Microgrid System Design, Control, and Modeling Challenges and Solutions

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SEL ES Technology Director

Agenda

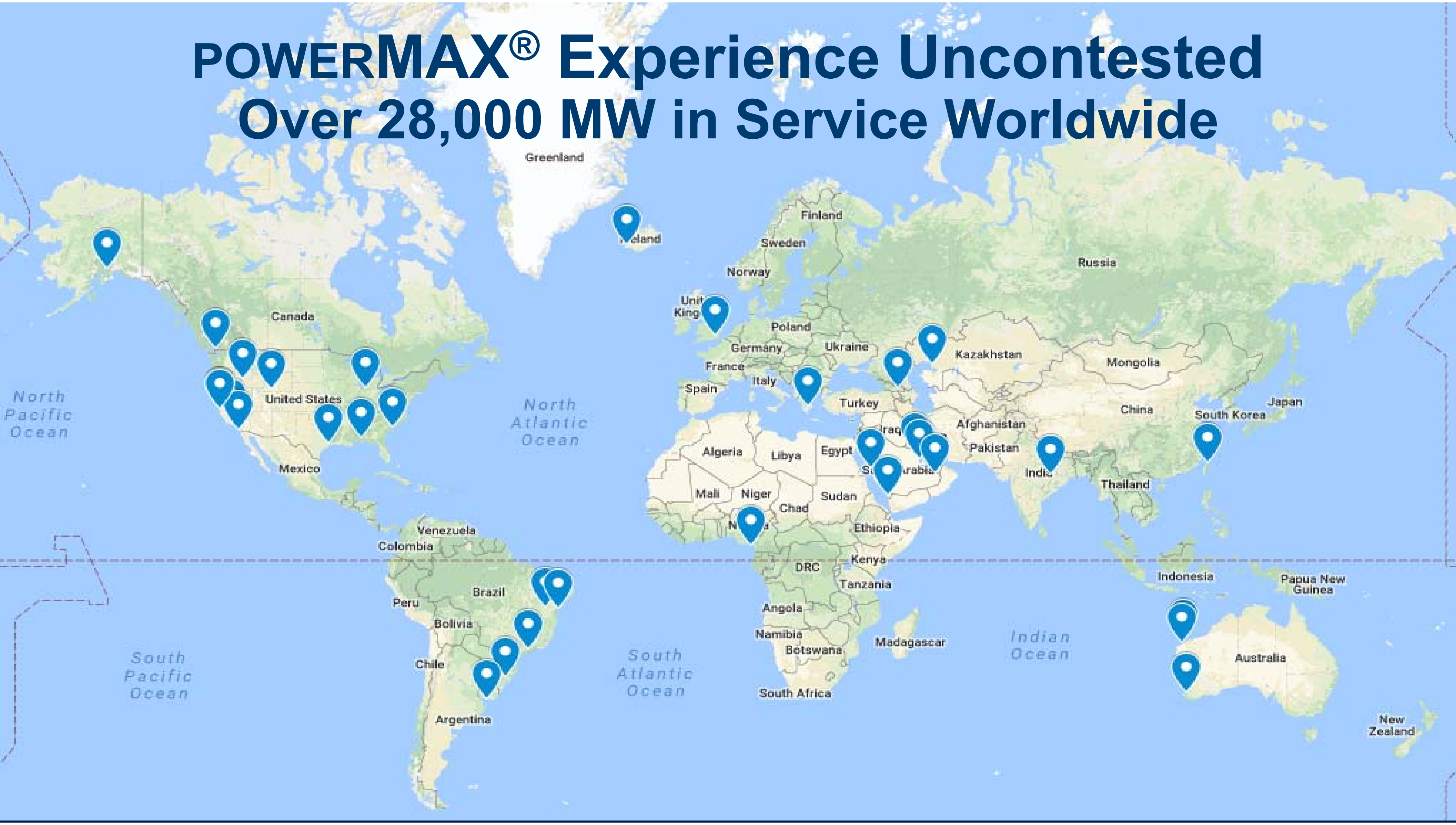
- Example Projects
- Challenges
- Design Principles
- Reconnection
- Seamless Islanding
- Frequency Resilience
- Visualization
- Modelling
- What is Next?

Microgrid Examples

PowerMAX® System Family Tree

PowerMAX Technology	Typical Customer	System Size
Utilities	Bulk Electric Power Transmission & Generation	> 1 GW
Industrial Power Management	Oil & Gas, Heavy Industries	> 100 MW
Commercial Microgrids	Communities, Universities	> 10 MW
Garrison Microgrids	Fixed Military Installations	< 10 MW
Mobile Microgrids	Disaster Relief, Forward Operating Bases	< 0.5 MW

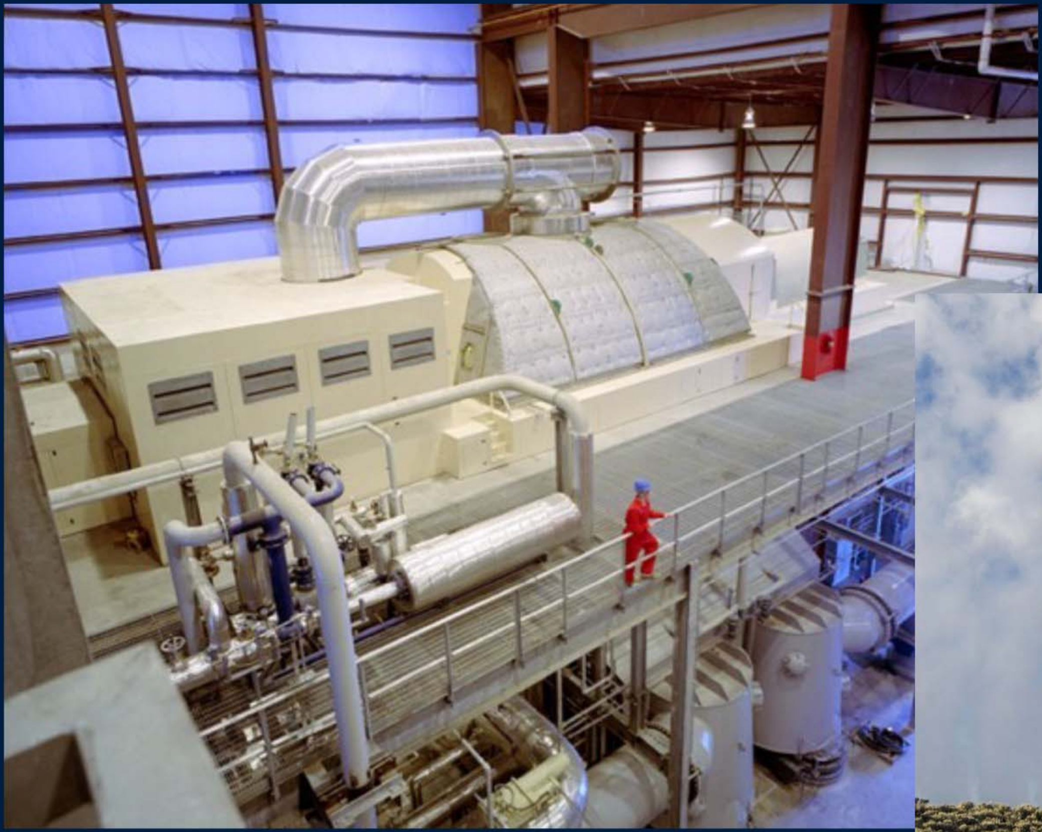
POWERMAX® Experience Uncontested
Over 28,000 MW in Service Worldwide



How Others Use SEL Equipment for Microgrids and DERs

	Do it yourself	
Segment	Simple Microgrids	Simple DER PCC Interconnection
Technology	Relays	Relays, RTACS + Grid connect library
Project Funding	any	Independent power producers or Utilities
Customer Examples	Entergy	Utilties - XM (Columbia) Southern companies, Also Energy, New York Power Authority with Tesla batteries
Approximate Project Cost	$5K	$20K
Approximate Project Size	< 10MW	<100MW
ES office	Local Office	Local Office

PowerMAX® for Utilities is Purpose Built for Gigawatt Scale Generation



PowerMAX® for Industrials
Designed for Heavy Industrial Customers

PowerMAX® for Commercial Customers

Award Winning Controls for Complex Grids > 10MW

Paris Island
PowerMAX® Garrison

- Awarded to Ameresco via ESPC
- SEL PowerMAX being commissioned now

"This is most comprehensive seamlessly integrated DoD Project" - Ameresco

PowerMAX® Mobile Technology

Interoperable, Simple solution for <0.5MW Microgrids

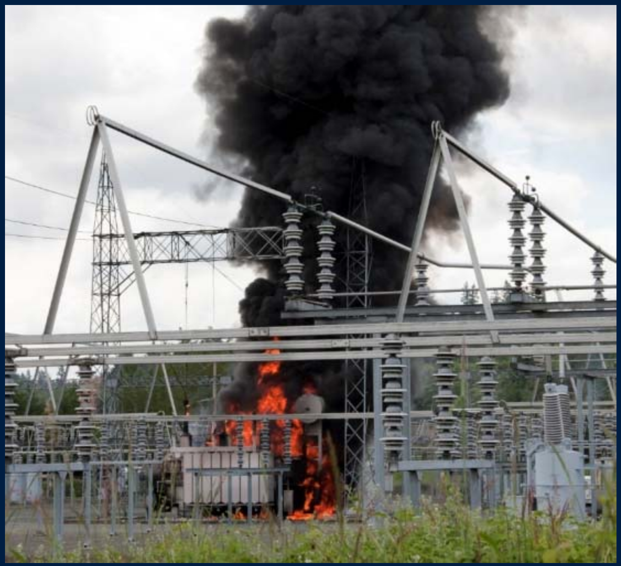
A4

- Red Cross
- FEMA
- Private Disaster Relief
- Forward Operating Base (FOBB)

Microgrid Challenges

Protective Relays Are Mandatory

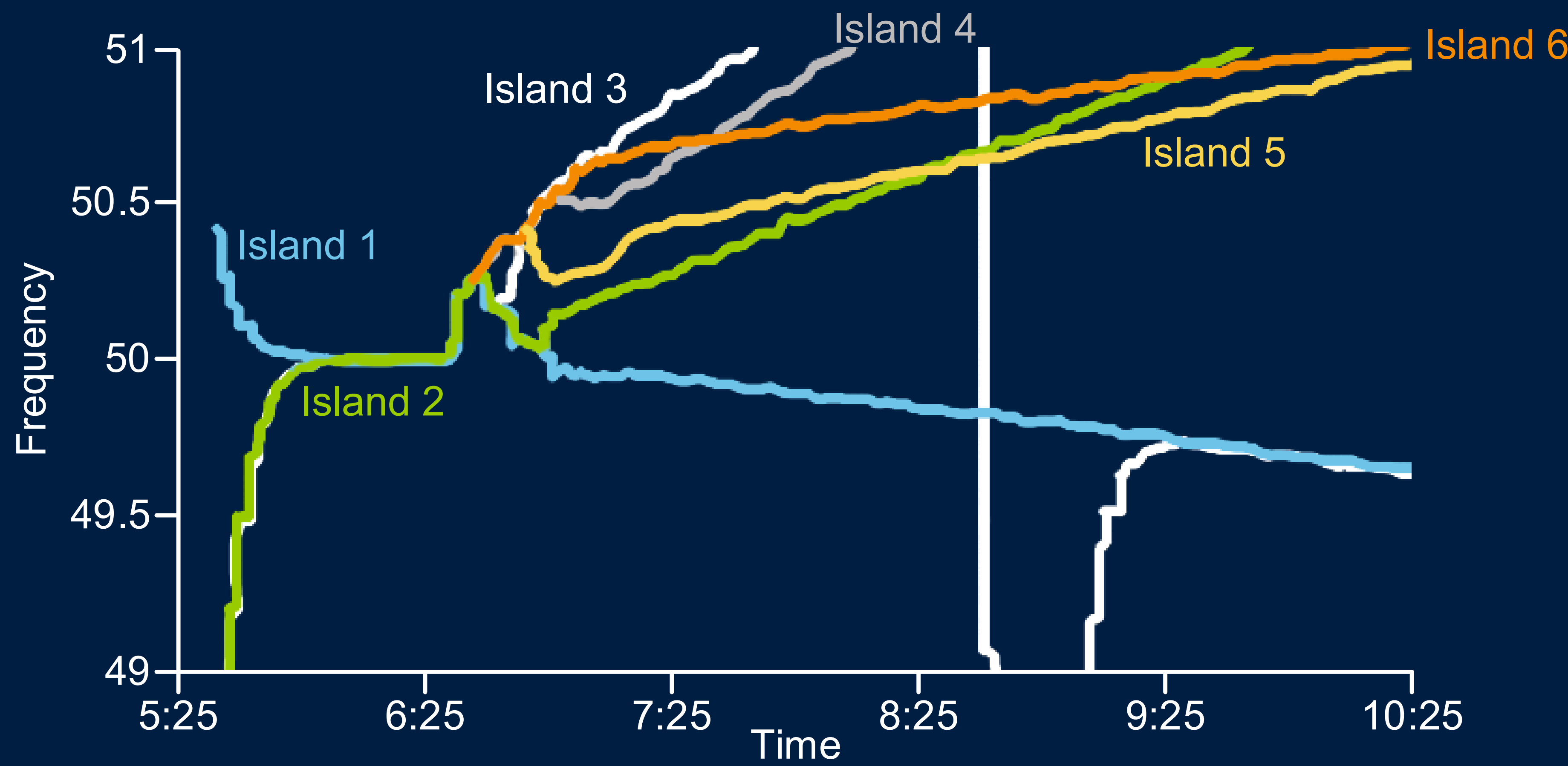
Protect Assets, Environment, and People



CR68
SM32

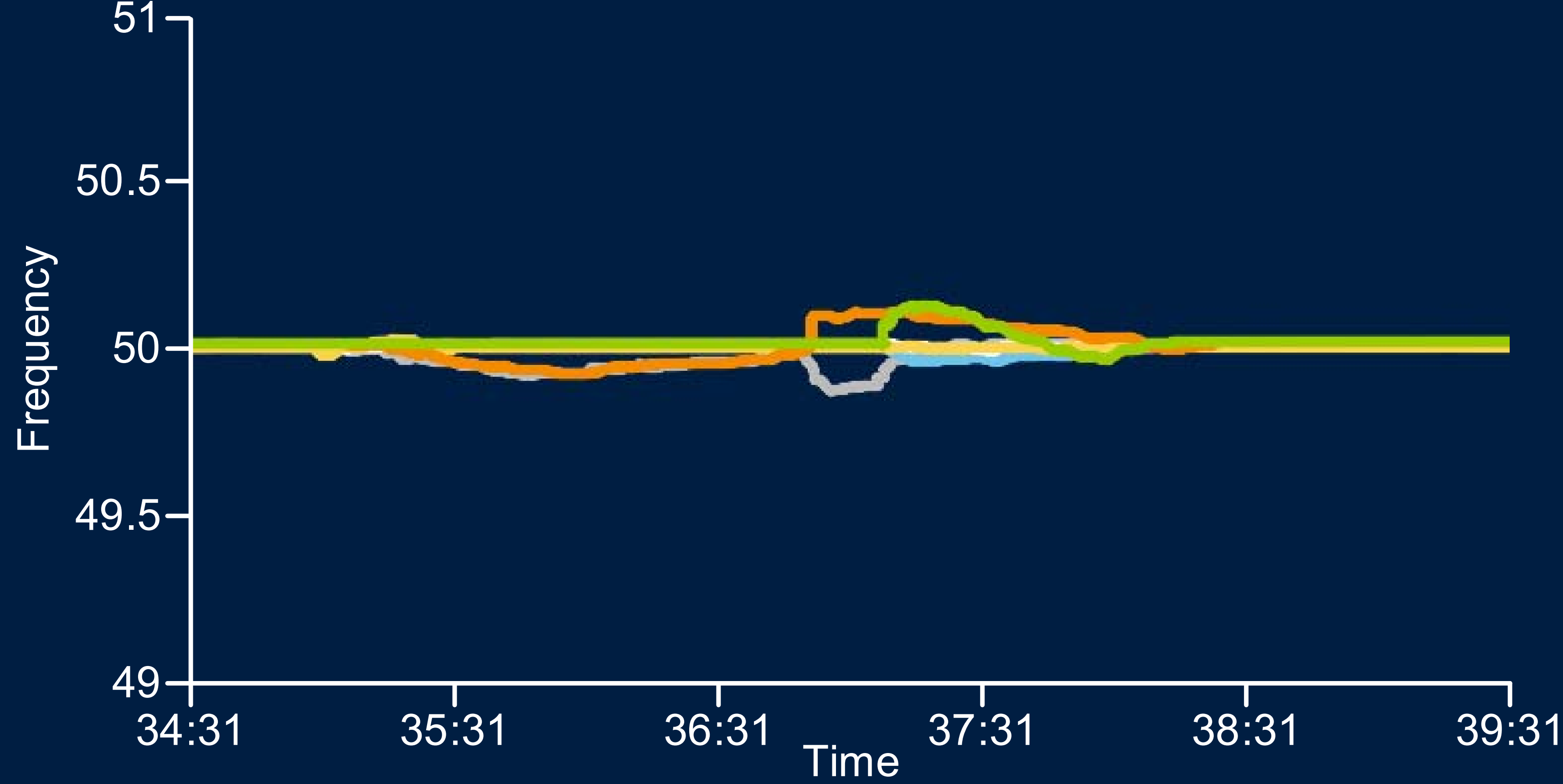
Not Resilient

Power System Split Into Six Islands Collapses

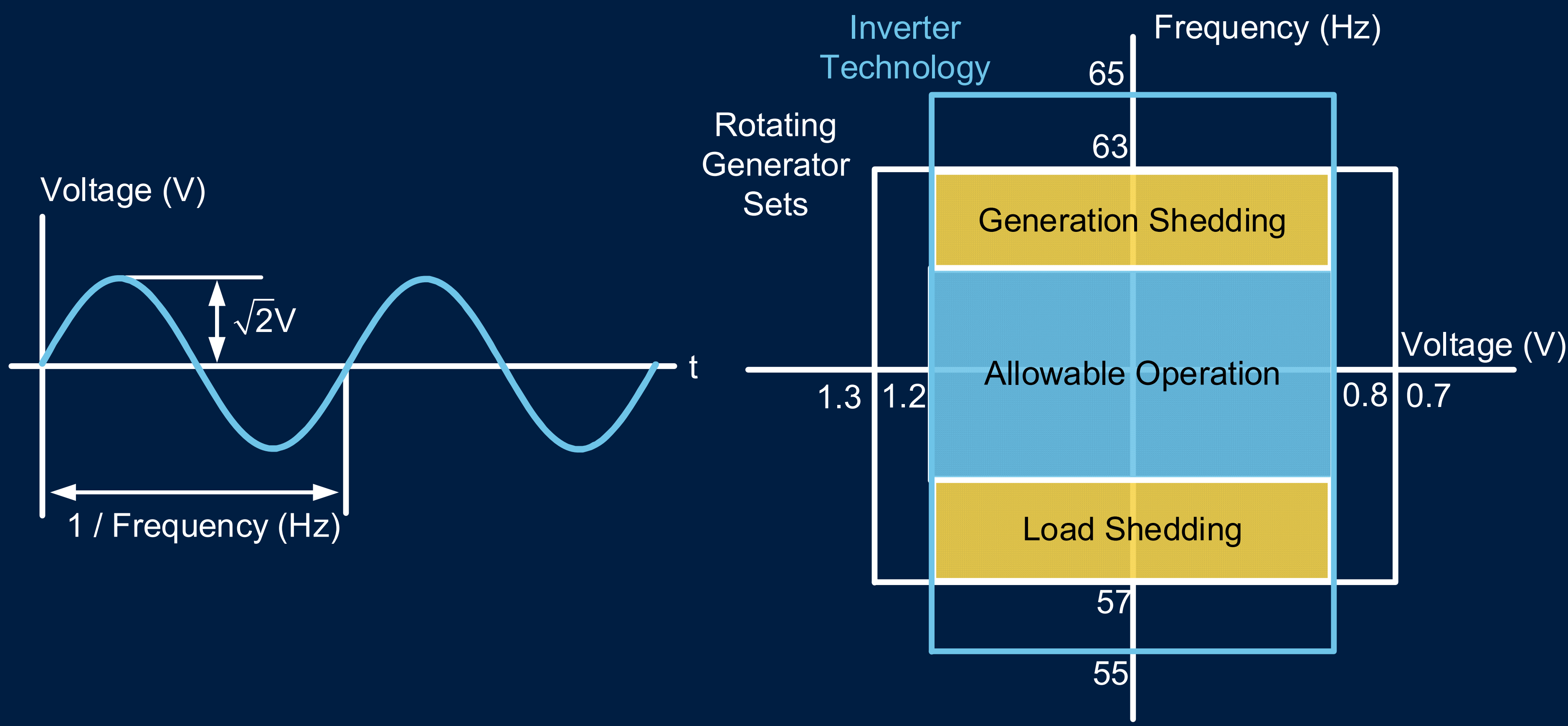


Resilient

Same Six Islands With Mature Microgrid Technology

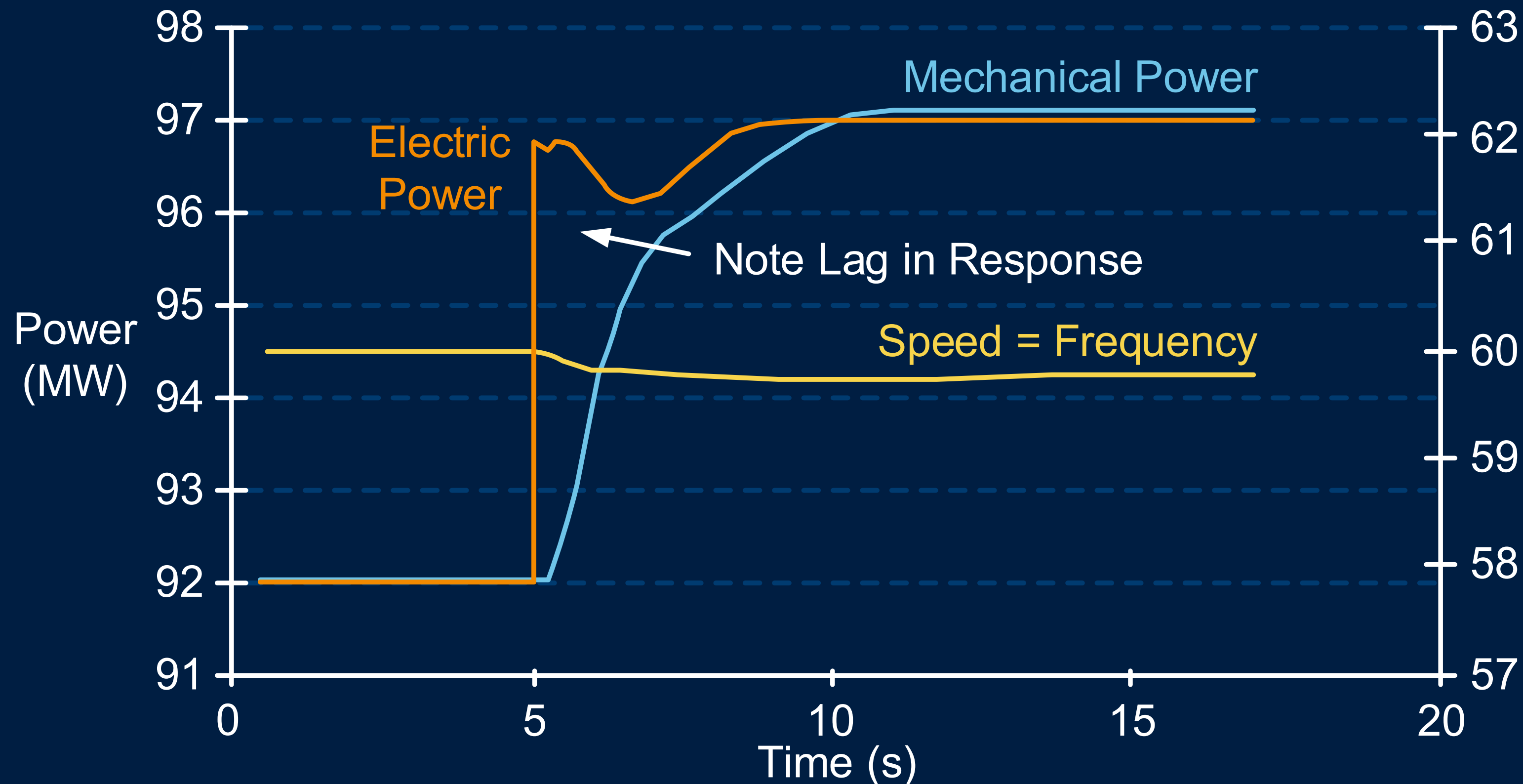


Frequency and Voltage are Resilience Metrics



Engines Cannot Respond Instantaneously

Frequency Decay Is Extraction of Kinetic Energy From Inertia



System Inertia

System inertia (H) is J • (kg • m^2) in terms of pu

$$H = \frac{J \bullet (kg \bullet m^2)}{MVA} = \text{seconds}$$

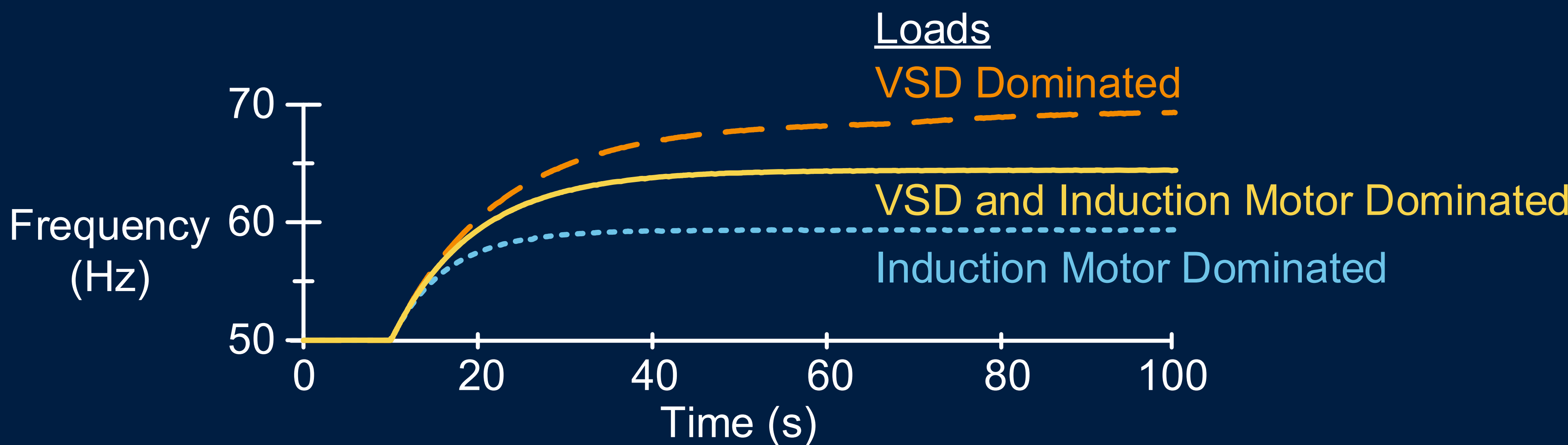
Frequency decay is driven by power disparity and inertia

$$\frac{df}{dt} = \frac{P_{disparity}}{2Hf}$$

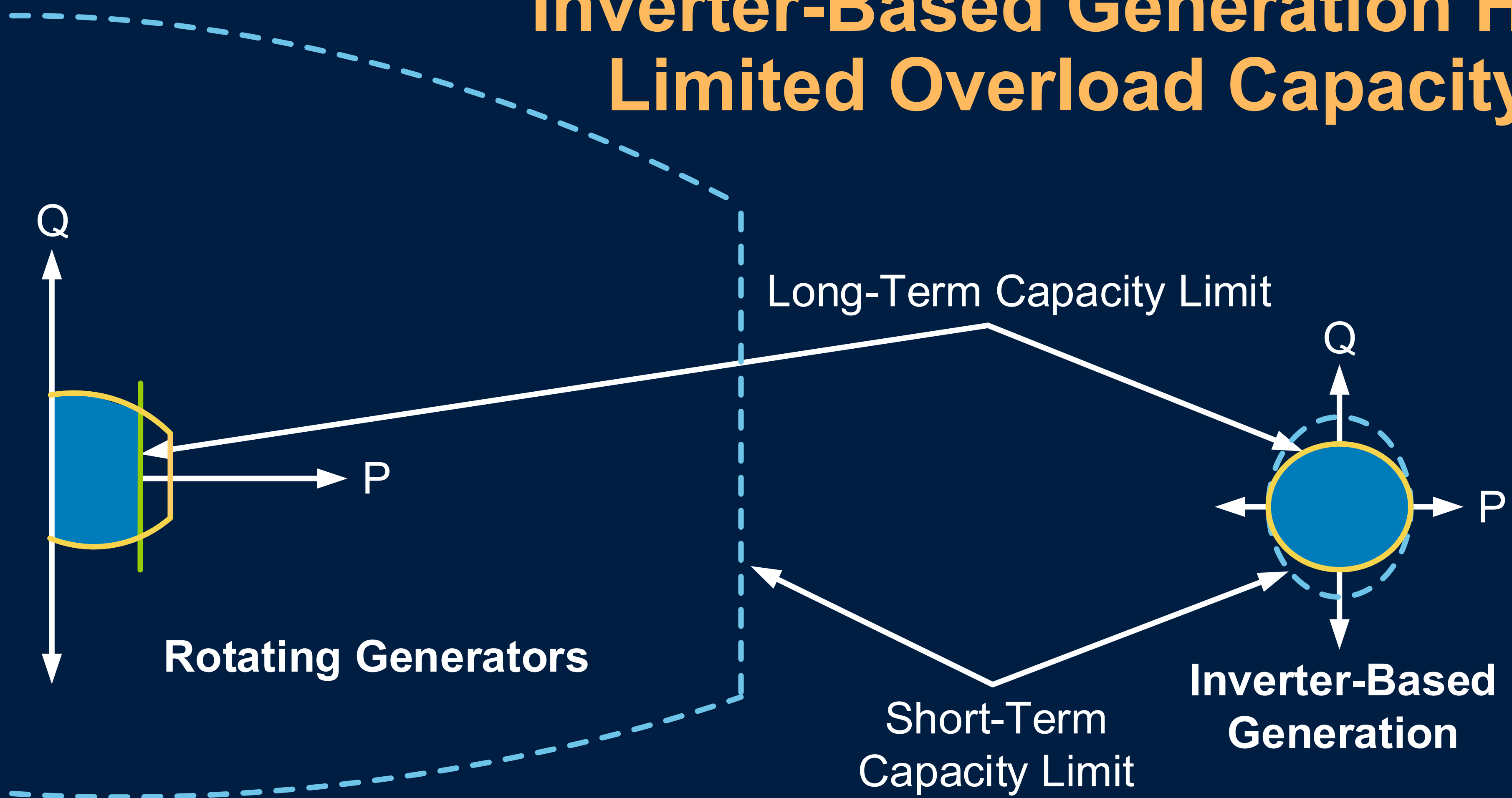
Load Composition Affects Frequency Stability

Noninertial Effects

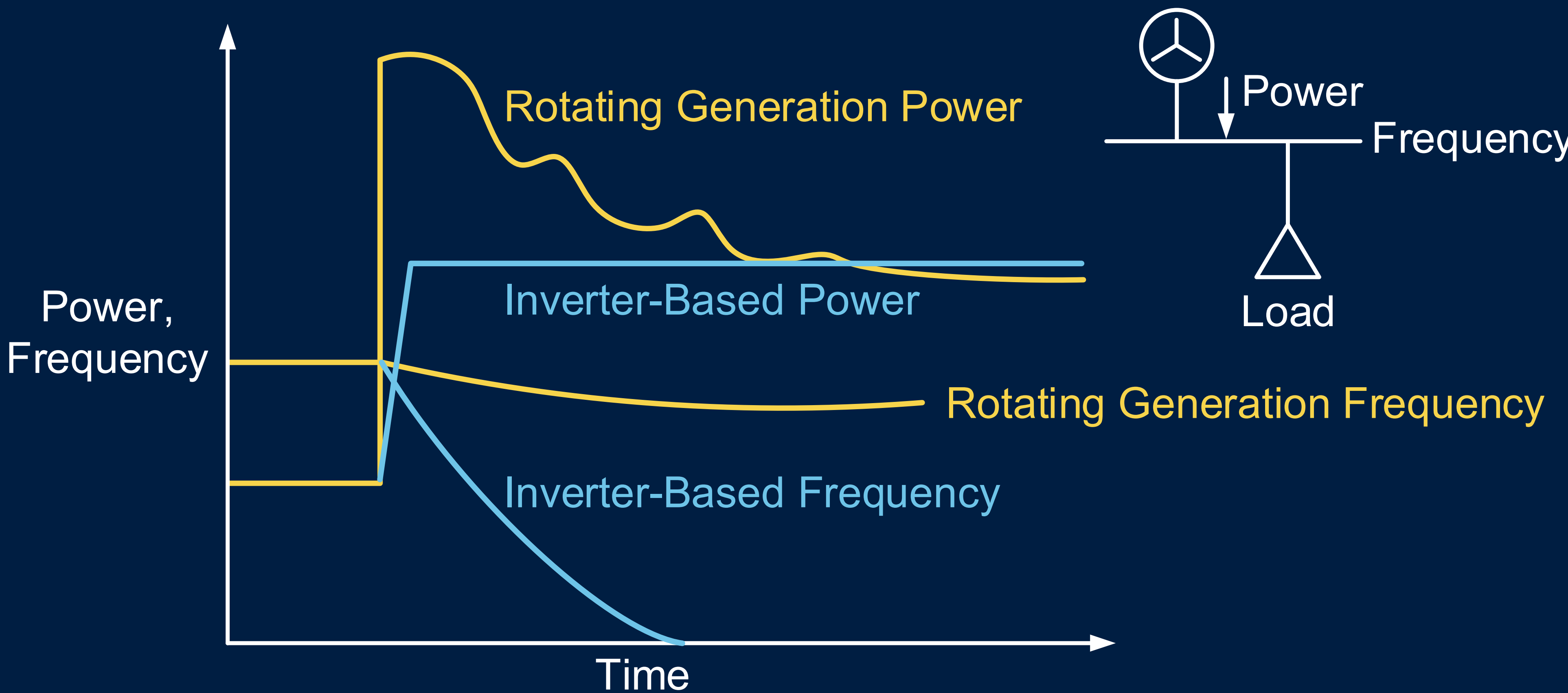
- Electric loads increase transients
- Motors reduce transients



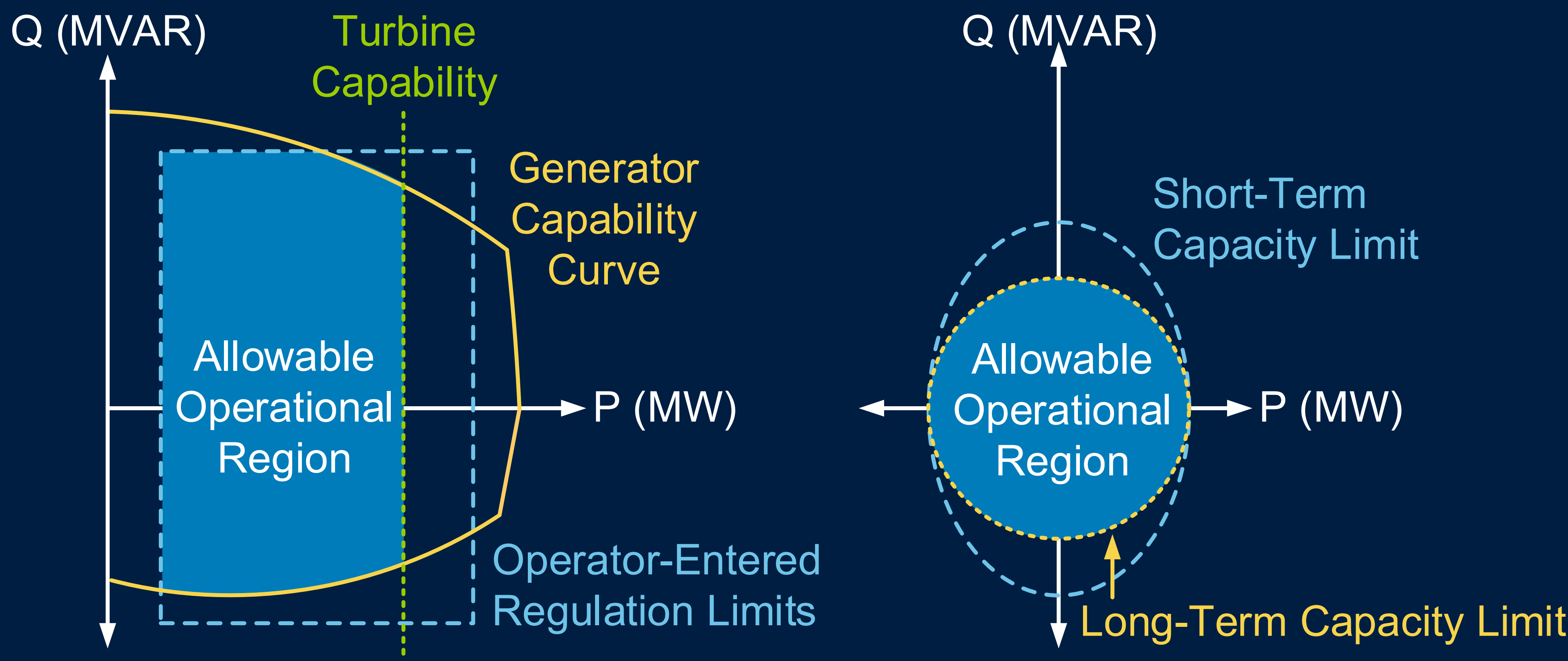
Distributed Energy Resource (DER) Inverter-Based Generation Has Limited Overload Capacity



Load Balancing Must Happen *Faster* With DER Inverter-Based Generation

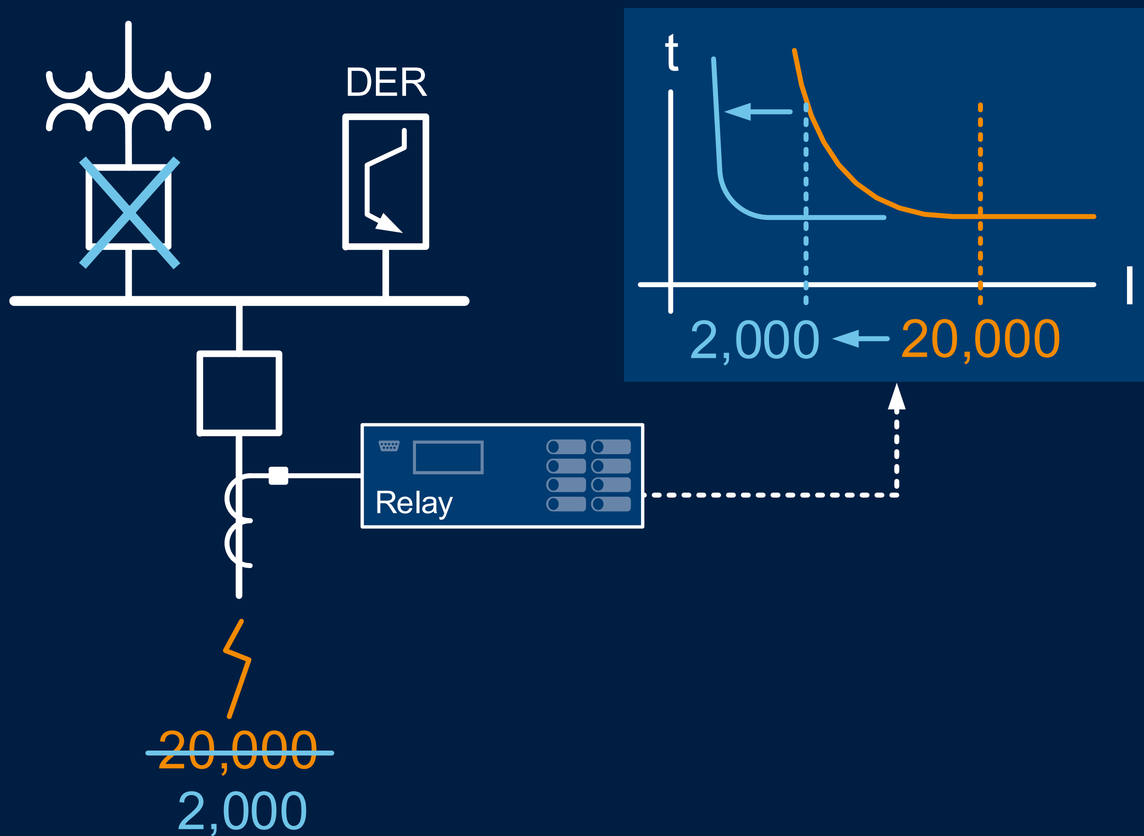


Controller Must Understand DER Capability

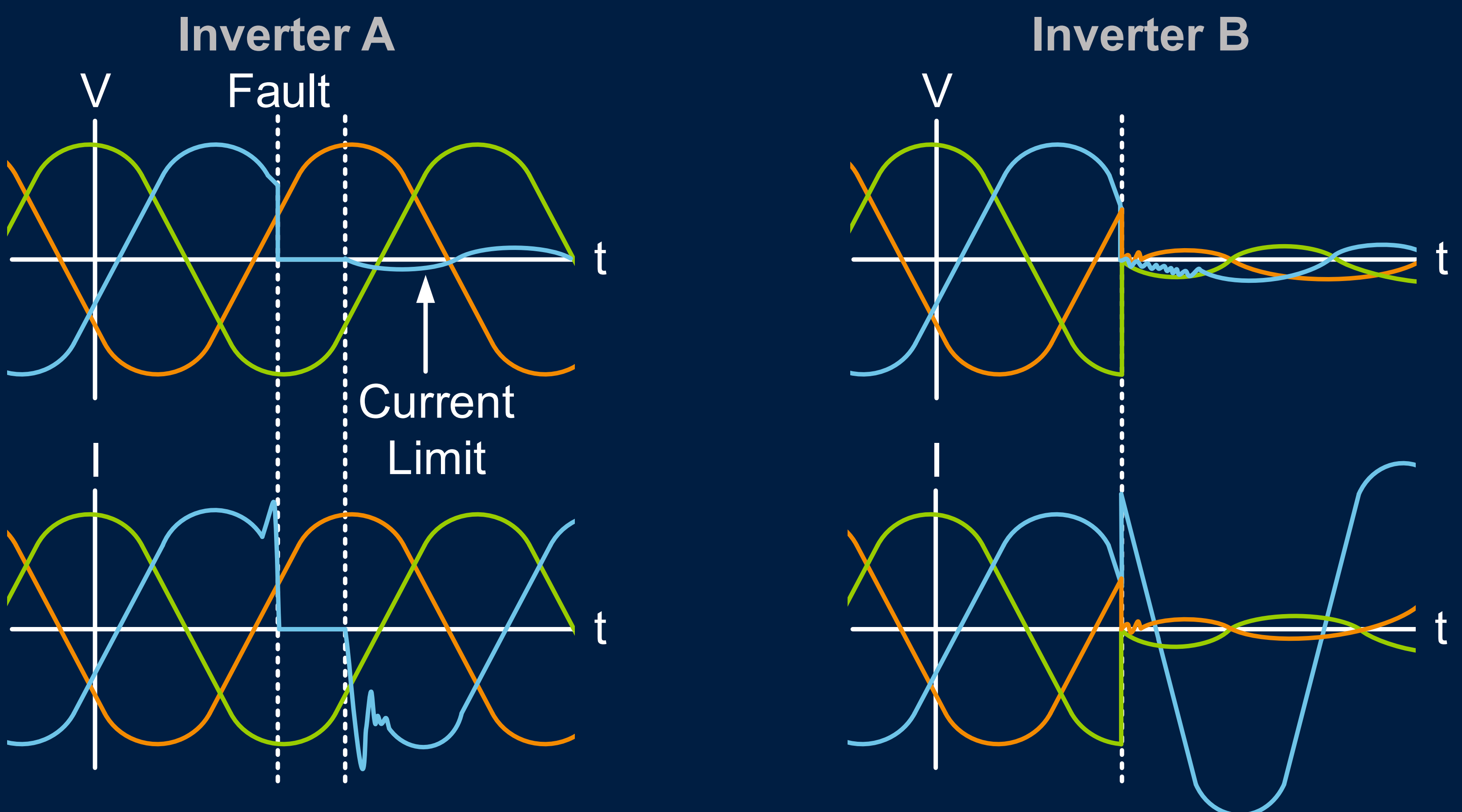


Protection Must *Adapt* to Changing Fault Conditions

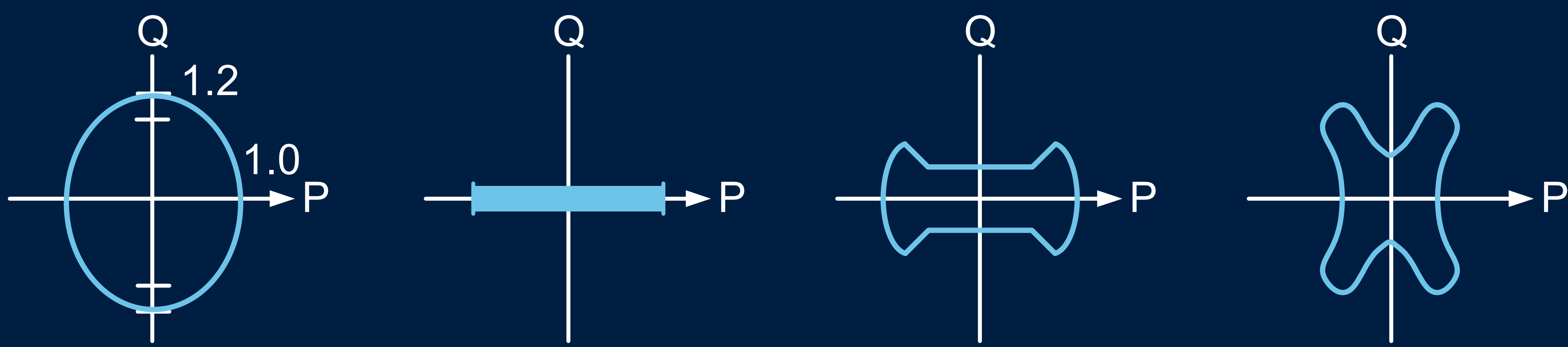
- Fault levels
- Grounding
- Directions
- Impedances



DER Inverter Behavior Is Subject to Human Preference



DER Inverter Behavior Is Subject to Human Error



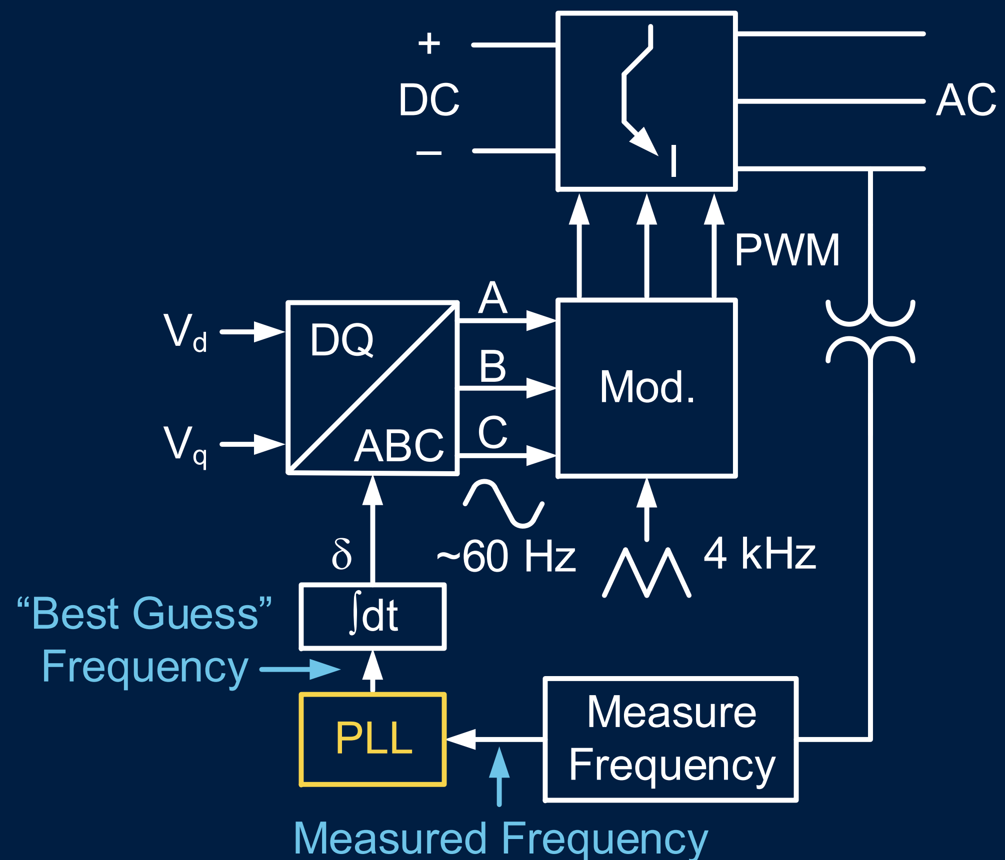
4-Quadrant Battery

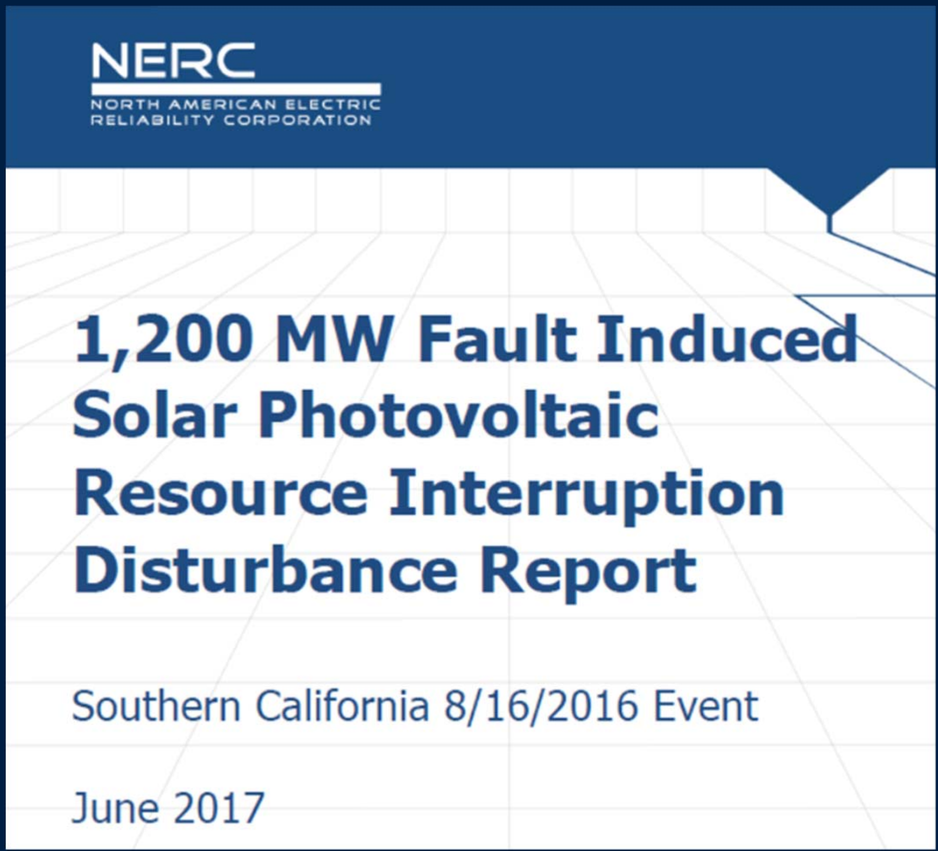
Power-Only Battery

Software Engineer Mistake

Software Engineer Mistake

DER Inverter Phase-Locked Loops (PLLs) Fail When You Need Them Most





NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

1,200 MW Fault Induced Solar Photovoltaic Resource Interruption Disturbance Report

Southern California 8/16/2016 Event

June 2017

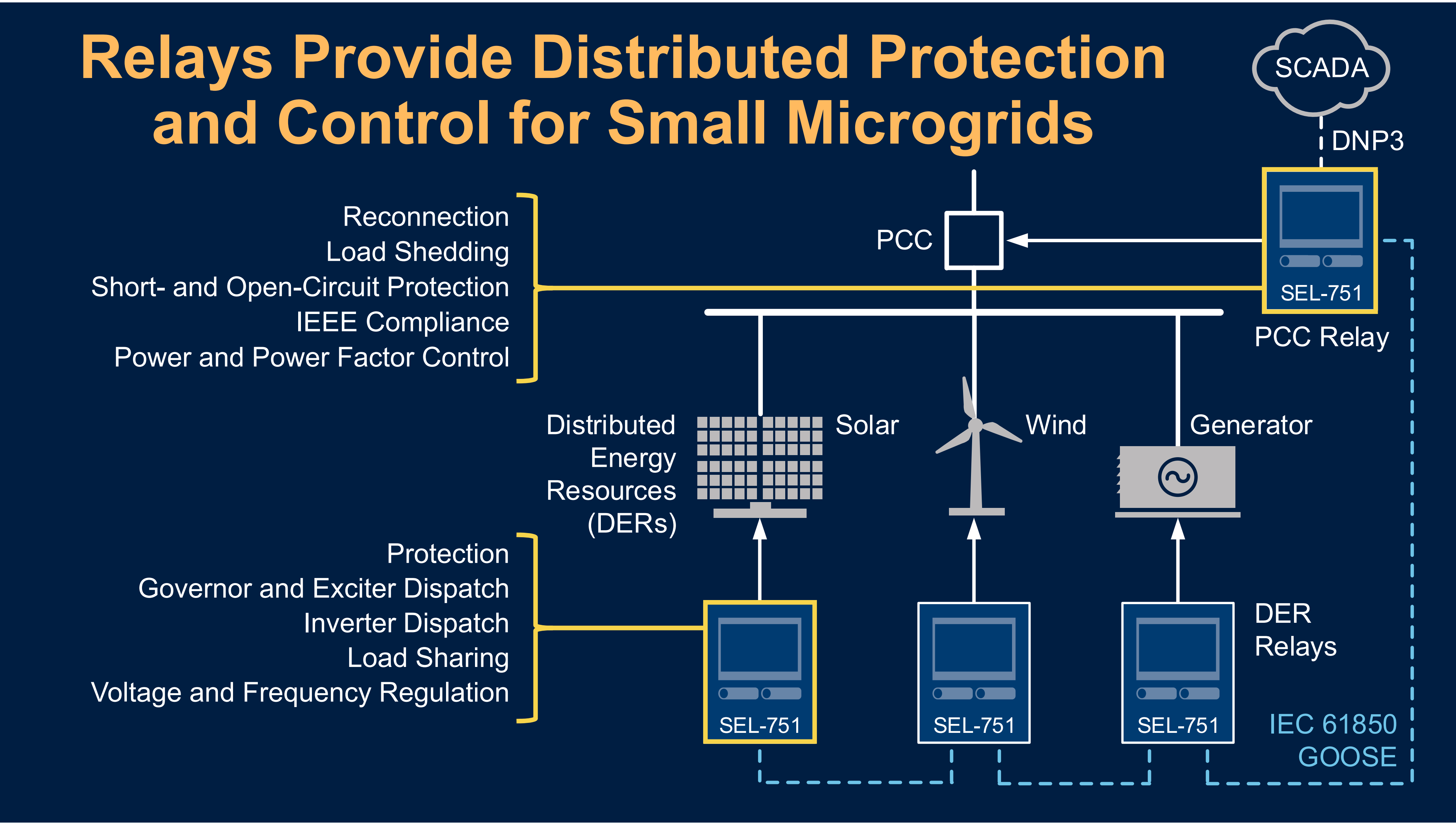

Design

Requirements for Technology

1. Safe
2. Reliable (resilient)
3. Economical

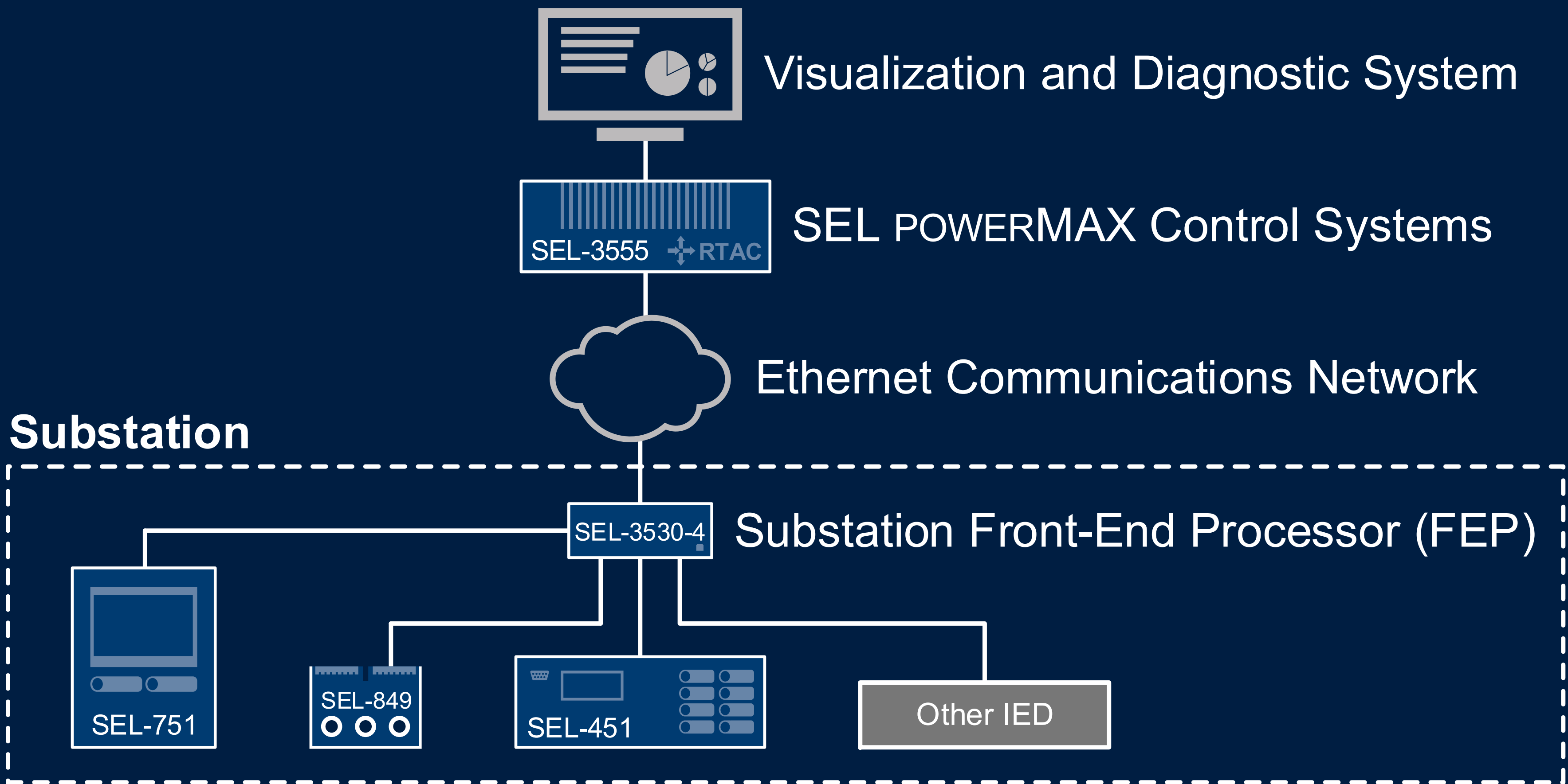
Relays Are the Foundation of Microgrid Controls

- Multifunction protection
- Remote I/O
- Metering
- Power quality monitoring
- Programmable logic controller function
- IEC 61850 compliance
- MIRRORED BITS® high-speed communications
- Continuous self-diagnostics
- Synchrophasors
- DC battery monitoring
- Front-panel interface that replaces all control switches and pushbuttons

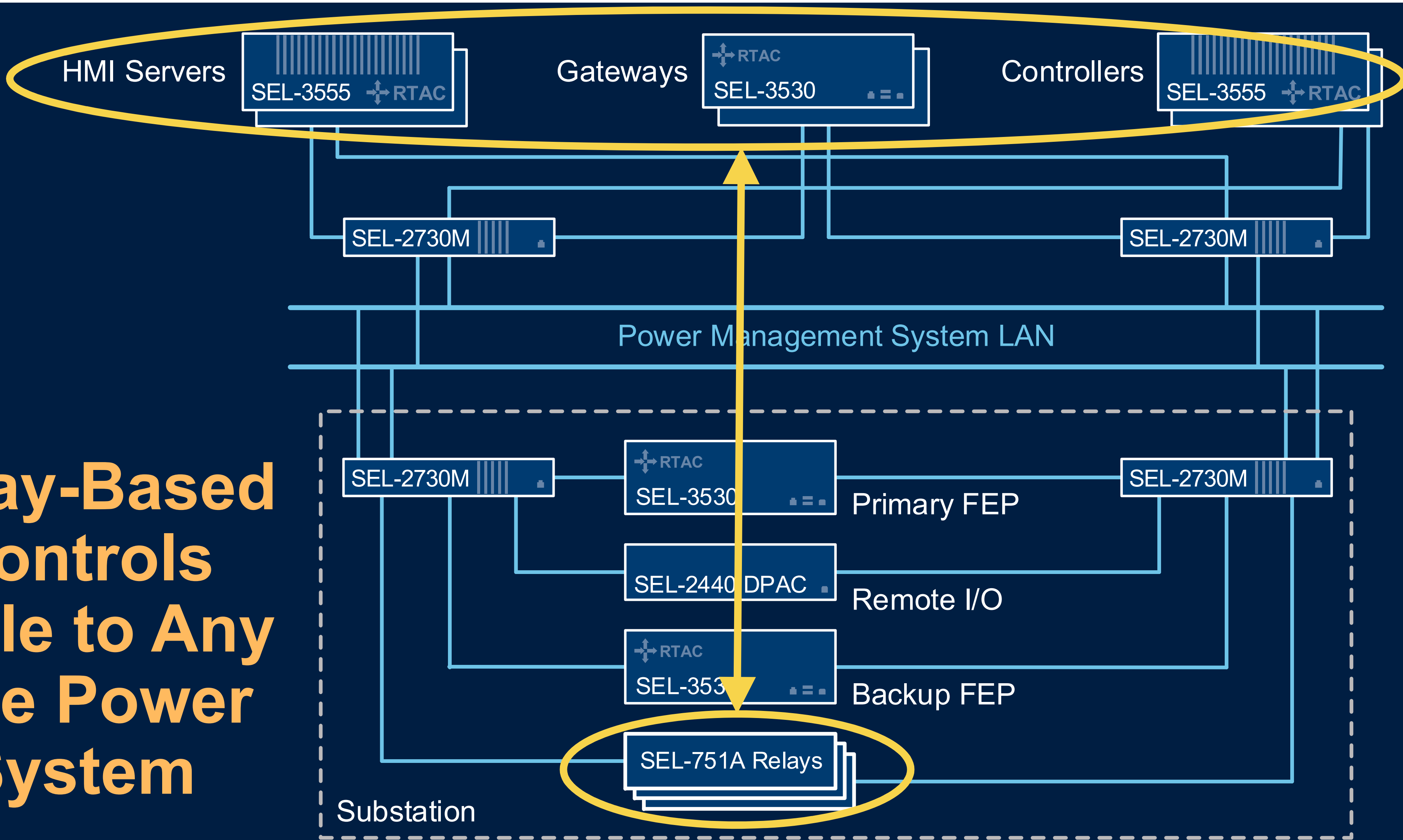


Relays Provide Distributed Protection and Control for Small Microgrids
SCADA
DNP3
Reconnection
Load Shedding
Short- and Open-Circuit Protection
IEEE Compliance
Power and Power Factor Control
PCC
SEL-751
PCC Relay
Distributed Energy Resources (DERs)
Solar
Wind
Generator
Protection
Governor and Exciter Dispatch
Inverter Dispatch
Load Sharing
Voltage and Frequency Regulation
SEL-751
SEL-751
SEL-751
DER Relays
IEC 61850 GOOSE

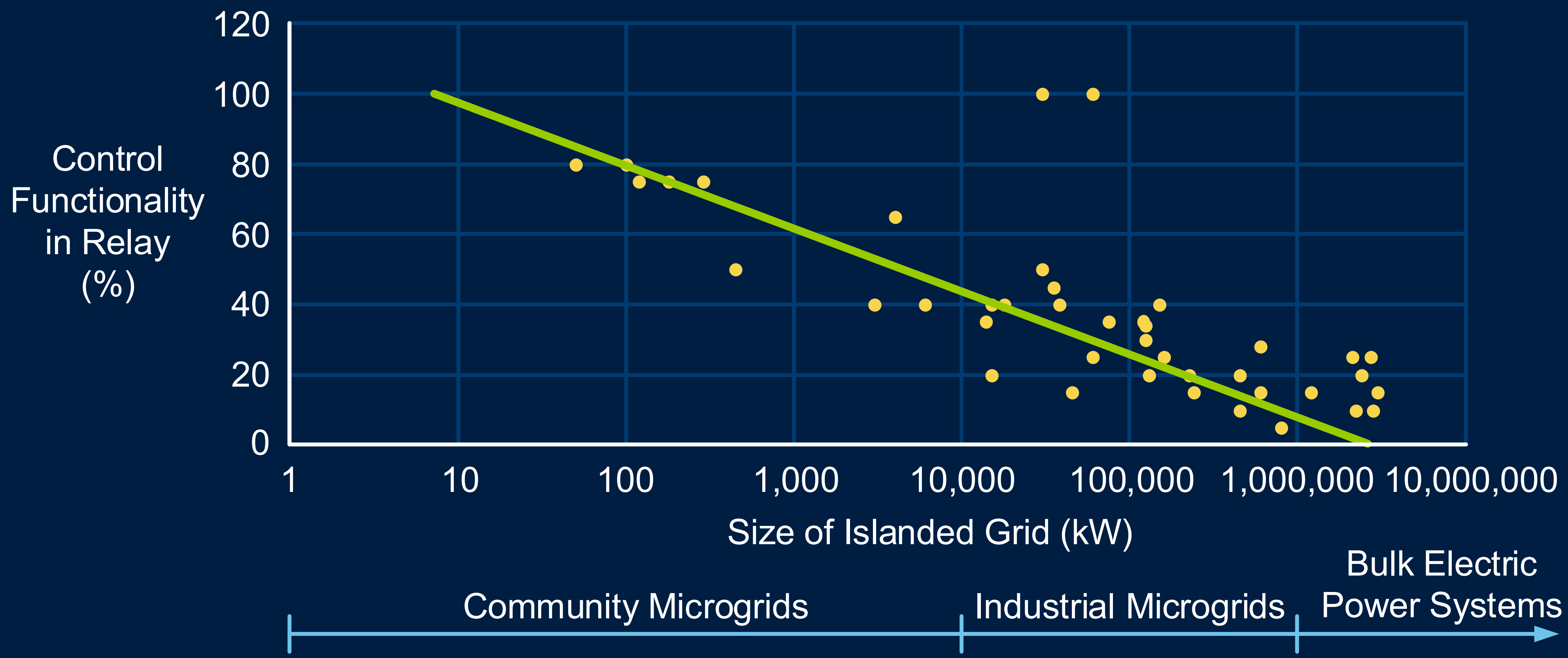
Centralized Controllers Communicate to Relays



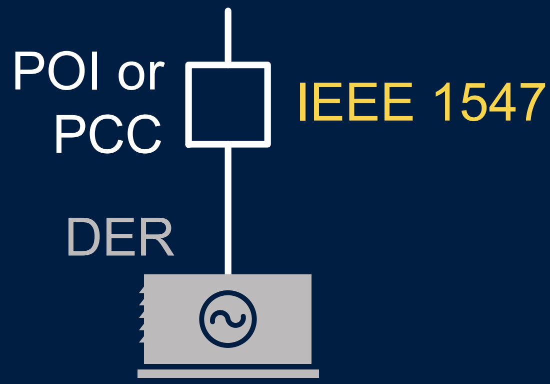
Relay-Based Controls Scale to Any Size Power System

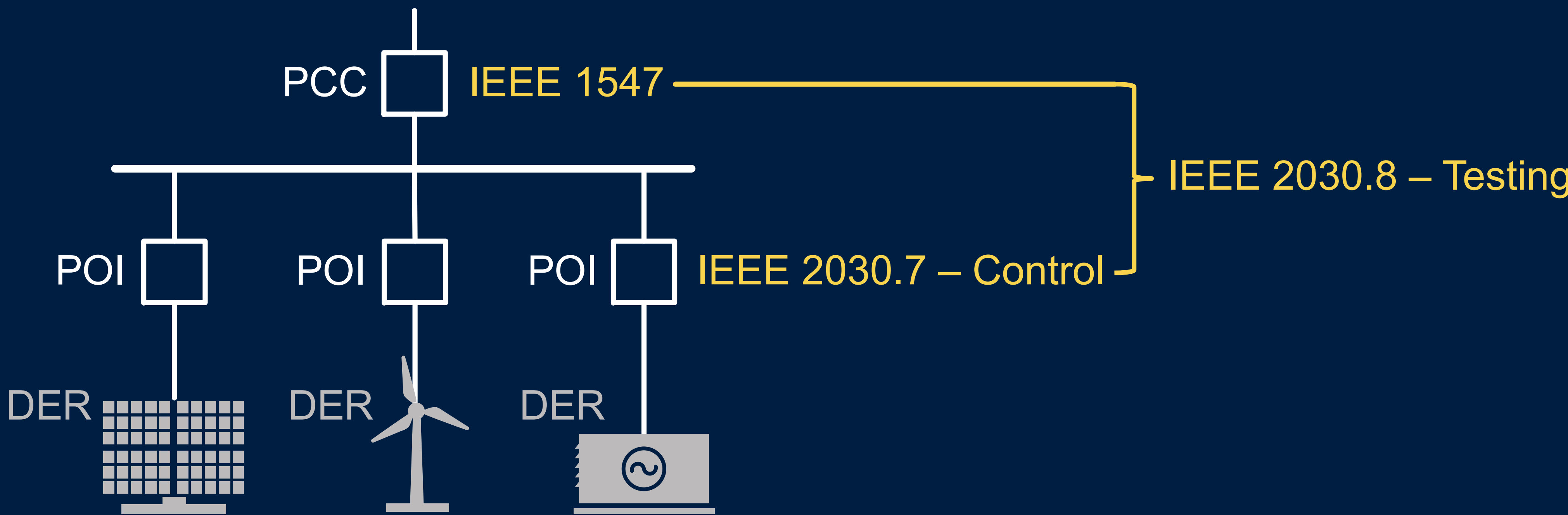


Use Relays for Small Grids; Use Relays and Controllers for Larger Grids



Distributed Energy Resource (DER) is a catch-all name for traditional and intermittent sources



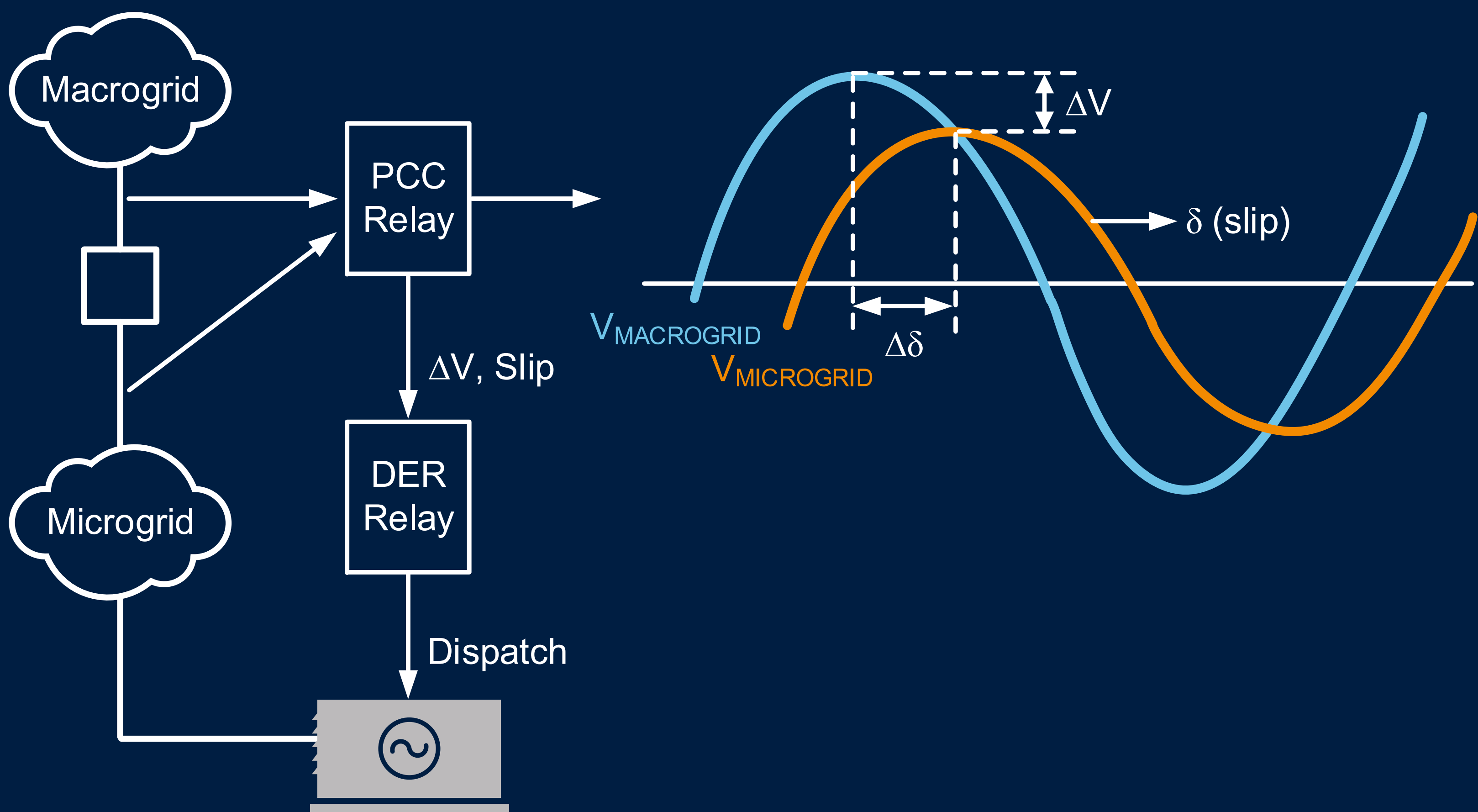


IEEE 2030.8-2018 Requires Three Types of Mandatory Data Collection Which are in SEL relays!

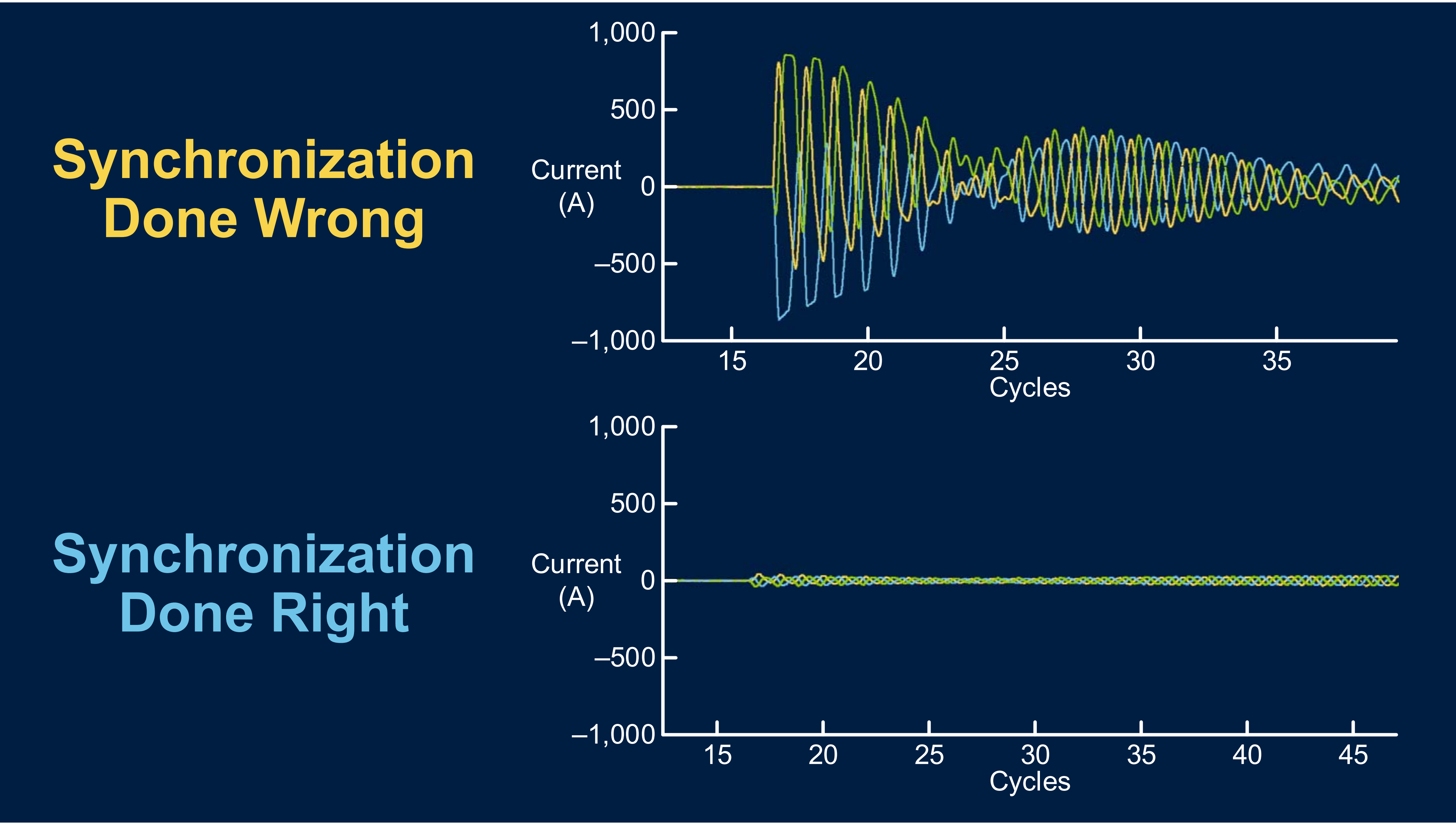
Requirement
Sequence of Events (SOE)
Event oscillography
Continuous data collection

Reconnection

PCC Reconnection Is a Relay Function



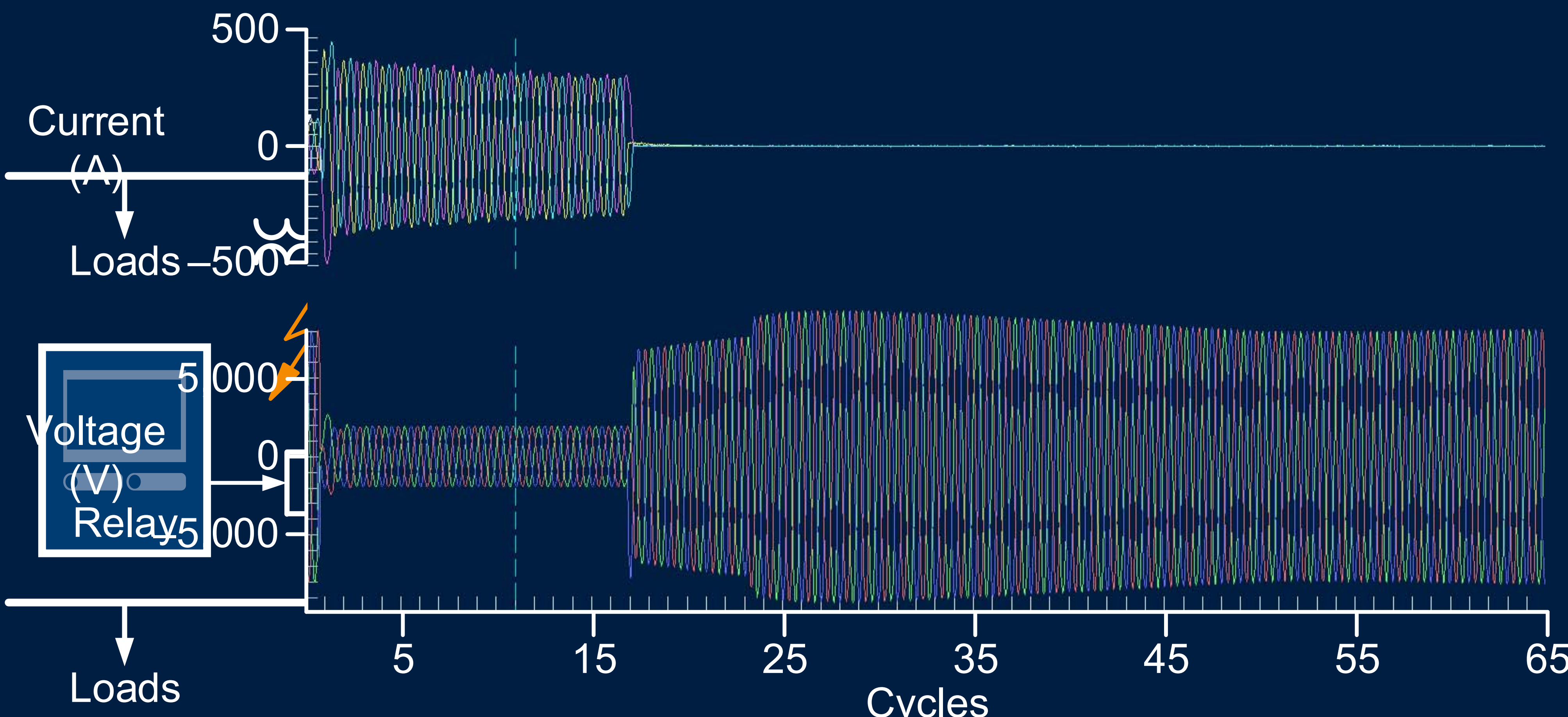

1 240mV/ 2 880mV/ 3 600mV/ 4 600mV/
0.0s
DC
DC
DC
DC
DC R
Avg
Freq
Freq
Trigger Menu
Trigger Type
Edge
Source



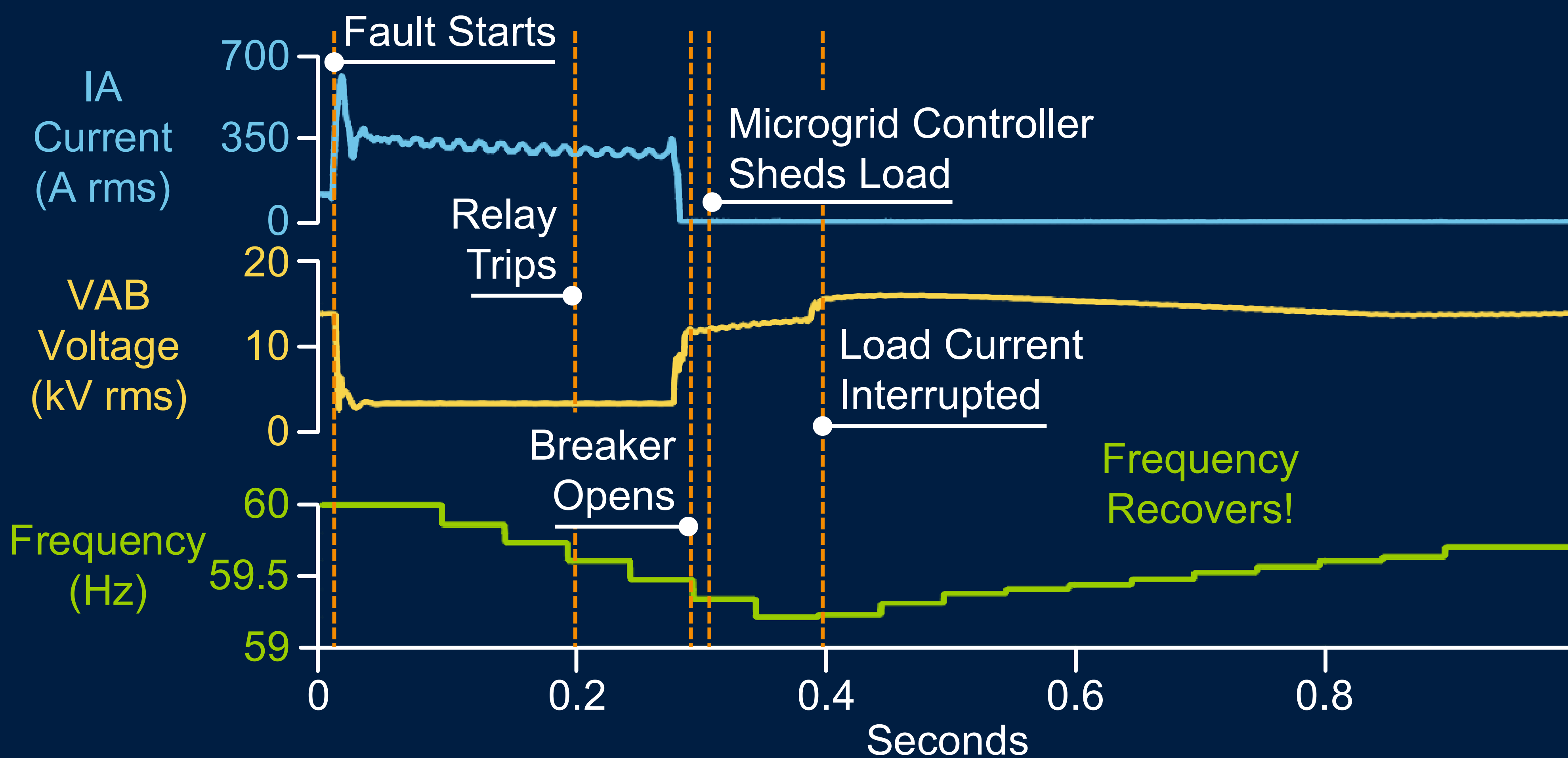
Synchronization
Done Wrong
Current
(A)
1,000
500
0
–500
–1,000
15
20
25
30
35
Cycles
Synchronization
Done Right
Current
(A)
1,000
500
0
–500
–1,000
15
20
25
30
35
40
45
Cycles


Seamless Islanding

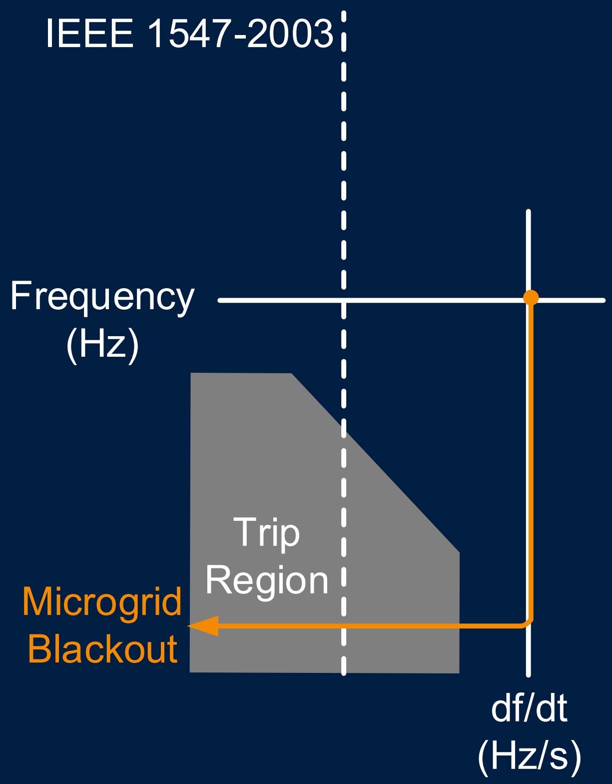
PCC Disconnection Is Protective Relay Function

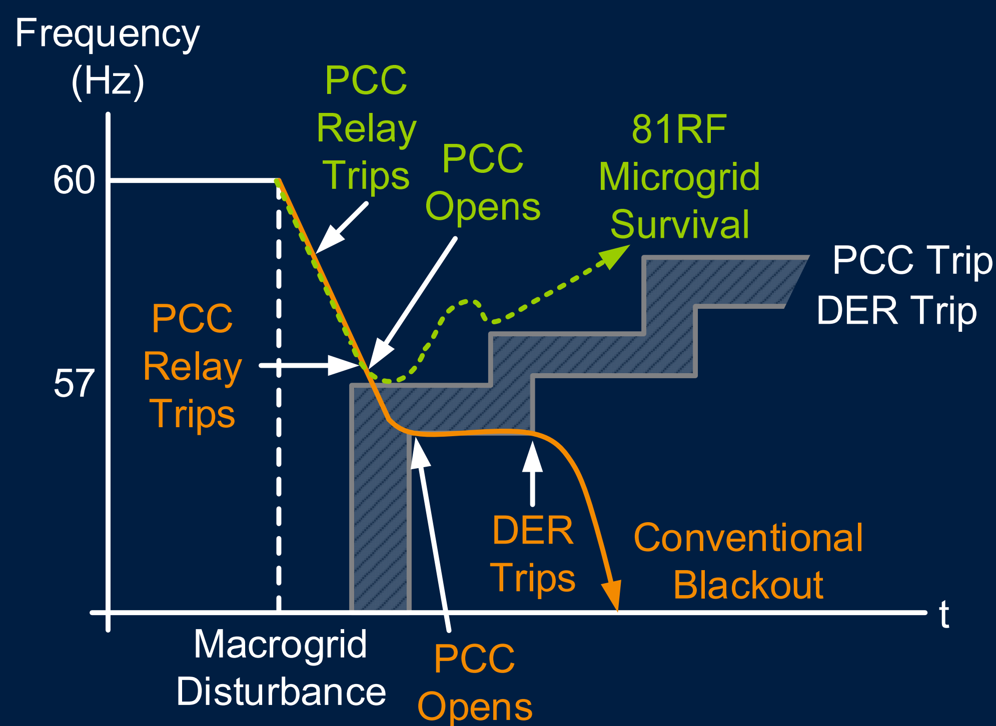


PCC Disconnection Is Protective Relay Function



Fast 81RF Element Improves Seamless Islanding





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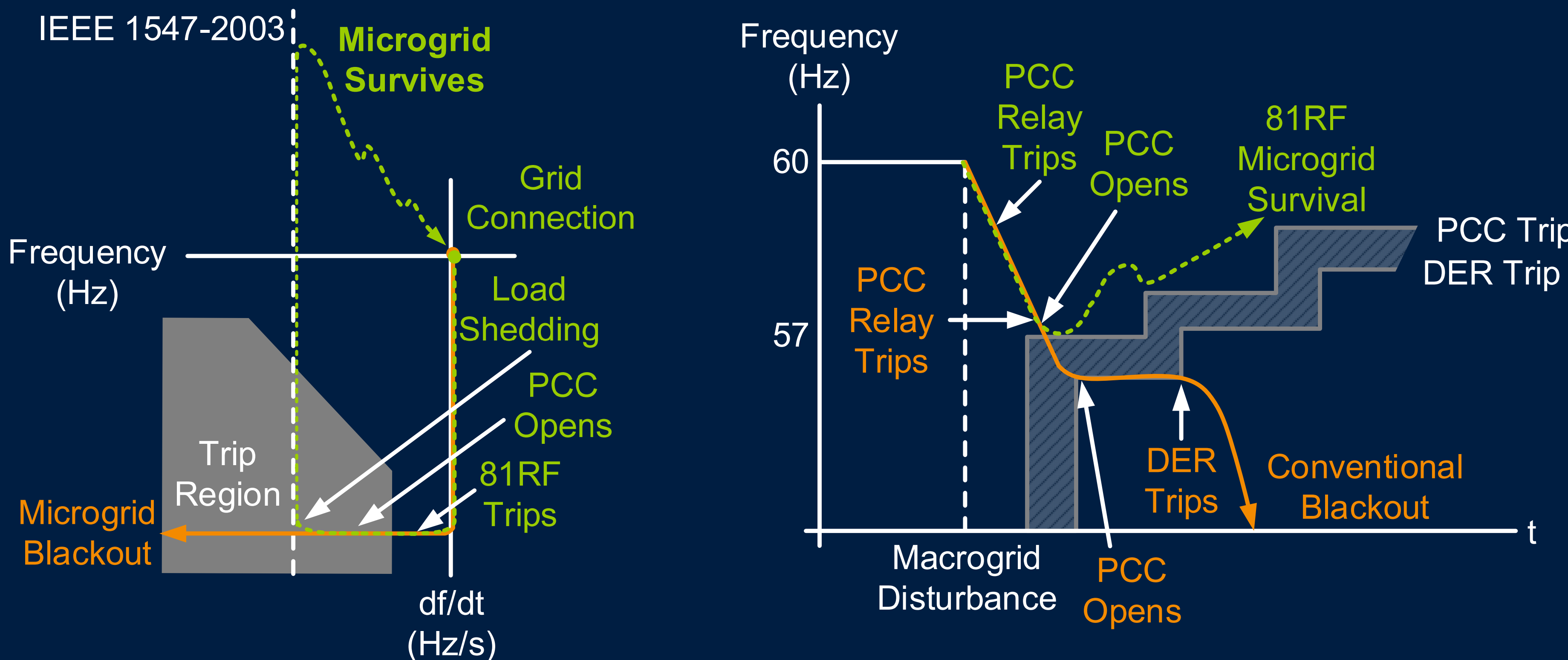
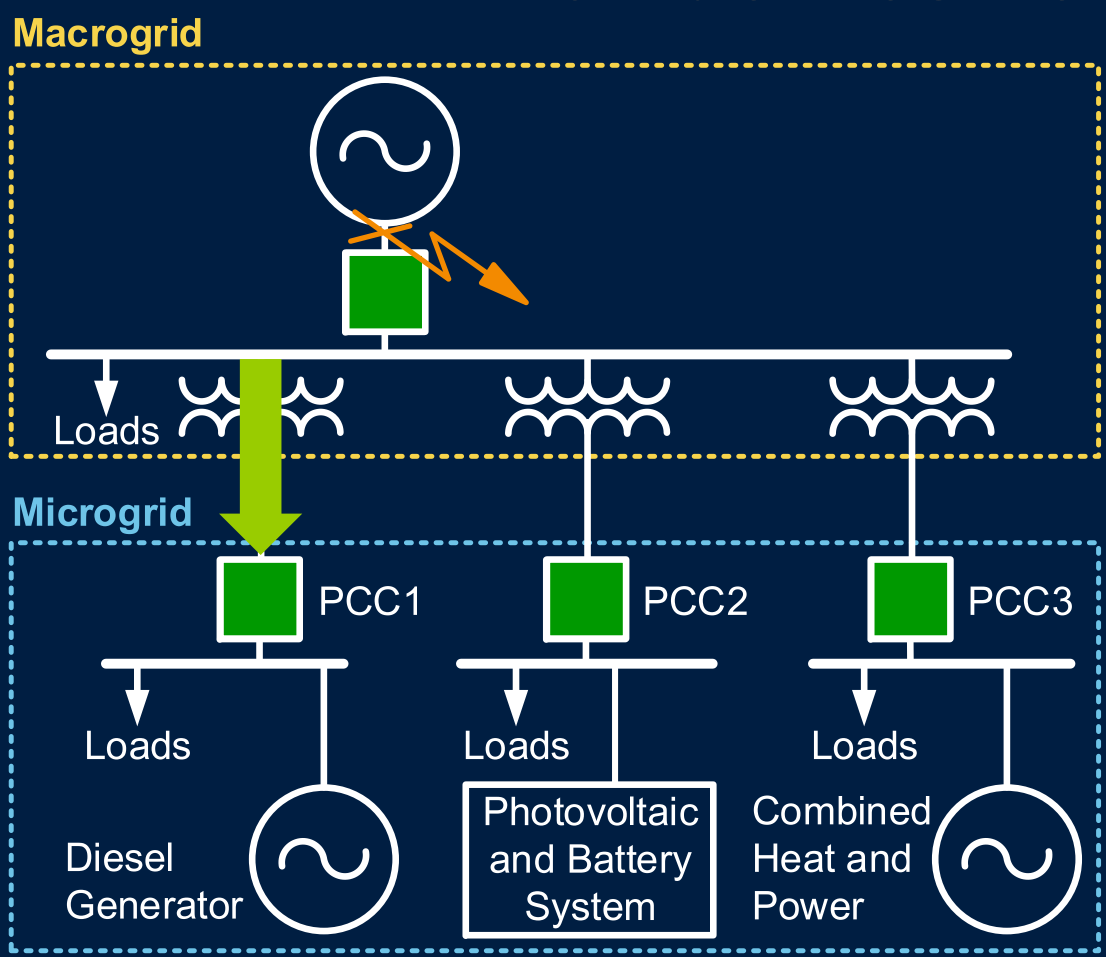
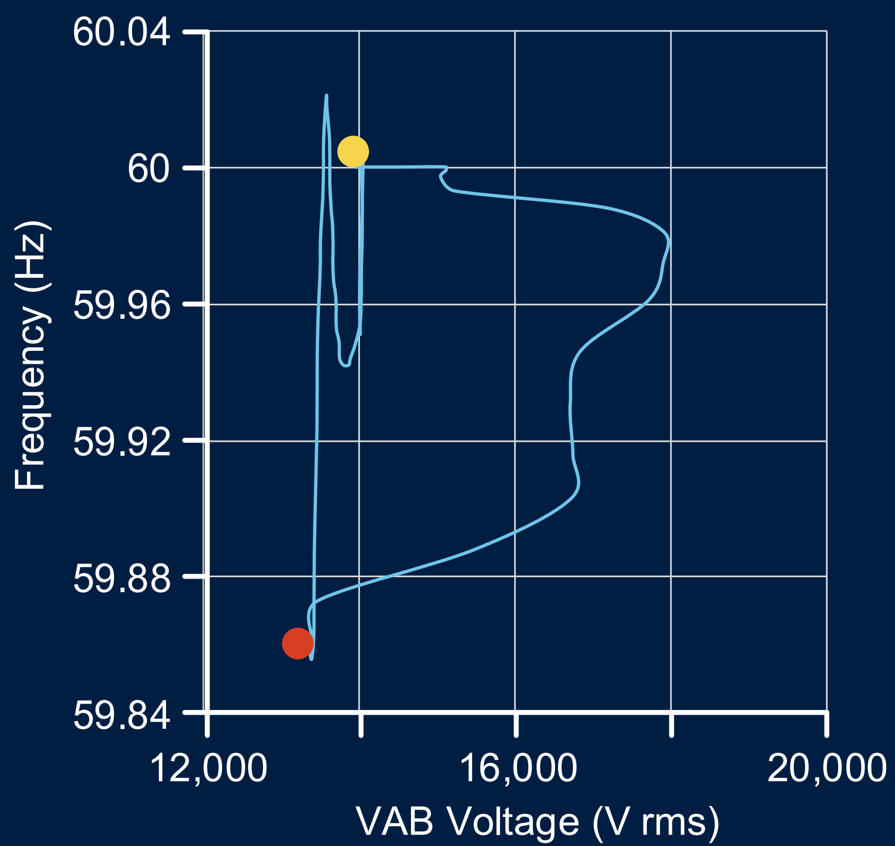
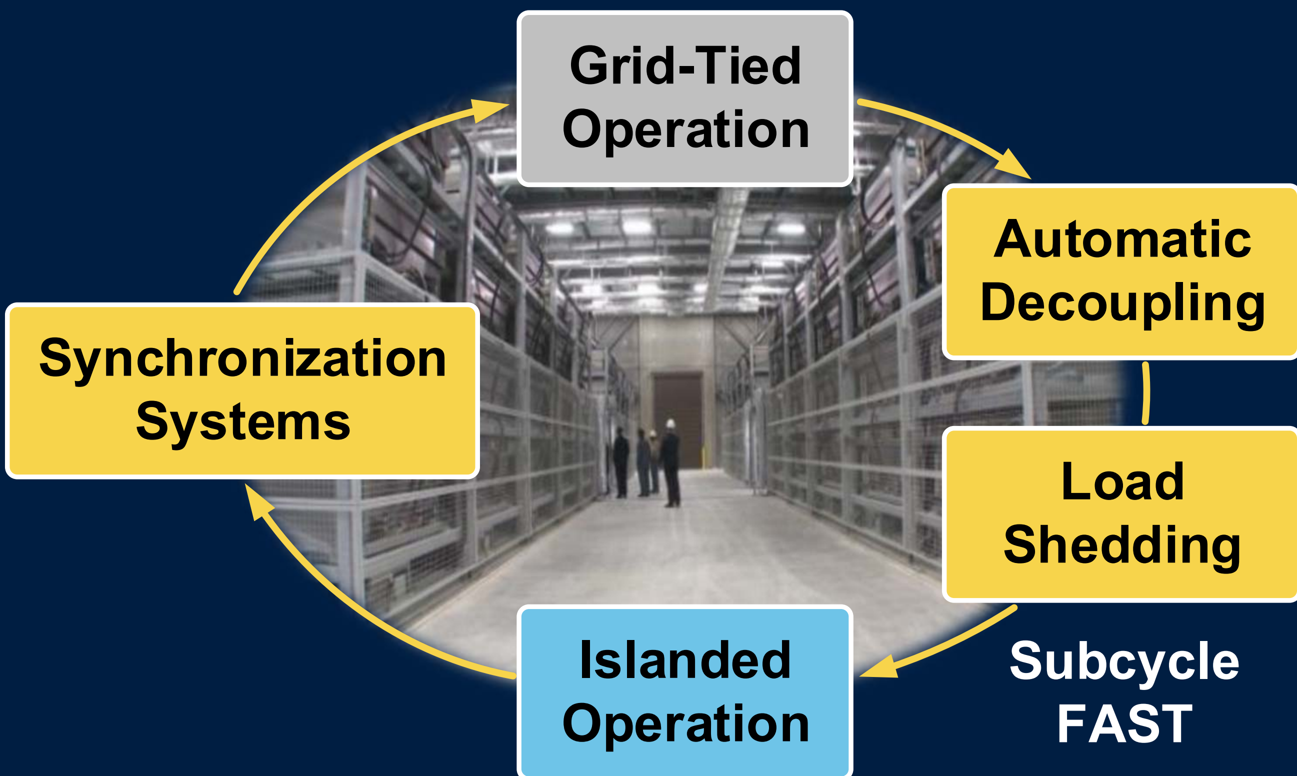


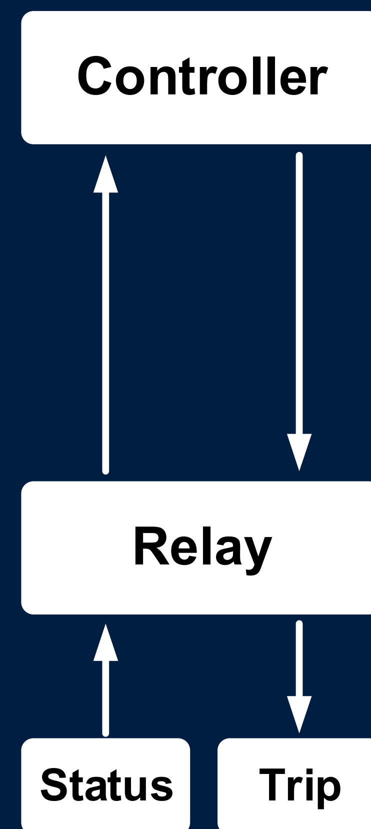
Integrated Relays and Controllers Provide Resilient Behavior



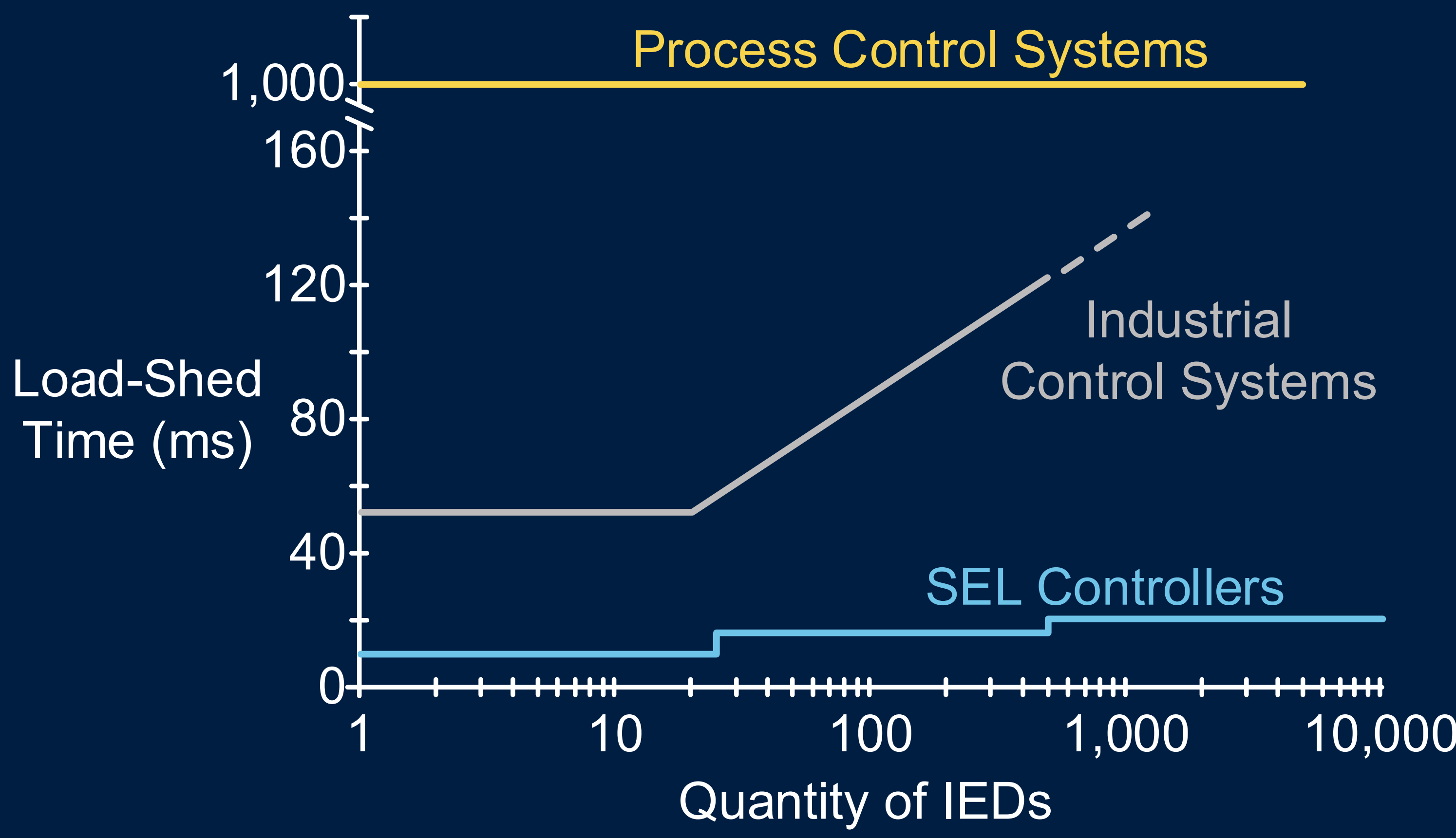


Seamless Islanding Requires Fast Load Shedding

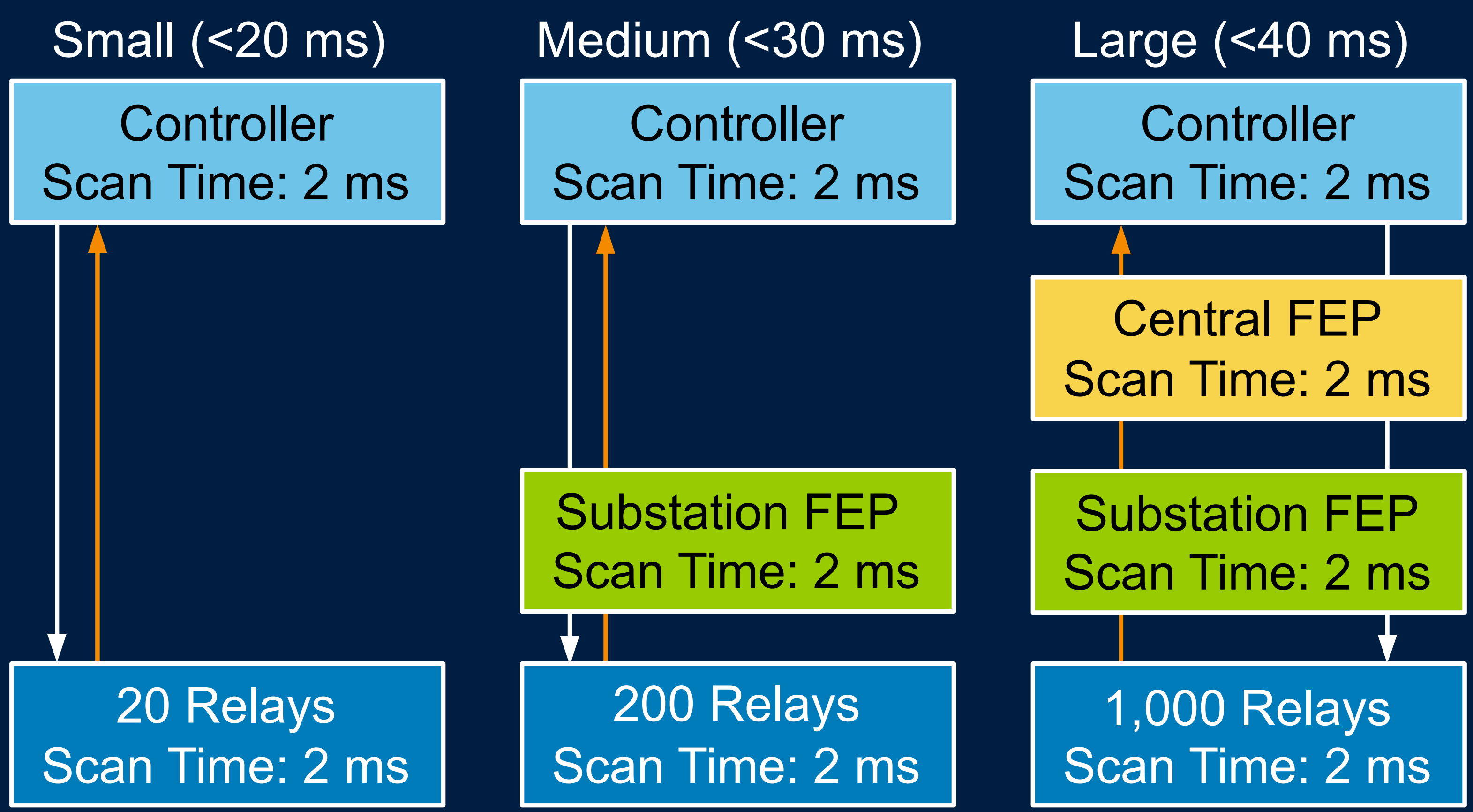




Make Sure Your Controller Is up to the Task



Fast and Scalable Architectures Are Required



Contingency Load-Shedding Calculation

$$L_n = P_n - \sum_{g=1}^{m} IRM_{ng}$$

where:

n = contingency (event) number

m = number of generators in system

g = generator number, 1 through m

L_n = amount of load selected for n event (kW)

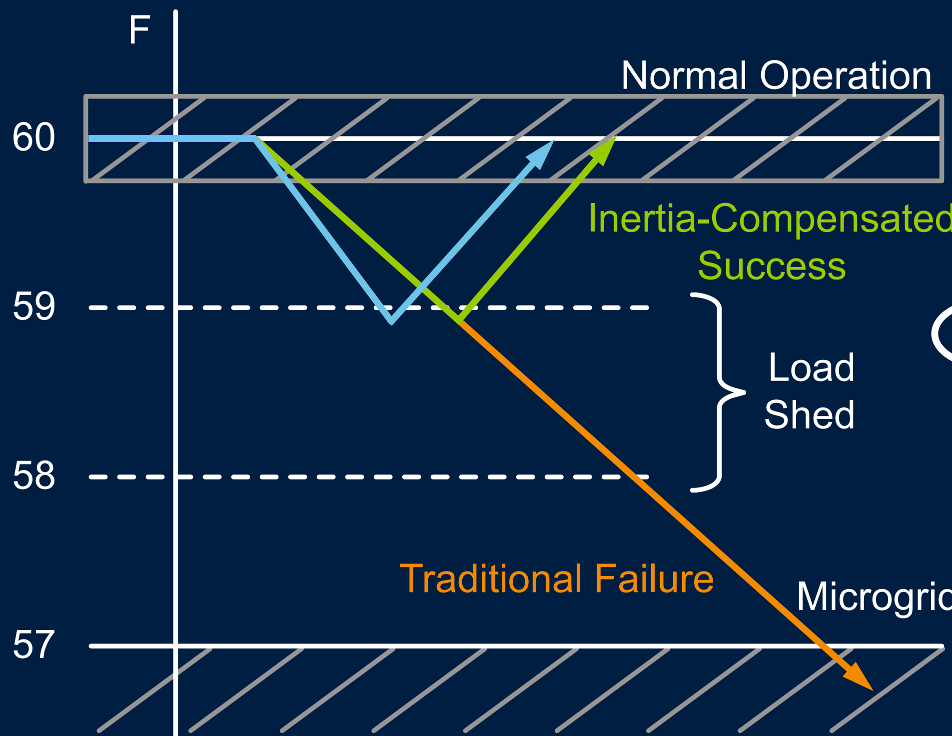
P_n = power disparity caused by n event (kW)

IRM_{ng} = incremental reserve margin of all remaining generators after n events (kW)

Inertial Based Load-Shedding Systems Operate when a Contingency Load Shedding System is out of service

- Broken wires
- DC battery failures
- Breaker contact failures
- Governor problems
- Fuel or air problems
- Improper maintenance
- Incomplete commissioning

Inertia and Load Composition Compensated Load Shedding Systems stop Blackouts

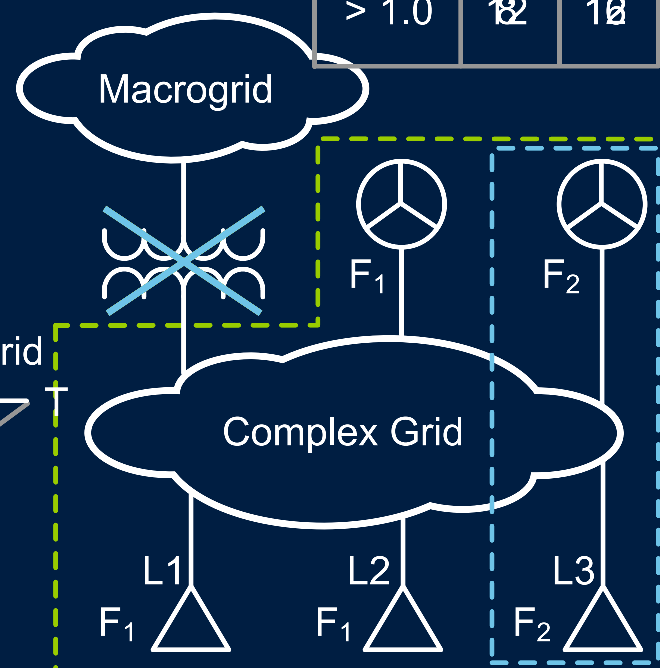


Load Shed ~ H • DFDT = 8 • 1 = 8 MW

Load Shed ~ H • DFDT = 4 • 2 = 8 MW

MW Load to Shed

DFDT \ F	59	58
< 0.5	2/4	4/8
0.5 to 1.0	4/8	8/12
> 1.0	8/12	12/16



Fast Load Shedding Makes Seamless Islanding Possible

Fastest

Contingency based

Inertial compensated

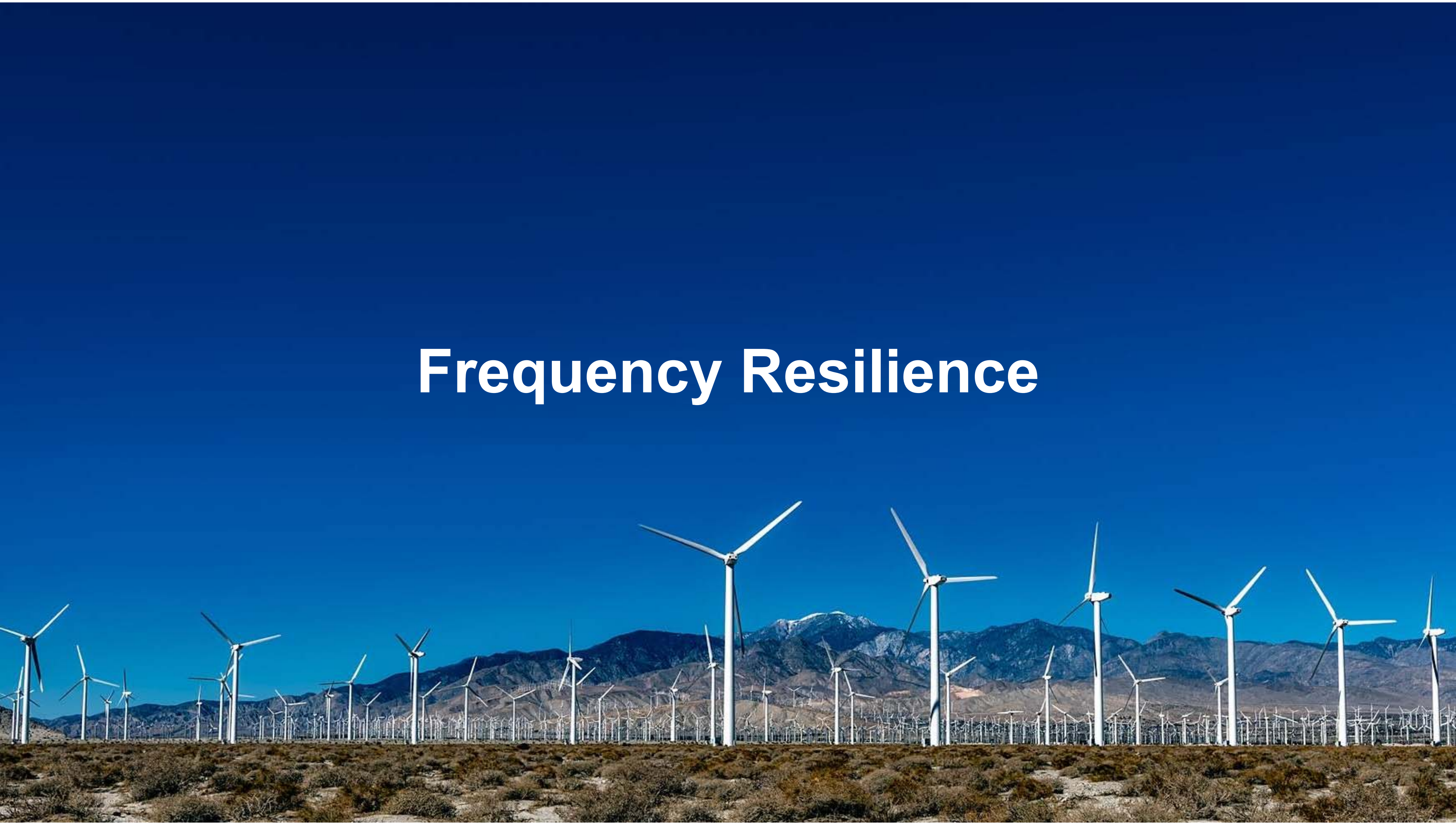
Frequency based

Overload

Manual

Slowest

Frequency Resilience

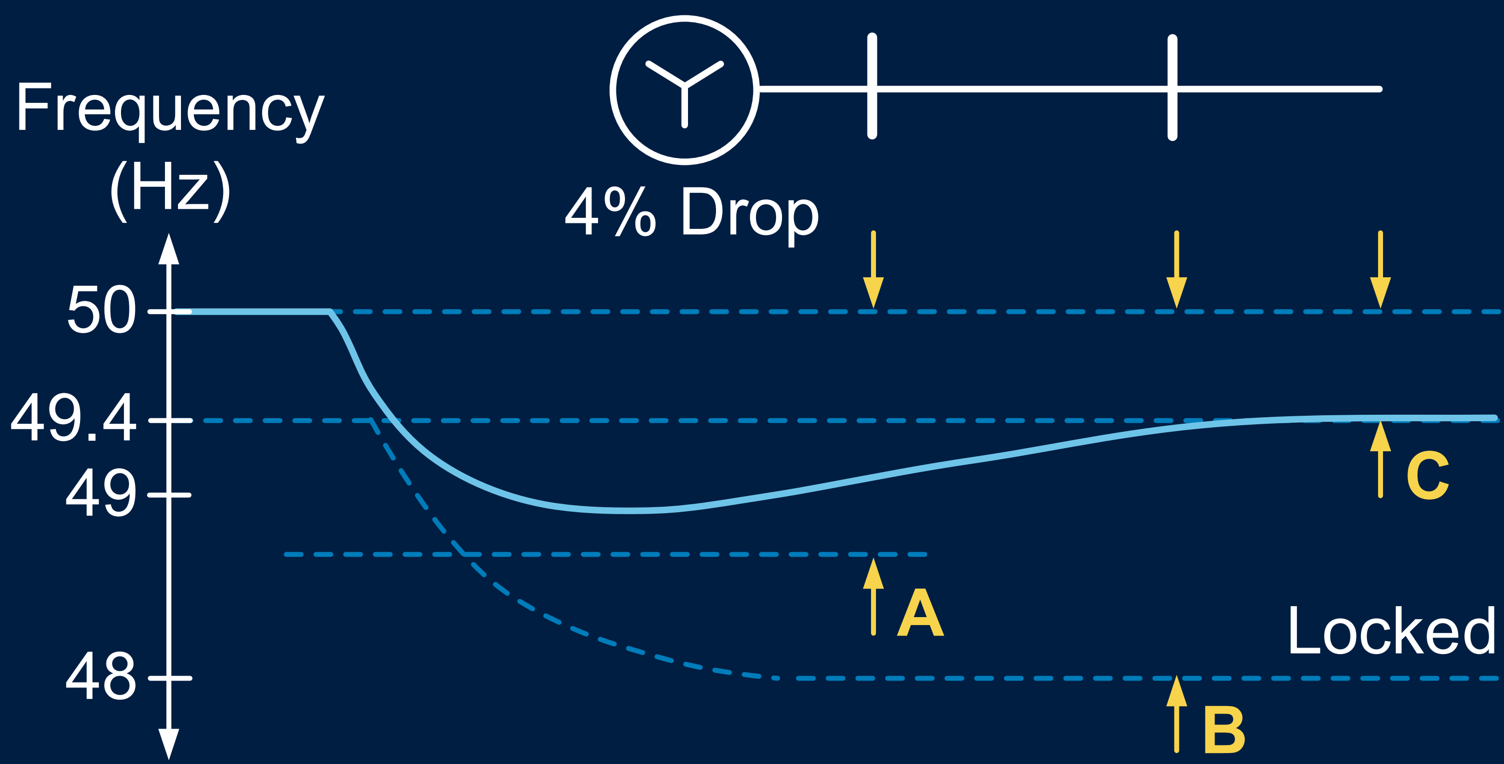


What Affects Power System Resilience?

- Frequency response characteristic (FRC)
- Major disturbances
- Inverter misoperation
- Voltage and MVAR margins
- Frequency and MW margins
- Economics

FRC Example – Large Offshore Natural Gas Liquefaction Plant

Sudden 0.3 pu Load Increase



Three Common FRC Variants

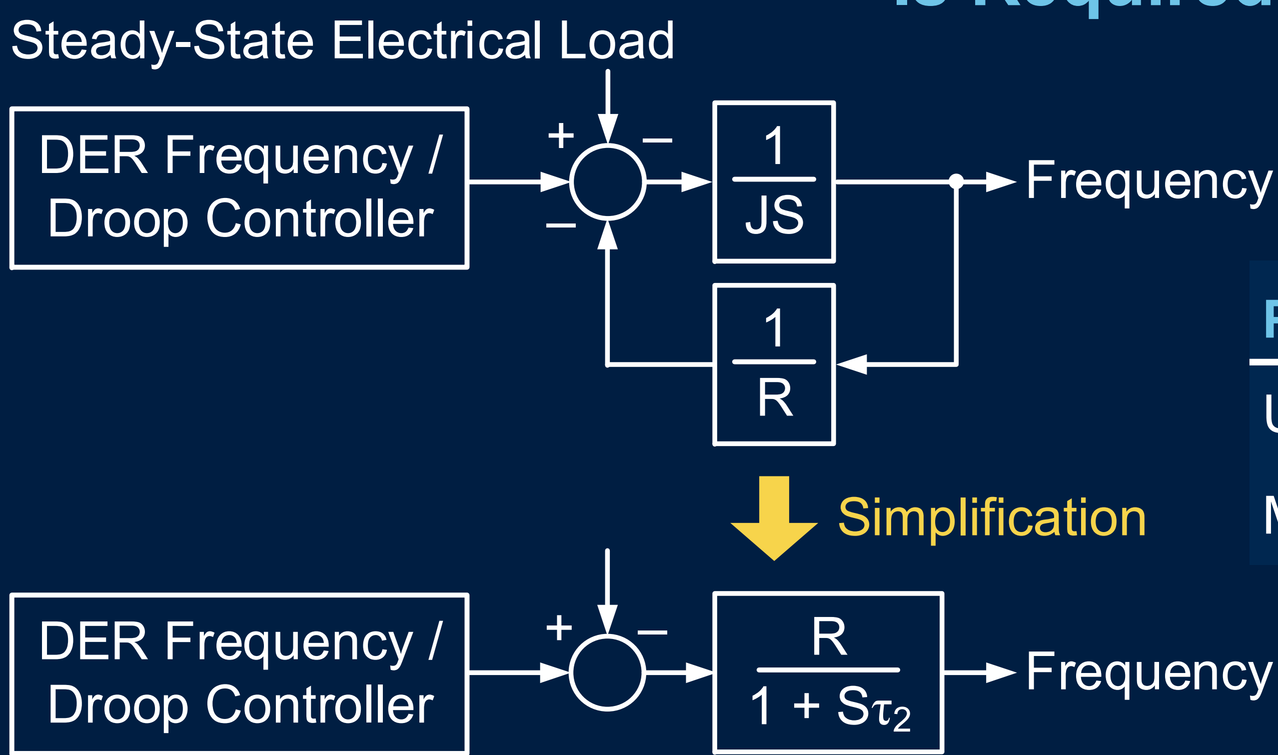
Location	FRC Type	Calculation	FRC
Point A	Transient	50 • 0.3 / (50 – 48.7)	**11.5**
Point B	Locked rotor (extraction mode)	50 • 0.3 / (50 – 48)	**7.5**
Point C	System long-term (system droop characteristic)	50 • 0.3 / (50 – 49.4)	**25**

Solutions for Poor FRC

- Use better engine and voltage controls
- Add inertia
- Add motor loads with windage
- Limit electronic loads with variable speed drive (VSD)
- Use batteries
- Include load shedding or curtailment
- Include generation shedding or runback

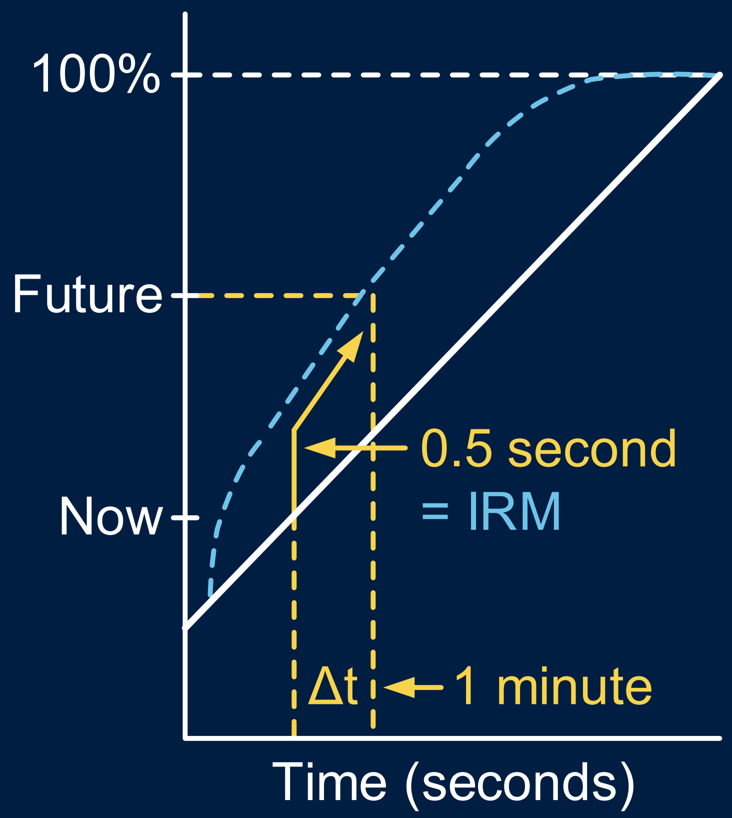
Step 1 – Identify Grid Time Constants

How Much Responsive Generation Is Required to Ensure Stability?



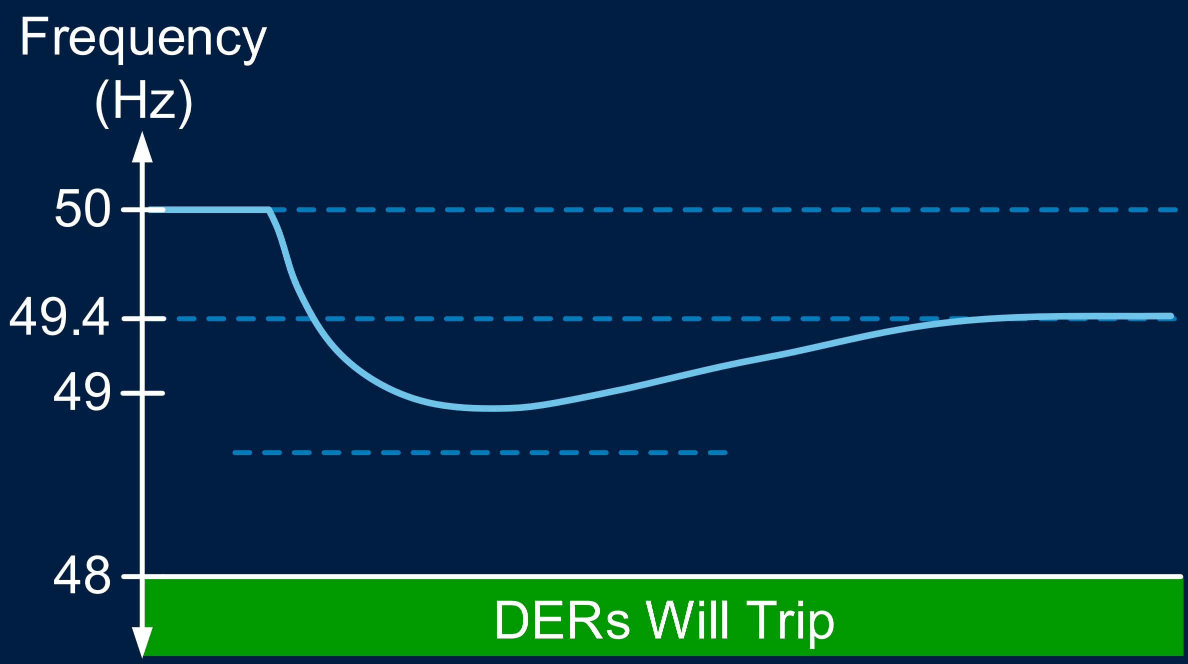
Power System	τ_2 (seconds)
Utility	0.5–1.2
Microgrid	0.25–2.5

Step 2 – Tabulate Incremental Reserve Margin (IRM)



DER	Rating (kW)	IRM (%)	IRM (kW)
Photovoltaic	200	0	0
Battery (slow)	1,000	5	50
Battery (fast)	1,000	100	1,000
Steam extraction turbine	1,200	0	0
Combined heat and power	900	10	90
Gas turbine	1,500	40	600
Diesel generator set	1,000	40	400
Totals	6,800	31.5	2,140

Step 3 – Compare Total IRM to Largest Disturbance



Event	kW
Small motor	200
Load commutated inverter drive	2,000
Large feeder	5,000
Small feeder	800
Available IRM	2,140

Visualization

Time-Synchronized Condition Monitoring

Load Selection Screens Teach Operators to Dispatch Grid Differently

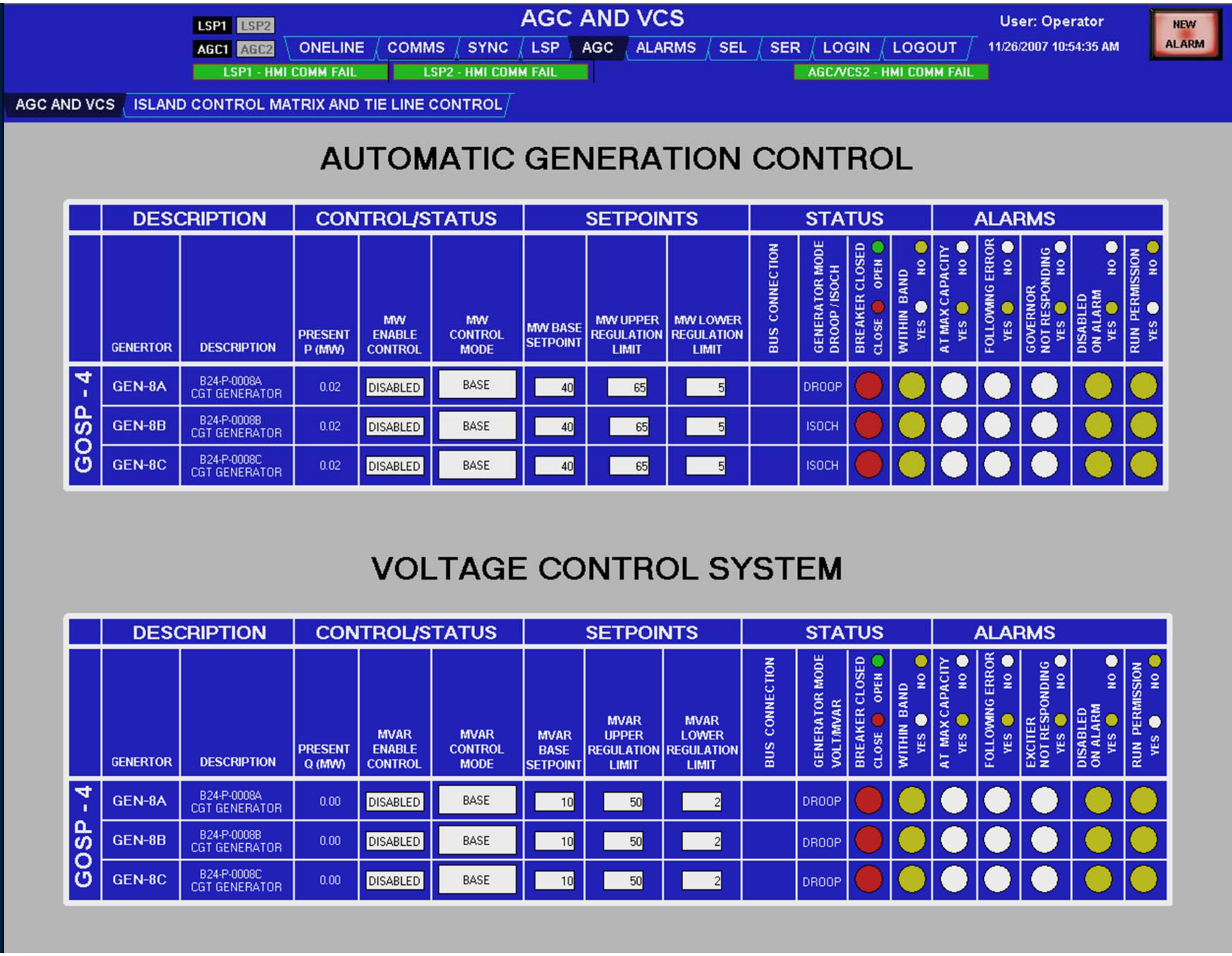
Contingency	#	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
NGL BC B721	1	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
NGL BC B723	2	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
NGL BC B722	3	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
NGL BC B720	4	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
GOSP-4 BC B712	5	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
GOSP-4 BC B714	6	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
GOSP-4 BC B713	7	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
GOSP-4 BC B711	8	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
GOSP-4 BC B612	9	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
GOSP-2 BC B505	10	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
NGL/G4 Tie A	11	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
NGL/G4 Tie B	12	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
GOSP-4 Intertie A	13	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
GOSP-4 Intertie B	14	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
GOSP-4 GOSP-2 Tie	15	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
NGL/GOSP-3 Tie A	16	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
NGL/GOSP-3 Tie B	17	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
GOSP-3 BC B701	18	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
GOSP-3 BC B702	19	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
GOSP-3 BC B703	20	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18

Simplified Graphics for Small Microgrids

GEN	STATUS	CONTROL ENABLE	RATING kVA	kW	kVAR	START/ STOP TIMER (Sec)	EFFICIENCY (kWH/Gal)	FUEL REMAIN-ING (HRS)	FUEL REMAIN-ING (Gal)	WET STACKING ALARM	WET STACKING CONTROL STATUS
Gil1	On		30	0	0	30	0.33	999	36.0		Disabled
Gil2	On		30	0	0	30	0.33	999	38.4		Disabled
Tay1	On		30	0	0	30	0.33	999	67.0		Disabled
Tay2	On		30	0	0	30	0.33	999	73.5		Disabled
TQG1	On		60	0	0	30	0.33	999	43.0		Disabled
TQG2	On		60	0	0	30	0.33	999	41.3		Disabled
CAT1	On		100	0	0	30	0.33	999	101.4		Disabled
CAT2	On		100	0	0	30	0.33	999	112.2		Disabled

TOTAL kW	0.0 kW
TOTAL kVAR	0.0 kVAR
% P	0.0 %

DER Dispatch Control Screens



PRIMARY LOAD SHED | SECONDARY LOAD SHED | LOAD SHED RESET | TEST COMMANDS

PRIMARY LOAD SHED CONTINGENCIES

OK	1 -	L1 TRIP
OK	2 -	G1 20kV TRIP
OK	3 -	G1 10kV TRIP
OK	4 -	G2 TRIP
OK	5 -	L2 TRIP
OK	6 -	G3 20kV TRIP
OK	7 -	G3 10kV TRIP
OK	8 -	G4 20kV TRIP
OK	9 -	G4 10kV TRIP
OK	10 -	TIE TRIP/BUS A
OK	11 -	TIE TRIP/BUS B

SECONDARY LOAD SHED CONTINGENCIES

OK	15 -	UNDER FREQ 1 BUS A
OK	16 -	UNDER FREQ 2 BUS A
OK	17 -	UNDER FREQ 1 BUS B
OK	18 -	UNDER FREQ 2 BUS B

LSP1 CODE RUNNING:	339917

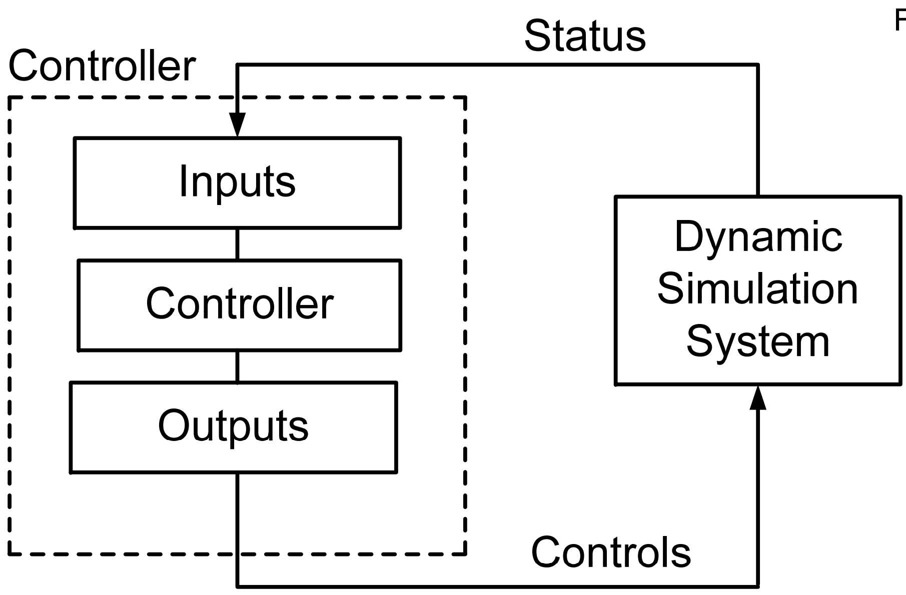
CONTINGENCY:	1
AVAILABLE CAPACITY (MW):	104.00
MEASURED LOAD (MW):	108.00
REQUIRED TO SHED (MW):	4.00
SELECTED TO SHED (MW):	4.14
20 KV BUS:	A B
ENABLED:	YES
TRIGGER SIGNALS AVAILABLE:	YES
SATISFIED:	YES

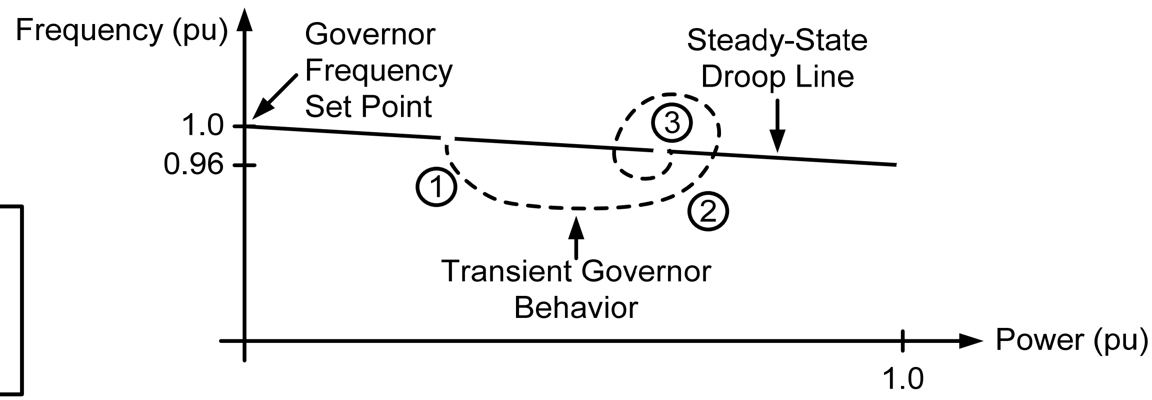
UNDER FREQUENCY LOAD SHED (MW)	
MW TO SHED AT LEVEL 1:	2.00
MW TO SHED AT LEVEL 2:	2.00

Simplified Load-Shedding Configuration

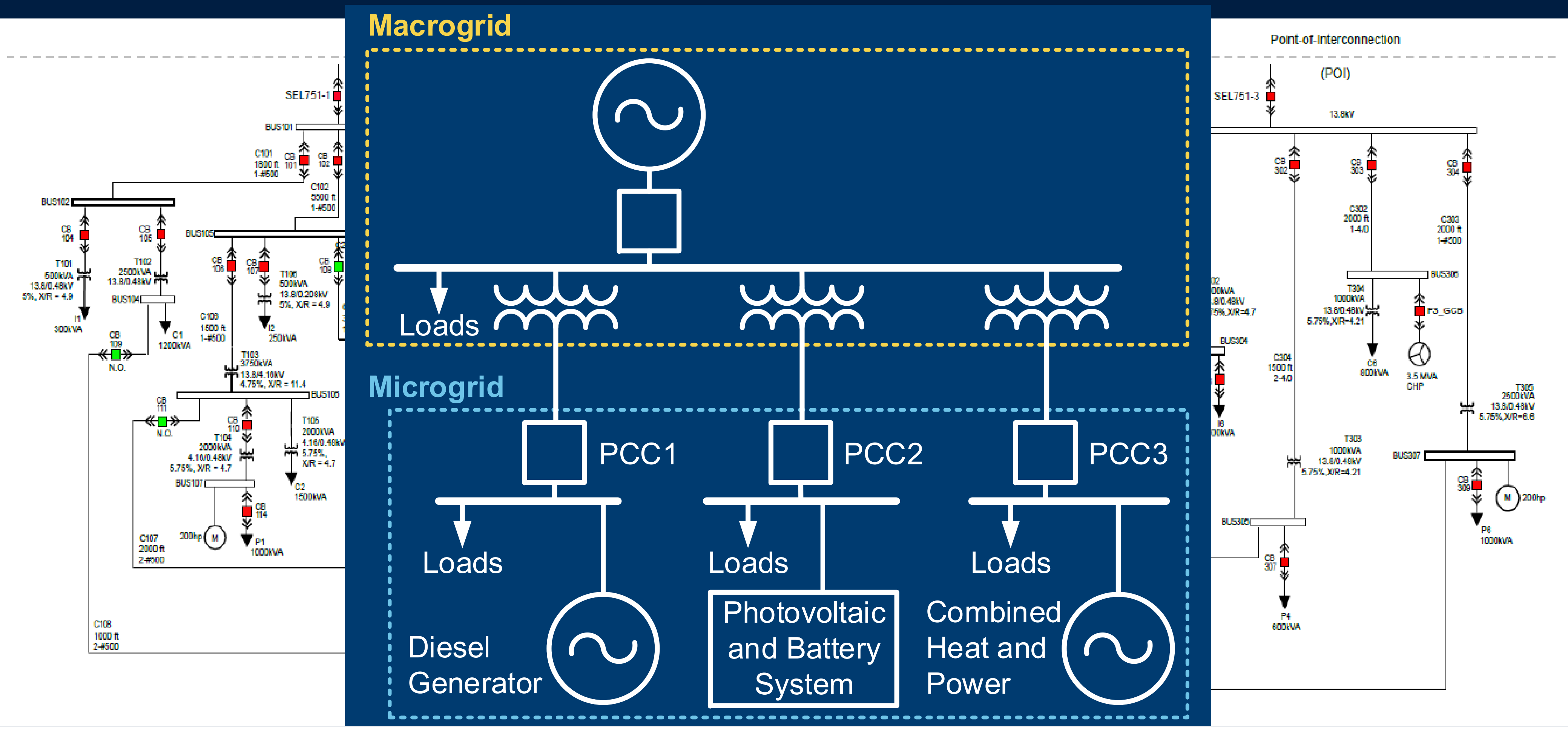
Modeling

cHIL Modelling Mandatory for big PowerMAX jobs

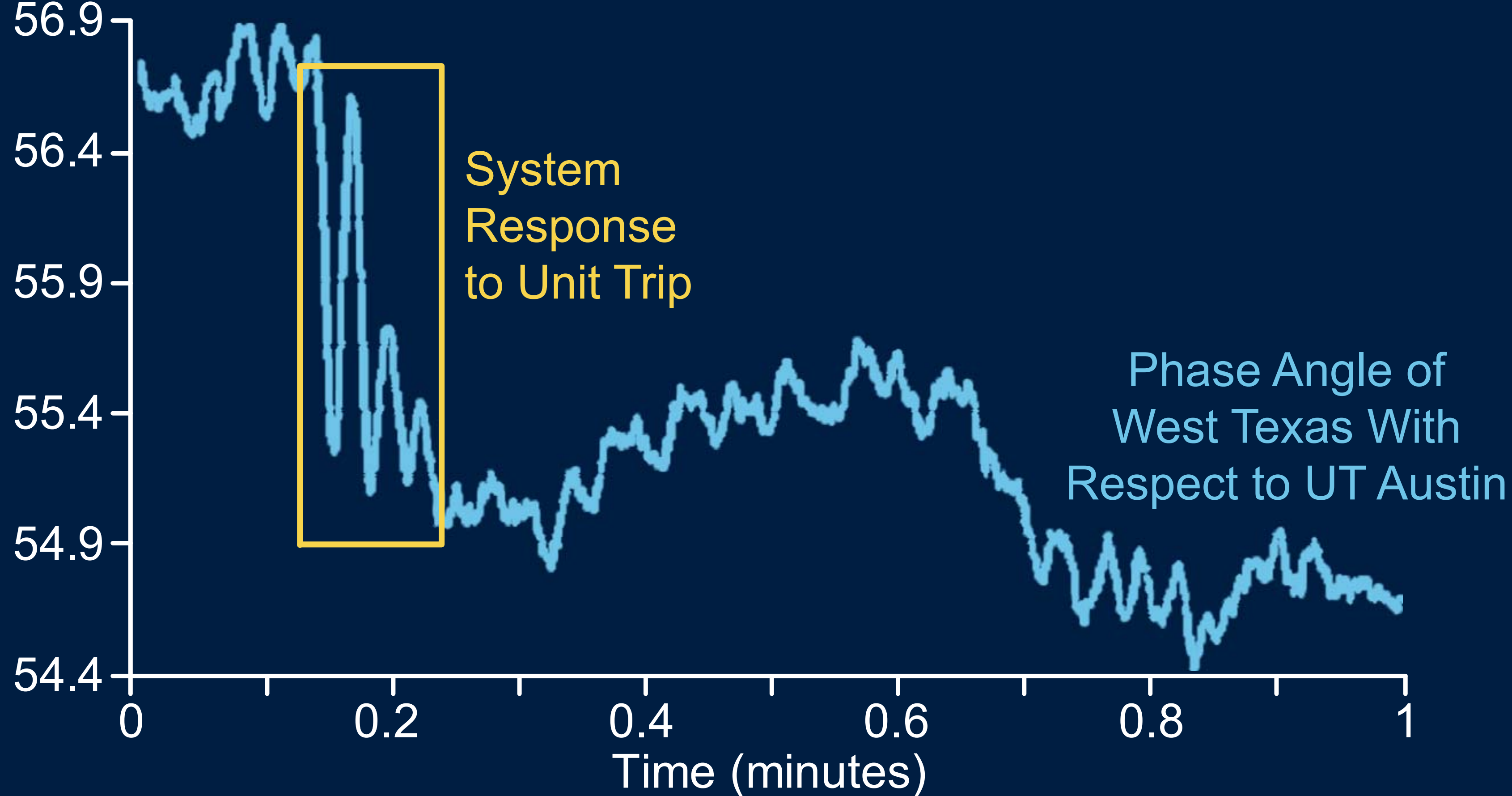




Hardware-in-the-Loop (HIL) Testing Controls Quality

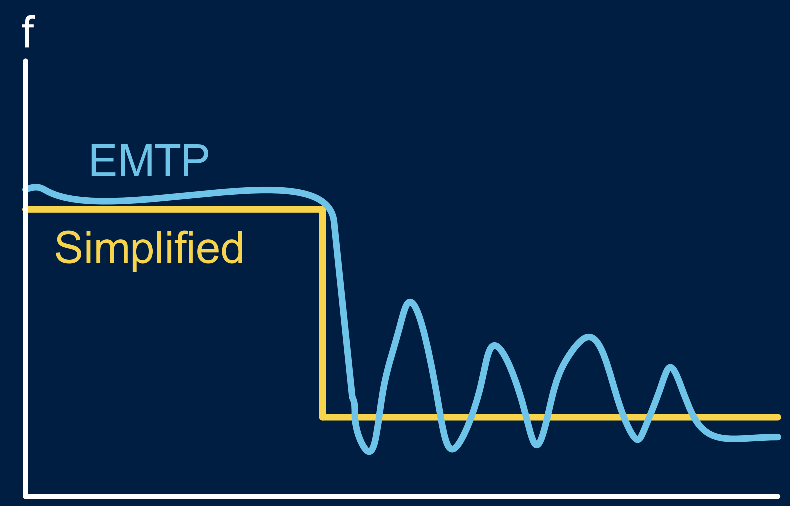


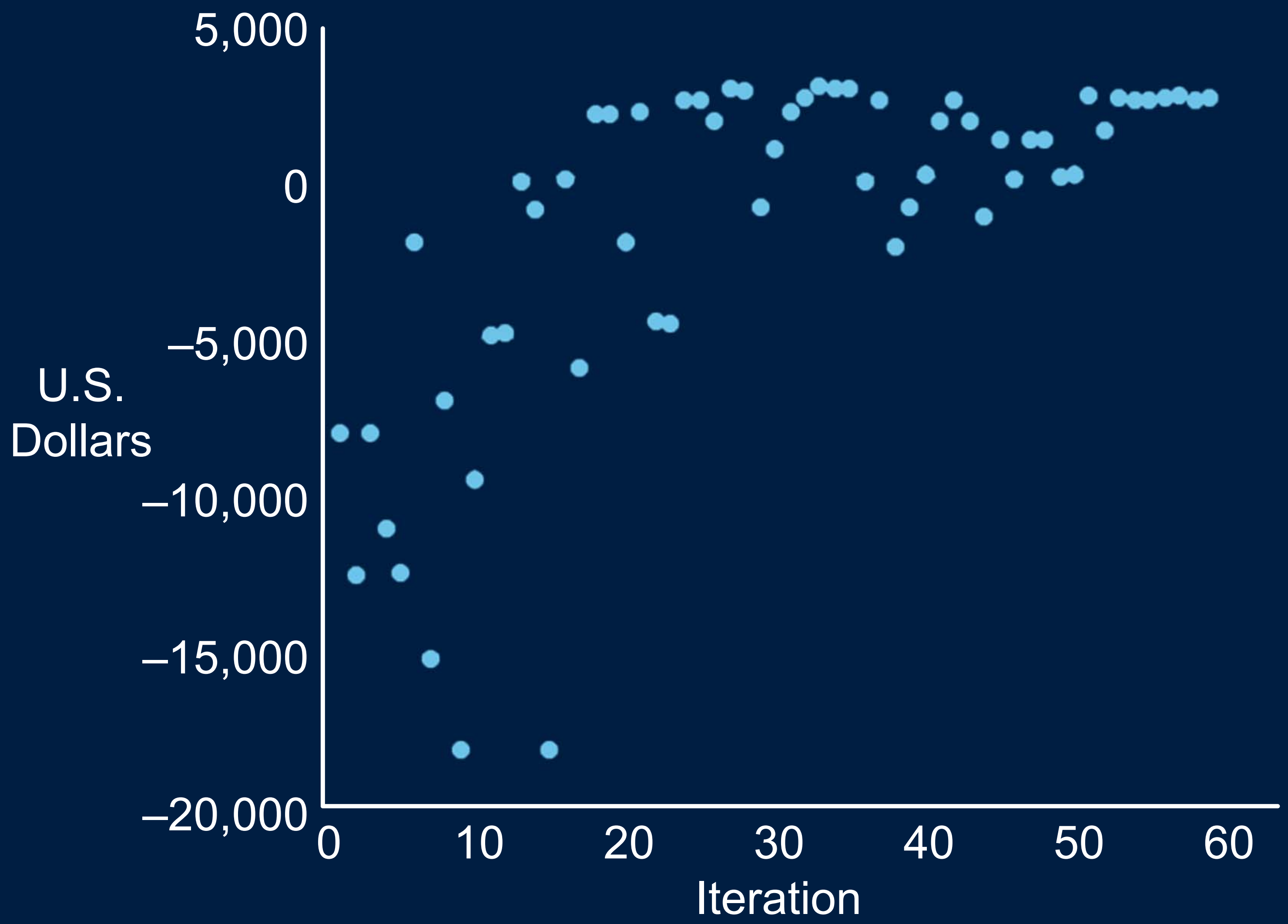
Capturing Live System Dynamics Enables Engineers to Build Accurate Models



Not All Simulation Software Is Appropriate for Testing Microgrid Control and Protection

Function	Simplified	EMTP (Not Real Time)	EMTP (Real Time) cHIL
Relay coordination	✓		
Rotor angle stability		✓	✓
Frequency stability		✓	✓
Voltage collapse		✓	✓
Power flow	✓	✓	✓
IRM / DRM and UF / OF coordination		✓	✓
Voltage collapse		✓	✓
Motor starting	✓	✓	✓
FAT simulation			✓
Operator training			✓

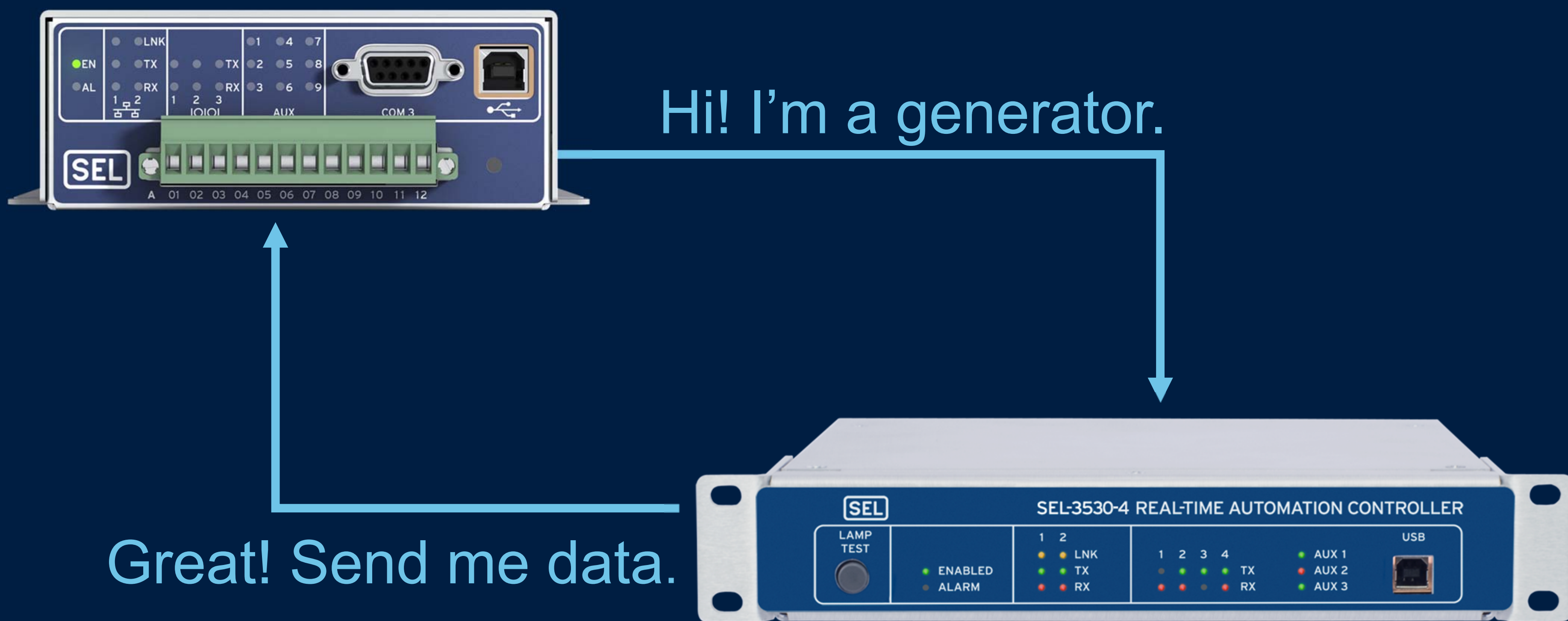




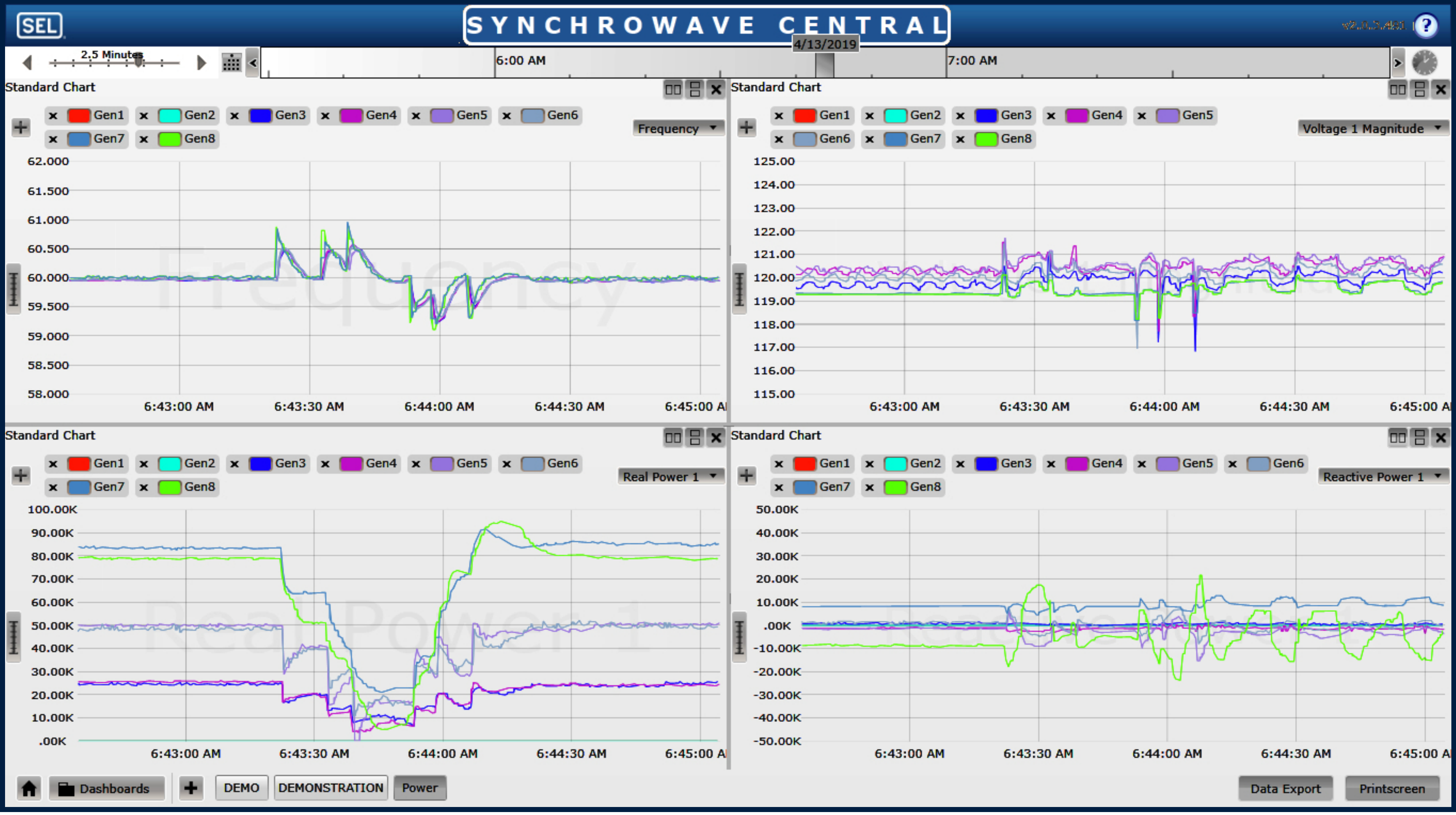
Testing Improves Quality

What Is Next?

“Self Driving” Power System
Publish - Subscribe Communications



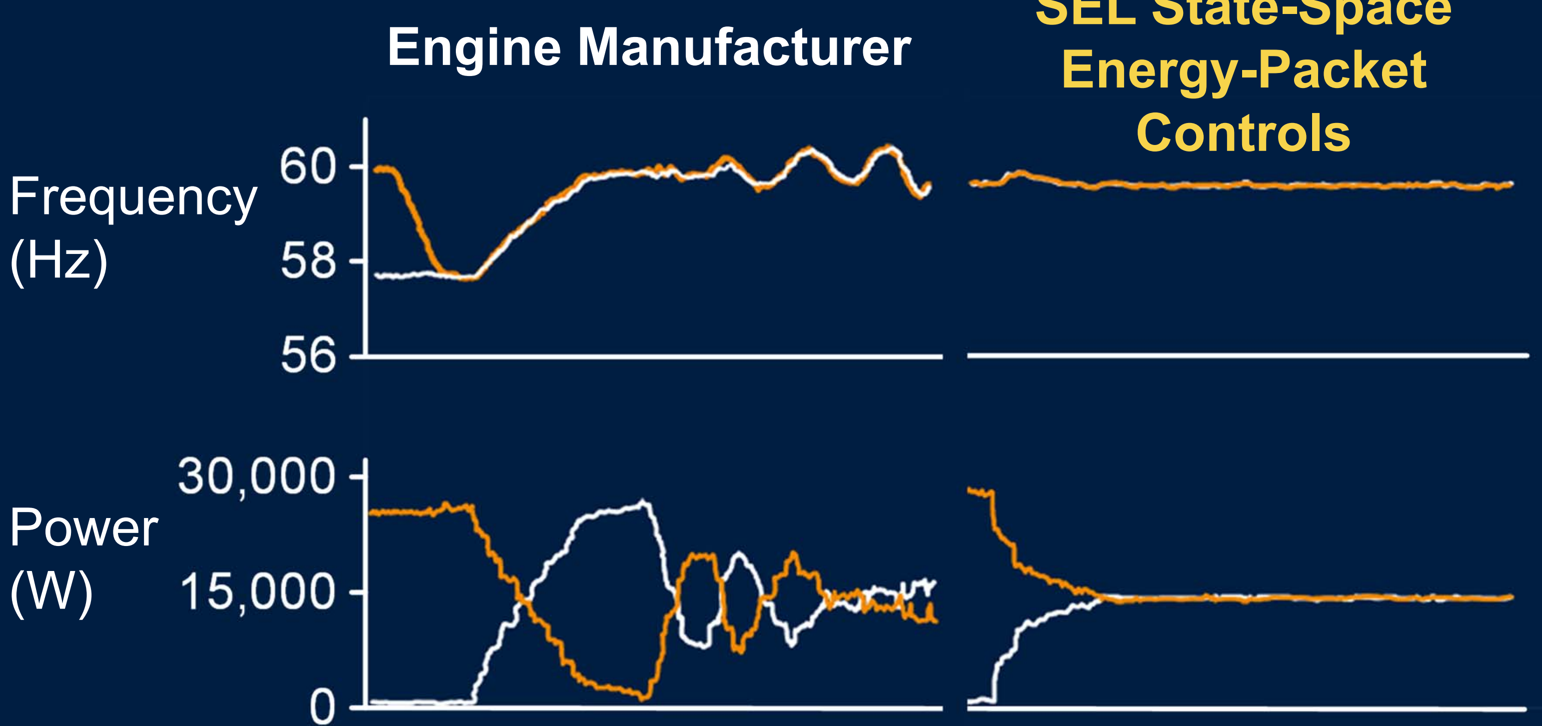
Complete Interopability Between Generators of Different sizes & Manufacturers



Interoperable
Making All DERs Play Nicely Together

Resilience Mode

Superior Load Sharing and Frequency Control Performance



No overshoot

No integral windup

No oscillations

No tuning

Fully interoperable

Conclusions

- Design for resilience
- Use relays for simple microgrid systems
- Use relays + centralized controllers for complex microgrid systems
- Test all controls and protection systems with cHIL
- Use OT SDN for networking and security


Questions?