Lessons Learned From Hardware-in-the-Loop Testing of Microgrid Control & Protection Systems

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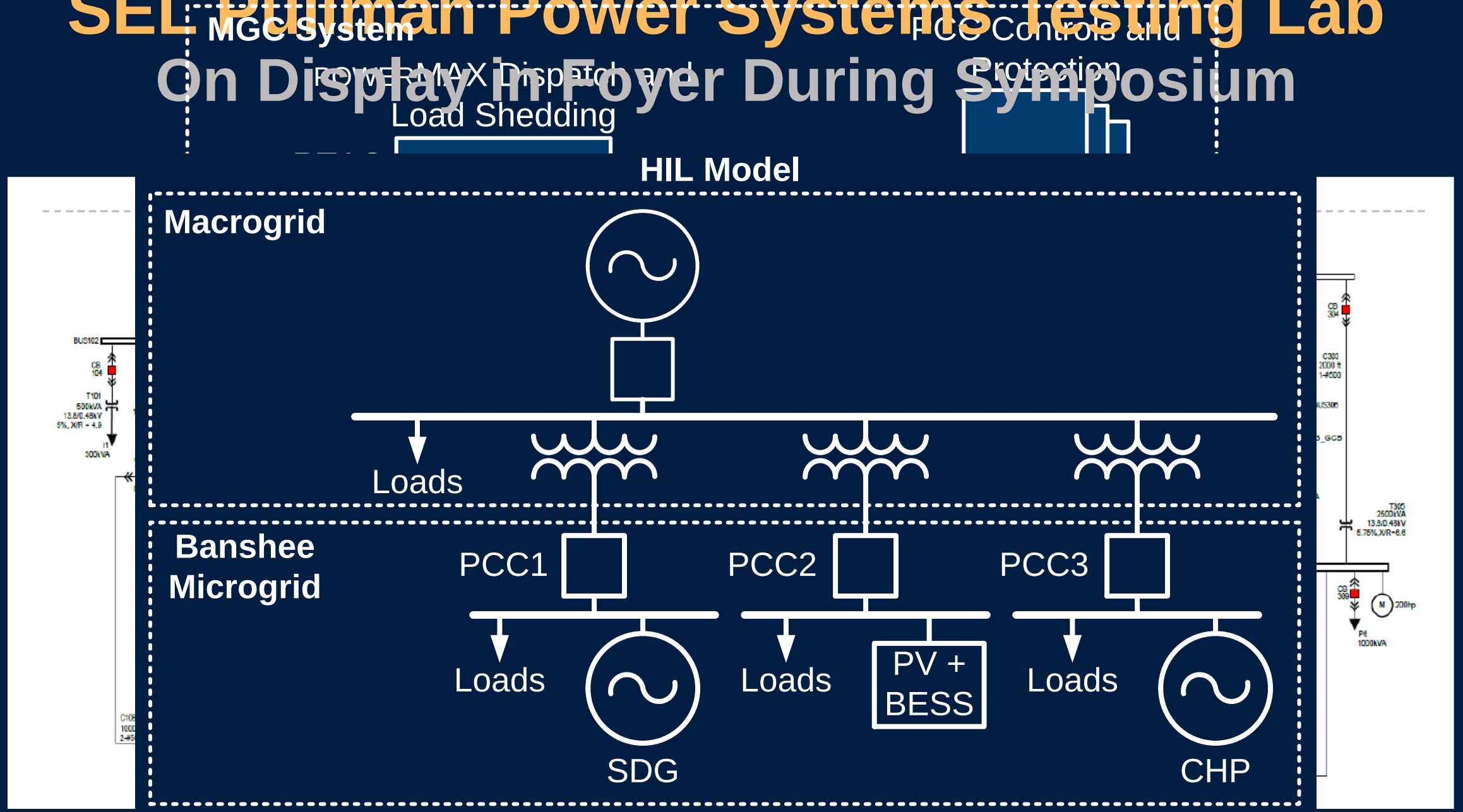
SEL's Contribution to the MIT Lincoln Laboratories Symposium

- SEL powerMAX® microgrid controller
- Full factory acceptance tests (FATs)
- High-speed support electronics
- Integration interface for MIT Lincoln Laboratories OPAL-RT simulator
- SEL-751 Feeder Protection Relays and programming
- Banshee model ported to real-time digital simulator (RTDS)

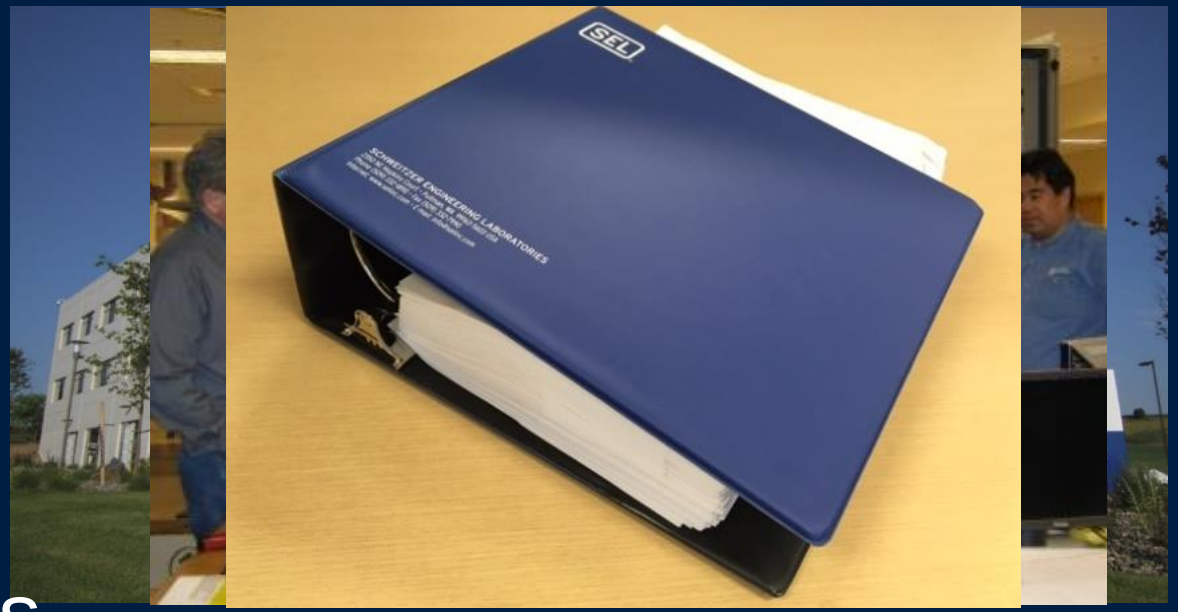
SEL Engineering Services Uses Hardware-in-the-Loop (HIL) Testing Daily

SEL Pullman Power Systems Testing Lab On Display in Foyer During Symposium

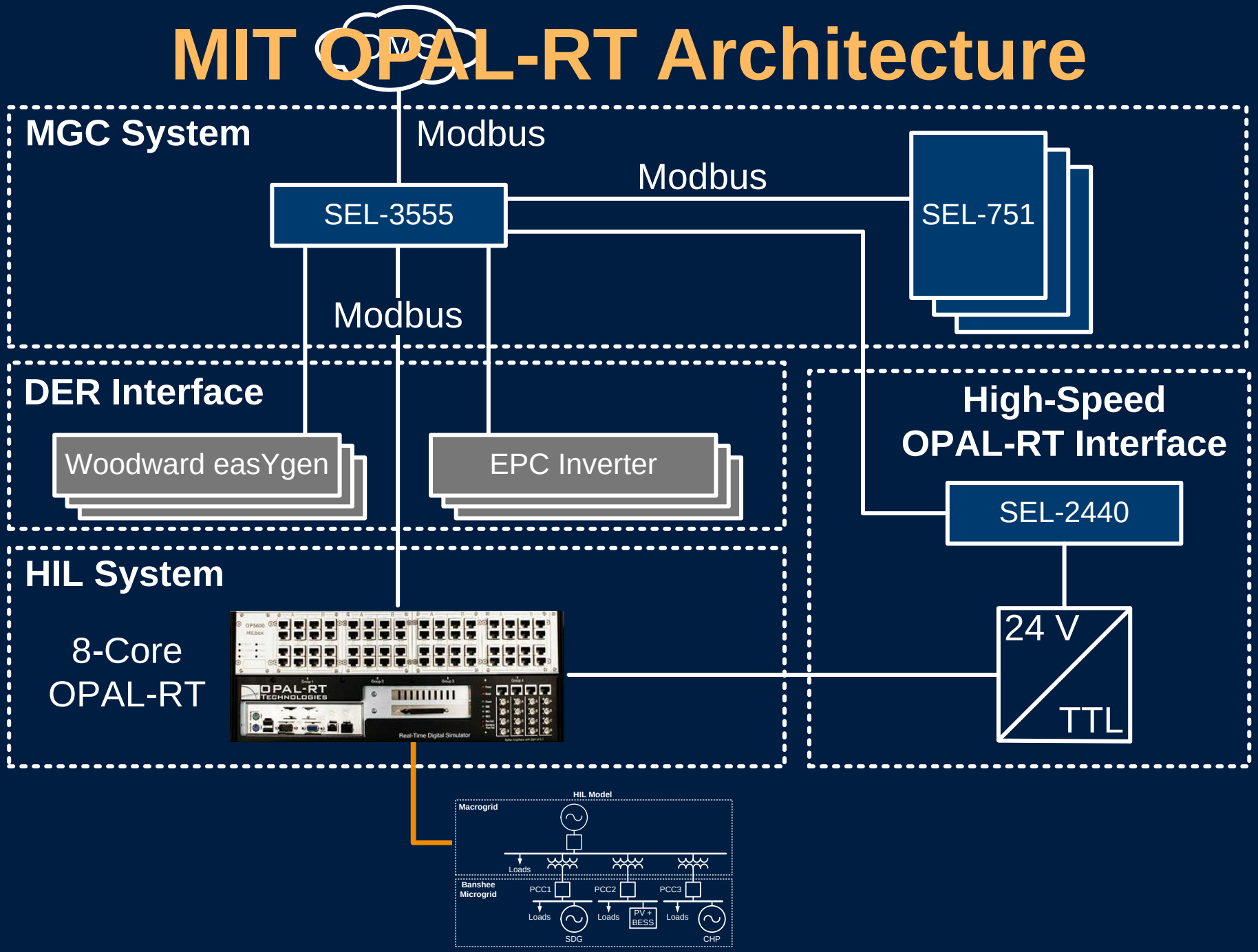


SEL POWERMAX HIL FAT Completed Via Webinar

- Positive and negative sequences
- Go and no-go scenarios
- Combinational testing
  - Initial power system conditions
  - Dispatch order
  - Triggering scenario

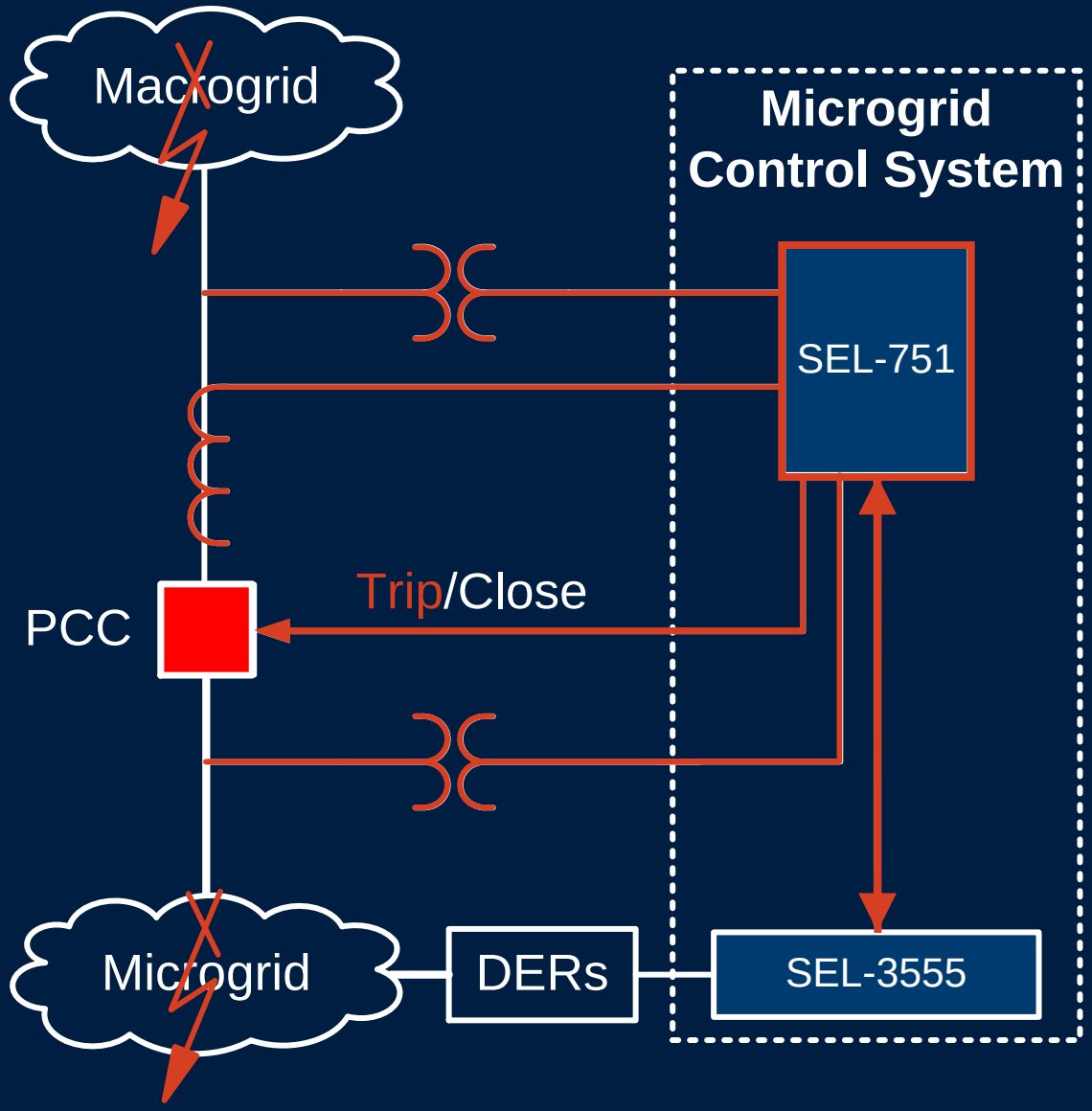


MIT OPAL-RT Architecture

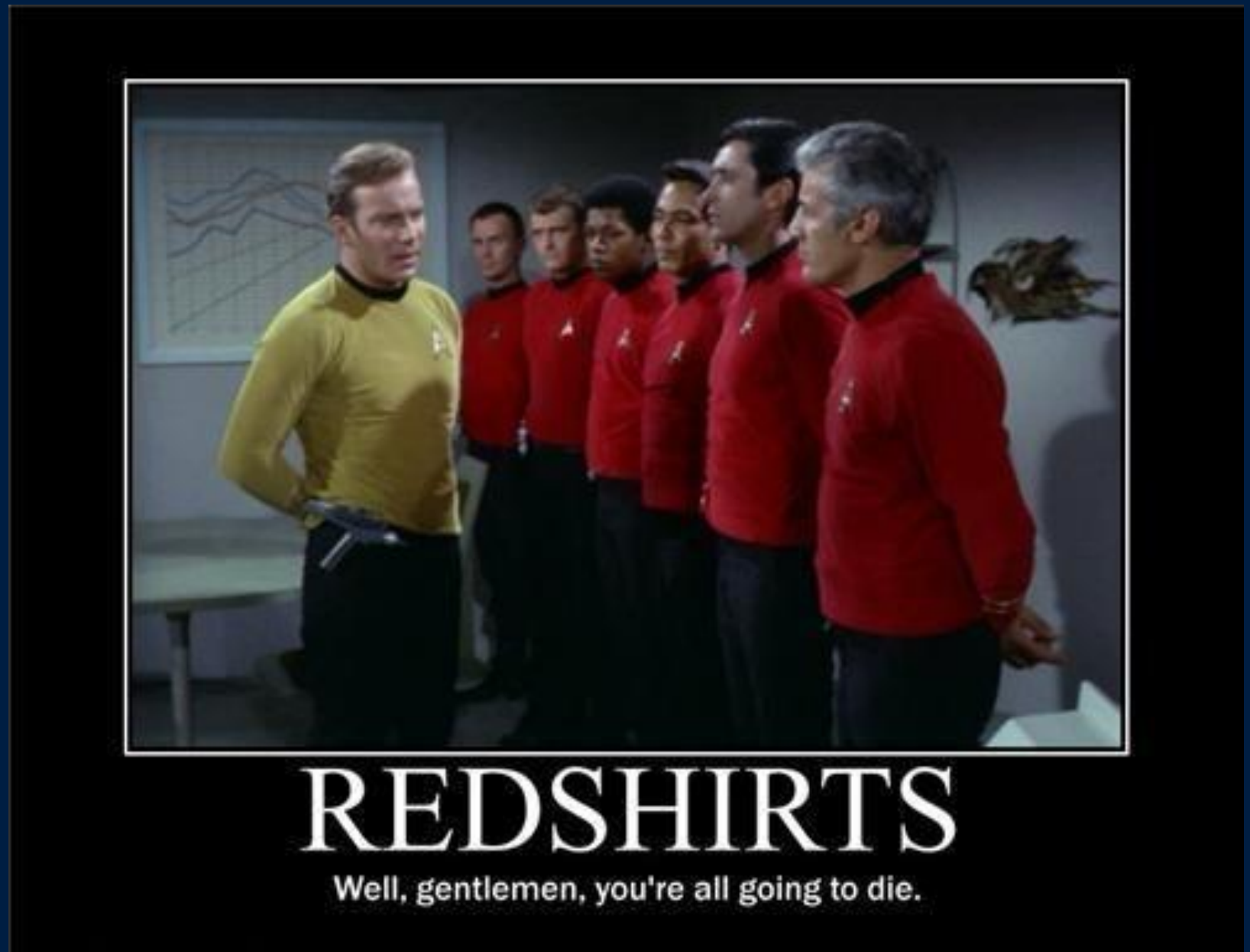


Protective Relay at PCC
Provides ~50% of Control Functionality

- Grid reconnection
- Unintentional islanding
- Protection for expensive assets
- IEEE 1547-2003 compliance
- Metering
- Pass-through control



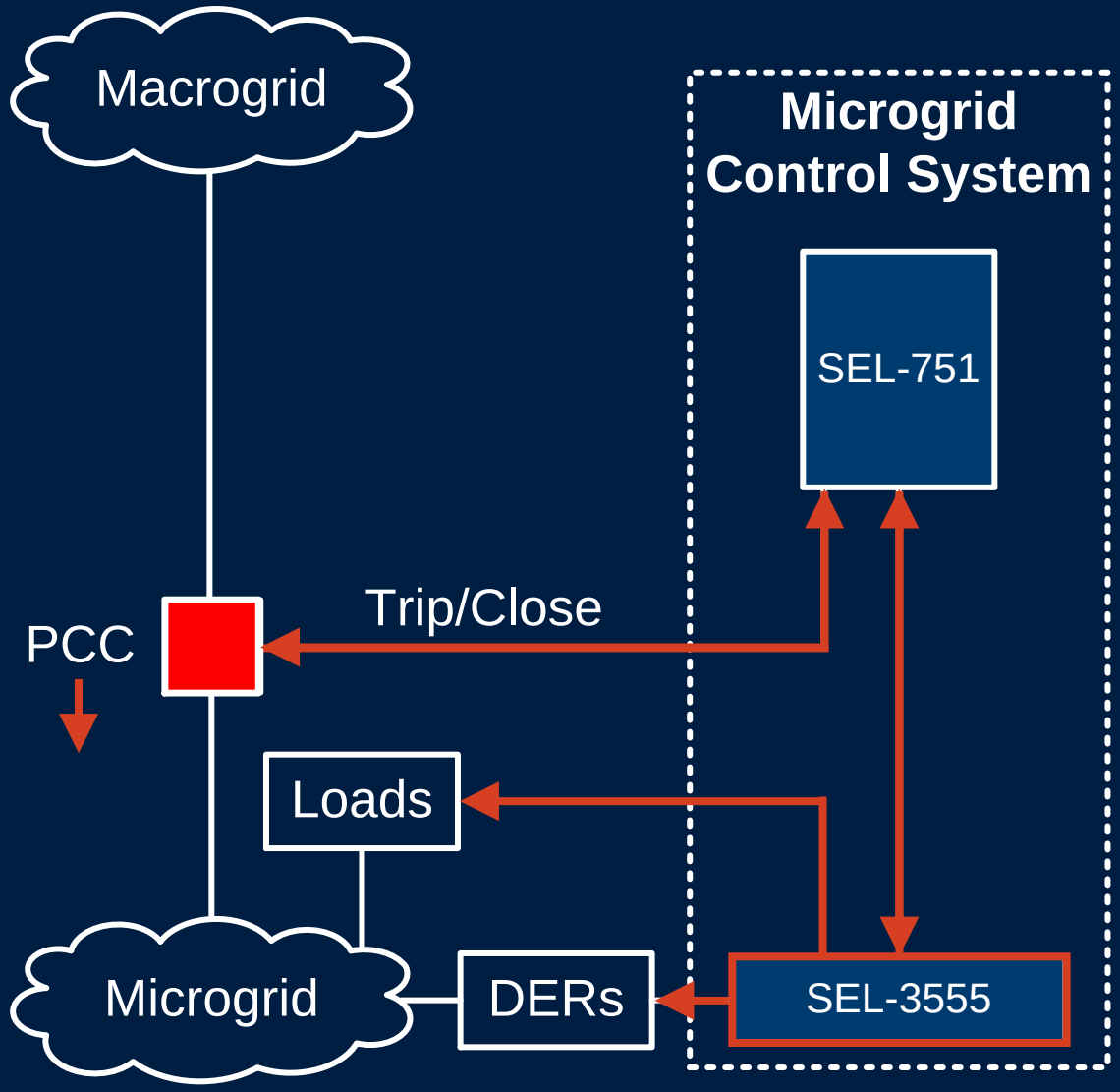
Remember…Red Is DEAD!!!



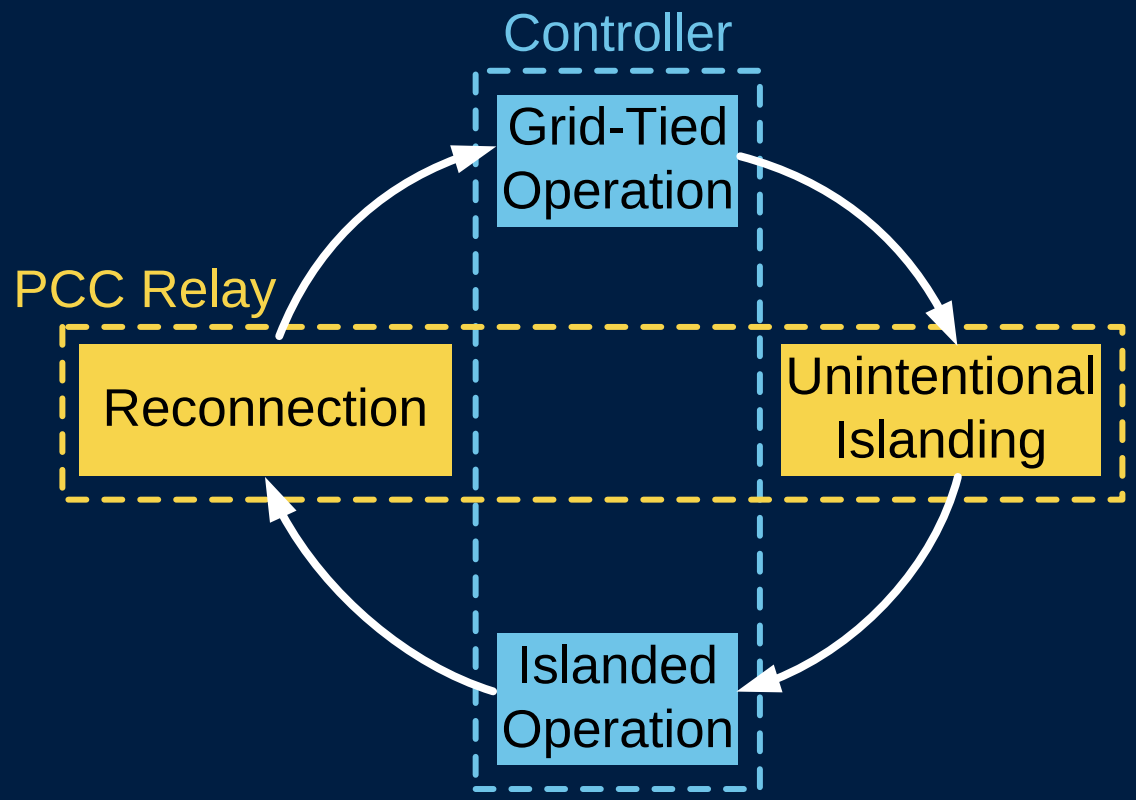
Microgrid Controller

Load Shedding, Dispatch, and Islanded Regulation

- Load shedding
- Intentional islanding
- PCC dispatch
- PF control
- Voltage regulation
- Frequency regulation

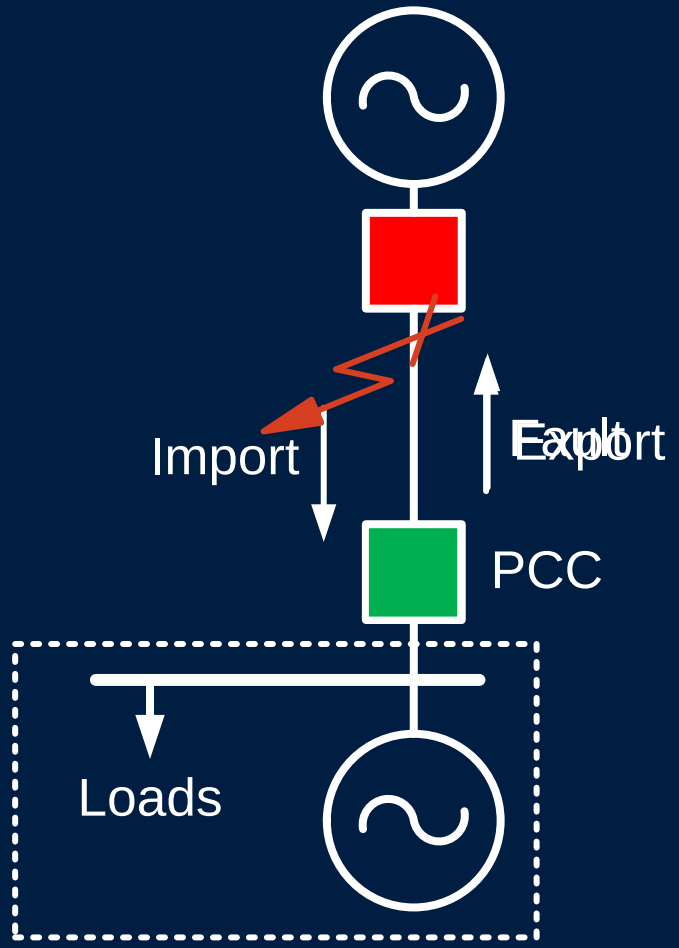


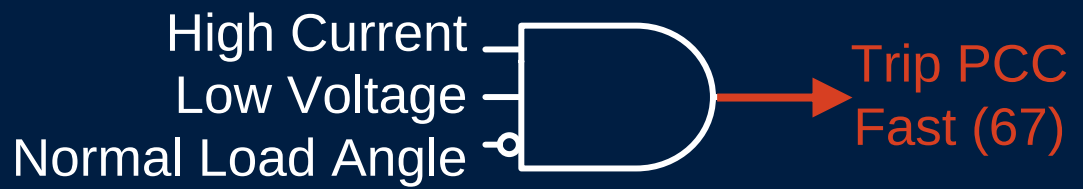
Relays and Controllers Work Together

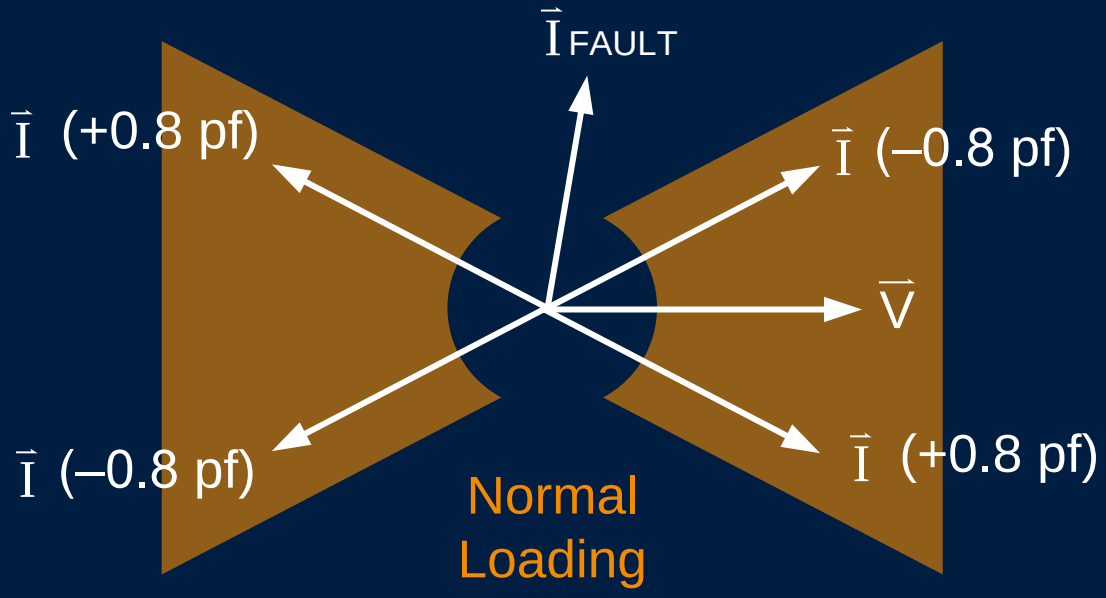


Example: Directional Current Protection (67)

Opens PCC During Short-Circuit Conditions

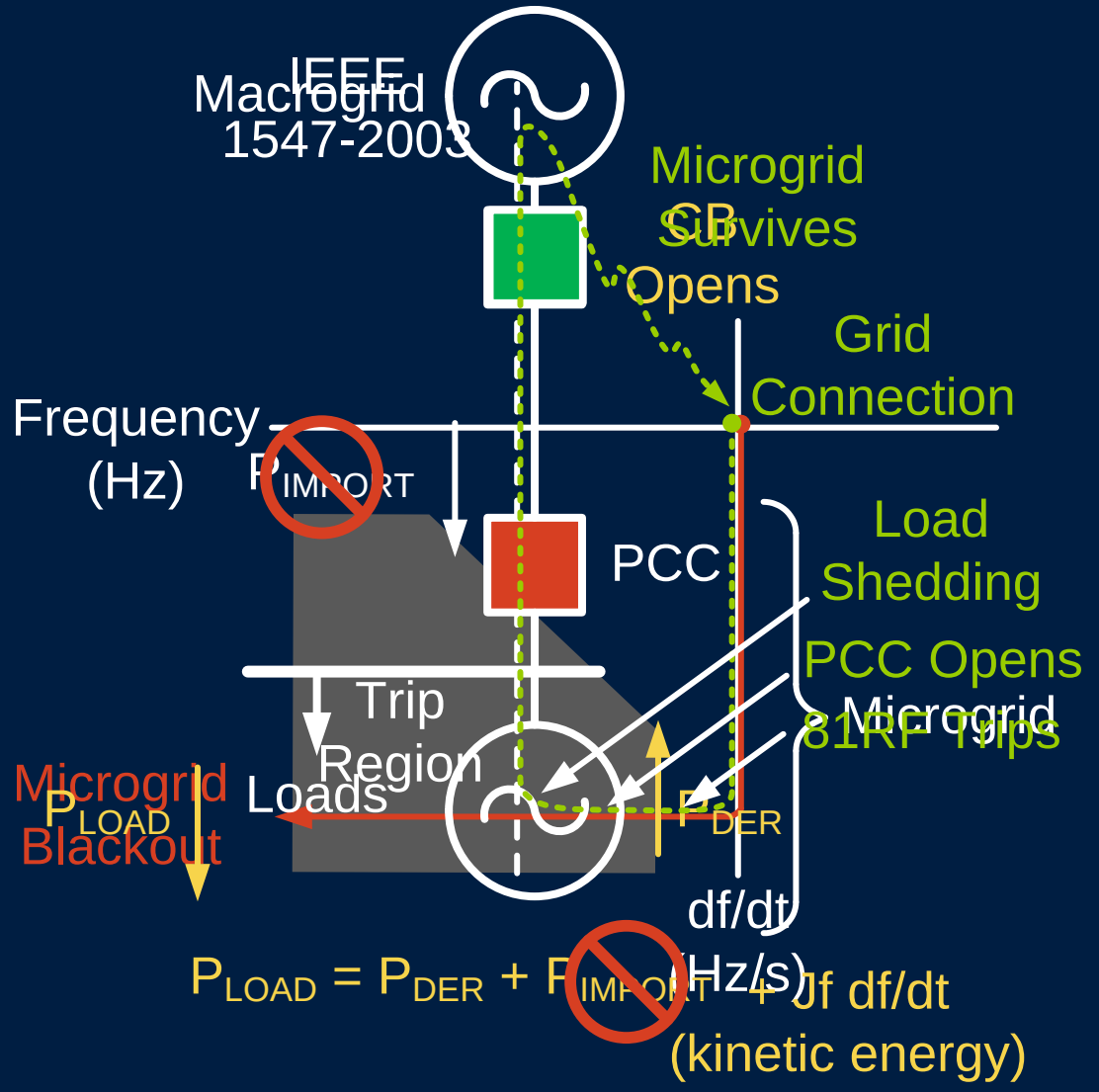


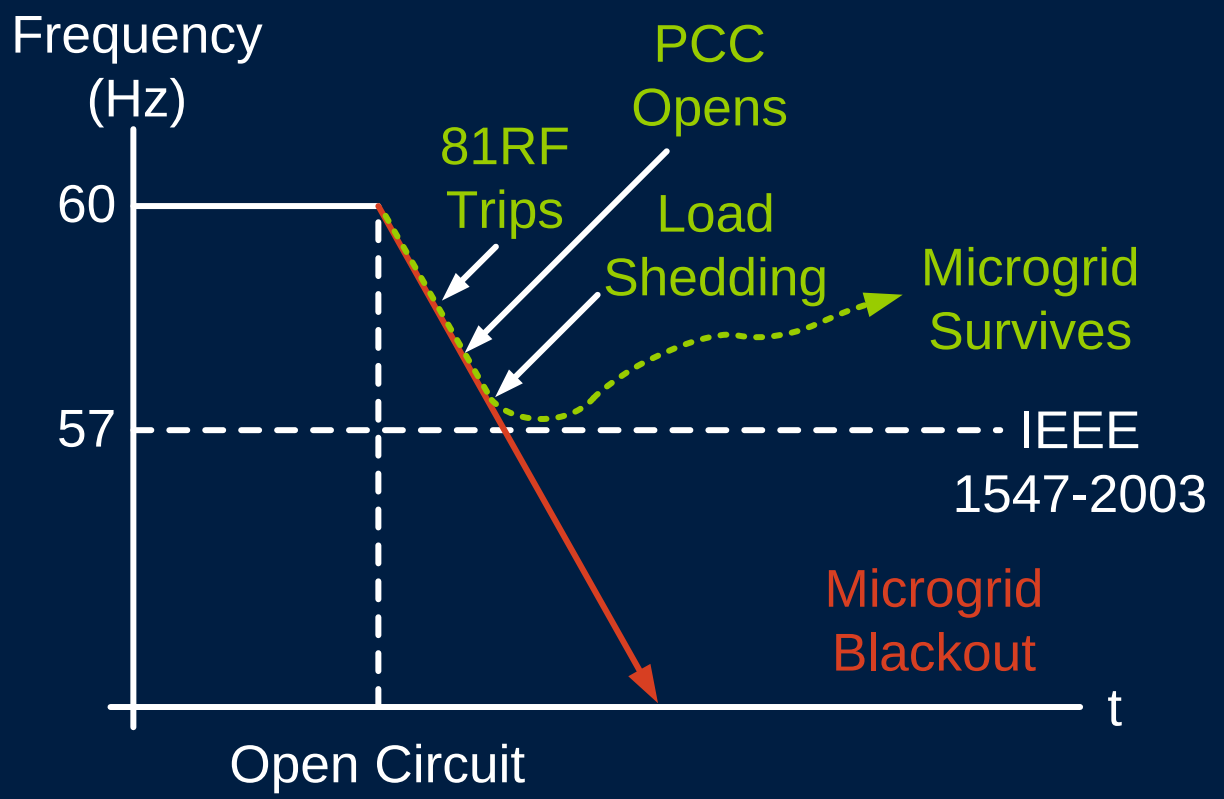




Fast Rate-of-Change-of-Frequency Element (81RF)

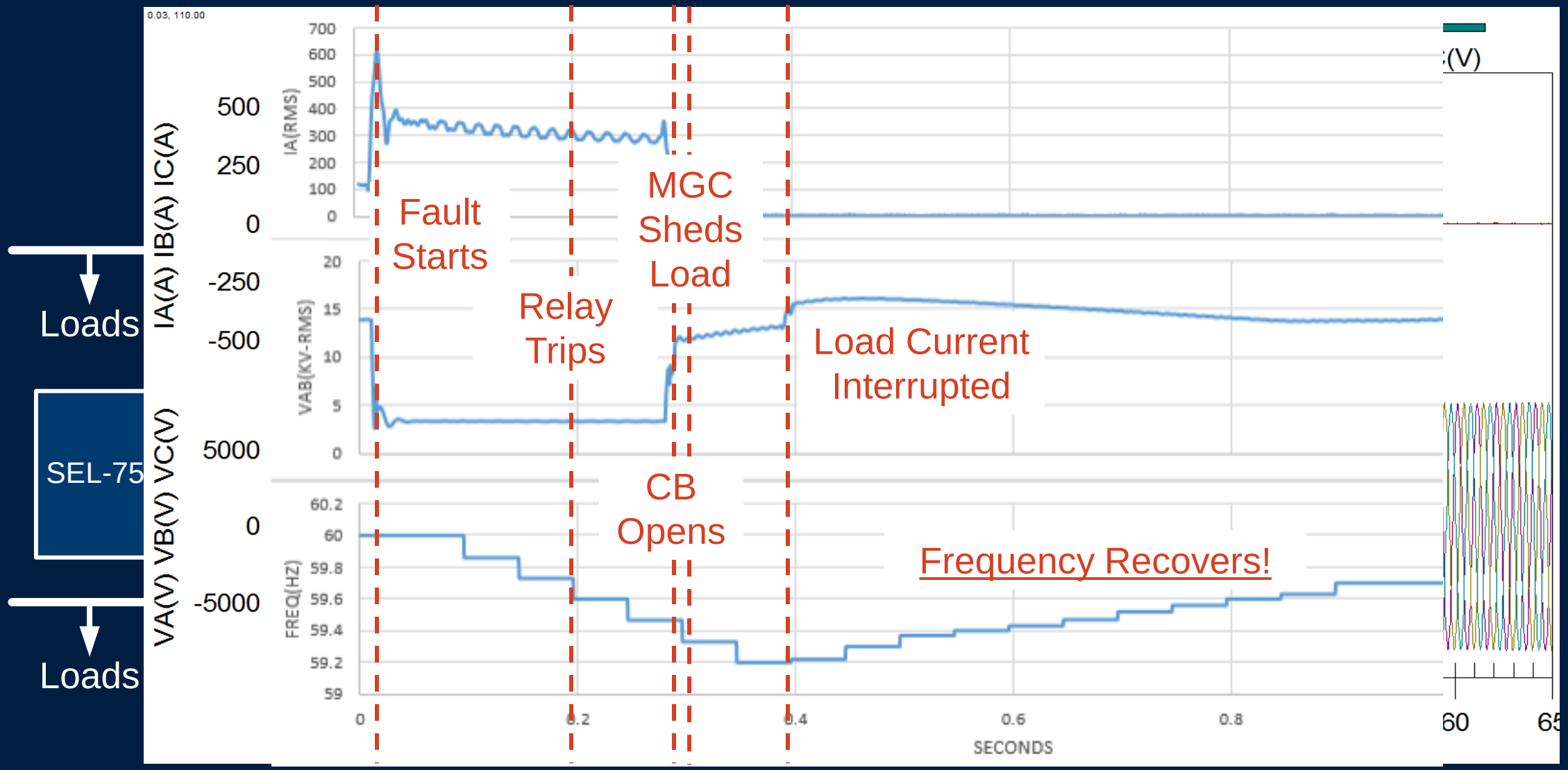
Opens PCC During Open-Circuit Conditions





MIT LL Simulated Utility Disconnection Event

What the Relay Recorded!

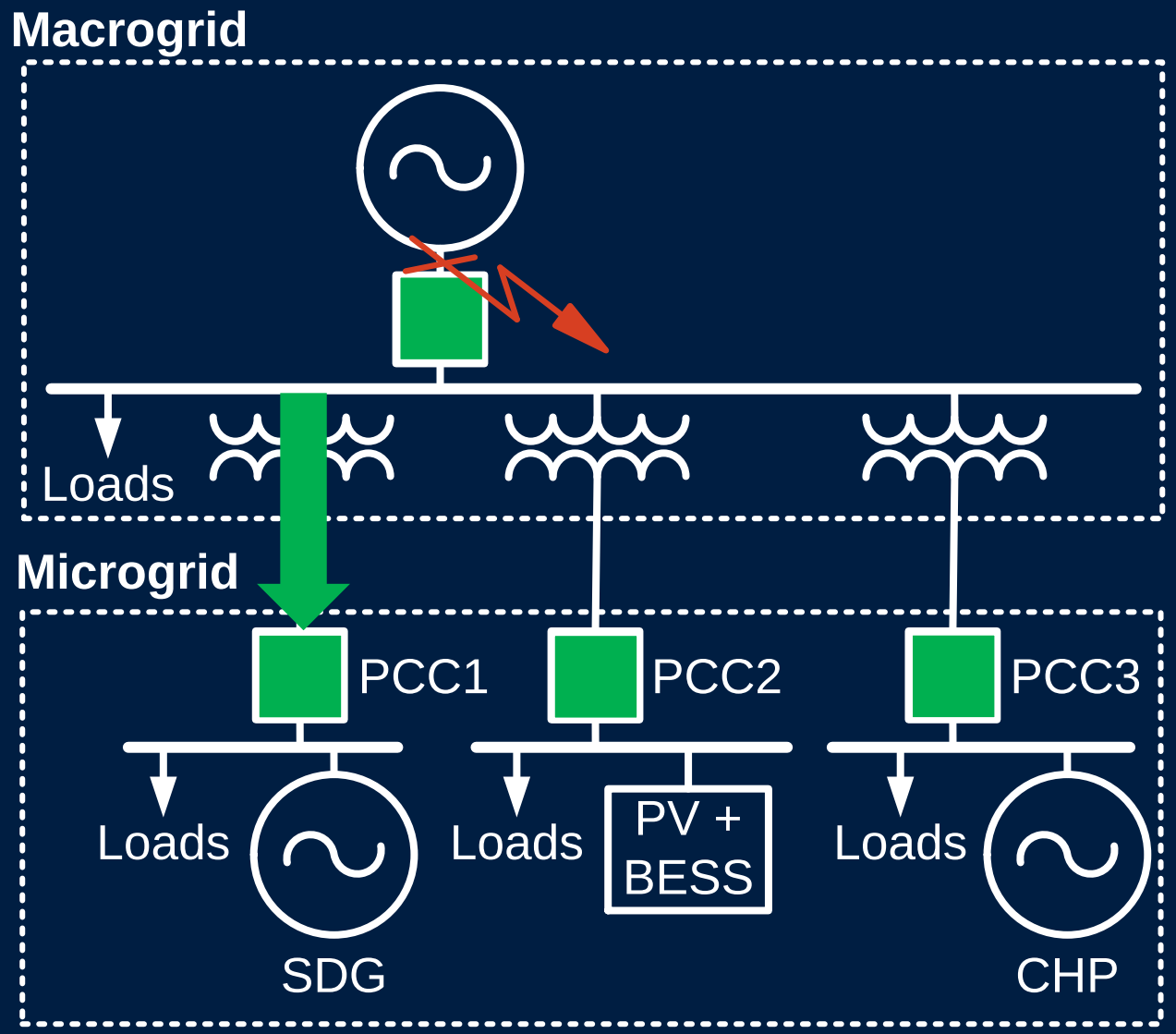


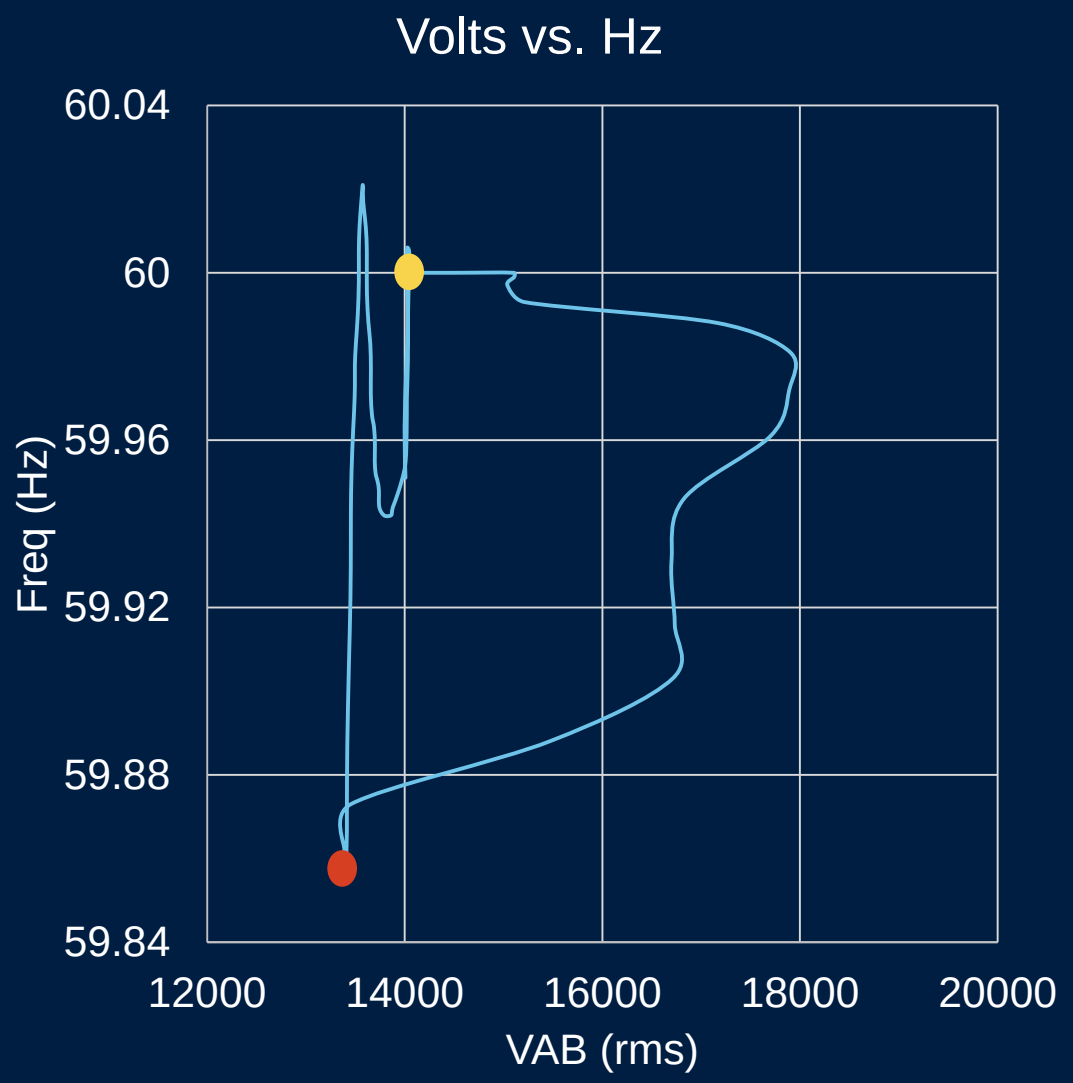
Microgrid Resiliency Requires FAST Load Shedding

Problem to Mitigate	Load-Shedding Speed	
Frequency collapse	FAST	**Subcycle (faster than 16 ms)**
Voltage collapse	FAST	
DERs out of step	FAST	
DER overload	SLOW	**Slow (~1 second)**
Synchronization assist	SLOW	
PCC curtailment	SLOW	
PCC demand charge avoidance	SLOW	

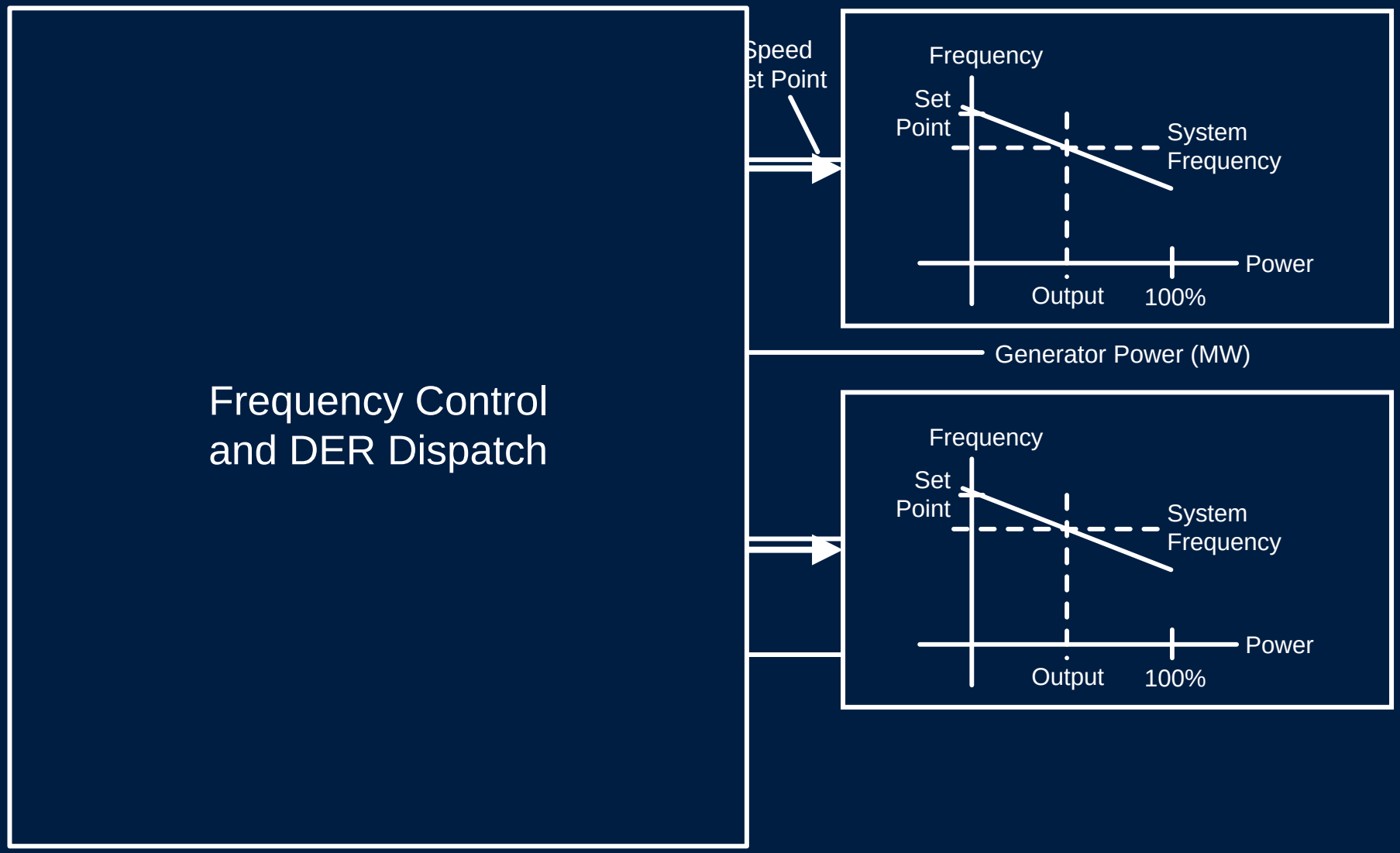
The Ultimate: Triple Seamless Islanding Event!

Only Possible With Integrated Relays and Controllers





Islanded Microgrid Voltage and Frequency Are More Robust With DERs in Droop Mode

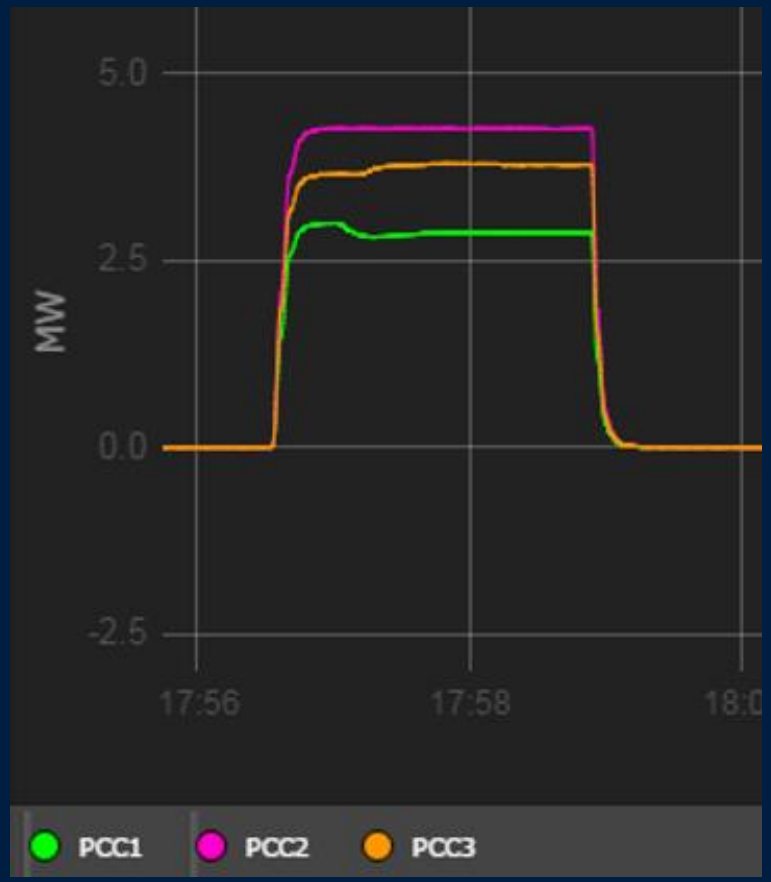


Lesson Learned: Adaptive Feedforward (FF) Techniques Are Superior to PID Methods

Typical PID Problems

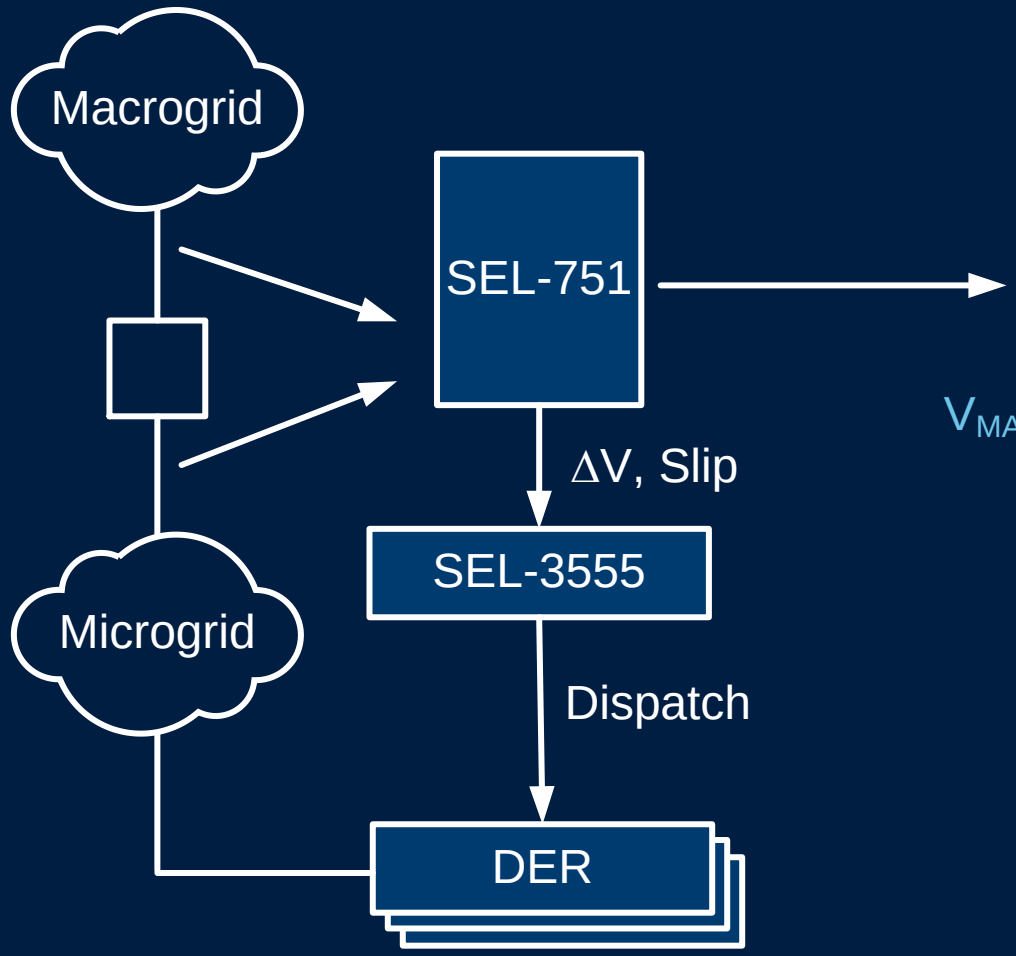
- Changing load conditions
- Not-so-bumpless transfers
- Low-load instability
- Overshoot
- Integral windup

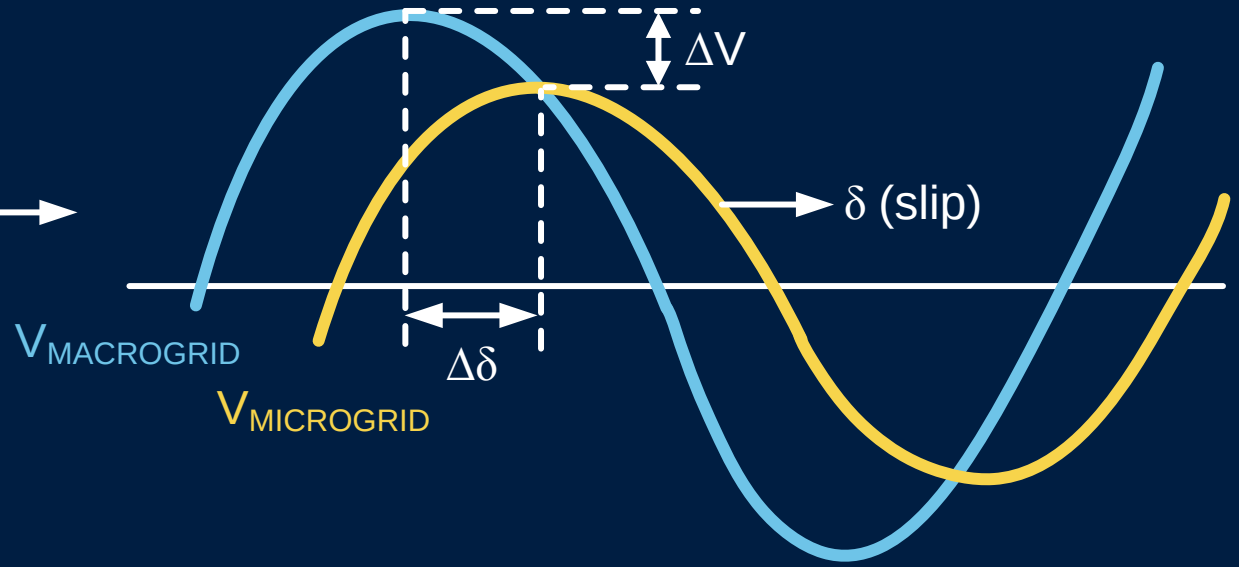
Adaptive FF

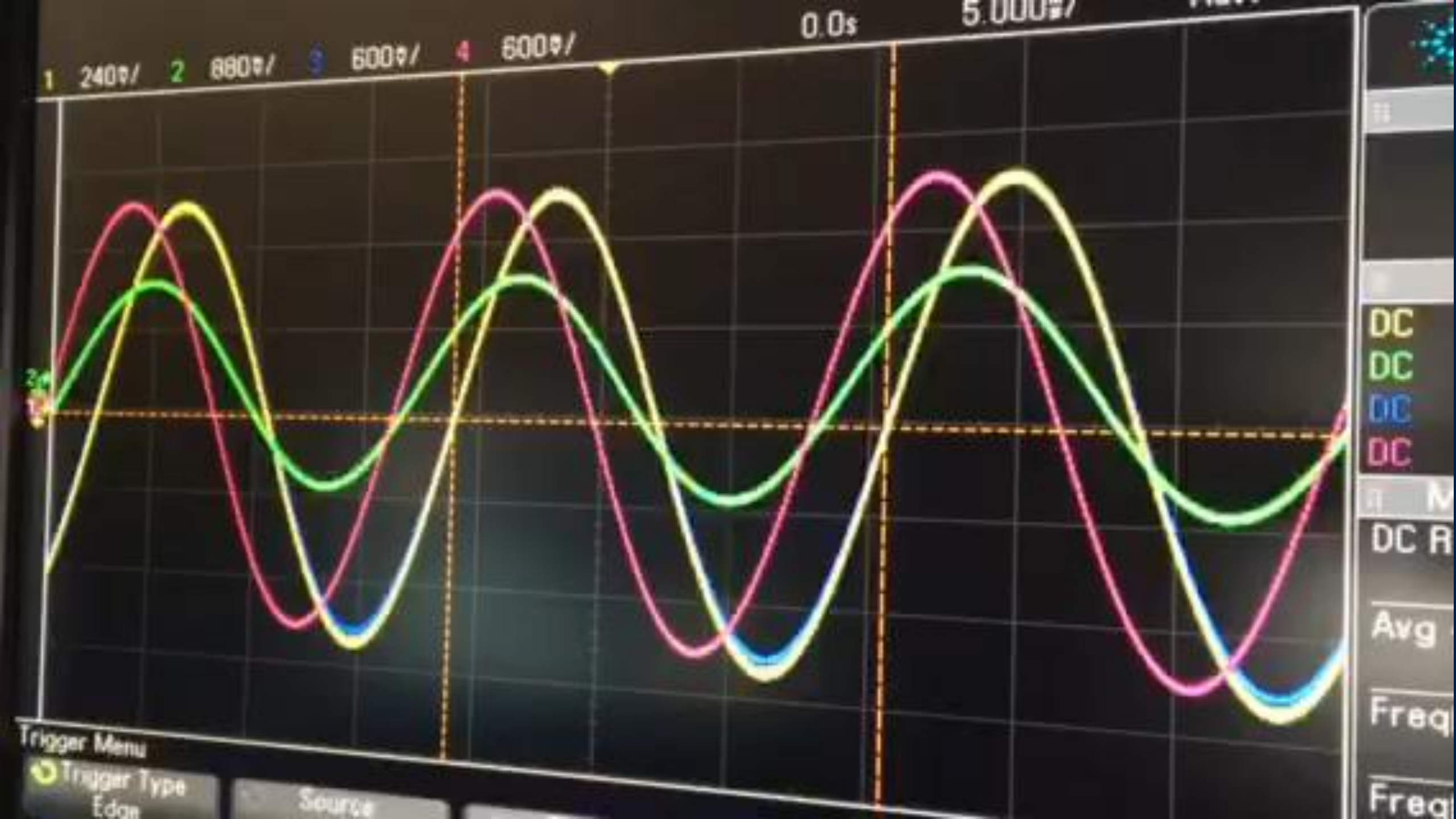


Simple Grid Reconnecting Method

Works With All DERs






0.0s
5.000
1 240
2 880
600
4 600
DC
DC
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DC R
Avg
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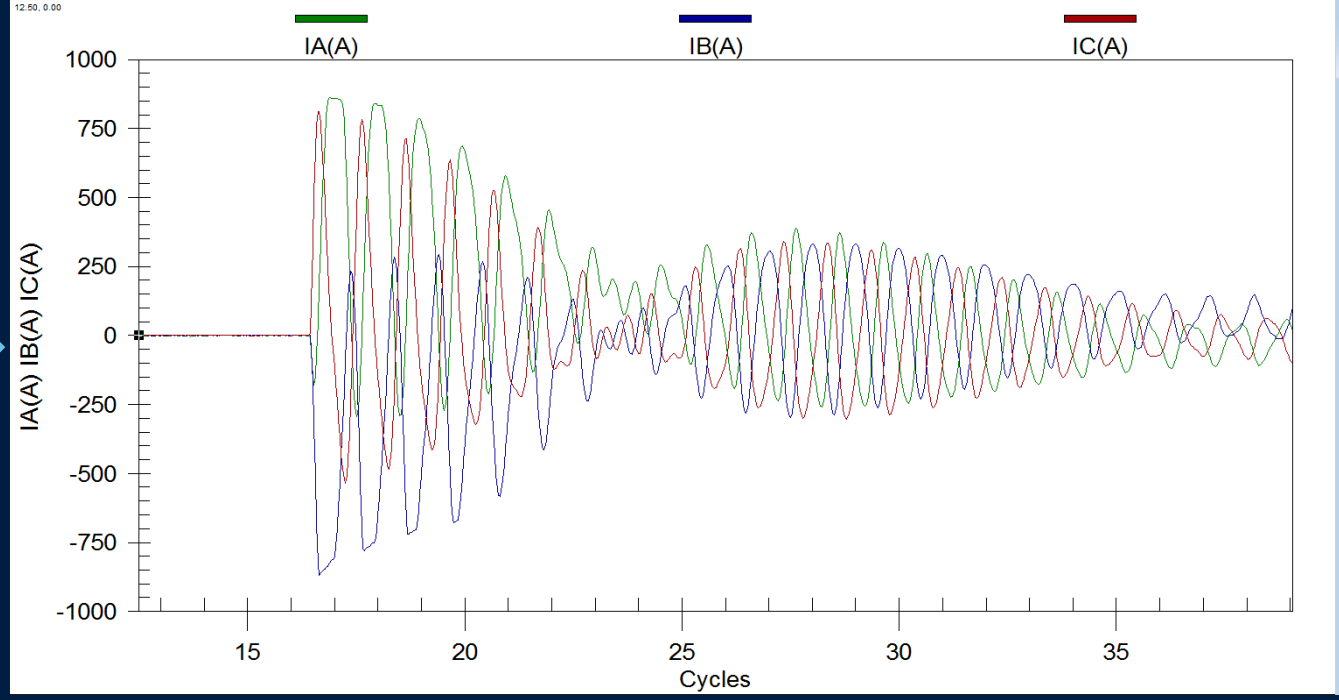
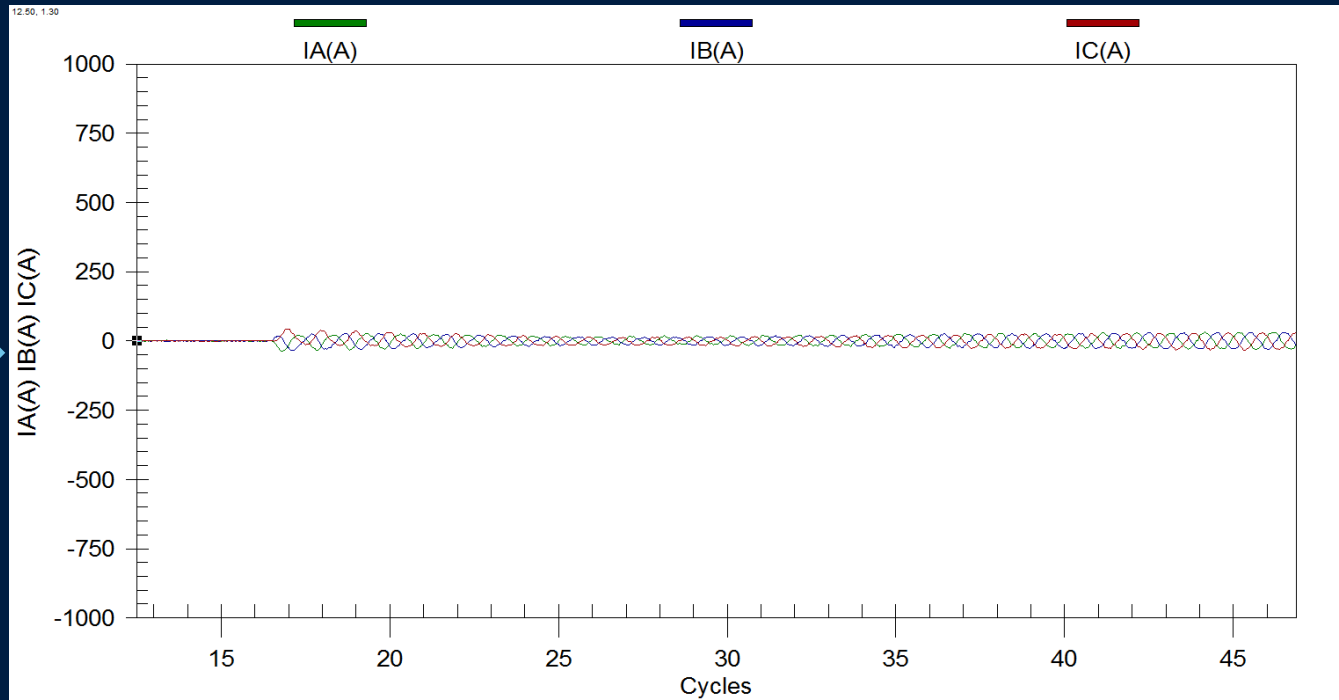
Freq
Trigger Menu
Trigger Type
Edge
Source

Synchronization Done Wrong



Synchronization Done Right



What Did We Find and Improve During HIL Testing?

- PV, battery, and inverter RTDS models were improved
- Fourth-generation POWERMAX library was improved
- Community microgrids can tolerate more load shedding than industrial, military, or utility schemes
- Protection + controls = microgrid control system
- Both macro- and microgrids must be modeled

What Challenges Remain?

- ✓ Automatic islanding
- ✓ Reconnection
- ✓ Protection
- ✓ Island frequency and voltage
- ✓ Grid-connected dispatch
- ✓ HIL model accuracy
- ✓ Economic cost optimization
- ✓ Generator integration
- ✓ Triple seamless islanding
- ✓ DMS and OPAL-RT communications
- ✗ Inverter (BESS and PV) integration

Great Teamwork!

SEL

- Will Allen
- Bharath Nayak
- Will Edwards
- Jonathon Kegan
- Scott Manson

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- Erik Limpaecher
- Kendall Nowocin
- Christopher Smith
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- Raajiv Rekha