Power System Driven Hardware in the Loop Simulations at Florida State University's Center for Advanced Power System

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TCIPG Seminar
University of Illinois
Dec 2 2011, Champaign, IL

Outline

- Overview of CAPS
- Hardware in the Loop (HIL) Concepts and Challenges
  - Real Time Simulators
  - Interfaces
  - Examples
- CAPS Facility Expansions
- Concluding Remarks

FSU Center for Advanced Power Systems

- Established at Florida State University in 2000 under a grant from the Office of Naval Research
- Lead Member of ONR Electric Ship R&D Consortium
- Focus on research and education related to application of new technologies to electric power systems
- ~$8 million annual research funding from ONR, DOE, Industry
- DOD cleared Facility at Secret Level

Research Focus

- Electric Power Systems
- Advanced Modeling and Simulation
- Advanced Control Systems
- Power Electronics Integration and Controls
- Thermal Management
- High Temperature Superconductivity
- Electrical Insulation/Dielectrics

–44,000 square feet laboratories and offices located in Innovation Park, Tallahassee; over $25 million specialized power and energy capabilities funded by ONR, DOE

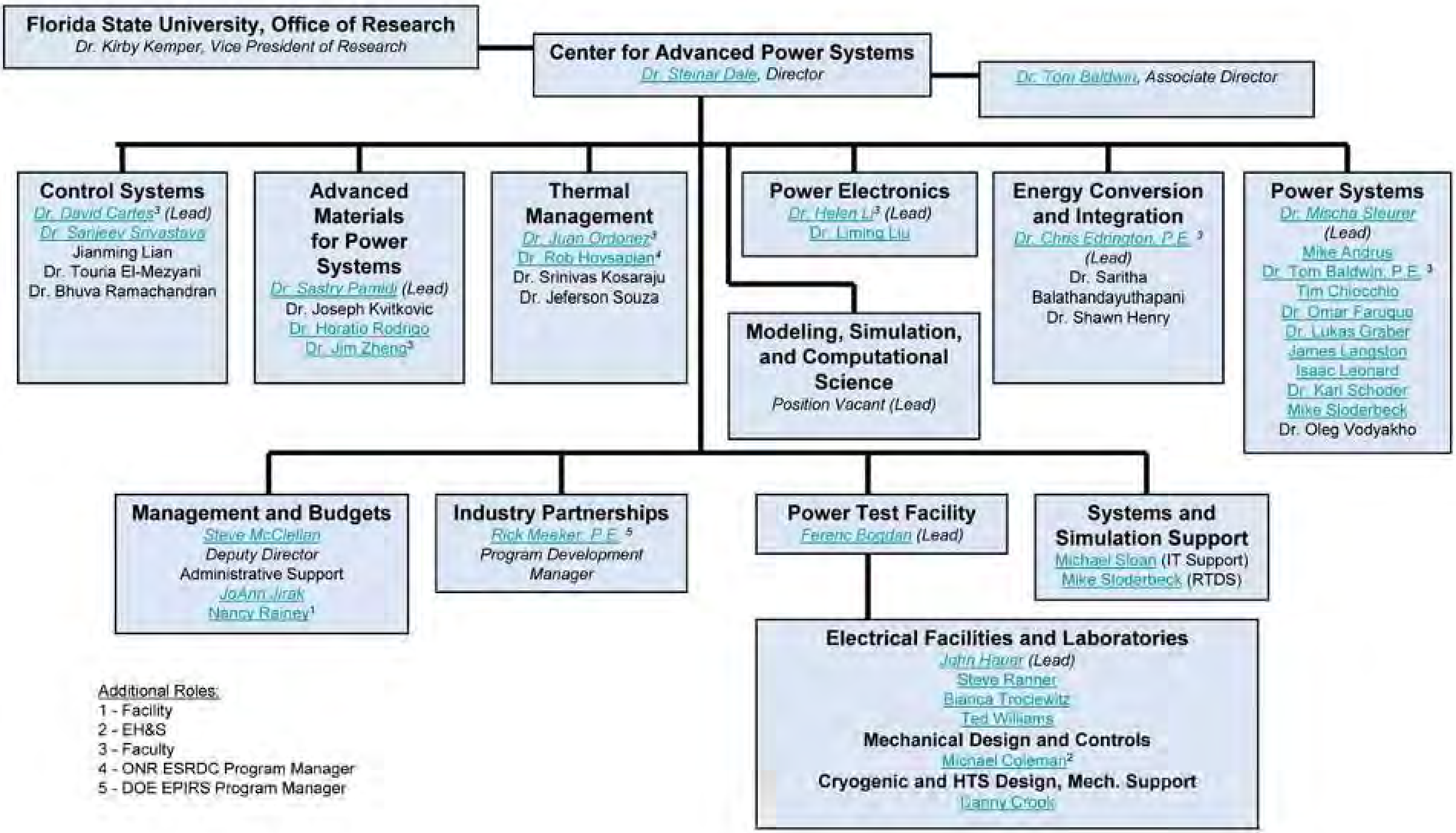
–Employs approx. 100, including

  –46 scientists, engineers and technicians, post-doc.'s and supporting staff,

  –7 FAMU-FSU College of Engineering faculty

  –44 Students

CAPS Organization



Florida State University, Office of Research
Dr. Kirby Kemper, Vice President of Research

Center for Advanced Power Systems
Dr. Steinar Dale, Director

Dr. Tom Baldwin, Associate Director

Control Systems
Dr. David Cartes[3] *(Lead)*
Dr. Sanjeev Srivastava
Jianming Lian
Dr. Touria El-Mezyani
Dr. Bhuva Ramachandran

Advanced Materials for Power Systems
Dr. Sastry Pamidi (Lead)
Dr. Joseph Kvitkovic
Dr. Horatio Rodrigo
Dr. Jim Zheng[3]

Thermal Management
Dr. Juan Ordonez[3]
Dr. Rob Hovsapian[4]
Dr. Srinivas Kosaraju
Dr. Jeferson Souza

Power Electronics
Dr. Helen Li[3] *(Lead)*
Dr. Liming Liu

Modeling, Simulation, and Computational Science
Position Vacant (Lead)

Energy Conversion and Integration
Dr. Chris Edrington, P.E.[3]
(Lead)
Dr. Saritha Balathandayuthapani
Dr. Shawn Henry

Power Systems
Dr. Mischa Steurer
(Lead)
Mike Andrus
Dr. Tom Baldwin, P.E.[3]
Tim Chiocchio
Dr. Omar Faruque
Dr. Lukas Graber
James Langston
Isaac Leonard
Dr. Karl Schoder
Mike Sloderbeck
Dr. Oleg Vodyakho

Management and Budgets
Steve McClellan
Deputy Director
Administrative Support
JoAnn Jirak
Nancy Rainey[1]

Industry Partnerships
Rick Meeker, P.E.[5]
Program Development Manager

Power Test Facility
Ferenc Bogdan (Lead)

Systems and Simulation Support
Michael Sloan (IT Support)
Mike Sloderbeck (RTDS)

Electrical Facilities and Laboratories
John Hauer (Lead)
Steve Ranner
Bianca Trociewitz
Ted Williams
Mechanical Design and Controls
Michael Coleman[2]
Cryogenic and HTS Design, Mech. Support
Danny Crook

Additional Roles:
1 - Facility
2 - EH&S
3 - Faculty
4 - ONR ESRDC Program Manager
5 - DOE EPIRS Program Manager

Major Collaborative Research and Education Initiatives in Energy with CAPS Participation

ELECTRIC SHIP RESEARCH
ESRDC
AND DEVELOPMENT CONSORTIUM

http://www.esrdc.com/

- *Florida State University*
- *Mississippi State University*
- *University of South Carolina*
- *University of Texas at Austin*
- *Massachusetts Institute of Technology*
- *Purdue University*
- *U.S. Naval Academy and Naval Post Graduate School*

FESC Florida Energy Systems Consortium

Universities Addressing Florida's Energy Needs

http://www.floridaenergy.ufl.edu/

FAU Florida Atlantic University · Florida Gulf Coast University · Florida State University · New College of Florida · UCF · UF University of Florida · UNF University of North Florida · USF University of South Florida · UWF

Future Renewable Electric Energy Delivery and Management (FREEDM) Systems

Engineering Research Center (ERC)

http://www.freedm.ncsu.edu/

NC STATE UNIVERSITY · FLORIDA A&M UNIVERSITY · FLORIDA STATE UNIVERSITY · MISSOURI S&T · ASU ARIZONA STATE UNIVERSITY

ETH Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

RWTH AACHEN UNIVERSITY

The Sunshine State Solar Grid Initiative (SUNGRIN)

Florida State University · University of Central Florida · USF University of South Florida · FRCC · FPL · JEA · FMPA Florida Municipal Power Agency · Lakeland Electric · OUC The Reliable One · GRU More than Energy · SunPower · Satcon · amec

Early Stage Prototype Testing

Needs

- Test under different (grid) conditions
- Modification of configuration(s)
- Repeatability: Capability for exact reproduction of testing conditions

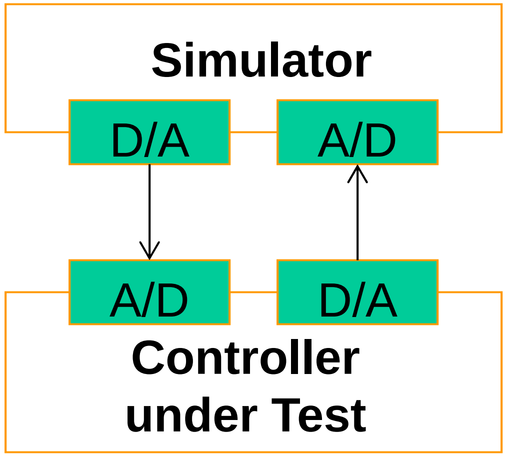
Drawbacks of conventional testing

- Expenses in construction
- Time intensive
- Facilities for high power are rare
- Extreme scenarios endanger equipment

Possible solution

  - Power HIL

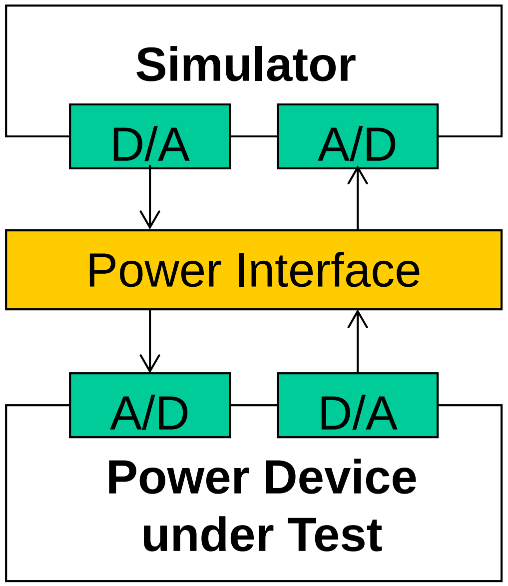
Controller Hardware in Loop (CHIL) and Power Hardware in loop (PHIL)



- Controller HIL Simulation
  - Controller under test
  - Low level transmitting signals (+/-15V, mA)
  - A/D and D/A converters are adequate for the interface

Power HIL Simulation

- Power device (load, sink) under test
- High level transmitting signals (kV, kA, MW)
- Power amplifiers required for interface



FSU-CAPS Power Testing Facility

FSU-CAPS Power Testing Facility

12.5 kV and 4.16 kV transformers

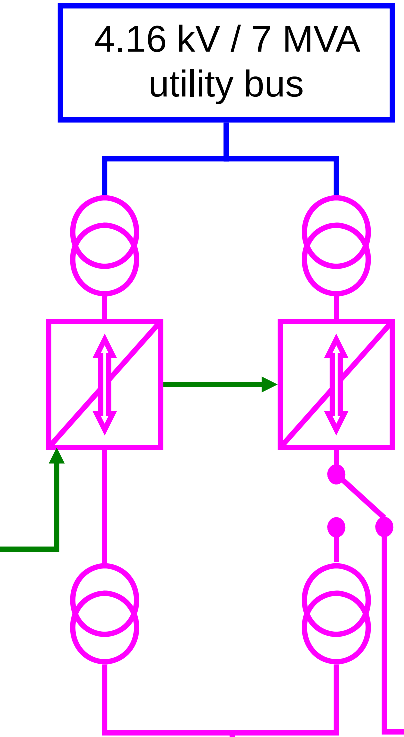
12.5 kV and 4.16 kV switchgear

2 x 8 MVA / 5 MW variable speed drives

2 x 2.5/5 MW dynamometers

5 MW Electrical PHIL Facility at FSU-CAPS

Real Time Simulator RTDS



4.16 kV / 7 MVA utility bus

Voltage / current reference / feedback from / to RTDS

6.25 MVA / 5 MW Variable Voltage Source (VVS) Converter “Amplifier“

f_S = 10 kHz effective

Bandwidth ≈ 1.2 kHz

0….4.16 (8.2) kV / 6.25 MVA experimental **AC** bus (ungrounded)

0…1.15 kV / 2.5 MW experimental **DC** bus (ungrounded)

0-480 V / 1.5 MVA experimental **AC** bus (ungrounded)

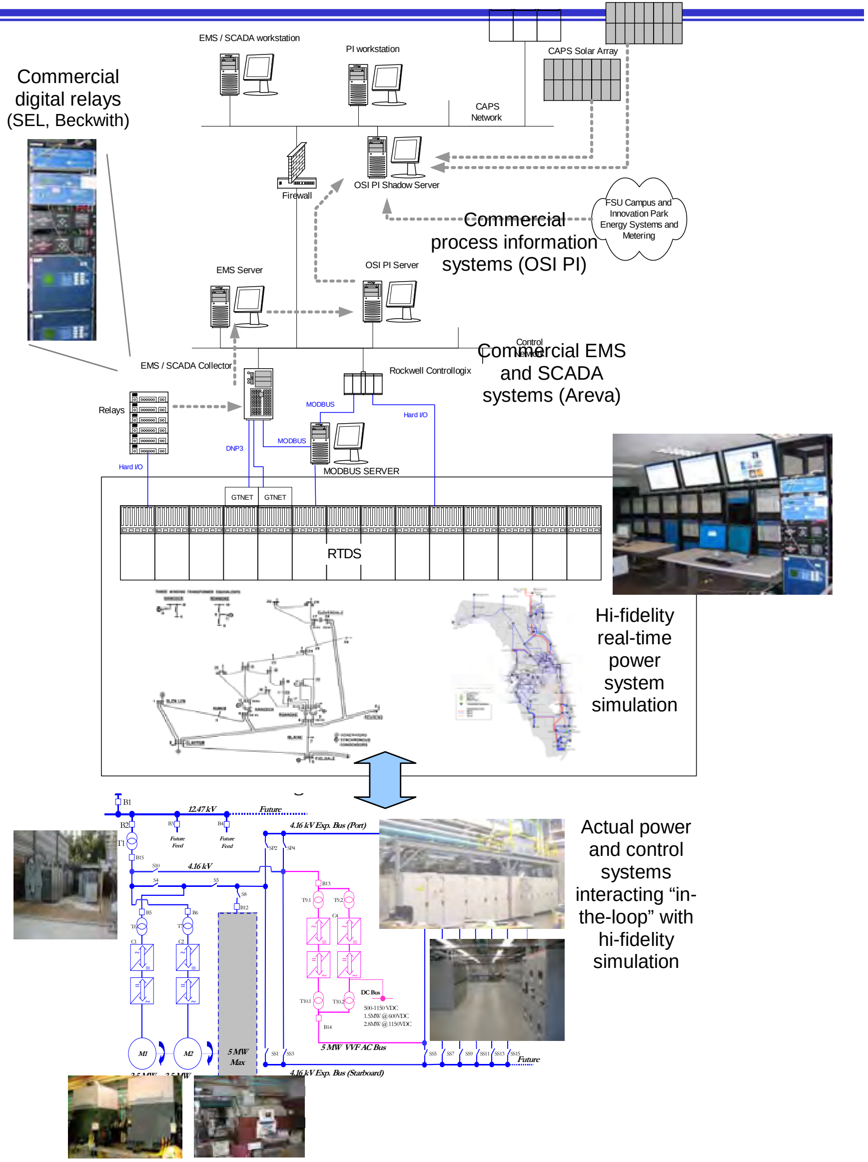
CAPS Facility Capabilities

Power System Simulation, Control, and Information Systems Development, Test, Evaluation, and Demonstration Facility

- 7.5 MVA, 4.16kV test and evaluation facility
  - 5 MW variable voltage / variable frequency converter
  - 5 MW dynamometer
  - High-speed machine capability, to 24,000 RPM
  - Switchgear and transformers
- Real-time Digital Simulator (RTDS)
  - Down to <2 μSec time step in real-time
- Integrated Hardware-in-the-Loop (HIL) testbed → 5 MW testbed + RTDS
- Low power dynamometers and converters
- AC Loss and Quench Stability Lab
- Cryo-cooled systems lab
- Cryo-dielectrics Lab
  - With high voltage test capability

Additions and Enhancements in Progress

- MVDC test capability to +/- 24 kV



Commercial digital relays (SEL, Beckwith)

Commercial process information systems (OSI PI)

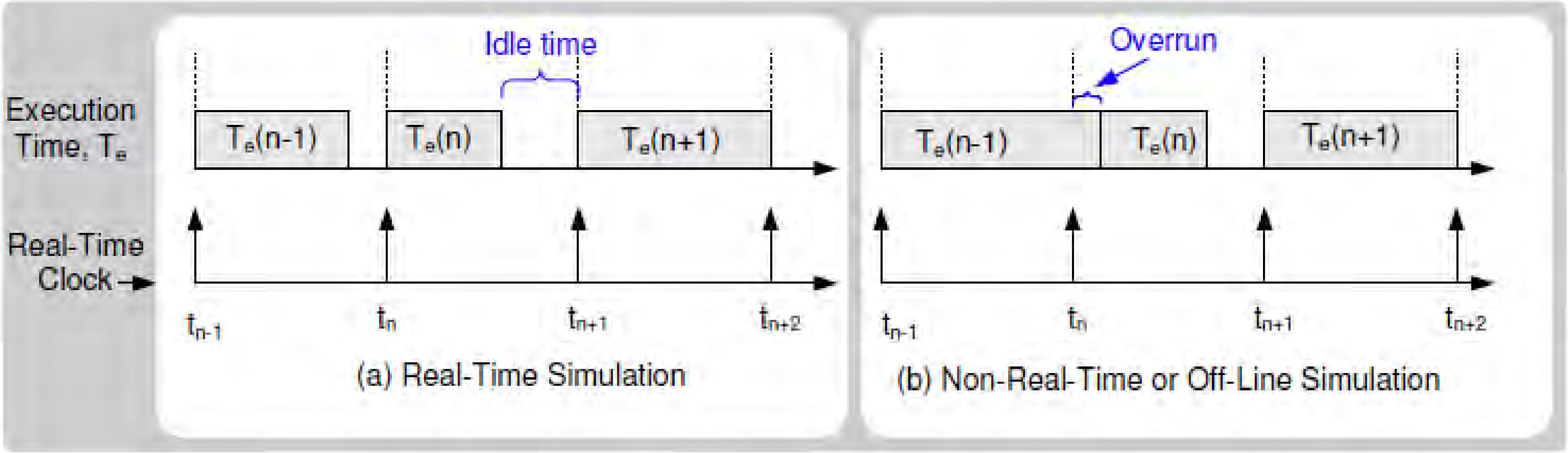
Commercial EMS and SCADA systems (Areva)

Hi-fidelity real-time power system simulation

Actual power and control systems interacting “in-the-loop” with hi-fidelity simulation

Real-Time Computer Simulation

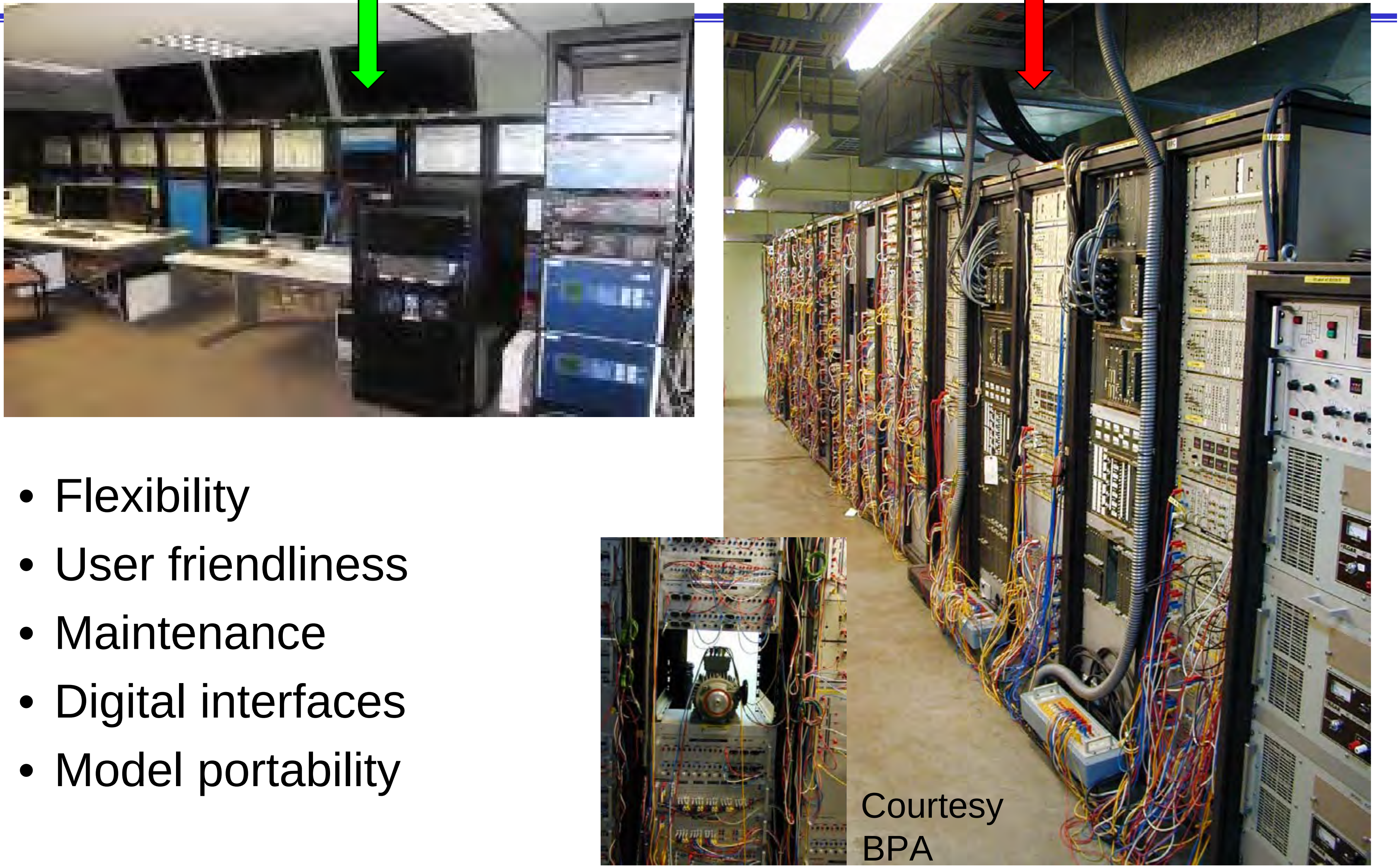
- What does it mean?
  - Real-Time simulation means producing the true system behavior or dynamics through simulation at the same rate as it happens in an actual physical system
- Main Characteristics
  - Simulation must be completed within the specified time-step
  - Should be able to interface with physical hardware



(a) Real-Time Simulation

(b) Non-Real-Time or Off-Line Simulation

Transient Network Simulators
Digital versus Analog



- Flexibility
- User friendliness
- Maintenance
- Digital interfaces
- Model portability

Courtesy
BPA

Power Systems Simulations at CAPS

REAL-TIME – using RTDS

- Large-scale electromagnetic transient simulator
- EMTP type simulation covers load-flow, harmonic, dynamic, and transient regime
- 111,200 MFLOPS; 14 “racks”, parallel processing
- Real-time simulation, with time steps down to <2 μs.
- Real-time simulation of 756 electrical nodes, plus hundreds of control and other simulation blocks
- Extensive digital and analog I/O for interfacing hardware to simulation (>2500 analog, >200 digital). Can connect in real-time to any electrical node within the simulation.
- MODBUS TCP, DNP 3.0 and IEC 61850 interfaces also available.
- Capability for remote access over VPN link

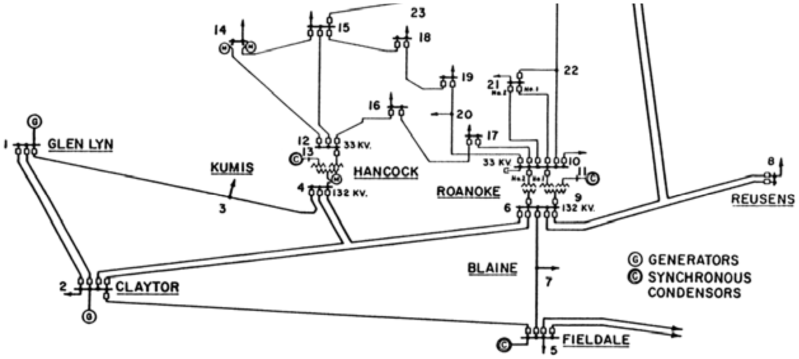
Other simulation tools in-use at CAPS:

- PSS/E, PSCAD/EMTDC, MATLAB/Simulink, ATP, PSPICE, ANSYS, DSPACE, OPAL-RT

RT simulator lab at CAPS

Example: IEEE 30-bus System

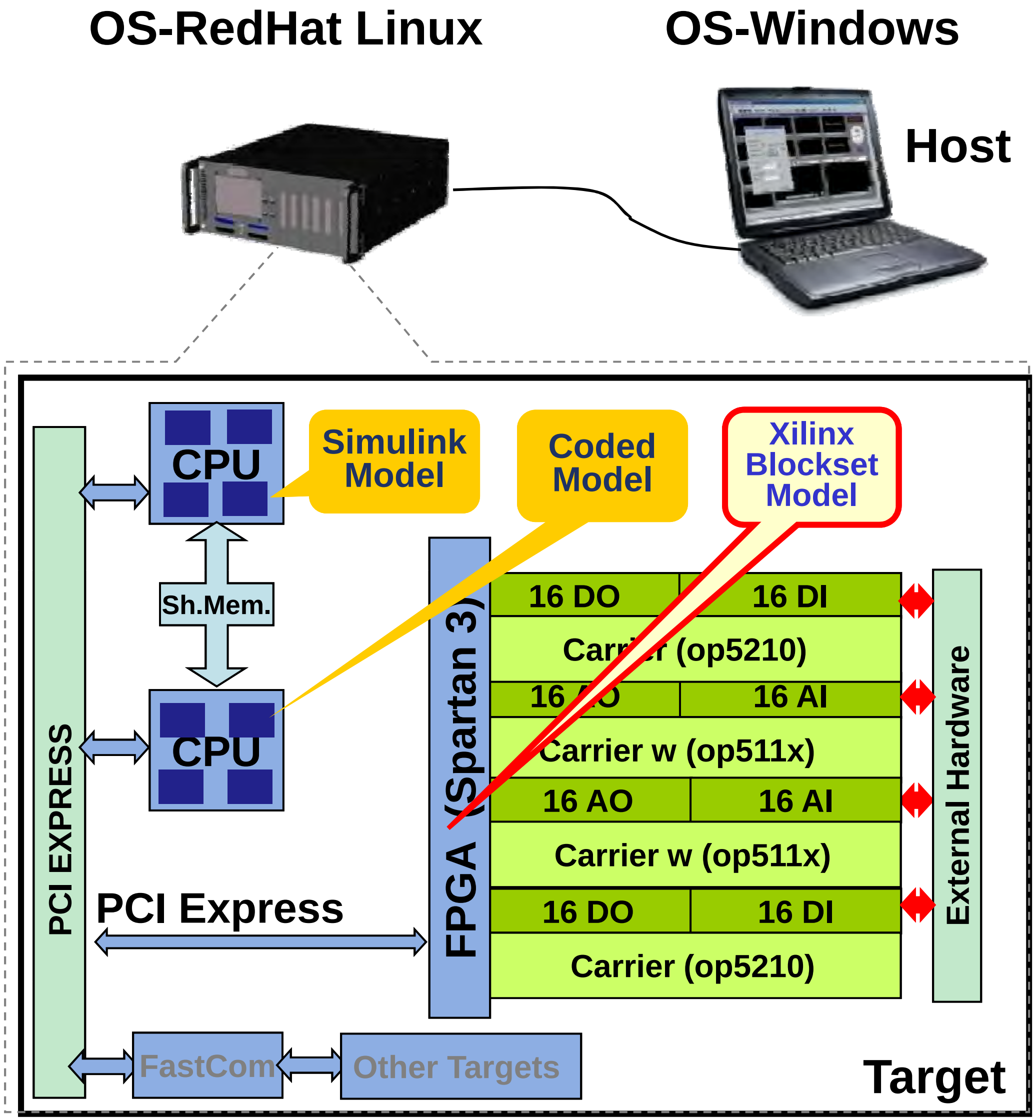
- 5 racks, dt=65 μs
- 6 machines incl. governor & v-regulator
- 36 transmission lines
- 70 breakers

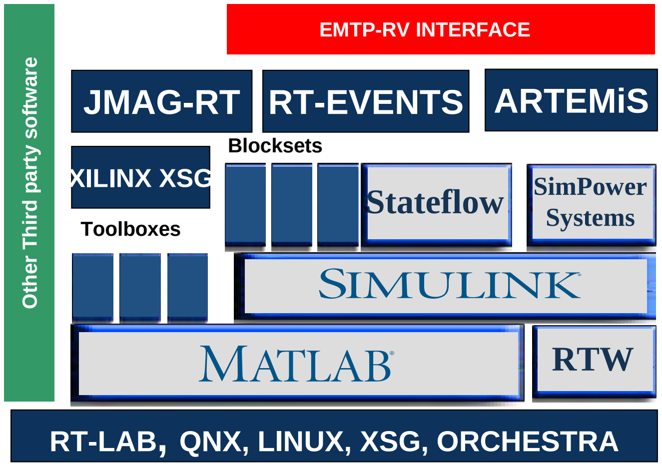


OPAL-RT Real-Time Simulator

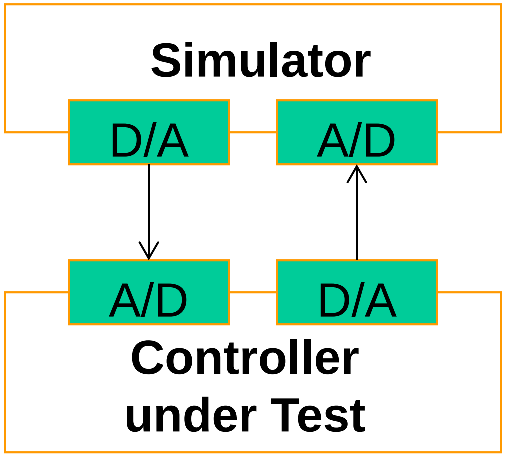
Key Features-

1. General purpose CPU based
2. Simulink based model development
3. MATLAB, C/C++, FORTRAN code can be simulated
4. Supports multi physics-domain simulations
5. Reconfigurable FPGA based I/O
6. Supports user developed models





Examples of Controller Hardware in the Loop (CHIL) Simulation Projects



Controller Hardware in the Loop (CHIL) Testing of STATCOM controller

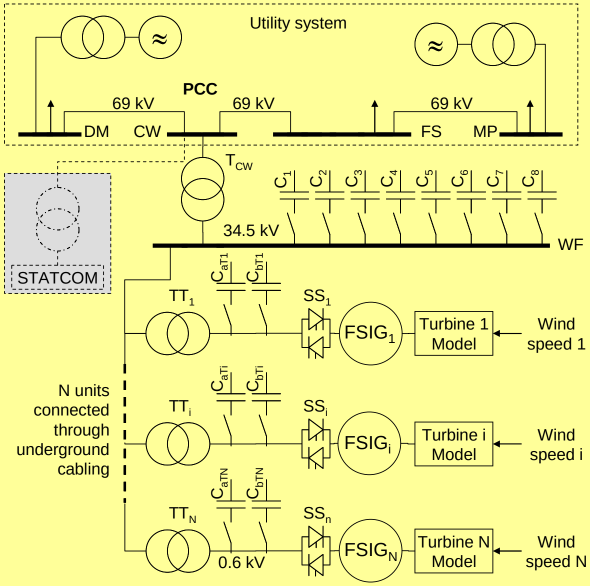
Real Time Digital Simulator

Simulated System response

D/A

A/D

Hardware response



External Hardware

2 V_{LL}, 3 I_L

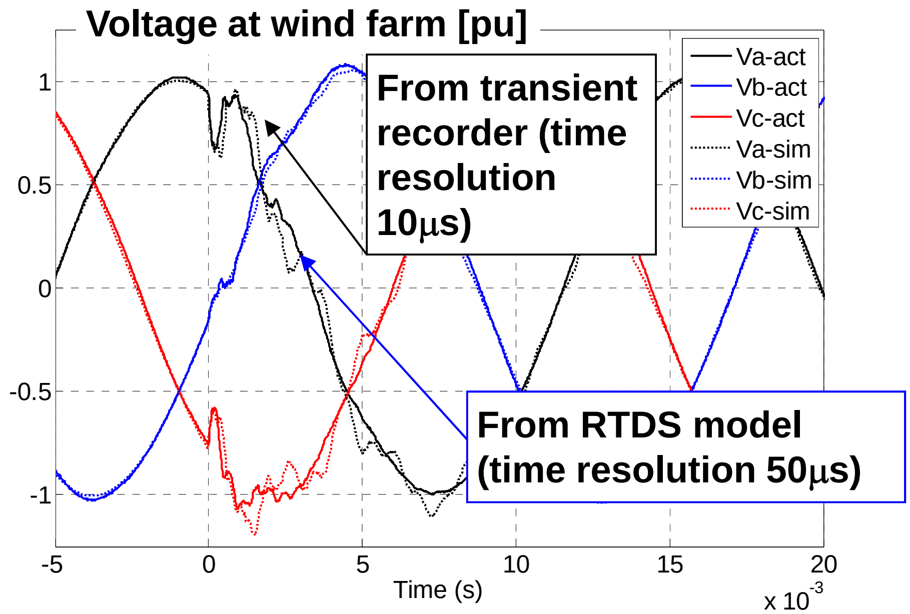
24 firing pulses

STATCOM controller by NCSU

- BPA System
  - 85 µs time-step size, 1 Rack
- Wind Farm – 83 fixed speed induction generators
  - Modeled with 36 individual turbines
  - 85 µs time-step size, 12 Racks
- Statcom
  - Simulated with 2 µs time-step, 1 Rack

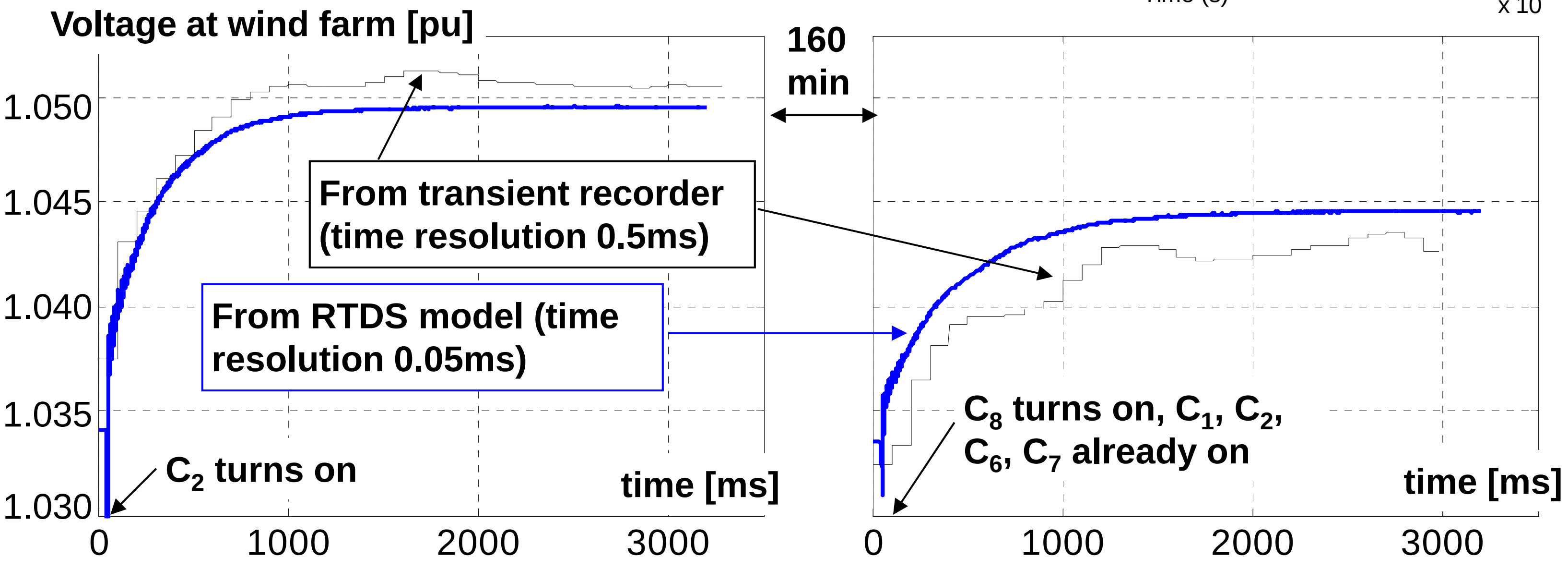
Model Validation - Capacitor Switching

- Power system model was rigorously validated against various data provide by Bonneville Power Administration
- RT simulation model captured all the provided data sets reasonably well


Voltage at wind farm [pu]

From transient recorder (time resolution 10μs)

From RTDS model (time resolution 50μs)


Voltage at wind farm [pu]

160 min

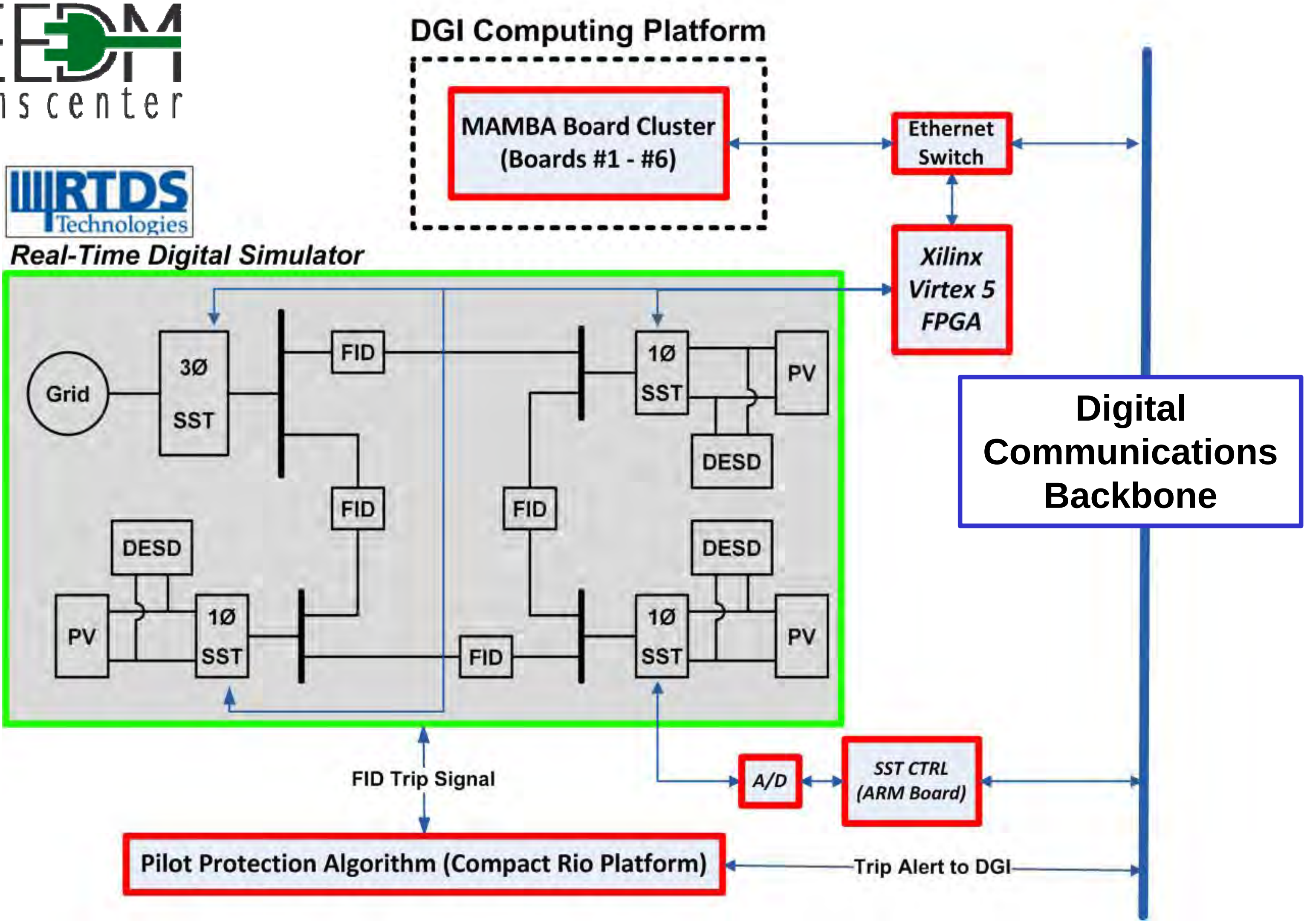
From transient recorder (time resolution 0.5ms)

From RTDS model (time resolution 0.05ms)

C_2 turns on

C_8 turns on, C_1, C_2, C_6, C_7 already on

HIL Test Bed for Distributed Grid Intelligence



DGI Computing Platform

Real-Time Digital Simulator

Digital Communications Backbone

Pilot Protection Algorithm (Compact Rio Platform)

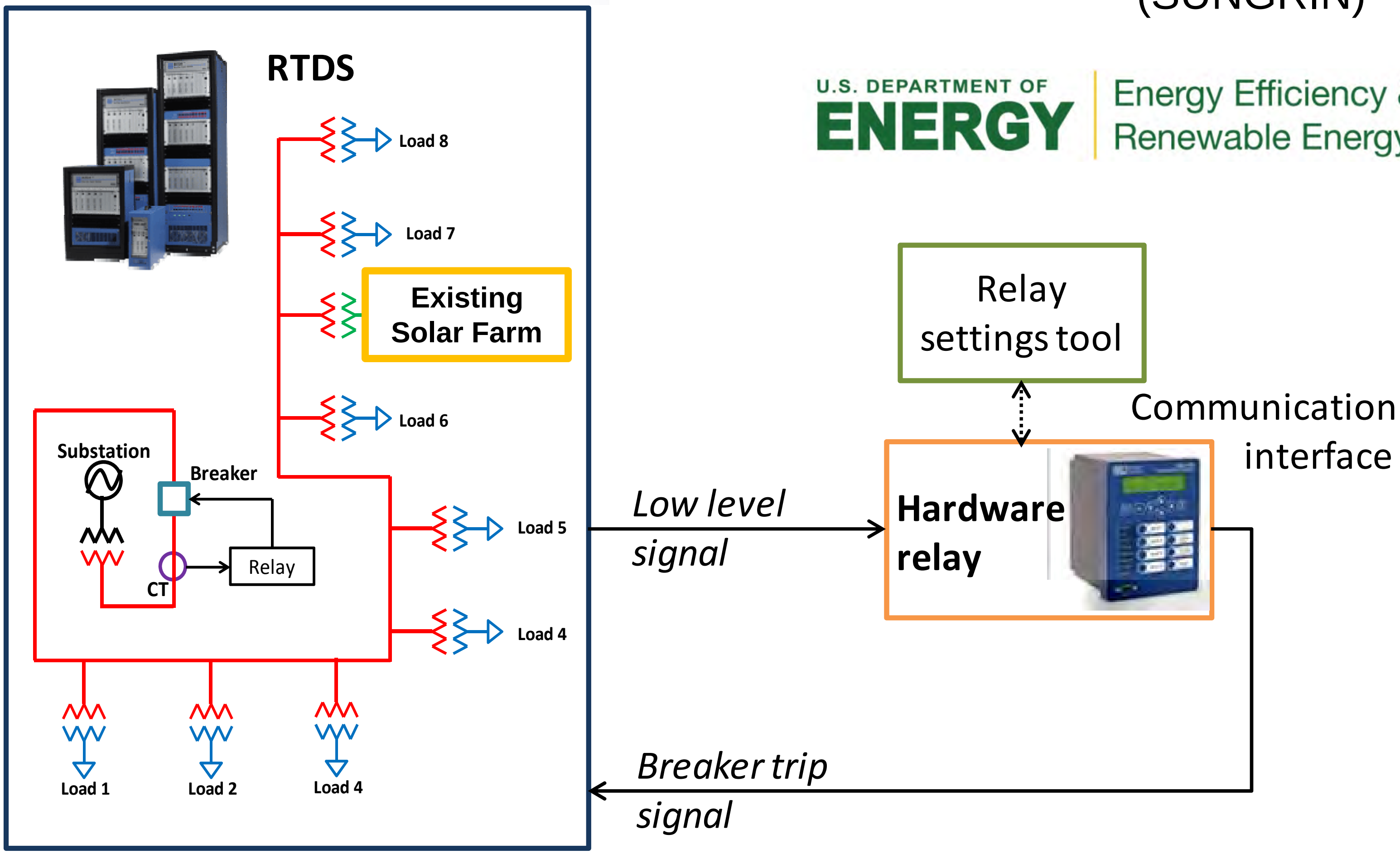
HIL Test Bed for High Penetration PV Studies

Circuit model based on Jacksonville Electric Authority feeder

JEA

Sunshine State Solar Grid Initiative (SUNGRIN)

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy



Relay settings tool

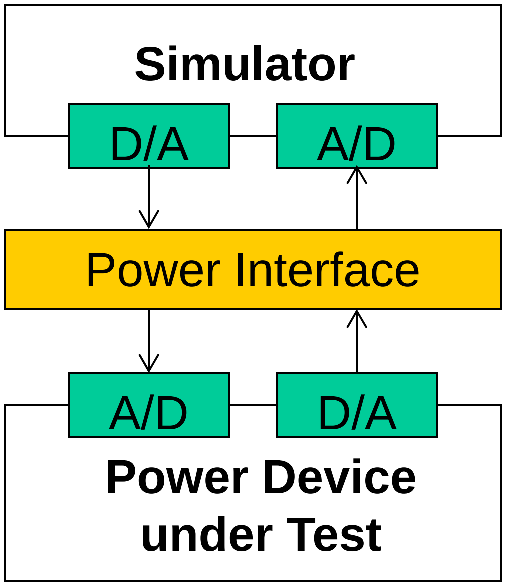
Communication interface

Low level signal

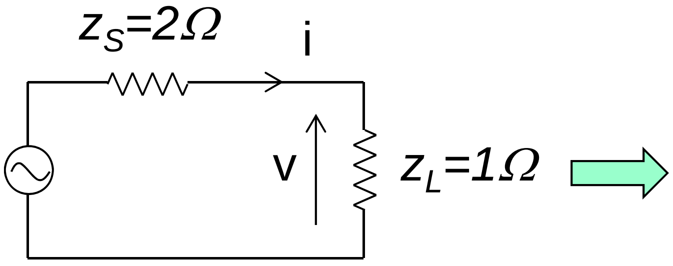
Hardware relay

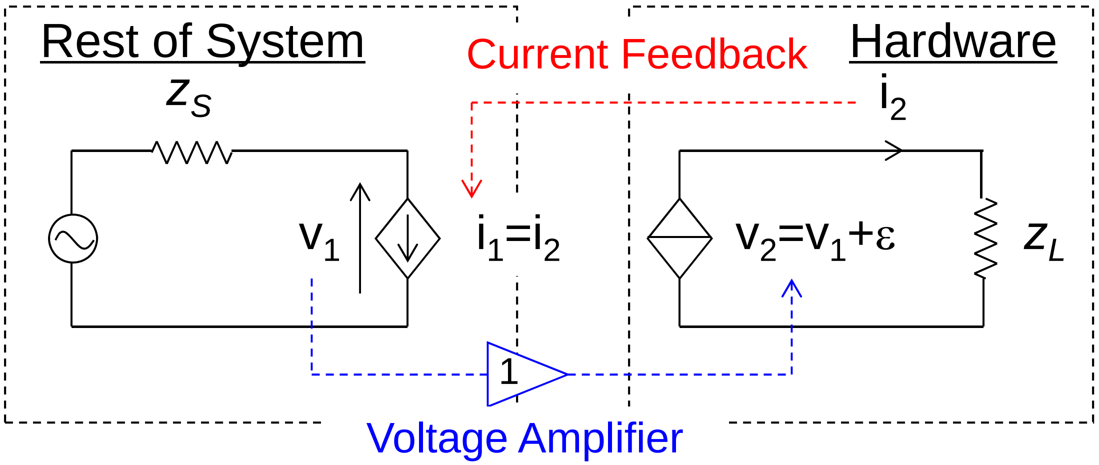
Breaker trip signal

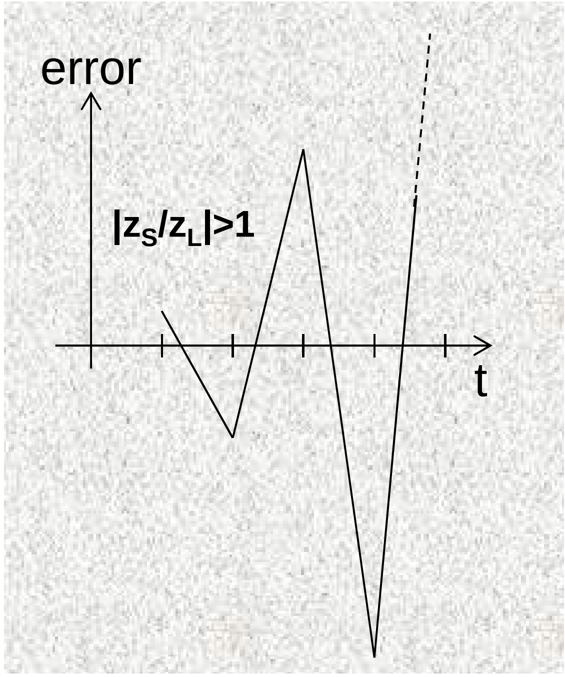
Examples of Power Hardware in the Loop (PHIL) Simulation Projects



PHIL Interface Algorithm Instabilities



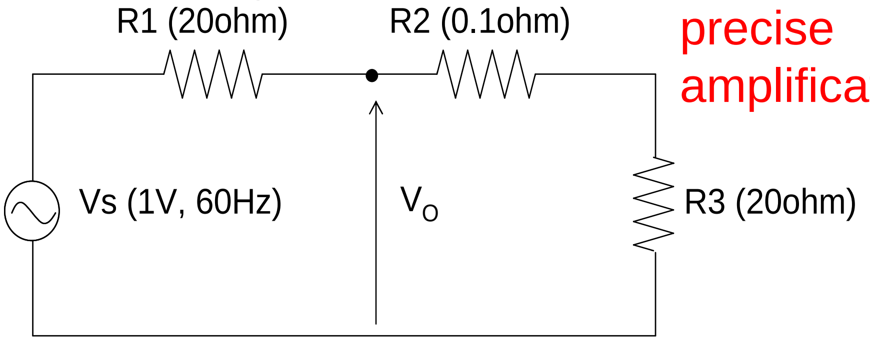




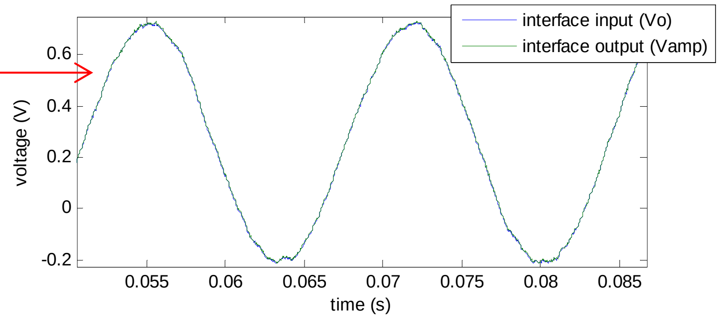
- Step k:
  - $\Delta v_2(k) = \varepsilon$, & $i_2 = v_2/z_L$ ➔ $\Delta i_2(k) = \varepsilon/z_L$
- Step k+1:
  - $\Delta i_2(k) = \varepsilon/z_L$, & $v_1 = v_S - i_1 * z_S$ ➔ $\Delta v1(k+1) = -\varepsilon * z_S/z_L$
- Result:
  - Error ε is amplified by a factor of $-z_S/z_L$

Imperfect Interface Causes Simulation Errors

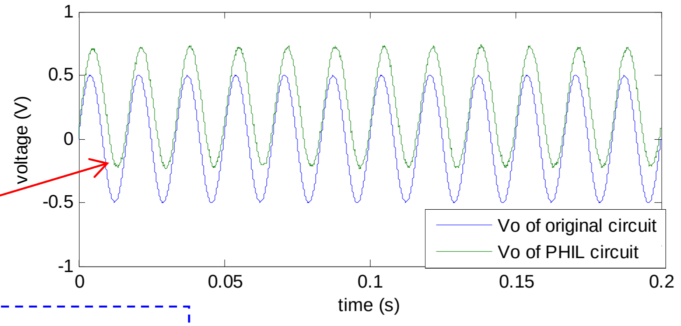
Original Circuit



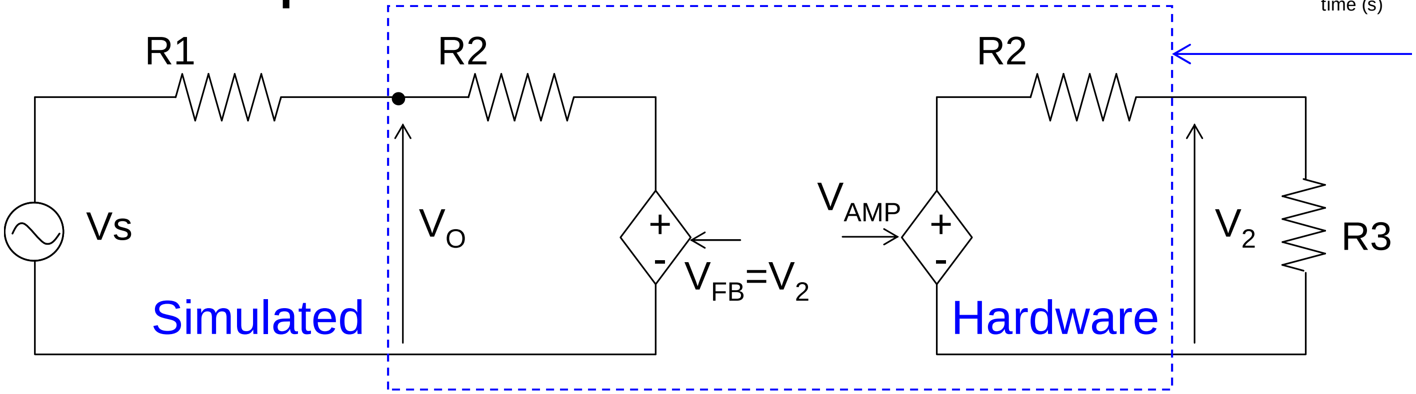
Highly precise amplification



Large error in the PHIL simulation result



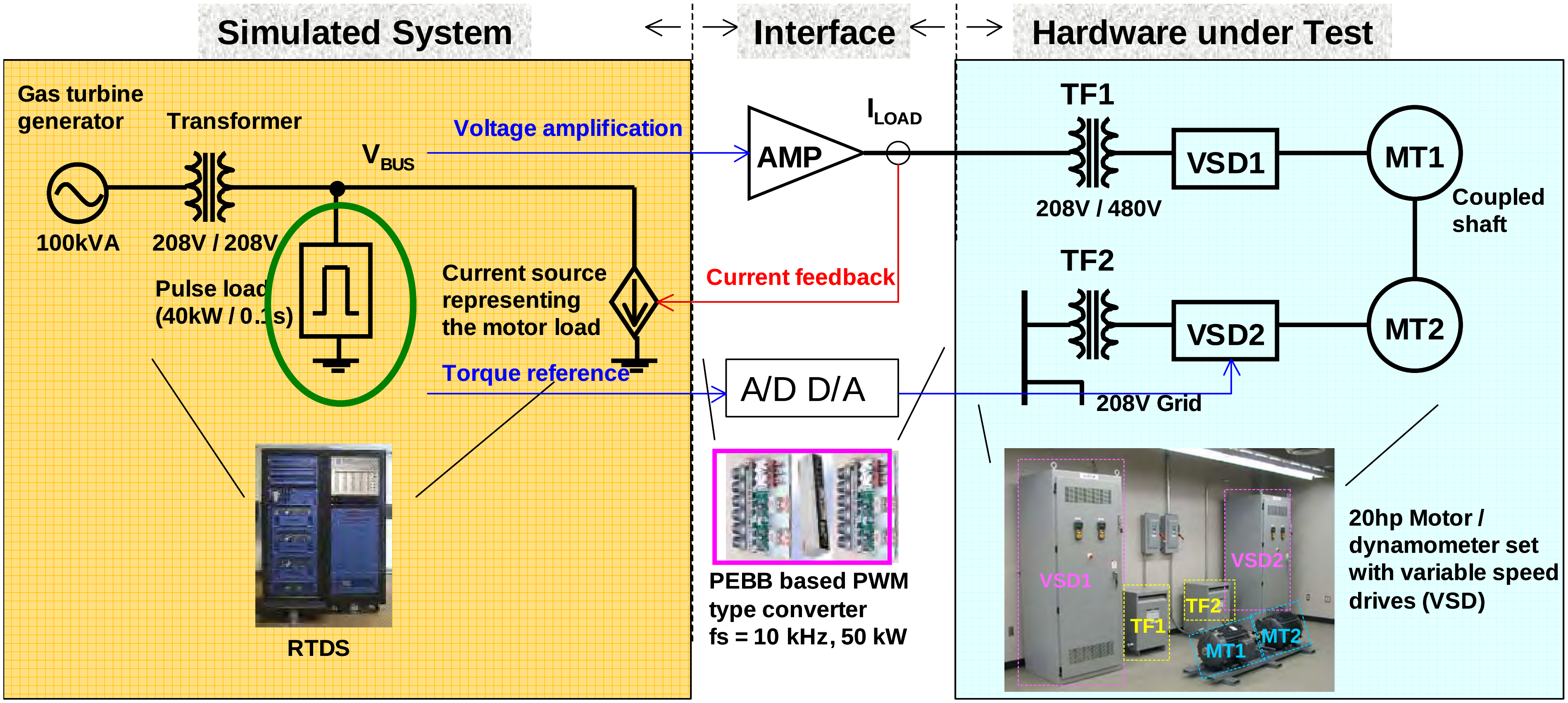
PHIL Implementation



Interface uses relaxation method where a common component is implanted both in hardware and in software

W. Ren, M. Steurer, T. L. Baldwin, "Improve the Stability of Power Hardware-in-the-Loop Simulation by Selecting Appropriate Interface Algorithm", in Proc. of the ICPS 2007, Edmonton, ALB, Canada, May 6-10 2007

Example: Simulated Pulse Load Event



Simulated System ← → **Interface** ← → **Hardware under Test**

Gas turbine generator

Transformer

100kVA

208V / 208V

V_{BUS}

Voltage amplification

Pulse load (40kW / 0.1s)

Current source representing the motor load

Torque reference

RTDS

AMP

I_{LOAD}

Current feedback

A/D D/A

PEBB based PWM type converter fs = 10 kHz, 50 kW

TF1

208V / 480V

VSD1

MT1

Coupled shaft

TF2

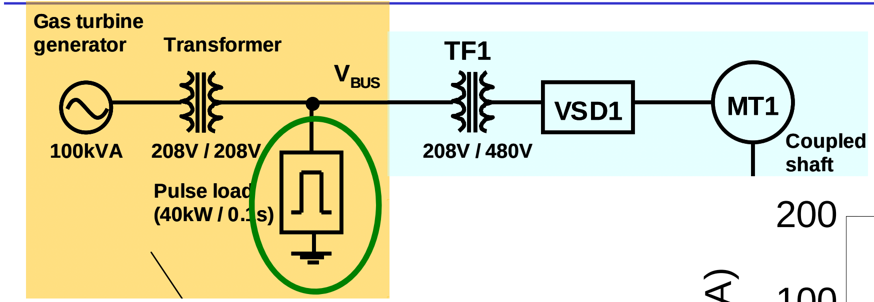
VSD2

MT2

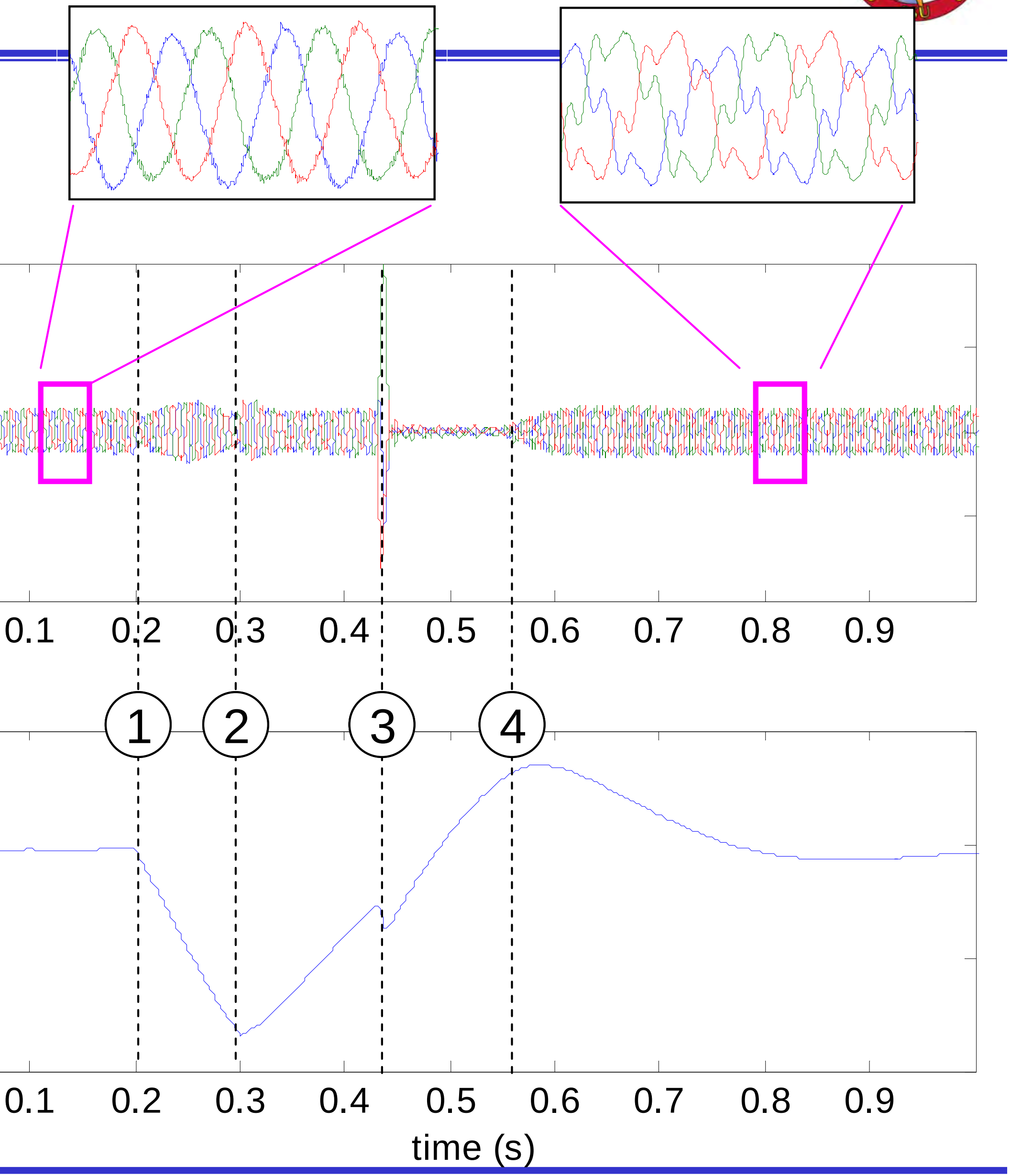
208V Grid

20hp Motor / dynamometer set with variable speed drives (VSD)

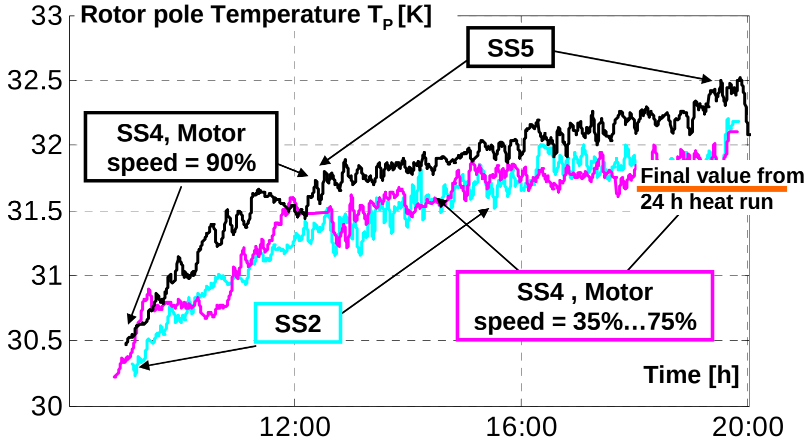
VSD1 During Simulated Pulse Load Event



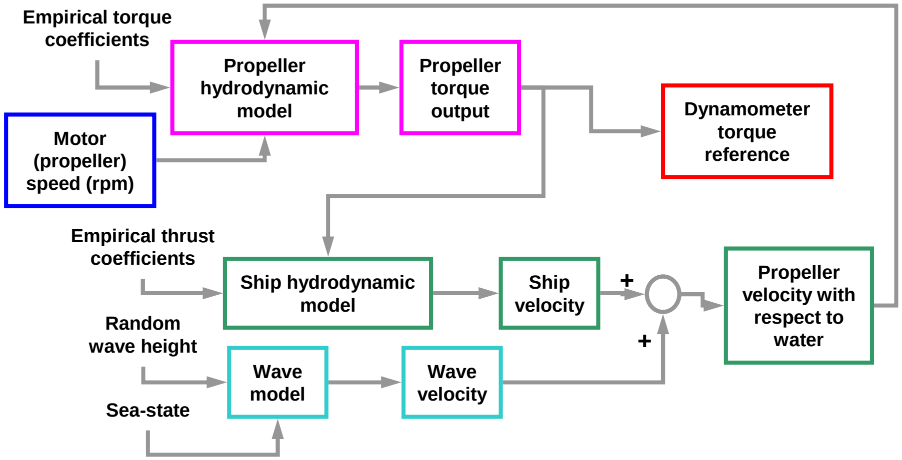
1. Pulse load on => GT speed decreases
2. Pulse load off => GT speed increases
3. VSD1 active front end trips
4. VSD1 DC link depleted until free wheeling diodes conduct



PHIL Investigations of Rotor Heating in a 5 MW HTS Propulsion Motor



Rotor Heating from High Sea-States

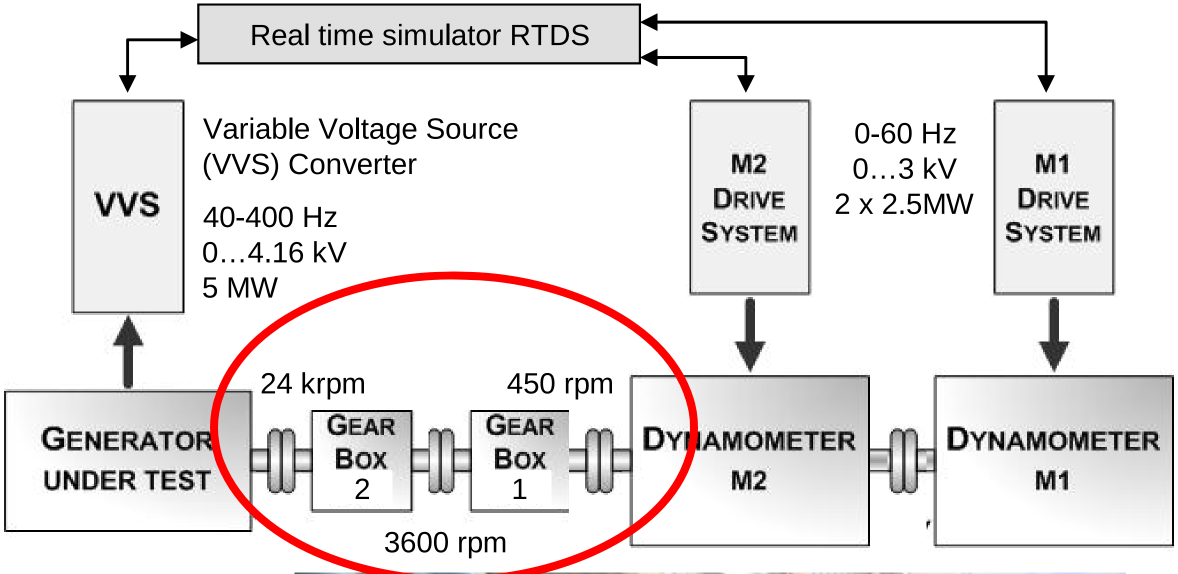


Sea-State Hydrodynamic Model

M. Steurer, S. Woodruff, T. Baldwin, H. Boenig, F. Bogdan, T. Fikse, M. Sloderbeck, and G. Snitchler, ”Hardware-in-the-Loop Investigation of Rotor Heating in a 5 MW HTS Propulsion Motor”, presented at the Applied Superconductivity Conference 2006, Seattle, WA, USA, and accepted for publication in the IEEE Trans. Applied Superconductivity

New: High Speed Machinery Facility

- Gear box from DURIP grant
- Applications
  - Testing medium and high-rpm machinery
- Uniqueness at CAPS
  - Dynamic torque from real time models of mechanical prime movers or loads
  - Dynamic voltage/current from real time models of electrical source or load
- Commissioned April 2011



Real time simulator RTDS

VVS

Variable Voltage Source (VVS) Converter

40-400 Hz
0…4.16 kV
5 MW

M2 DRIVE SYSTEM

0-60 Hz
0…3 kV
2 x 2.5MW

M1 DRIVE SYSTEM

GENERATOR UNDER TEST

24 krpm

GEAR BOX 2

450 rpm

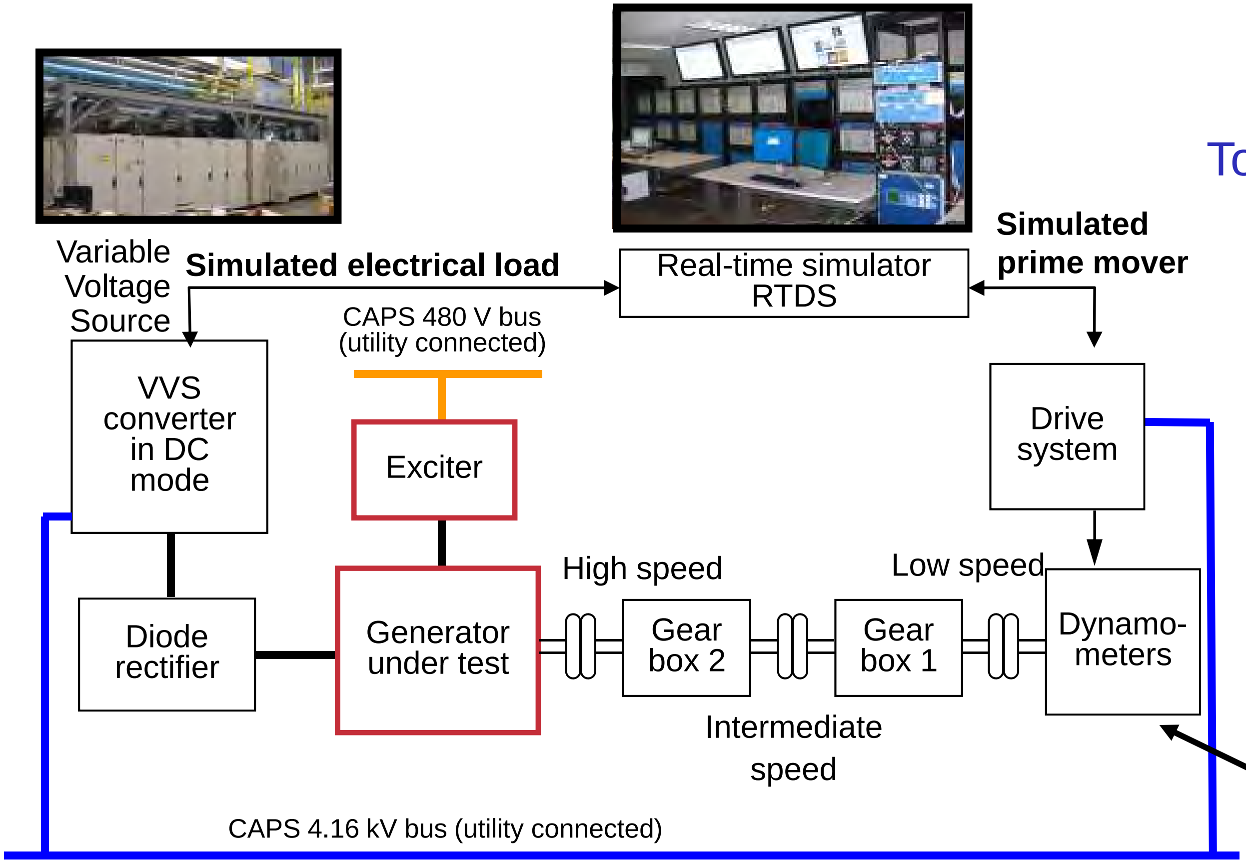
GEAR BOX 1

3600 rpm

DYNAMOMETER M2

DYNAMOMETER M1

PHIL Experiments
High-Speed Generator Testing


Variable Voltage Source

Simulated electrical load

Real-time simulator RTDS

Simulated prime mover

CAPS 480 V bus (utility connected)

VVS converter in DC mode

Exciter

Drive system

High speed

Low speed

Diode rectifier

Generator under test

Gear box 2

Gear box 1

Dynamo-meters

Intermediate speed

CAPS 4.16 kV bus (utility connected)

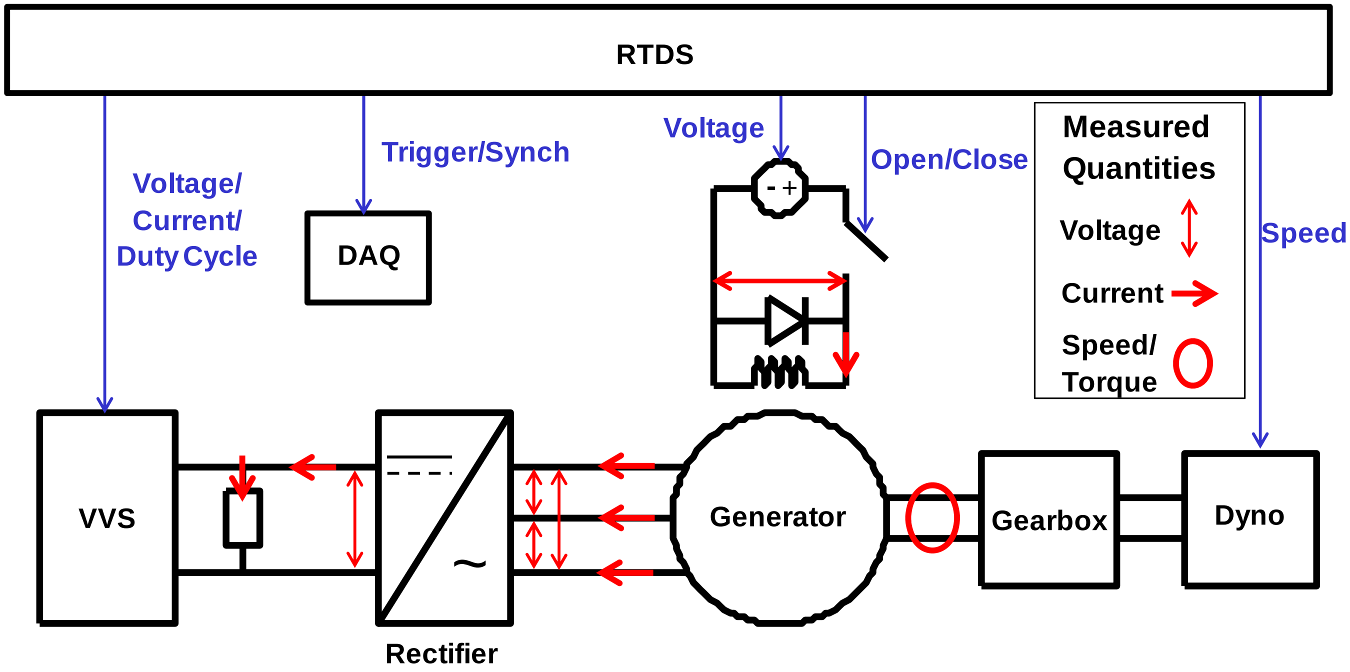
Moved from CHIL:

- Excitation controls
- Initially: ns-range time steps

To full-scale PHIL

- Startup, shutdown procedure
- Steady-state
- Dynamic loading (ramping)

PHIL Experiments
High-Speed Generator Testing



Control

- Speed, electrical load
- Experiment

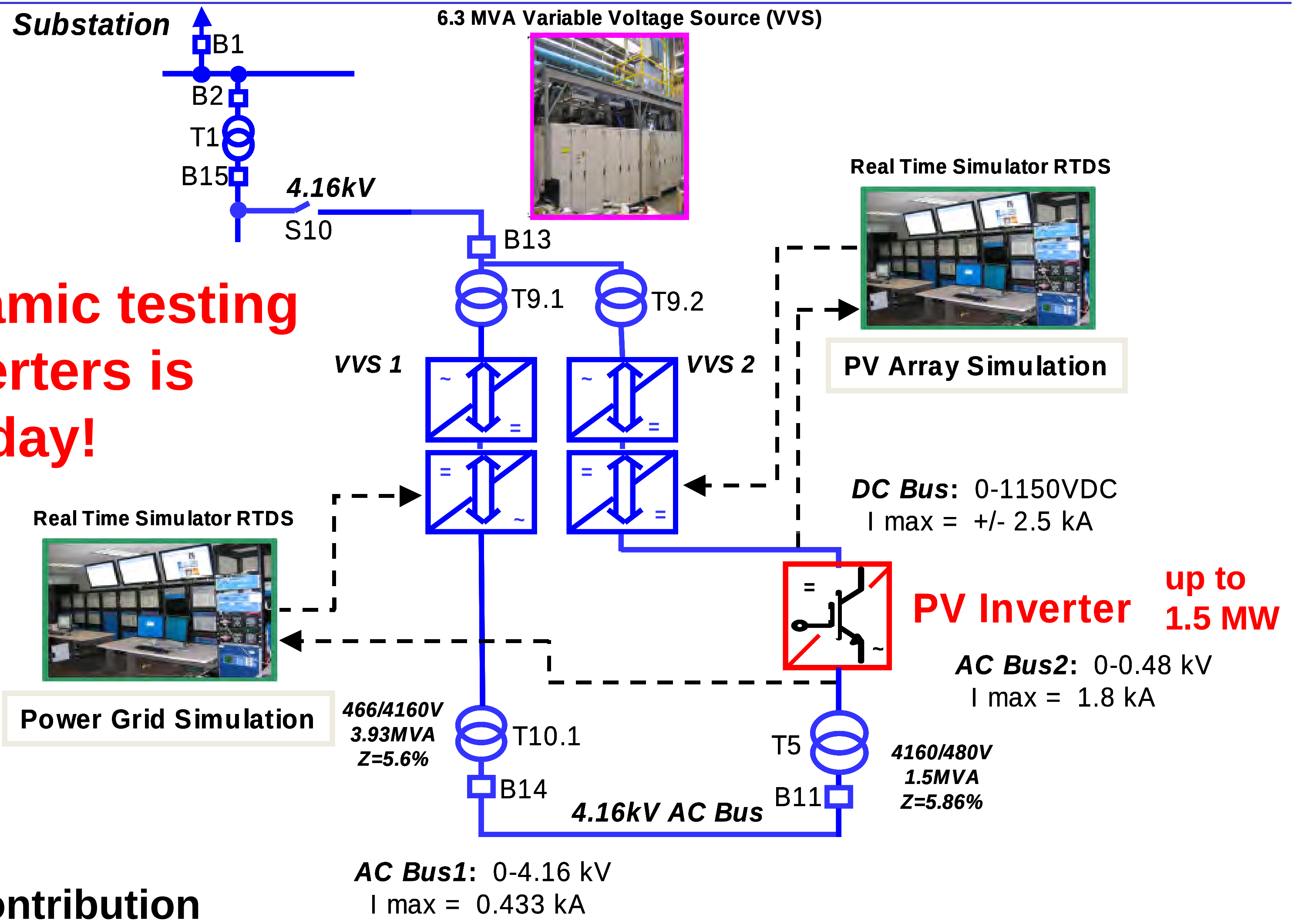
Monitoring and logging

- RTDS (30 µs), NI (1 µs)
- V, I, oil flow, and temperature

Protection

- Voltage, current, torque, and vibration
- Warning and trip levels
- Shutdown procedure and 'crash-safe'
- All elements developed and debugged through simulated PHIL
- Offline data analysis

Dynamic PHIL Testing of Large PV Inverters



Highly dynamic testing of PV converters is possible today!

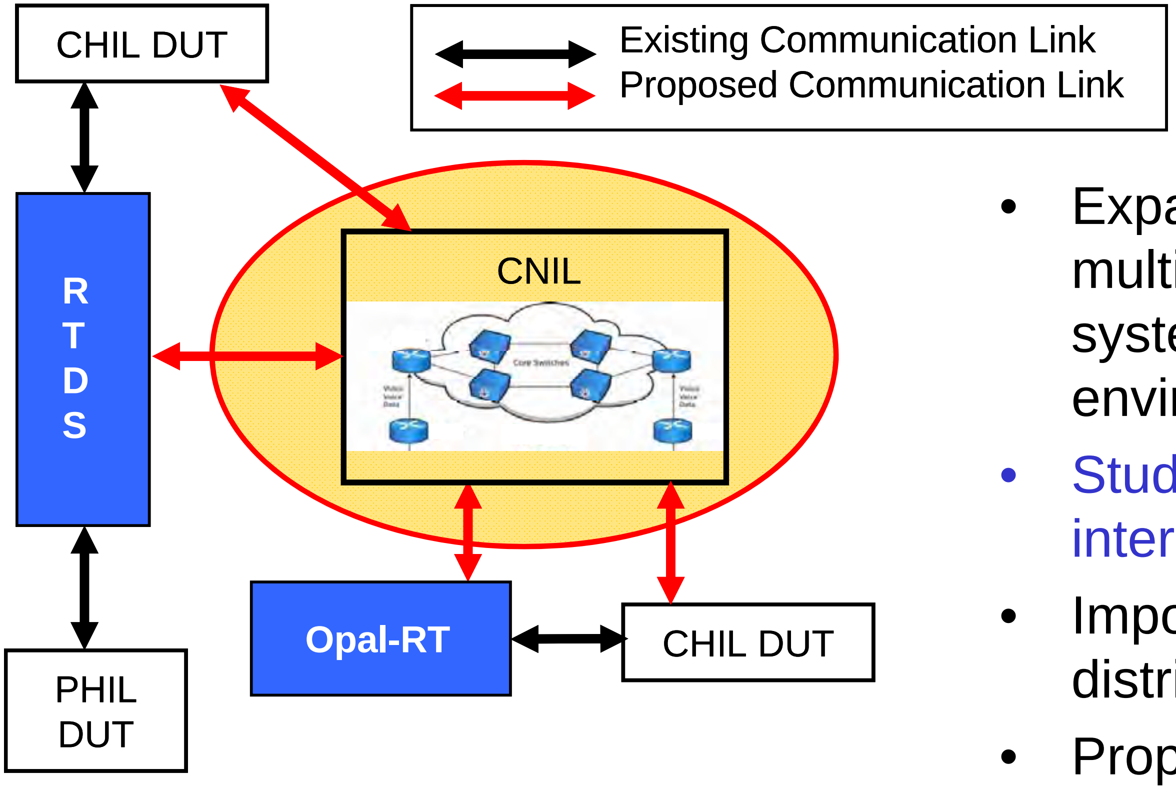
LV ride through

Anti islanding

Fault current contribution

Unbalanced voltage condition

Expansion: Real Time Integrated Controls Network Simulation Environment



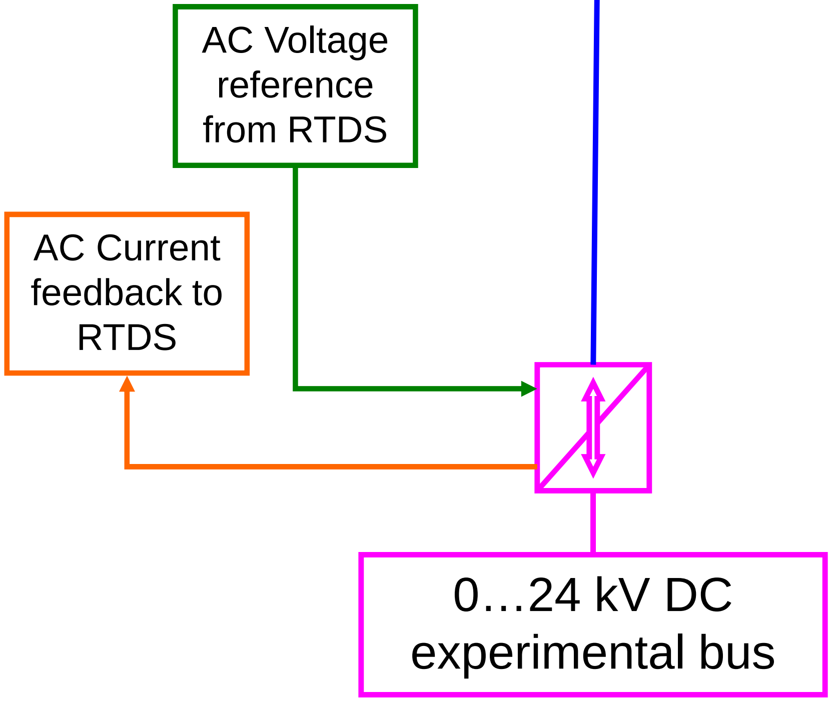
↔ Existing Communication Link
↔ Proposed Communication Link

HIL	Hardware in the loop
CHIL	Control HIL
DUT	Device under test
CNIL	Control Network in the loop
PHIL	Power HIL

- Expanding towards real-time multi-domain cyber-physical system simulation environments
- Study tightly coupled, complex interactive systems
- Important for networked distributed systems
- Proposed under DURIP (Defense University Research Instrumentation Program), pending funding

Expansion - 5 MW MVDC “Amplifier”

- Continuous power rating 5 MW
- Full 4-quadrant operation
- Output voltage range
  - 0…24 kV
- No-load and full load voltage THD ≤ 1%
- Output filter cut-off frequency 1000 Hz
- Ungrounded up to 24 kV



Utility bus

AC Voltage reference from RTDS

AC Current feedback to RTDS

0…24 kV DC experimental bus

Discussion

- Advanced machinery and power electronics technologies
  - Integration challenges
- Increased modeling and simulation efforts
  - Verification, validation and accreditation, certification
- Power HIL
  - Substantially improve development cycle
  - Discover hidden issues early
  - Improve models
- Large-scale M&S including statistical methods to evaluate probabilistic aspects
  - Uncertainties of component parameters
  - Sensitivities for design optimizations
- Challenges
  - Real-time simulation of models
    - Dedicated tools and hardware
    - Fidelity of models need careful consideration
  - Approach to interfacing device under test
    - Stability concerns: case-by-case evaluation

Related PHIL Efforts

Korea Electrotechnology Research Institute (KERI)

- Superconducting magnetic energy storage (SMES) device to a real-time simulation (10kJ, 300 A)

Grenoble Electrical Eng. Lab. (G2ELAB/Grenoble-INP)

- STATCOM performance at a wind farm and a grid-connected solar photovoltaic system, 10 kVA

University of Strathclyde

- Loss of mains connection detection (machine based, 80 kVA)

CENER – National Renewable Energy Centre

- Wind turbine and converter testing, 6/8 MW

In development

- Clemson University: 15 MW wind turbine-generator/converter
- NREL: 1 MW converter (general) and 7 MW dedicated wind
- Austrian Institute of Technology: 700kW PHIL for renewable energy devices
- University of Aachen: 5 MW PHIL for rotating machines and converters

Conclusion and Outlook

- State-of-the-art Power HIL
  - Feasibility of MW-range setups
  - Planned expansions
    - Medium voltage direct current
    - Industrial communication systems
- Focus on laboratory prototypes
  - Early stage components testing
- Make CHIL and PHIL main stream approach
  - Potential high value in early-stage de-risking / TRL acceleration – need further work and case-studies to quantify
- Move to systems-of-systems testing
  - Integration of various domains
  - Power, control, electrical, thermal, communication systems
- Virtual environments for Microgrids and Smart(er) Grids
  - Component testing, SCADA integration, feeder M&S, testing distributed and wide area control schemes, real-time data generation & analysis
  - Current lack of models: use PHIL to facilitate model standards
  - High-penetration scenarios: predict consequences

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The Center for Advanced Power Systems (CAPS) currently serves several industry clients and is well positioned to accommodate others. A brief background, history, and capabilities are described in the overview and capabilities document.

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