Silicon Carbide Research for Reliable Electric Power: Design and Test

National Center for Reliable Electric Power Transmission

A Center for Advanced Power Electronics

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Problem Statement

Research advanced power electronic solutions for grid-connected applications

- **Fault currents continue to rise in urban centers and the use of FCLs provides an attractive way to extend the useful life of existing breakers (continuation)**
- **A substantial amount of energy storage is being added to the power grid; power electronic interfaces for improved efficiency and robust, modular control of power flow are needed (started in FY08)**

Prior Results (Sept. 2005)

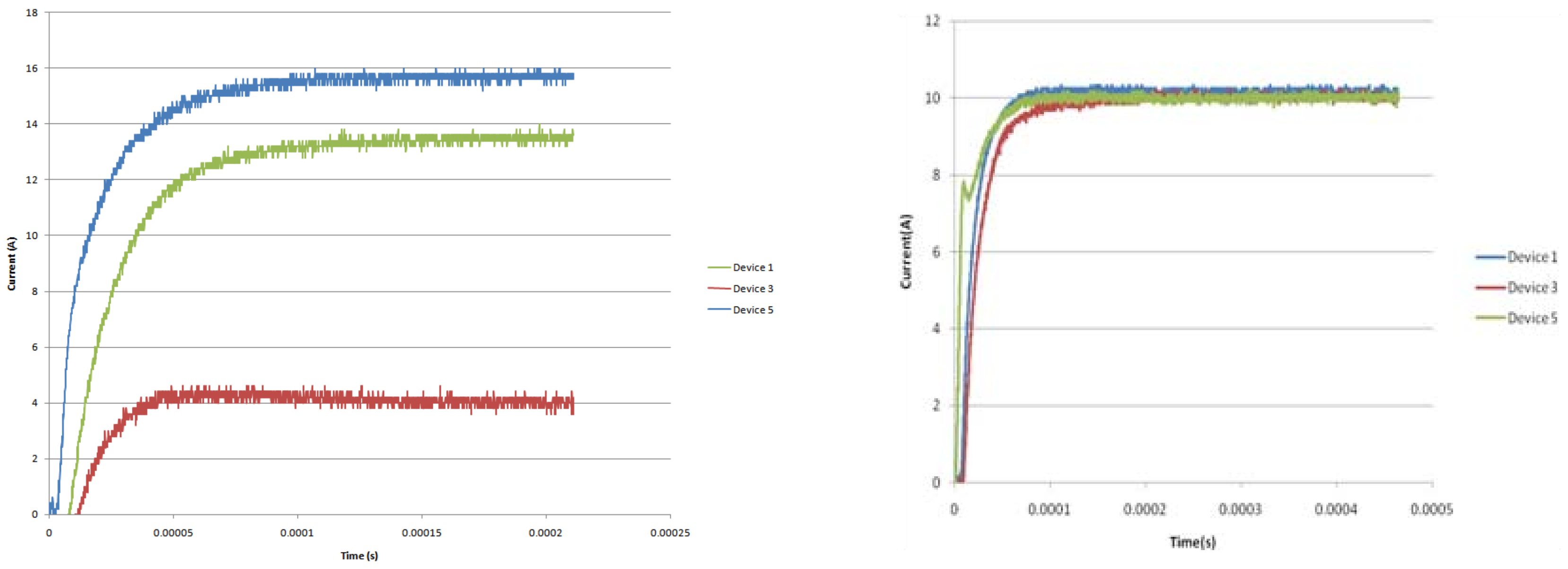
- **Power MOSFET model for Si and SiC applications**
- **Power packaging system for SiC in press pack**
- **Multi-level power converter for DER applications**
- **FCL topology and system studies**
- **Design and construction of unique test facility**

Outline

- Design and test of fault current limiters
  - Seeking the best devices
  - Power packaging of SiC
- Circuit design for energy storage
- Design of an advanced power electronic test facility

Paralleling SiC Thyristors

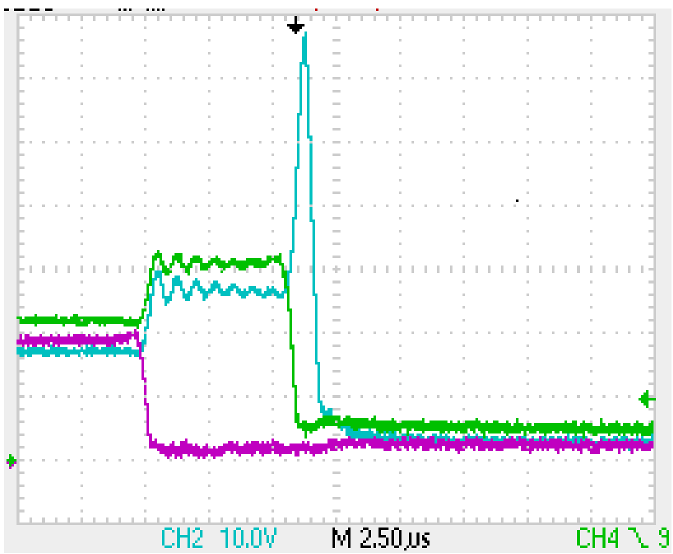
- Desired current ratings for a solid state fault current limiter far exceed that of a single SiC device so they must be operated in parallel
- The SiC thyristor, a bipolar device, exhibits characteristics similar to those of a S-GTO which will be used in the final prototype
- Several methods were used to promote current sharing, but ultimately it was deemed that using series impedances was the most effective

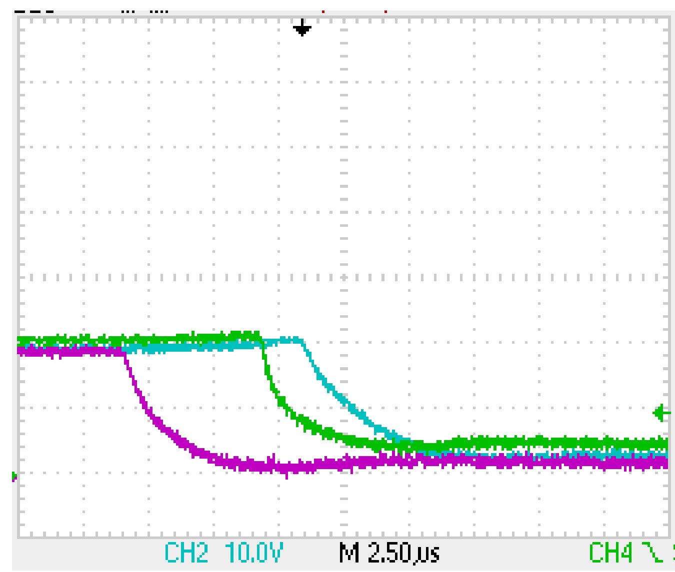


Current distribution before and after series compensation

Series Connection of SiC Thyristors

- **Voltage levels seen by solid state fault current limiters would require several devices to be connected in series**
- **Voltage sharing in the steady and transient states can be attained by designing the appropriate sharing network and selecting the proper voltage sharing resistor for the devices**

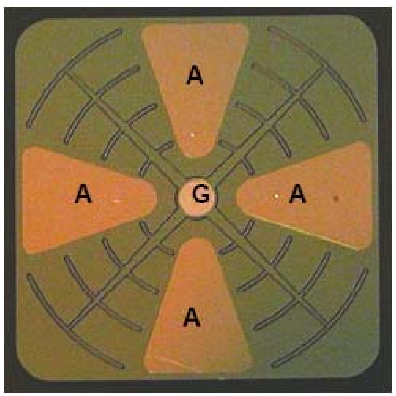


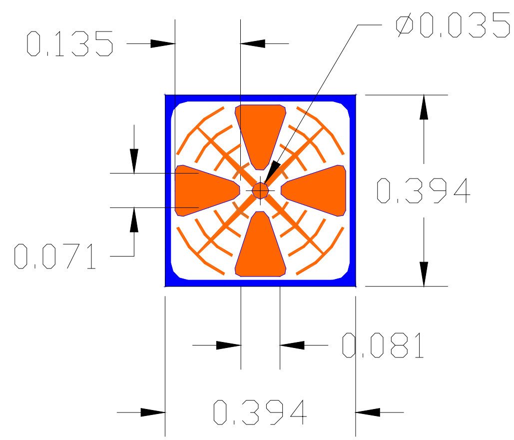


Voltage sharing during turn-on before and after use of sharing network

Thyristor Module Packaging

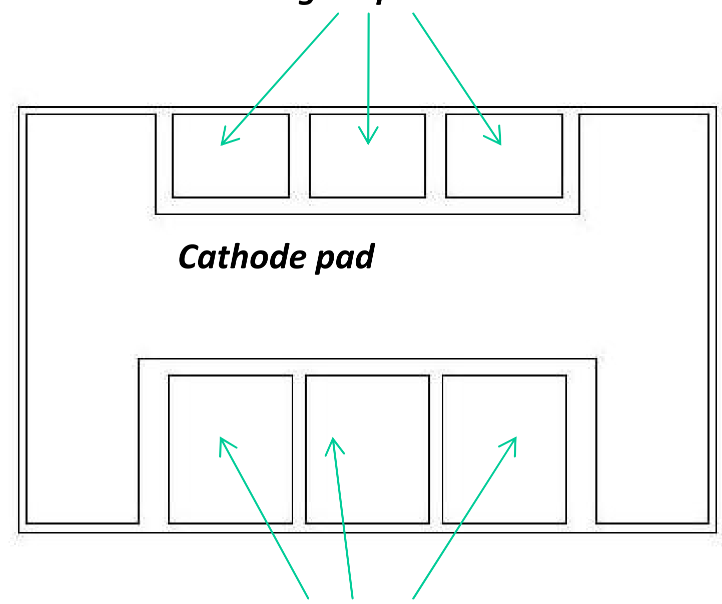
- Three SiC thyristors (dimensions: 10 mm x 10 mm) rated at 5 kV, 100 A
- Connected in parallel to enhance current handling capability and packaged in a single module package





- Metallization on the devices is Au/Ni and passivation is polyimide
- Backside of the device is the cathode of the thyristor

Module substrate

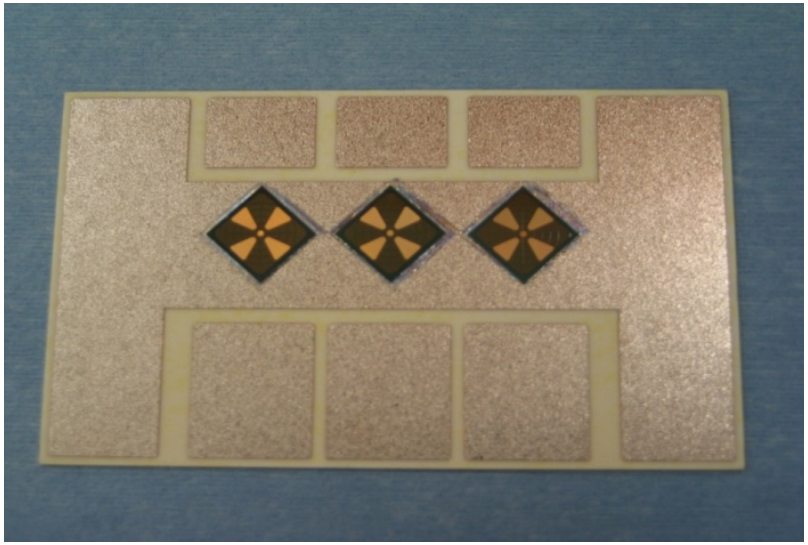


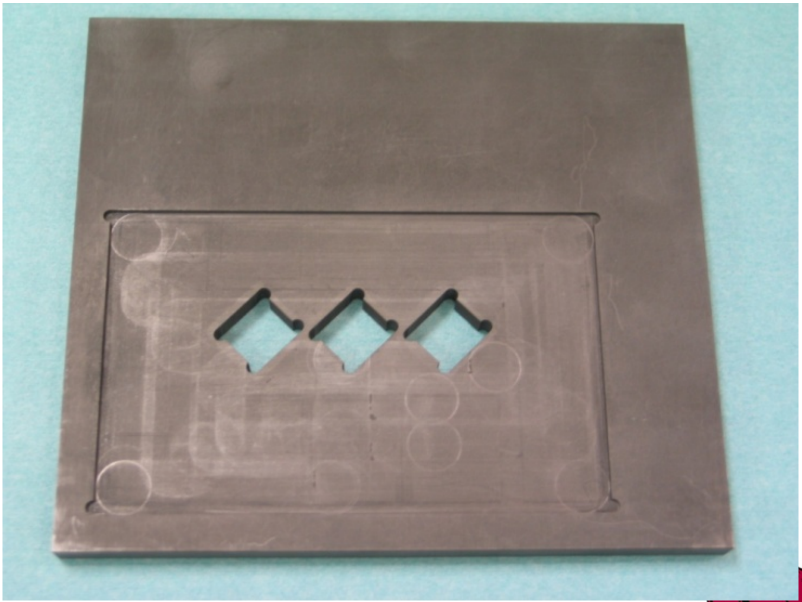
- Module substrate is a direct bond copper (DBC) substrate
- DBC layout: nickel plated pads for attaching die and for wire bonding
- DBC substrate fabrication – dry film photo-lithography process

1. Nickel-plated DBC board
2. Print photoplot – a dark film mask
3. Apply dry film photoresist on the DBC board
4. Exposure to UV light with the photoplot
5. Unwanted photoresist was removed by a developer
6. Exposed nickel was then chemically etched
7. DBC board was diced

Die Attach

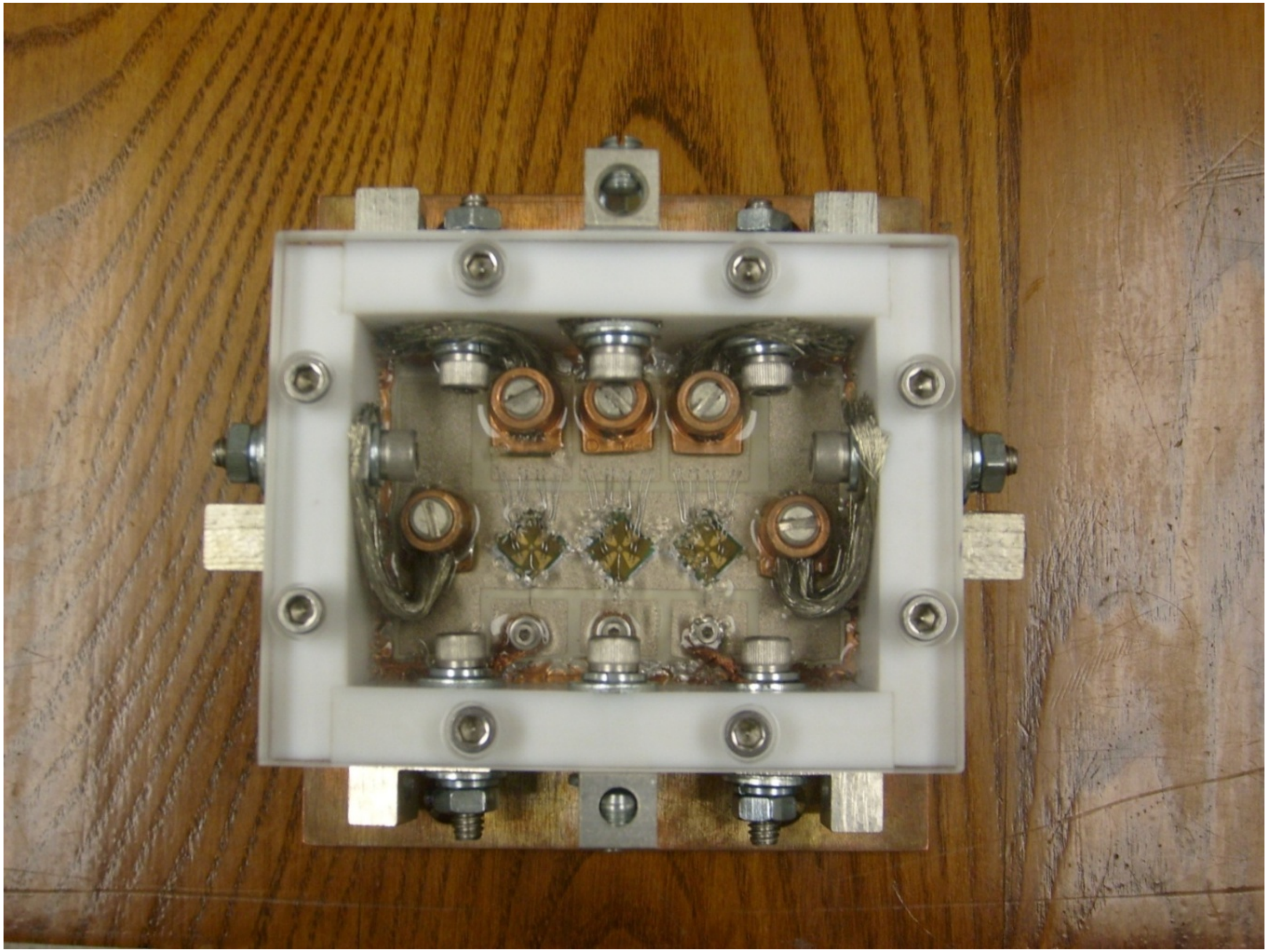
- Die arrangement on the substrate: lined up in a row as shown to ease wire bonding
- Die attach process:
  - SST 3130 vacuum furnace: temperature and the inert gas environment are programmed and precisely controlled
  - Custom tooling insert made of graphite to hold the devices and substrate in place as shown
  - 97.5Pb1.5Ag1Sn solder preform with a melting point of 309℃
  - Pre-form was cut to 11mm x 11mm, slightly bigger than the dimensions of the die
  - Cleaning procedure – dilute acid clean of the substrate; SST furnace clean of the preform with a dedicated cleaning profile





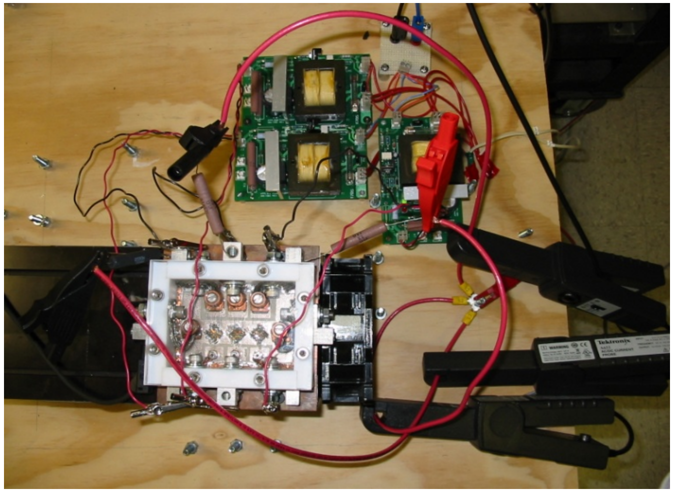
Substrate Attach and Connections

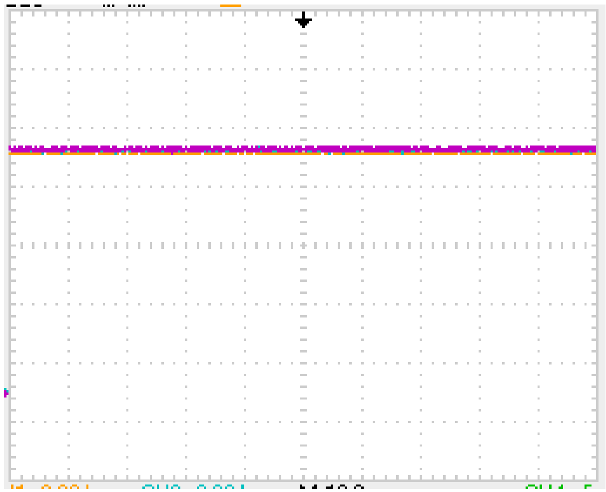
The Complete Thyristor Module



Switching Position Design

- Results from parallel and serial testing used to design a high power switching position in which each device will share voltage and current equally
- To optimize current sharing, packages containing paralleled thyristors will be used and the values of series impedances, snubber network components, and voltage sharing resistors will be determined for all devices

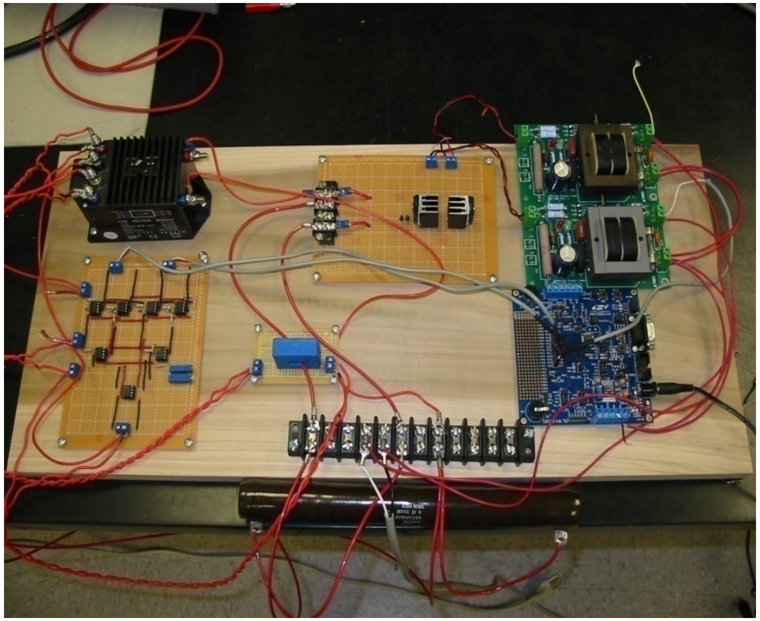


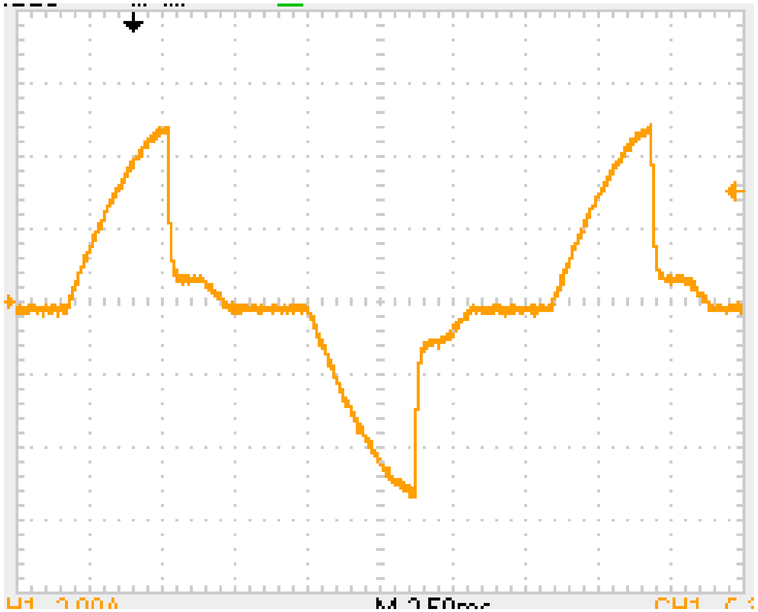


Test setup and initial test results showing current balance

FCL Prototype

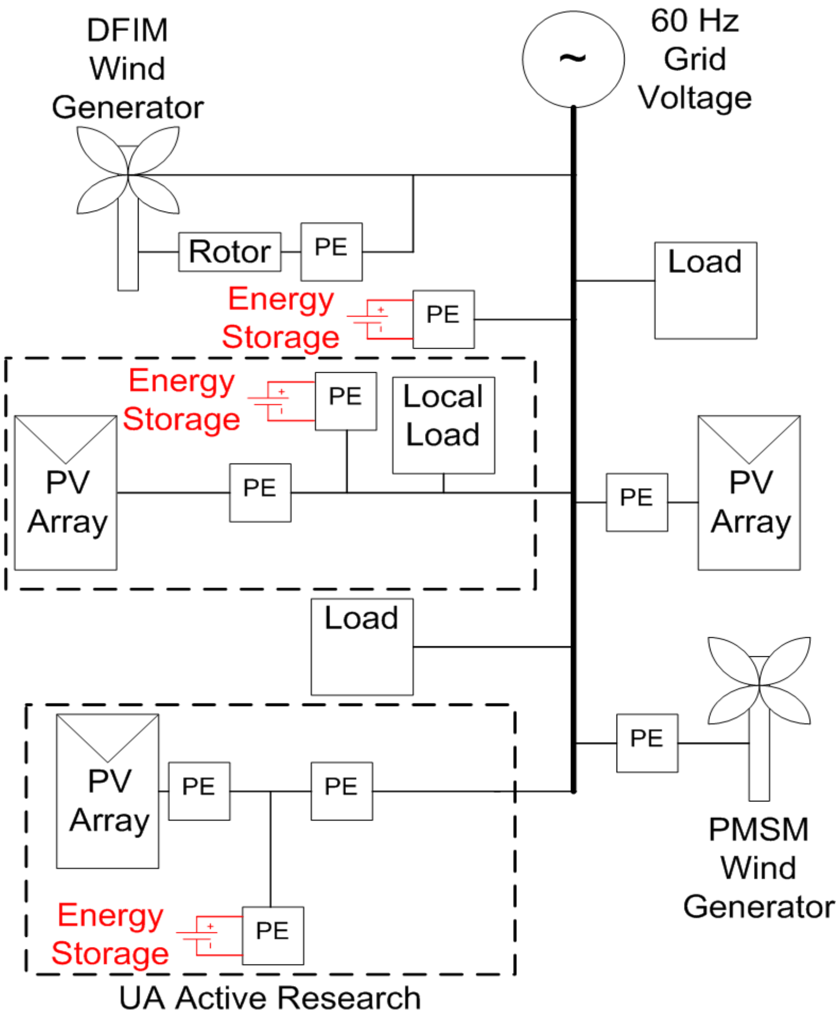
- **A scaled down FCL prototype has been constructed and tested; currently using Si IGBTs for control development and debug**
- **System will be able to interrupt and limit fault current and resume full conduction in the event that the fault disappears**





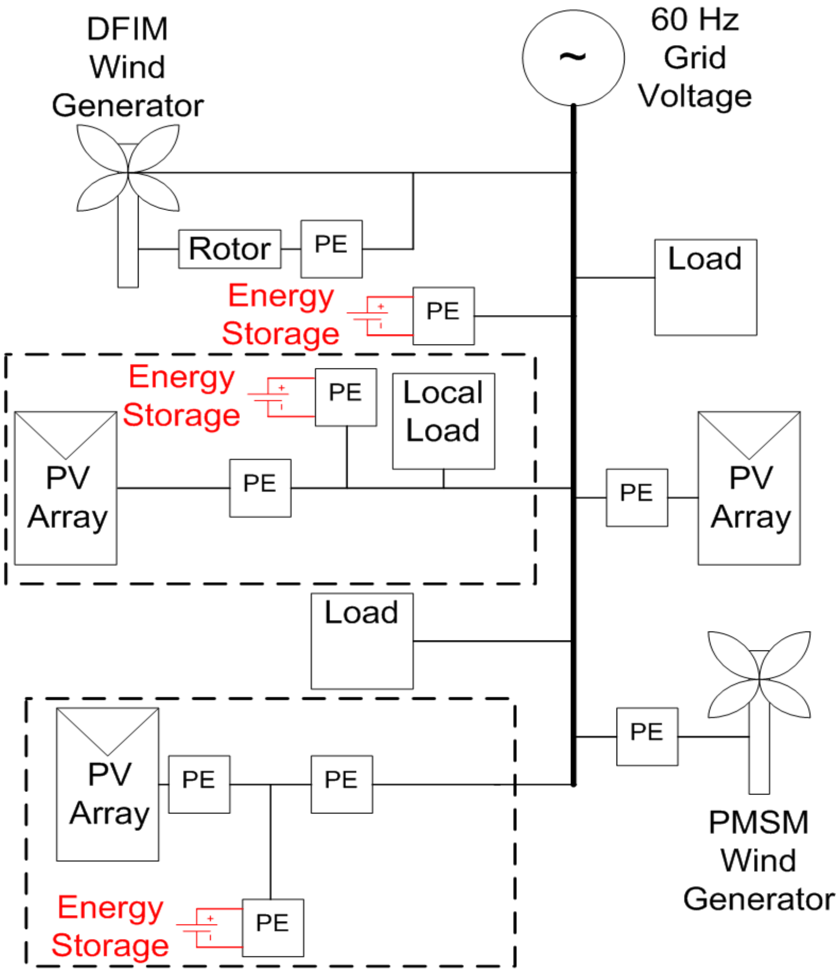
FCL test setup and initial testing results showing current limiting

Energy Storage in the Future Grid



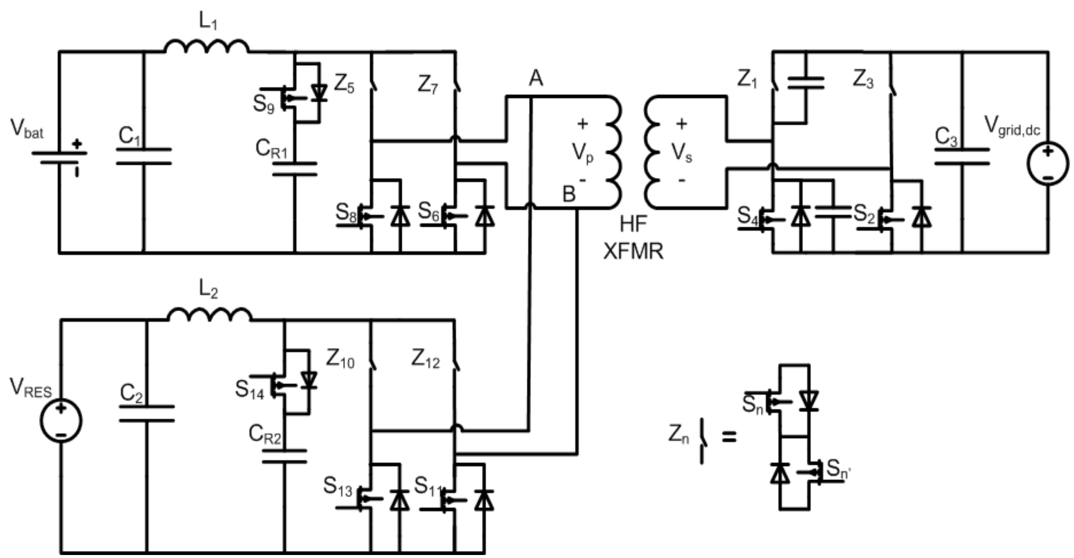
- **Energy storage is a key component of the future grid both as a standalone system and as a supplement to other systems**
- **As a standalone system, energy storage can provide power quality compensation, voltage and frequency control, uninterruptible power supply, and spinning reserve.**
- **As a supplement to renewable energy resources, energy storage can make intermittent power sources such as wind and solar into reliable, continuous power supplies suitable for use as primary power sources, instead of as secondary sources behind traditional power sources such as coal.**
- **As a supplement to traditional power sources, energy storage can be used for load leveling or to respond to price fluctuations in the energy market.**

Solutions for Integrating Energy Storage and Renewable Energy Resources



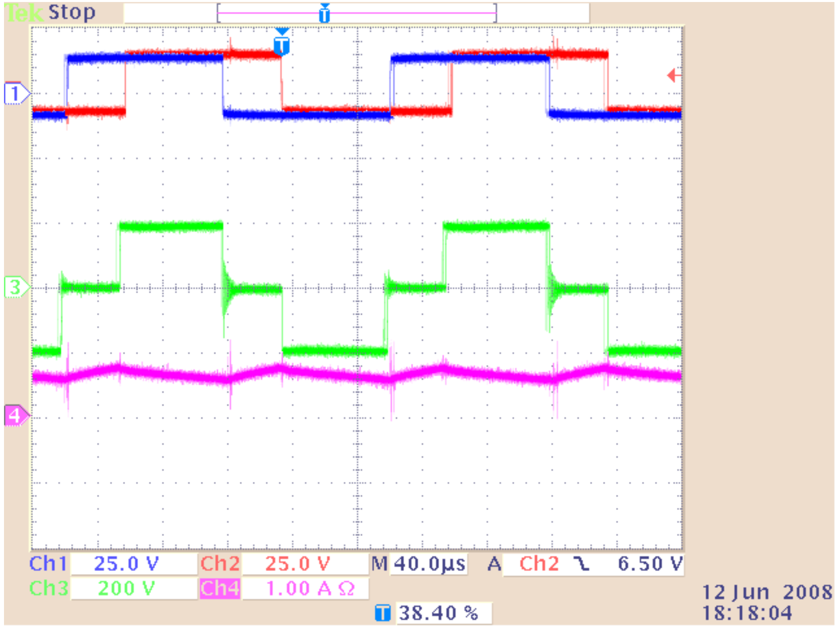
- **There are three main proposed solutions for integration:**
  1. **Use the power lines as a common bus—cheaper PE interfaces, but numerous redundant parts (such as isolation transformers)**
  2. **Integrate the two systems in a microgrid — allows consolidation of common parts, but must regulate internal bus for local loads**
  3. **Integrate the two systems in a multiport converter — allows consolidation without local loads, but PE interfaces are more complicated**

UA Proposed Solution

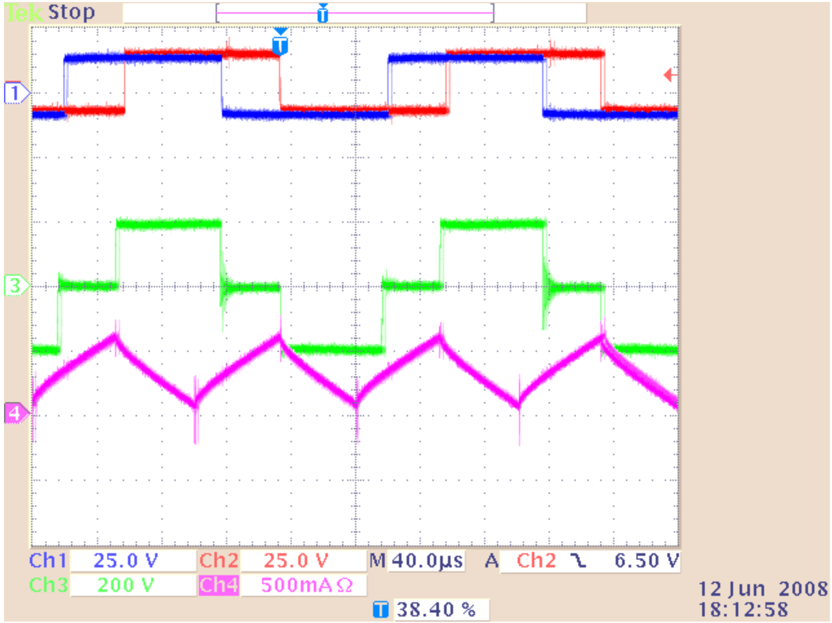


- **Multiport converter topology uses common transformer, reducing part count for total system.**
- **High frequency transformer link results in smaller passives.**
- **Connecting sources in parallel at the transformer makes system highly modular and easy to expand.**
- **Bidirectional switches enable power flow in multiple directions, so some sources may provide power to load, others may charge energy storage devices, and some energy storage devices may provide power to load, all controlled by the duty cycles of each individual converter and the common bus voltage at the transformer — modular control.**

Experimental Results



Energy Storage Current



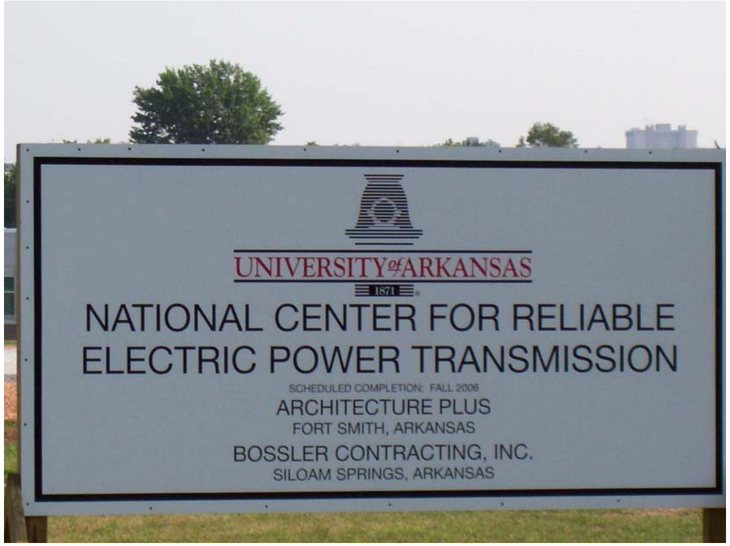
RES Current

Channel 1: $V_{gs,S5}$; Channel 2: $V_{gs,S6}$; Channel 3: $V_{XFMR,S}$; Channel 4: $I_{SourceInductor}$

Both currents are positive, showing that both sources contribute to the load

Prototype Test & Evaluation Facility

- 7000 ft^2 building
- 6 MVA
- Variable voltage (200 V – 15 kV)
- Variable frequency (50-400 Hz)
- Regenerative drives for programmable loads
- Cost-effective facility for businesses, national labs, and universities
- IEEE 1547; UL 1741 - DR
- Ribbon-cutting Oct. 31, 2008!



NCREPT Test Facility Diagram

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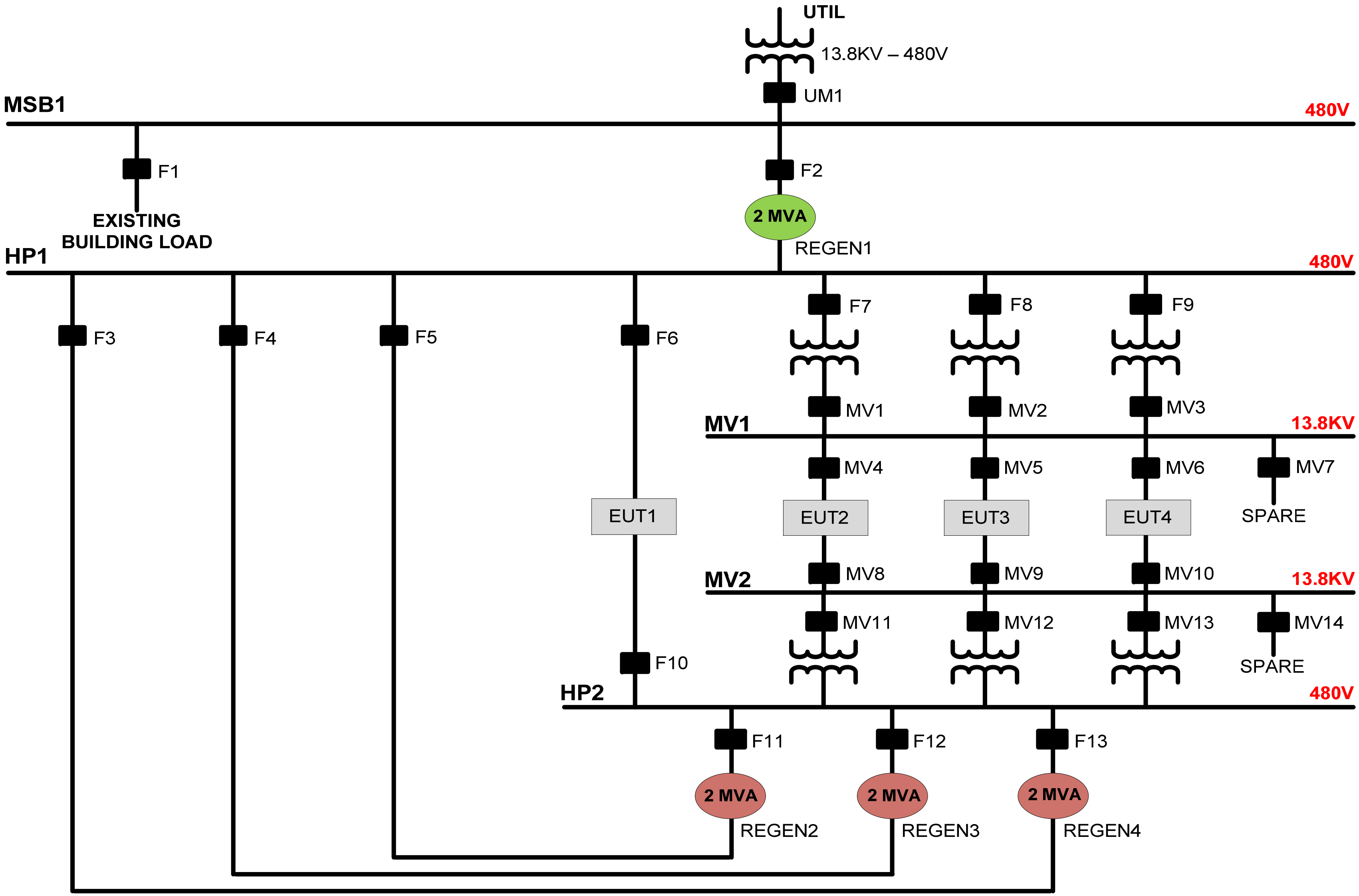
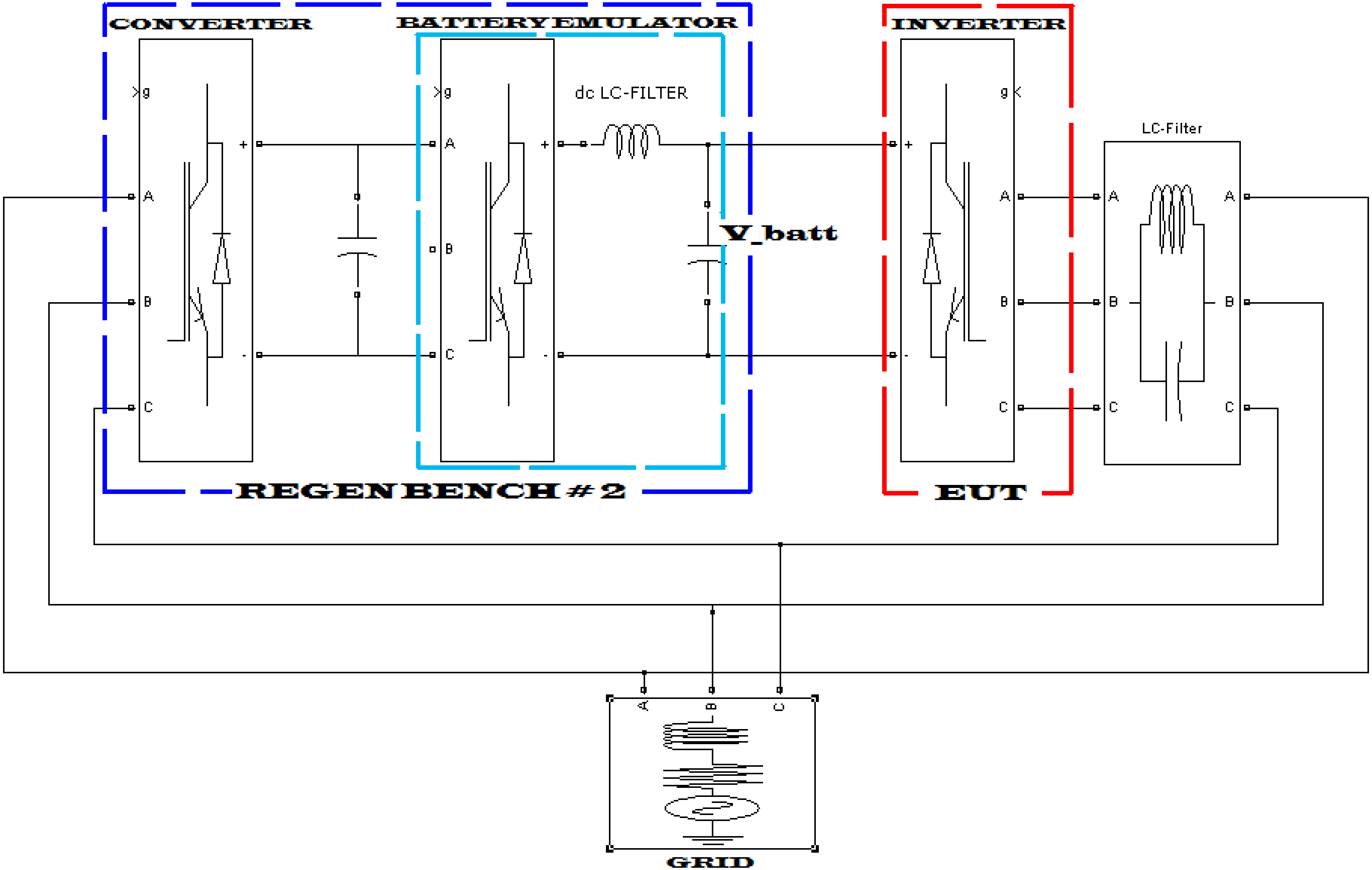


Battery Emulator for Testing Grid-Connected Inverters

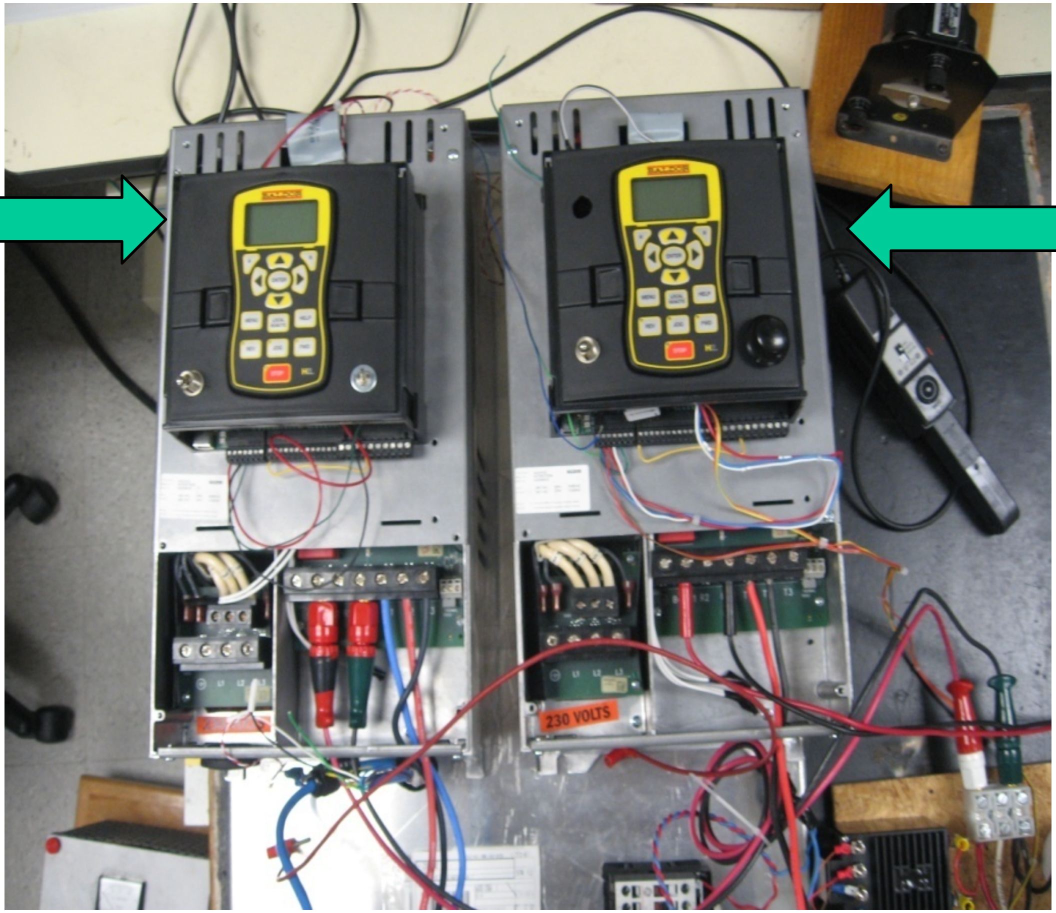


Schematic of System Setup

Prototype Setup

BATTERY EMULATOR

INVERTER



Baldor H2 Drives

NaS Battery System Emulator during Discharge Mode

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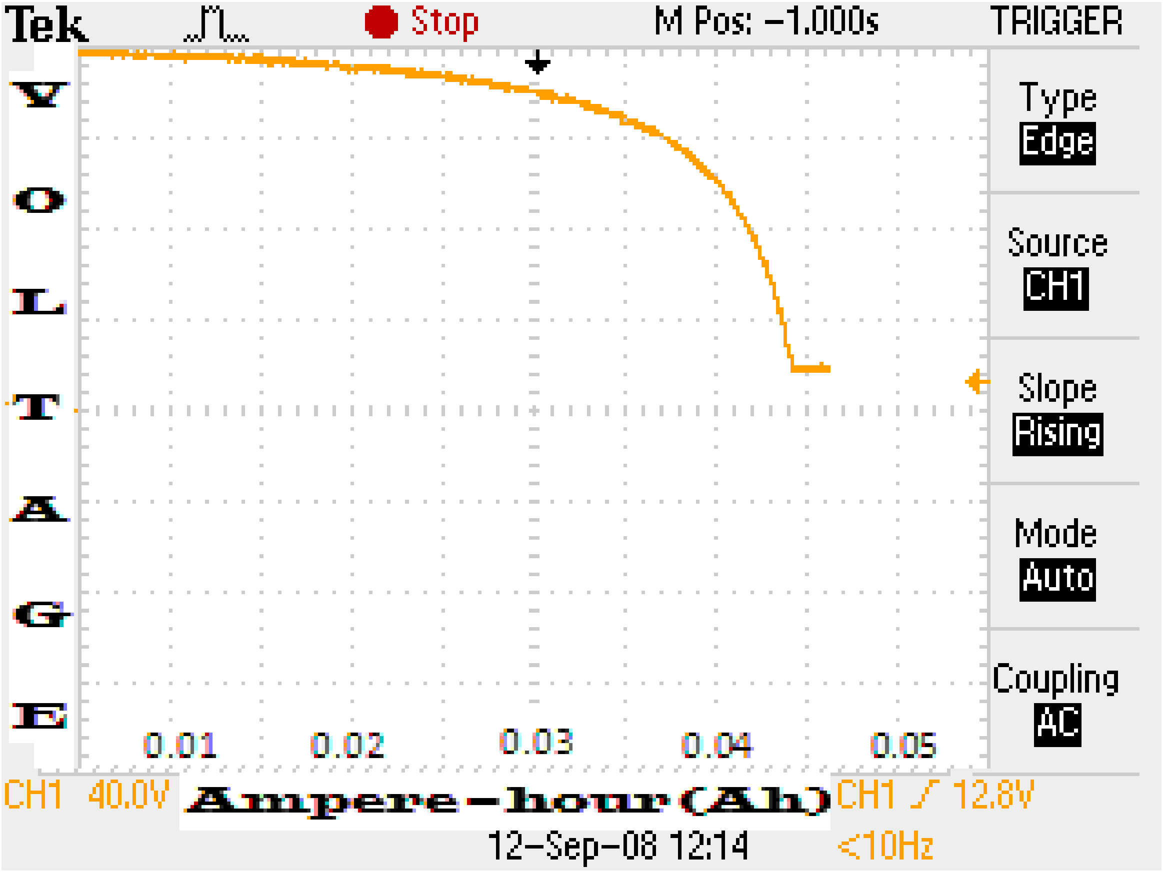

Experimental results of the battery emulator during discharge mode

Summary/Conclusions

- ✓ Progress is being made on both protection devices and energy storage
- ✓ New thyristor device model has been developed
- ✓ New power packaging techniques have been developed and are being utilized in FCL and other power module prototypes
- ✓ Next stage of FCL prototype in SiC is under construction using thyristors
- ✓ FCL test procedures are being put in place for testing in 2009
- ✓ Energy storage converter research has progressed
- ✓ Battery emulation in the NCREPT test facility has progressed

Future Tasks

- **Developing 8 kV/ 1 kA switching position with SiC S-GTOs for FCL prototype**
- **Continue investigating power packaging techniques in die attach, substrate attach, and passivation.**
- **Test ours and other FCL prototypes**
- **Produce higher power prototype of energy storage circuits**
- **Develop closed loop control system to monitor and direct power flow**
- **Experimentally validate bidirectional power flow**
- **Deploy the battery emulation work in NCREPT's test facility**

Recent Publications

National Center for Reliable Electric Power Transmission

1. O. S. Saadeh, H. A. Mantooth, J. C. Balda, A. K. Agarwal, A. S. Kashyap, “The Modeling and Characterization of Silicon Carbide Thyristors,” *39th IEEE Power Electronics Specialists Conf (PESC),* 2008.
2. H. A. Mantooth, O. Saadeh, E. Johnson, J. C. Balda, S. S. Ang, A. B. Lostetter, R. M. Schupbach, “Solid-State Fault Current Limiters: Silicon versus Silicon Carbide,” *2008 PES General meeting (PESGM)*, July 2008.
3. E. Johnson, O. S. Saadeh, J. C. Balda, H. A. Mantooth, S. S. Ang, “An Analysis of Paralleled SiC Bipolar Devices,” *39th IEEE Power Electronics Specialists Conf (PESC)*, 2008.
4. B. Ozpineci, M. S. Chinthavali, L. M. Tolbert, A. Kashyap, H. A. Mantooth, “A 55 kW three-phase inverter with Si IGBTs and SiC Schottky diodes,“ *IEEE Trans. On Industry Applications*, accepted, 2008.
5. J. Carr, D. Hotz, A. Ong, J. Balda, H. A. Mantooth, A. Agarwal, “Assessing the Impact of SiC MOSFETs on Converter Interfaces for Distributed Energy Resources, *IEEE Industry Applications Society Meeting*, 4 pgs., Oct. 2007, New Orleans, LA.
6. J. Carr, D. Hotz, A. Ong, J. Balda, H. A. Mantooth, A. Agarwal, “Assessing the Impact of SiC MOSFETs on Converter Interfaces for Distributed Energy Resources, *IEEE Transactions on Industry Applications*, accepted.
7. R. J. Castillo, D. Molina, M. Huertas, J. C. Balda, H. A. Mantooth, "Testing of Power Electronic Modules for Distributed Systems at the National Center for Reliable Electric Power Transmission," *IEEE Energy 2030 Conference*, 2008.
8. J. A. Carr, D. Hotz, J. C. Balda, H. A. Mantooth, A. Ong, "Assessing the Impact of SiC MOSFETs on Converter Interfaces for Distributed Energy Resources," *Industrial Applications Society Annual Meeting*, 23-27 Sept. 2007, pp. 336-341.
9. J. A. Carr, D. Hotz, J. C. Balda, H. A. Mantooth, A. Ong, "Assessing the Impact of SiC MOSFETs on Converter Interfaces for Distributed Energy Resources," *IEEE Transactions on Power Electronics*, accepted.
10. J. A. Carr, B. Rowden, J. C. Balda, "A Three-Level Full-Bridge Zero-Voltage Zero-Current Switching Converter With a Simplified Switching Scheme," *IEEE Transactions on Power Electronics*, accepted.
11. J. A. Carr, J. C. Balda, Y. Feng, H. A. Mantooth, "Fault Current Limiter Placement Strategies and Evaluation in Two Example Systems," *IEEE Energy 2030 Conference*, 2008.
12. J. A. Carr, J. C. Balda, H. A. Mantooth, "A Survey of Systems to Integrate Distributed Energy Resources and Energy Storage on the Utility Grid," *IEEE Energy 2030 Conference*, 2008.