# Lessons Learned from PHIL Experiments with Power Converters and Fault Current Limiters

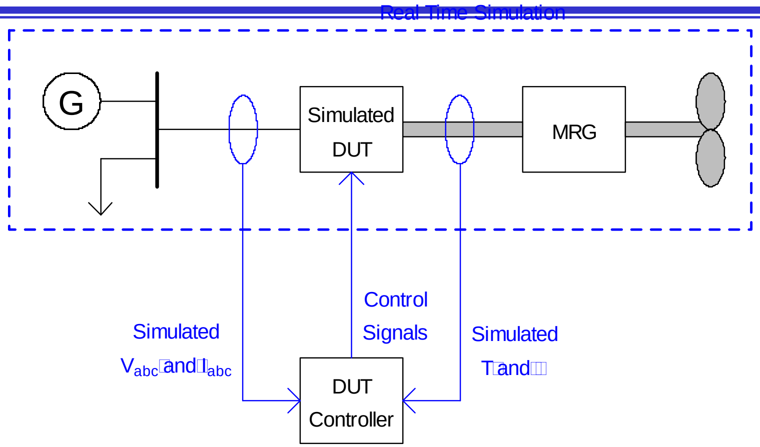
J. Langston, M. Steurer, K. Schoder
Center for Advanced Power Systems
Florida State University

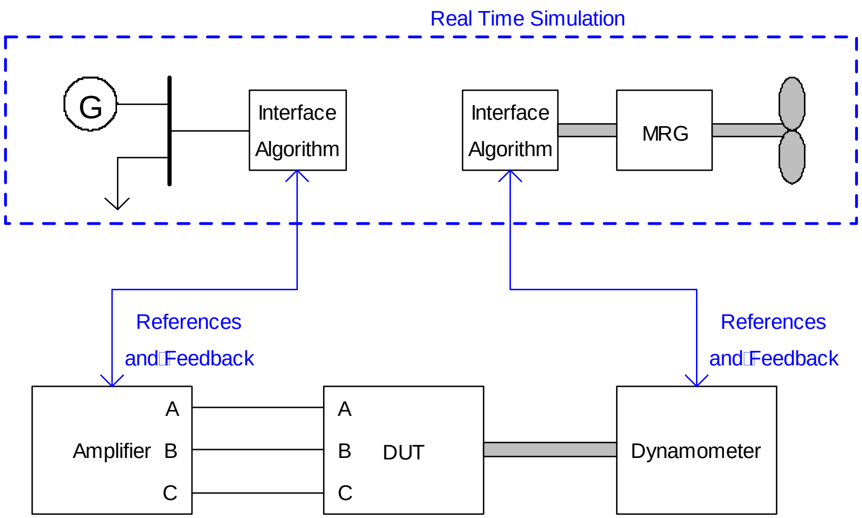
# Overview

I. PHIL
II. Lessons Learned
    I. Stability
    II. Engagement of PHIL Interfaces
    III. Accuracy
    IV. Flexibility of PHIL Interfaces
    V. Protection of PHIL Experiments
    VI. Other Points
III. Conclusion

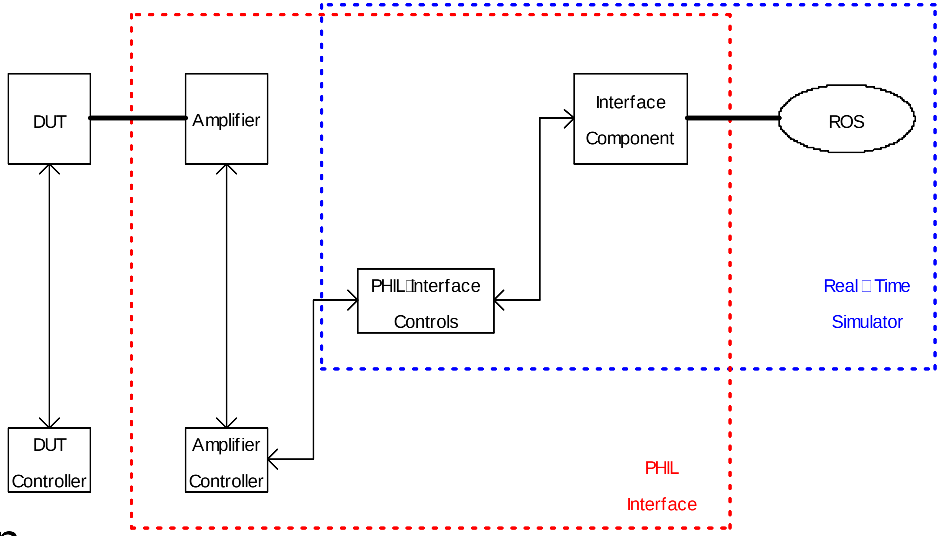
# HIL Simulation Approach

- A device under test (DUT) is interfaced to a simulated environment through HIL interfaces to a real-time simulation model
- Allows
  - DUT to be exercised in a wide range of potentially realistic environments
  - Execution of extreme conditions within controlled lab environment
  - DUT to be tested with systems not yet constructed
  - DUT to be exercised to extremes of interface specifications including controlled transients
- Controller HIL (CHIL)
  - HIL Interfaces use control level (low voltage) signals for I/O
- Power HIL (PHIL)
  - Power amplifiers and/or actuators are used for interfacing
  - Power flow over PHIL interface



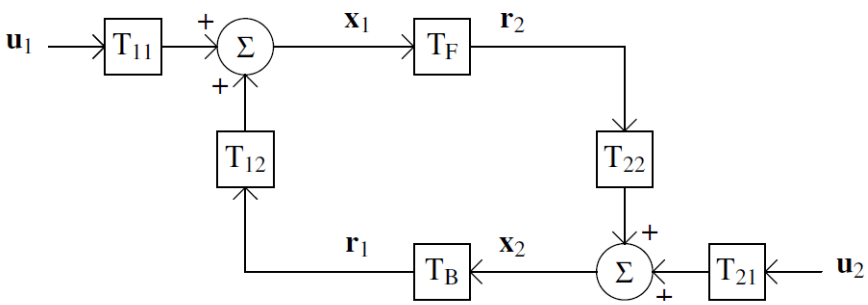



# Challenges Associated with HIL Simulation

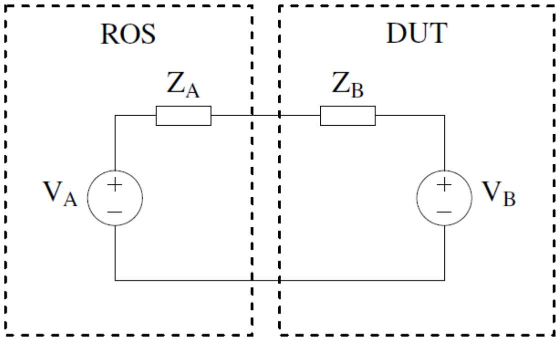



- Non-ideal interfaces
  - Time delays associated with I/O, controllers for actuators and amplifiers, etc.
  - Limited bandwidth of amplifiers and actuators
- Restrictions of real-time simulation
  - Typically fixed time-step size simulations with minimum achievable time-step size
  - Limitations on the size and complexity of simulated systems due to finite computational resources
- Limitations of amplifiers and actuators (max power, torque, speed, etc.)
- Assessment of the impact of HIL Interfaces (particularly PHIL)
- Accuracy of models used for surroundings
  - Common issue with modeling and simulation activities, in general – establishing confidence in the models.
  - Synergy between model verification and validation (V&V) and HIL simulation

# Stability of PHIL Experiments




PHIL System [1]

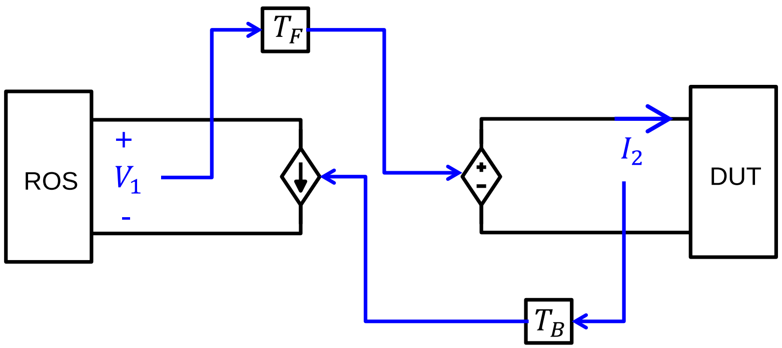



Example ROS and DUT

$$W = -1 + \det(I + G_{OL})$$ [2]

$$G_{OL-ITM-VT} = -\frac{Z_A}{Z_B} T_{mI} T_A$$

$$G_{OL-ITM-IT} = -\frac{Z_B}{Z_A} T_{mV} T_A$$



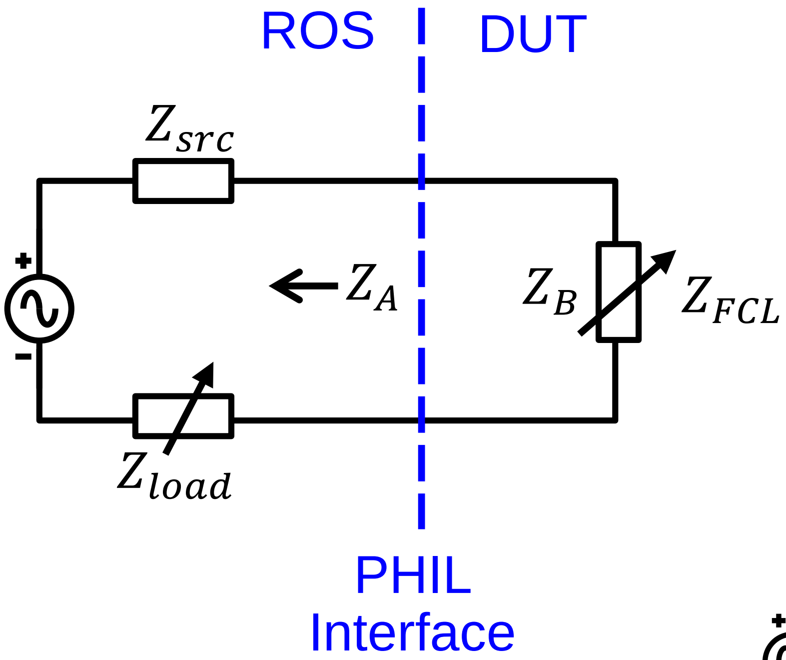

Voltage Type Ideal Transformer Model Interface Algorithm

[1] Wei Ren, M. Steurer, and T.L. Baldwin. Improve the stability and the accuracy of power hardware-in-the-loop simulation by selecting appropriate interface algorithms. *Industry Applications, IEEE Transactions on*, 44(4):1286-1294, July 2008.

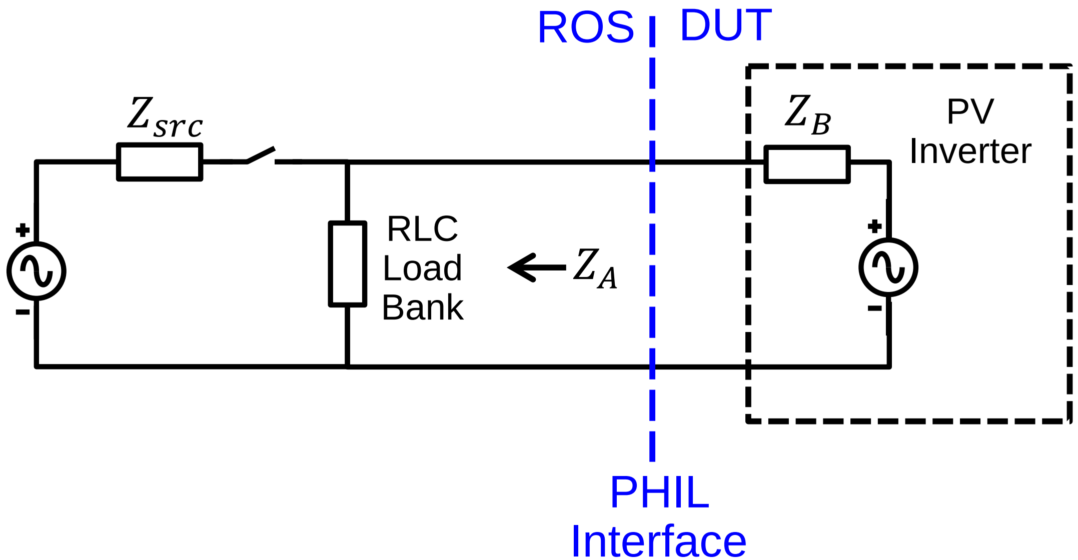
[2] Alexander Viehweider, Felix Lehfuss, and Georg Lauss. Interface and stability issues for SISO and MIMO power hardware in the loop simulation of distribution networks with photovoltaic generation. *International Journal of Renewable Energy Research (IJRER)*, 2(4):631-639, 2012.

# Examples of PHIL Experiments Presenting Challenges in Terms of Stability

Fault Current Limiters




Island Detection Tests for PV Inverters



# Engagement of PHIL Interfaces

DC ITM-IT IA

- Allow PHIL interfaces to be gradually engaged to couple DUT and simulated ROS
- Can allow stability issues to be detected prior to full instability
- Bring systems to steady state and allow for smooth transition to PHIL experiment
- Example:  Testing a 1.2 MW, 4.16 kV AC / 1 kV DC Power Conversion Module for Shipboard Applications ([1] on next slide)

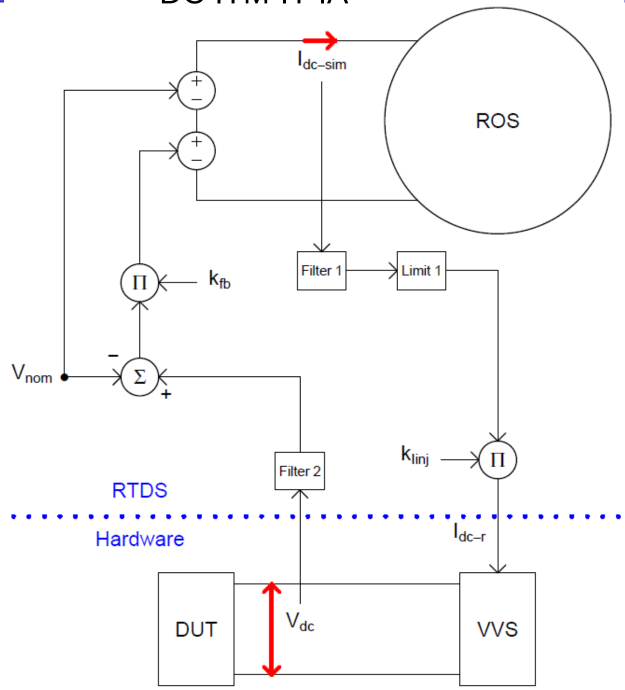
Surrounding System [1]

Current with ITM IA [1]

# Engagement of PHIL Interfaces

- Allow PHIL interfaces to be gradually engaged to couple DUT and simulated ROS
- Can allow stability issues to be detected prior to full instability
- Bring systems to steady state and allow for smooth transition to PHIL experiment
- Example:  Testing a 1.2 MW, 4.16 kV AC / 1 kV DC Power Conversion Module for Shipboard Applications ([1] on next slide)

DC ITM-IT IA




Surrounding System [1]

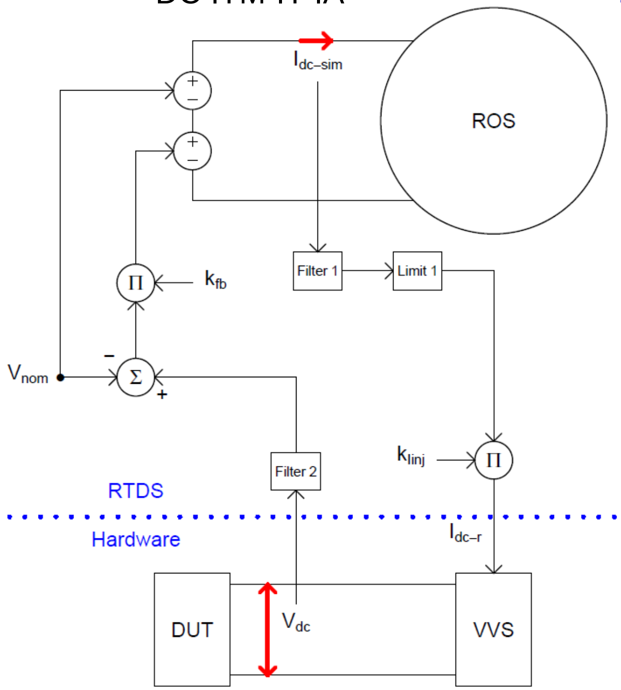
Current with ITM IA [1]

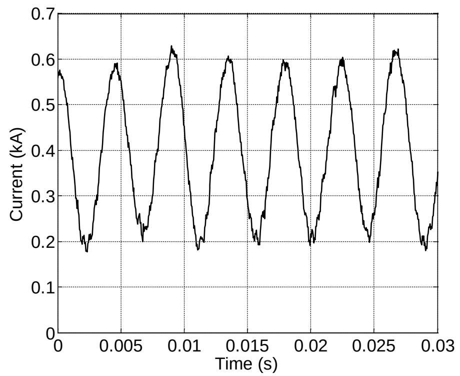
# Engagement of PHIL Interfaces

- Allow PHIL interfaces to be gradually engaged to couple DUT and simulated ROS
- Can allow stability issues to be detected prior to full instability
- Bring systems to steady state and allow for smooth transition to PHIL experiment
- Example: Testing a 1.2 MW, 4.16 kV AC / 1 kV DC Power Conversion Module for Shipboard Applications ([1] on next slide)

Surrounding System [1]

DC ITM-IT IA

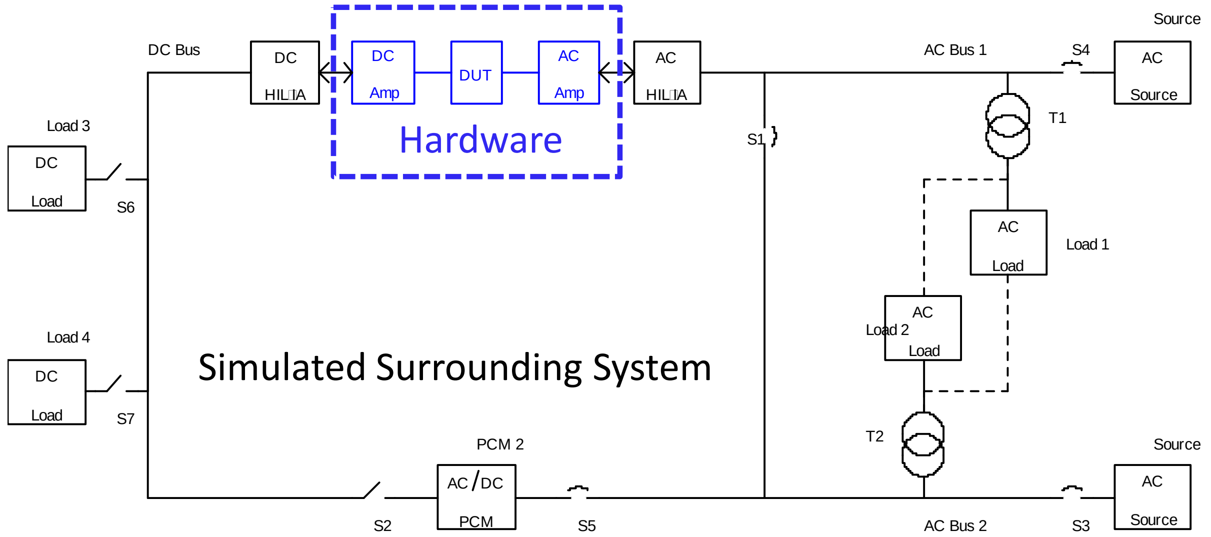



Current with ITM IA [1]

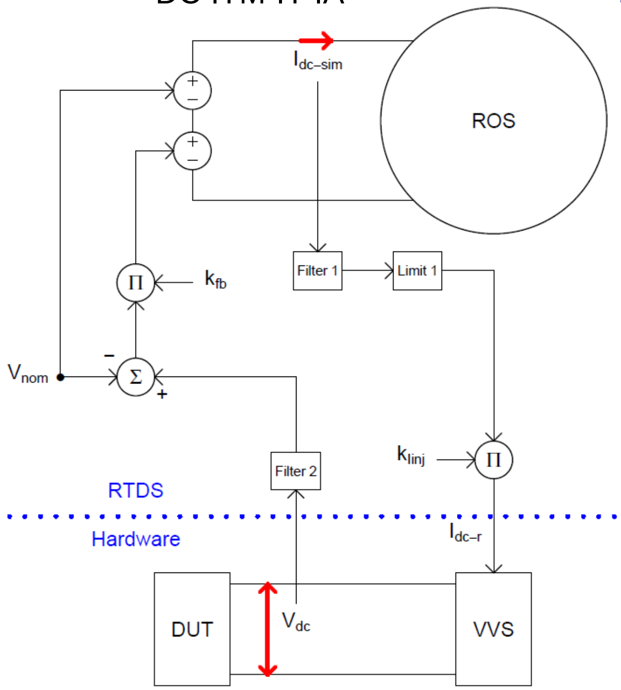
# Engagement of PHIL Interfaces

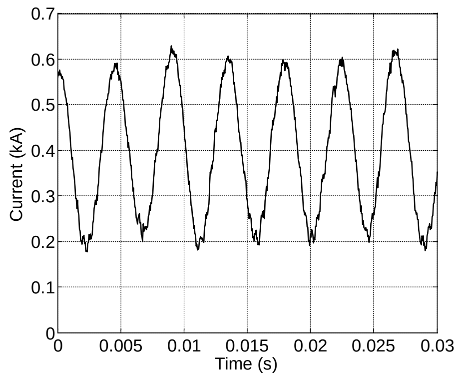
- Allow PHIL interfaces to be gradually engaged to couple DUT and simulated ROS
- Can allow stability issues to be detected prior to full instability
- Bring systems to steady state and allow for smooth transition to PHIL experiment
- Example: Testing a 1.2 MW, 4.16 kV AC / 1 kV DC Power Conversion Module for Shipboard Applications ([1] on next slide)




Surrounding System [1]

DC ITM-IT IA



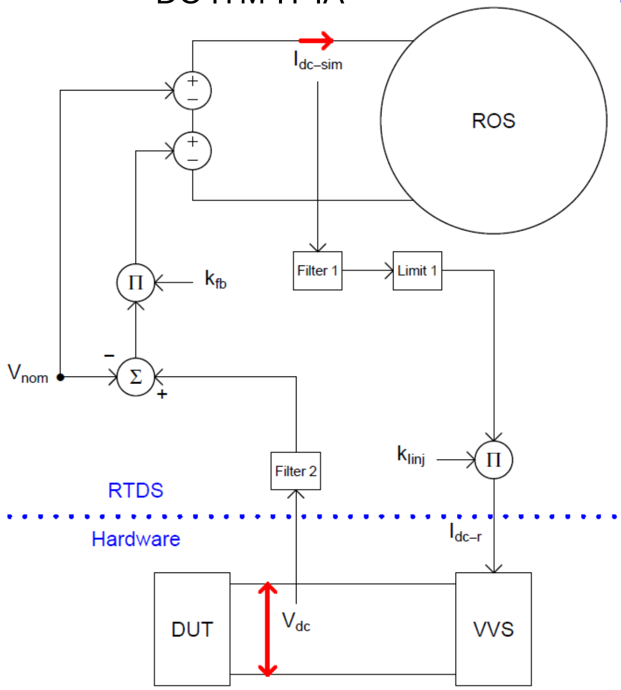




Current with ITM IA [1]

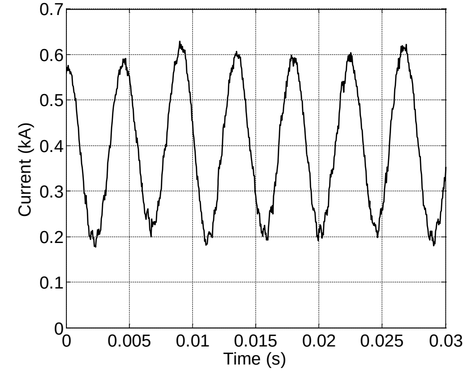
# Engagement of PHIL Interfaces

- Allow PHIL interfaces to be gradually engaged to couple DUT and simulated ROS
- Can allow stability issues to be detected prior to full instability
- Bring systems to steady state and allow for smooth transition to PHIL experiment
- Example: Testing a 1.2 MW, 4.16 kV AC / 1 kV DC Power Conversion Module for Shipboard Applications ([1] on next slide)

DC ITM-IT IA



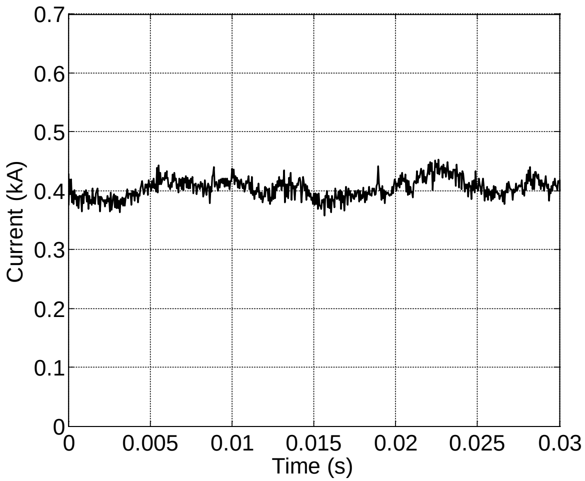

Surrounding System [1]



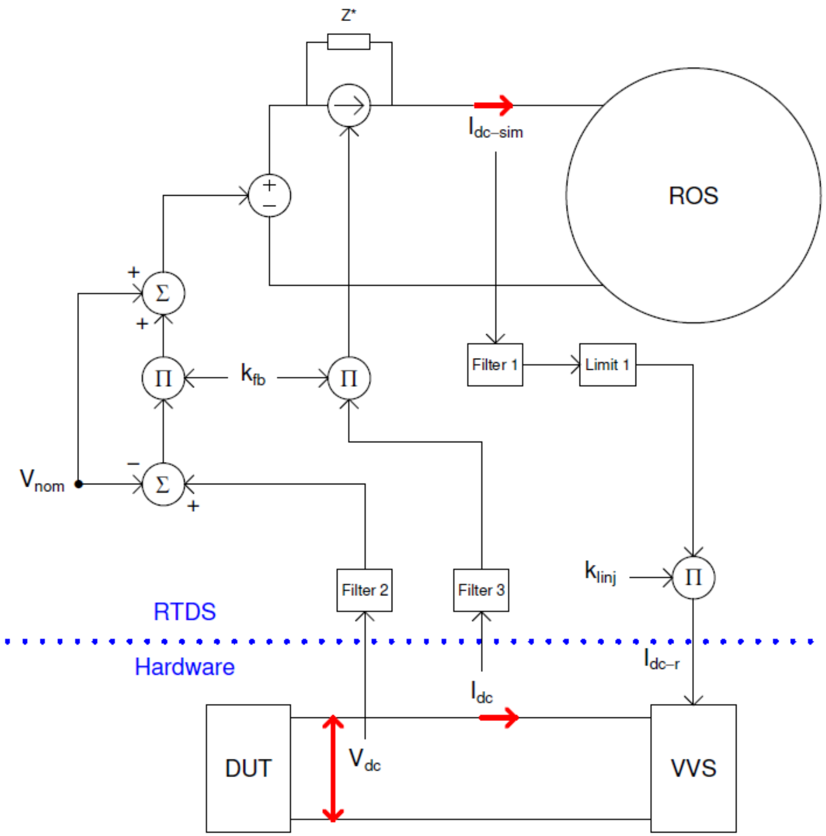

Current with ITM IA [1]

# Engagement of PHIL Interfaces

- Example: Testing a 1.2 MW, 4.16 kV AC / 1 kV DC Power Conversion Module for Shipboard Applications [1]
- Employed current-type Damping Impedance Method (DIM) IA [2]




Current with DIM IA [1]



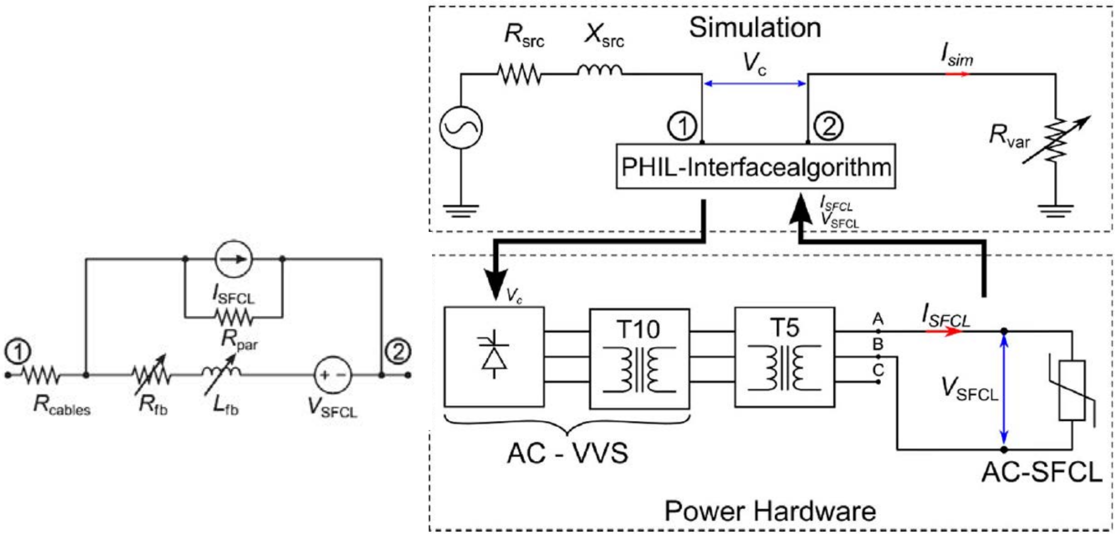

DC DIM-IT IA


[1] J. Langston, F. Bogdan, J. Hauer, K. Schoder, M. Steurer, D. Dalessandro, T. Fikse, J. Cherry, and S. Gonstead, "Megawatt-scale power hardware-in-the-loop simulation testing of a power conversion module for naval applications," Electric Ship Technologies Symposium (ESTS), 2015 IEEE, pp.268,275, 21-24 June 2015.

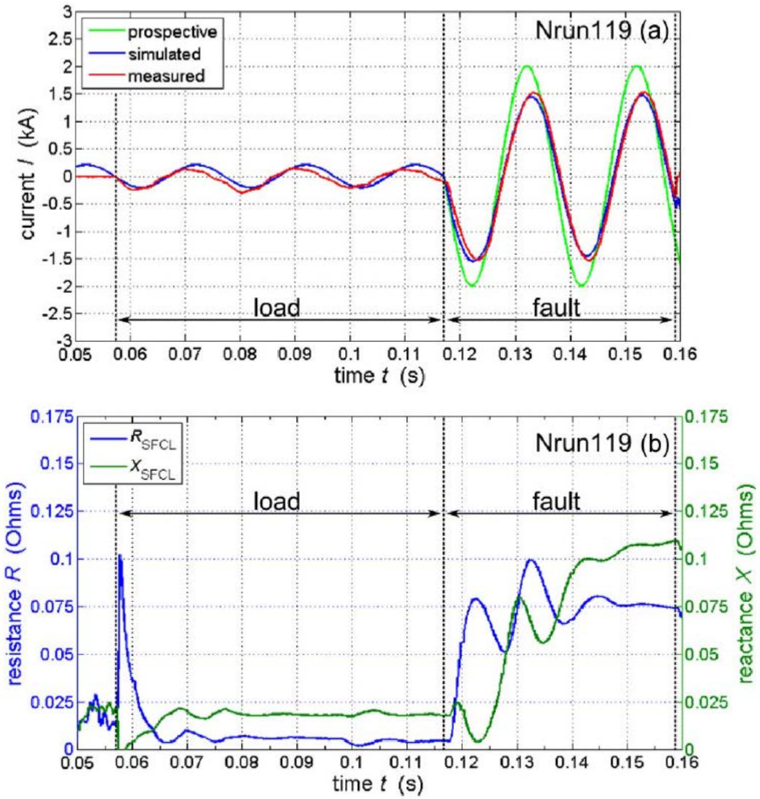
[2] Richard Mack Mersenski. Evaluation of a new power-hardware-in-the-loop (PHIL) interface algorithm for current controlled amplifiers. Master's thesis, University of South Carolina, 2011.

# Engagement of PHIL Interfaces

- Example: PHIL Testing of Air Core Superconducting FCL [1]
- Used Modified DIM IA [2]
- Initialized damping impedance to known pre-quench impedance
- Used a few cycles of pre-fault, load current to allow the impedance to be estimated and all feedback of the IA engaged




PHIL Setup and ROS [1]




Voltage and DUT Impedance [1]


[1] Naeckel, O.; Langston, J.; Steurer, M.; Fleming, F.; Paran, S.; Edrington, C.; Noe, M., "Power Hardware-in-the-Loop Testing of an Air Coil Superconducting Fault Current Limiter Demonstrator," *Applied Superconductivity, IEEE Transactions on* , vol.25, no.3, pp.1,7, June 2015.

[2] Sanaz Paran and CS Edrington. Improved power hardware in the loop interface methods via impedance matching. In Electric Ship Technologies Symposium (ESTS), 2013 IEEE, pages 342-346. IEEE, 2013.

# Accuracy

- Example: Load Rejection Test with 1.2 MW, 4.16 kV AC / 1 kV DC Power Conversion Module for Shipboard Applications ([1] on next slide)

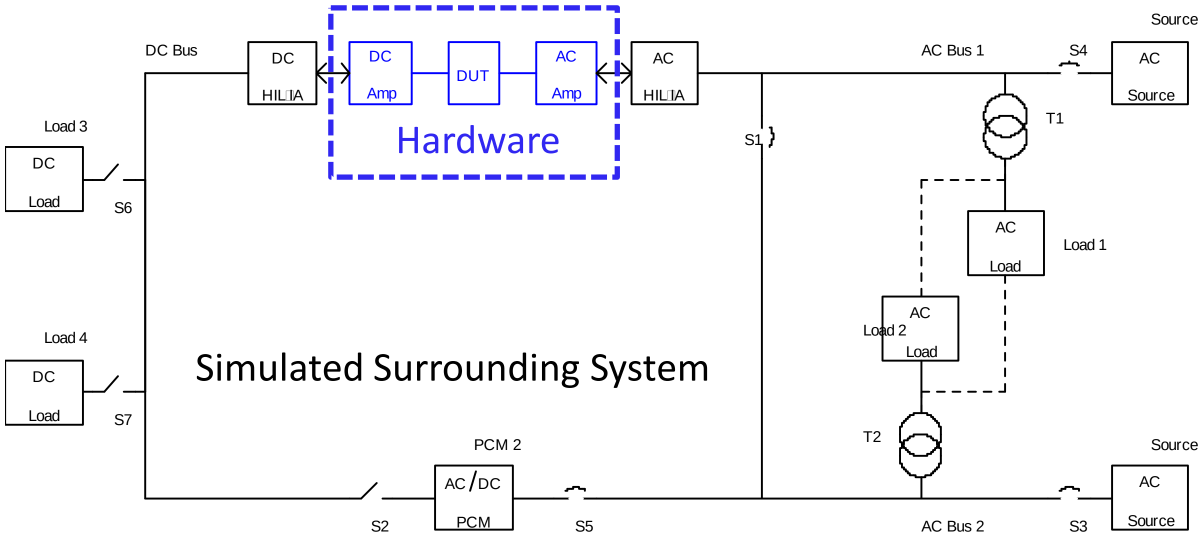
Oscillations in Current
with ITM IA [1]

Surrounding System [1]

[1] J. Langston, F. Bogdan, J. Hauer, K. Schoder, M. Steurer, D. Dalessandro, T. Fikse, J. Cherry, and S. Gonstead, “Megawatt-scale power hardware-in-the-loop simulation testing of a power conversion module for naval applications," Electric Ship Technologies Symposium (ESTS), 2015 IEEE, pp.268,275, 21-24 June 2015.

# Accuracy

- Example: Load Rejection Test with 1.2 MW, 4.16 kV AC / 1 kV DC Power Conversion Module for Shipboard Applications ([1] on next slide)




Surrounding System [1]

Oscillations in Current with ITM IA [1]


[1] J. Langston, F. Bogdan, J. Hauer, K. Schoder, M. Steurer, D. Dalessandro, T. Fikse, J. Cherry, and S. Gonstead, “Megawatt-scale power hardware-in-the-loop simulation testing of a power conversion module for naval applications," Electric Ship Technologies Symposium (ESTS), 2015 IEEE, pp.268,275, 21-24 June 2015.

# Accuracy

- Example: Load Rejection Test with 1.2 MW, 4.16 kV AC / 1 kV DC Power Conversion Module for Shipboard Applications ([1] on next slide)

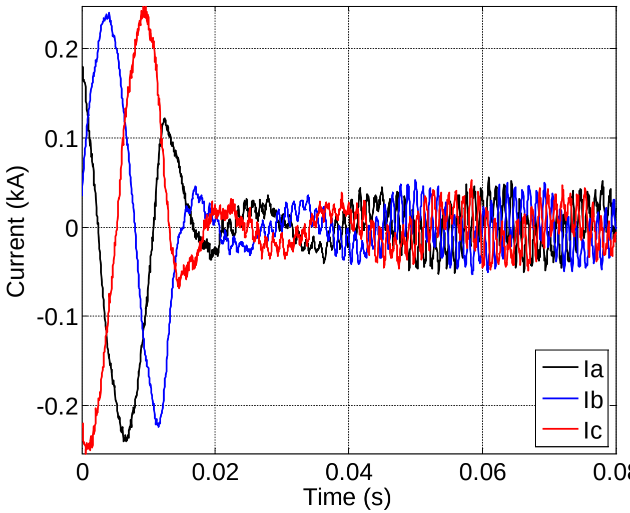
Oscillations in Current
with ITM IA [1]

Surrounding System [1]

[1] J. Langston, F. Bogdan, J. Hauer, K. Schoder, M. Steurer, D. Dalessandro, T. Fikse, J. Cherry, and S. Gonstead, “Megawatt-scale power hardware-in-the-loop simulation testing of a power conversion module for naval applications," Electric Ship Technologies Symposium (ESTS), 2015 IEEE, pp.268,275, 21-24 June 2015.

# Accuracy

- Example:  Load Rejection Test with 1.2 MW, 4.16 kV AC / 1 kV DC Power Conversion Module for Shipboard Applications ([1] on next slide)




Oscillations in Current with ITM IA [1]

Surrounding System [1]

[1]  J. Langston, F. Bogdan, J. Hauer, K. Schoder, M. Steurer, D. Dalessandro, T. Fikse, J. Cherry, and S. Gonstead, “Megawatt-scale power hardware-in-the-loop simulation testing of a power conversion module for naval applications," Electric Ship Technologies Symposium (ESTS), 2015 IEEE, pp.268,275, 21-24 June 2015.

# Accuracy

- Example: Load Rejection Test with 1.2 MW, 4.16 kV AC / 1 kV DC Power Conversion Module for Shipboard Applications ([1] on next slide)

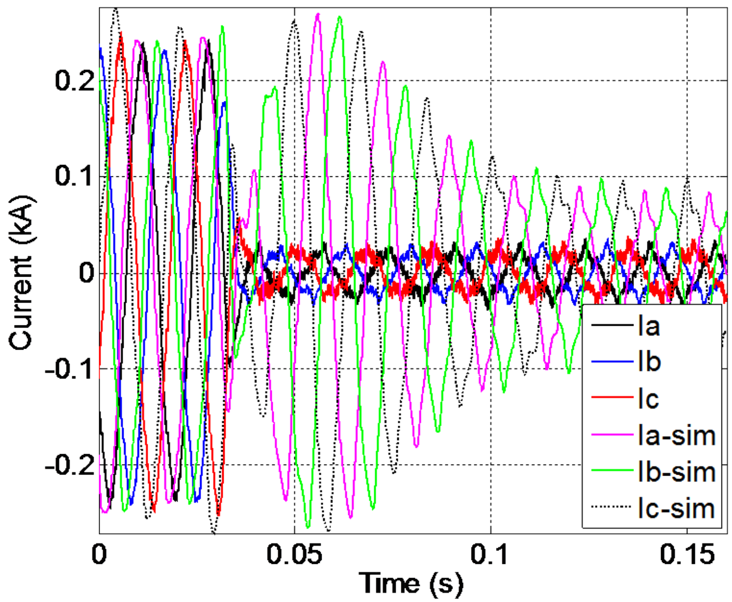
Currents Using DIM IA
(Lower Damping Impedance) [1]

Currents Using DIM IA
(Higher Damping Impedance) [1]

[1] J. Langston, F. Bogdan, J. Hauer, K. Schoder, M. Steurer, D. Dalessandro, T. Fikse, J. Cherry, and S. Gonstead, “Megawatt-scale power hardware-in-the-loop simulation testing of a power conversion module for naval applications," Electric Ship Technologies Symposium (ESTS), 2015 IEEE, pp.268,275, 21-24 June 2015.

# Accuracy

- Example: Load Rejection Test with 1.2 MW, 4.16 kV AC / 1 kV DC Power Conversion Module for Shipboard Applications ([1] on next slide)




Currents Using DIM IA
(Lower Damping Impedance) [1]

Currents Using DIM IA
(Higher Damping Impedance) [1]


[1] J. Langston, F. Bogdan, J. Hauer, K. Schoder, M. Steurer, D. Dalessandro, T. Fikse, J. Cherry, and S. Gonstead, “Megawatt-scale power hardware-in-the-loop simulation testing of a power conversion module for naval applications," Electric Ship Technologies Symposium (ESTS), 2015 IEEE, pp.268,275, 21-24 June 2015.

# Accuracy

- Example: Load Rejection Test with 1.2 MW, 4.16 kV AC / 1 kV DC Power Conversion Module for Shipboard Applications ([1] on next slide)

Currents Using DIM IA
(Lower Damping Impedance) [1]

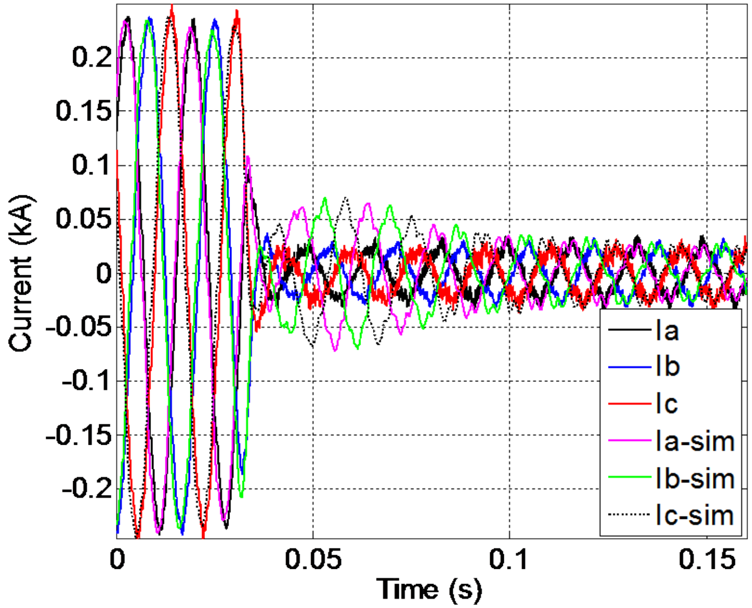
Currents Using DIM IA
(Higher Damping Impedance) [1]

[1] J. Langston, F. Bogdan, J. Hauer, K. Schoder, M. Steurer, D. Dalessandro, T. Fikse, J. Cherry, and S. Gonstead, “Megawatt-scale power hardware-in-the-loop simulation testing of a power conversion module for naval applications," Electric Ship Technologies Symposium (ESTS), 2015 IEEE, pp.268,275, 21-24 June 2015.

# Accuracy

- Example: Load Rejection Test with 1.2 MW, 4.16 kV AC / 1 kV DC Power Conversion Module for Shipboard Applications ([1] on next slide)

Currents Using DIM IA
(Lower Damping Impedance) [1]



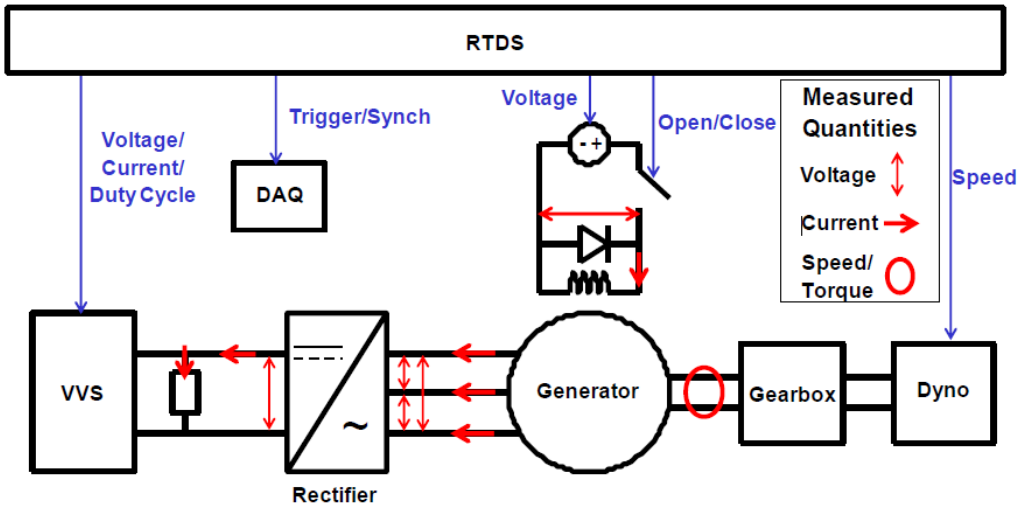

Currents Using DIM IA
(Higher Damping Impedance) [1]

[1] J. Langston, F. Bogdan, J. Hauer, K. Schoder, M. Steurer, D. Dalessandro, T. Fikse, J. Cherry, and S. Gonstead, “Megawatt-scale power hardware-in-the-loop simulation testing of a power conversion module for naval applications," Electric Ship Technologies Symposium (ESTS), 2015 IEEE, pp.268,275, 21-24 June 2015.

# Protection Systems

- Important to protect the DUT
- Gracefully shut down the experiment if a problem is encountered
- Take (only) appropriate actions in response to detected problems
- Example: Testing 1.2 MW, 15,000 RPM High Speed Generator [1]

- Protection Elements
  - Over-voltage
  - Over-current
  - Over-speed
  - Over-torque
- Protection Actions
  - Open closed-loop controls
  - Open excitation switch
  - Ramp VVS (load) current to zero
  - Ramp dynamometer speed to zero
  - Step dynamometer speed reference to zero

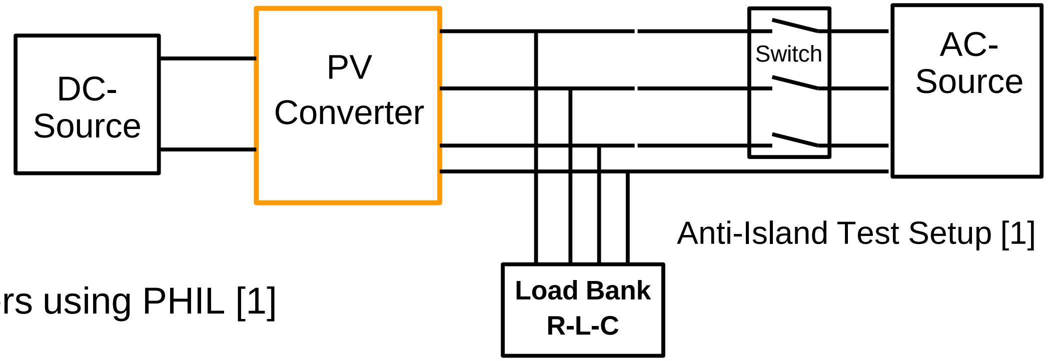



Test Setup [1]

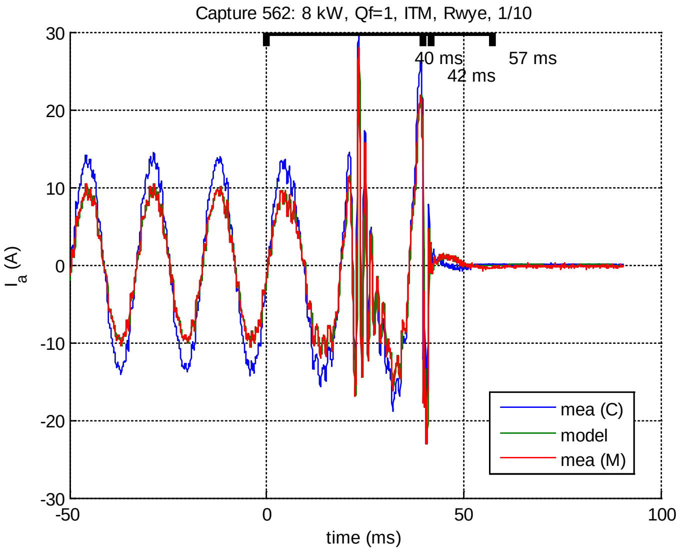

[1] J. Langston, M. Steurer, K. Schoder, J. Hauer, F. Bogdan, I. Leonard, T. Chiocchio, M. Sloderbeck, A. Farrell, J. Vaidya, and K. Yost, “Megawatt Scale Hardware-in-the-Loop Testing of a High Speed Generator,” Proc. 2012 ASNE Day, Arlington, VA, February 9-10, 2012.

# Protection Systems

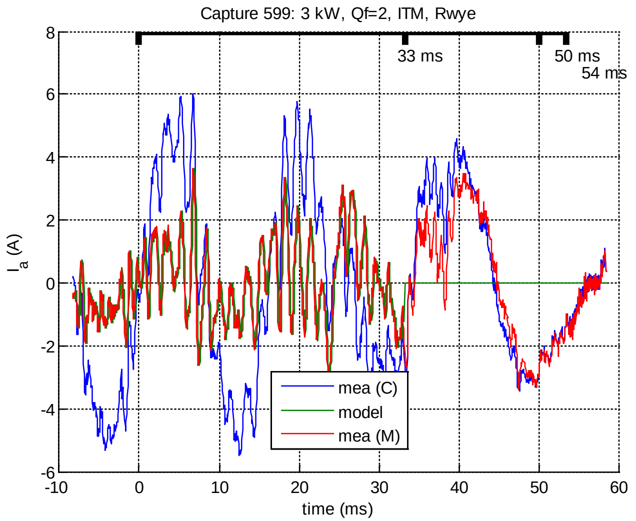
- Methods to detect the onset of instability
  - Frequency
  - Voltage/current distortion
  - Time-based
  - Others
- Example: Anti-Islanding Tests of PV Inverters using PHIL [1]




Anti-Island Test Setup [1]




Stable Case [1]




Marginally Stable Case [1]

[1] M. Steurer, K. Schoder, J. Langston, J. Hauer, and B. Mather, “Progress on Power Hardware-in-the-Loop Based Anti-Islanding Testing of PV Converters,” Presentation at the Second International Workshop on Grid Simulator Testing of Wind Turbine Drivetrains, September 17-18, 2014, North Charleston, South Carolina, USA.

# Other Points

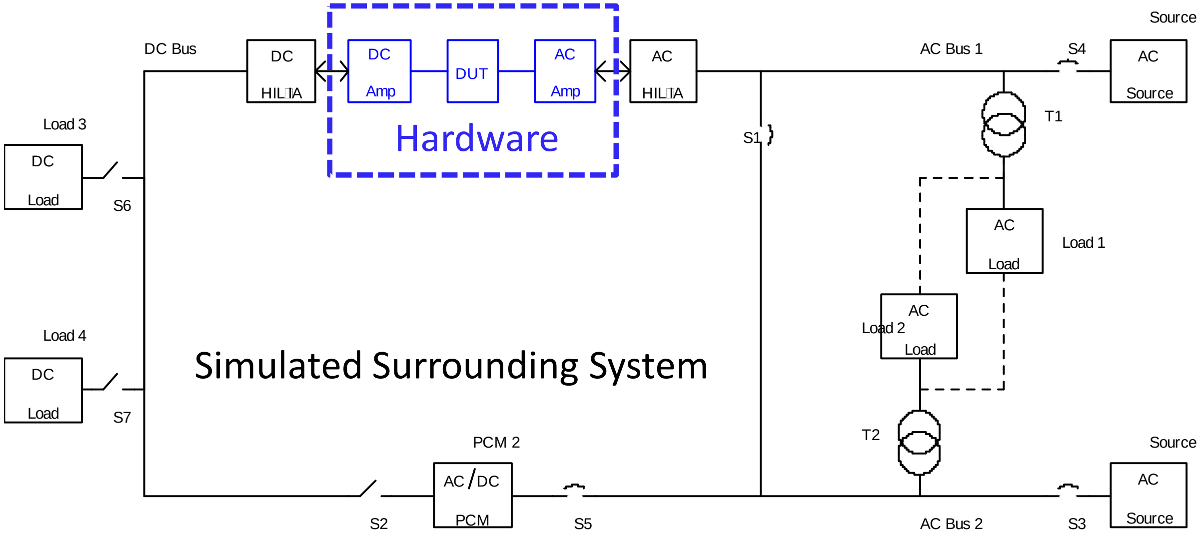
- Simulation Mode
- Information Collection
  - Capture Reference Signals
  - Collect Trending Information Including Settings
- Minimize Surrounding System
- Detailed Checklists and Procedures
- Attention to Detail

Surrounding System [1]

[1] J. Langston, F. Bogdan, J. Hauer, K. Schoder, M. Steurer, D. Dalessandro, T. Fikse, J. Cherry, and S. Gonstead, “Megawatt-scale power hardware-in-the-loop simulation testing of a power conversion module for naval applications," Electric Ship Technologies Symposium (ESTS), 2015 IEEE, pp.268,275, 21-24 June 2015.

# Other Points

- Simulation Mode
- Information Collection
  - Capture Reference Signals
  - Collect Trending Information Including Settings
- Minimize Surrounding System
- Detailed Checklists and Procedures
- Attention to Detail




Surrounding System [1]


[1] J. Langston, F. Bogdan, J. Hauer, K. Schoder, M. Steurer, D. Dalessandro, T. Fikse, J. Cherry, and S. Gonstead, “Megawatt-scale power hardware-in-the-loop simulation testing of a power conversion module for naval applications," Electric Ship Technologies Symposium (ESTS), 2015 IEEE, pp.268,275, 21-24 June 2015.

# Other Points

- Simulation Mode
- Information Collection
  - Capture Reference Signals
  - Collect Trending Information Including Settings
- Minimize Surrounding System
- Detailed Checklists and Procedures
- Attention to Detail

Surrounding System [1]

[1] J. Langston, F. Bogdan, J. Hauer, K. Schoder, M. Steurer, D. Dalessandro, T. Fikse, J. Cherry, and S. Gonstead, “Megawatt-scale power hardware-in-the-loop simulation testing of a power conversion module for naval applications," Electric Ship Technologies Symposium (ESTS), 2015 IEEE, pp.268,275, 21-24 June 2015.

# Conclusions

- Stability and Accuracy Key for PHIL Experiments
- Points
  - Stability
  - Engagement of PHIL Interfaces
  - Accuracy
  - Flexibility of PHIL Interfaces
  - Protection of PHIL Experiments
  - Simulation Mode
  - Information Collection
  - Minimize Surrounding System
  - Detailed Checklists and Procedures
  - Attention to Detail