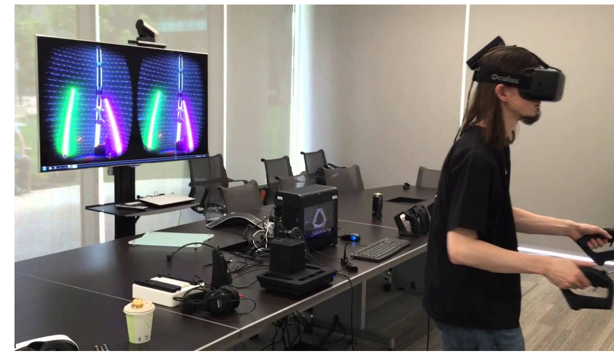
What do **society** needs to think about w.r.t. *autonomous* CP power systems?

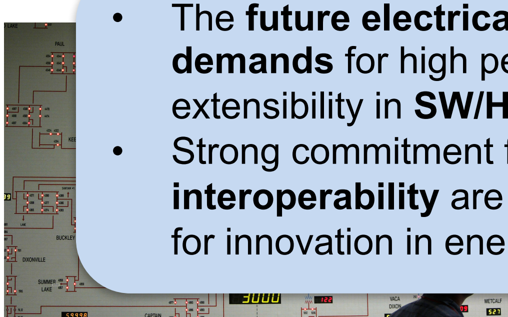
The Socio-Economical Perspective? Evolution of different technological markets

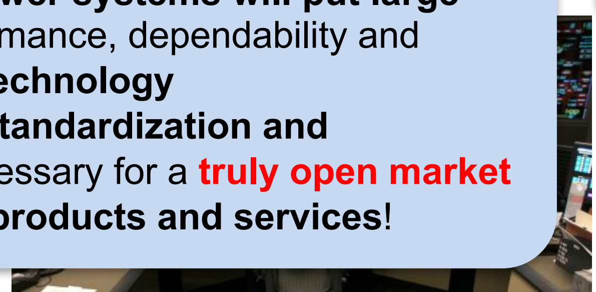
What do **society** needs to think about w.r.t. <u>*autonomous*</u> CP power systems?

1980s	1990s-2000s	Today





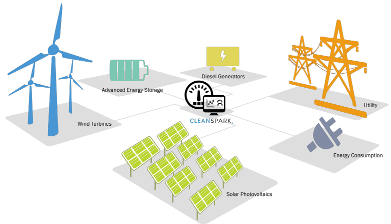




- The **future electrical power systems will put large demands** for high performance, dependability and extensibility in **SW/HW technology**
- Strong commitment for **standardization and interoperability** are necessary for a **truly open market** for innovation in energy **products and services**!

… otherwise we might stay totally 80s-90s

The Socio-Economical Perspective?
Technology Governance



Socio-Economic Aspects

Societal Needs and Requirements

How to provide society with **"autonomy"** for developing smart grids?

Knowledge Build-up **Know-how**

Techno-Economic Aspects

What **technology** is needed for Smart Grids?

Technical Requirements

New Technology

Develop
Use
Adapt

Necessary Condition: Technology may provide means of "autonomy" for the use and management of a smart grid. This means we may achieve an autonomous "technical" system.

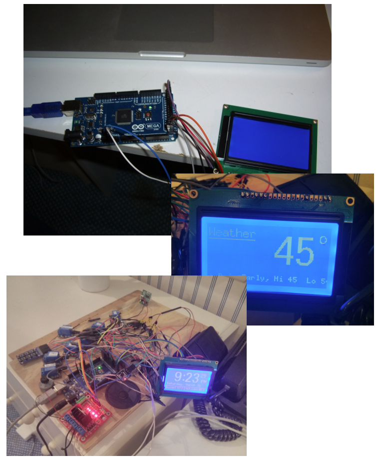
Sufficient Condition: Technology must be developed within ***a framework that provides autonomy in the means of its creation and adaptation***.
Otherwise the full autonomy of communities cannot be fully guaranteed.

Should the model for technology governance satisfy both necessary and sufficient conditions?
Is democratization of technology of interest and even possible?

The Socio-Economical Perspective: New Technology Development Models.

What do **society** needs to think about w.r.t. *autonomous* CP power systems?

Home Automation



Home Automation (HAMMOND)

Goal:

To have a central, yet modular and expandable home automation system. I will use an Arduino Mega tethered to a Raspberry Pi to sense and control home environment parameters like temperature, lights, blinds, and miscellaneous appliances. The Raspberry Pi will provide the more processor-

https://paulsieradzki.wordpress.com/projects/home-automation-hammond/

Smart Meter

OpenEnergyMonitor

Get Started | Hardware | Emoncms | Resources | Labs | Online Store

Home

Raspberry Pi

With the addition of an RFM69Pi expansion board, the Raspberry Pi is able to receive data via wireless from other **OpenEnergyMonitor modules** such as an **emonTx** or **emonGLCD**. A Raspberry Pi can forward data to an emoncms sever, and/or log data locally to an SD card or hard drive.

Personal Open source Business Explore Pricing Blog

openenergymonitor / **emonhub**

forked from TrystanLea/emonhub

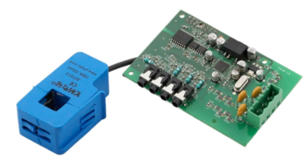
Code | Issues 1 | Pull requests 0 | Pulse | Graphs

Python service linking and decoding input to MQTT & Emoncms

KICKSTARTER

SmartPi - Turn your Raspberry Pi into a SmartMeter

https://www.kickstarter.com/projects/1240982104/smartpi-turn-your-raspberry-pi-into-a-smartmeter



Why are these grass root solutions allow for fast and – seem, apparently –efficient development?

Open hardware: How and why it works

Applying open source concepts to physical objects

Jeffrey M. Osier-Mixon
Technical Writer
MontaVista Software, Inc.

IBM

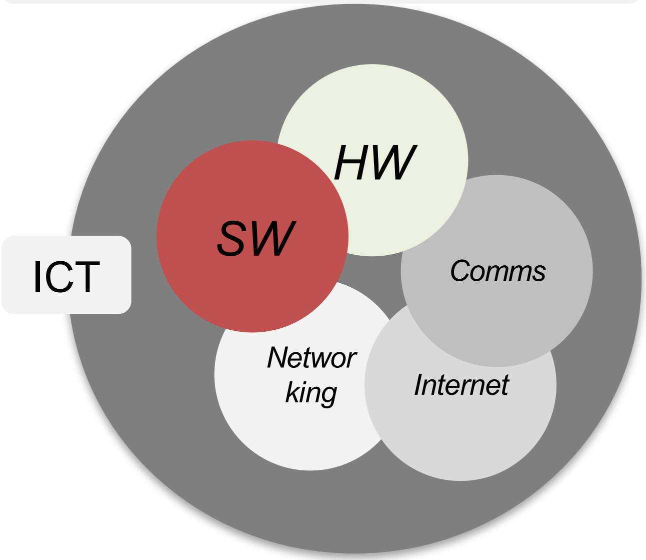
- The potential to "develop the unexpected," as Peter Brown said, by using parts and products in ways never envisioned by their original creators.
- **it is eminently possible to use something free to create something better and then freely pass that benefit on to others.**
- That is what the open source movement is about: using the power of collaboration to accelerate innovation!

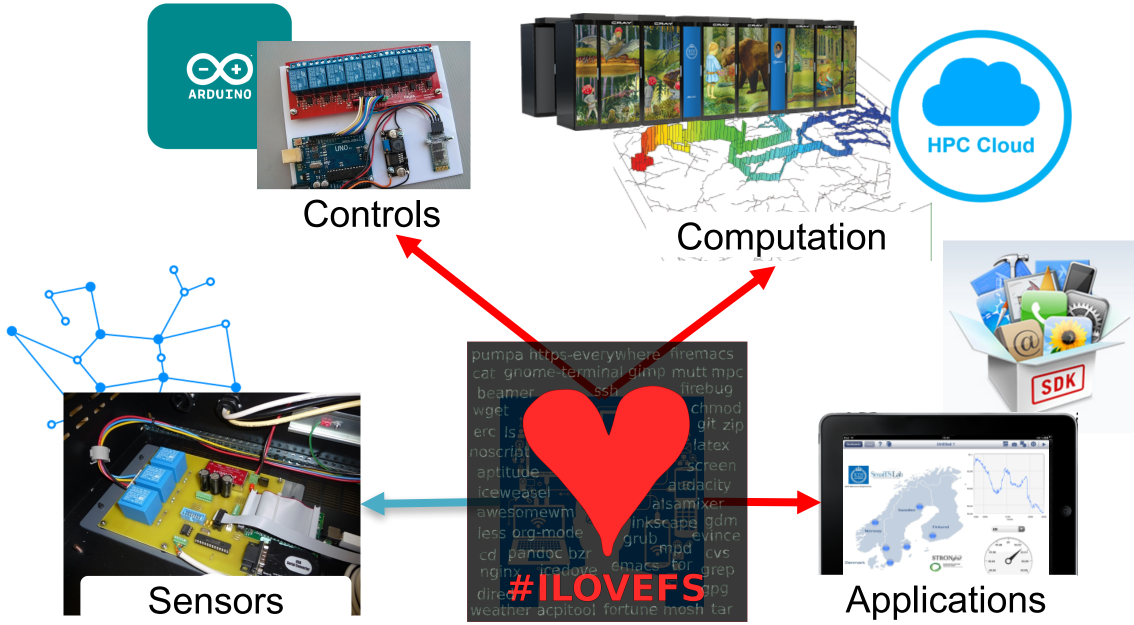
This is an example of Democratization of technology through COTS (Commercial Off-The-Shelf) Technologies using an Open Software and Hardware Foundation.

The Socio-Economical Perspective: in the era of pervasive software

What do **society** needs to think about w.r.t. *autonomous* CP power systems?

Multiple Domains in
Cyber-Physical Power Systems





Software is now even encapsulating entire Devices and Systems

Software is becoming pervasive:
we need a long term strategy for developing and maintaining the foundational building blocks involved in technology used in critical infrastructure!

We need a **governance model** for that.

We need to define "autonomy" in a ***software defined world.***

The Socio-Economical Perspective: The Role Software in the “Cyborg” World

What do **society** needs to think about w.r.t. <u>*autonomous*</u> CP power systems?

He speaks with RLS Steeper on a weekly basis, working with them to test new software for the hand. They use his feedback to upgrade and refine the product.

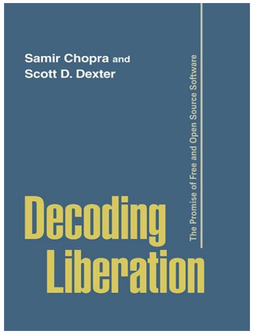
Figure 1. iStan

Figure 2. Muse software

Compromising a Medical Mannequin
by University of South Alabama’s William Bradley Glisson, Todd Andel, Todd McDonald, Mike Jacobs, Matt Campbell and Johnny Mayr

Listening to Brain Microcircuits for Interfacing With External World—Progress in Wireless Implantable Microelectronic Neuroengineering Devices

Political and Philosophical Implications for ”Autonomy” in the Cyborg-Future



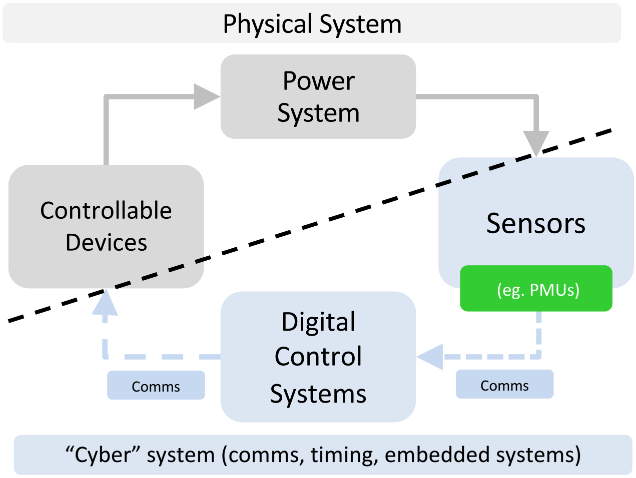
Code may advance and counteract political imperatives: in this context, free software **is not just a question of managing technology but of determining the contours of our selves and the politics we choose**. (pp. 145)

The ability to control one’s interactions with the machine *is not a specialized, esoteric concern, but* ***is a core freedom in the cyborg world.*** *(pp. 165)*

The degree to which software code is accessible, manipulable, and alterable, **is precisely the degree to which we maintain our autonomy**, our freedom, our very humanness. (J. McWilliams, 2013)

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!**

Thank you!

SmarTS Lab
Smart Transmission Systems Laboratory

- Questions?
- Our group's website:
- https://www.kth.se/en/ees/omskolan/organisation/avdelningar/epe/research/smart-transmission-systems-laboratory-smarts-lab-1.627203

The scientific man does not aim at an immediate result.
He does not expect that his advanced ideas will be readily taken up.
His work is like that of the planter - for the future.
His duty is to **lay the foundation for those who are to come, and point the way.**
(*Nikola Tesla*)

- Plan:
- Slide about title of workshop
  - Link to:
    - work of joseph stiglitz and other
      - The great divide
      - Learning communities
    - Other: FOSS promise, Cyber-Society
    - MBSE why this methodology and tooling has the potential of better knowledge transfer etc
      - John Baras material on manufacturing

    - Open Science
- Slide about the title of my Talk including
  - Cyber-physical system
  - How terribly slow it has been, few companies, etc.

- MBSE:
  - Testing & Verification
  - Validation
- Challenges and OpportunitieS:
  - HLA: Standards and who drives them. Need for OSS foundation.
  - Design space exploration: open standard, language implementations, and model-exchange
  - Code-Generation and COTS: COTS and OSS – hwat is happening now with the miliary industry
  - Methodologys for Testing, V&V
- Conclussions

Evolution of Measurement Data Sources

- How have the data sources evolved?
  - Analogy with how we have changed tracking our weight!

Analog Scale

- One measurement,
- at very uncertain time and
- with limited precision

Digital Scale v.1.

- More points,
- At more certain time (internalclock with limited time accuracy),
- and better precision in weigth measurement
- Measurements only available locally

Digital Scale v.2.:

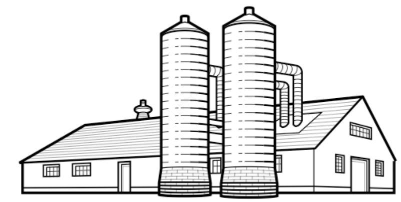
- More measurements of different **variables** available
- **Adds connectivity and some networking but data lives in a SILO:**
- only used in one/few computers
- with only the vendor's software)

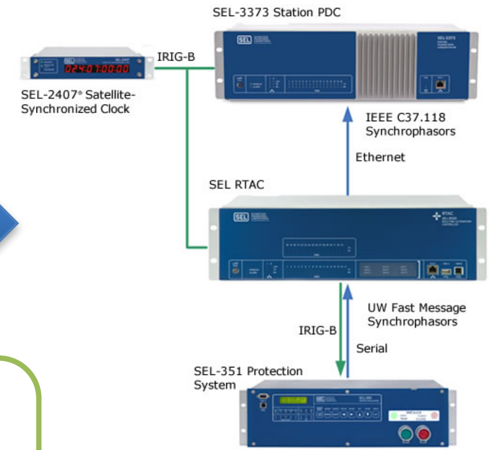
Smart Digital Scale

- Fully **networked** (Bluetooth, WiFi, over IP Network.
- Full data **connectivity**: accessible from SmartPhone, computer.
- **Data integration in a platform. Data no longer lives in SILOS:** (Apple Health)
- **The scale is secondary, it's all about the app!**
- Data is displayed in App
- Data can be correlated with other health data sources (e.g. Band)

Evolution from Analog Meters to PMUs

- How have power system monitoring sources evolved?



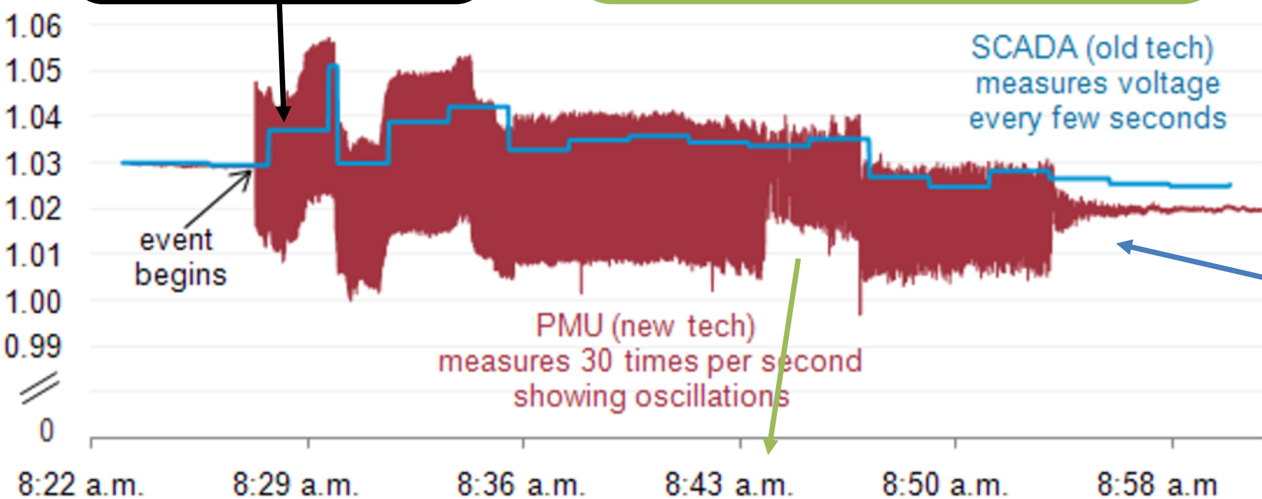


Analog:
One point, at very uncertain time and limited precision

Digital RTU and SCADA:

A few points, within an uncertain time window, and better precision.

Limited networking and connectivity.



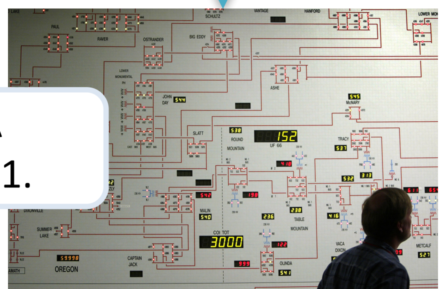
PMU
- A lot of points, at a lot of places
- At exact GPS stamped times, and with more accurate precision
- with many measured and derived variables

- Has better **connectivity, but data lives in SILOS:**
- Historical data locked-in to vendor's database
- Real-time data difficult to exploit outside the vendor's system

Evolution of the Control Room

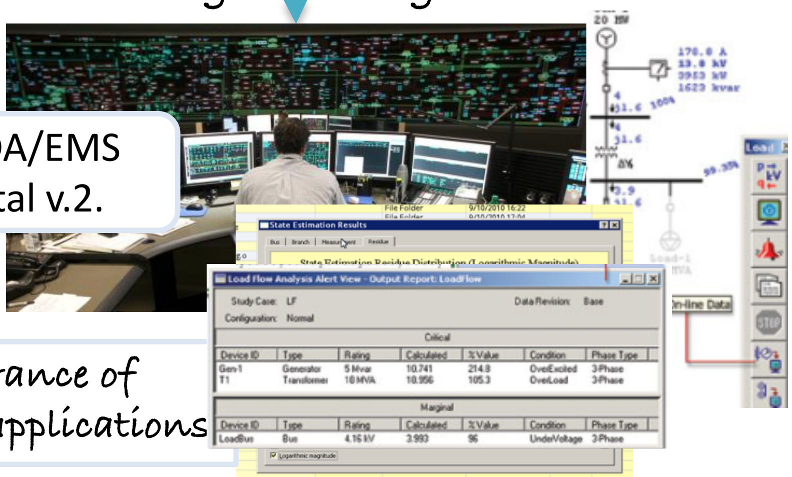
Analog Tech.

From analog to digital



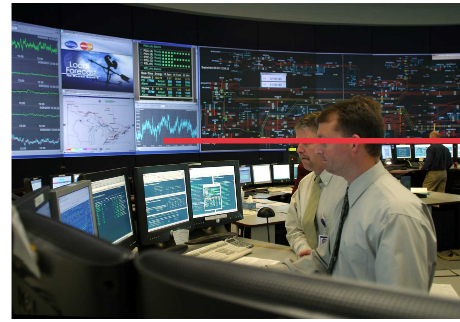
SCADA
Digital v.1.

From digital to digital "+"



SCADA/EMS
Digital v.2.

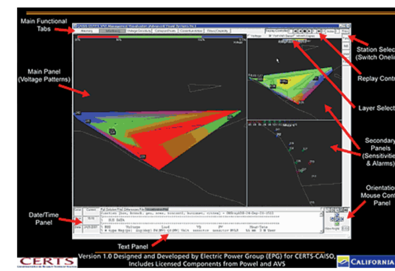
Appearance of EMS applications



SCADA/EMS+ PMU

PMU data starts being used in control rooms for monitoring displays & alarming (2002 –

Today: SCADA/EMS+ PMU + *PMU Applications for Monitoring a few Specific Conditions*



The Future?