A Fresh Look at Practical Shunt Reactor Protection

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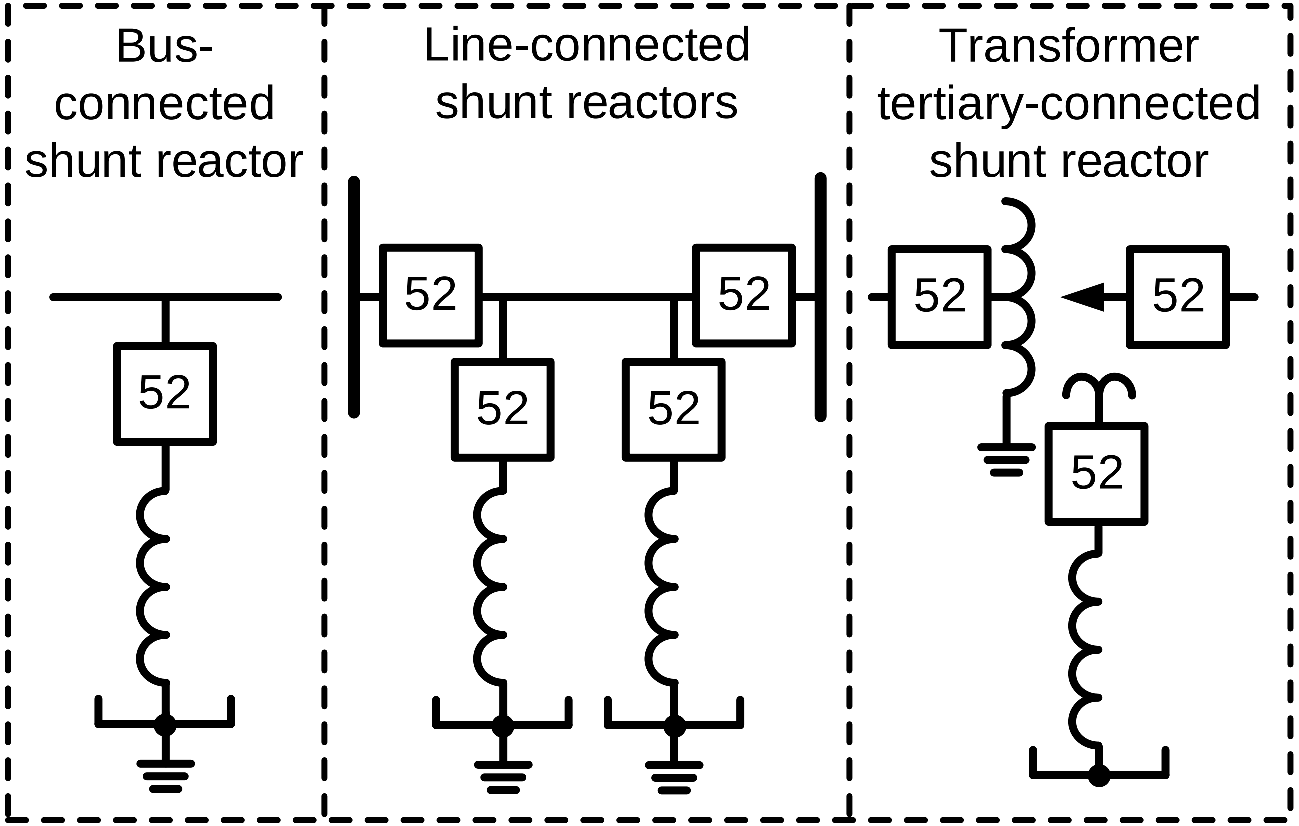
Shunt reactor applications

- Regulate system voltage under light loading
- Reactor connections
  - Bus-connected
  - Line-connected
    - Solidly grounded
    - Ground (4th) reactor (SPT applications)
  - Tertiary-connected (typically ungrounded)



Reactor types

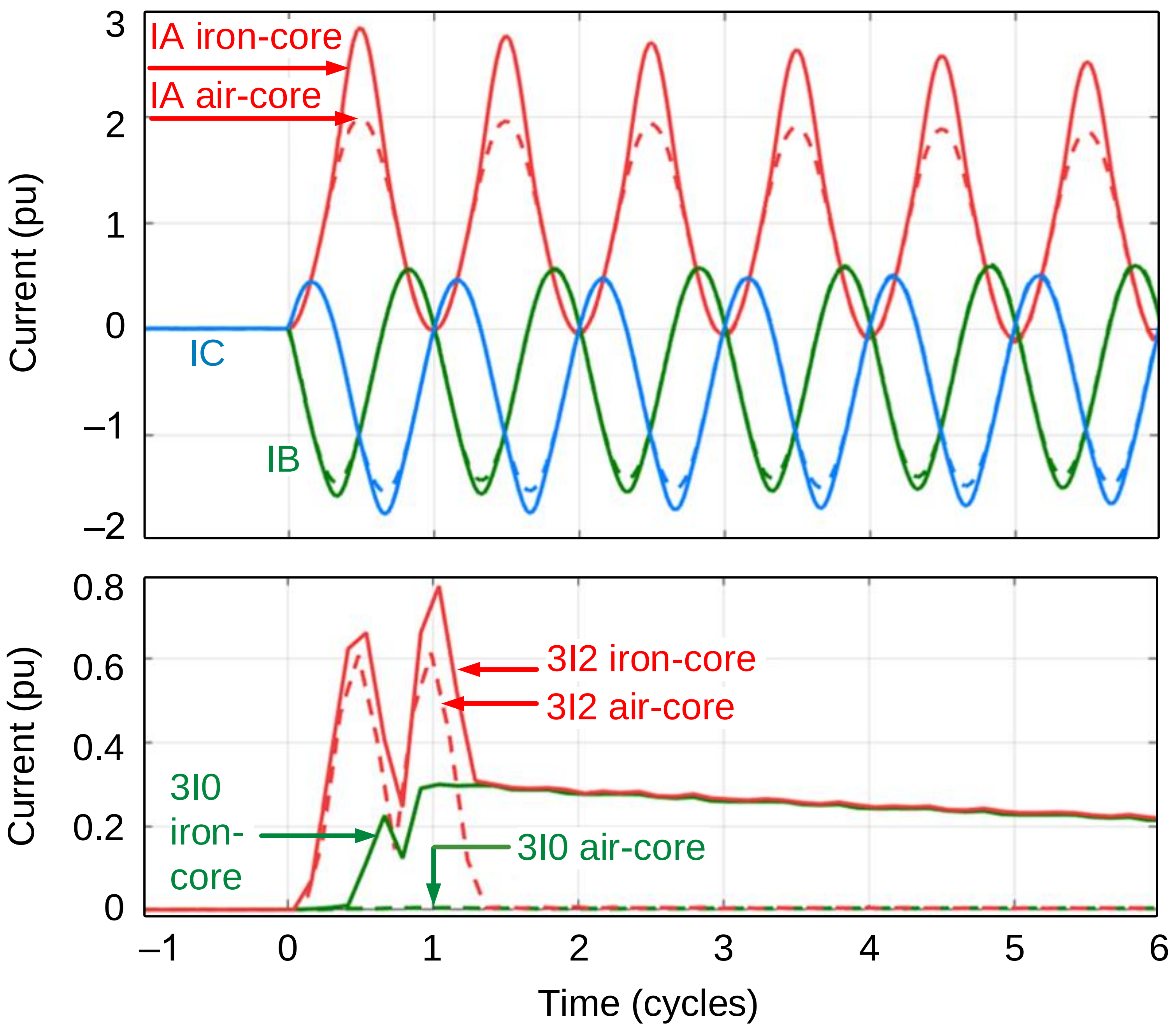
Iron core

- Gapped core
- Usually oil-immersed

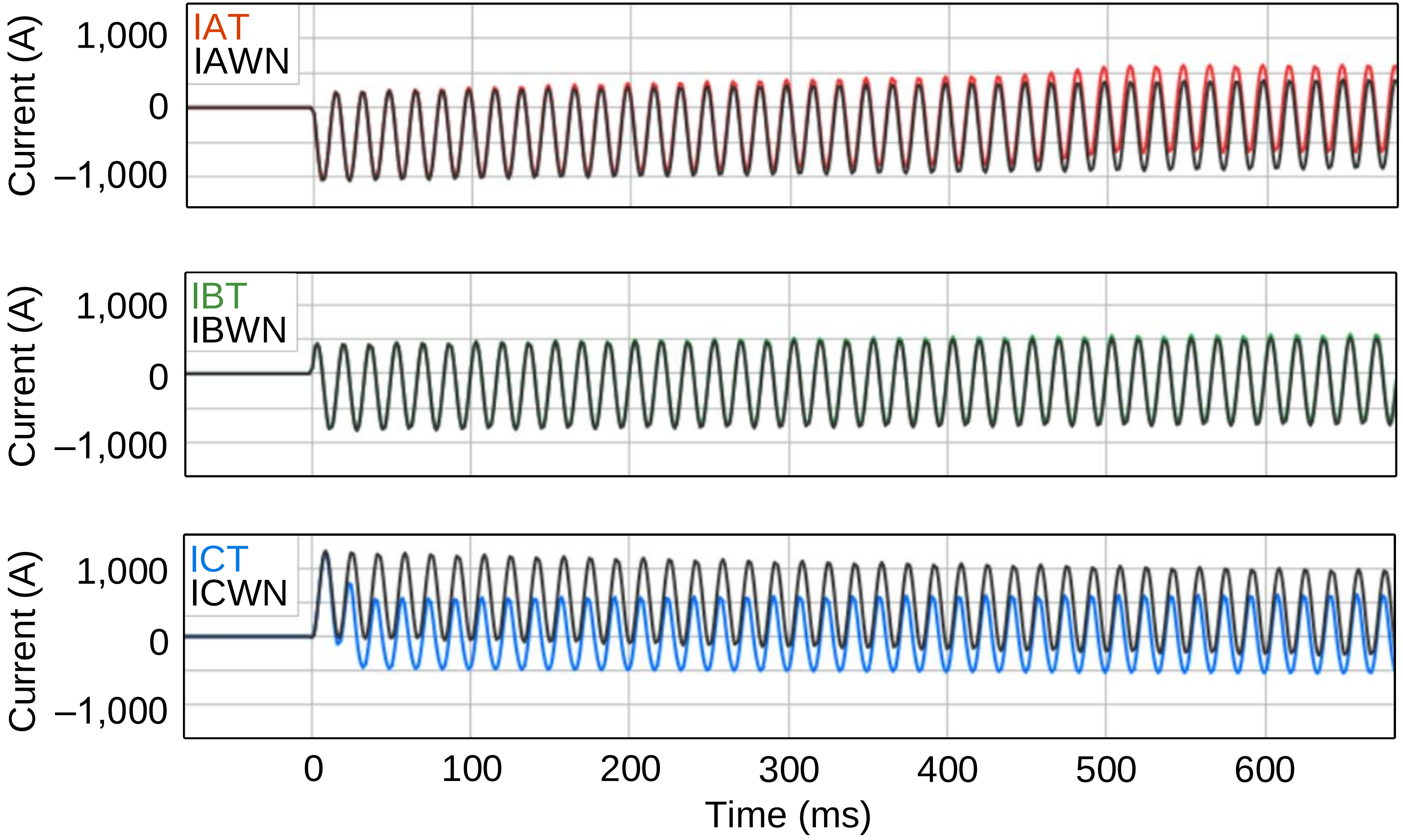
Air core

- Environmental concerns
- Older unit at lower voltage
- Newer units up to 550 kV

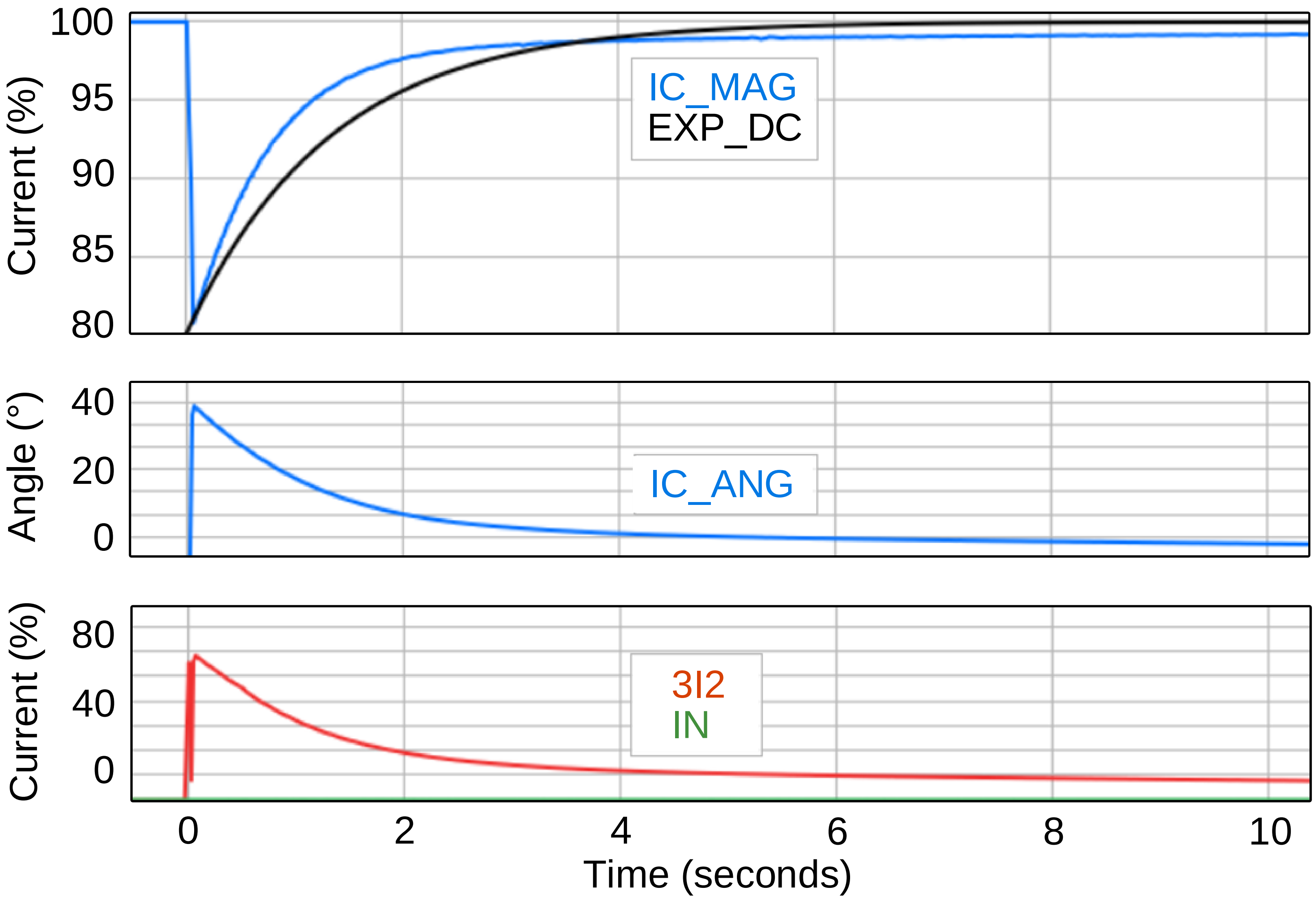
Reactor energization



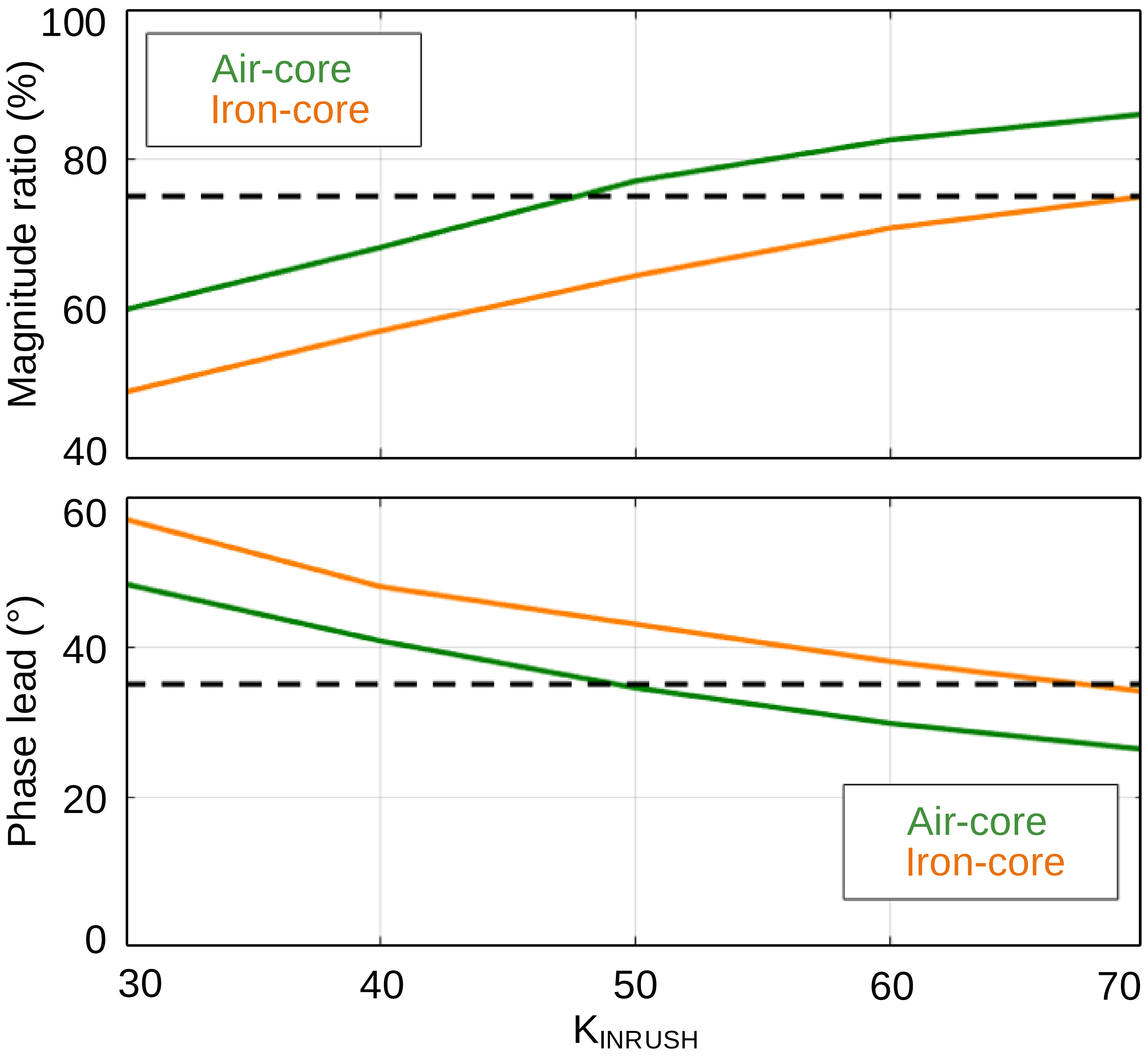
CT saturation (loss of dc) – air-core reactor



Measurement errors

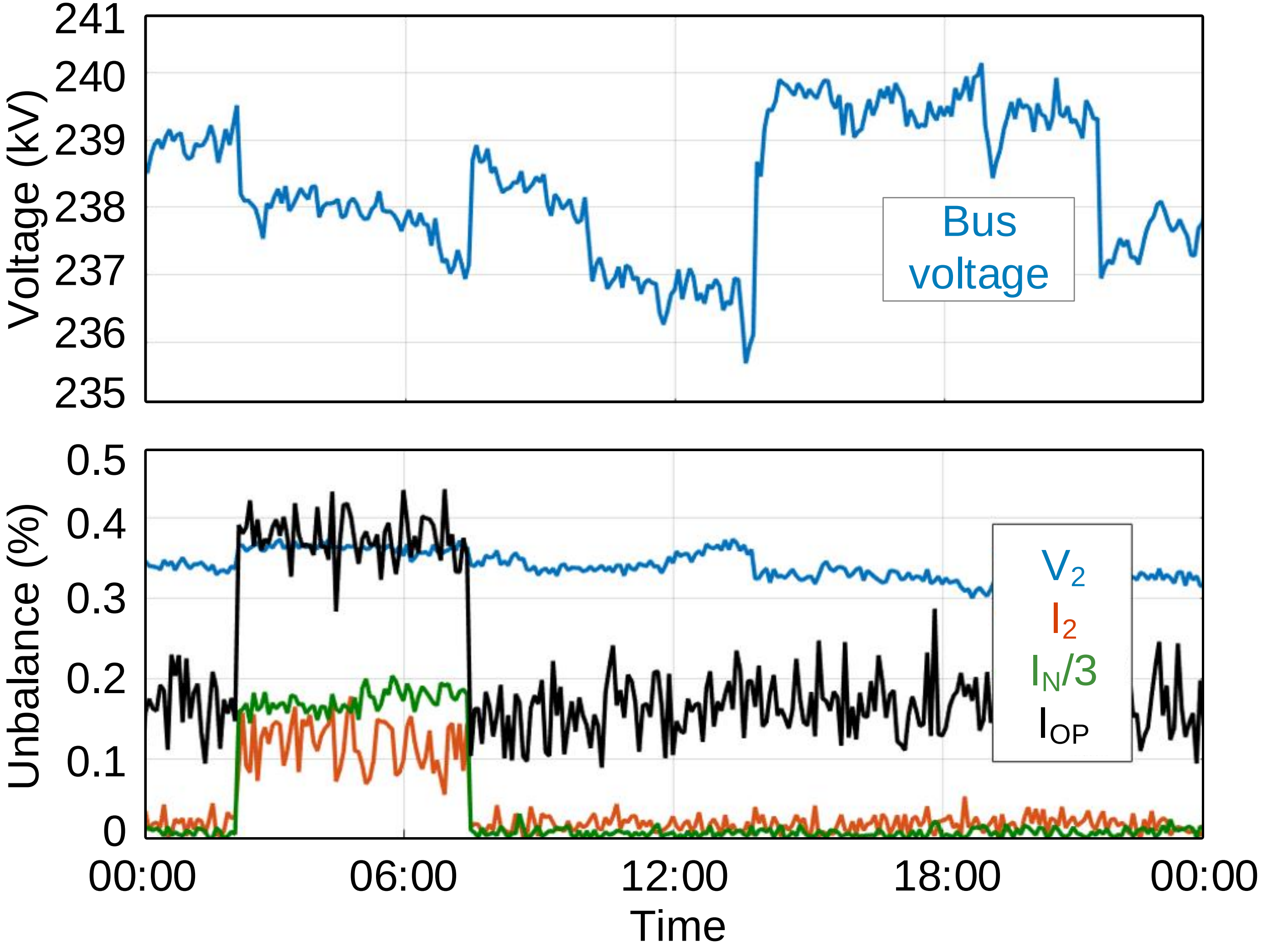


Measurement errors

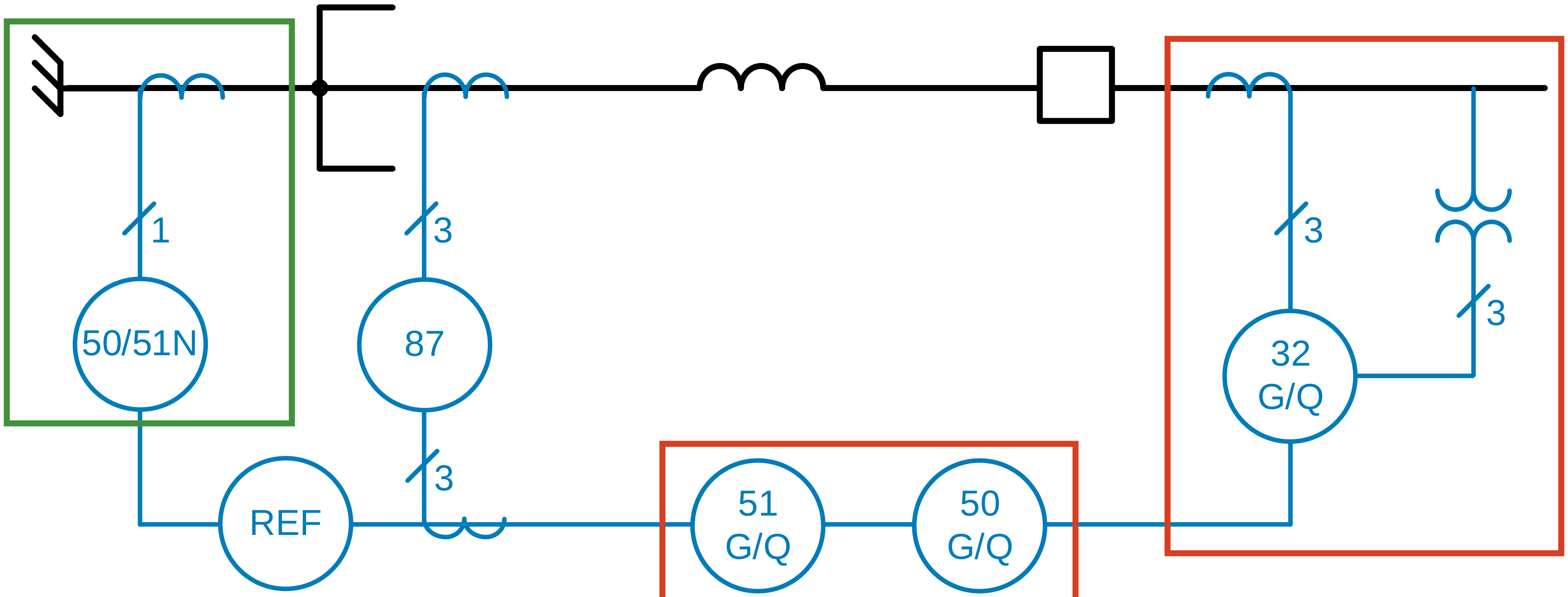


$$K_{INRUSH} = \frac{V_{SAT}}{(I_{RATED} / CTR) \cdot (R_{CT} + R_B)}$$

Measurement errors

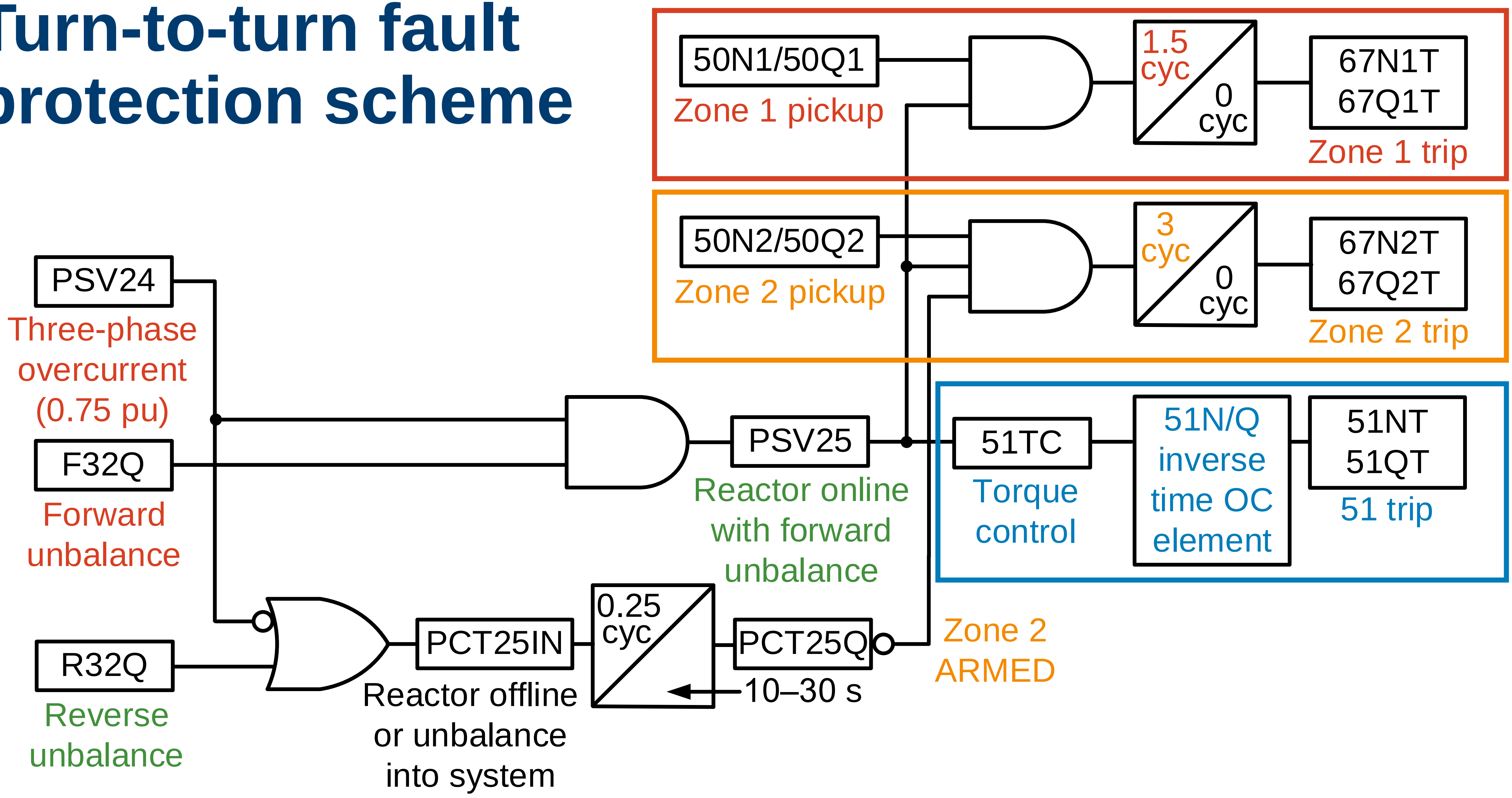


Functional overview



Turn-to-turn fault protection

Turn-to-turn fault protection scheme



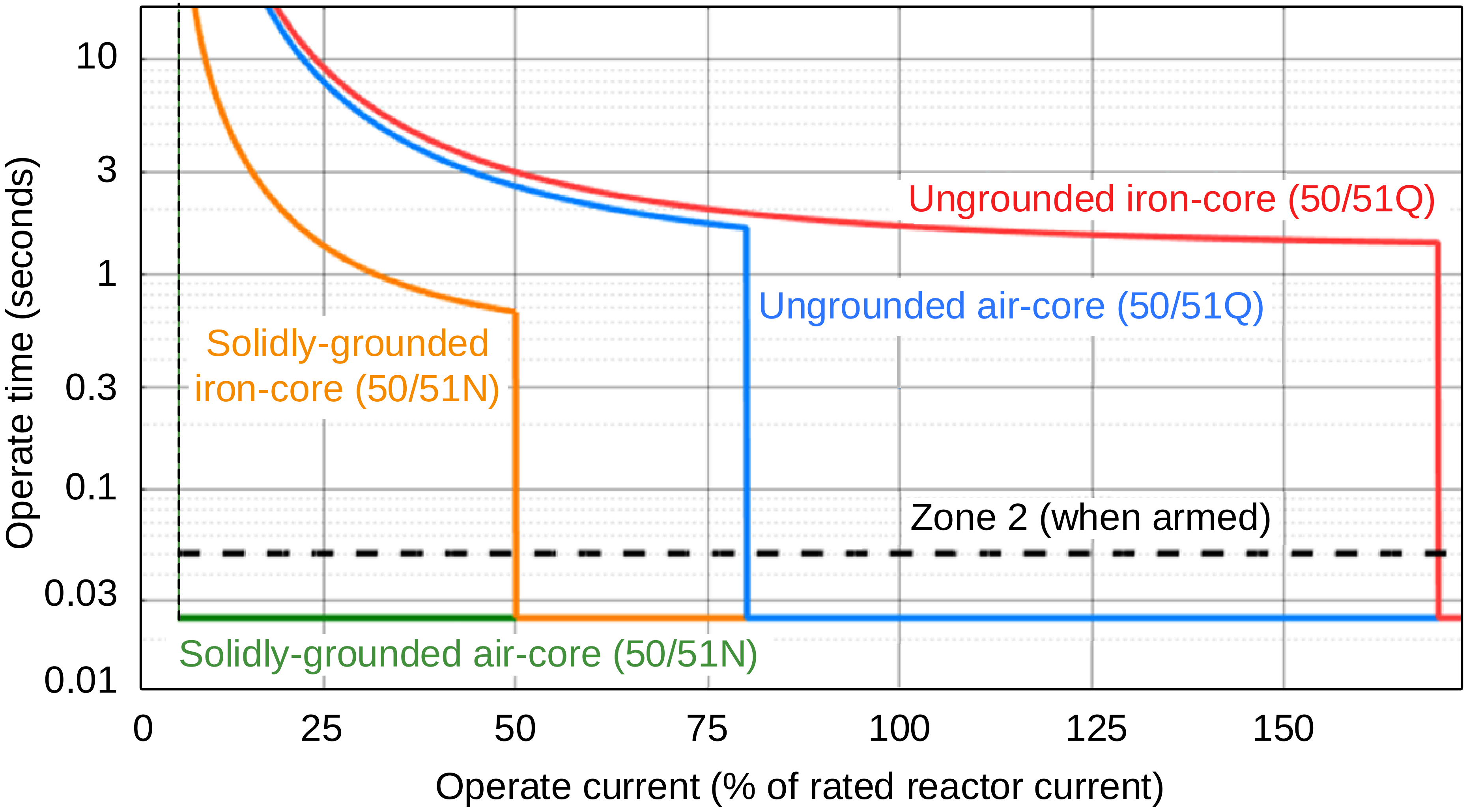
Settings

Four-reactor bank protection scheme gains dependability by using both IN and 3I2

Reactor type	50/51 current used	50/67 Zone 1	50/67 Zone 2	51 inverse-time
Solidly grounded air-core	Neutral current (IN)	Pickup: 6% Delay: 1.5 cycles	—	—
Solidly grounded iron-core	Neutral current (IN)	Pickup: 50% Delay: 1.5 cycles	Pickup: 6% Delay: 3 cycles Arming delay: 10 seconds	Pickup: 6% Curve: U2 Time dial: 2.5

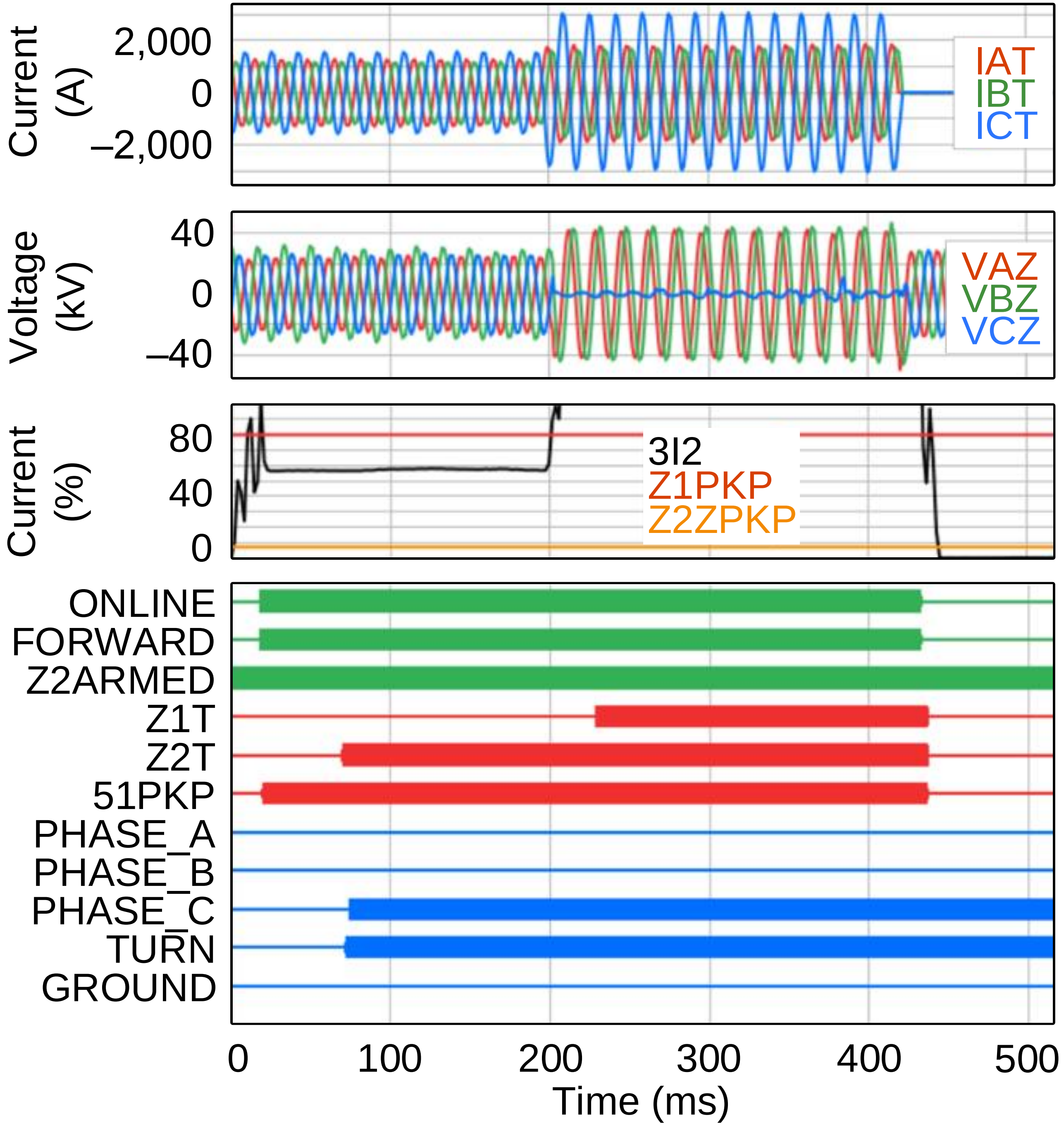
Reactor type	50/51 current used	50/67 Zone 1	50/67 Zone 2	51 inverse-time
Ungrounded air-core	Negative-sequence current (3I2)	Pickup: 80% Delay: 1.5 cycles	Pickup: 6% Delay: 3 cycles Arming delay: 30 seconds	Pickup: 10% Curve: U2 Time dial: 6
Ungrounded iron-core	Negative-sequence current (3I2)	Pickup: 170% Delay: 1.5 cycles	Pickup: 6% Delay: 3 cycles Arming delay: 30 seconds	Pickup: 10% Curve: U2 Time dial: 7

Operating times



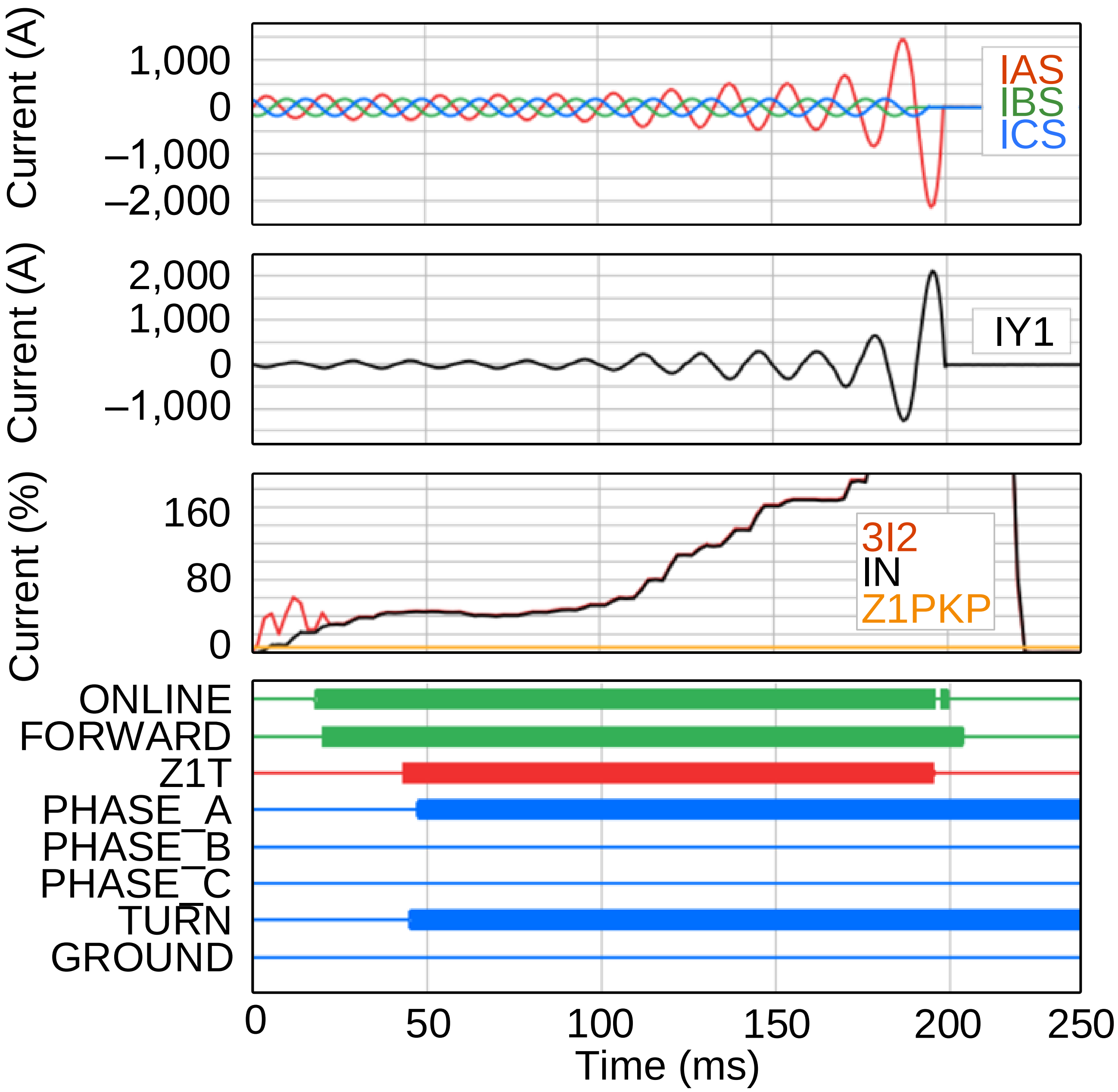
34.5 kV MV reactor

- Ungrounded air-core reactor
- Turn fault field event on 34.5 kV, 50 MVAR reactor from Xcel Energy



115 kV HV reactor

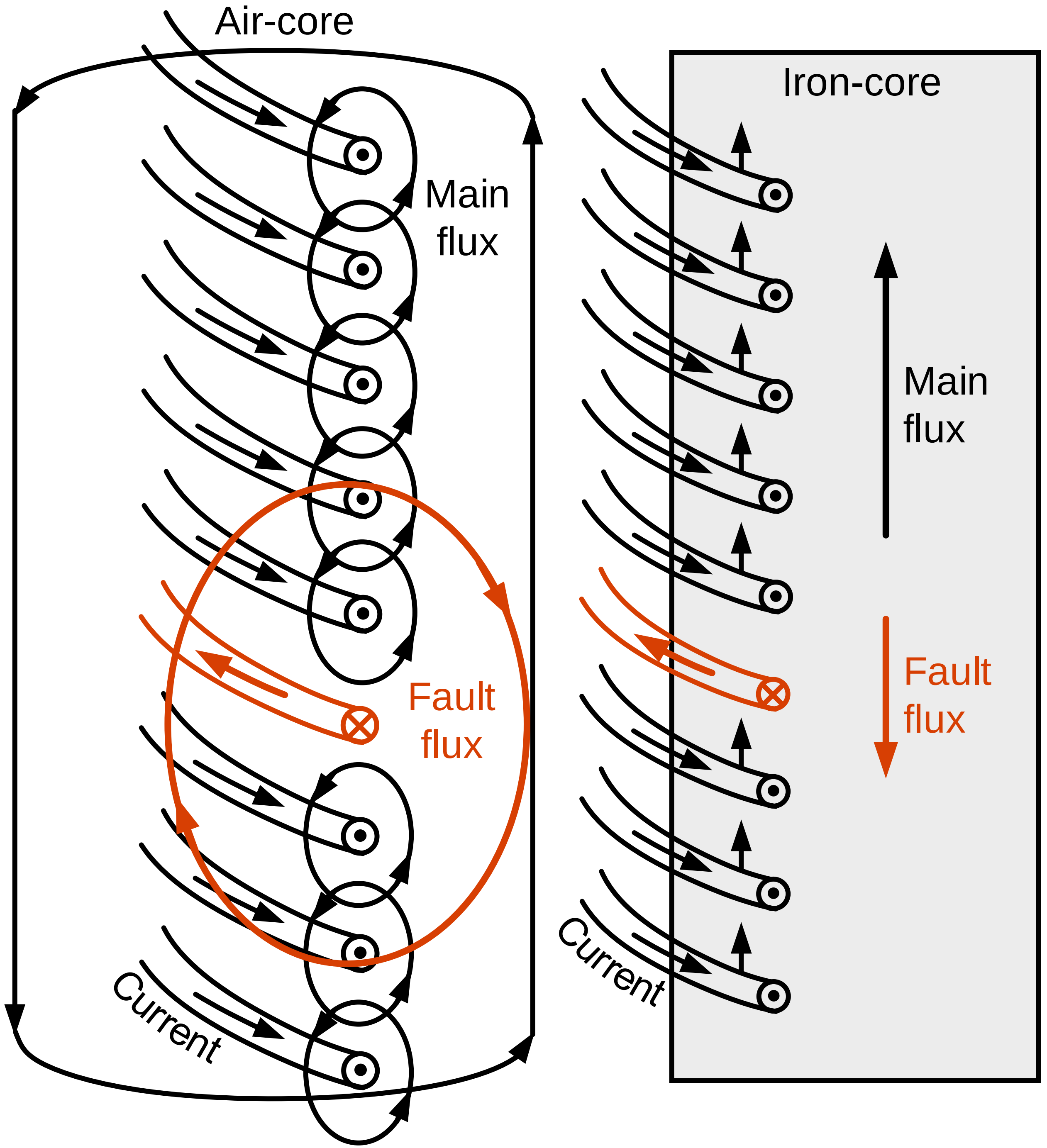
- Solidly-grounded air-core reactor
- Turn fault field event on 115 kV, 25 MVAR reactor from Xcel Energy



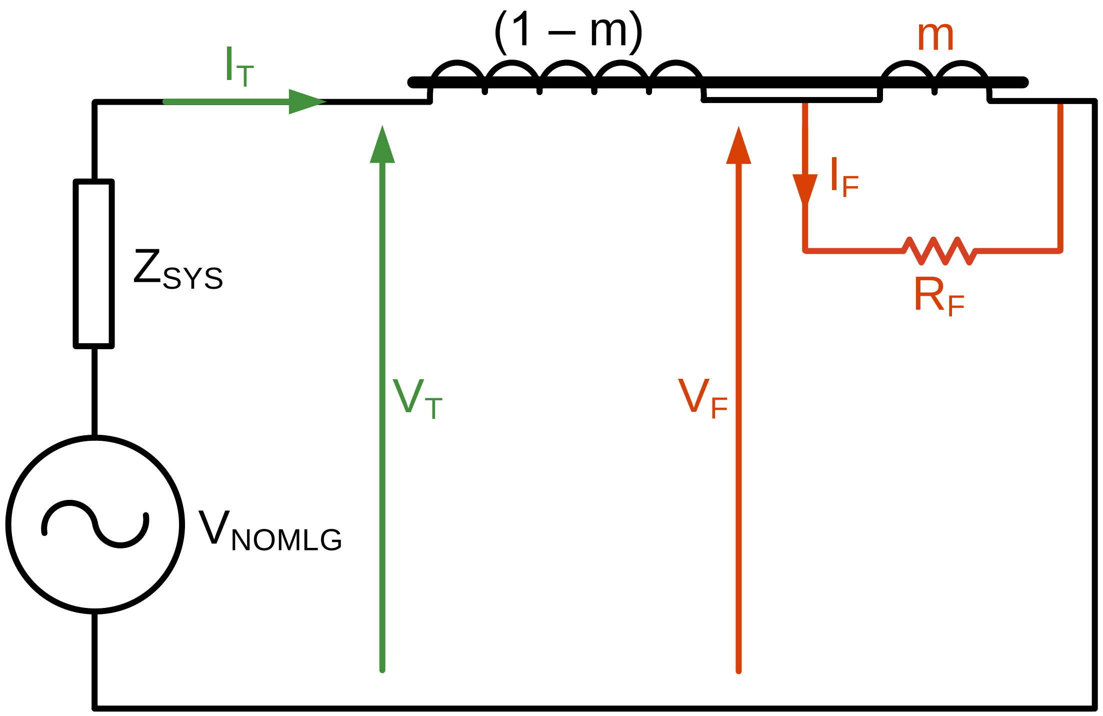
Turn fault sensitivity

Flux during turn fault

- Iron core presents low-reluctance path and channels faulted flux for complete coupling
- Air-core fault flux scatters and attenuates further from faulted turns



Reactor turn fault model



Enter values in green (Radius, Height, & M_{min} only needed for air-core reactor type) $pu := 1$

$S_{rated} := 50 \cdot 10^6$ $V_{LL} := 238 \cdot 10^3$ $XR := 377$ $Z_{sys} := 9.29 \cdot e^{j \cdot 86deg}$

$V_{LN} := \frac{V_{LL}}{\sqrt{3}}$ $I_{rated} := \frac{S_{rated}}{\sqrt{3} \cdot V_{LL}}$ $I_{rated} = 121.292$

$X_1 := j \cdot \frac{V_{LL}^2}{S_{rated}}$ $X_1 = 1.133j \times 10^3$ $R_1 := \frac{|X_1|}{XR}$ $R_1 = 3.005$

$R_F := 1 \cdot 10^{-4}$ $m_F := 0.21544\%$ $radius := 4.2ft$ $height := 2 \cdot 11ft$

$M_{max} := 0.9$ $M_{min} := \frac{radius}{height}$ Multiply M_{min} by 2 if air-core turn fault occurs mid-coil

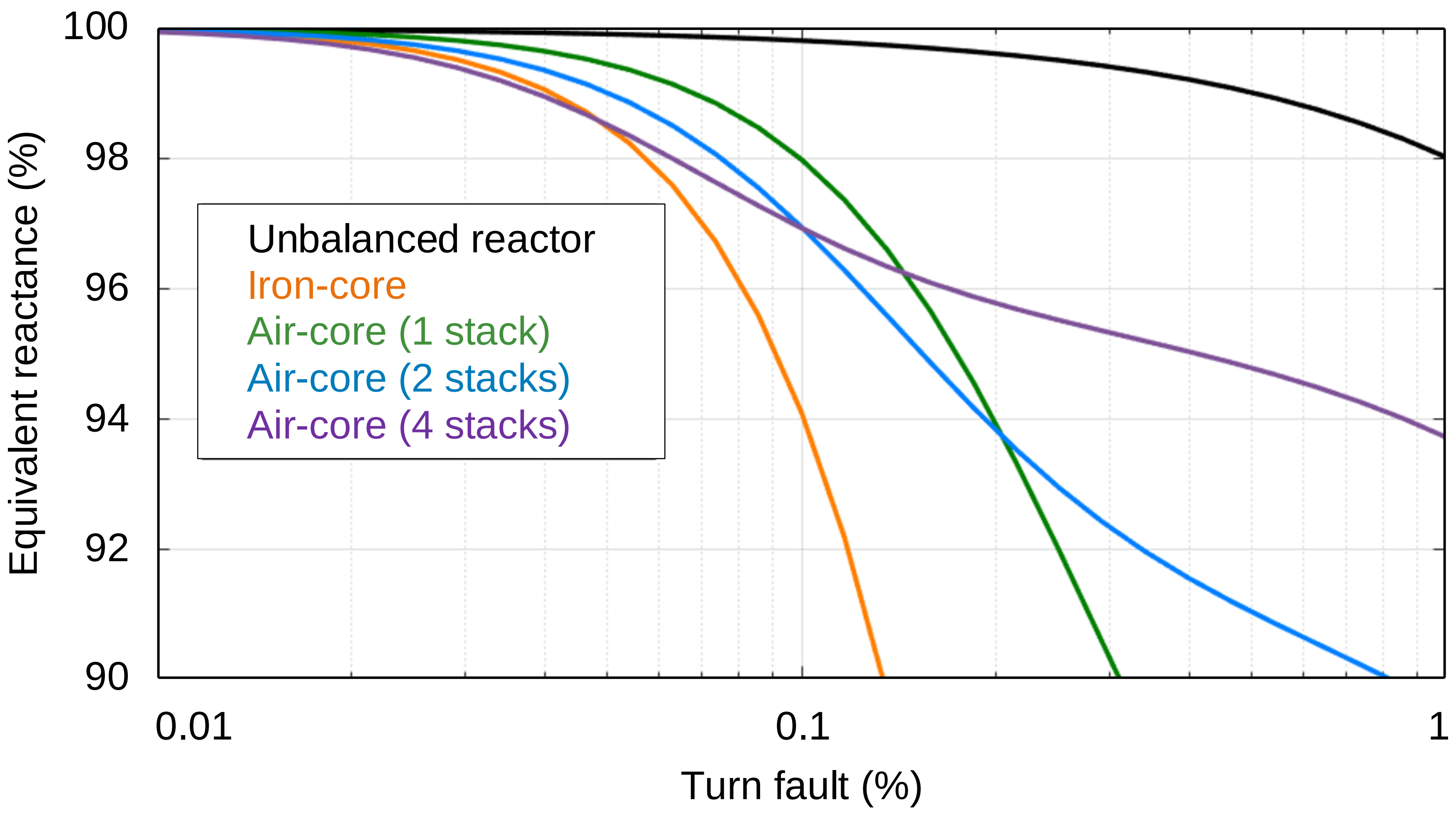
M_{TF} & M_{FT} given below for air-core. Redefine both with "M_{max}" if simulating iron-core.

$M_{TF} := m_F \cdot M_{min} + (1 - m_F) \cdot M_{max}$ $M_{FT} := (1 - m_F) \cdot M_{min} + m_F \cdot M_{max}$

$$\begin{pmatrix} V_F \\ I_F \\ I_T \\ V_T \end{pmatrix} := \begin{bmatrix} 1 & -R_F & 0 & 0 \\ -1 & -m_F \cdot (m_F \cdot X_1 + R_1) & m_F \cdot [[m_F + (1 - m_F) \cdot M_{TF}] \cdot X_1 + R_1] & 0 \\ 1 & -m_F \cdot M_{FT} \cdot X_1 \cdot (1 - m_F) & (1 - m_F) \cdot [(1 - m_F + m_F \cdot M_{FT}) \cdot X_1 + R_1] & -1 \\ 0 & 0 & Z_{sys} & 1 \end{bmatrix}^{-1} \cdot \begin{pmatrix} 0 \\ 0 \\ 0 \\ V_{LN} \end{pmatrix}$$

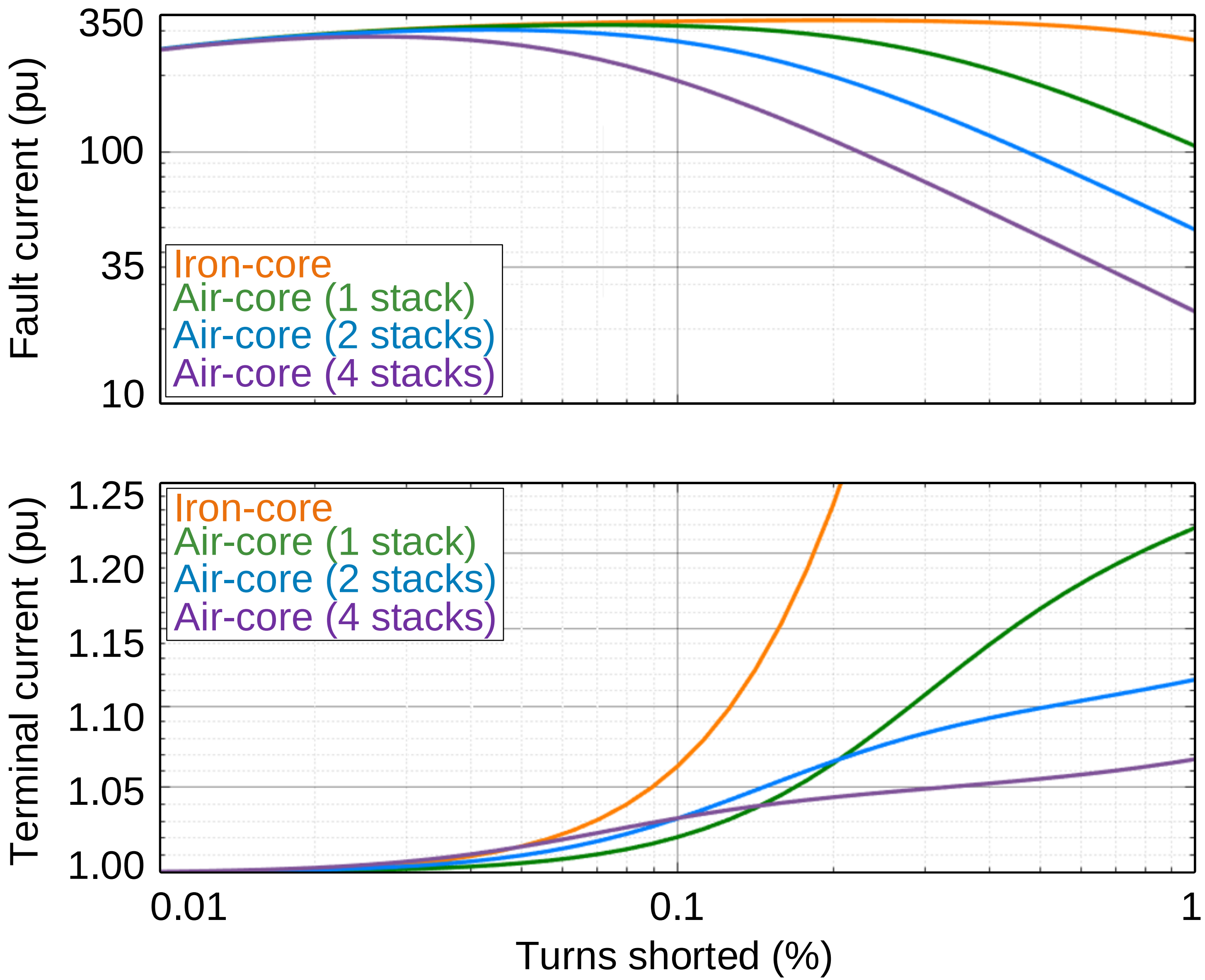
$m_F = 0.2 \cdot \%$ $\frac{|I_F|}{I_{rated}} = 277 \cdot pu$ $\frac{|I_T|}{I_{rated}} = 1.063 \cdot pu$ $\frac{|V_T|}{V_{LN}} = 99.1 \cdot \%$

Impedance of faulted phase



Turn fault currents

- Air-core reactor sensitivity: 0.2% of turns
- Iron-core reactor sensitivity: 0.1% of turns



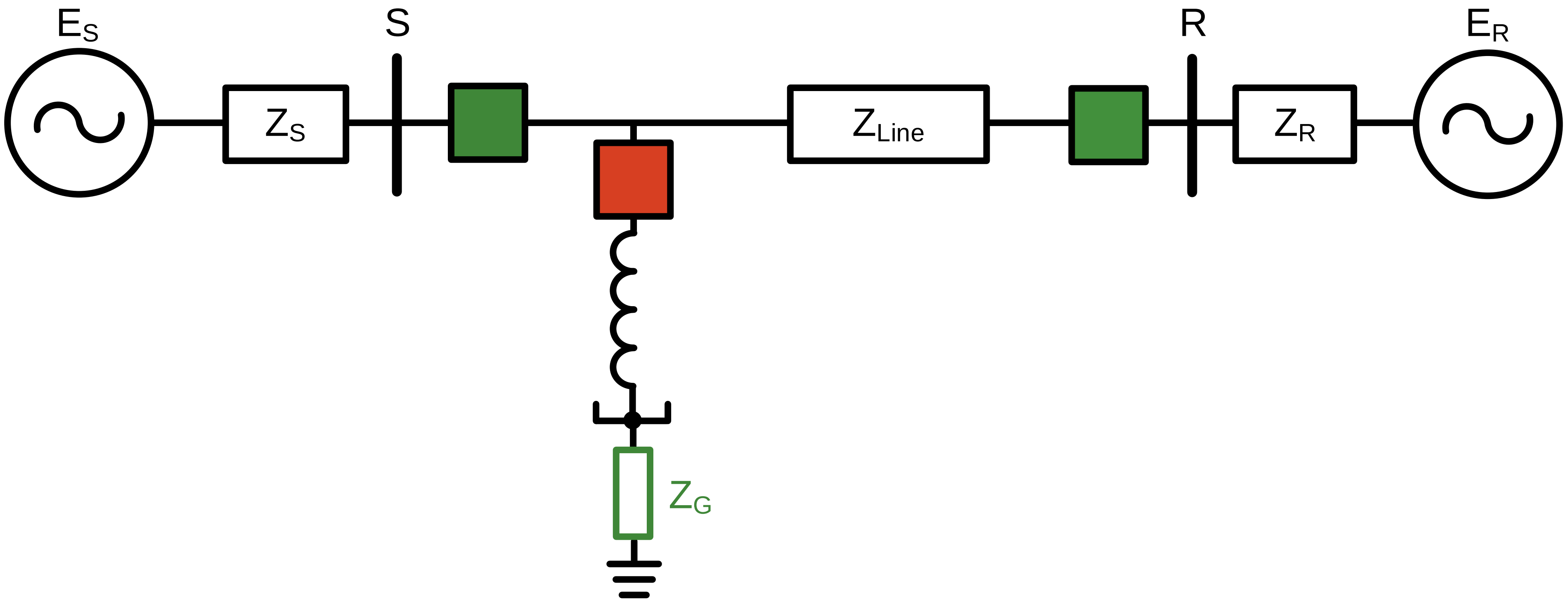
How many turns?

Parameter	3I	4I	5I	6I
Voltage (kV)	230	345	400	500
MVAR	50	150	150	175
Frequency (Hz)	60	60	50	60
Current (A)	126	251	217	202
Winding height (in)	56.7	67.2	59.1	70.9
Inductance (mH)	2,806	2,105	3,395	3,789
Turns/phase	1,982	1,170	1,470	1,570

Parameter	1A	2A	3B	3A	4A	5A	6A
Voltage (kV)	13.8	34.5	238	238	345	420	500
MVAR	20	50	50	50	120	120	125
Frequency (Hz)	60	60	60	60	60	50	60
Current (A)	837	837	121	121	201	165	144
Radius (in)	60.5	41.3	35.3	66.2	68.1	73.1	68.2
Inductance (mH)	25.3	63	3,005	3,005	2,631	4,679	5,305
Turns/phase	90	207	3,943	2,096	1,834	2,644	3,322

Line reactors

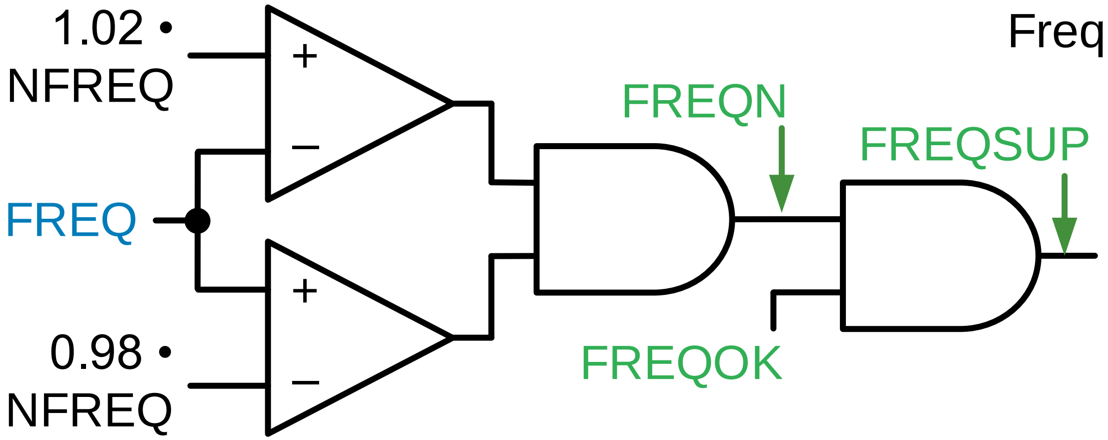
Line de-energization

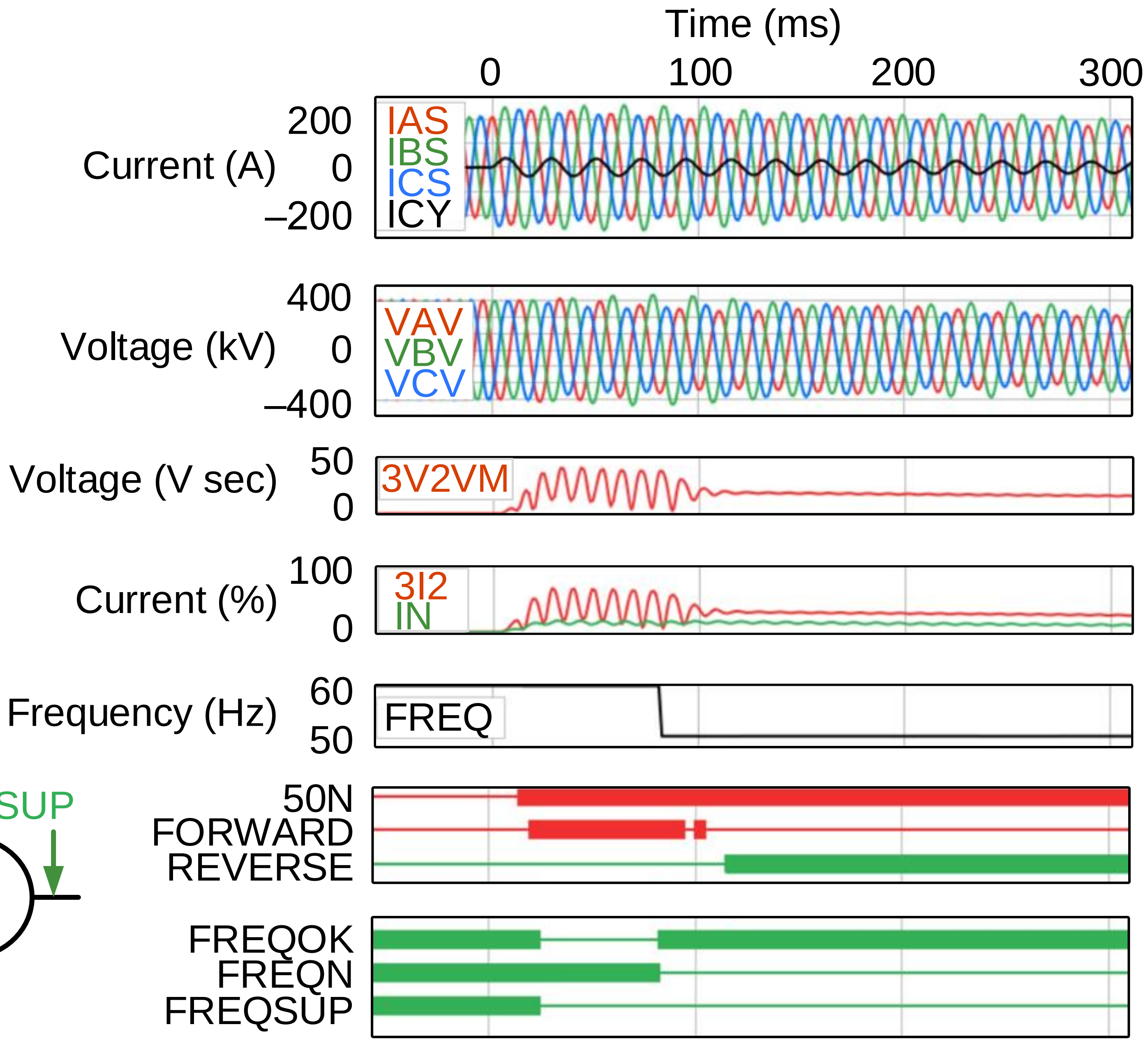


Ringdown

$$f_{LC} = f_{SYS}\sqrt{\frac{X_C}{X_L}} = f_{SYS}\sqrt{\frac{MVAR_L}{MVAR_C}}$$

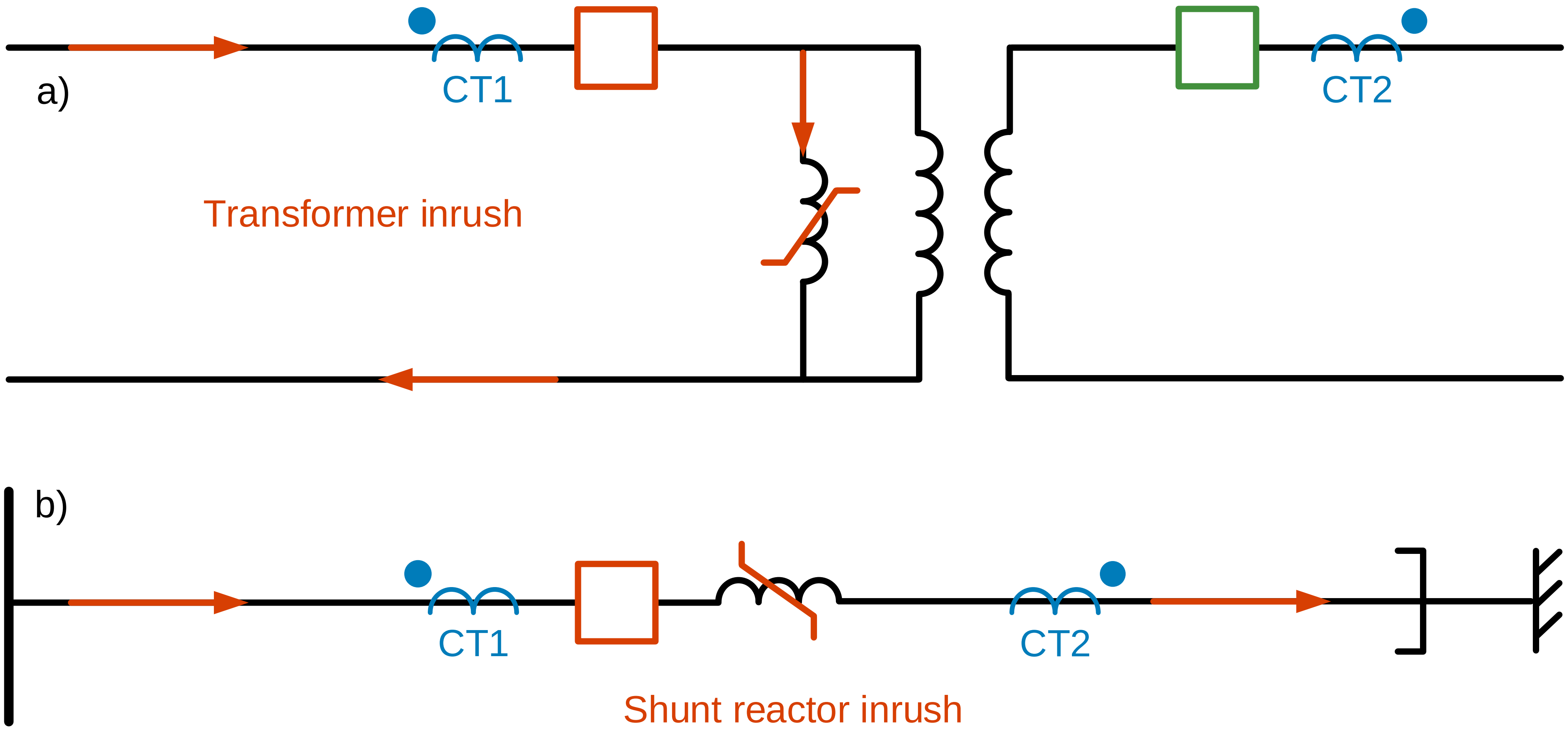
$$f_{LC} = 60\,\text{Hz} \bullet \sqrt{0.75} = 52\,\text{Hz}$$



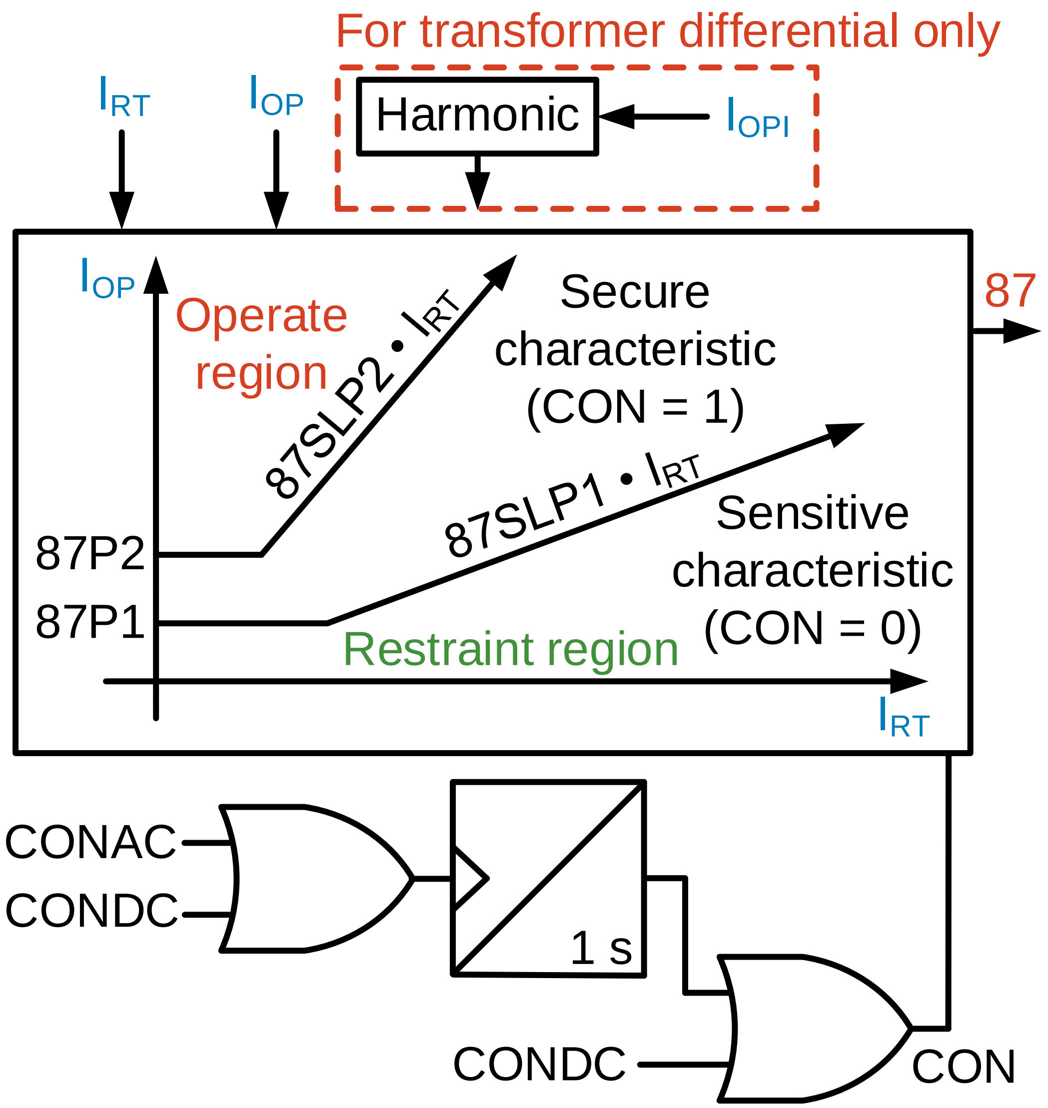


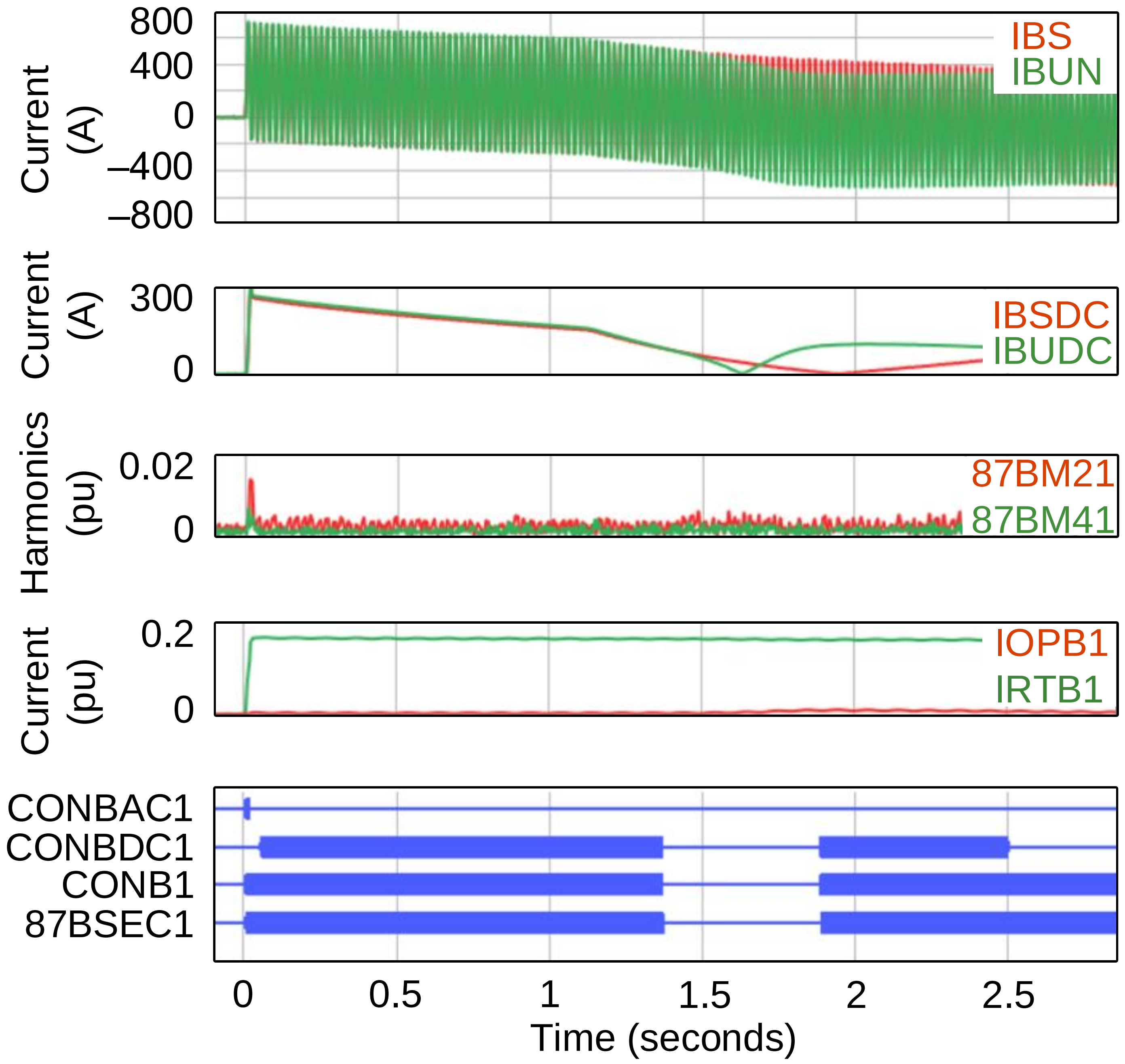
Reactor differential

Transformer vs. reactor inrush



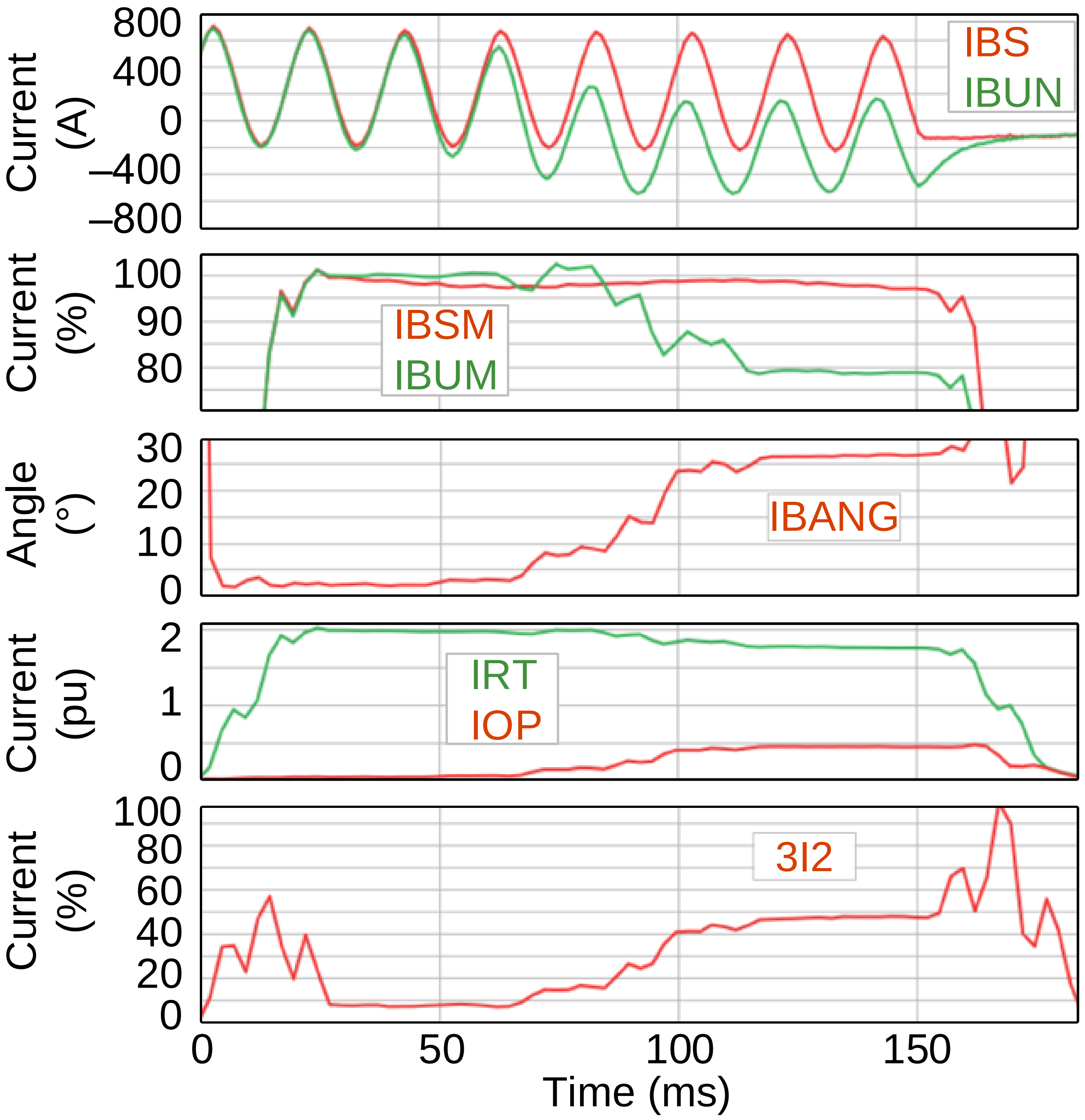
DIFFERENTIAL ELEMENT





Iron-core inrush field event

- Field event error
  - Magnitude: 22% error
  - Phase: 27 degrees
- CT guidance, testing, and field experience
  - Magnitude: 25% error
  - Phase: 35 degrees



Iron-core inrush field event

Secure slopes

- $IRT = |I_T + I_N|$

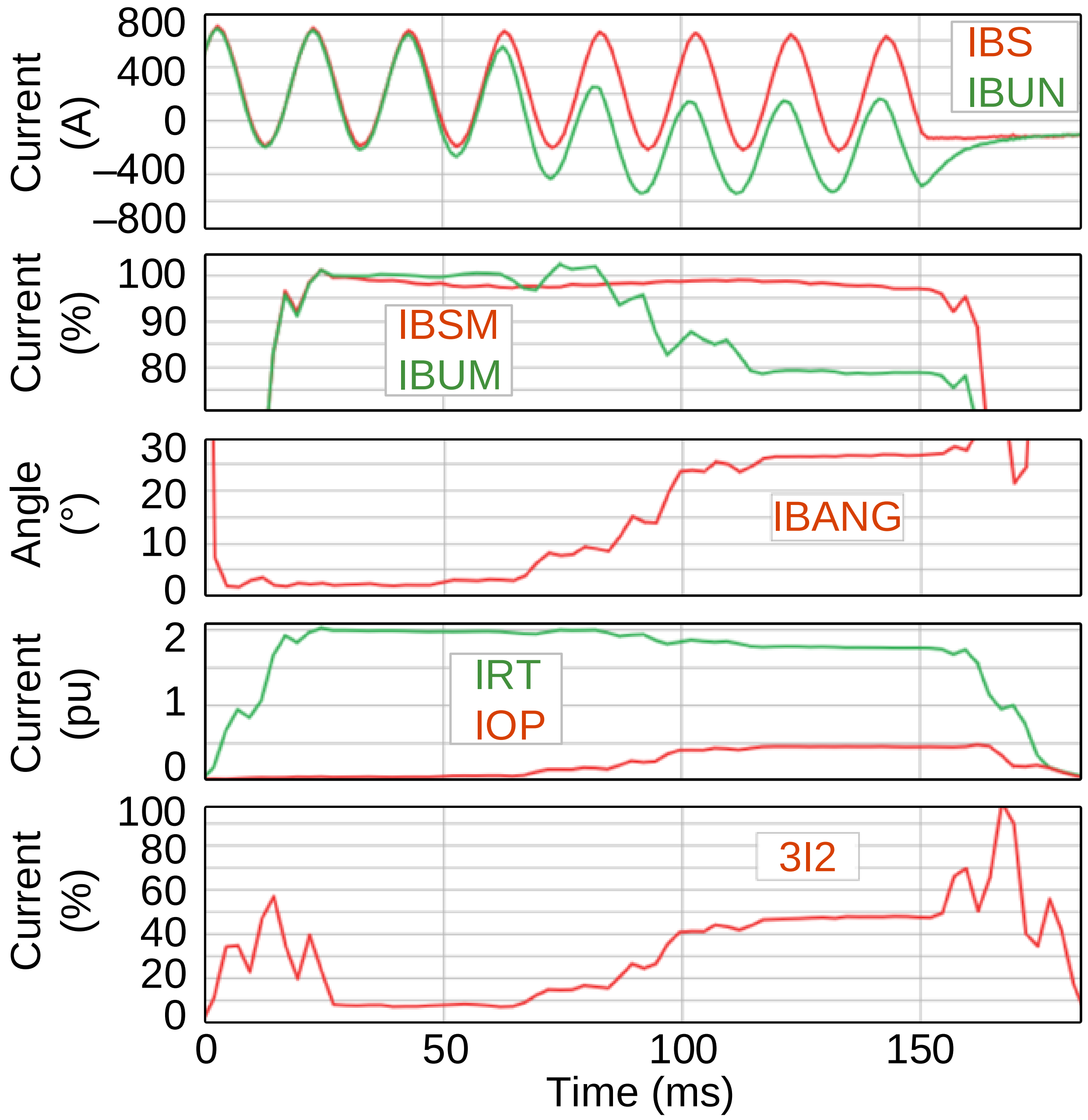
  35% (to 50%)

- $IRT = |I_T + I_N| / 2$

  70% (to 100%)

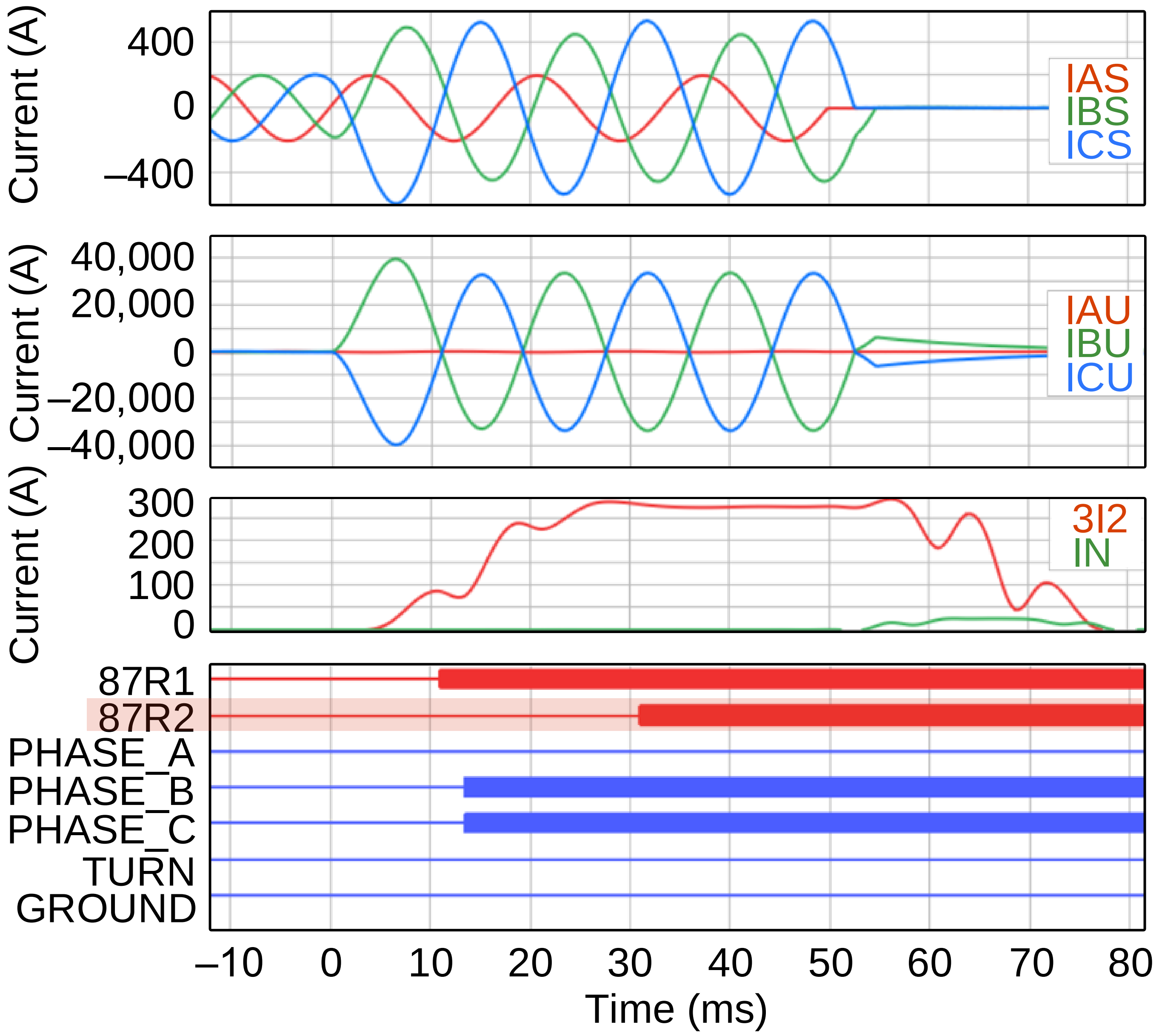
- $IRT = max(I_T, I_N)$

  60% (to 80%)



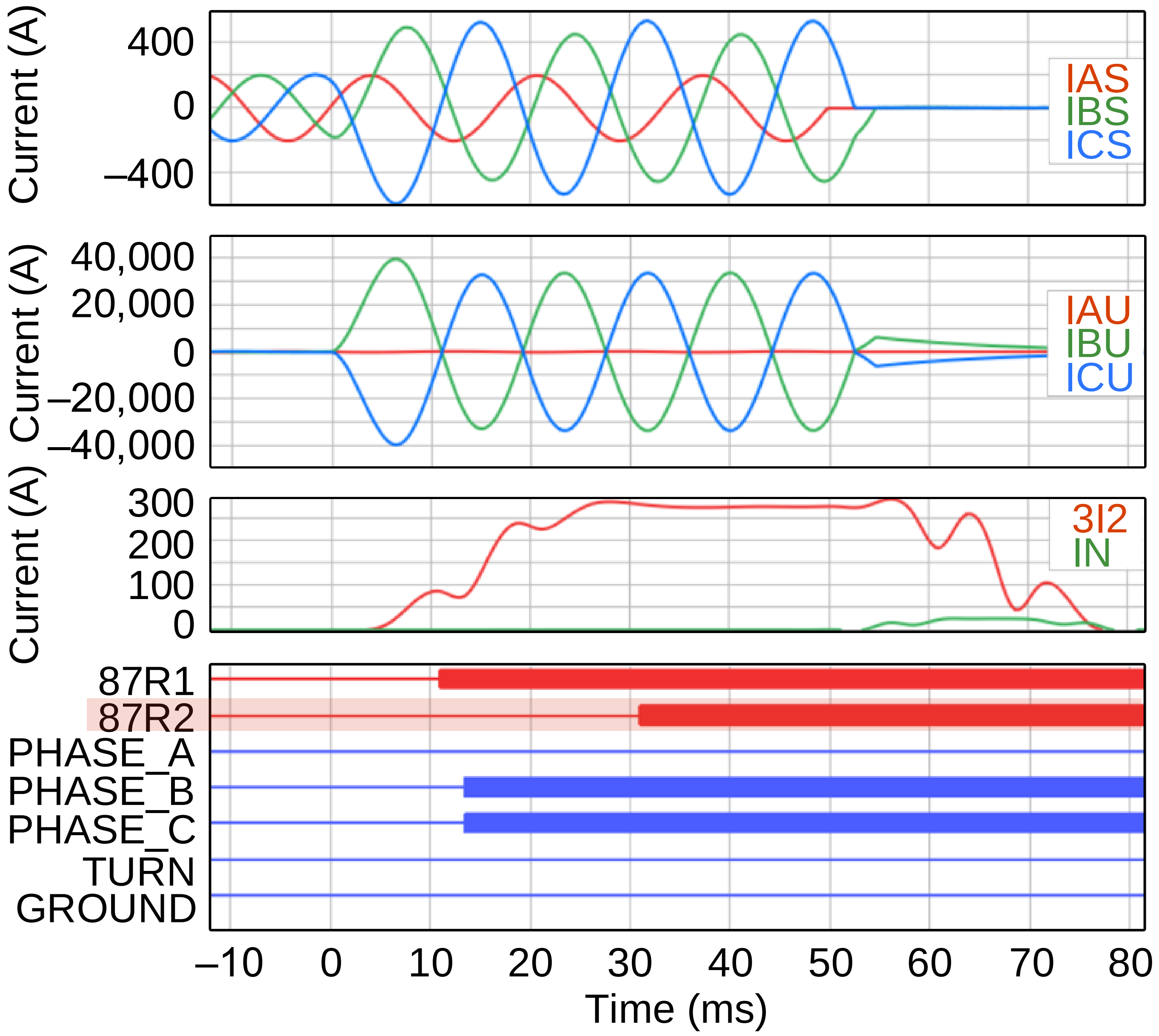
BC fault

- Neutral end, 1%–1%
- Neutral-side currents are much greater than terminal-side currents
- 87R1 (no harmonic blocking/restraint) is fast
- 87R2 (with harmonic blocking/restraint) is slow



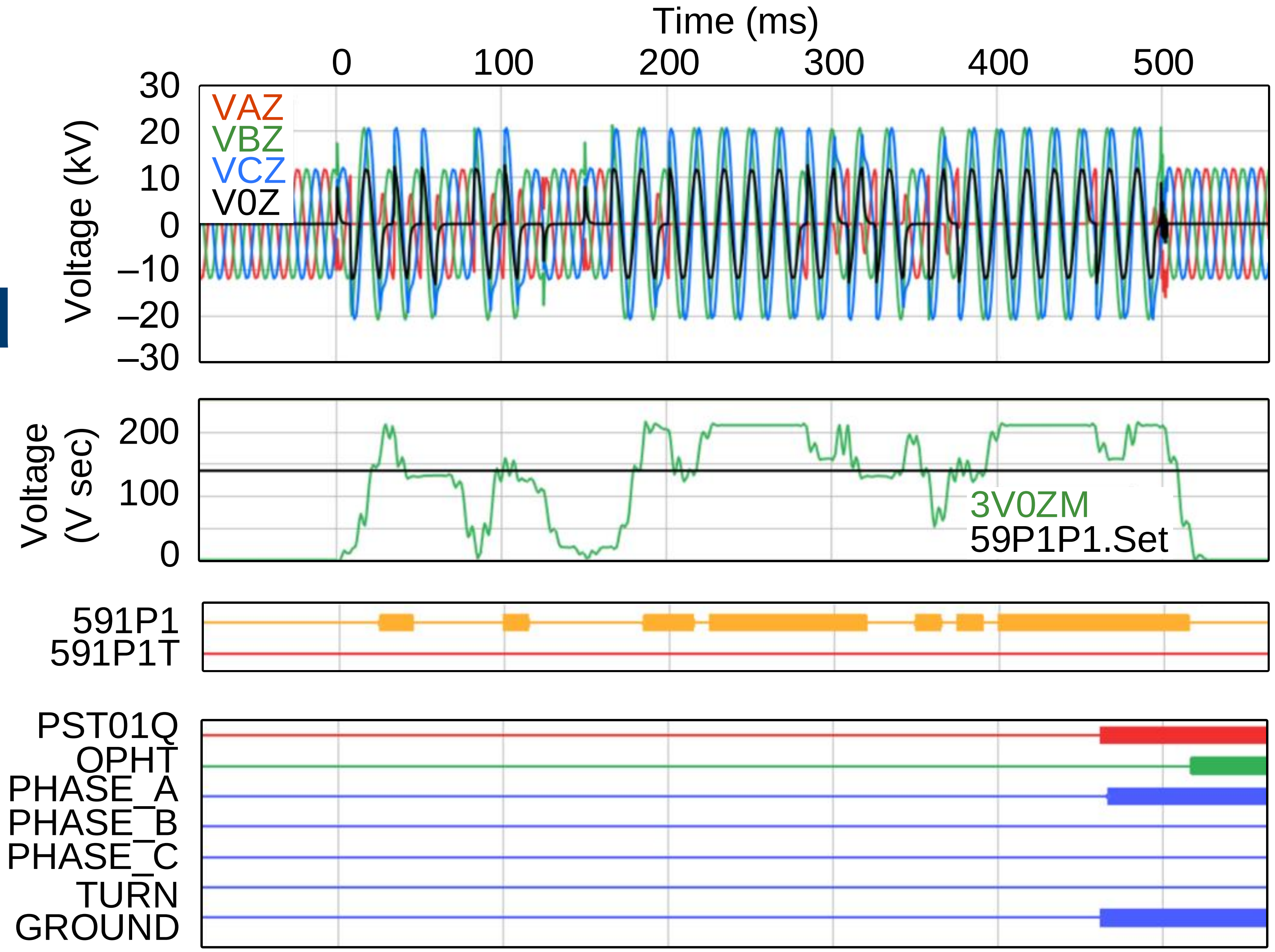
BC fault

- CT saturation can further slow down 87 element
- Secure slope settings are used instead of harmonics-based security



Ground fault

Dependability for intermittent ground fault on ungrounded reactor or bus



Conclusion

- Reactors require sensitive protection
  - Iron-core presents fire hazard
  - Air-core physics produce lower magnitude turn faults
- Reactor protection security has challenges
  - CT saturation
  - Magnetizing inrush
  - Resonant ringdown

Conclusion

- Turn-fault scheme is fast, secure, and sensitive
  - 67 Zone 1 (1.5 cycles), 67 Zone 2 (3 cycles when armed), and directionally supervised 51 element
  - Sensitivity: 0.1% iron core, 0.2% air core
- 87 element reliably detects phase and ground faults
- REF adds ground fault protection sensitivity in four-reactor banks
- 59G in ungrounded banks benefits from timers for arcing faults

Questions?