FREEDM SYSTEMS CENTER

Fault Isolation Device - Seminar

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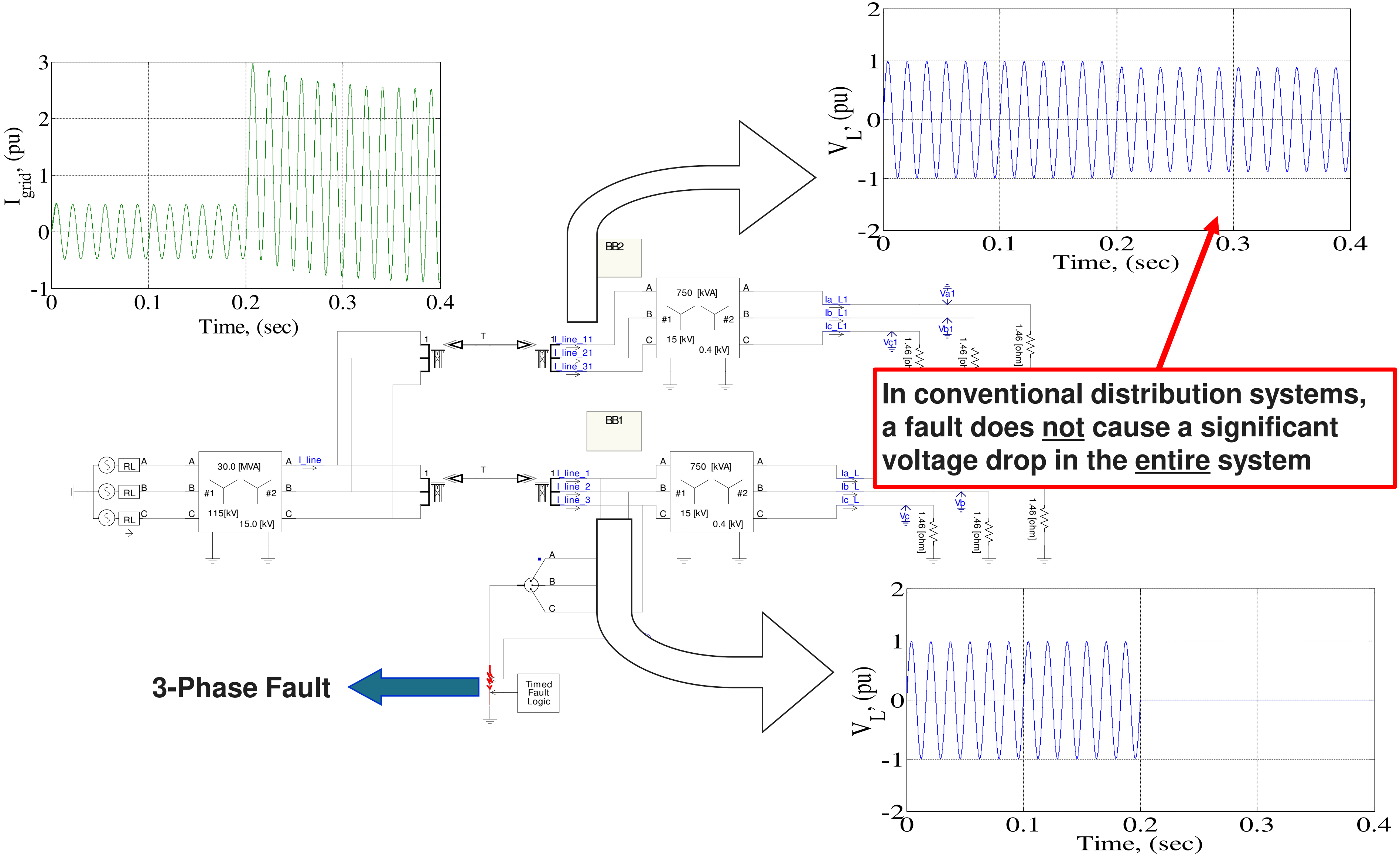
Fault Currents in Conventional Systems



Fault Currents in FREEDM Systems

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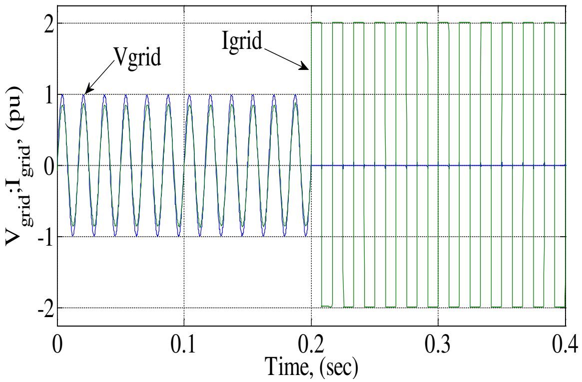
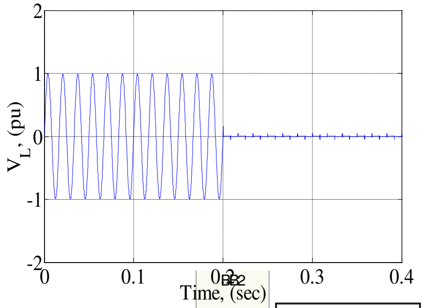
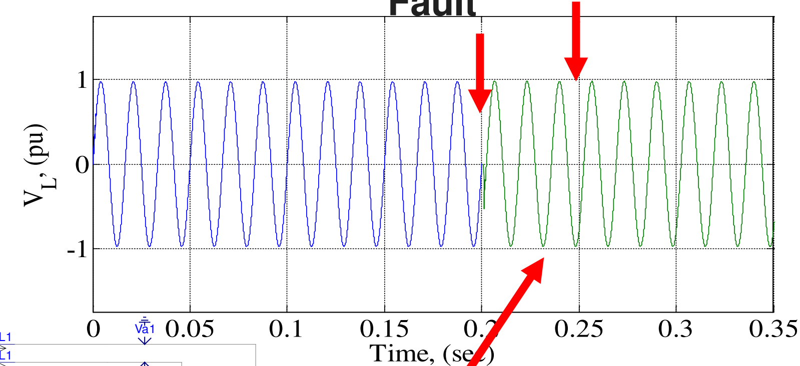
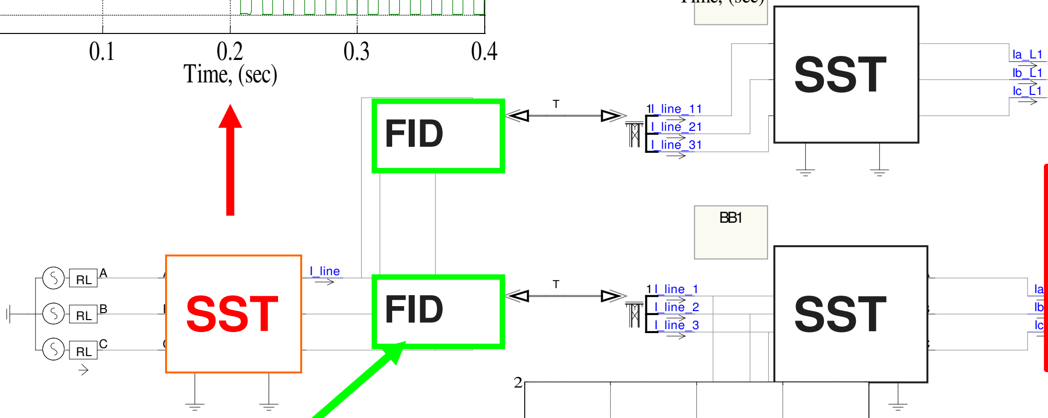
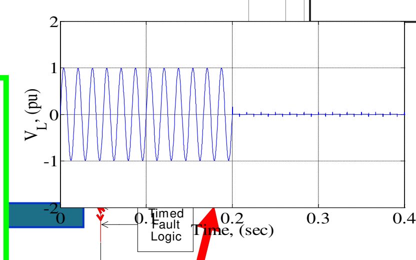




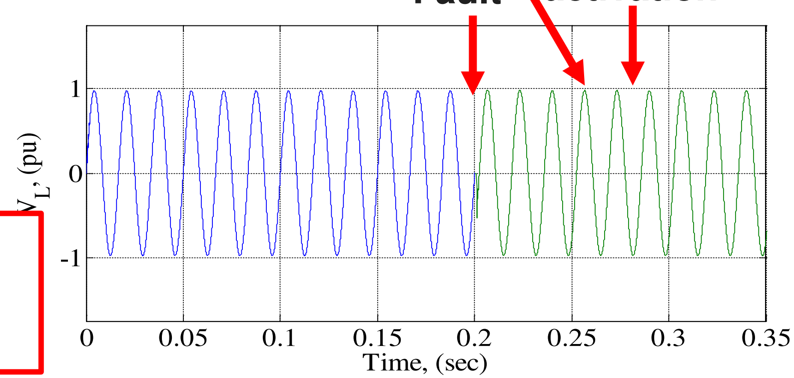




In FREEDM systems, the Distributed Energy Storage Device (DESD) of SST provide the power so the customers will not lose the power in case of fault



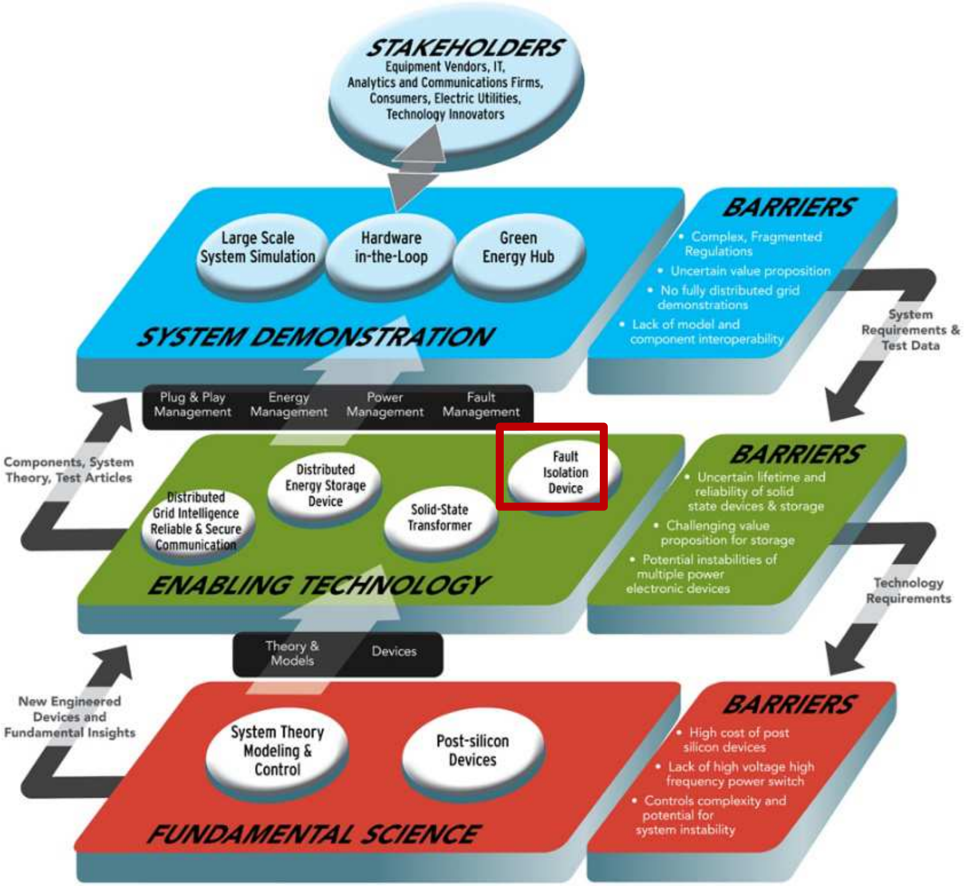
The Fault Isolation Device (FID) has to provide ultra fast isolation of the fault to quickly restore system voltage for continuous operation



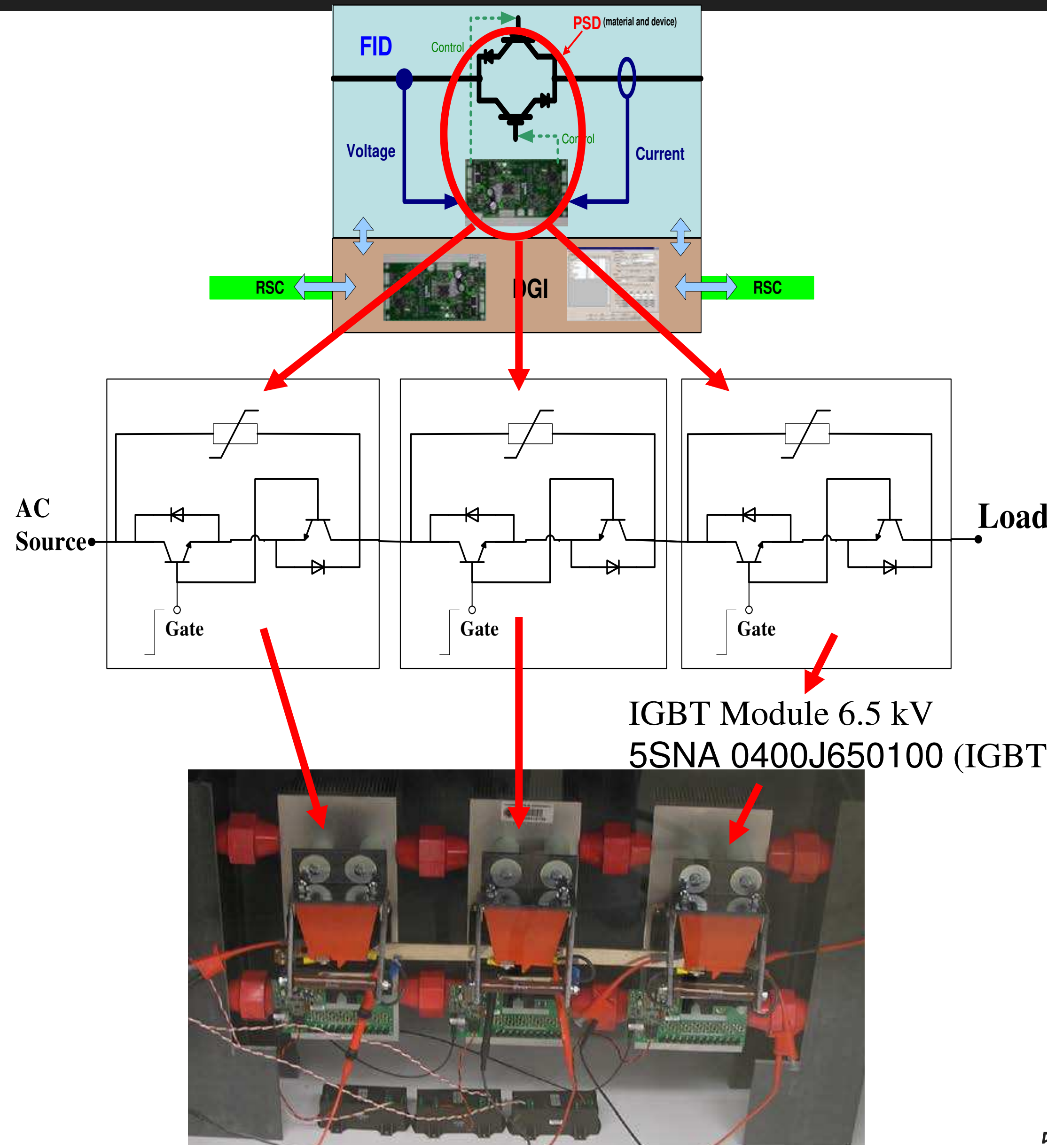
The inherent fault current limitation causes a significant voltage drop in the <u>entire</u> system

FID Thrust Objectives

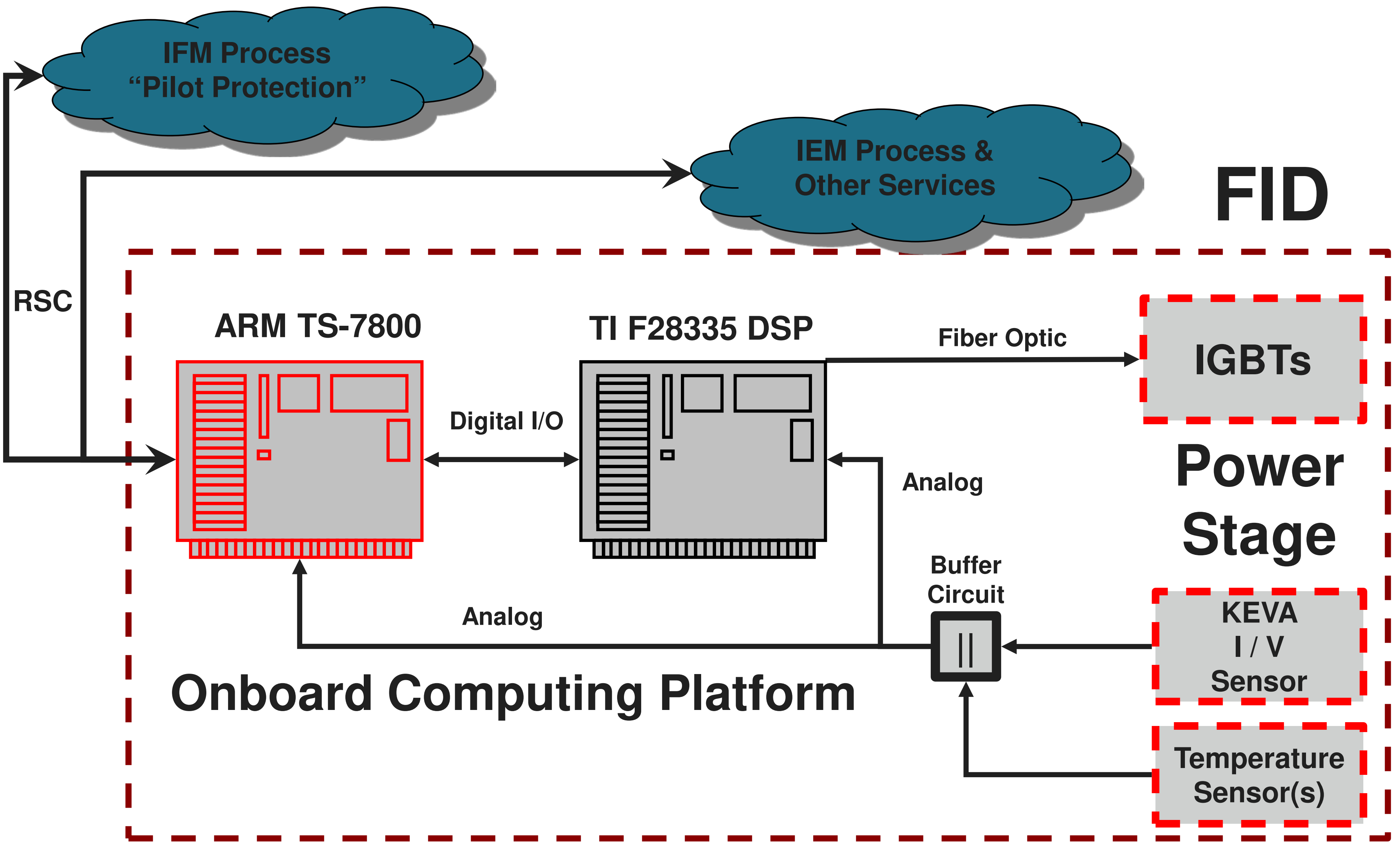
- Develop and demonstrate FID technology evolution
  - Gen-1…Gen-3
- Target: 15 kV class single-phase switch
  - Carry $150A_{rms}$ (3.2 MVA @12.5kV, 3-phase)
  - Interrupt $200A_{rms}$
  - Open/close within <1ms
  - >99.99% efficient (total 3 phase losses 300 W)



Gen-1 Solid-State FID



Gen-I FID Controller and Communication



Testing Fault Isolation Device (FID)

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NSF

Real Time Simulator RTDS

4.16 kV utility bus

5 MW Converter "Amplifier"

AC current feedback to RTDS

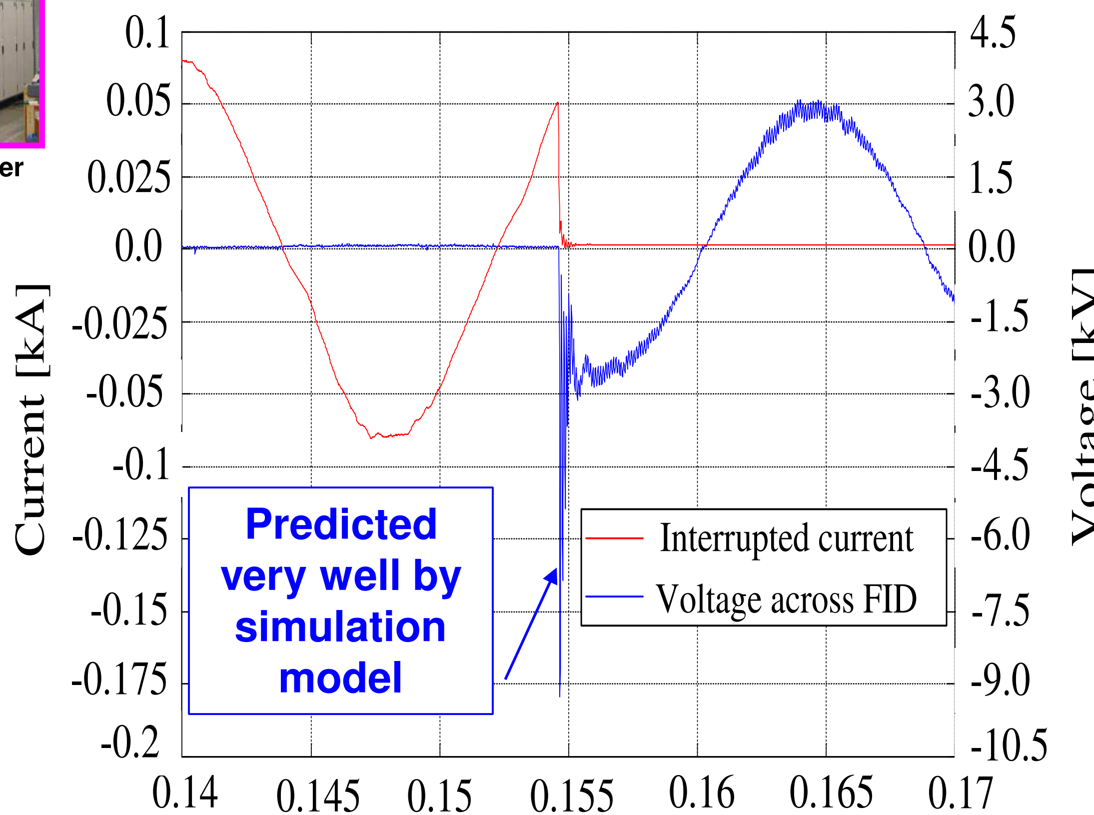
AC voltage reference from RTDS

4.16 kV experimental bus

Solid state switch
3 x 6.5 kV IGBT modules

Using active di/dt control with IGBTs to reduce magnitude of TRV

V_{source}=2.8 kV peak, $I_{interrupted}$=50 A



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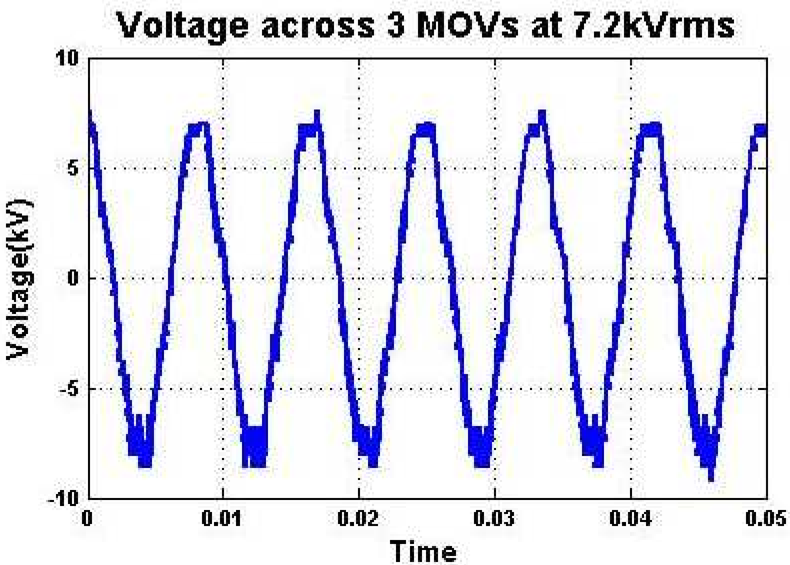
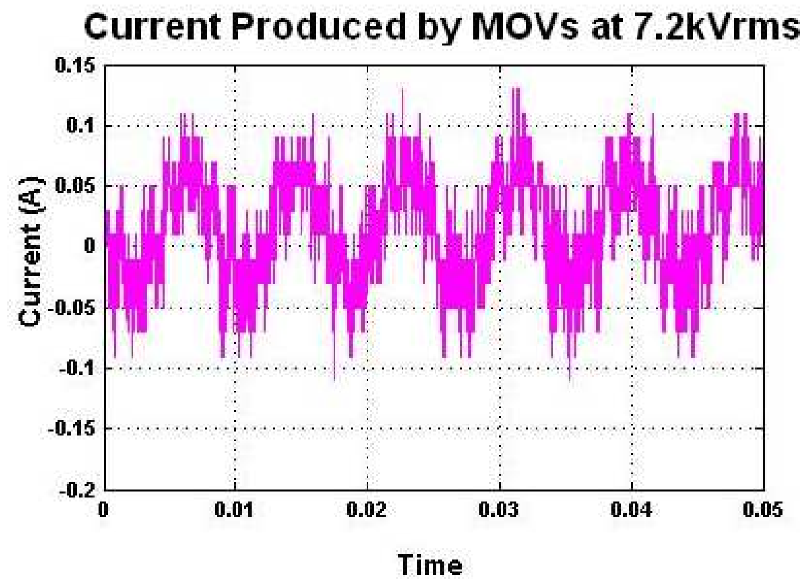
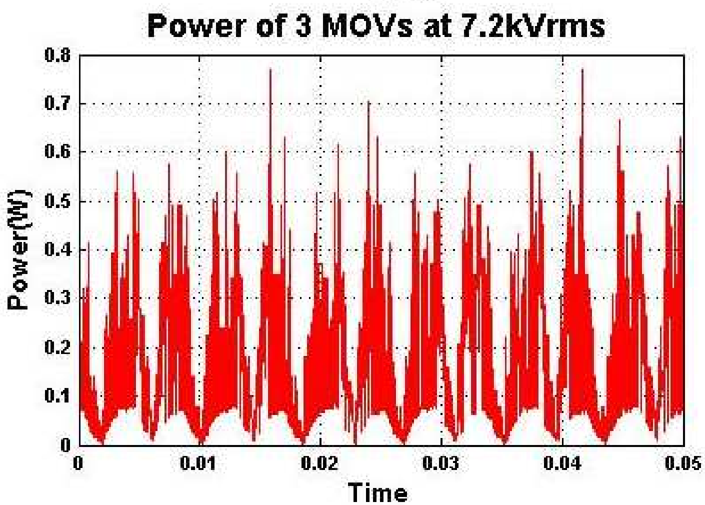
HV Testing – MOV @ 7.2 kV

MOVs at the required 7.2kVrms Steady State Voltage



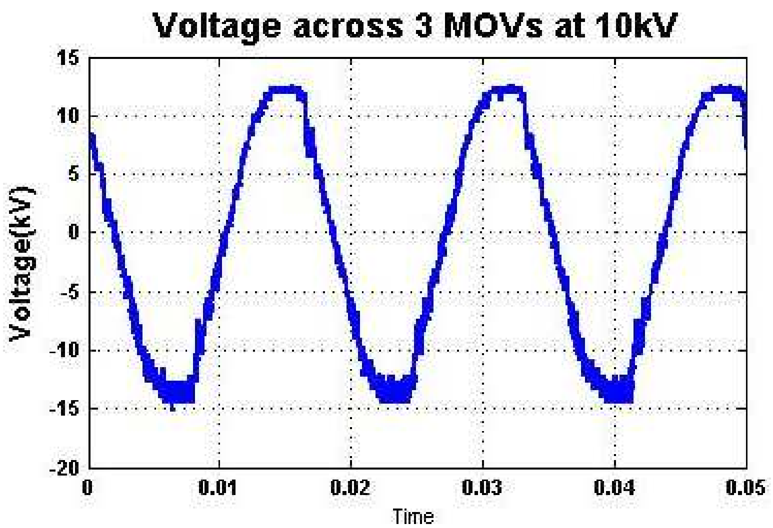


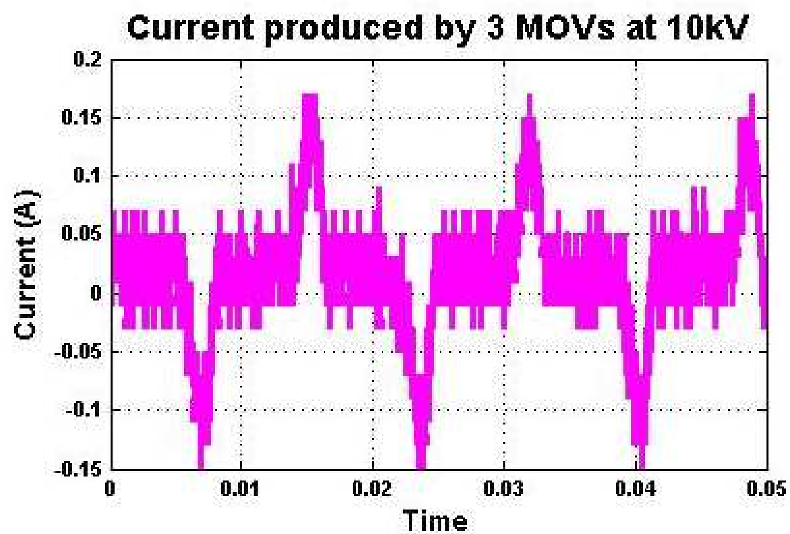


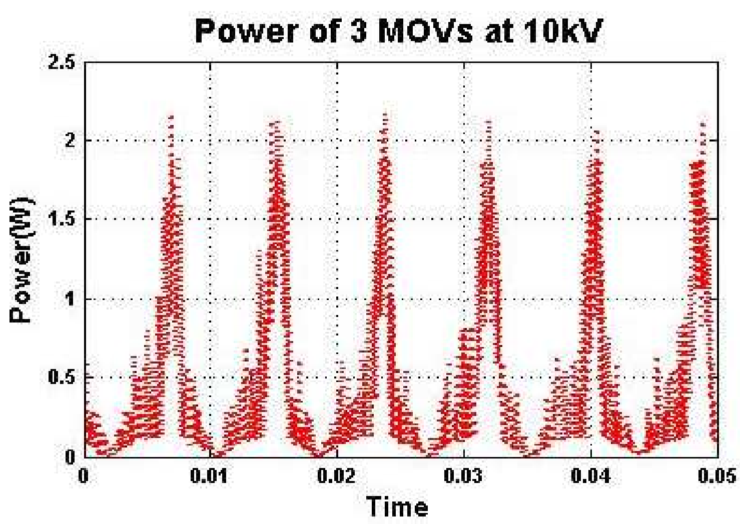
- **Notes:**
  - No current flowed at this voltage level
- **Conclusions:**
  - The FID was properly operational at required steady state voltage

HV Testing – MOV @ 10 kV

MOVs at 10kVrms Steady State Voltage



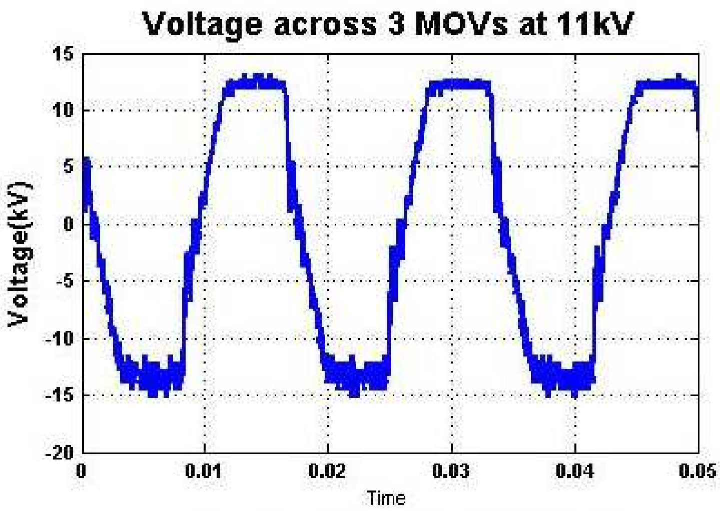


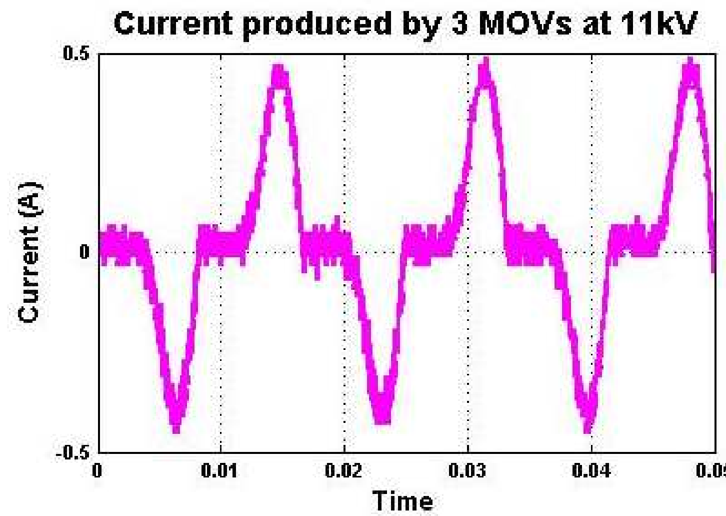


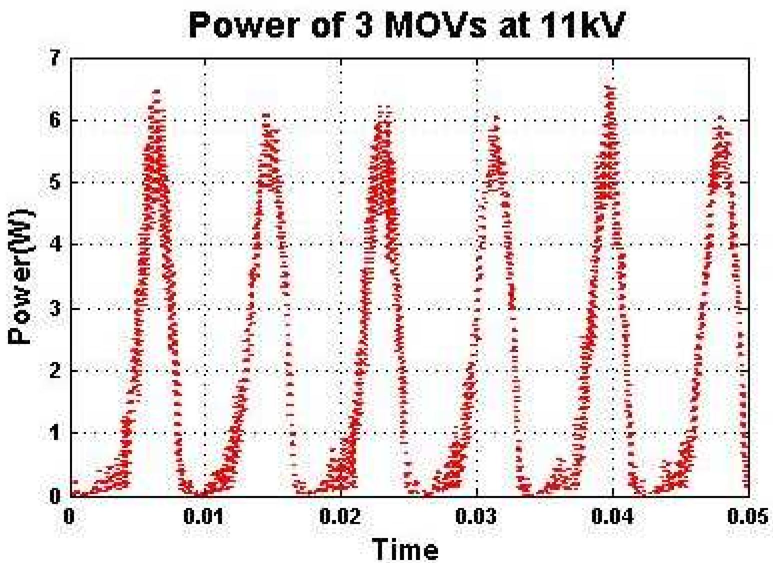
- **Conclusions:**
  - Current conduction began at 10kVrms
  - Power is still lower than the max dissipation spec of 2.5W
  - **10kVrms is the Max Operational Steady State Voltage of the FID**

HV Testing – – MOV @ 11 kV

MOVs at 11kVrms Steady State Voltage

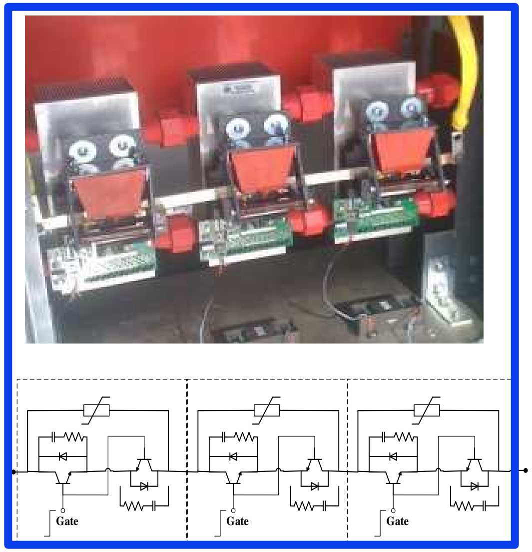


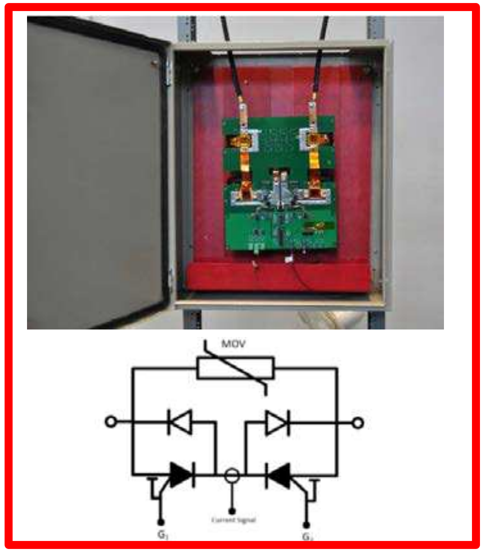


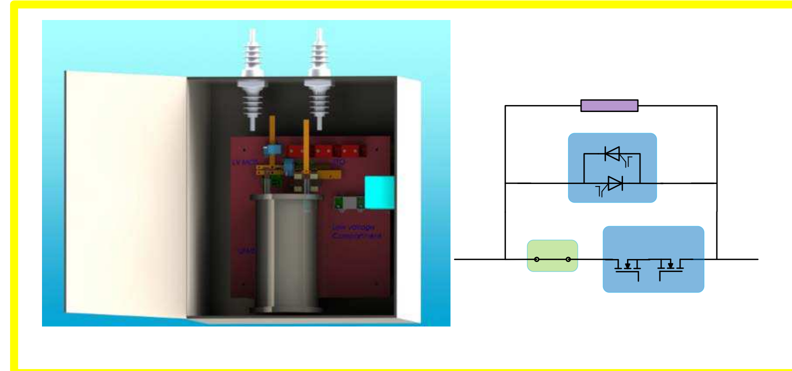


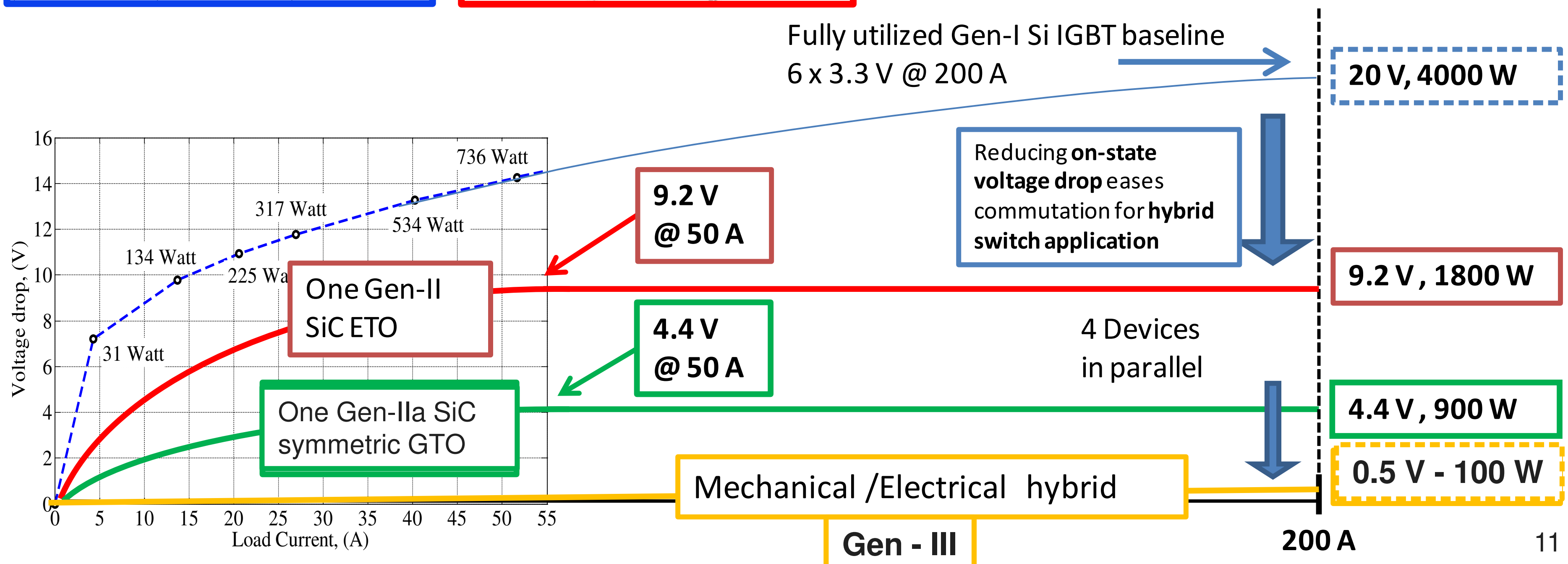
- **Conclusions:**
  - Power is has risen above the max dissipation spec of the MOVs (2.5W)
  - MOVs began heating up
  - **FID cannot be operated at Steady State voltages higher than 10kVrms**

3 (and ½) Generations of FIDs





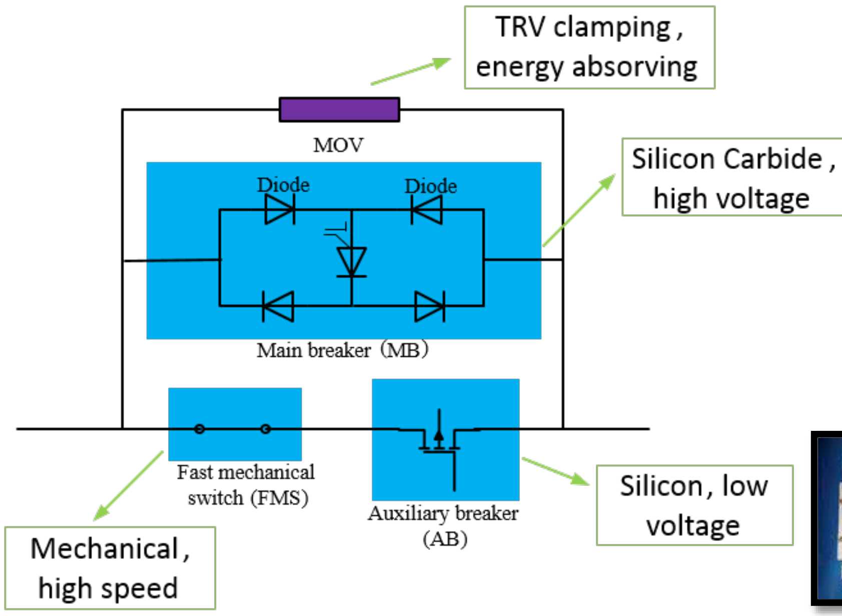


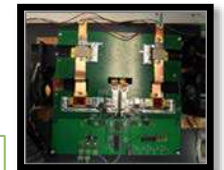


Gen 3 FID

0.1 V, 20 W

200A, 15 kV mechanical disconnect switch Open in < 1ms

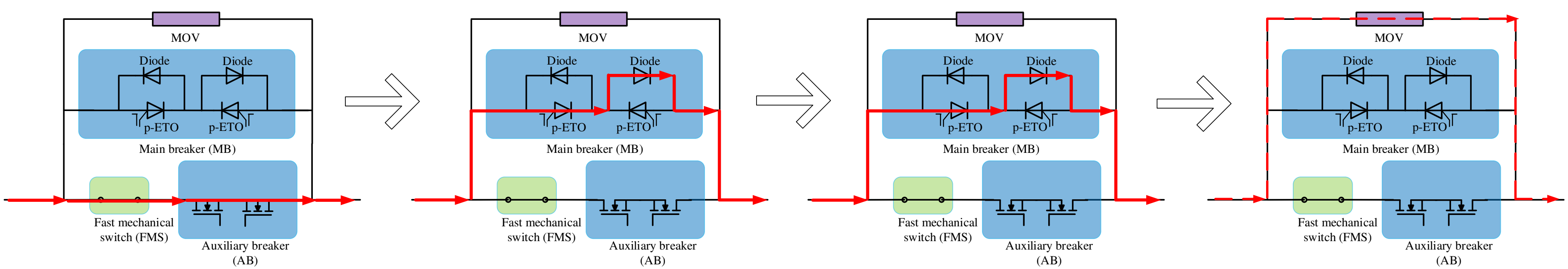




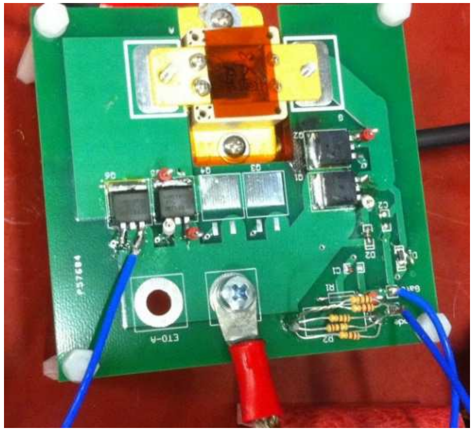
15 kV, 200 A, SiC p-ETO, bi-directional

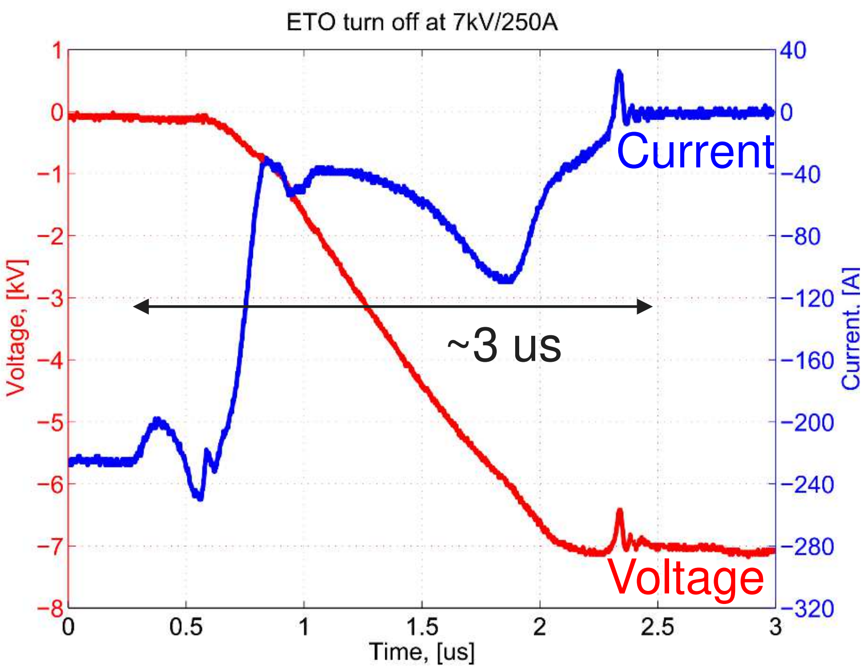
200 (400) A, MOSFET Rds(on) < 1mOhm Vbr = 100

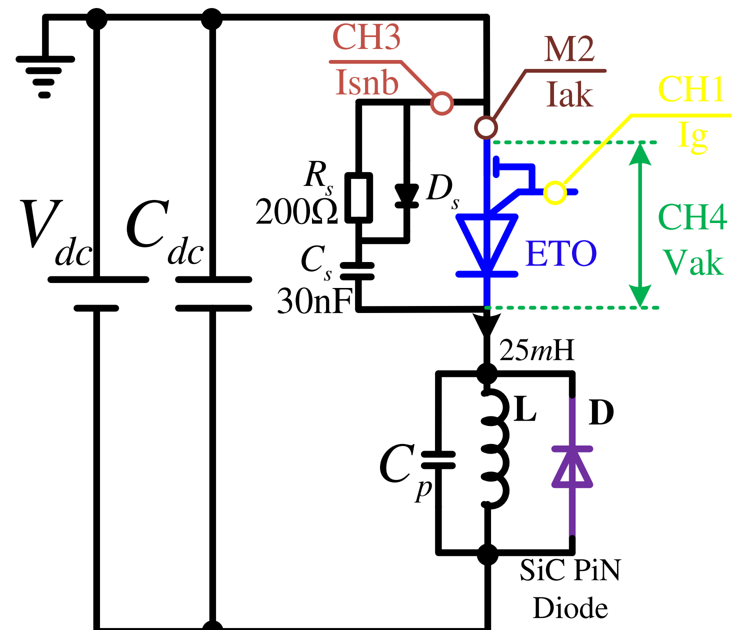
0.1 V, 20 W



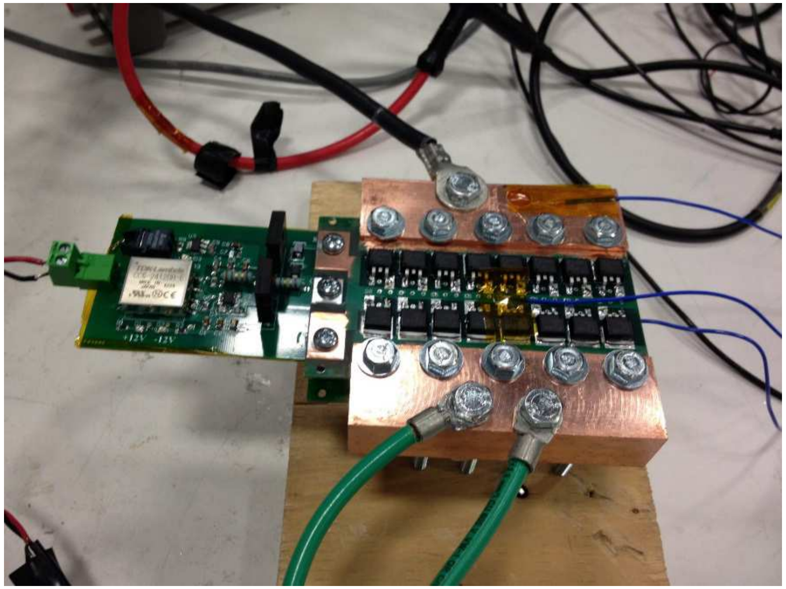
Testing the ETO

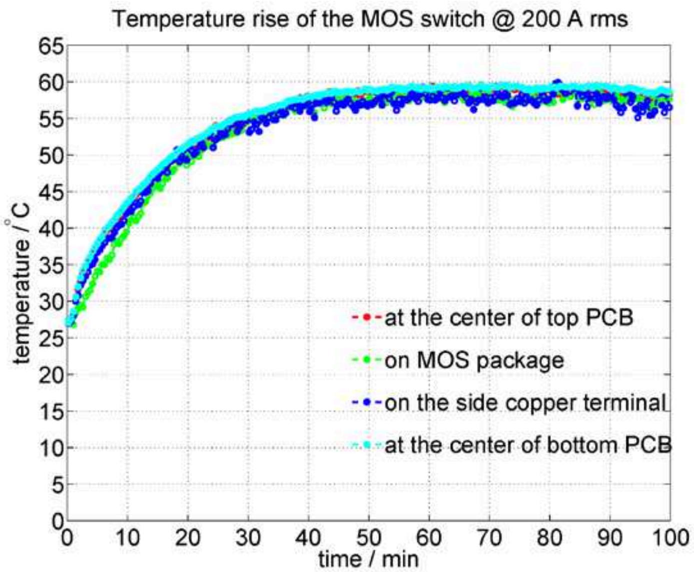


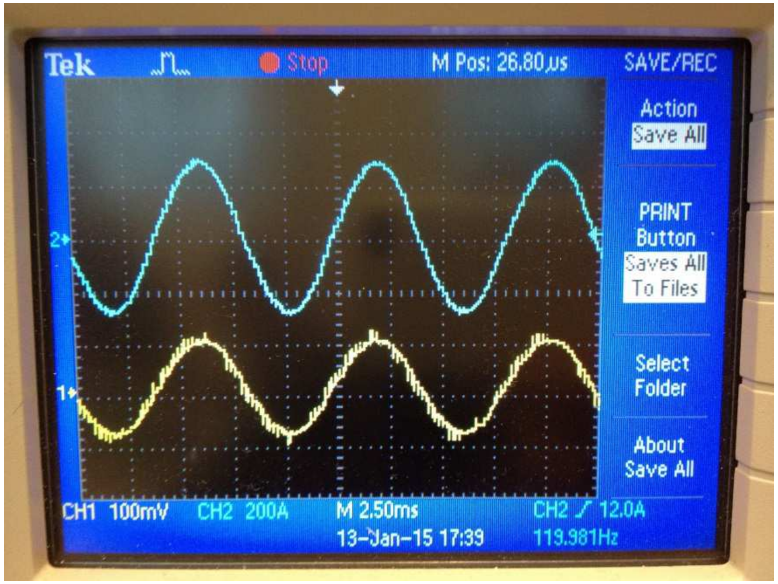




Testing the MOSFET

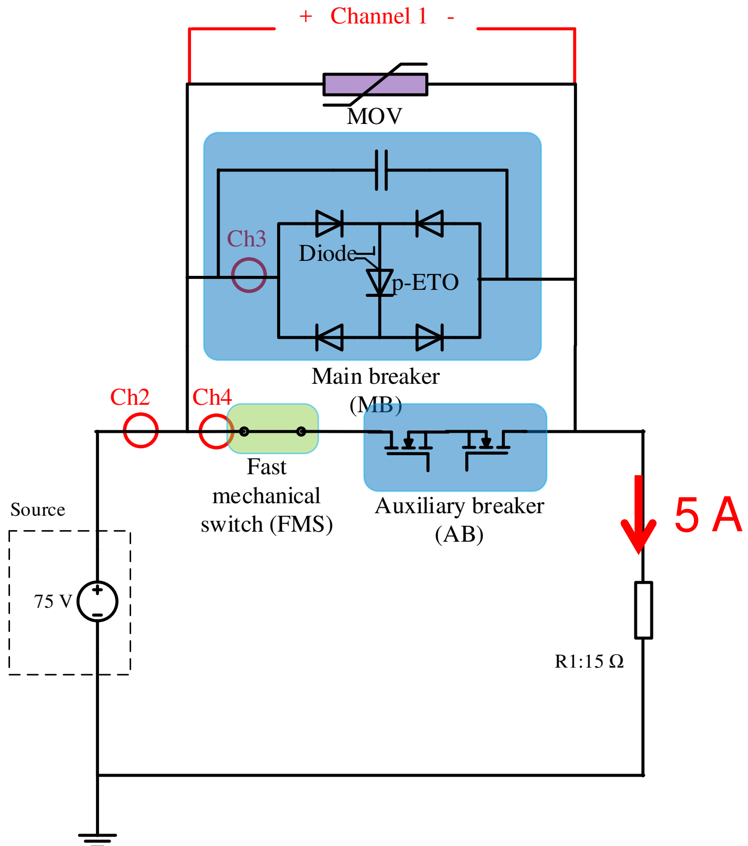


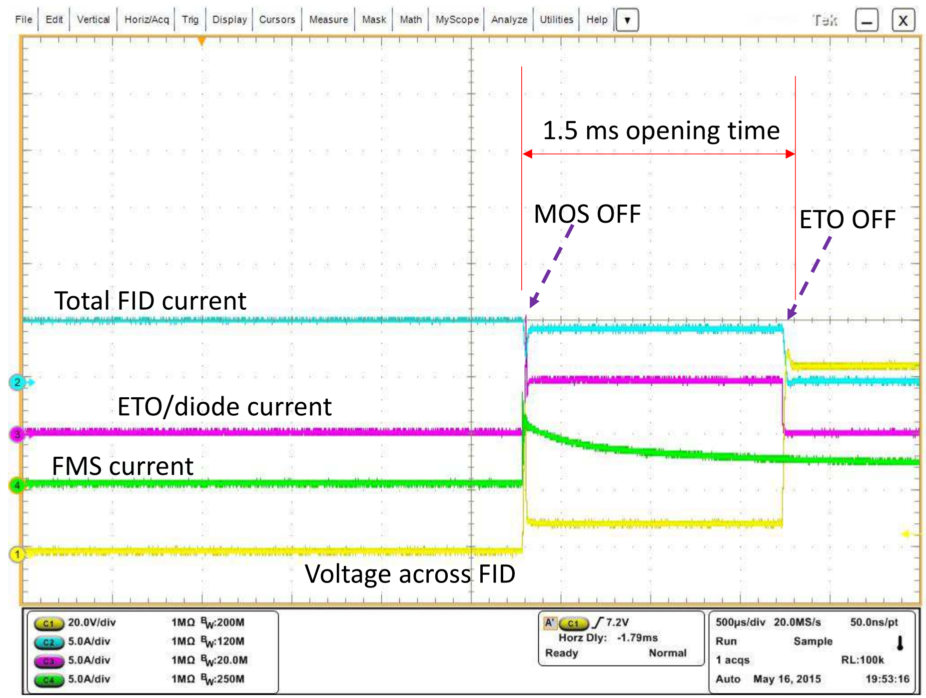


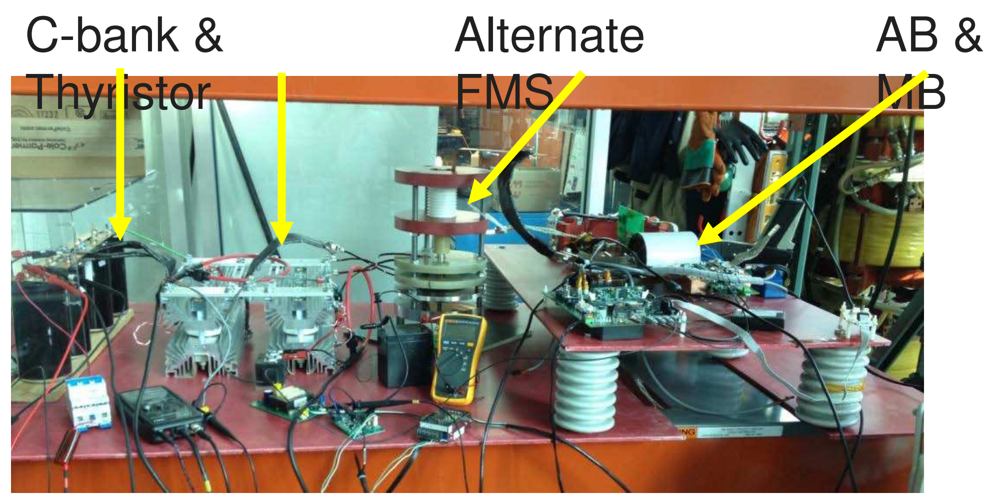


- ✓ Low loss:
  100 mV voltage drop at 280 A.
- ✓ Low temperature rise:
  33 °C at 200 A rms.
- ✓ Compact design:
  5”X 5”X2”, no fan required.

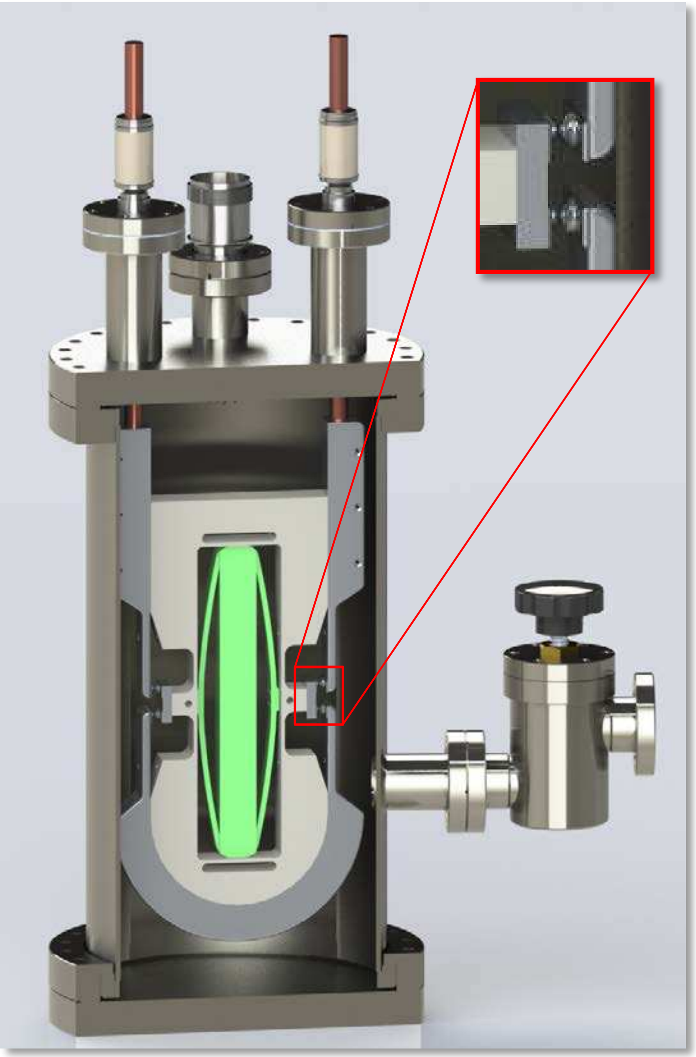
Demonstrating Operating Sequence



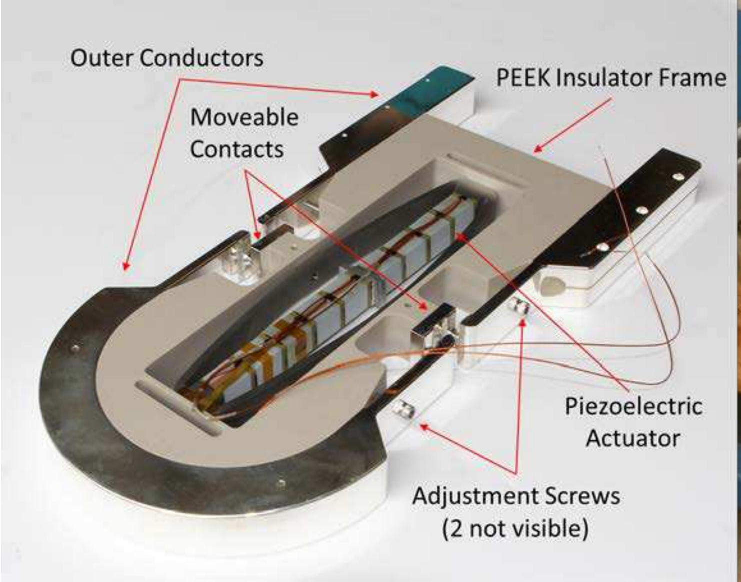




Piezoelectric Actuated Fast Mechanical Disconnect Switch (FMS)

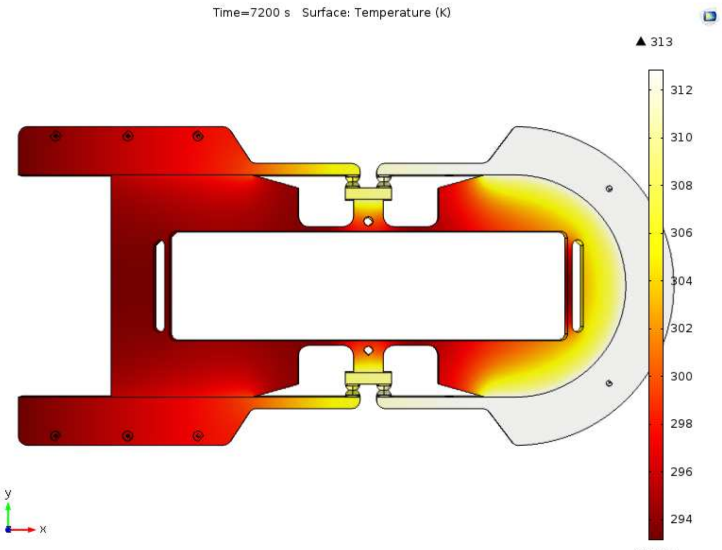


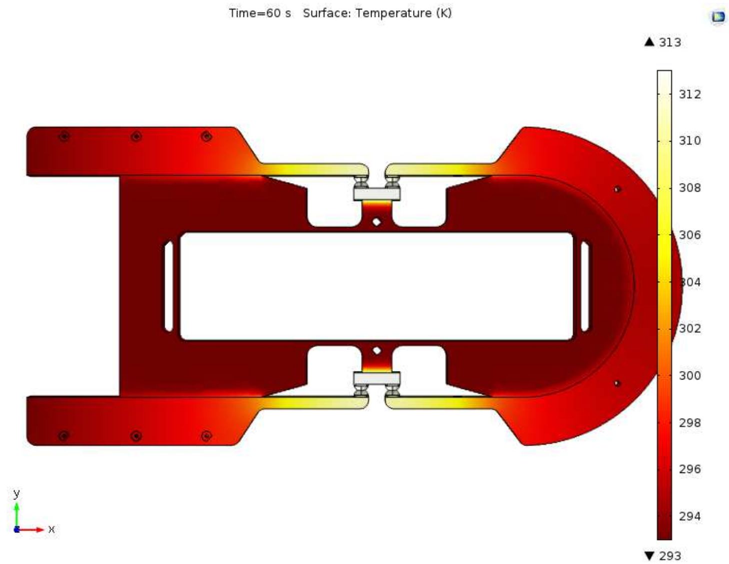
- 15 kV_{RMS}, 200 A
- Opening in < 1 ms
- Losses in on-state: < 5 W

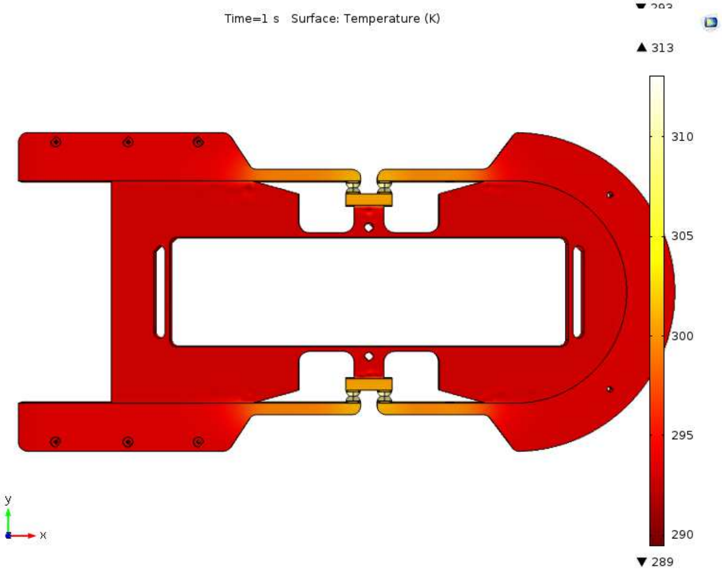


US Patent Application No. 15/214,015, filed 7/19/2016

Max Current Simulation

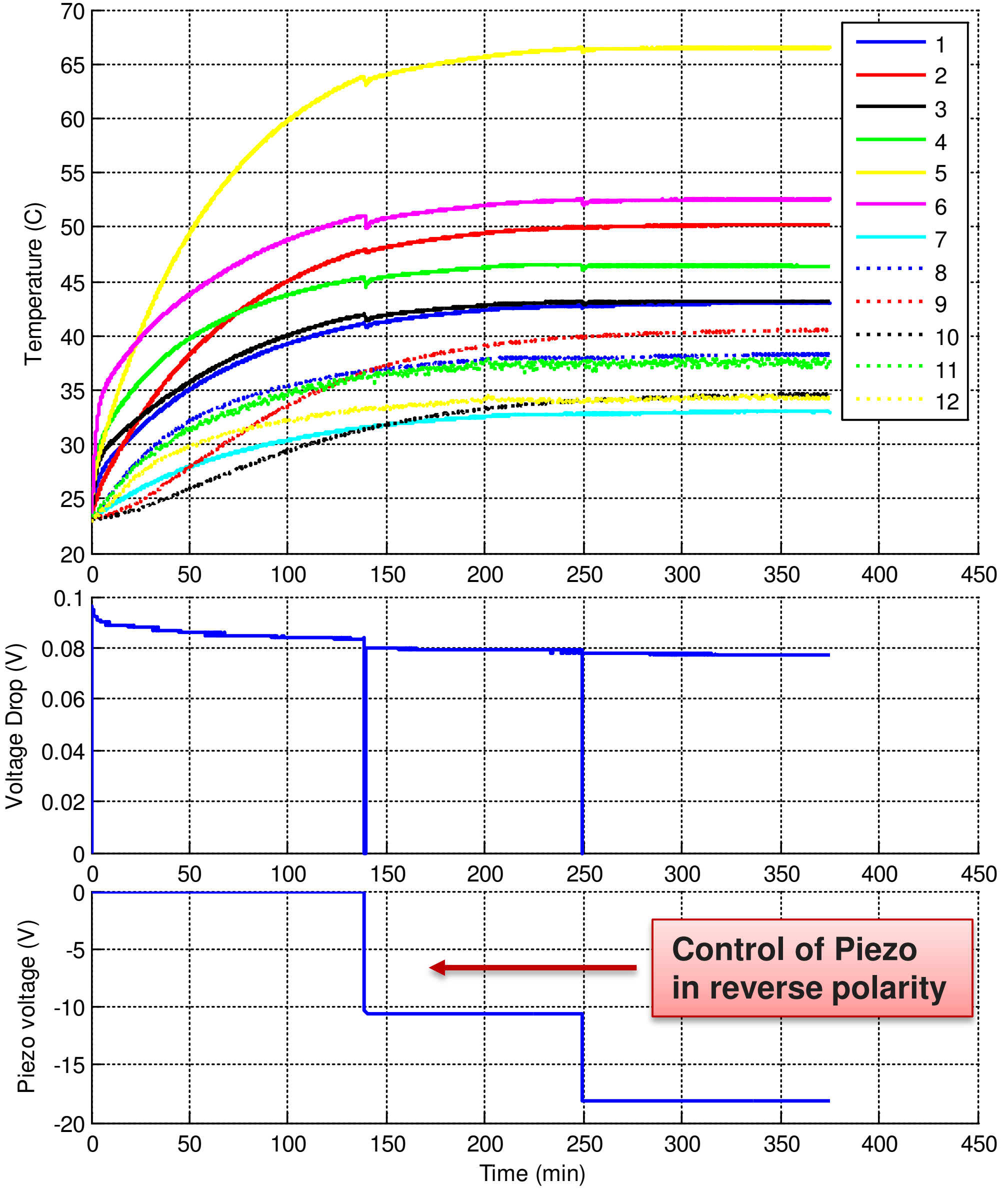


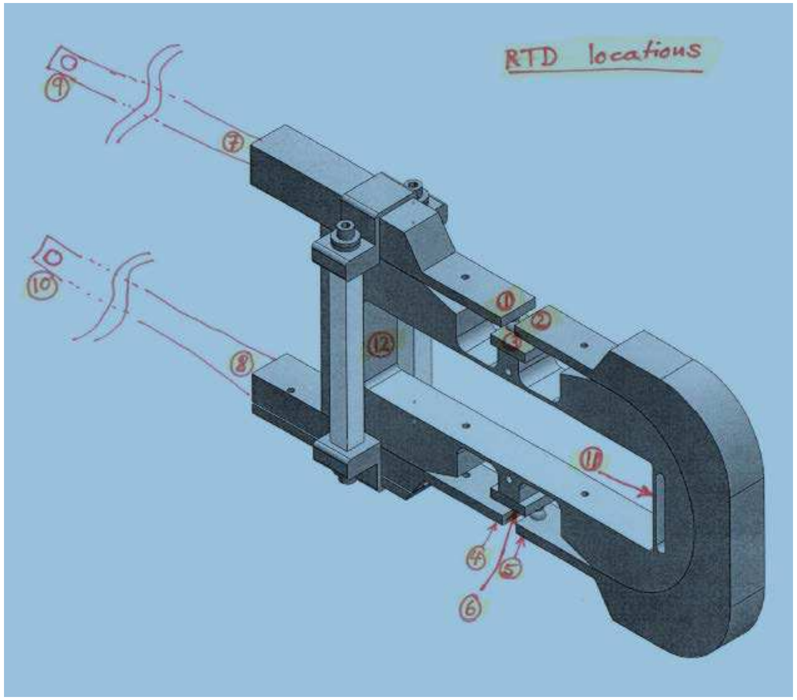




- Constrained maximum current simulation: (20K temperature increase)
  - Steady state: 300 A max
  - 1 minute transient: 730 A max
  - 1 second transient: 3050 A max

Project Y8.ET4.1 – FMS
Heat run in low vacuum with constant 150 A





- for the 200A test
  – Temperature not stabilized
  – Still hotspot reaching 90 C
  – All other sensors at 70 C

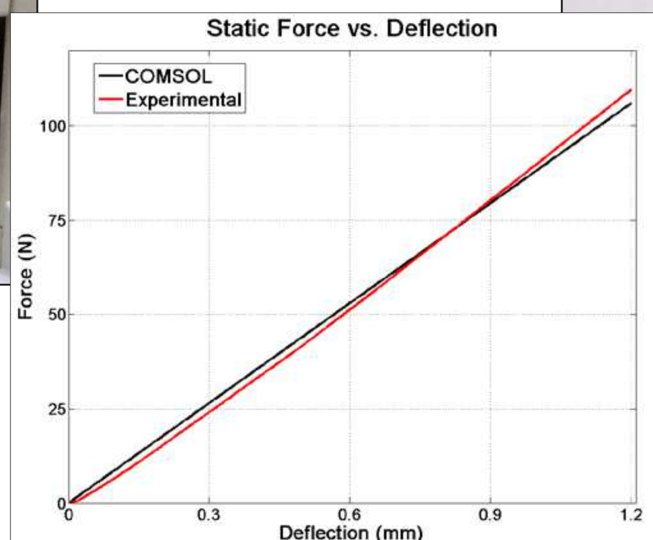
FMS Static Testing

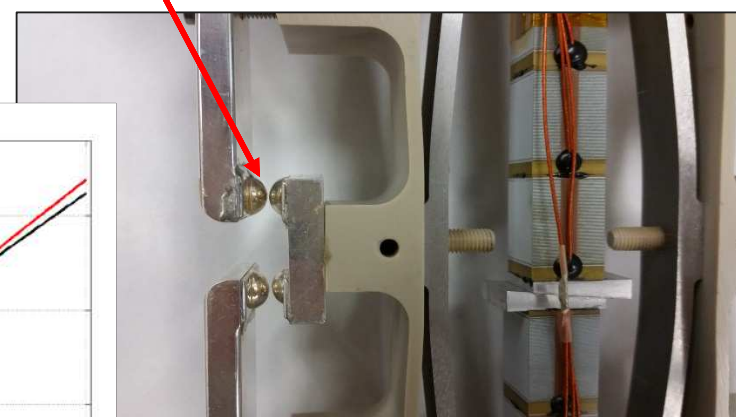
Mechanical Compression Test

- Frame statically compressed to total deflection of 1.2 mm (expected 1.0 mm)
- Total Force ≈ 110 N
- Comparison with COMSOL model

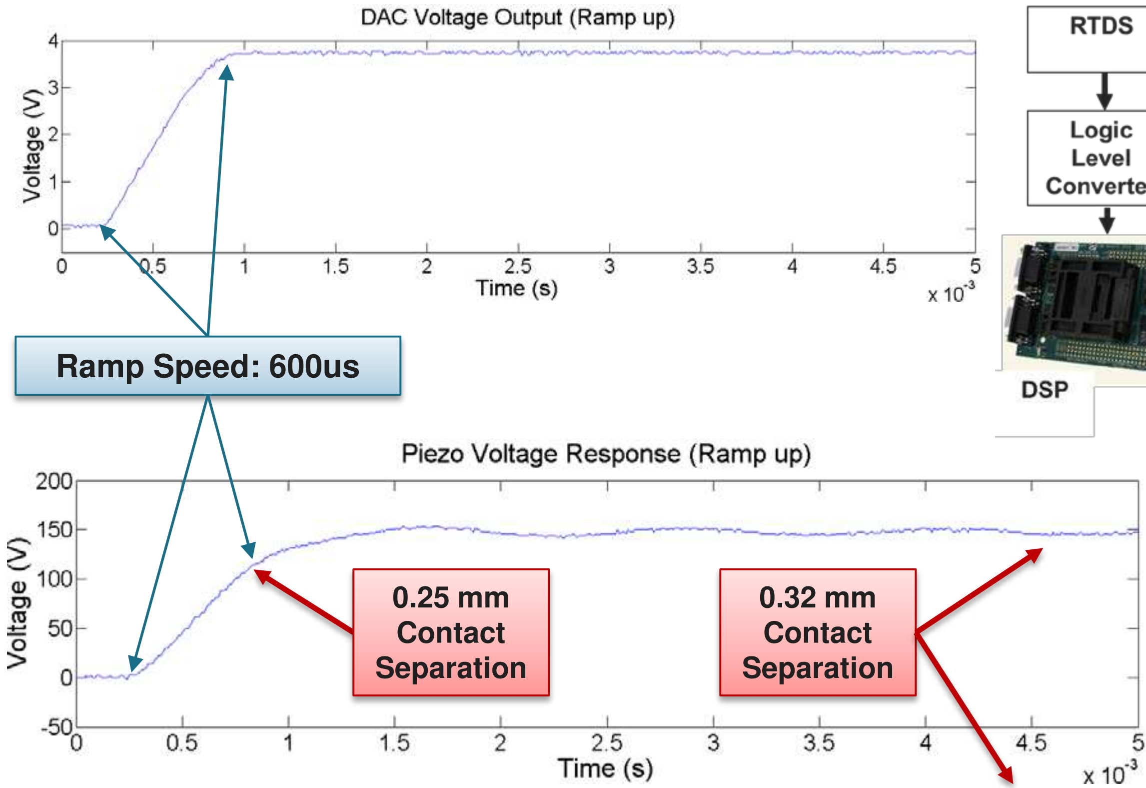
Contact Separation Test

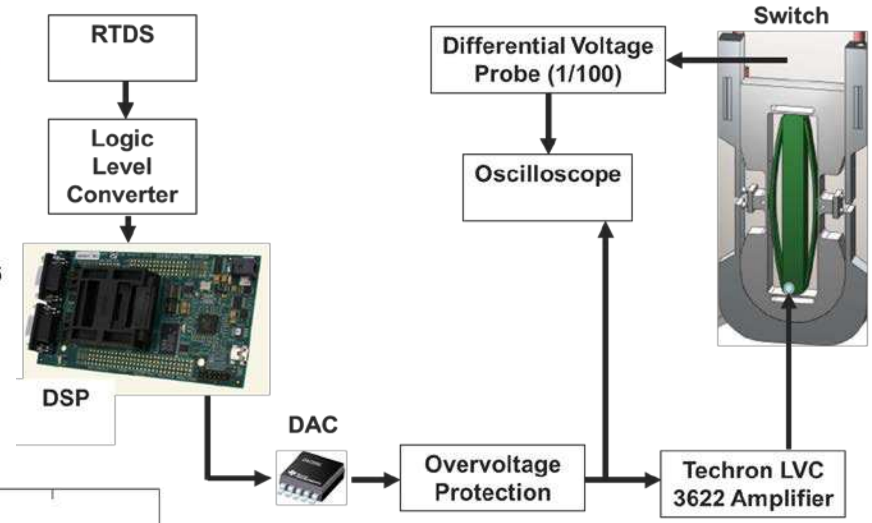
- Measurement of physical distance between contactors
- 150 V applied to piezo
- Total contact separation 4 x 0.4mm

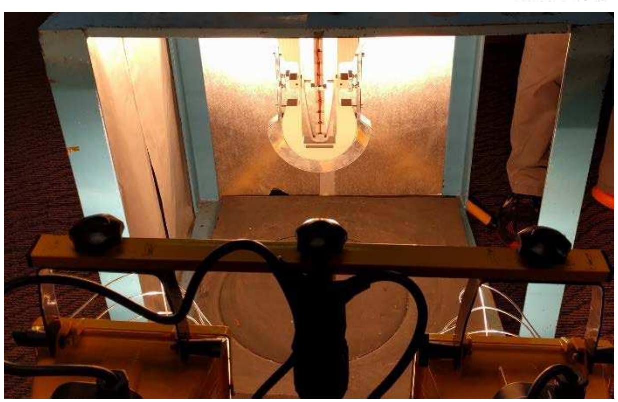


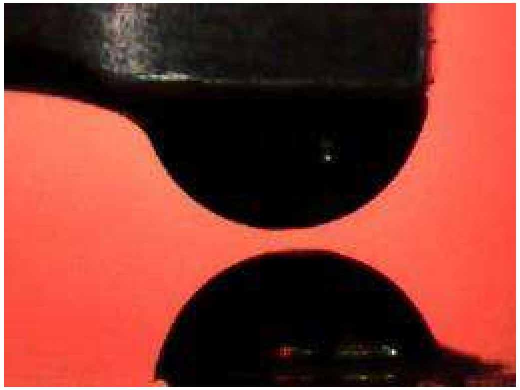


Dynamic Response in Air and DSP Controller Validation





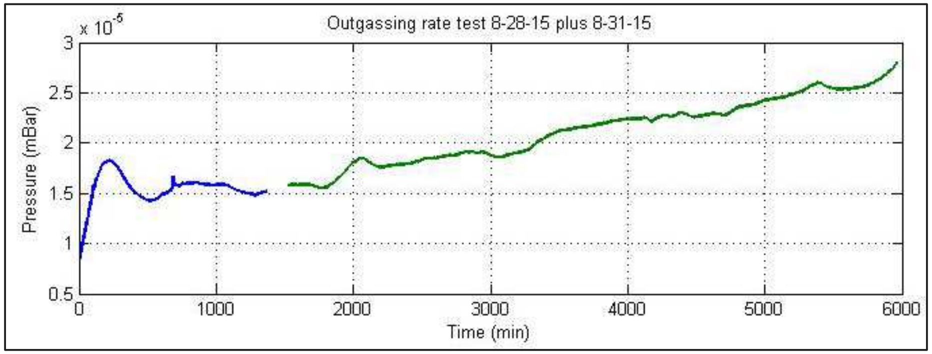


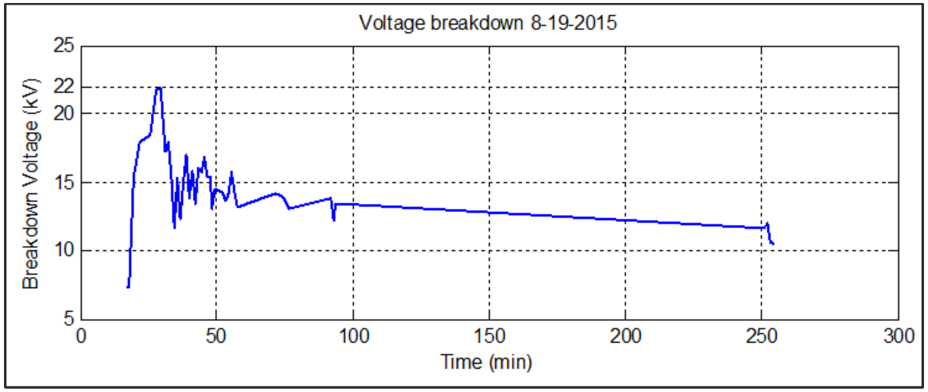


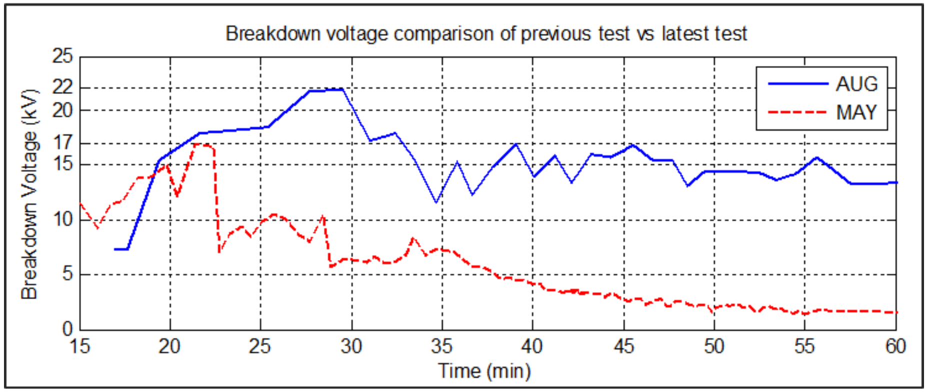
FMS
Voltage Breakdown test under vacuum

- Chamber maintained proper vacuum for 100 hrs, without getter pump

- Voltage breakdown tested with 4 x 0.5 mm contact spacing
  - ~22 kV max
  - ~15 kV steady state

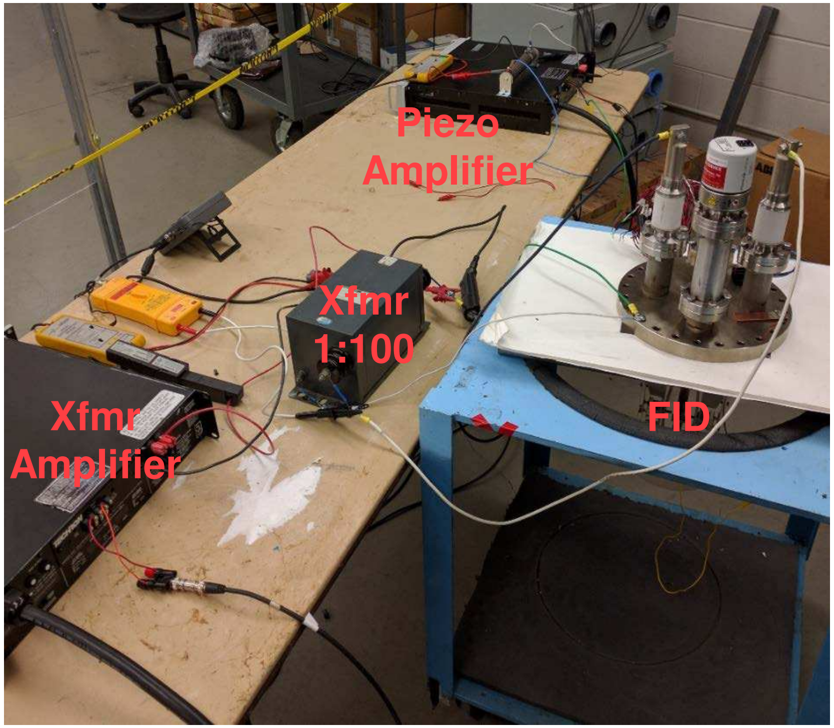




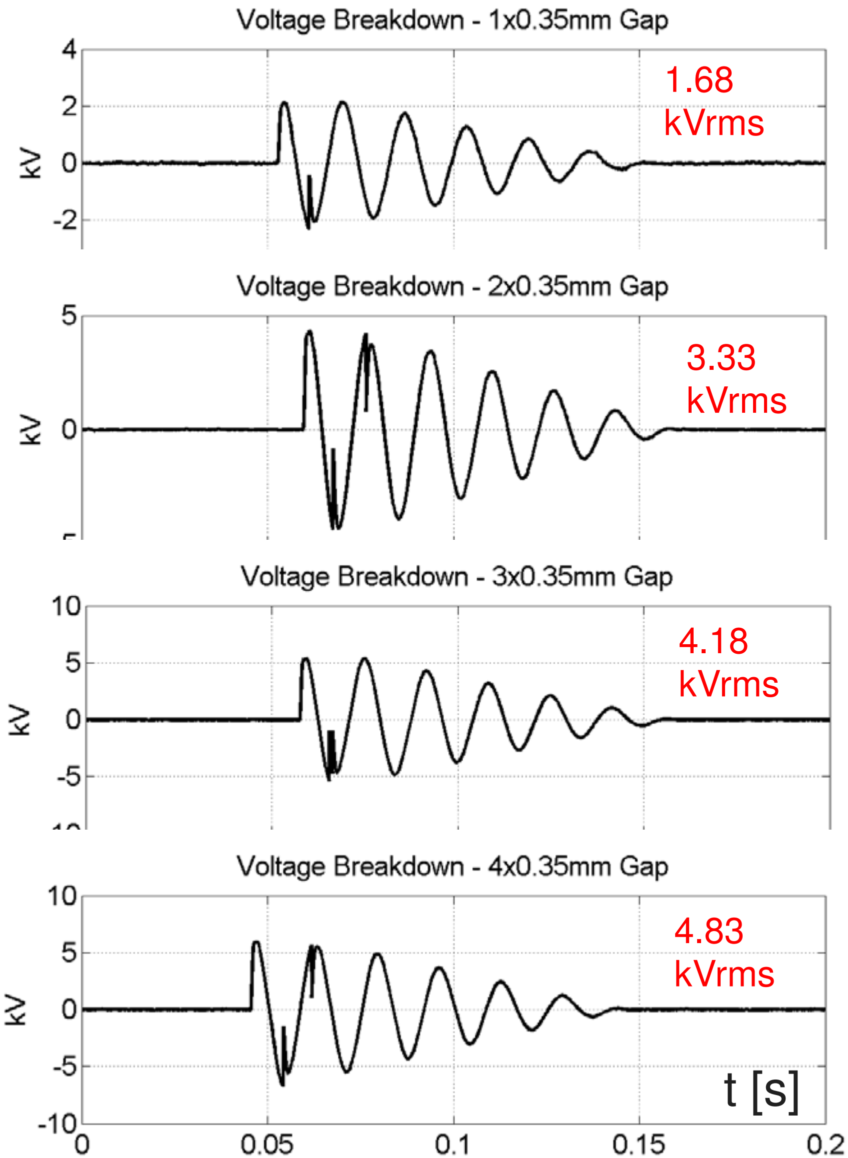


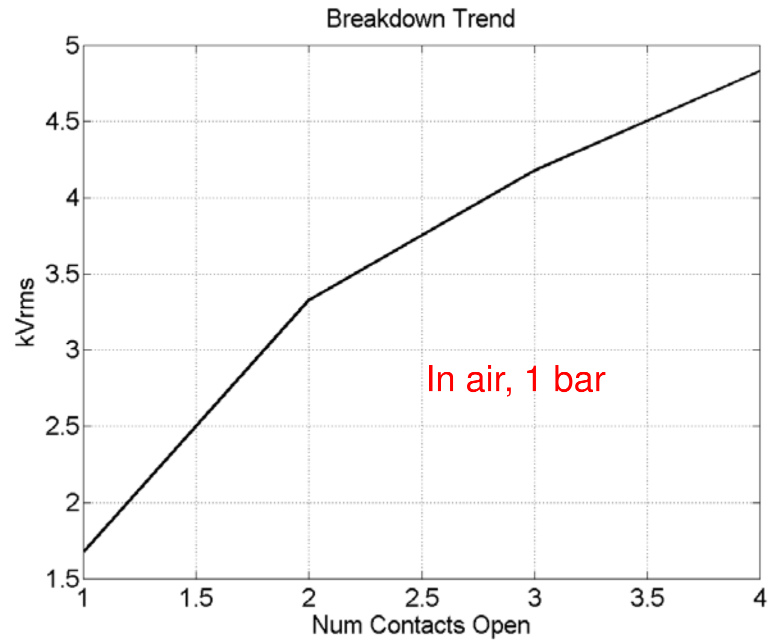
Voltage Withstand Test (1 atm) with Piezo Actuator

- AC Voltage Pulse applied across terminals of FID
  - RTDS -> Techron Amp -> 1:100 Xfmr -> FID terminals
  - 10 Mohm resistor connected to Xfmr secondary terminals
  - Xfmr Primary Voltage and Current Measured
  - Voltage and Current measured at FID terminals
  - Pulse =
    - 60 Hz, 10 cycles, starting at peak of AC waveform, 10 V/s down ramp, peak magnitude is varied
- Piezo controlled with RTDS amplified DC signal
  - RTDS -> Techron Amp + 15 ohm resistor -> Piezo
  - Voltage measured across Piezo
  - Contact separation – 4 x 0.35 mm



Voltage Breakdown Test Results

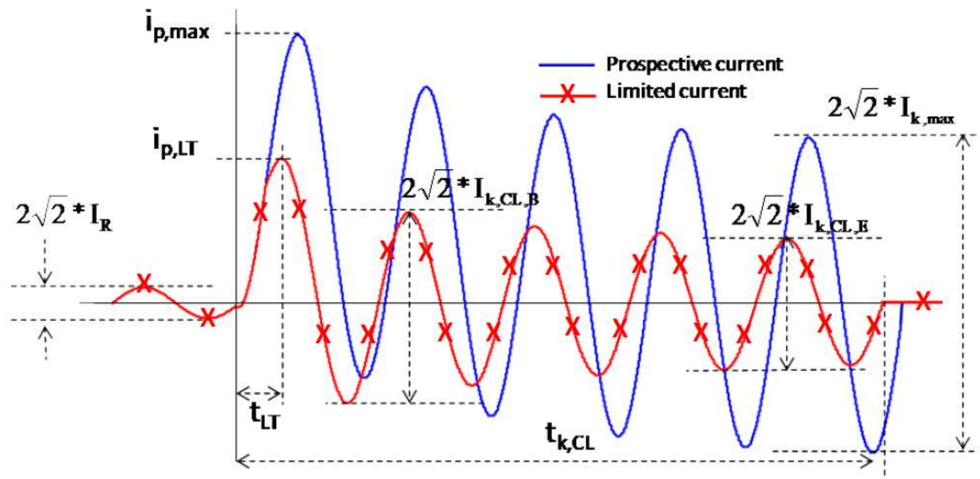




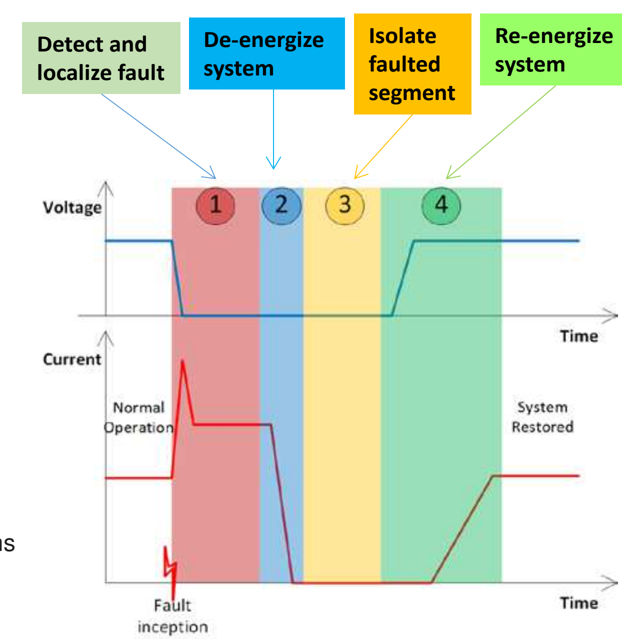
- Repeat in vacuum
- Measure at different gap distances
- Confirm DC capability (using voltage grading resistors)

Future Pathways for FID Technology

- Fault current limiter
  - For legacy systems with high fault current levels
  - Requires higher speed of FMS
- DC applications
  - Growing trend towards MVDC
  - Requires resistive voltage balancing between contacts in FMS
- Breaker free system architectures
  - Fully utilize the fault current breaking capability of the SSTs
  - Use FMS alone to isolate fault after complete system de-energization



IEEE Std. C37.302™-2015, "IEEE Guide for Fault Current Limiter (FCL) Testing of FCLs Rated above 1000 V AC"



M. Sloderbeck, D. Soto, H. Ravindra, M. Steurer, A. Challita, "Megawatt Scale Demonstration of High Speed Fault Clearing and Power Restoration for MVDC Systems Utilizing Fast Disconnect Switch", in Proc. AMTS, Philadelphia, May 25-26, 2016

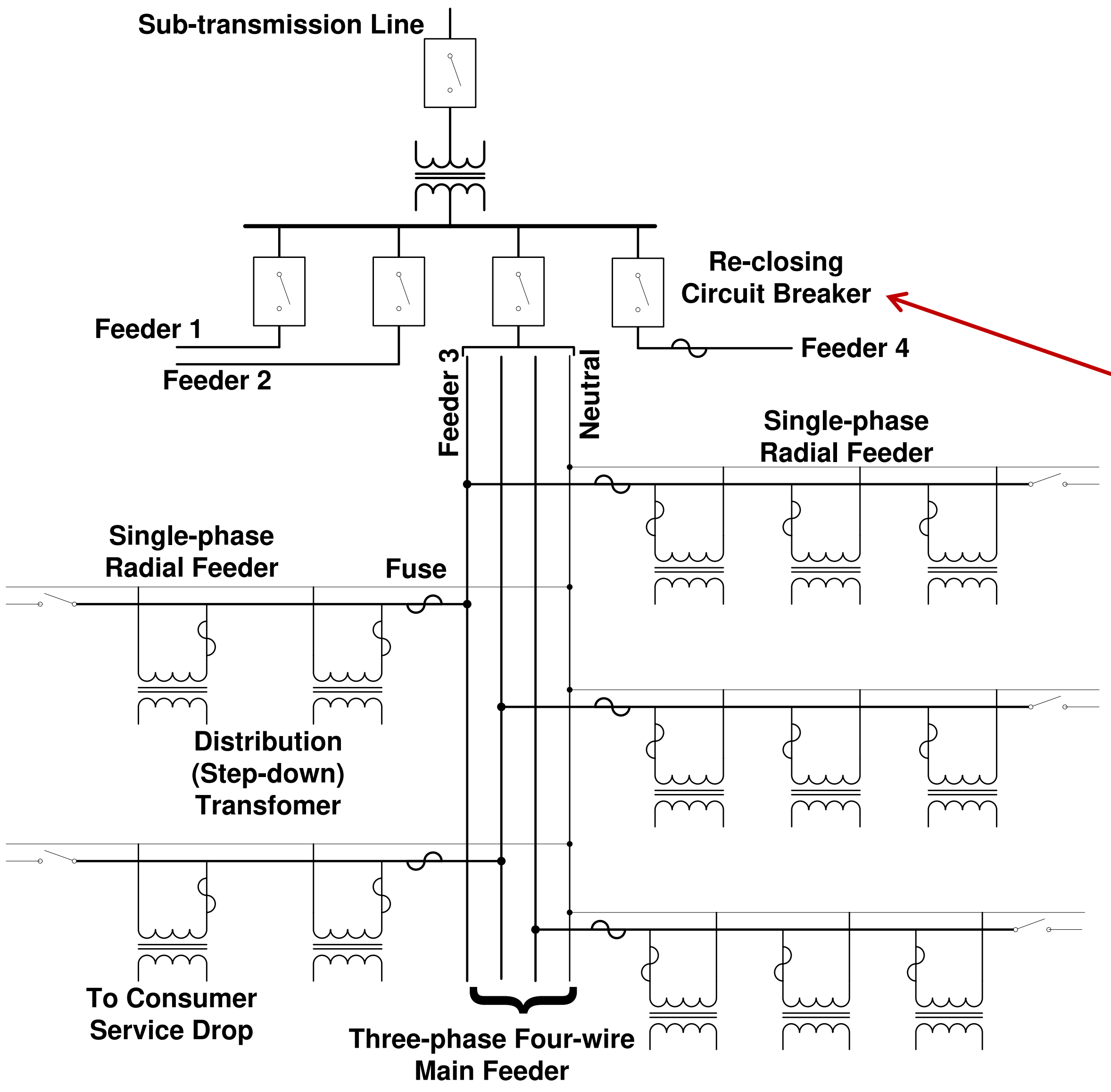
Pilot Directional Protection

George G Karady
Qiushi Wang & Zhenmin Tang

Presently used radial distribution system

- The distribution system today is a radial network, which is protected by fuses and fast acting reclosing circuit breakers.
- The circuit breaker is activated by overcurrent protection
- The most fault is produced by lightning which causes a flashover of an insulator. This generates a short circuit
- The fast acting circuit breaker interrupts the current and recloses circuit with about 15-second delay.
- This means that the customer has only a very short outage, which dips the lights and slows down air-conditioners.
- In a distribution system with cables most fault is permanent and recloser is not used

Presently used radial distribution system



- The three-phase main feeders are protected by a reclosing circuit breaker
- This switches off the feeder in case of a fault, and after a few cycles, the breaker recloses and restores the energy supply.
- This is an effective way of protection for overhead distribution circuits because most faults on an overhead line are temporary.
- The rest of the system is fuse protected

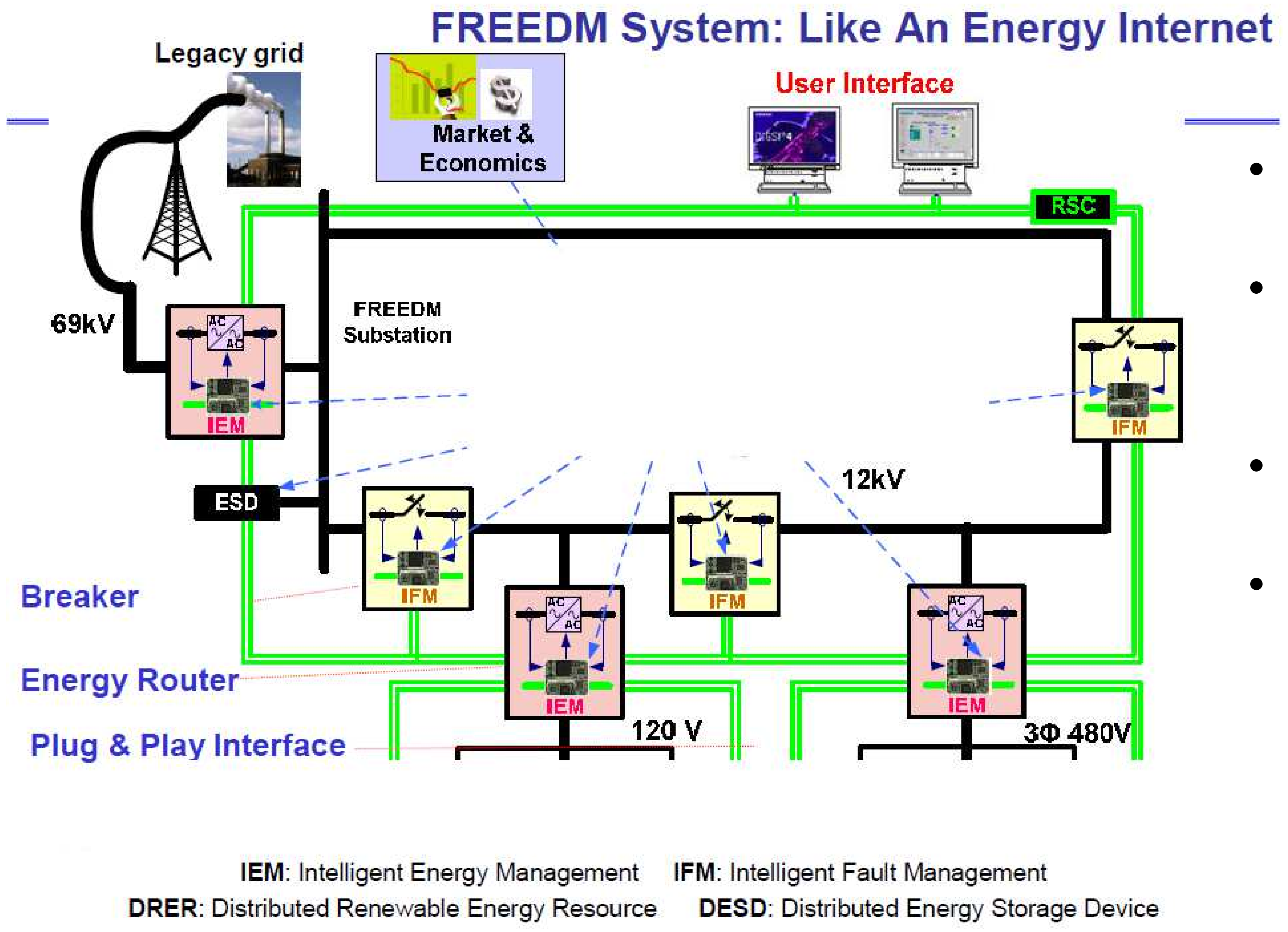
FREEDM System

- In 2008, the National Science Foundation chose NC State to lead an effort to create a modern power grid.
- At the FREEDM Systems Engineering Research Center, universities from the United States have joined forces with industry partners to develop a more secure, sustainable environmentally friendly electric grid.
- At the FREEDM Center, we're building the internet of energy: a network of distributed energy resources that intelligently manages power using secure communications and advanced power electronics. Our research priorities include power electronics packaging, controls theory, solid state transformers, fault isolation devices, and power systems simulation and demonstration.
- For students, FREEDM offers research opportunities at five universities: NC State, Florida Agricultural and Mechanical, Florida State, Arizona State and the Missouri University of Science and Technology. On all these campuses, the next generation of energy-focused scientists and engineers can help develop the next-generation electric grid

FREEDM System Vision

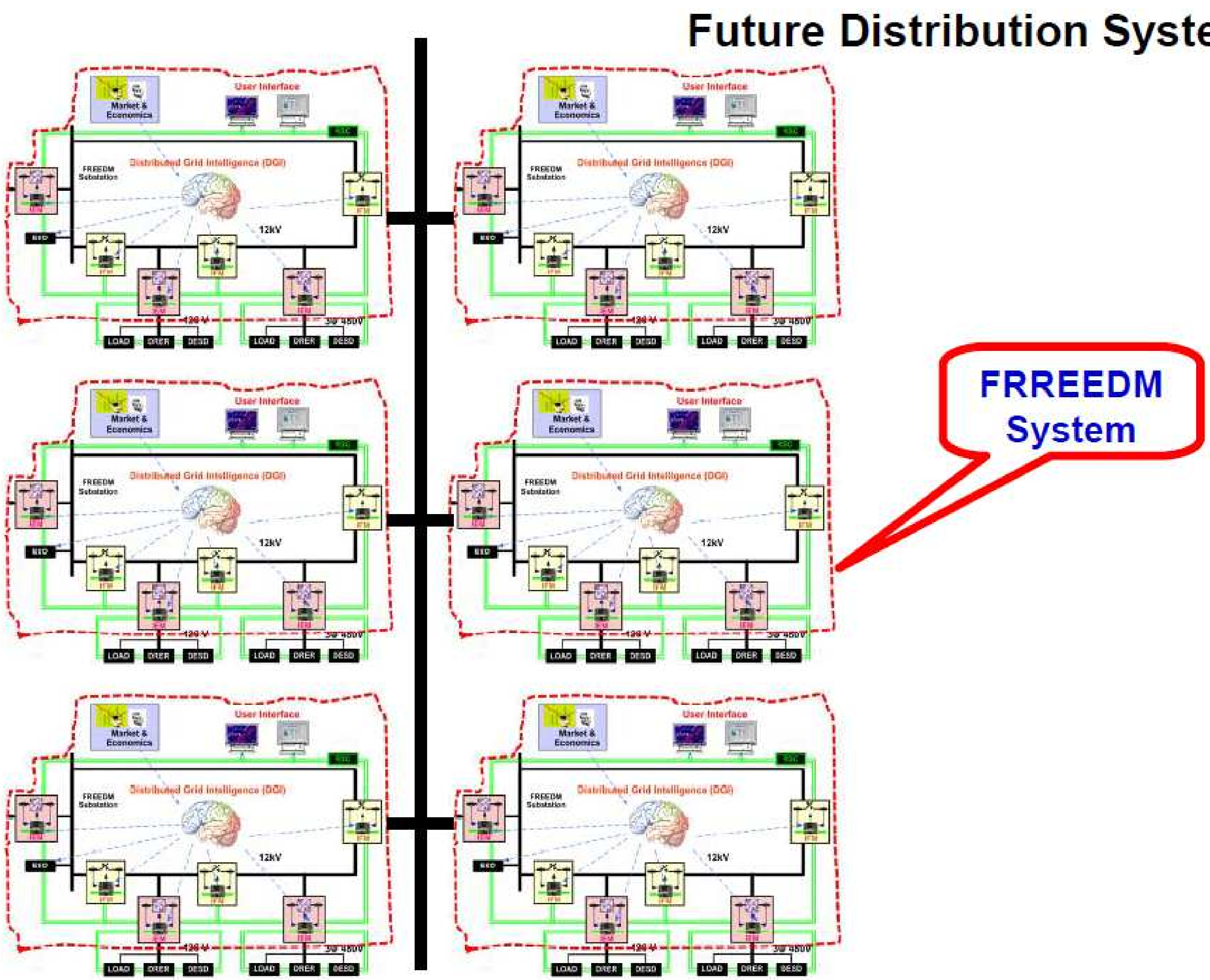
- To develop an efficient and revolutionary new distribution power grid
- Utilizing revolutionary **power electronics** technology and **information technology**
- Integrating distributed and scalable alternative energy sources and storage with existing power systems
- Automate the management of **load**, **generation** and storage
- Major components are: Solid state Transformer (SST) and Electronic circuit breaker (FID)

Slide is copy from: A.Huang: FREEDM System Vision, Grand challenges and Research Roadmap. Webinar 2010



- **The FREED distribution system is a loop system**
- **The loads are supplied by Solid state Transformers (SST)**
- **The loop is divided into sections**
- **Each section is protected by two Electronic circuit breakers (FID)**

Slide is copy from: A Huang: FREEDM System Vision, Grand challenges and Research Roadmap. Webinar 2010

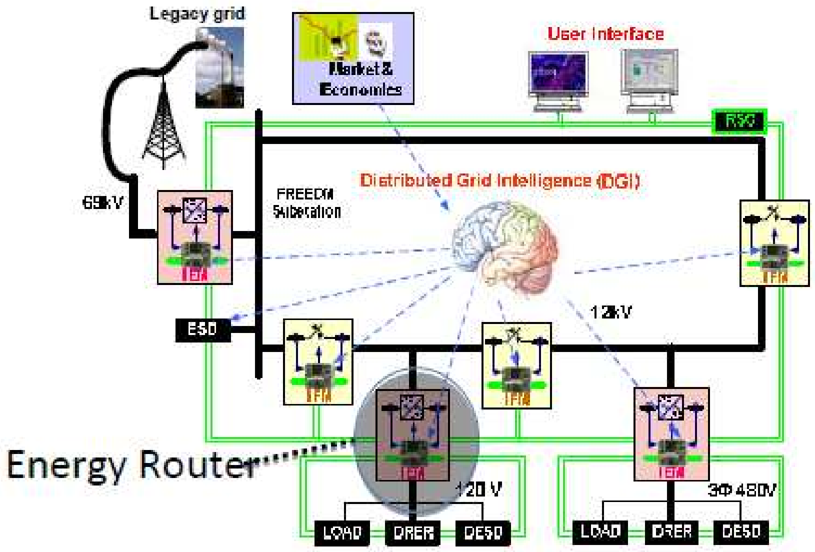


- **The FREEDM distribution system is built with interconnected loops**
- **The loop system requires the fast identification and elimination of the fault by FID's.**
- **FID's switch of only the section where the fault occurred**
- **This calls for a selective differential type protection**
- **ASU applied the pilot differential protection**

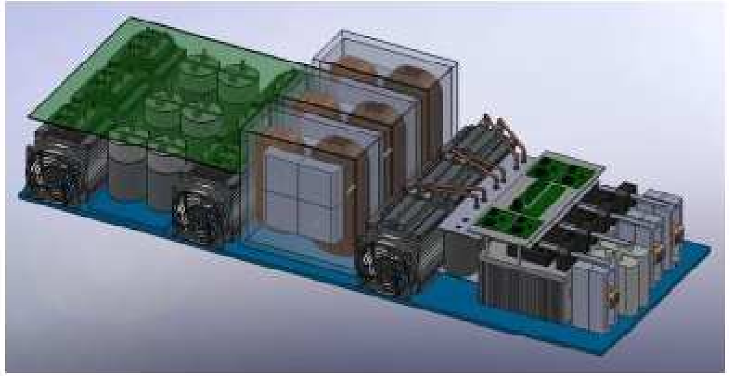
Slide is copy from: A. Huang: FREEDM System Vision, Grand challenges and Research Roadmap. Webinar 2010

Solid State Transformer as the Energy Router

- Solid State transformer at the heart of the energy router
- High voltage, high frequency power conversion with 15kV silicon carbide devices



6.5 kV/25A IGBT Module



Gen-I Solid State Transformer

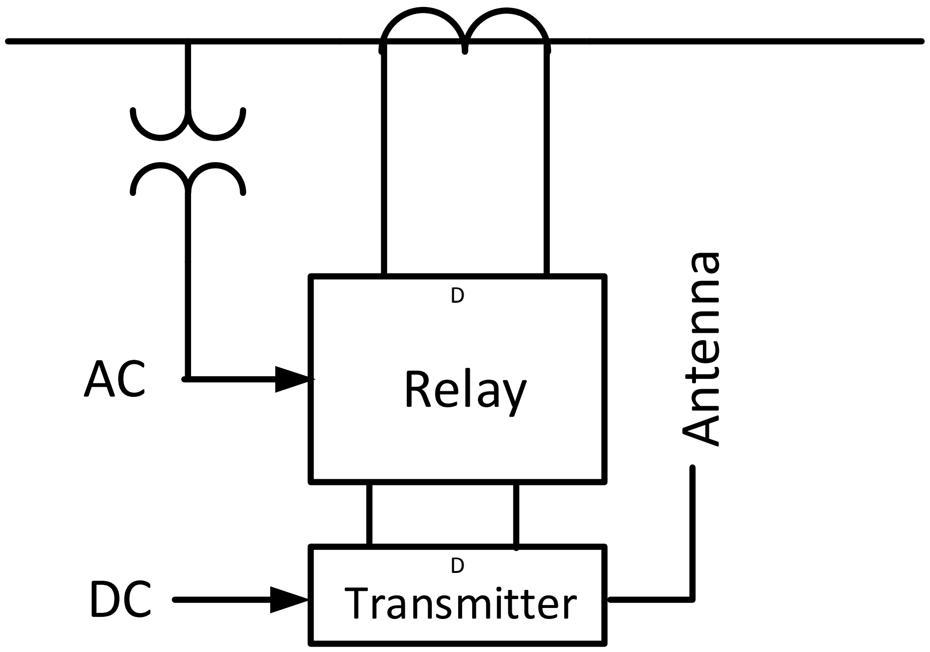
FREEDM SYSTEMS CENTER

FREEDM Loop Protection Concept

- The FREEDM system is a loop with several sections, each of them is protected by two fast acting FID devices.
- The loop system requires differential or pilot protection to identify the fault location and only switch off the section with the fault.
- In case of overhead type transmission the reclosing can further improve the system reliability.

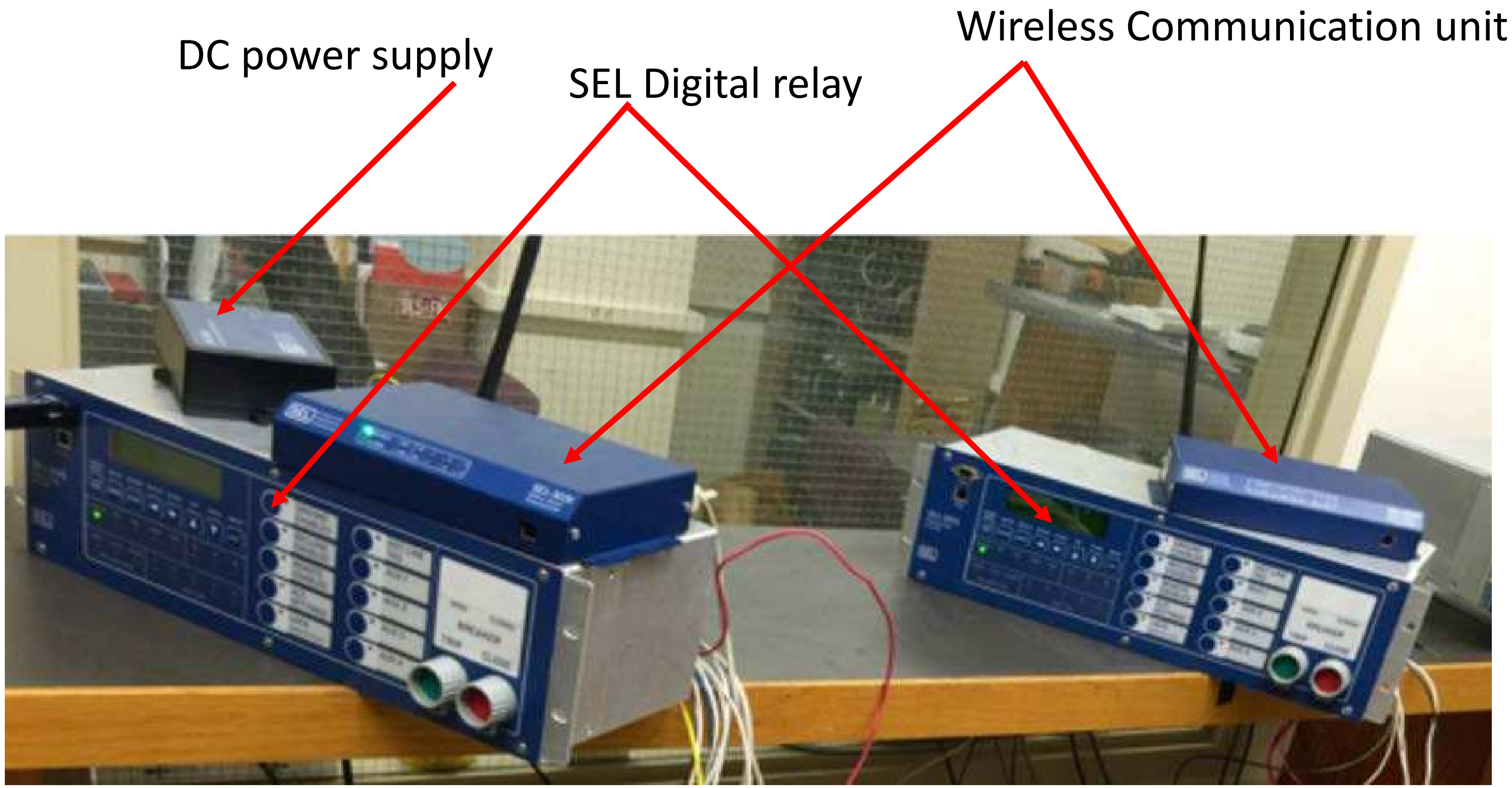
Pilot Directional Protection

- Pilot Directional protection use Schweitzer Laboratory produced SEL-351S relays with a wireless communication link.
- Each SEL relay is supplied by a current transformer and a voltage transformer generated signals and configured to measure the current direction and the current and voltage amplitude.
- The fault is detected by the sudden voltage reduction and increase of current.
- During the normal operation directional element of the SEL relay is in block state. But during faults, it produces F (forward) or R (reverse) signal depending up on the direction of fault current.



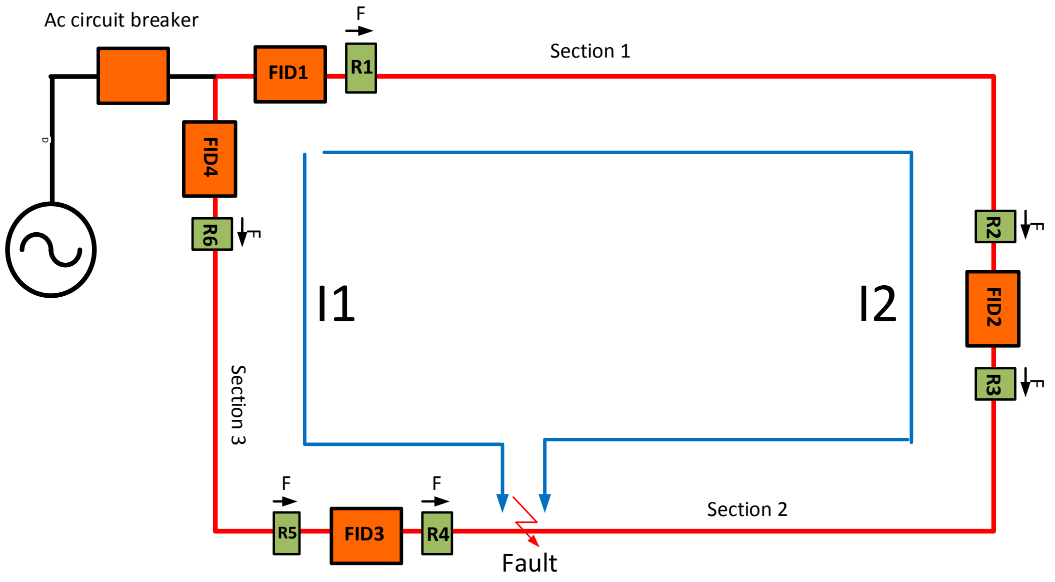
Pilot Directional Protection

- The picture shows two of the Wireless Directional Protection system.
- Each relay is connected with the measurement device and at the top of the relay is the wireless communication unit supplied by the DC source.



Description of Pilot Directional Protection Operation

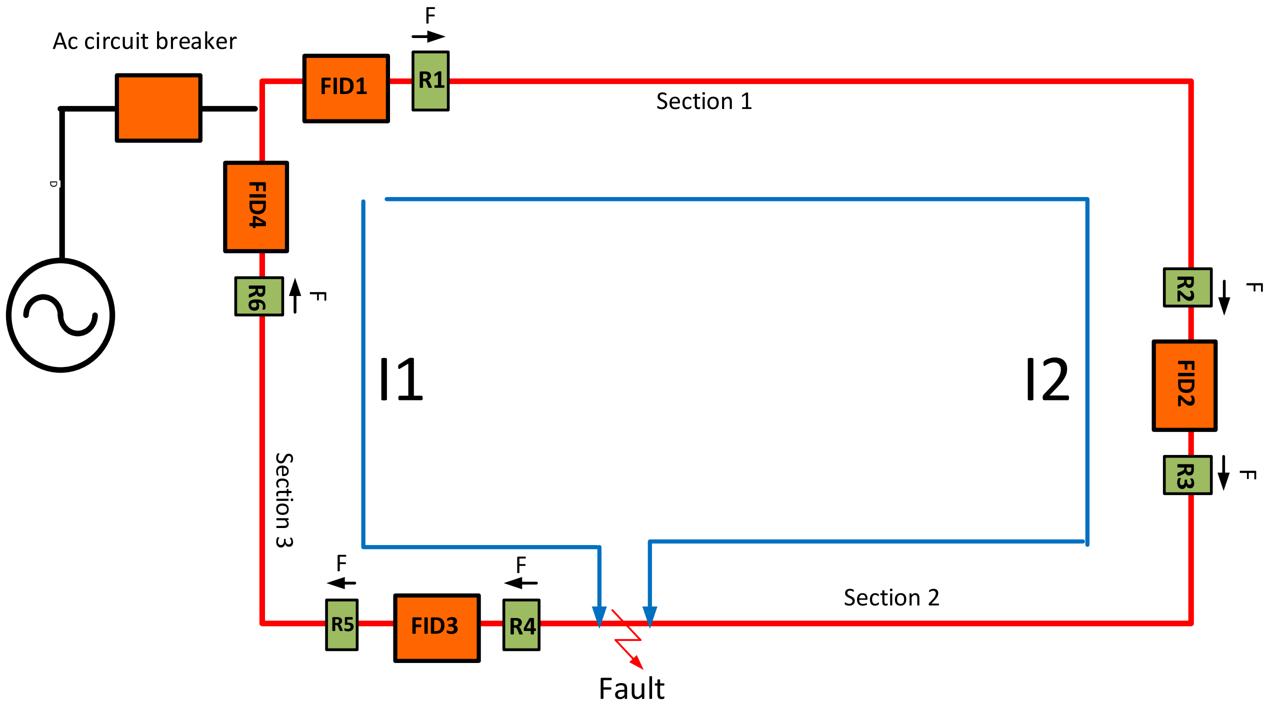
Pilot Directional Protection



- Figure shows that a fault in Section 2 produces two currents I1 and I2
- Relays R1,R2,R3 measure forward current and transmit F signal to the adjacent relays

- As an example R2 sends F signal to R1 and R3 only.
- Relays R4,R5,R6 measure revers current and transmit R signal to the adjacent relays.
- As an example R5 sends R signal to R4 and R6

Pilot Directional Protection

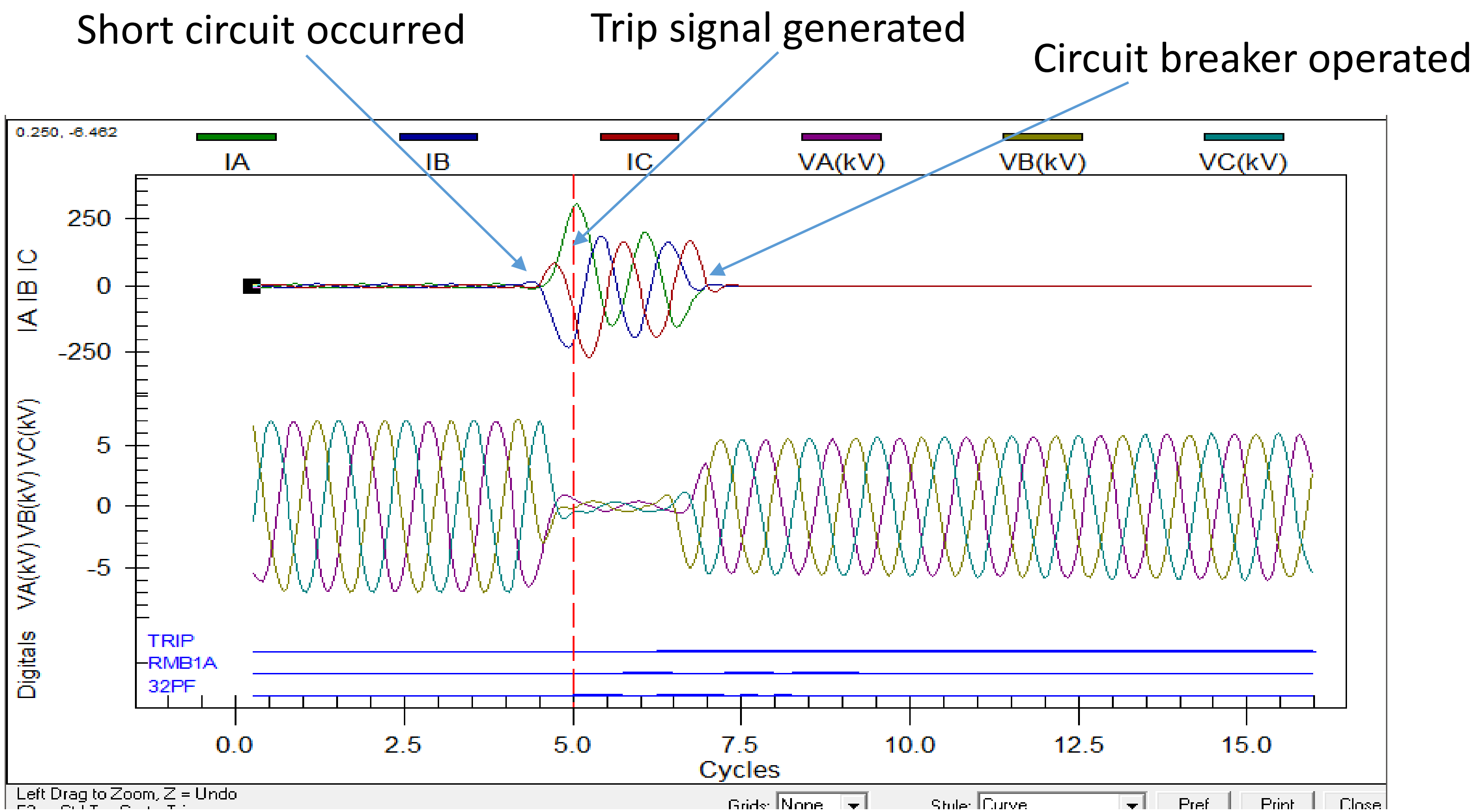


- In Section 1 both relays R1 and R2 measures F signal and also receive F signal, which prevents trip signal generation.
- In Section 3 both R5 and R6 measures R signals which also eliminates FID operation.

- In Section 2 relay R3 measures F and R4 measures R signal, which results generation of trip signals by both relays.
- The trip signal opens both FID 2 and FID 3, which eliminates the fault, while the rest of the system remain in operation.

Pilot Directional Protection

Demonstration of relay operation and short circuit current interruption

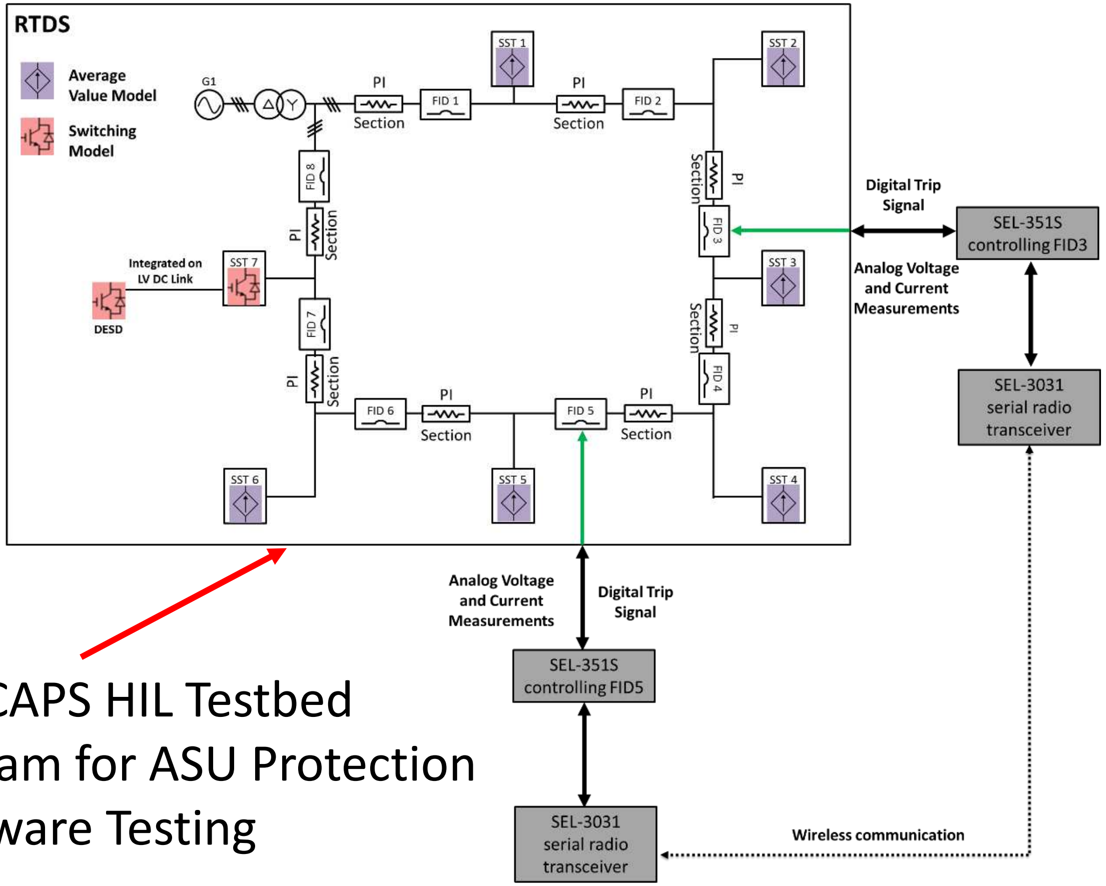


- Upper part of the figure shows three phase sort-circuit current, which initiate relay operation.
- The relay typical detects the short circuit within a half cycle, less than **8 ms**.
- The relay generated DC trip signal activates the FID which interrupts the short circuit current.
- This case a low voltage magnetic relay was used, which operated within 2.5 cycles

Verification of Pilot Directional Protection Operation

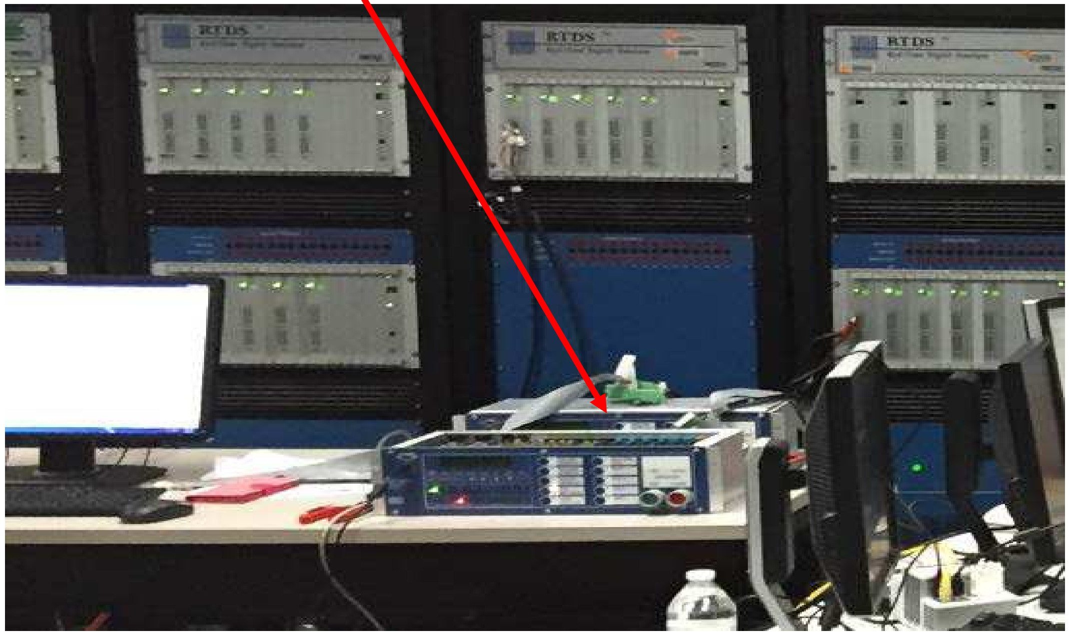
Verification of Pilot Directional Protection Operation

The Pilot Directional Protection system was successfully tested in Florida State University RTD system.



FSU-CAPS HIL Testbed Diagram for ASU Protection Hardware Testing

Pilot directional protection



Verification of Pilot Directional Protection Operation

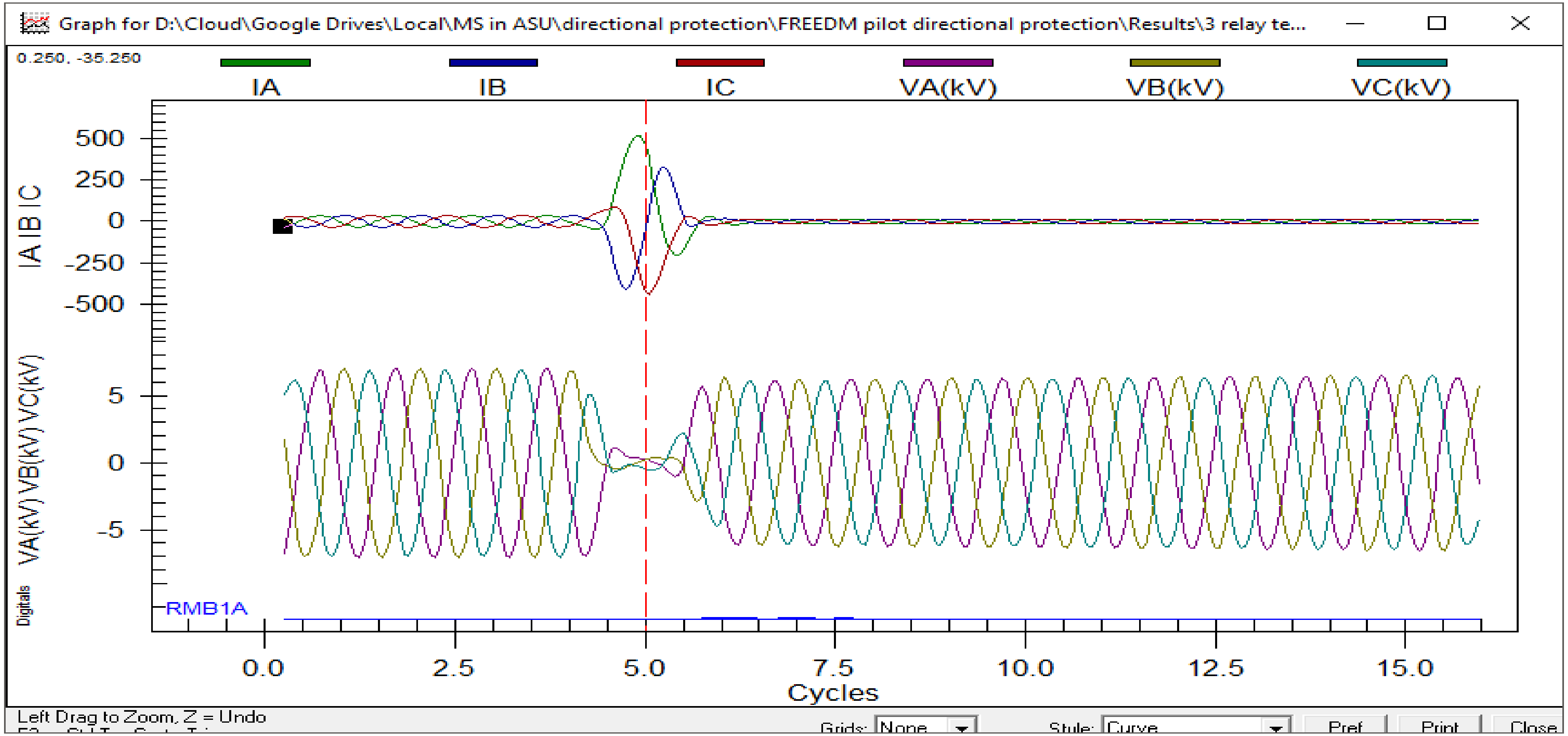
- In this test, the FREEDM loop system is simulated by real-time digital power simulator (RTDS), in the Center for Advanced Power Systems (CAPS) at Florida State University.
- ASU provided two SEL-351S directional protection systems are interfaced with RTDS to physically detect the fault location and send trip signal to FID's.
- The input of the relays are small ac voltage signals representing secondary currents and voltages at different monitoring locations of the loop system from RTDS
- The output of the relay is connected to a function block called Fault Isolation Device (FID) in RTDS
- Once FID receives trip signal from SEL-351S relay, it will cut off the fault current within the protection zone in RTDS.
- SEL-351 relay builds wireless communication with other relays via SEL-3031 radios system; SEL-3031 radio provides 9MHz mirrored bits wireless connection.

Verification of Pilot Directional Protection Operation

	Fault direction	Fault direction	Fault direction
Relay at FID 3	Forward	Forward	Reverse
Relay at FID 5	Forward	Reverse	Forward
Trip signal	No trip	Trip generated	No trip

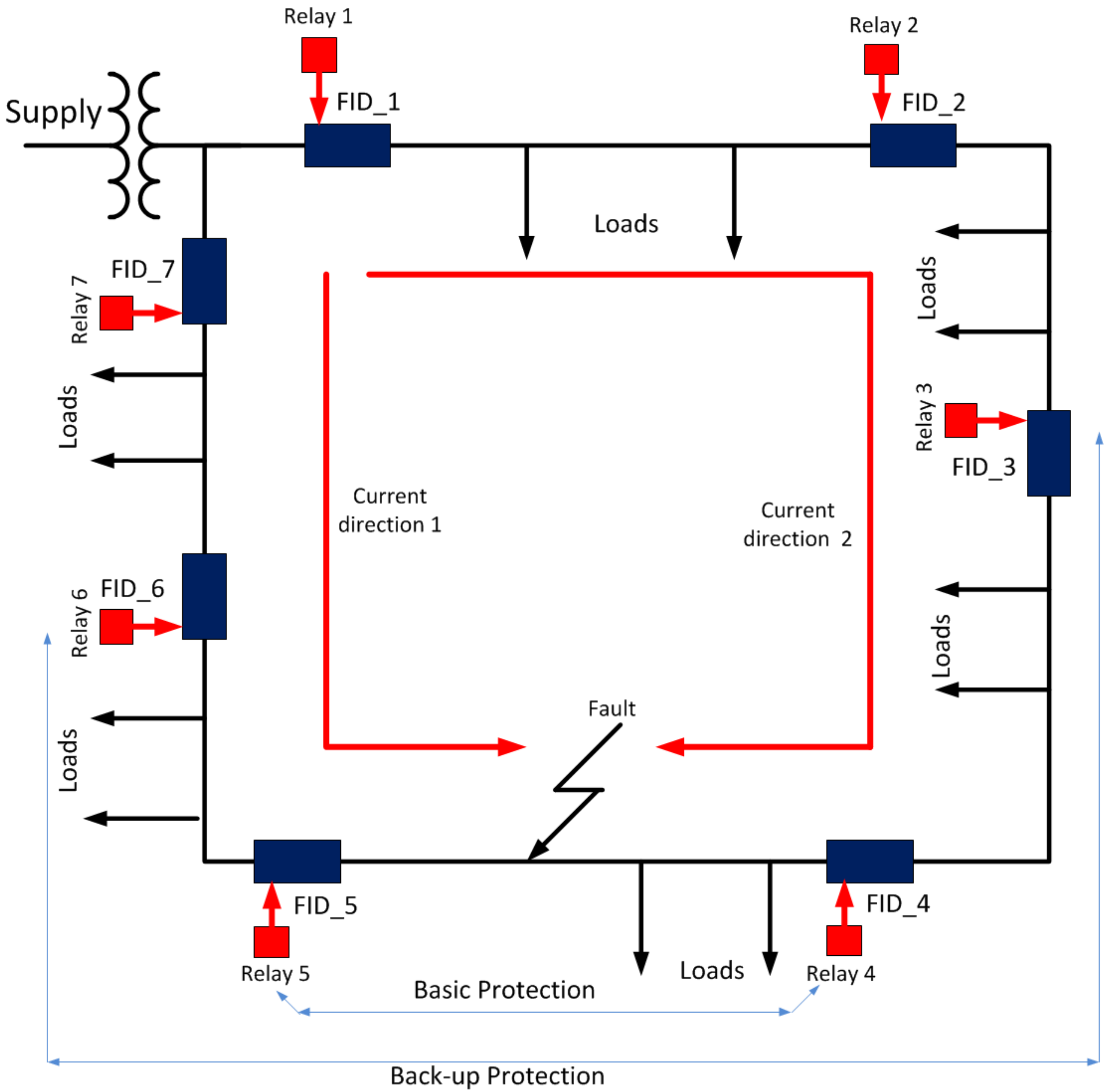
Trip logic for FID 3 and FID 5

Verification of Pilot Directional Protection Operation



Relay Event Report for FID 3, when the fault occurs between FID3 and FID 5

Back-up Pilot Directional Protection



Back-up protection

- The figure shows the FREEDM loop with a fault in section FID4-FID5
- All relay measures the current directions.
- Relays 1,2,3and 4 measures current forward direction 1
- Relays 5,6 and 7 measures current reverse direction 2
- The relays can communicate the measured direction (1 or 2) wirelessly to each others less than few milliseconds.

Back-up Pilot Directional Protection

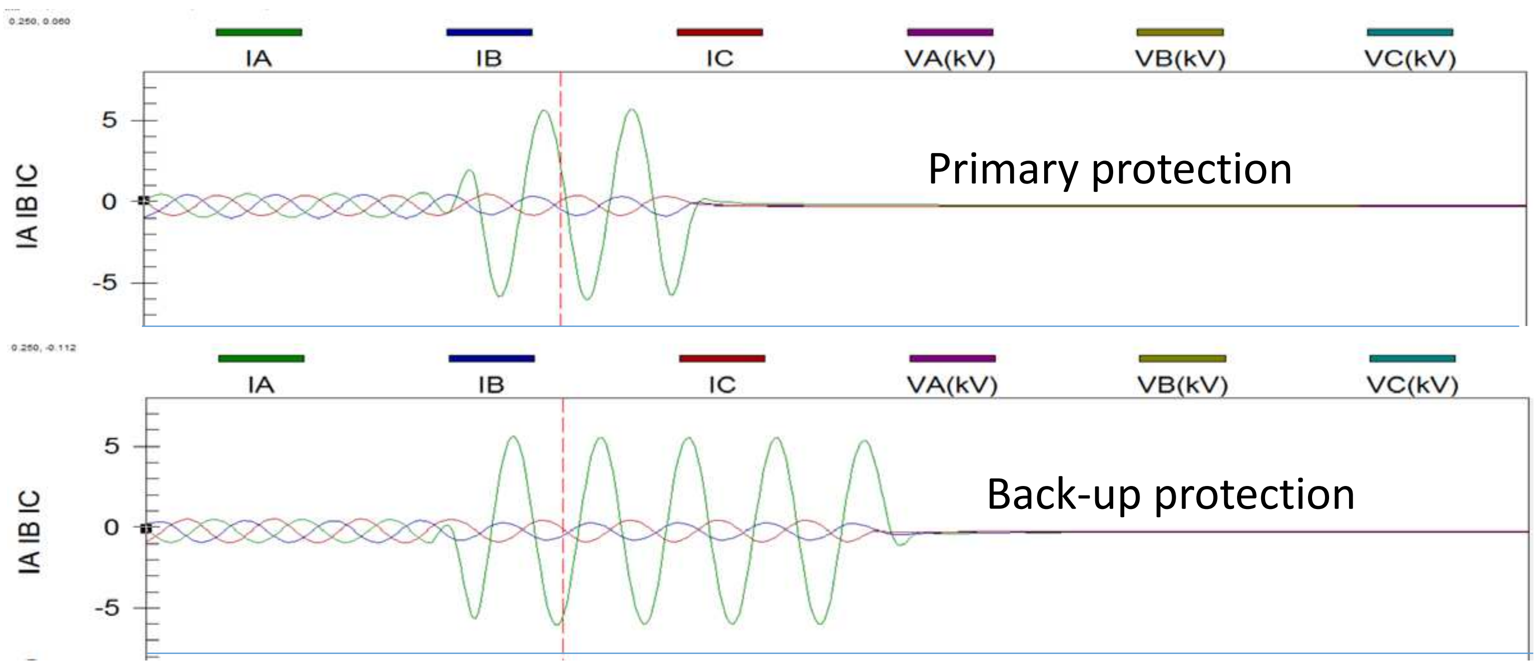
- The relays send trip signal to the FID if in a section one relay measures current direction 1 and the other 2
- This give us the idea that we can use the system for provide back up protection
- Example: trip signal generated in case of fault in the section terminated by FID4 and FID 5 when Relay 4 measures direction 1 and Relay 5 direction 2 or vice-versa
- Simultaneously Relay 3 also measures direction 2 and Relay 6 measures direction 1.
- These signals are sent to each other results trip signals for FID 3 and FID 6
- The sufficient delay of these trip signals provide back up protection when FID 4 and 5 is not tripped.
- ASU programed the relays to perform the described process.
- The logic diagram for the back up protection is in the next slide

Back-up Pilot Directional Protection

Fault location	Back up protection	Time delay
FID 1 & 2	Relay 3 & 7	5ms
FID 2 & 3	Relay 1 & 4	5ms
FID 3 & 4	Relay 2 & 5	5ms
FID 4 & 5	Relay 3 & 6	5ms
FID 5 & 6	Relay 4 & 7	5ms
FID 6 & 7	Relay 6 & 1	5ms

Backup Pilot Directional Protection

This figure demonstrates the operation of the primary and backup protection



- Figure shoes that both protection sensed the fault in the same time (dotted vertical line)
- FID operated around after 2.5 cycle in case of primary protection
- FID operated after 4.5 cycle in case of Backup protection

Integration of Pilot Directional Protection in the FID Electronic Circuit breaker

Integration of Pilot Directional Protection in the FID

- The presently built protection system use large and expensive digital relays, which can not be integrated into the FID device.
- ASU started the development of a small protection computer that can be incorporated in the FID.
- The work began with the elaboration of an algorithm to measure the current direction.
- The current direction can be measured by calculating the FREEDM loop positive and negative sequence impedances.
- In case of unsymmetrical fault the negative sequence impedance can be used for detection of current direction.
- If the calculated Z_2 is smaller than forward threshold impedance, the fault is in forward direction to a relay.
- If the calculated Z_2 is greater than reverse threshold impedance, the fault is in reverse direction to a relay.

Integration of Pilot Directional Protection in the FID

- The negative sequence impedance is negligible in case of symmetrical three phase fault and the voltage is also close to zero.
- The developed method compares with the present positive sequence impedance with the corresponding positive sequence components a few cycles before.
- The difference in the positive voltage and positive current is used to determine the direction of fault current in the system.
- The current direction is determined by combining both positive sequence and negative sequence component method.
- In the FREEDM loop, each section is protected by two FID’s. Each of them will be equipped by a small computer which determines the current direction and communicates to the other.

Integration of Pilot Directional Protection in the FID

- The fault is in the loop when the measurement current directions are opposite.
- In this case, both relays will send a trip signal to the corresponding FID and to isolate the fault
- ASU developed a MATLAB program to perform this operation
- The program is installed on two laptop computers equipped with a data acquisition device
- The system was successfully tested using the ASU's Analog protection unit