

WHY ARE WE HERE? MISOPERATION UPDATE

2026 Protection Workshop

August 2026

Thomas Teafatiller, Principal Engineer

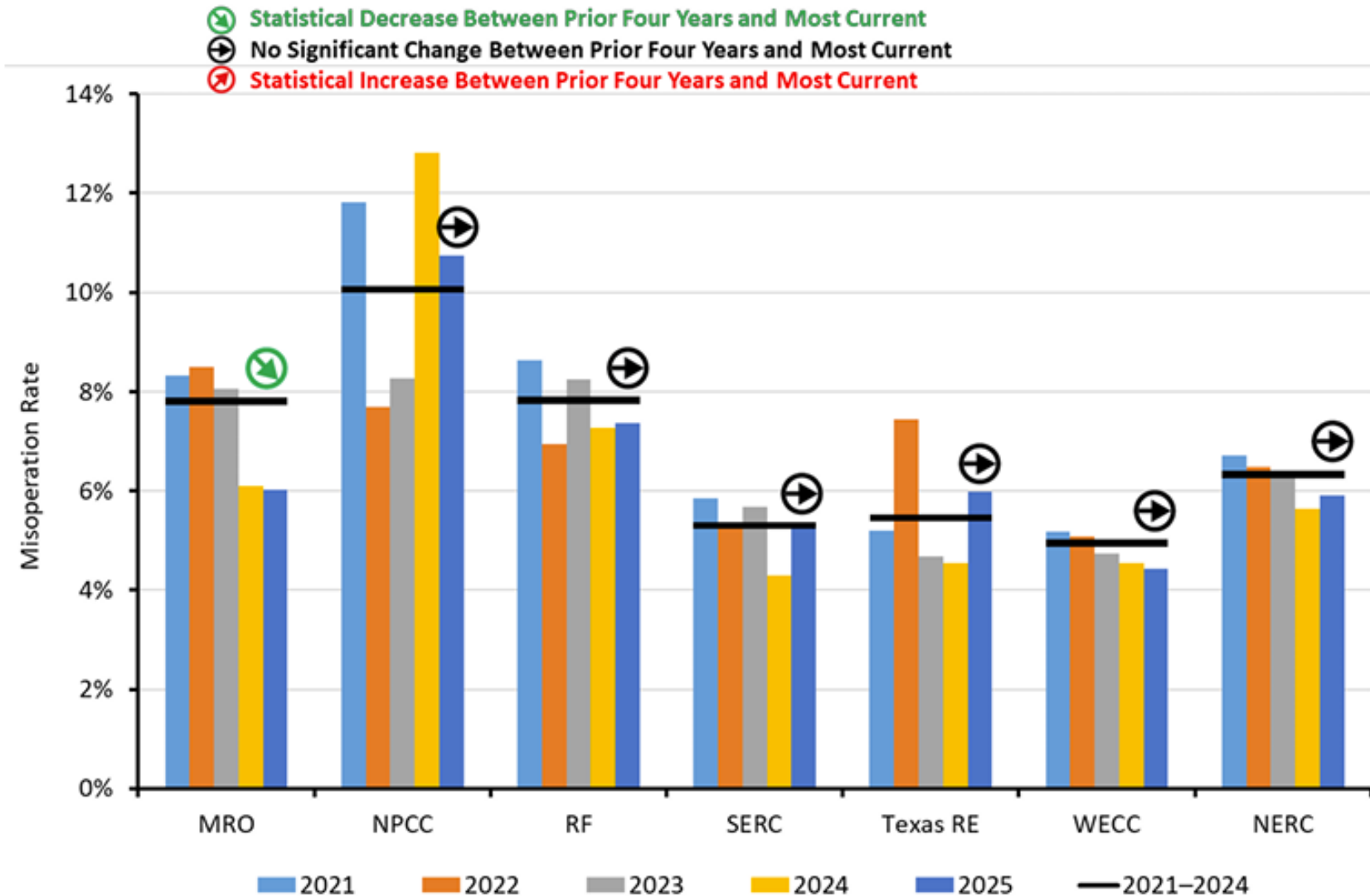


RELIABILITY FIRST

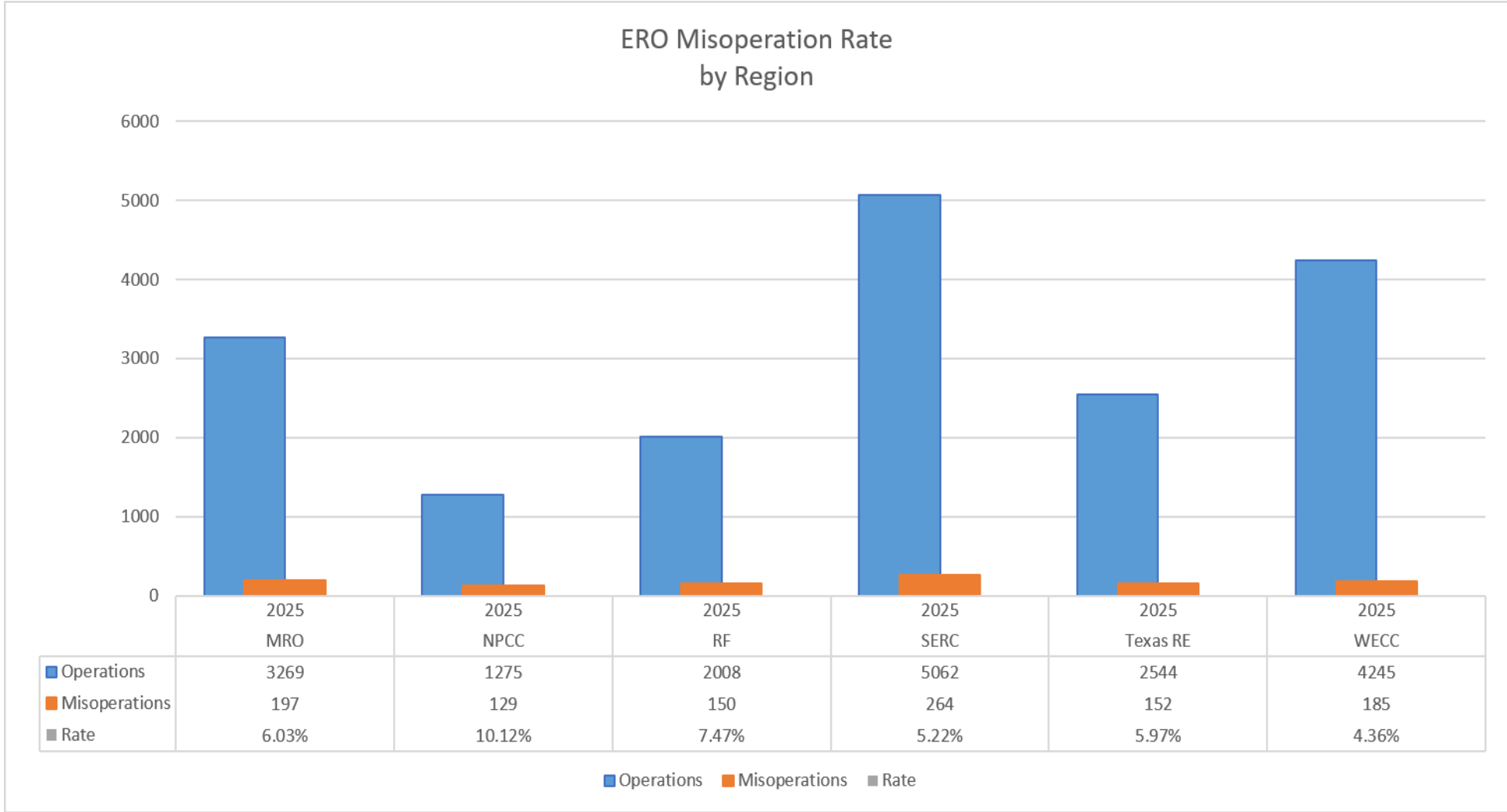
OVERVIEW

- Review and compare RF Misoperation performance across the ERO
- Analyze the Misoperation performance of RF in 2025 and discuss performance trends

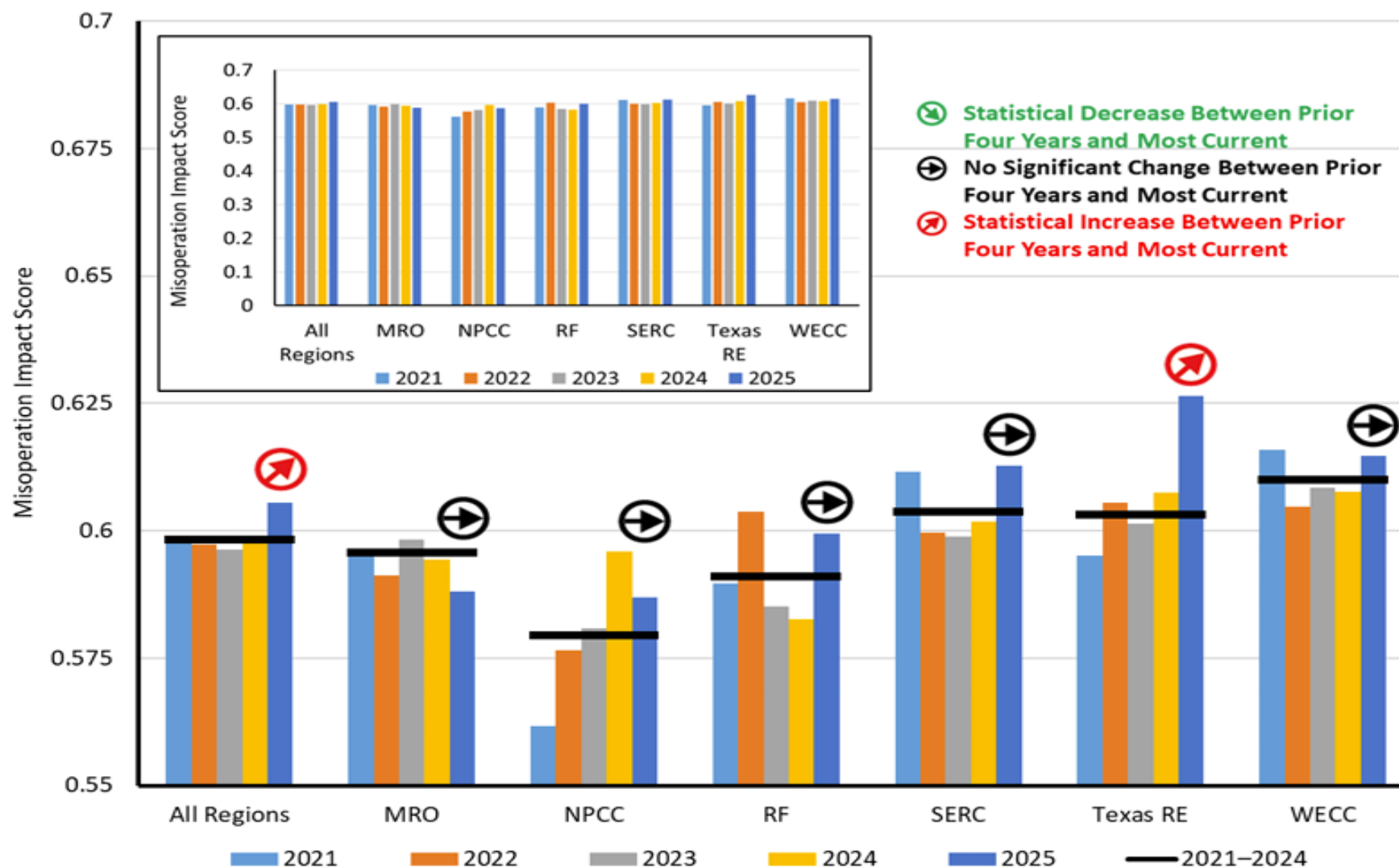
ERO MISOPERATION TRENDS



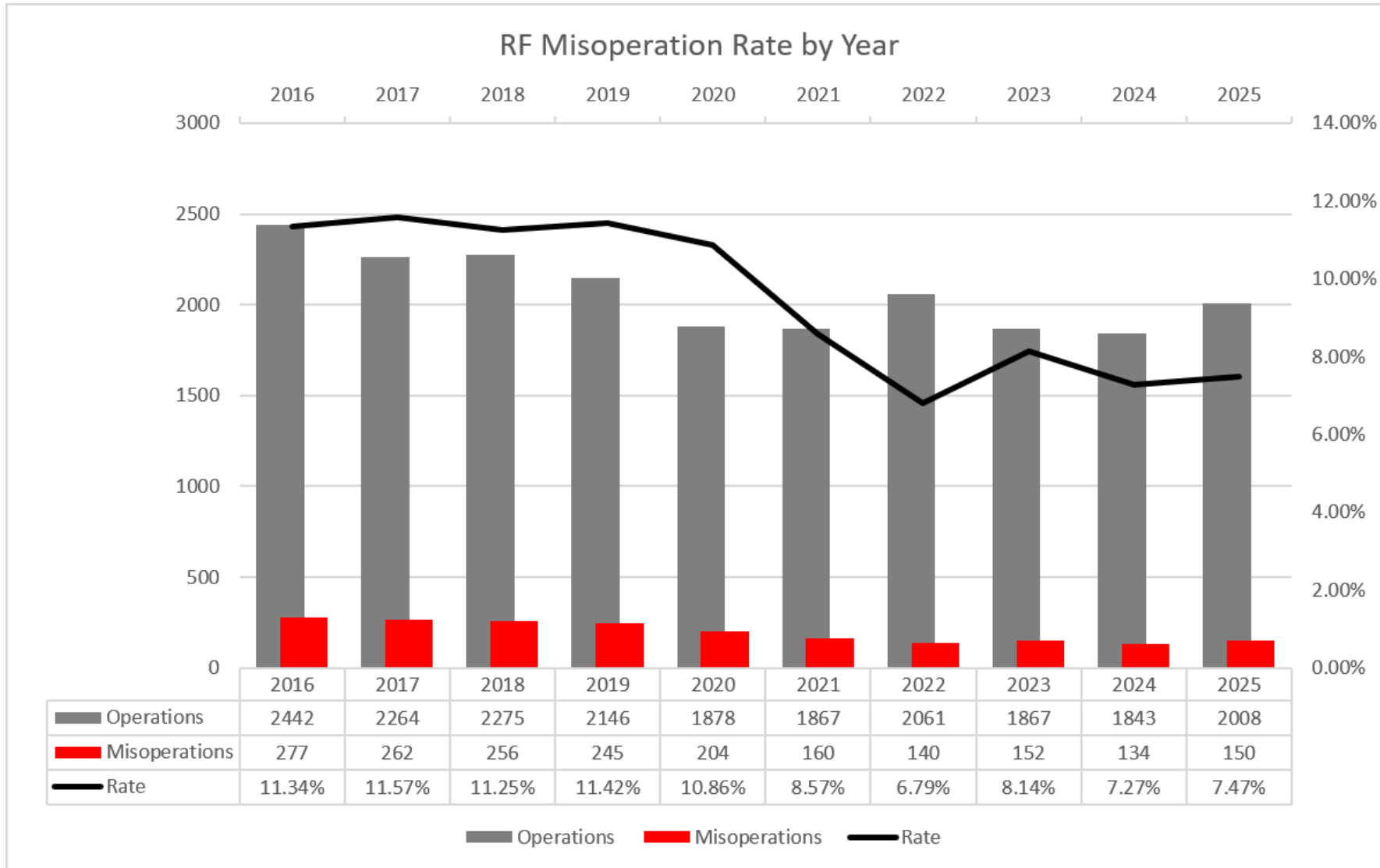
2025 ERO MISOPERATION RATE



MISOPERATION IMPACT SCORE

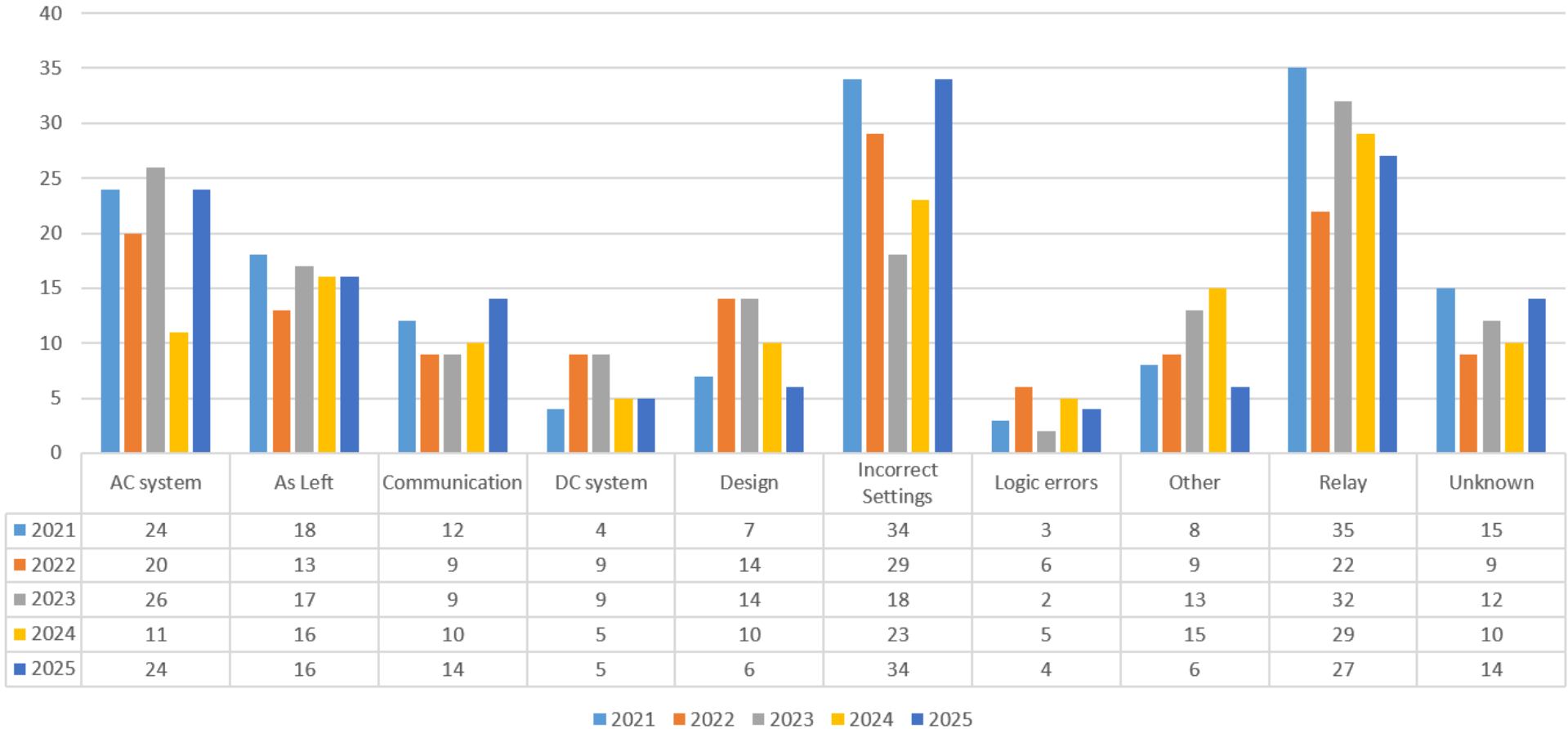


RF MISOPERATION RATE



RF MISOPERATIONS CAUSES

Misoperations Count
by Cause & Year



SUMMARY

- Protection System Operations, Misoperations, and the Misoperation rate have all remained relatively constant since 2022.
- Incorrect Settings is the most numerous cause and trending upward since 2023.
- With increases in Misoperations in 2025, RF is monitoring Misoperations caused by AC Systems, Communications, and Unknowns.
- RF facilitates discussion around lessons learned and potential performance improvements quarterly with its Protection Subcommittee.
 - Publishes biennial Misoperation Assessment
 - Peer review of Misoperation submittals
 - Perform one-on-one outreach, as needed
 - Monitors repeat Misoperations and events that cause multiple simultaneous Misoperation
 - Lead discussions around establishing Misoperation root cause and closing out Corrective Action Plans



QUESTIONS & ANSWERS

Thomas Teafatiller

Thomas.Teafatiller@rfirst.org



Case Study: Detection of Turn-to-Turn Faults in a Load Tap Changer Mechanism

Craig Cosgrove
MATEP LLC

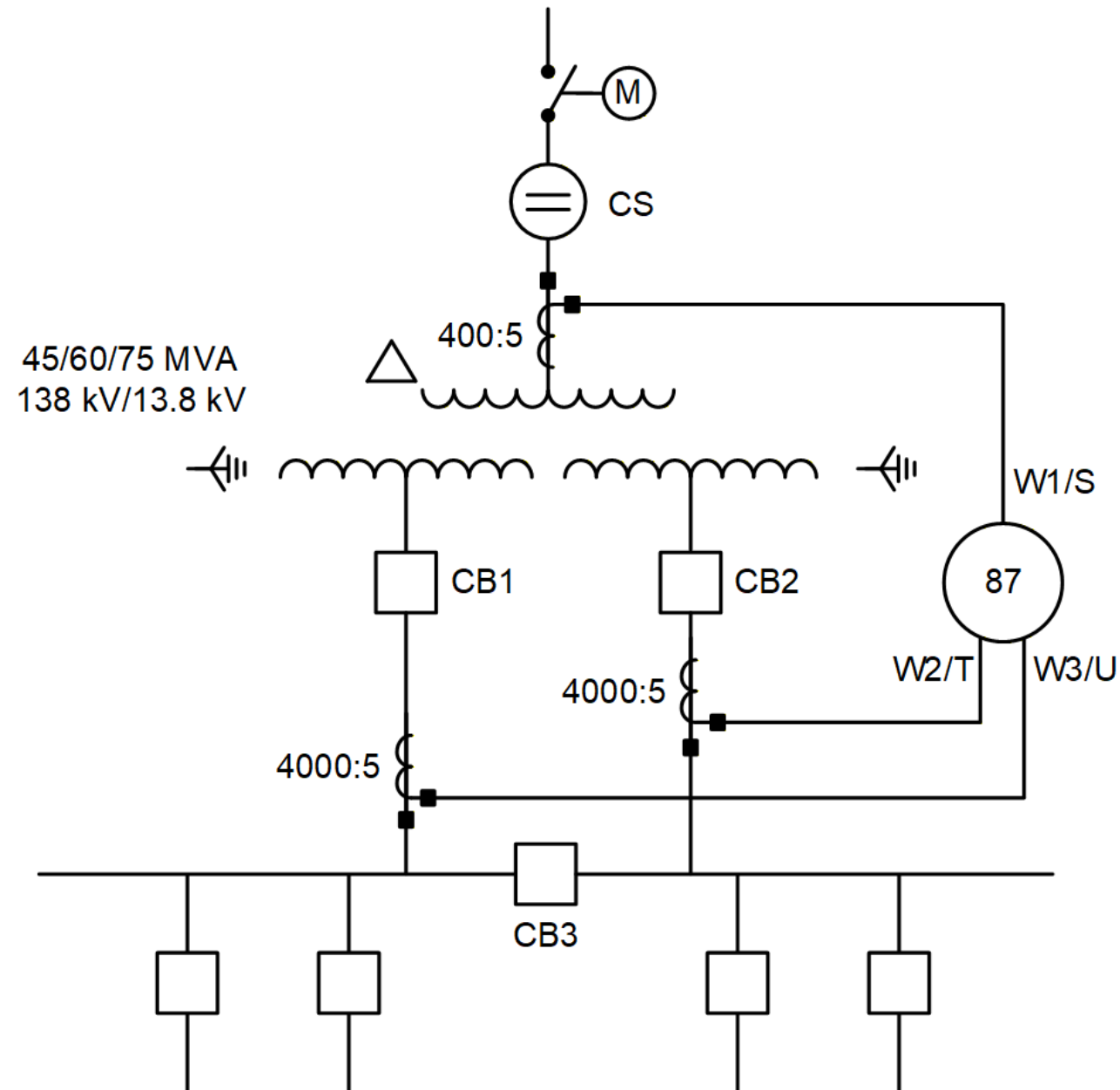
Austin Burfield and Zachary Summerford
Schweitzer Engineering Laboratories, Inc.

Overview

- Case study and physical investigation
- Initial operation analysis
- Phase differential protection overview
- Sensitivity concerns
- Phase differential performance
- Negative-sequence differential performance
- Differential performance comparison
- Summary

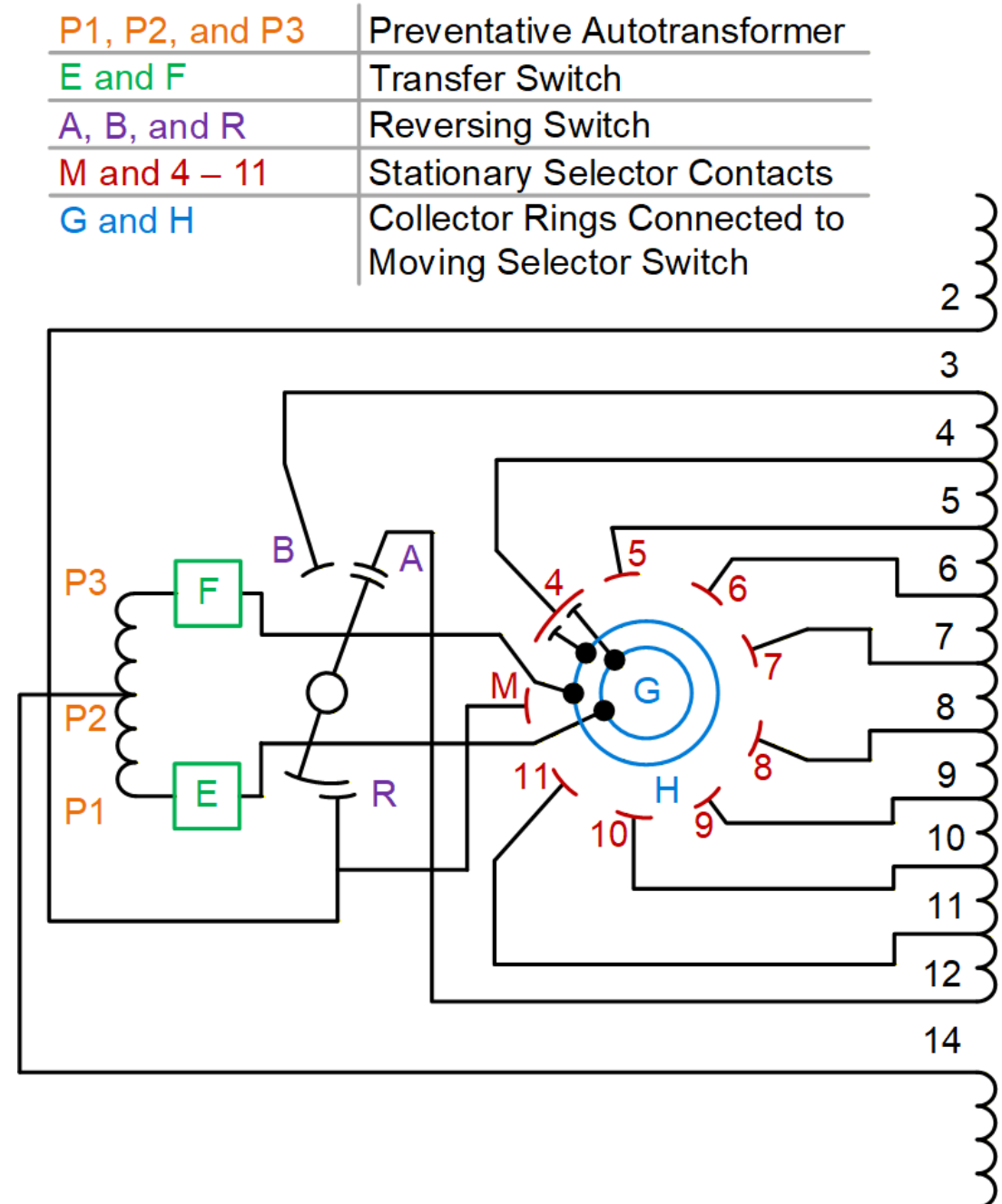
Case study conditions

- Maintenance was performed on Transformer X winding on-load tap changer (OLTC) mechanism one year prior
- Protection included 50/51, 87R, 87U, and SPR within main tank only
- OLTC tank did not include SPR
- System operator was notified of a phase differential trip of the unit
- Inspection found oil discharge around the transformer X winding OLTC tank



Physical investigation and damage

- Oil was drained from OLTC tank for inspection
- Severe damage was found to the cable insulation, conductors, and OLTC stationary and moving selector contacts
- Oil was carbonized and had significant gassing, causing breakdown in dielectric
- OLTC arcing should have occurred inside arc chutes, reducing risk of oil breakdown
- Repair required replacement of OLTC components, cabling, bulkhead, and draining and replacement of OLTC and main tank oil

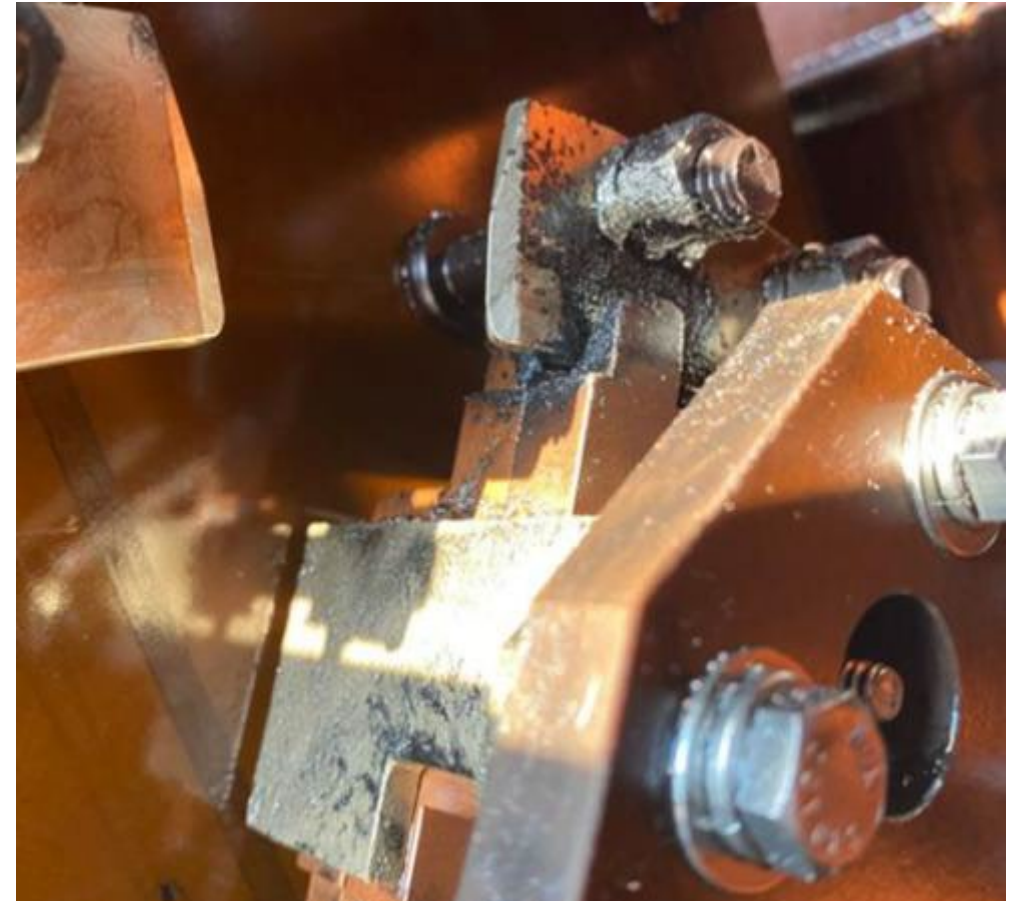


Damage to OLTC mechanism

BULKHEAD TAP BOARD AND TAP CABLES

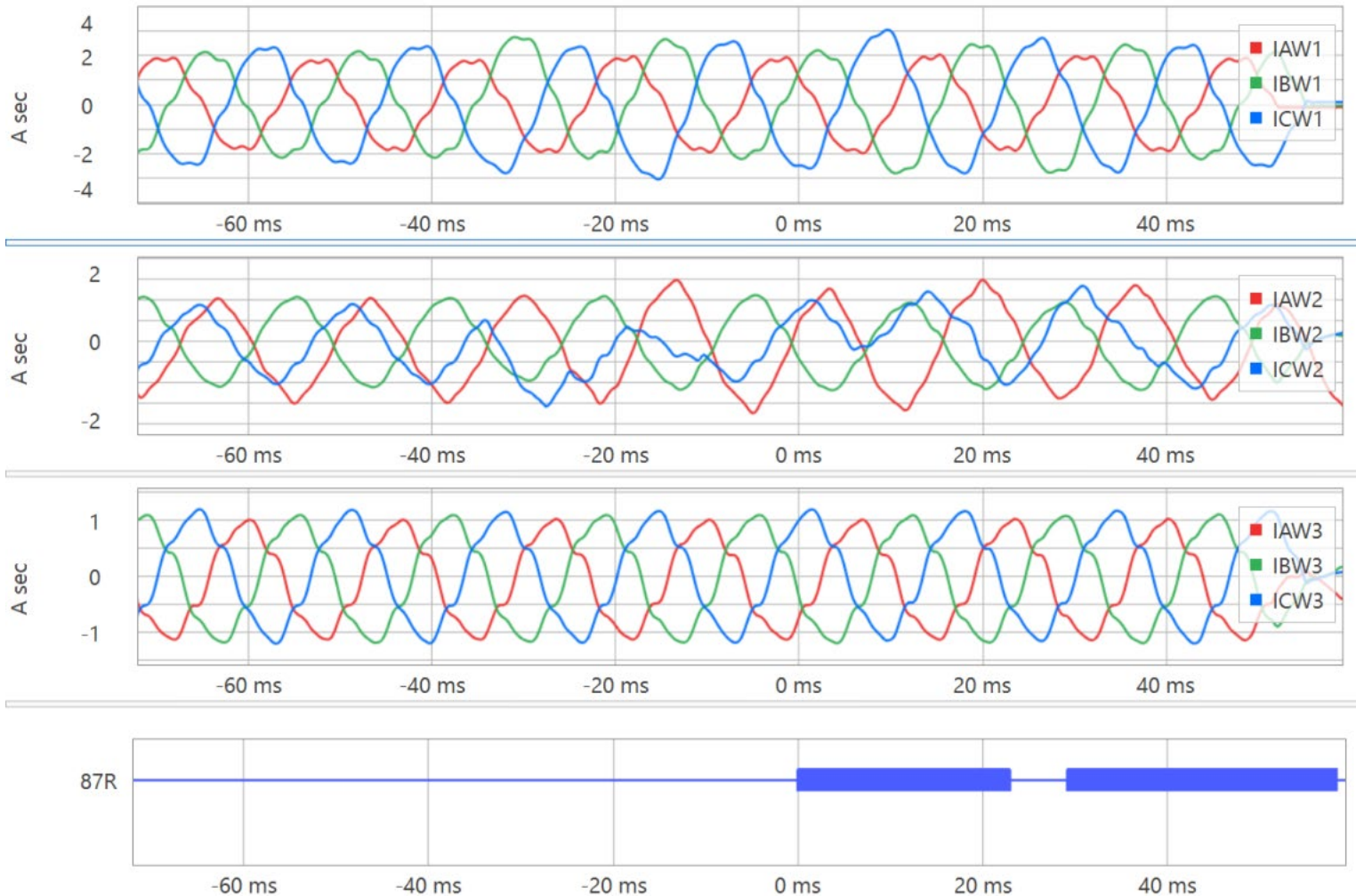


MOVING AND STATIONARY CONTACTS



Initial operation data analysis

- Phase currents are irregular throughout the event
- High harmonic content can be seen in all windings
- Winding 2 (X) is most irregular
- ICW2 changes 2 cycles prior to event trigger



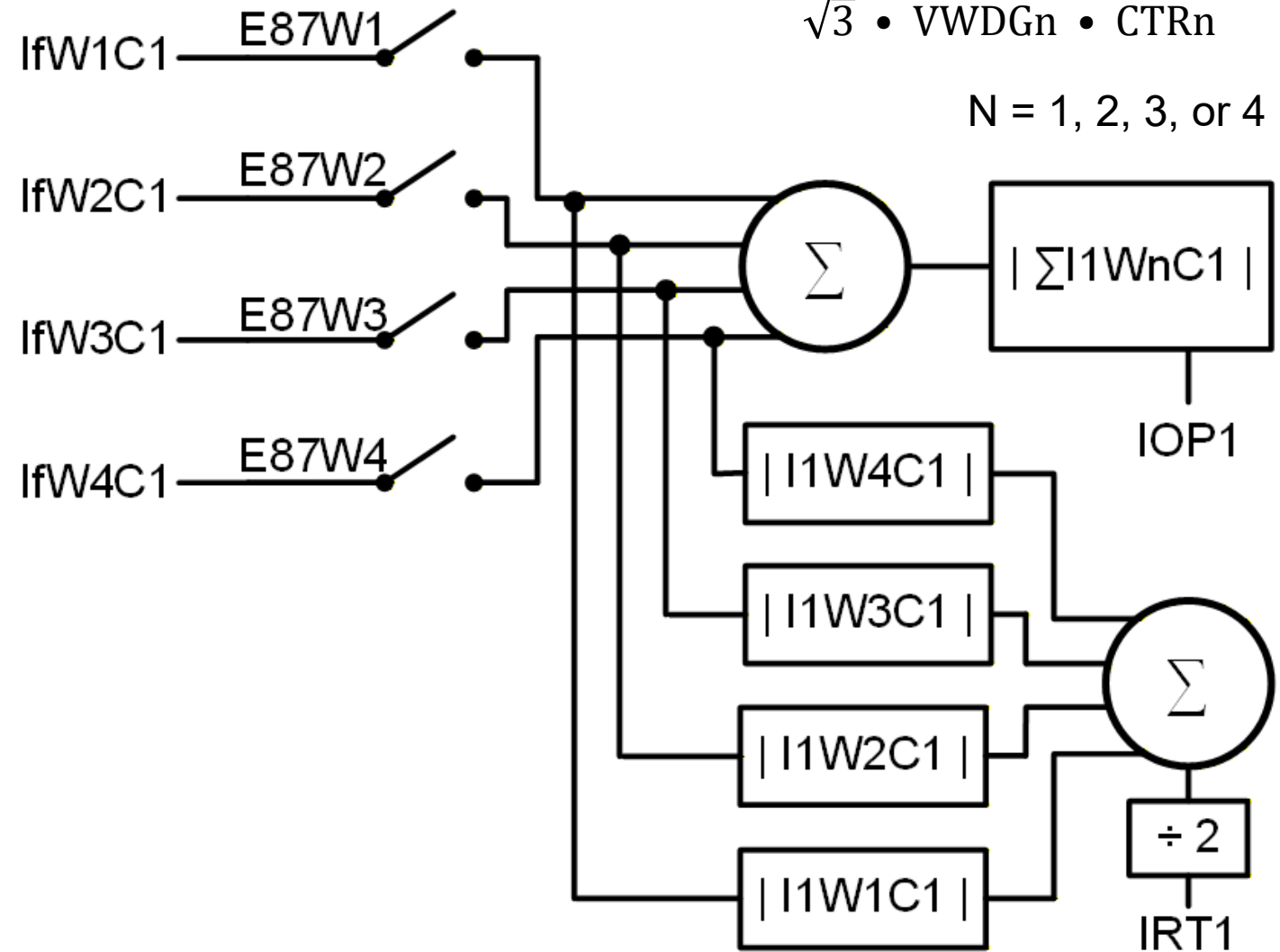
Fundamentals of phase differential protection

- Phase currents are tapped to correct winding nominal voltage differences
- Phase currents are matrix compensated to correct for winding connection differences
- Operate and Restraint currents are calculated in pu of transformer MVA at nominal
- Operate current is the difference of all winding currents
- Restraint current is the sum of all winding currents

$$\begin{bmatrix} I1WnC \\ I2WnC \\ I3WnC \end{bmatrix} = [CTC(m)] \cdot \begin{bmatrix} IAWnC \\ IBWnC \\ ICWnC \end{bmatrix}$$

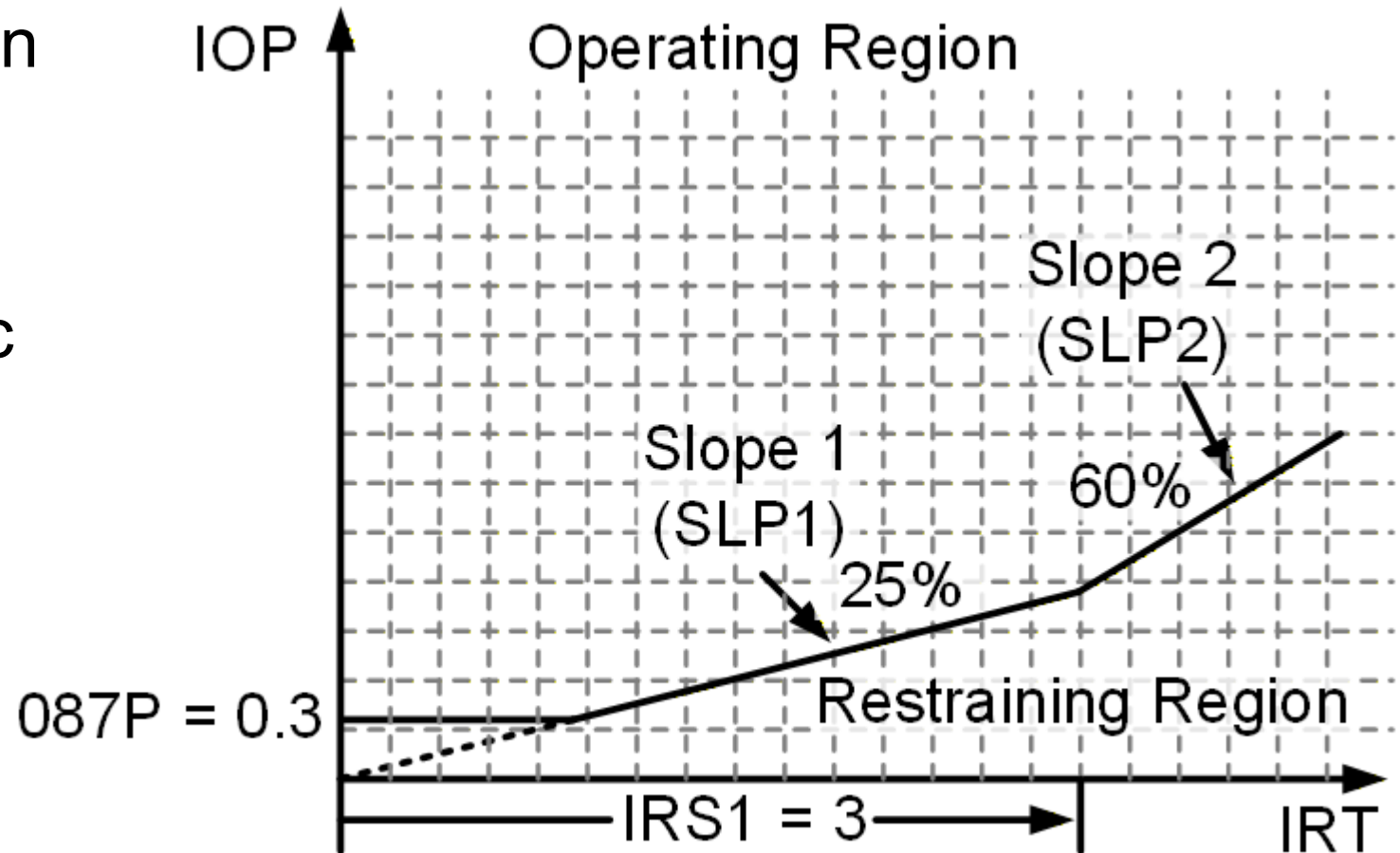
$$TAPn = \frac{MVA \cdot 1,000}{\sqrt{3} \cdot VWDGn \cdot CTRn} \cdot C$$

N = 1, 2, 3, or 4



Phase differential element operation

- Trip when IOP/IRT falls in the operate region
- Minimum pickup O87P
- Dual-slope characteristic
 - SLP1, low chance of CT saturation
 - SLP2, significant chance of CT saturation
 - IRS1 Slope 1 limit

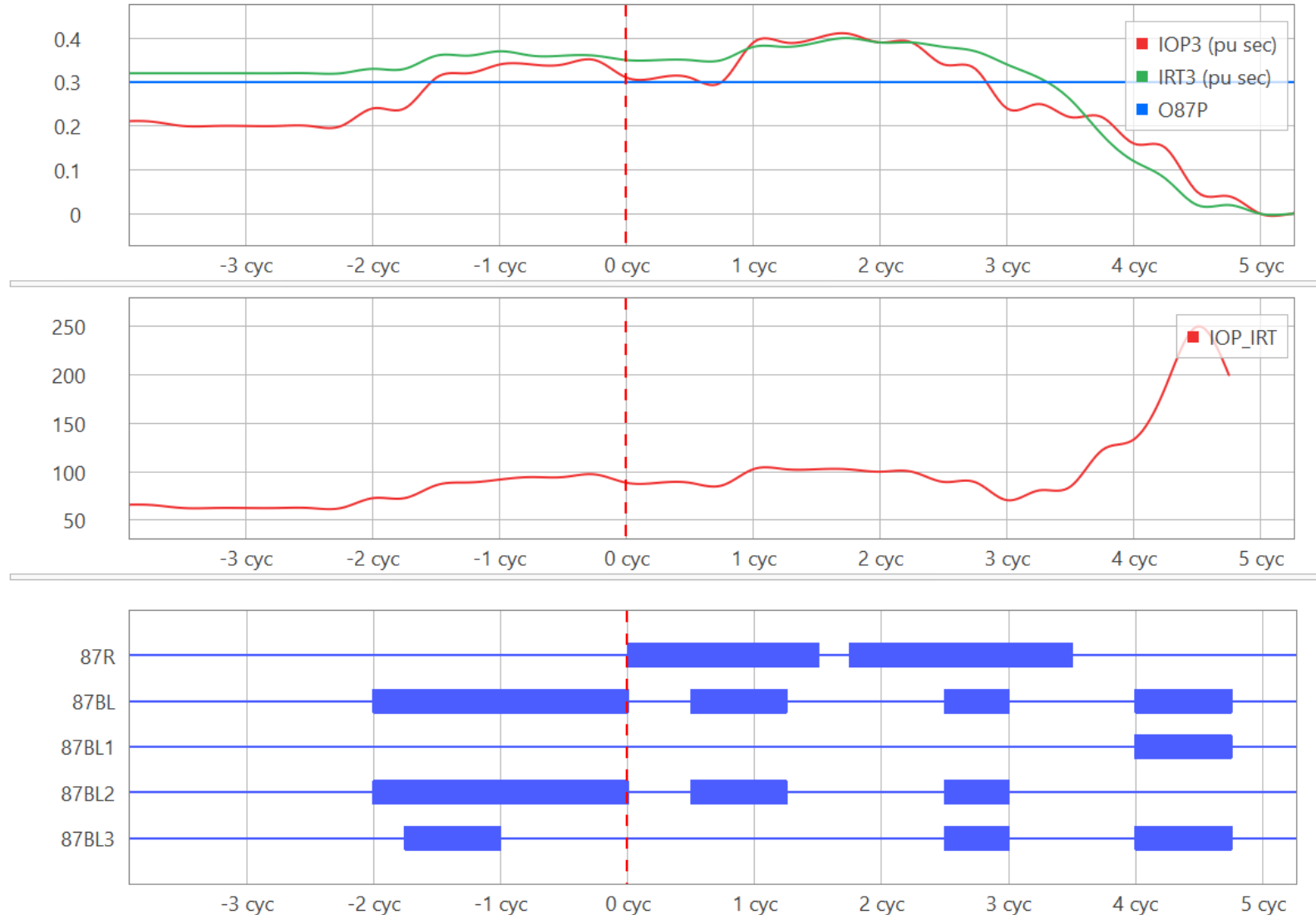


Sensitivity challenges for phase differential

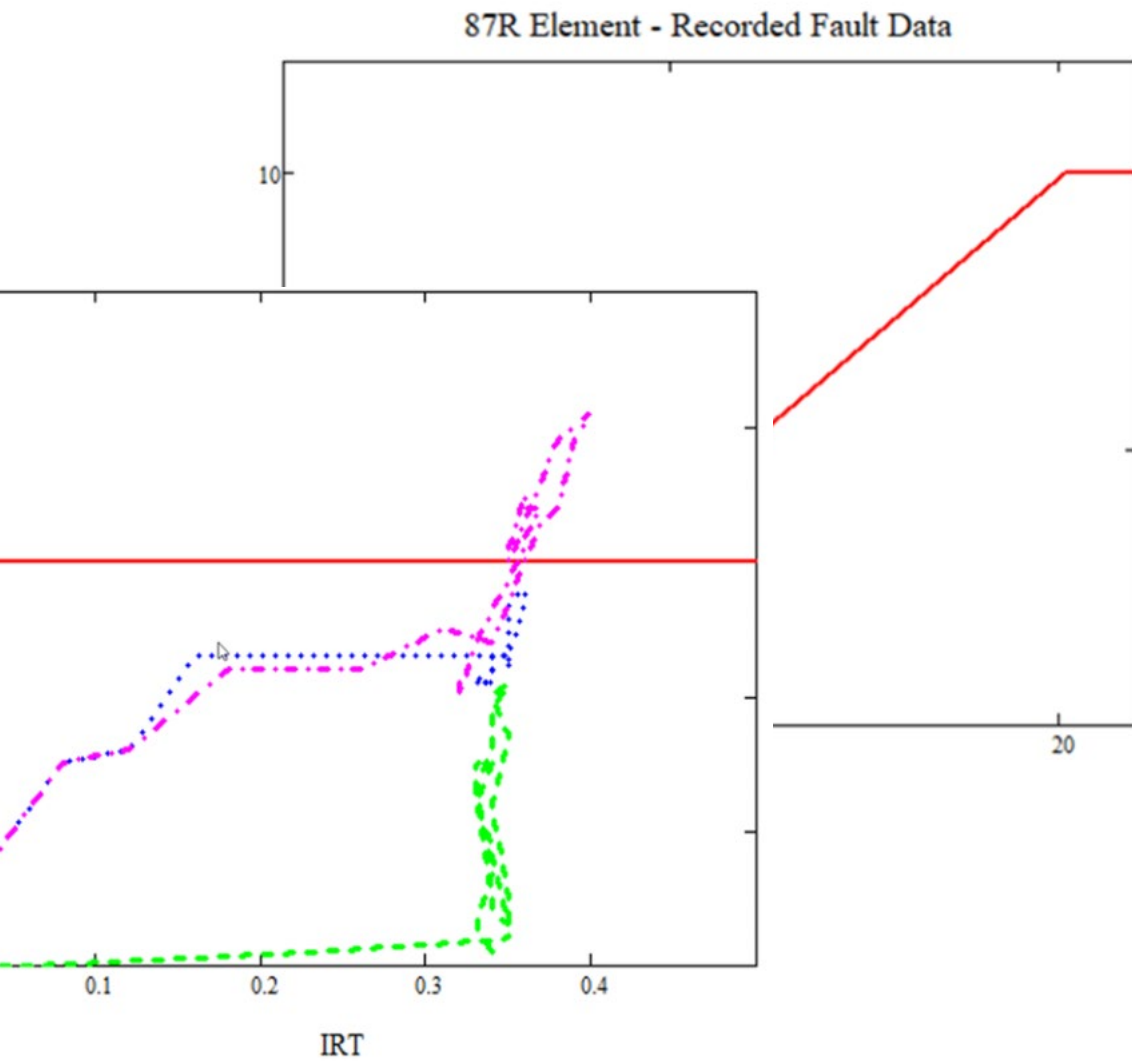
- Error sources increase O87P and slope
 - Core magnetization current
 - CT error
 - OLTC
- MVA rating for tap calculation—65°C emergency rating was used
- H winding is rated double X and Y windings—FLA contribution of winding only contributes 0.5 pu to 87 element calculations
- Under increased load, 87R requires increased IOP to plot inside the operate zone

Phase differential event analysis

- $IOP3 > 0.2$ pu from start of recording
- $IOP/IRT > 50\%$ from start of recording
- Change observed in ICW2 raw data correlates to increase in IOP3 above O87P
- Harmonic blocking delayed 87R operation

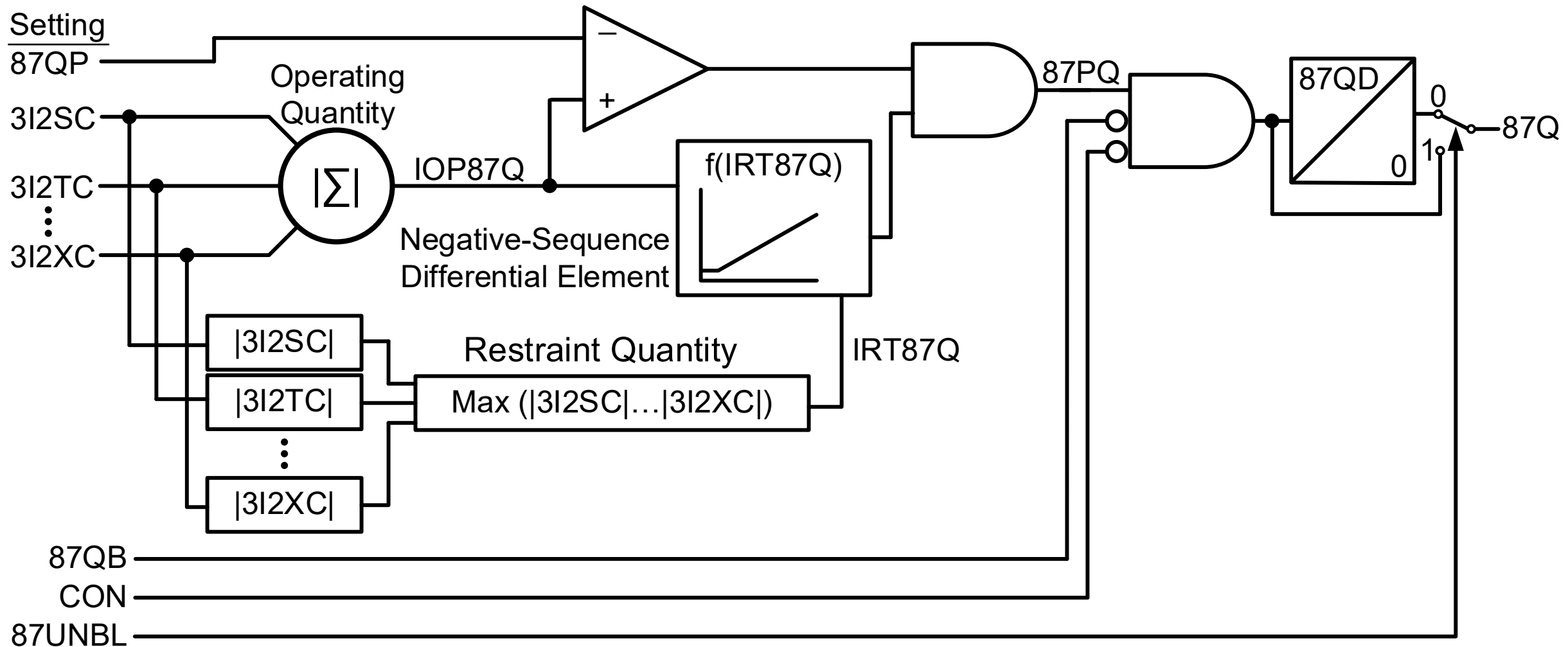


87R sensitivity illustrated



Negative-sequence differential overview

Balanced load does not contribute 3I2 and therefore does not increase IOPQ required to operate 87Q

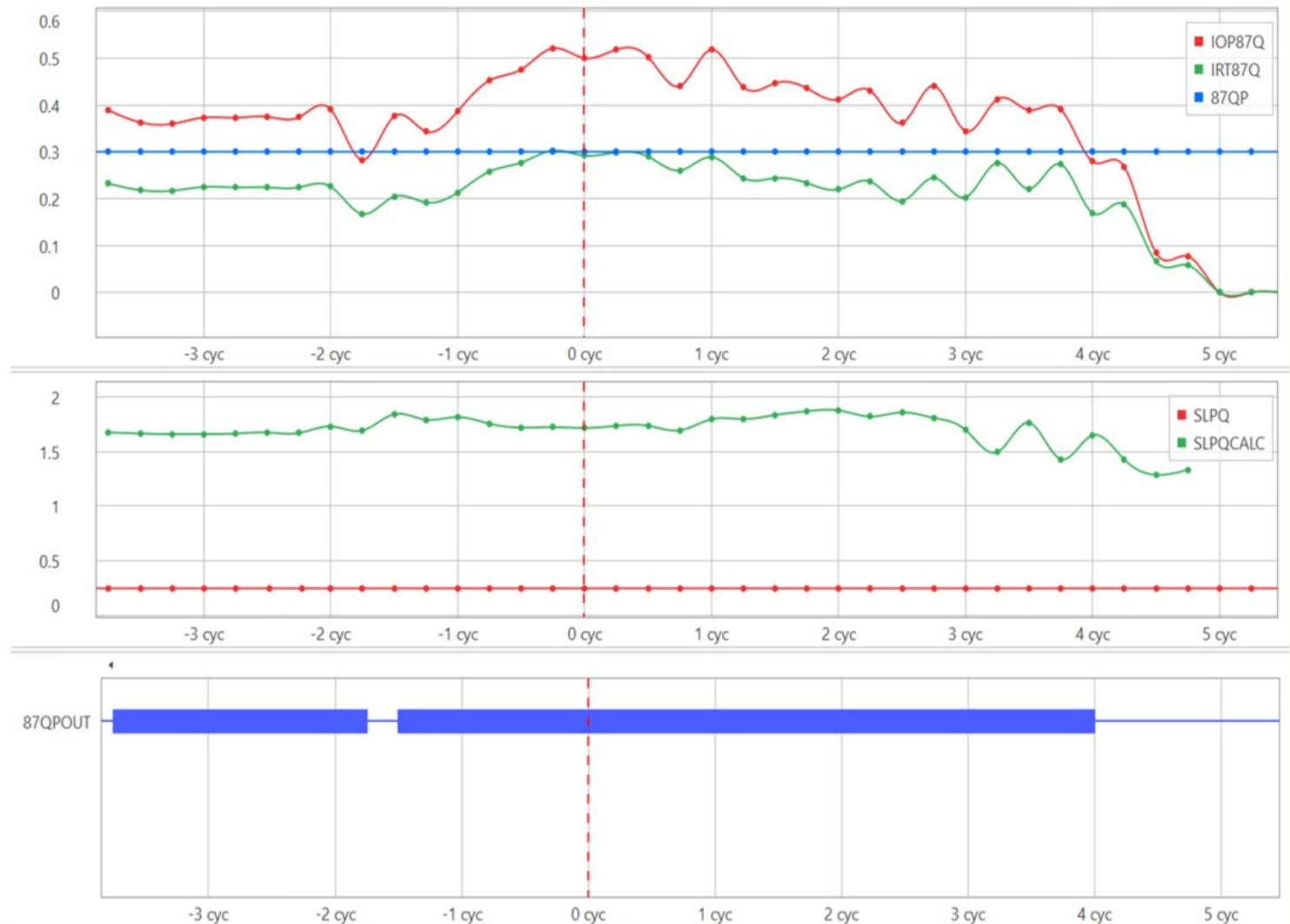


Simulation of 87Q Element

- Analytic approach
 - Filtered event recording of in-service relay used
 - Custom calculations in event analysis software used to build and plot 87Q vs. time, using calculated phasor values
 - Mathcad used on filtered samples to build phasors and plot 87Q locus in IRTQ vs. IOPQ plane
- Event replay
 - Raw event recording used to create COMTRADE event file
 - Secondary injection test set used to generate secondary currents
 - Event played into relay that includes the 87Q element

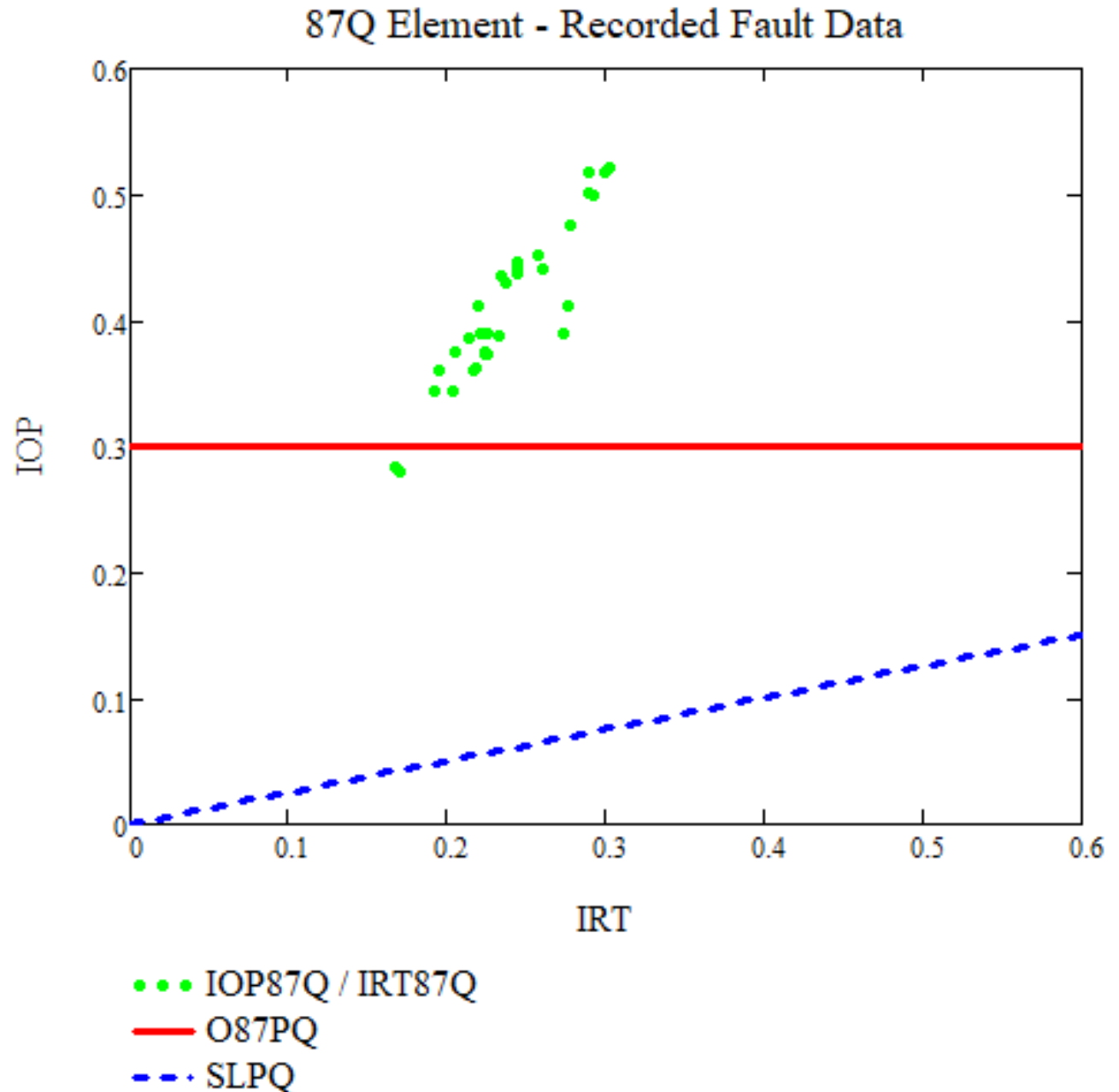
Custom calculations

- $IOPQ > O87P$ for nearly all data points
- Ratio of IOPQ to IRTQ (SLPQ) $> 150\%$ during event
- 87Q element is asserted at first sample possible



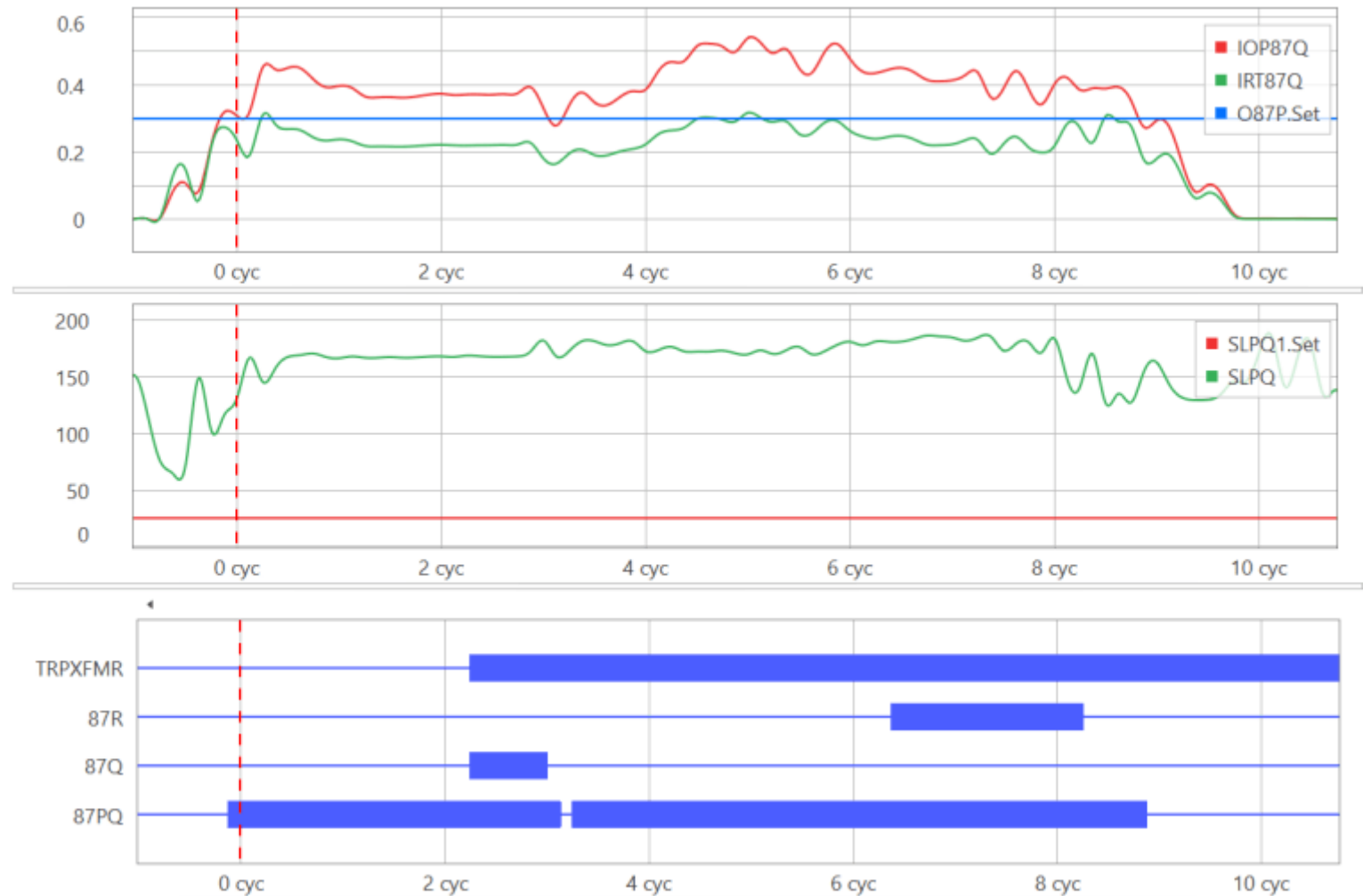
IRTQ vs. IOPQ locus using Mathcad

- Most data points $> O87P$
- Unaffected by load flow
- Lower contribution to IRTQ



Event replay using 87Q-enabled relay

- Metering tests used to ensure proper replay
- Steady state test performed including balanced through feed of 3I2 to show IOPQ = 0 pu
- 87PQ asserts less than 1 cycle after test initiation
- 87Q asserts after fixed 2 cycle delay
- 87P asserts 4 cycles after 87Q



Comparison of 87R vs. 87Q

Phase Differential

- Desensitized for low-level and turn-to-turn faults
- Affected by load current
- Operates as three individual elements
- Designed to be secure for high-level faults
- No intentional delay

Negative-Sequence Differential

- Sensitivity to low-level unbalanced faults
- Unaffected by load current
- Operates on current from all three phases
- Delay was used to add security for high-level faults

Summary

- Turn-to-turn faults can challenge the sensitivity of 87R elements
- Low-level persistent faults can evolve to cause significant damage over time
- Quick reaction by sensitive protection elements can reduce outage time and repair costs
- Relay event records can be used to evaluate element performance in service devices and to evaluate other protection methods
- 87R and 87Q can be deployed together to provide comprehensive transformer differential protection

Questions?

Blackouts in Brazil and Spain

WHAT WE CAN LEARN



Ricardo Abboud, Fellow Engineer

Fundamental concepts

Mvar support is critical for voltage stability

Mvar absorbed by the line

$$Q_L = X_L \cdot I^2$$

Mvar injected by the line

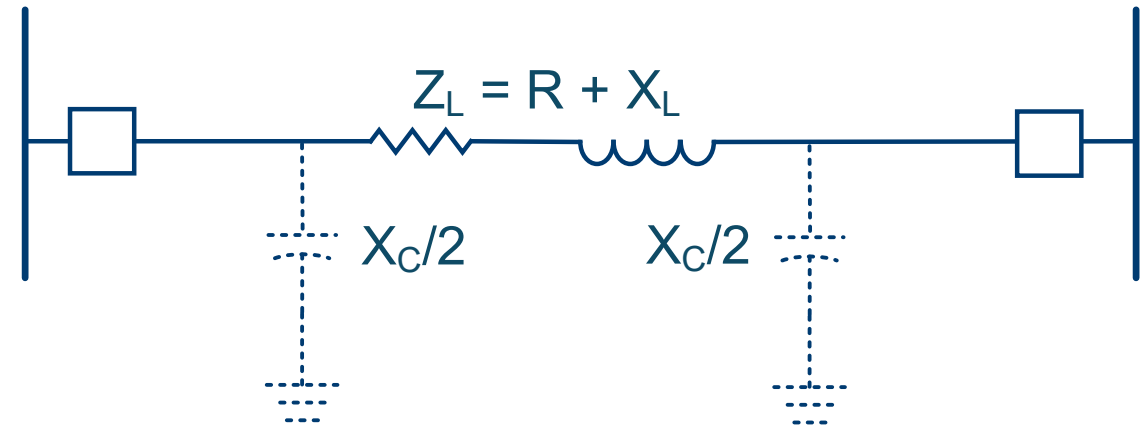
$$Q_C = \frac{V^2}{X_C}$$

$Q_L > Q_C$ contributes to undervoltage

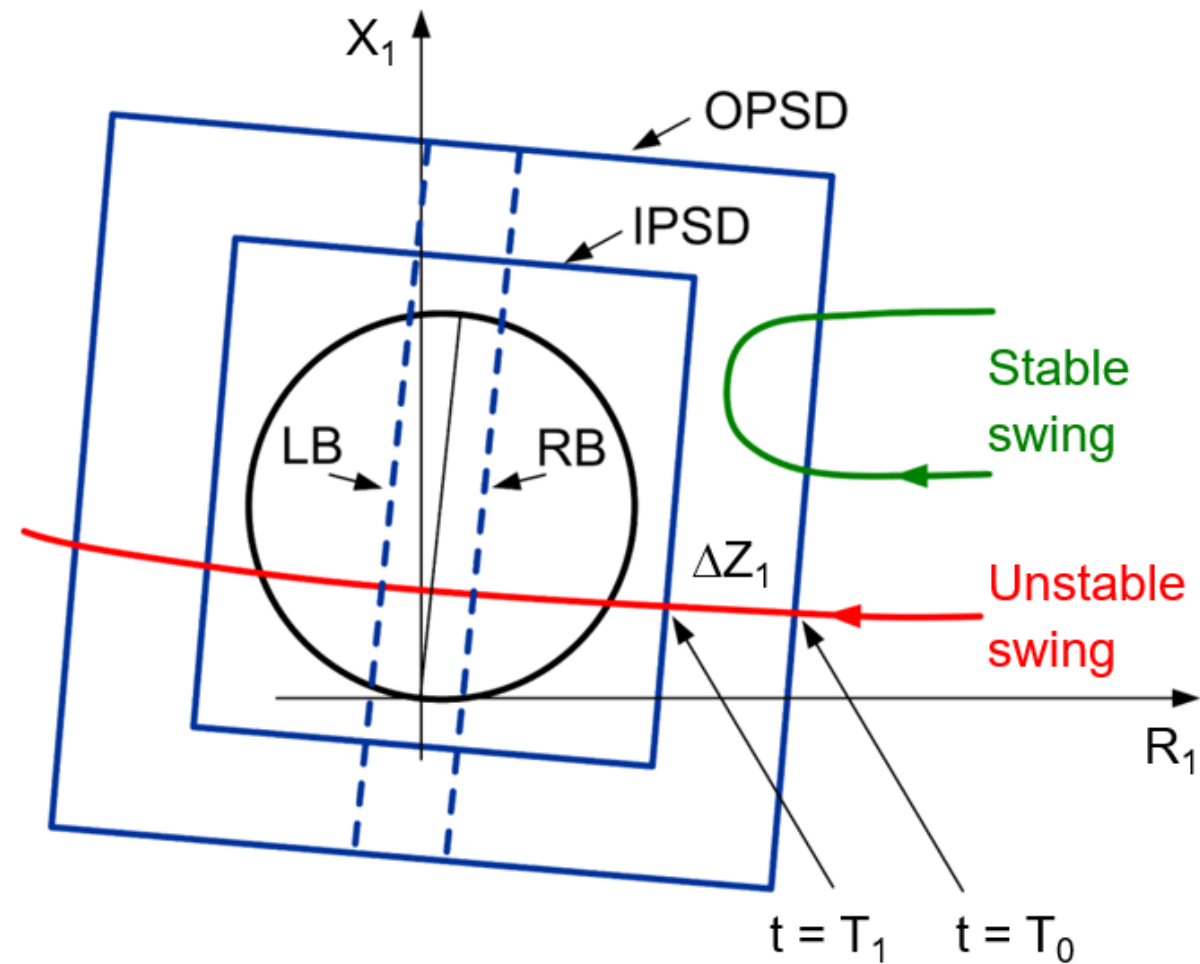
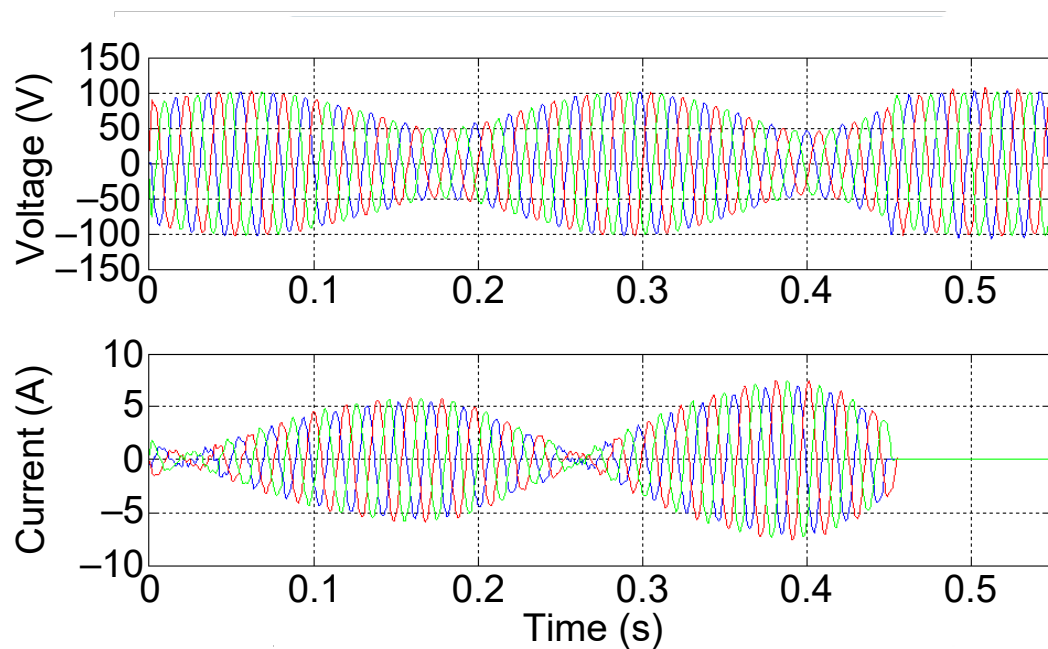
$Q_C > Q_L$ contributes to overvoltage

$Q_C = Q_L$ Surge Impedance Load (SIL)

Transmission line π model



Power swing blocking (68) and out-of-step tripping (78)



Protection Philosophy for Power Swings

- Block tripping for stable swings – power swing blocking (68)

$$|T_1 - T_0| > T_{Block}$$

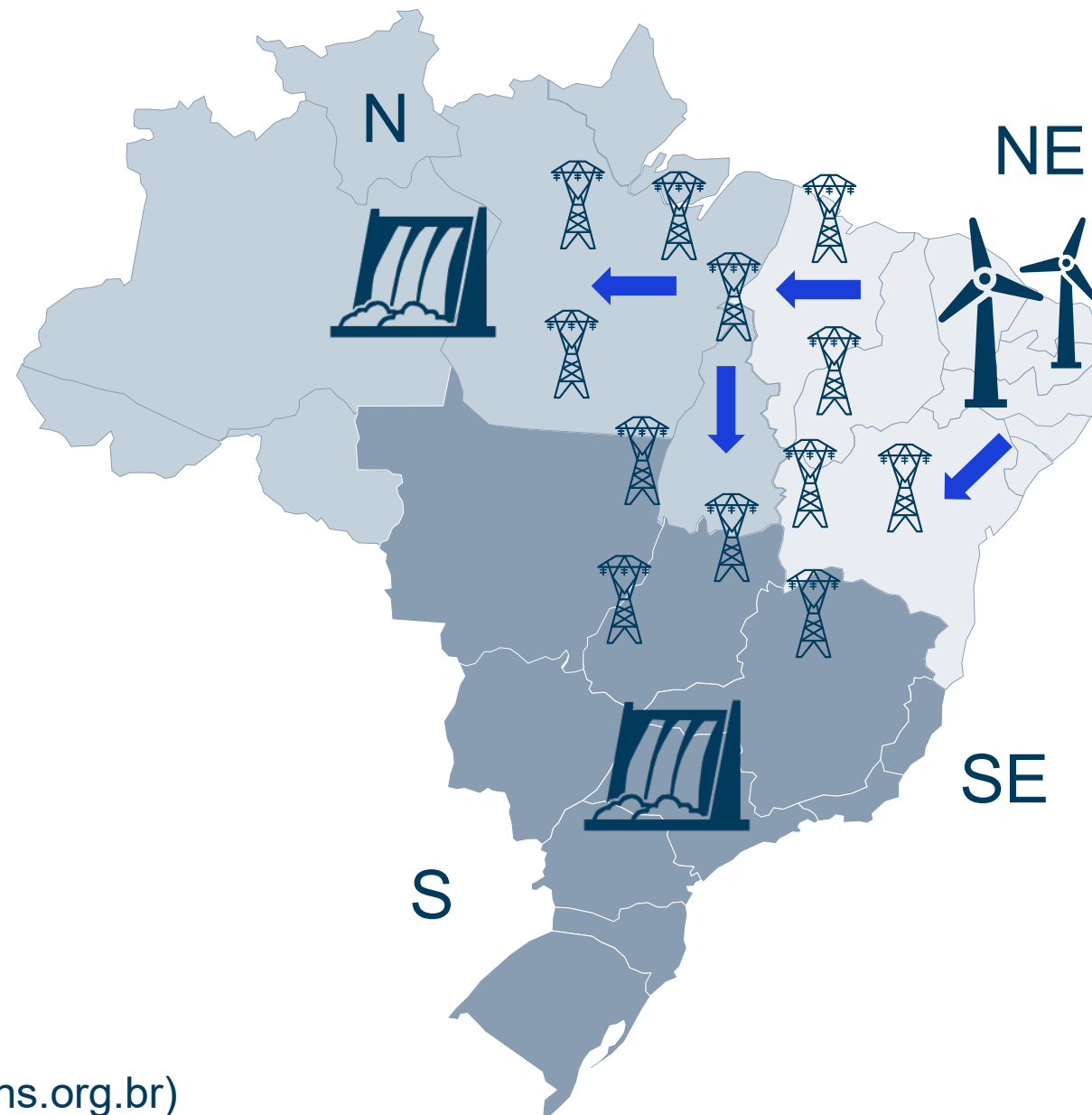
- Separate the system into islands for out-of-step conditions – out-of-step tripping (78)

$$T_{Fault} < |T_1 - T_0| < T_{Block}$$

Brazilian electrical system major incident, August 2023

Brazilian grid typical day

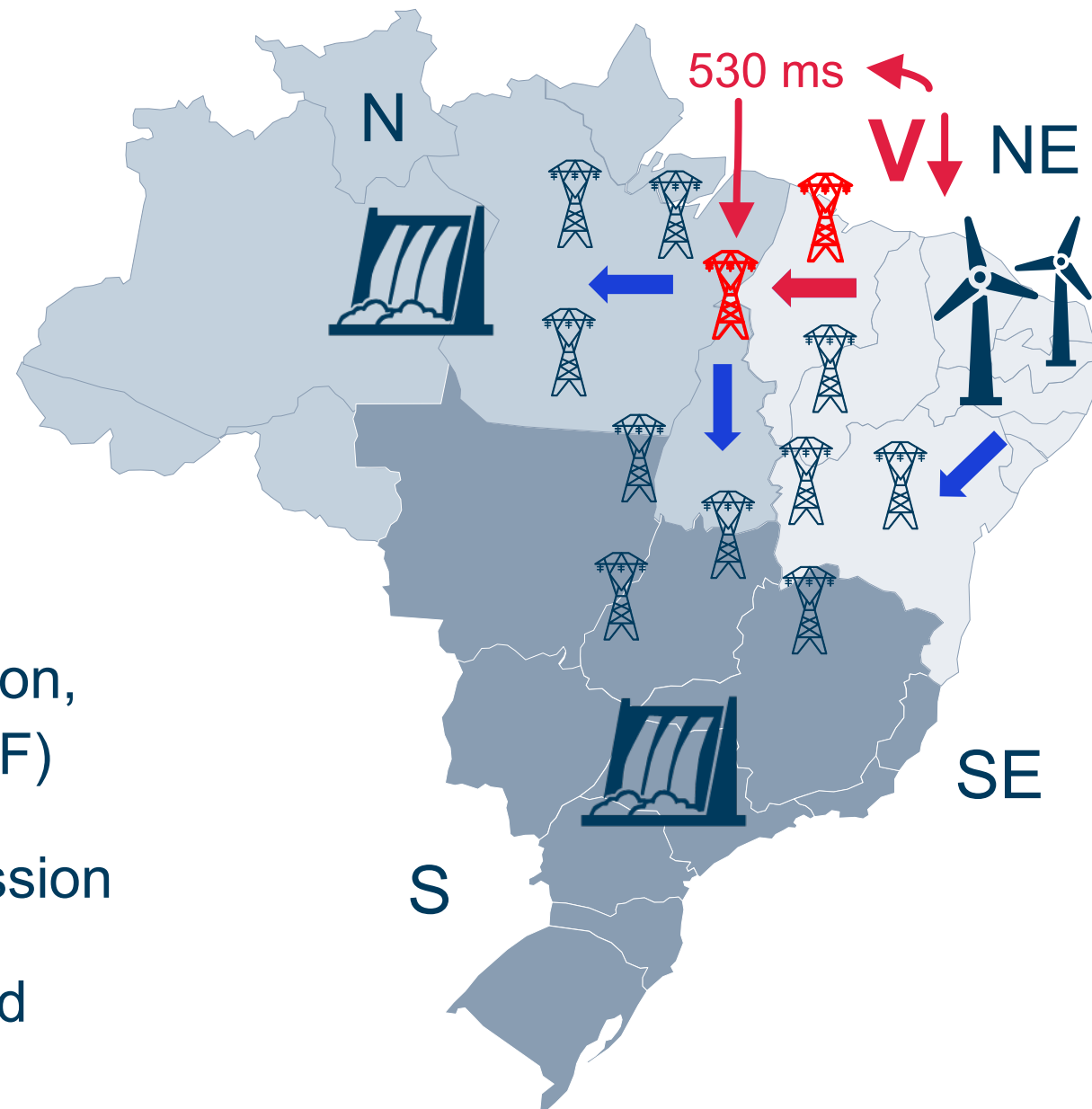
Region	Synchronous	IBR
National	65%	35%
N	90%	10%
NE	15%	85%
SE/S	85%	15%



Source: Operador Nacional do Sistema Elétrico (ons.org.br)

Disturbance on August 15, 2023, at 8:30 a.m.

- NE was exporting large MW, close to the limit
- 500 kV line experienced misoperation, protection logic scheme error (SOTF)
- Voltage dropped in the NE transmission
- 530 ms later, OOST scheme caused four 500 kV lines to trip



Subsequent events

- Multiple transmission lines tripped
 - Lines overload, large Mvar absorption
 - Pronounced undervoltage
- Power swing
 - Out-of-step tripping
 - Distance elements misoperations
- Frequency drop – UFLS schemes tripped 31 percent of total load

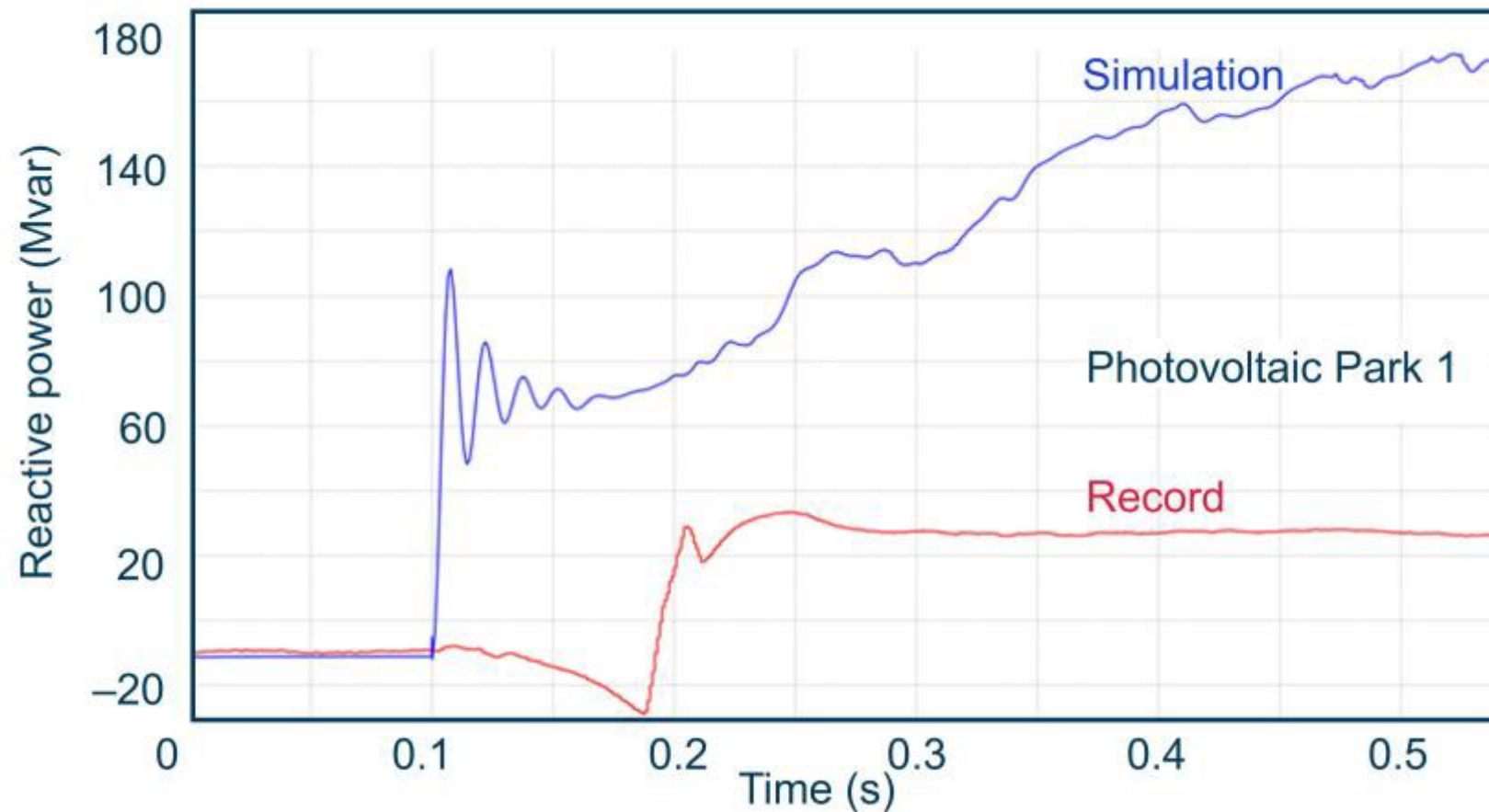


Lack of accurate system model makes stability studies ineffective

“The abrupt voltage reduction observed after the loss of a single transmission line was a consequence of the unexpected performance of wind and photovoltaic farms observed in the field, far below that obtained by the National System Operator (ONS) in its power system studies, which are carried out using mathematical models sent by the transmission and generation asset owners to ONS.”

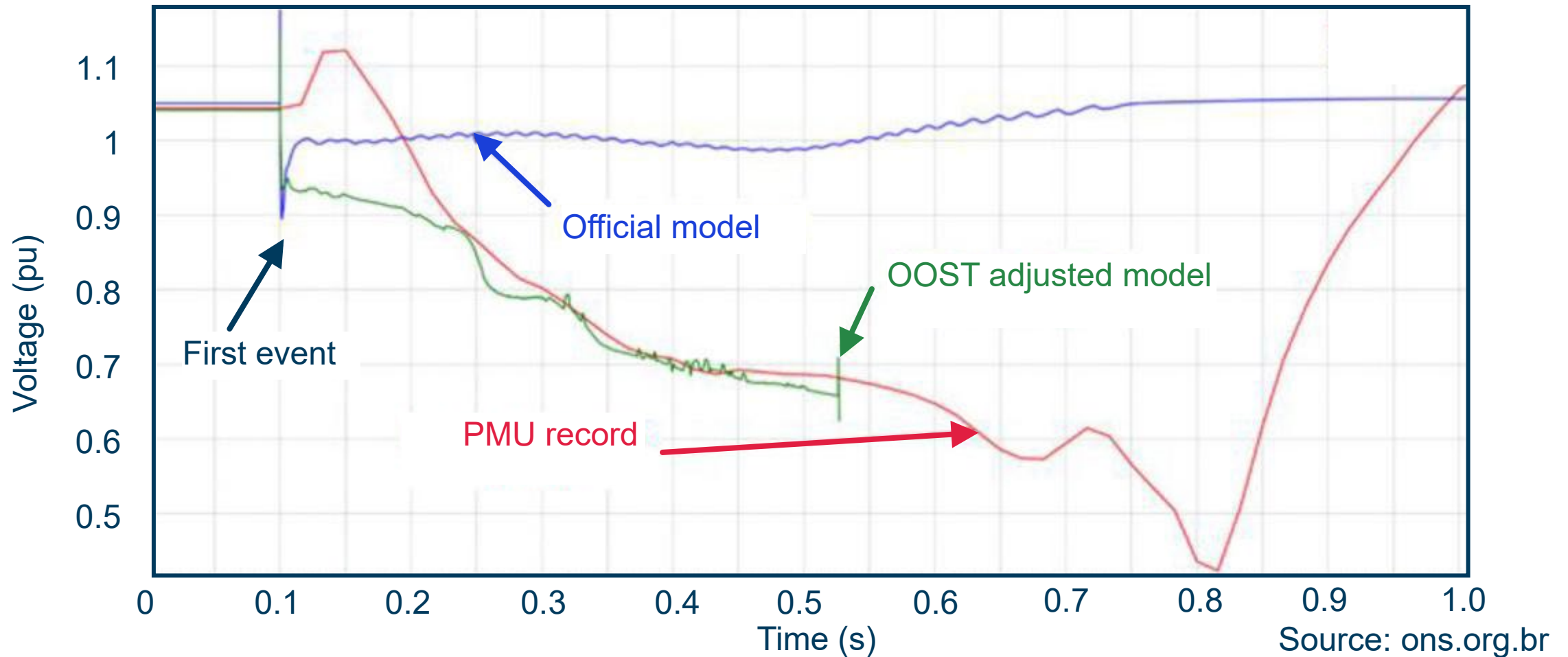
Source: ons.org.br

Some IBR sources did not provide expected reactive power support



Source: ons.org.br

Adjusted model produces coherent result



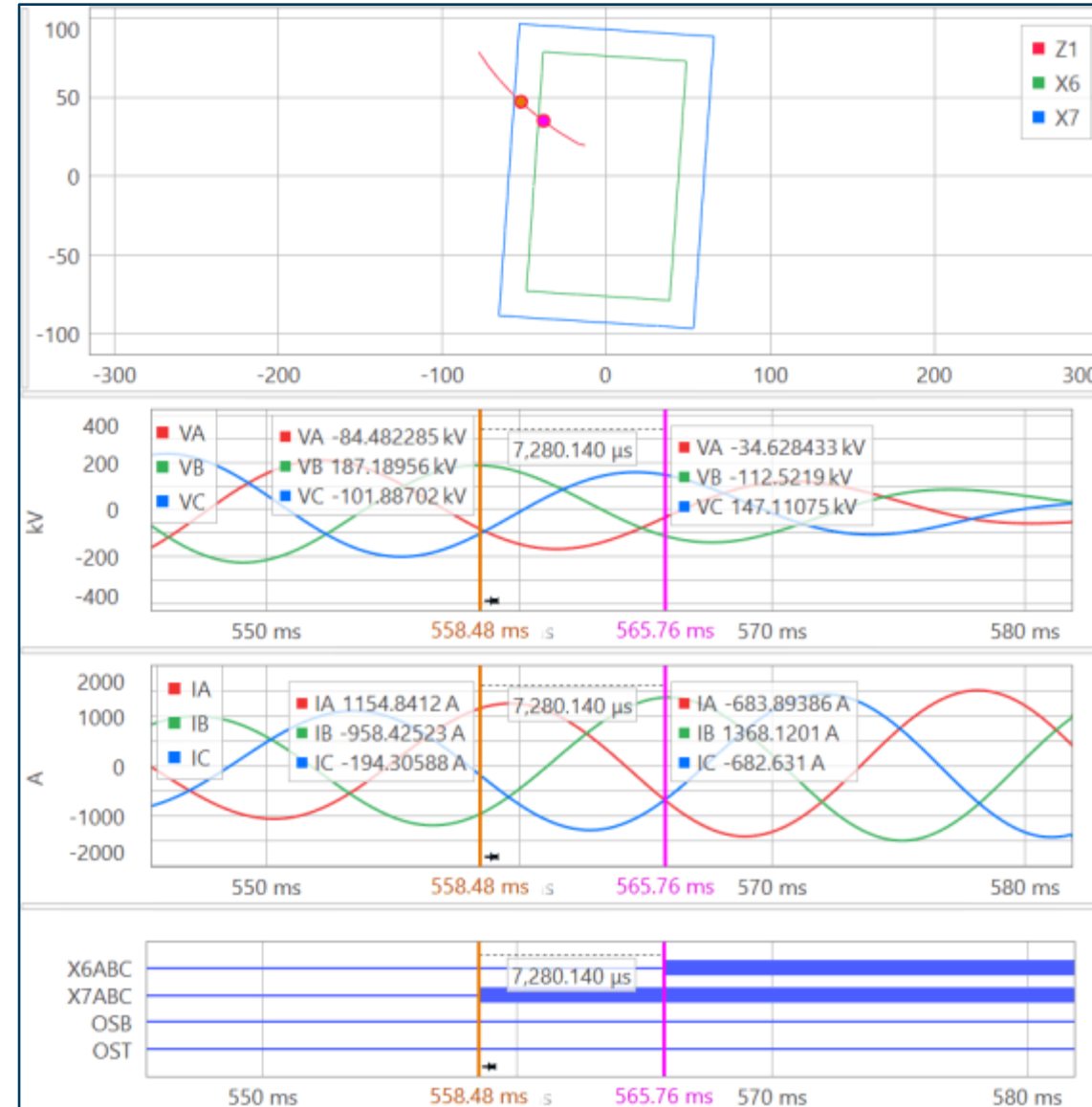
Traditional PSB did not provide expected results

- Inverter-based generation lowers system inertia, power swings are faster
- Traditional double blinder schemes may not operate
- Several PSB and OOST did not work as expected during the disturbance



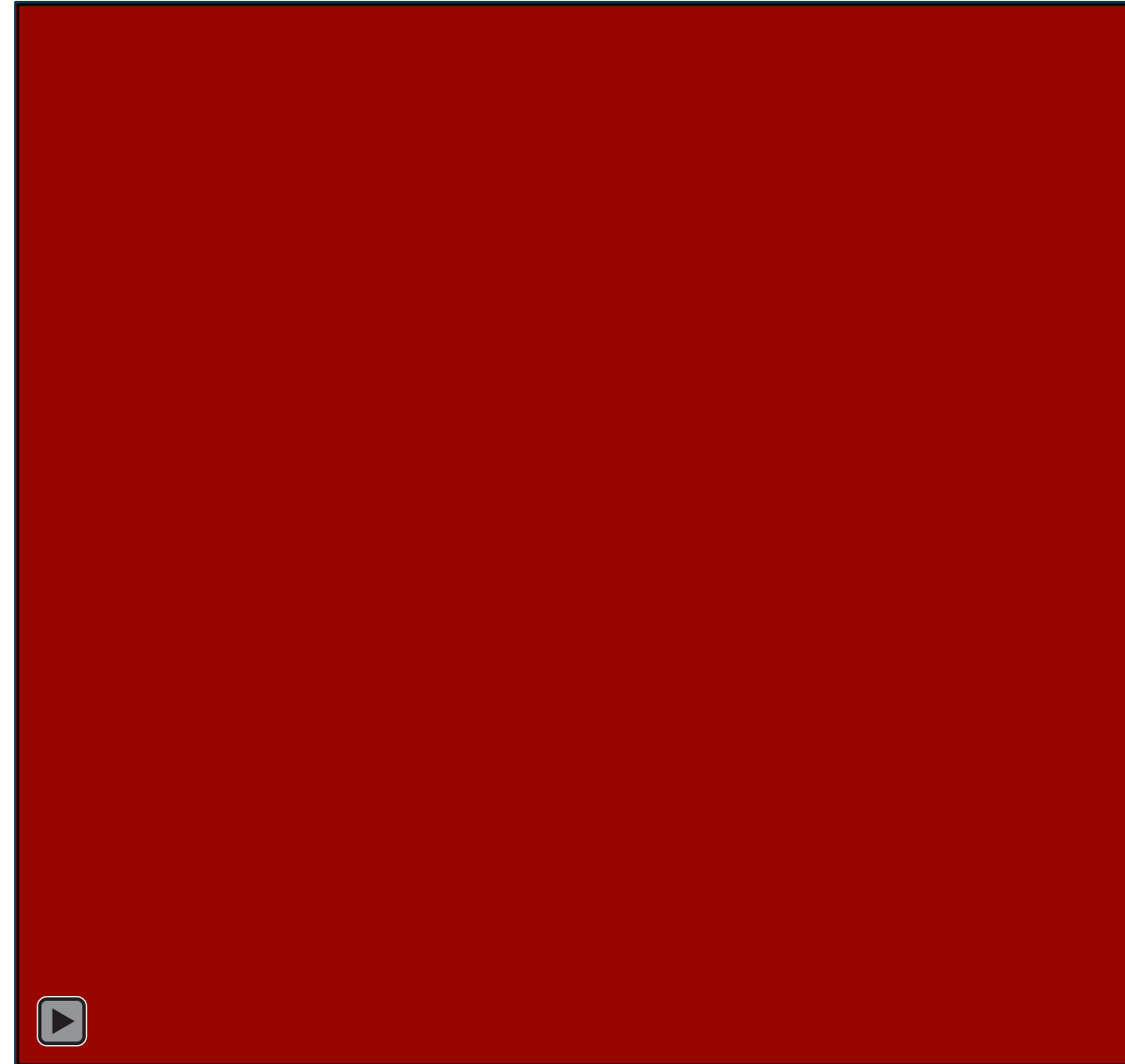
Faster power swings defeat traditional PSB

- Traditional PSB and OOST implementations
 - Distance elements are not blocked, relay may see power swing as a fault
 - OOST element does not trip
- During disturbance, Z1 crossed blinders in less than a half cycle



New dZ/dt PSB operates reliably

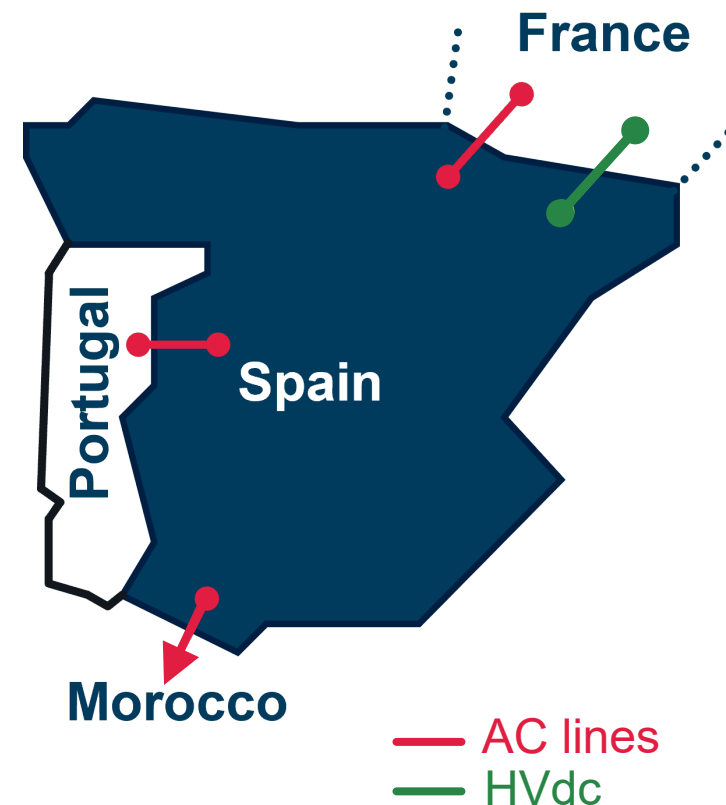
- New method in SEL-T401L Ultra-High-Speed Line Relay measures dZ/dt
- dZ/dt is measured continuously
- Blinders are not needed
- New method operates properly with low inertia systems



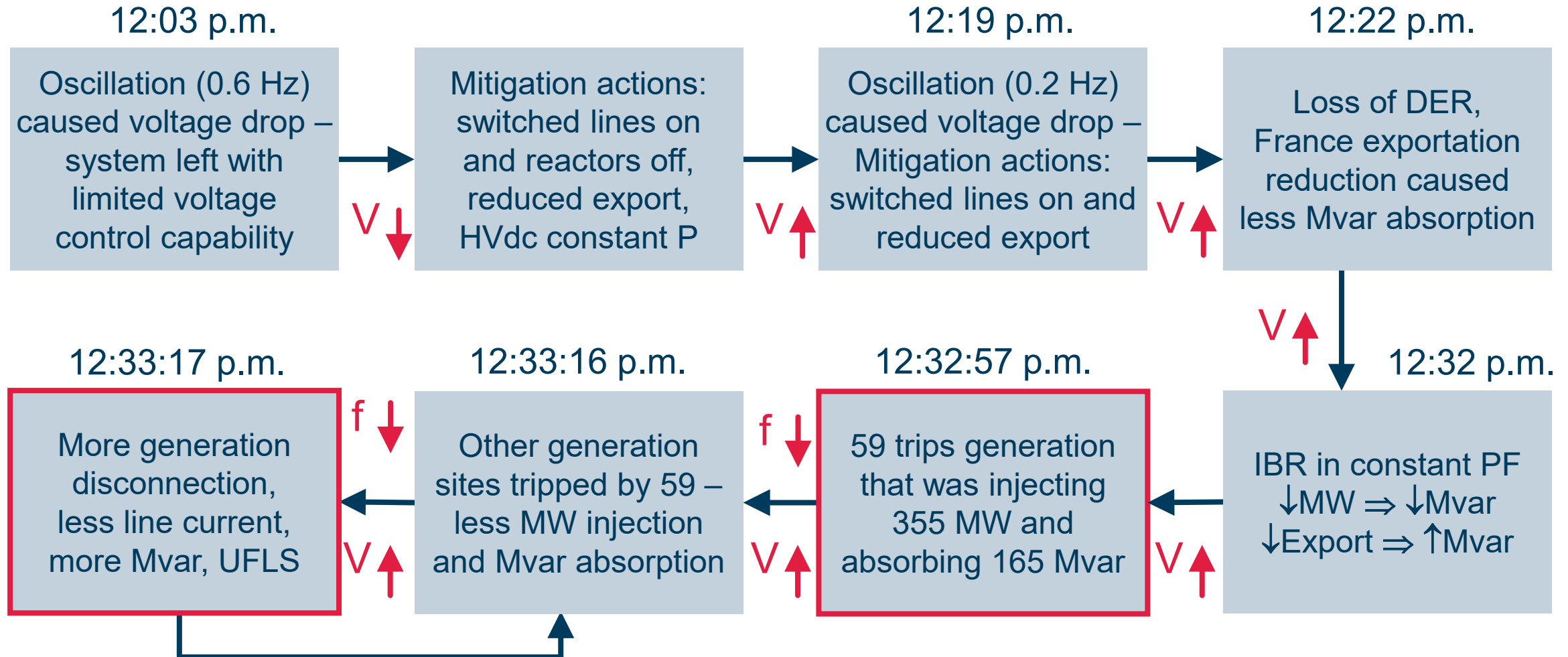
Spanish peninsular electrical system major incident, April 2025

Spanish electrical system on April 28, 2025

- Demand, 27 GW at 12:00 p.m.
- Generation, 80% renewables
 - Solar 54%
 - Wind 10%
- Export, 4.6 GW
- IBR sources in power factor control mode, no contribution to regulate voltage



Sequence of events on April 28, 2025



Power demand tracking April 20, 2025



Source: demanda.ree.es

IBR control may cause oscillations

“During the incident analysis, it was determined that the oscillation (0.6 Hz) was not natural to the system but rather forced. This oscillation is observed with significant amplitude at a Photovoltaic Plant...”

“...it is therefore likely that the oscillation was originated from an internal control malfunction or anomaly within the plant...”

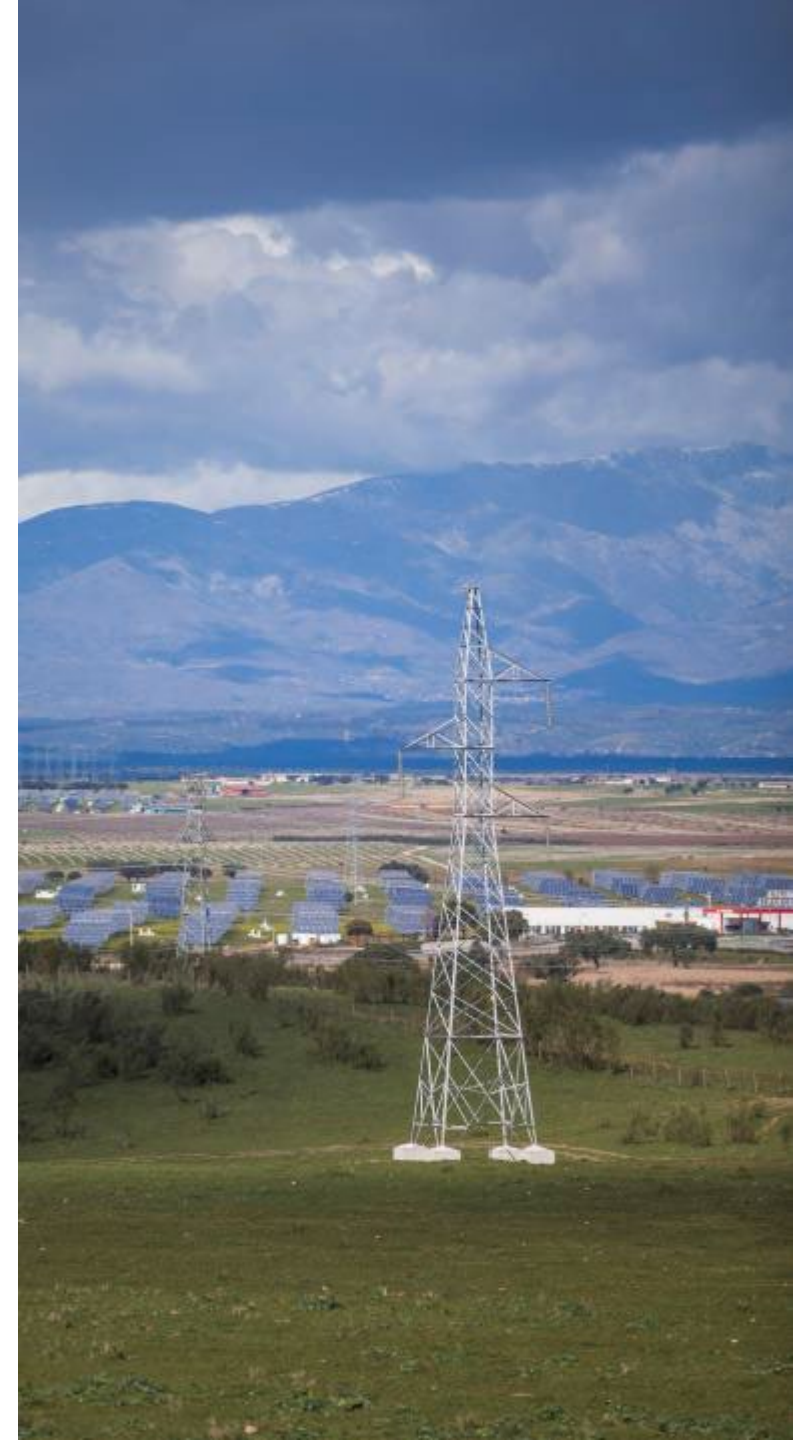
“The oscillation from the plant prompted the implementation of mitigation measures aimed at damping the system-wide oscillations, which in turn reduced the system’s voltage control margins.”

Source: “Blackout in Spanish Peninsular Electrical System the 28th of April 2025” by Red Eléctrica

Conclusions

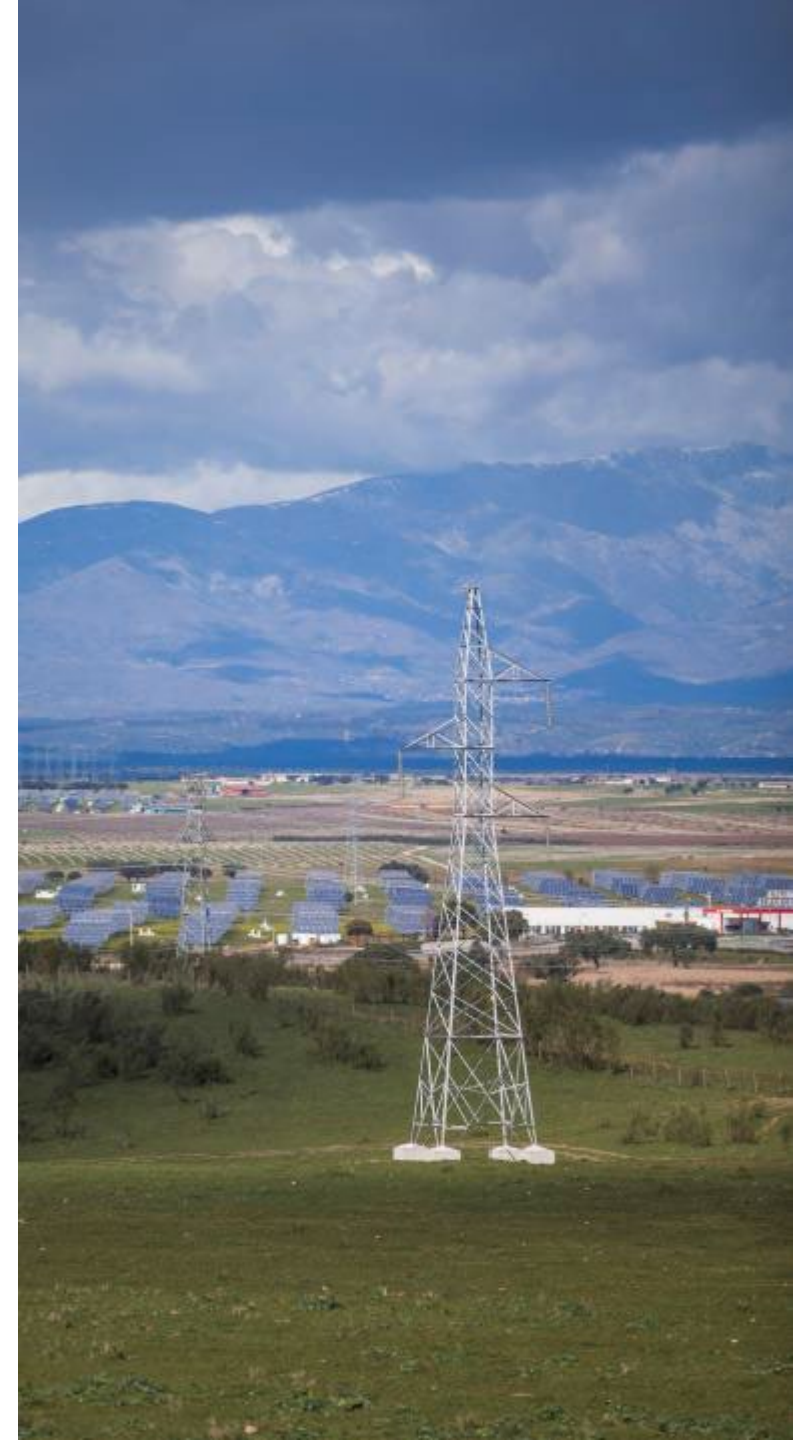
Conclusions

- Accurate model of IBRs is essential to support reliable system studies
- Modern, adaptative, and fast RAS are important components to keep electrical systems stable with IBRs
- Incorporation of existing HVdc lines in RAS enhances flexibility and efficiency of the scheme



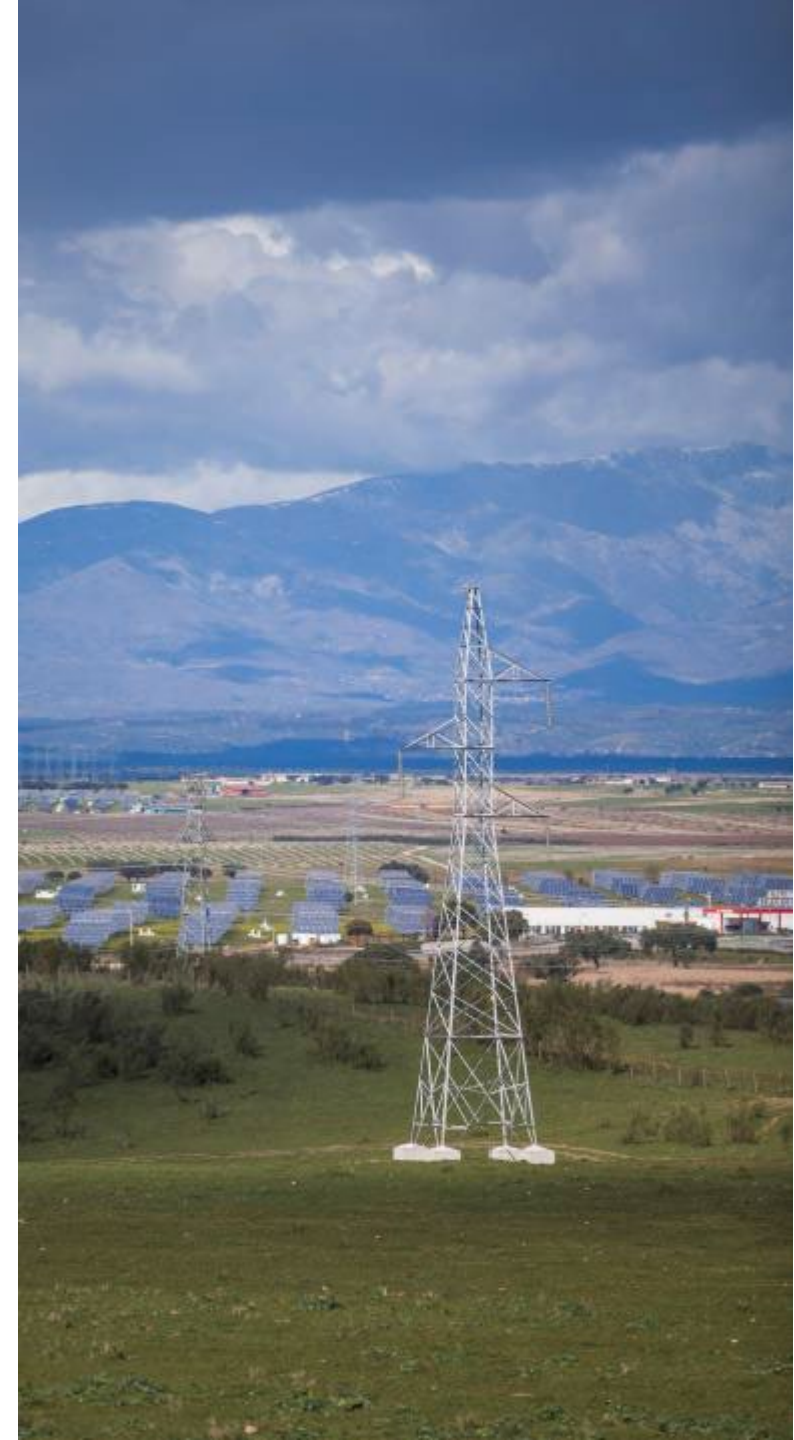
Conclusions (cont.)

- Enhanced PSB and OOST algorithms are required for systems with low inertia
- Deployment of WAMS is mandatory for real-time operation and post-event analysis
- Revisions are needed for voltage control practices and standards for all resources, including DER and IBR



Conclusions (cont.)

- SSO detection, mitigation, and real-time corrective actions with POD may be required before large penetration of IBRs
- ES are experts in and have solutions for RAS, WAMS, studies, and SSO mitigation



Thank you



Milliseconds matter

MONITORING FAST LOAD CHANGES IN MODERN POWER SYSTEMS



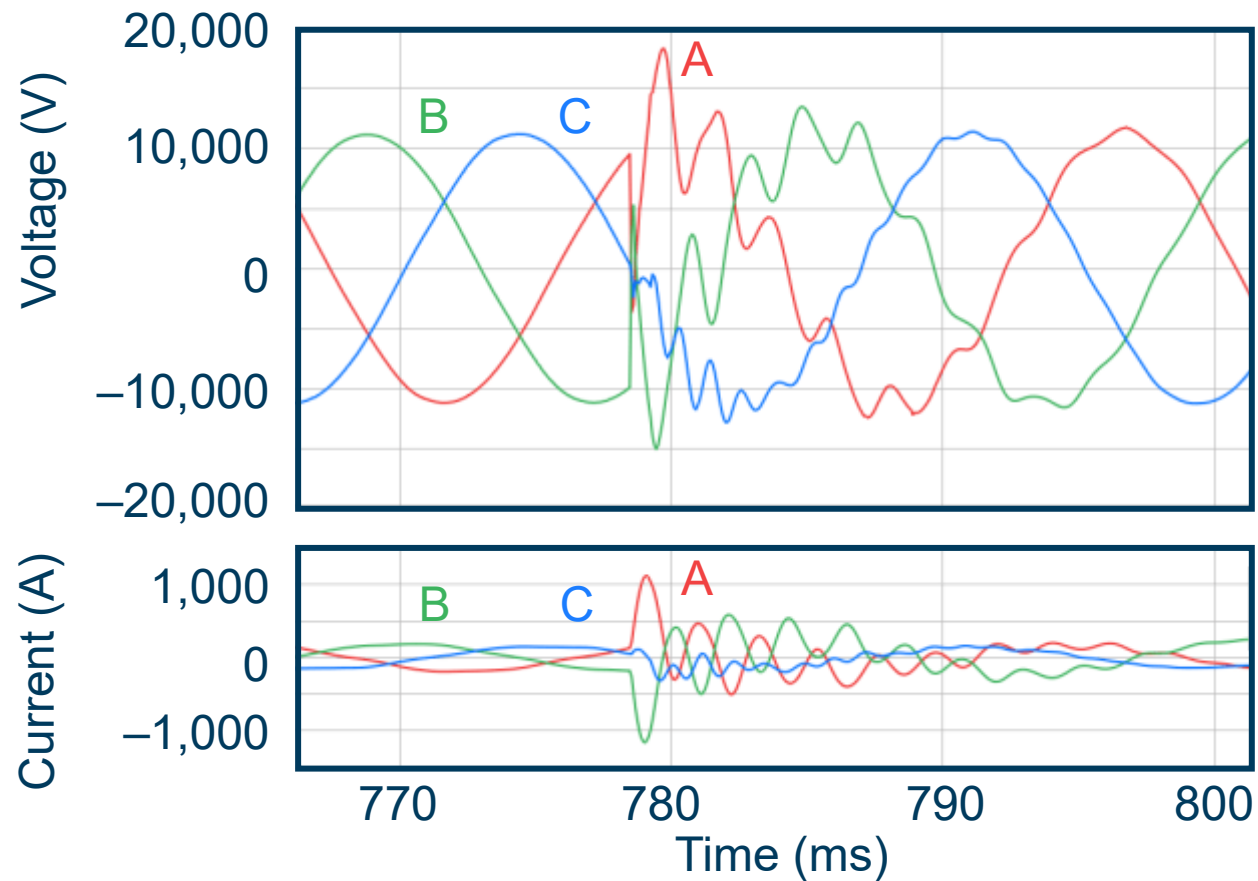
Richard D. Kirby, PE, Senior Engineer

“We can’t detect why our 13.8 kV cap bank vacuum bottles keep blowing up. We are very interested in using an SEL-T35 with continuous data recording in our substation so we can provide the manufacturer with data to help resolve our issue.”

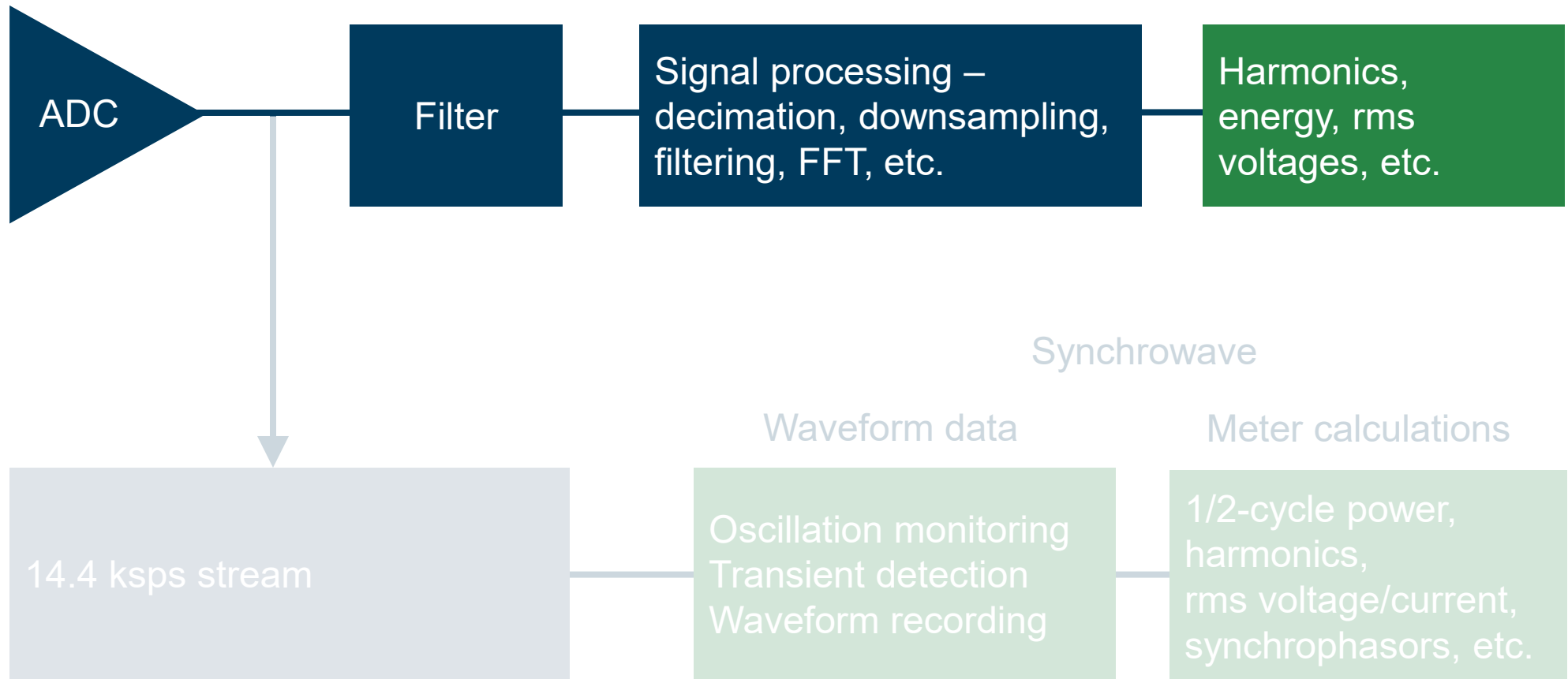
—American Castings



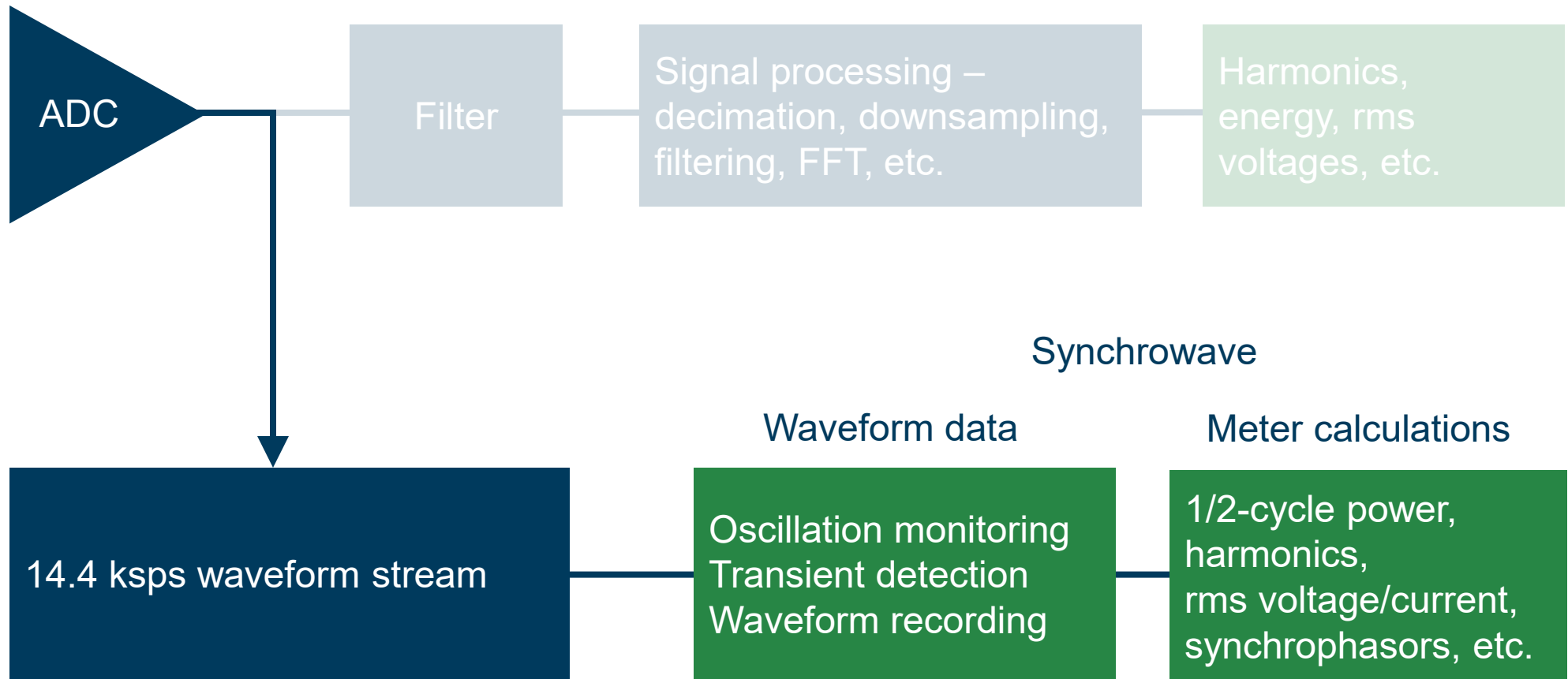
American Castings captures switching transient within an hour of installation



Traditional monitoring loses dynamic information



Continuous streaming captures all content

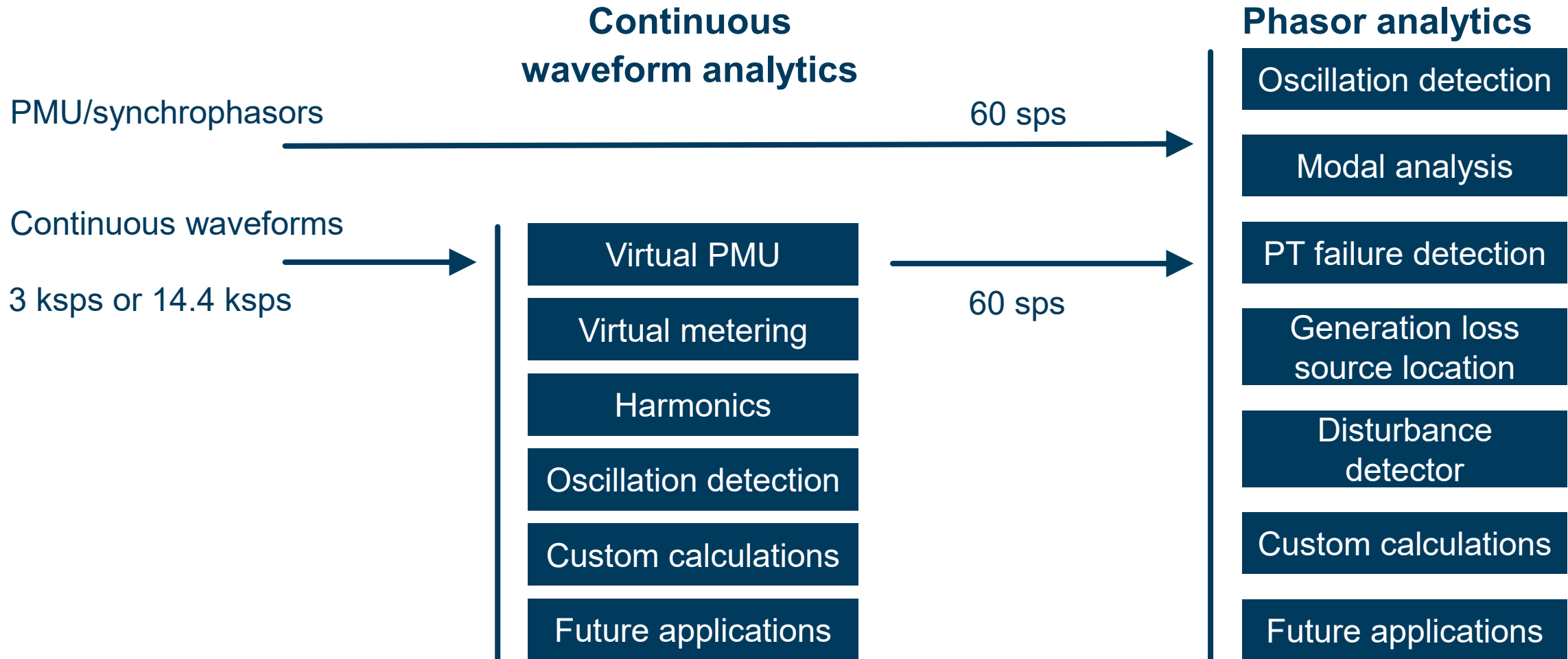


Transform wave data into meter values



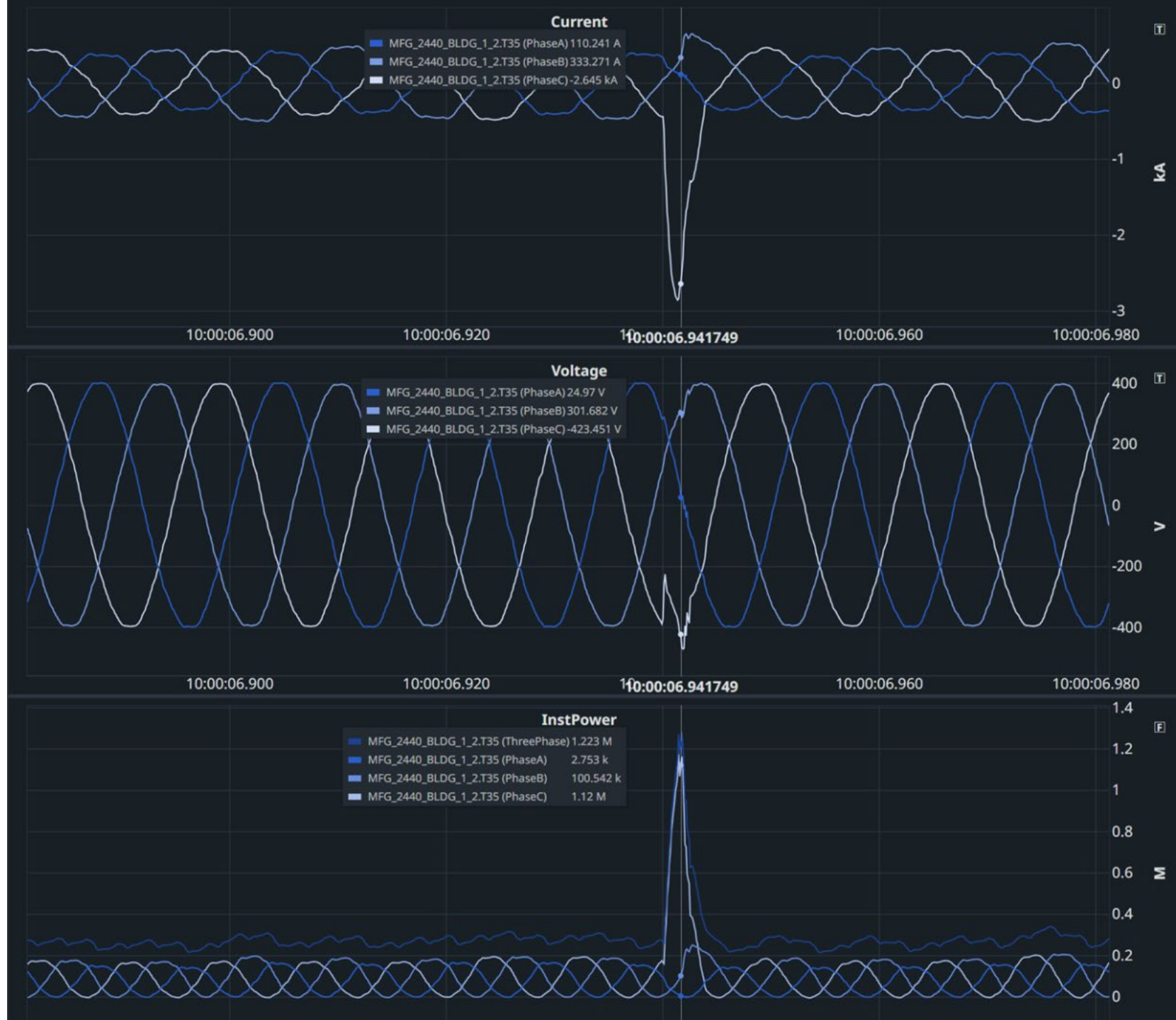
Quantity	Description
V, I, and Φ	1 cycle rms, fundamental
Frequency	1/2 cycle frequency
W, Q, and S	1 cycle rms, fundamental
Symmetrical components	1 cycle rms
Synchrophasors	50, 60 sps
Harmonics	20th or 100th
Flicker	PLT, PST

Combine waveform and phasor analytics with Synchrowave



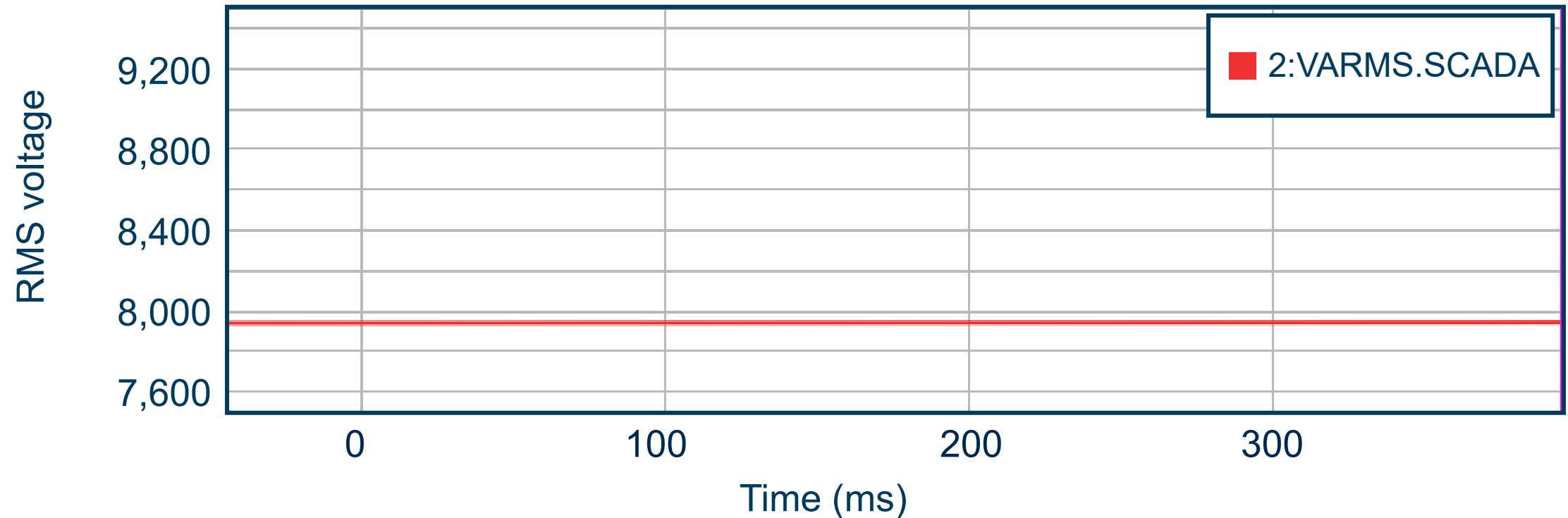
Detect power system disturbances

- Create custom notifications
- Link to directly to event data

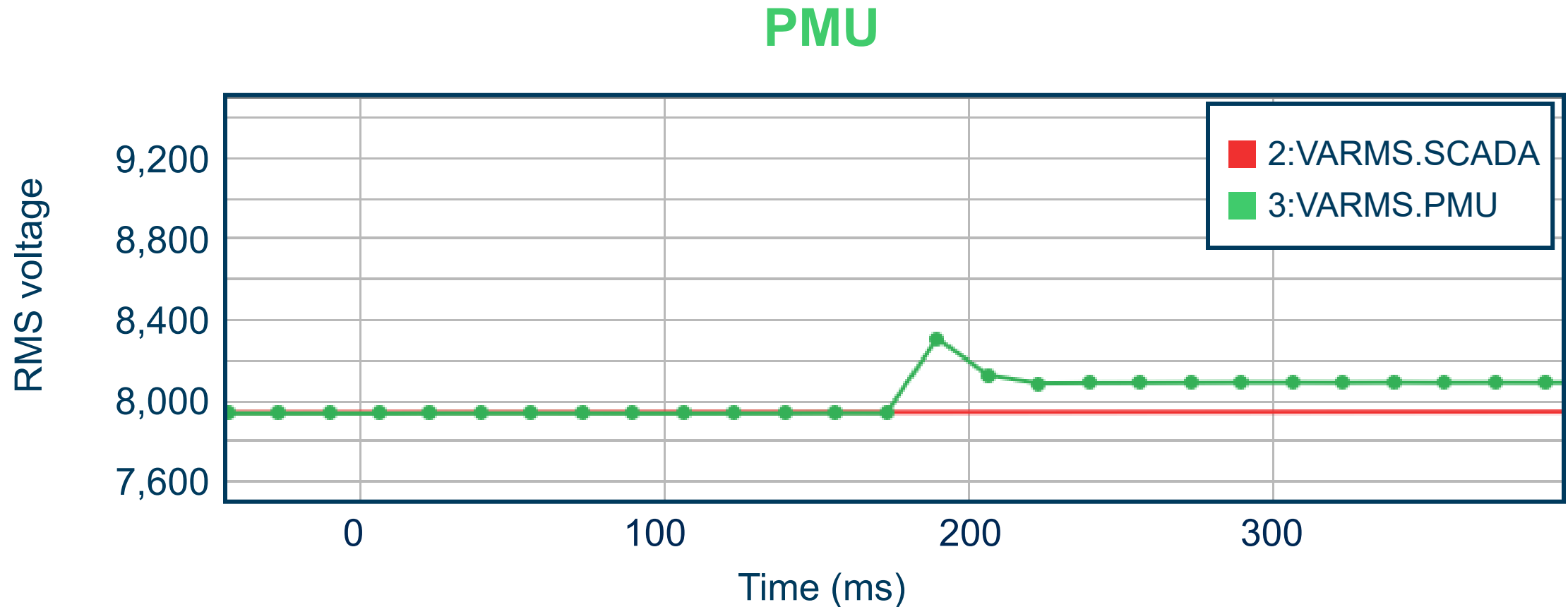


Three-second SCADA misses transient

SCADA

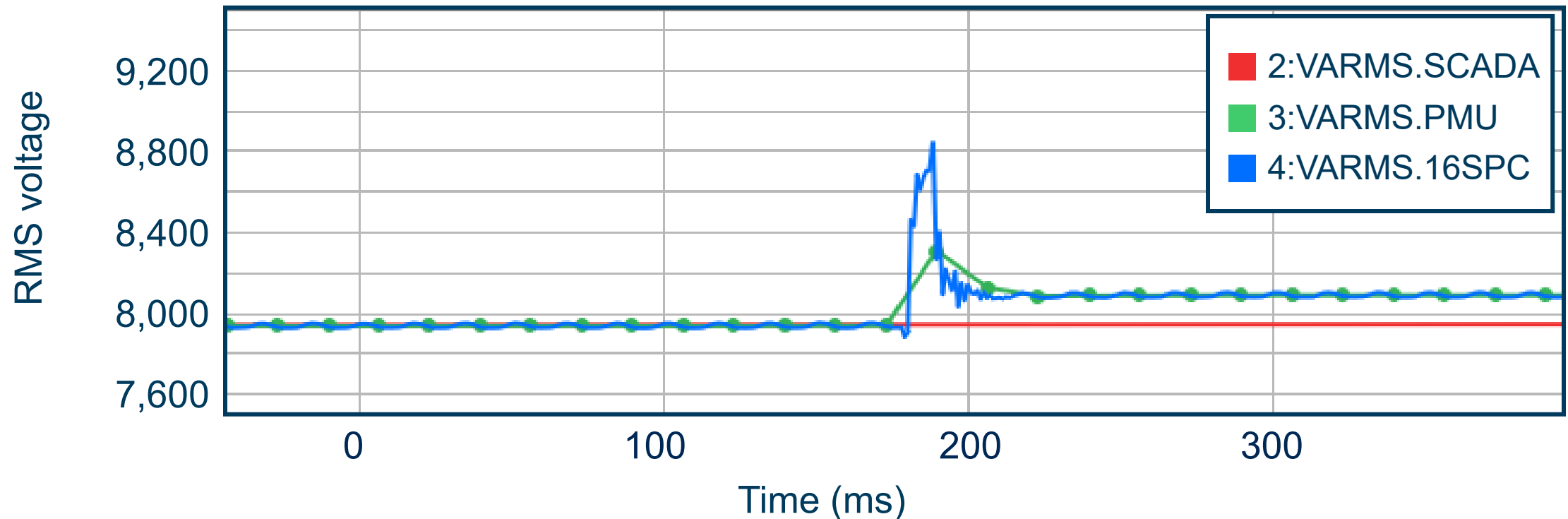


60 sps PMU data starts to see transient



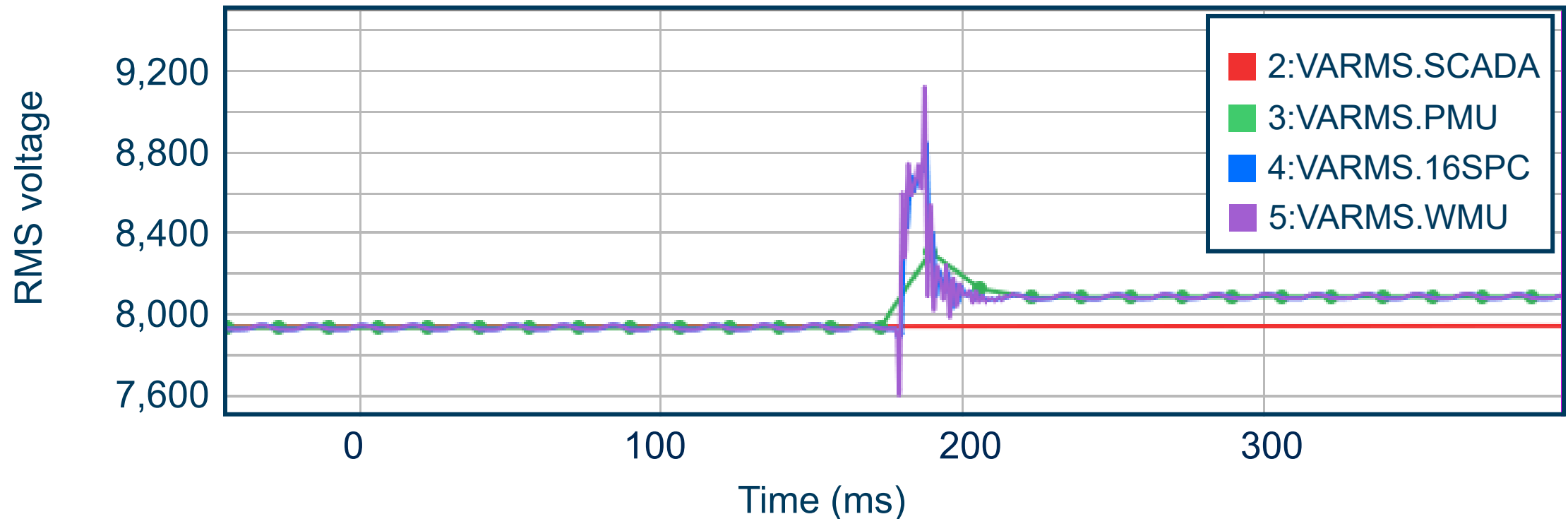
Relay event reports approximate transient

16 samples per cycle



Continuous recording at 14.4 ksp/s captures peak and ringing

14.4 ksp/s



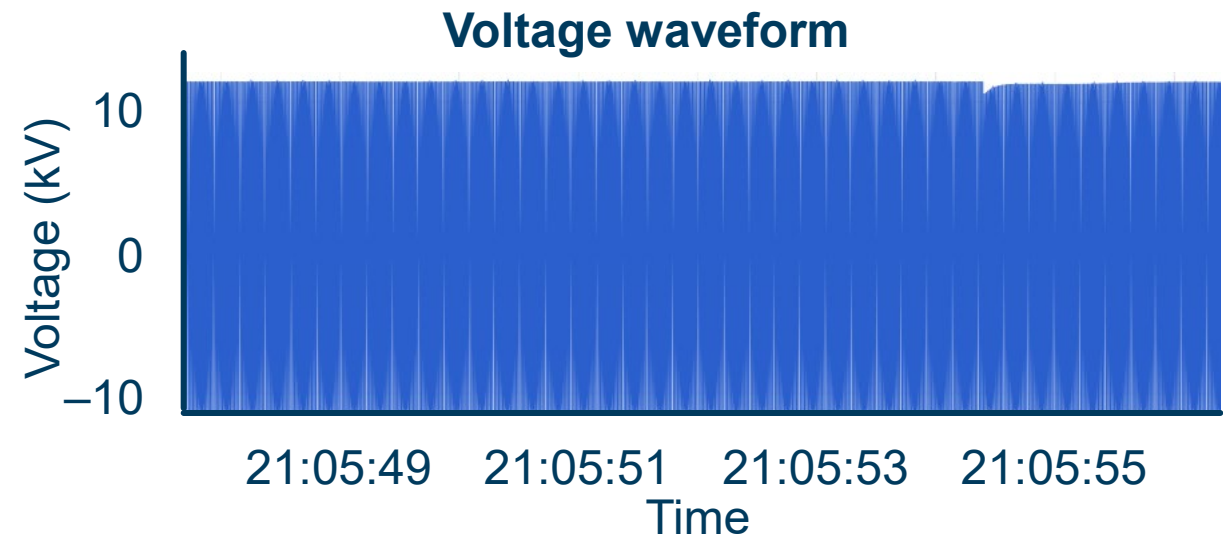
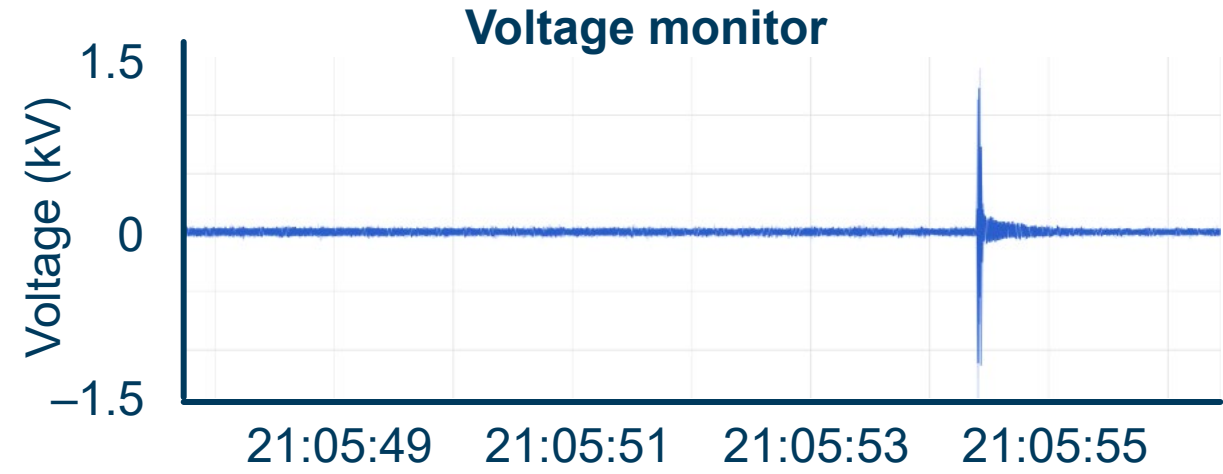
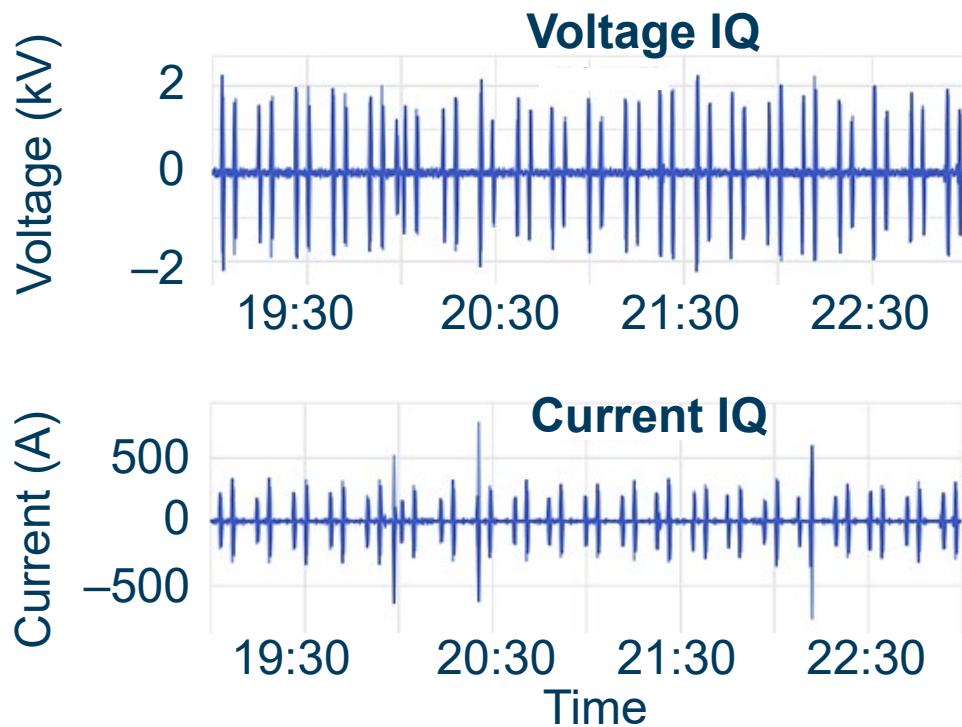
Perform advanced custom calculations

- Constant variables
- Array variables
- Wait timers
- Time variables
- Math operators (+, −, /, *)
- Comparison operators (=, ==, <>, !=, >, >=, <=)
- Math functions (SQRT, SUM, AVG, LOG, SIN, MIN, MAX, etc.)
- Complex number functions (REAL, IMAG, MAG, ANG, etc.)
- Power system functions (SEQ0, SEQ1, and SEQ2)
- Filter functions (FIR and IIR)
- IF statements

Incremental quantities

Easily identify disturbances

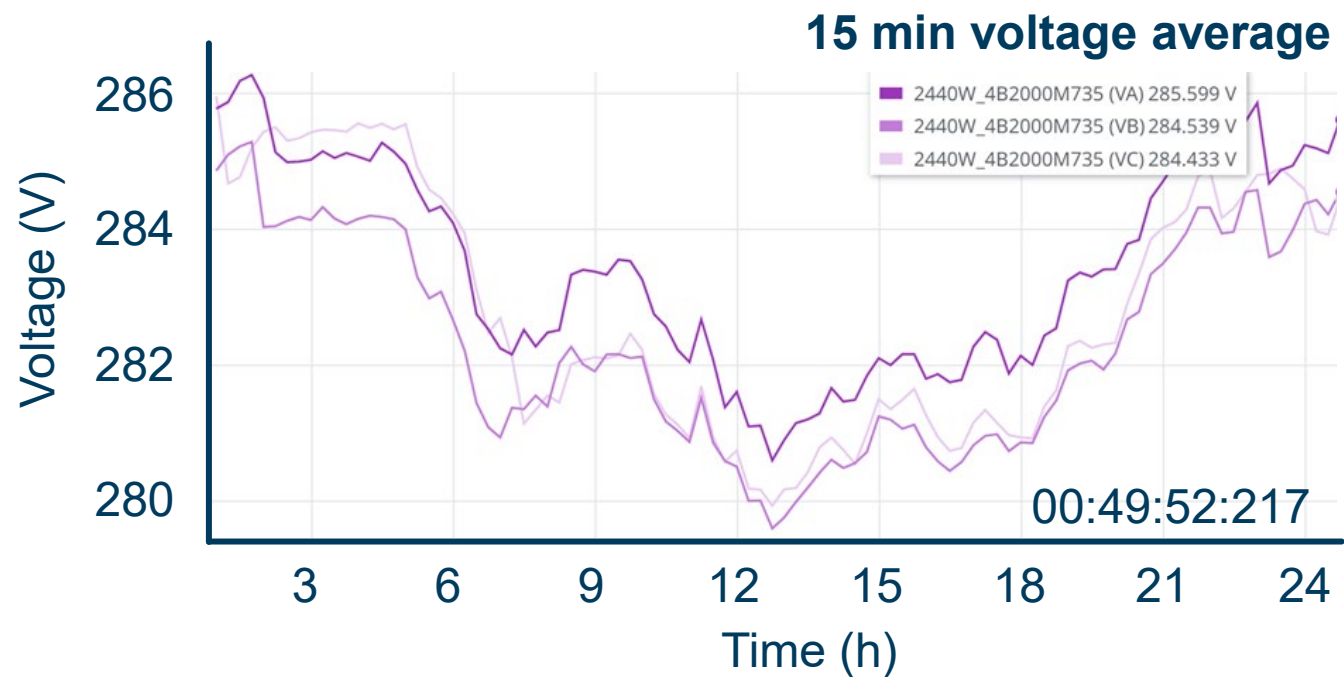
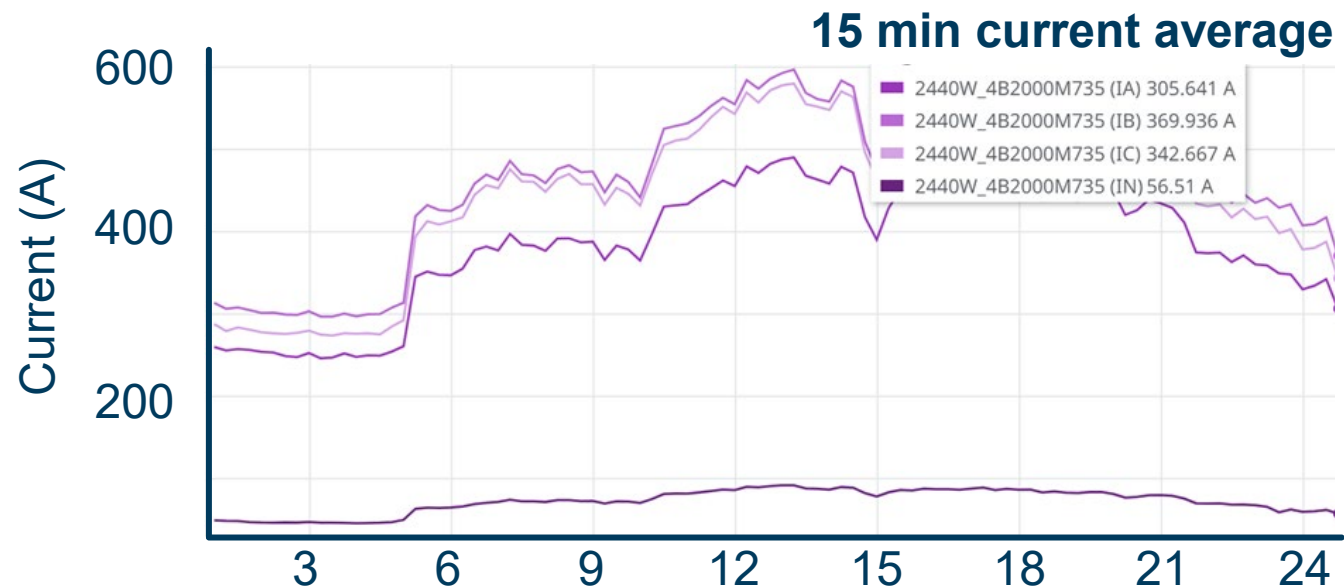
$$IQx[k] = x[k] - x[k - 240]$$



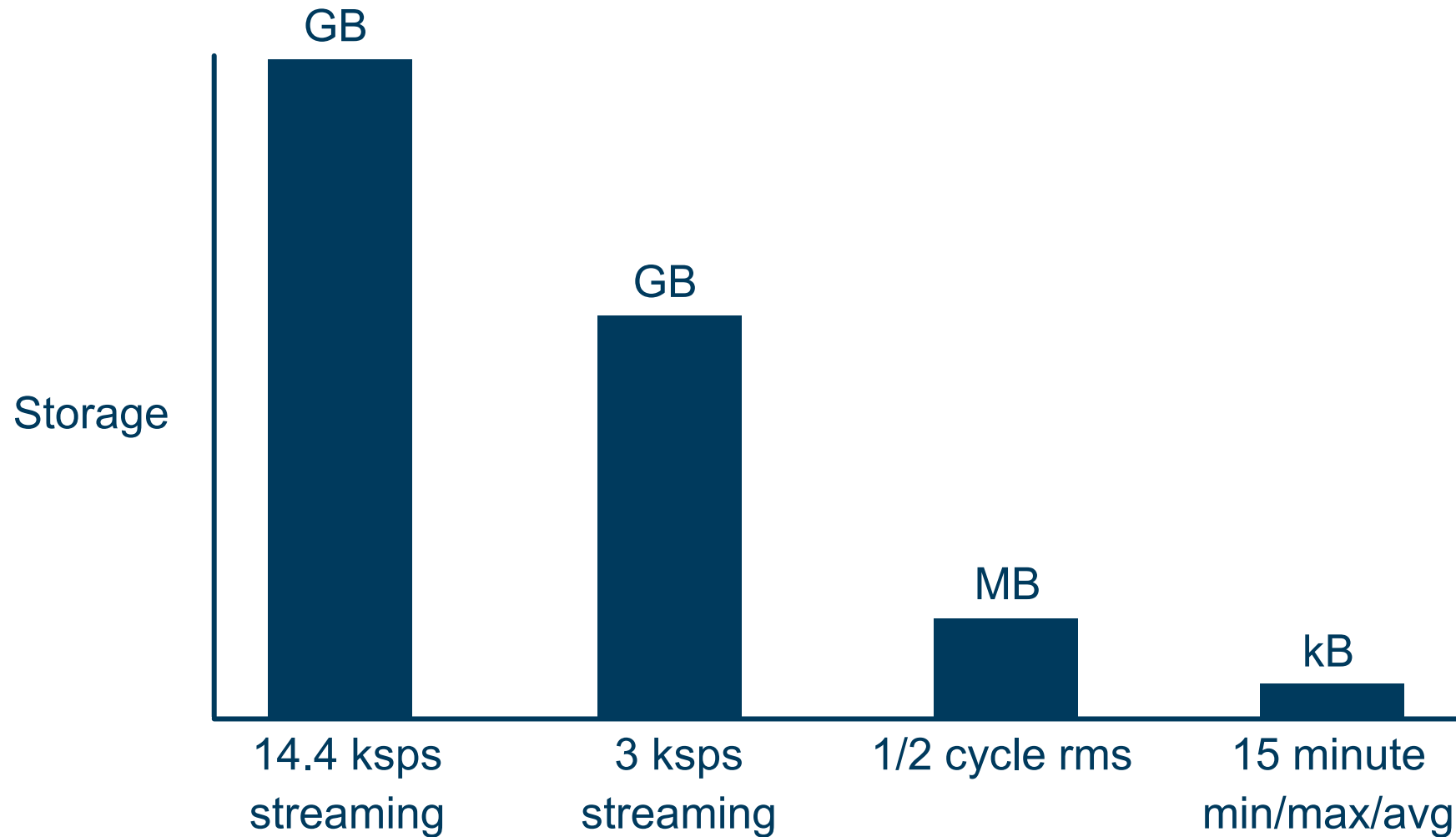
Trend data with enhanced software load profiles

Acquisition rate from 50 ms to 7,200 s

- RMS
- SUM
- COUNT
- COI
- MAX
- MIN
- AVG
- EOI



Optimize data storage



Meet modern PQ compliance in one package

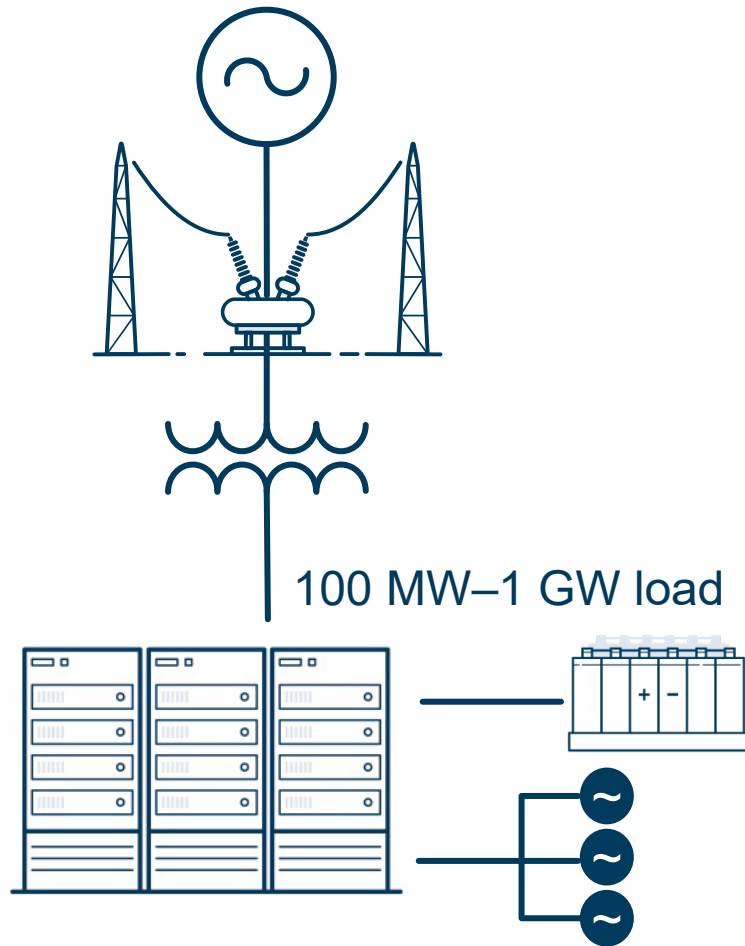
Standard	Compliant
IEEE 519	✓
IEEE 2800	✓
PRC-0028	✓
IEEE 1547	✓
EN 50160	✓

Harmonic Voltage Compliance

! = Fail ⚠ = Warn

Harmonic	VA Limit	VA Measured	VB Limit	VB Measured	VC Limit	VC Measured
THD	12%	8.66%	12%	8.49%	12%	8.66%
2	7.5%	4.86%	7.5%	4.69%	7.5%	4.86%
3	7.5%	5.38%	7.5%	5.21%	7.5%	5.38%
4	7.5%	5.9%	7.5%	5.73%	7.5%	5.9%
5	7.5%	6.42%	7.5%	6.24%	7.5%	6.42%
6	7.5%	6.93% ⚠	7.5%	6.76% ⚠	7.5%	6.93% ⚠
7	7.5%	7.45% ⚠	7.5%	7.28% ⚠	7.5%	7.45% ⚠
8	7.5%	7.97% !	7.5%	7.8% !	7.5%	7.97% !
9	7.5%	8.49% !	7.5%	8.31% !	7.5%	8.49% !
10	7.5%	4.69%	7.5%	4.52%	7.5%	4.69%
11	7.5%	5.21%	7.5%	5.04%	7.5%	5.21%
12	7.5%	5.73%	7.5%	5.55%	7.5%	5.73%
13	7.5%	6.24%	7.5%	6.07%	7.5%	6.24%
14	7.5%	6.76% ⚠	7.5%	6.59%	7.5%	6.76% ⚠

Modern load dynamics are changing how we monitor and control the power system

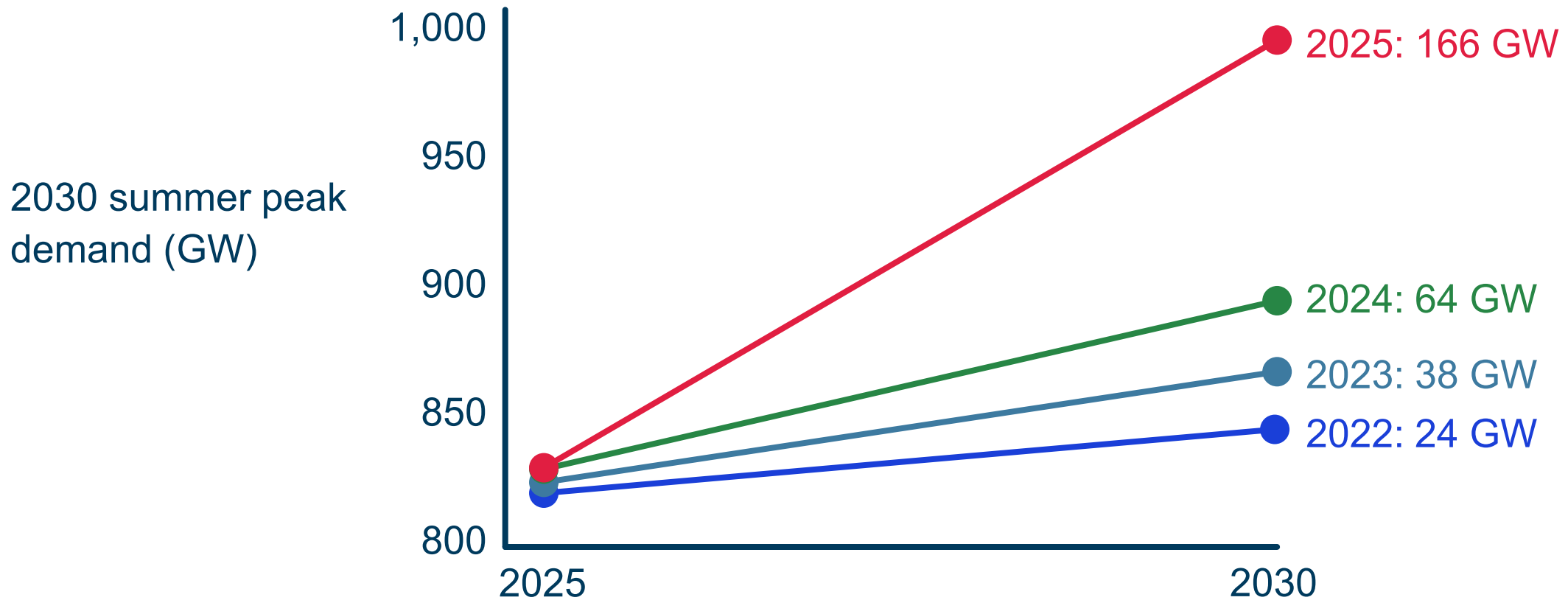


AI searches consume 10–100 times more energy than a standard text search

AI search type	Energy consumed (Wh)
Google search	0.3
ChatGPT (small-sized LLM)	0.24–0.34
ChatGPT (medium-sized LLM)	5
Image generation	1.7
Video generation (6 seconds/8 frames per second)	115
One mile in an electric vehicle	250

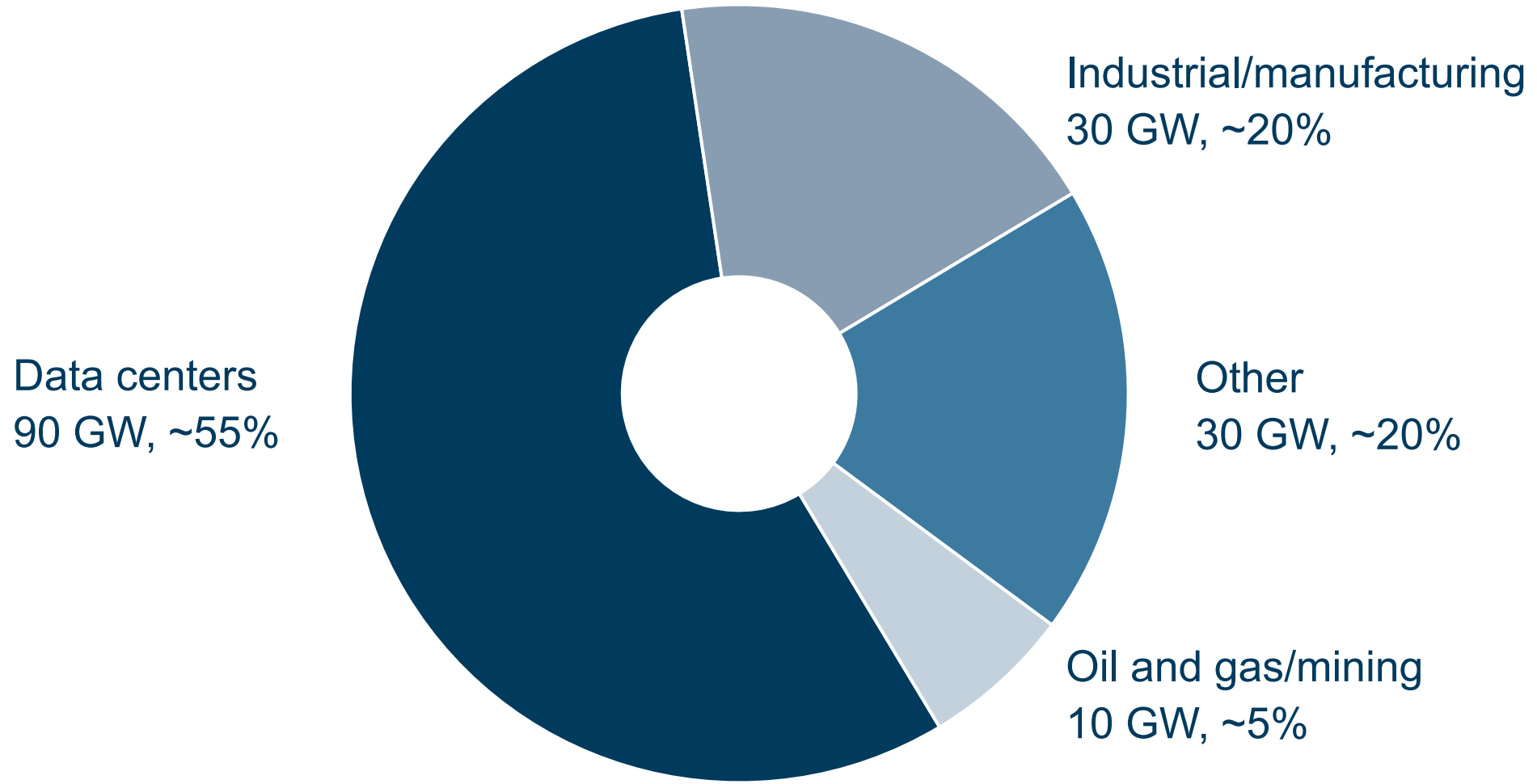
Five-year nationwide summer peak growth

Aggregate of forecasts submitted to FERC in 2022–2025



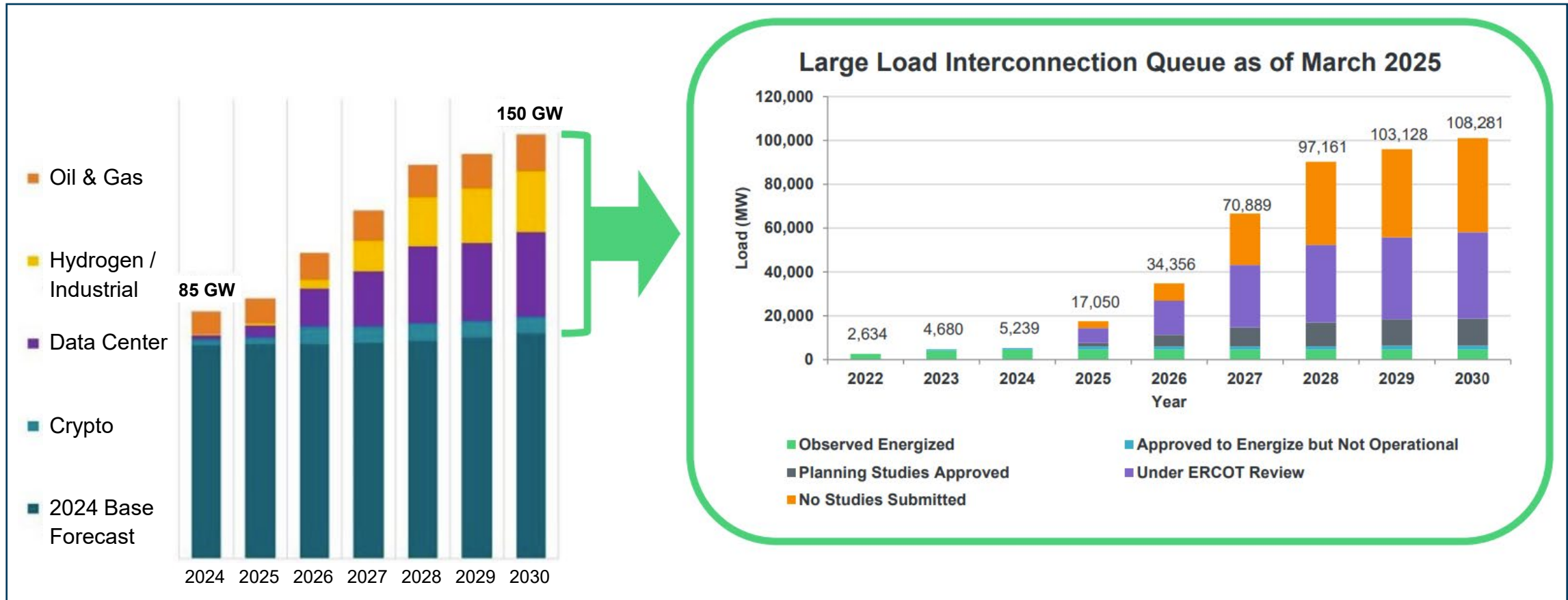
Source: gridstrategiesllc.com/wp-content/uploads/Grid-Strategies-National-Load-Growth-Report-2025.pdf

Drivers of load growth, 2025–2030



Source: gridstrategiesllc.com/wp-content/uploads/Grid-Strategies-National-Load-Growth-Report-2025.pdf

What is happening in ERCOT?



Source: [nerc.com/globalassets/who-we-are/standing-committees/rstc/llwg/lltf_april_meeting__technical_workshop_presentations_.pdf](https://www.nerc.com/globalassets/who-we-are/standing-committees/rstc/llwg/lltf_april_meeting__technical_workshop_presentations_.pdf)

AI data center load profiles

CLASSIFICATION OF LARGE LANGUAGE MODEL (LLM) WORKLOADS

Training

- Model trains on a vast dataset
- It is the most power-intensive phase with sustained high GPU utilization
- It may last days, weeks, or even months, and uninterrupted power is crucial

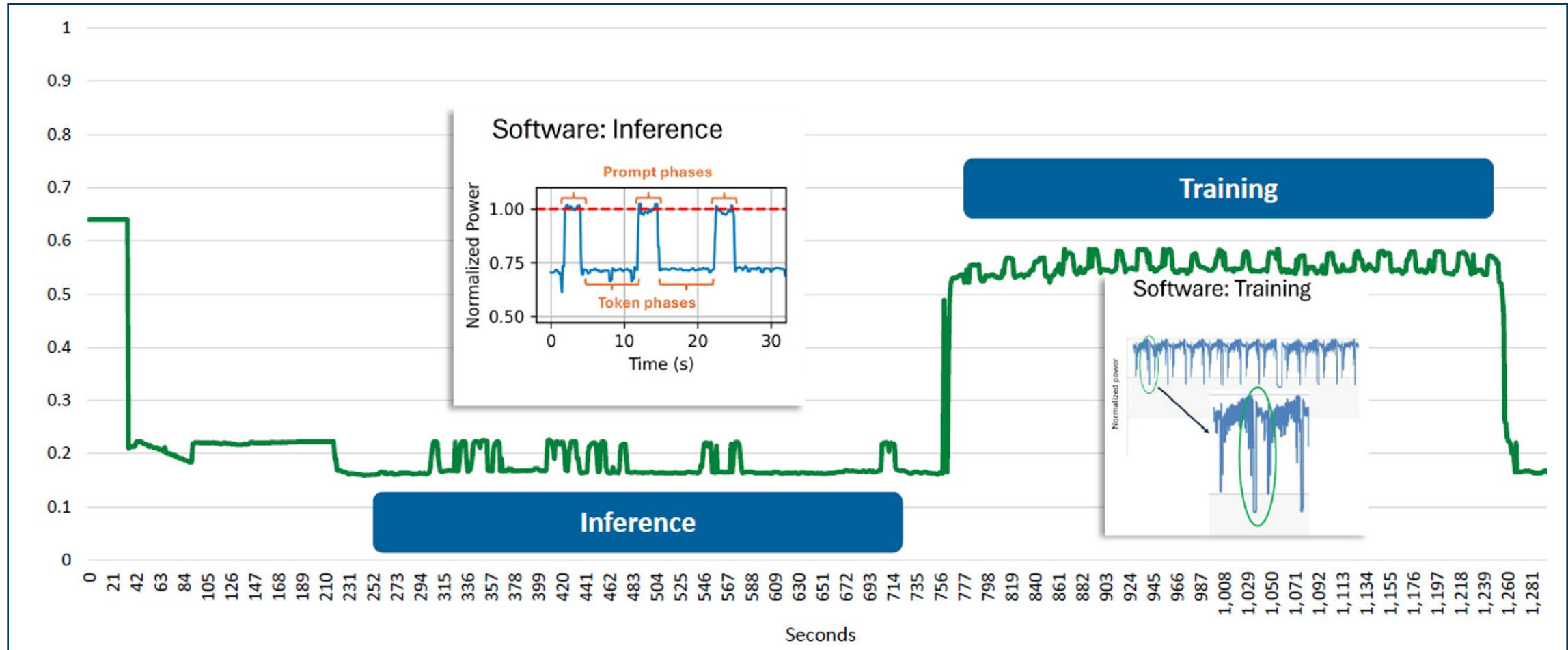
Fine-tuning

- Involves adapting a pre-trained model to a specific domain
- Requires moderate to high power consumption
- Involves intermittent high GPU utilization, typically for shorter duration

Inference

- Involves application of trained models to new data
- Is least power-intensive phase
- Requires variable, user-driven power usage
- Variability leads to short bursts of power consumption

AI inference and training loads

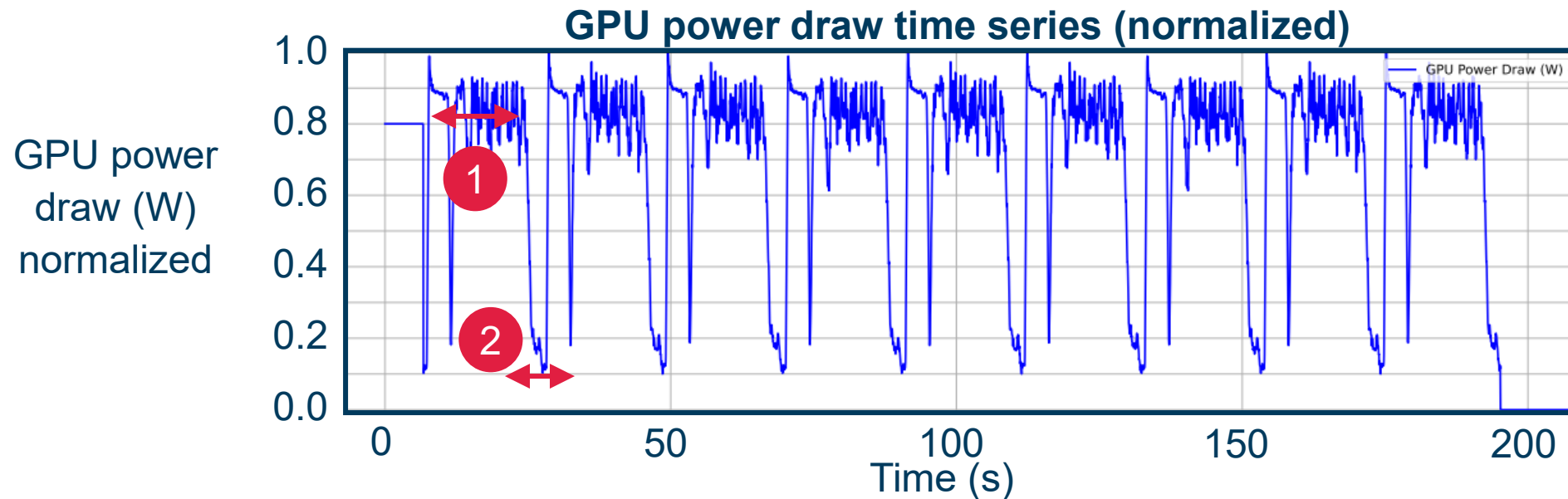


Source: IEEE PES Webinar, "Data Centers and Grid Reliability in a Rapidly Evolving Landscape," June 2025.

AI training runs create large load changes

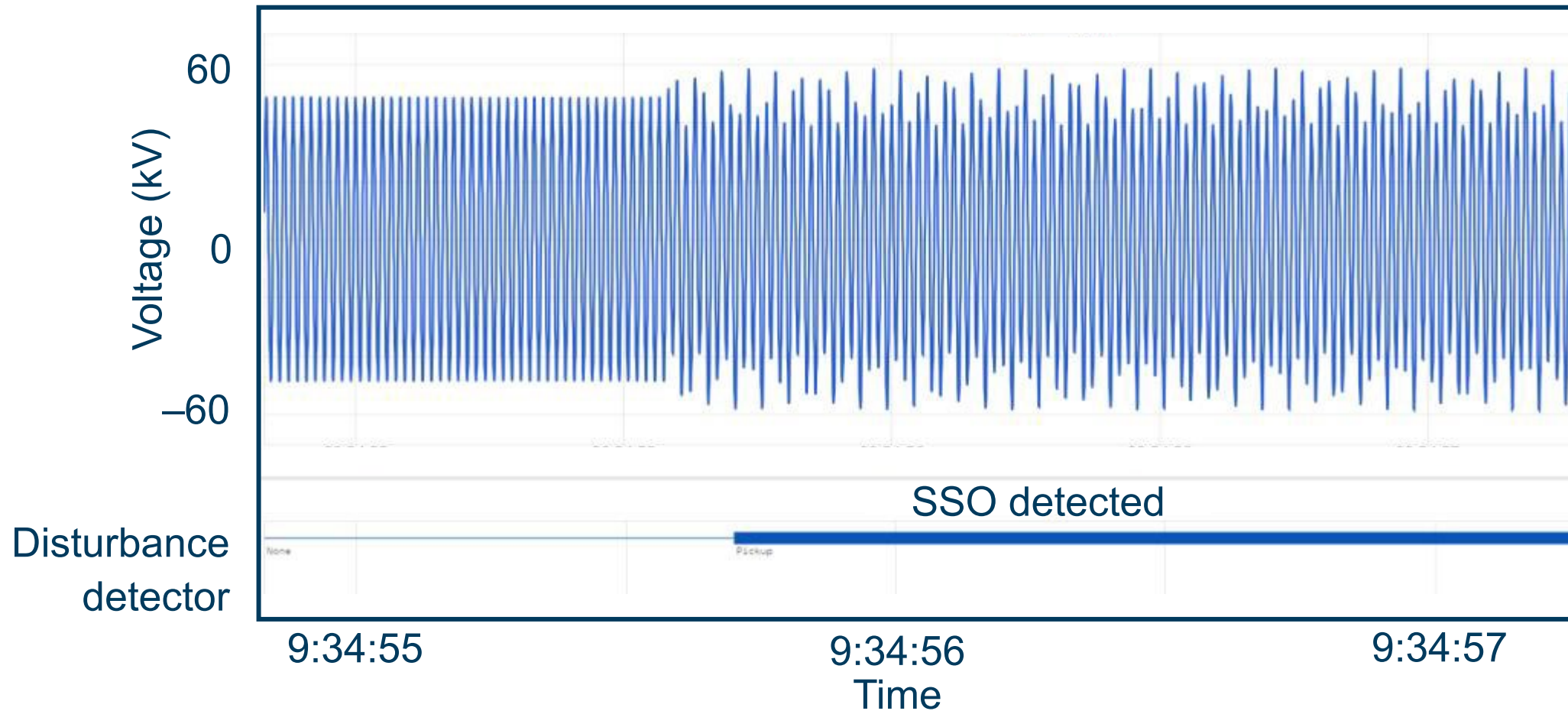
High variability in power consumption during training of AI LLMs

- Synchronized compute-heavy phase of GPU units **1**
- Synchronized communications-heavy phase of GPU units **2**



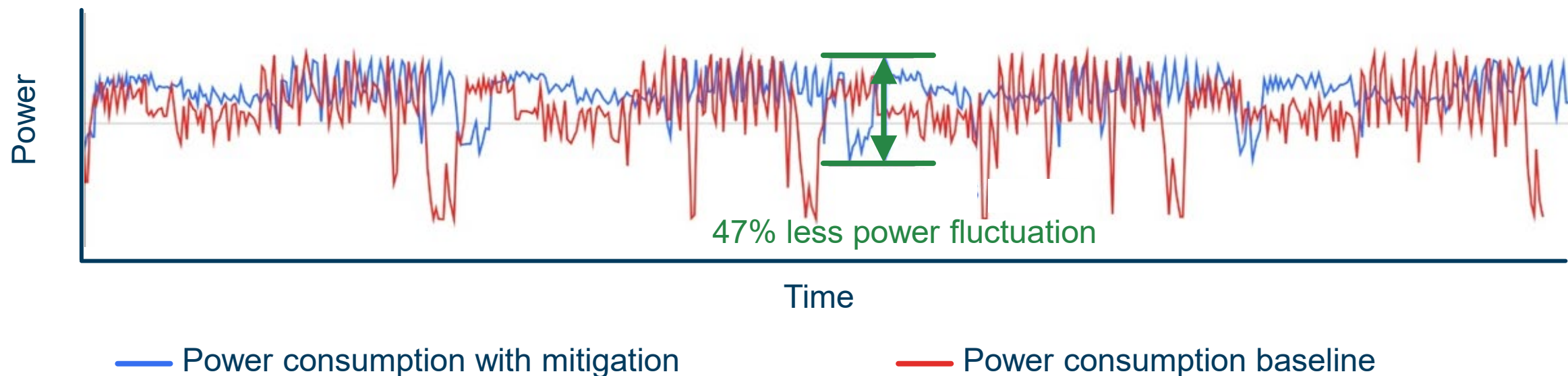
Deployment sizes have grown from <10 MW to >100 MW for foundational model training that requires several tens of thousands of GPUs

Large power fluctuations can cause oscillations



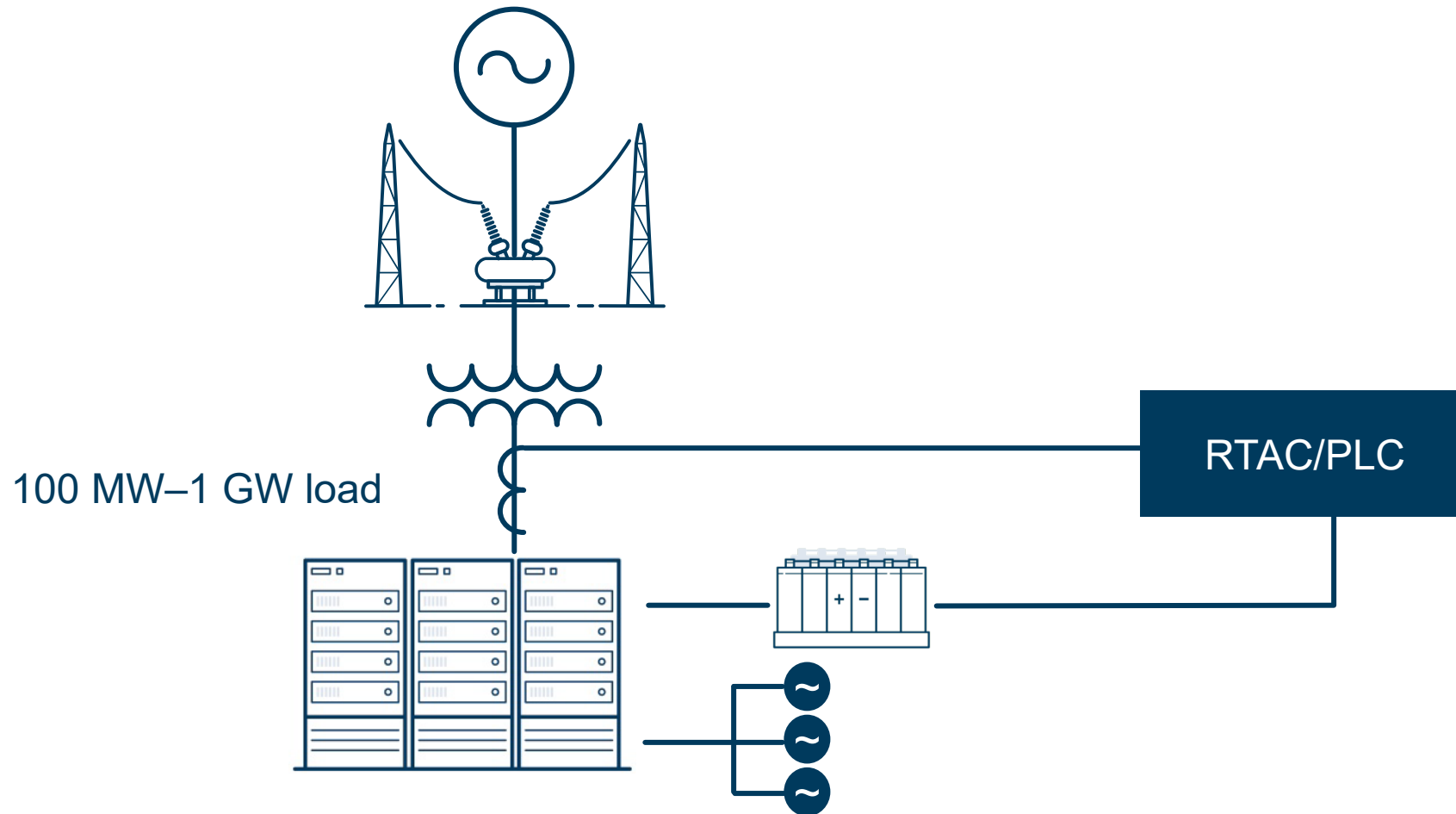
Google working to smooth machine learning computational workloads

Power fluctuation with and without compiler-based mitigation



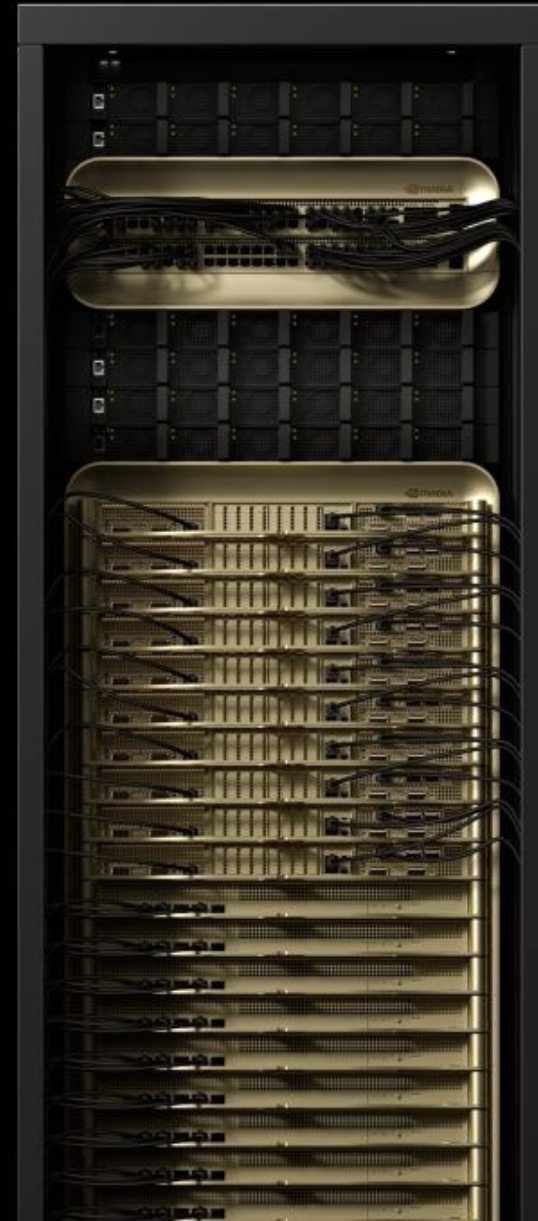
Source: cloud.google.com/blog/topics/systems/mitigating-power-and-thermal-fluctuations-in-ml-infrastructure

BESS systems dampen AI loads



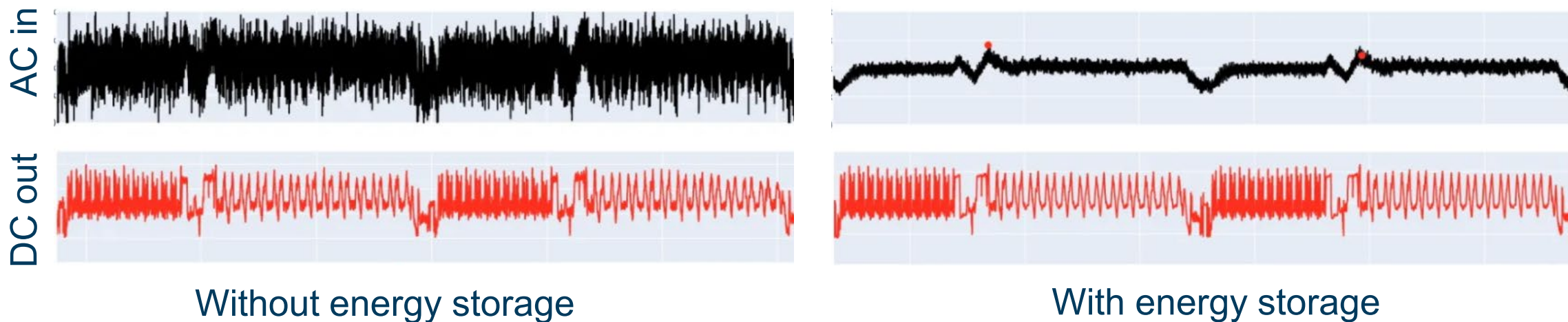
NVIDIA is building energy storage into specialized servers

Source: [developer.nvidia.com/
blog/how-new-gb300-nvl72-
features-provide-steady-power-for-ai](https://developer.nvidia.com/blog/how-new-gb300-nvl72-features-provide-steady-power-for-ai)



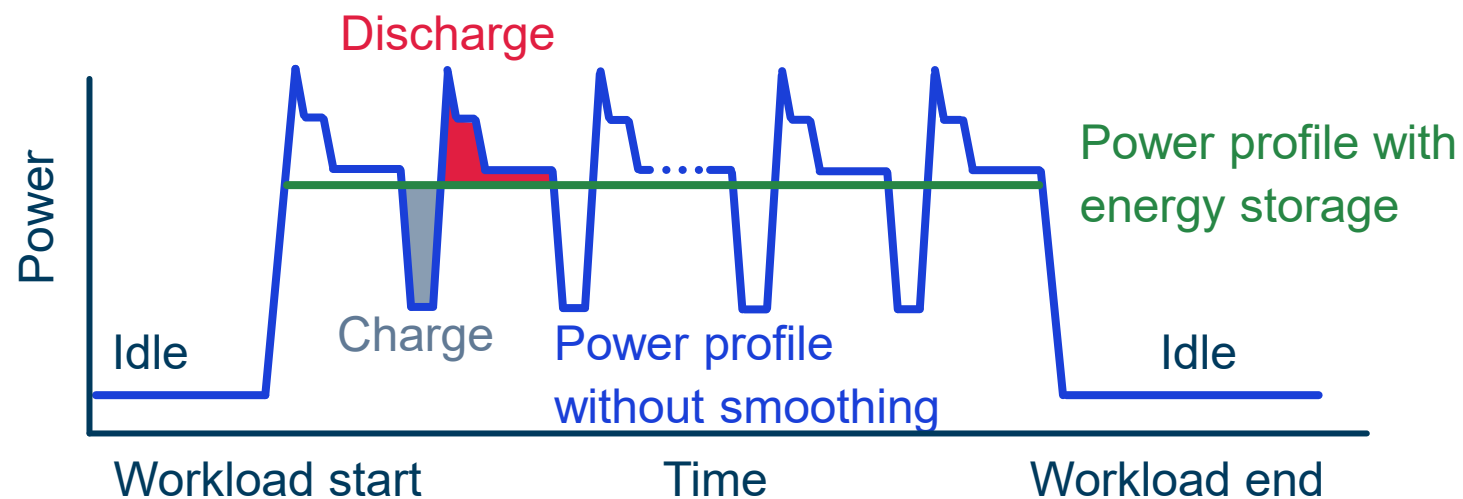
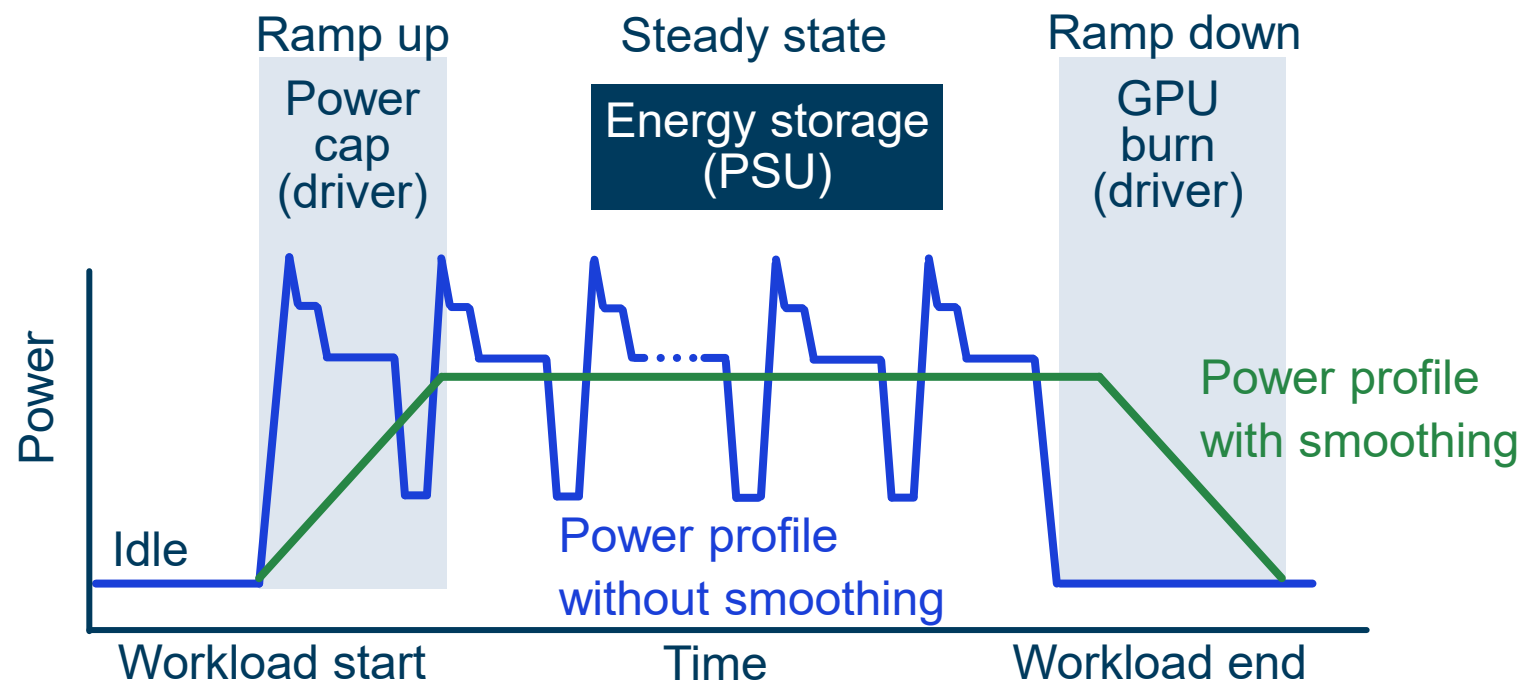
Server energy storage reduces load fluctuations

Megatron LLM power shelf load profile



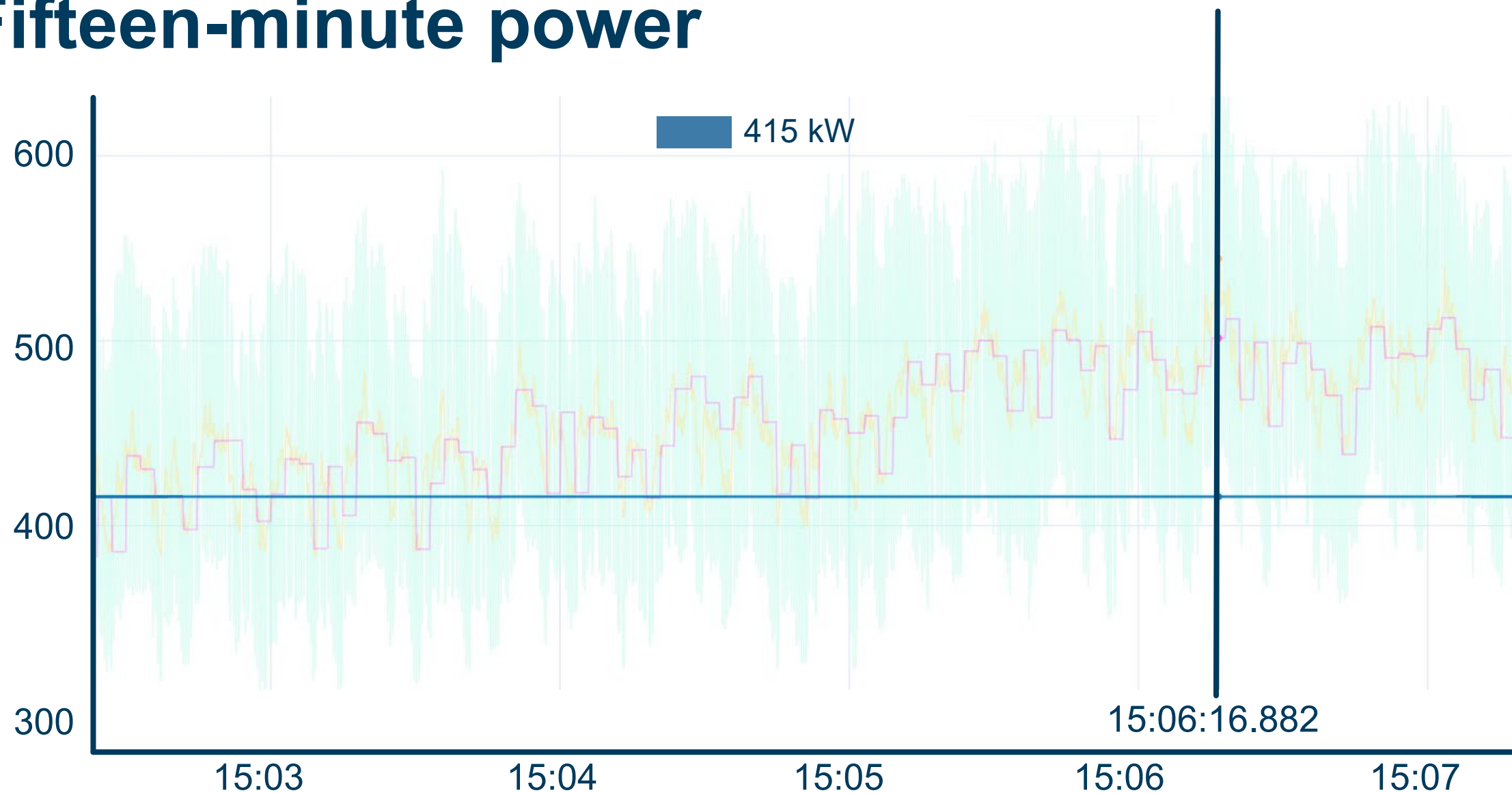
Source: [developer.nvidia.com/
blog/how-new-gb300-nvl72-
features-provide-steady-power-for-ai](https://developer.nvidia.com/blog/how-new-gb300-nvl72-features-provide-steady-power-for-ai)

Batteries smooth power draw

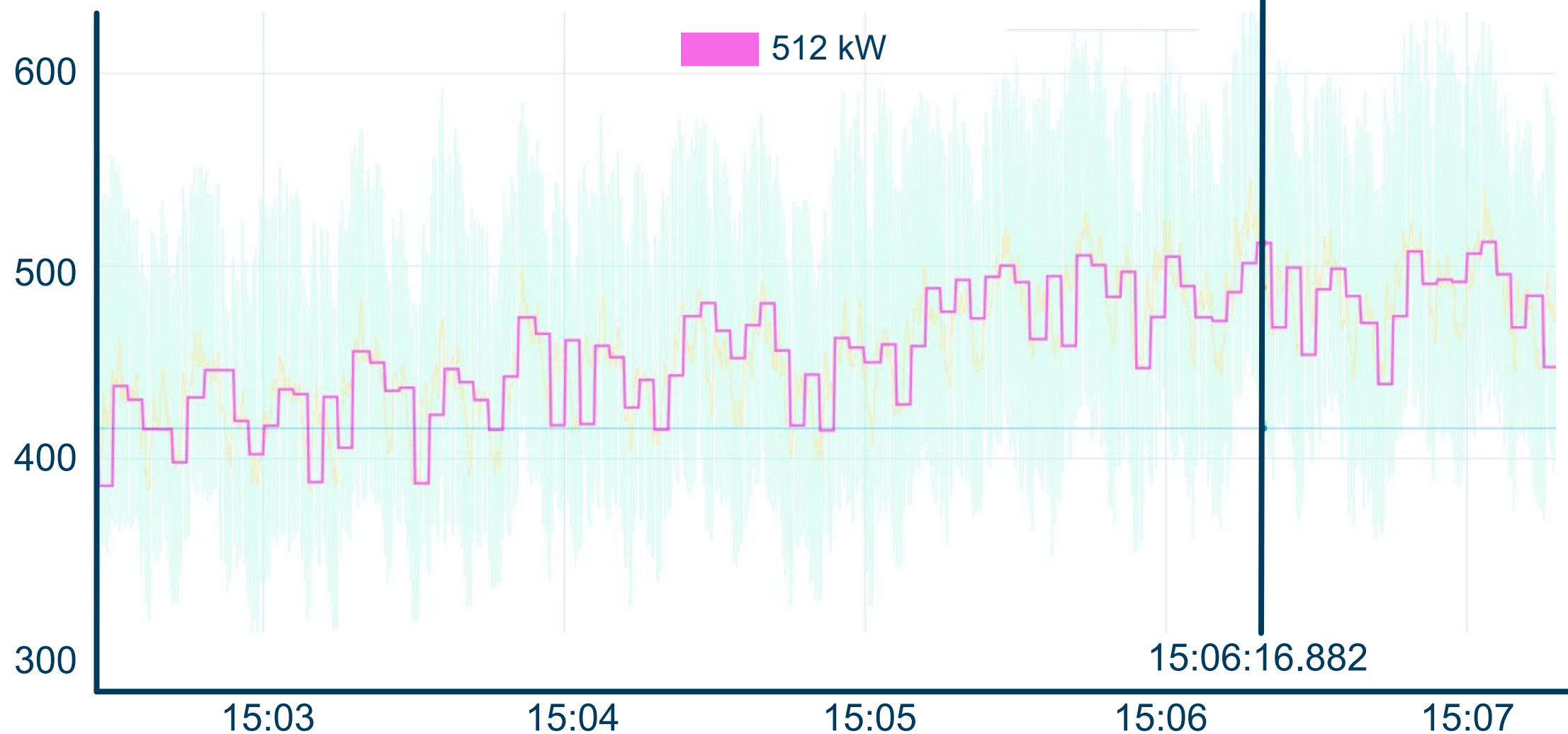


Source: developer.nvidia.com/blog/how-new-gb300-nvl72-features-provide-steady-power-for-ai

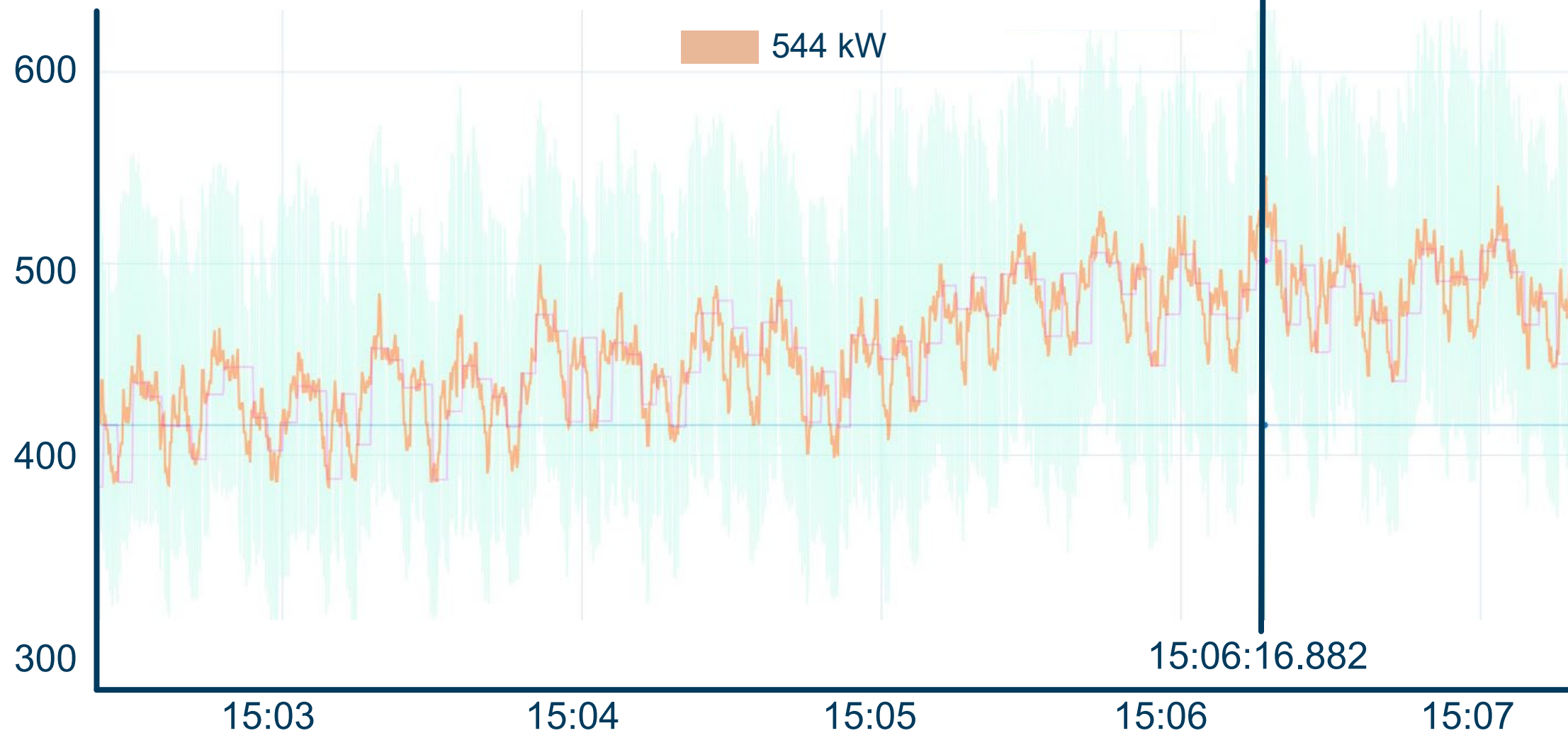
Fifteen-minute power



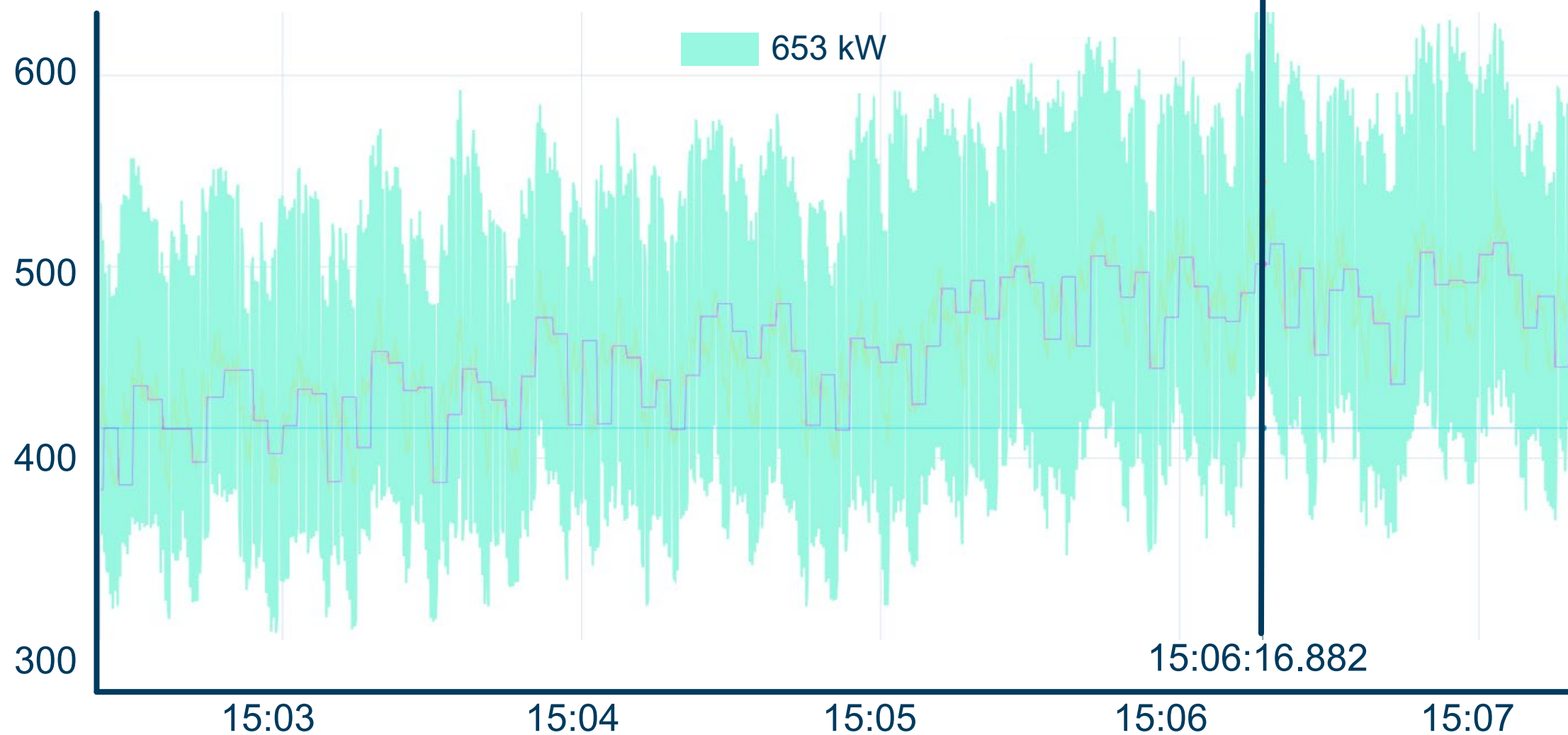
Three-second power



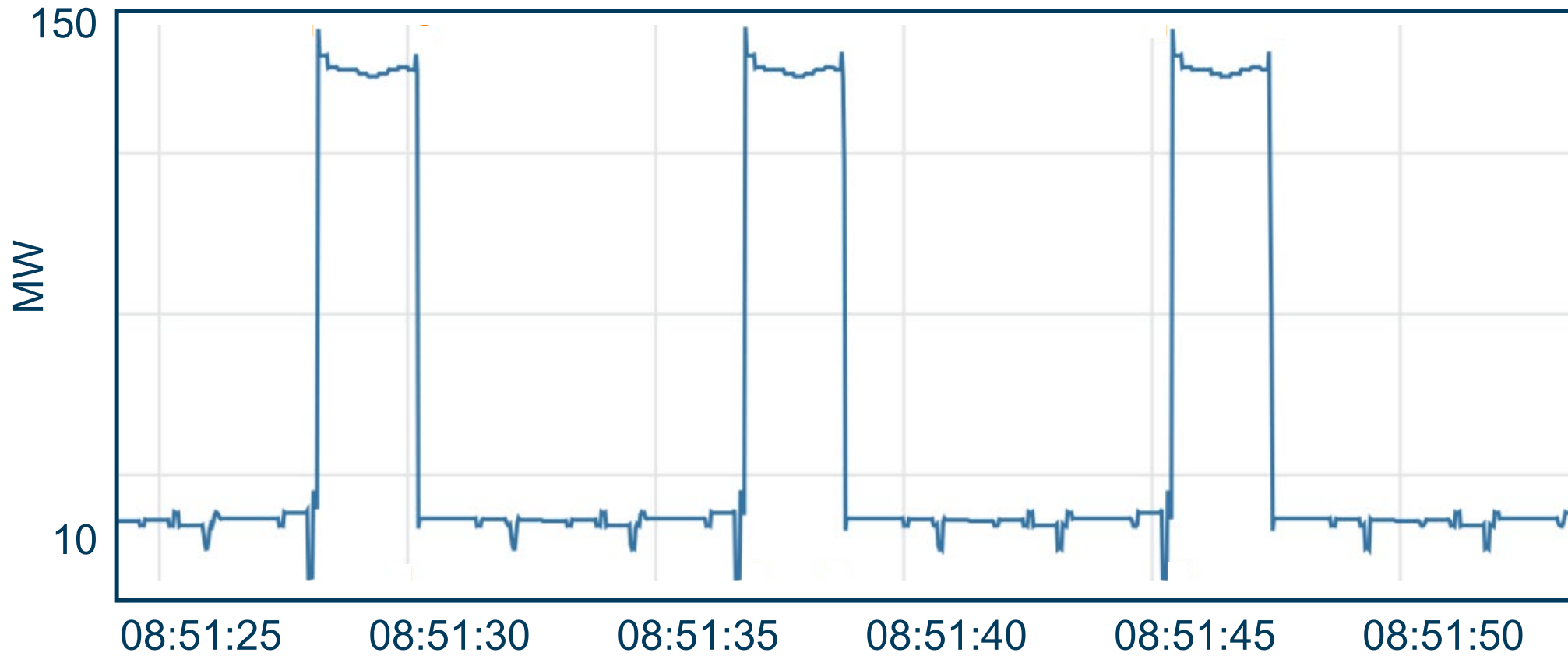
200 ms power



1 ms power



Millisecond control requires millisecond measurements



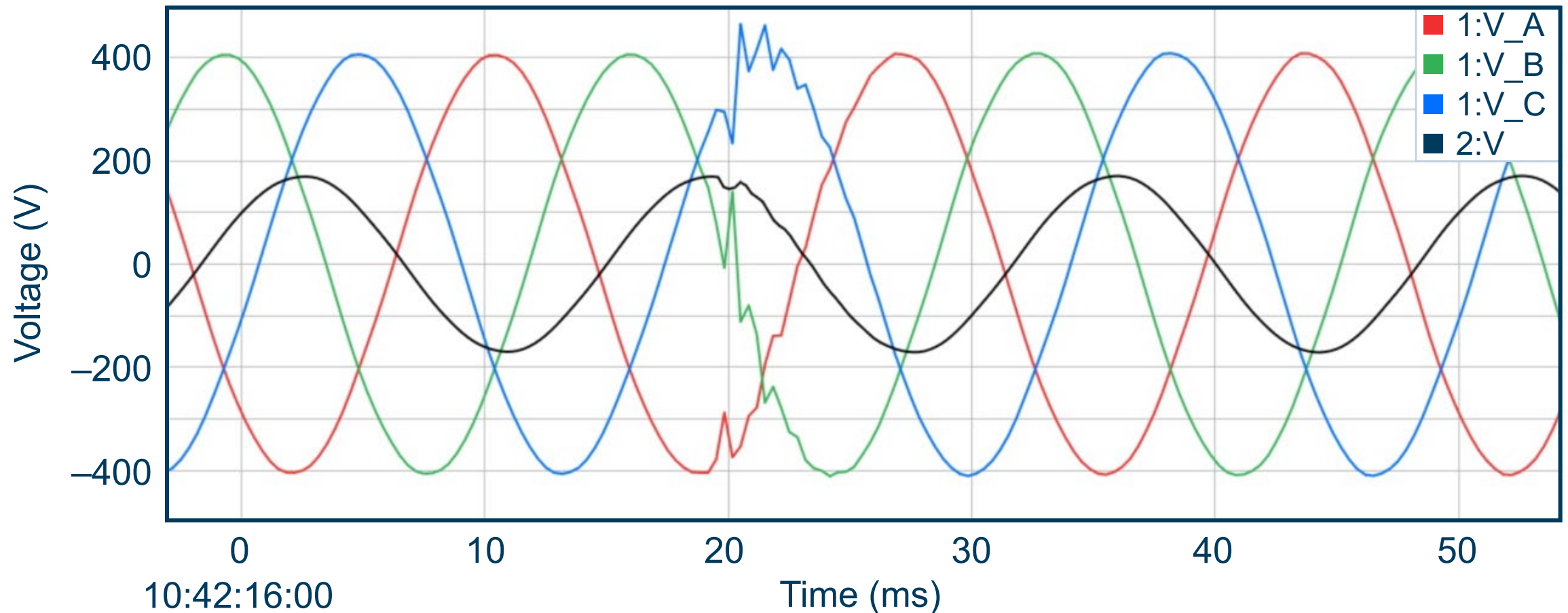
Source: selinc.com/api/download/141012/?lang=en

SCADA measurements are too slow for AI loads

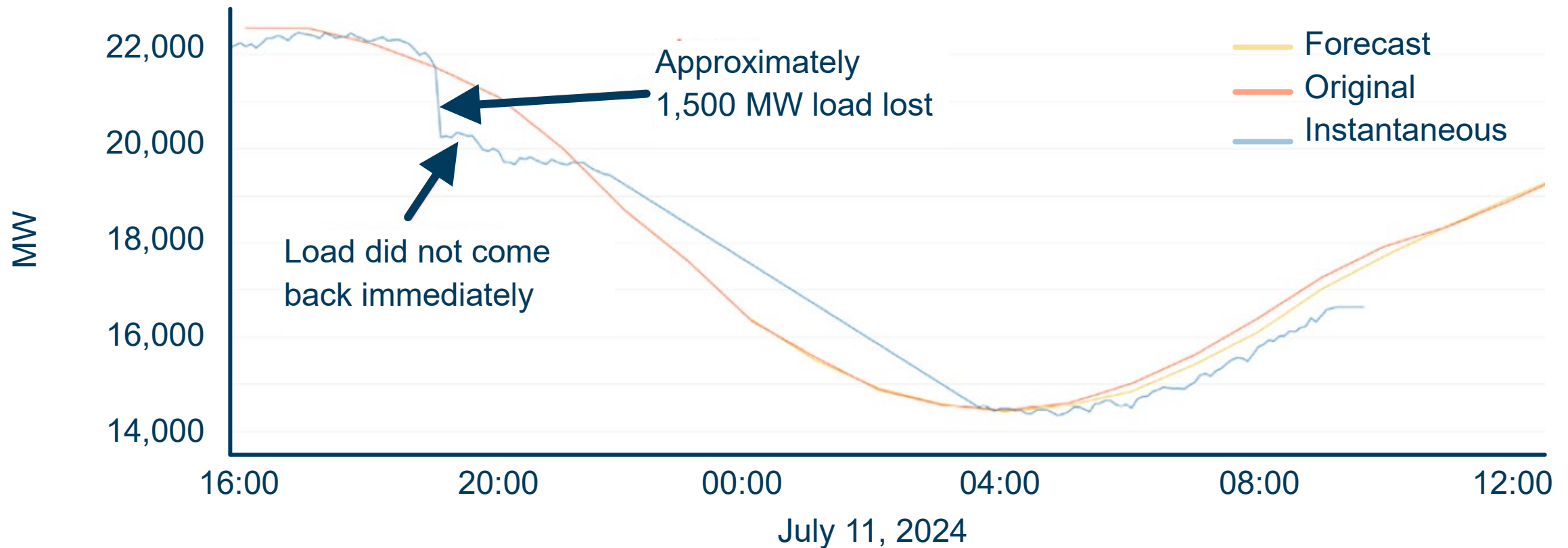


Time window	Peak (kW)
15 min	415
3 s	512
200 ms	544
1 ms	653

Synchronized waveforms correlate MV capacitor switching and LV disturbance



NE data center islanding causes wide-area voltage and frequency disturbances



Source: [nerc.com/pa/rrm/ea/Documents/Incident_Review_Large_Load_Loss.pdf](https://www.nerc.com/pa/rrm/ea/Documents/Incident_Review_Large_Load_Loss.pdf)

NERC recommends utility action after NE load loss incident

- Require dynamic models at interconnections
- Perform load loss studies
- Review reclosing schemes
- Monitor for load losses
- Ensure operating agreements include ramp rates

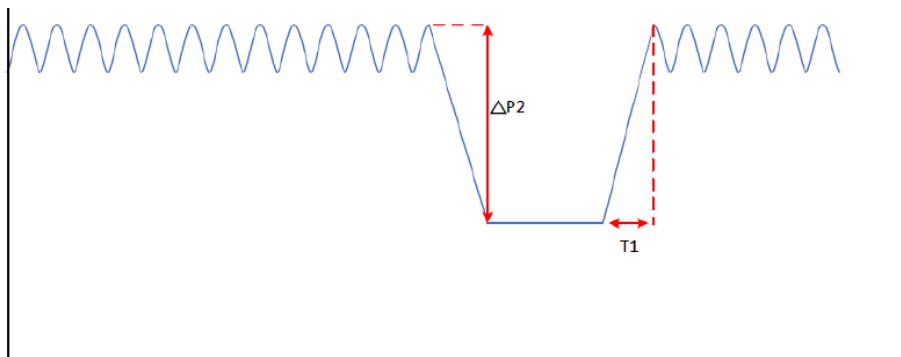
ATC POWER OSCILLATIONS AND RAMP RATE LIMITS (9.1)

Constant	Limit	Unit
$\Delta P2$	25	MW
T1	5	Seconds
P3	50	MW
R2	0.5	MW/seconds (MW/s)

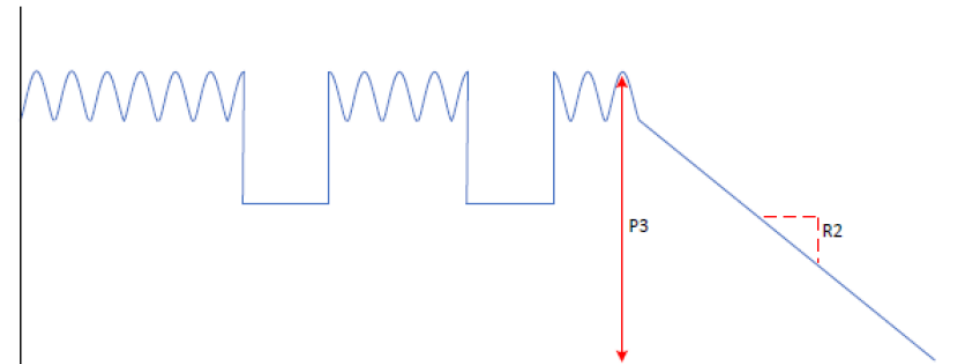
Load active power oscillations and ramp rate limits

Customer's equipment/facility shall be designed and operated within the maximum allowable variation limit of steady state (continuous load operation) active power oscillations as follows and as measured at the point of connection to the ATC transmission system. Note that these values are the total aggregate values for all sites at a given point of interconnection, or at multiple sites if oscillations are driven by common processes across multiple sites.

Criterion 1: Repetitive changes in load active power must be $<\Delta P2$ for any period of time $<T1$ seconds calculated using a sliding time window



Criterion 2: Any changes (increase or decrease) in active power $>P3$ MW should be limited to $<R2$ MW/s



SEL recommends modeling and verification to ensure deterministic power system controls

Model	Loads and sources
Simulate	Step changes
Verify	Actual system dynamics
Monitor	Intertie and plant loads
Control	Onsite generation
Protect	Utility interties

**Live monitoring
system available at
synchrophasors.com**



Conclusion

- AI load profile impacts could lead to bulk power system equipment damages
- Consequences could include damage to utility equipment, violation of tariffs, and potential disconnection of load
- CWM allows entities to measure impacts of large load swings to develop and inform mitigation strategies



Thank you





Dependable and Secure Line Current Differential Protection Over Packet-Based Wide-Area Networks With Parallel Redundancy Protocol

**Brian Smyth, Motaz Elshafi, Kale McCarthy, and
Douglas Taylor**
Schweitzer Engineering Laboratories, Inc.

Outline

- Introduction
- Line current differential protection principles
- Solutions for 87L data alignment
- WAN connectivity models
- Proposed WAN solutions with PRP
- Testing and results
- Conclusions

Introduction

- 87L stringent communications network requirements
 - Wide-area TDM networks – synchronous serial interface implementation (IEEE C37.94 and G.703)
 - TDM – strict latency, path symmetry, and path redundancy minimizes data loss
- Utilities transition to Ethernet interfaces and MPLS and VSN WANs
 - Direct fiber per application is not always feasible or cost-effective
 - Most requirements can be achieved by MPLS (with traffic engineering and QoS) and VSN (offering TDM-like performance)

Introduction

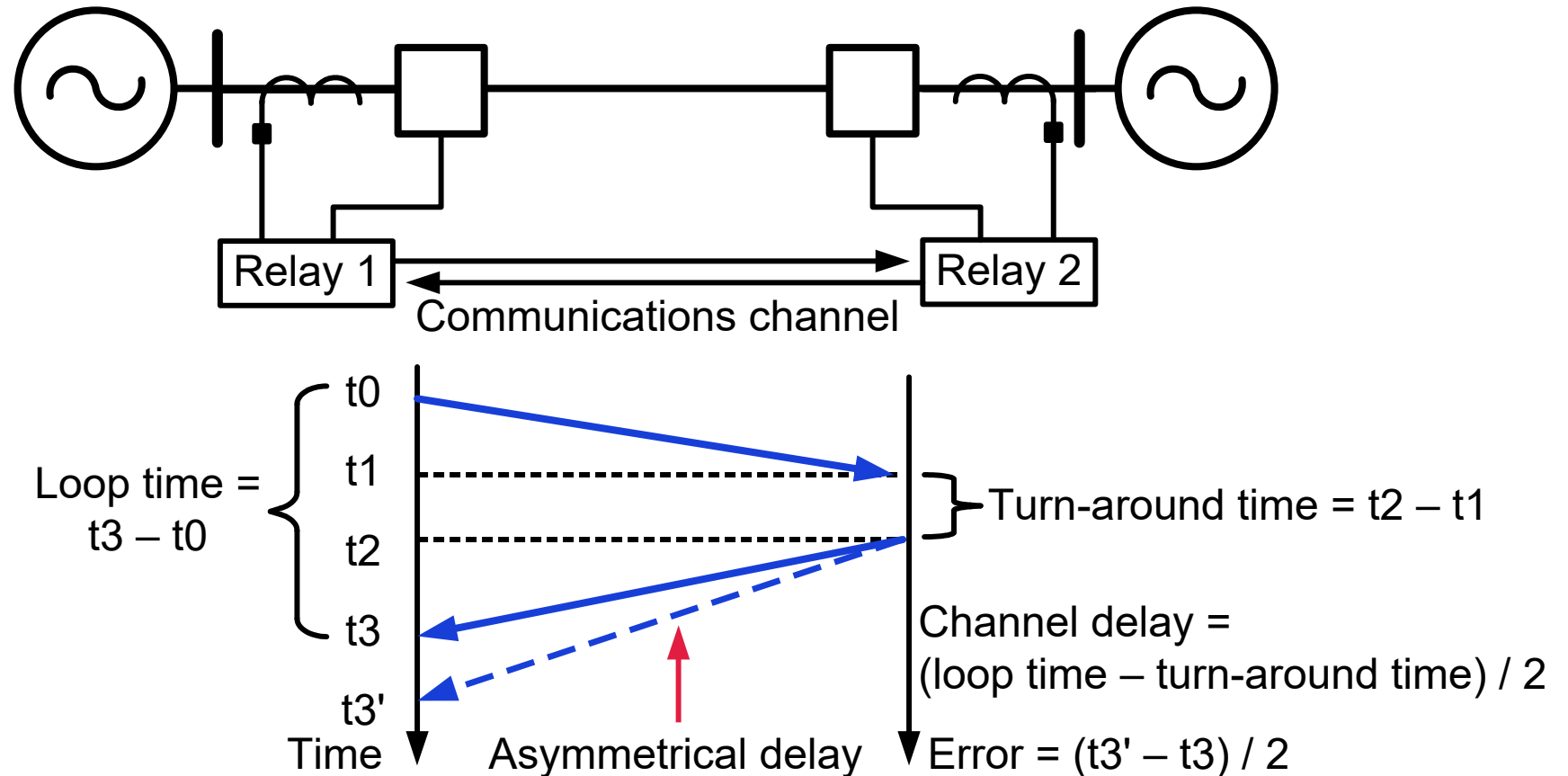
Our vision

- Repurpose a useful capability in relays deployed for LAN communications with PRP
- Validate whether it could improve 87L relay communications resiliency over WANs
- Demonstrate that PRP has the potential to bring hitless failover performance, especially with independent paths and different WAN connectivity types
- Note – we suggest adding PRP on top of available path-healing technologies within each WAN



Line current differential principles

- Two methods for aligning protection packet data samples
 - Channel-based (ping-pong)
 - External time-based
- Time-based data alignment is necessary for 87L over Ethernet



Solutions for 87L data alignment

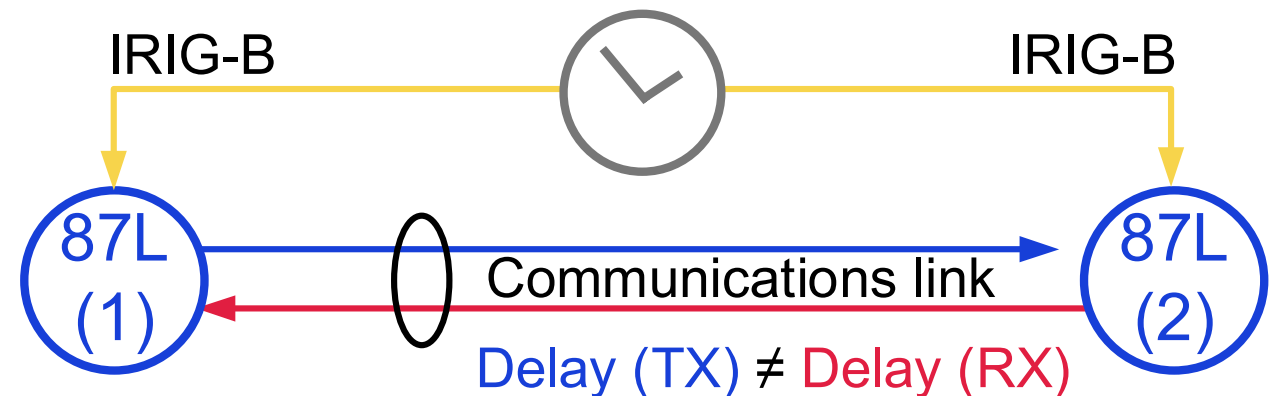
Channel-based

- Is great when communications channel is symmetrical
- Does not require a globally synchronized time source at the relay
- Uses a ping-pong message exchange to
 - Calculate round-trip delay
 - Estimate one-way delay
- Is sensitive to channel asymmetry

Solutions for 87L data alignment

External time-based

- Is needed for asymmetrical or nondeterministic communications channel
- Requires globally synchronized time source at the relay
- Time-stamps packets with globally synchronized time at transmission
- Uses time-stamped messages to calculate RTD and one-way channel delay
- Is not impacted by channel asymmetry



Line current differential principles

Advantages of modern relays using Ethernet interface for 87L

- Single Ethernet interface (capable of communicating across multiple channels)
- Extended support for protection of four or more terminals
- New network time synchronization possibility (IEEE 1588 PTP)

Line current differential principles

How 87L relays process packets

- 87L expects continuous, sequential data to avoid erroneous calculations
- Ideally, a network should be engineered to avoid losing sequential data upon path switching should a fiber or node disruption occur
- Path switching (if not hitless) could lead to packets arriving out of sequence, forcing the relay to record one or more lost packets and pause 87L functions
- Once the relay receives steady data again, it resumes 87L functions

How can we enhance Ethernet WAN communications for 87L?

Key channel performance requirements for protection

- As per IEEE 1646 and IEC TR 61850-90-12
- Challenge – minimize path restoration time and reduce to 0 ms

Scheme	Latency (ms)	Asymmetry (ms)	Restoration time (ms)
87L	5	<0.5	5
Pilot protection	8	5	5
DTT	10	5	5

Improving channel restoration performance

- Good** While native MPLS supports path healing, communications can experience extended restoration times
- Better** VSN provides 5 ms service restoration
- Best** PRP technology can provide a hitless solution

Proposed solution with PRP

PRP purpose – provide hitless performance from any single Ethernet network failure

- The Ethernet frame is duplicated across two independently switched LANs, known as LAN A and LAN B
- LANs have redundant paths, allowing a path disruption across one LAN to be transparent to the end application
- The first copy to arrive is the one that is processed
- The slower of the two PRP frames is dropped, and the end application receives a single copy of the frame

Proposed solution with PRP

- Although designed for redundant LANs, a network admin could leverage PRP when interfacing Ethernet-connected 87L relays over two independent WANs
- Three connectivity models were used for validation of WAN A and B
 - Direct fiber
 - MPLS
 - VSN

Results



Lab testing – WANs with similar delays

- We established a baseline and confirmed communication links experienced no lost packets under ideal conditions where both WANs were functional
- We failed from WAN A to WAN B and back
- Analyzed relay-generated 87L reports which showed no lost packets
- Failures were hitless as expected

87L communications report – WAN B failed

87L APPLICATION STATUS

2E - Two terminals over Ethernet
MASTER

MEDIUM/PROTOCOL	Configuration	Status
Ethernet Port A	1000BASE-SX, PRP	In use
Ethernet Port B	1000BASE-SX, PRP	DOWN
Synchronization	External-time-based	High precision

TIME SOURCE	Local Status	Remote Status
	Locked	Locked

CHANNEL ADDRESSING

Local Address	01-30-a7-01-01-01
Remote Address 1	01-30-a7-02-02-02
VLAN Tag	1

PRP	In use
PRP	DOWN

STATISTICS

Channel Status	OK
Channel Role	In use
Receive Status	OK
Synch Config	Ext-time-based
Synch Status	Ext-time-based
Synch Accuracy	High precision
Time Status	Locked
High Lost Packet Count	OK
Receive Delay (ms)	0.1

Lost Packet Count 40s	0
Lost Packet Count 24hr	0

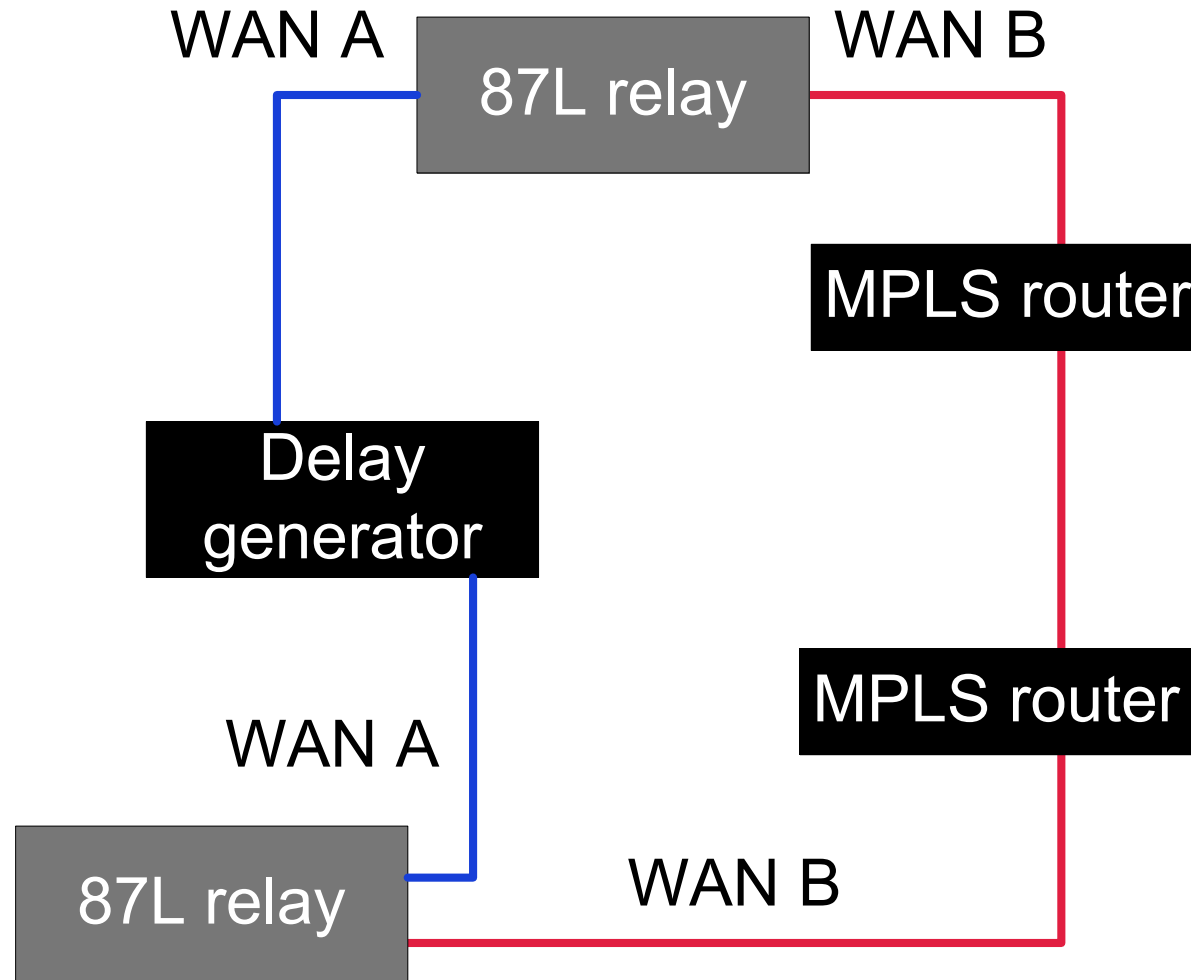
Lost Packet Count 40s	0
Lost Packet Count 24hr	0

Test results – WANs with similar delays

Test case	WAN A	WAN B	Difference in latency between WAN A and WAN B (ms)	Dropped packets upon WAN B failure
1	Direct fiber	Direct fiber	0	0
2	VSN	Direct fiber	0.1	0
3	VSN	MPLS	0.1	0
4	MPLS	Direct fiber	0	0
5	MPLS	MPLS	0	0

Communications experienced a hitless failover after every single WAN failure event due to PRP

Lab testing – WANs with varied delays



Test results – WANs with varied delays

Test case	Difference in latency between WAN A and WAN B (ms)	Dropped packets upon WAN B failure
1	0.5	0
2	1.0	0
3	2.0	0
4	3.0	0
5	3.5	0
6	4.0	0
7	5.0	0
8	10.0	2

The data shown is specific to the tested relay and how it determines a dropped 87L packet

87L communications report – WAN B failed

87L APPLICATION STATUS

2E - Two terminals over Ethernet
MASTER
ALARM ON CHANNEL 1

MEDIUM/PROTOCOL	Configuration	Status
Ethernet Port A	1000BASE-SX, PRP	In use
Ethernet Port B	1000BASE-SX, PRP	DOWN
Synchronization	External-time-based	High precision

TIME SOURCE	Local Status	Remote Status
	Locked	Locked

CHANNEL ADDRESSING

Local Address	01-30-a7-01-01-01
Remote Address 1	01-30-a7-02-02-02
VLAN Tag	1

PRP	In use
PRP	DOWN

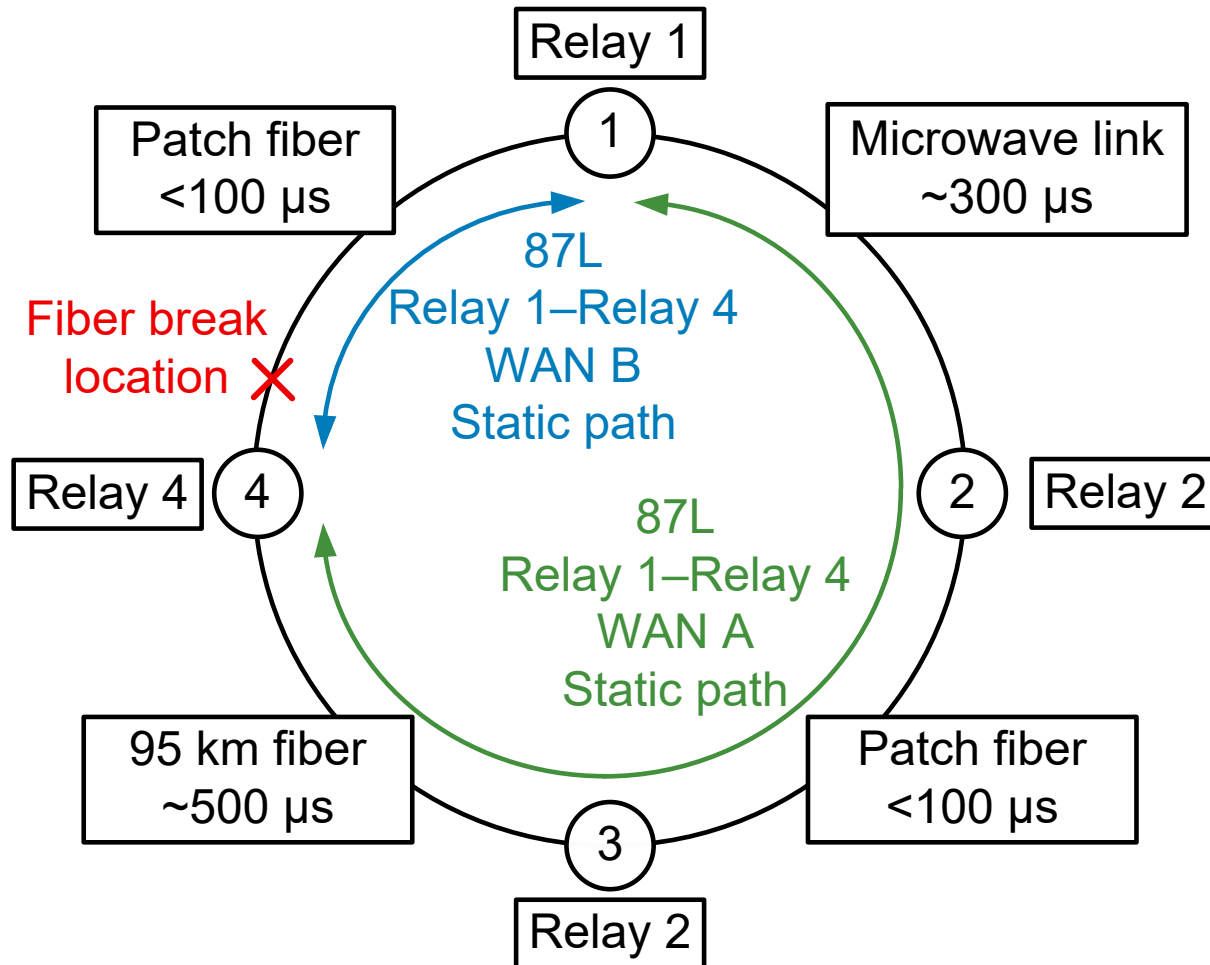
STATISTICS

Channel Status	Channel 1
Channel Role	ALARM
Receive Status	In use
Synch Config	OK
Synch Status	Ext-time-based
Synch Accuracy	Ext-time-based
Time Status	High precision
High Lost Packet Count	Locked
Receive Delay (ms)	ALARM

Lost Packet Count 40s	2
Lost Packet Count 24hr	2

Lost Packet Count 40s	2
Lost Packet Count 24hr	2

Testing with MPLS at a utility lab



- A single MPLS network provides separate logical paths between Relay 1 and 4
- Each path represents a WAN
- A disruption in WAN B caused no dropped 87L packets

Testing with MPLS at a utility lab

87L APPLICATION STATUS

4E - Four terminals over Ethernet
MASTER

MEDIUM/PROTOCOL	Configuration	Status
Ethernet Port A	1000BASE-SX, PRP	In use
Ethernet Port B	1000BASE-LX, PRP	In use
Synchronization	External-time-based	High precision

TIME SOURCE	Local Status	Remote Status
	Locked	Locked

CHANNEL ADDRESSING

Local Address	01-30-a7-05-01-04
Remote Address 1	01-30-a7-05-01-01
Remote Address 2	01-30-a7-05-01-02
Remote Address 3	01-30-a7-05-01-03
VLAN Tag	100

STATISTICS	Channel 1	Channel 2	Channel 3
Channel Status	OK	OK	OK
Channel Role	In use	In use	In use
Receive Status	OK	OK	OK
Synch Config	Ext-time-based	Ext-time-based	Ext-time-based
Synch Status	Ext-time-based	Ext-time-based	Ext-time-based
Synch Accuracy	High precision	High precision	High precision
Time Status	Locked	Locked	Locked
High Lost Packet Count	--	--	--
Receive Delay (ms)	0.1	0.4	0.5
Lost Packet Count 40s	0	0	0
Lost Packet Count 24hr	0	0	0

MAXIMUM VALUES

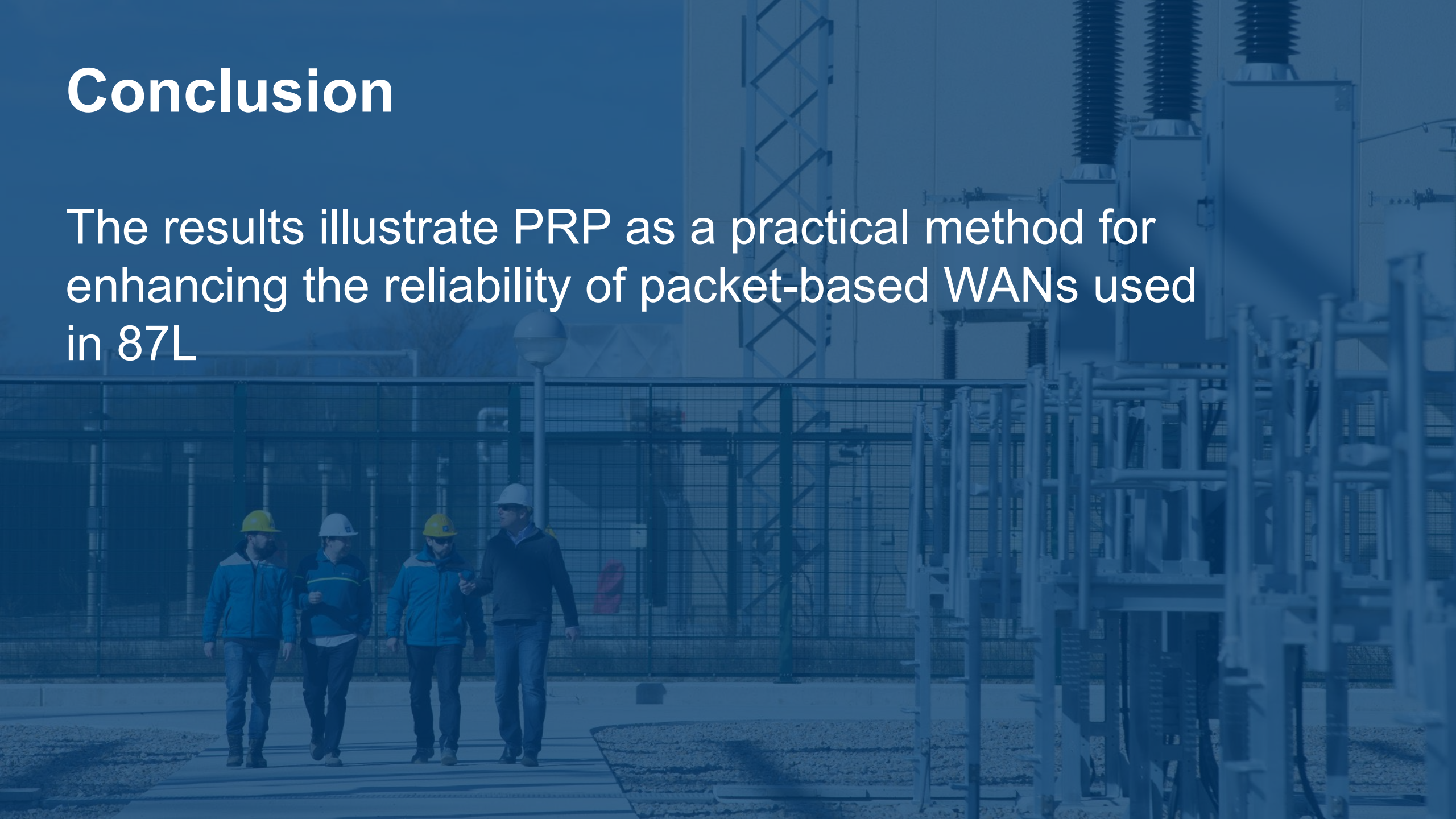
Channel 1	Date and Time (UTC)
Lost Packet Count 24hr 0	03/26/2025 23:18:04
Receive Delay (ms) 1.0	03/26/2025 23:24:23.922

PRP	In use
PRP	In use

Lost Packet Count 40s	0	0	0
Lost Packet Count 24hr	0	0	0

Conclusion

The results illustrate PRP as a practical method for enhancing the reliability of packet-based WANs used in 87L



Questions?



For more information

Paper

Presented at the 79th Annual Conference for Protective Relay Engineers
College Station, Texas March 30–April 2, 2026.

Full paper is available at <https://selinc.com/api/download/141726/>

Contacts

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The effects of renewables and inverter-based resources on effective protection and control of the electric power system



Ellery A. Blood, Ph.D.

SEL

2026-08-05

Reliability First – 12th Annual Protection System Workshop

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Part 1 – Power systems are changing

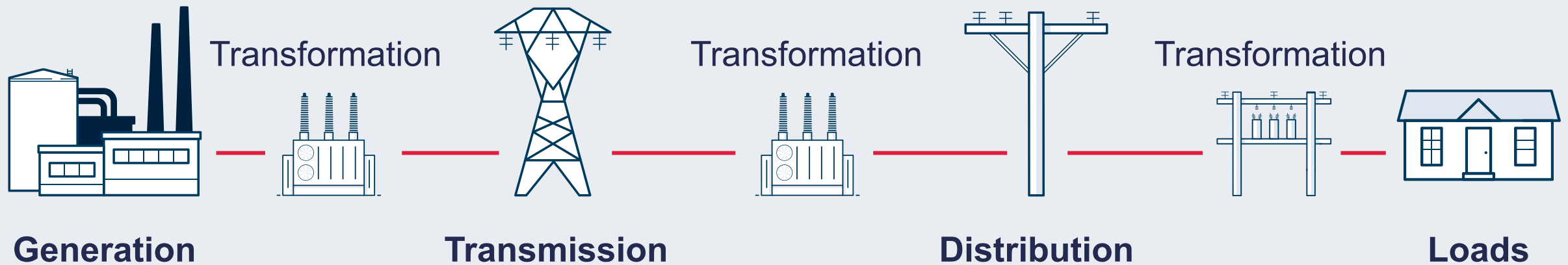
Agenda – Part 1

POWER SYSTEMS ARE CHANGING

- Power system evolution
- Reduced redundancy
- Reduced inertia
- Inconsistent fault current



Power systems move energy at the speed of light



**Synchronous
generators are
the main power
system sources**



Power systems are changing



Two major power system changes

Capital investment rate has lagged load growth rate

- Power systems lost redundancy
- They require wide-area protection

Inverter-based resource (IBR) applications have grown fast

- Solar and wind IBRs are weather-dependent, non-dispatchable sources
- IBRs do not add mechanical inertia and affect fault current
- IBRs have stricter transient current limits

Inertia – resistance to change speed

Acceleration

Vehicle stores mechanical energy

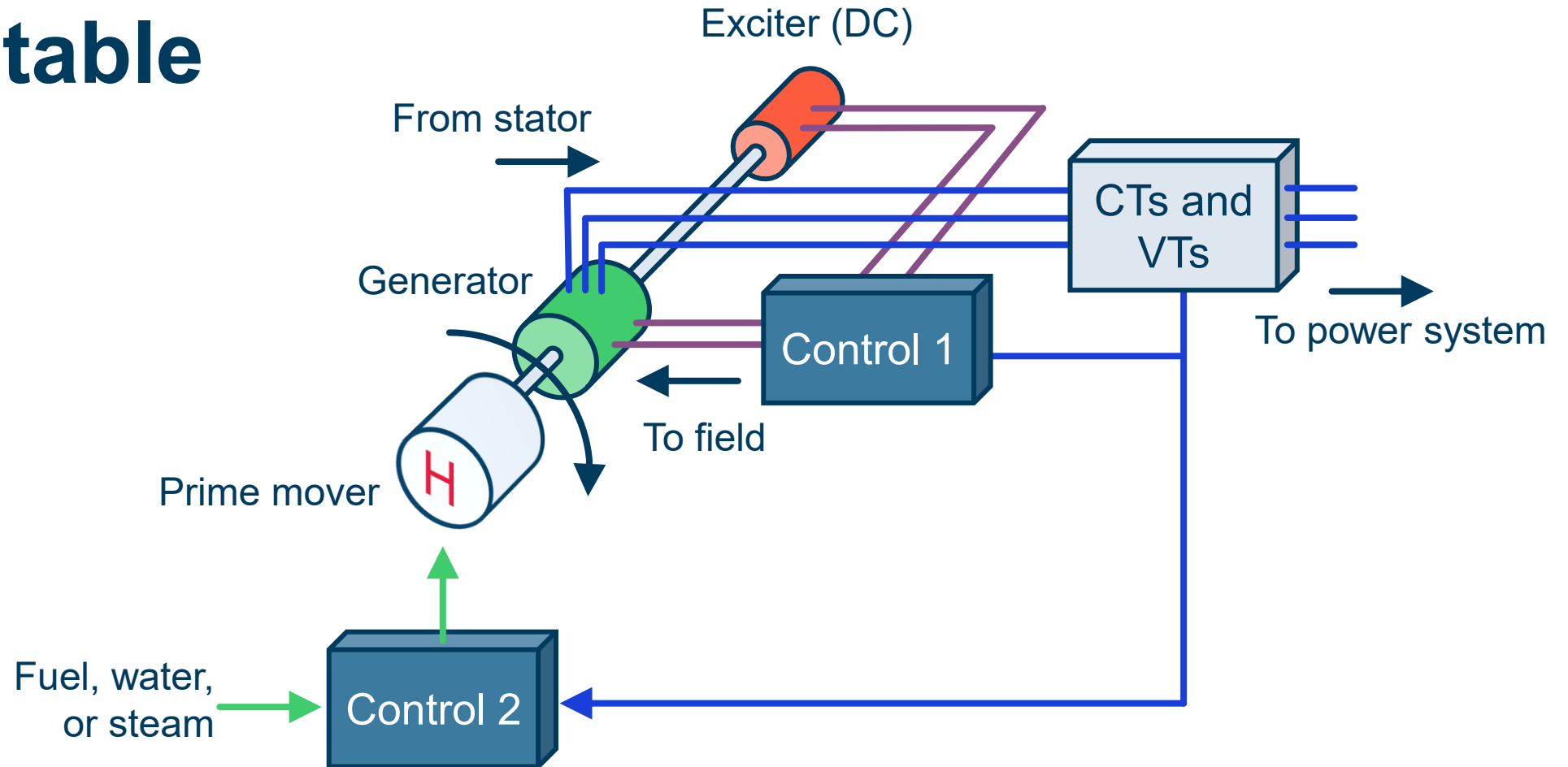
Deceleration or braking

Vehicle loses mechanical energy

Truck speed changes more slowly than car speed (higher inertia)

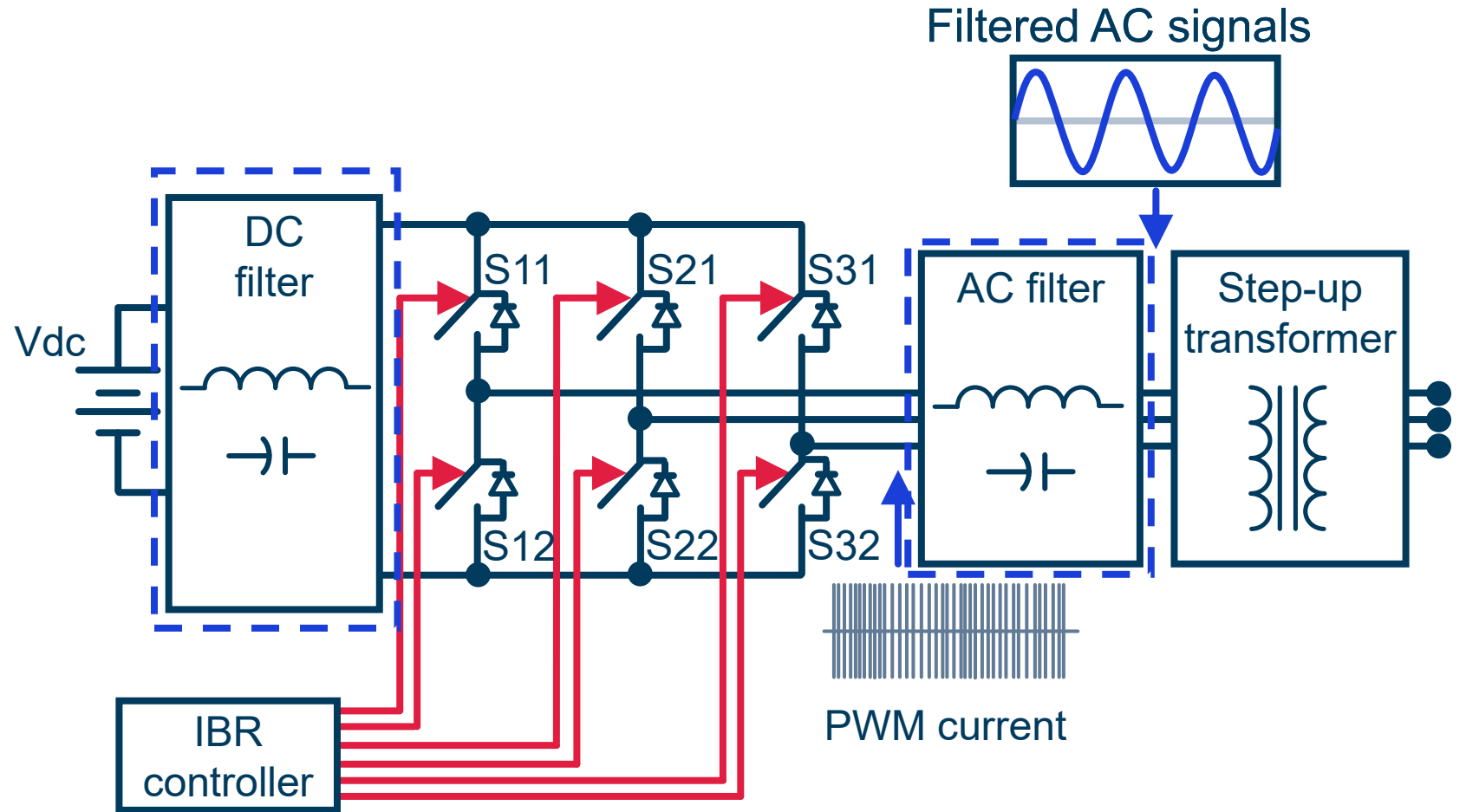


Synchronous generator behavior is predictable



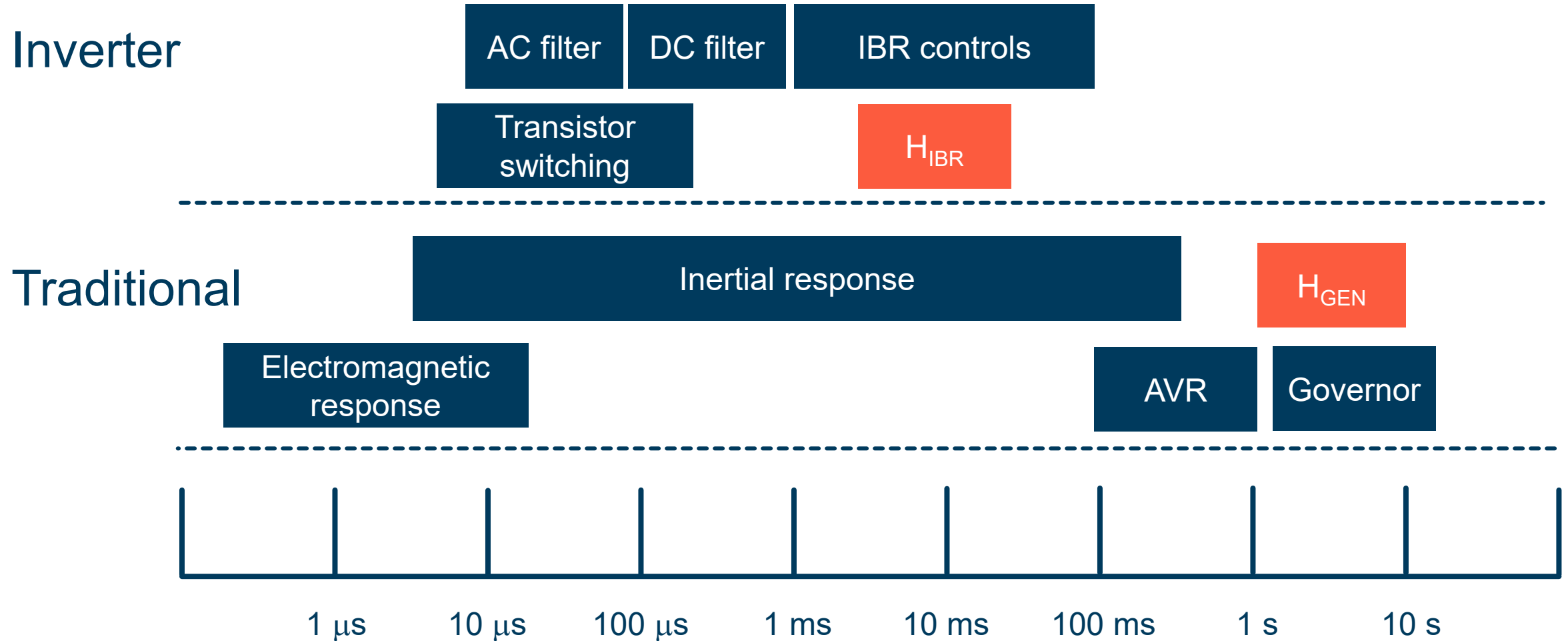
IBRs vs. synchronous generators

- Response times
- Fault current
- P-Q capability



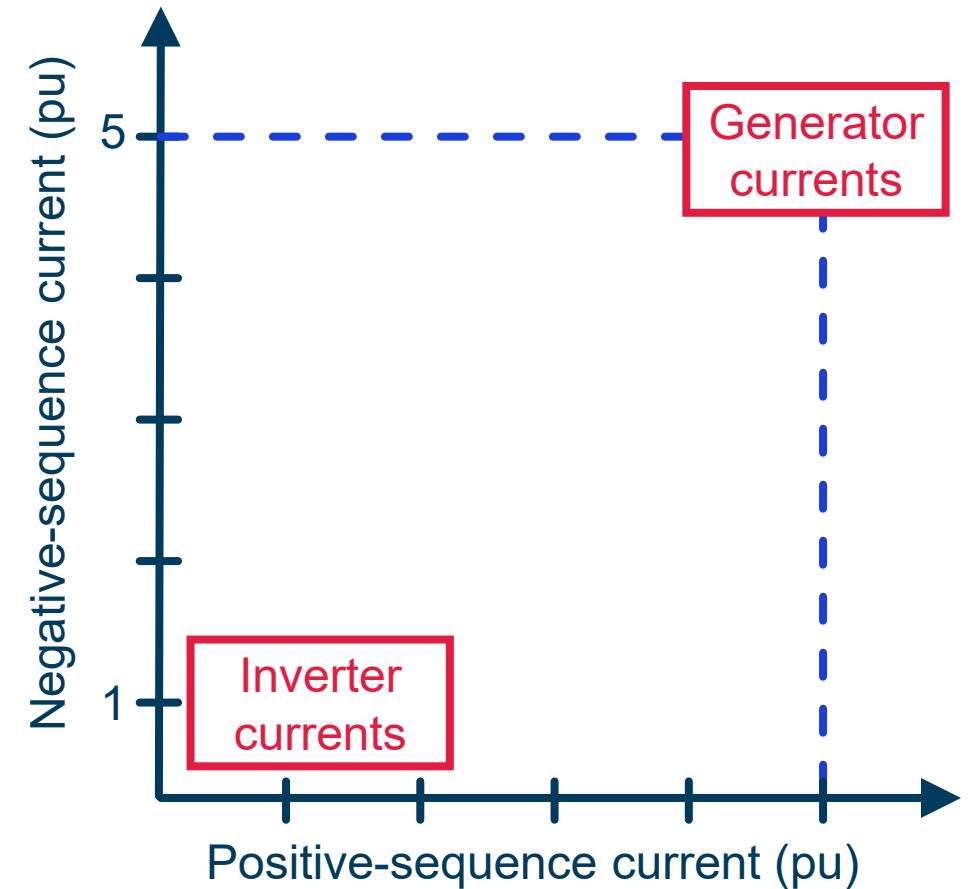
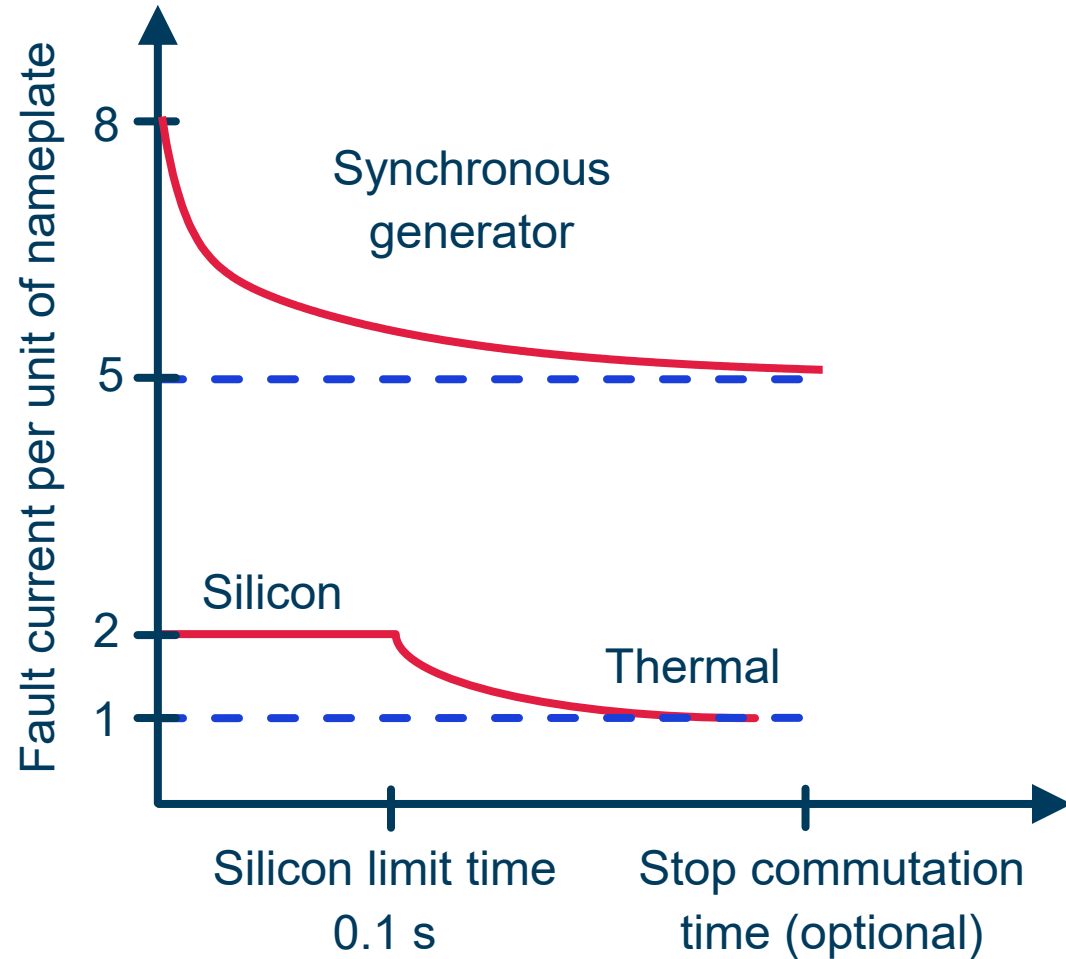
IBRs vs. synchronous generators

RESPONSE TIMES



IBRs vs. synchronous generators

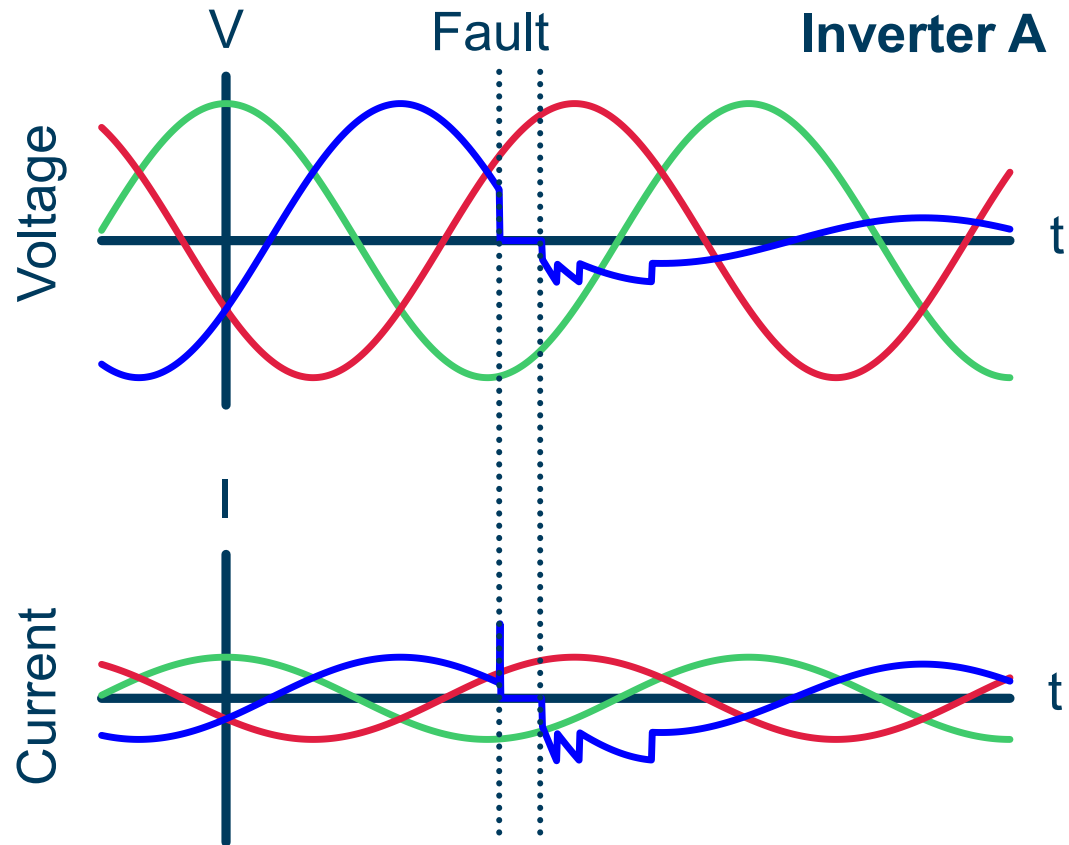
FAULT CURRENT MAGNITUDE



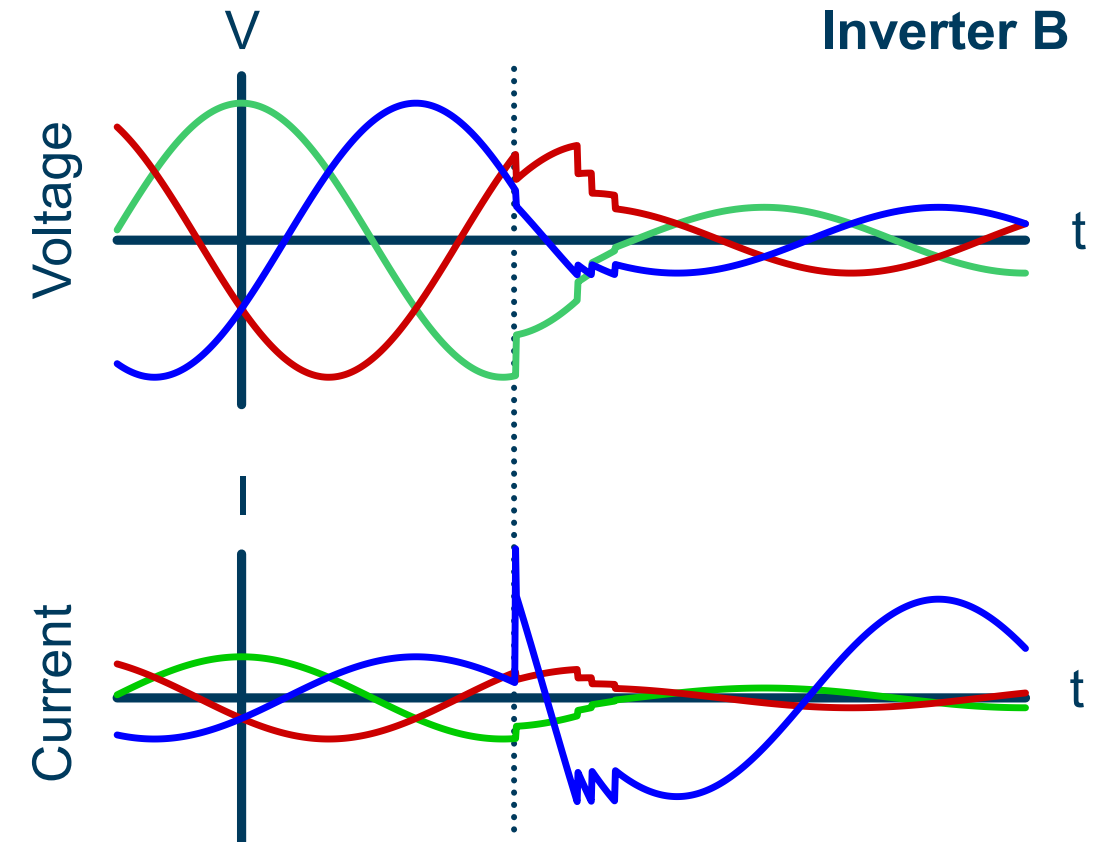
IBRs vs. synchronous generators

FAULT CURRENT BEHAVIOR

Goal – enforce balanced current

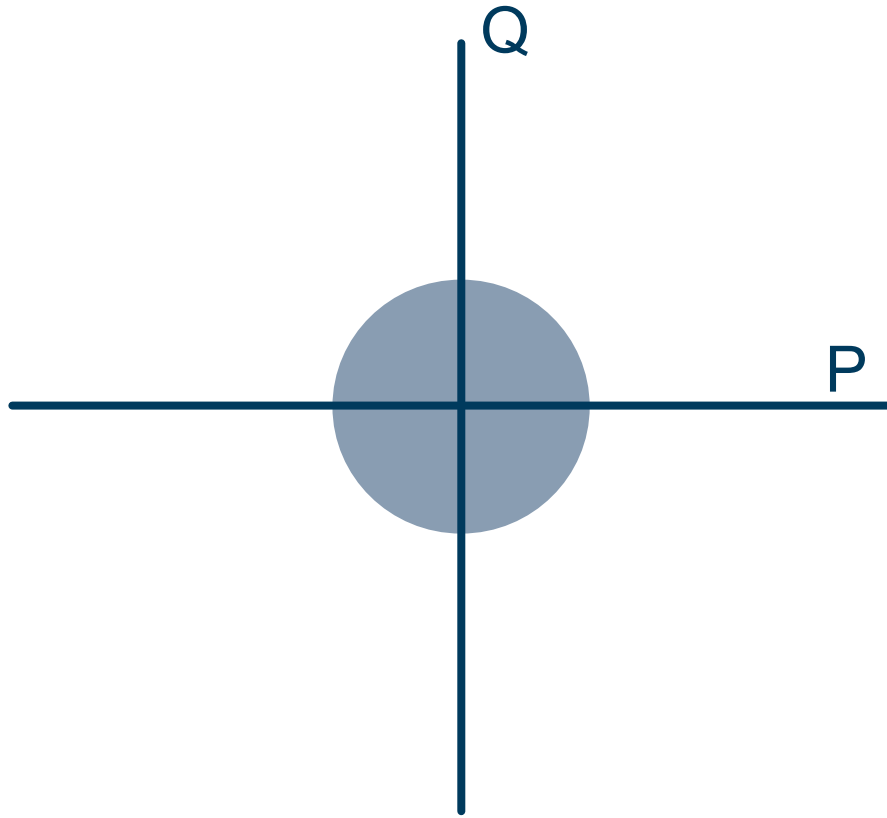


Goal – enforce balanced voltage

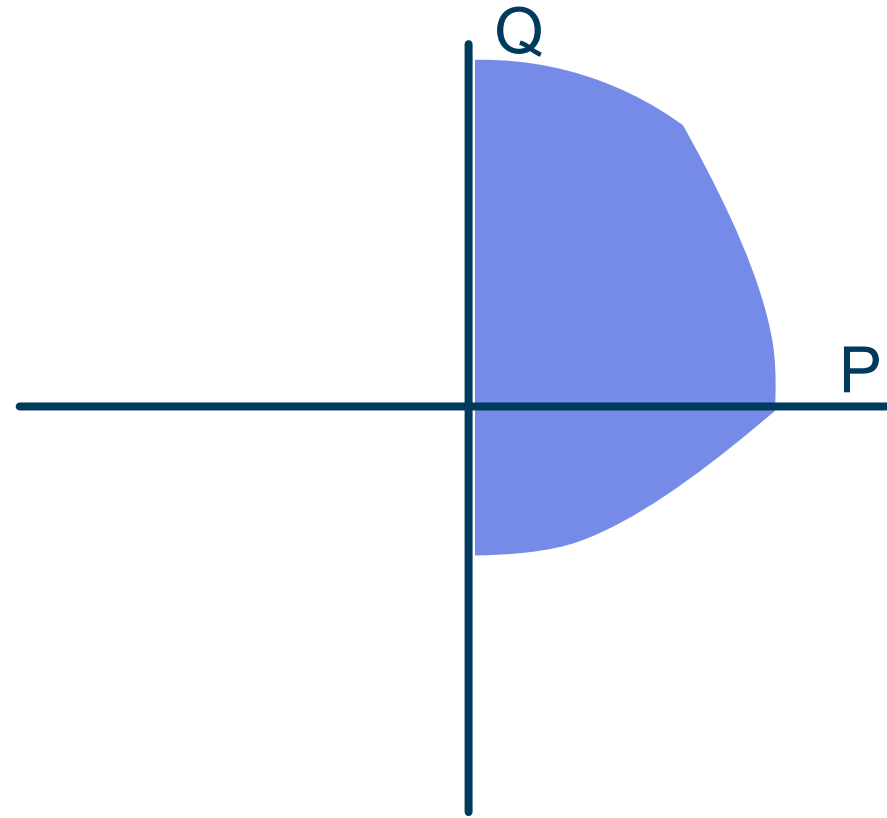


IBRs vs. synchronous generators

P-Q CAPABILITY REGION



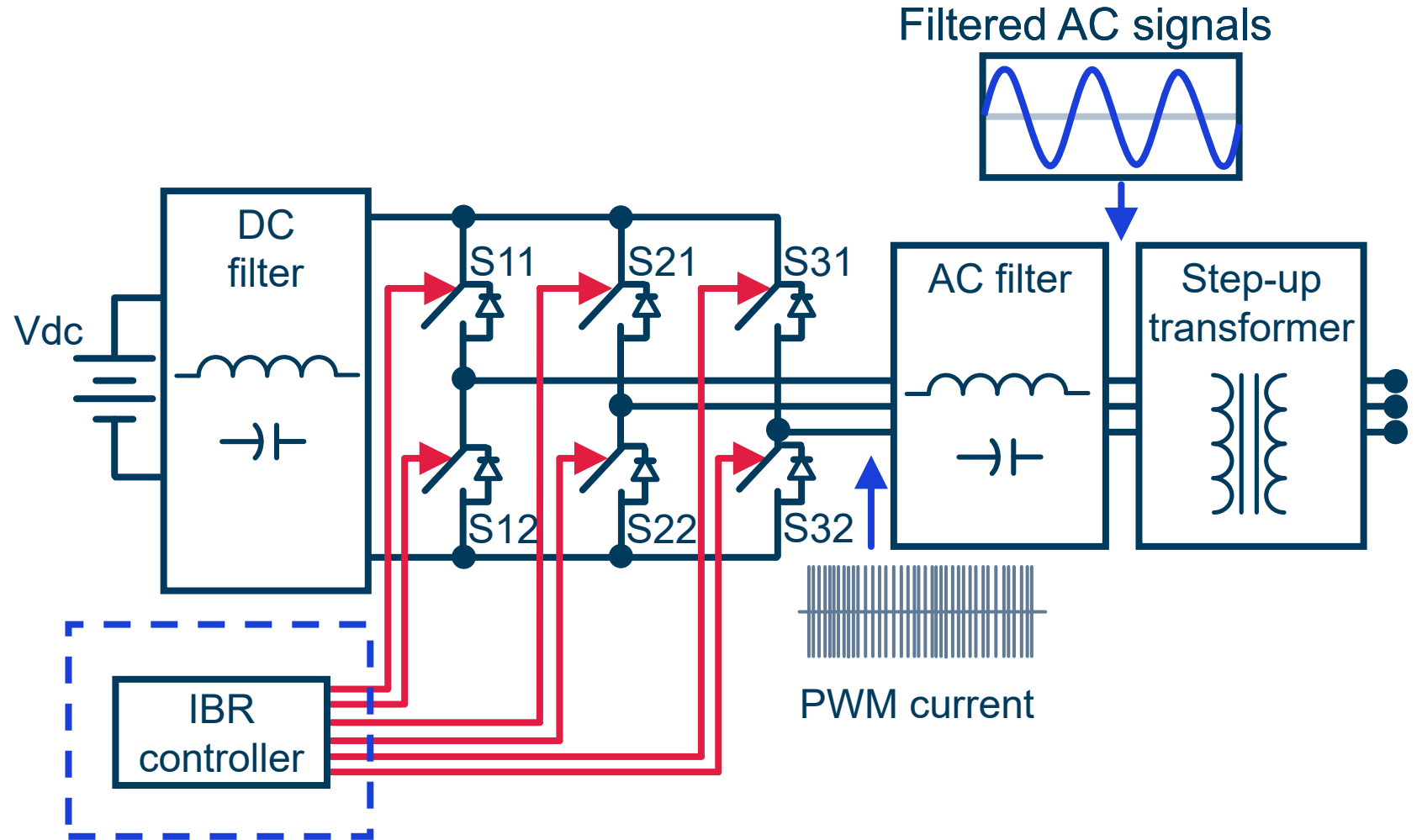
Inverter



Traditional

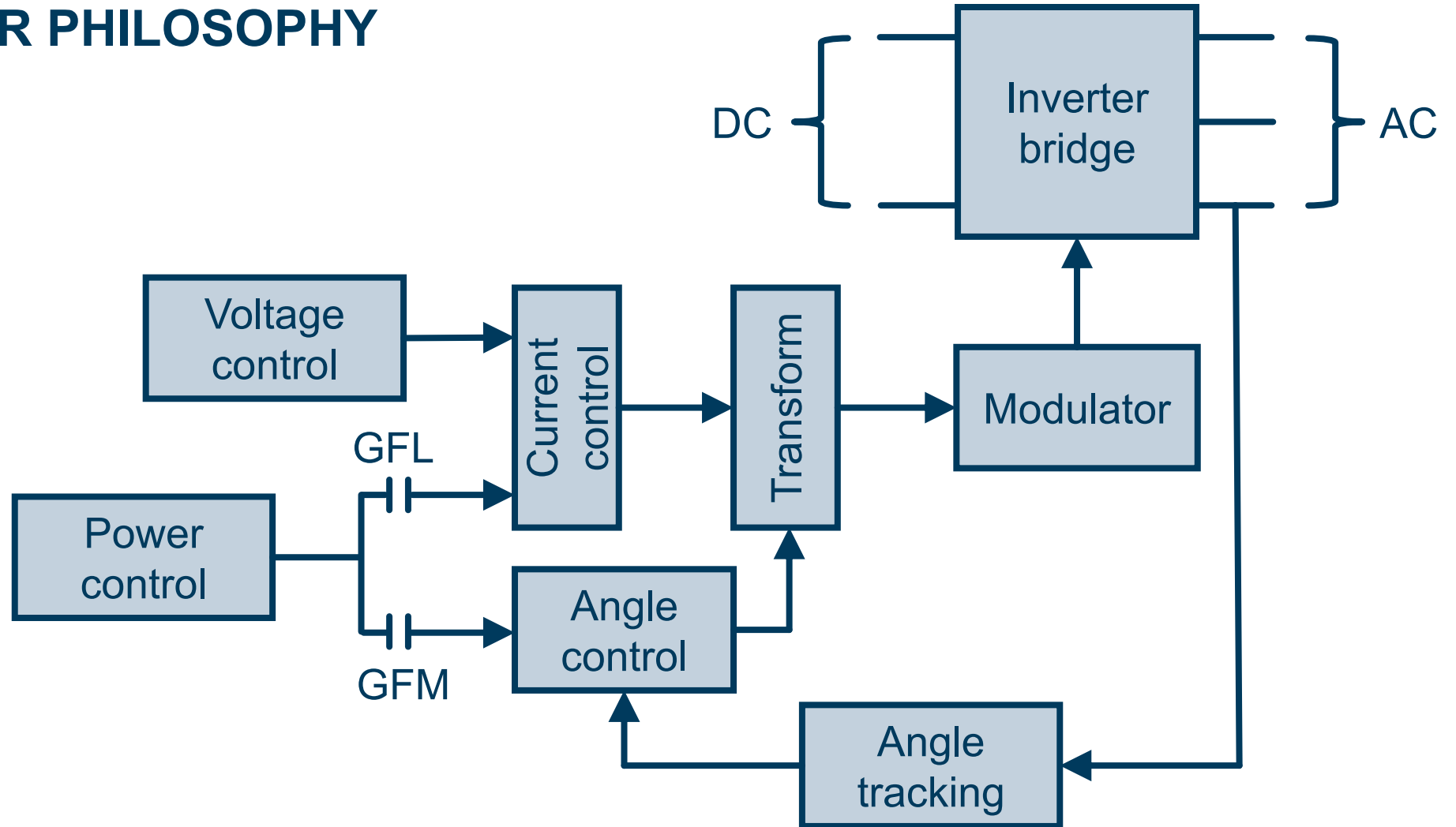
Inside an inverter

Control firmware



IBRs vs. synchronous generators

CONTROLLER PHILOSOPHY



Grid-following inverter (GFL)

- Follows power system voltage signal
- Shuts down for large voltage or frequency disturbances
- Does not contribute to grid strength
 - Does not dampen power oscillations
 - Does not provide inertia
- Has limited overcurrent capability
- Is used in most IBR installations

Grid-forming inverter (GFM)

- Internal machine model mimics electromechanical generators – requires dispatchable P source (BESS)
- Contributes to grid strength
- Dampens power oscillations
- Provides virtual inertia
- Has limited overcurrent capability
- Higher cost than GFLs
 - Higher-capacity electronic components
 - Requires energy storage

Part 2 – What these changes mean

Agenda – Part 2

WHAT THESE CHANGES MEAN

- Transient stability
- Voltage stability
- Line protection challenges

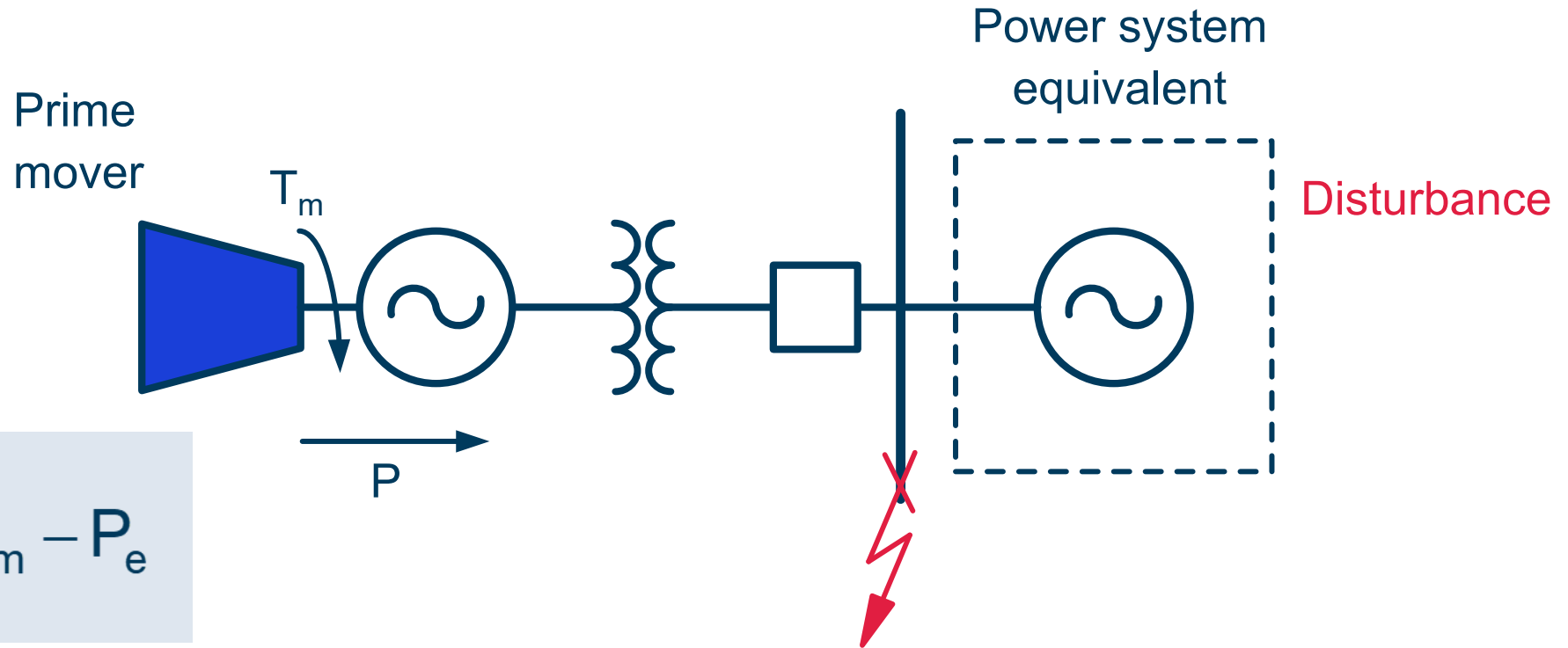




IBRs challenge power system transient stability

INERTIA

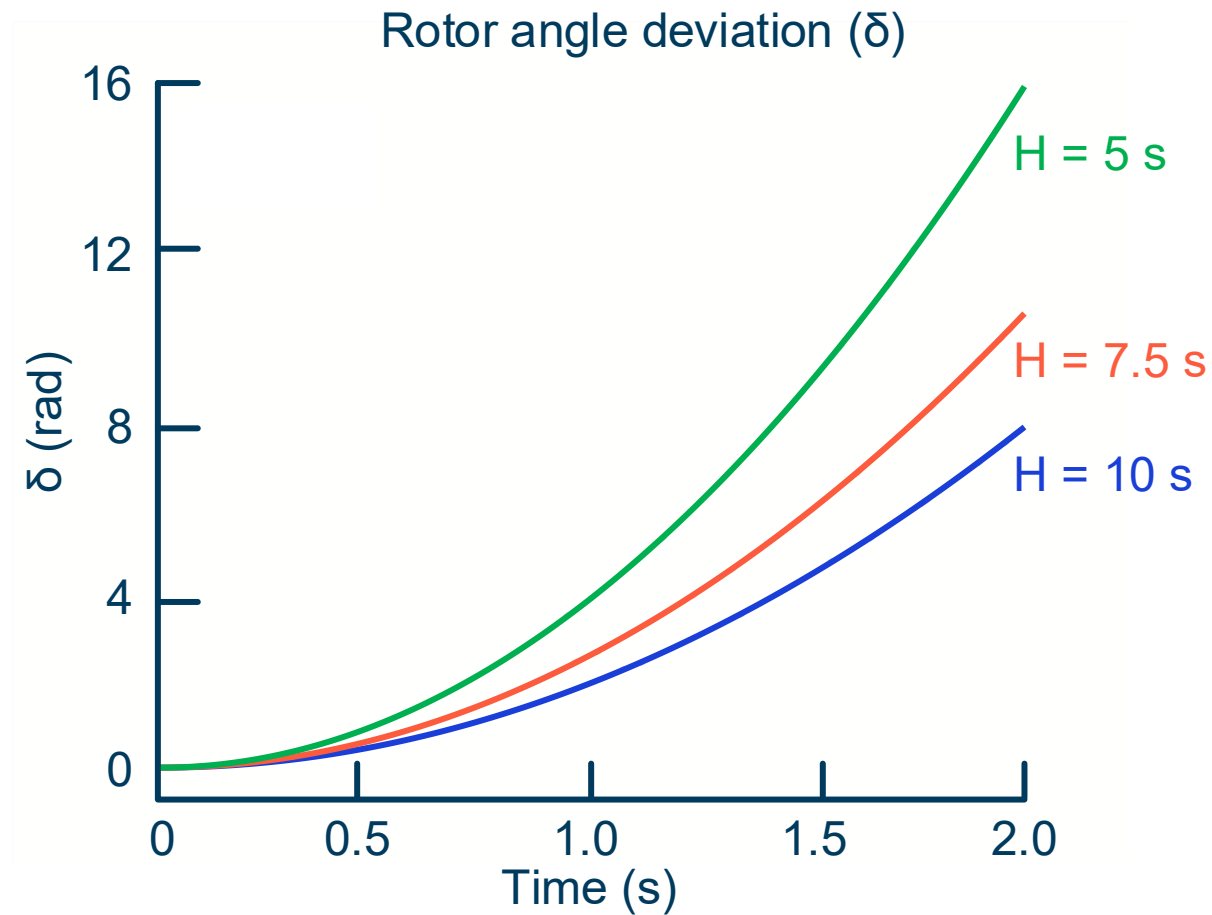
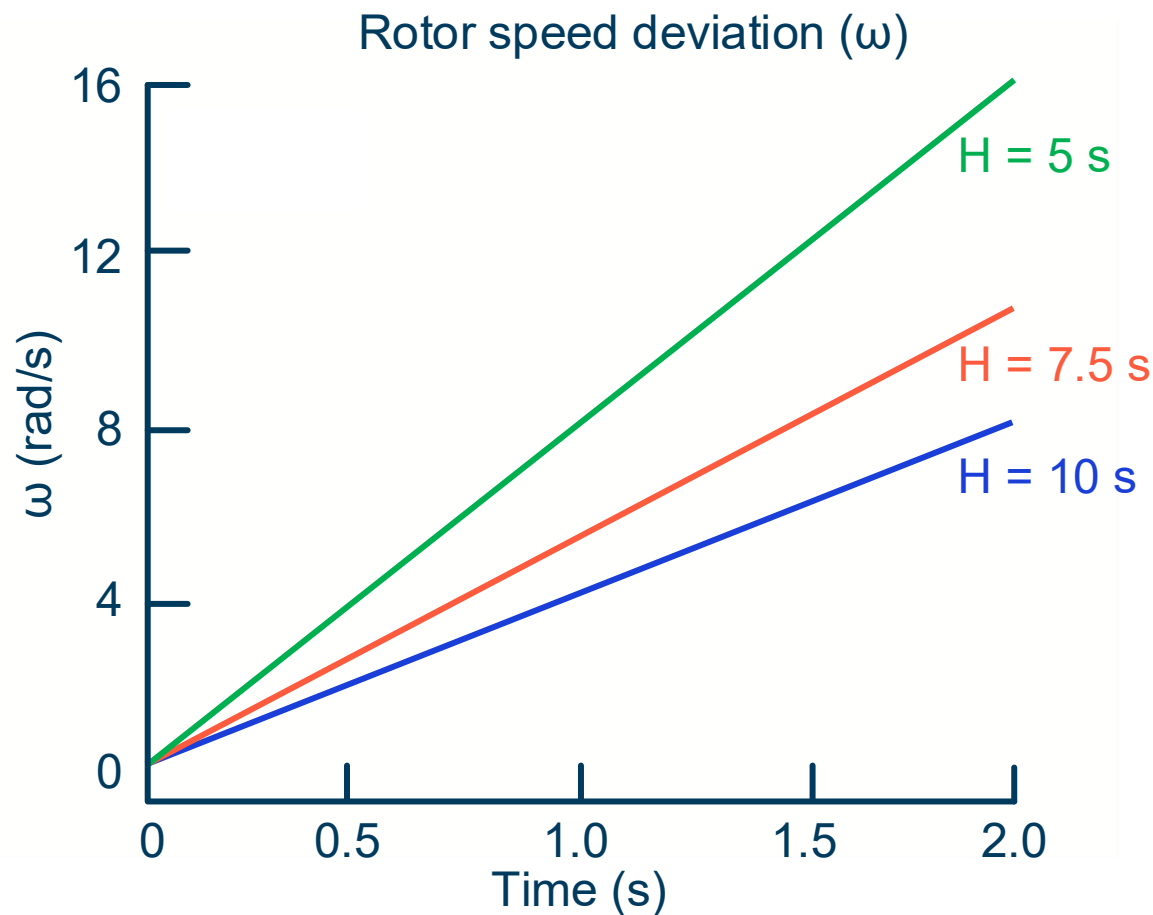
Disturbances break power system equilibrium



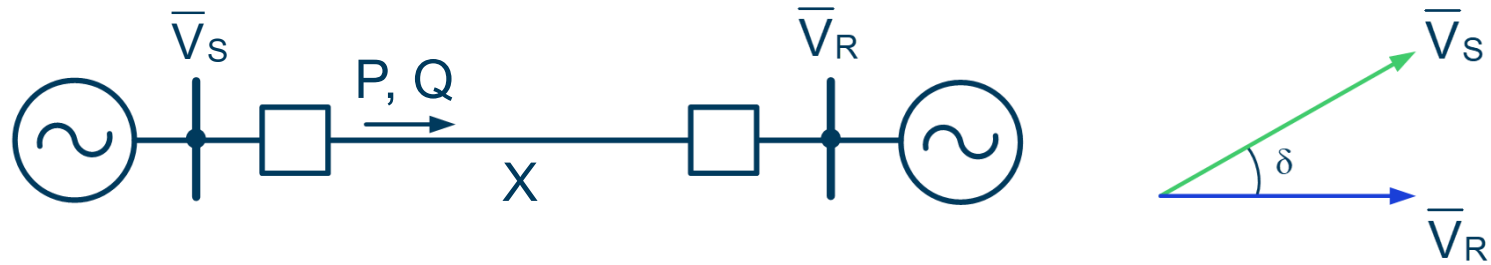
$$\frac{2H}{\omega_s} \cdot \frac{d^2\delta}{dt} = P_m - P_e$$

$$\frac{2H}{\omega_s} \cdot \frac{d\omega}{dt} = P_m - P_e$$

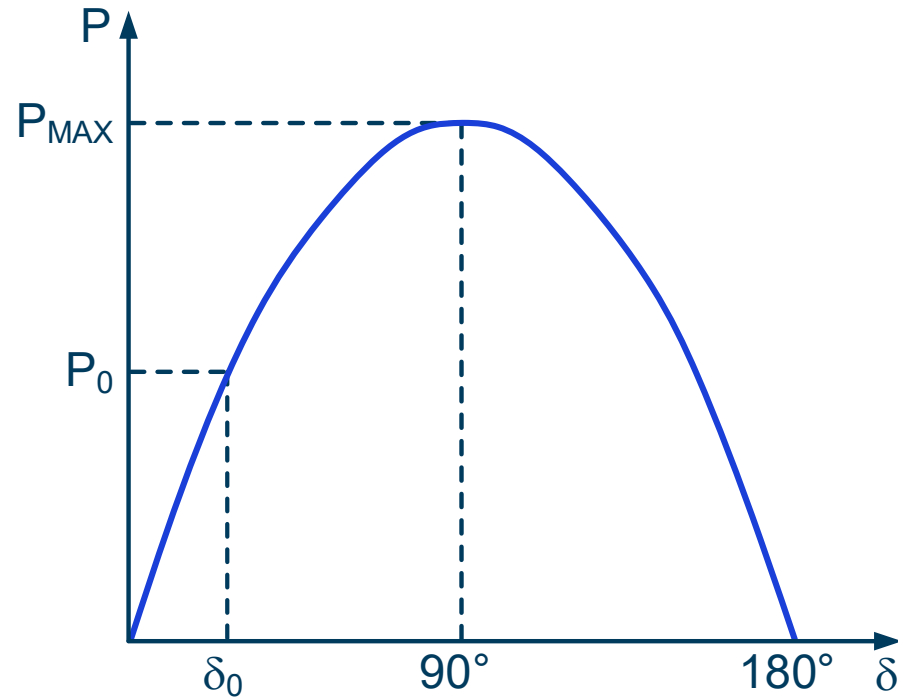
The lower the inertia, the faster the angle and frequency change



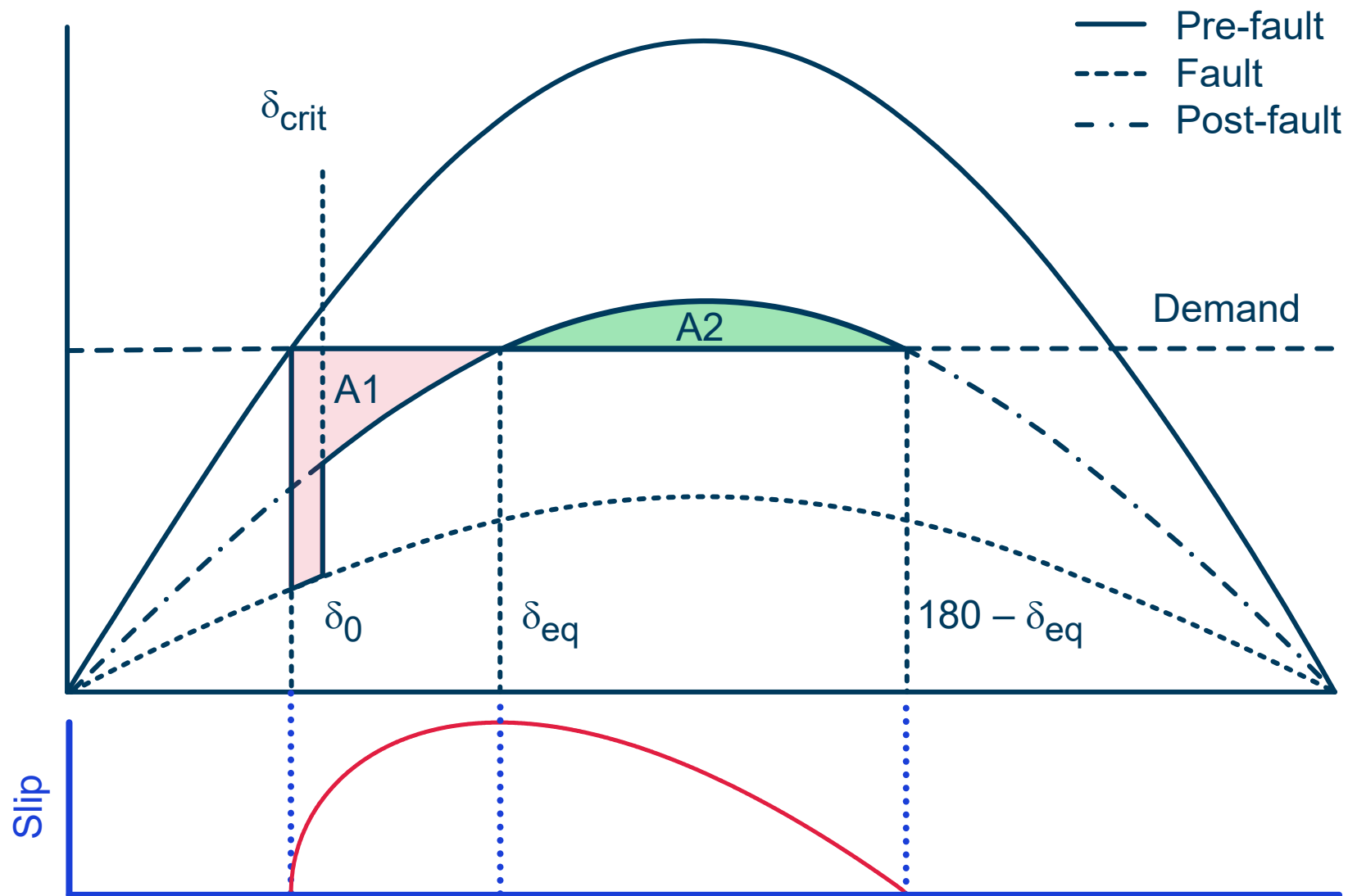
Active power transfer



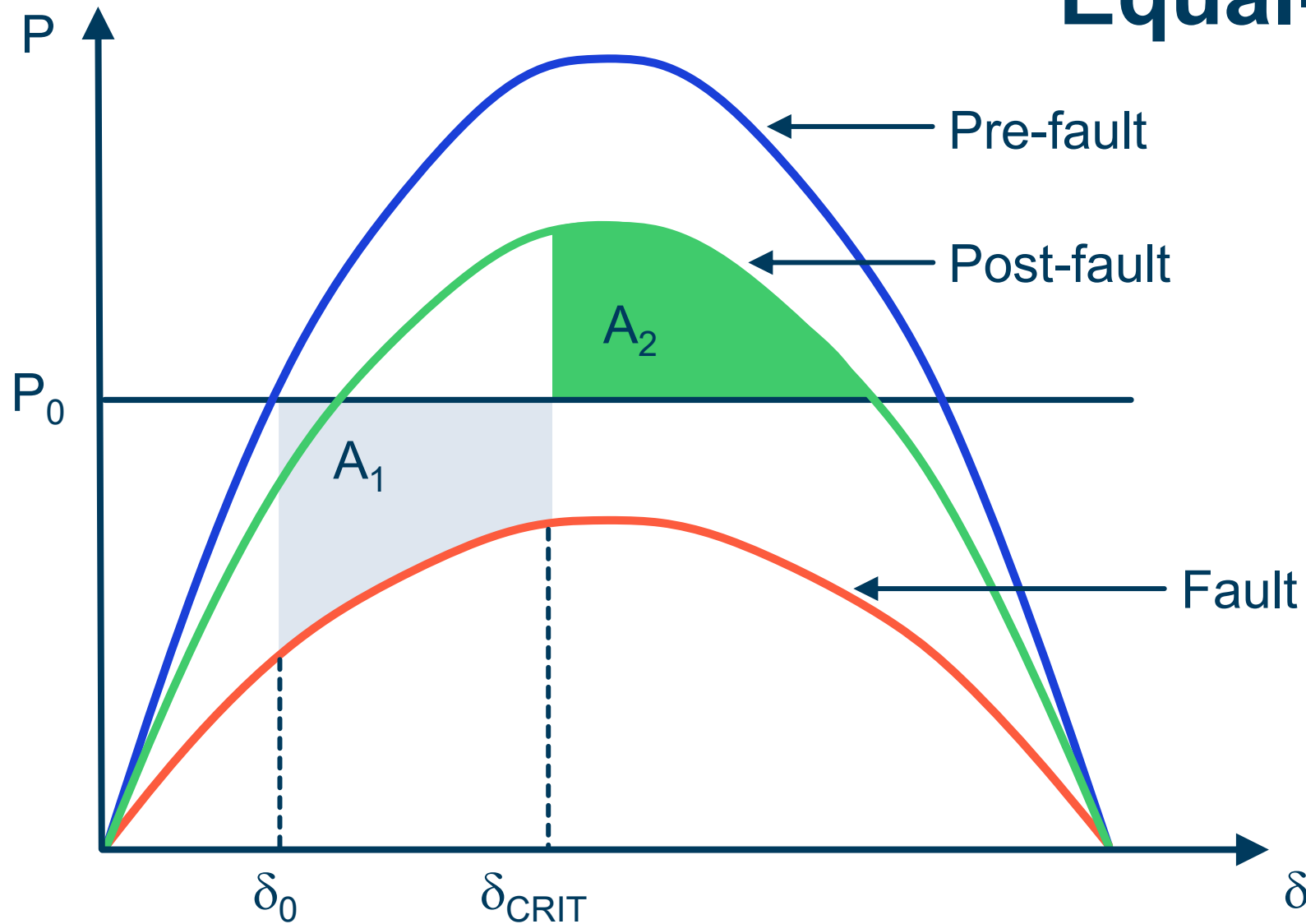
$$P = \frac{V_S V_R}{X} \sin \delta$$



Equal area criterion



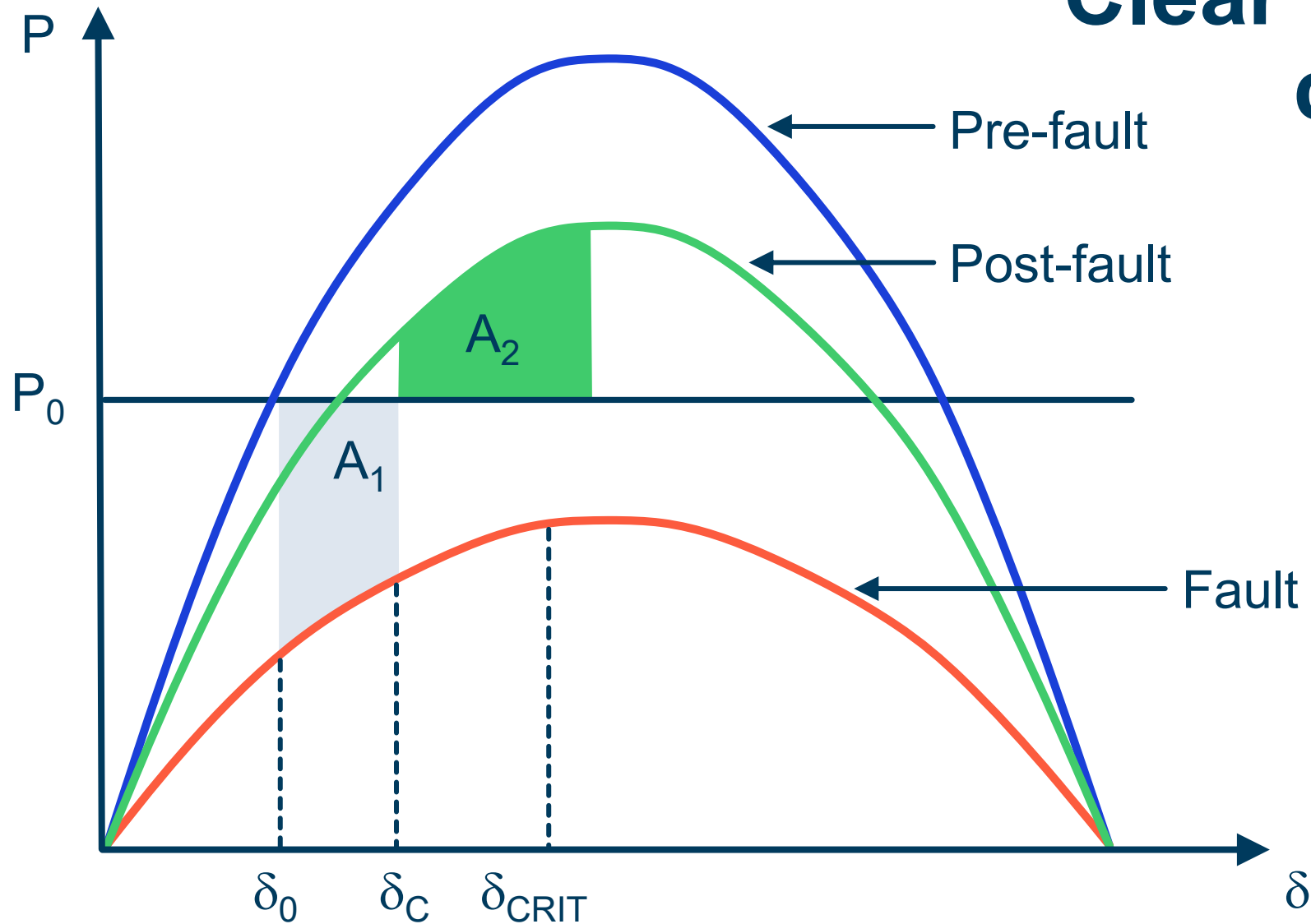
Equal-area criterion



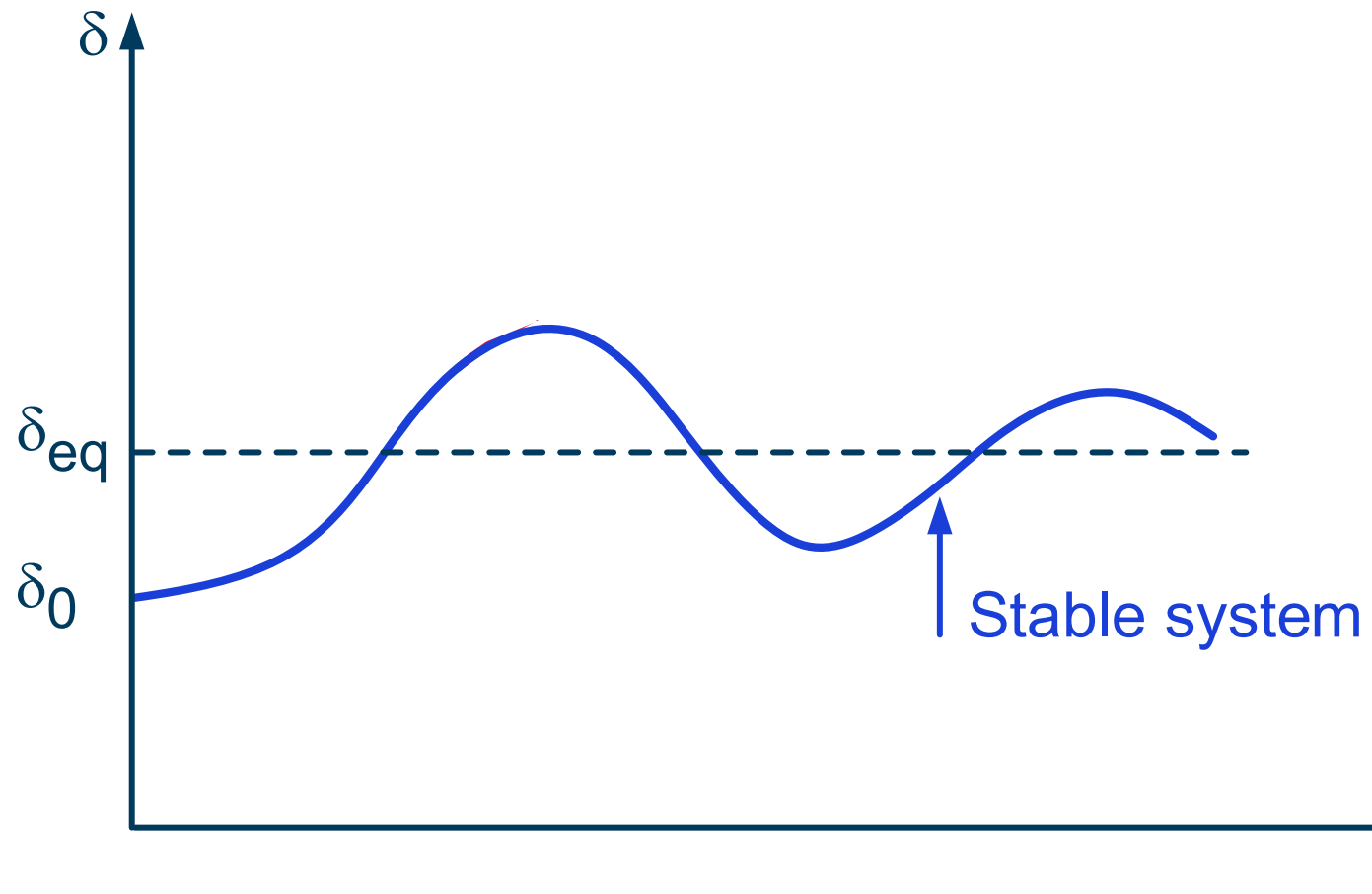
**CRITICALLY
STABLE SYSTEM**

**Clear before critical
clearing angle**

STABLE SYSTEM

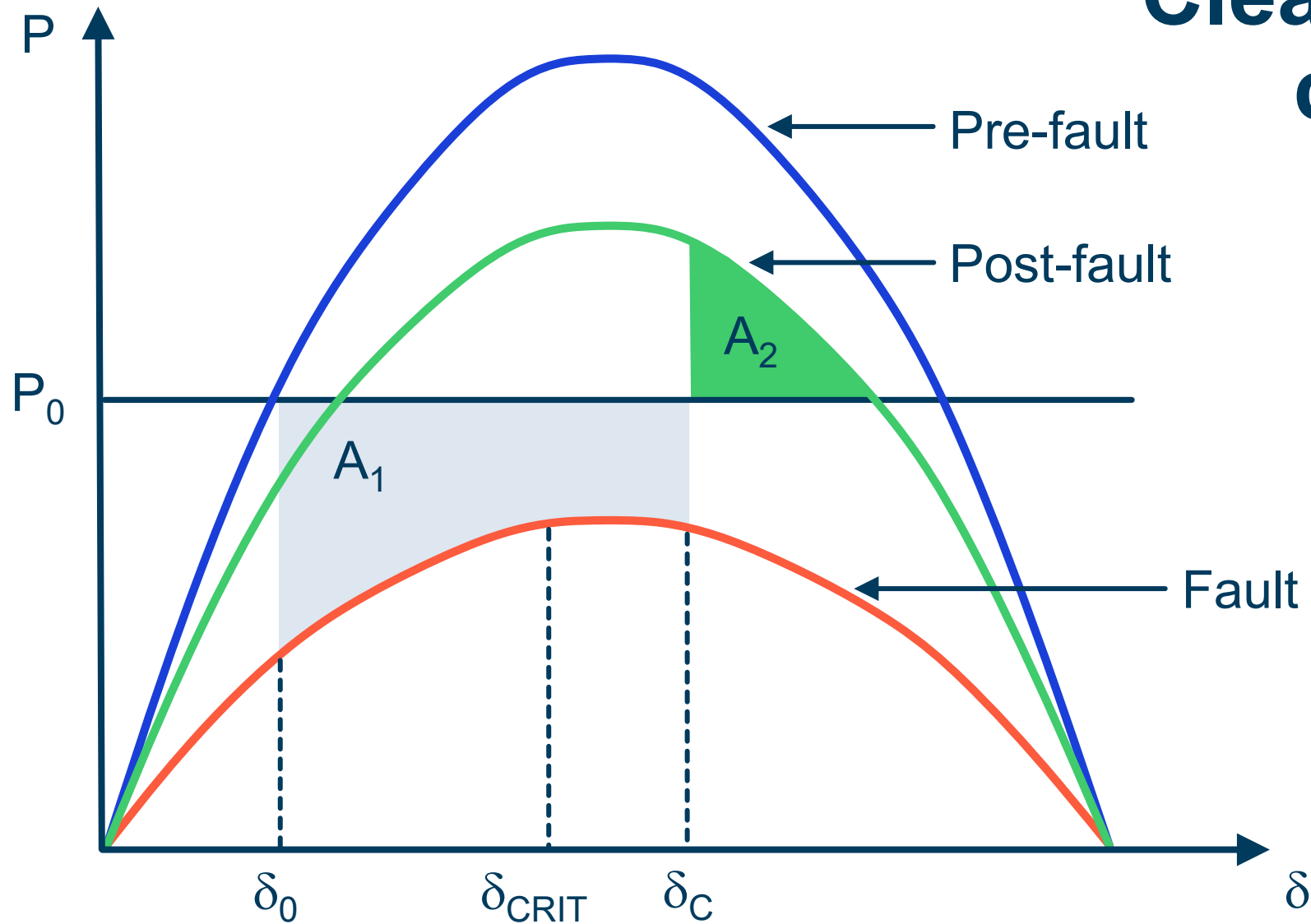


Stable power swing

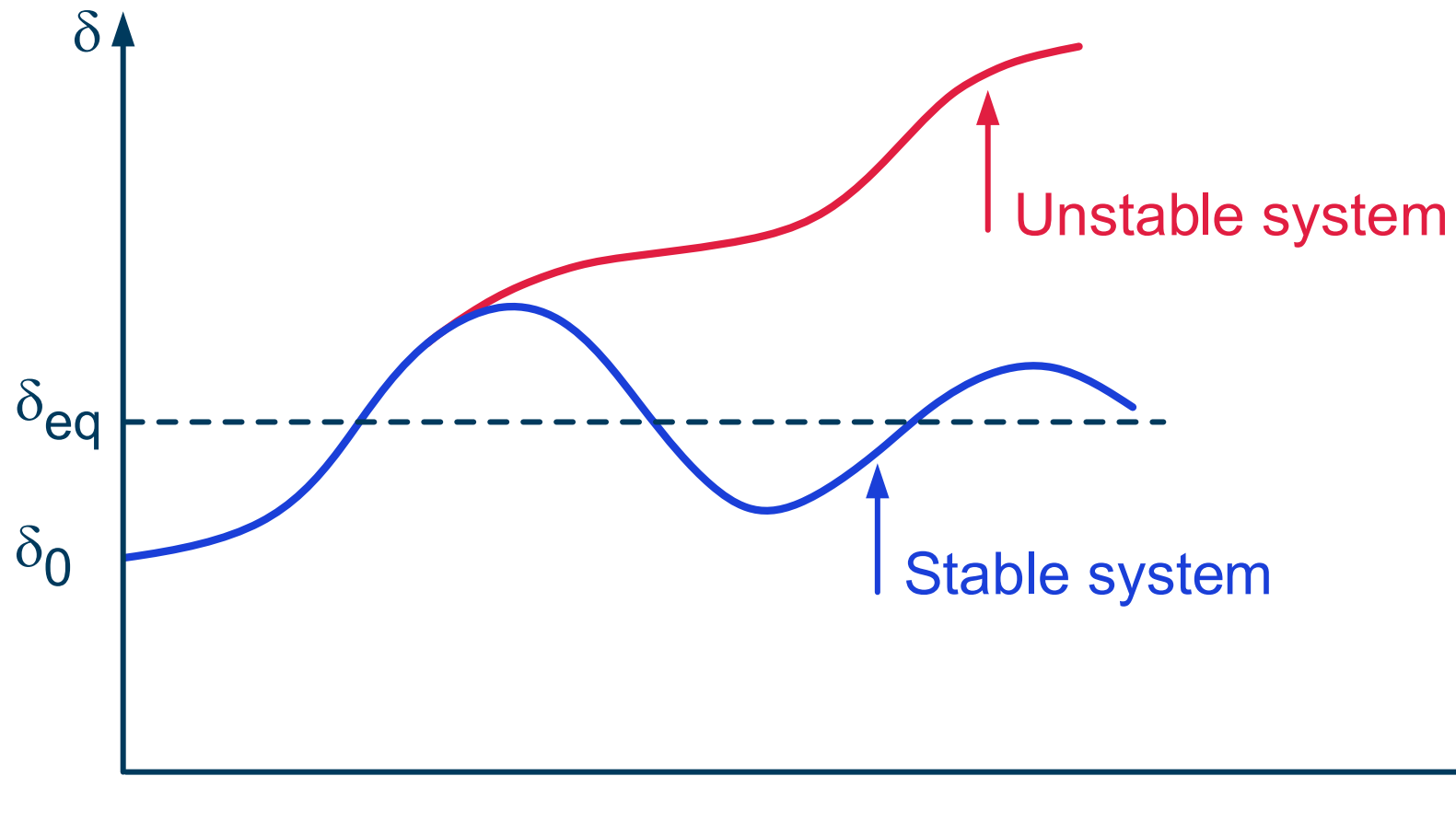


Clear **after** critical
clearing angle

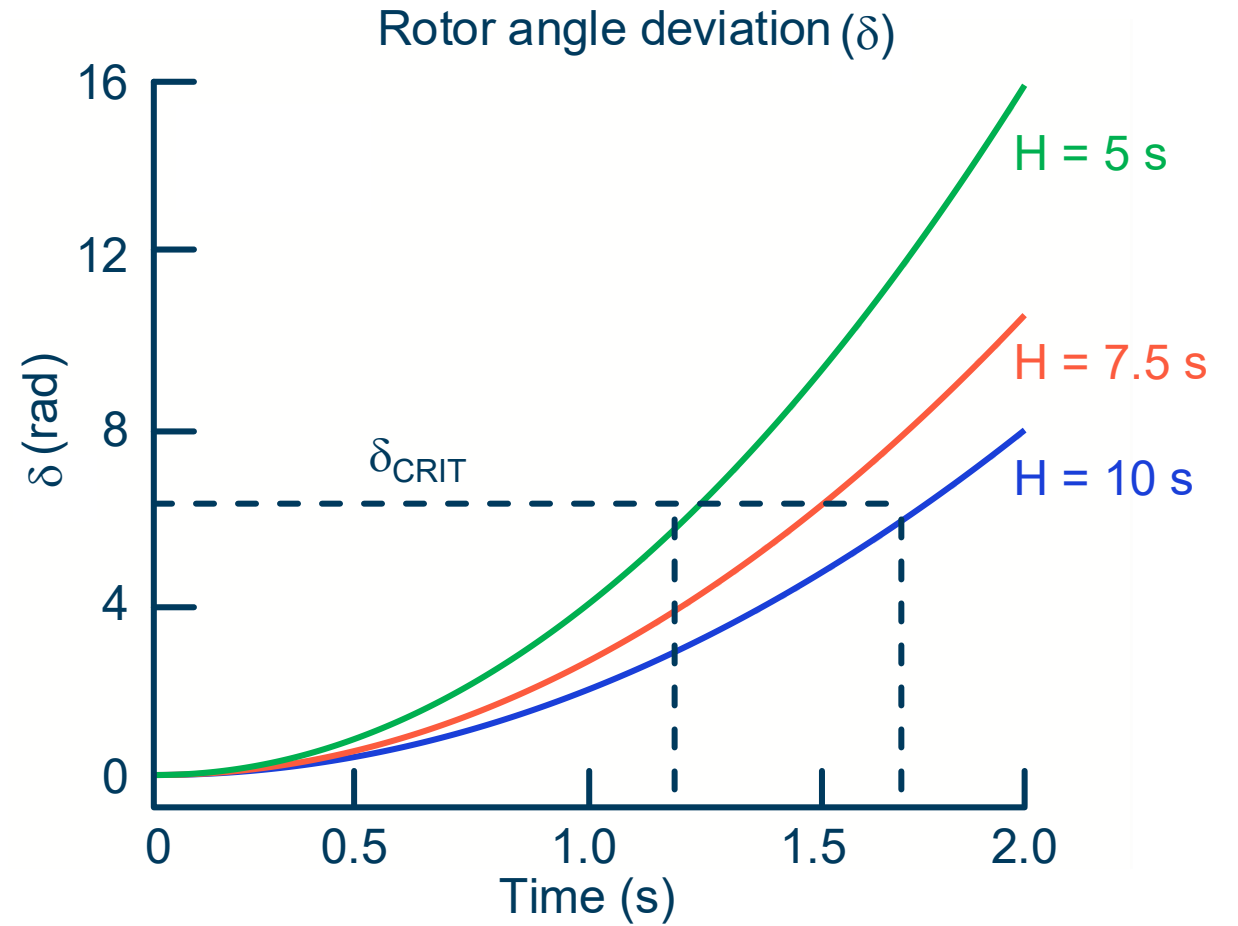
UNSTABLE SYSTEM



Stable and unstable power swings



**With less inertia,
the critical clearing
angle arrives sooner**

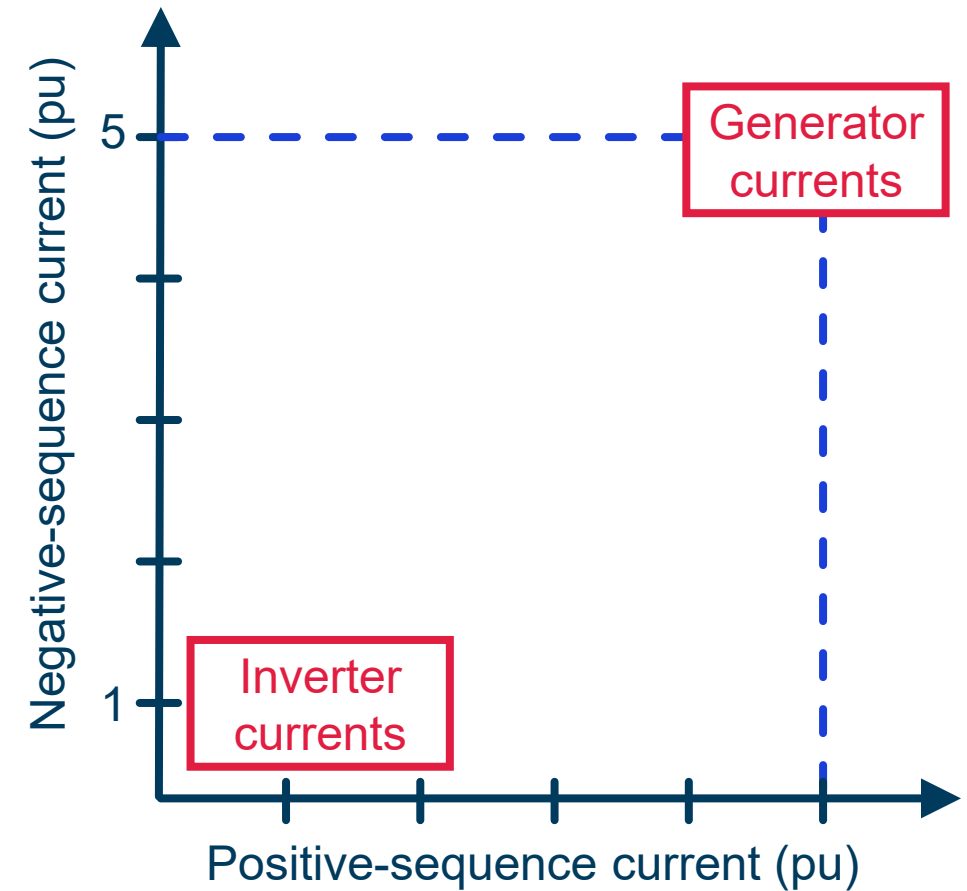
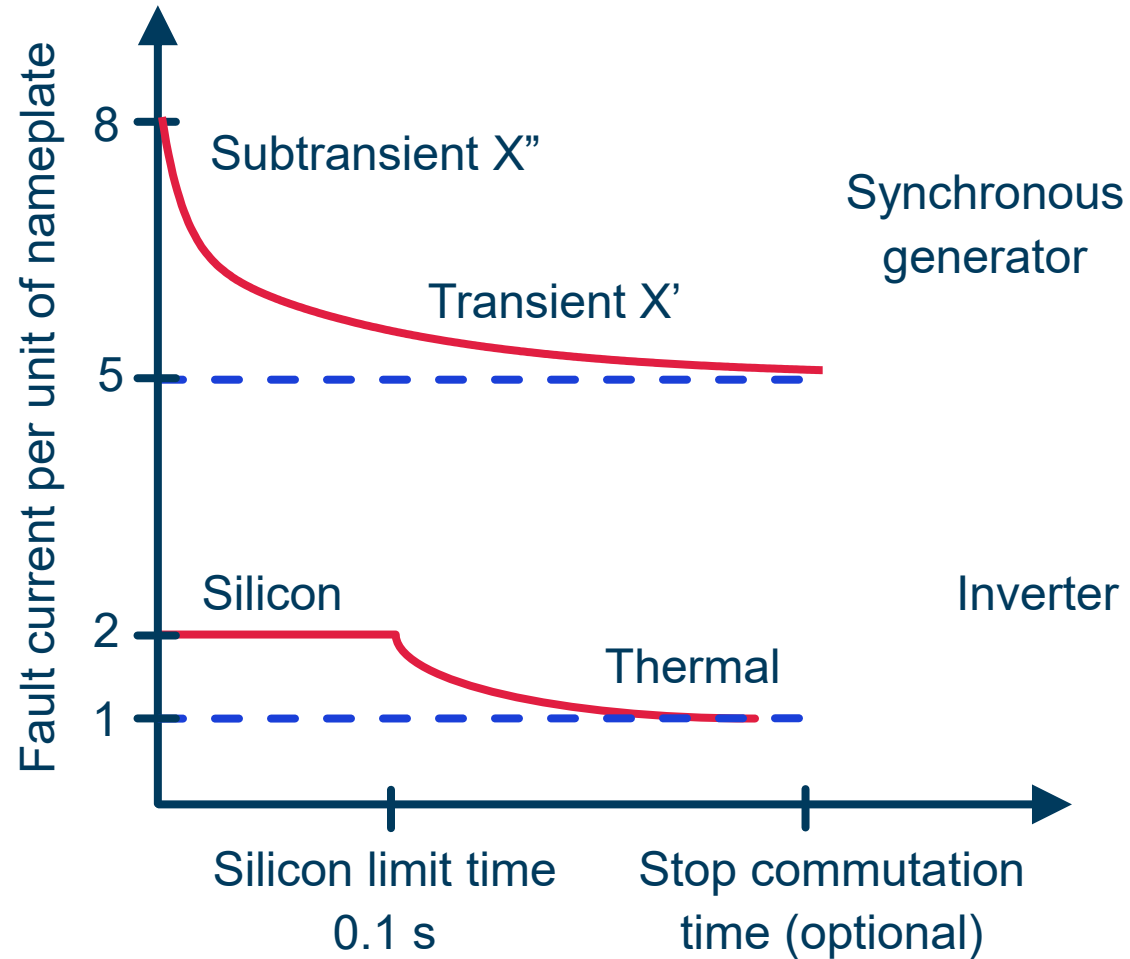




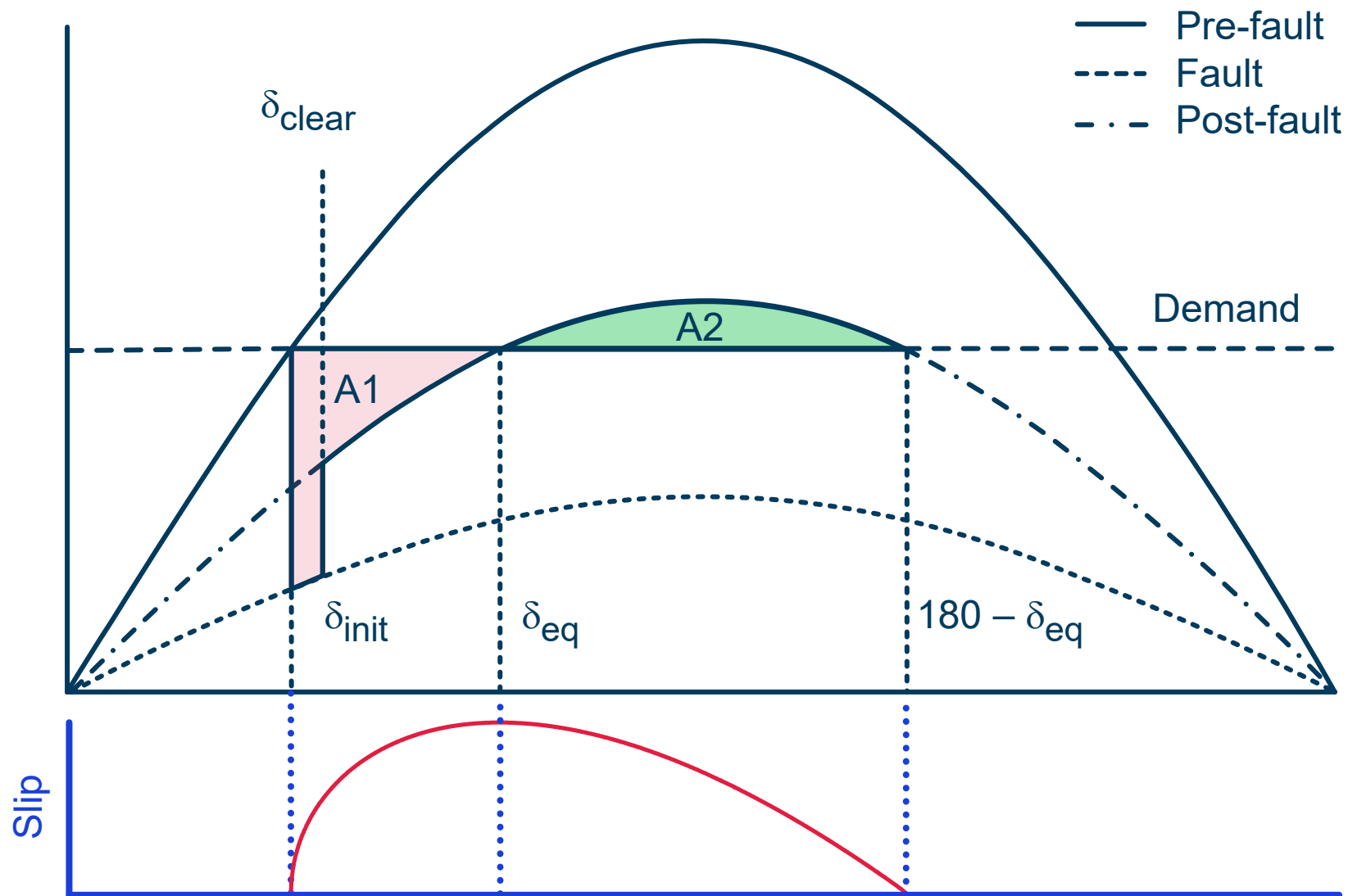
IBRs challenge power system transient stability

CURRENT SOURCING LIMITATIONS

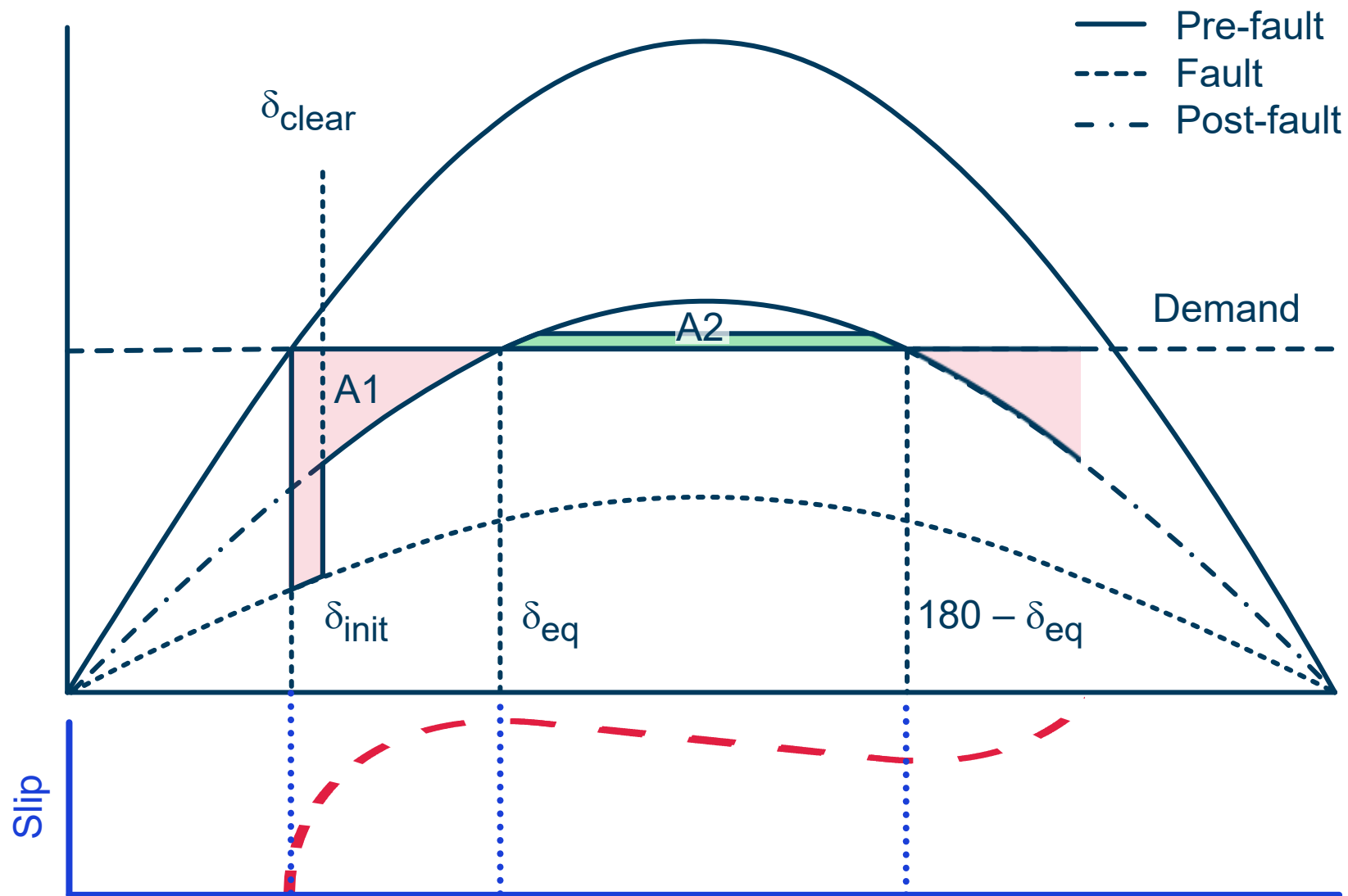
IBR fault current is more limited



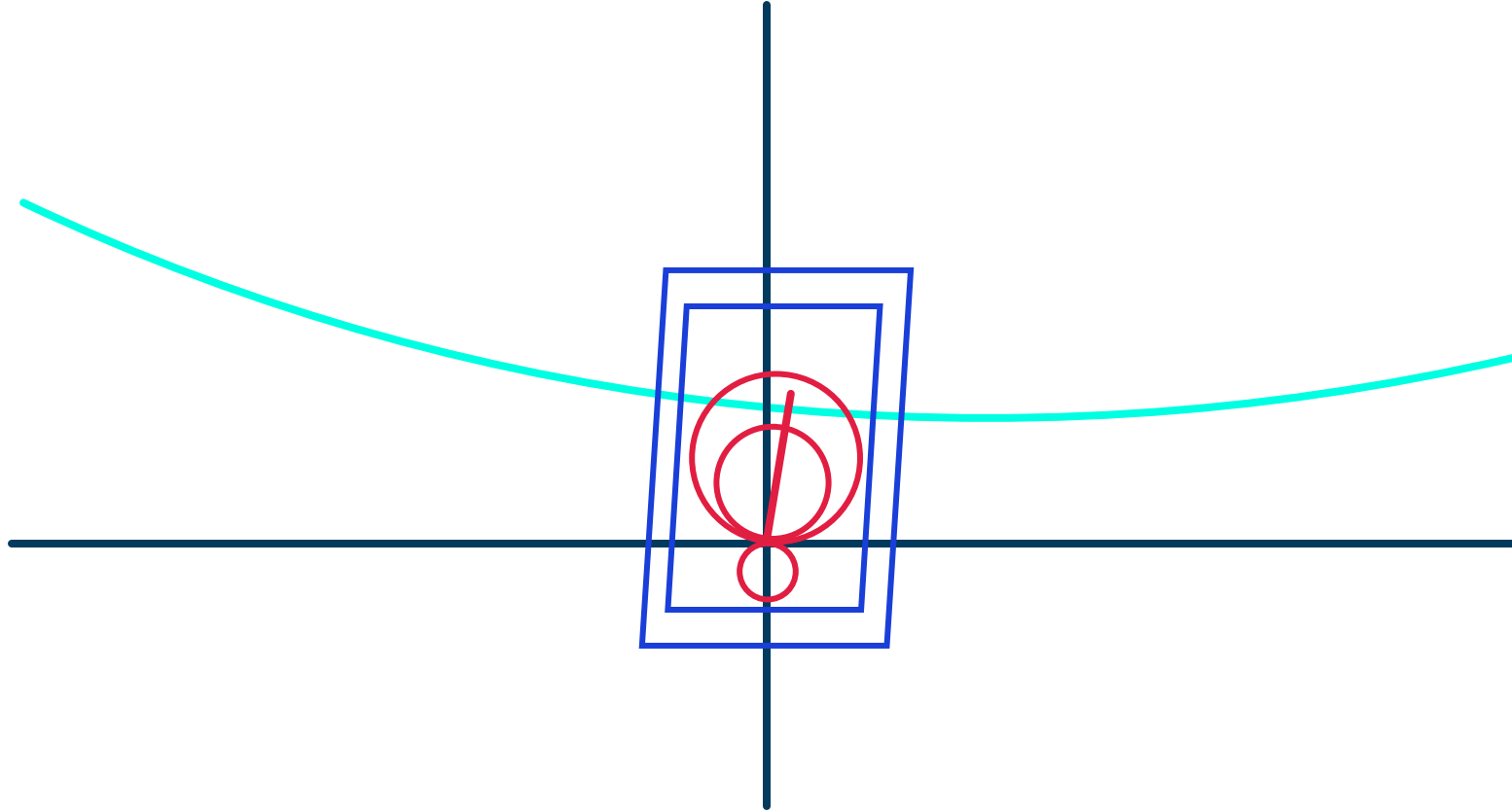
Equal area criterion



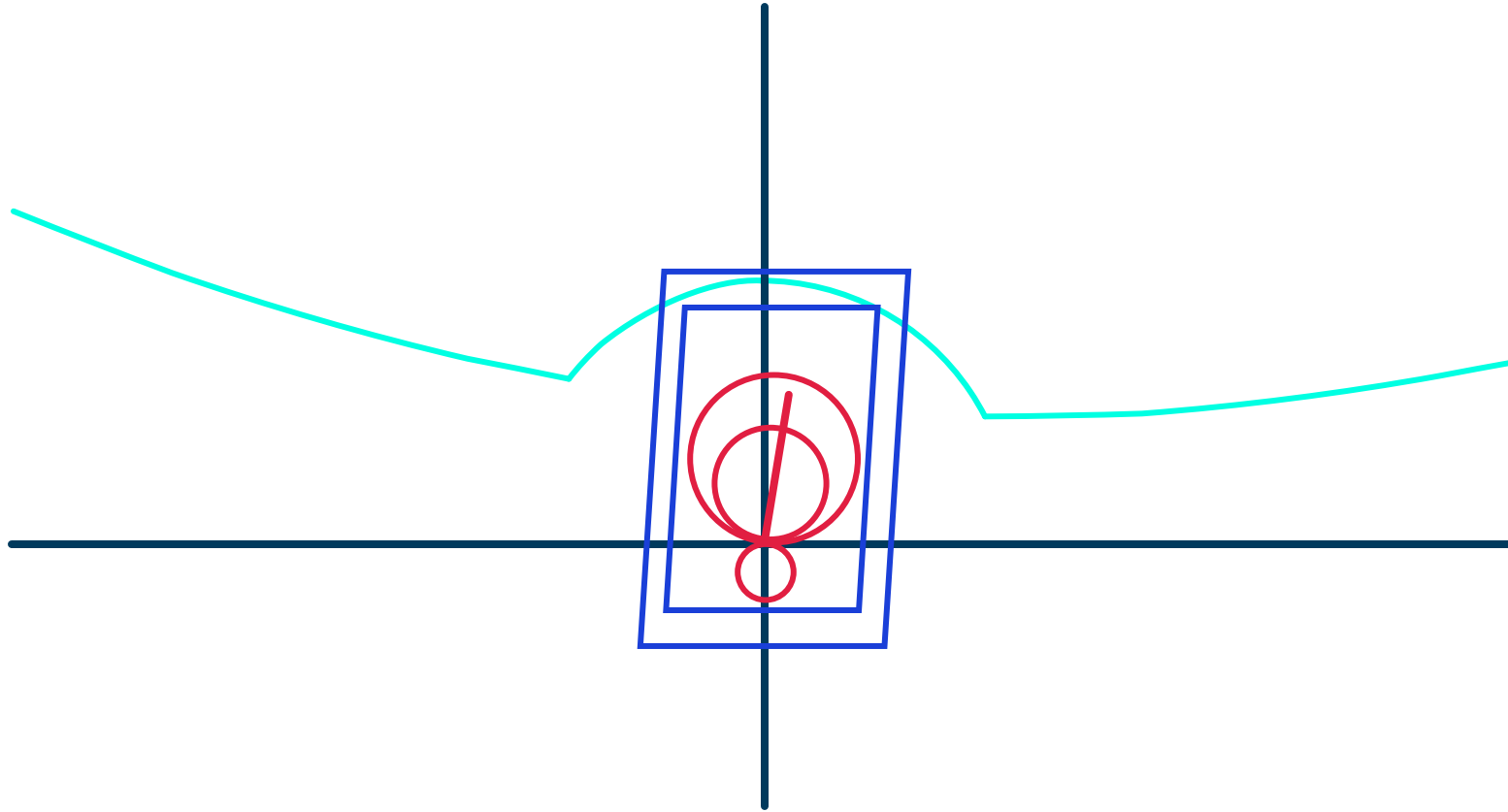
Equal area criterion (current limit)



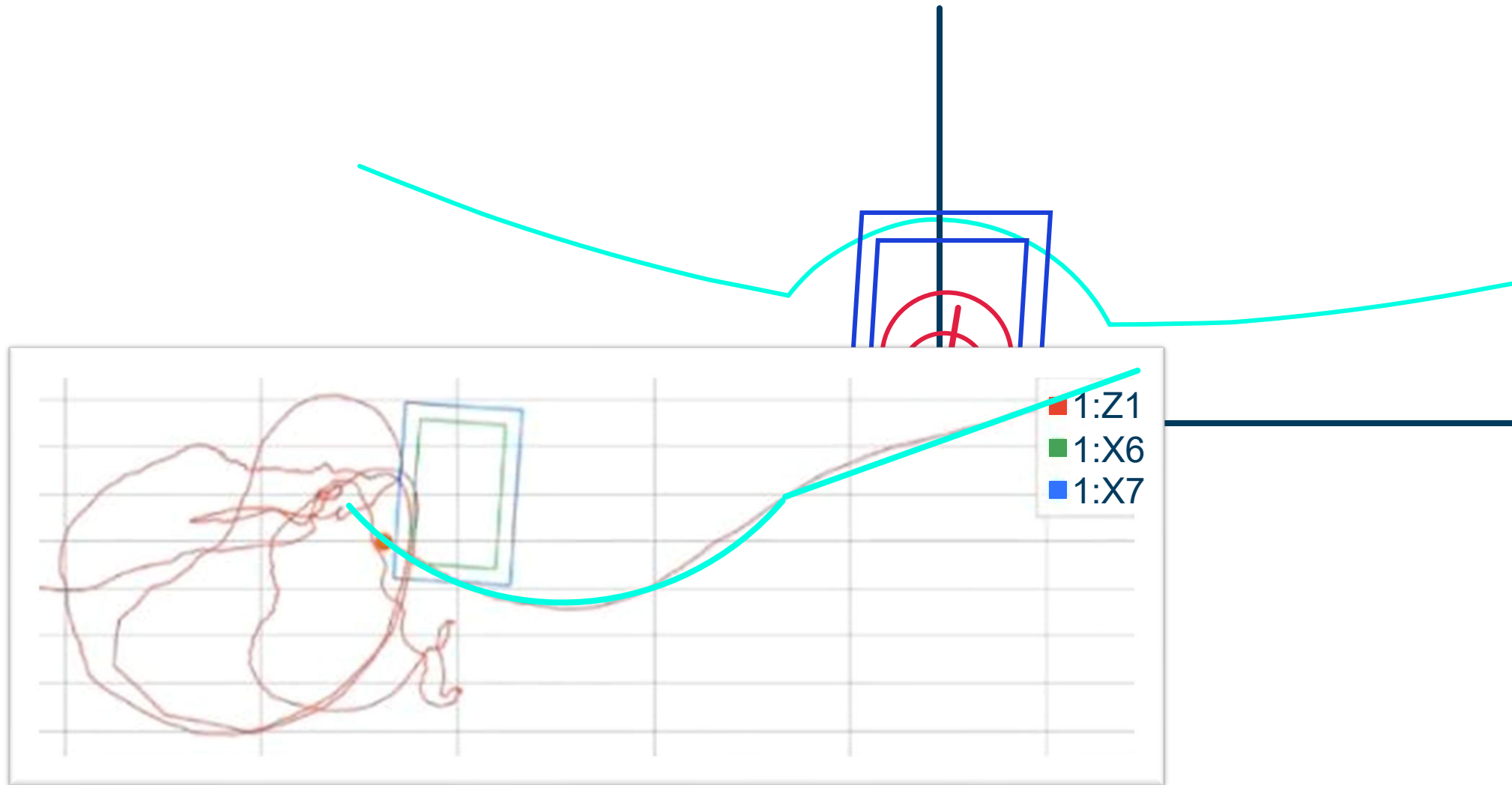
OOS impedance trajectory



OOS impedance trajectory (current limited)



OOS impedance trajectory (current limited)





IBRs challenge power system protection

Protective relay were designed for systems with synchronous generators

- High inertia prevents fast frequency changes
- High fault currents facilitate fault detection
- Negative-sequence current follows negative-sequence voltage

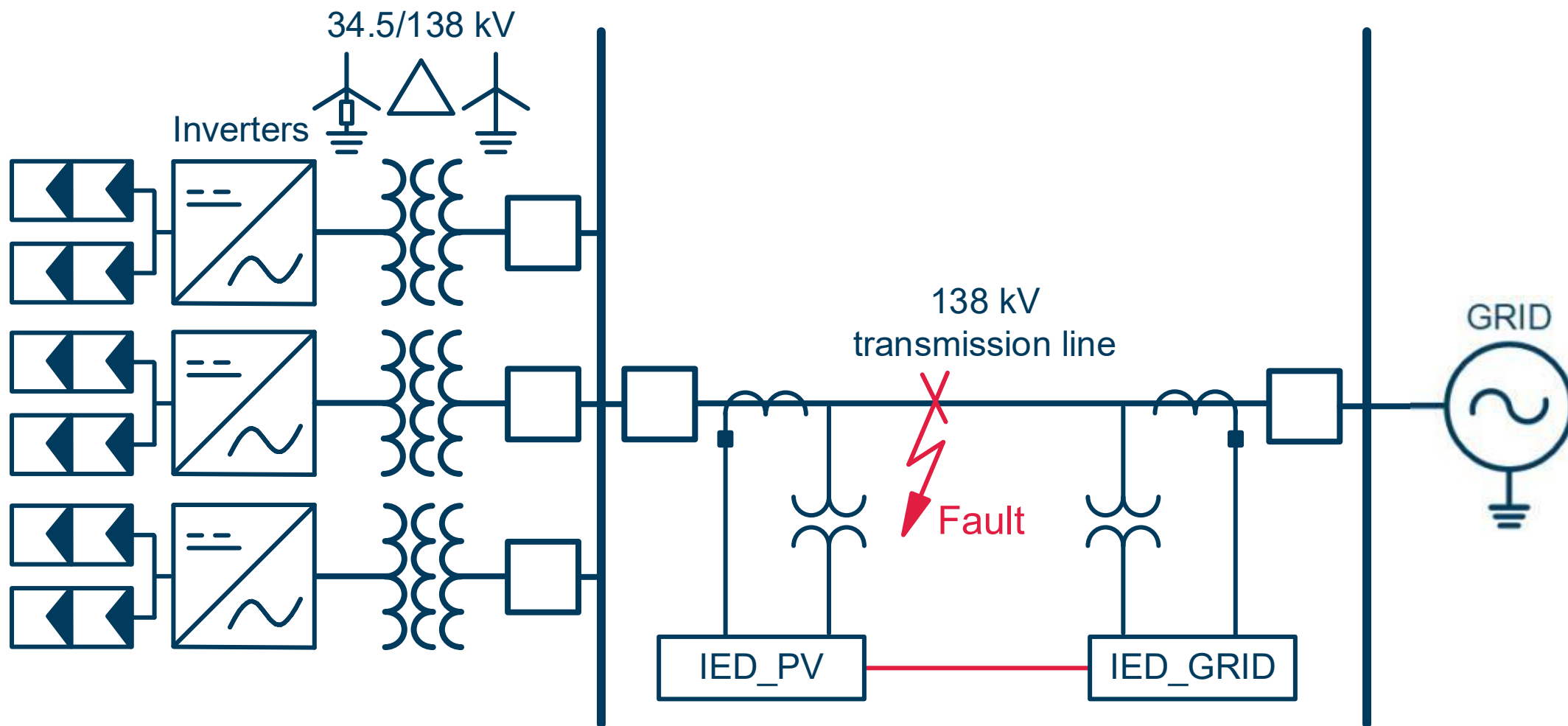


Protection elements affected by IBRs

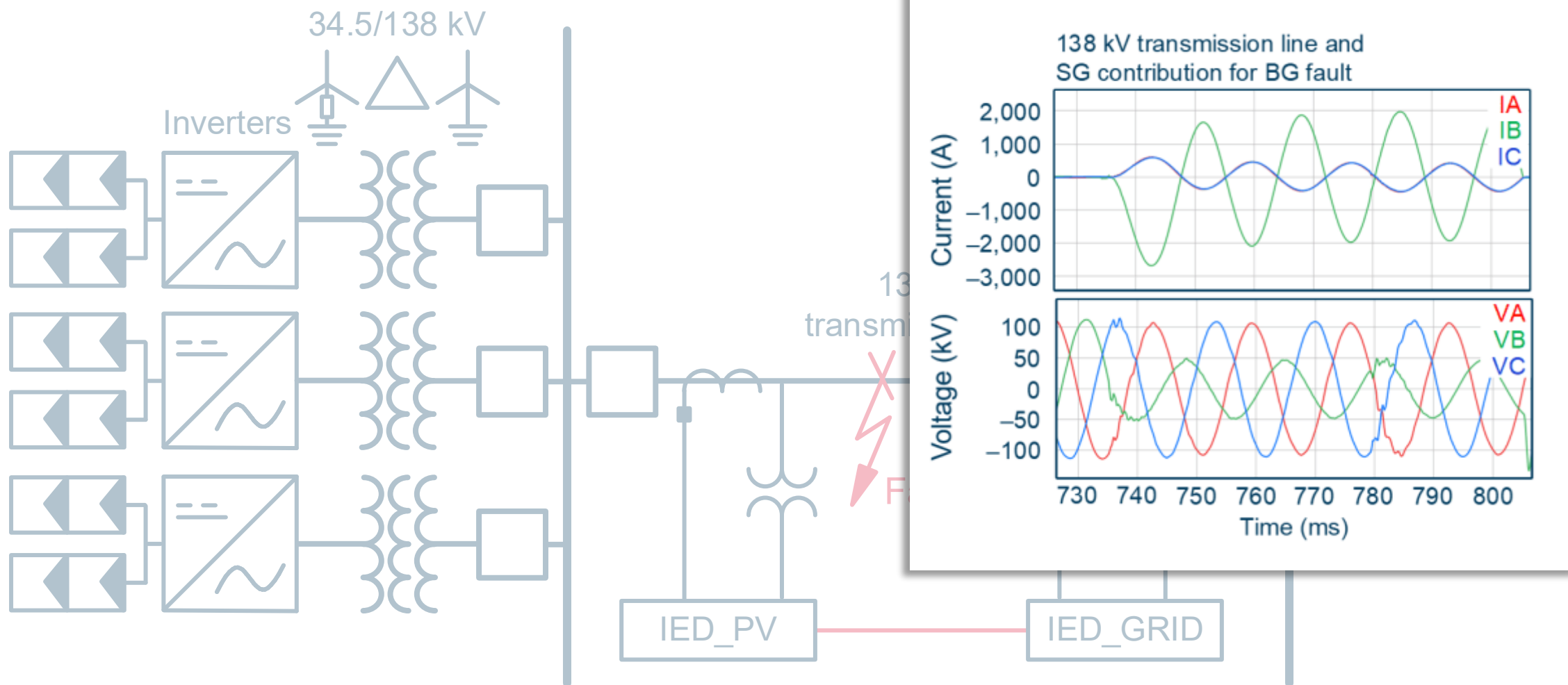
- **Power swing blocking and out-of-step tripping –**
IBRs affect impedance trajectories
- **Mho distance elements –**
Low inertia affects memory polarization
- **Quadrilateral distance elements –**
IBR controls affect polarizing I_2 angle
- **Negative-sequence directional elements –**
IBRs affect operating I_2 angle



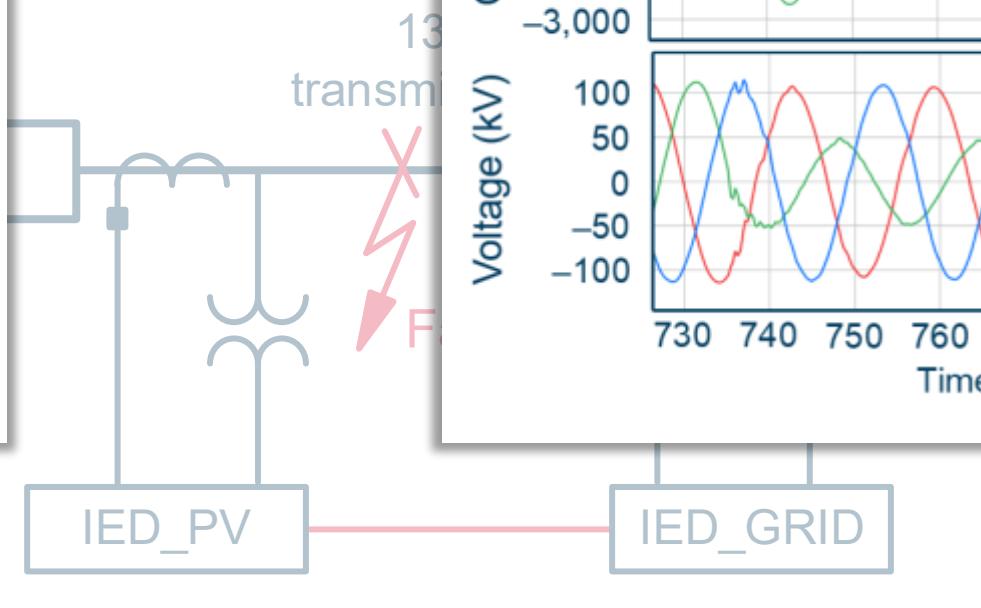
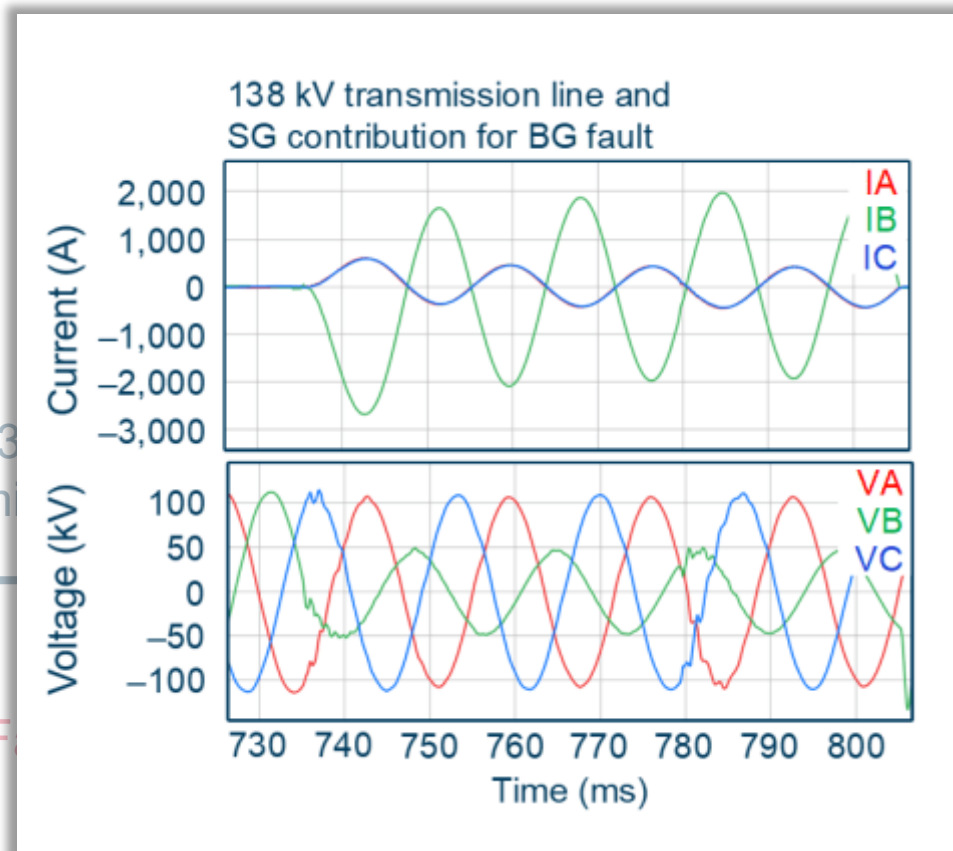
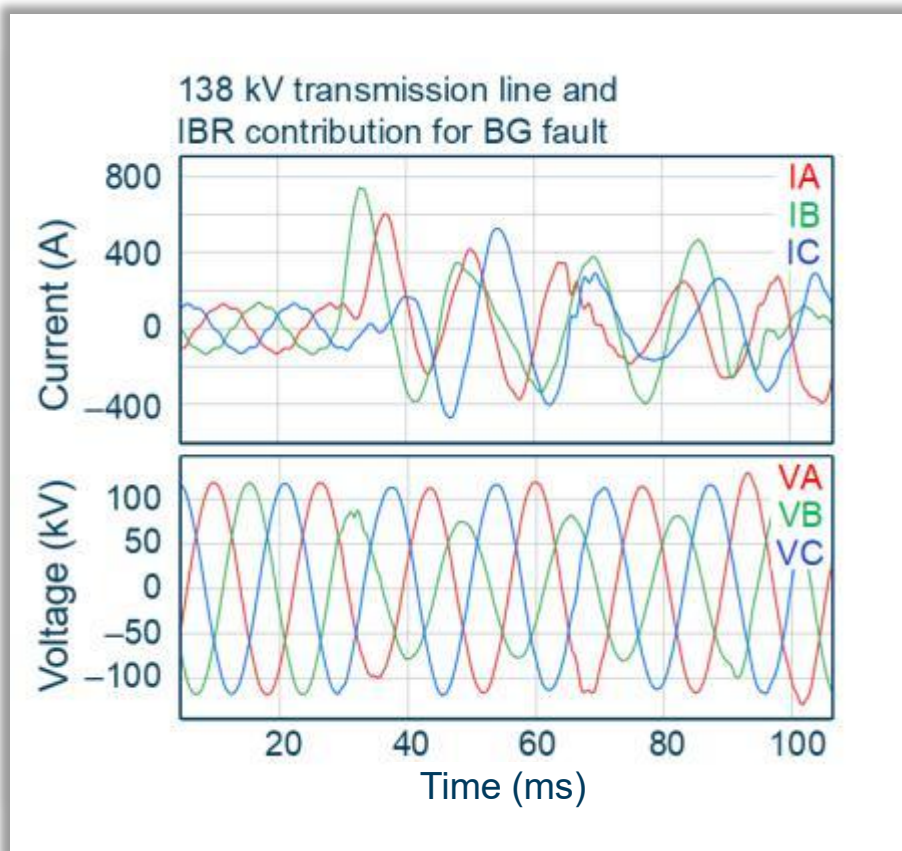
Example power system with internal fault



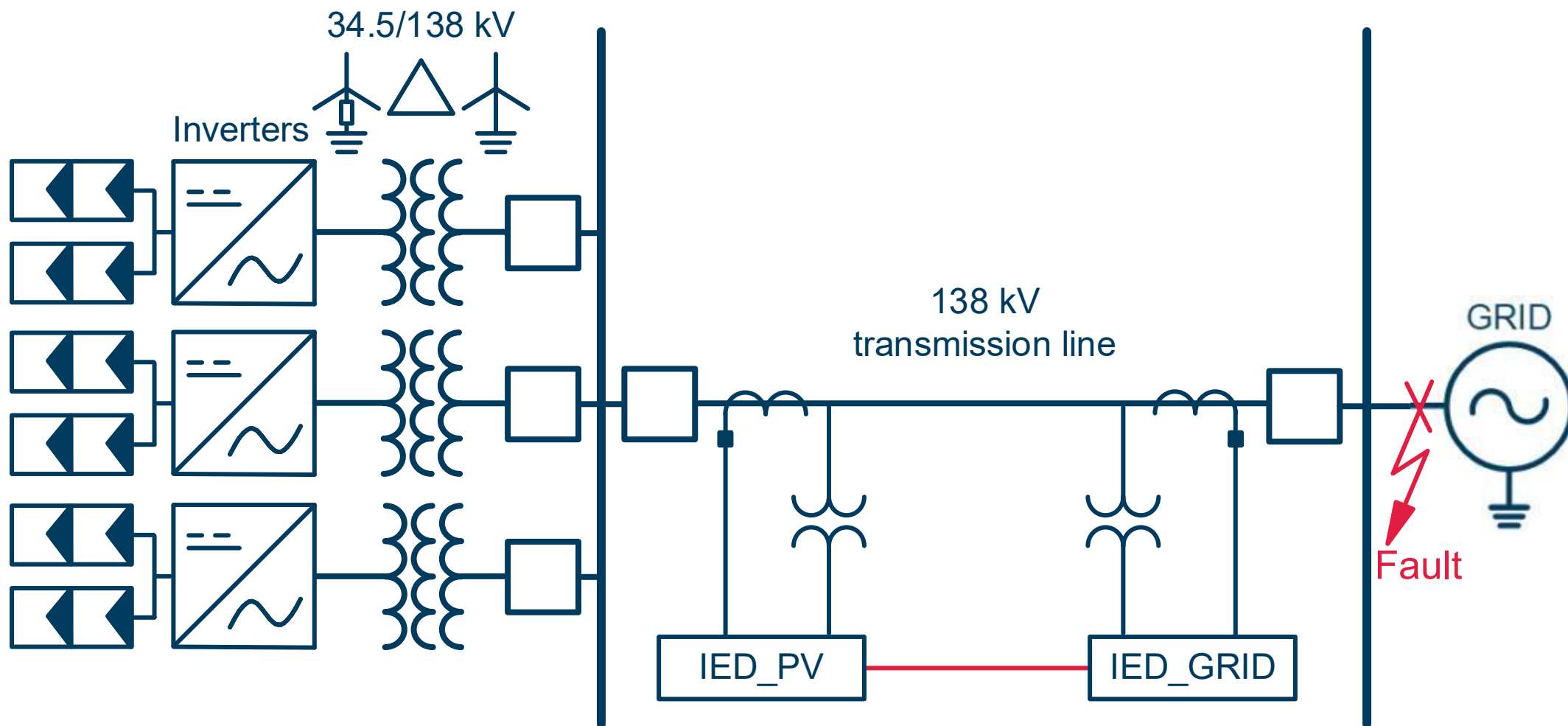
Example power system with internal fault



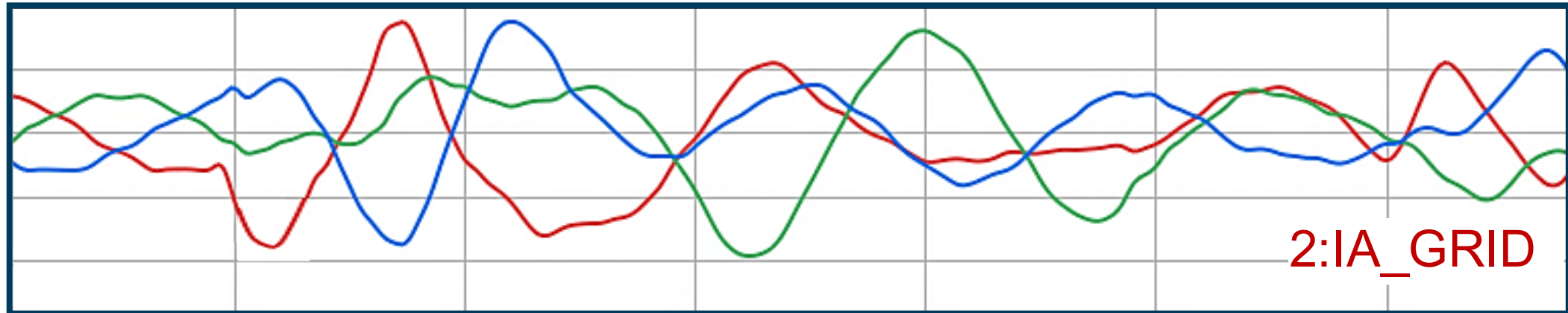
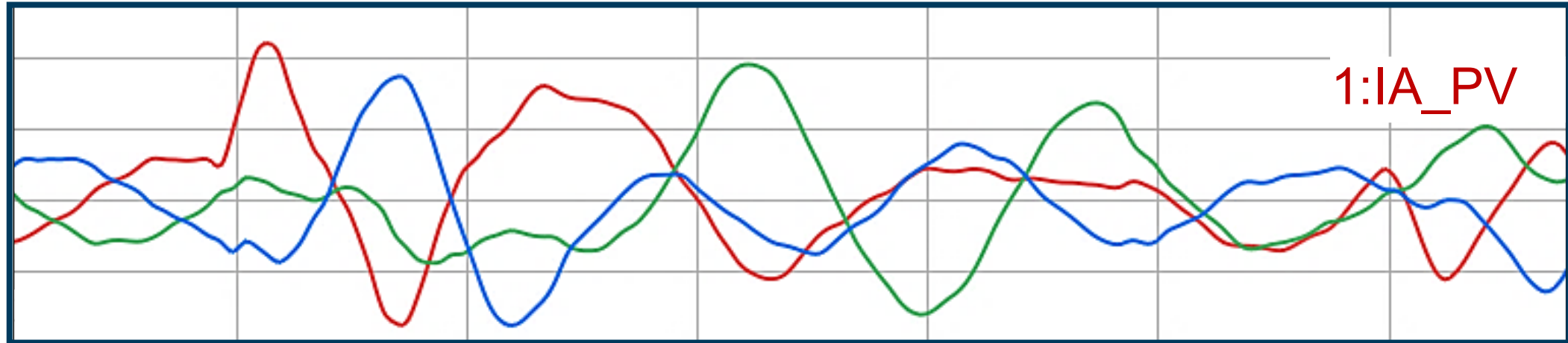
Example power system with internal fault



Example power system with external fault

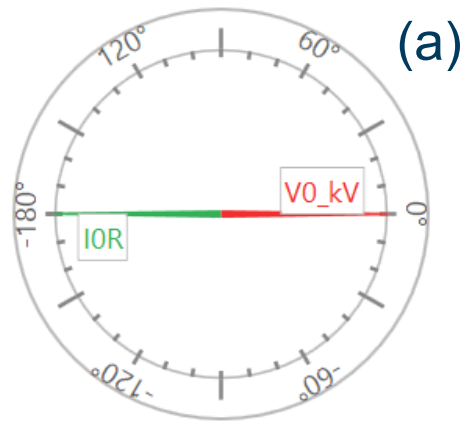
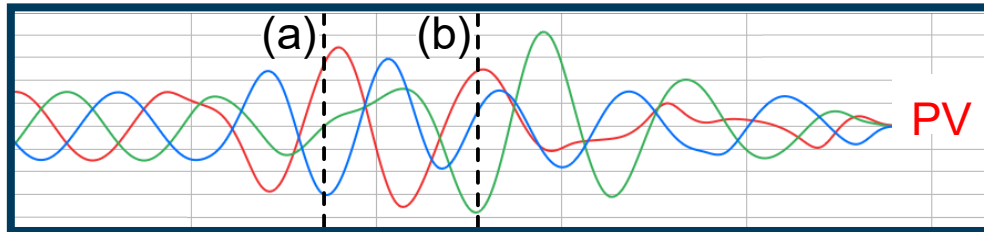


Measured signals for external AG fault



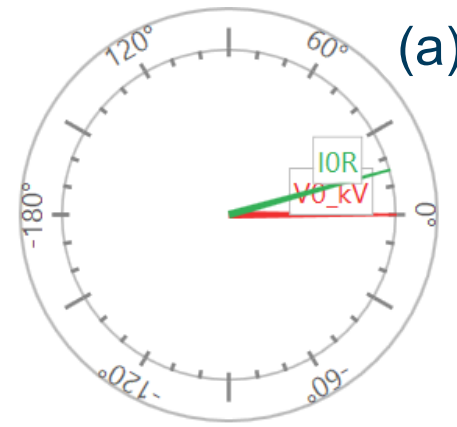
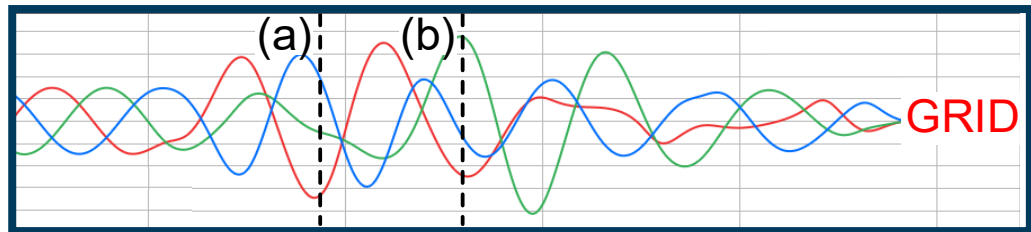
Step-up transformers provide reliable I_0

Relationship between V_0 and I_{0R} consistent with forward fault during entire event



IED_PV

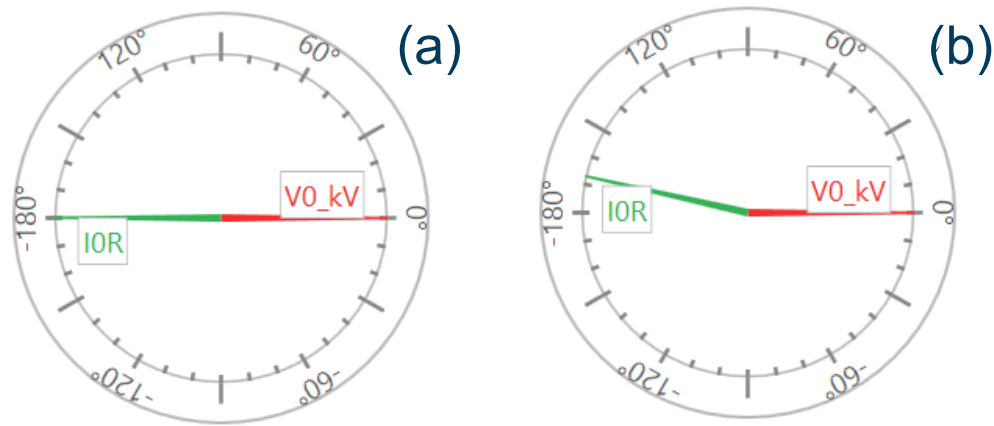
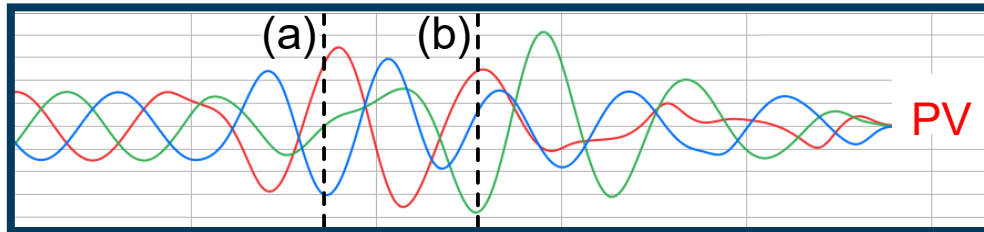
Relationship between V_0 and I_{0R} consistent with reverse fault during entire event



IED_GRID

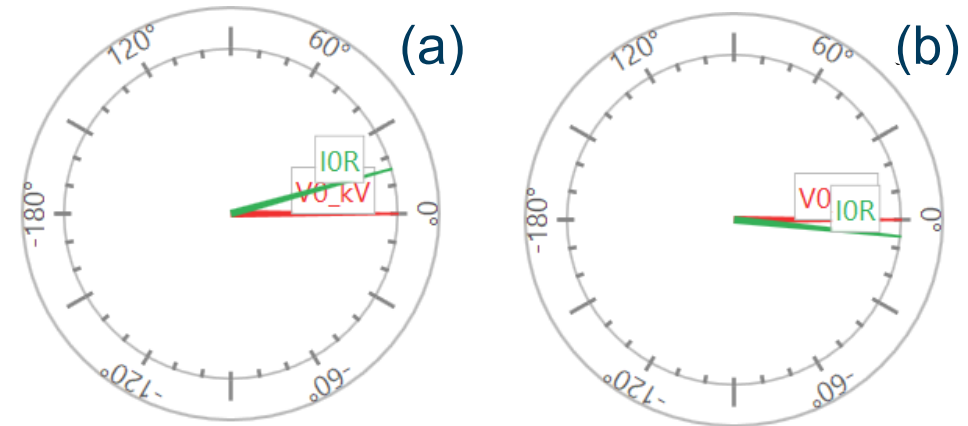
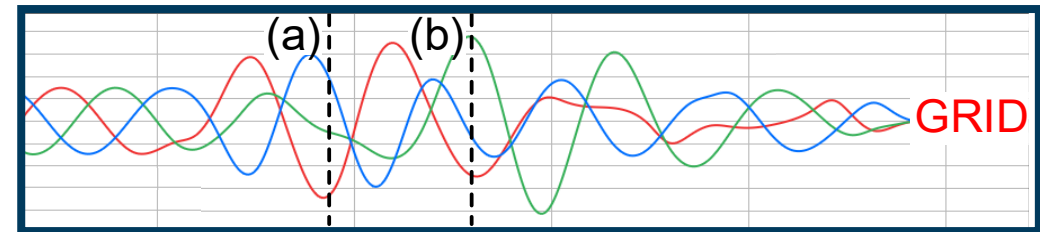
Step-up transformers provide reliable I_0

Relationship between V_0 and I_{0R} consistent with forward fault during entire event



IED_PV

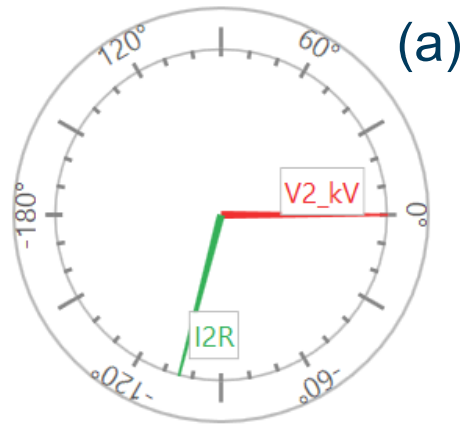
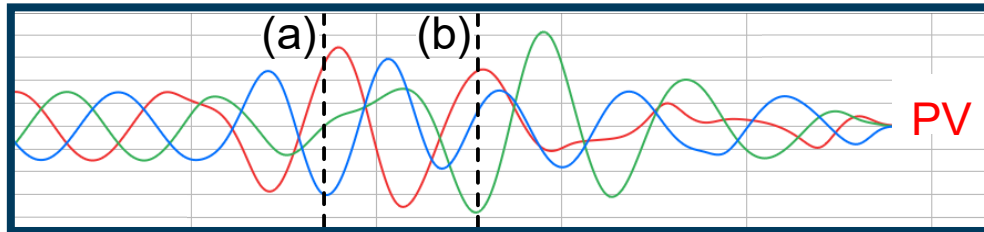
Relationship between V_0 and I_{0R} consistent with reverse fault during entire event



IED_GRID

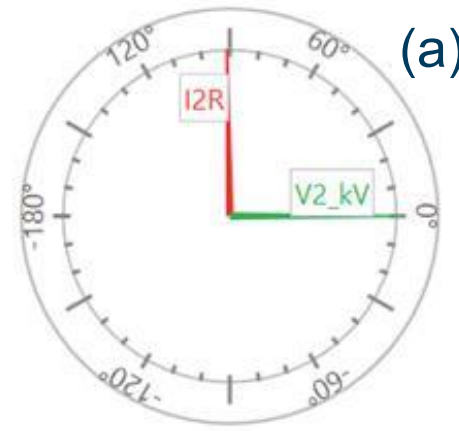
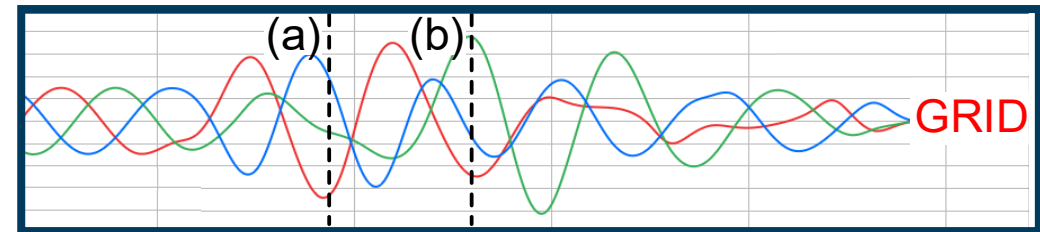
IBR sources distort I_2

Relationship between V_2 and I_{2R}
consistent with forward fault (a) and
after with reverse fault



IED_PV

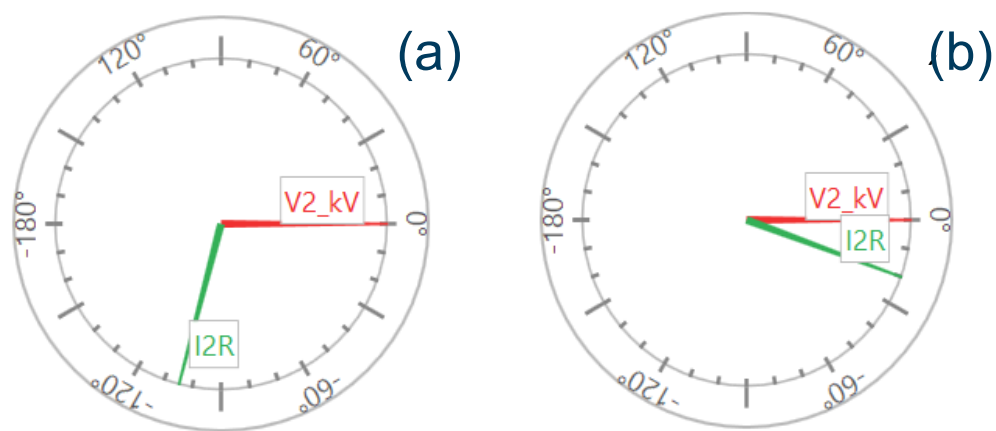
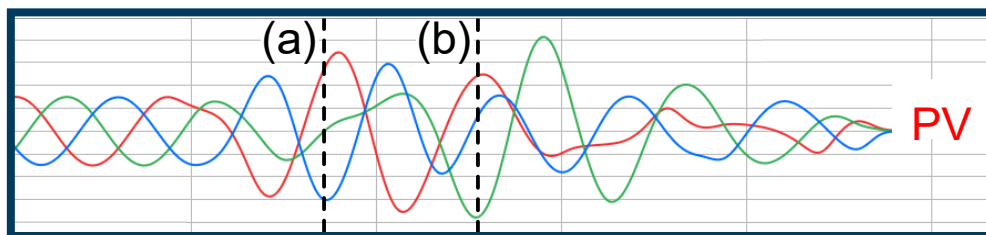
Relationship between V_2 and I_{2R}
in undefine region (a) and after
with forward fault (b)



IED_GRID

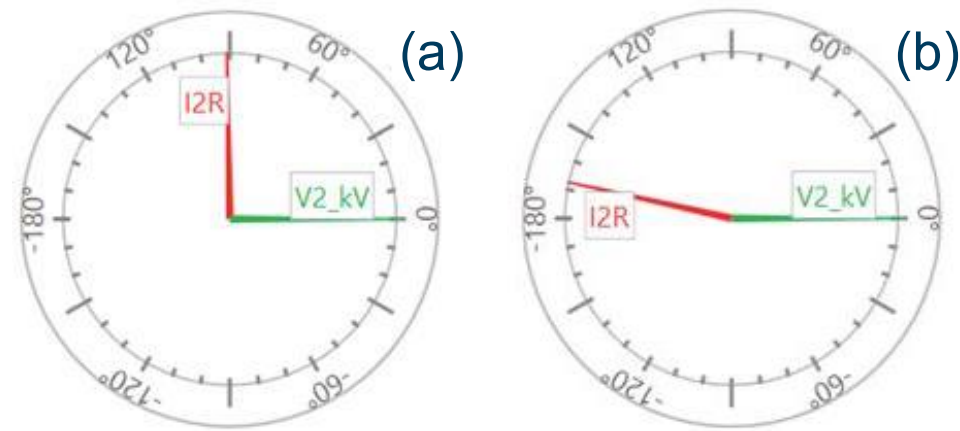
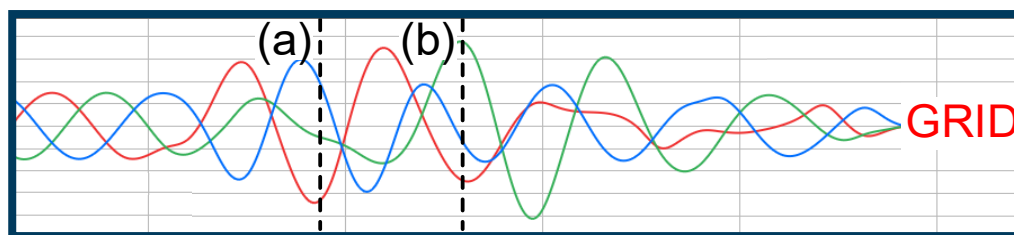
IBR sources distort I_2

Relationship between V_2 and I_{2R}
consistent with forward fault (a) and
after with reverse fault



IED_PV

Relationship between V_2 and I_{2R}
in undefine region (a) and after
with forward fault (b)



IED_GRID

Summary

- Power system changes are
 - Reducing inertia
 - Reducing current sourcing capacity
 - Causing protection challenges
- The results of the changes are
 - Increased instability
 - Protection design/analysis challenges



Thank you



Transformer Differential Tripping on Inrush Currents

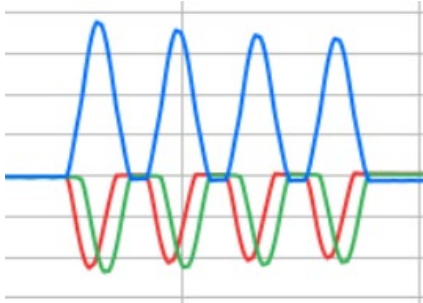
Daniel Zhang

**Pacific Gas and Electric
San Ramon, California**

**12th Annual Protection System Workshop
ReliabilityFirst Corporation
August 5, 2026**



Transformer Inrush Currents



When inrush currents?

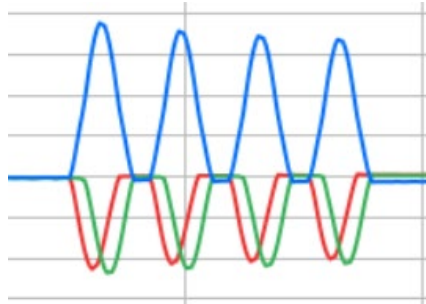
- Energize a transformer
- Clear an external fault
- Energize an adjacent transformer

Factors affecting inrush currents

- Source voltage magnitude and impedance
- Closing angle or instant of switching
- Transformer Design and Manufacturing:
 - ❖ Rated MVA and voltage
 - ❖ Flux path: 3-phase-3-leg, 3-phase-5-leg, single-phase bank
 - ❖ Winding: Wye (Grounded/Ungrounded) Delta
 - ❖ Winding placement: winding diameters, inner or outer winding
 - ❖ Magnetic Core material and dimension
- Residual flux magnitude and direction

Impacts on protection

- **Transformer differential** and overcurrent can overtrip on inrush currents



About 15 differential overtripping events at PG&E

- Relay G - 60/21/7.2kV 30MVA Transformer 1
- Relay G - 115/12/7.2kV 27MVA Transformer 2
- Relay S1 - 115/12/7.2kV 45MVA Transformer 3
- Relay S1 - 115/12/7.2kV 45MVA Transformer 4
- Relay S2 - 115/12/7.2kV 45MVA Transformer 5
- Relay S3, 138/13.8kV 40MVA Transformer 6 (Non-PG&E Transformer)
- Relay M - 240/13.8kV 130MVA Transformer 7

Causes of Overtripping on Inrushes

- Insufficient inrush currents
- Insufficient 2nd harmonic
- Differential Settings
 1. Compensated differential current
 2. Harmonic restraint/blocking
 3. Independent/common harmonic blocking
 4. Per phase/2-out-of-3

Transformer Differential Overtrip on Inrush Currents

Relay-G Tripping Transformer 1 & Transformer 2

Transformer 1 (30MVA, 60/21/7.2 kV)

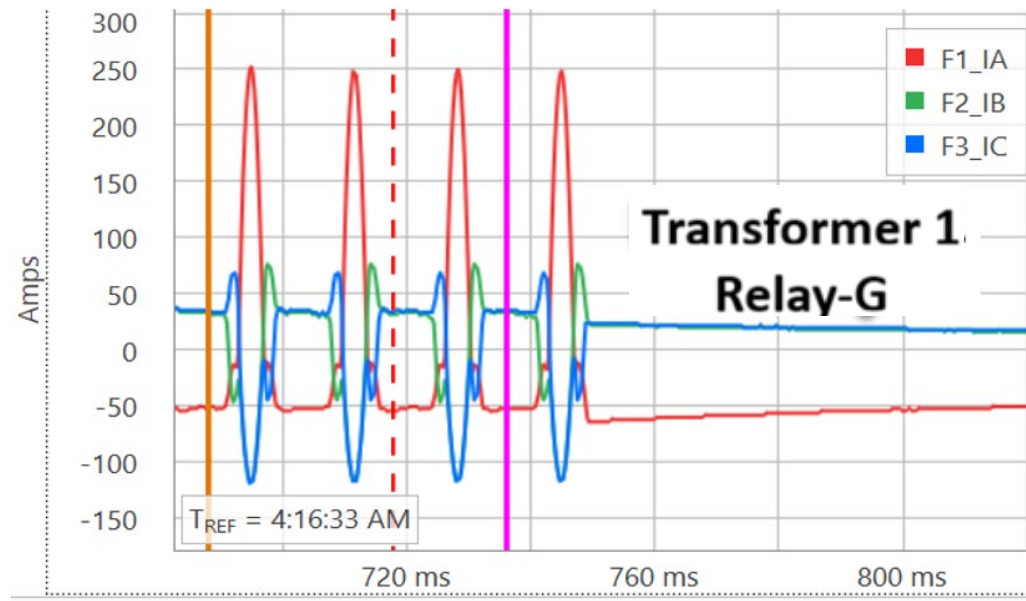
- Relay-G (Set A) trip on inrush;
- Set B Diff - no trip

Transformer 2 (27MVA, 115/12.5/7.2 kV)

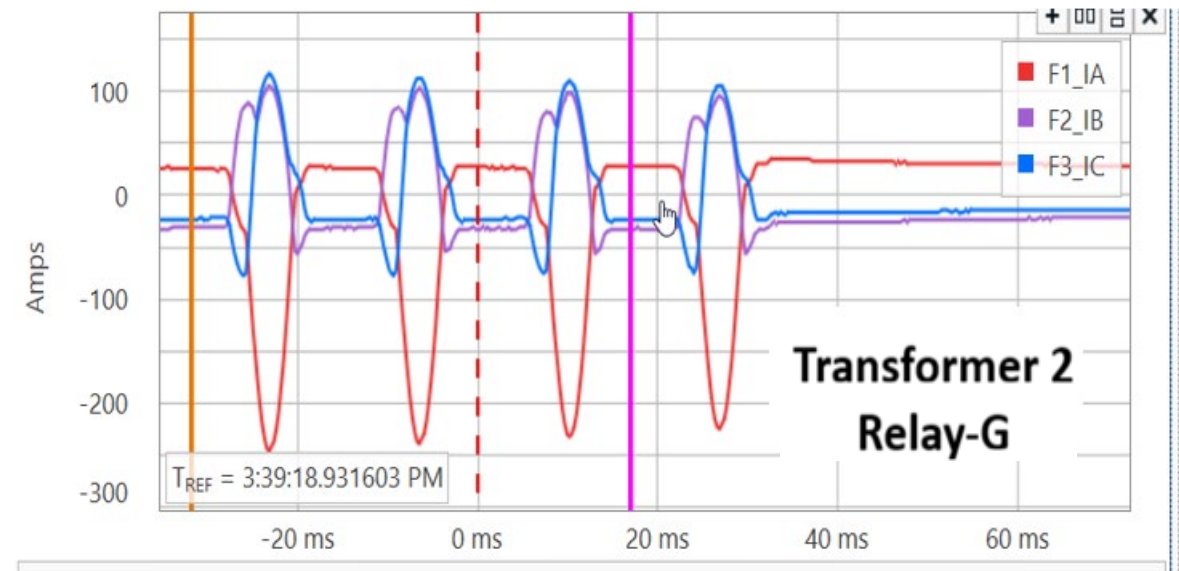
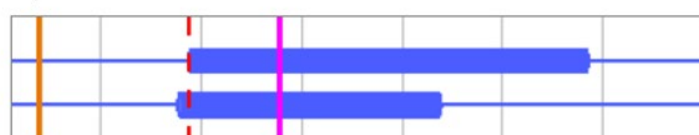
- Relay-G (Set A) trip on inrush;
- Set B Diff - no trip

Set A 2nd Harmonic Block:

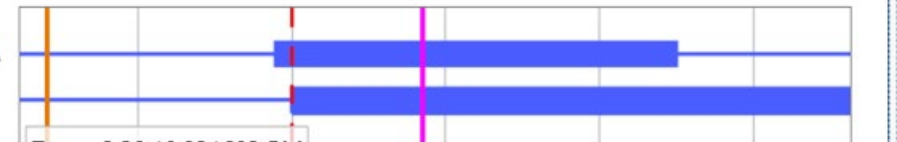
- 15%,
- 2-out-of-3



PROT_TRIP_On
XFMR_PCNT_DIFF_OP_A

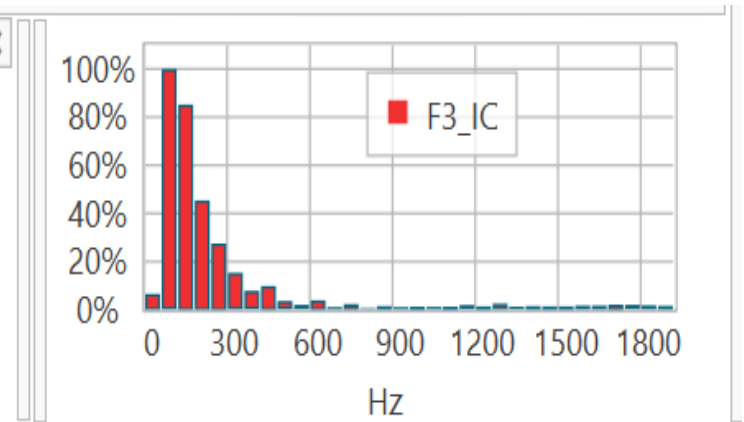
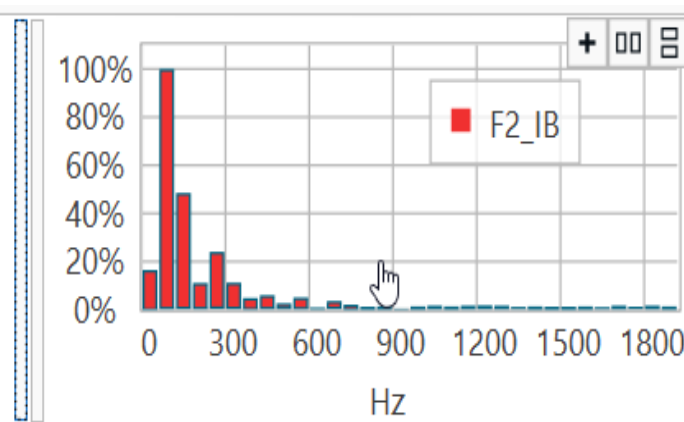
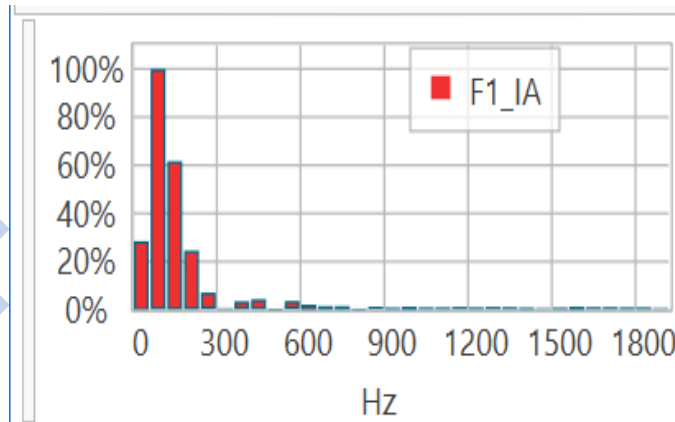
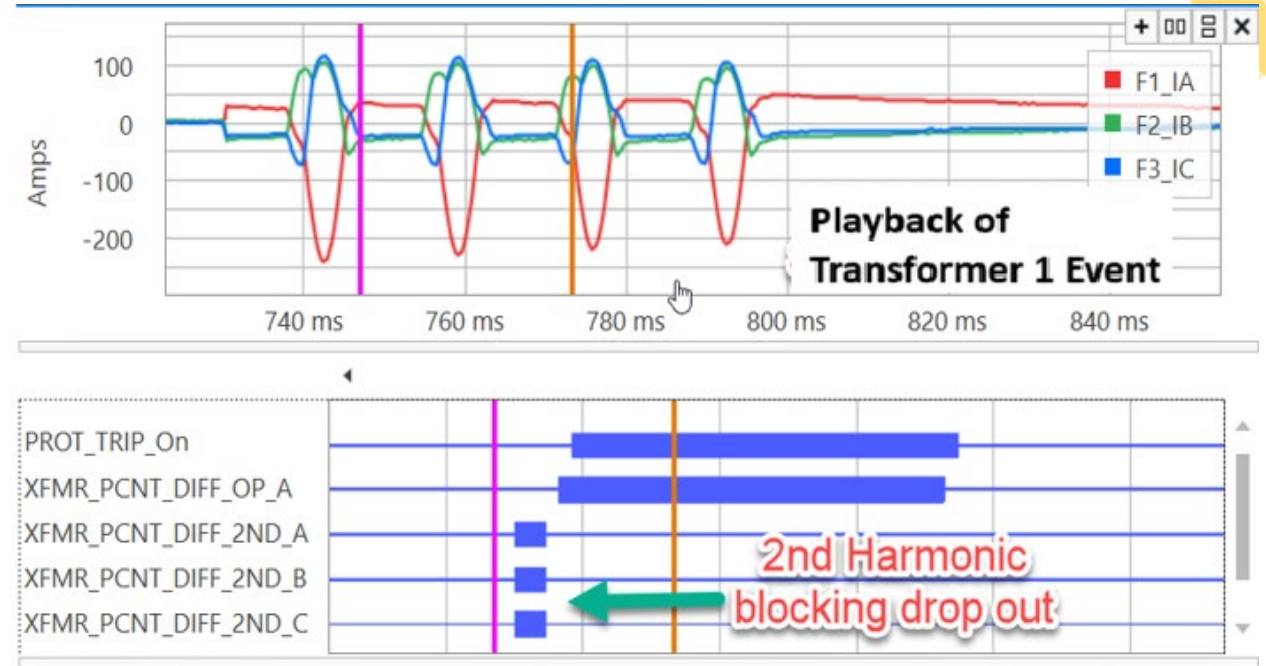


XFMR_PCNT_DIFF_OP_A
PROT_TRIP_On



Why Relay-G Tripped on Inrushes?

- Relay vendor Played back Transformer 1 event and found that 2nd harmonic blocking dropped off, then Diff operated
- Not enough 2nd harmonic ??
- Not really, 2nd harmonic are at least 48% among three phases.



Sufficient 2nd Harmonic, But not Sufficient Inrush

- Sufficient 2nd harmonic, the blocking still dropped off.
- Per Relay-G firmware release note, cutoff of diff current is set at 0.04pu.
- The diff currents dropped below 0.04pu when Relay-G tripped.

Transformer 1			Transformer 2		
30MVA	60/21/7.2kV	CT: 1000/5	27MVA	115/12/7.2kV	CT: 1200/5
Ia_phasor	75 A	0.075 pu	Ia_phasor	80A	0.067 pu
Ib_phasor	40A	0.04 pu	Ib_phasor	48.5A	0.04 pu
Ic_Phasor	40A	0.04 pu	Ic_Phasor	37.8A	0.032 pu

Transformer Protection Systems –

P Improved percent differential 2nd harmonic inhibit mode at low differential currents

726-2

Applicable:

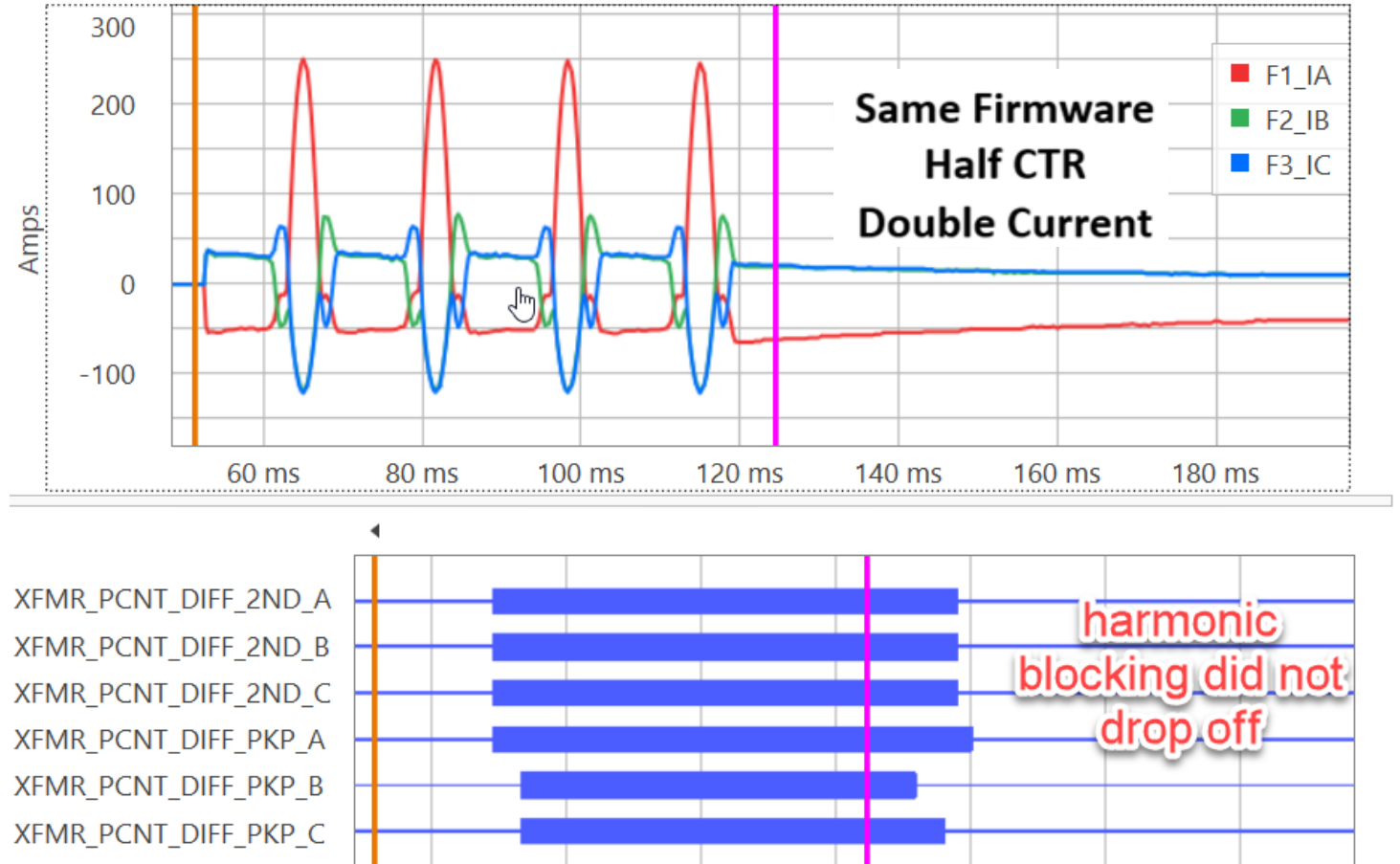
A cutoff of 0.04 pu prevents inaccurate measurement, for example when the differential current is less than 0.04 pu, the differential current and its 2nd harmonics component are forced to zero. This can lead to a false trip during transformer energization when both components in any phase (specifically Ibd and Icd) drop below 0.04 pu in two out-of-three inhibit mode.

This firmware release fixes the issue. The two-out-of-three 2nd harmonic inhibit logic is applied only if all three phase differential currents exceed the cutoff level of 0.04 pu. In cases where differential current in any phase drops below 0.04 pu, the logic is reverted to one-out-of-two logic, ensuring reliable inhibit during energization.

This issue exists in all previous firmware revisions.

Playback Transformer 1 Event

- Relay vendor helped to playback Transformer 1 event:
 - Use Relay-G FW 7.28
 - Double current, and half CT ratio (increase relay current above 0.04pu)
- In either case, Relay-G did not trip on inrush.



Root Cause & Corrective Actions

Root Cause for Relay-G Trip:



Not due to lack of 2nd harmonic, but due to the small magnitudes of inrush currents, which forced the diff current and harmonic blocking to zero in two phases.

Only one phase had the inrush current above the cutoff.

Under 2-out-of-3 blocking, it fails to block differential from tripping.

Corrective Actions

Under investigation.

May perform more lab tests to evaluate the new firmware.

No action. Overtripping doesn't happen often; and is an acceptable risk.

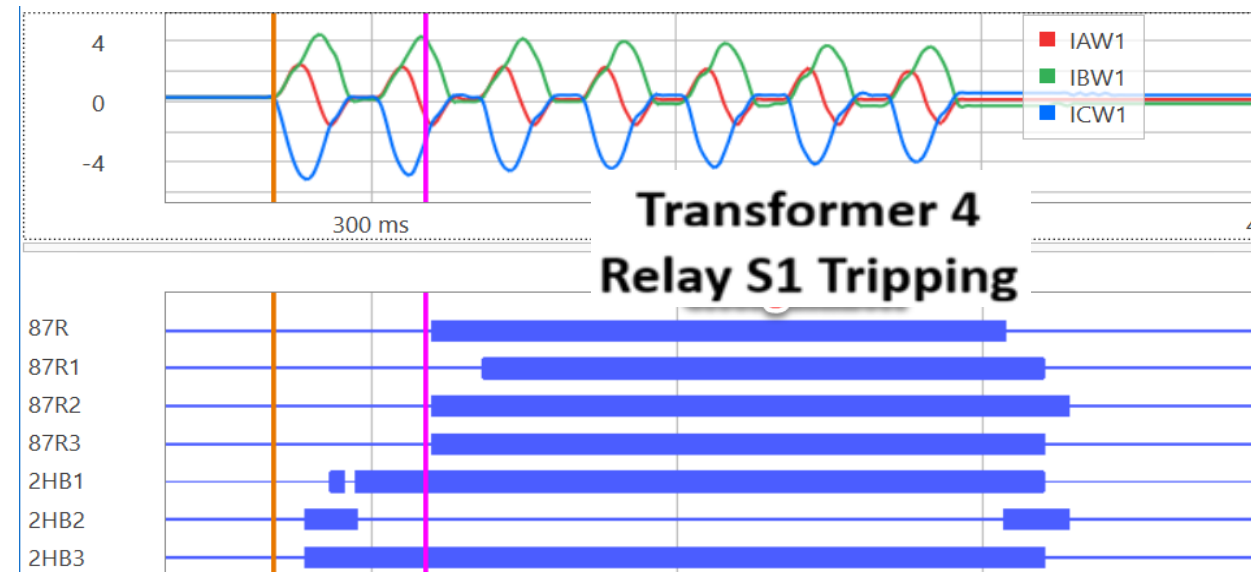
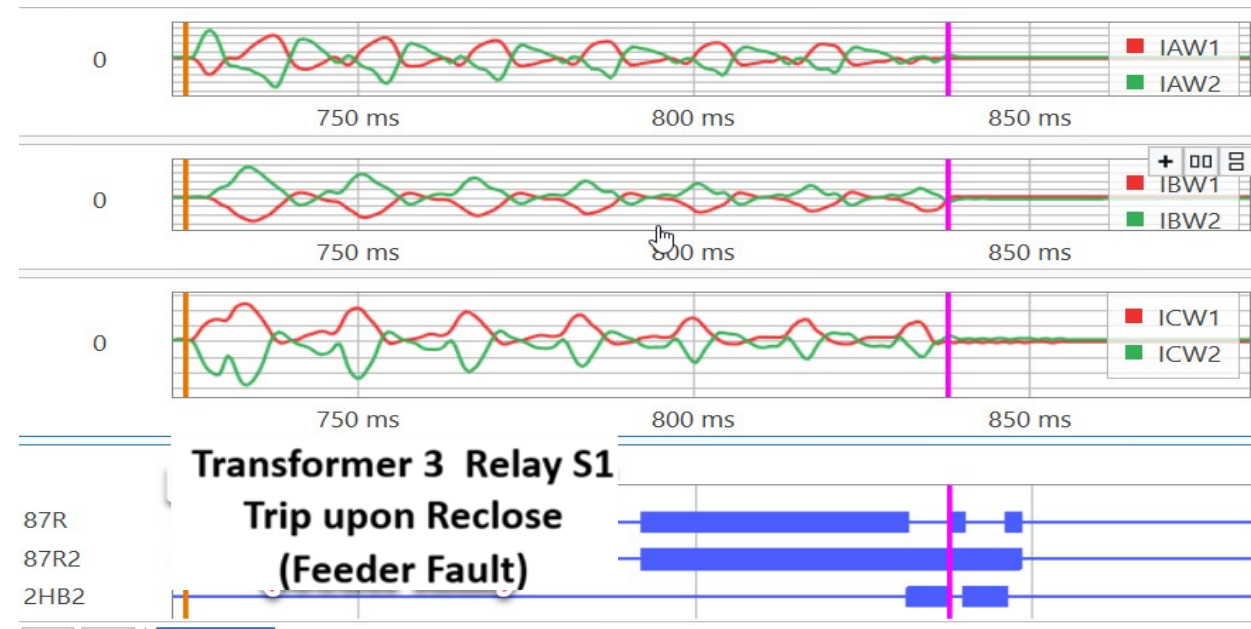
Change Harmonic Blocking from 2-out-of-3 to Per Phase. It prevents the two overtrips. But it might create a different problem, which we will see shortly.

Firmware upgrade: Per Relay-G FW release notes, FW 5.84, 6.06, and 7.26 or newer had this problem addressed

Possible but may not desirable, lower CT ratio to increase relay currents.

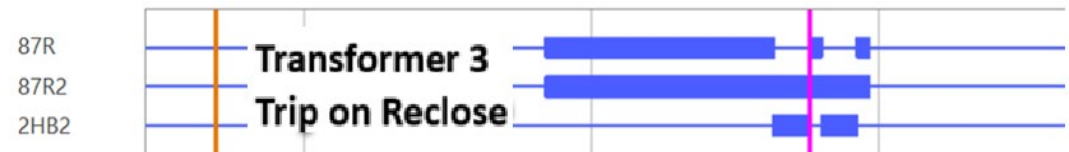
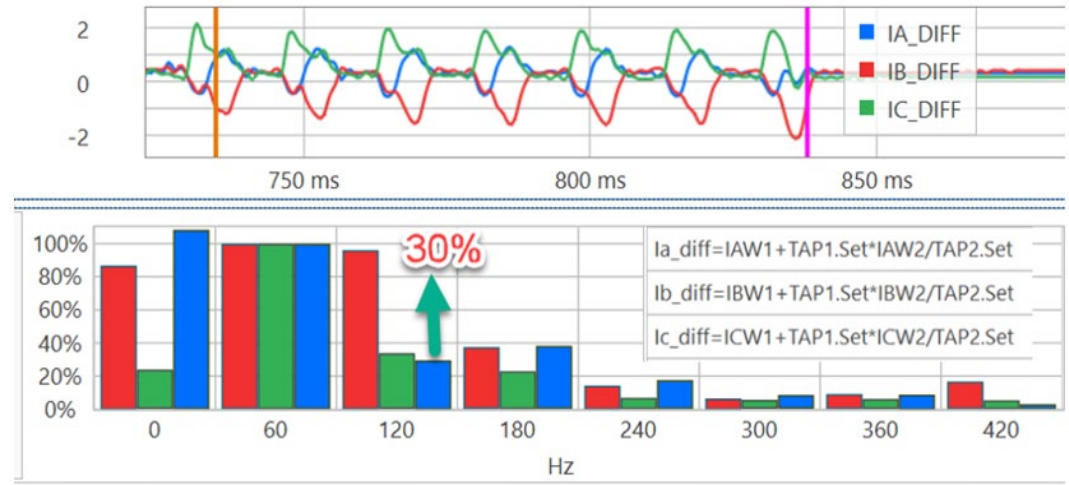
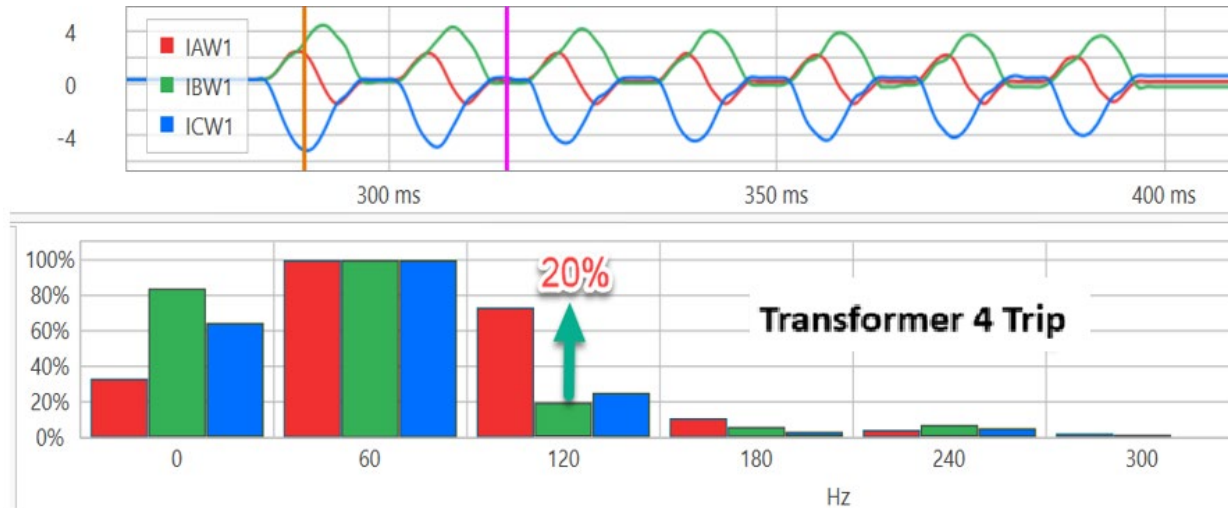
RELAY-S1 OVERTRIP ON INRUSHES

- Transformer 3 upon reclose after clearing a feeder fault.
Relay-S1 **IHBL=N**
- Transformer 4 upon energization.
Relay-S1 **IHBL=Y**
- Transformer 5 upon energization
Relay-S2 **HRSTR=Y**
- Why? Not sufficient 2nd harmonic ??



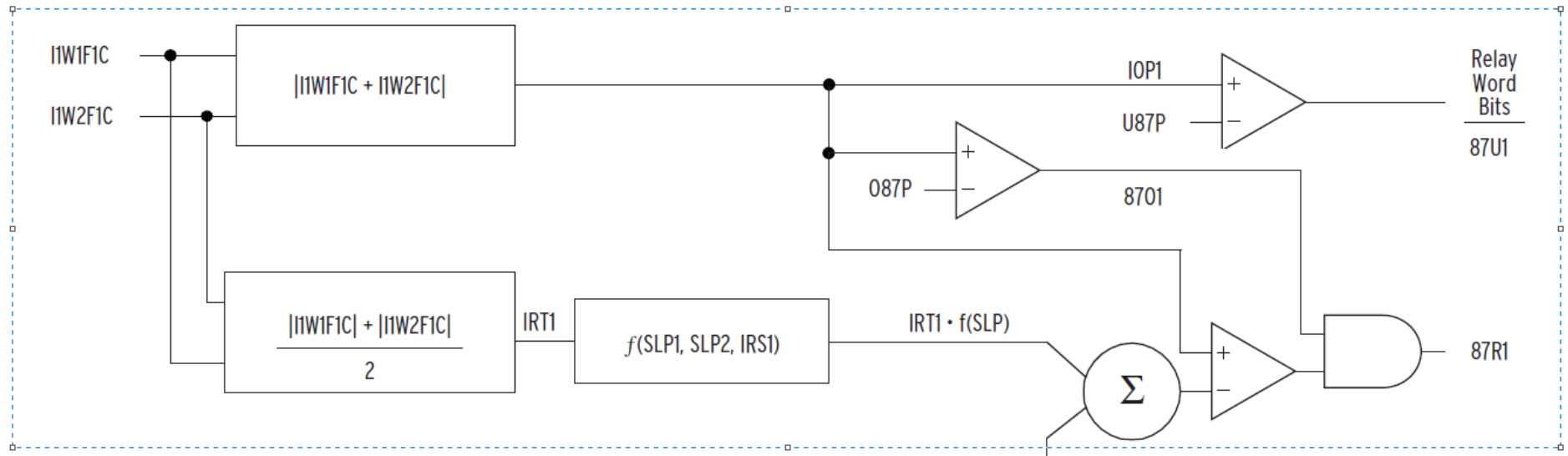
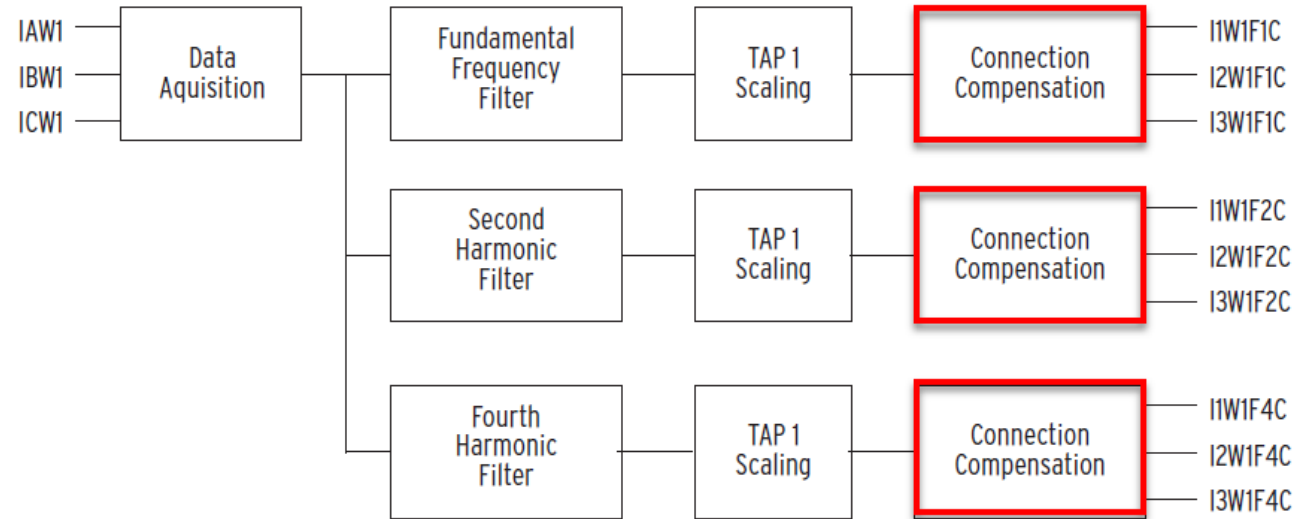
Harmonic Analysis

- Transformer 4 has at least 20% 2nd harmonic in phase inrush current. (IHBL=Y)
- Transformer 3 has at least 30% 2nd harmonic in phase inrush current (IHBL=N)
- More than 15% setting, why differential operated?



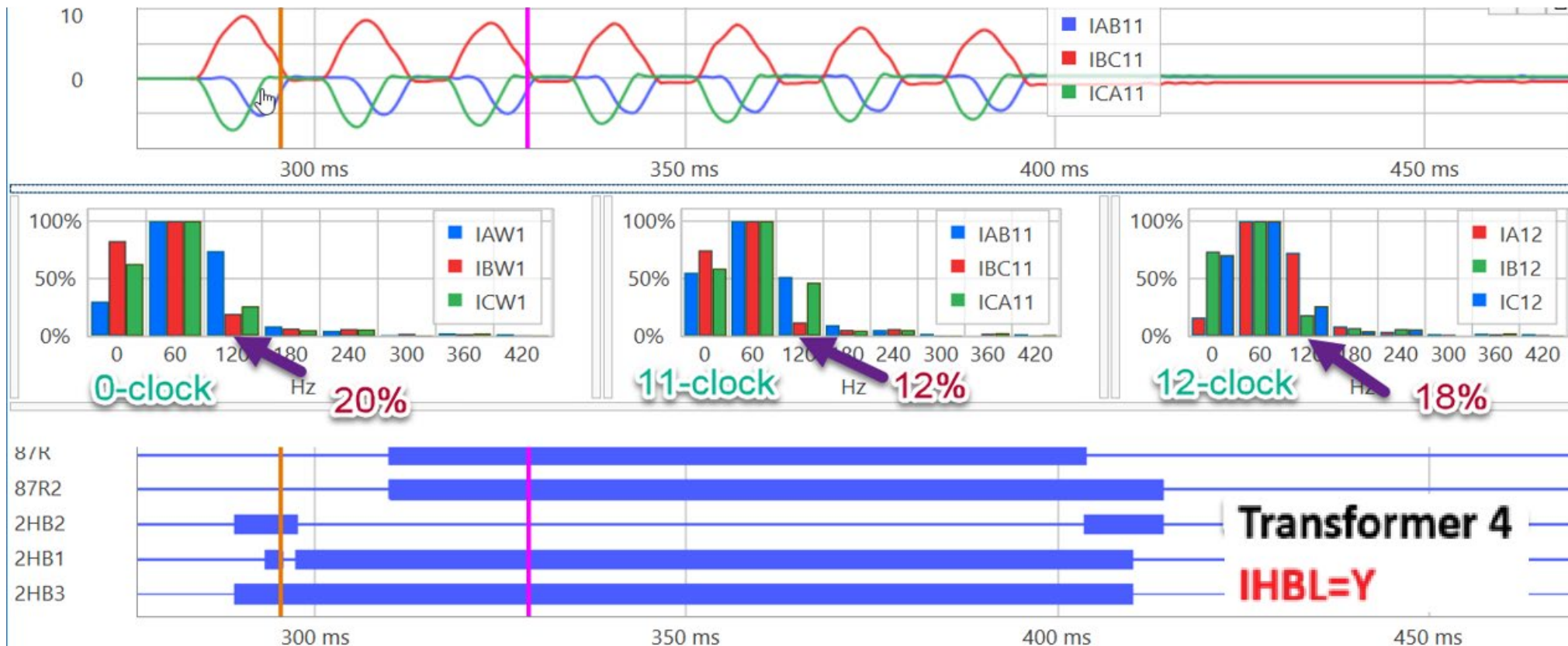
Why 2nd Harmonic blocking failed

- Let's examine Relay-S1 manual
- Relay uses currents after **connection compensation**, not the phase currents directly.



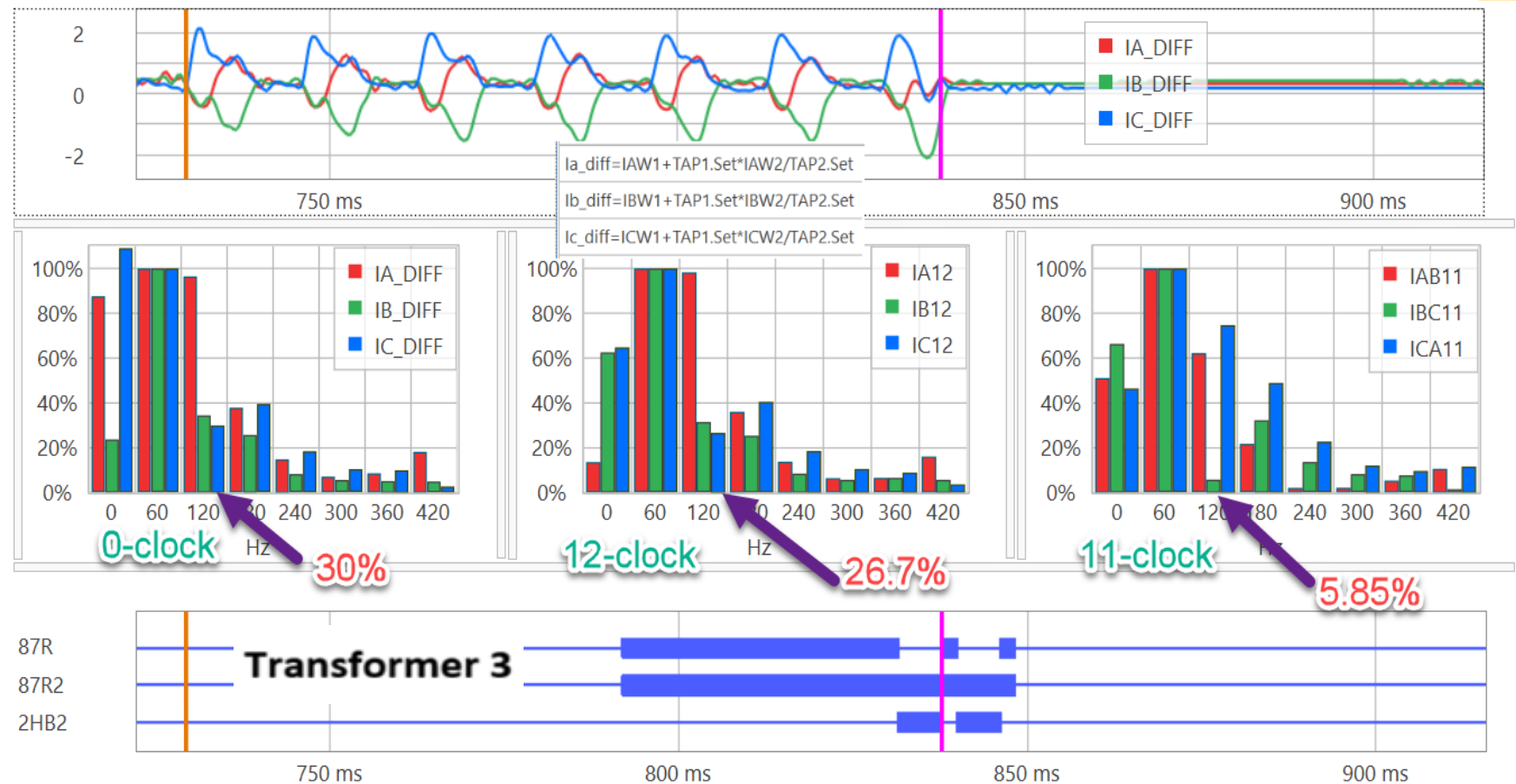
Harmonic Analysis after Connection Compensation

- Transformer 4 2nd harmonic dropped to 12%, which is less than 15% threshold.
- Same thing happened for Transformer 3 and Transformer 5
- Harmonic level changes after the connection compensation.
- Different connection compensation (e.g., 0-,1-,11-,12- clock) will also change the harmonic level.



Transformer 3 Harmonic Analysis

- Comparison of 0-, 11- and 12-clock connection compensation
- 2nd harmonic level vary when use different connection compensation



$$CTC(0) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$CTC(11) = \frac{1}{\sqrt{3}} \cdot \begin{bmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix}$$

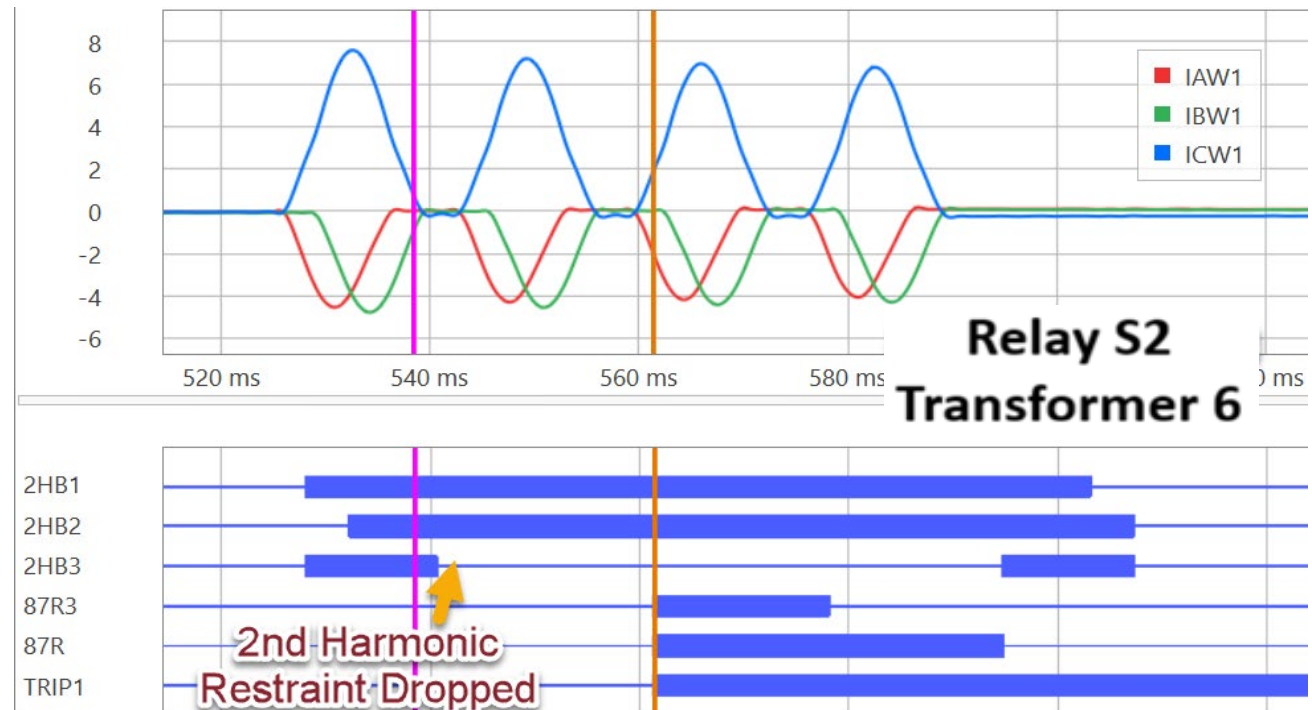
$$CTC(12) = \frac{1}{3} \cdot \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}$$

Relay-S2 Trip on Inrush

- Relay-S2 tripped on inrush
- Transformer 6, 138-D /13.8-Y kV, 40MVA
- Selected settings:
 - PCT2=15;
 - PCT4=OFF;
 - HRSTR= Y;
 - W1CTC=0;
 - W2CTC=1;

$$CTC(0) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

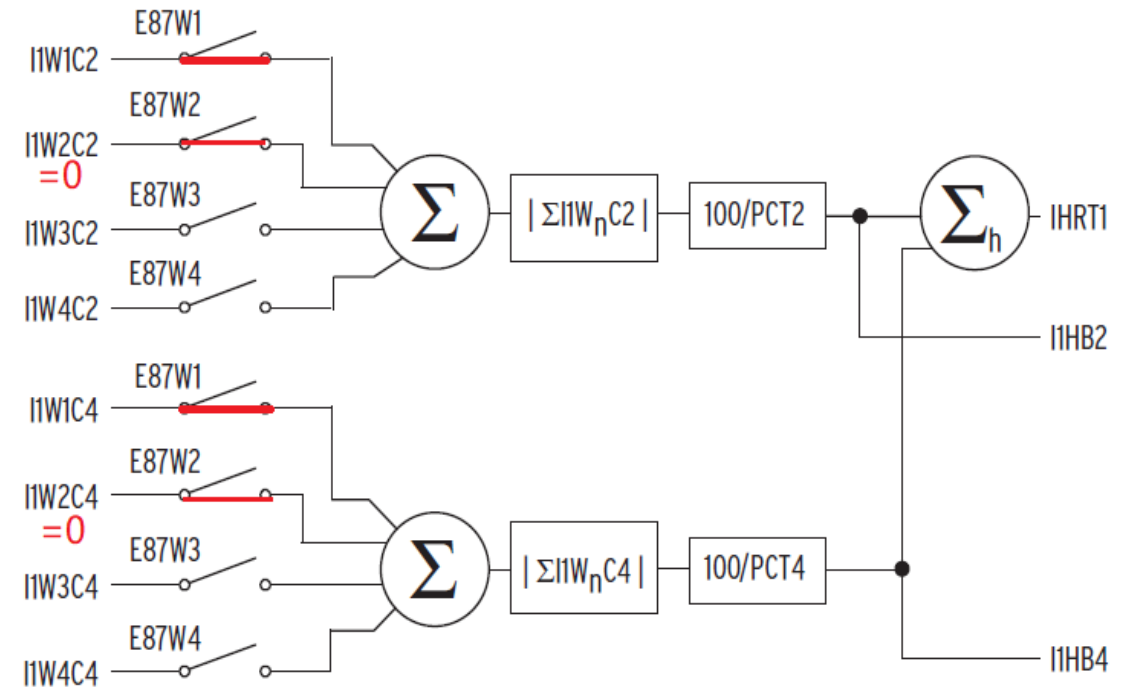
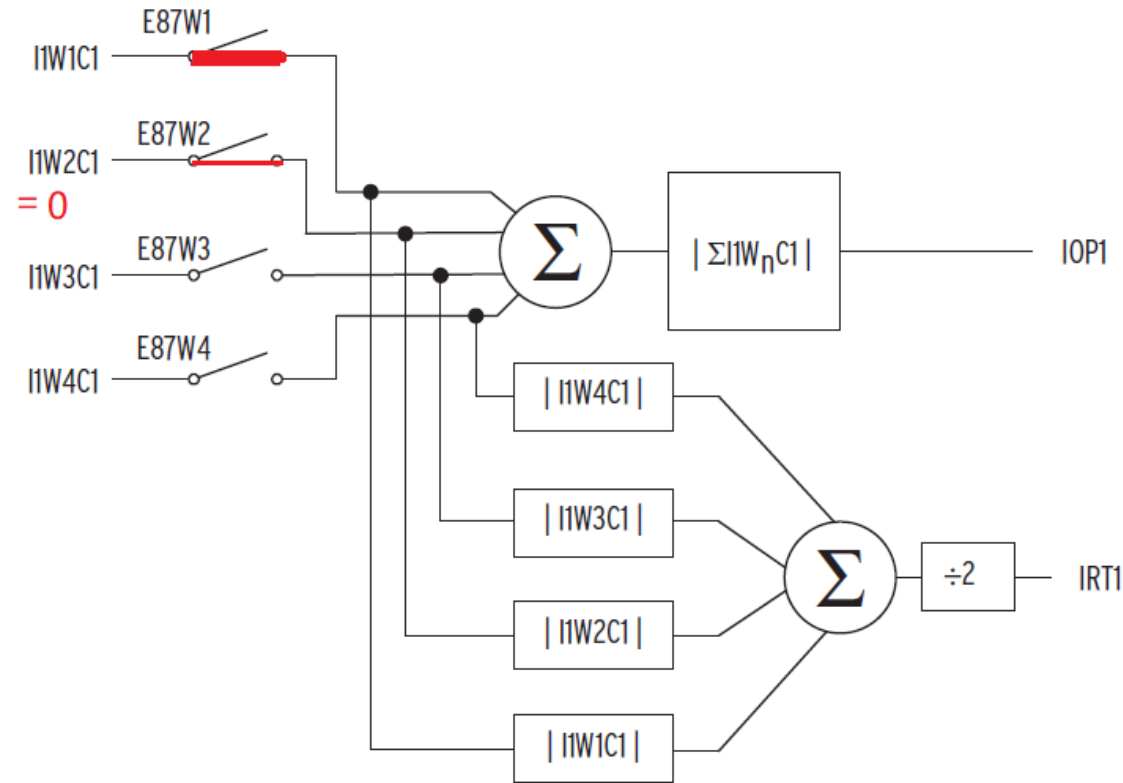
$$CTC(1) = \frac{1}{\sqrt{3}} \cdot \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix}$$



Relay-S2 Harmonic Restraint

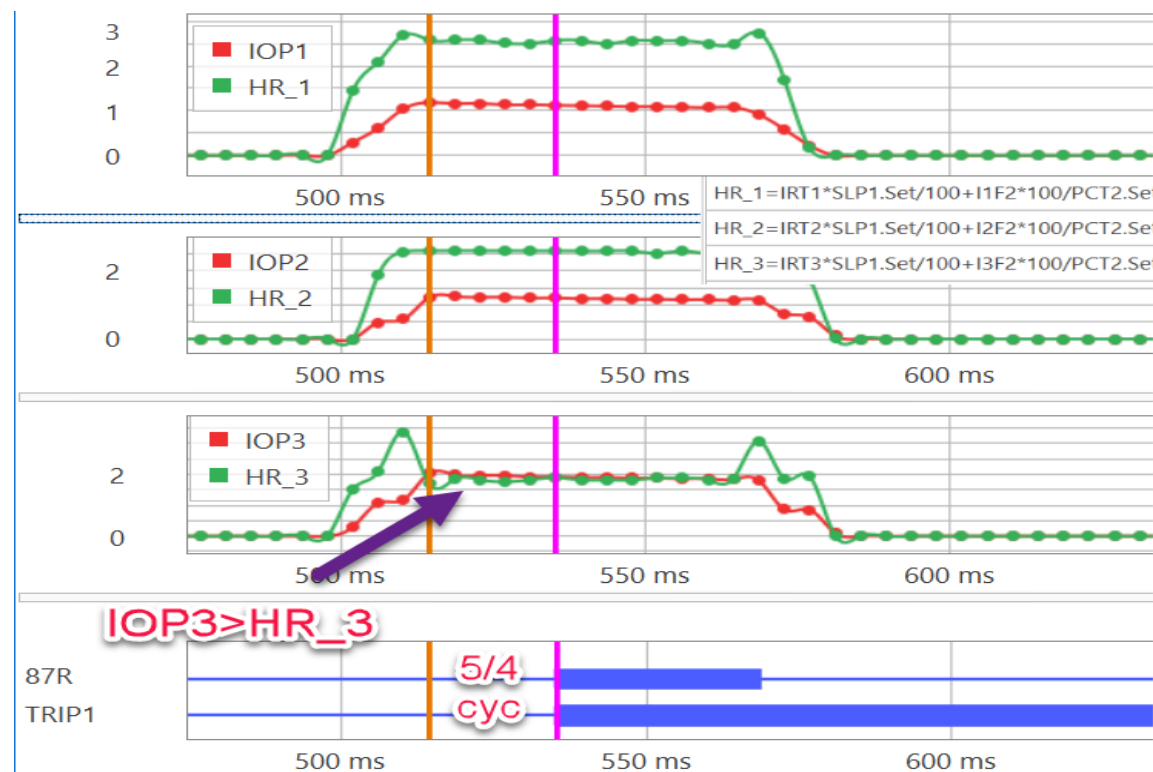
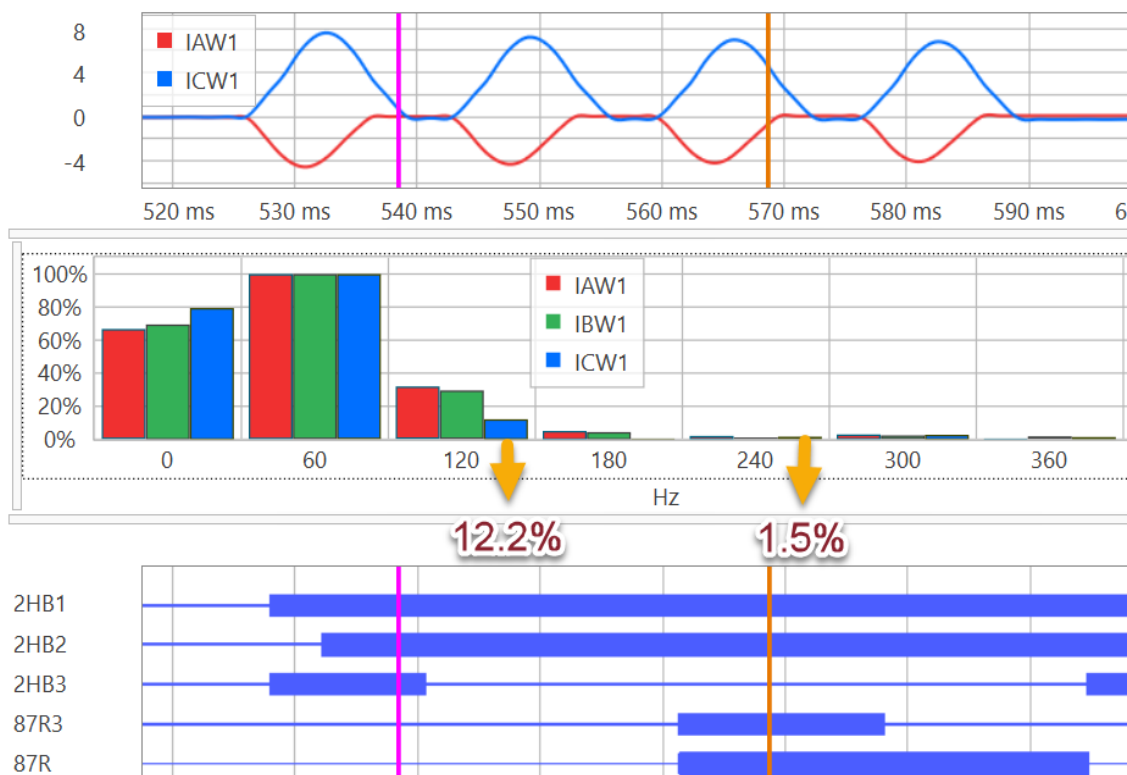
$$IOP = SLP1 \cdot IRT + c$$

$$c = (100/PCT2 * \Sigma I W_n C2) + \text{Not used } (100/PCT4 * \Sigma I W_n C4)$$



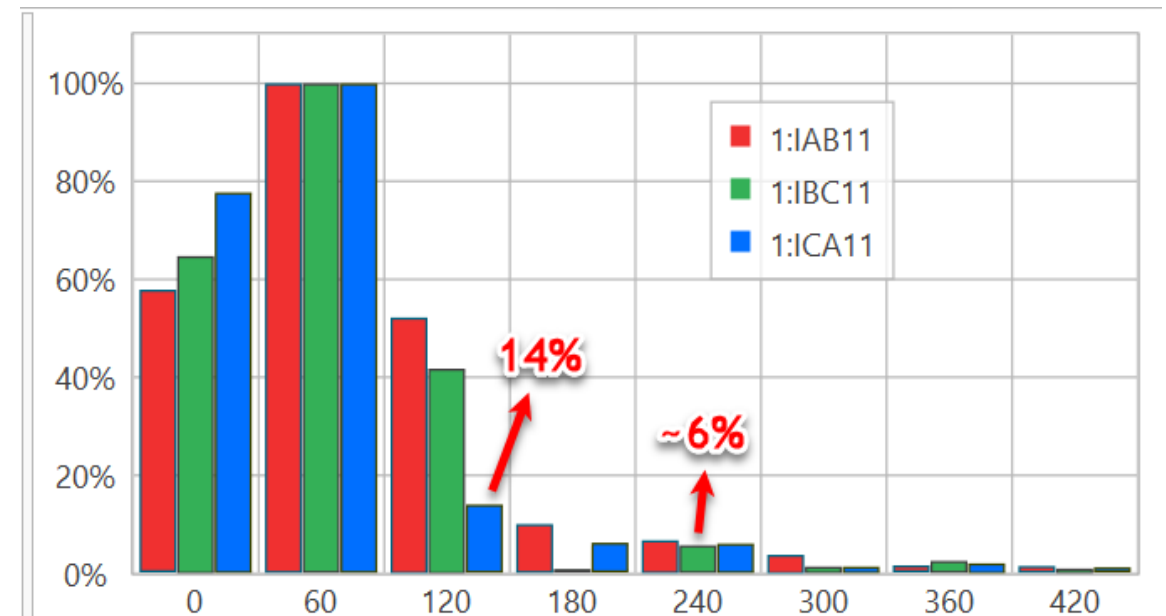
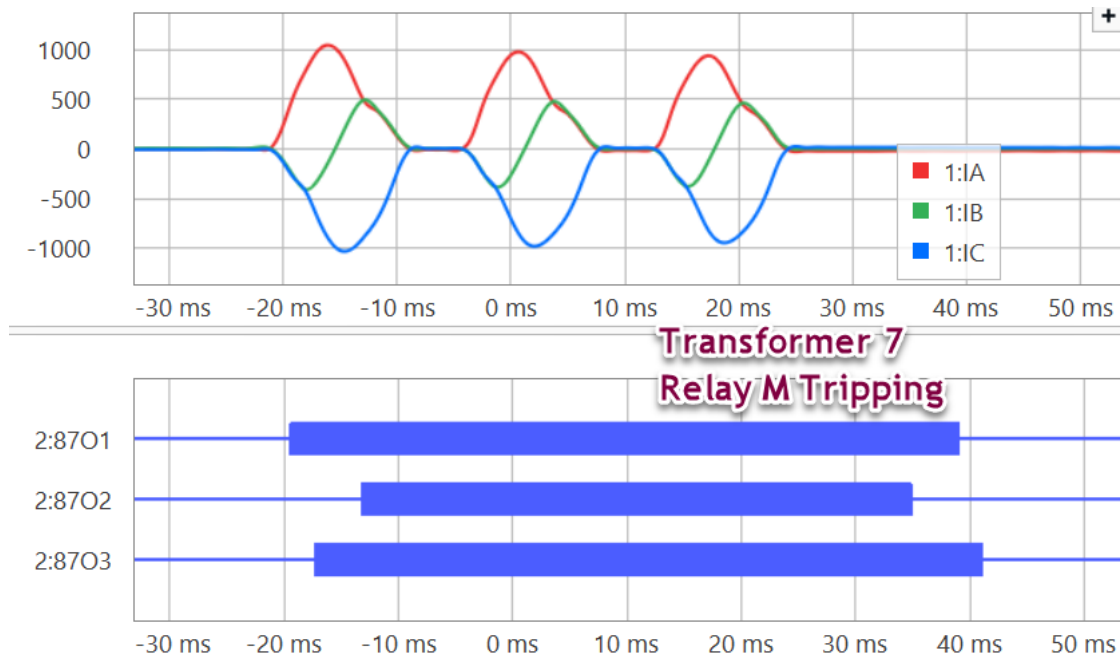
Relay-S2 Tripping on Inrush

- Not sufficient 2nd harmonic in C-Phase, failed to restraint 87R3
- It is not uncommon to have 2nd harmonic less than 15% in one phase.
- May need to reduce the threshold for harmonic restraint, add 4th harmonic to restraint or apply common harmonic blocking
- Recall Relay-G overtripping, if change setting to per-phase, it can overtrip due to insufficient 2nd harmonic



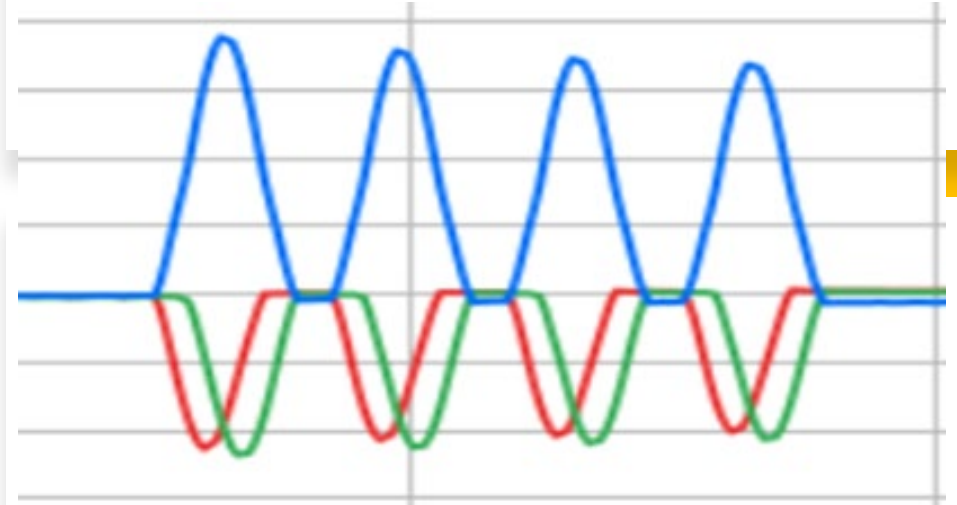
Relay M (Set A) Overtripped Set B Diff Narrowly Missed

- Transformer 7: 240 (Yg)/13.8(D) kV 130MVA
- Relay M uses Even Harmonic Restraint : $Id_{24} = \sqrt{Id_2^2 + Id_4^2}$
- Id_{24} set at 15% at tripping. Reduced to 10% after tripping.
- Set B Diff uses both 2nd and 4th harmonic for restraint, each set at 15%. (PCT2= 15 PCT4 = 15)
- If only applied 2nd harmonic, Set B Diff would also have tripped.
- Lowest 2nd harmonic is around 14%, less than 15% threshold.



Summary

- Review Relay-G, Relay-S1, Relay-S1 and Relay-S2, Relay-M overtrip for inrush currents (3 vendors & 5 relay models)
- Causes of overtrip include insufficient inrush current (Relay-G), insufficient 2nd harmonic (Relay-S2), connection compensation setting (Relay-S1), etc.
- Differential settings can affect the chance of overtrip
 - Harmonic blocking or restraint
 - Independent, common or 2-out-of-3 blocking
 - Harmonic (2nd, 4th, etc.) thresholds
- Connection compensation (0-, 11-, -12-clock) can also impact the harmonic level.
- Newer transformers tend to have lower inrush current and 2nd harmonic; therefore, transformer differential is more prone to overtrip.



Thank you!
&
Questions?

