Controller and Power Hardware-In-Loop Methods for Accelerating Renewable Energy Integration

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- FSU/CAPS System Simulation and Power Testing Competence
- Controller Hardware-In-Loop (CHIL) and Power Hardware-In-Loop (PHIL) Simulations
- Examples of CHIL and PHIL Experiments

FSU - Center for Advanced Power Systems

- Established at Florida State University in 2000 under a grant from the US Office of Naval Research (ONR)
- Focus on research and education related to application of new technologies to electric power systems
- Member of ONR Electric Ship R&D Consortium

  FSU, MSU, USC, UT-Austin, MIT, Purdue,
  Naval Academy/Navy Post Graduate School

Grant No. N0014-02-1-0623

ELECTRIC SHIP RESEARCH ESRDC AND DEVELOPMENT CONSORTIUM

U.S. Department of Energy
Grant No DE FG02 05CH11292

Staffing:

– 36 scientific, engineering and supporting staff, including

– 9 faculty (9 mo teach and 12 mo none teach)

– 5 post docs

– 4 visiting scientists

– >20 graduate students from FAMU-FSU CoE

– 34,000 square feet **offices** and **laboratories**

– Facility based on grants from the US Office of Naval Research (ONR) and the US Department of Energy (DOE): $20 million capital investment

– Annual Operating budget: $4 million

– Preparing for the the ability to perform **classified research**

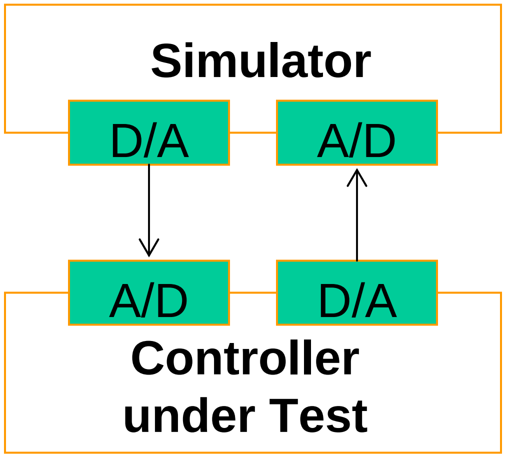
CAPS Large-Scale High-Fidelity Transient Power System Simulation

- Largest **real-time digital simulator** (RTDS) installation in any university, worldwide
- Systems studies sized up to **250 three-phase buses** at **50/2μs time steps**
- High-speed analog I/O to enable **realistic control and power HIL experiments**
- Additional off-line simulation tools, i.e.: *EMTDC*, *Matlab*, *PSS/E*
- Established expertise in **understanding the details** of novel and legacy power system apparatus and their **interaction with the system**
- **Knowledge in system simulation** methods, analysis, and interpretation of results

CAPS High Power Laboratories

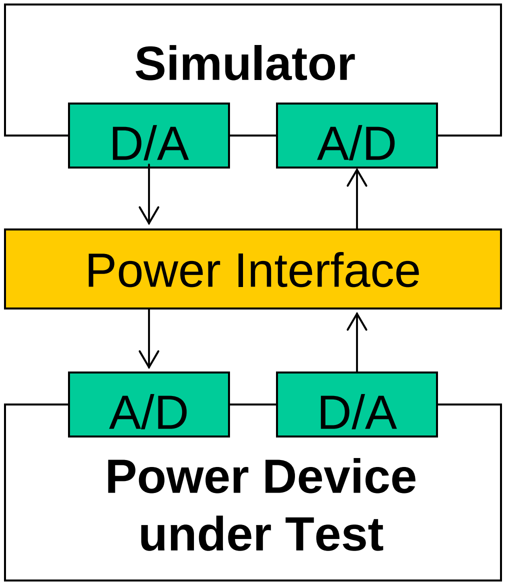
- Power apparatus and systems laboratory up to **5 MW @ 12.47 & 4.16 kV**
- Integrated with the RTDS for unique **power and control HIL experiments**
- **Established expertise** in advanced testing of apparatus under simulated system conditions

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



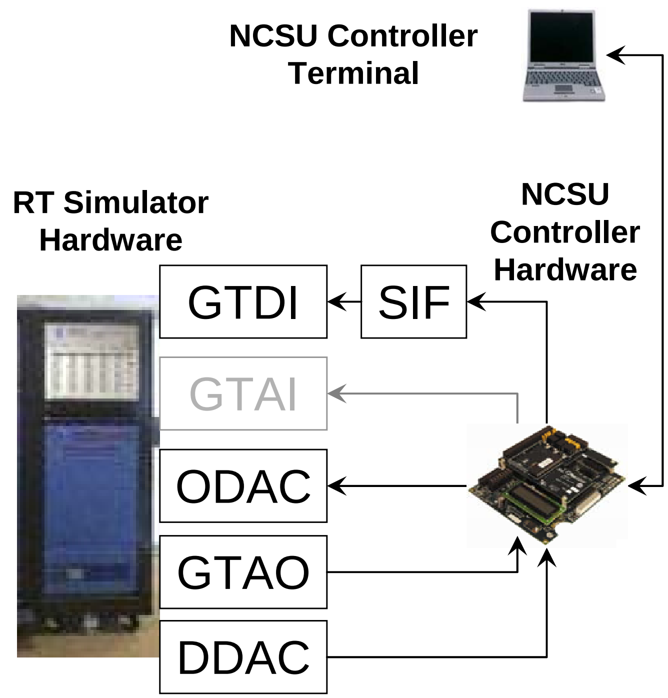
- Controller HIL Simulation
  - Controller under test
  - Low level transmitting signals (+/-15V, mA)
  - A/D and D/A converters are adequate for the interface

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

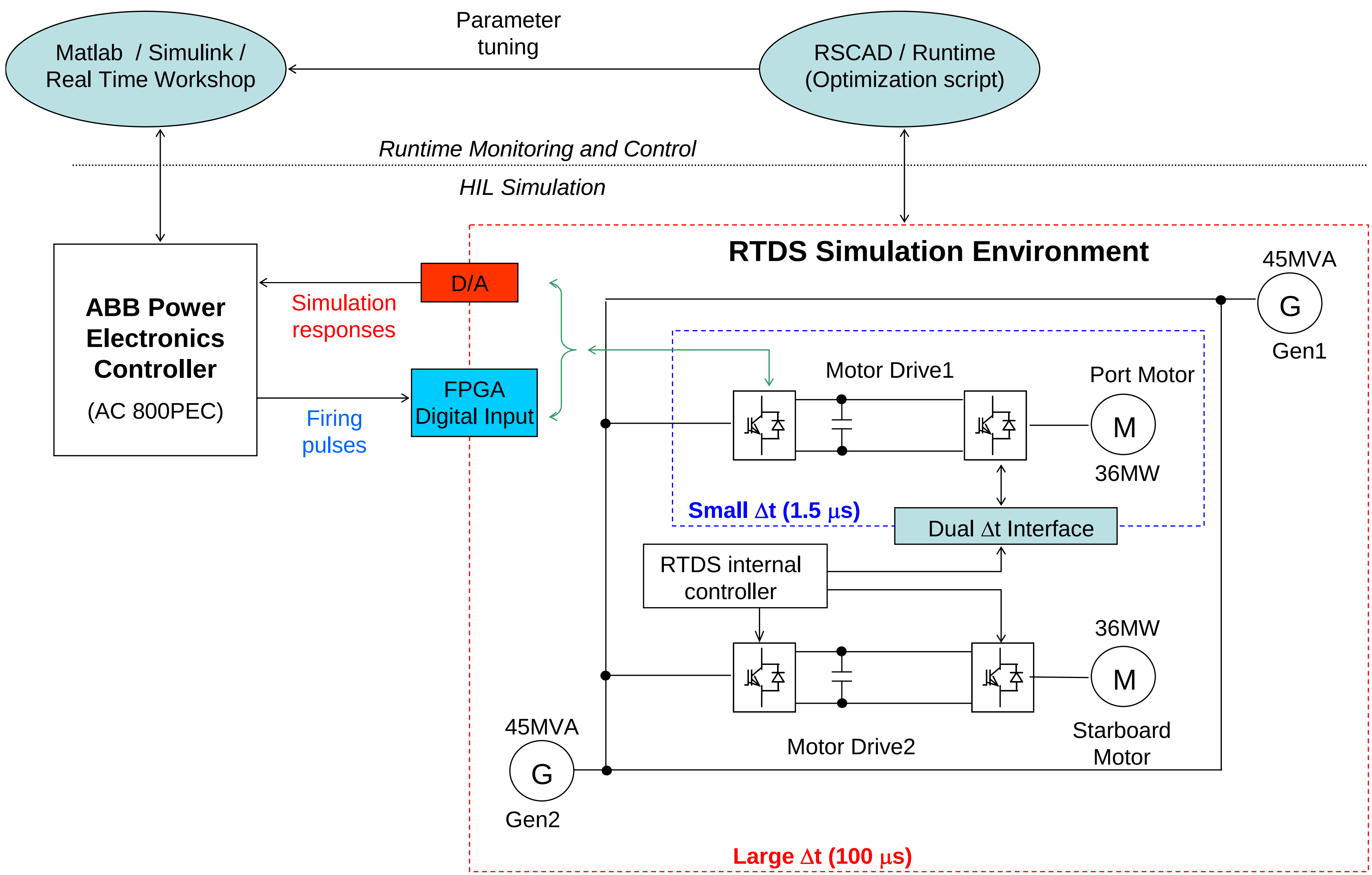


Why CHIL Simulations?

- Mitigate risks for all stakeholders
- Will allow optimal tuning of control parameters for fastest possible commissioning
- Will potentially reveal
  - Hidden issues in control algorithm and real-time controller run-time environment
  - Unpredicted interactions between and surrounding utility system (i.e. protection equipment, capacitor-bank switching, etc.)
  - Unpredicted interactions between the equipment and other controlled devices (i.e. near by FACTS)
- The key for success of HIL testing is a system model that contains sufficient detail such as
  - Realistic model capturing system behavior
  - Sufficient detail of surrounding control and protection systems
  - Sensor characteristics (e.g. saturation)
  - …



RT-HIL Simulation Based Optimization with RTDS Small Δt-Loop Capability



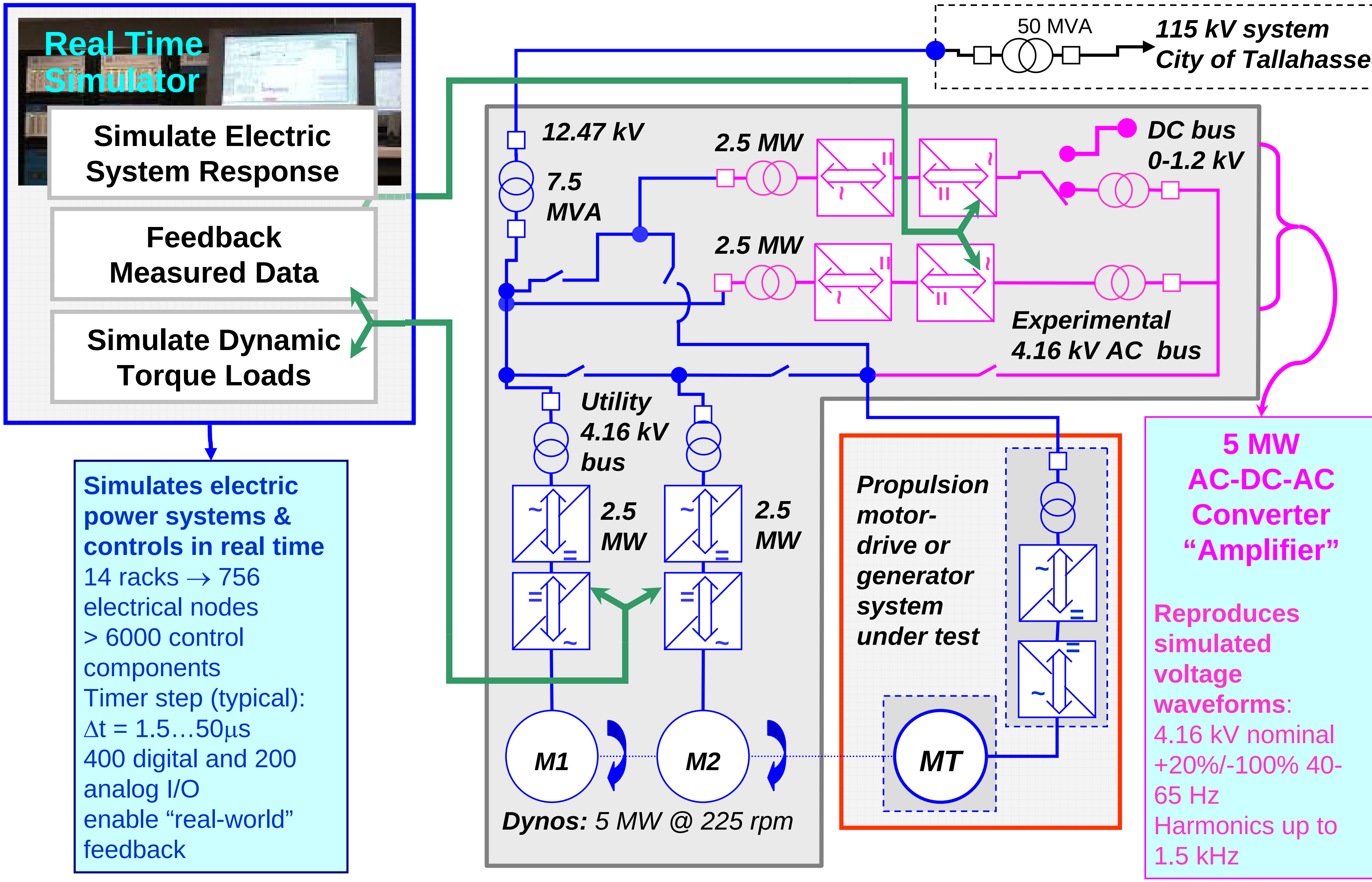
Why PHIL Simulations?

- Will allow highly dynamic testing of R&D prototype power apparatus
  - Complex operating scenarios (i.e. faults, pulse loads, etc.) become possible in a controlled lab environment
- Will potentially reveal
  - Thermal management performance
  - Power control performance under realistic system conditions
  - Problems with any details not considered in software model of the hardware under test (HUT)
- The key for realistic PHIL testing of electrical equipment is the unique 4.16kV/6.25MVA variable AC/DC bus facility
  - Complete commissioning expected 3Q of 2007

5 MW HTS Propulsion Motor at CAPS during electromechanical PHIL testing in 2004

5 MW RTDS-PHIL Facility at CAPS

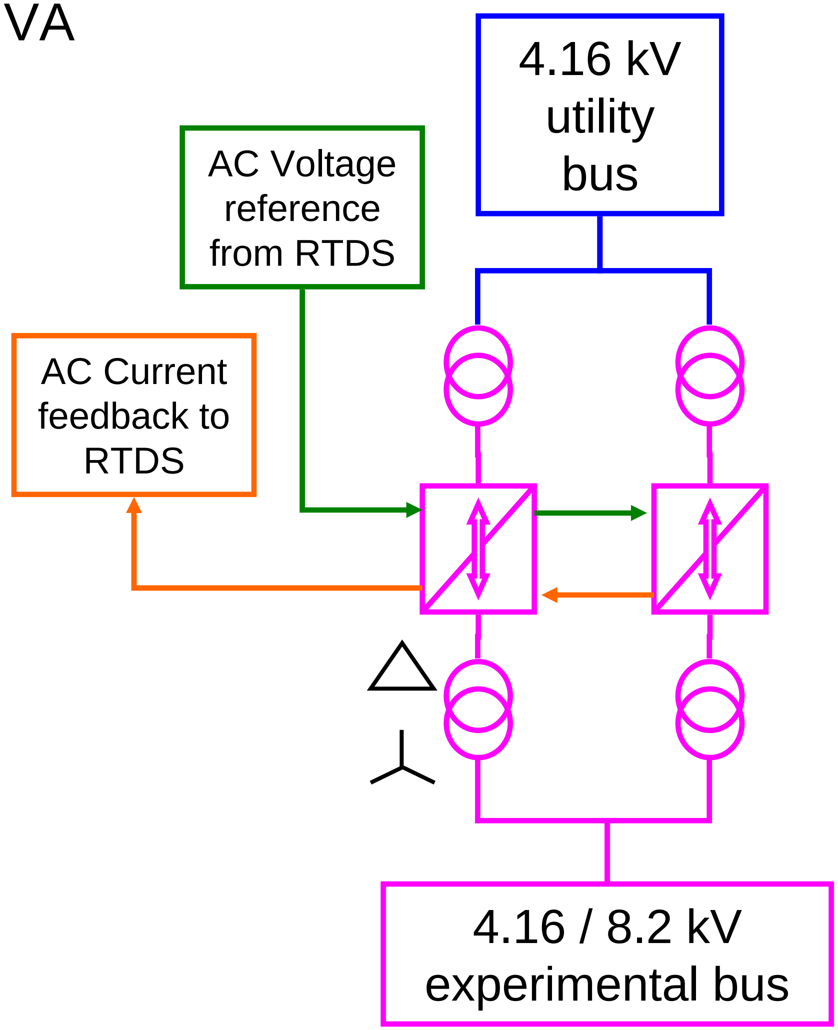
PHIL…Power-Hardware-in-Loop



Equipment manufactured, complete
Commissioning expected early 2Q 2007

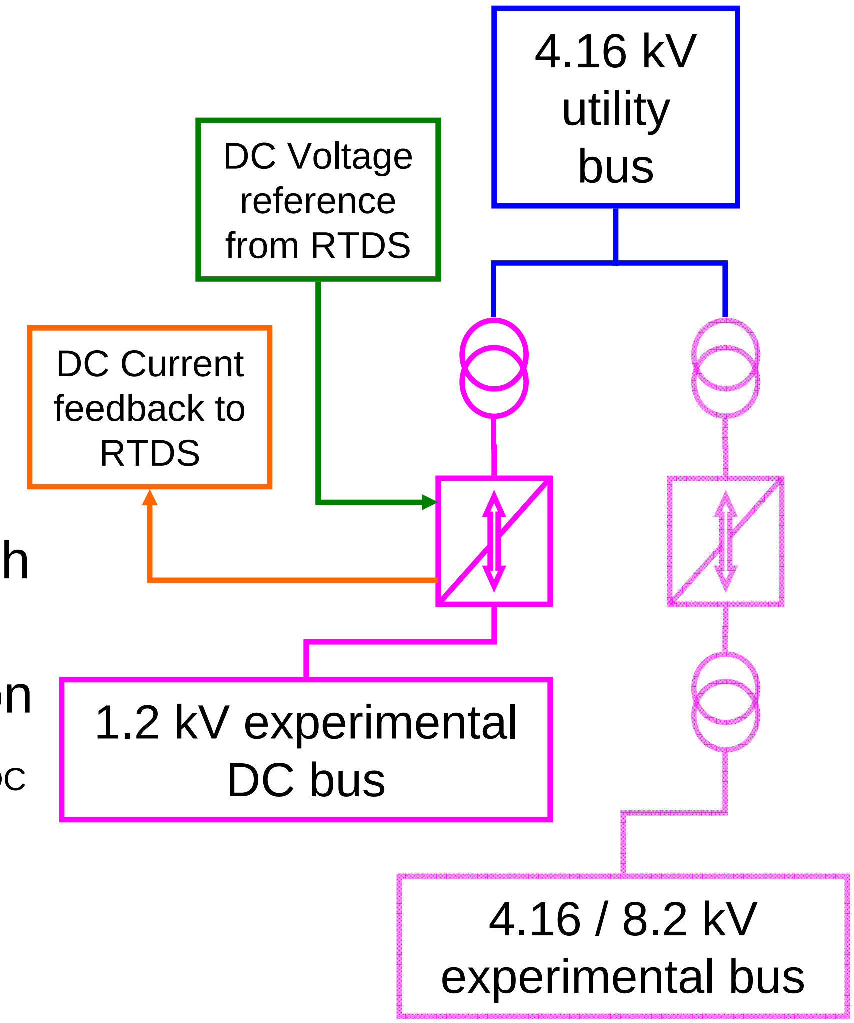
5 WM PEBB-based "signal amplifier" Key Specifications – AC source

- Continuous power rating 5 MW / 6.25 MVA
- Full 4-quadrant operation
- Output voltage range
  - 0…120% (4.16 kV nominal setting),
  - 0…100% (8.2 kV setting, 50% power)
- Y output w/ accessible neutral
- Current overload capability
  - 130% 10s every 10 min
  - 165% 1s every min
  - 193% 87ms every min
- Base frequency range 40 – 65 Hz
  - 400 Hz possible for short time
- No-load and full load voltage THD $\leq$ 1%
- Experimental side switching frequency
  - IGBT devices 5 – 8 kHz
  - Twin configuration effective 10 – 16 kHz
- Filter cut-off frequency 1800 Hz

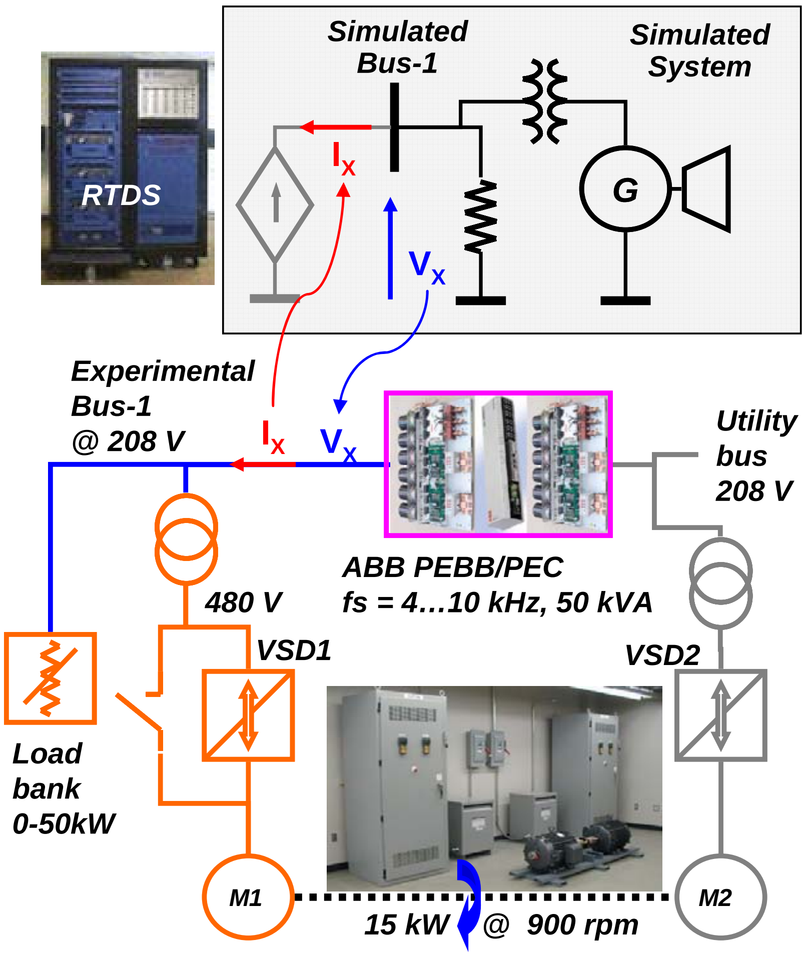


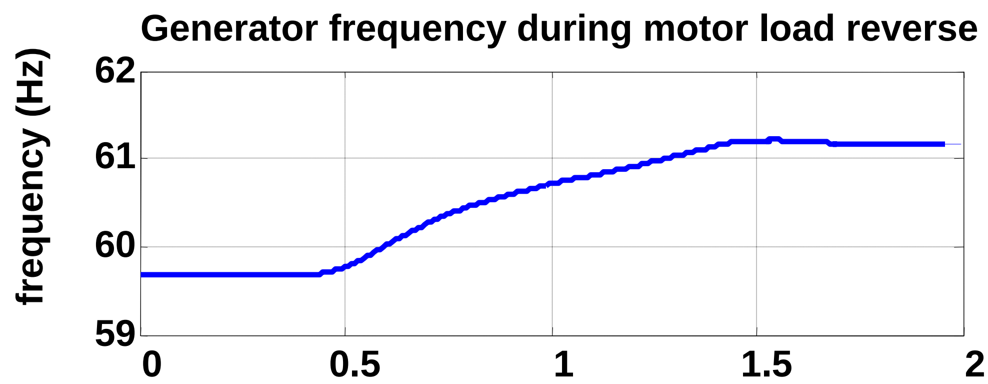
5 WM PEBB-based "signal amplifier" Key Specifications – **DC source**

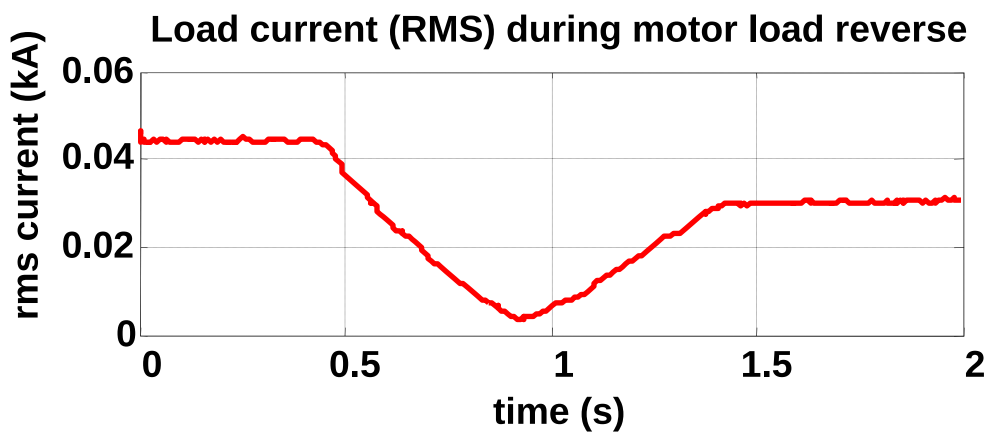
- Continuous current rating 2.5 kA
- Full 4-quadrant operation
- Output voltage range
  - 0.6…1.15 kV (1.5 – 2.8 MW)
  - 0…0.6 (reduced linearity)
- Bi-polar DC **ungrounded**
- Full-load voltage regulation ≤ 1%
- Closed loop voltage control bandwidth limit ≥ 1 kHz (for 200 V step request)
- Facilitates combined AC/DC operation
  - 2.5 MW/4.16 kV_{AC} and 2.5 MW/1 kV_{DC}



16 kW PHIL of a Gas Turbine with Motor Drive

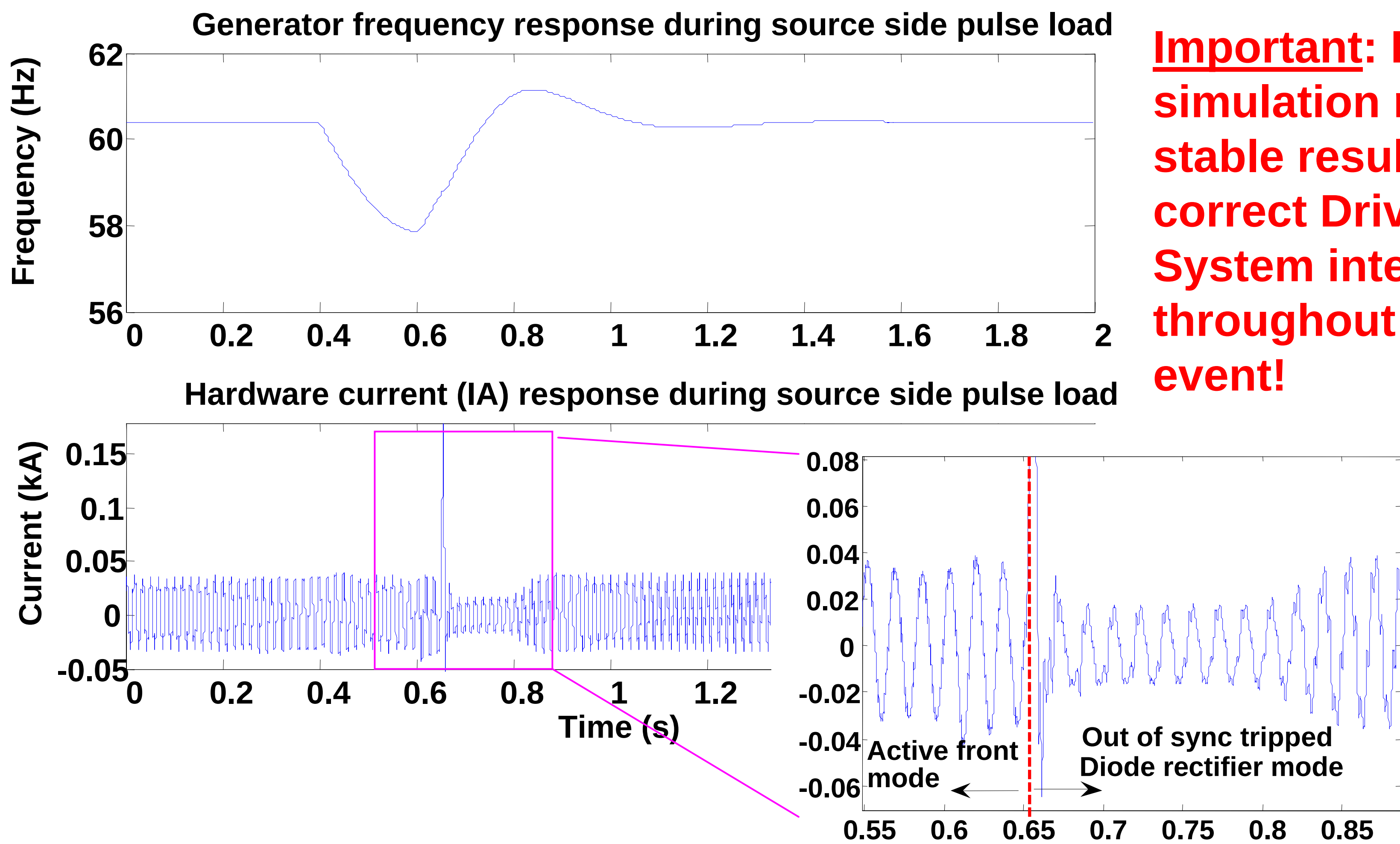






Experimental results from
50 kW PEBB system

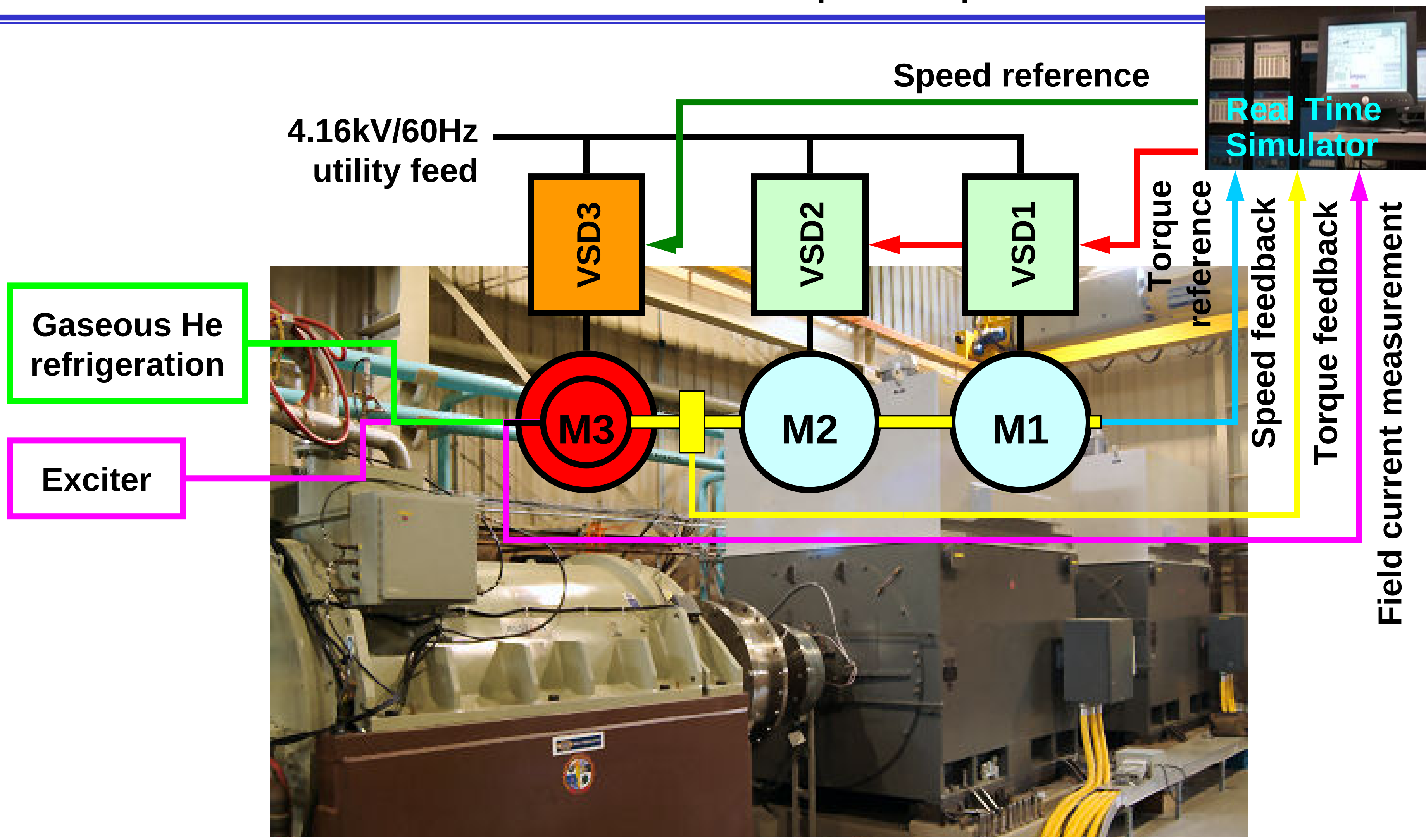
16 kW PHIL of a Motor Drive Trip after Pulse Load



<u>Important</u>: PHIL simulation remained stable resulting in correct Drive-System interaction throughout the event!

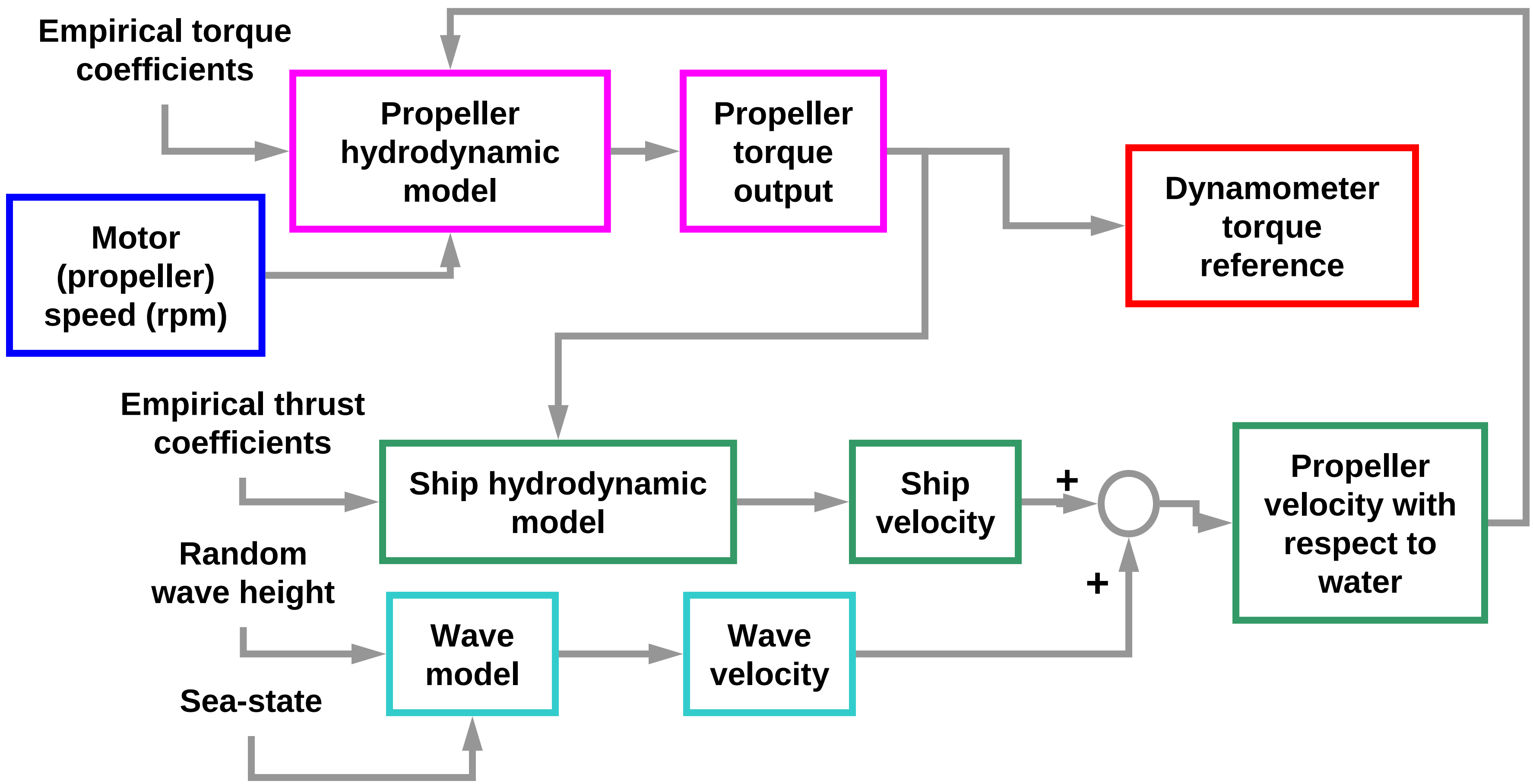
Experimental results from 50 kW PEBB system

5 MW HTS Propulsion Motor
Power Hardware-in-Loop Setup at CAPS

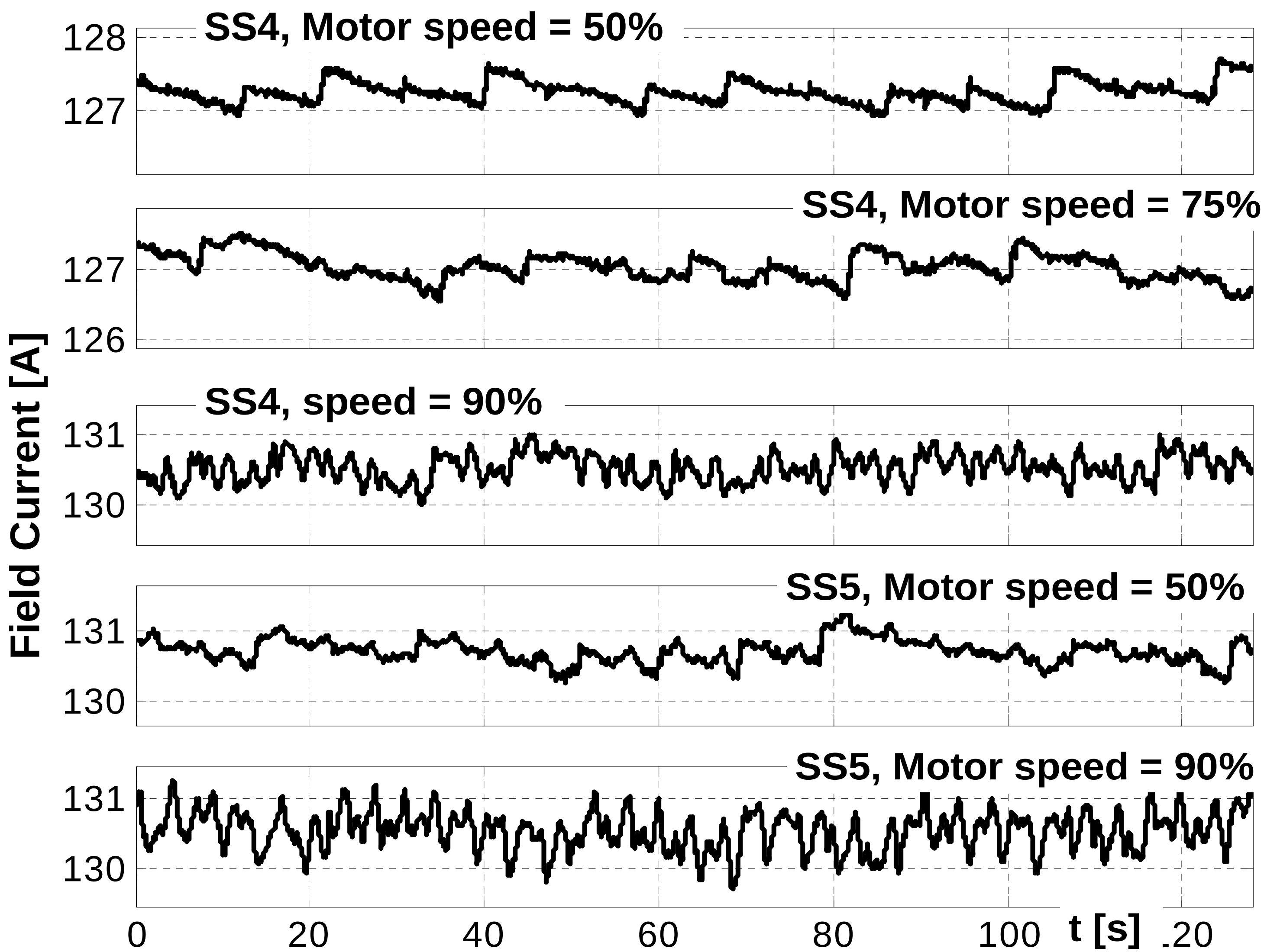


M. Steuer, S. Woodruff, T. Baldwin, H. Boenig, F. Bogdan, T. Fikse, M. Sloderbeck, and G. Snitchler, "Hardware-in-the-Loop Investigation of Rotor Heating in a 5 MW HTS Propulsion Motor", presented at the Applied Superconductivity Conference 2006, Seattle, WA, USA, and accepted for publication in the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

Sea-State Hydrodynamic Model

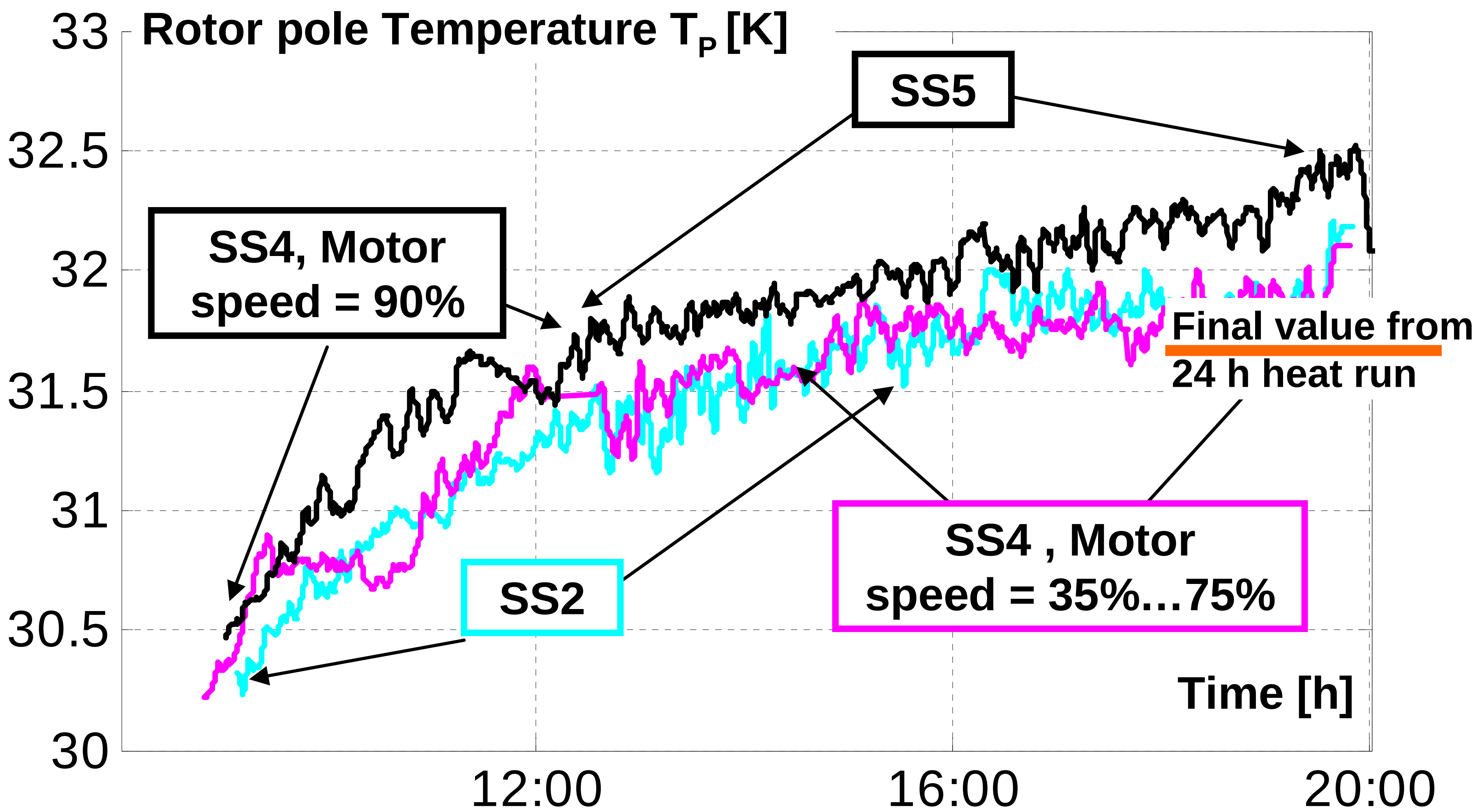


Field Current Waveforms



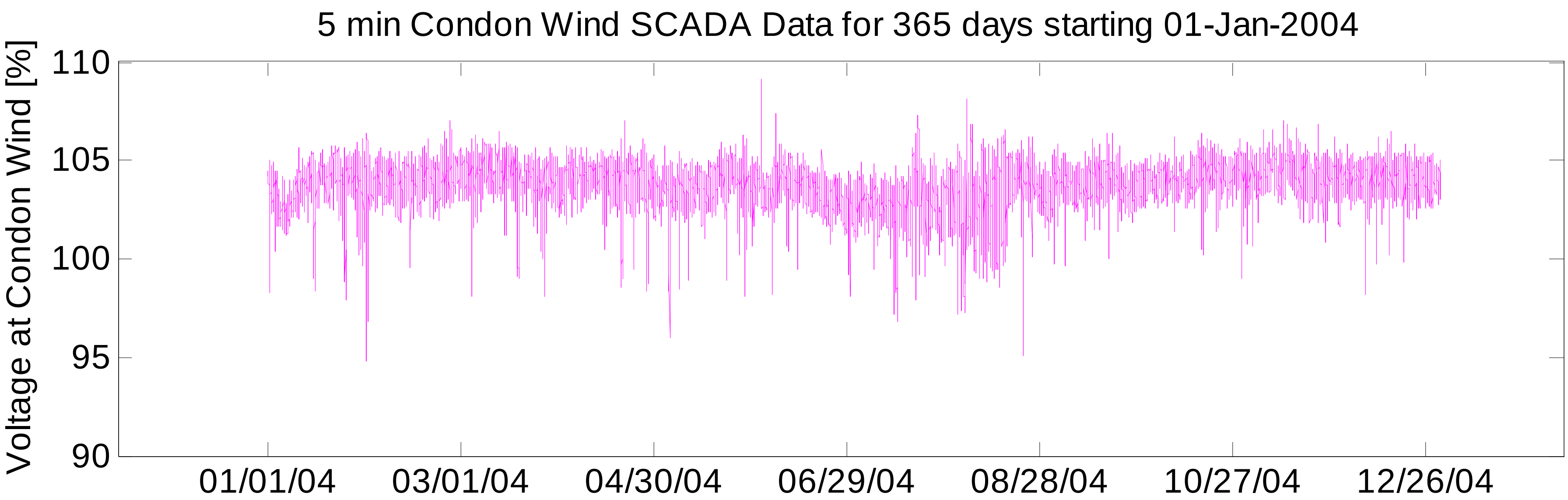
Axis limits: Field current: ±1A

Heating from Sea-State Multi Frequency Torque Oscillations

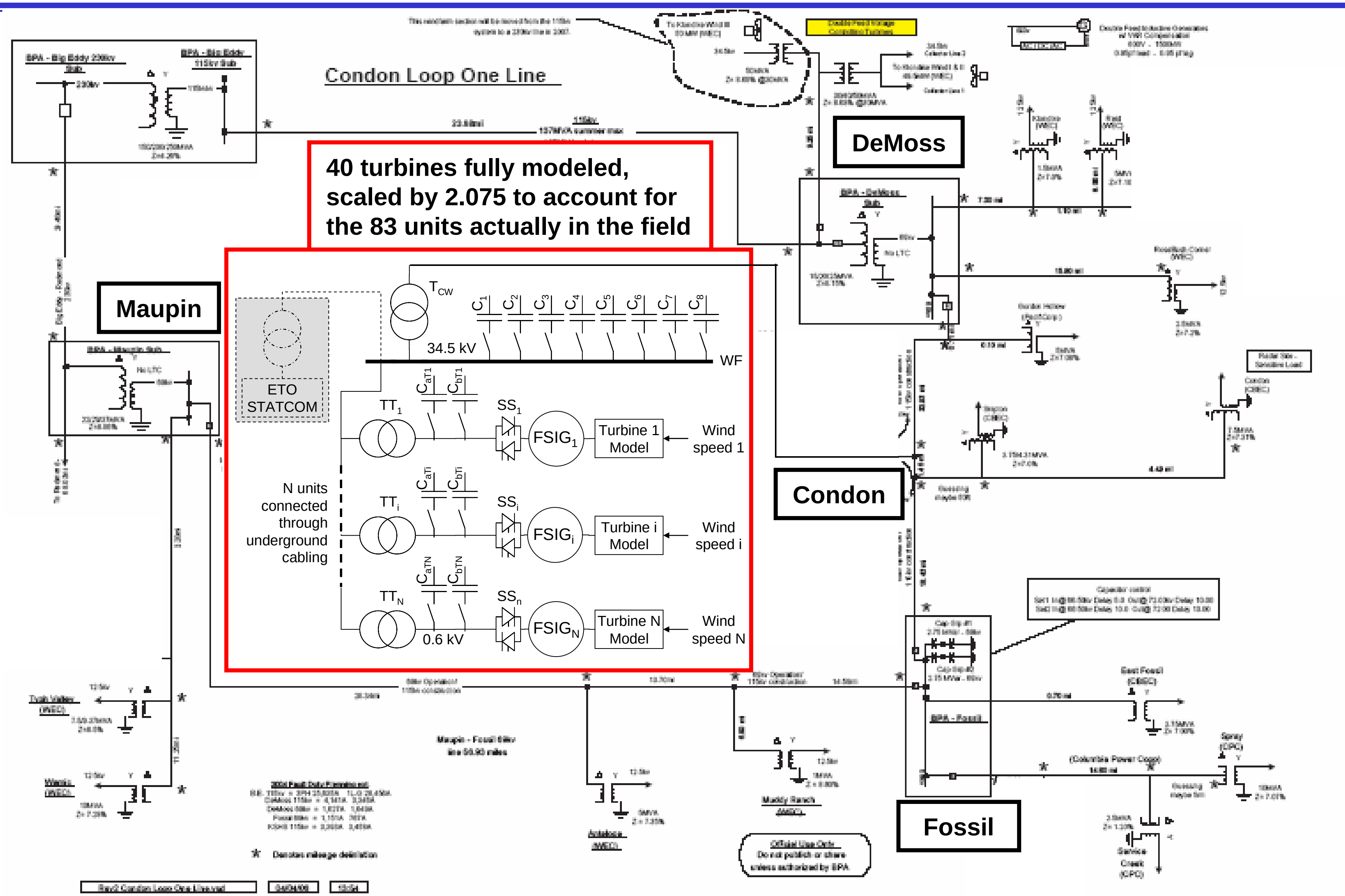


Testing 10 MVA STATCOM for Wind Farm

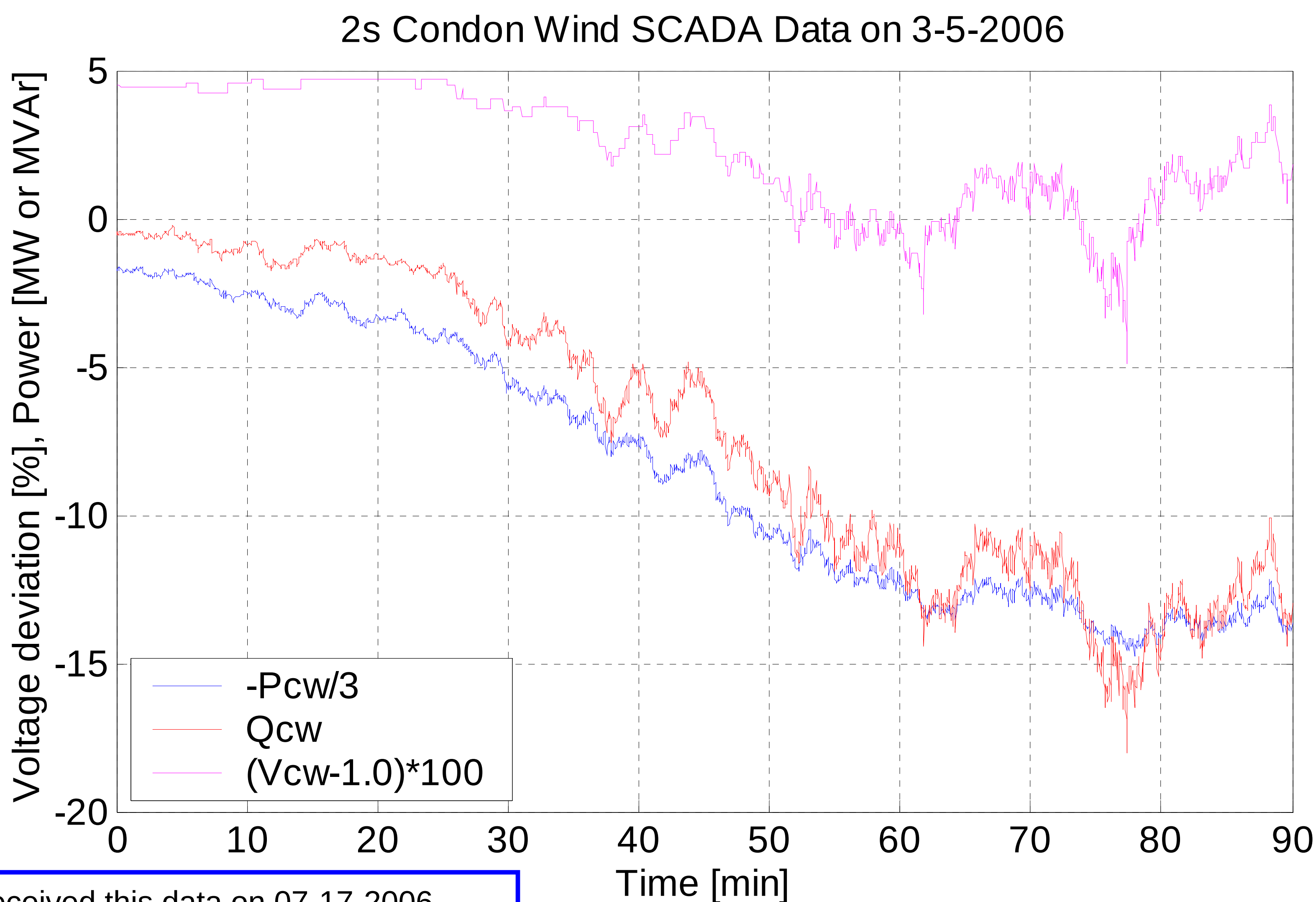
- Investigate feasibility and performance of NCSU's ETO STATCOM on an existing wind farm with voltage fluctuation problems
  - Provide guidance to BPA & NCSU on STACOM sizing and wind farm behavior
  - Test new controller in CHIL setup
  - Test power converter ion PHIL setup
- Investigate high-fidelity wind farm aggregation



40-turbine RTDS model with generic STATCOM

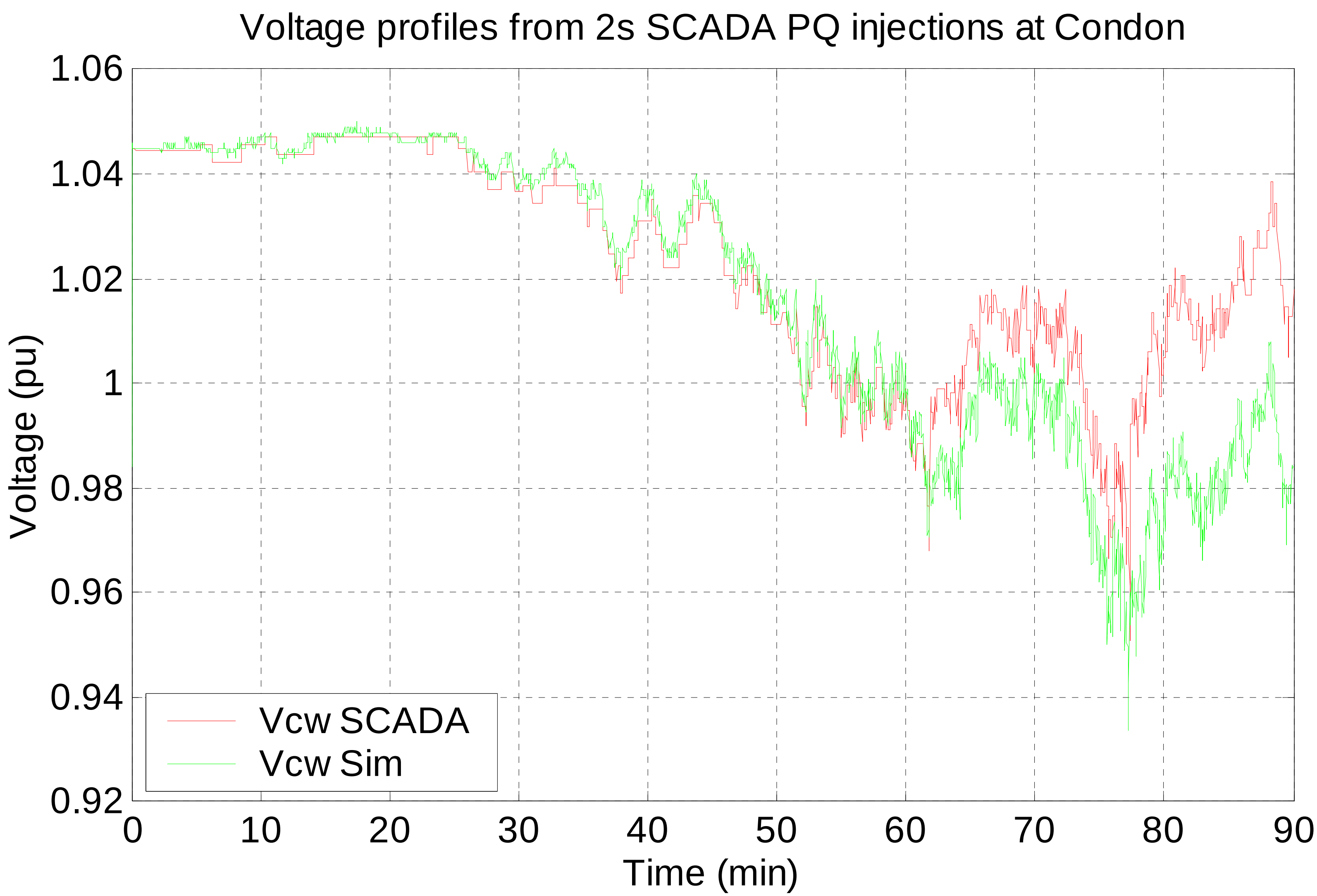


BPA model validation with SCADA data

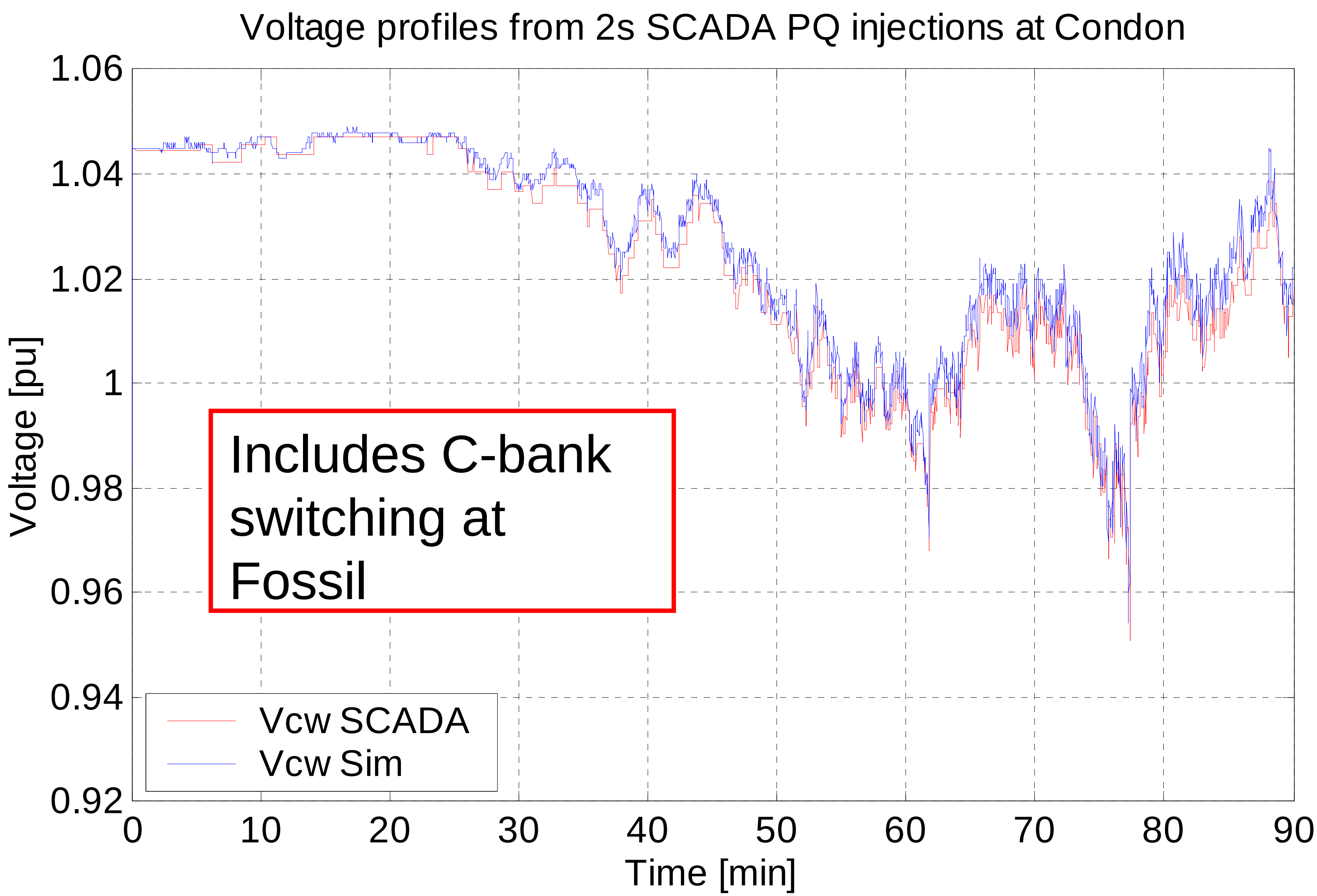


FSU received this data on 07-17-2006

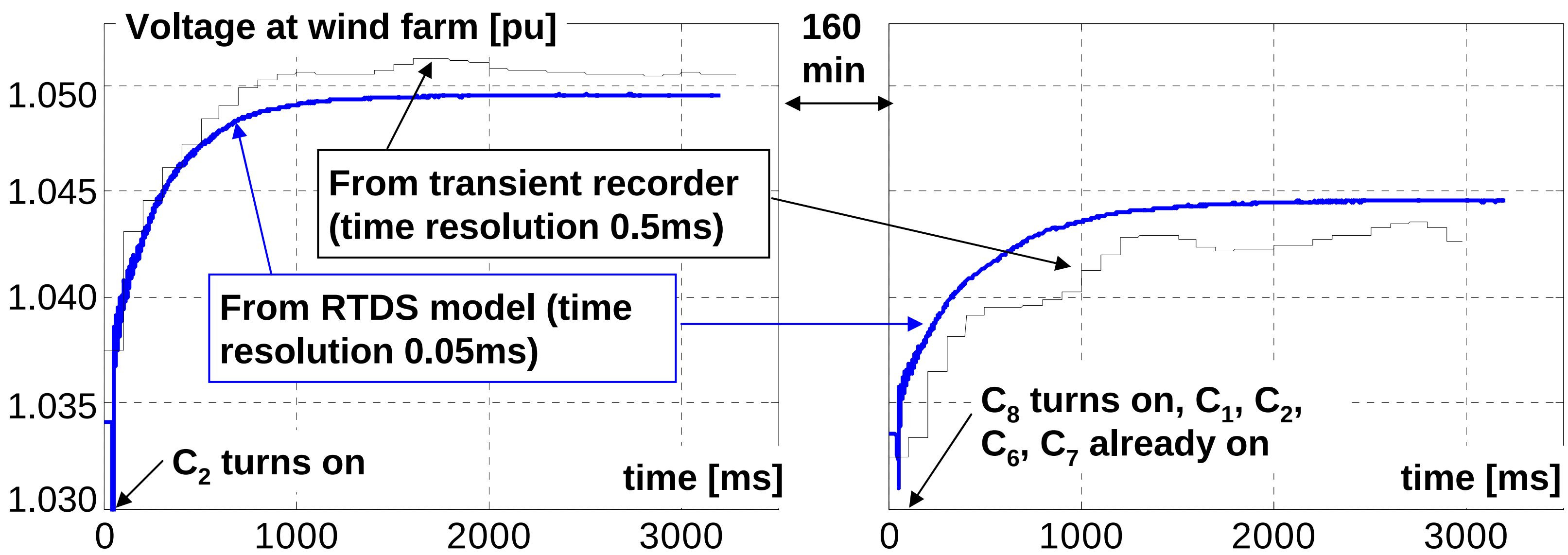
BPA model validation with SCADA data



BPA model validation with SCADA data



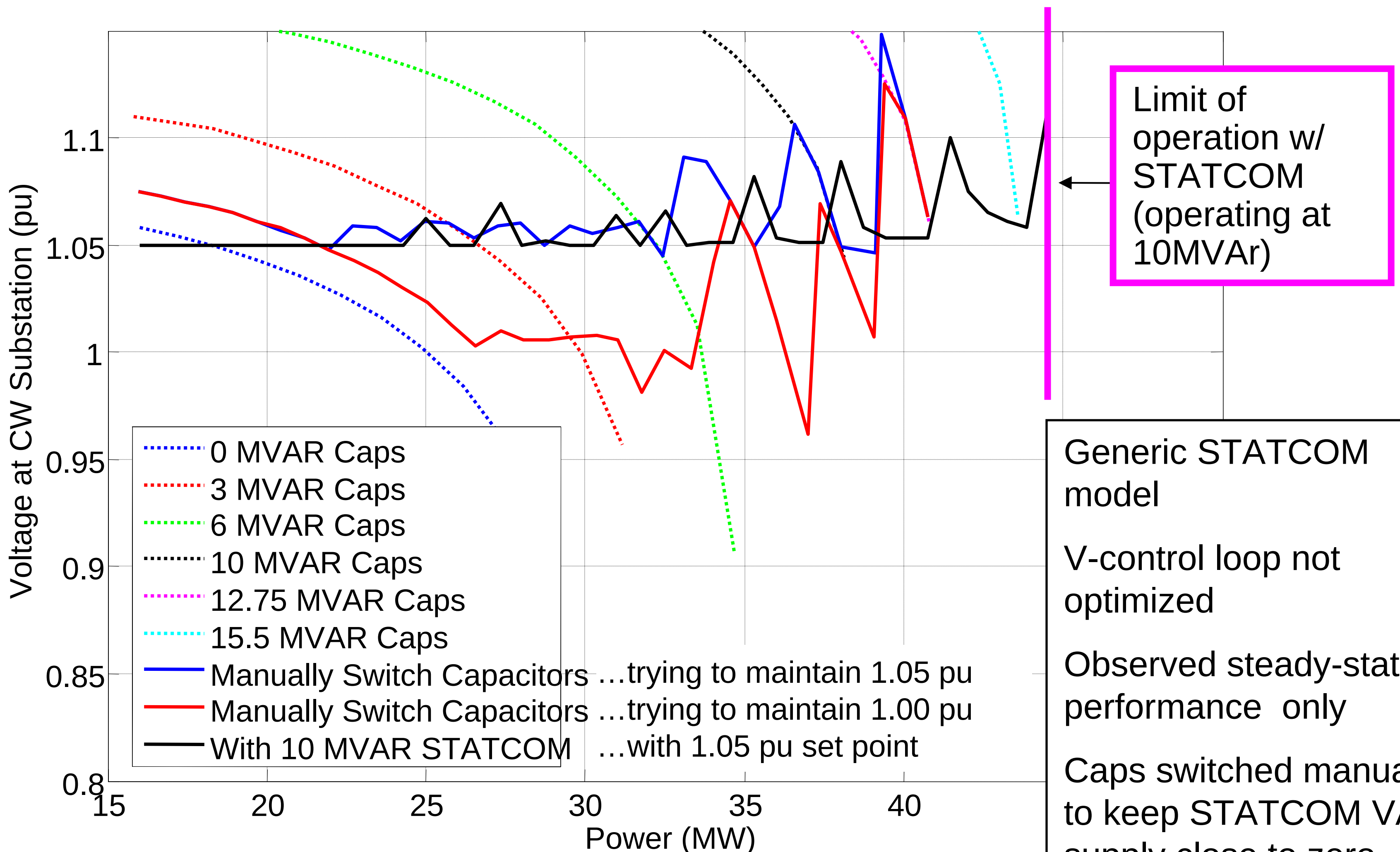
Model validation against 2 kHz data records



When cap switching control at Condon Wind works properly, the voltage stays within BPA criteria as FSU studies predicted
- As confirmed by BPA (11/22/2006)

Sea West control panel (photo Steurer, Aug 2006)

Impact of STATCOM with DeMoss Connection Open



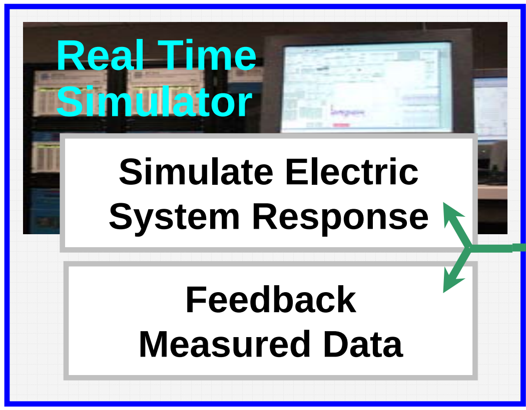
Generic STATCOM model

V-control loop not optimized

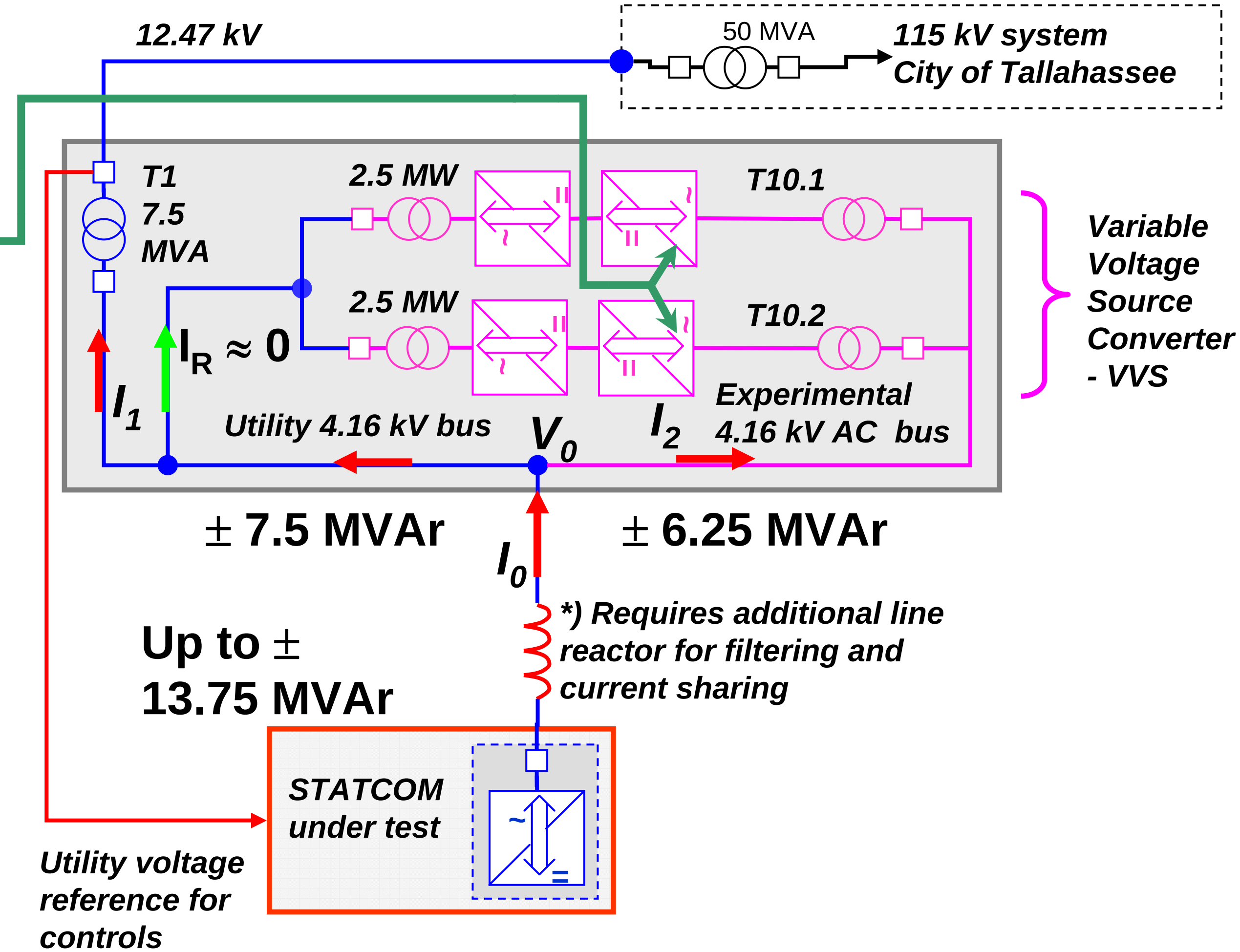
Observed steady-state performance only

Caps switched manually to keep STATCOM VAR supply close to zero

Possible Testing of a 13.75 MVA STACOM in RTDS-PHIL Facility at CAPS

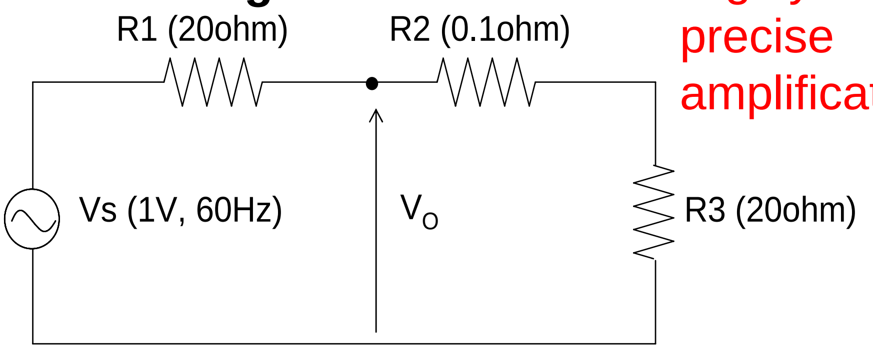


- Full power capability for 10 MVA rating
- Current regulation
- Limited system and wind farm dynamics

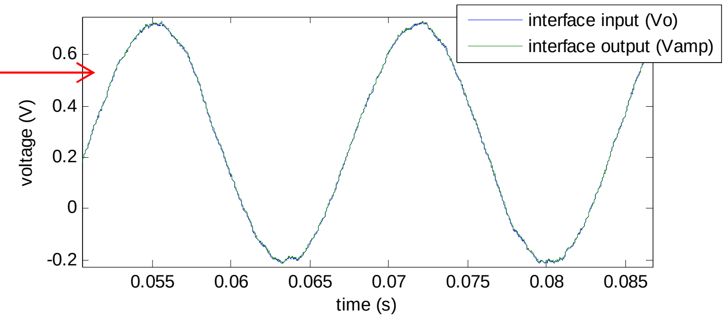


Imperfect Interface Causes Simulation Errors

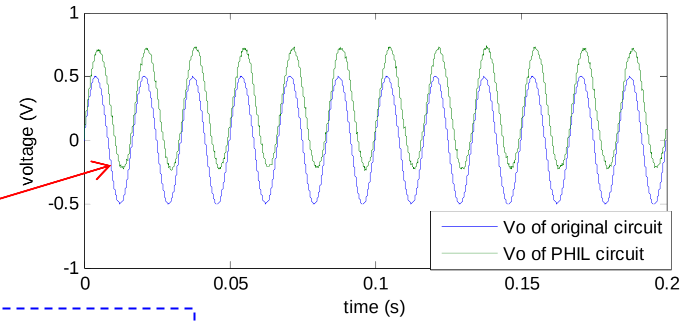
Original Circuit



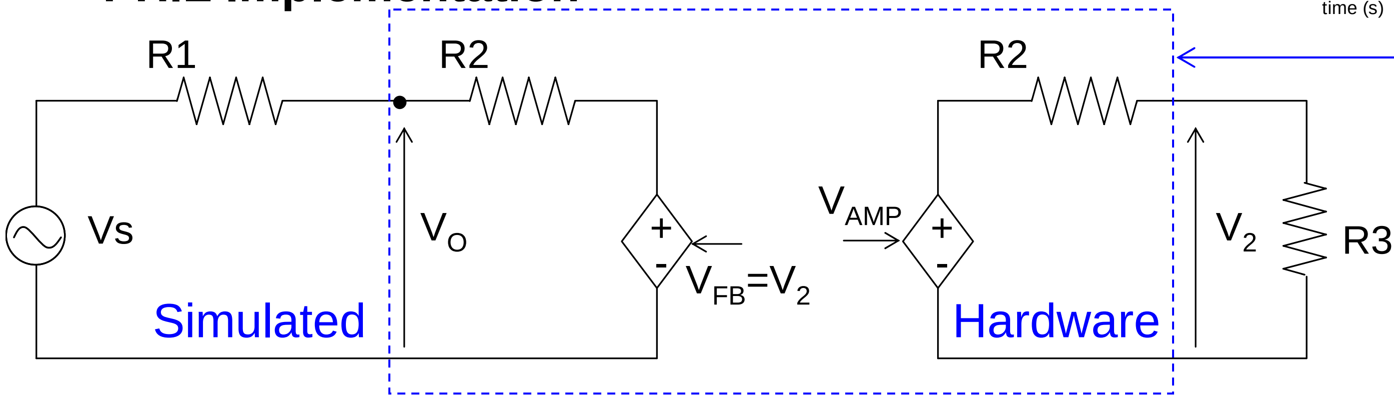
Highly precise amplification



Large error in the PHIL simulation result



PHIL Implementation



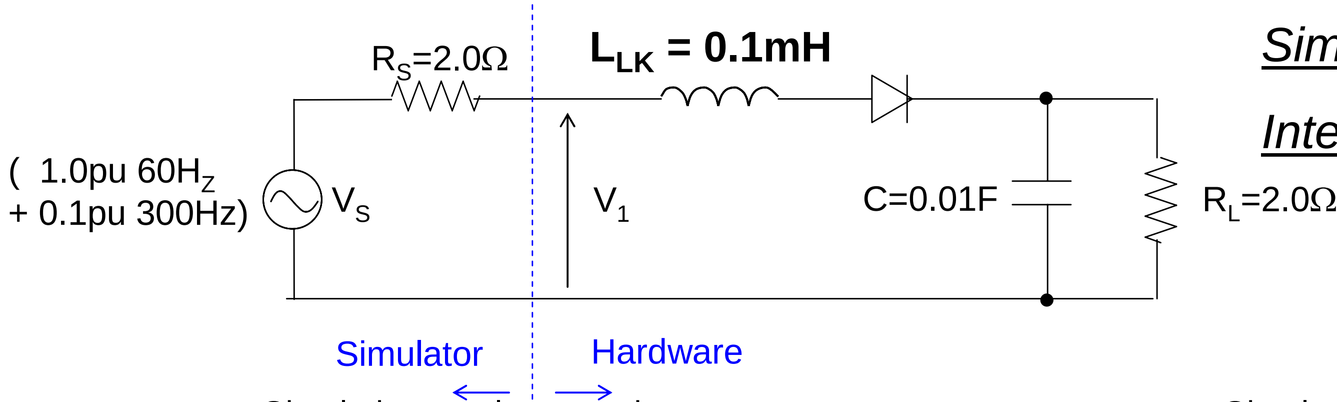
Interface uses relaxation method where a common component is implanted both in hardware and in software

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 to be held in Edmonton, ALB, Canada, May 6-10 2007

Concluding Remarks

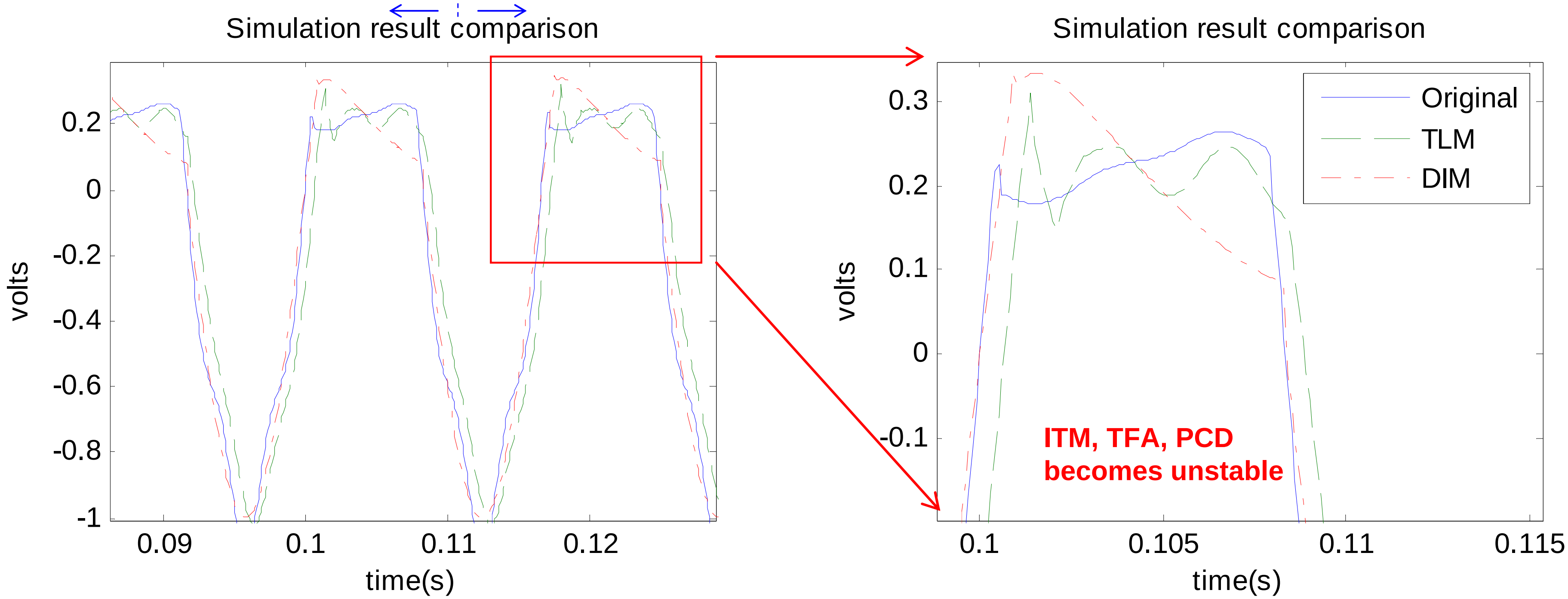
- Increasing integration of power electronics and other advanced technologies into utility power systems and renewable energy systems requires improved modeling and simulation methods, tools, and expertise
- CHIL, and especially PHIL, can reveal hidden issues not well modeled in off-line simulations
- PHIL requires further research to improve overall simulation accuracy compromised by the inherent PHIL interface characteristics
- Large computational power of CAPS RTDS setup can help with model development and validation otherwise impossible with PC based simulations

PHIL Test Case – Nonlinear Load



Simulation time step: 100μs

Interface time delay: 500μs



Lead Compensation