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

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SDG&E Distribution System

- 22,000 miles of lines
- 60% underground and 40% overhead
- Grounded three- and four-wire systems
- Nominally 12kV and 4kV
- High penetration of distribution PV requires new solutions for monitoring, protection, and control

Advanced SCADA Devices (ASD)

ASD was developed to meet the present and future needs of all of SDG&E's distribution system stakeholders.

The system design uses the most advanced relay, phasor measurement, radio, and IT communications technology that can implement more than 60 Use Cases or applications defined up front.

Advanced SCADA Features

- Increased accuracy of voltage and current
- Phase angles from across circuit
- GPS time-stamped data
- 30 synchrophasor sets per second for fast measurement
- IEC 61850 GOOSE messaging for real-time control
- Remote engineering access and event reports
- Advanced security features

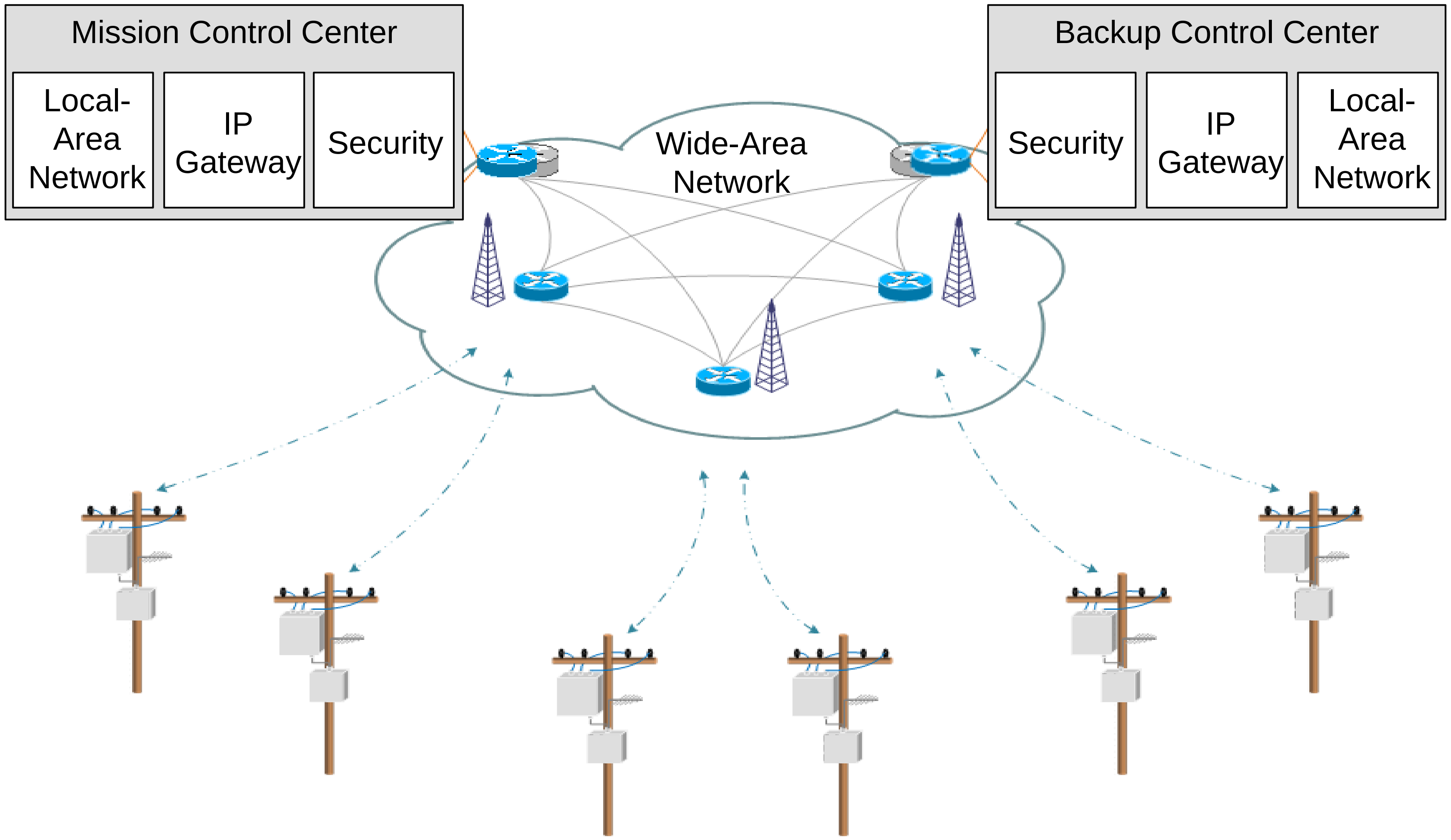
Advanced SCADA Project Applications

More Than 60 Use Cases Defined

- Driven by high penetration of distribution PV
- Voltage profile monitoring and control
- Selective load shedding and restoration
- Power quality monitoring
- Apparatus and system condition monitoring
- Falling conductor protection (patent pending)

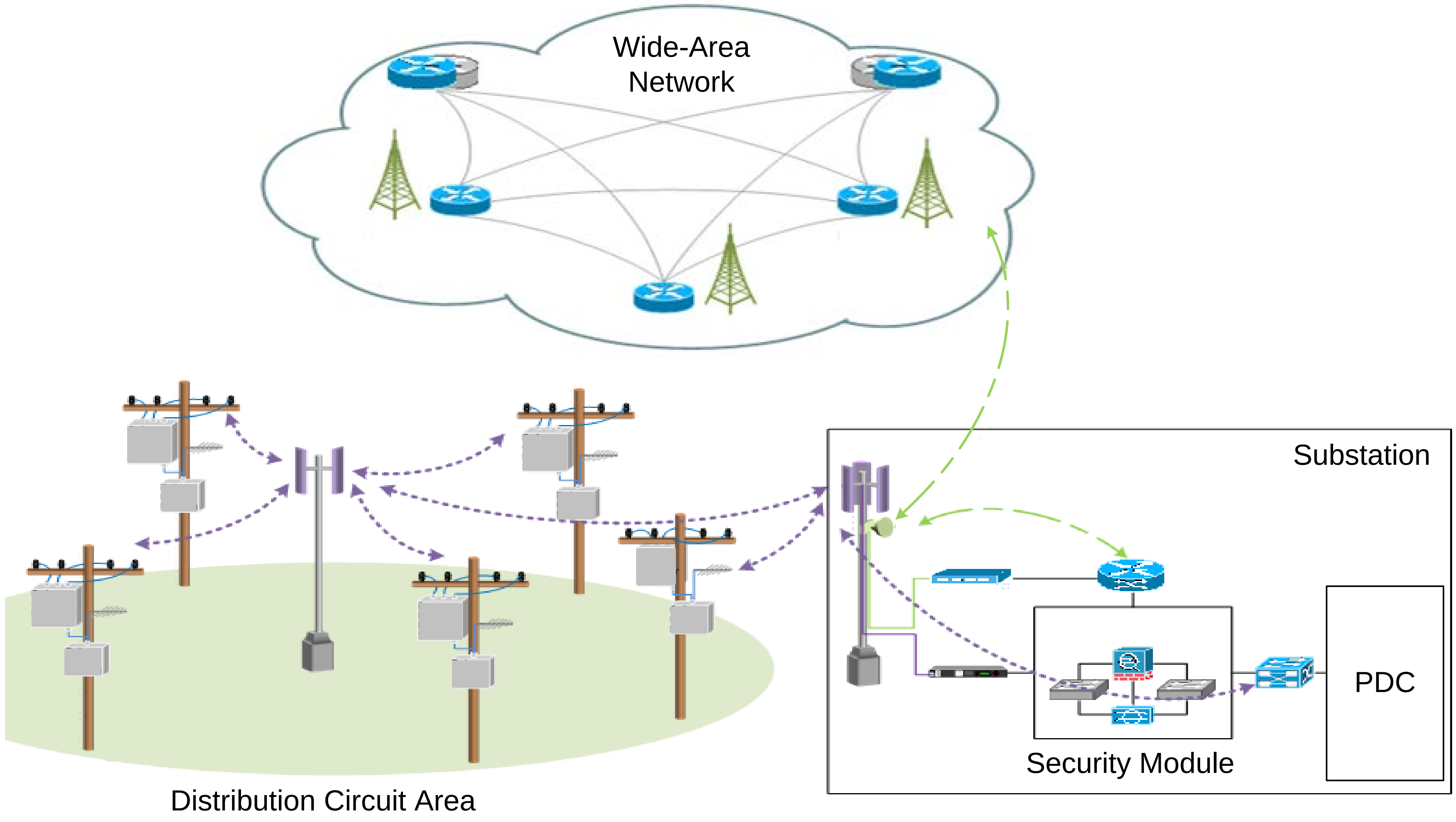
SCADA System Architecture

Traditional



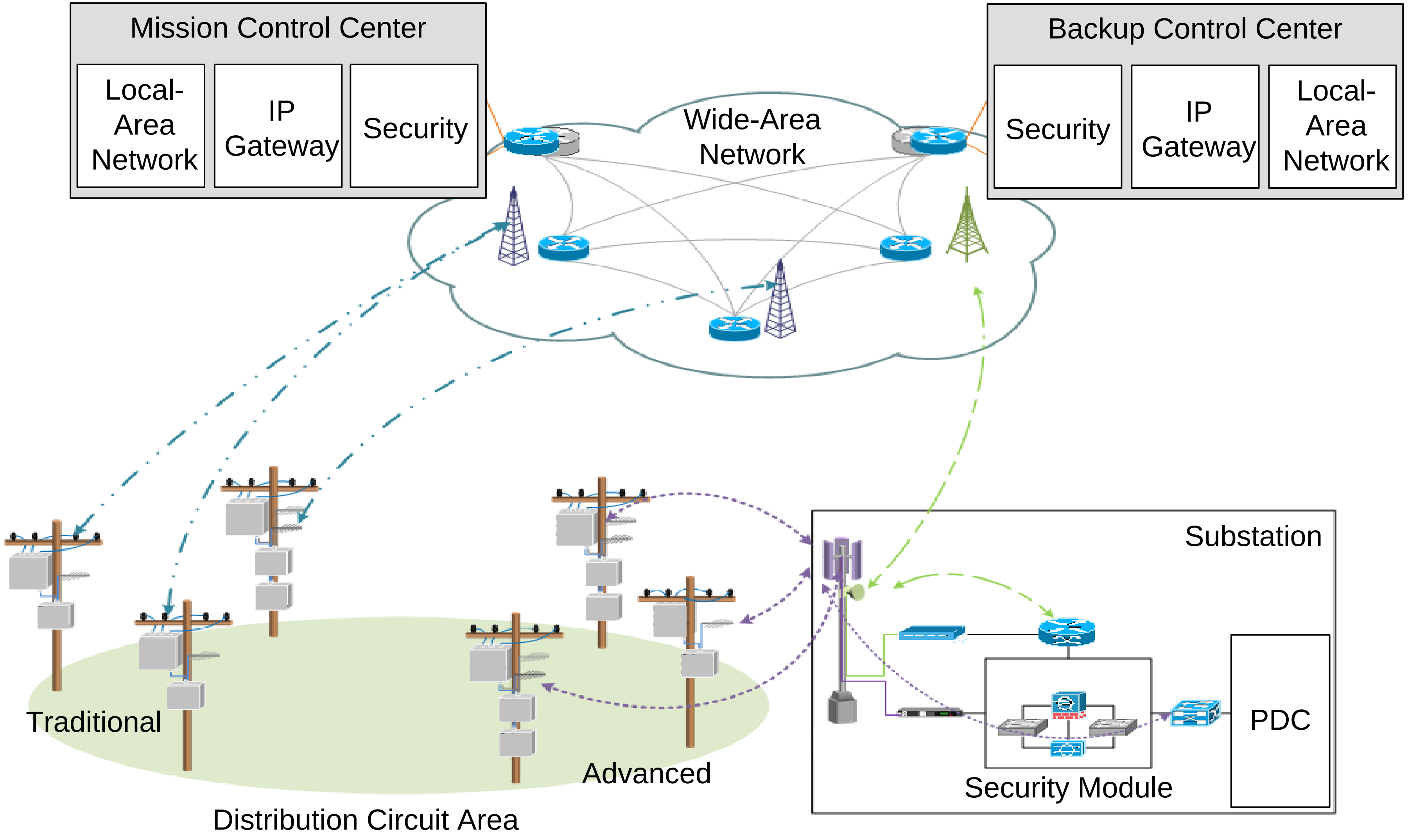
SCADA System Architecture

Advanced

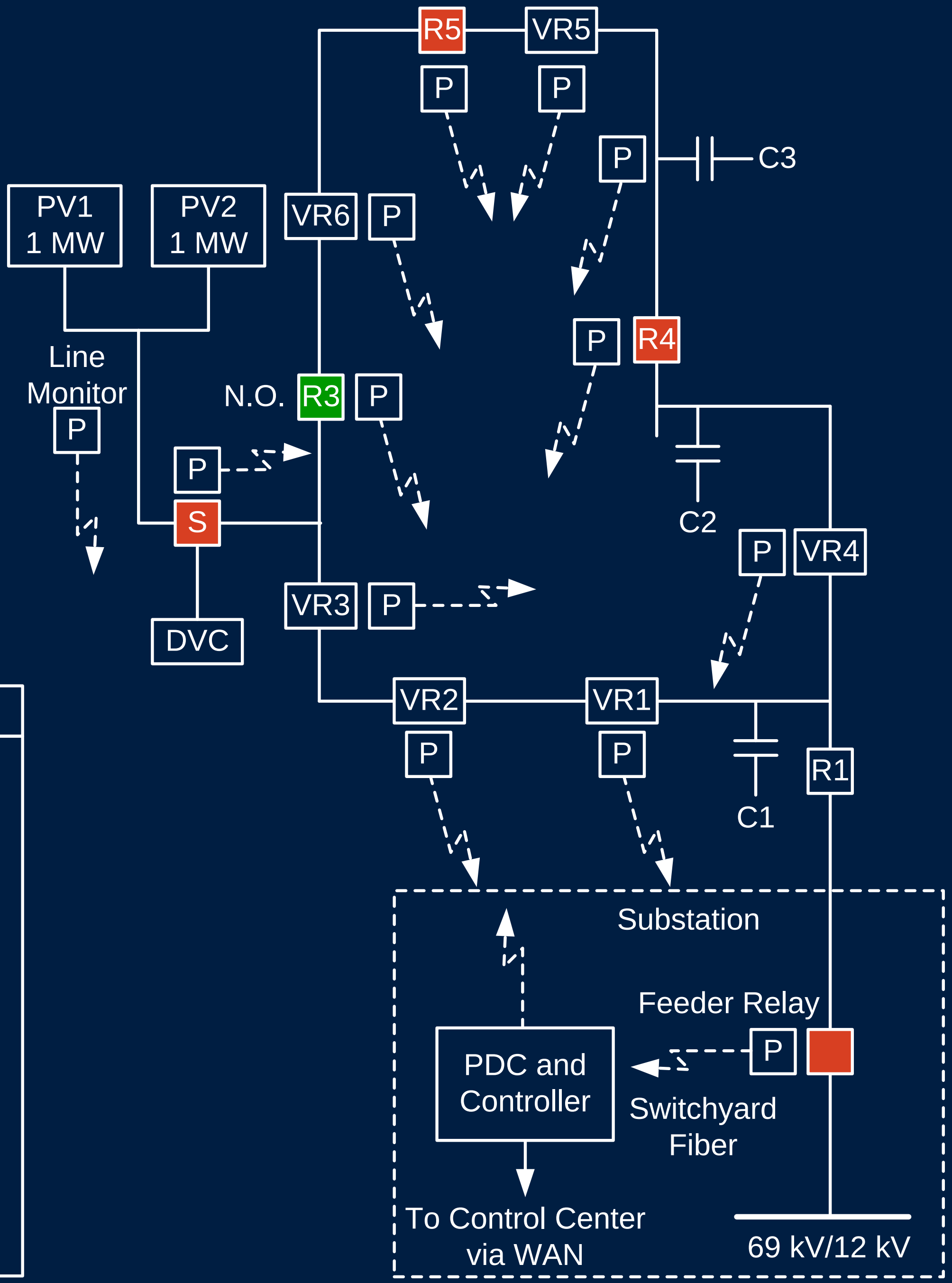


SCADA System Architecture

Traditional and Advanced Overlay

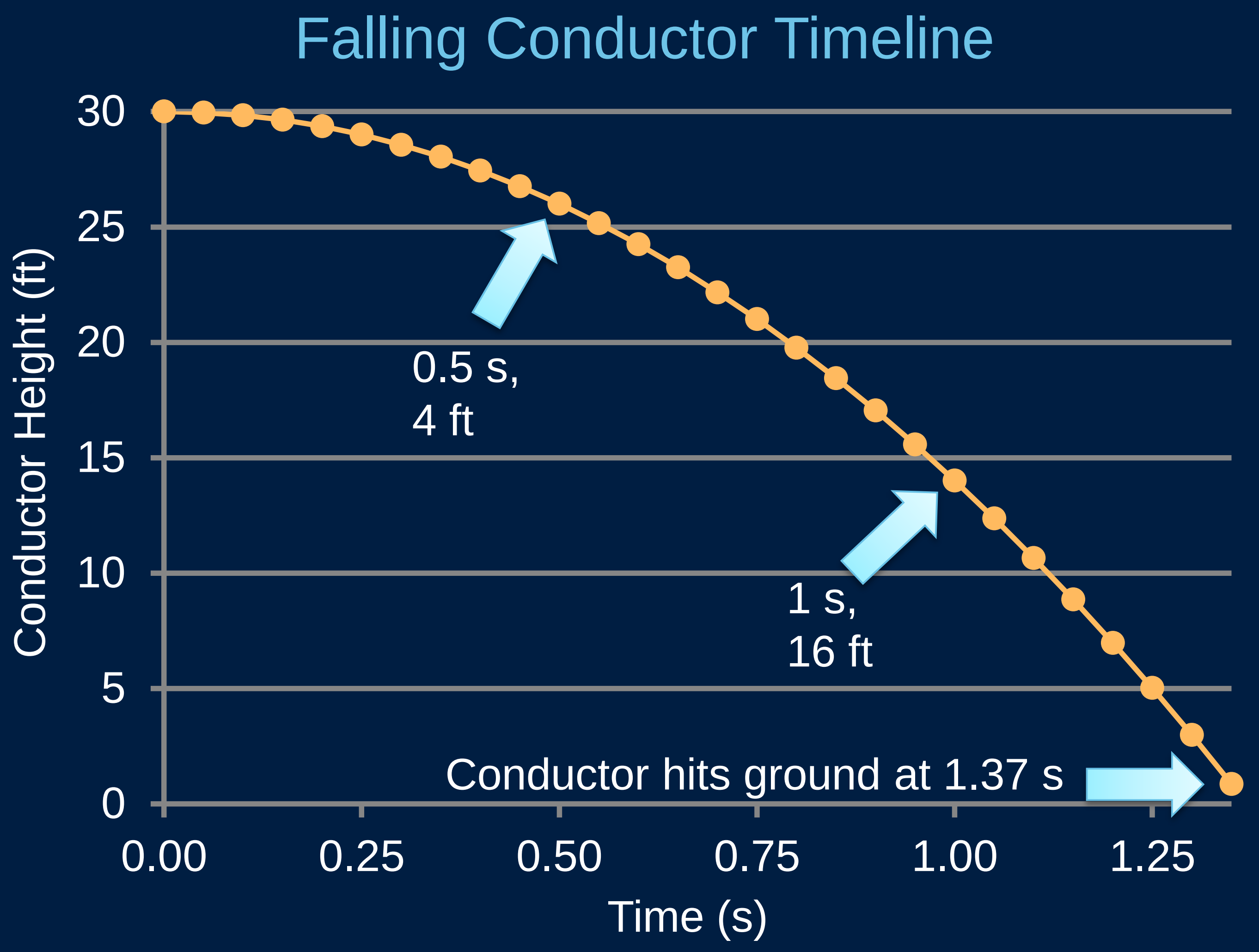


Advanced SCADA Locations



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

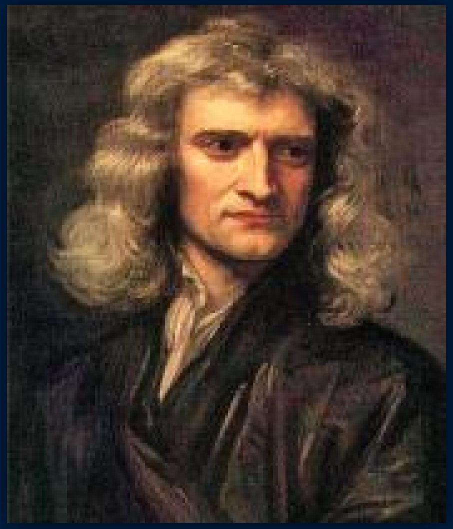
Detect Broken Conductor and Trip Circuit Before Line Hits the Ground?



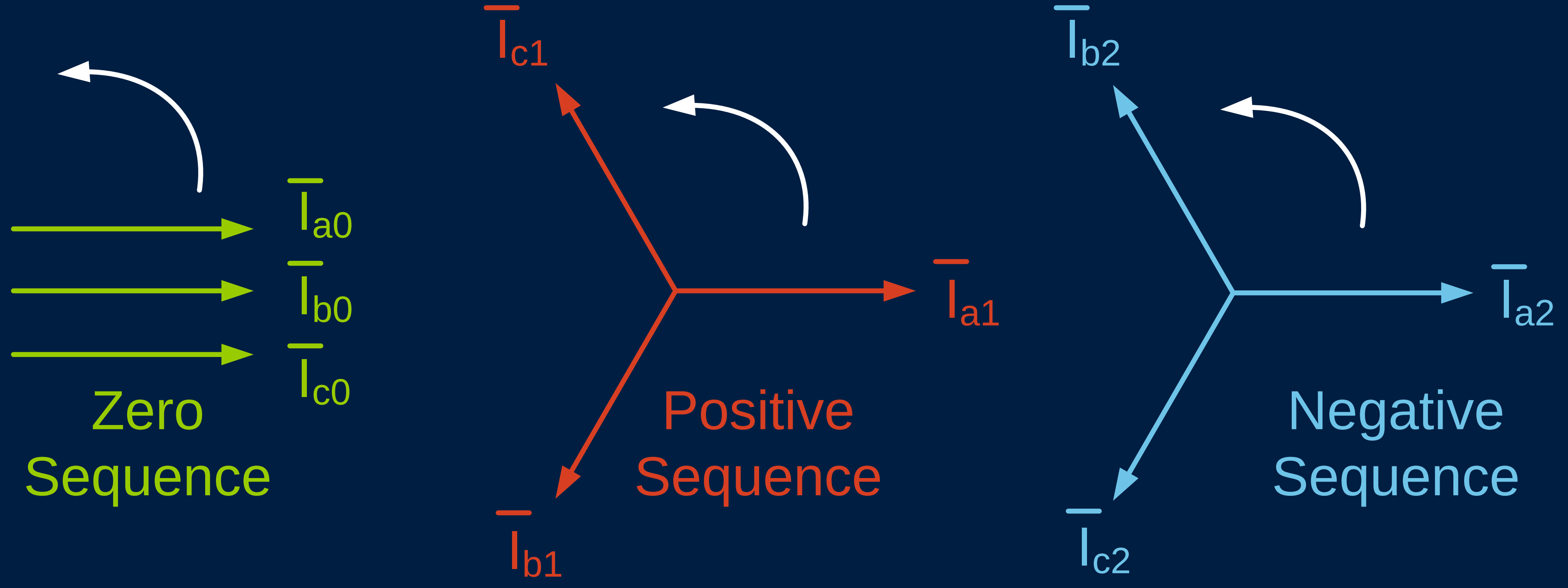
$$d = \frac{1}{2}gt^2 \rightarrow t = \sqrt{\frac{2d}{g}}$$

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

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



Sequence Components Analysis



Single Phase

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

Balanced

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

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

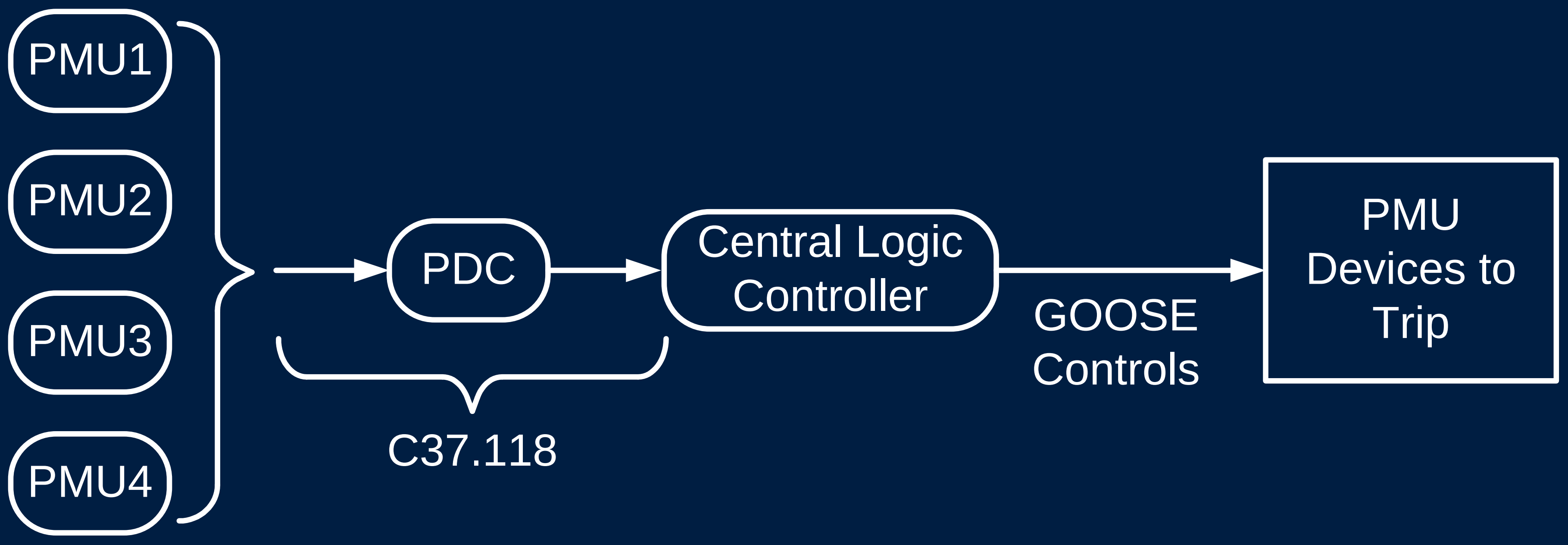
Balanced

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

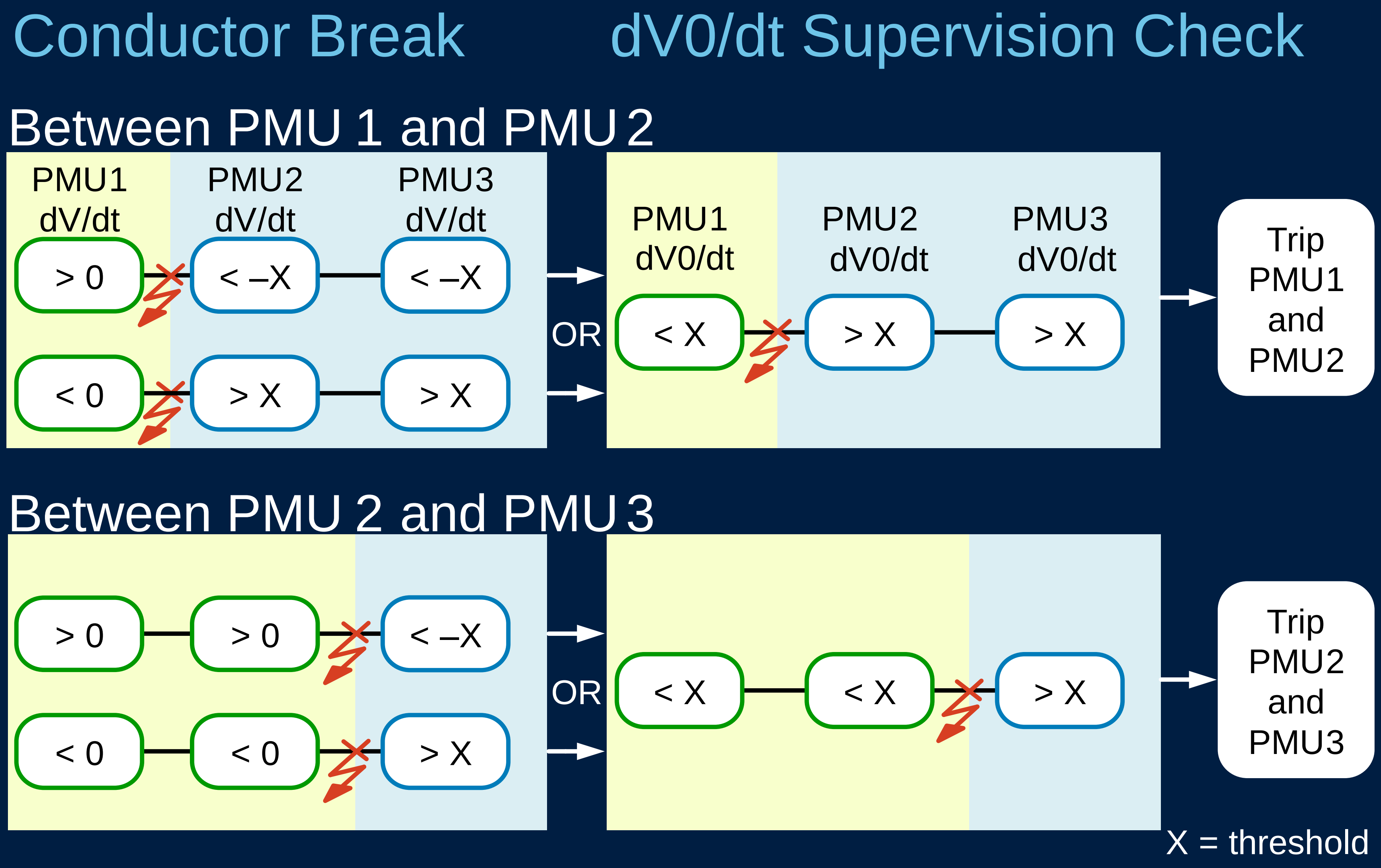
$\bar{I}_{c2} = a^2\bar{I}_{a2}$

Detection Methods

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

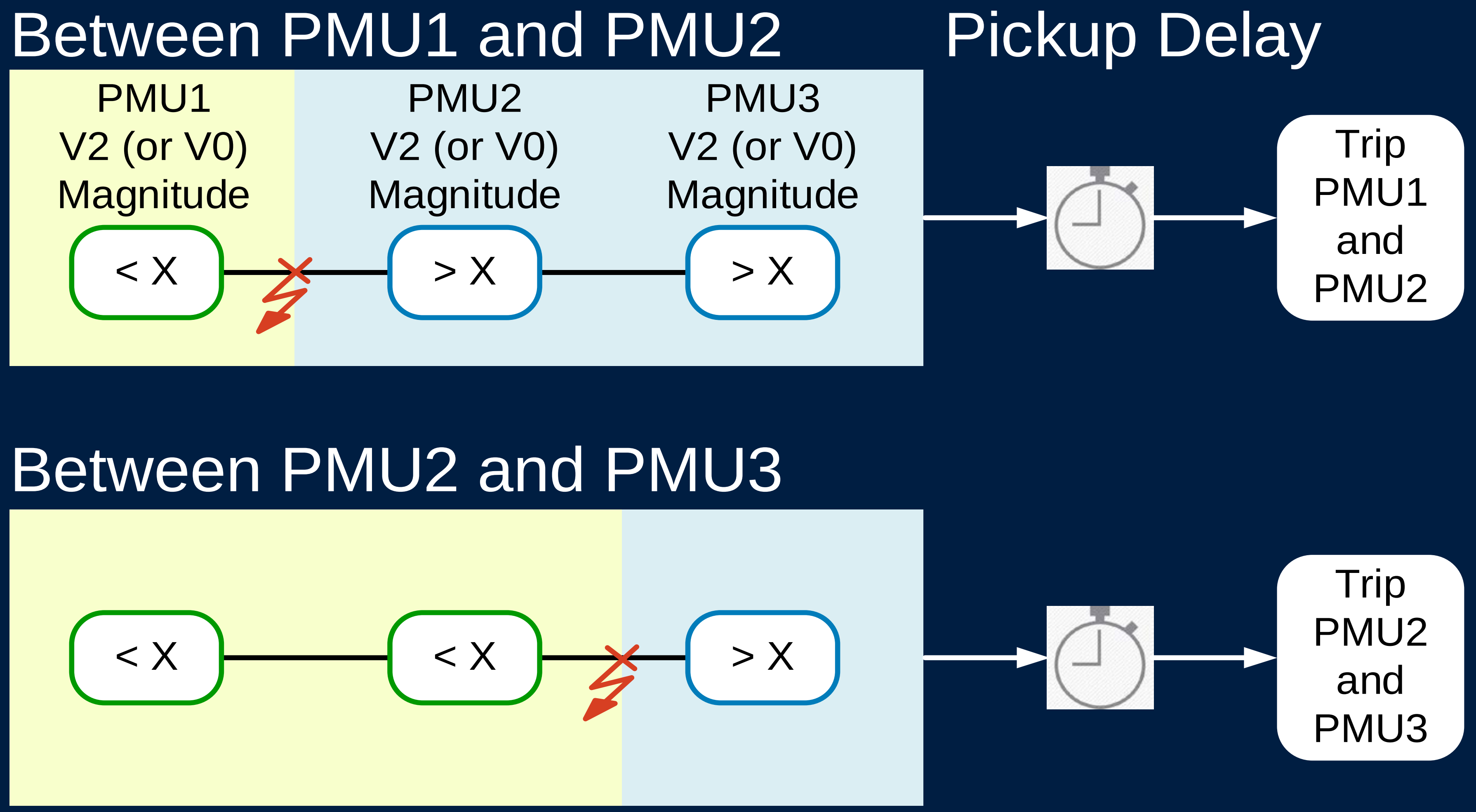


dV/dt Method

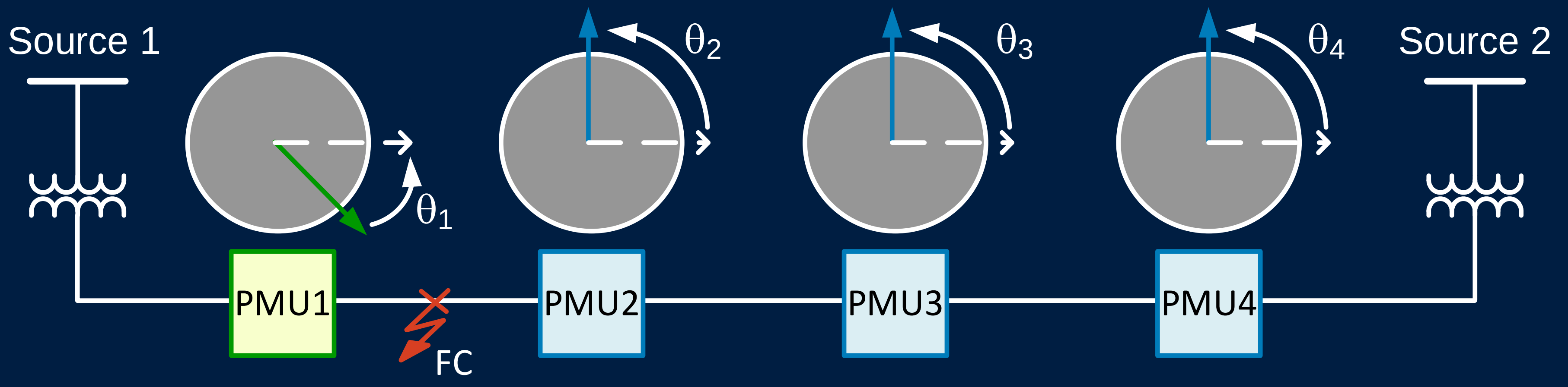

Conductor Break
dV0/dt Supervision Check
Between PMU 1 and PMU 2
PMU1 dV/dt
PMU2 dV/dt
PMU3 dV/dt
> 0
< –X
< –X
< 0
> X
> X
OR
PMU1 dV0/dt
PMU2 dV0/dt
PMU3 dV0/dt
< X
> X
> X
Trip PMU1 and PMU2
Between PMU 2 and PMU 3
> 0
> 0
< –X
< 0
< 0
> X
OR
< X
< X
> X
Trip PMU2 and PMU3
X = threshold

V2 and V0 Magnitude Method

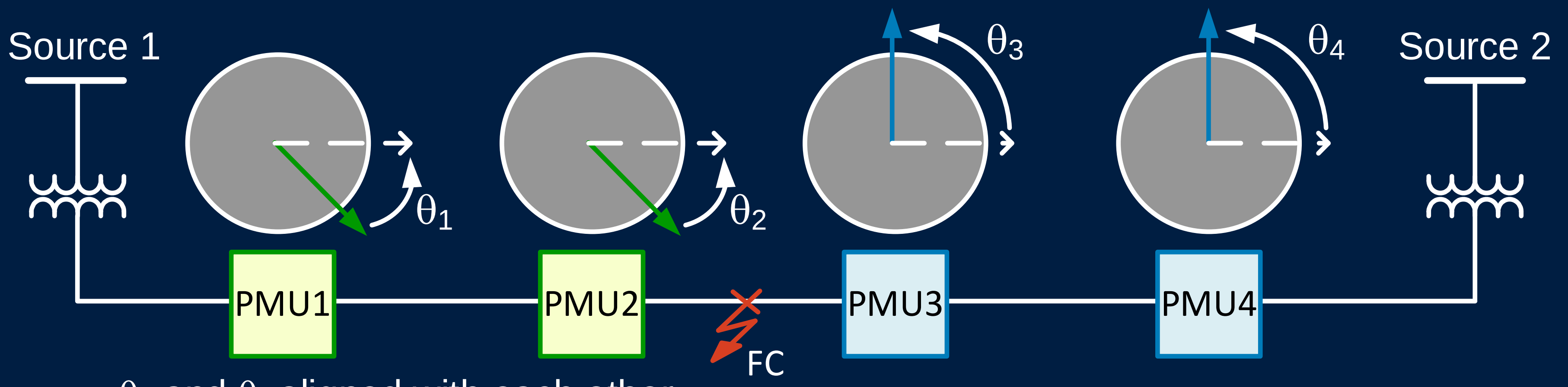
Conductor Break



V2 and V0 Angle Method



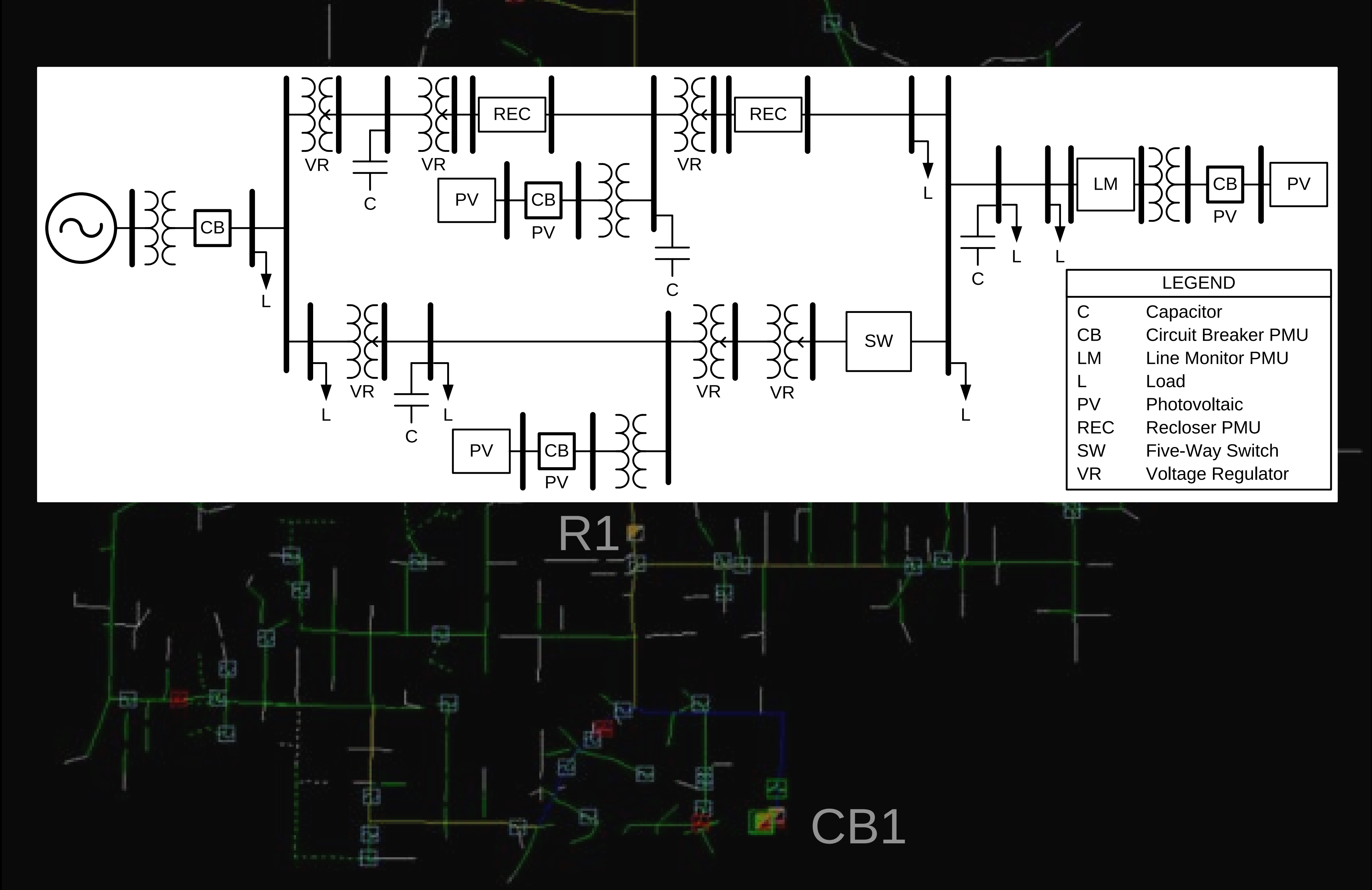
θ_1 not aligned with the other PMUs



θ_1 and θ_2 aligned with each other
θ_3 and θ_4 aligned with each other

θ is V2 or V0 angle

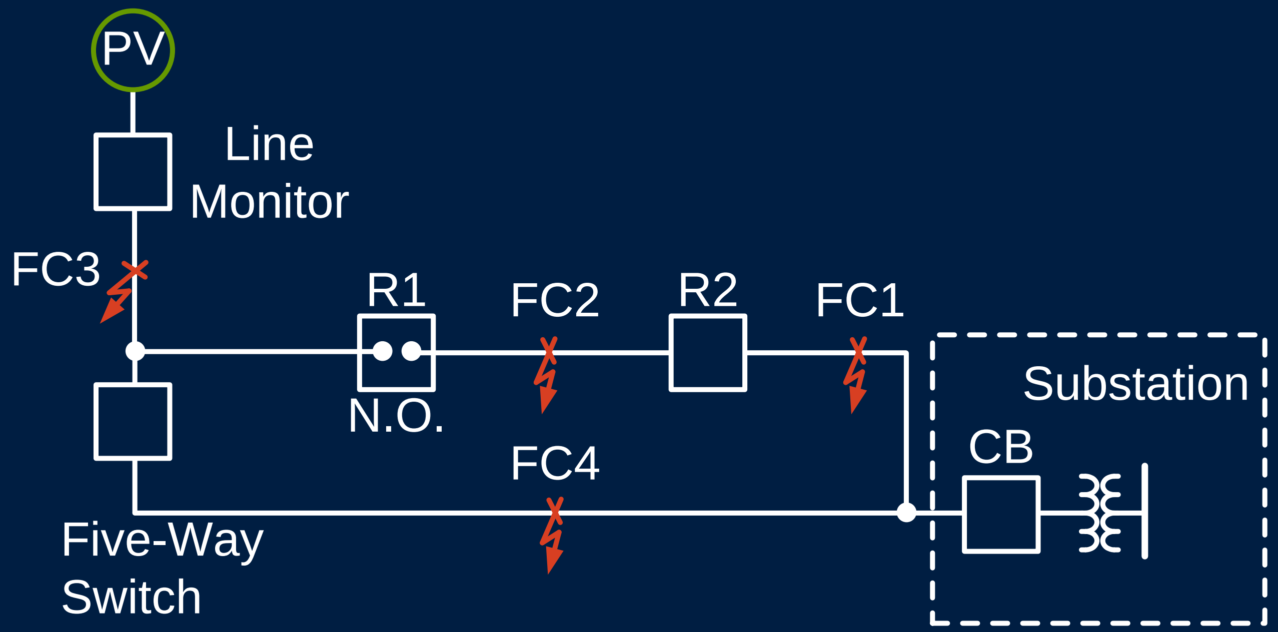
RTDS Feeder Model



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



Security Testing

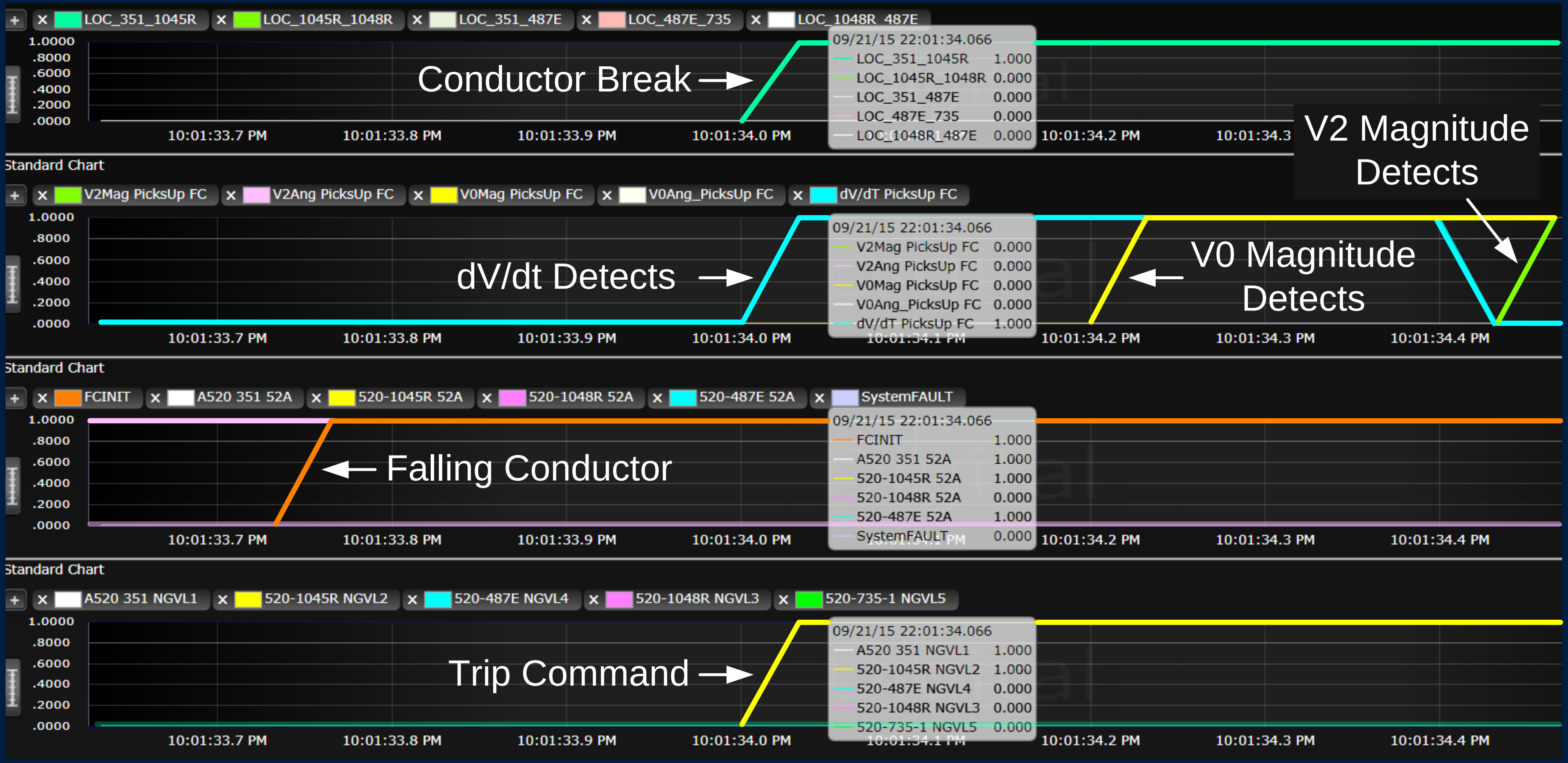
- Capacitor bank switching
- Voltage regulator tap unbalance
  - Angle method for ≈ 4.5% voltage (6 taps)
  - V0 magnitude method for ≈ 10% voltage (15 taps)
- Largest single-phase load switching
- PV operation
- Internal / external faults

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

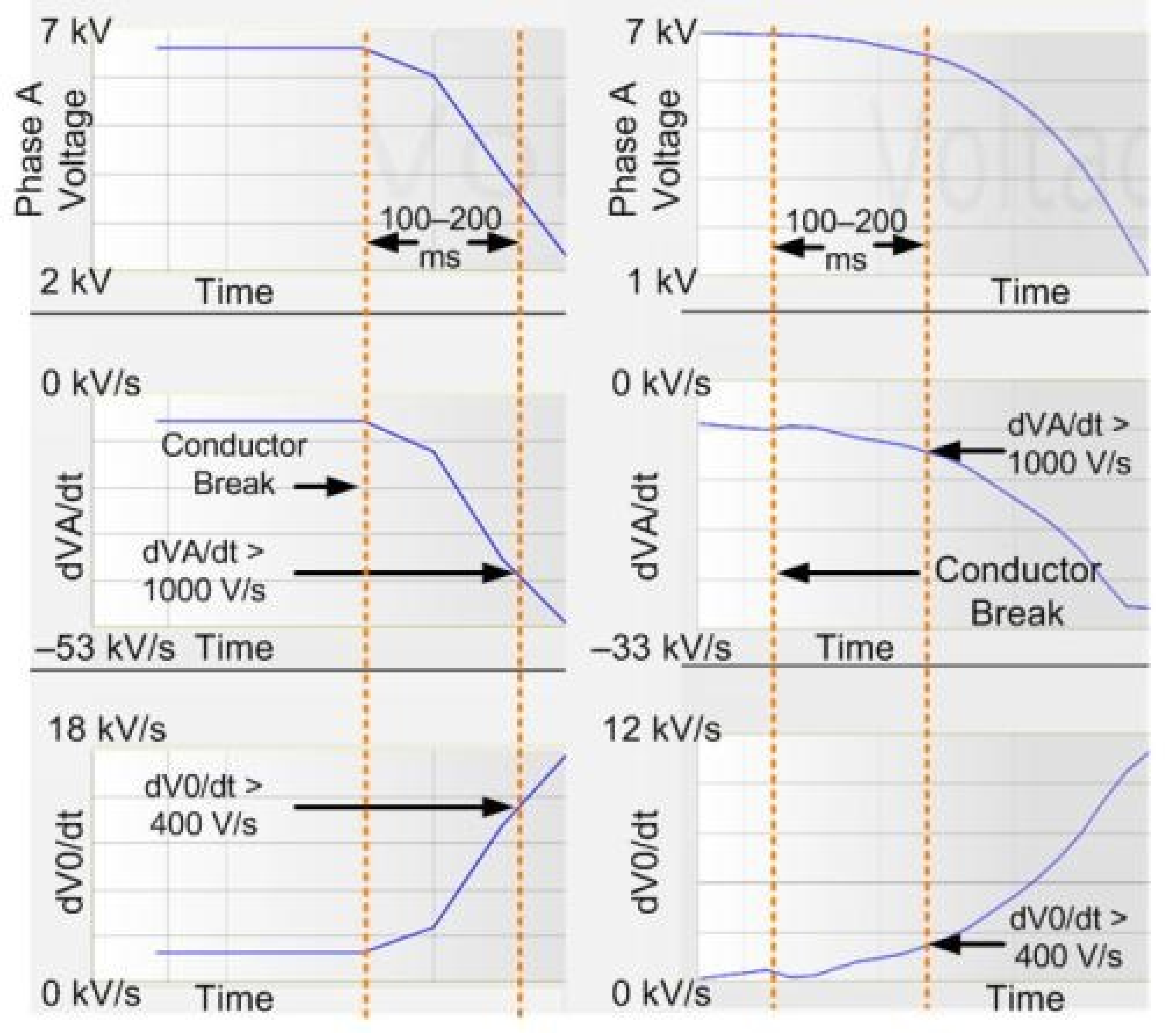
Results

dV/dt and Magnitude Methods



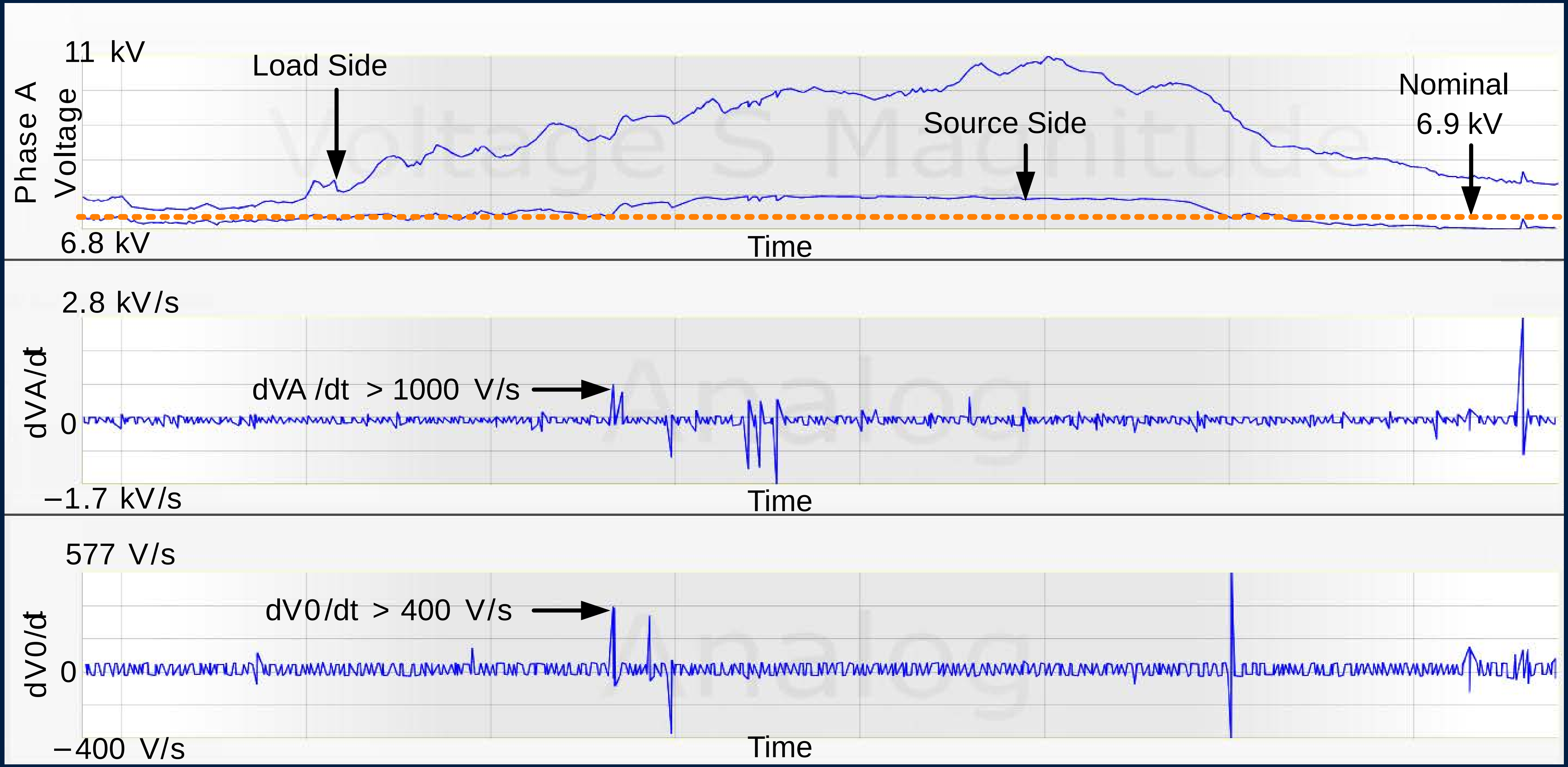
Breaking Arc – Field Versus Lab Tests

Field Result RTDS Model

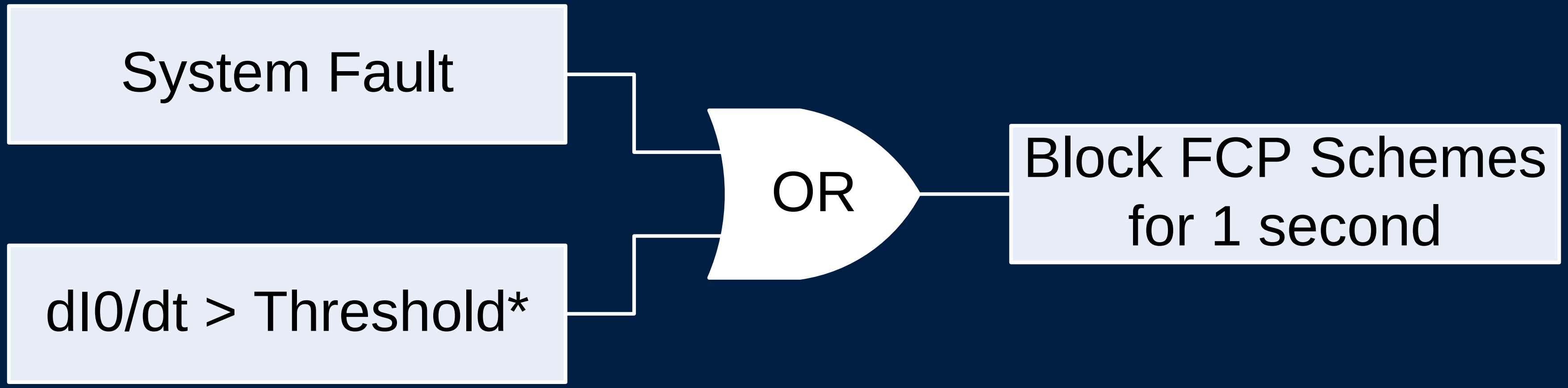


Synchrophasors show detailed circuit behavior

Capacitive voltage sensor discoveries



dI0/dt Supervision



- Threshold based on RTDS testing results
- dI0/dt spikes at CB PMU used to block falling conductor detection algorithms
- Temporary faults can be blocked using this supervision

System Protection is a Balancing Act

- **SPEED** FAST TO MINIMIZE DAMAGE
- **SENSITIVITY** RELAY SEES FAULT
- **SELECTIVITY** REMOVE FAULTED ELEMENT ONLY
- **SECURITY** DO NOT TRIP FALSELY
- **SIMPLICITY** SIMPLE CONTROL SCHEMES

FCP Compliments Existing Layers of Protection

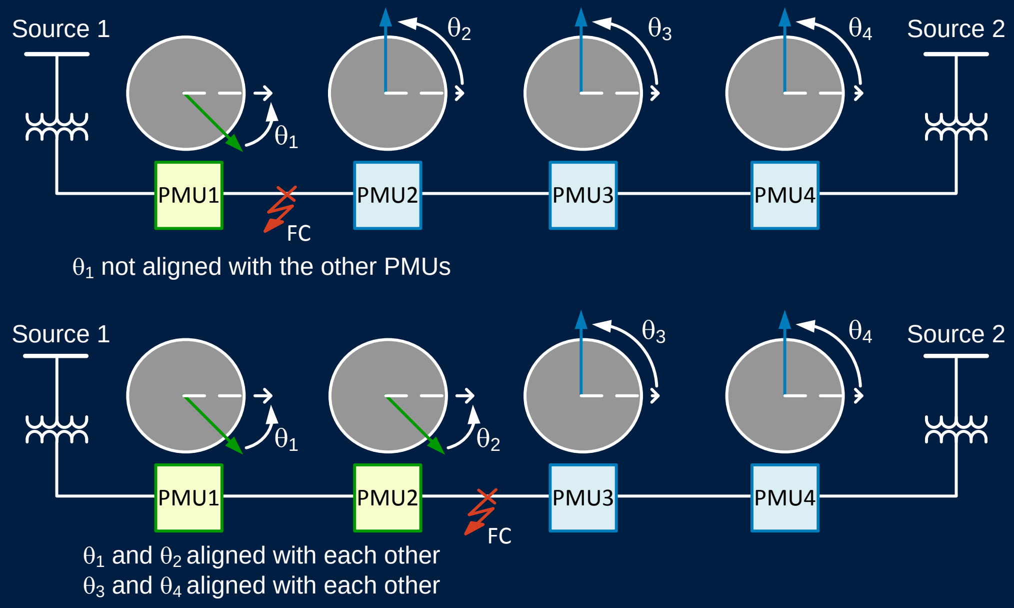
- FCP – Falling Conductor Protection detects break in conductor
  - Fastest – trips before the fault
  - Coordination – FCP should be first
- Overcurrent – Time and Instantaneous
  - Simple implementation
- SGF – Sensitive Ground Fault detects high-impedance ground fault
  - Slow – 3.5 to 5.5 seconds
  - Could Trip on Load
- Advanced SGF - More sensitive than SGF using adaptive set point, spike counting, and/or harmonics
  - Slower – > 5 seconds
  - Coordination between devices is unlikely

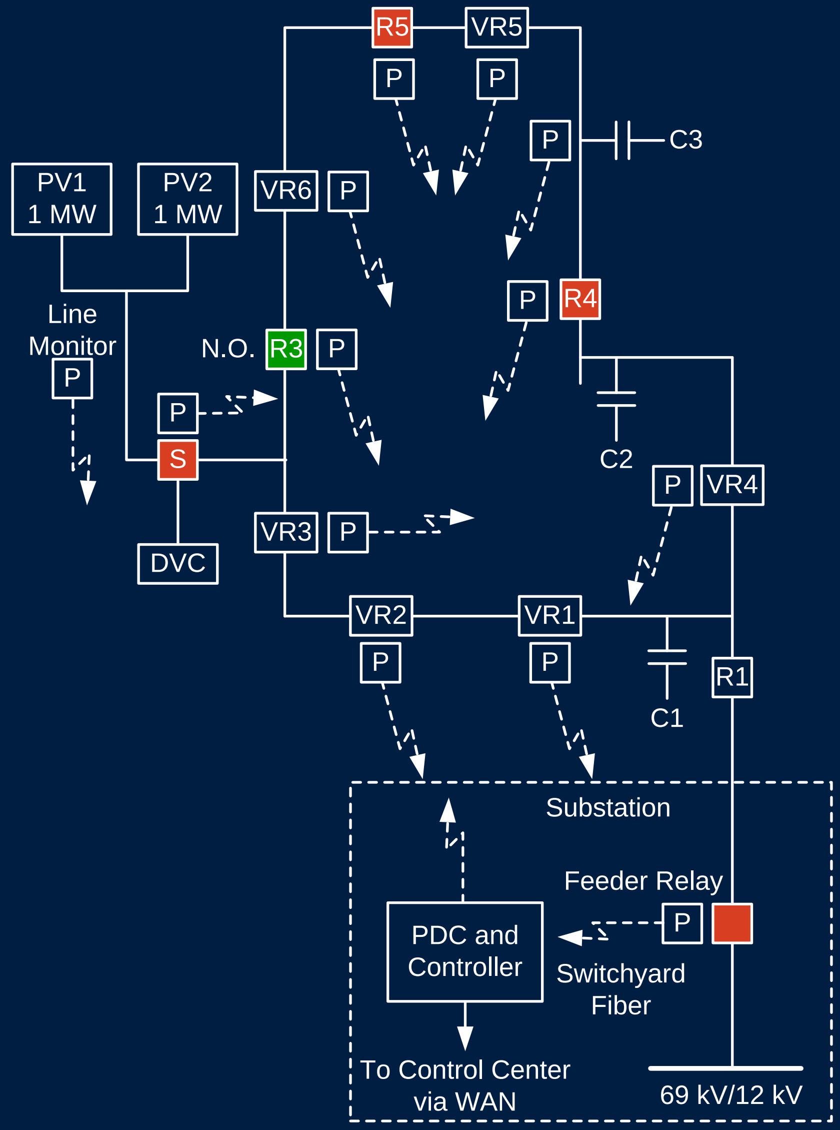
FCP Limitations

- Does not detect wire down without break
- Needs fast Ethernet path to circuit PMUs
- Uses voltage from each protected circuit path end – a journey of years for coverage
- Learning features of new technology

Ease of Application

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





Summary

- Advanced SCADA has 60 use cases including FCP
- FCP isolates broken conductors in 0.2 – 0.5 s (half the distance to the ground) preventing the fault
- FCP is dependable in lab test including high PV penetration
- FCP mitigates HILP events – fire and hazard reduction
- Confidence built from secure and reliable field performance
- Compliments existing protection
- Scalable design needs only circuit layout information

Next Steps

- FCP of first equipped circuit commissioned on 11/18/2016
- 3 additional circuits equipped and commissioned in 2017
- Pursuing ongoing funding to reduce fire risk and enhance public safety
- Installing new IEDs with PMU capable devices with moderate additional cost
- SDG&E will be well positioned for future PV penetration

Questions?