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

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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
Major Collaborative Research and Education Initiatives in Energy with CAPS Participation

- 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
- Florida State University
- Mississippi State University
- University of South Carolina
- University of Texas at Austin

Future Renewable Electric Energy Delivery and Management (FREEDM) Systems

Engineering Research Center (ERC)

The Sunshine State Solar Grid Initiative (SUNGRIN)
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

5 MW MVAC and LVDC facility

Offices and labs

5 MW MVDC facility (future)
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

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

Voltage / current reference / feedback from / to RTDS

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)

0-480 V / 1.5 MVA experimental AC bus (ungrounded)
CAPS Facility Capabilities

- 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
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
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

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

OS-RedHat Linux
OS-Windows

Host

CPU

Simulink Model

Coded Model

XilinX Blockset Model

16 DO  16 DI

Carrier (op5210)

16 AO  16 AI

Carrier w (op511x)

16 DO  16 DI

Carrier (op5210)

Other Targets

FastCom

PCI Express

FPGA (Spartan 3)

PCI EXPRESS

EMTP-RV INTERFACE

Other Third-party software

J MAG-RT RT-EVENTS ARTEMiS

XILINX XSG RT-LAB, QNX, LINUX, XSG, ORCHESTRA

SIMULINK MATLAB RTW

Stateflow SimPower Systems
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

External Hardware

Simulated System response

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 provided by Bonneville Power Administration.
- RT simulation model captured all the provided data sets reasonably well.

![Voltage at wind farm graph]

- From transient recorder (time resolution 0.5ms)
- From RTDS model (time resolution 0.05ms)
- From RTDS model (time resolution 50μs)
- From transient recorder (time resolution 10μs)

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

160 min
HIL Test Bed for Distributed Grid Intelligence

DGI Computing Platform

MAMBA Board Cluster (Boards #1 - #6)

Ethernet Switch

Xilinx Virtex 5 FPGA

Digital Communications Backbone

Real-Time Digital Simulator

Pilot Protection Algorithm (Compact Rio Platform)

Trip Alert to DGI
HIL Test Bed for High Penetration PV Studies

Circuit model based on Jacksonville Electric Authority feeder

Sunshine State Solar Grid Initiative (SUNGRIN)

RTDS

Substation

Breaker

CT

Load 1

Load 2

Load 4

Load 6

Load 7

Load 8

Existing Solar Farm

Relay settings tool

Communication interface

Low level signal

Breaker trip signal

Hardware relay

12/2/2011
Examples of Power Hardware in the Loop (PHIL) Simulation Projects
PHIL Interface Algorithm Instabilities

\[ z_S = 2\Omega \]
\[ z_L = 1\Omega \]

\[ \Delta v_2(k) = \varepsilon, \quad \Delta i_2(k) = \varepsilon/z_L \]
\[ \Delta i_2(k) = \varepsilon/z_L, \quad \Delta v_1(k+1) = -\varepsilon z_S/z_L \]

Error \( \varepsilon \) is amplified by a factor of \(-z_S/z_L\)
Imperfect Interface Causes Simulation Errors

**Original Circuit**
- R1 (20ohm)
- R2 (0.1ohm)
- Vs (1V, 60Hz)
- VO

**Highly precise amplification**

**PHIL Implementation**
- Interface uses relaxation method where a common component is implanted both in hardware and in software

**Simulated**
- Vs
- VO

**PHIL**
- V_FB = V2
- V4MP

**Hardware**
- V2
- R3

**Large error in the PHIL simulation result**

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**: Gas turbine generator, Transformer, Voltage amplification, Current source representing the motor load, Torque reference.
- **Interface**: AMP, I_{LOAD}, Current feedback, Torque reference, A/D D/A.
- **Hardware under Test**: TF1, TF2, VSD1, VSD2, MT1, MT2, VSD1, VSD2, 208V Grid, 20hp Motor / dynamometer set with variable speed drives (VSD).

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- Gas turbine generator: 100kVA, Transformer: 208V / 208V, Pulse load: (40kW / 0.1s).
- Current feedback: PEBB based PWM type converter, fs = 10 kHz, 50 kW.
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
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
PHIL Experiments
High-Speed Generator Testing

Moved from CHIL:
- Excitation controls
  Initially: ns-range time steps
To full-scale PHIL
- Startup, shutdown procedure
- Steady-state
- Dynamic loading (ramping)

Simulated electrical load
- VVS converter in DC mode
- Diode rectifier
- Generator under test

Real-time simulator RTDS
- Exciter
- Gear box 2
- Gear box 1
- Dynamo-meters

Simulated prime mover
- Drive system

Variable Voltage Source
- CAPS 480 V bus (utility connected)
- CAPS 4.16 kV bus (utility connected)
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

Measured Quantities
- Voltage
- Current
- Speed/Torque

DAQ

Open/Close

Trigger/Synch

Voltage/Current/Duty Cycle

VVS Gearbox DynoGenerator

Rectifier

RTDS

Gearbox

Dyno

Speed

Voltage

V, I, oil flow, and temperature

TCIPG_Seminar_Steurer
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

DC Bus: 0-1150VDC
I max = +/- 2.5 kA

PV Inverter up to 1.5 MW

AC Bus1: 0-4.16 kV
I max = 0.433 kA

AC Bus2: 0-0.48 kV
I max = 1.8 kA

Unbalanced voltage condition
Expansion: Real Time Integrated Controls Network Simulation Environment

- 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
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
How to do Business with CAPS

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.

CAPS provides a secure infrastructure and environment for all types of sensitive research. Physical, technical, and administrative measures ensure the security of our facility, on-site equipment and data. CAPS’ research facilities feature controlled entry and computing equipment configured to accommodate only authorized users and appropriate use. In addition, staff are regularly trained in security procedures. These measures provide controlled, auditable access to our facility and secure storage of data. Learn more about our Document Control procedures.

For additional information about doing business with the CAPS, contact Steve McClellan at (850) 645-2157.

http://www.caps.fsu.edu/documentcontrol.html