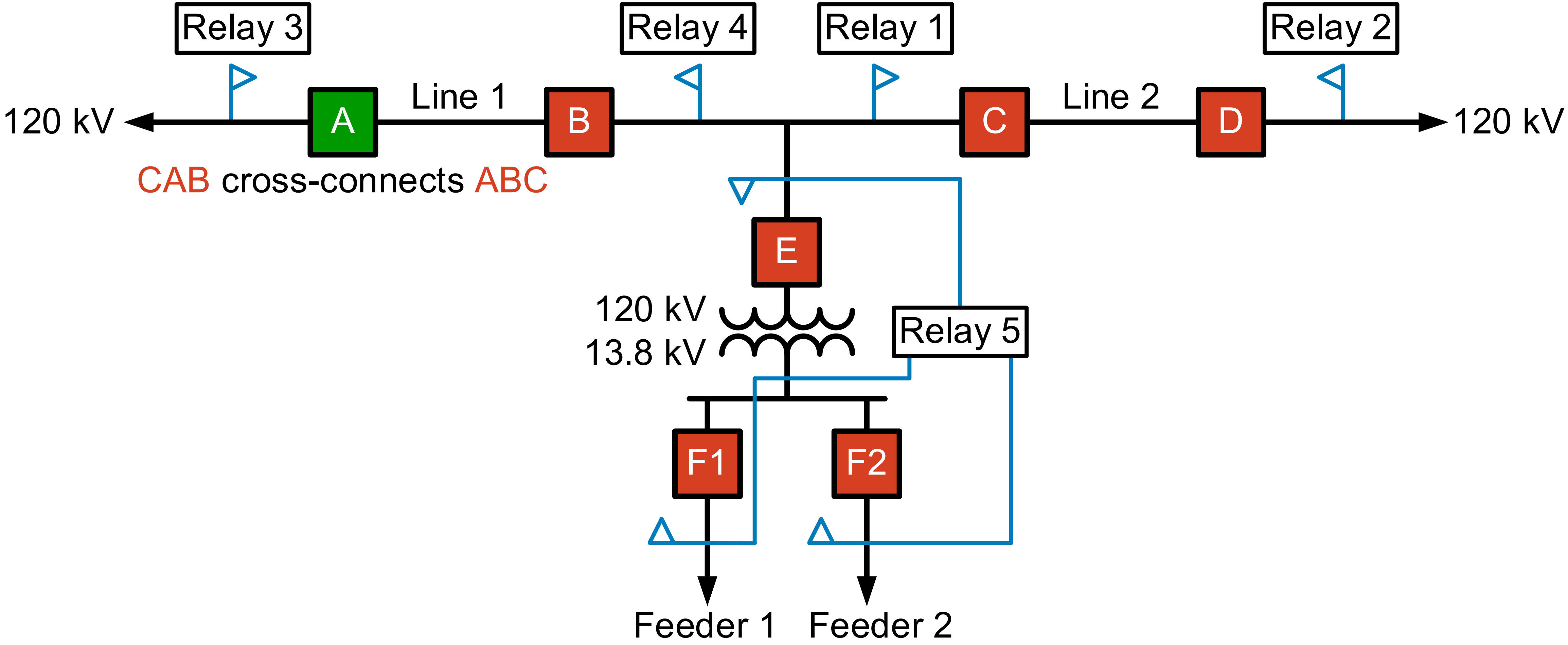
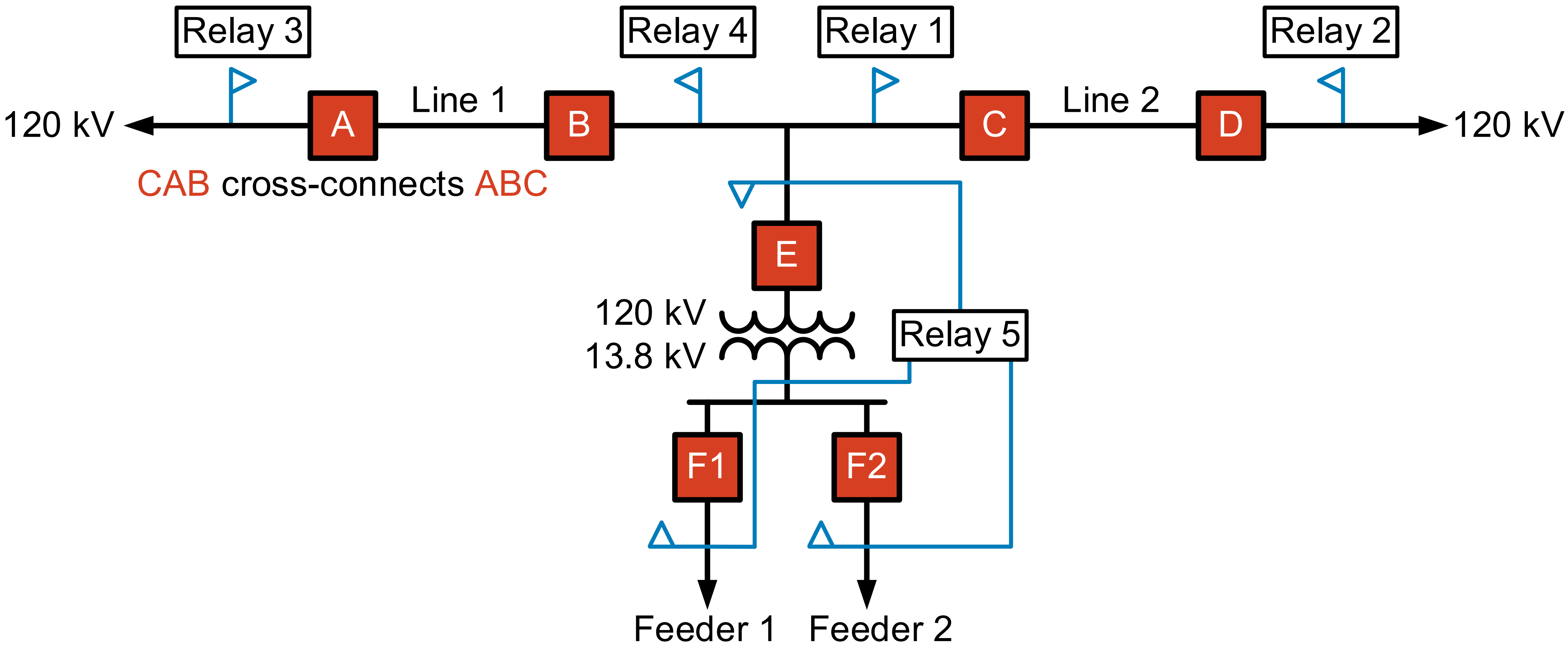
Getting the Lines Crossed—How a Three-Phase Series Fault Caused a Sequence of Relay Operations

Marcel Taberer, Ryan McDaniel, and Jon Larson
Schweitzer Engineering Laboratories, Inc.

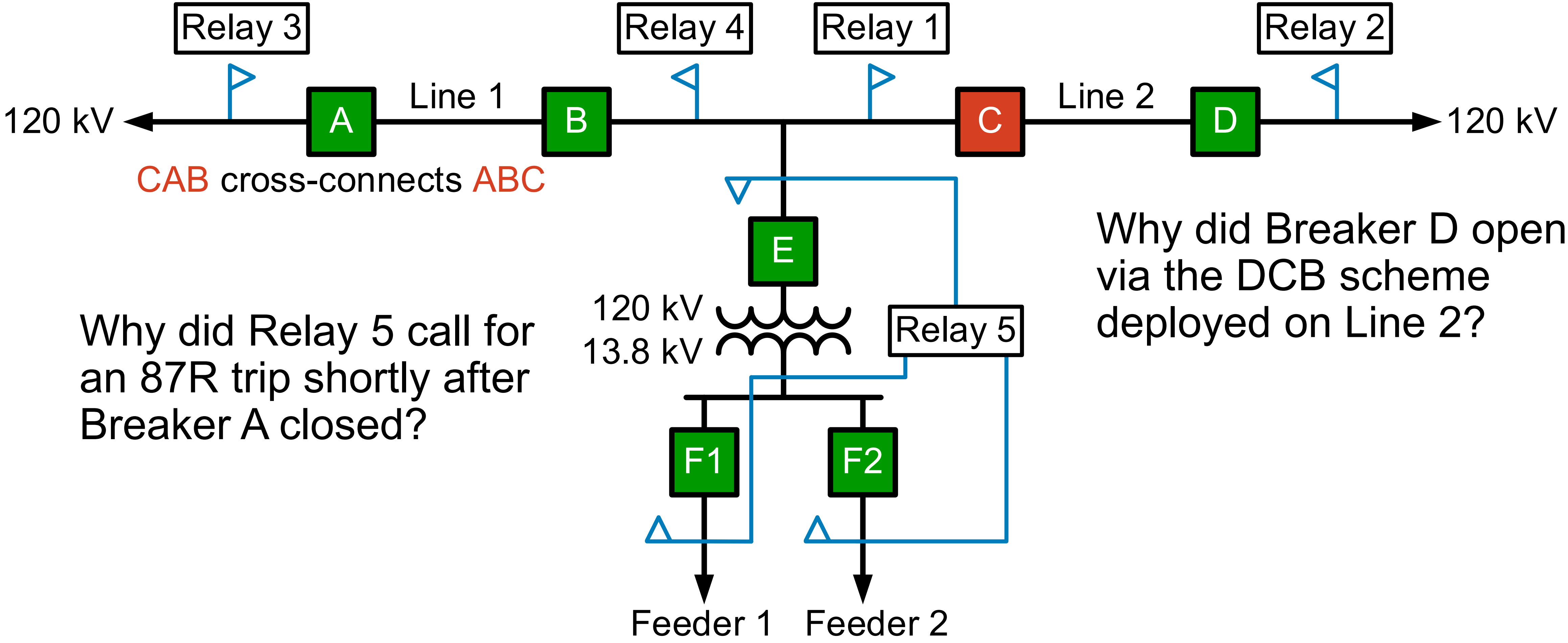
Overview of what actually happened



Overview of what actually happened



Overview of what actually happened



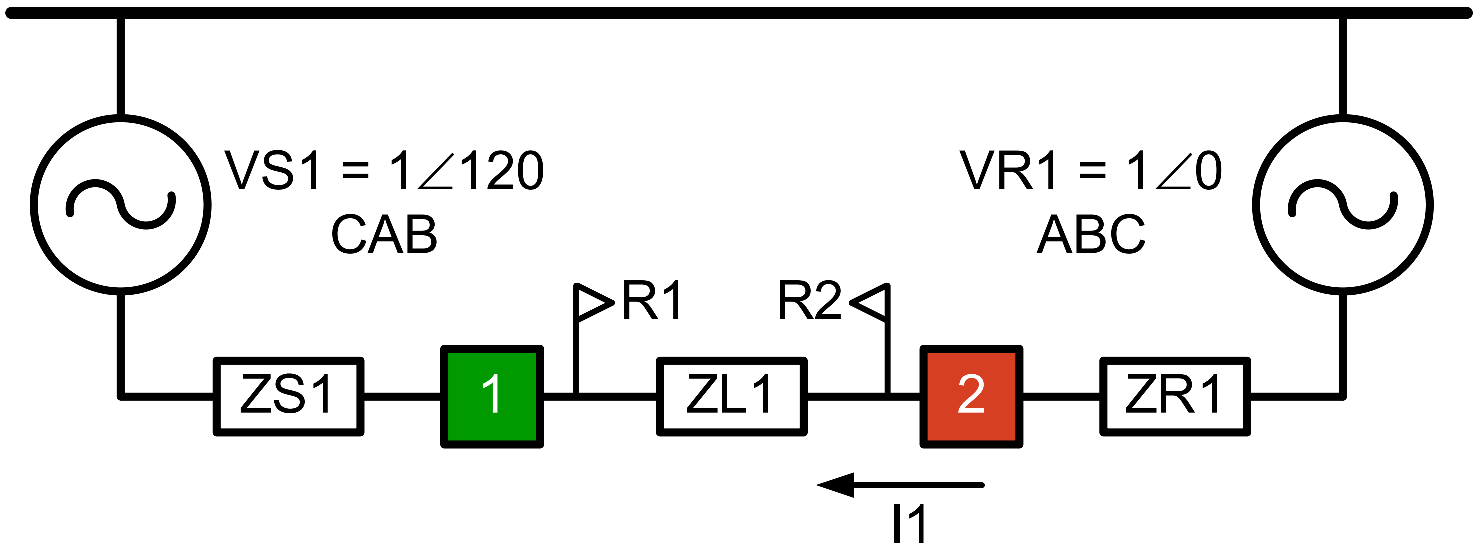
Why did Relay 5 call for an 87R trip shortly after Breaker A closed?

Why did Breaker D open via the DCB scheme deployed on Line 2?

Agenda

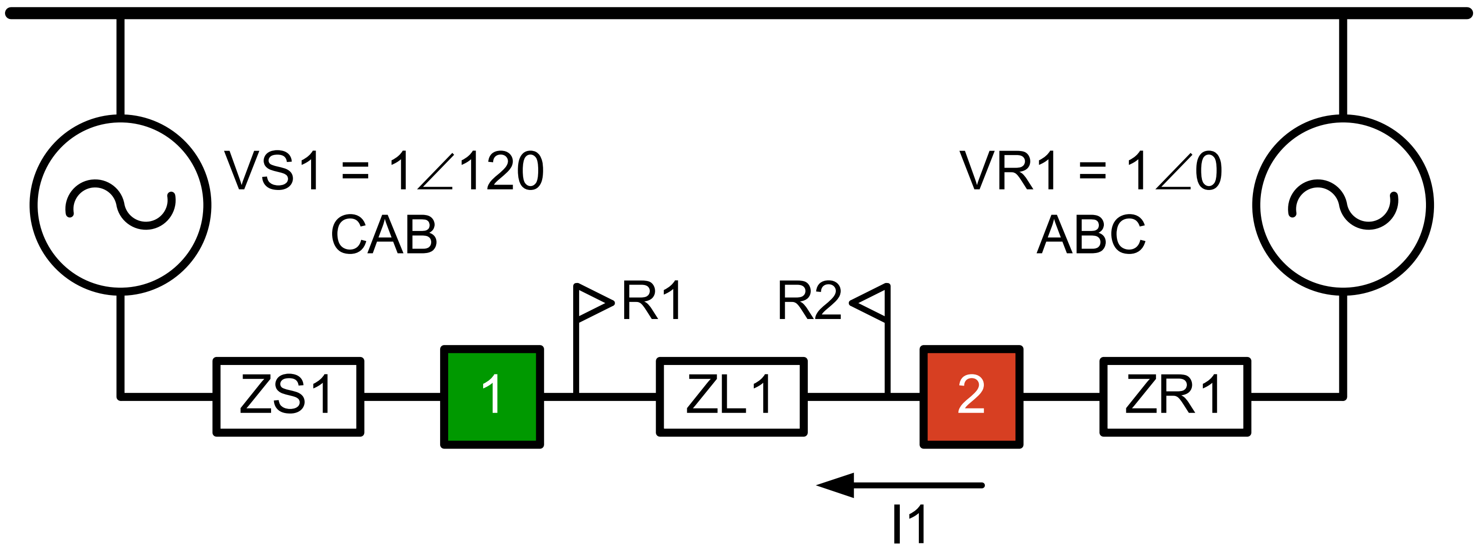
- Cross-connect theory
- Line protection on Lines 1 and 2
- Transformer differential analysis
- Inrush theory at a glance
- Conclusion

Three-phase series fault



Three-phase cross-connect fault develops when Breaker 1 closes

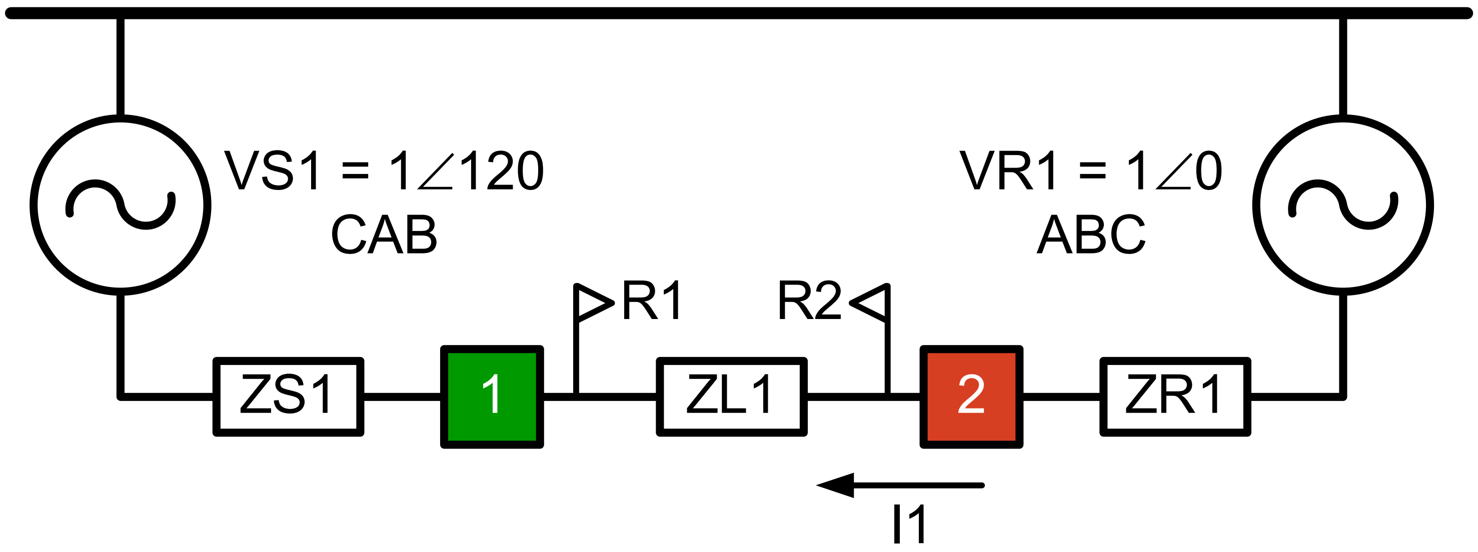
Three-phase series fault



$$I1R2 = \frac{VR1 - VS1}{ZS1 + ZL1 + ZR1}$$

$$V1R1 = \left(\frac{ZS1 + (ZL1 + ZR1) \cdot 1\angle 120}{ZS1 + ZL1 + ZR1} \right) \qquad V1R2 = \left(\frac{ZS1 + ZL1 + ZR1 \cdot 1\angle 120}{ZS1 + ZL1 + ZR1} \right)$$

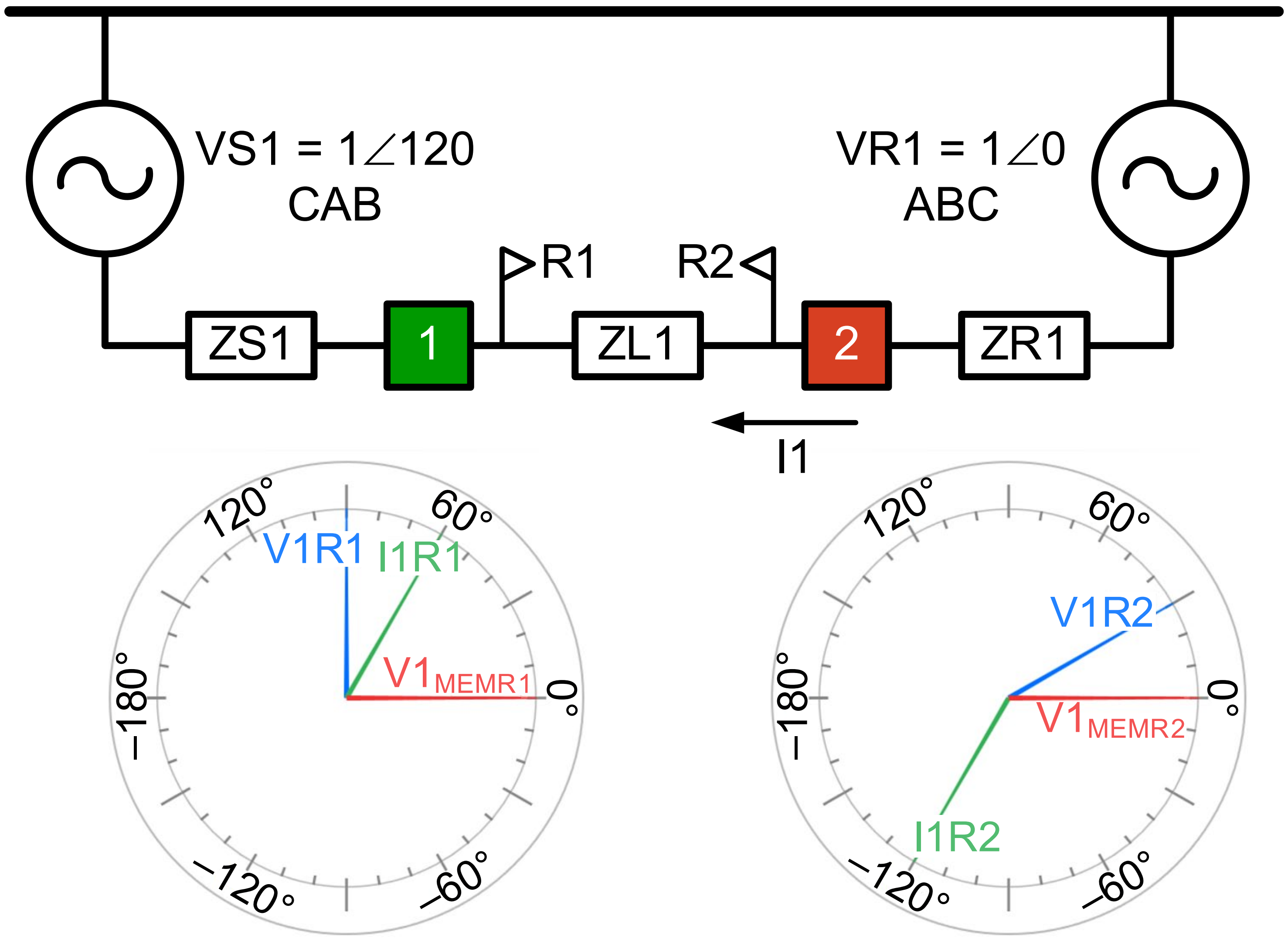
Three-phase series fault



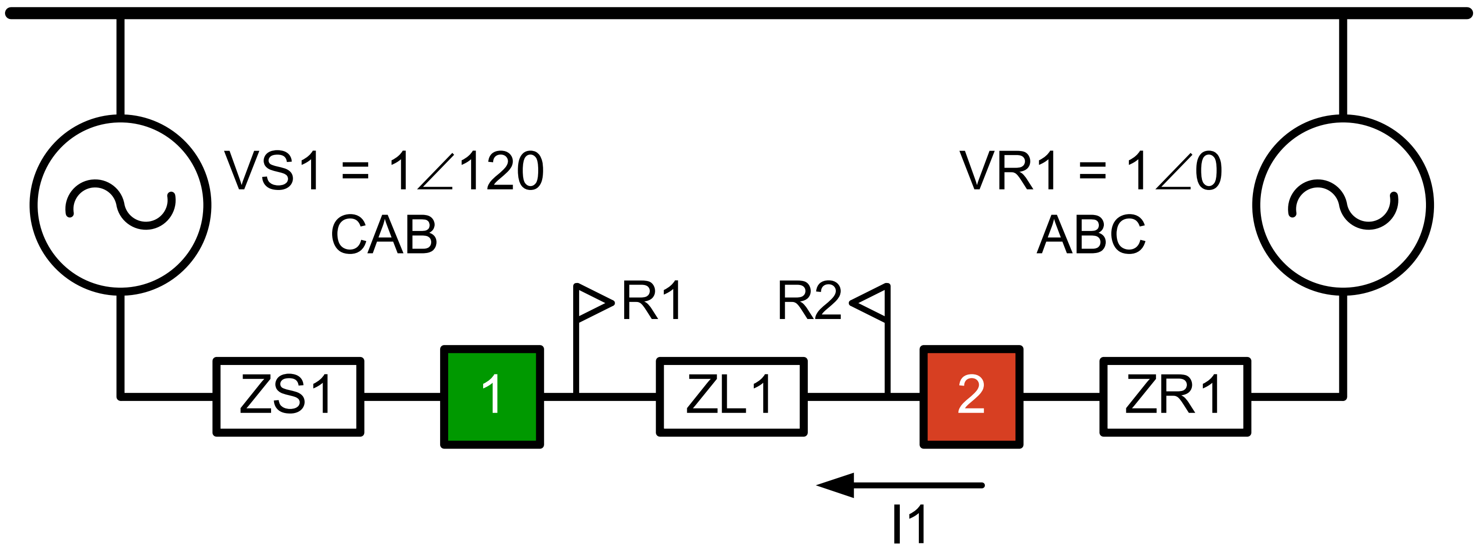
$$I1R2 = \frac{\sqrt{3}\angle -30}{3\angle 90} = \frac{1}{\sqrt{3}}\angle -120$$

$$V1R1 = \frac{1}{\sqrt{3}}\angle 90 \qquad V1R2 = \frac{1}{\sqrt{3}}\angle 30$$

Three-phase series fault

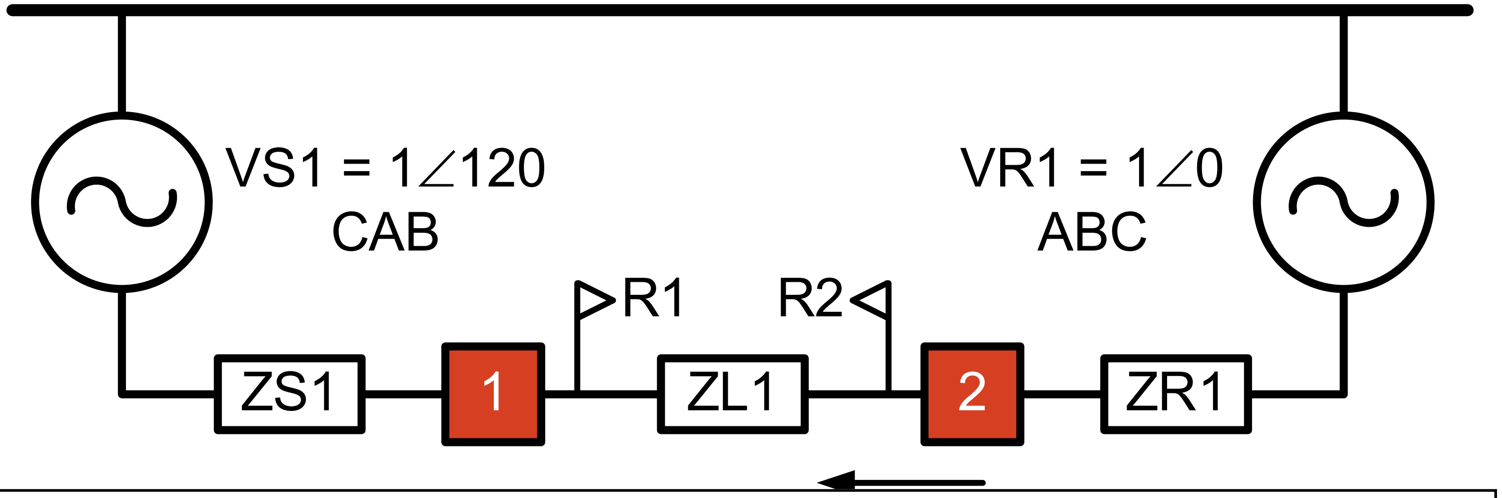


Three-phase series fault



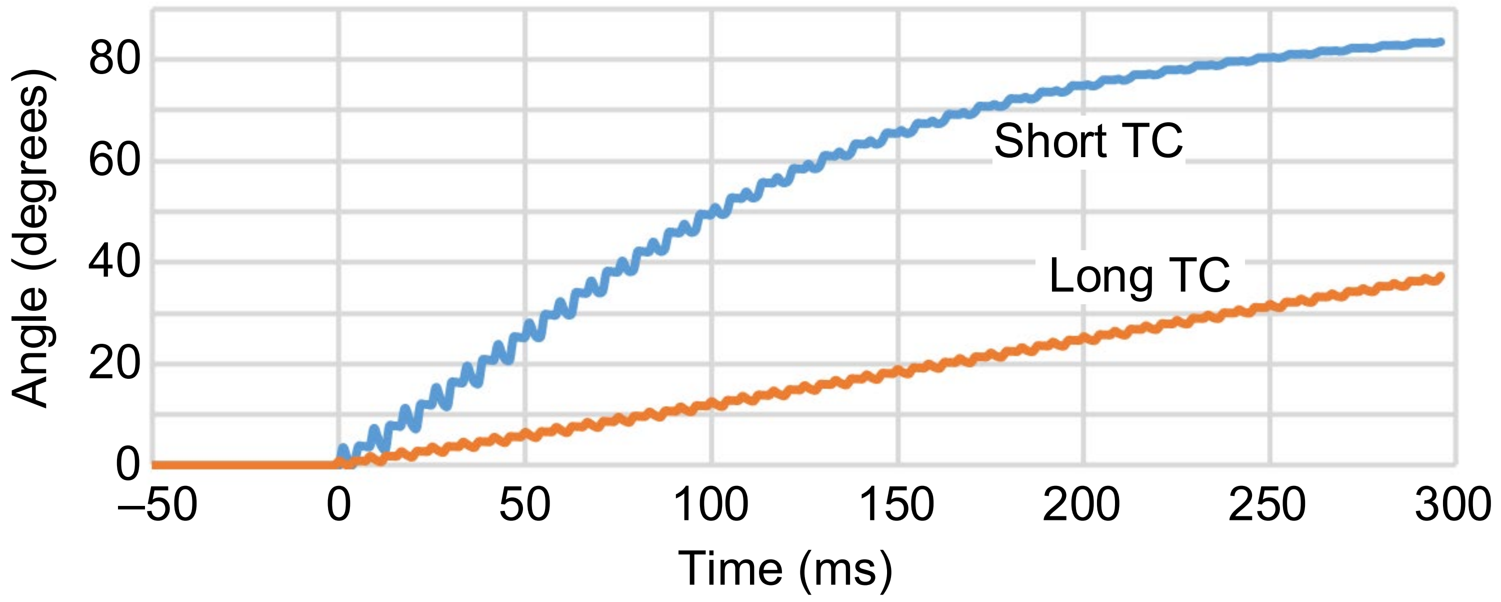
$$T32P_{MEM} = RE\left[\left(I1_{REPLICA}\right) \bullet \left(V1_{MEM}\right)^{*}\right]$$

Three-phase series fault



Memory time constant

- Long memory time constant – slow angle displacement from pre-fault voltage
- Short memory time constant – fast angle displacement from pre-fault voltage



Memory time constant

Long

- Dependable for close-in three-phase faults
- Maintains directionality for a long time

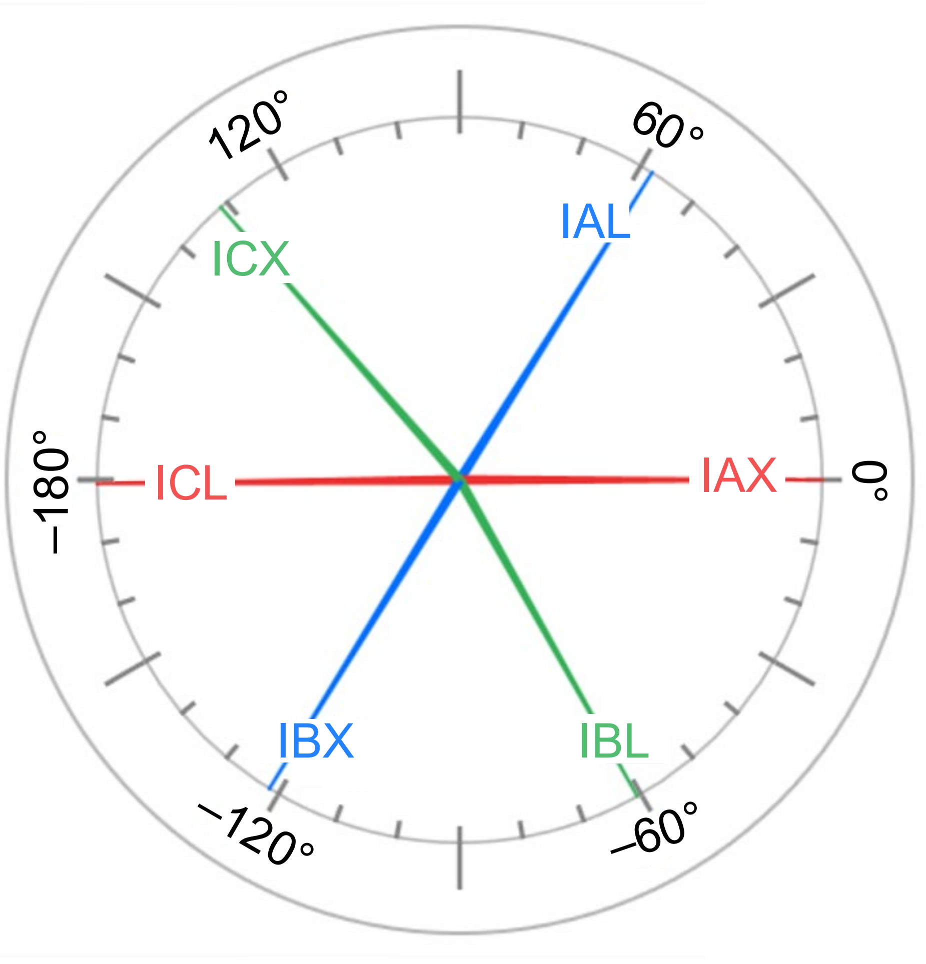
Short

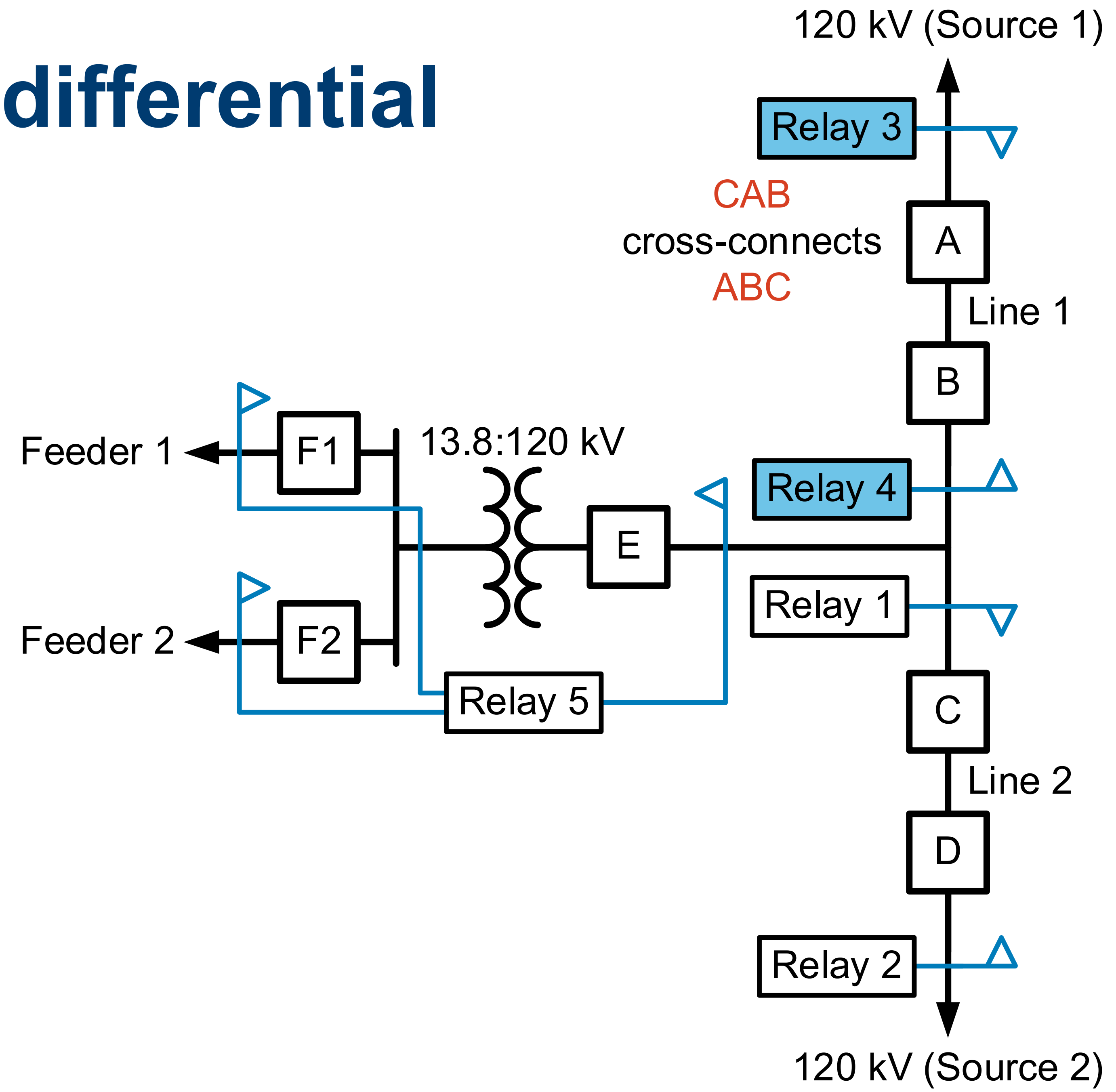
- Secure for excursion in frequency
- Maintains directionality for a short time

Event analysis

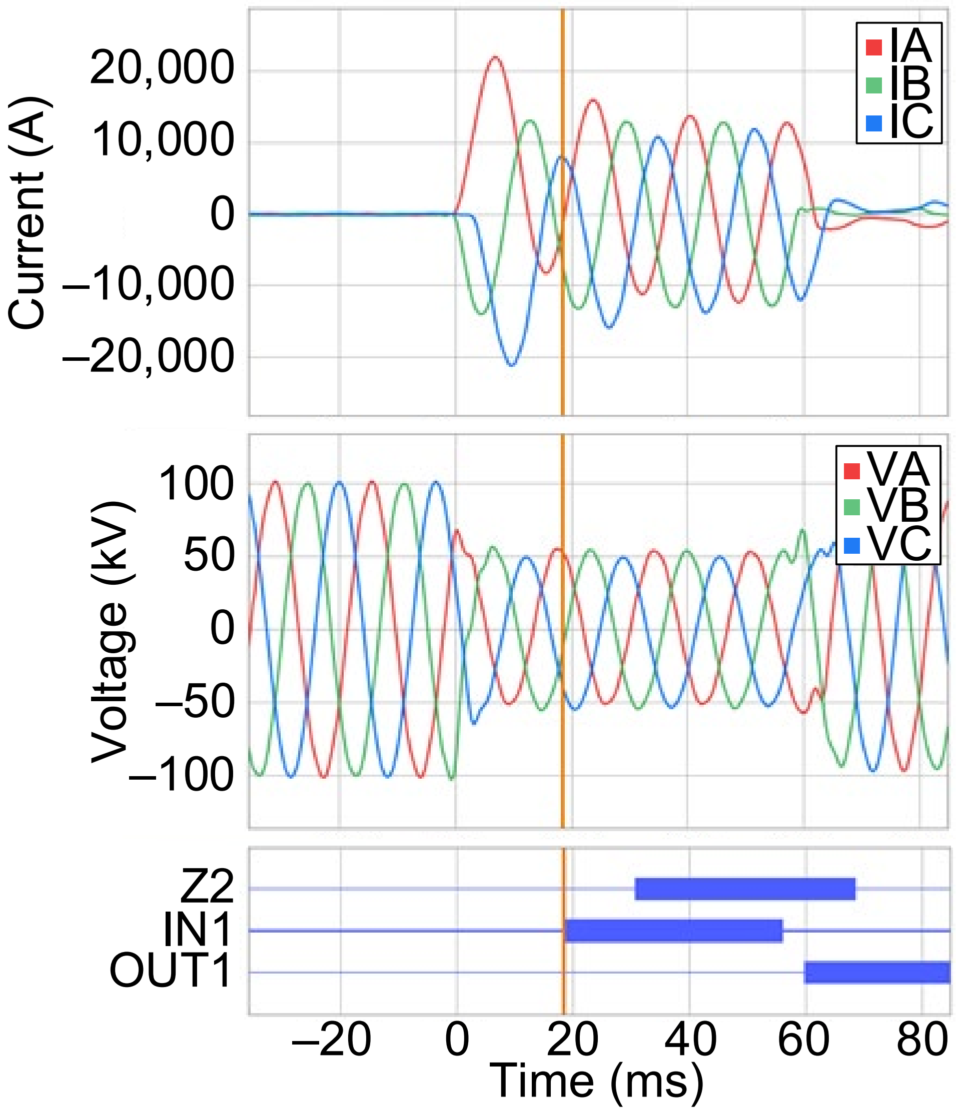
Transmission line relays

Line 1 – line current differential

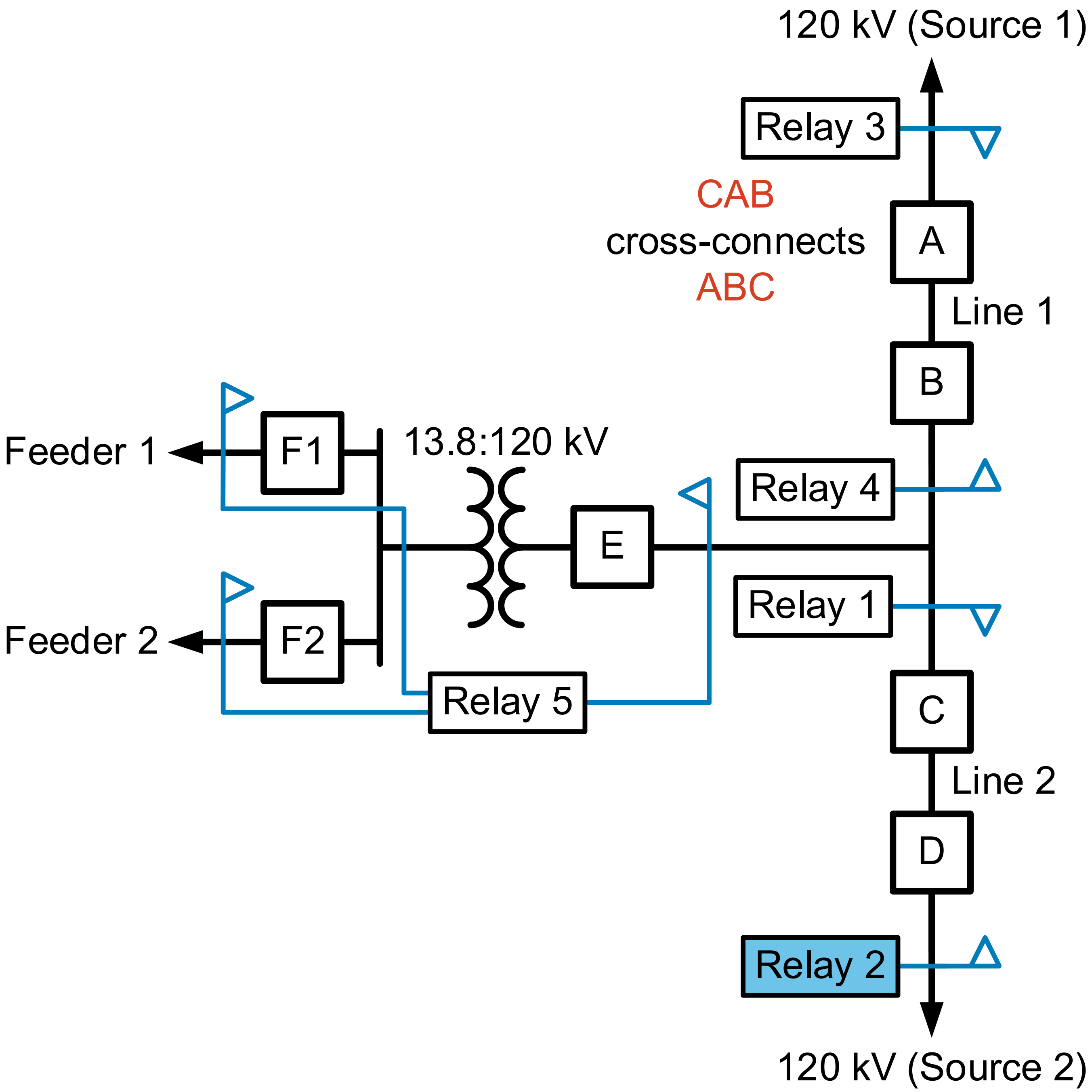




Line 2 – DCB

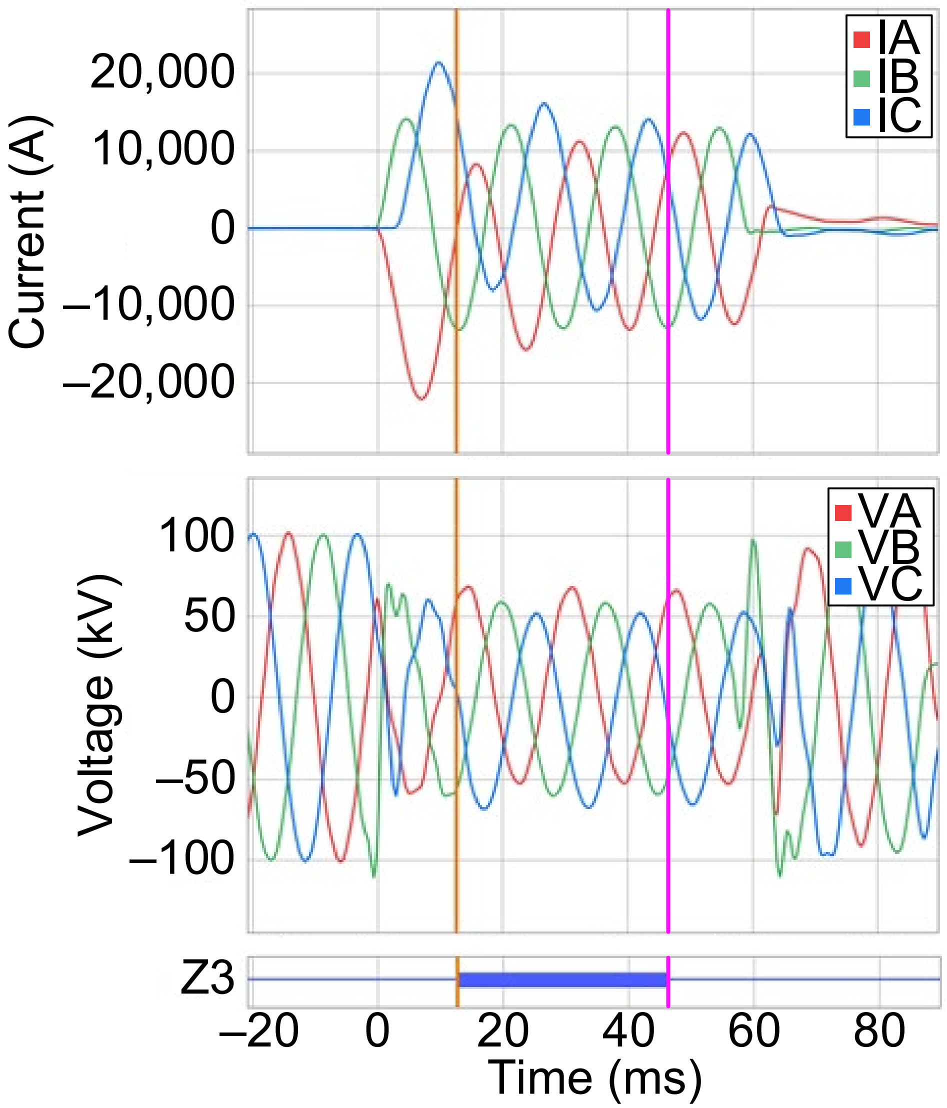


Current (A)
20,000
10,000
0
–10,000
–20,000
IA
IB
IC
Voltage (kV)
100
50
0
–50
–100
VA
VB
VC
Z2
IN1
OUT1
–20
0
20
40
60
80
Time (ms)

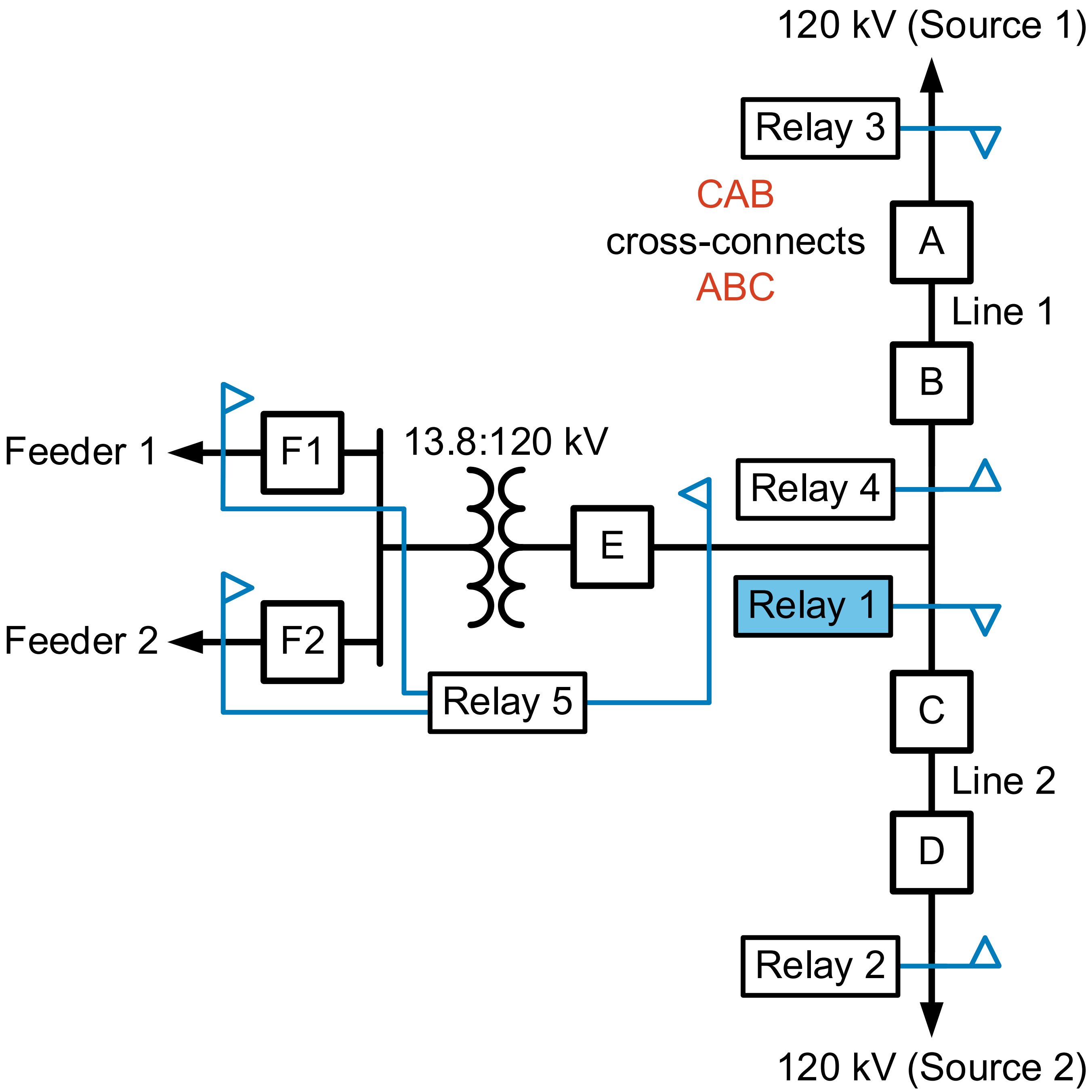


120 kV (Source 1)
Relay 3
CAB
cross-connects
ABC
A
Line 1
B
Feeder 1
F1
13.8:120 kV
Relay 4
E
Relay 1
Feeder 2
F2
Relay 5
C
Line 2
D
Relay 2
120 kV (Source 2)

Line 2 – DCB

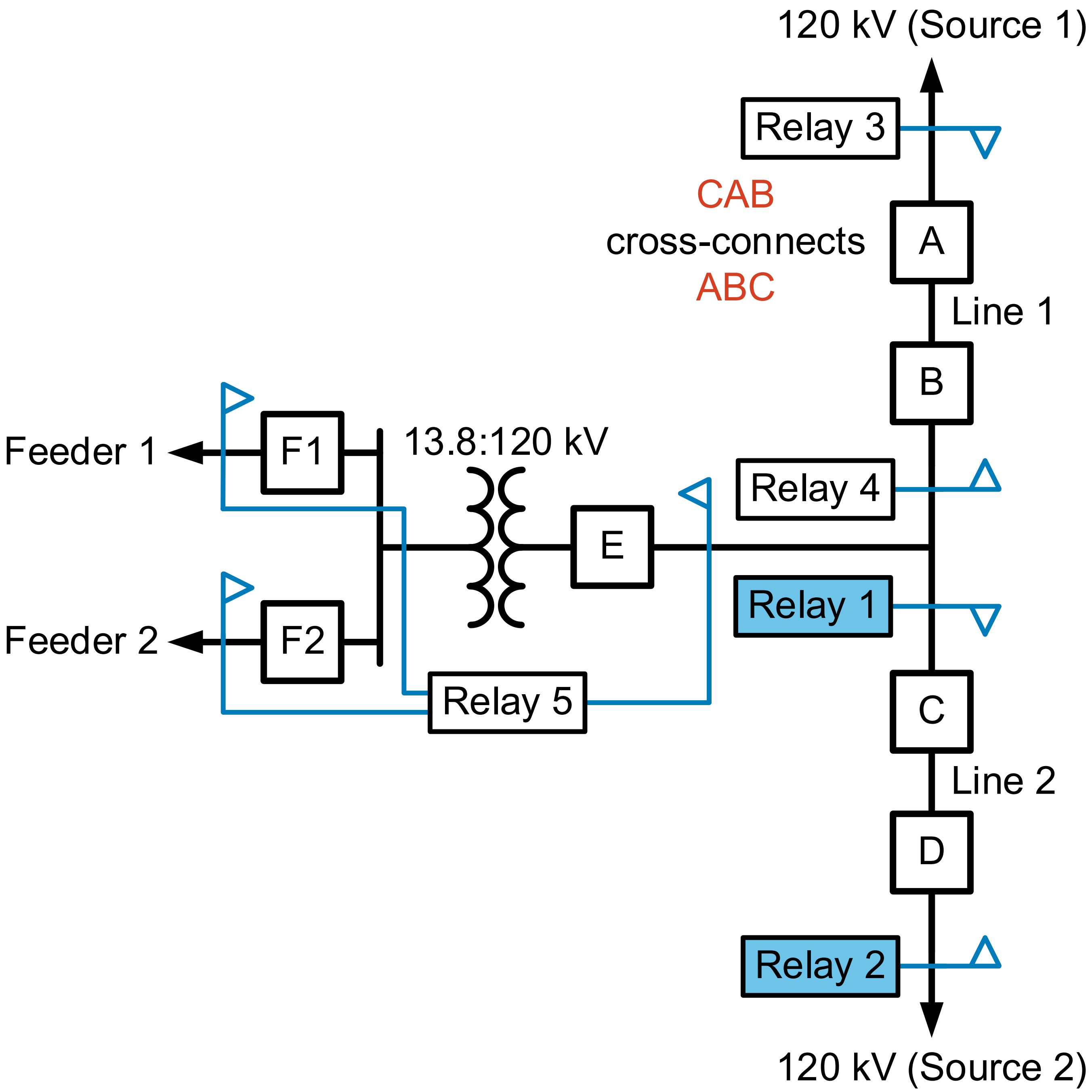


IA
IB
IC
20,000
10,000
0
–10,000
–20,000
Current (A)
VA
VB
VC
100
50
0
–50
–100
Voltage (kV)
Z3
–20
0
20
40
60
80
Time (ms)



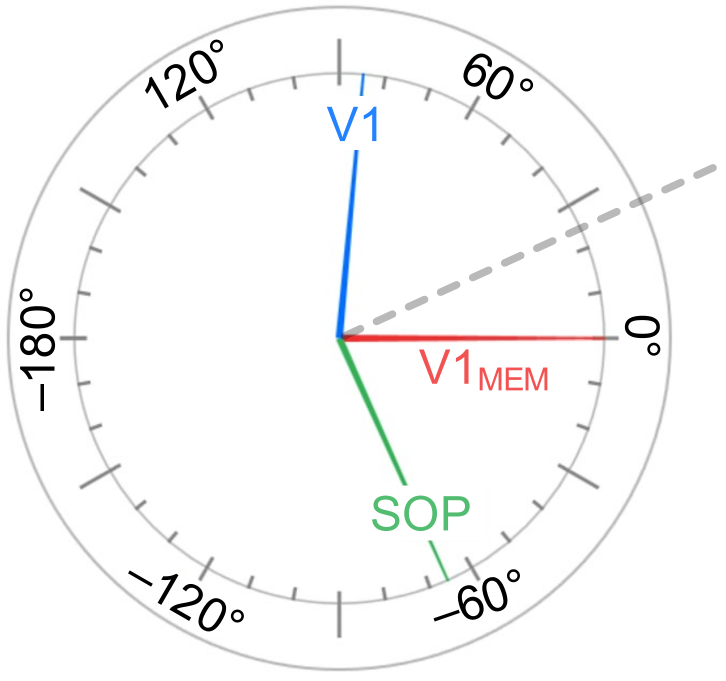
120 kV (Source 1)
Relay 3
CAB
cross-connects
ABC
A
Line 1
B
Feeder 1
F1
13.8:120 kV
Relay 4
E
Relay 1
Feeder 2
F2
Relay 5
C
Line 2
D
Relay 2
120 kV (Source 2)

Line 2 – DCB


120 kV (Source 1)
Relay 3
CAB
cross-connects
ABC
A
Line 1
B
Feeder 1
F1
13.8:120 kV
Relay 4
E
Relay 1
Feeder 2
F2
Relay 5
C
Line 2
D
Relay 2
120 kV (Source 2)

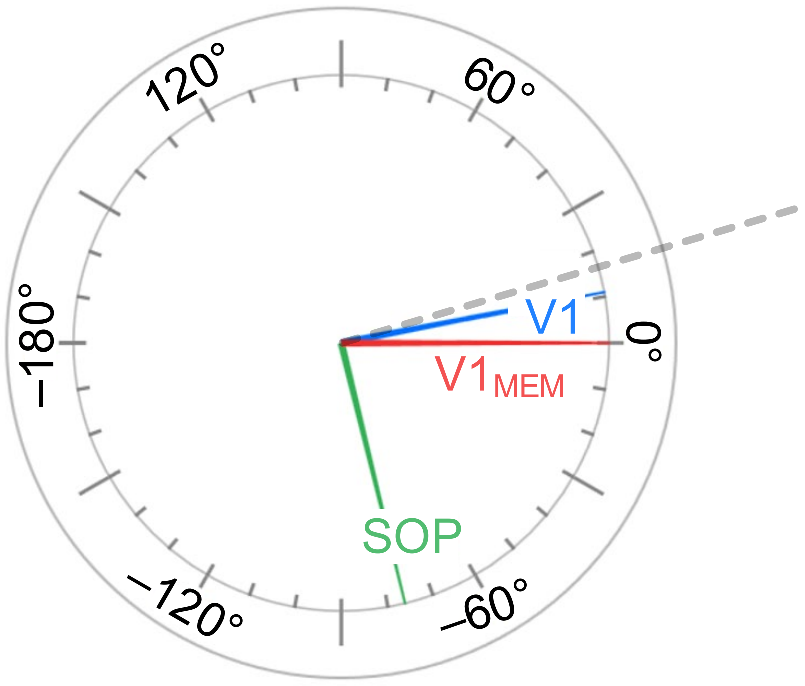
Line 2 – DCB

Relay 1



$$T21P = RE\left[SOP \bullet SPOL^{*}\right]$$

Relay 2

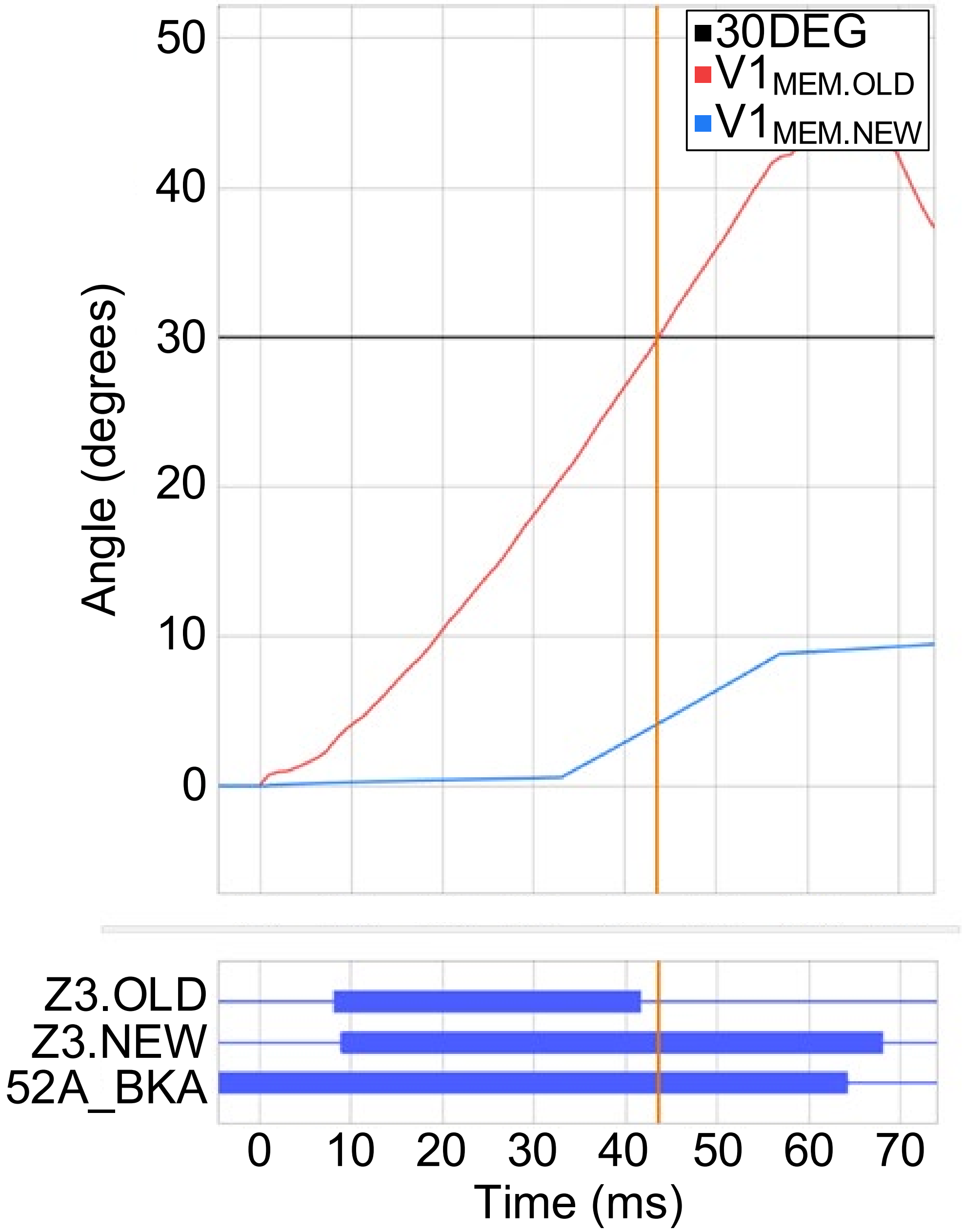


SOTF and line current differential

- Fast and dependable SOTF tripping aids in maintaining communication-scheme security on adjacent lines
  - 50P should be dependable in many systems without additional consideration
  - SOTF Reset must **not** be enabled
  - Undervoltage supervision, if used, must be set above 0.50 pu
  - Only trips breaker that forms cross-connect (selective)
- 87L protection is dependable

$V1_{MEM}$ enhancements

- $V1_{MEM.OLD}$ – 1993 vintage
  - No intentional memory expiration
  - Short memory TC
- $V1_{MEM.NEW}$ – 2020 vintage
  - Has intentional memory expiration
  - Is adaptive to changing system conditions
  - Provides improved security and dependability

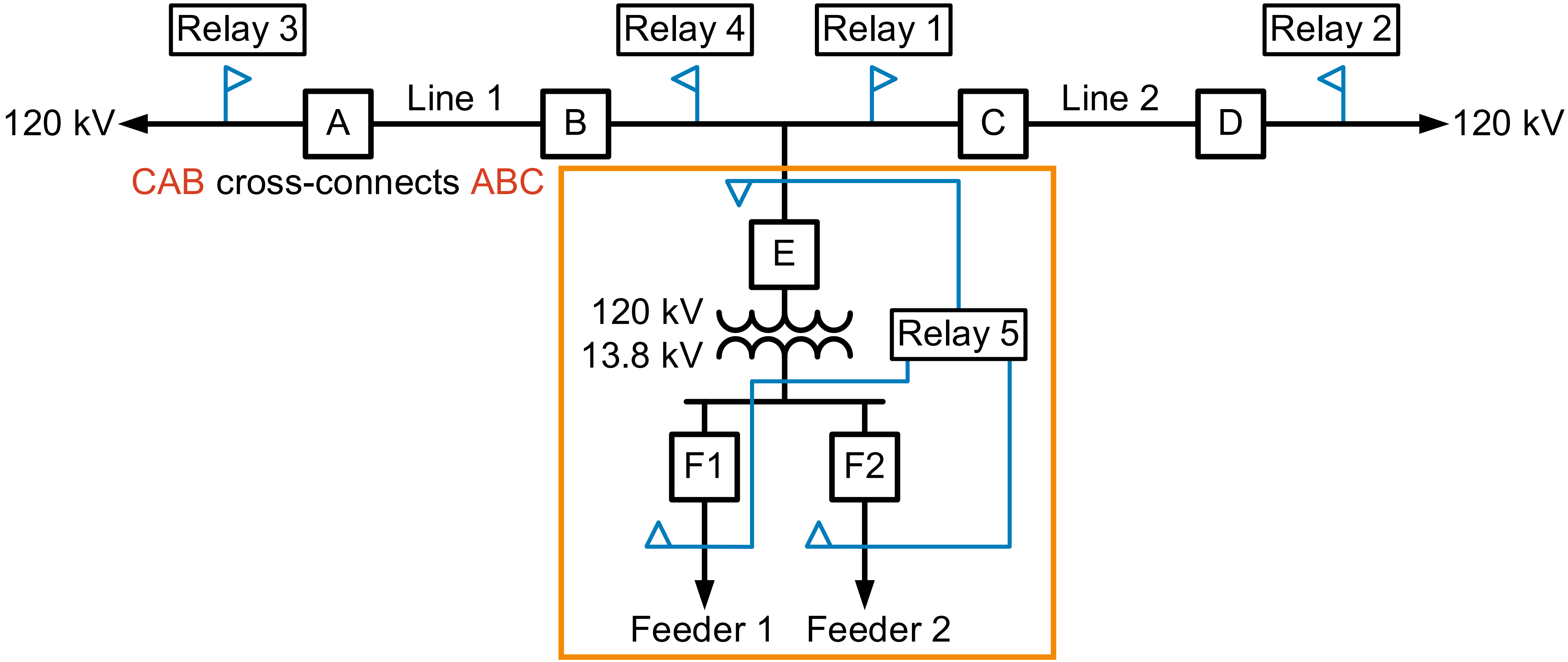


Event analysis

Transformer relay

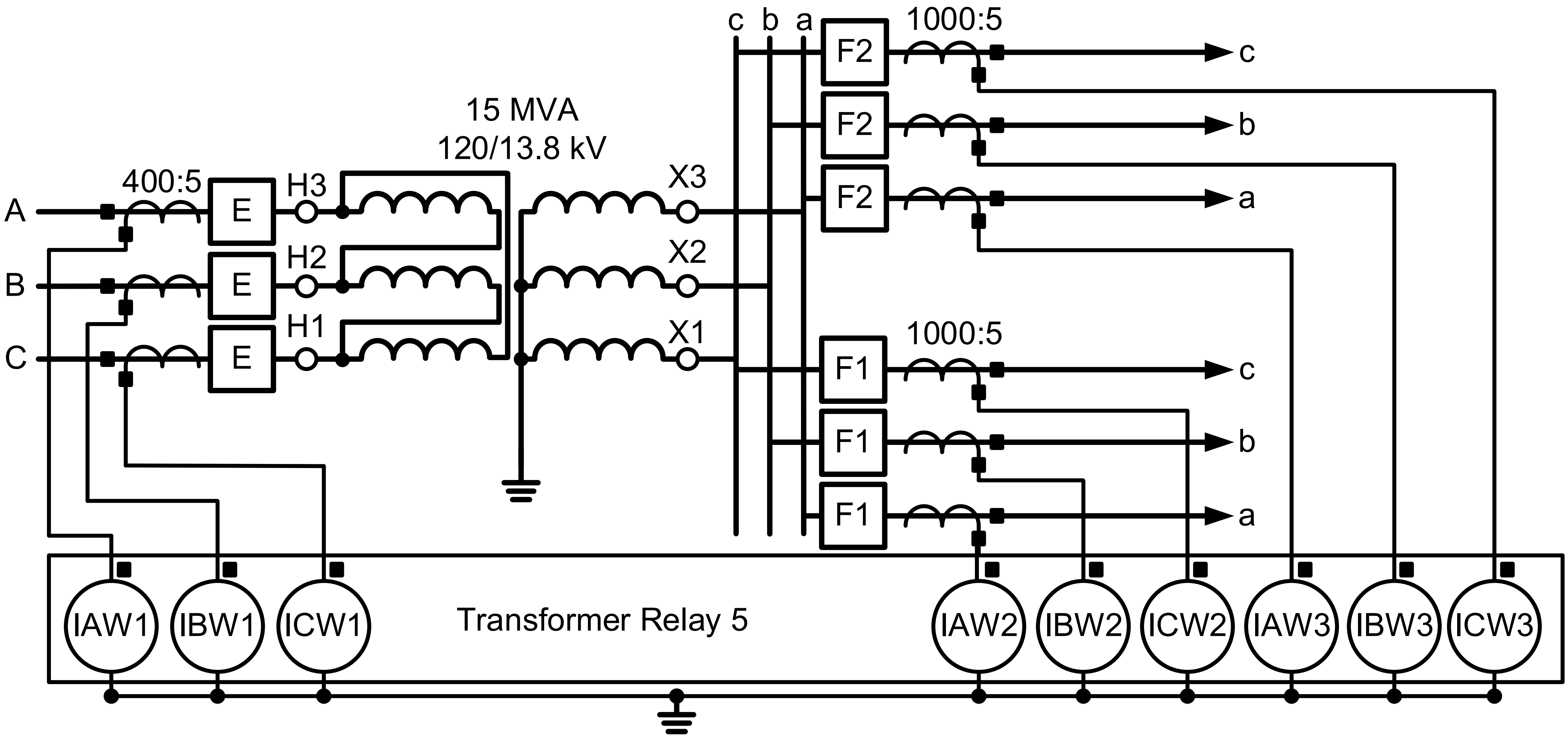
87R operation for three-phase series fault

Closer look at transformer differential relay



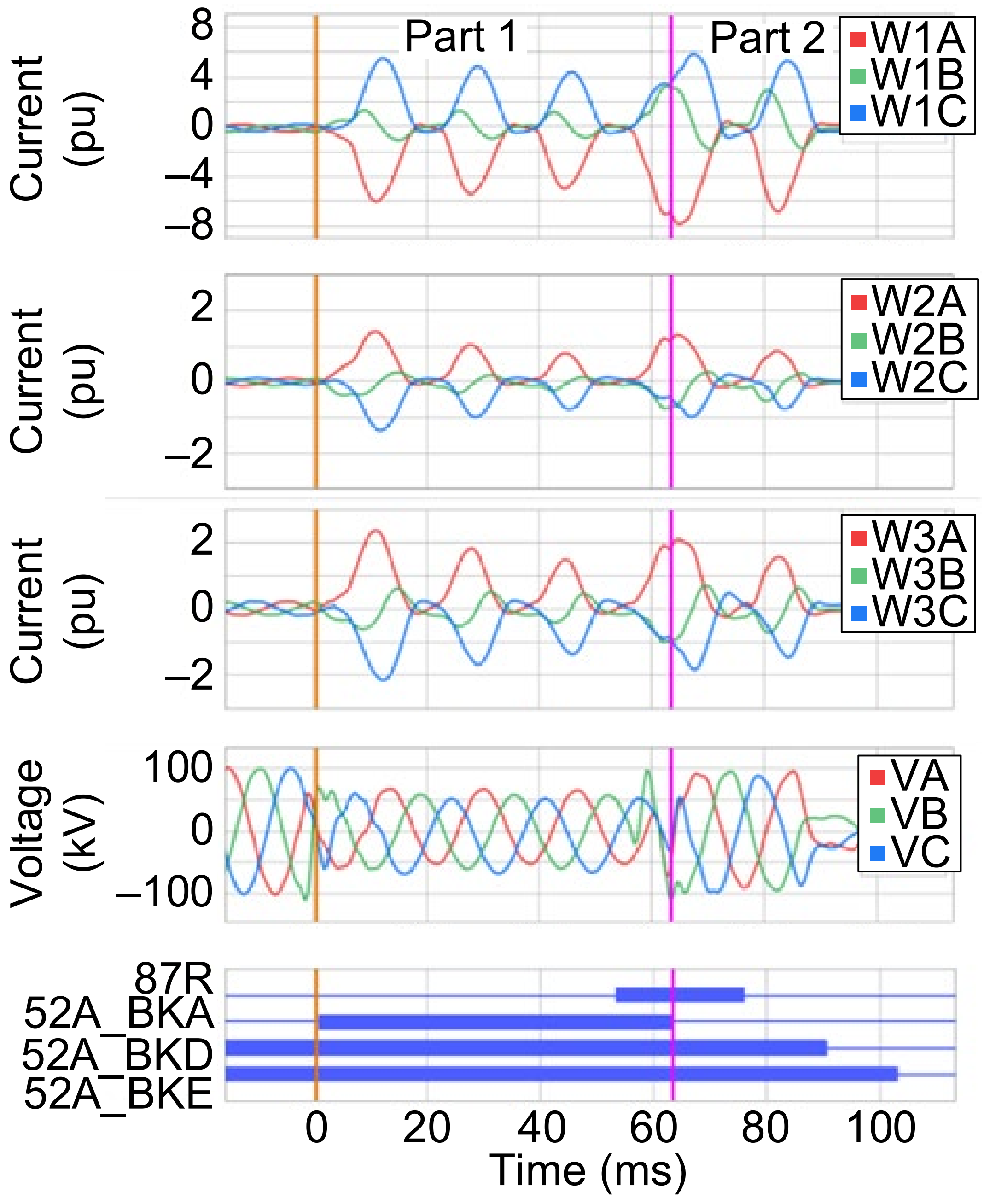
87R operation for three-phase series fault

Closer look at transformer differential relay



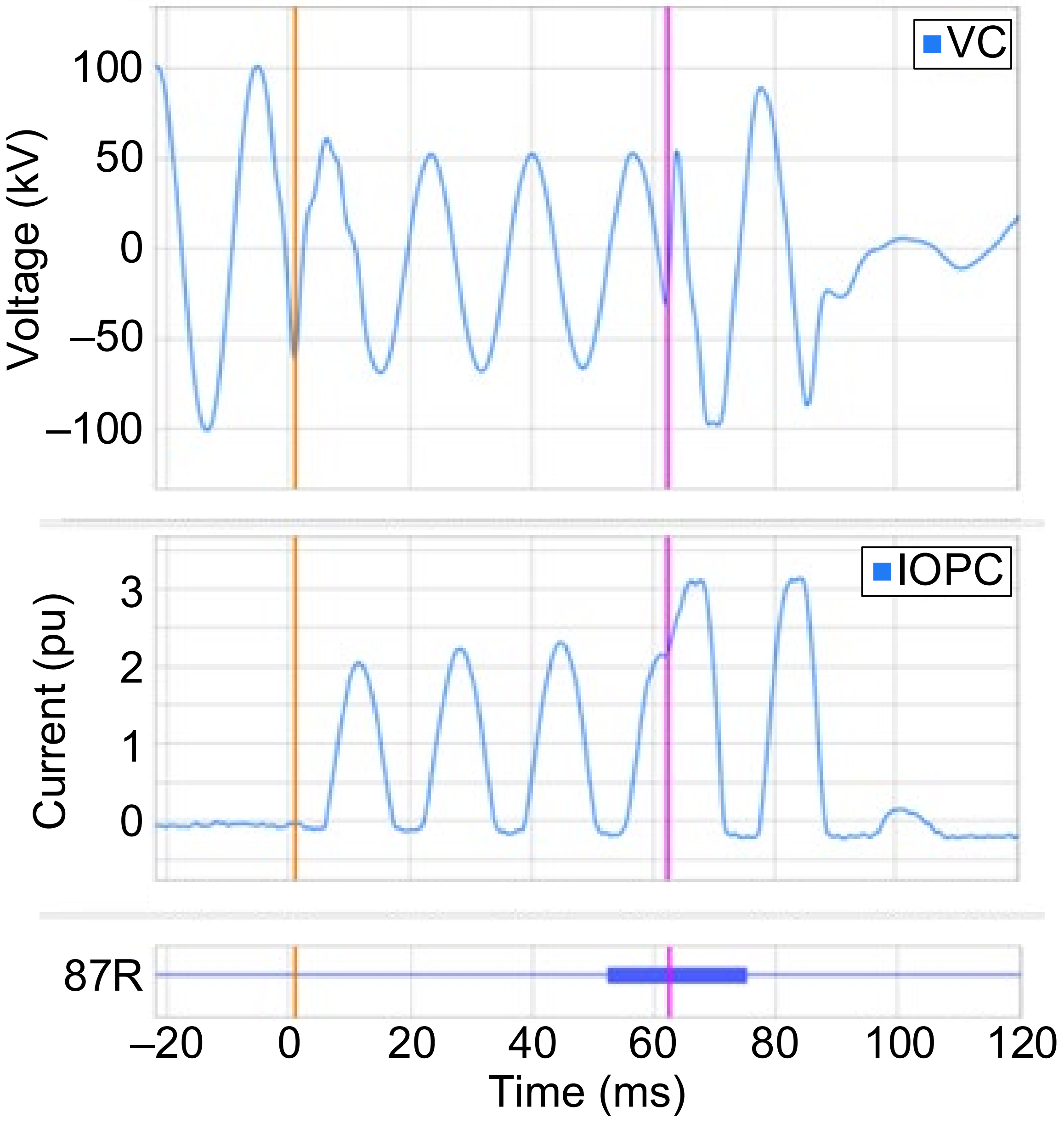
87R operation for three-phase series fault

Event analysis



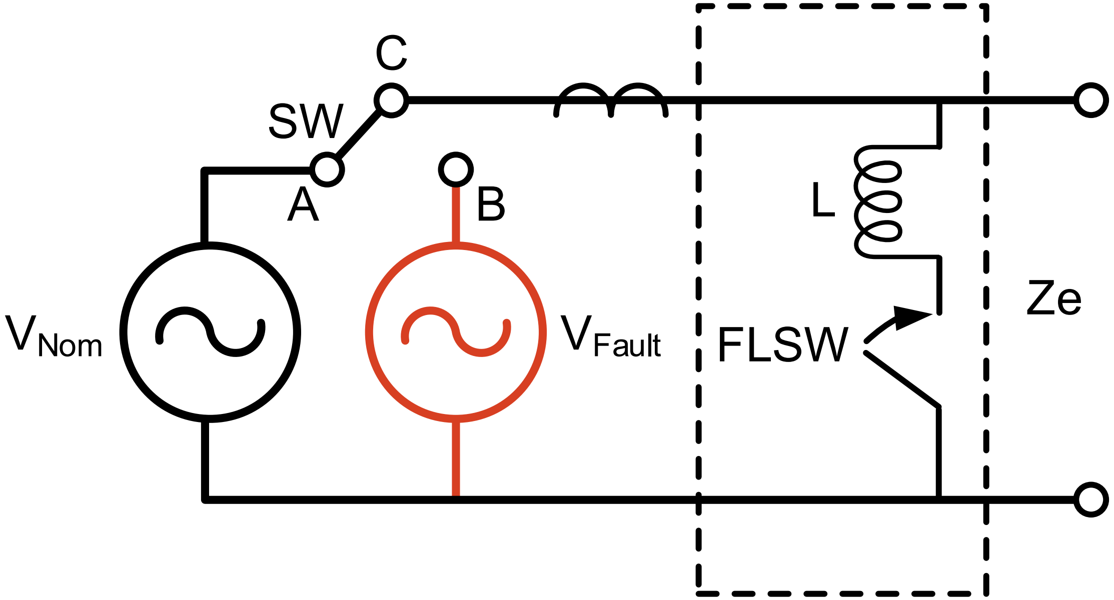
87R operation for three-phase series fault

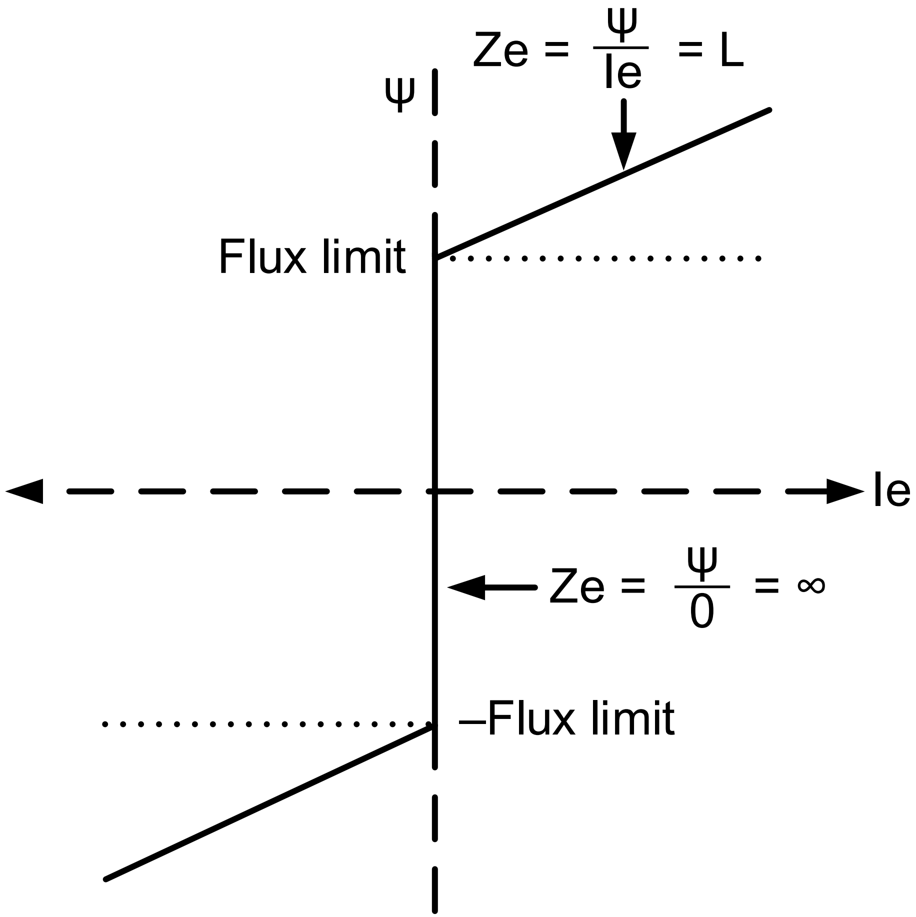
Phase C voltage and inrush current



87R operation for three-phase series fault

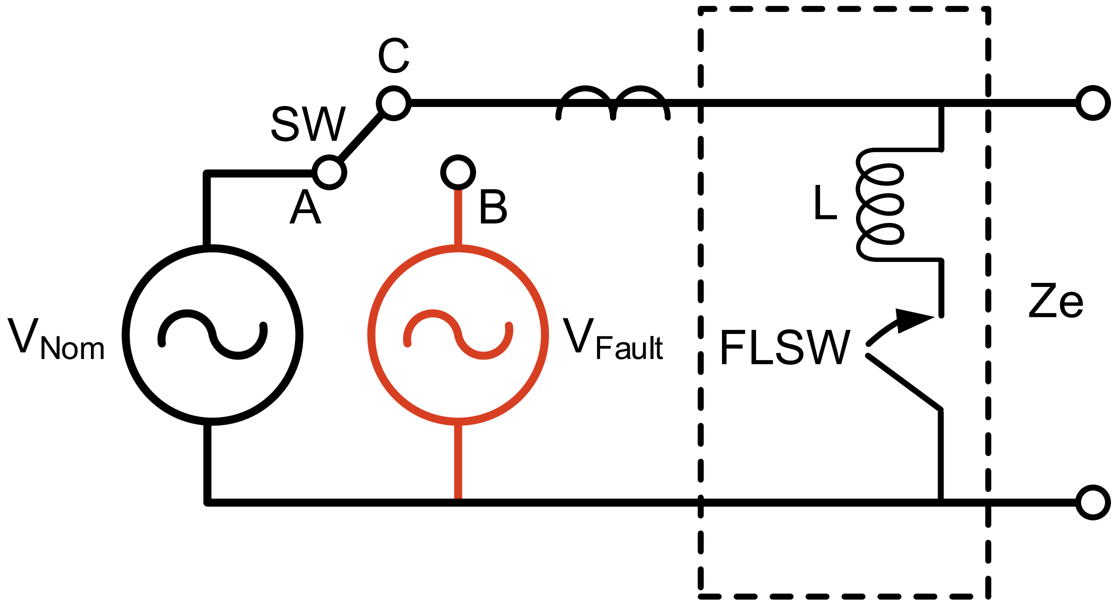
Inrush theory at bird's eye view

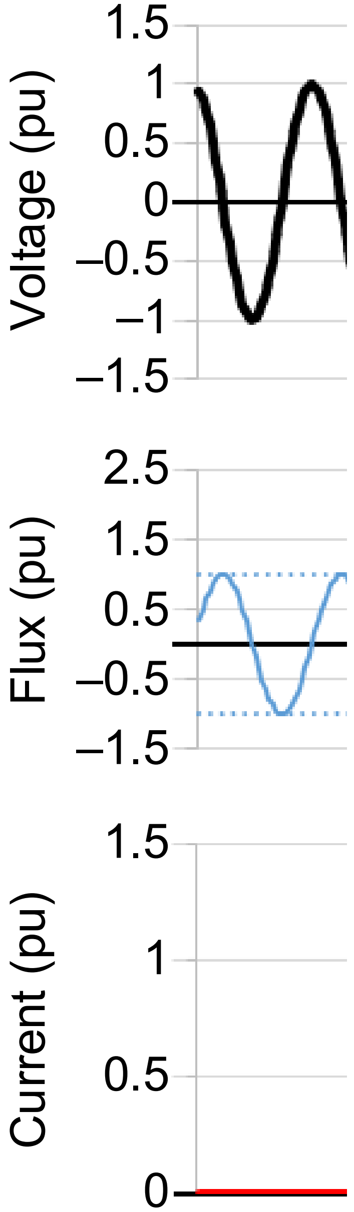




87R operation for three-phase series fault

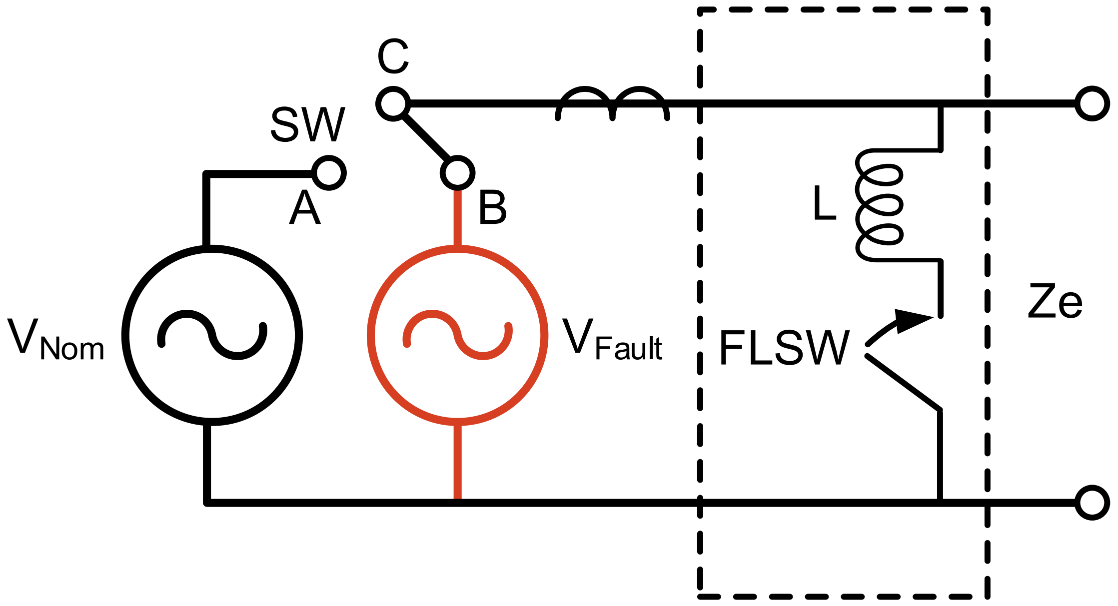
Inrush simulation replicating real-life capture

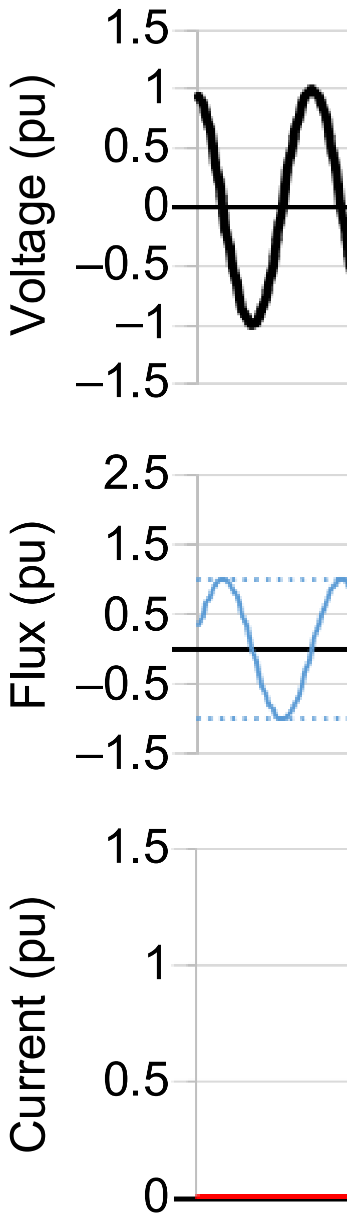




87R operation for three-phase series fault

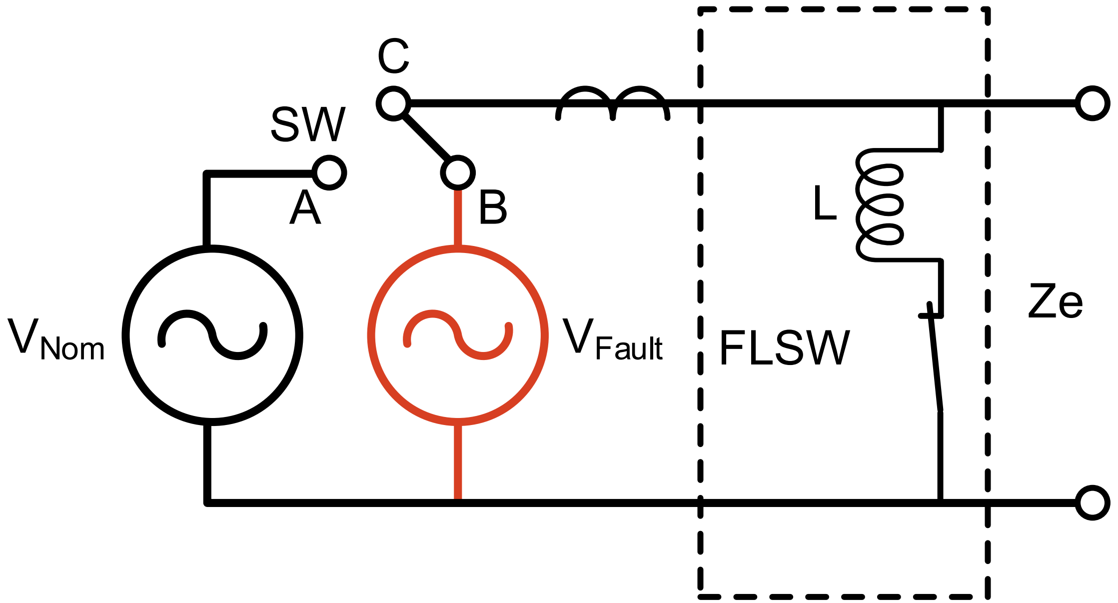
Inrush simulation replicating real-life capture

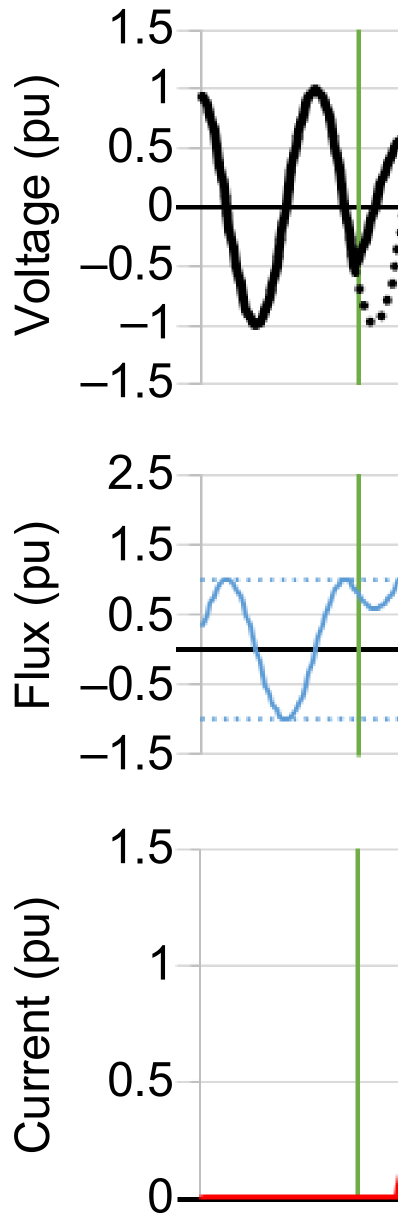




87R operation for three-phase series fault

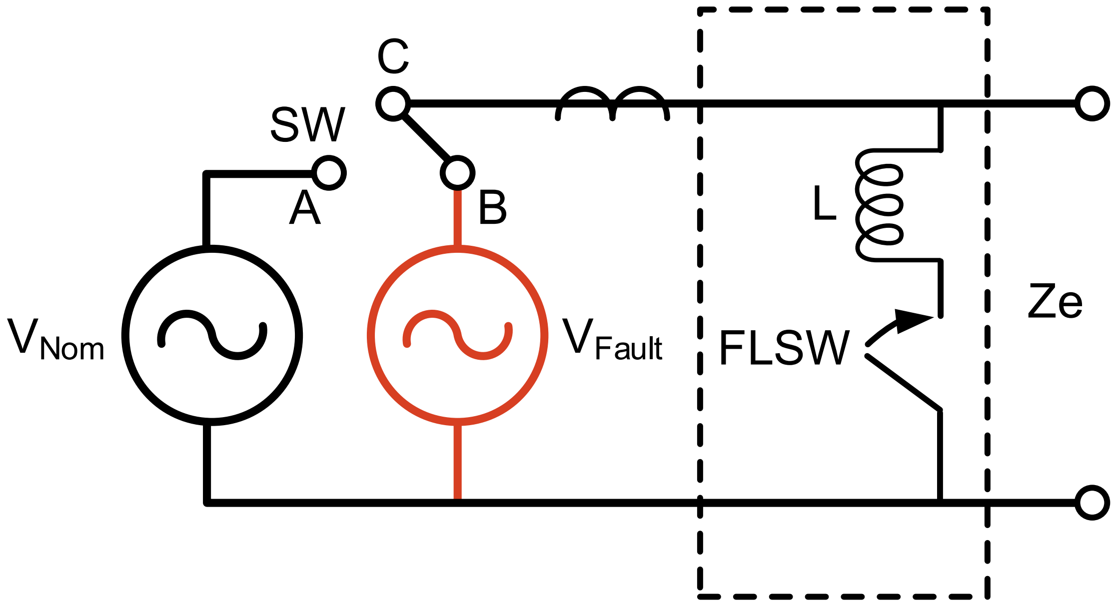
Inrush simulation replicating real-life capture

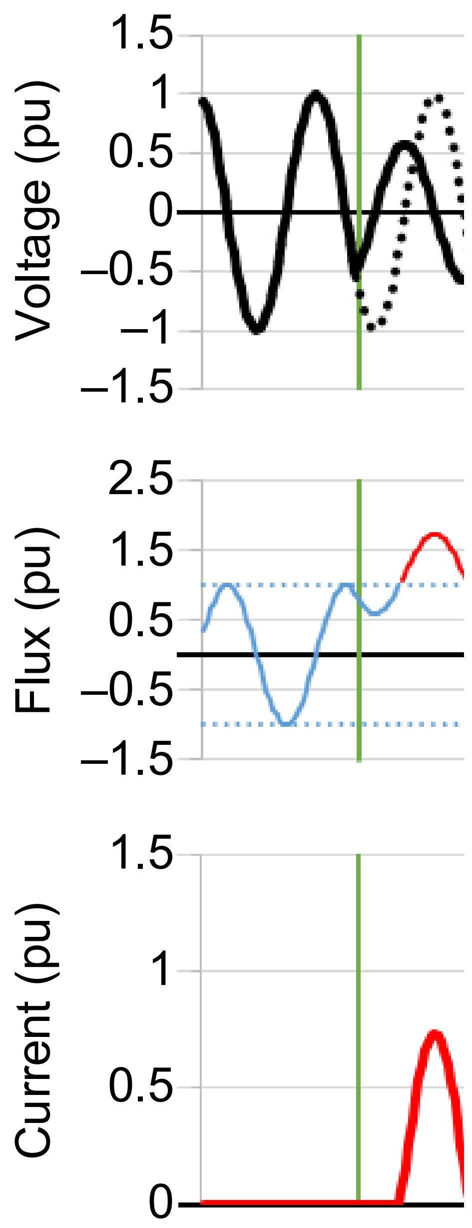




87R operation for three-phase series fault

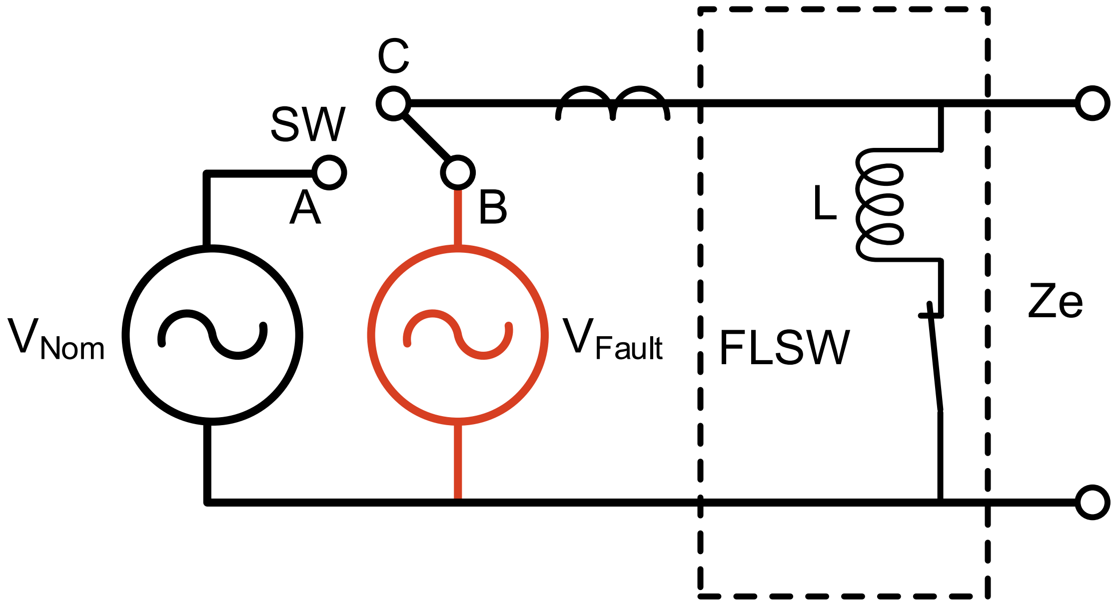
Inrush simulation replicating real-life capture

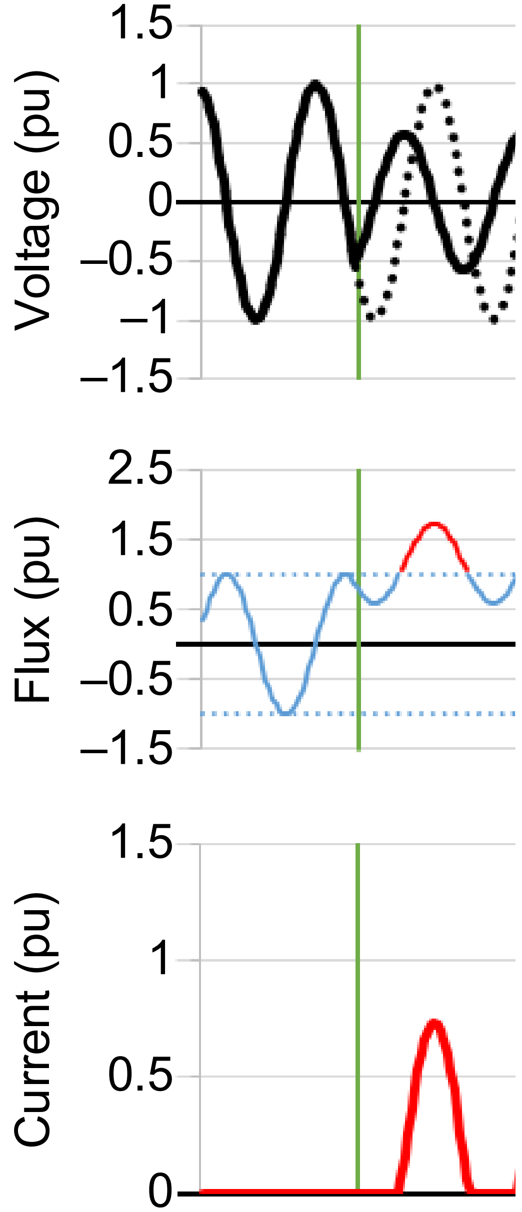




87R operation for three-phase series fault

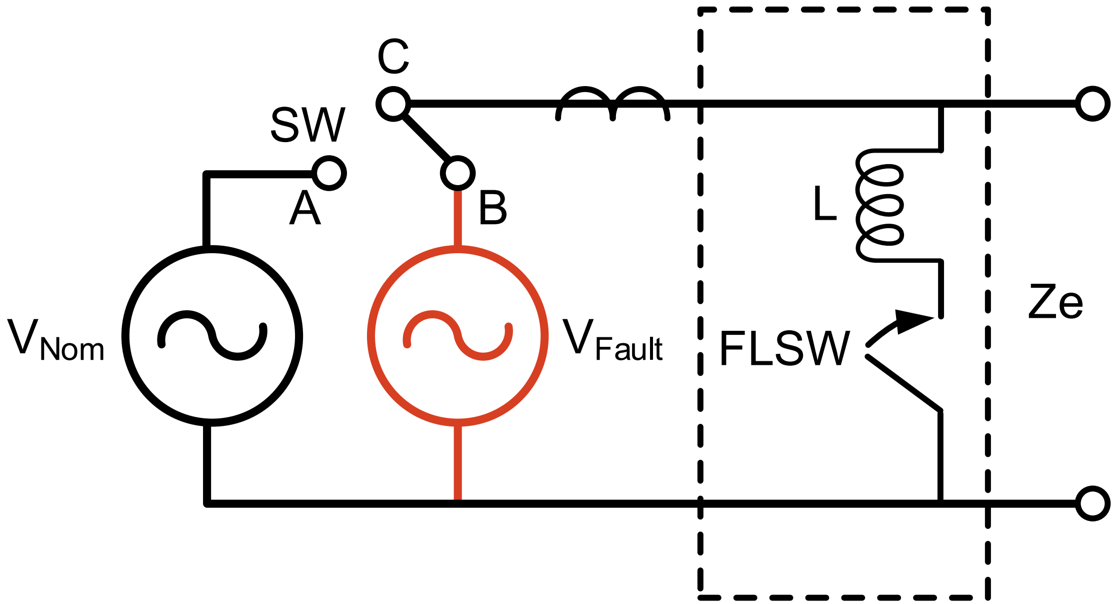
Inrush simulation replicating real-life capture

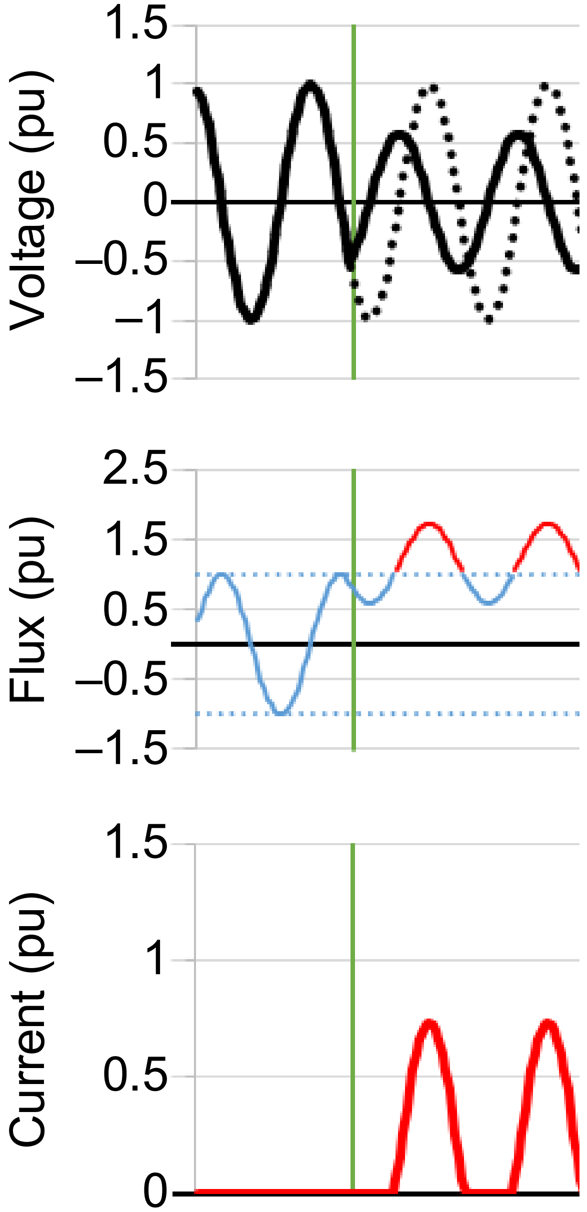




87R operation for three-phase series fault

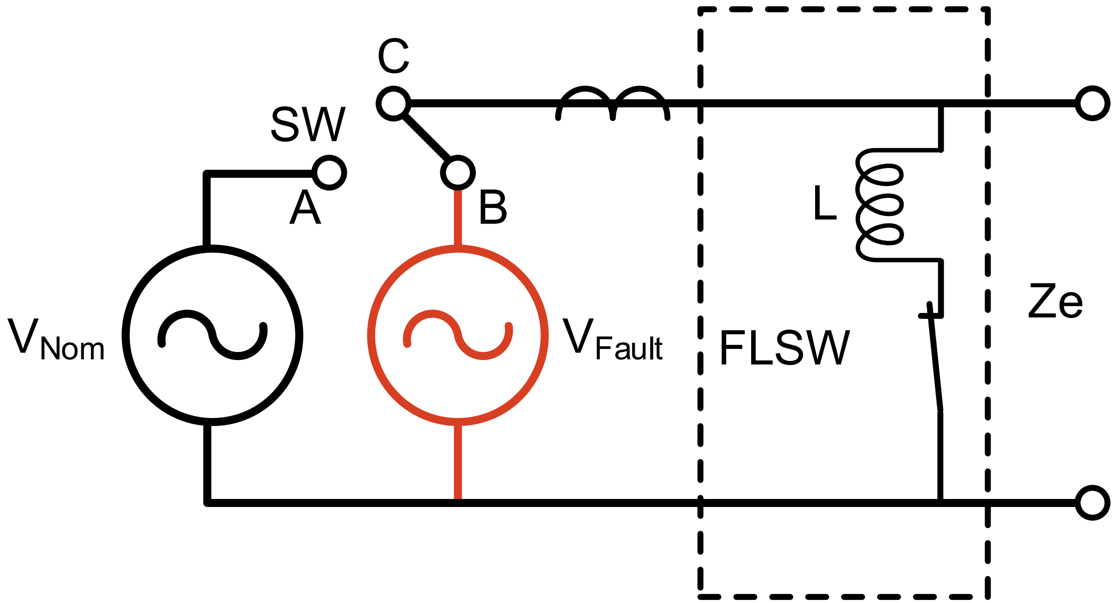
Inrush simulation replicating real-life capture

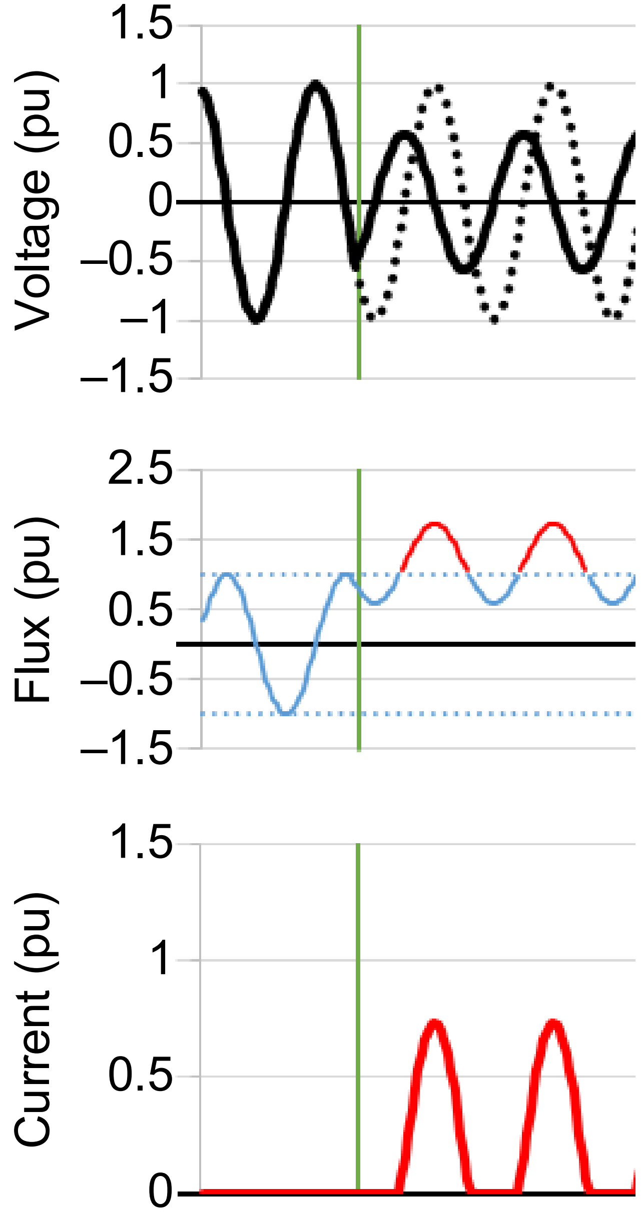




87R operation for three-phase series fault

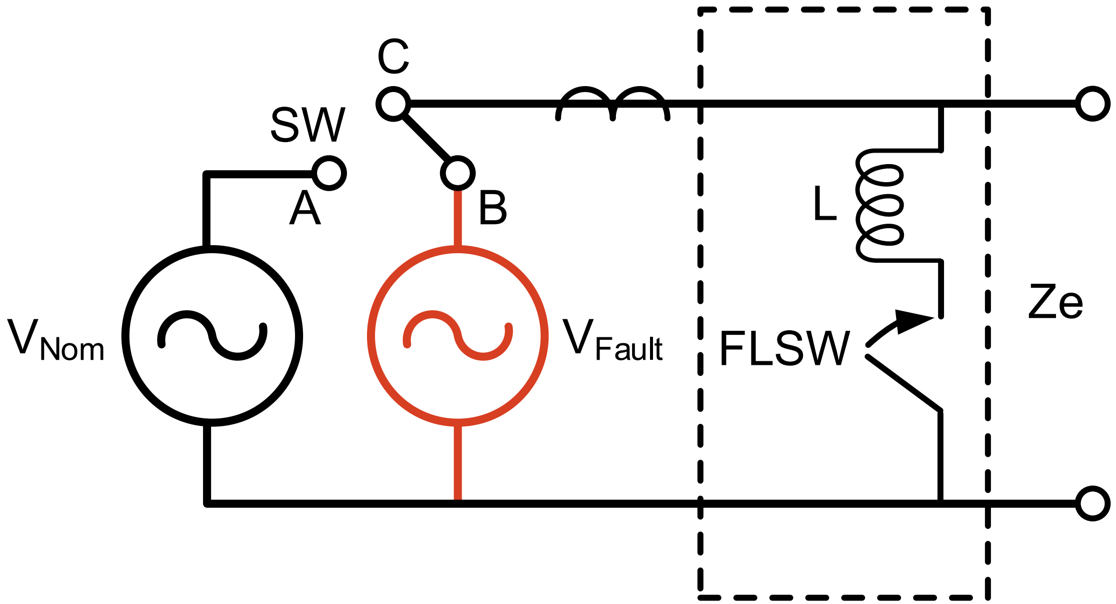
Inrush simulation replicating real-life capture

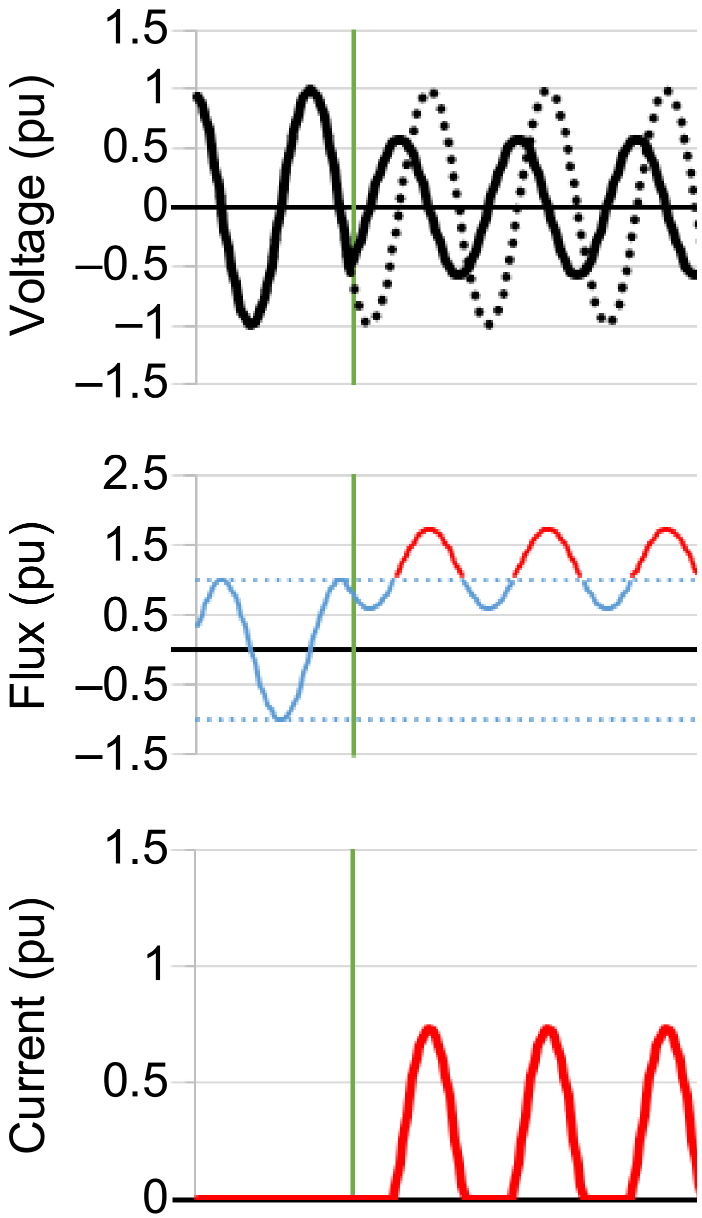




87R operation for three-phase series fault

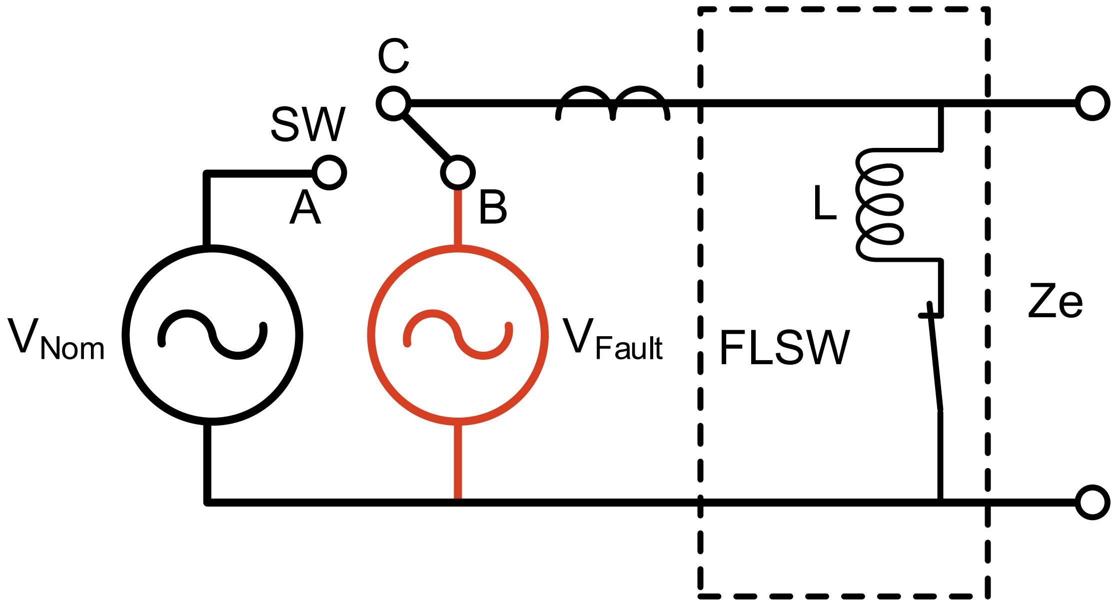
Inrush simulation replicating real-life capture

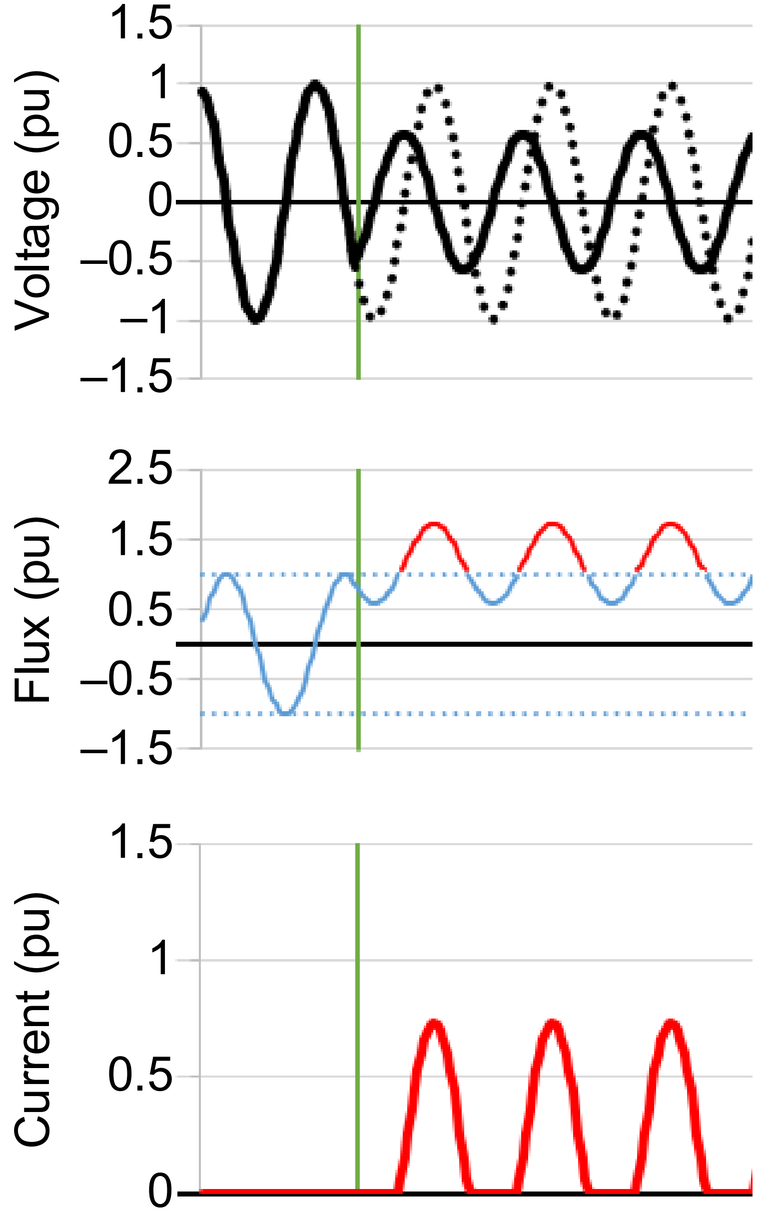




87R operation for three-phase series fault

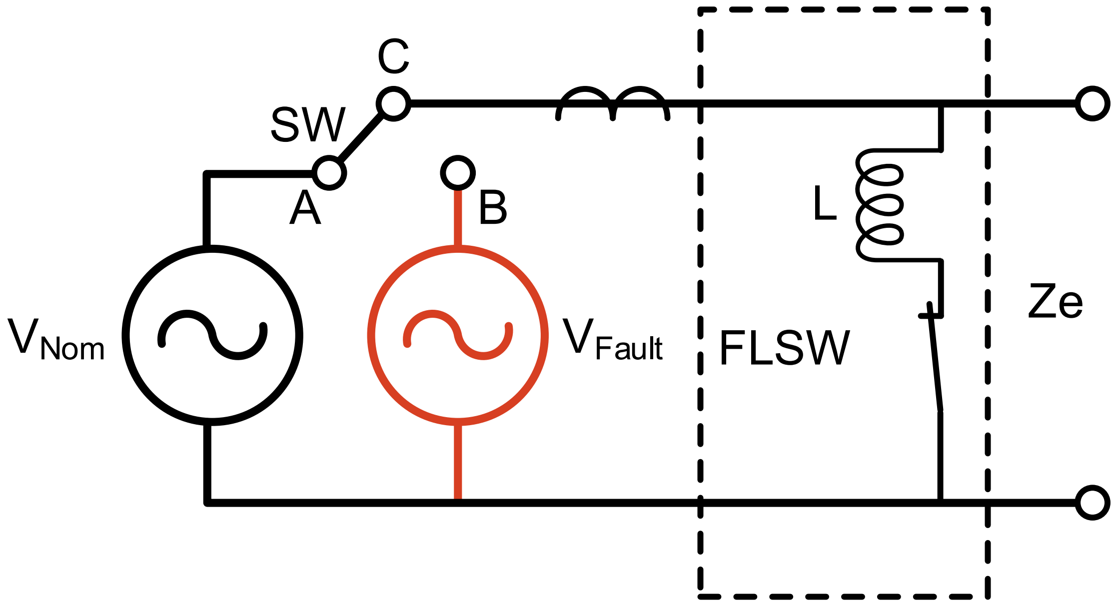
Inrush simulation replicating real-life capture

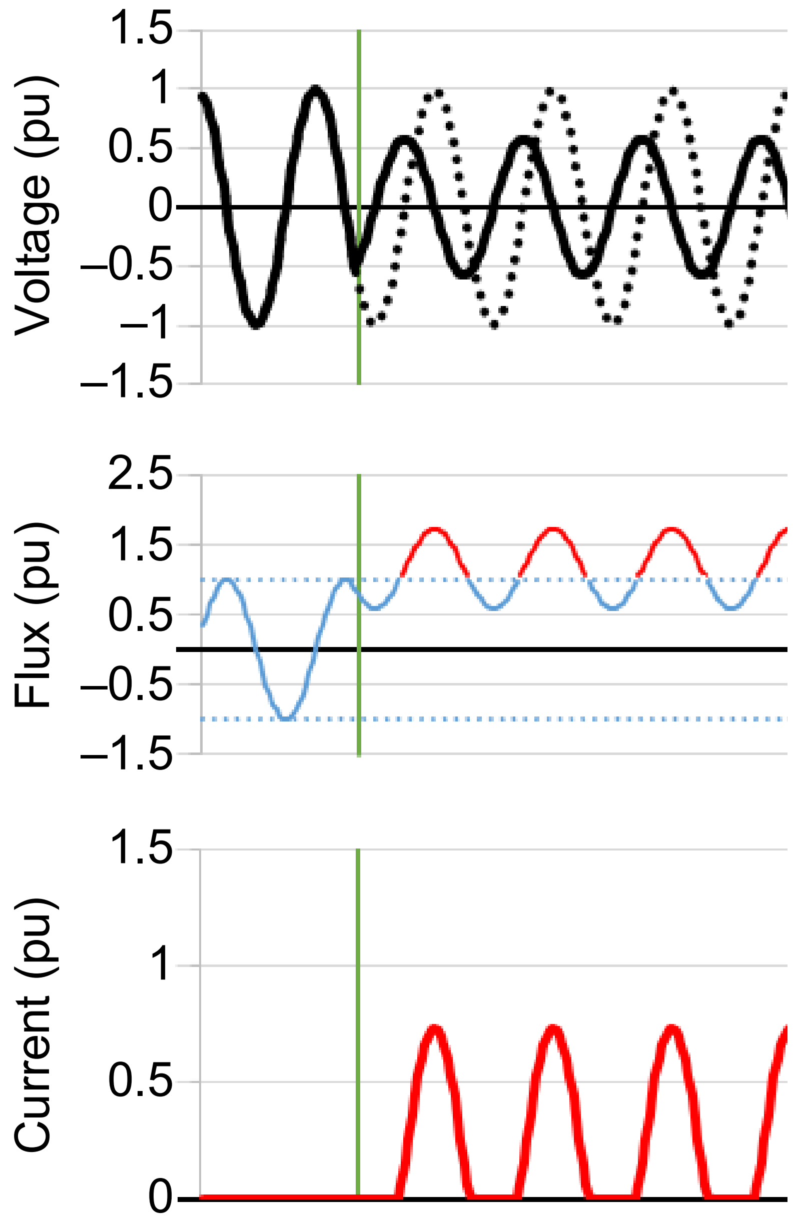




87R operation for three-phase series fault

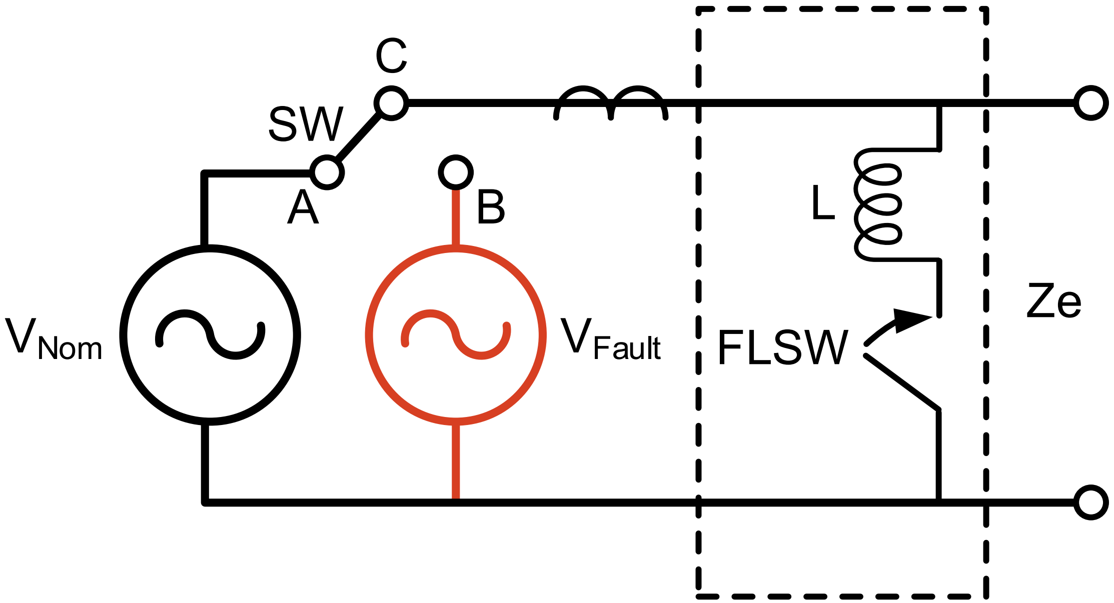
Inrush simulation replicating real-life capture

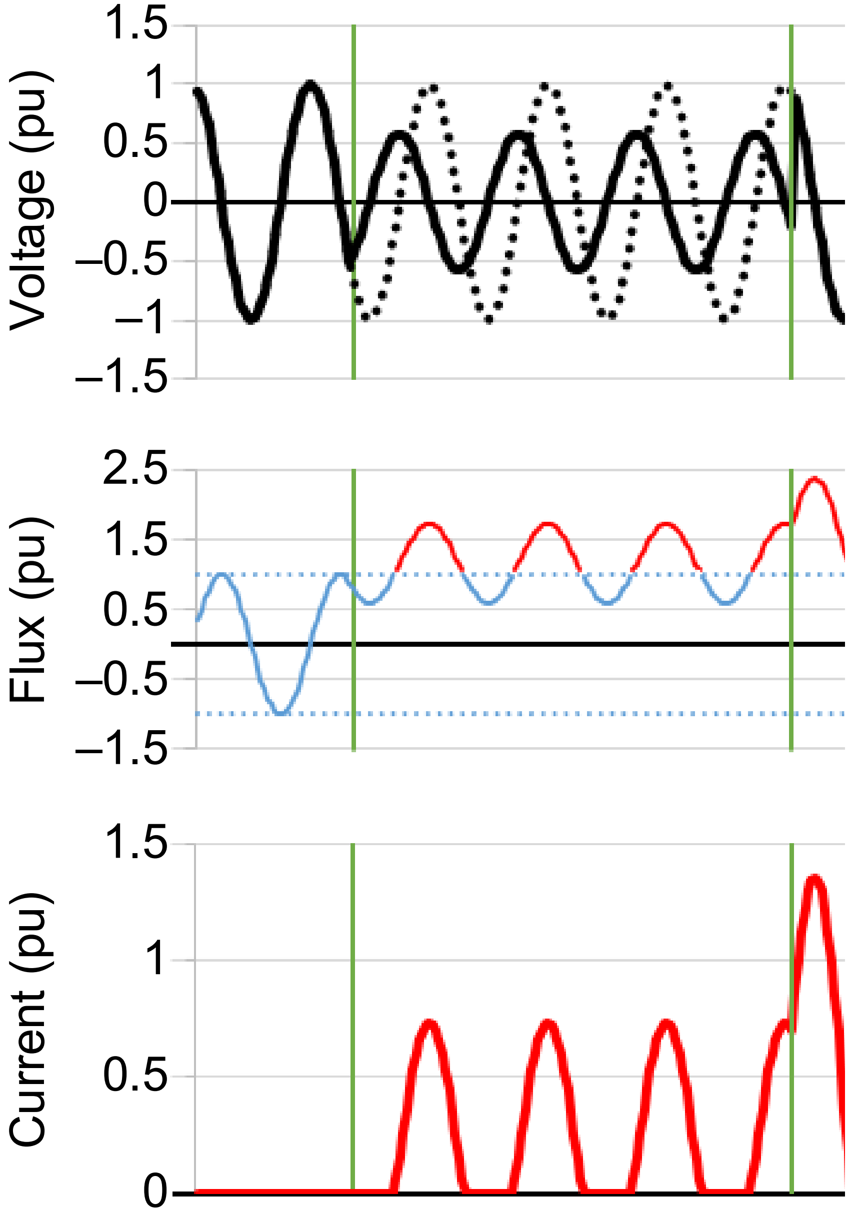




87R operation for three-phase series fault

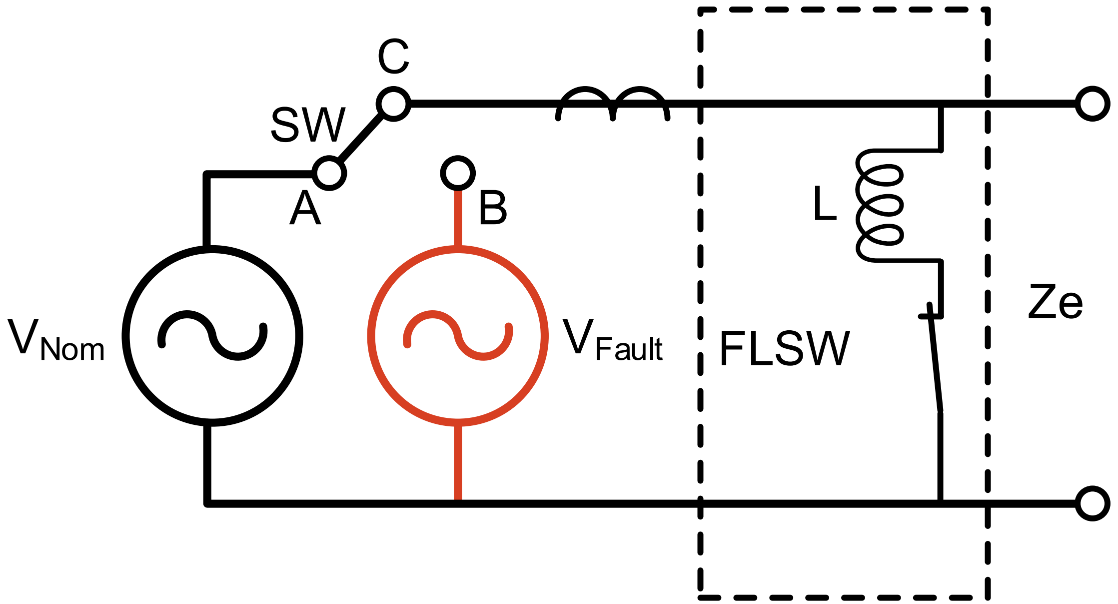
Inrush simulation replicating real-life capture

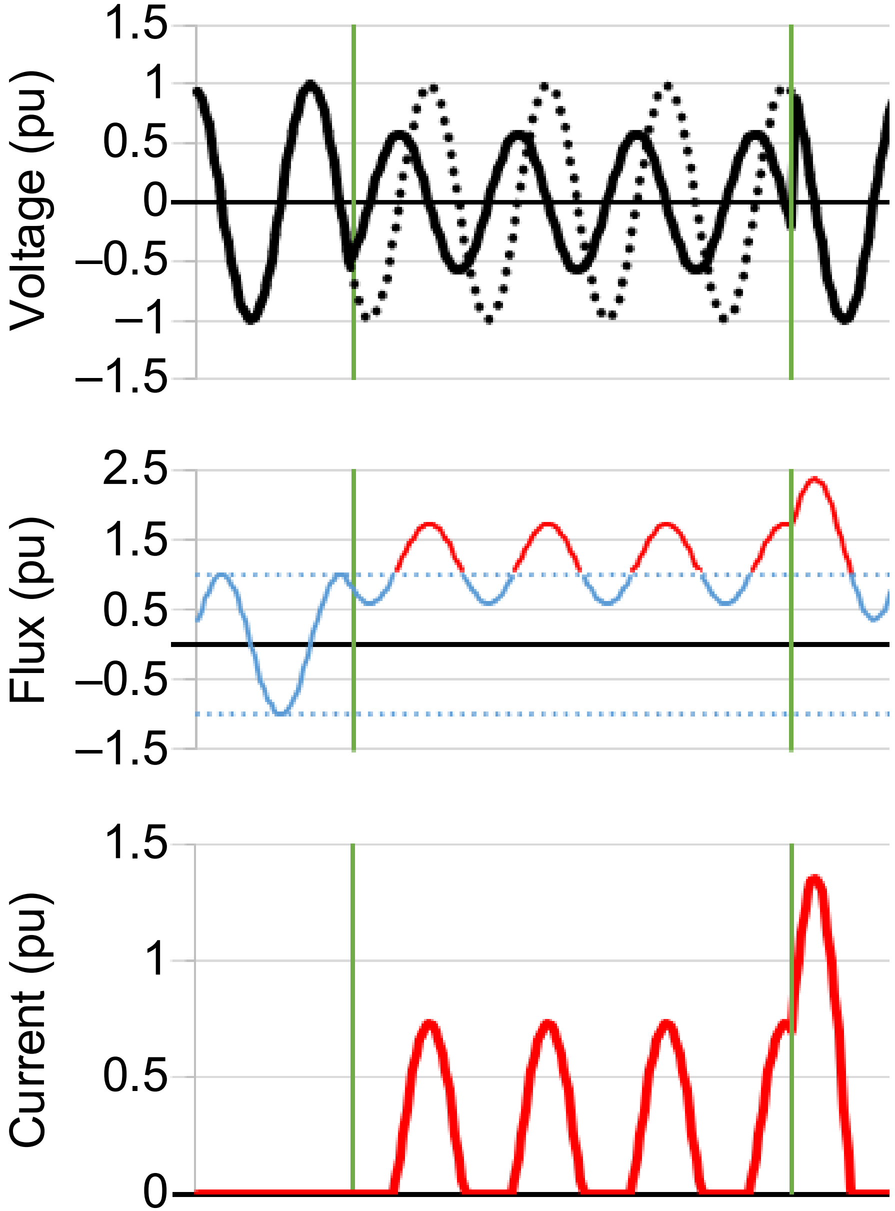




87R operation for three-phase series fault

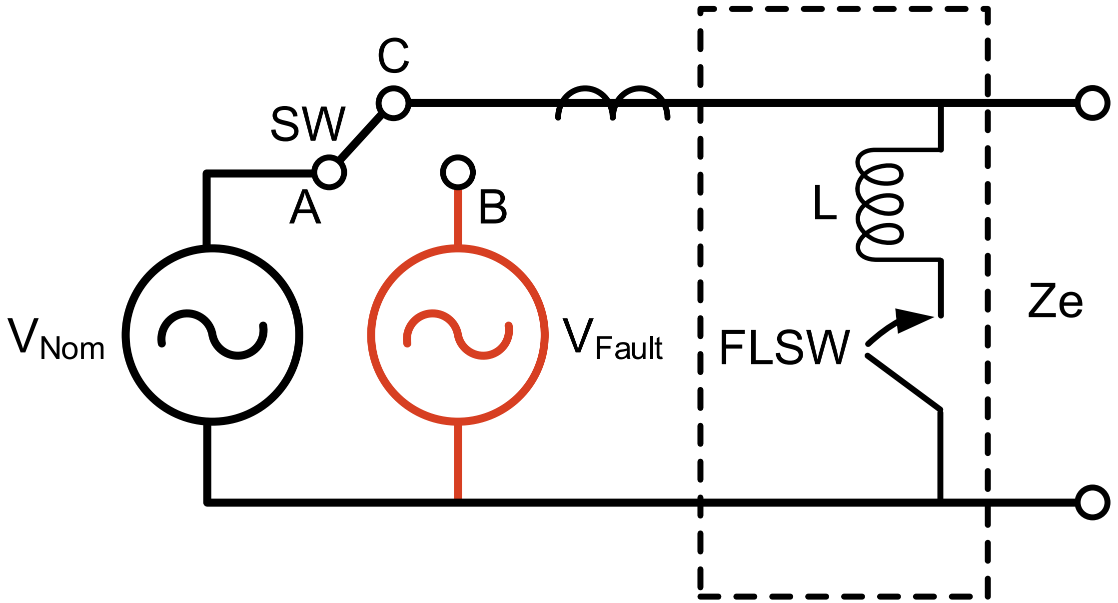
Inrush simulation replicating real-life capture

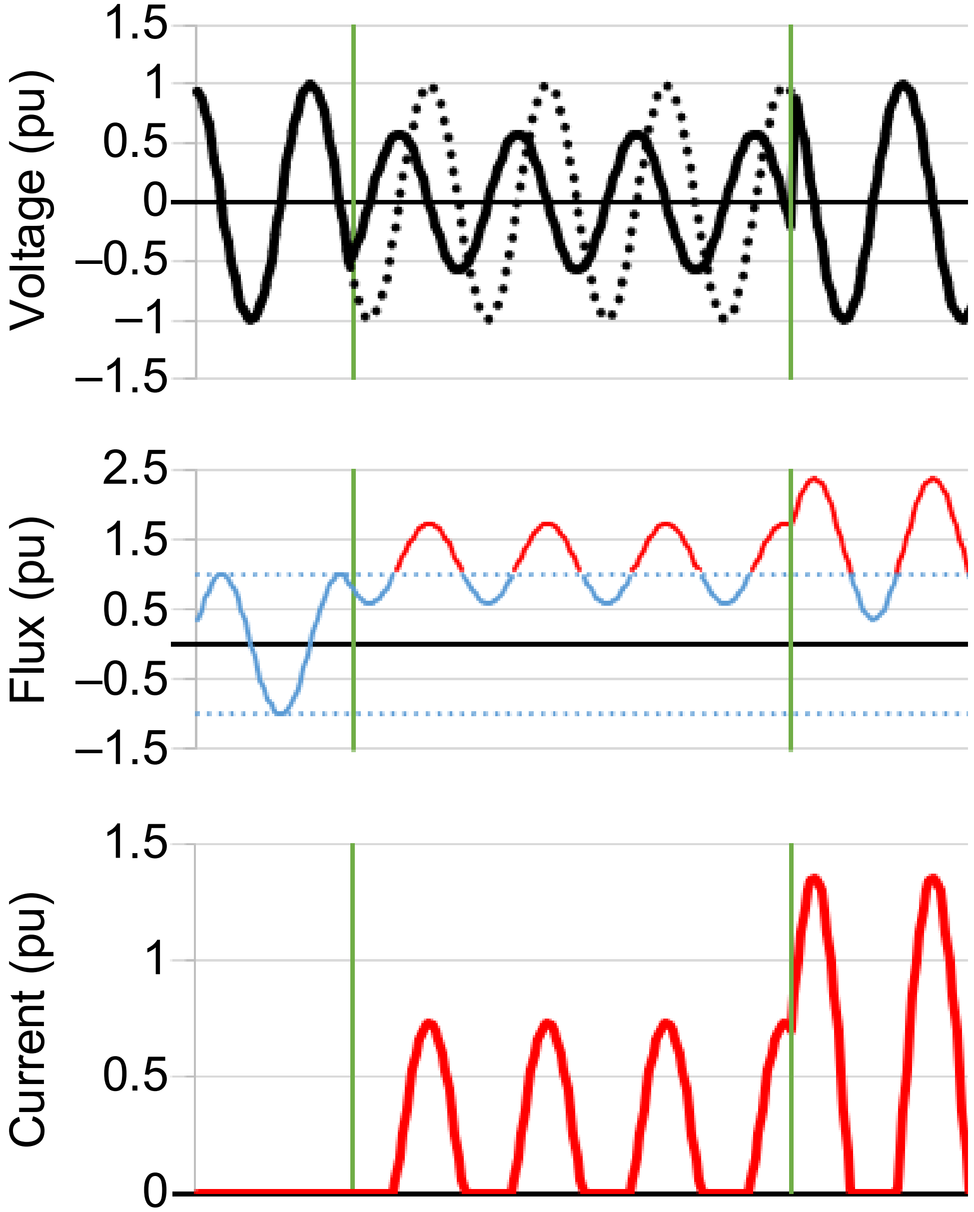




87R operation for three-phase series fault

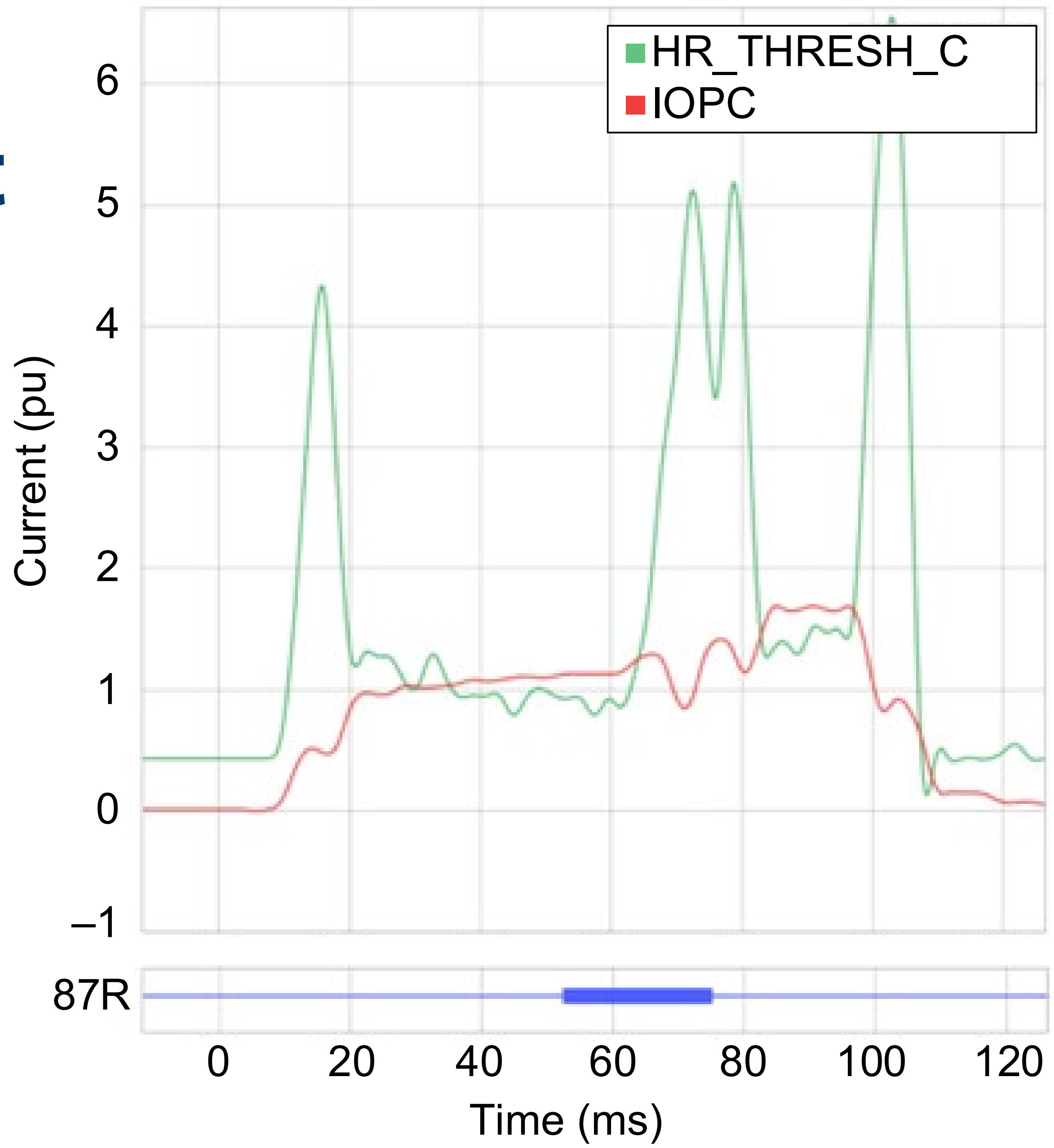
Inrush simulation replicating real-life capture





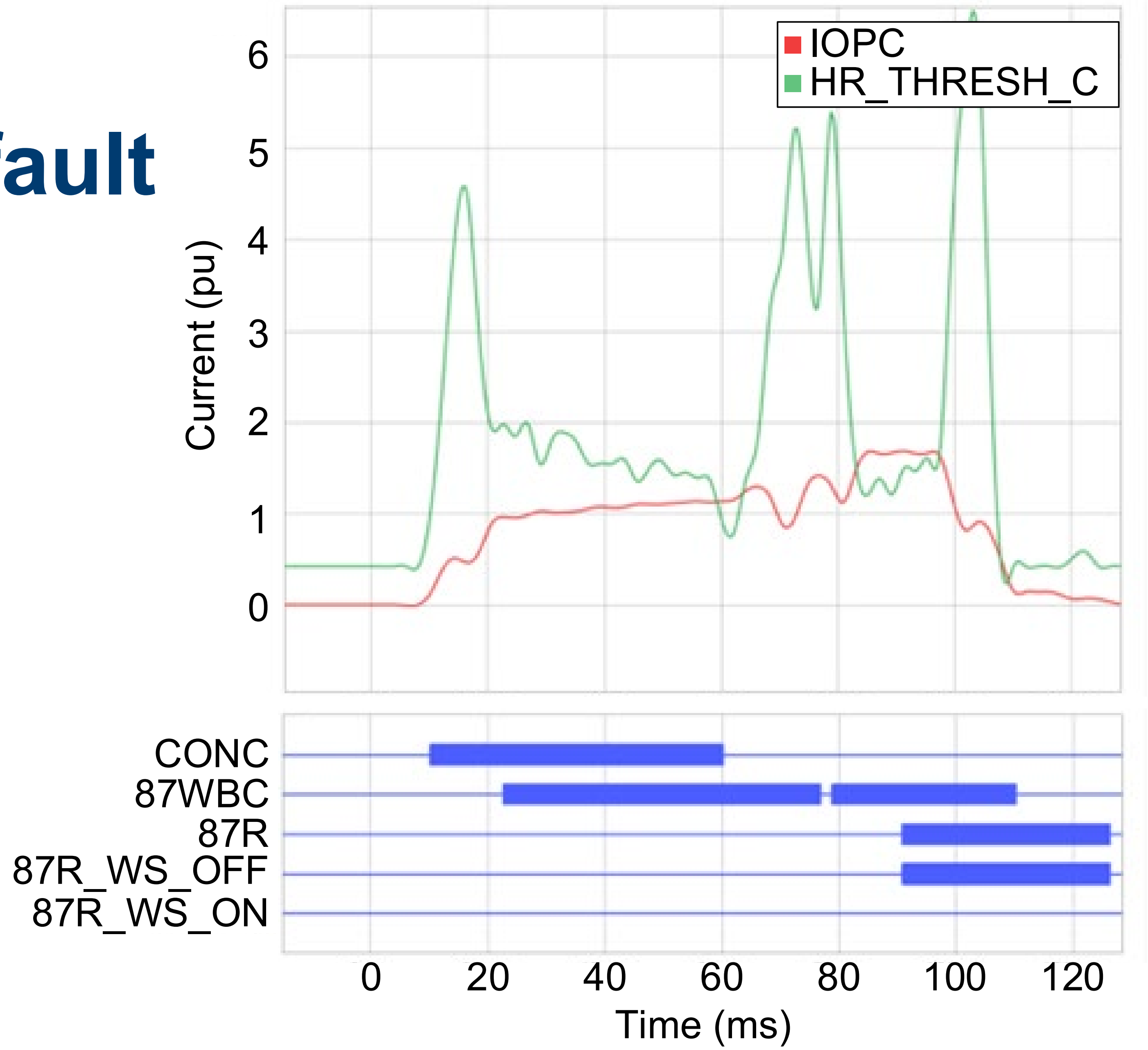
87R operation for three-phase series fault

In-service relay



87R operation for three-phase series fault

Advancements in 87R security



Conclusion

- Three-phase cross-connect faults are not the typical shunt fault type, so relay security can be challenged
- Distance relays, which rely on $V1_{MEM}$, may misoperate for this type of man-made fault
  - As a result, communications-assisted schemes, like DCB schemes, are susceptible to misoperation
  - Relay advancements in memory polarization provide additional security
- Inrush current is possible with low second-harmonic content
  - Relay advancements improve security on transformer differential relays

Questions?