Series Compensation, Power Swings, and Inverter-Based Sources and Their Impact on Line Current Differential Protection

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Outline

- Unusual system conditions
- 87L security and dependability
- 87L dependability considerations
  - Power swings
  - Series-compensated lines
  - Weak and inverter-based sources
- Conclusion

Unusual System Conditions

- Series-compensated lines
- Power swings
- Off-nominal frequency
- Weak sources
- Inverter-based sources
- Single-pole open conditions
- Cross-country faults

87L Security

- 87L elements are inherently secure (current in is current out unless a fault)
- Security challenges in practical applications
  - CT saturation
  - Channel asymmetry and current misalignment
  - Undetected channel data errors
  - Line charging current
- Challenges are well addressed by relay design

87L Dependability Concerns

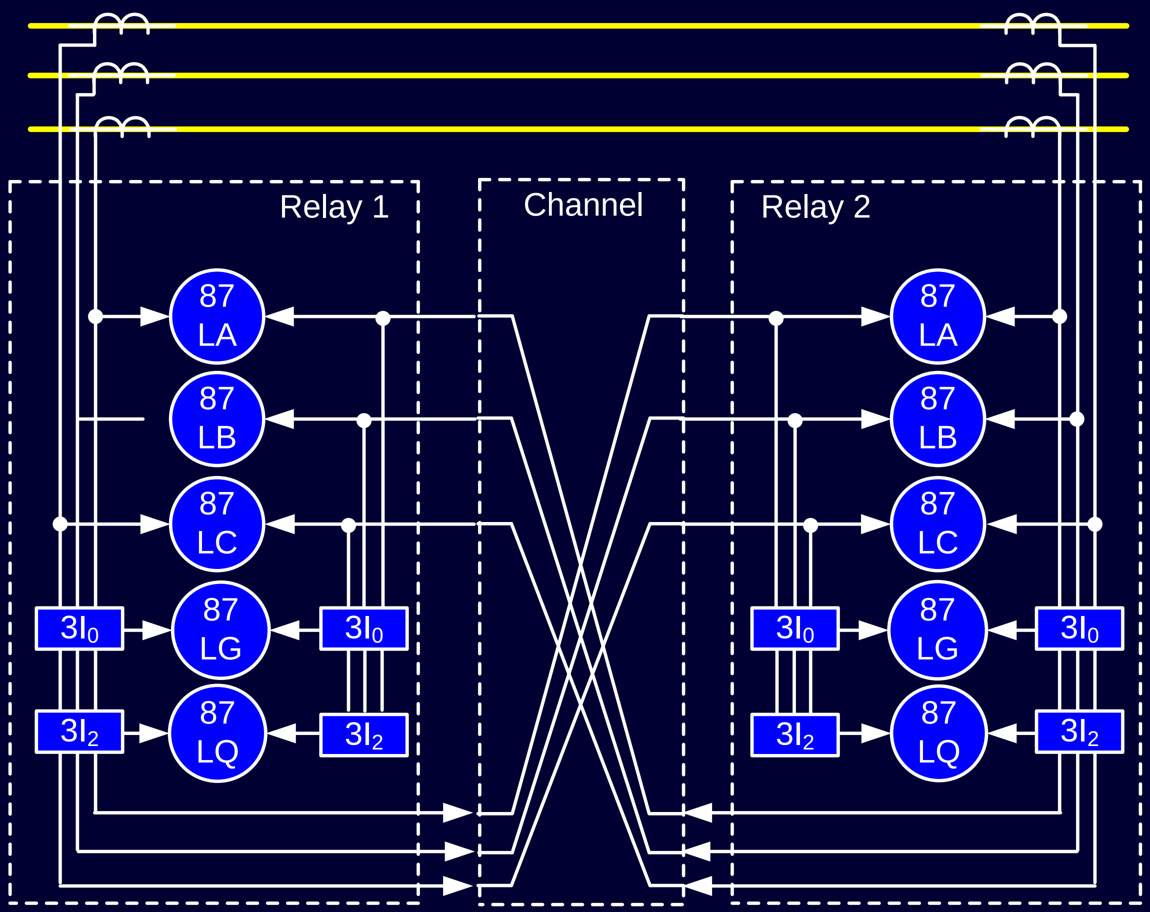
Will 87L Protection...

- Operate reliably under current inversions in series-compensated lines?
- Overrestrain during power swings?
- Lose accuracy due to off-nominal frequencies?
- Trip reliably with fault contribution from a wind farm?

Types of 87L Elements

- Differential elements respond to
  - Phase currents (87LP)
  - Negative-sequence currents (87LQ)
  - Zero-sequence currents (87LG)
- All three elements use the same data
- They may respond differently under unusual system conditions

87LQ and 87LG Do Not Decrease Security



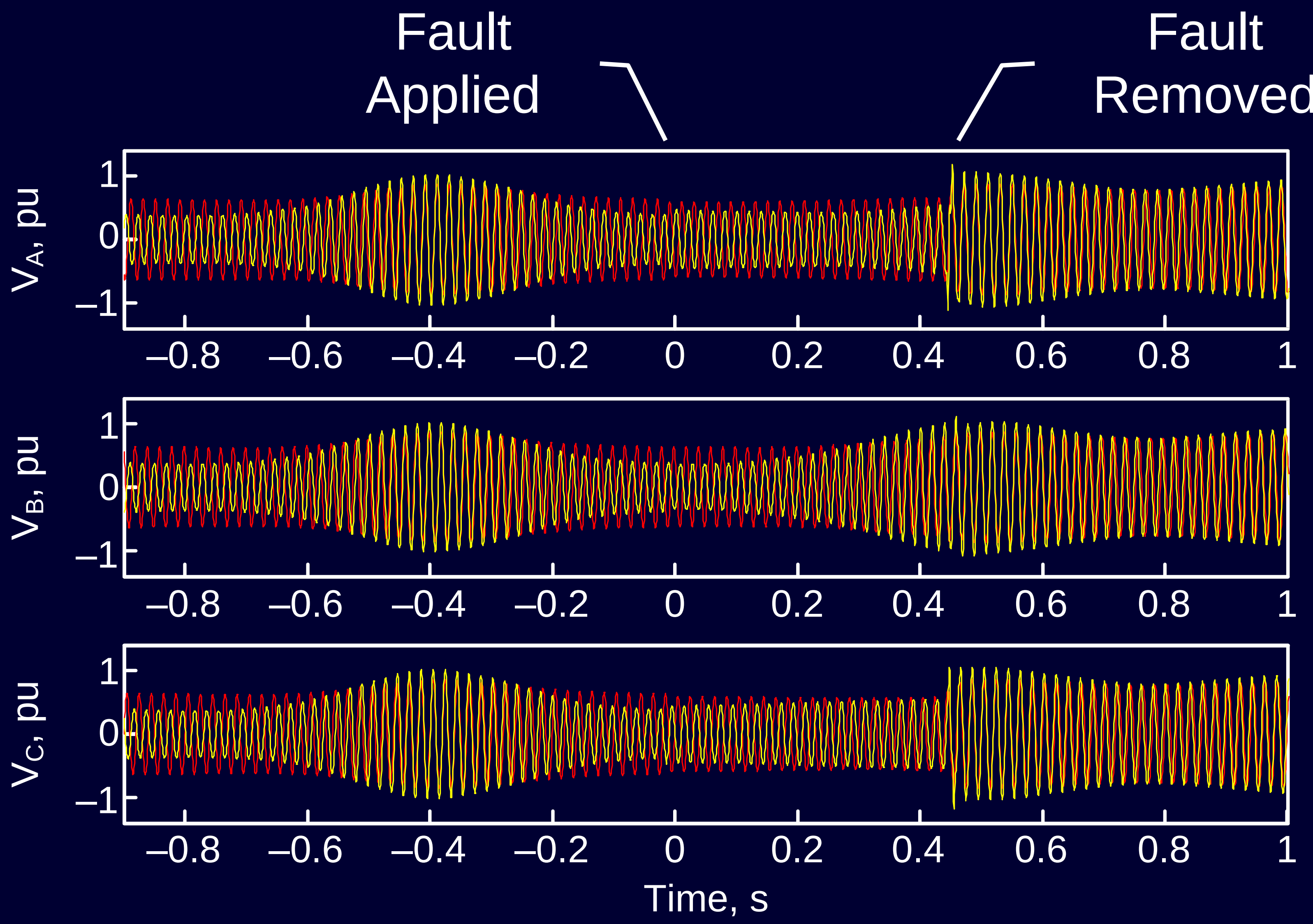
- 87LQ and 87LG have no extra failure modes
- 87LQ and 87LG are secure under CT saturation

Key Message

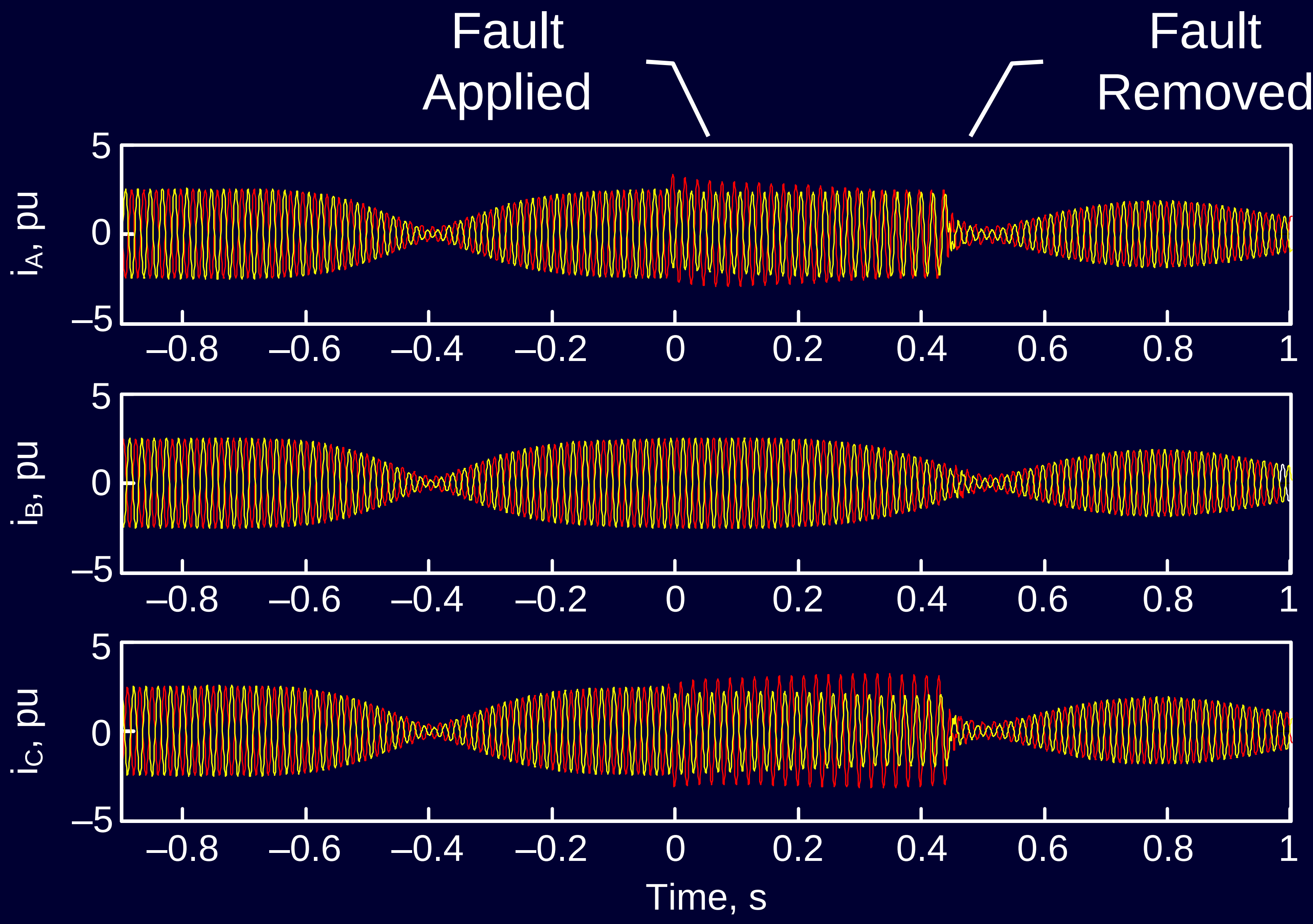
Enabling 87LP, 87LQ, and 87LG

- Does not impair security
- Allows different response under unusual conditions
- Increases dependability

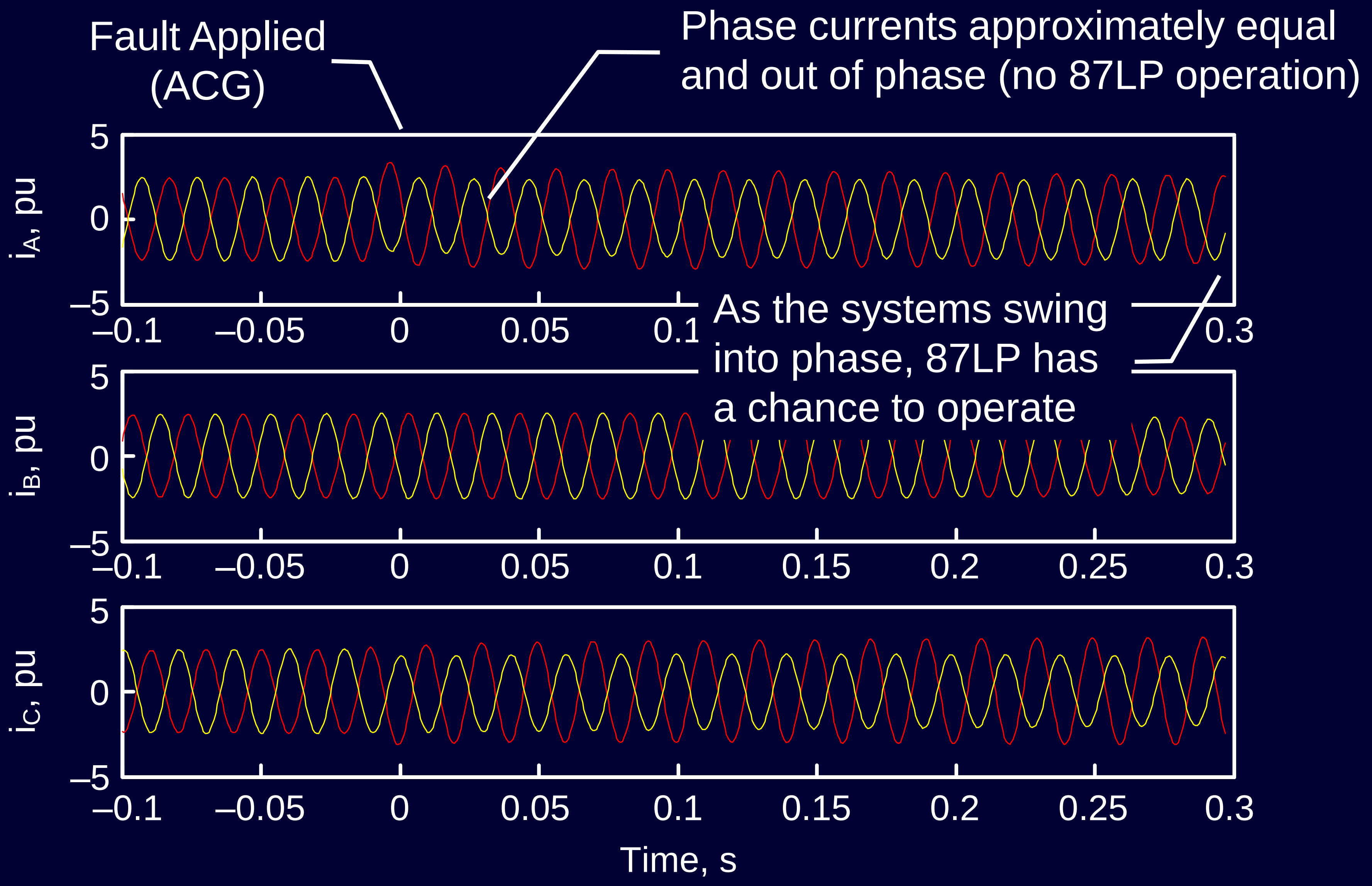
Dependability During Power Swings



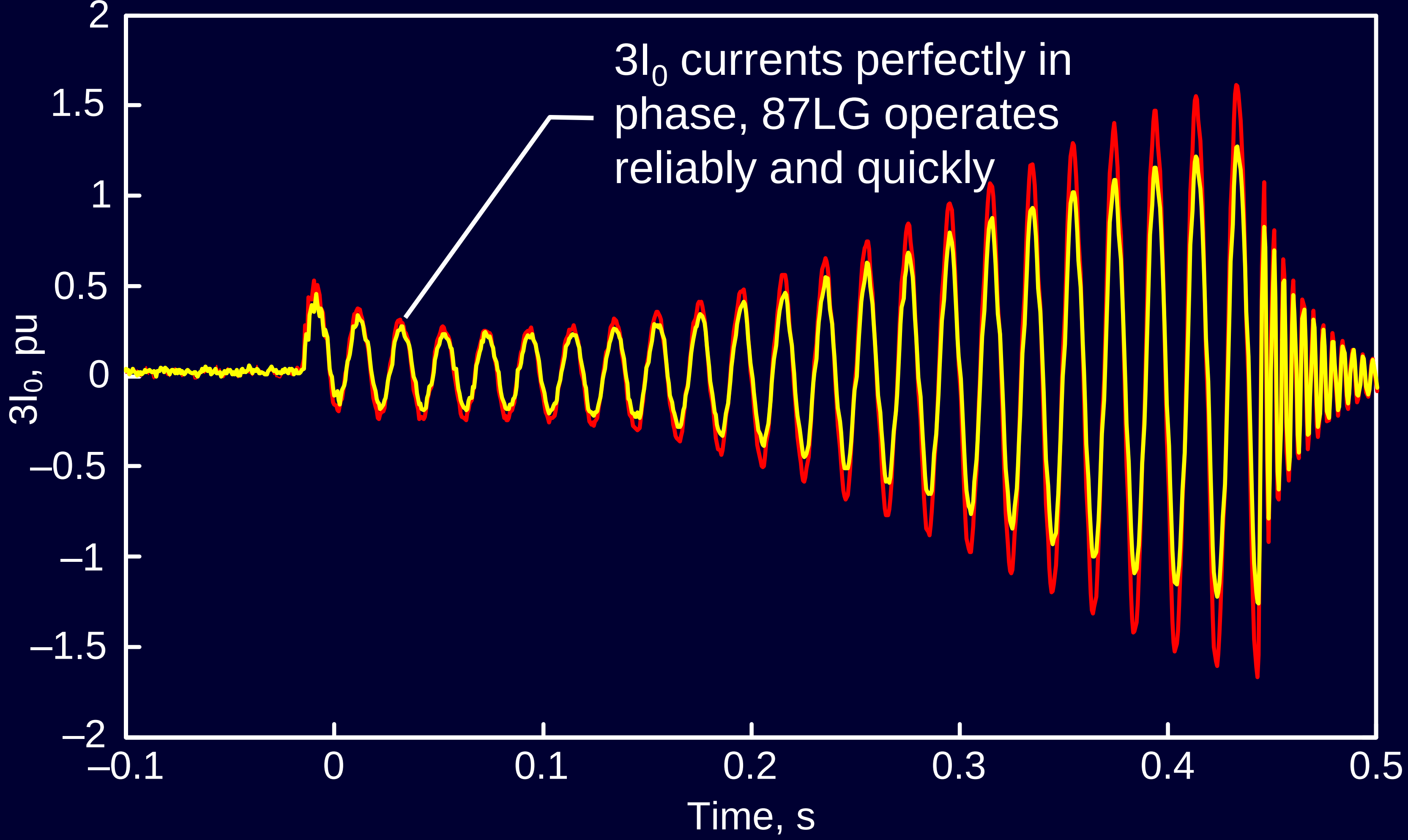
Dependability During Power Swings



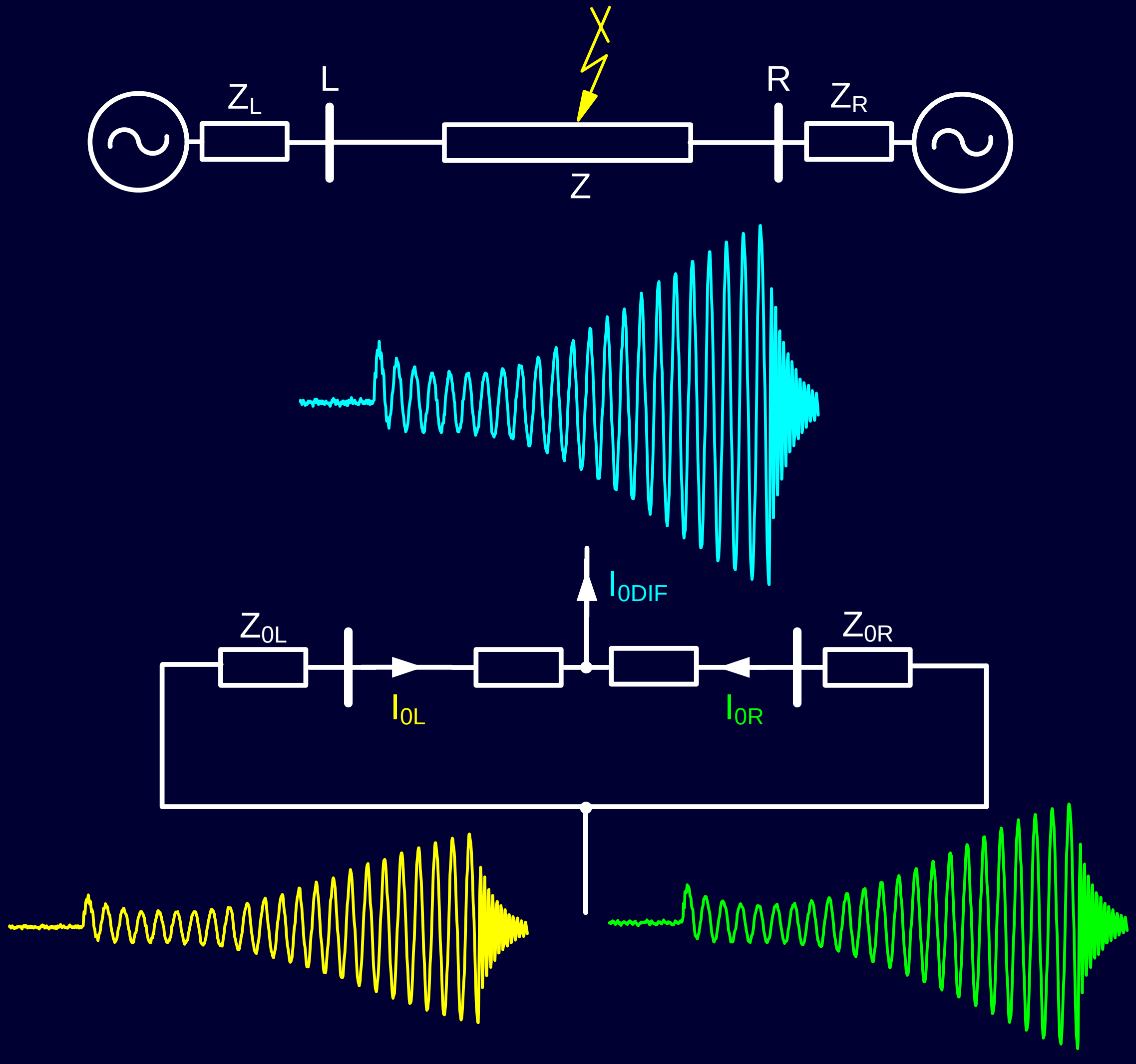
Dependability During Power Swings



Dependability During Power Swings

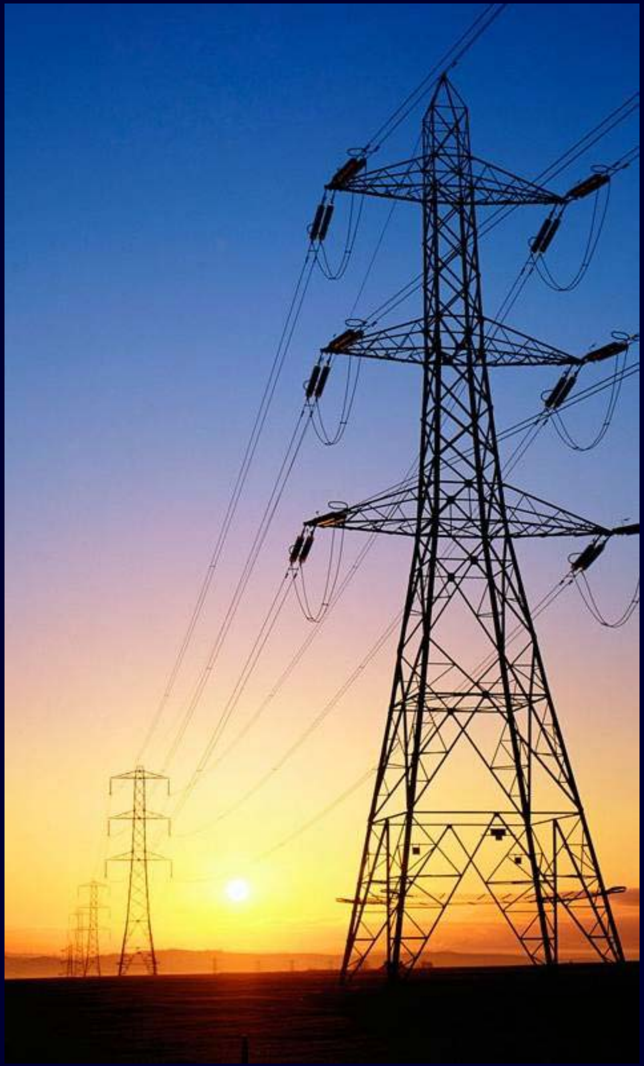


Why Is 87LG Element Not Affected?

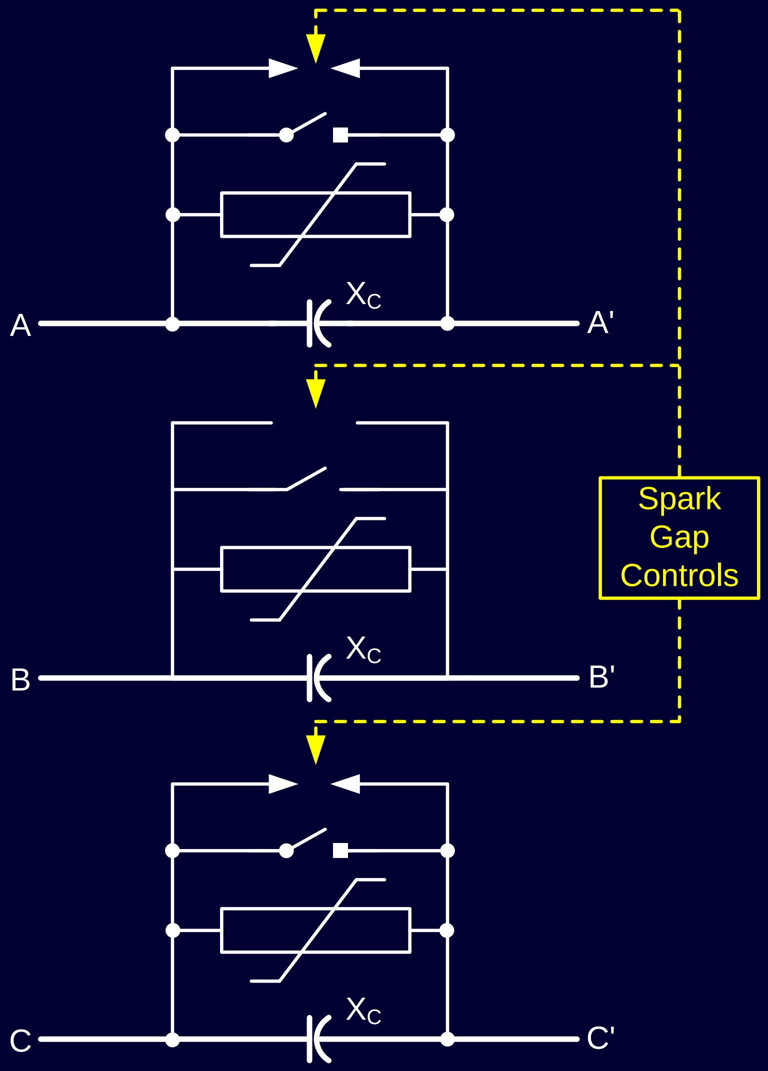


Power Swings and 87L

- 87L is inherently secure
- 87LP
  - Overrestrained
  - Slow operation
  - Lower sensitivity
- 87LG and 87LQ
  - Dependable
  - Fast
  - Sensitive

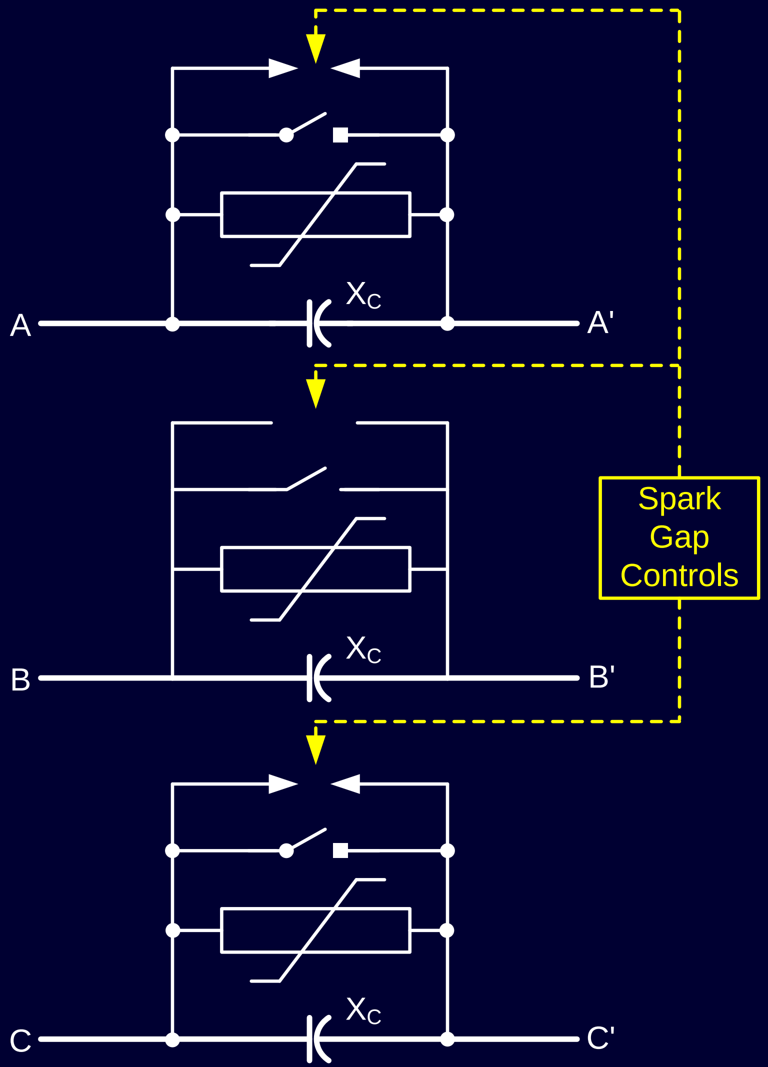


Series Capacitors



- Low-current faults are a concern (MOVs do not conduct)
- Capacitors can cause a fault loop to be capacitive (current inversion)
- Asymmetrical bypass complicates current flow

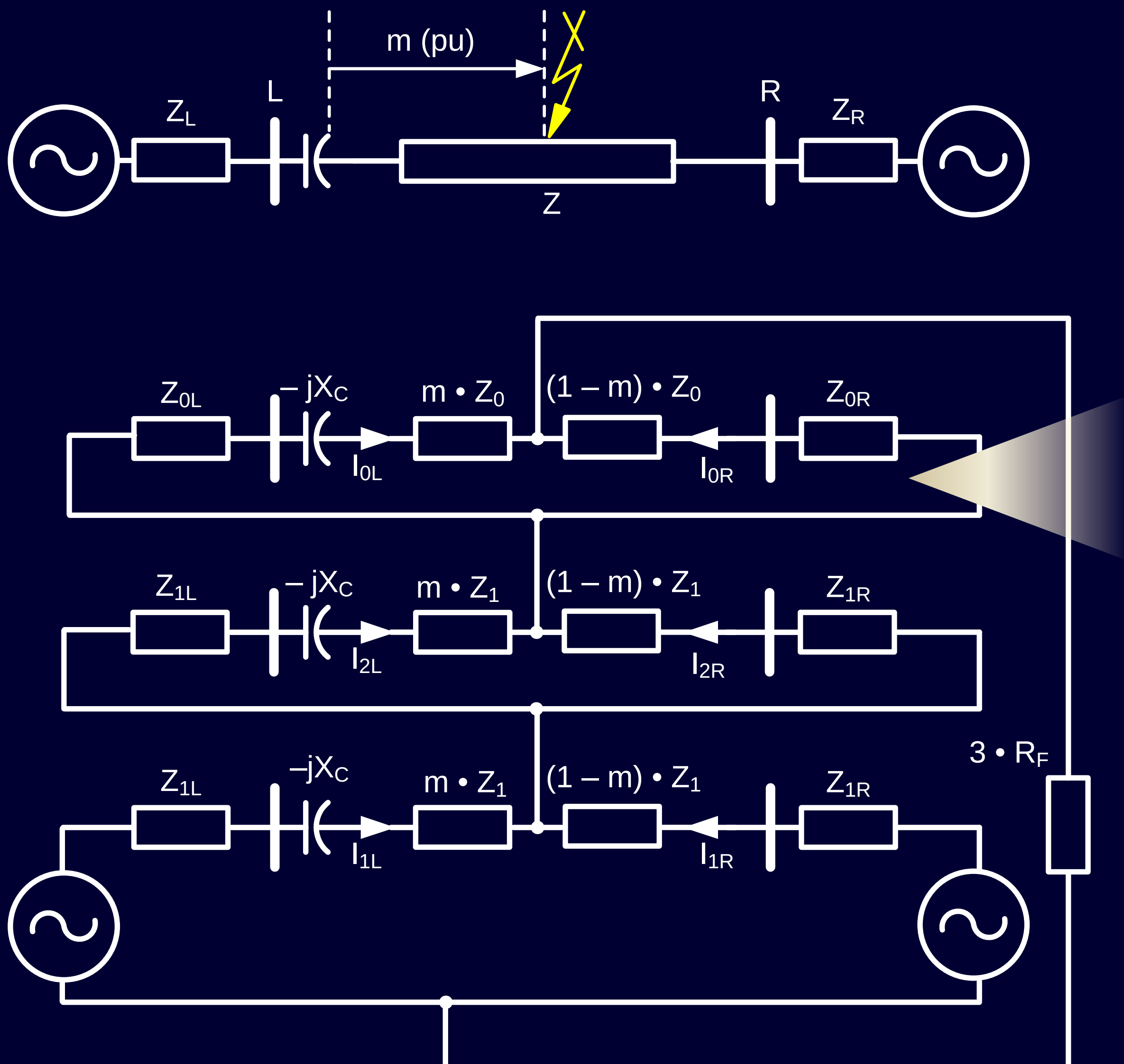
Low-Current Internal SLG Fault



$$Z_{ABC} = \begin{bmatrix} -jX_C & 0 & 0 \\ 0 & -jX_C & 0 \\ 0 & 0 & -jX_C \end{bmatrix}$$

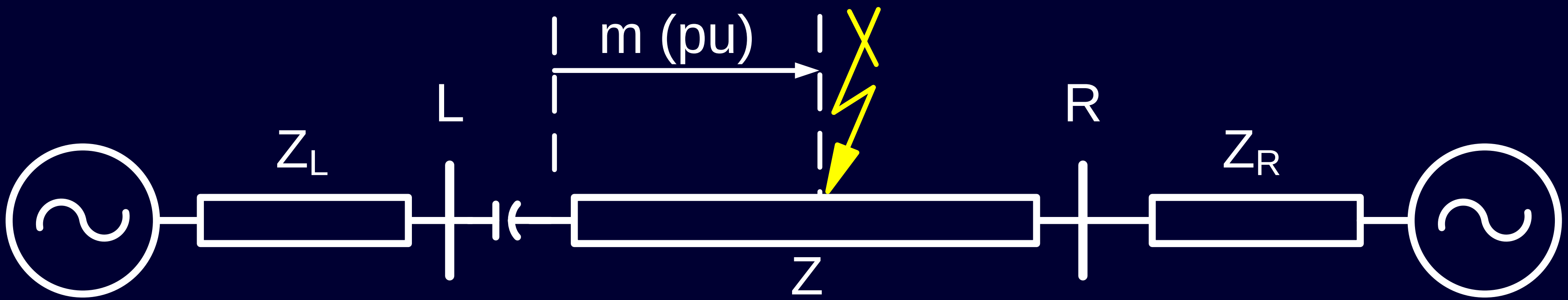
$$Z_{012} = -jX_C \bullet \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Low-Current Internal SLG Fault



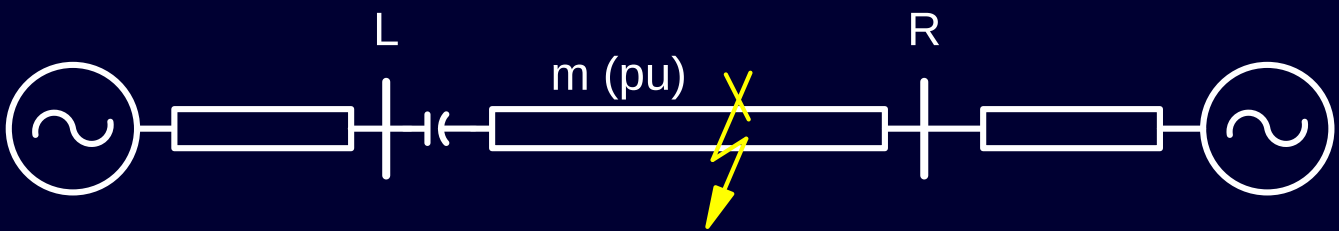
$$\frac{I_{0L}}{I_{0R}} = k_0 = \frac{Z_{0R} + (1 - m)Z_0}{Z_{0L} - jX_C + mZ_0}$$

Low-Current Fault Example



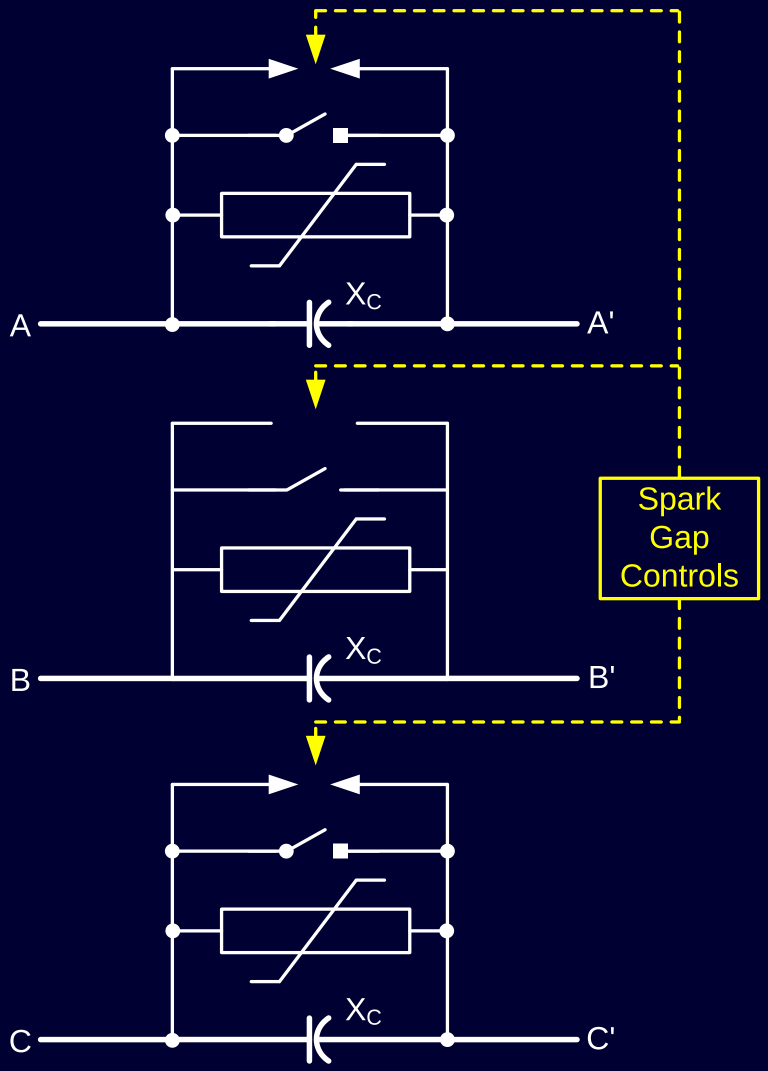
E	1 pu			1 pu$\angle$–40°
X_1	0.050 pu	75%	0.25 pu	0.20 pu
X_0	0.075 pu		0.75 pu	0.25 pu

Low-Current Fault Example



m (pu)	Low-Current SLG Fault	
	87G – k_0	87Q – k_2
0.1	23.6∠162°	3.76∠172°
0.2	21.5∠17°	4.53∠169°
0.3	6.84∠5.6°	5.87∠165°
0.4	3.72∠3.1°	8.7∠156°
0.5	2.38∠2.0°	16.3∠126°
0.6	1.63∠1.3°	14.5∠50°
0.7	1.15∠0.9°	6.65∠22°
0.8	0.82∠0.5°	3.84∠14°
0.9	0.58∠0.0°	2.51∠9.7°
1.0	0.40∠–0.4°	1.81∠7.7°

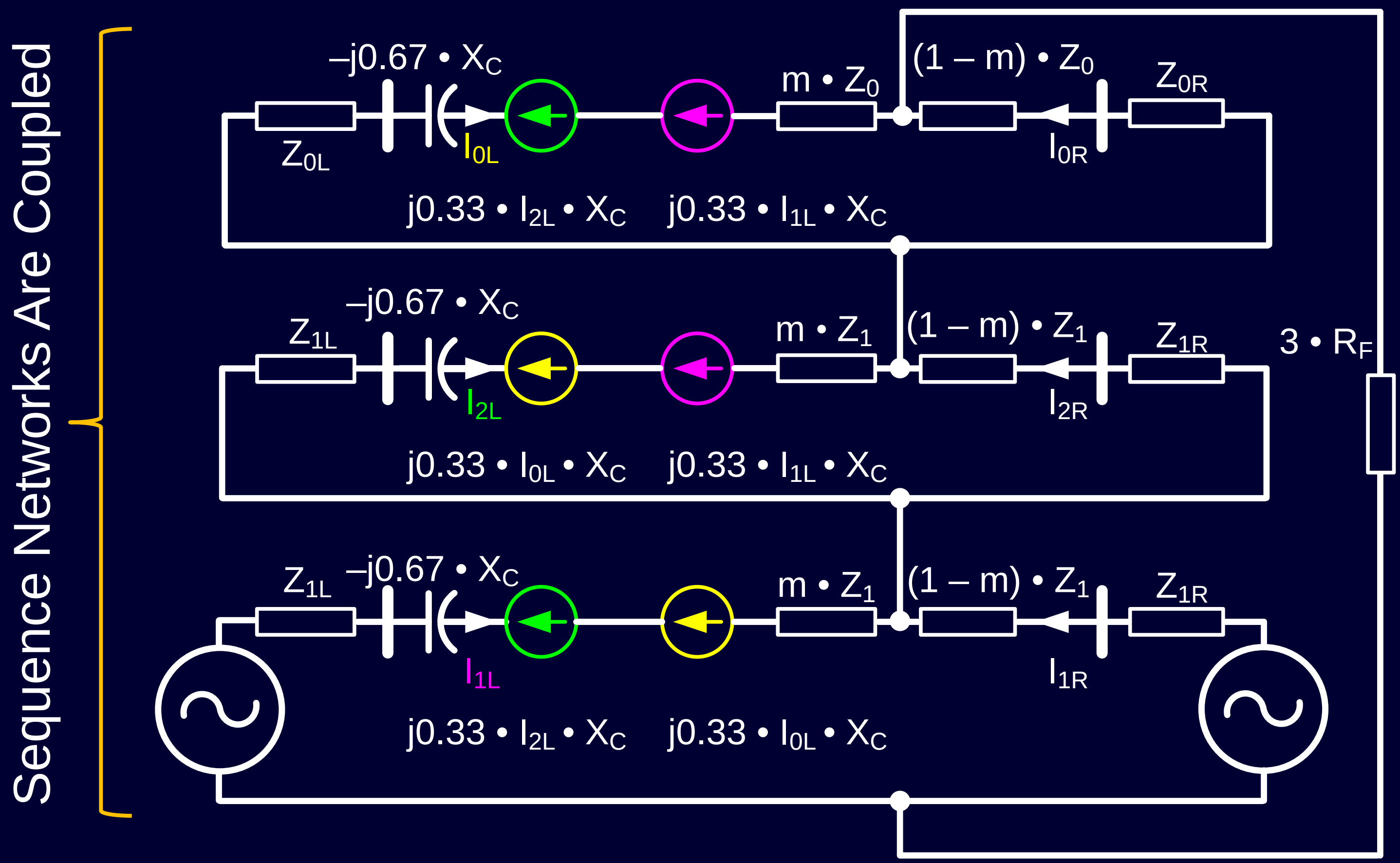
High-Current Internal SLG Fault



$$Z_{ABC} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & -jX_C & 0 \\ 0 & 0 & -jX_C \end{bmatrix}$$

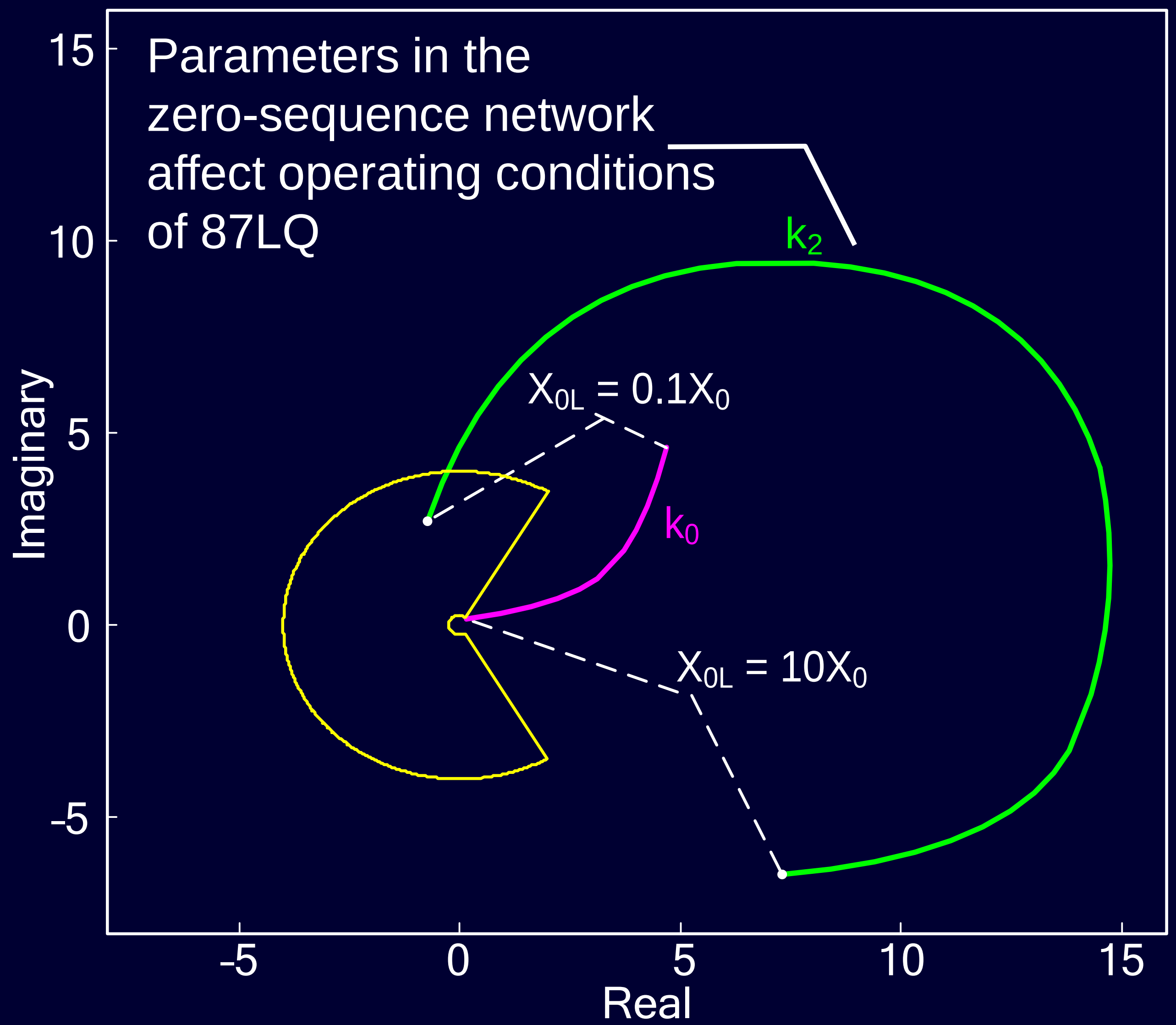
$$Z_{012} = -j\frac{X_C}{3} \bullet \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}$$

High-Current Internal SLG Fault

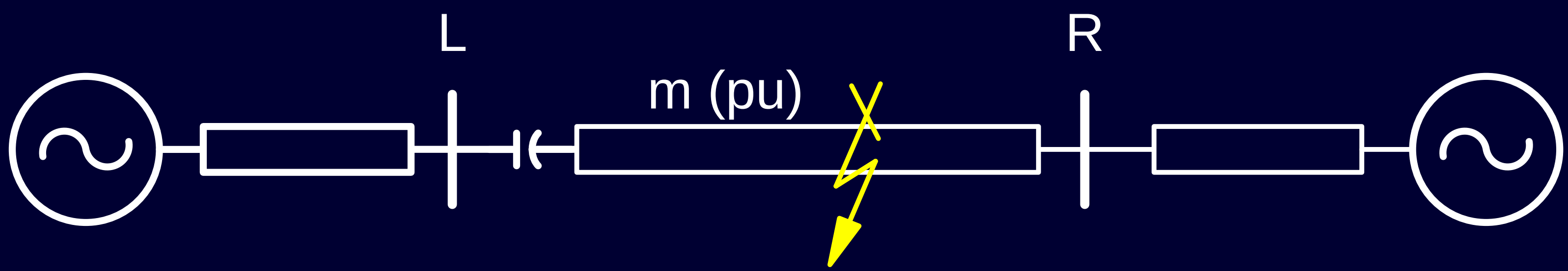


$$\frac{1+k_2}{1+k_0} = \frac{(Z_{1R} + (1- m)Z_1) - k_2(Z_{1L} - jX_C + mZ_1)}{(Z_{0R} + (1- m)Z_0) - k_0(Z_{0L} - jX_C + mZ_0)}$$

High-Current Internal SLG Fault



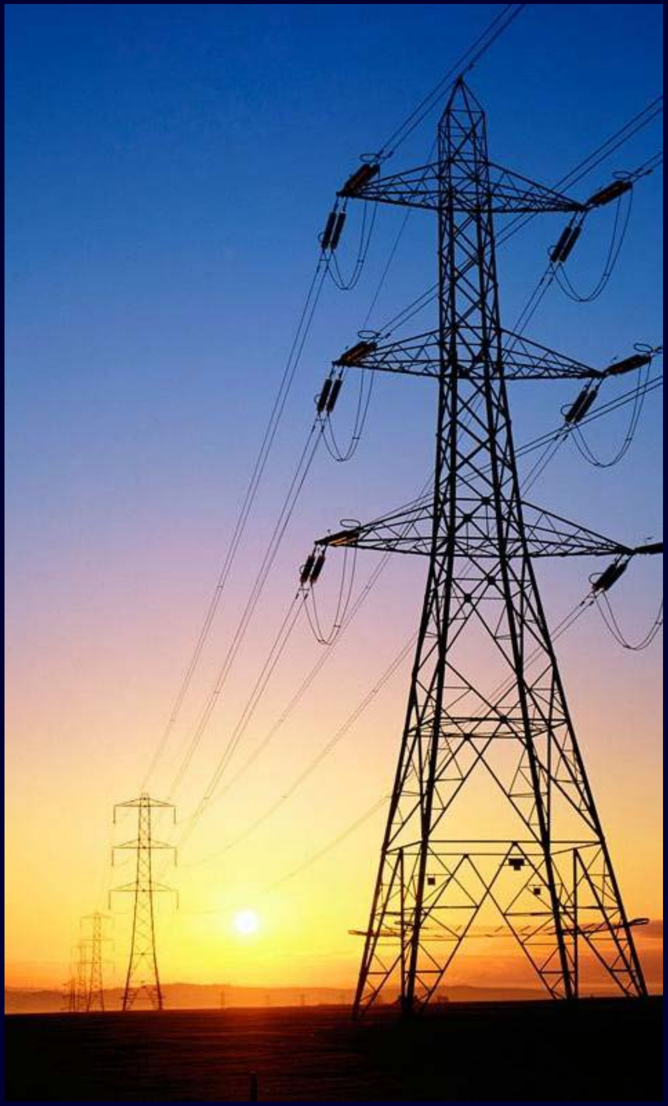
Example



m (pu)	Low-Current SLG Fault		High-Current SLG Fault	
	87G – k_0	87Q – k_2	87G – k_0	87Q – k_2
0.1	23.6∠162°	3.76∠172°	6.80∠42°	2.76∠106°
0.2	21.5∠17°	4.53∠169°	3.77∠18°	2.82∠73°
0.3	6.84∠5.6°	5.87∠165°	2.31∠8.1°	2.18∠37°
0.4	3.72∠3.1°	8.7∠156°	1.53∠1.8°	1.44∠8.7°
0.5	2.38∠2.0°	16.3∠126°	1.06∠–2.8°	0.98∠–13°
0.6	1.63∠1.3°	14.5∠50°	0.75∠–7.0°	0.71∠–32°
0.7	1.15∠0.9°	6.65∠22°	0.52∠–11°	0.56∠–49°
0.8	0.82∠0.5°	3.84∠14°	0.36∠–16°	0.48∠–64°
0.9	0.58∠0.0°	2.51∠9.7°	0.23∠–24°	0.42∠–74°
1.0	0.40∠–0.4°	1.81∠7.7°	0.14∠–36°	0.38∠–82°

Series Compensation and 87L

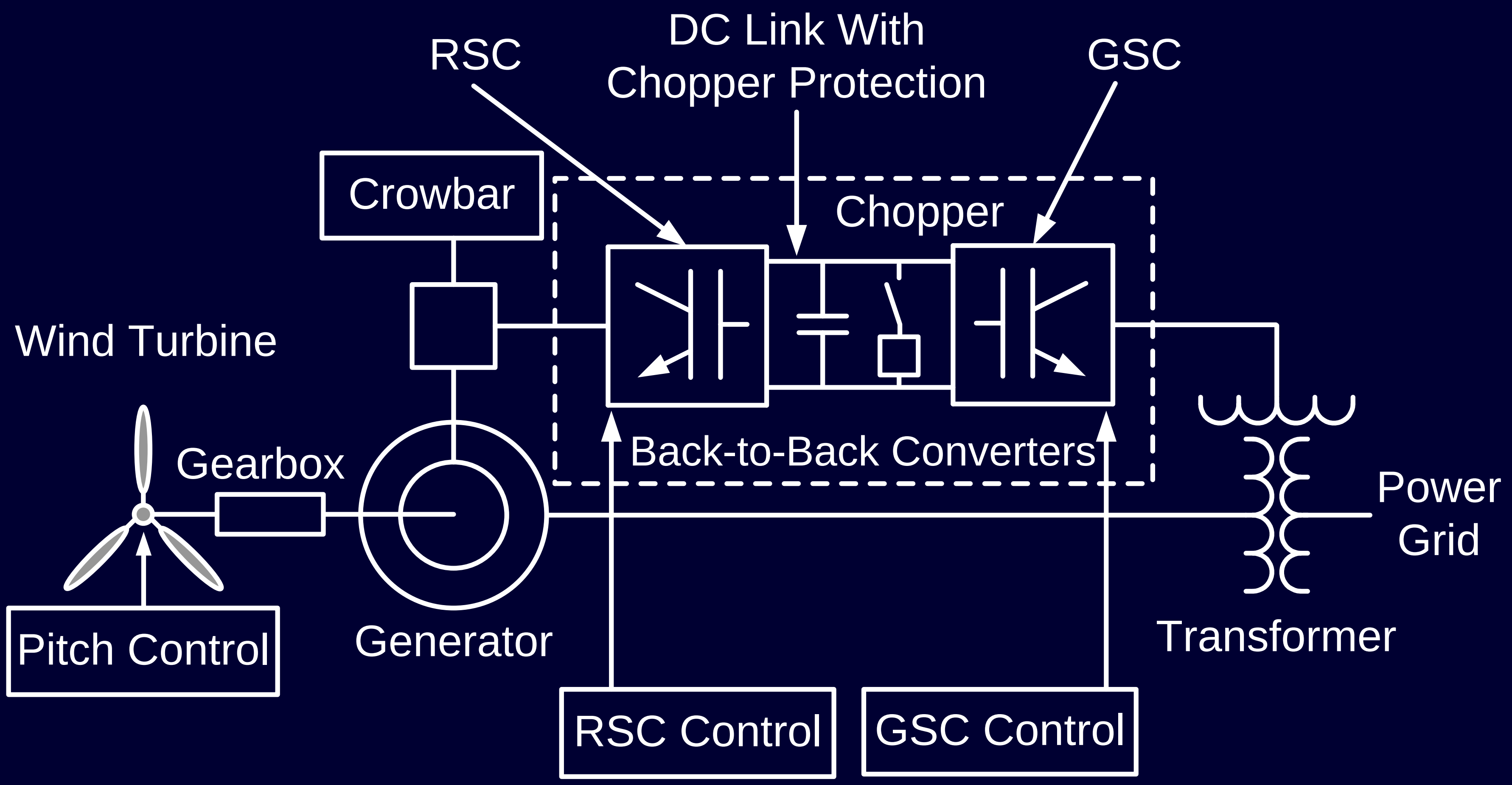
- 87L is inherently secure
- Current inversion affects 87LP, 87LQ, and 87LG differently
- Enable all three elements for better dependability, sensitivity, and speed



Inverter-Based Sources

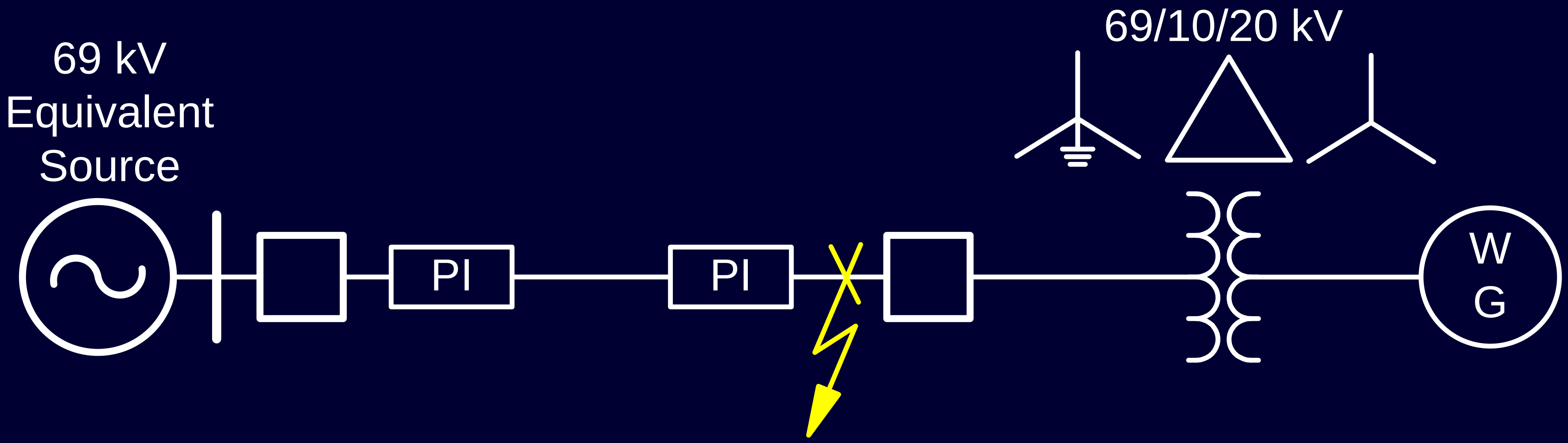
- Fault behavior not well understood
- Fault behavior driven by flexible design choices – difficult to discover
- Unease among protection engineers regarding setting selection and scheme performance
- Terminal with inverter-based source typically treated as weak terminal

Wind Farm Simulation Example



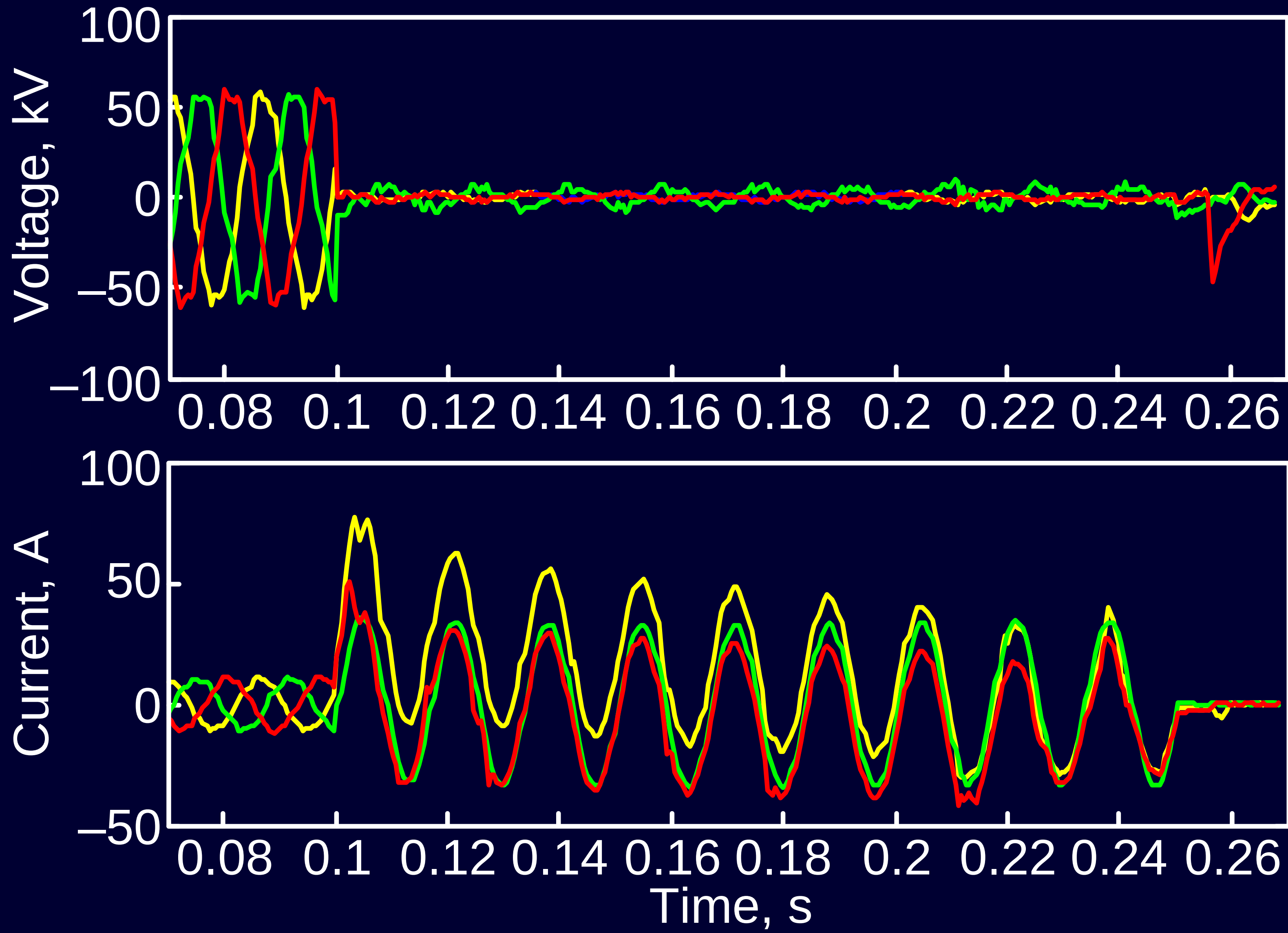
RSC = Rotor-Side Converter
GSC = Grid-Side Converter

Wind Farm Simulation Example



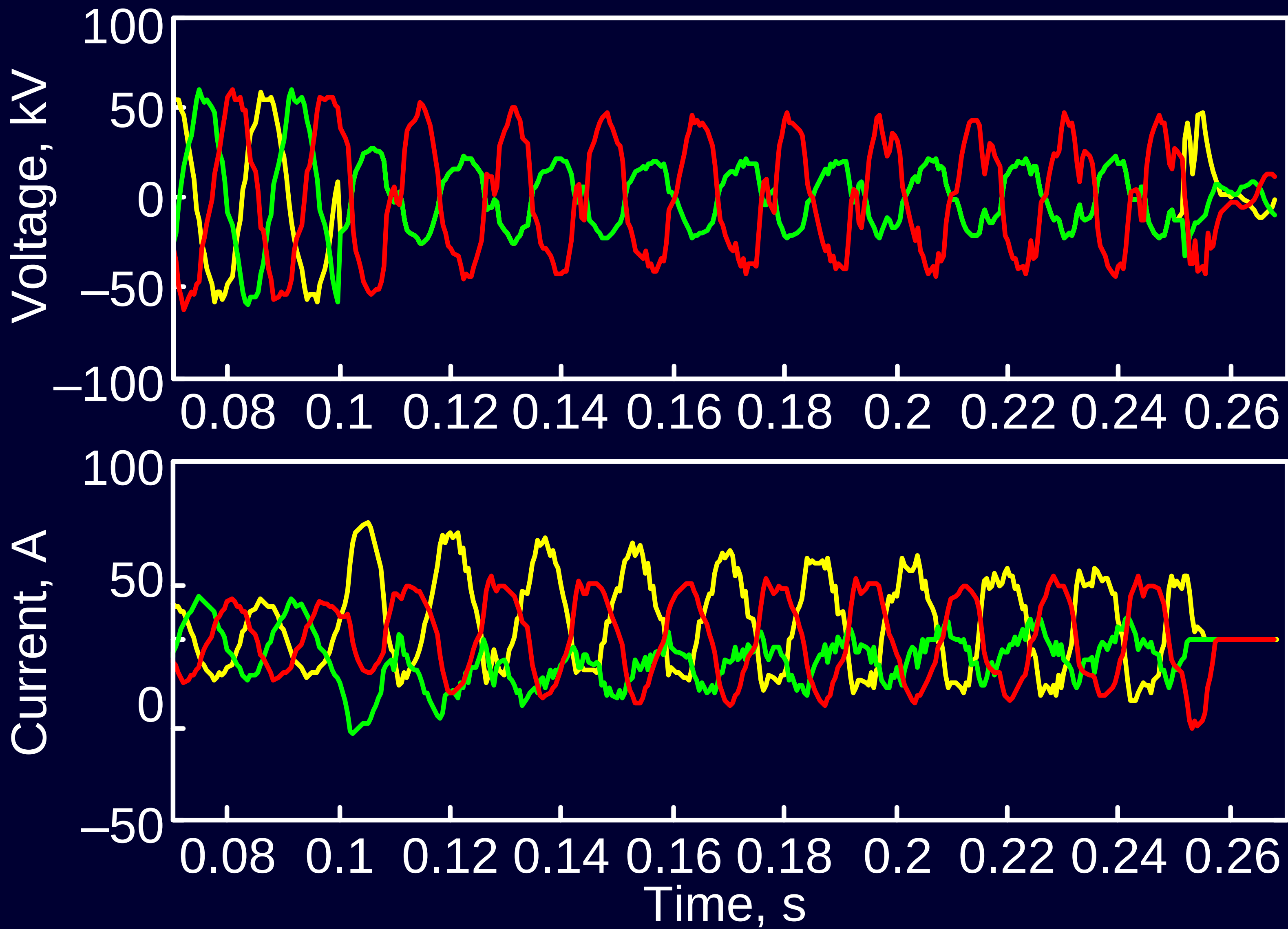
Wind Farm Simulation Example

SLG Fault



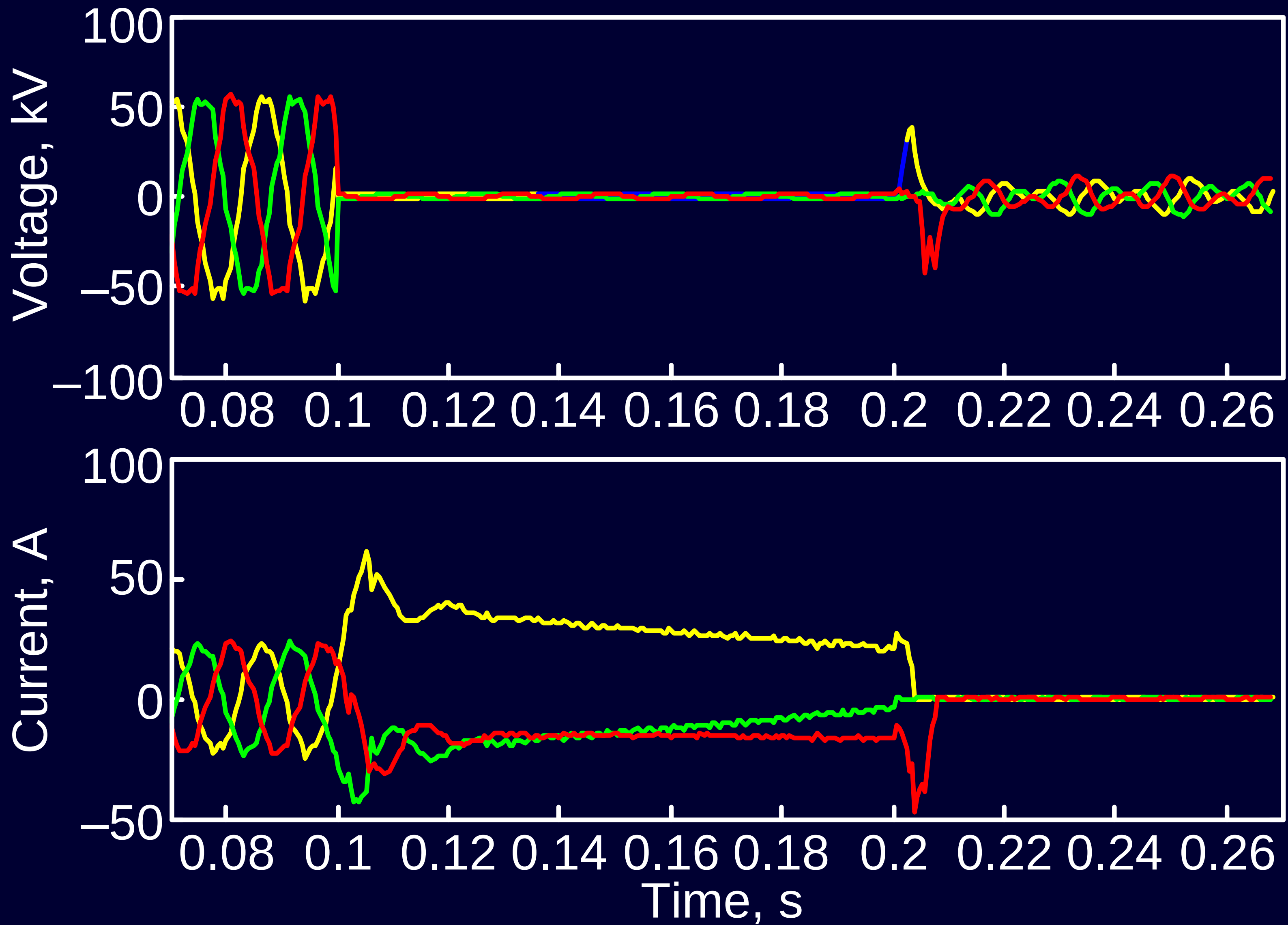
Wind Farm Simulation Example

LL Fault



Wind Farm Simulation Example

3P Fault



Inverter-Based Sources and 87L

- 87L is inherently secure
- Grounded transformer windings allow zero-sequence currents and support 87LG
- Inverter-based sources contribute to phase faults
- System contribution allows 87L to work reliably

Summary

- 87L protection is inherently secure
- 87LP, 87LQ, and 87LG elements respond to the same measurements
- Using all three elements does not diminish security
- 87L elements respond differently to faults under unusual system conditions
- Using all three elements increases dependability

Questions?