Detecting and Isolating Falling Conductors in Midair—First Field Implementation on Double-Phase Distribution Circuits

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Why do conductors break?

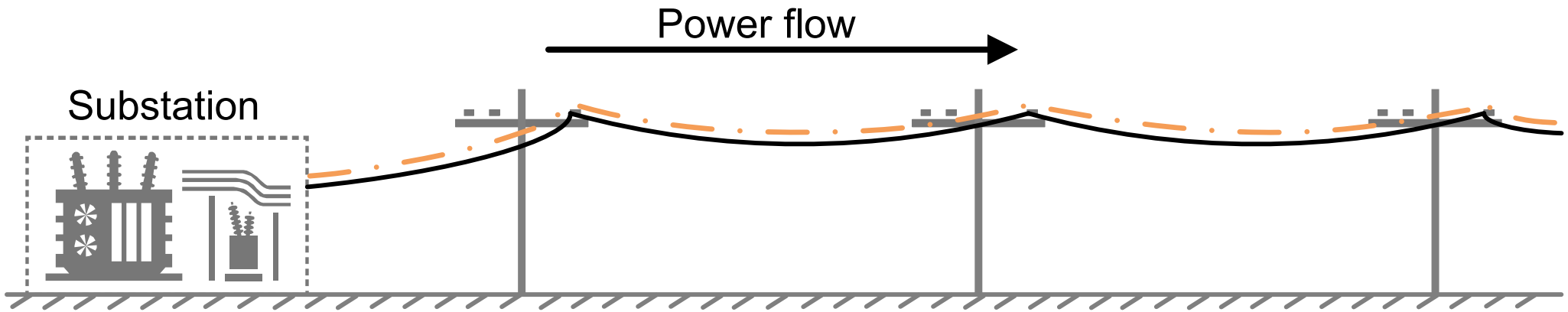
Defects and aging

- Corrosion
- Fatigue
- Fretting
- Etc.

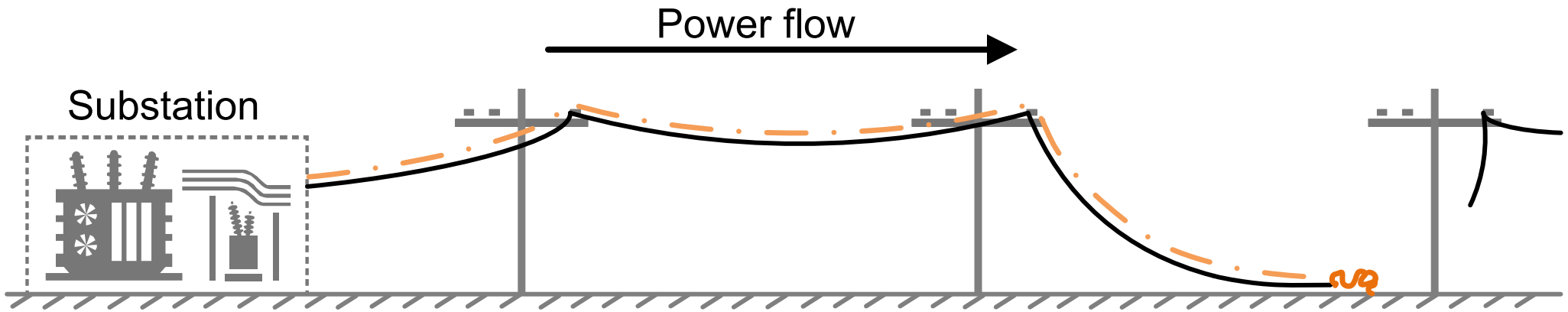
Localized damage

- Power arcs
- Lightning strikes
- Hardware abrasion
- Gunshots
- Fires
- Tree strikes
- Etc.

What happens when current-carrying conductor breaks?



What happens when current-carrying conductor breaks?



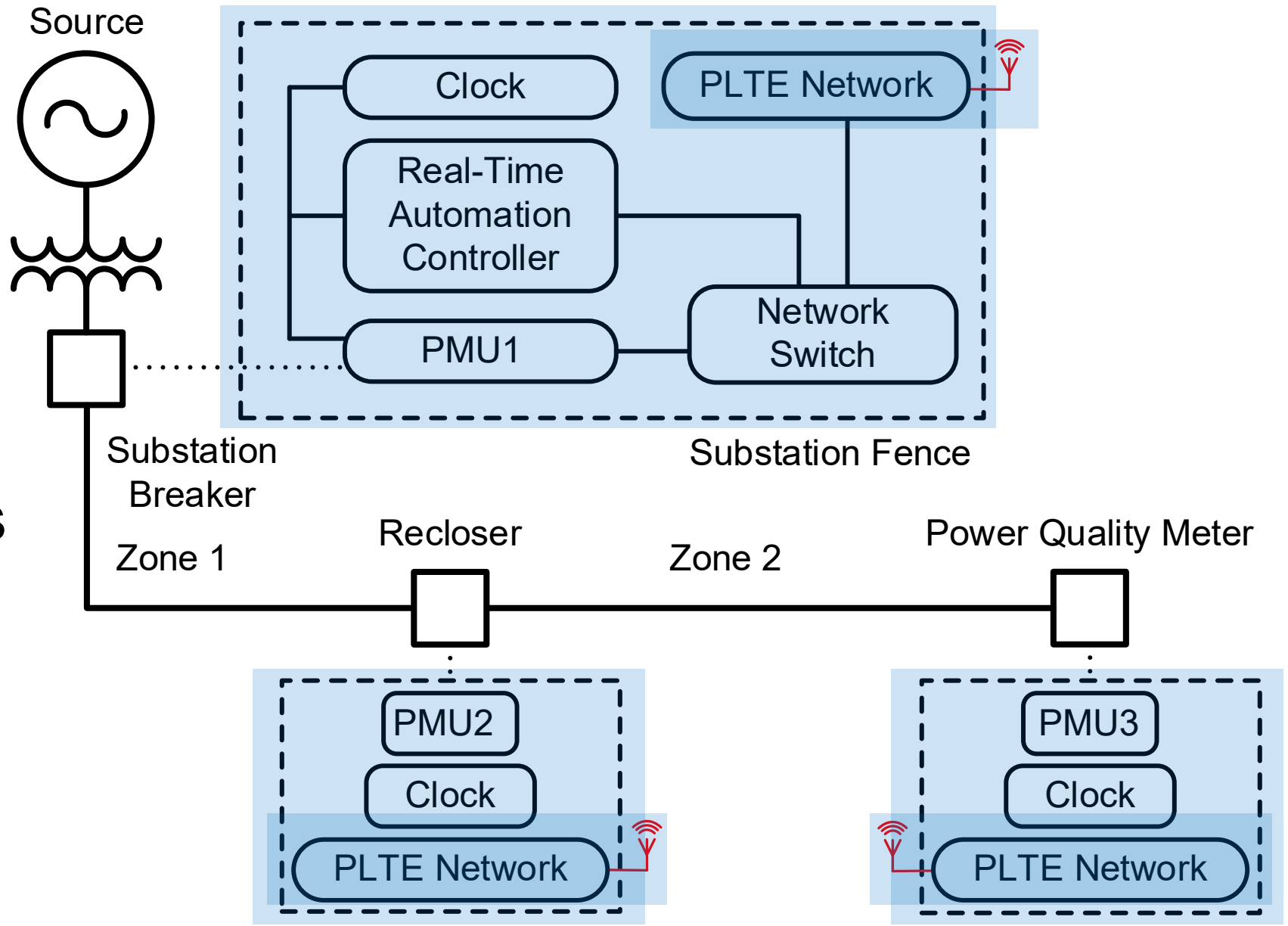
- HIF – may take from seconds to minutes to detect
- Arc flash

Source: Robert Lawton

FCP review

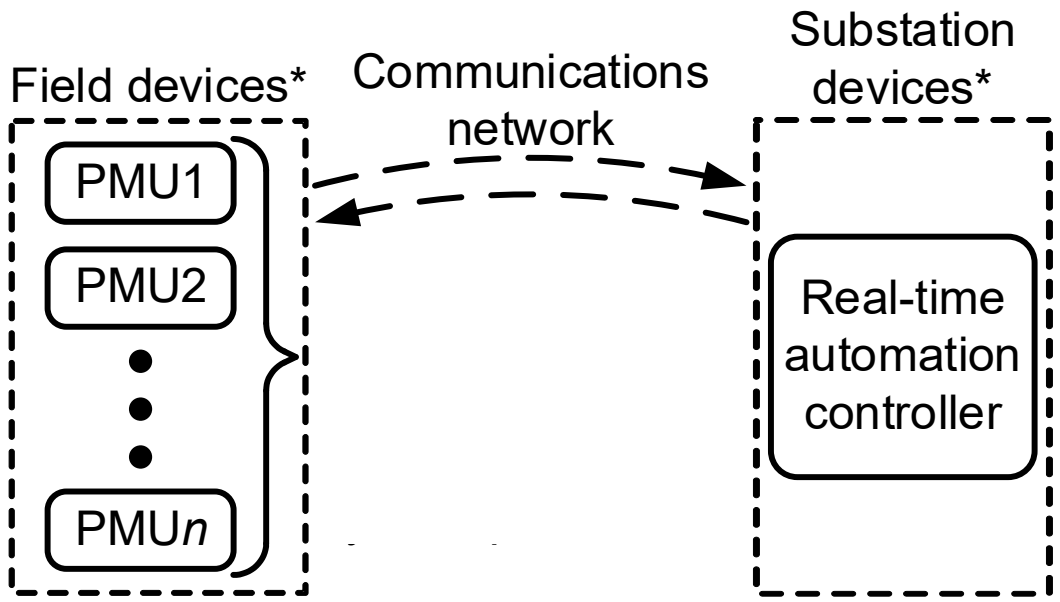
System architecture

- Substation devices
- Field devices
- Communications network



Data flow

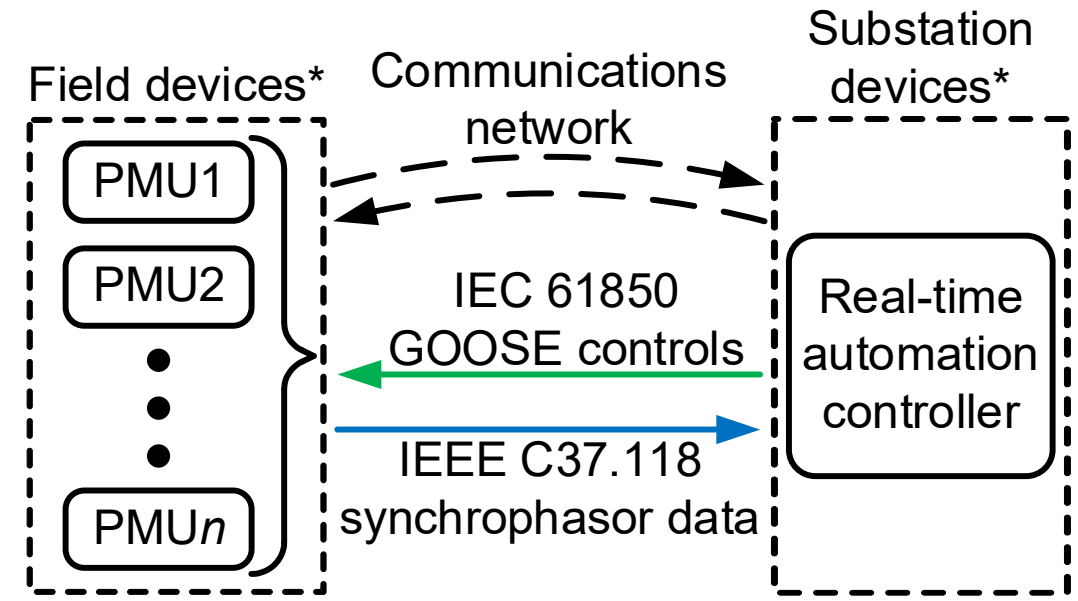
- IEDs
  - IEEE C37.118
  - IEC 61850 GOOSE protocol
- RTAC



*Devices have satellite-synchronized clock

Data flow

- Communications network
  - High speed and low latency
  - Ethernet radio, fiber optics, and PLTE
- IEDs – time-synchronized with high-accuracy clock

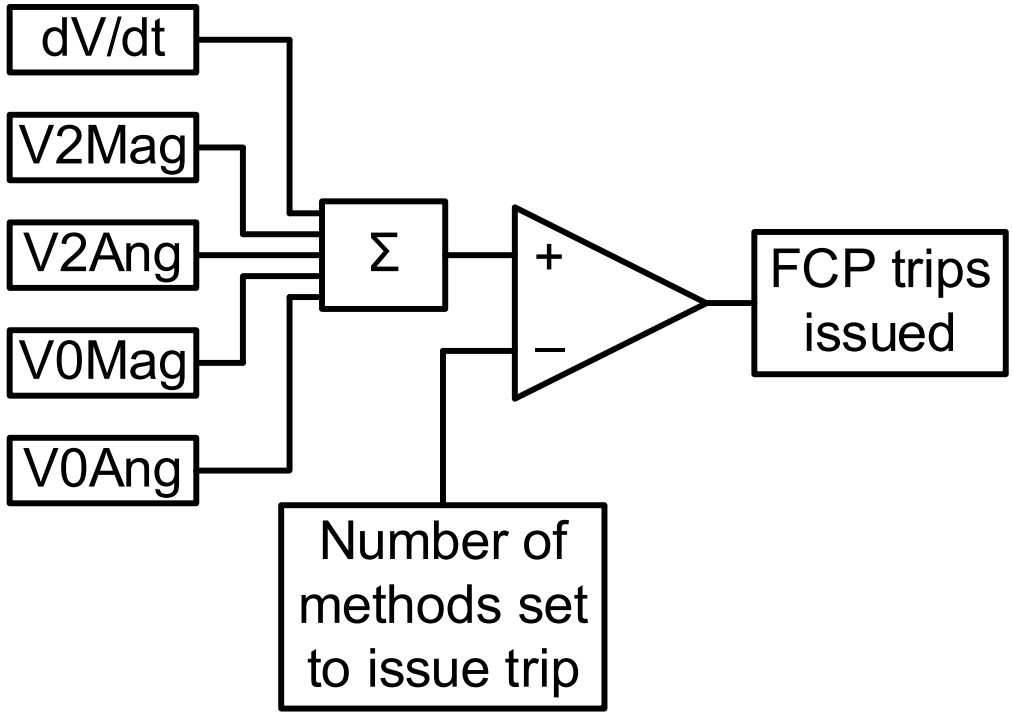


*Devices have satellite-synchronized clock

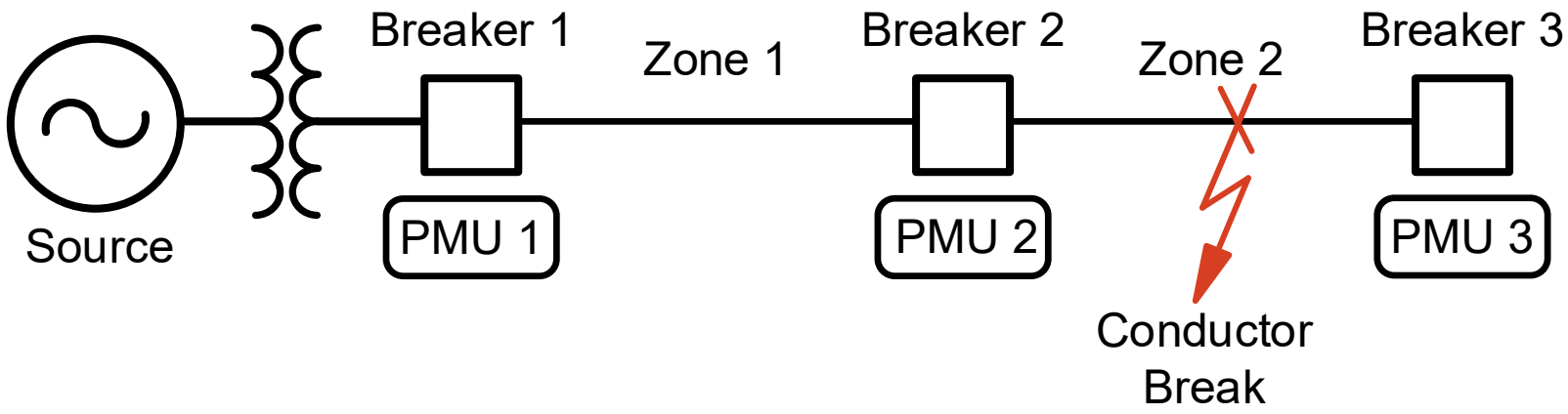
Detection methods

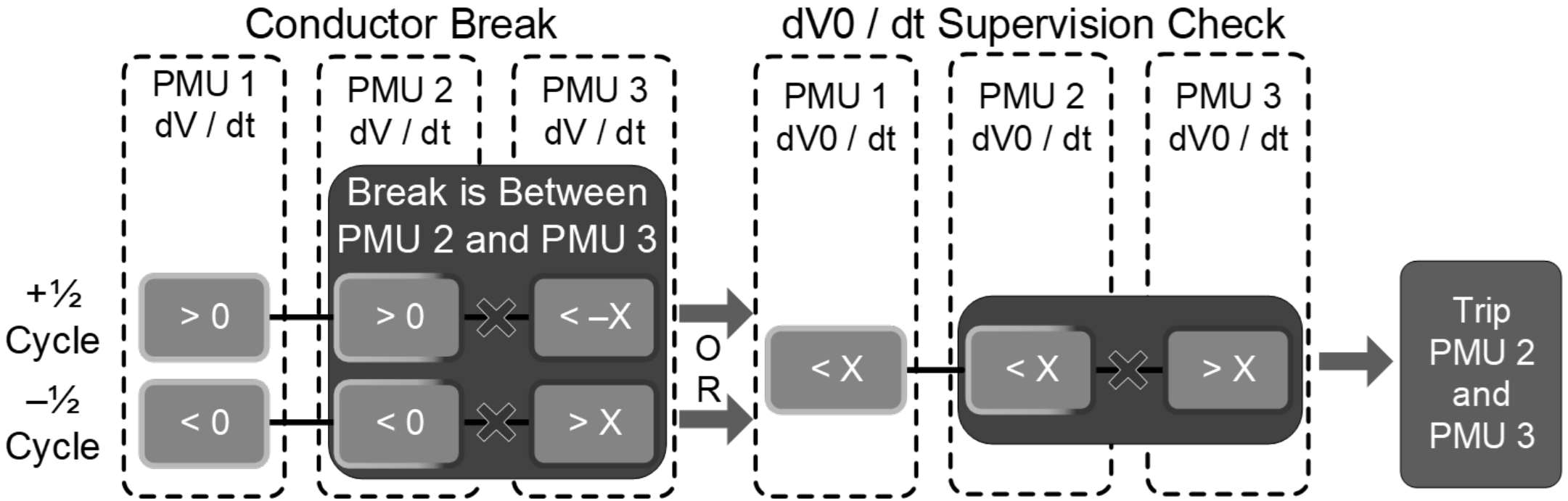
- Rate-of-change of phase voltage (dV/dt)
- Negative-sequence voltage magnitude (V2Mag)
- Negative-sequence voltage angle (V2Ang)
- Zero-sequence voltage magnitude (V0Mag)
- Zero-sequence voltage angle (V0Ang)

User-settable voting scheme to issue FCP trips

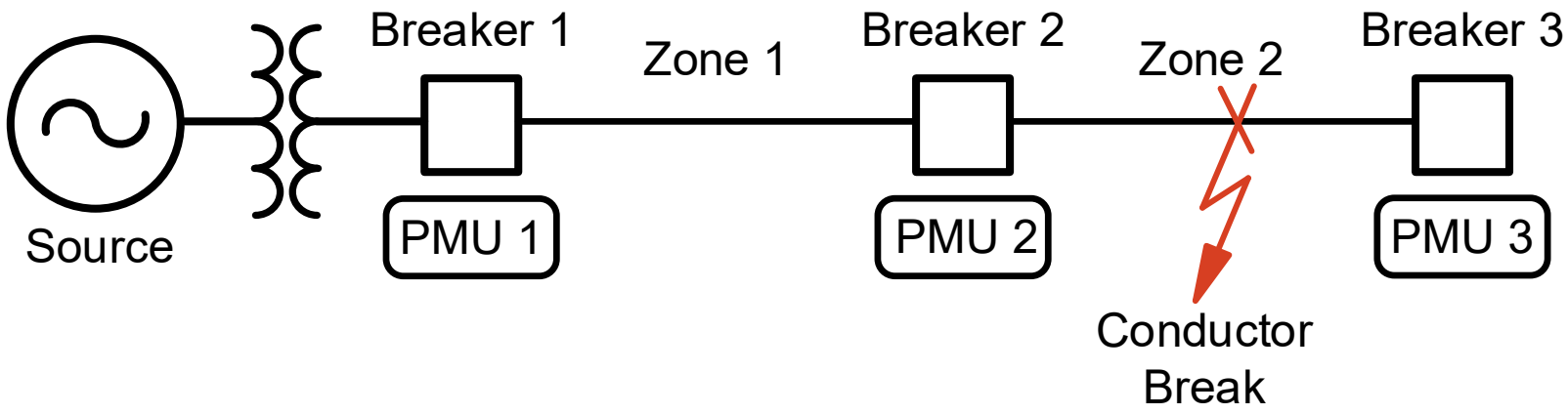


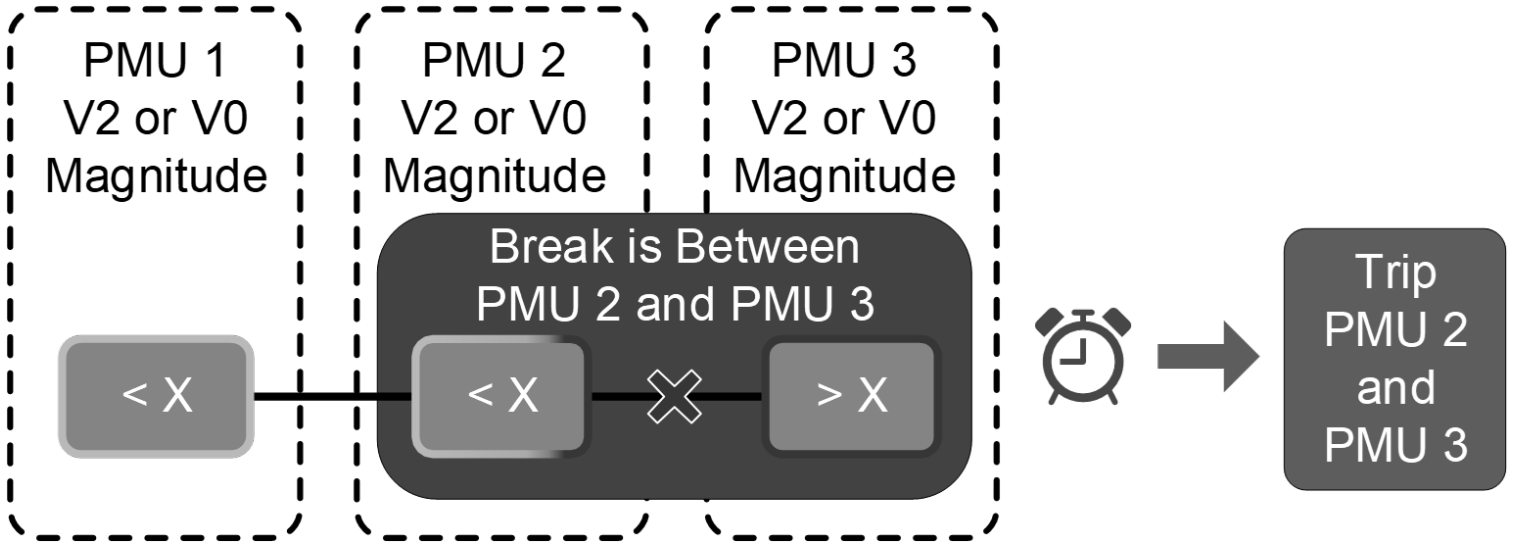
Detection method – dV/dt



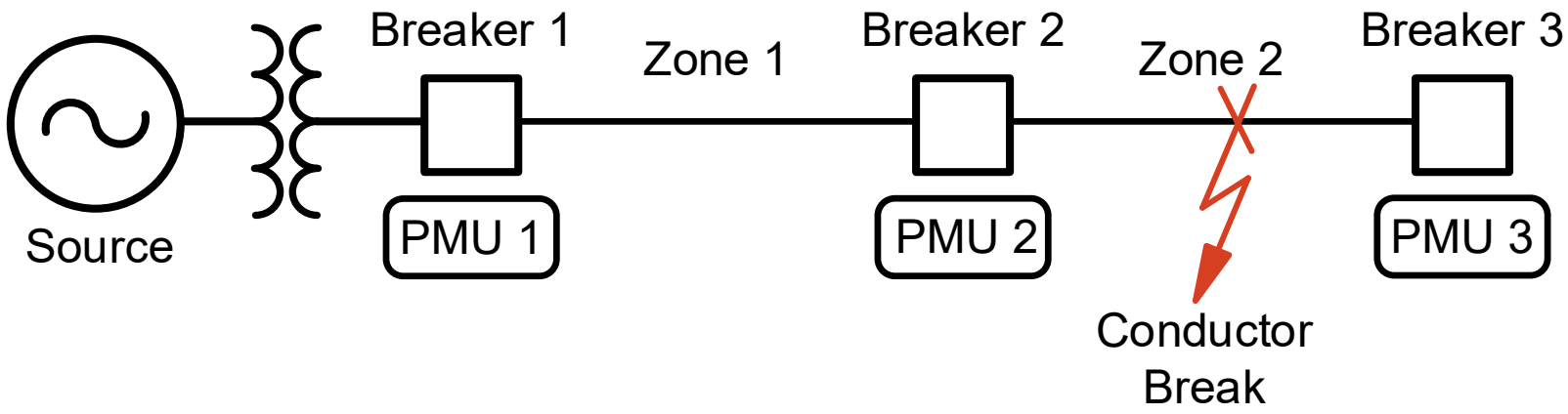


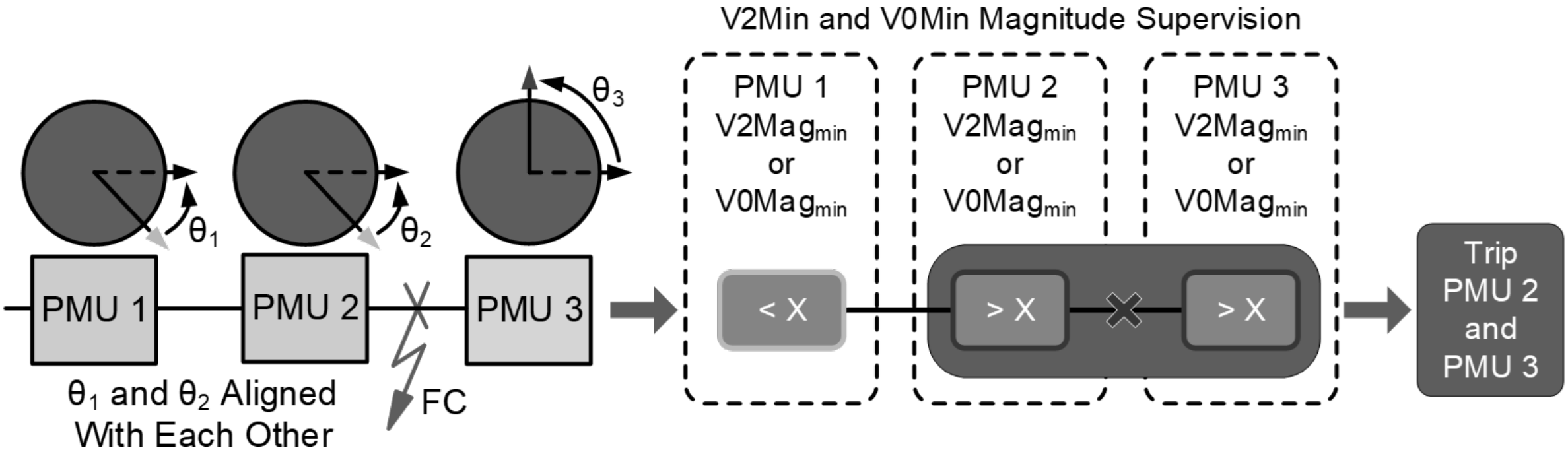
Detection method – V2Mag and V0Mag





Detection method – V2Ang and V0Ang





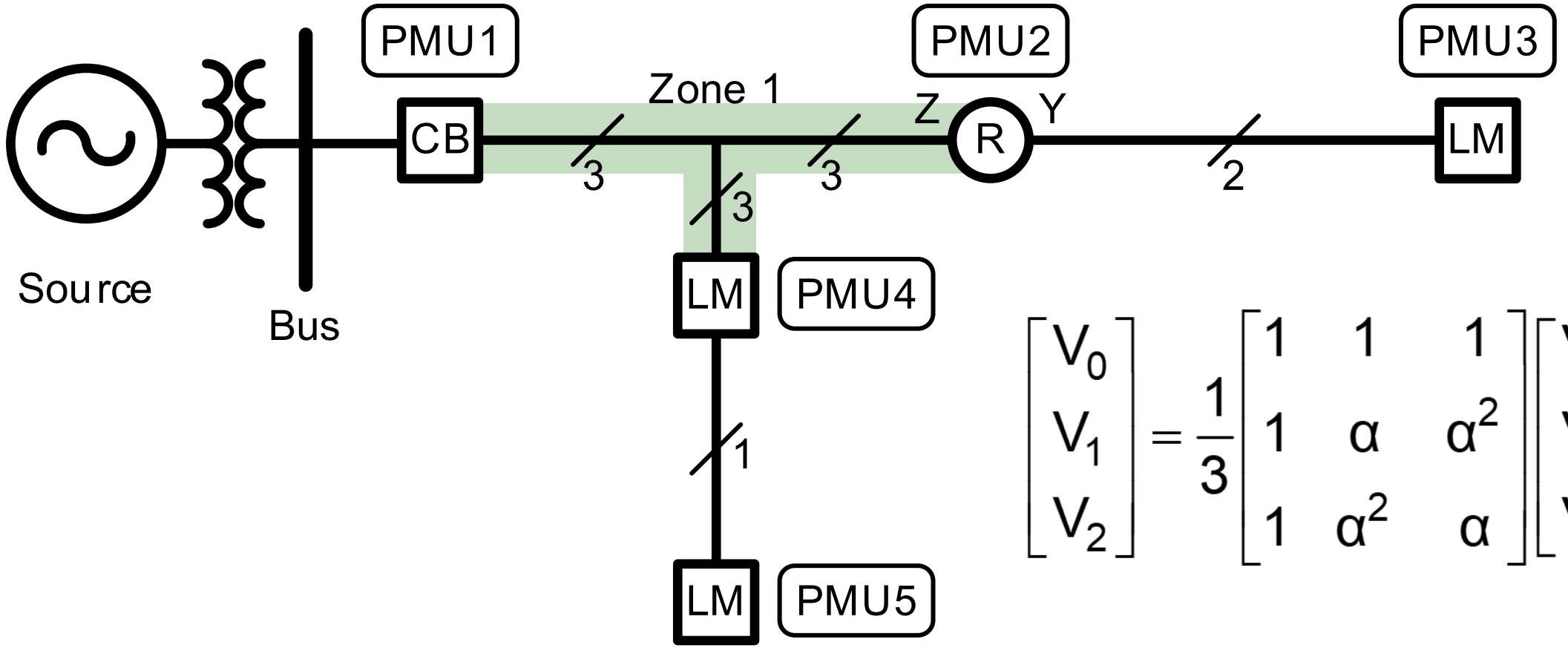
SDG&E distribution network

SDG&E overhead distribution network

- Approximately 6,500 miles of overhead distribution line infrastructure
- Grounded three- and four-wire systems
- Nominally 12 kV and 4 kV
- High penetration of distribution PV, which requires new solutions for monitoring, protection, and control
- FCP circuits in test mode, primarily three-phase with one FCP circuit in test mode containing double-phase laterals

Limitation of existing FCP scheme

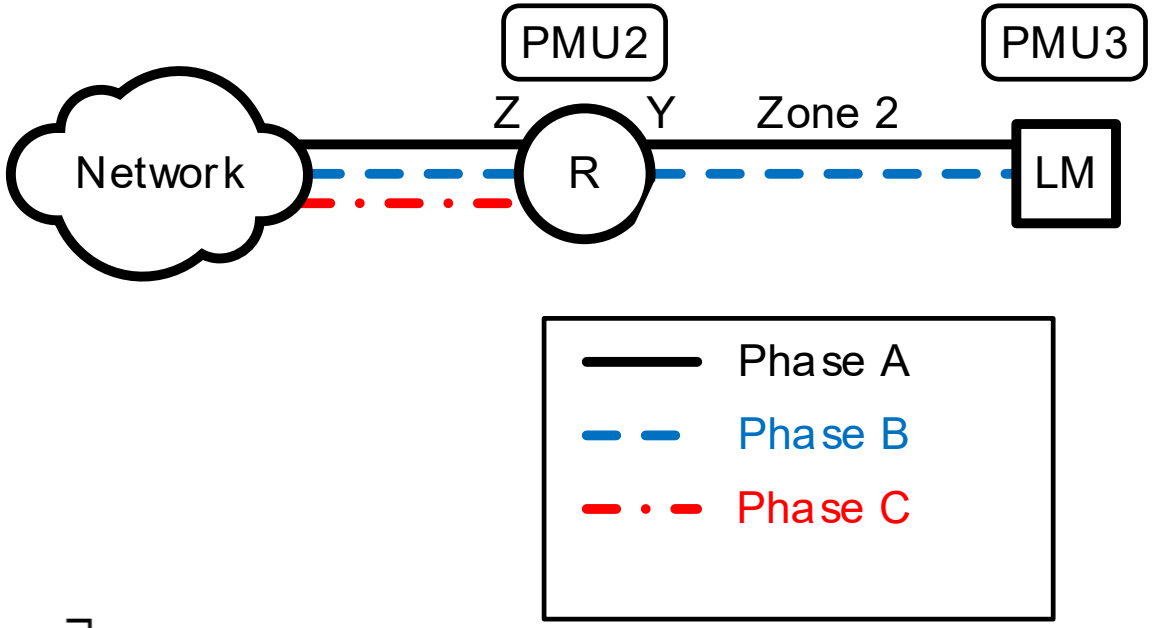
FCP scheme coverage



$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix} \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix}$$

FCP scheme in Zone 2

- Zone-referenced PMU – PMU2
- PMU3 – missing C phases
- Reconstruction of C phases from PMU2

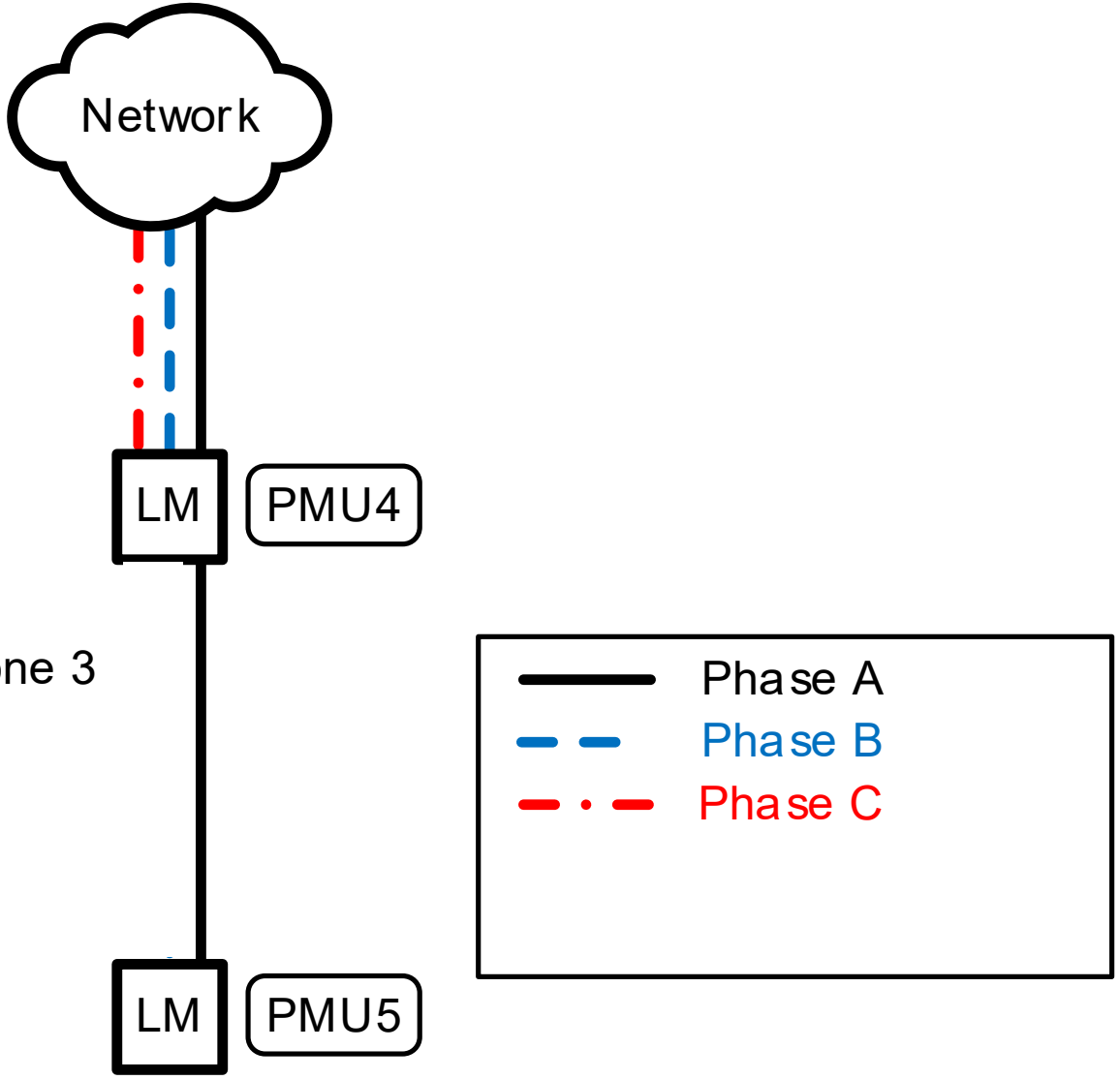


$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix}_{PMU3} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix}\begin{bmatrix} V_{A_{PMU3}} \\ V_{B_{PMU3}} \\ 0 \end{bmatrix}$$

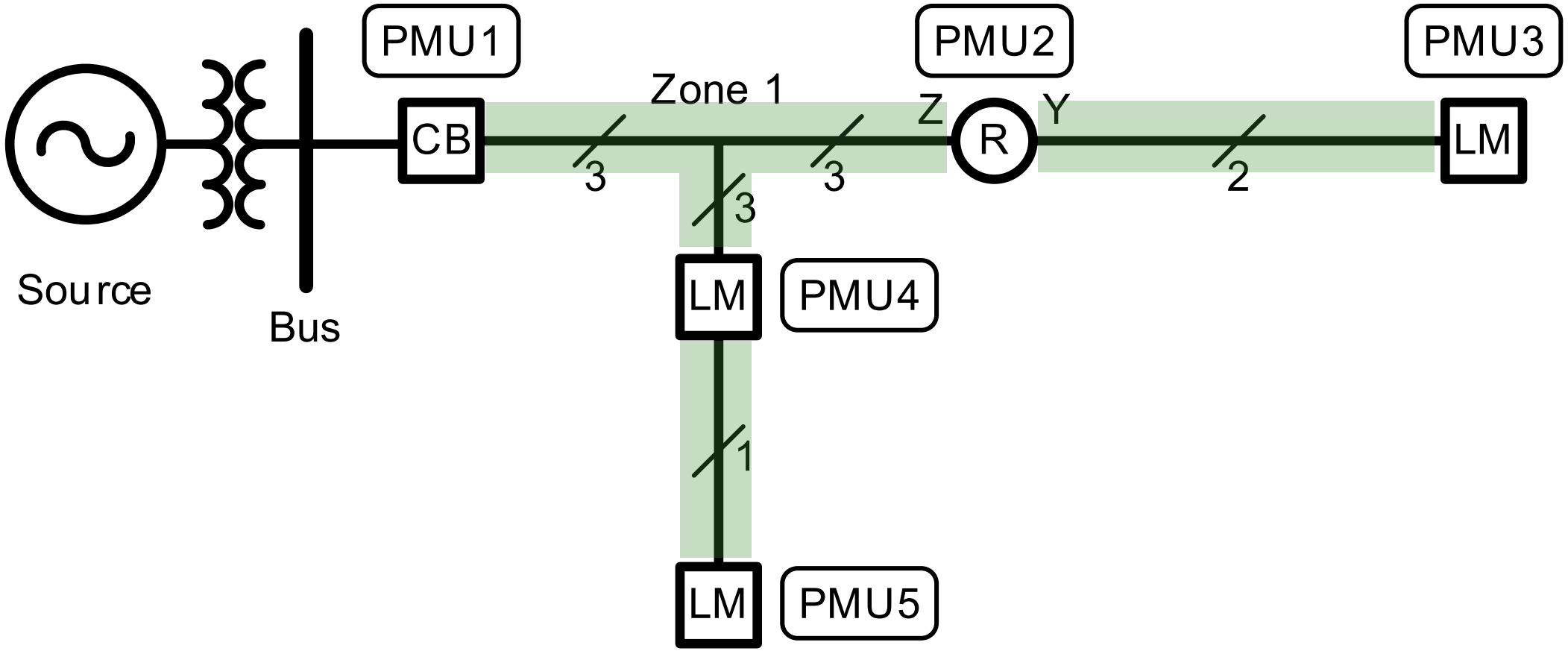
FCP scheme in Zone 3

- Zone-referenced PMU – PMU4
- PMU5 – missing B and C phases
- Reconstruction of B and C phases from PMU4

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix}_{PMU5} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix}\begin{bmatrix} V_{A_{PMU5}} \\ 0 \\ 0 \end{bmatrix}$$



FCP scheme coverage

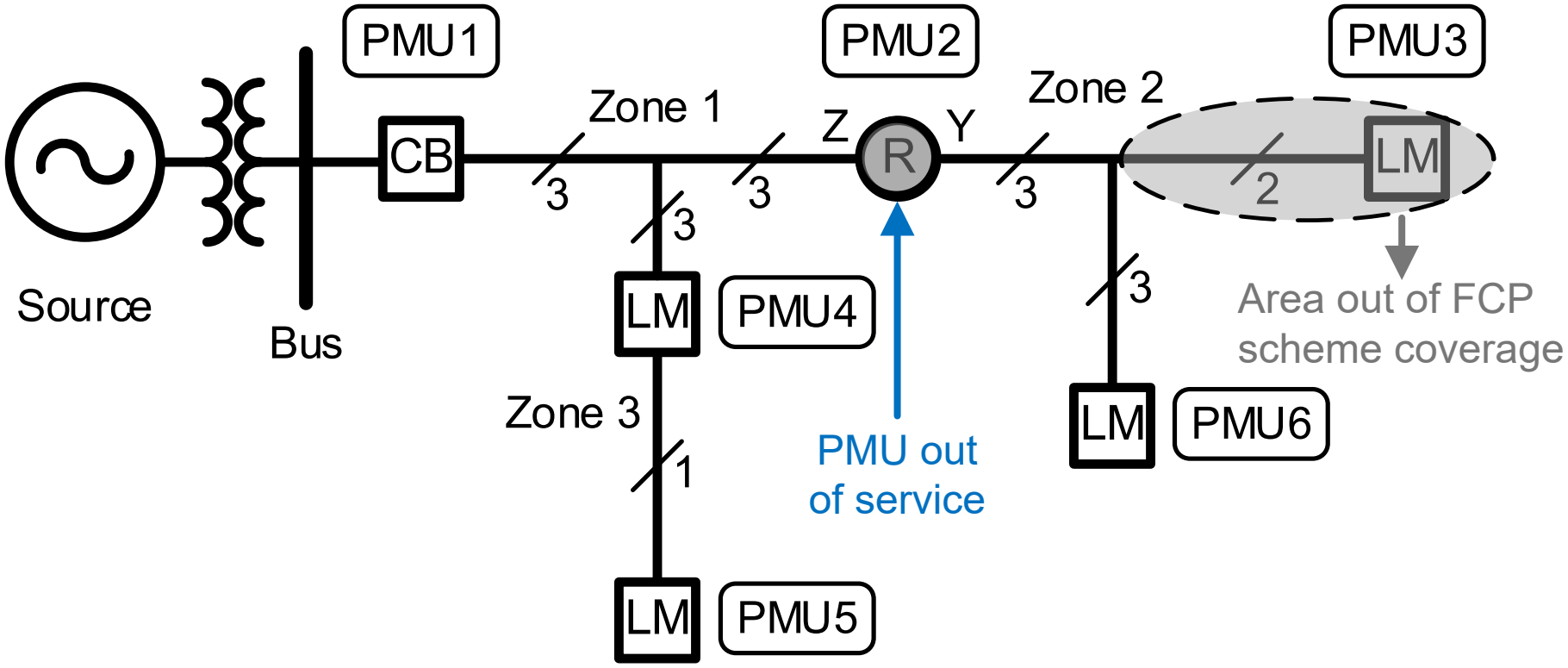


Hardware-in-the-loop testing

- Multiple falling conductor test locations
- Maintenance test
- Contingency test
  - Blown fuse
  - System faults
  - External disturbance
  - Device failure
- Automated batch test to calculate average trip time

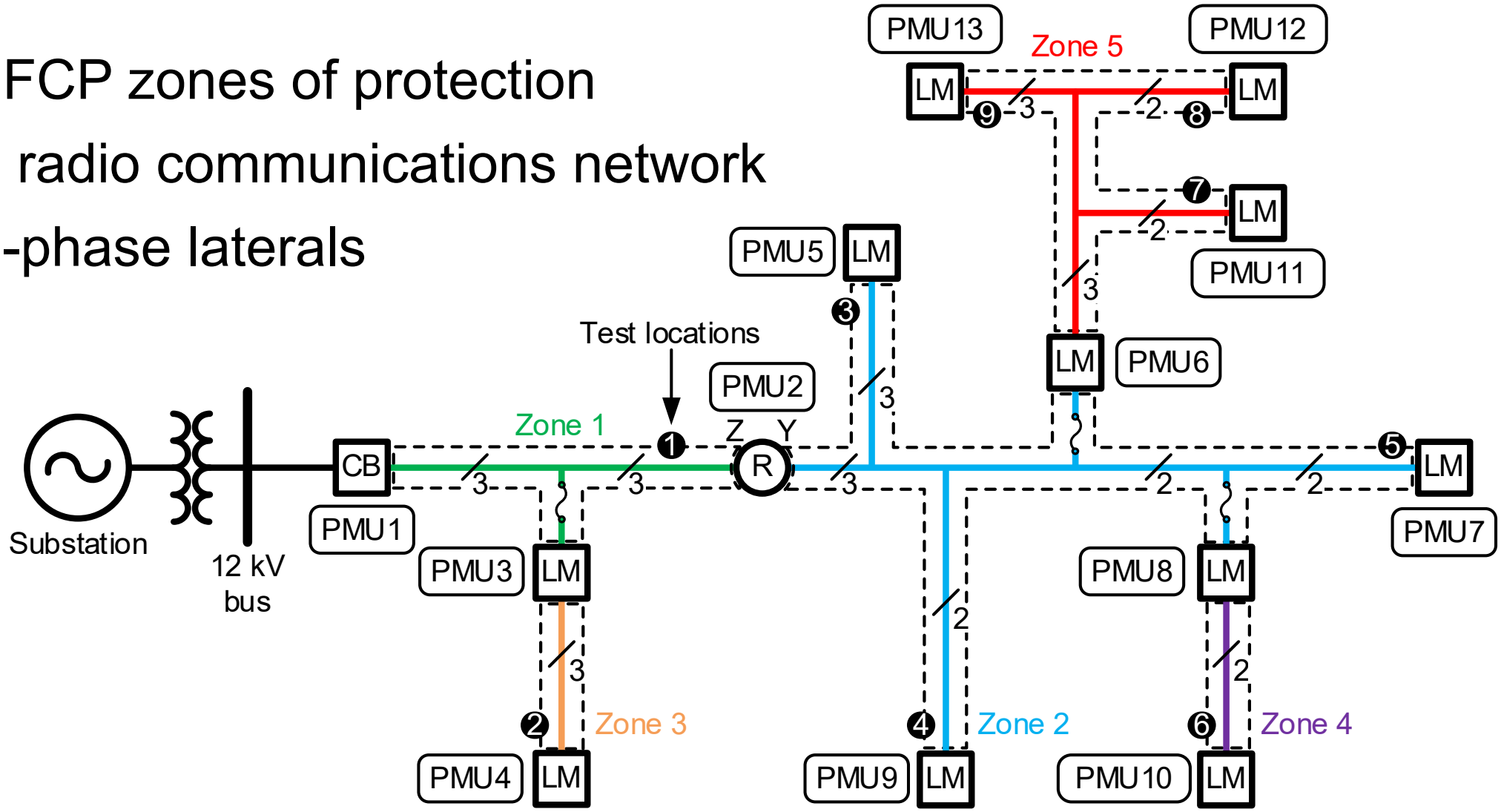
Limitations of modified FCP scheme

- System study – maximum voltage drop on the network
- Limits coverage if zone-referenced PMU device is out of service



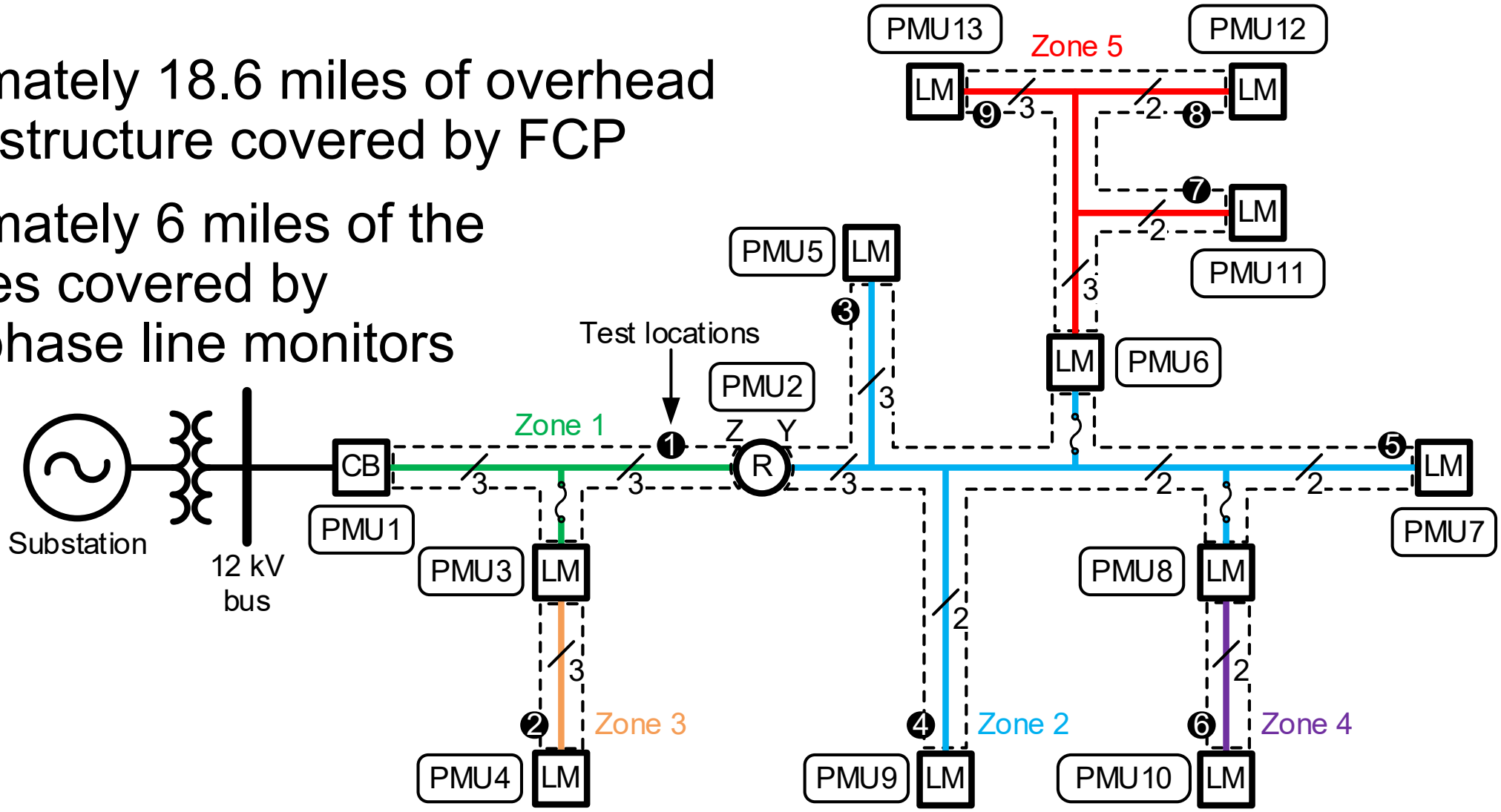
Field implementation – circuit

- 12 kV, 5 FCP zones of protection
- Wireless radio communications network
- 5 double-phase laterals



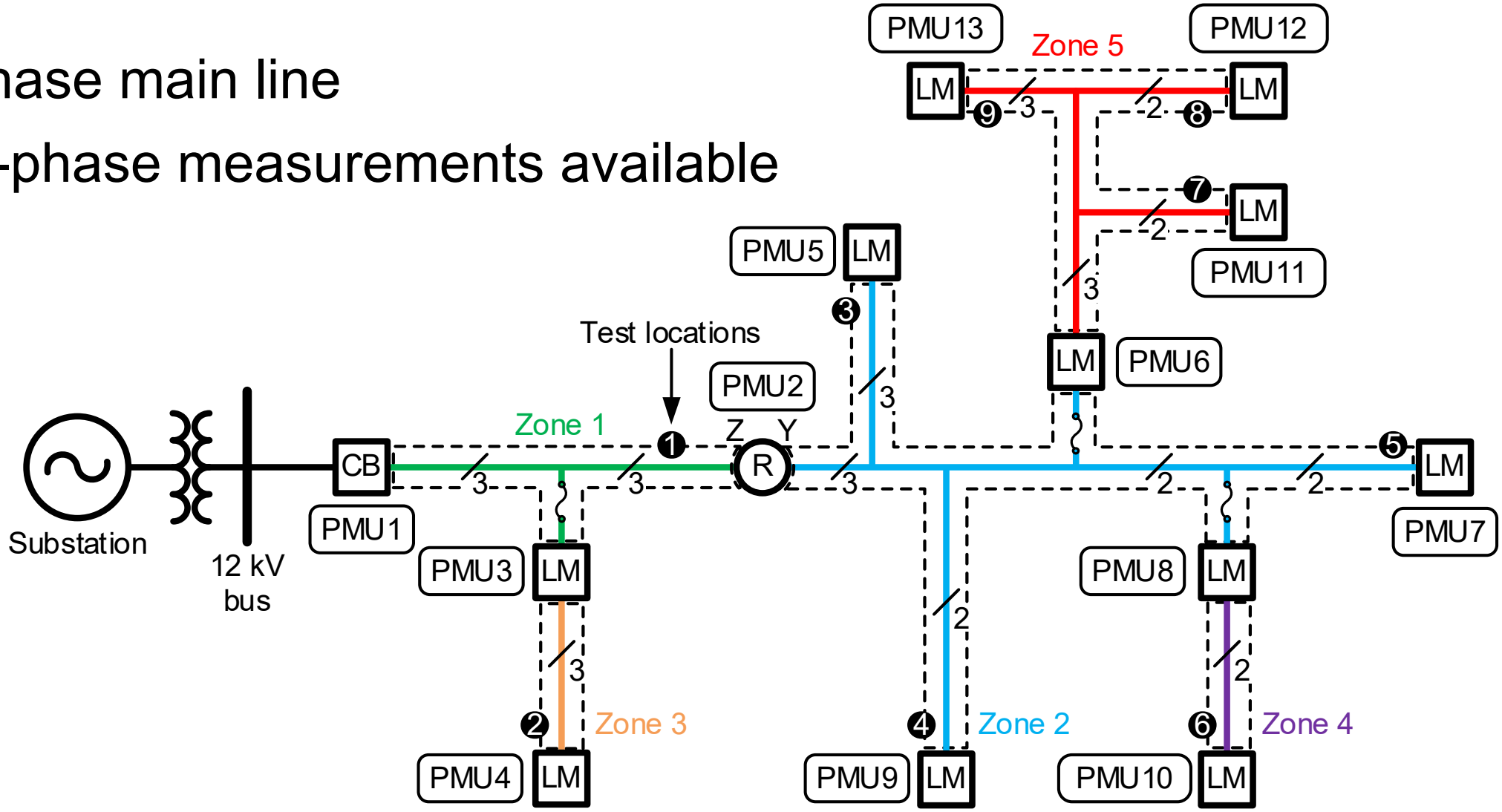
Field implementation – circuit

- Approximately 18.6 miles of overhead line infrastructure covered by FCP
- Approximately 6 miles of the 18.6 miles covered by double-phase line monitors



Location 1

- Three-phase main line
- All three-phase measurements available



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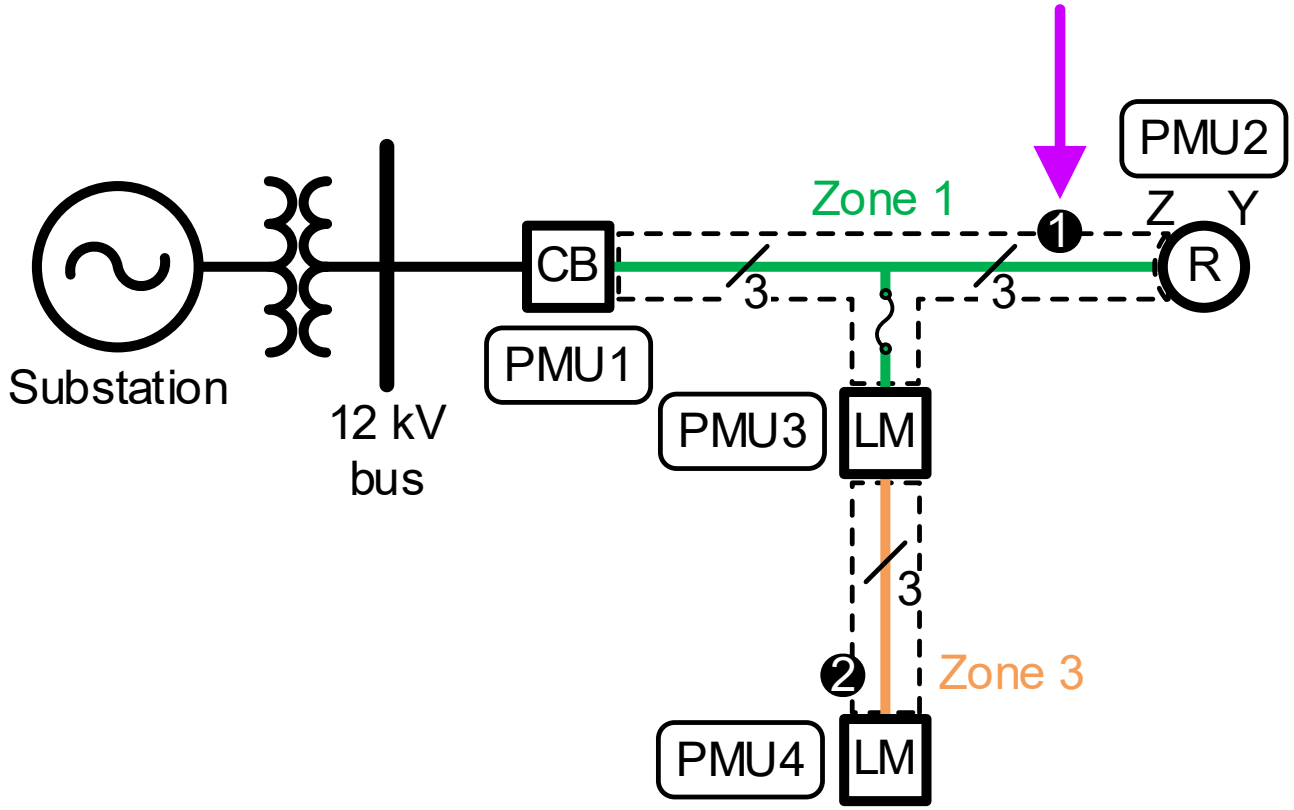
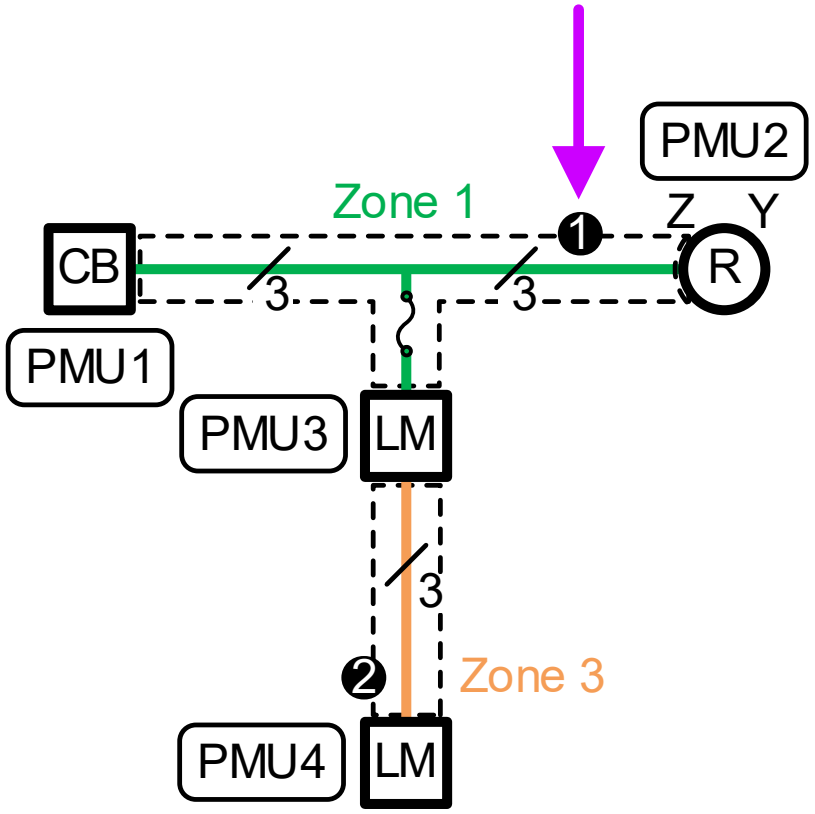
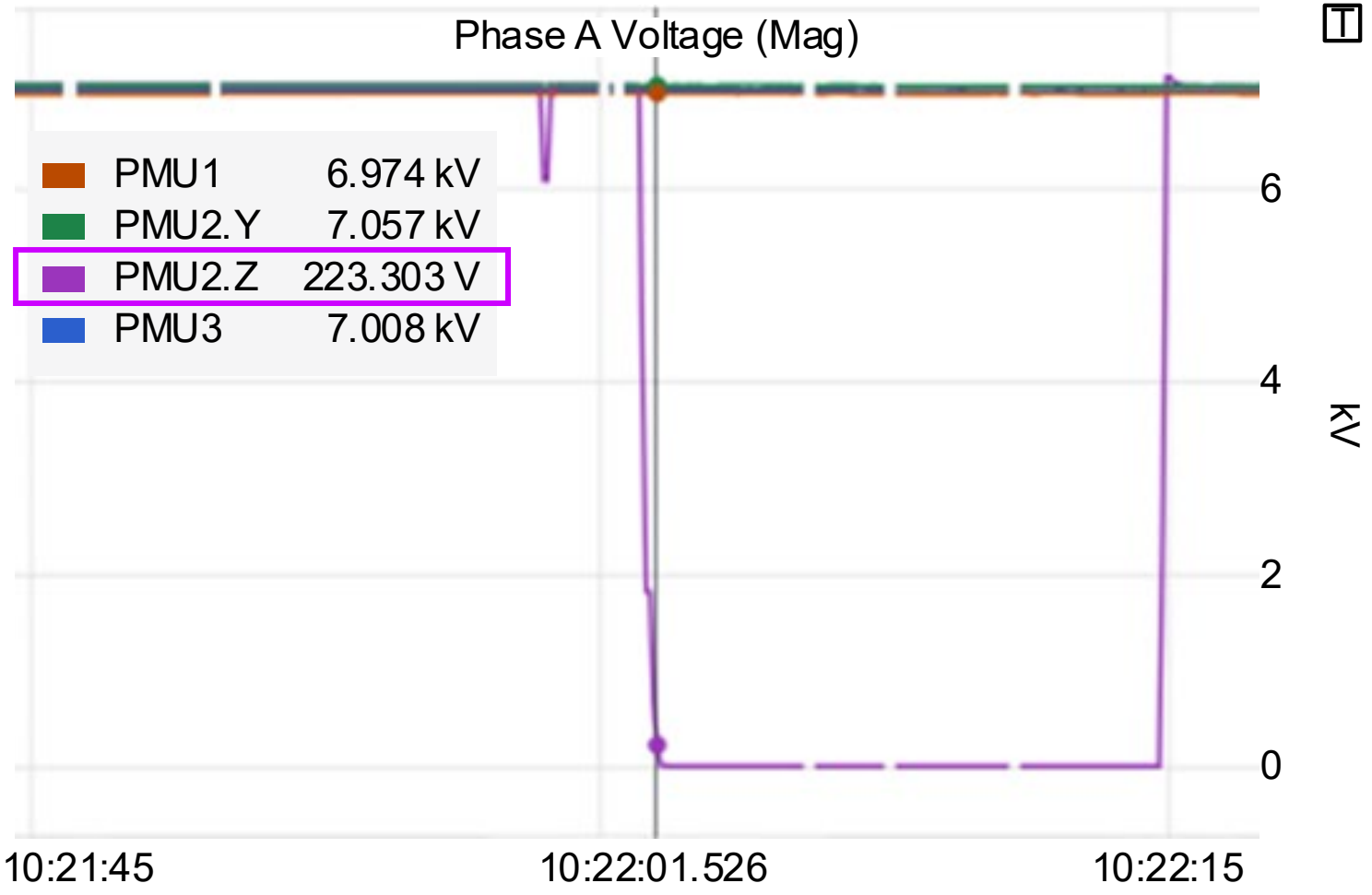
- All three-phase measurements available

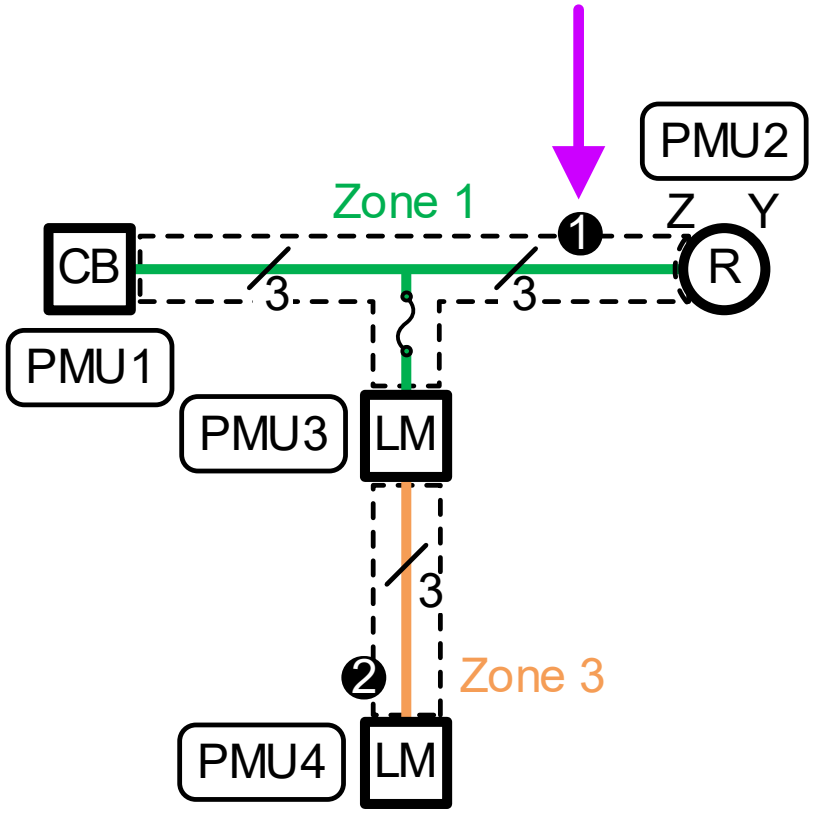


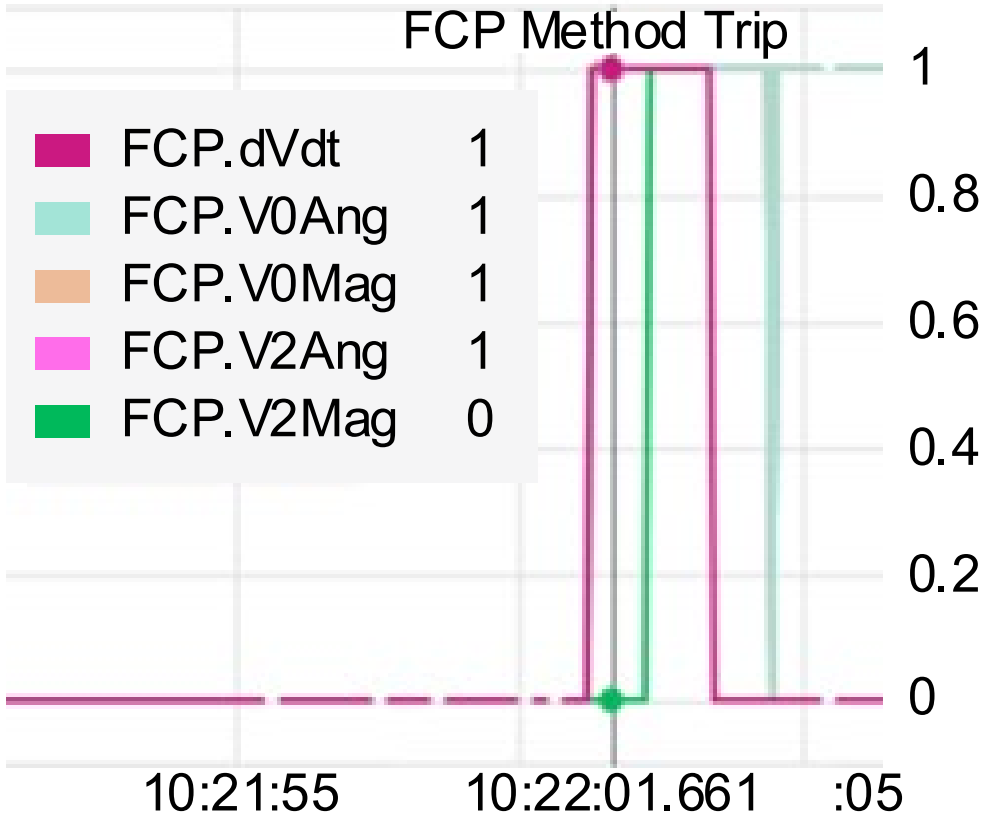
Location 1


PMU2
Zone 1
Z
Y
CB
R
3
3
PMU1
PMU3
LM
3
Zone 3
PMU4
LM

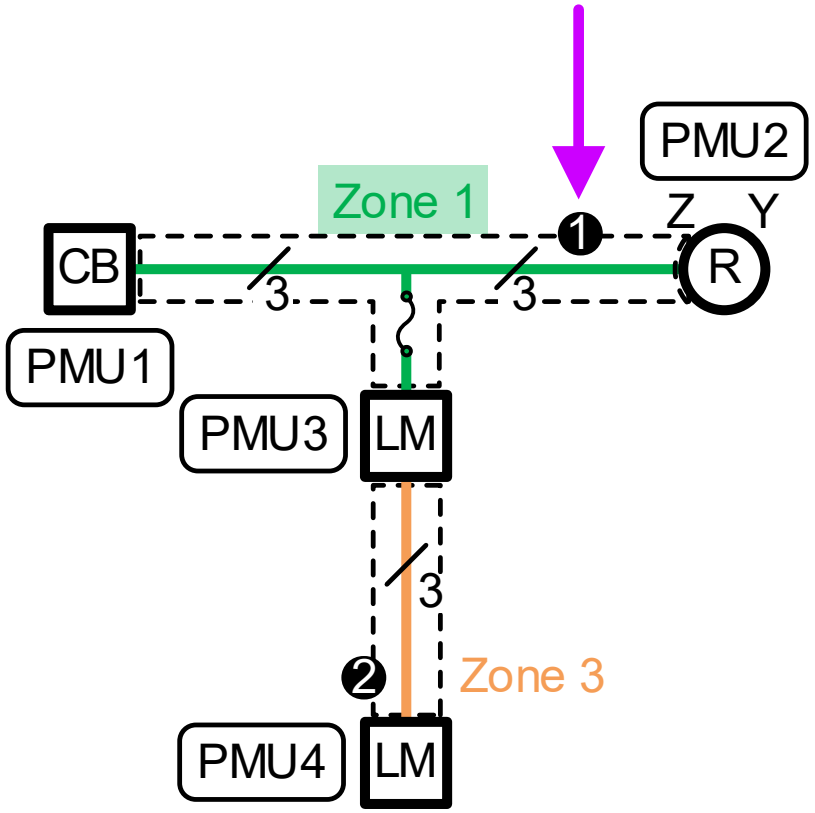

Phase A Voltage (Mag)
PMU1 6.974 kV
PMU2.Y 7.057 kV
PMU2.Z 223.303 V
PMU3 7.008 kV
6
4
2
0
kV
10:21:45
10:22:01.526
10:22:15

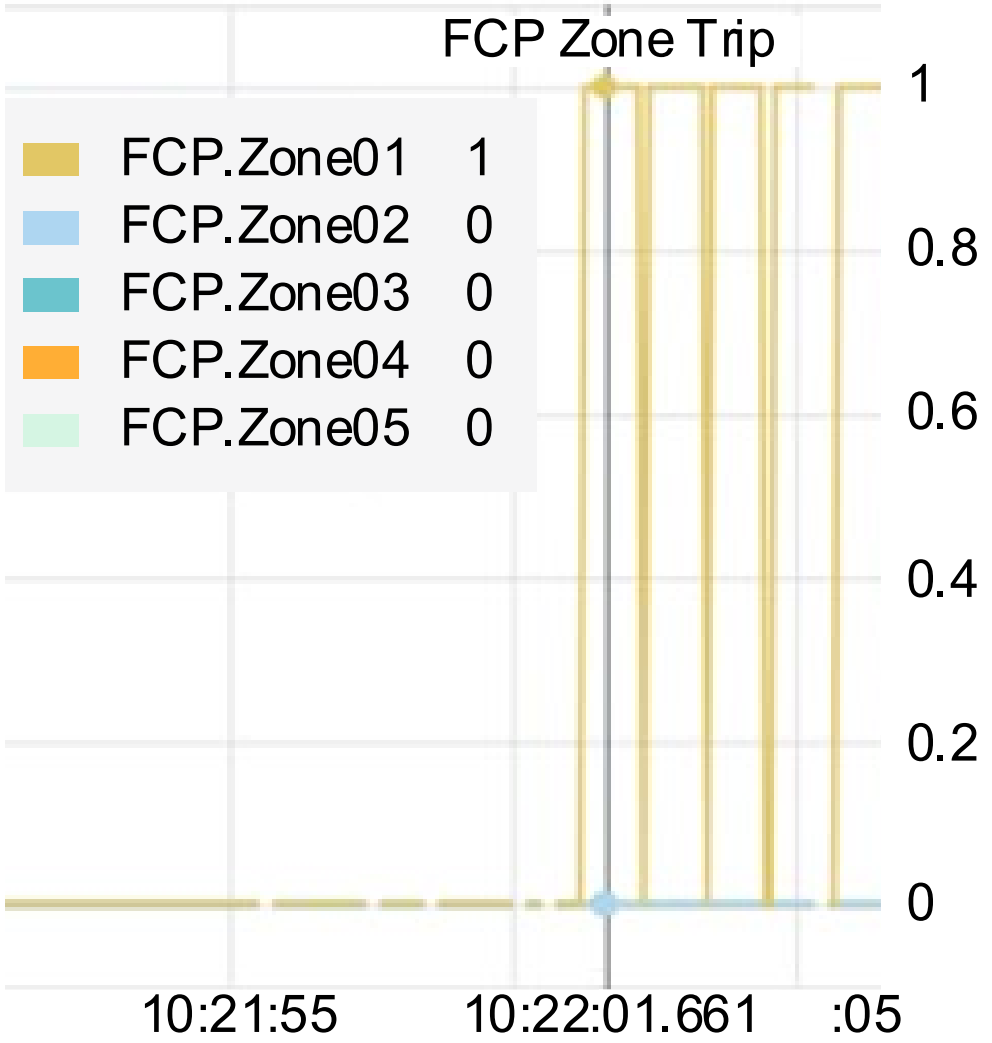
Location 1


PMU2
Zone 1
Z
Y
CB
R
3
3
PMU1
PMU3
LM
3
Zone 3
PMU4
LM

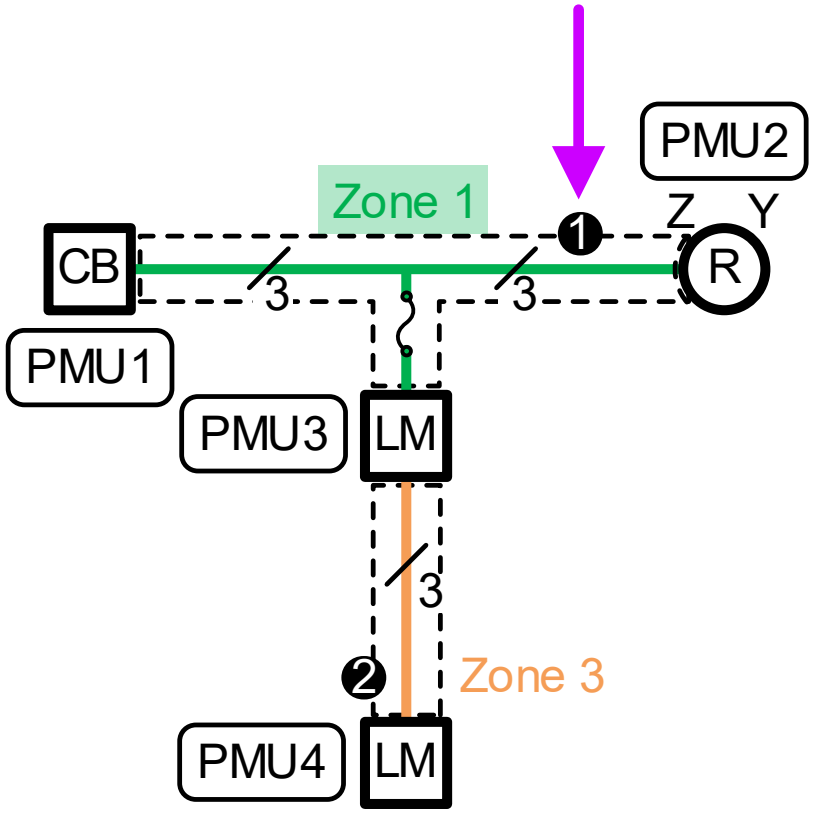

FCP Method Trip
FCP.dVdt 1
FCP.V0Ang 1
FCP.V0Mag 1
FCP.V2Ang 1
FCP.V2Mag 0
1
0.8
0.6
0.4
0.2
0
10:21:55
10:22:01.661
:05

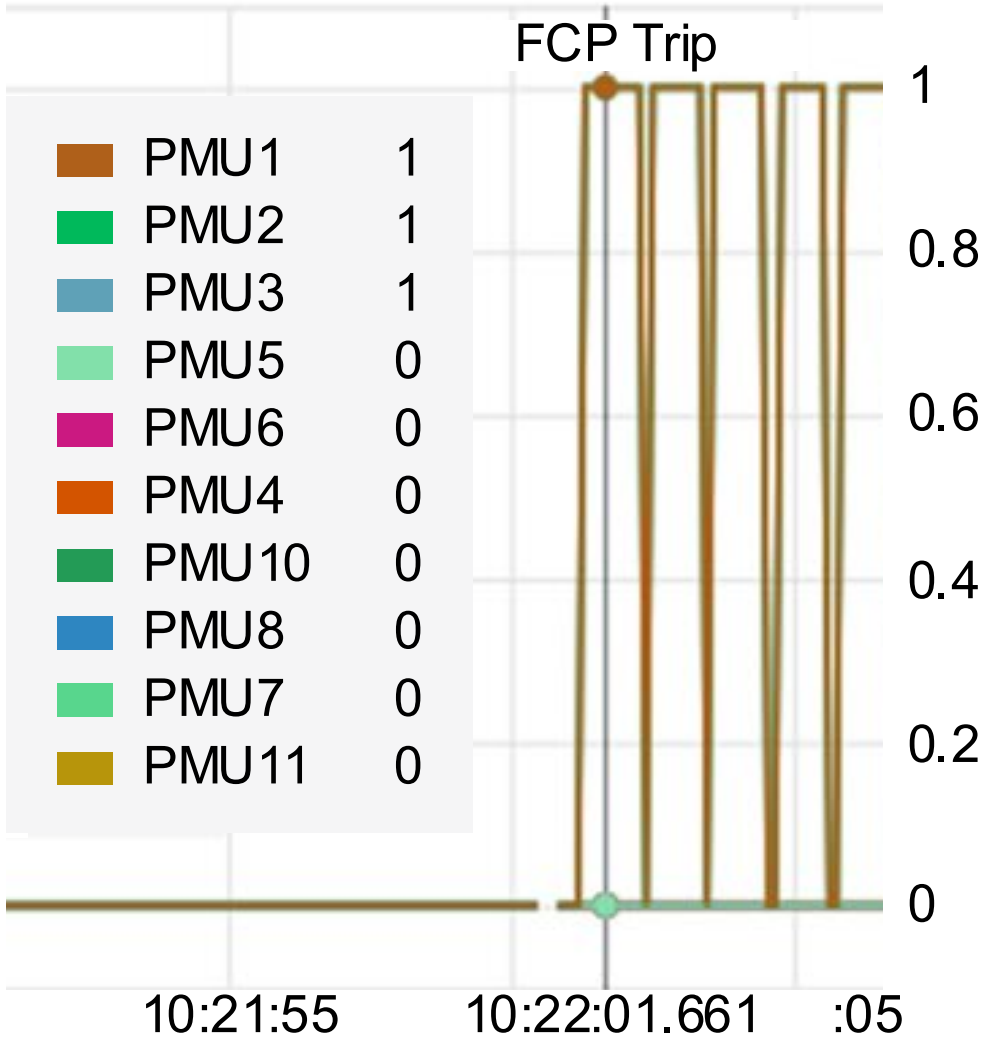
Location 1


PMU2
Zone 1
Z
Y
CB
R
3
3
PMU1
PMU3
LM
3
Zone 3
PMU4
LM


FCP Zone Trip
FCP.Zone01 1
FCP.Zone02 0
FCP.Zone03 0
FCP.Zone04 0
FCP.Zone05 0
1
0.8
0.6
0.4
0.2
0
10:21:55
10:22:01.661
:05

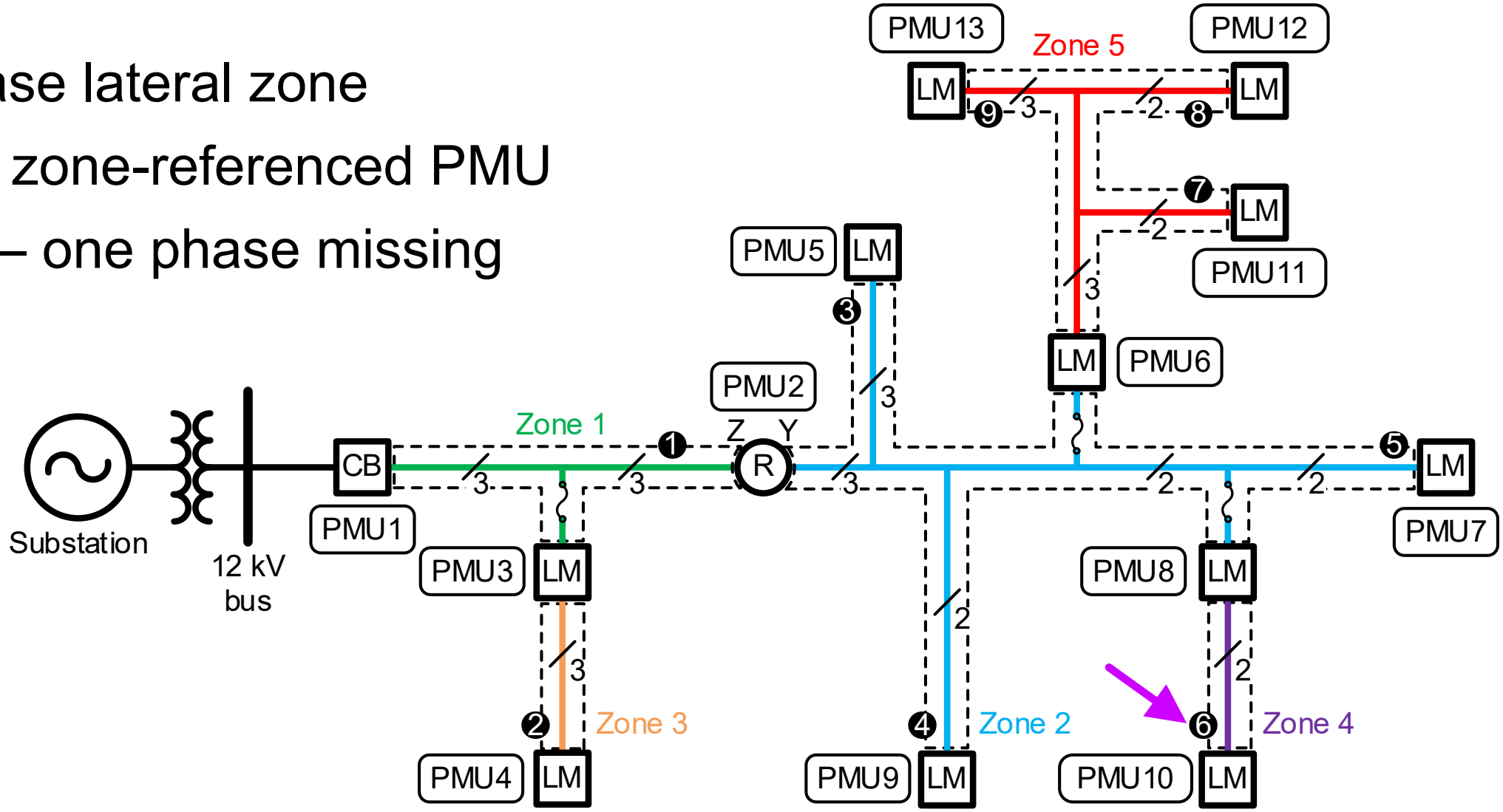
Location 1


PMU2
Zone 1
Z
Y
CB
R
3
3
PMU1
PMU3
LM
3
Zone 3
PMU4
LM


FCP Trip
PMU1 1
PMU2 1
PMU3 1
PMU5 0
PMU6 0
PMU4 0
PMU10 0
PMU8 0
PMU7 0
PMU11 0
1
0.8
0.6
0.4
0.2
0
10:21:55
10:22:01.661
:05

Location 6

- Two-phase lateral zone
- PMU8 – zone-referenced PMU
- PMU10 – one phase missing



Location 6

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- PMU8 – zone-referenced PMU
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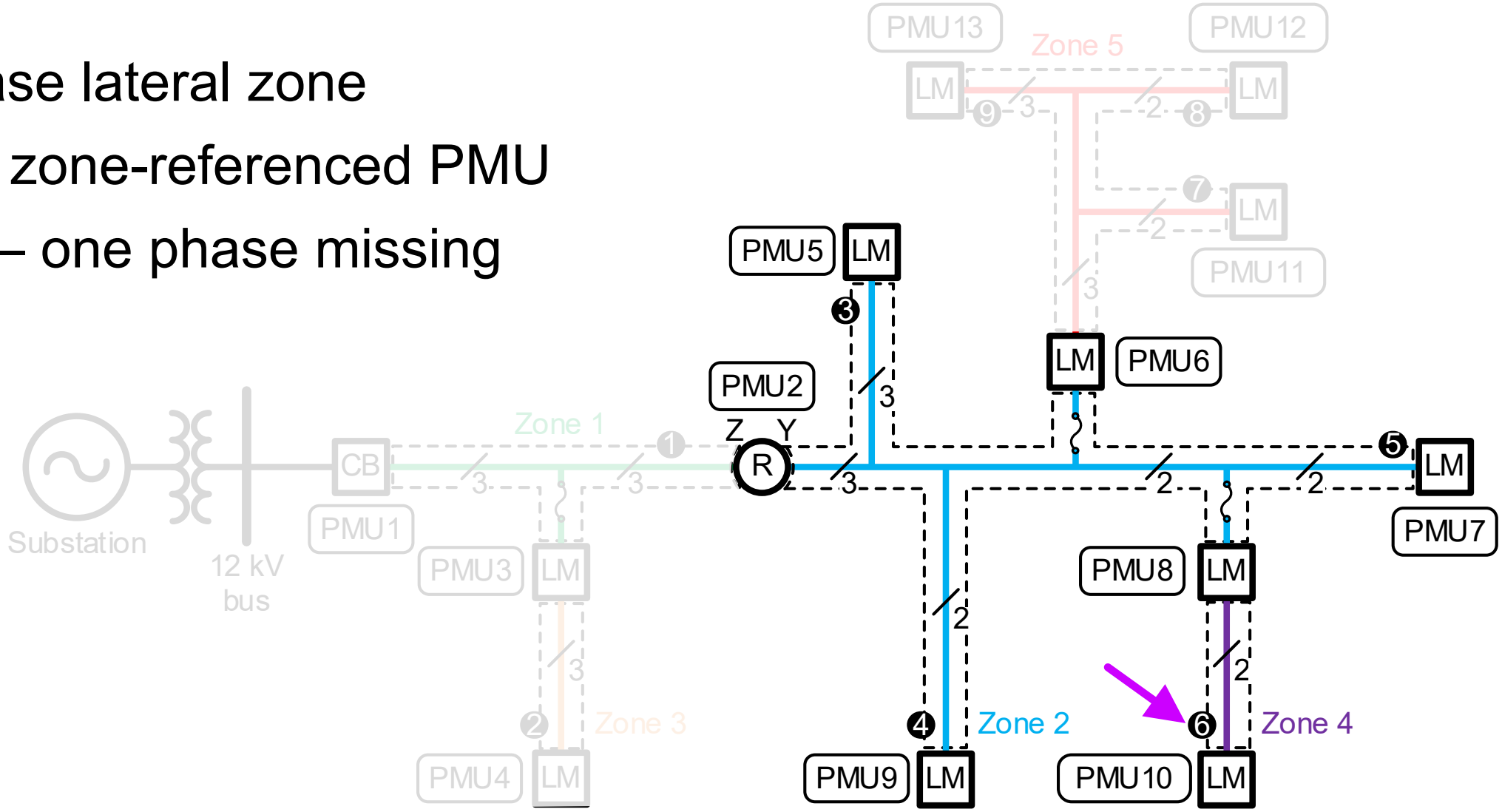

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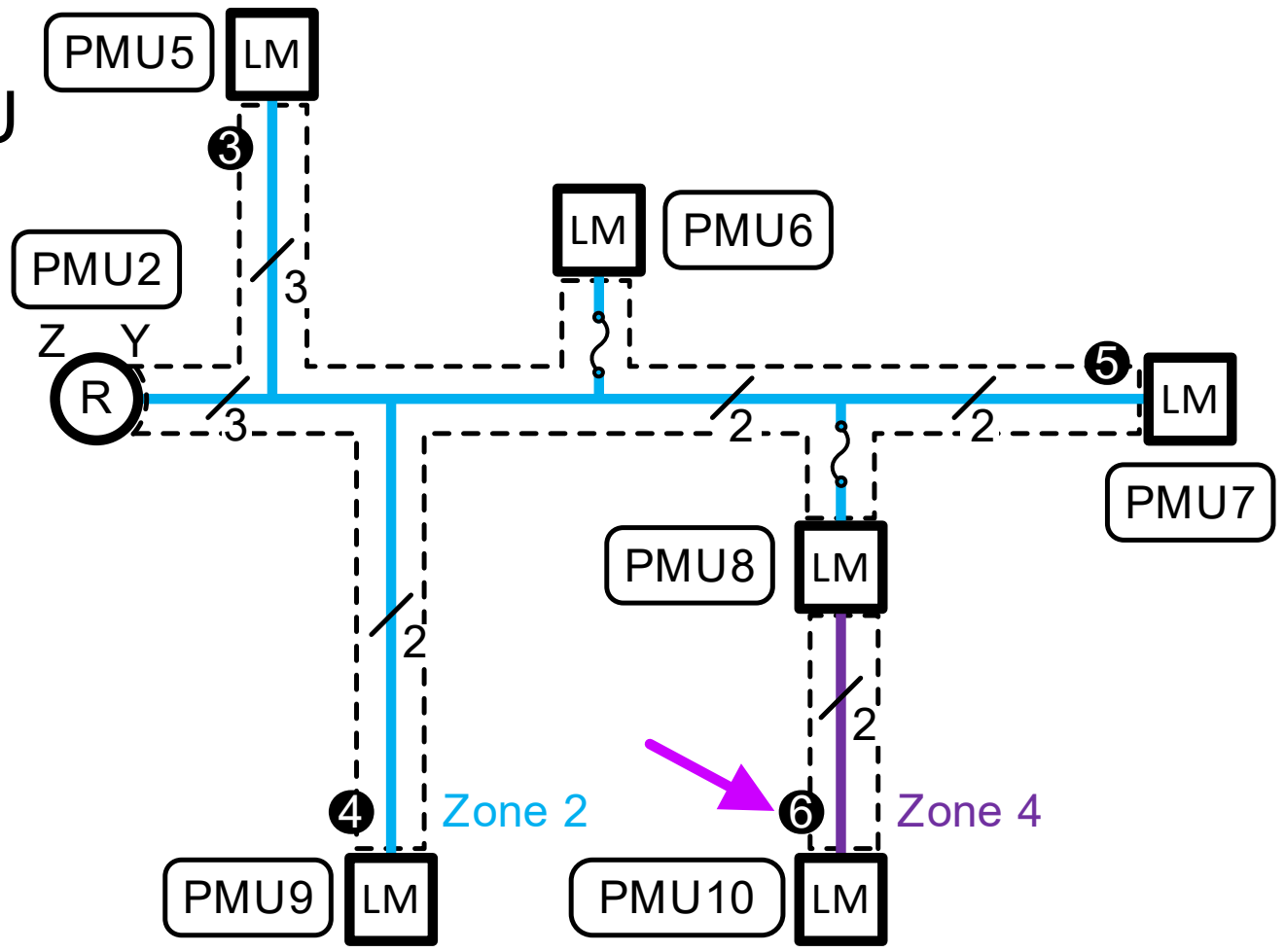
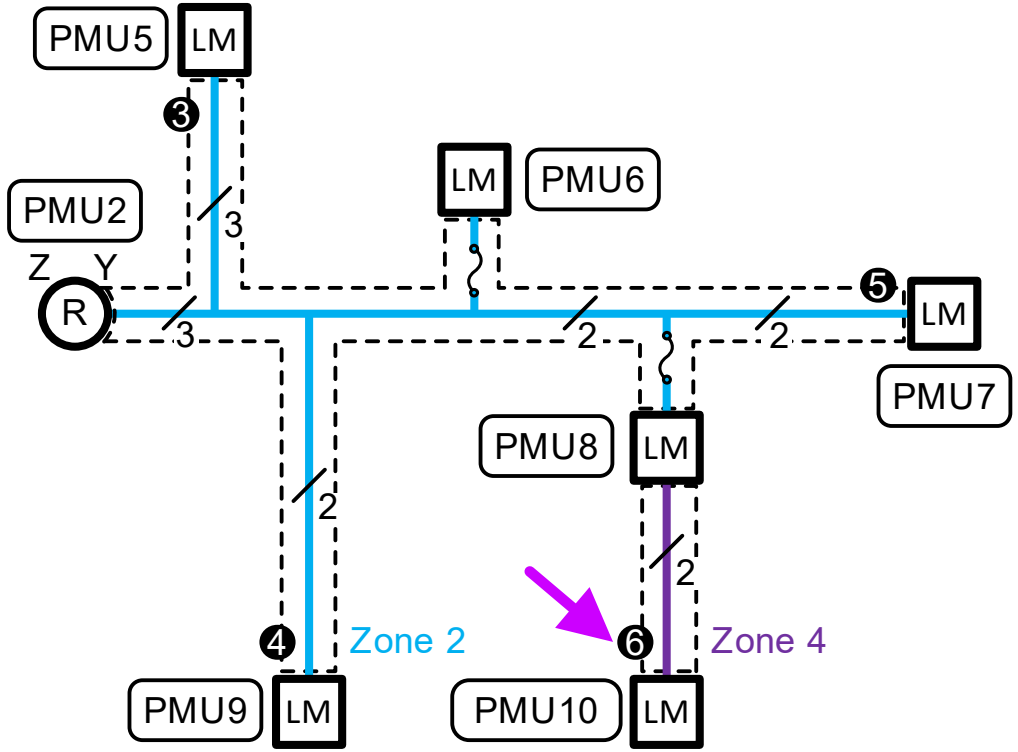
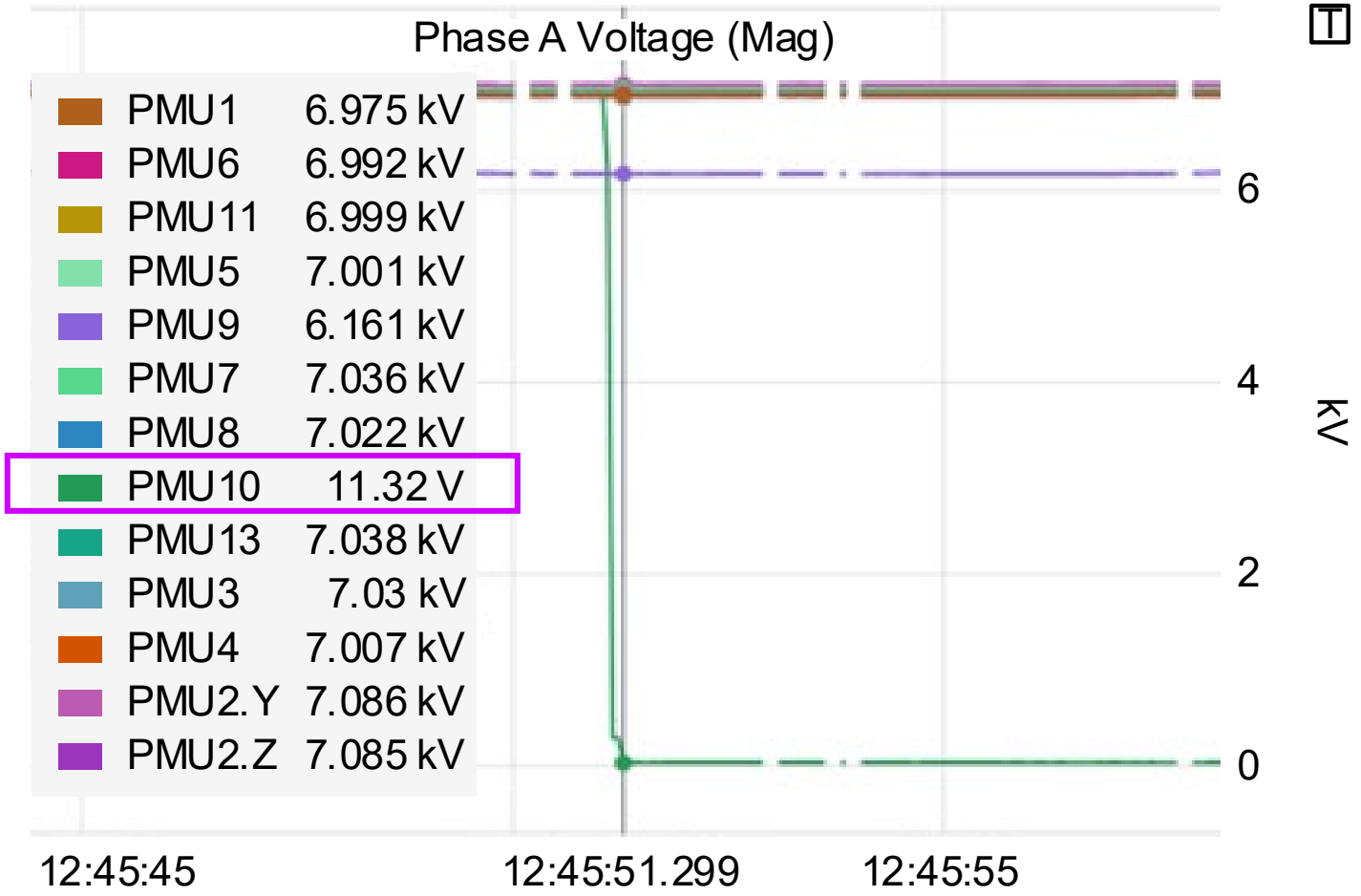
- PMU10 – one phase missing

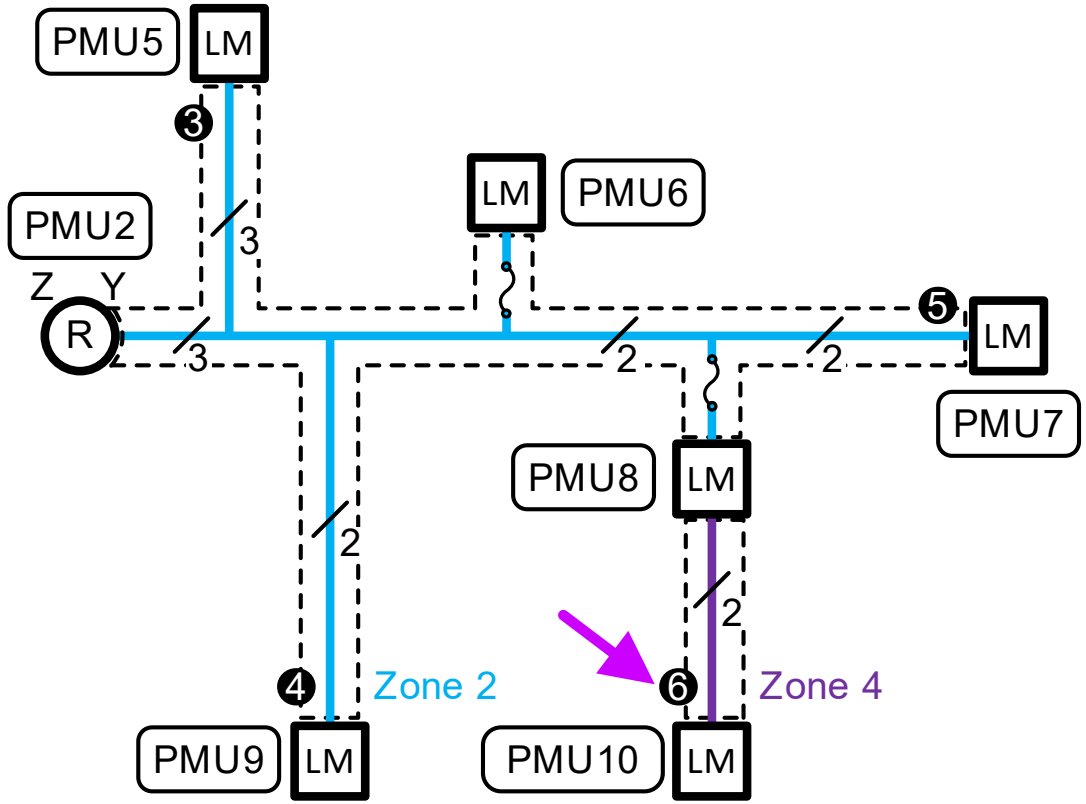


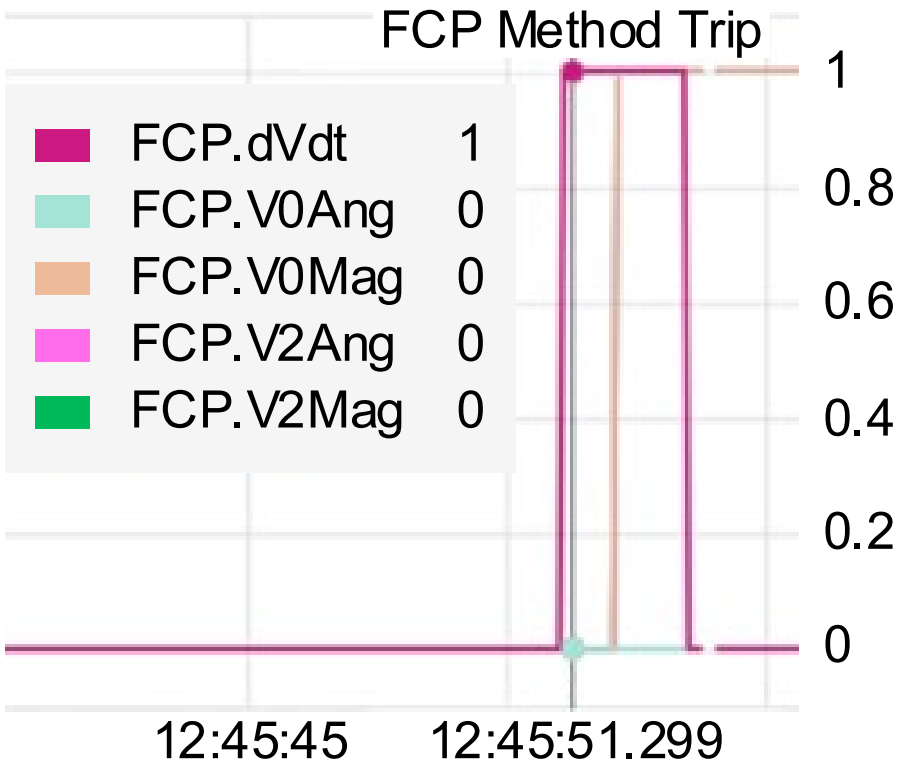
Location 6


PMU5
LM
3
PMU2
Z
Y
R
3
LM
PMU6
3
2
2
5
LM
PMU7
PMU8
LM
2
2
4
Zone 2
6
Zone 4
PMU9
LM
PMU10
LM

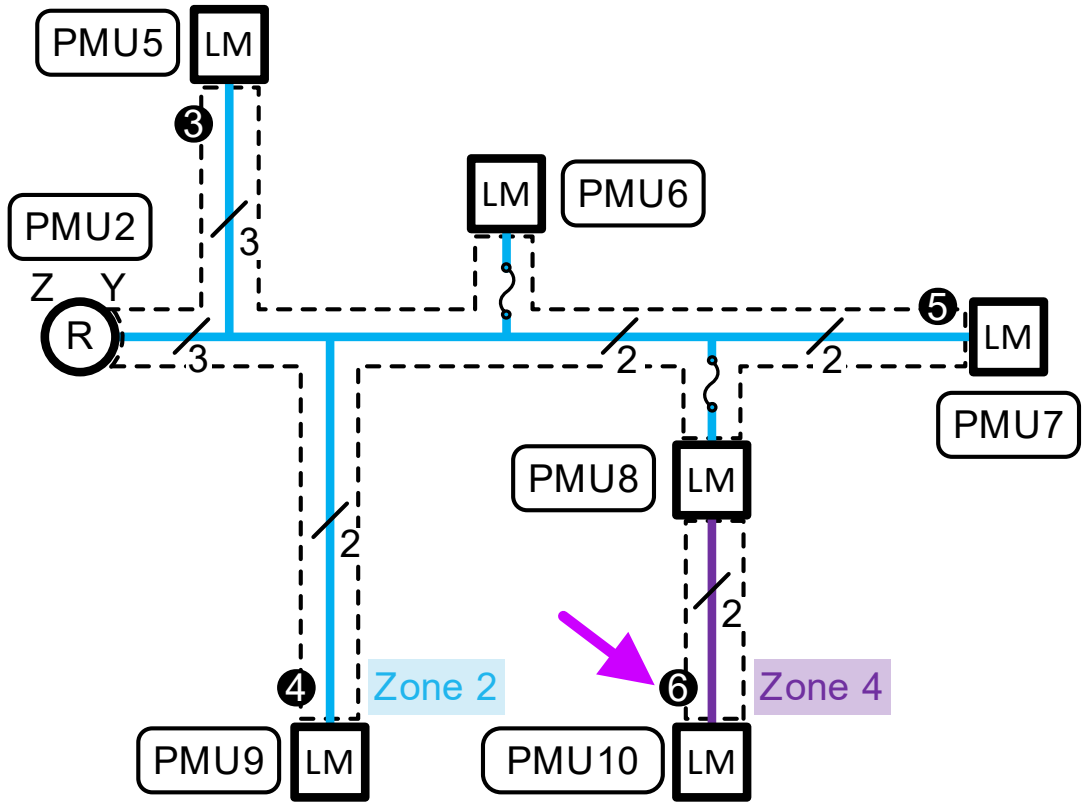

Phase A Voltage (Mag)
PMU1 6.975 kV
PMU6 6.992 kV
PMU11 6.999 kV
PMU5 7.001 kV
PMU9 6.161 kV
PMU7 7.036 kV
PMU8 7.022 kV
PMU10 11.32 V
PMU13 7.038 kV
PMU3 7.03 kV
PMU4 7.007 kV
PMU2.Y 7.086 kV
PMU2.Z 7.085 kV
6
4
2
0
kV
12:45:45
12:45:51.299
12:45:55

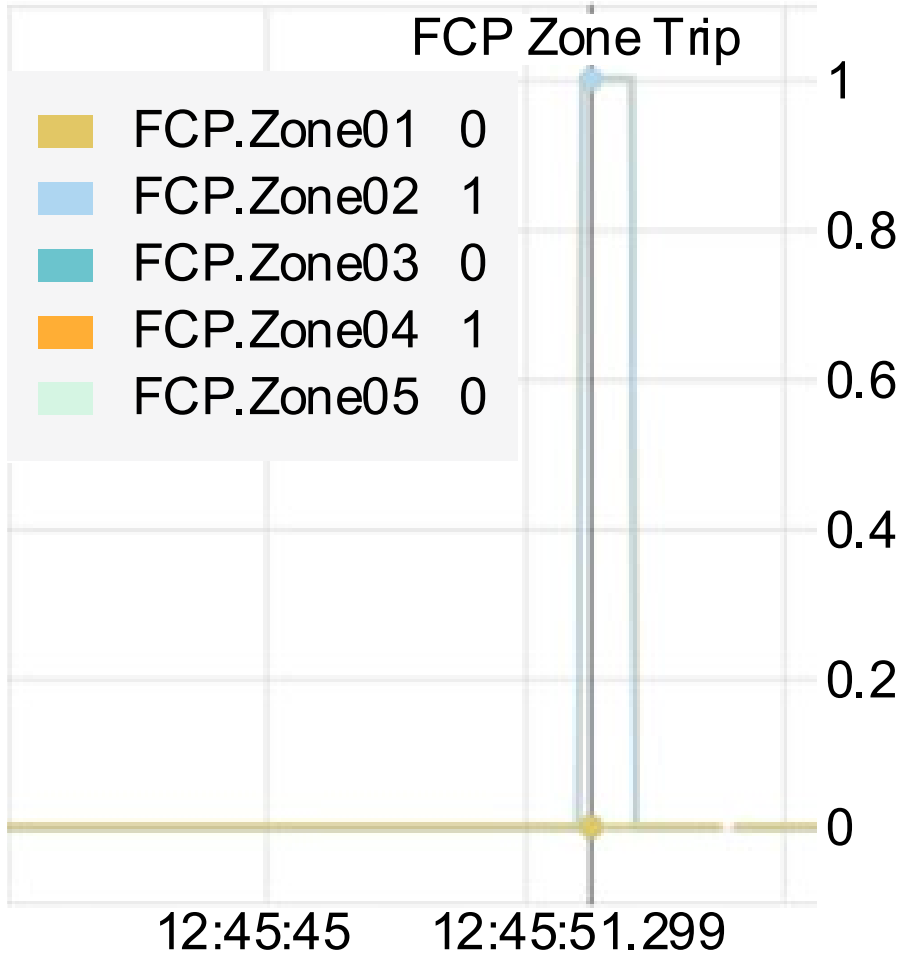
Location 6


PMU5
LM
3
PMU2
Z
Y
R
3
LM
PMU6
2
5
LM
PMU7
2
PMU8
LM
2
2
4
Zone 2
6
Zone 4
PMU9
LM
PMU10
LM

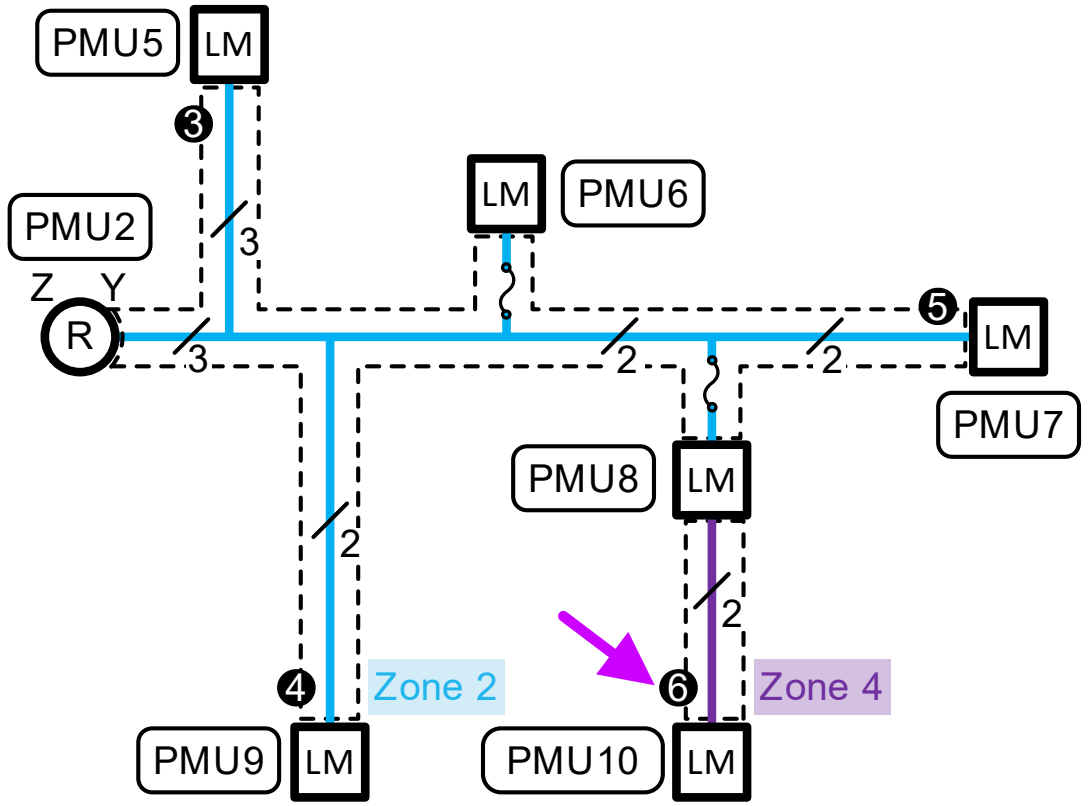

FCP Method Trip
FCP.dVdt 1
FCP.V0Ang 0
FCP.V0Mag 0
FCP.V2Ang 0
FCP.V2Mag 0
1
0.8
0.6
0.4
0.2
0
12:45:45
12:45:51.299

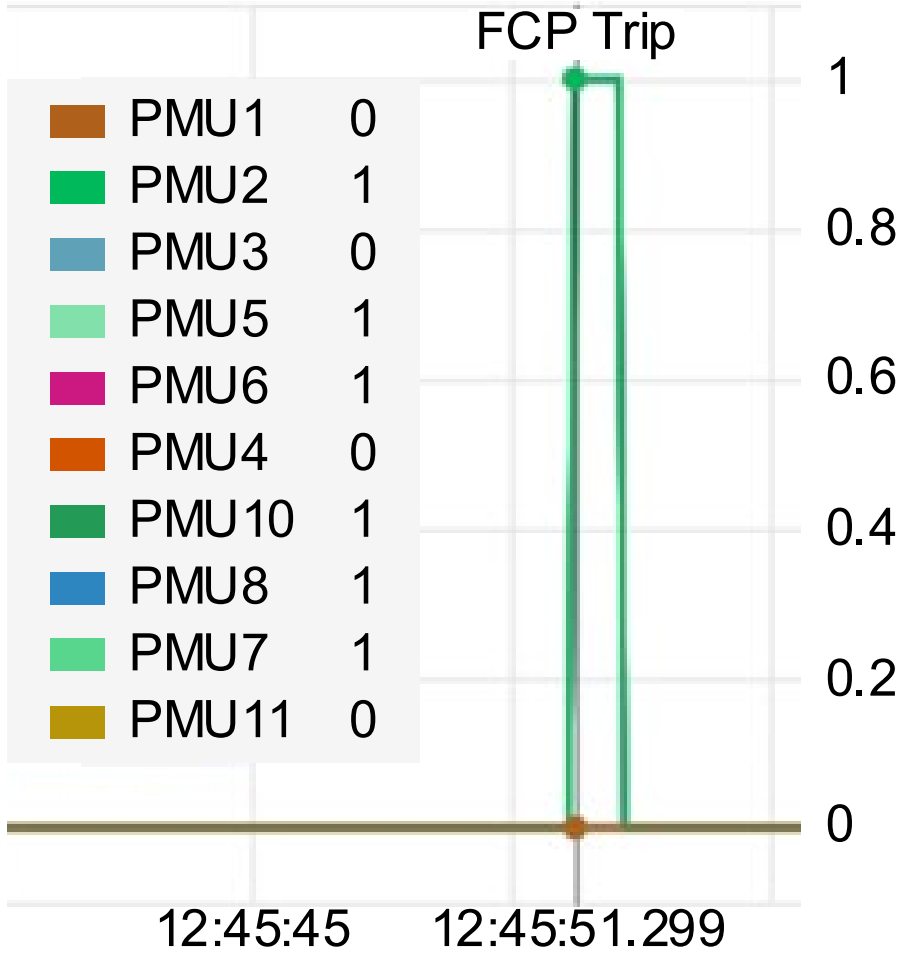
Location 6


PMU5
LM
3
PMU2
Z
Y
R
3
LM
PMU6
3
2
2
5
LM
PMU7
PMU8
LM
2
2
4
Zone 2
6
Zone 4
PMU9
LM
PMU10
LM


FCP Zone Trip
FCP.Zone01 0
FCP.Zone02 1
FCP.Zone03 0
FCP.Zone04 1
FCP.Zone05 0
1
0.8
0.6
0.4
0.2
0
12:45:45
12:45:51.299

Location 6


PMU5
LM
3
PMU2
Z
Y
R
3
LM
PMU6
3
2
2
5
LM
PMU7
PMU8
LM
2
2
4
Zone 2
6
Zone 4
PMU9
LM
PMU10
LM


FCP Trip
PMU1 0
PMU2 1
PMU3 0
PMU5 1
PMU6 1
PMU4 0
PMU10 1
PMU8 1
PMU7 1
PMU11 0
1
0.8
0.6
0.4
0.2
0
12:45:45
12:45:51.299

Conclusion

- Falling conductor detected and de-energized before it hits the ground
- Reconstruction of missing phase for double- and single-phase lateral
- Successful validation from lab and field results
- System study for maximum voltage drop
- Limited FCP coverage in case of devices out of service (security-biased)

Questions?