Catching Falling Conductors in Midair – Detecting and Tripping Broken Distribution Circuit Conductors at Protection Speeds

William O’Brien
San Diego Gas & Electric Company

Eric Udren
Quanta Technology, LLC

Bala Sridharan, Dennis Haes, and Kamal Garg
Schweitzer Engineering Laboratories, Inc.

SDG&E Distribution System

- 22,000 miles of lines
- 60% underground and 40% overhead
- 12.47, 12.0, and 4.16 kV
- Grounded at substation with three- and four-wire systems

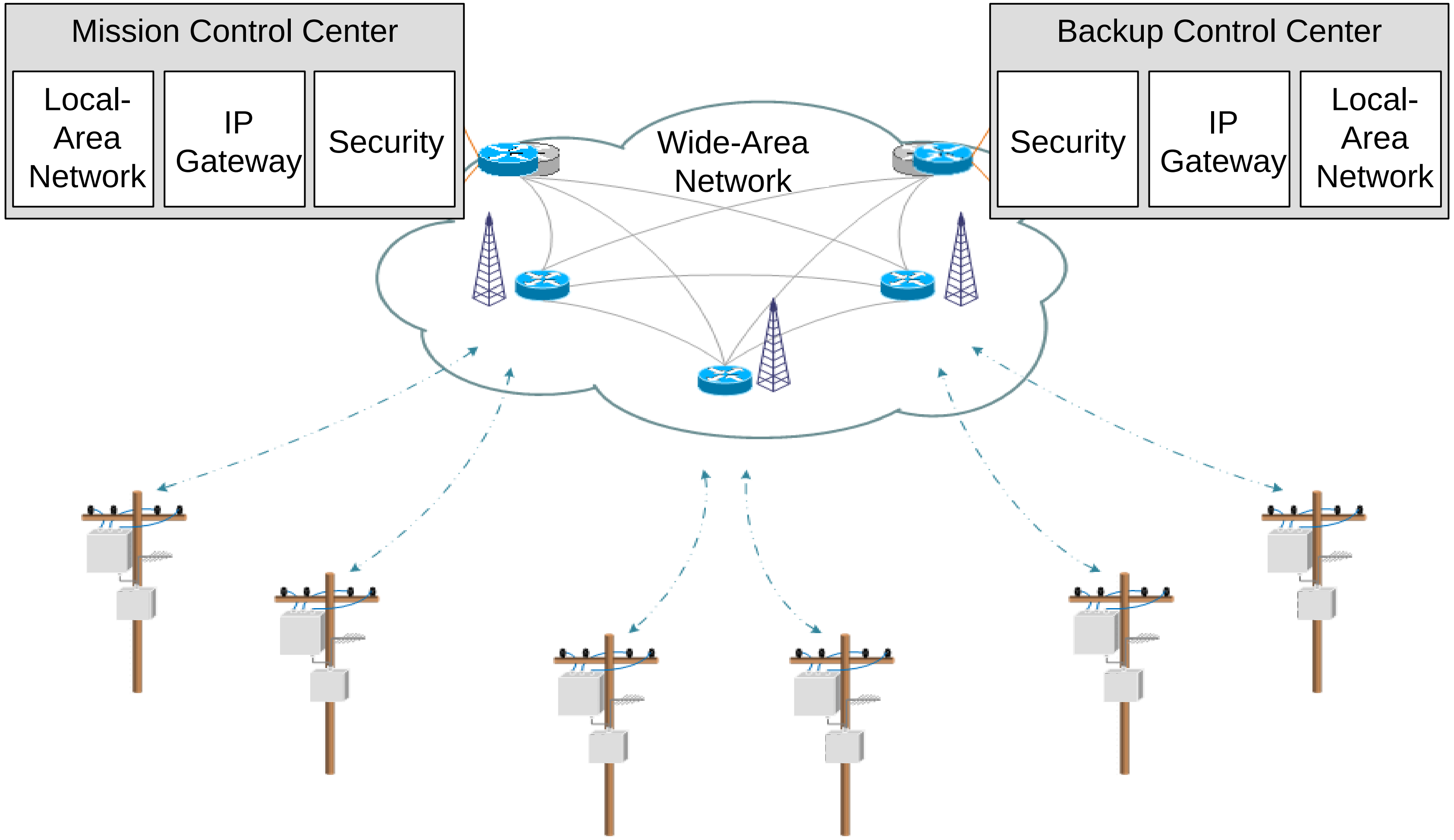
Advanced SCADA Planning

More Than 60 Cases Defined

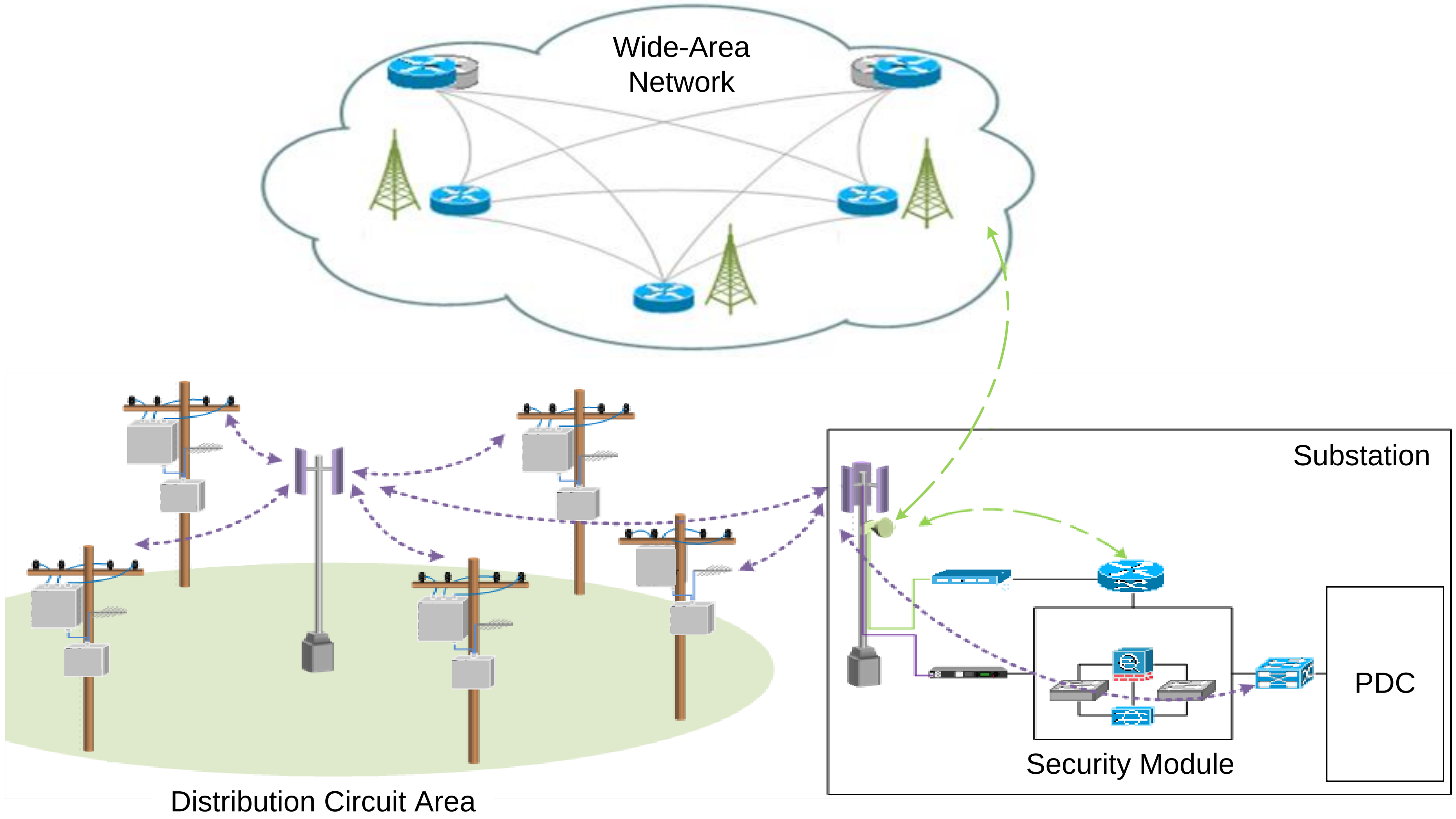
- Falling conductor protection (patent pending)
- Voltage profile monitoring and control
- Selective load shedding and restoration
- Power quality monitoring
- Apparatus and system condition monitoring
- Secure communications

SCADA System Architecture

Traditional

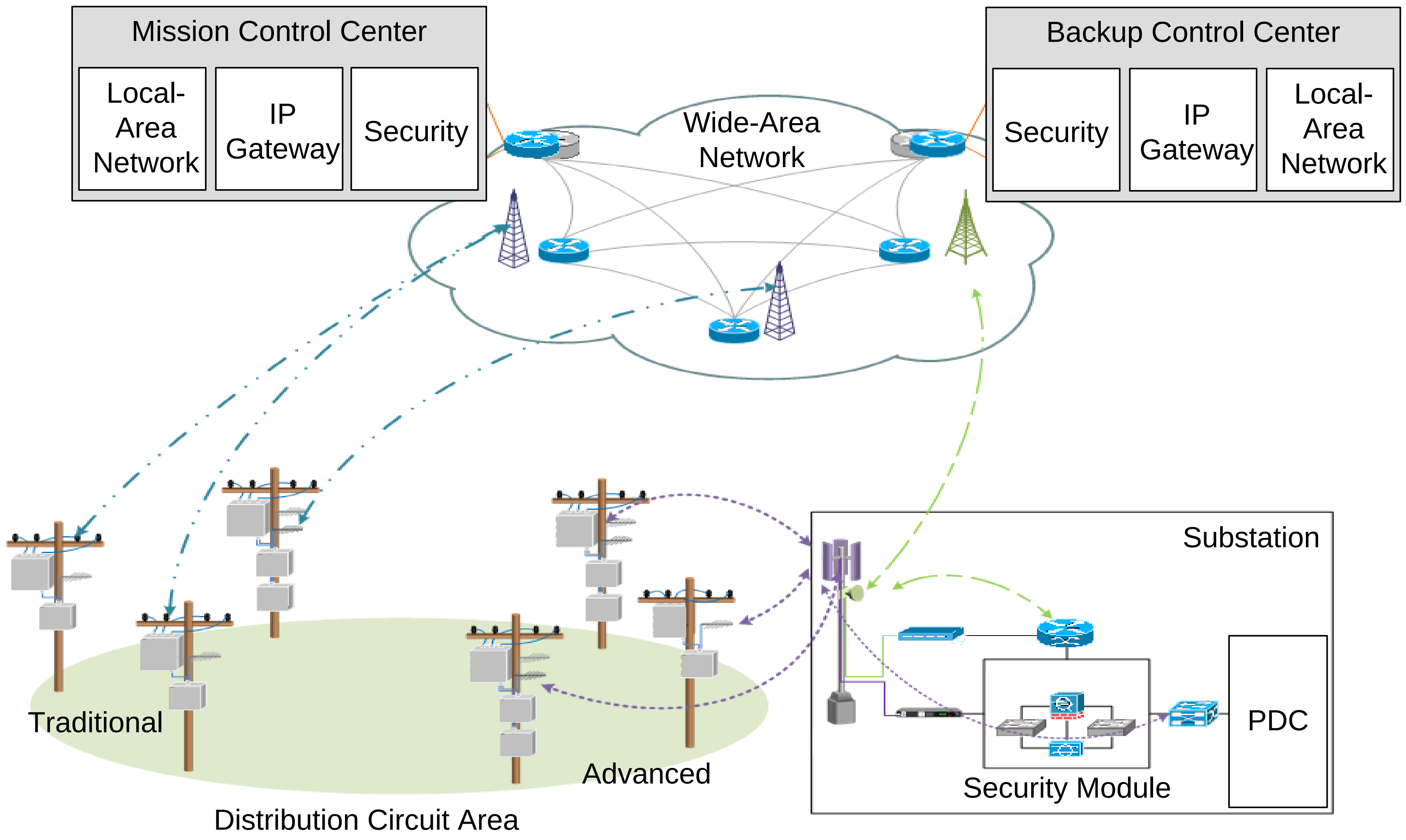


SCADA System Architecture
Advanced



SCADA System Architecture

Traditional and Advanced Overlay



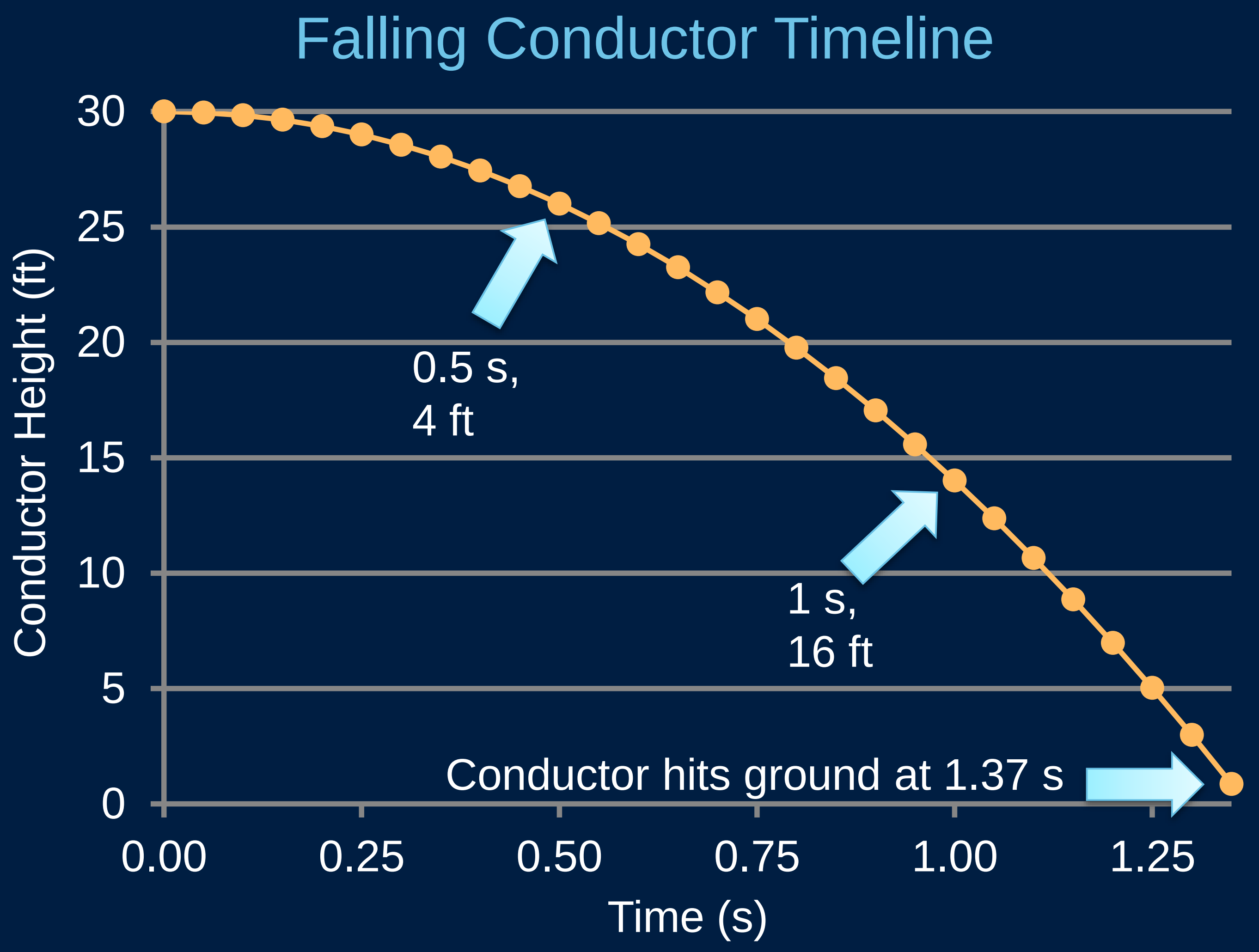
Advanced SCADA Features

- Increased accuracy – voltage and current sensors
- Phase angle
- GPS time-stamped data
- Remote engineering access and event reports
- High-speed, near real-time control

Advanced SCADA Features

- Advanced visualization
- Improved security
  - Log and audit access
  - Active directory passwords
  - Network anomaly detection sensor and technology

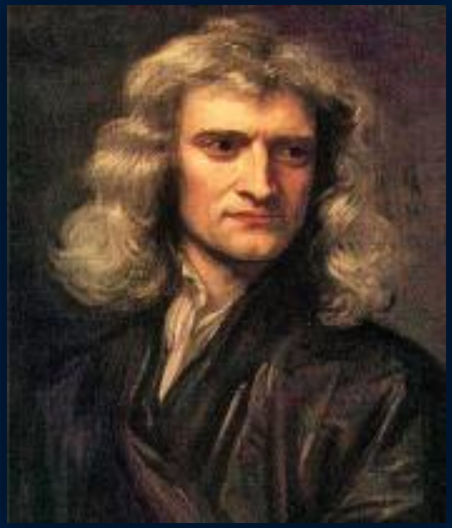
Detect Broken Conductor and Trip Circuit Before Line Hits the Ground?



$$d = \frac{1}{2}gt^2 \rightarrow t = \sqrt{\frac{2d}{g}}$$

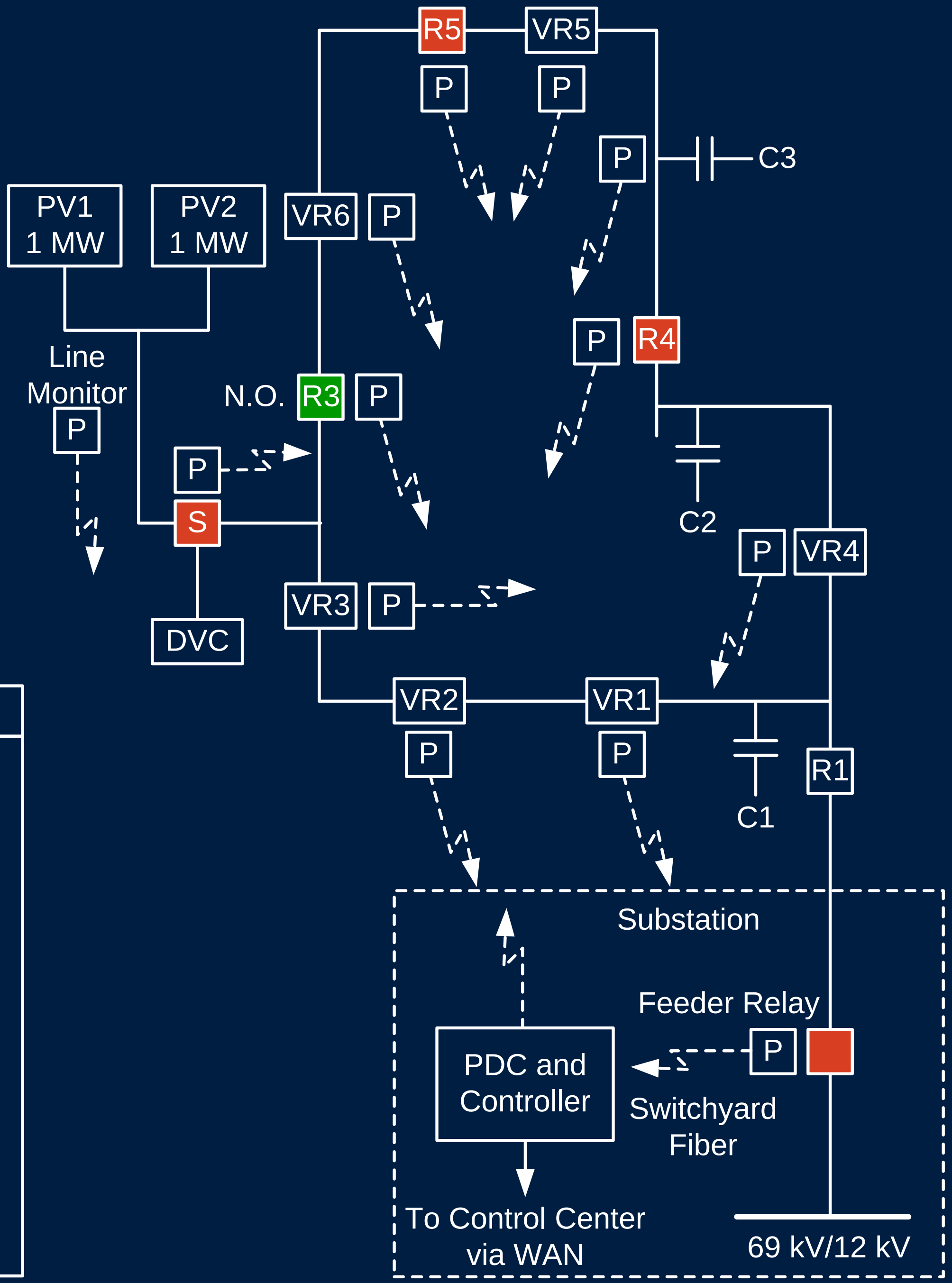
$$t = \sqrt{\frac{2(30)}{32.2}}$$

$$\text{time} \approx 1.37\,\text{s}$$



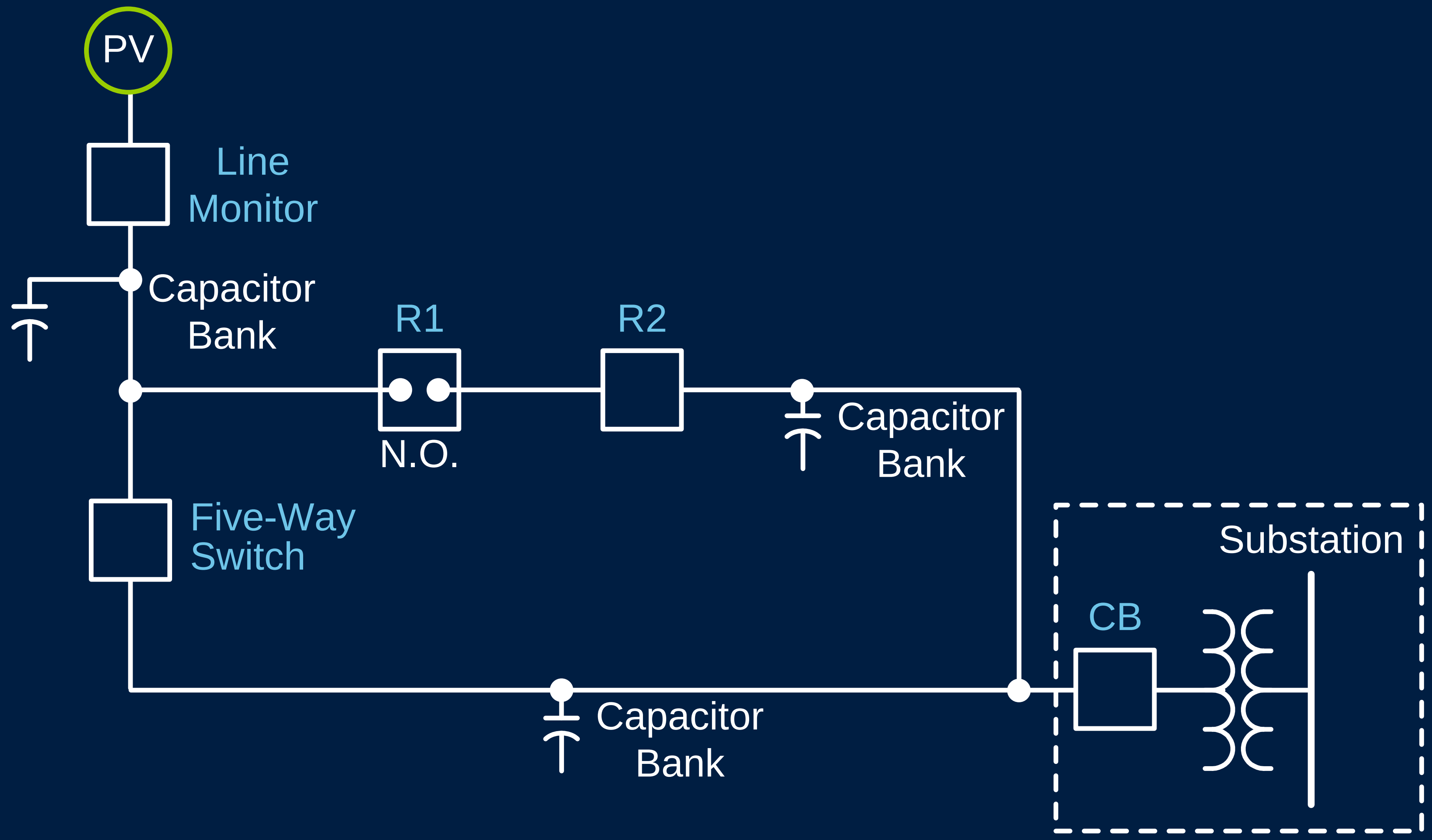
SDG&E Typical Feeder

LEGEND	
P	IED With PMU and Ethernet
R	Recloser
S	Multiport Circuit Switch
VR	Voltage Regulator
DVC	Dynamic VAR Compensator
PV	Photovoltaic
N.O.	Normally Open
WAN	Wide-Area Network

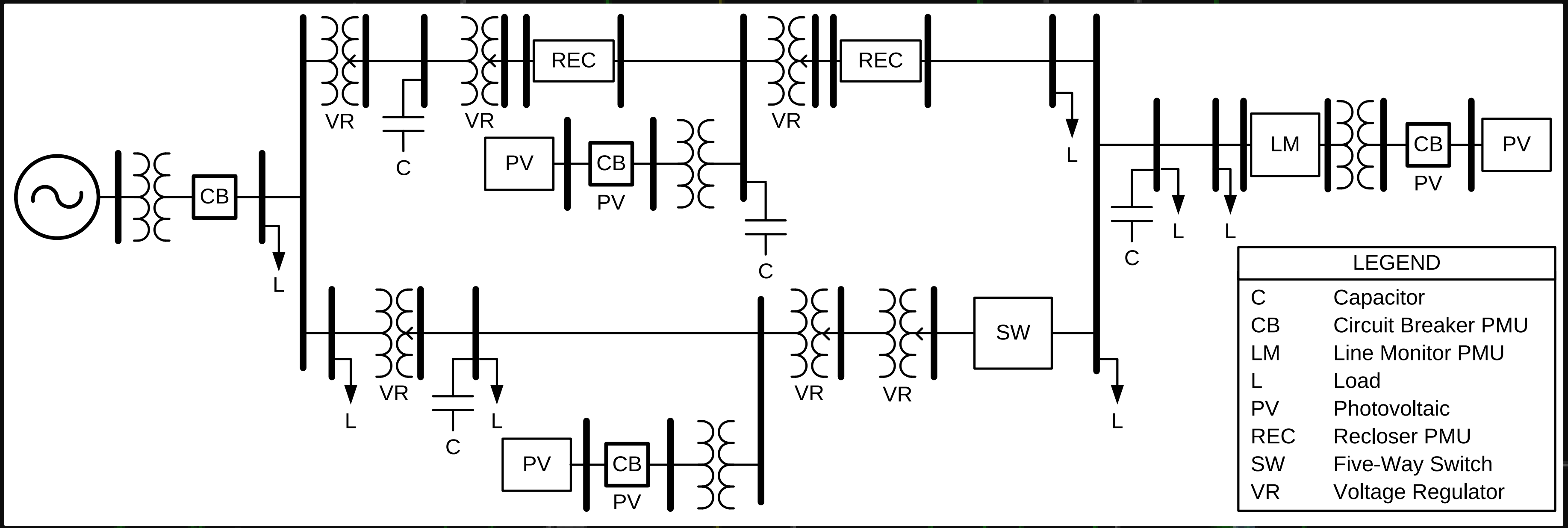


Feeder Model

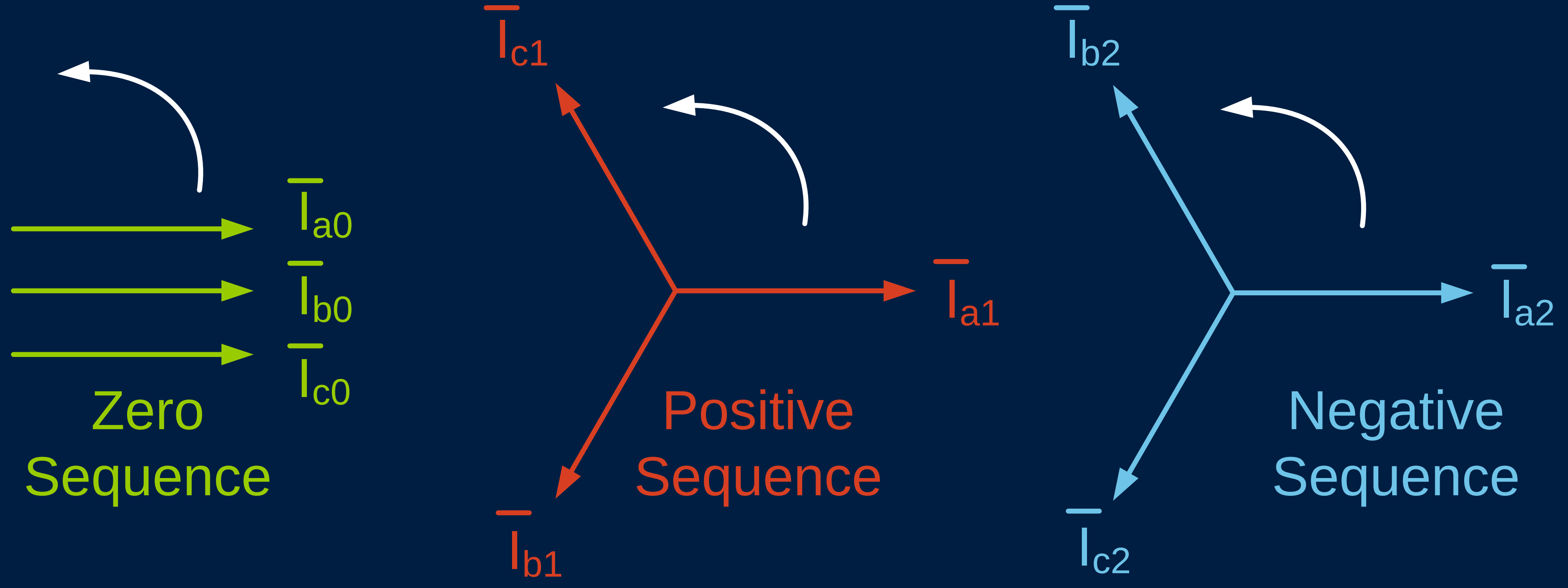
Falling Conductor PMU Locations



RTDS Feeder Model



Sequence Components Analysis



Single Phase

$\bar{I}_{a0} = \bar{I}_{b0} = \bar{I}_{c0}$

Balanced

$\bar{I}_{b1} = a^2\bar{I}_{a1}$

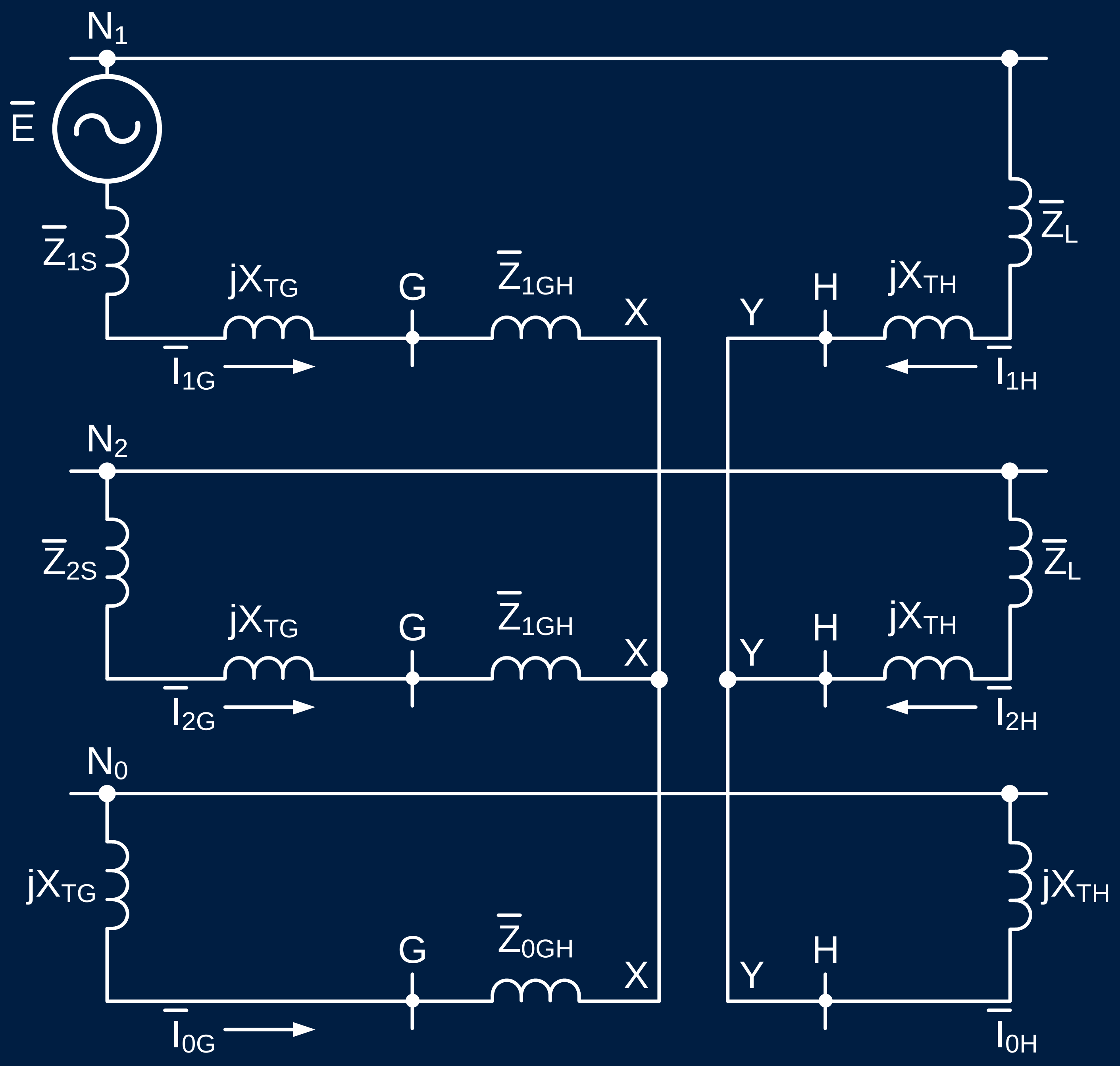
$\bar{I}_{c1} = a\bar{I}_{a1}$

Balanced

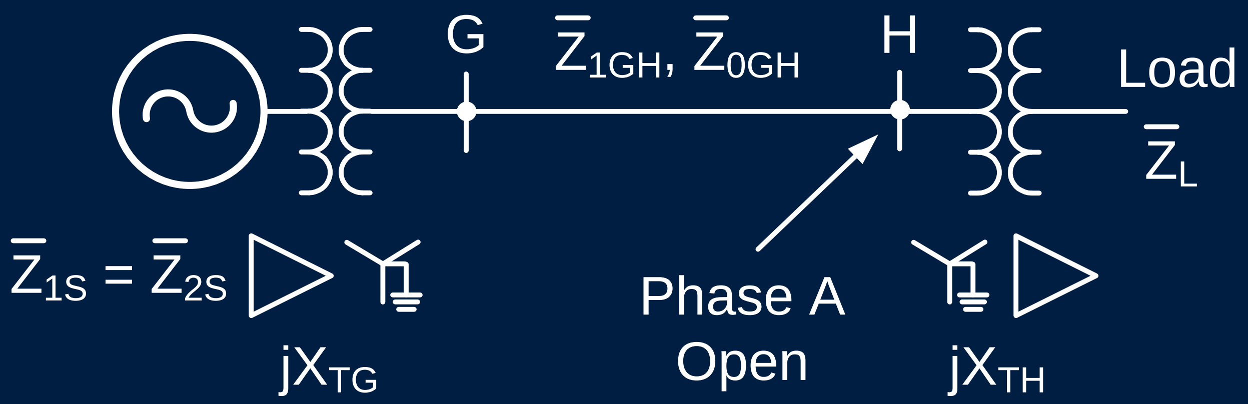
$\bar{I}_{b2} = a\bar{I}_{a2}$

$\bar{I}_{c2} = a^2\bar{I}_{a2}$

Open-Phase Analysis

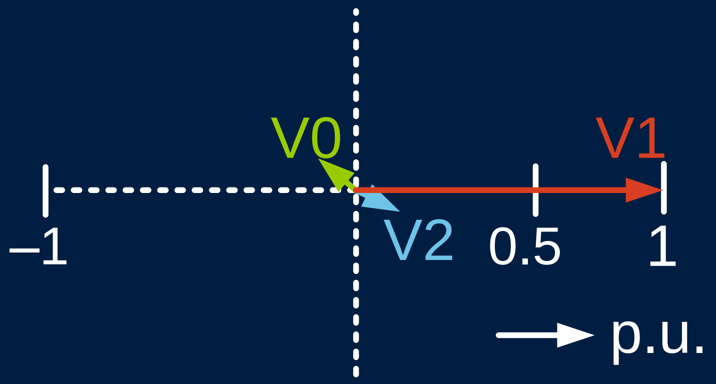


Open-Phase Analysis

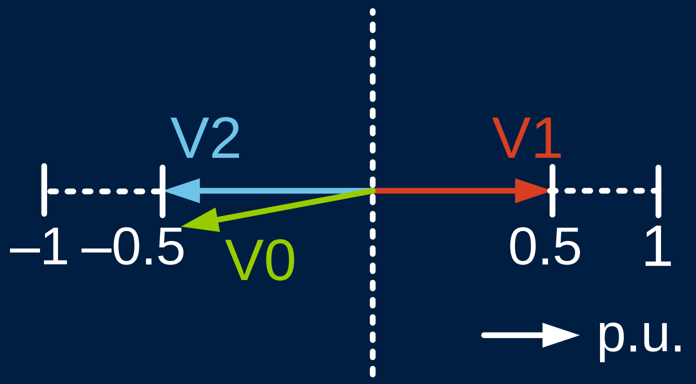


V_{NOM} = 1 p.u.

Before Break

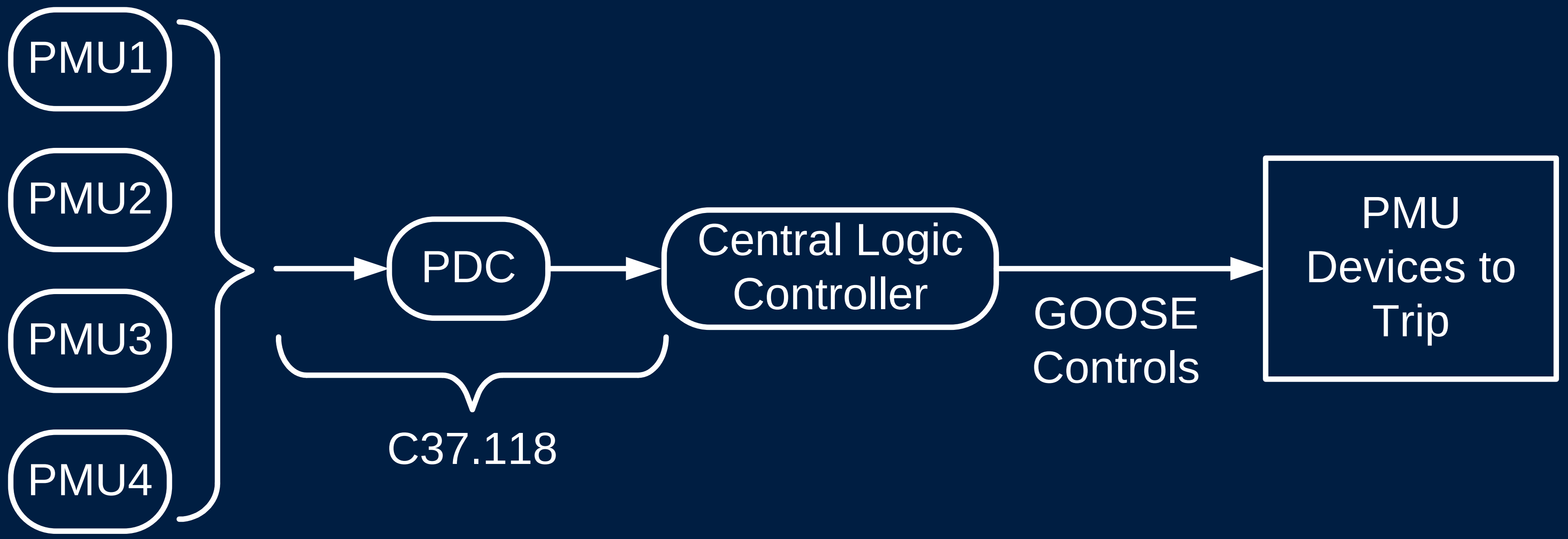


Phase A Break

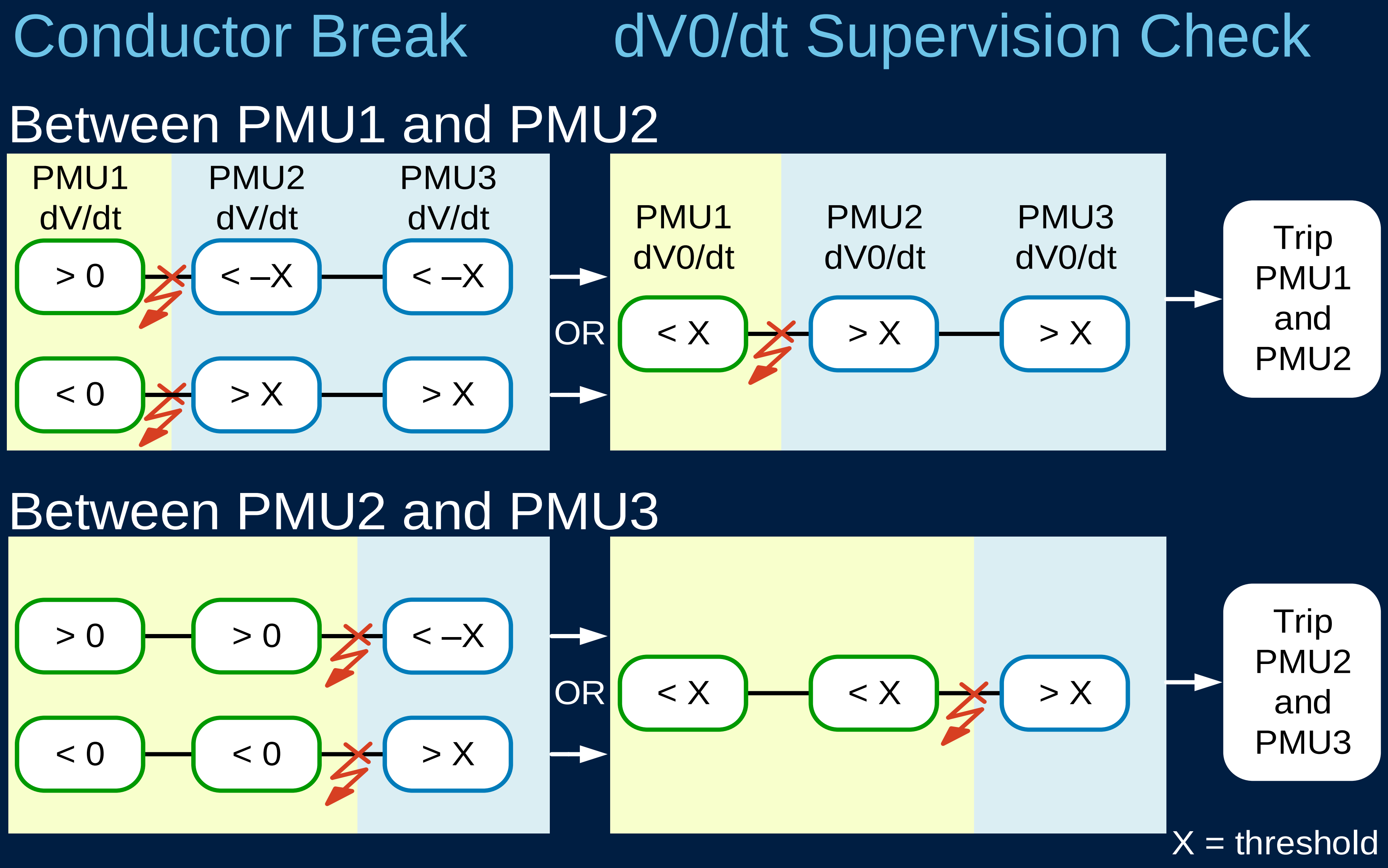


Detection Methods

- dV/dt (change detection)
- V0 and V2 magnitude
- V0 and V2 angle



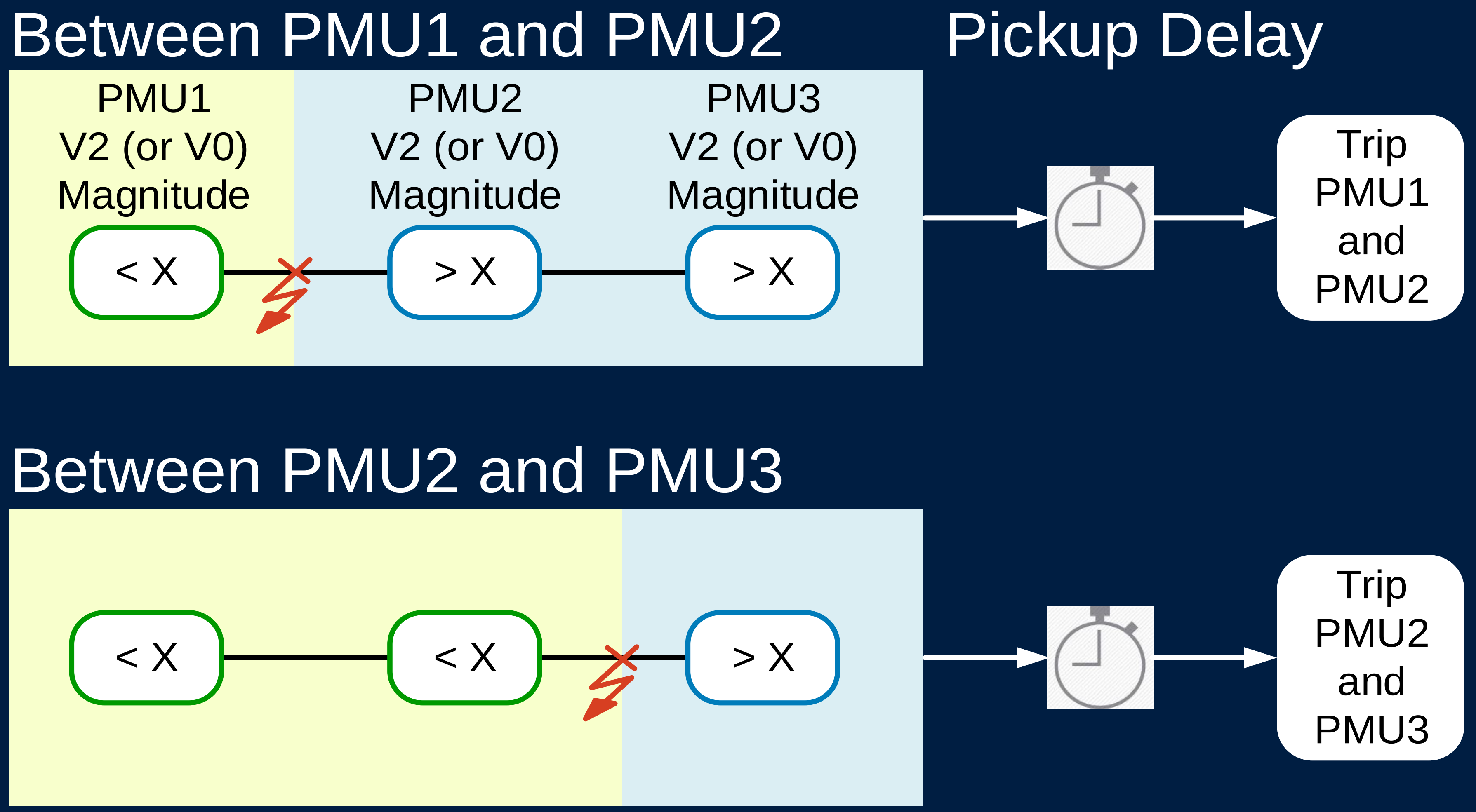
dV/dt Method



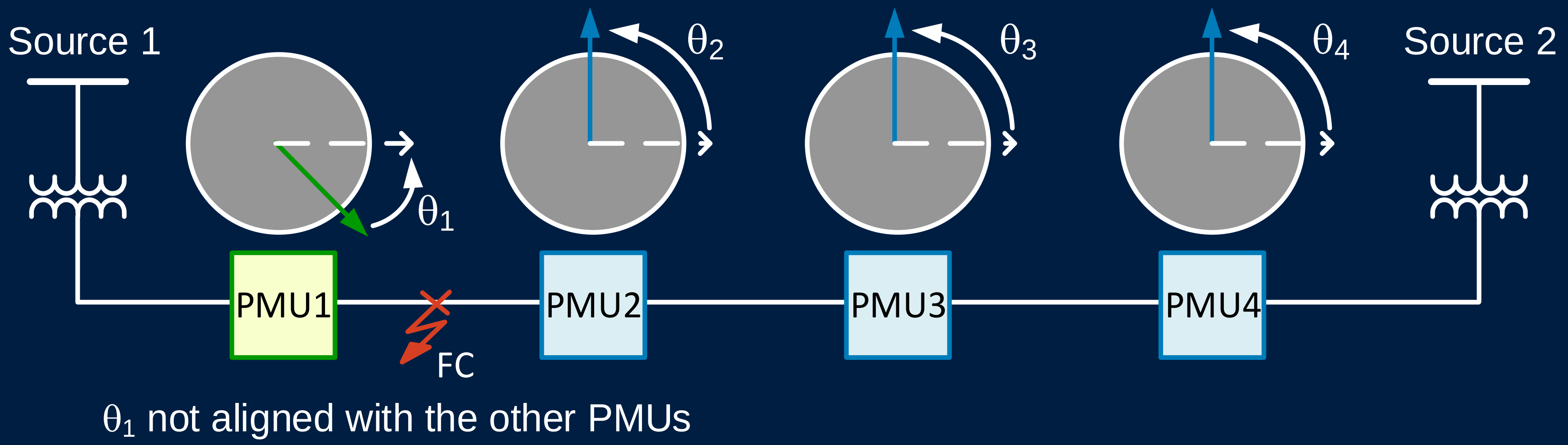
Conductor Break
dV0/dt Supervision Check
Between PMU1 and PMU2
PMU1 dV/dt
PMU2 dV/dt
PMU3 dV/dt
> 0
< –X
< –X
< 0
> X
> X
OR
PMU1 dV0/dt
PMU2 dV0/dt
PMU3 dV0/dt
< X
> X
> X
Trip PMU1 and PMU2
Between PMU2 and PMU3
> 0
> 0
< –X
< 0
< 0
> X
OR
< X
< X
> X
Trip PMU2 and PMU3
X = threshold

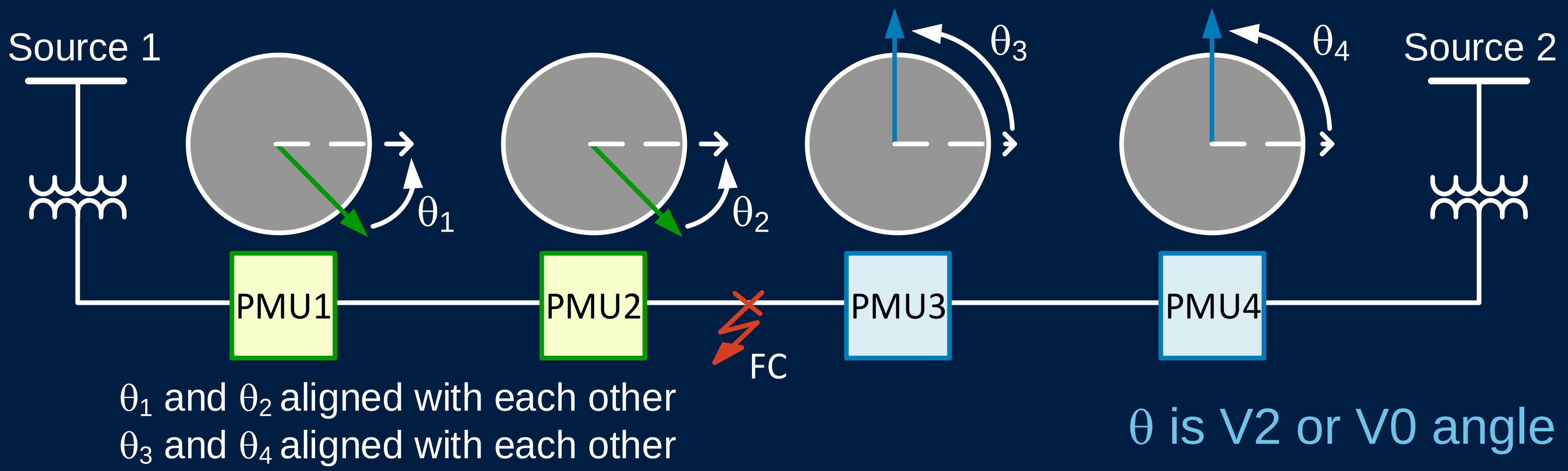
V2 and V0 Magnitude Method

Conductor Break



V2 and V0 Angle Method



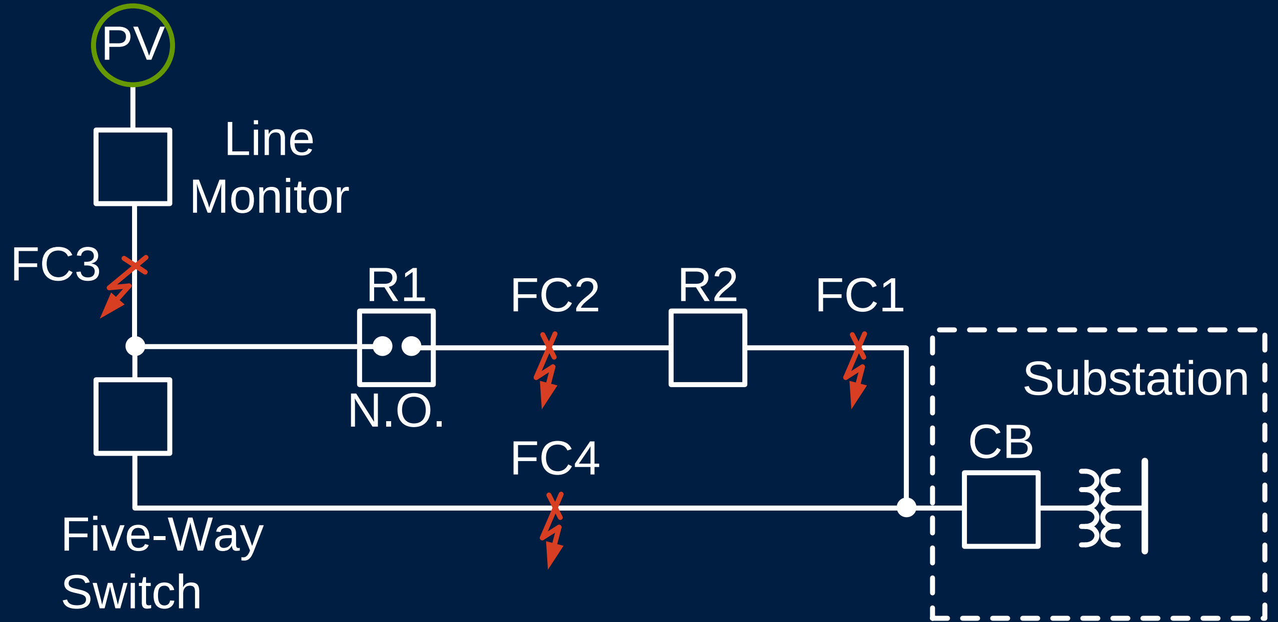


θ is V2 or V0 angle

Example Lab Test Results

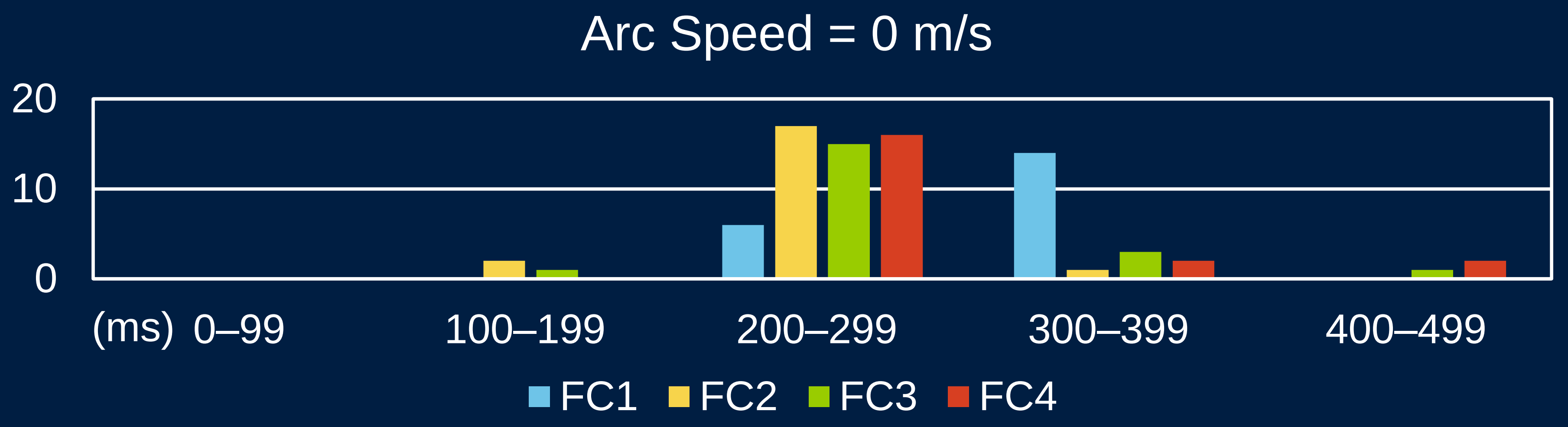
PV Off, Loop Open				
Load %	**FC1**	**FC2**	**FC3**	**FC4**
100	3	3	3	3
75	3	3	3	3
25	3	3	3	3

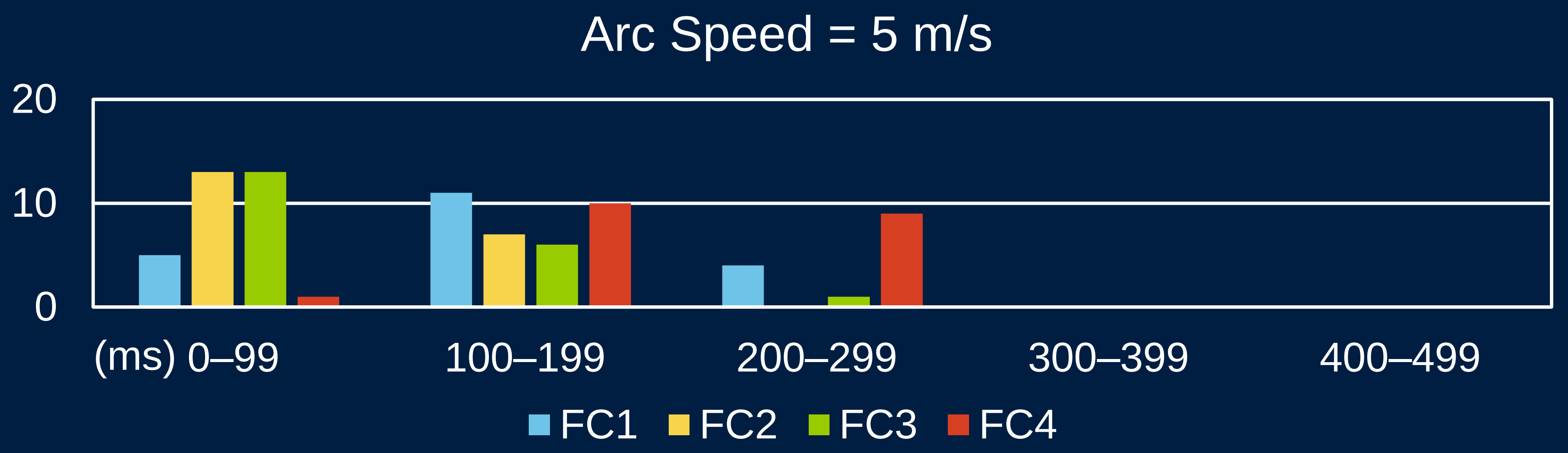
PV On, Loop Open					
Load %	**PV%**	**FC1**	**FC2**	**FC3**	**FC4**
100	100	3	3	3	3
	75	3	3	4	4
	50	3	3	3	3
	25	3	3	3	3
25	100	3	3	3	3
	75	3	3	3	3
	50	3	3	3	3
	25	3	3	3	3



Arc Speed and Results Comparison

Number of Test Cases Versus dV/dt Pickup Times





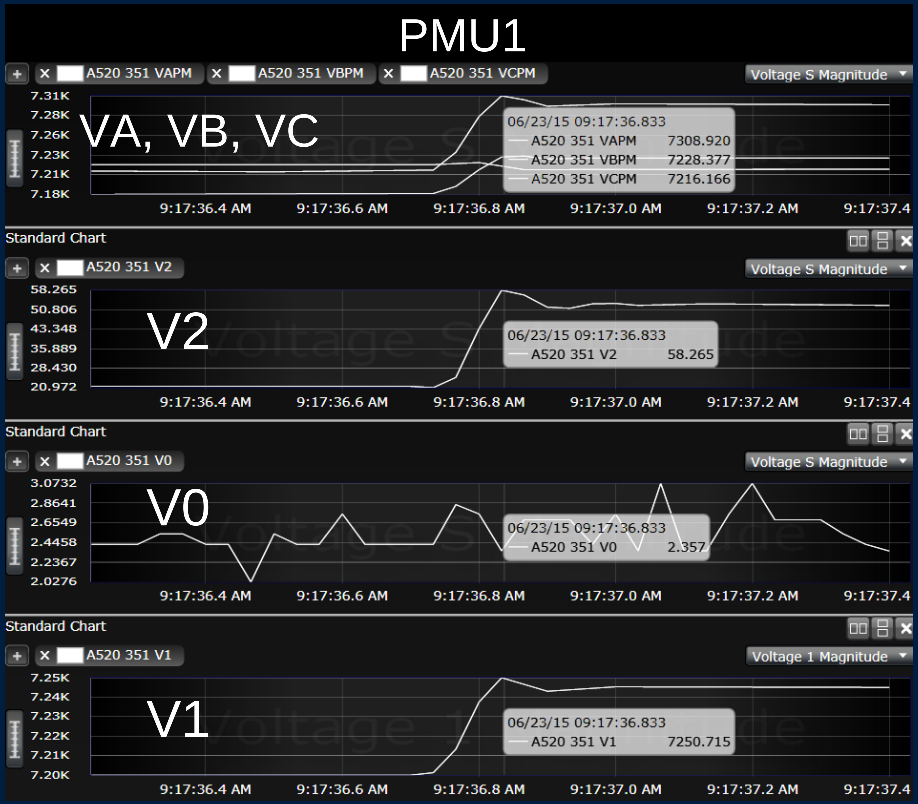
Security Testing

- Capacitor bank switching
- Voltage regulator tap unbalance
  - Angle method for ≈ 4.5% voltage (6 taps)
  - V0 magnitude method for ≈ 10% voltage (15 taps)
- Largest single-phase load switching
- PV operation
- Internal / external faults

Results

Detection Screen

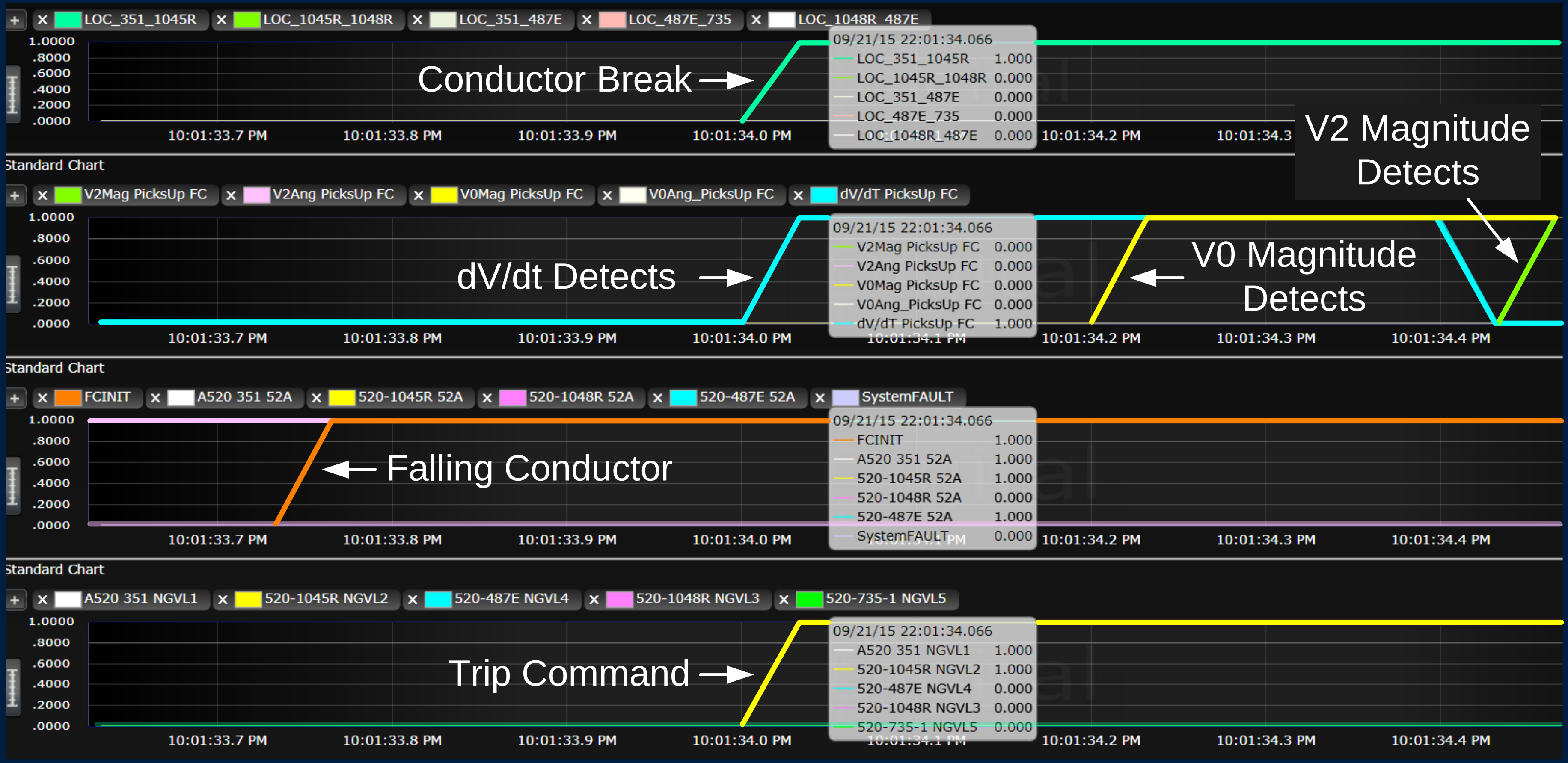
Inverter Response



- Conductor break between PMU1 and PMU2
- PV inverter source ON

Results

dV/dt and Magnitude Methods

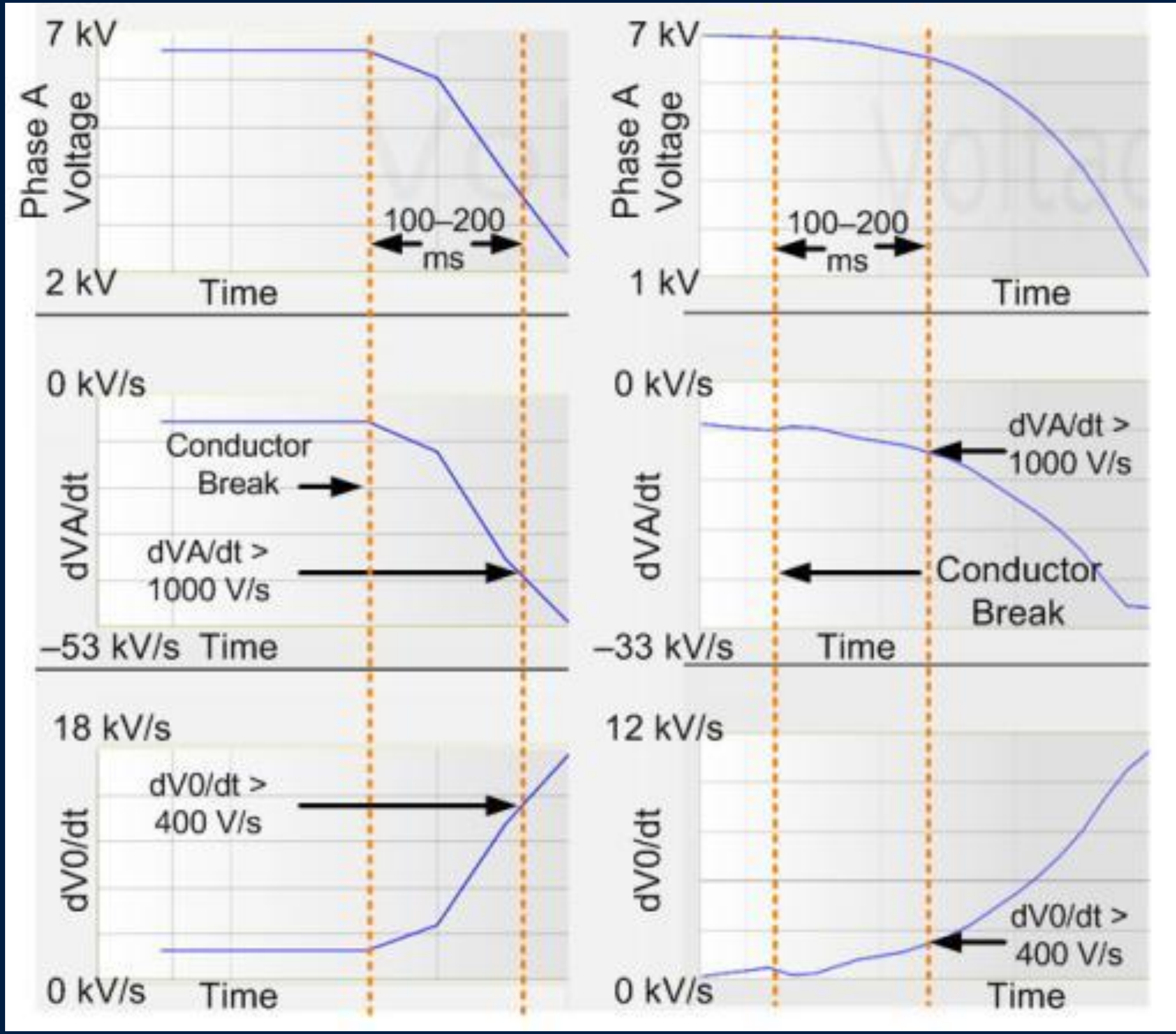


Field Installation and Testing

- First system installation in January 2015
- Falling Conductor Protection (FCP) in monitoring mode
- Simulation of conductor breaks with disconnect switch opening on recloser
- 100% correct operation
- Ethernet radio tuning required

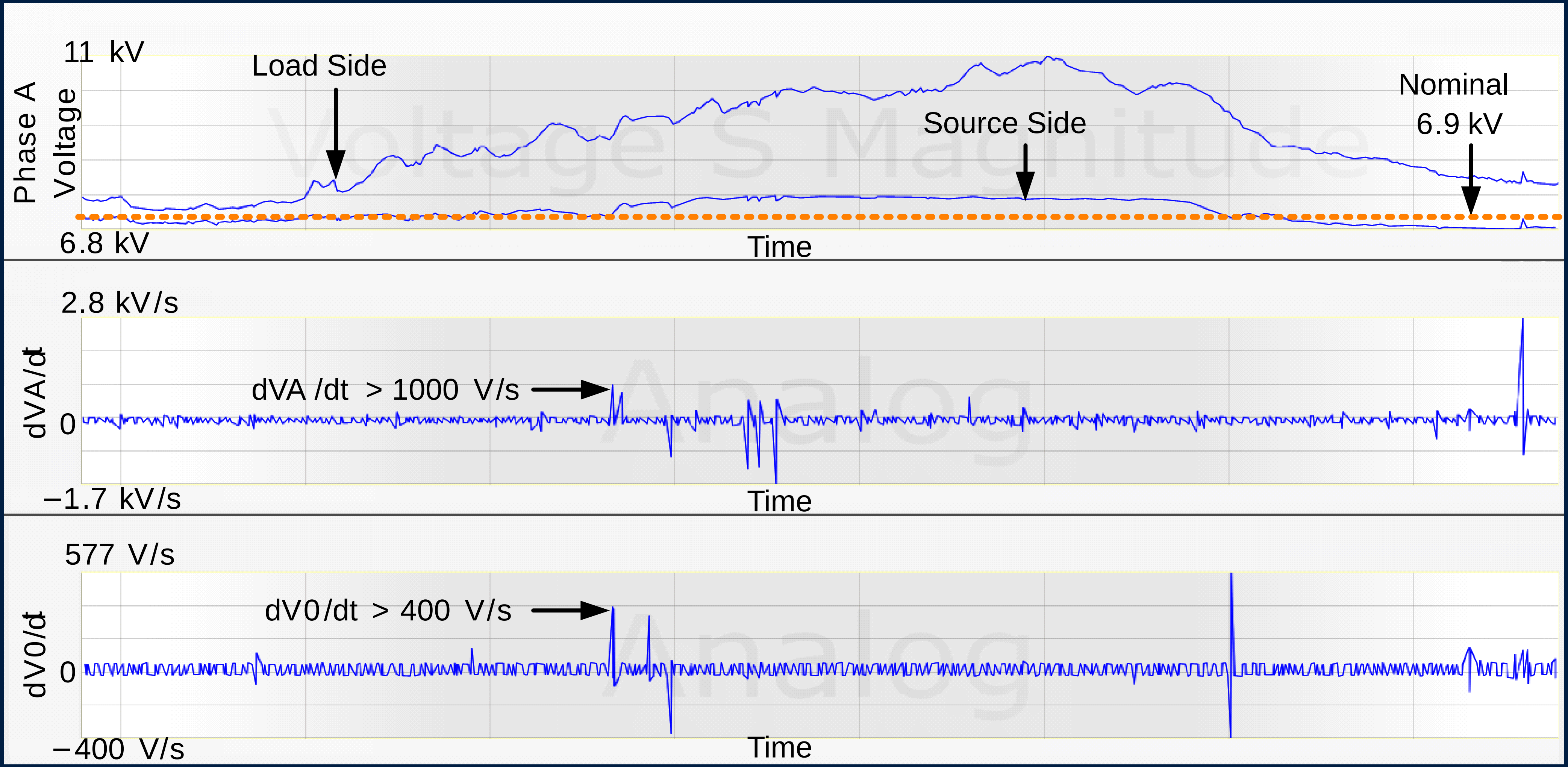
Breaking Arc – Field Versus Lab Tests

Field Result | RTDS Model



dV/dt Operation

Capacitive Voltage Sensors



More Installations Through 2016

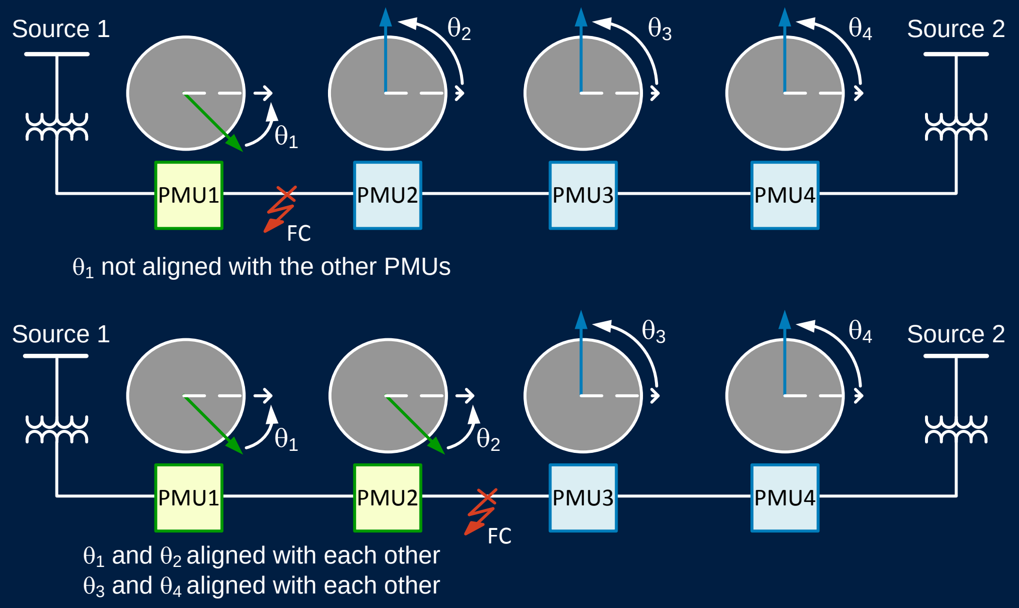
- Secure and reliable performance yields confidence
- FCP of first equipped circuit to go live – trip breakers, reclosers, and switches
- Eight more circuits will be equipped and commissioned in 2016

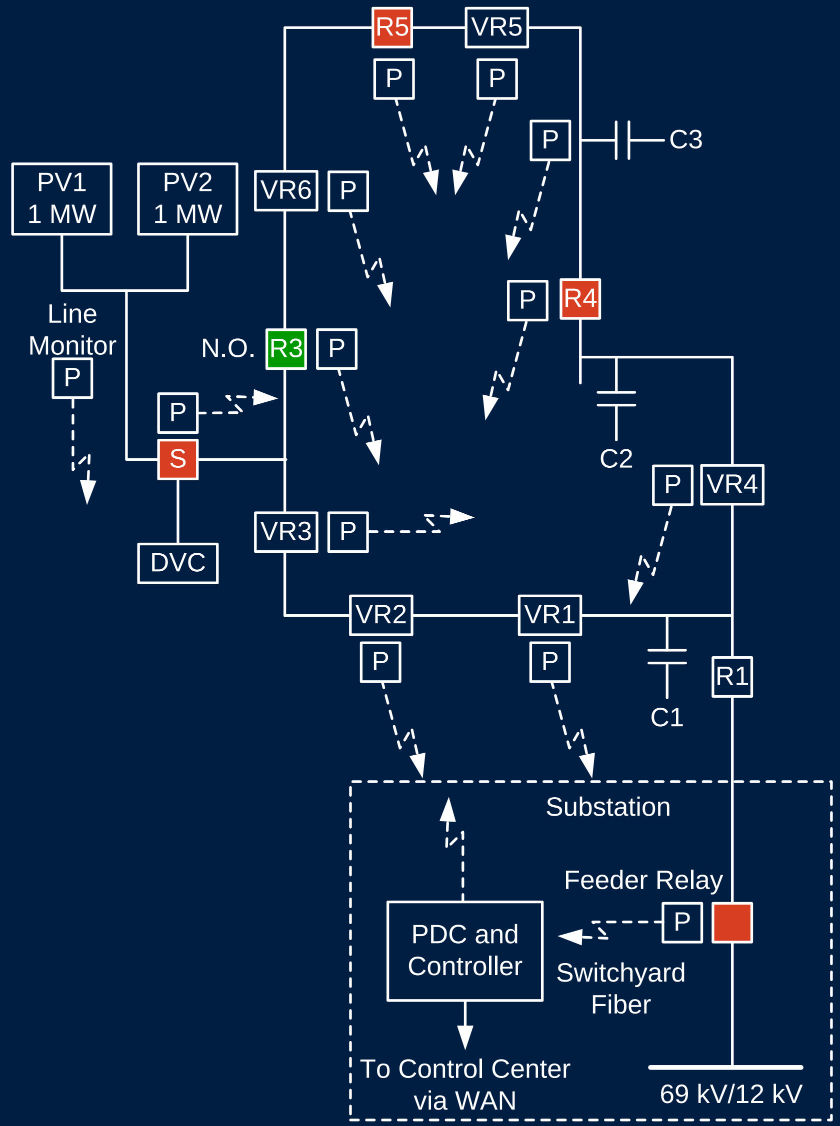
FCP Limitations

- HIF detection for wire down without break
- Solid, fast Ethernet path
- Voltage from each protected circuit path end – a journey of years
- Special measurement for dynamic volt/var control apparatus (fast SVC)
- New technology

Ease of Application

- Key requirement achieved – no circuit-dependent application settings
- FCP logic only needs topology of circuit and PMU IEDs





Making the Business Case

- FCP mitigates HILP events – fire and hazard reduction
- Big yet *soft* business case
- Replacing IEDs with PMU devices with moderate additional cost
- Monitoring and control of high DER circuits has *hard* business case

Conclusions

- Falling conductor takes ≈ 1.4 s to reach the ground
- FCP methods detect and isolate ≤ 0.7 s
- Change detection and steady-state detection algorithms operate in parallel

Conclusions

- Change detection picks up reliably for almost all falling conductor test cases
- Steady-state sequence methods (magnitude and angle) back up change detection in case of data packet loss
- Dependable FC detection observed in lab and field

Conclusions

- FCP tripping is being enabled at first installation
- Scalable design works on all studied circuits and needs only circuit layout information
- Eight more circuits to be commissioned in 2016, with more to come

Questions?