Considerations When Using Charging Current Compensation in Line Current Differential Applications

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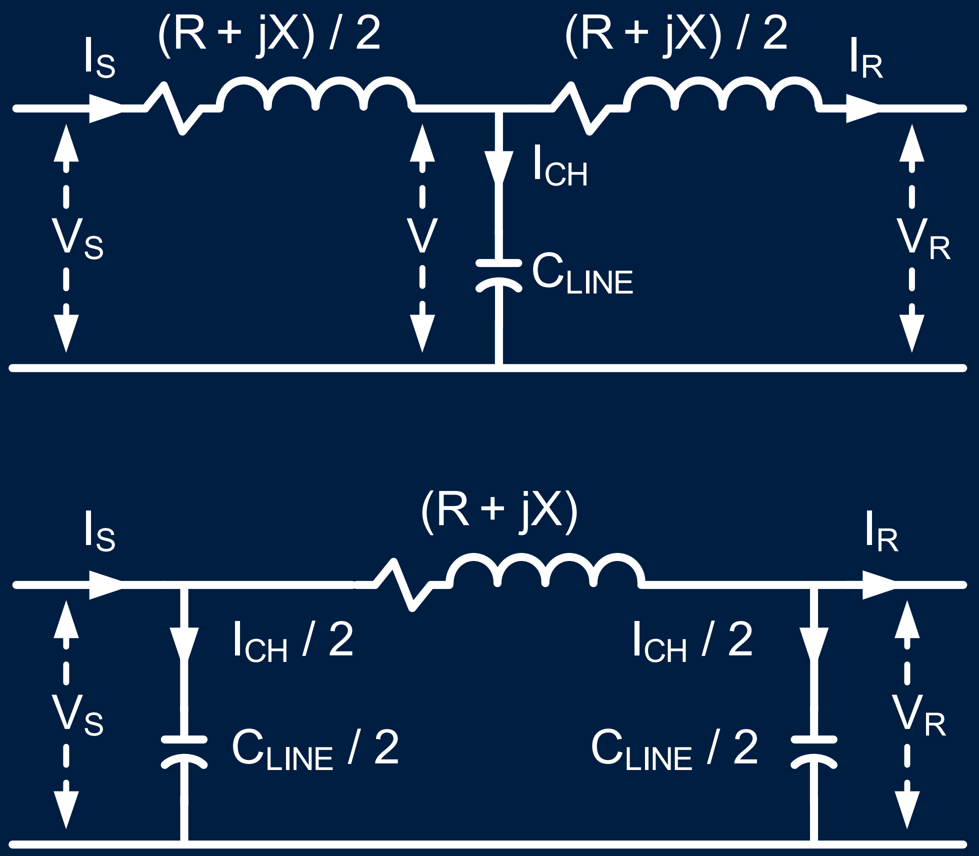
What Is Charging Current?

- Exists on all transmission lines and cables due to inherent capacitive reactance of conductors
- Depends on line length, voltage level, and whether conductor is overhead or underground
- Appears as standing differential current to 87L scheme
- Exists mainly in positive-sequence currents



$$I_{CH} = C_{LINE} \cdot \frac{dV}{dt}$$

Calculating Charging Current

Settings engineer often makes assumptions to simplify calculations (e.g., steady state, transposed line, balanced voltages)

$$I_{1CH} = j\omega C_1 V_{1\_AVE}$$

$$I_{1CH} = j\omega C_1 \frac{V_{PH-PH}}{\sqrt{3}}$$

$$I_{1CH} = j \cdot \frac{B_1}{1{,}000} \cdot \frac{V_{PH-PH}}{\sqrt{3}} \cdot \frac{CTR}{PTR}$$

(B_1 in secondary milliSiemens)

Protective relays may use other equation forms

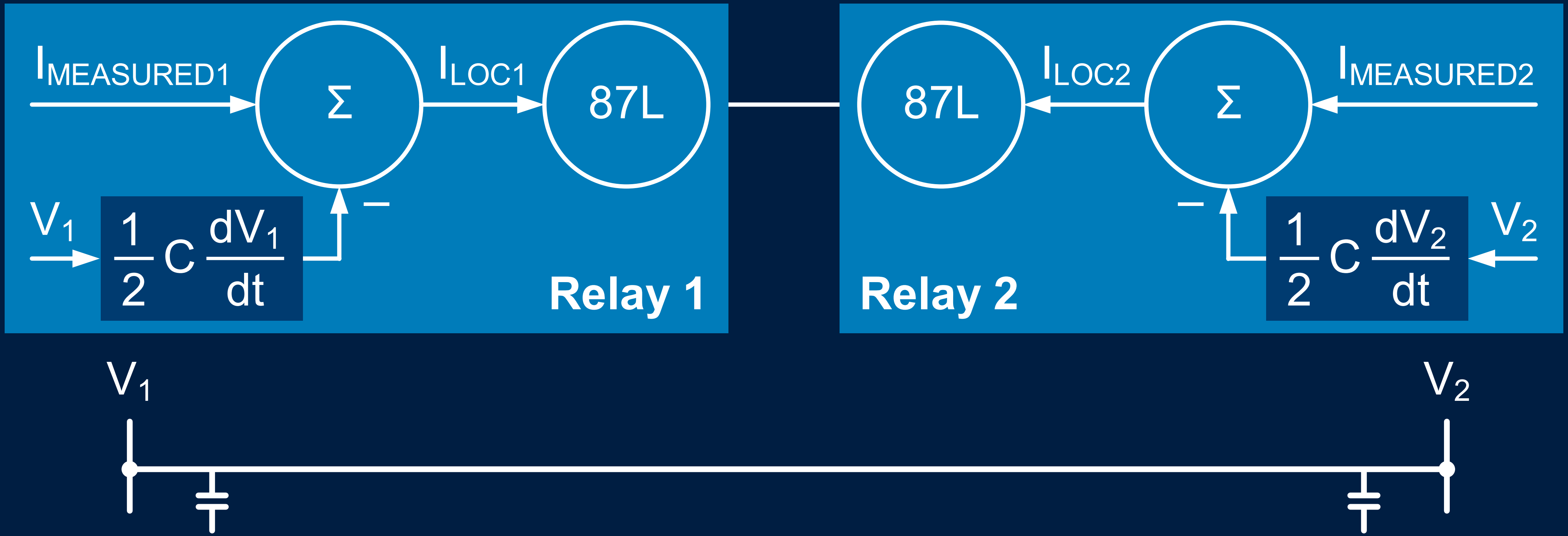
Typical Charging Current Values

Voltage Level (kV)	Charging Current Value (A / mi)
765	3.10–3.20
525	2.05–2.20
345	1.35–1.45
230	0.90–0.98
115	0.45–0.50
69	0.25–0.30

Charging Current Compensation Methods

- **Modified settings (reduced sensitivity)**
- **Current-based compensation (steady state removal)**
  - Relay subtracts fixed value entered as setting
  - Relay subtracts memorized average differential current
- **Voltage-based compensation**
  - Relay can calculate and subtract real-time charging current
  - Dynamic method is based on measured instantaneous line voltage values and zero- and positive-sequence line susceptance settings (B_0 and B_1)

Voltage-Based Compensation



$$I_{LOC1} = I_{MEASURED1} - 0.5 \cdot C_{LINE} \cdot \frac{dV_1}{dt} \qquad I_{LOC2} = I_{MEASURED2} - 0.5 \cdot C_{LINE} \cdot \frac{dV_2}{dt}$$

$$I_{DIF} = I_{LOC1} + I_{LOC2} = I_{MEASURED1} + I_{MEASURED2} - C_{LINE} \cdot \frac{d}{dt}\left(\frac{V_1 + V_2}{2}\right)$$

When to Apply Compensation

- There is no standard or guideline
- Settings engineer must
  - Understand and apply calculations for charging current
  - Evaluate impact on protection scheme
  - Determine if compensation is necessary

When to Apply Compensation

Example 1

Characteristic	Value
Line length	50 mi
System voltage	500 kV
B_1	9.8 µS / mi primary
CTBASE	2,000 A
I_{CH}	$\frac{500\ \text{kV}}{\sqrt{3}} \bullet 50\ \text{mi} \bullet 0.0098\ \text{mS / mi}$ = 141 A primary
I_{CHPU}	$\frac{141\ \text{A}}{2{,}000\ \text{A}} = 0.071$ per unit (pu)

$$\frac{I_{CHPU}}{87L\ \text{pickup}} \bullet 100\%$$

$$= \frac{0.071\ \text{pu}}{1\ \text{pu}} \bullet 100\%$$

$$= 7.1\%$$

Compensation Is Likely Not Required

When to Apply Compensation

Example 2

Characteristic	Value
Line length	250 mi
System voltage	500 kV
B_1	9.8 µS / mi primary
CTBASE	2,000 A
I_{CH}	$\frac{500\ kV}{\sqrt{3}} \cdot 250\ mi \cdot 0.0098\ mS / mi$ $= 707\ A$ primary
I_{CHPU}	$\frac{707\ A}{2{,}000\ A} = 0.354\ pu$

$$\frac{I_{CHPU}}{87L\ pickup} \cdot 100\%$$

$$= \frac{0.354\ pu}{1\ pu} \cdot 100\%$$

$$= 35.4\%$$

Compensation Method Should Be Considered

Line Reactors in Differential Zone

Reactor current can be included or excluded in differential protection (87L) zone

- **Included** – reactor CTs are not summed into relay
- **Excluded** – reactor CTs are summed into relay

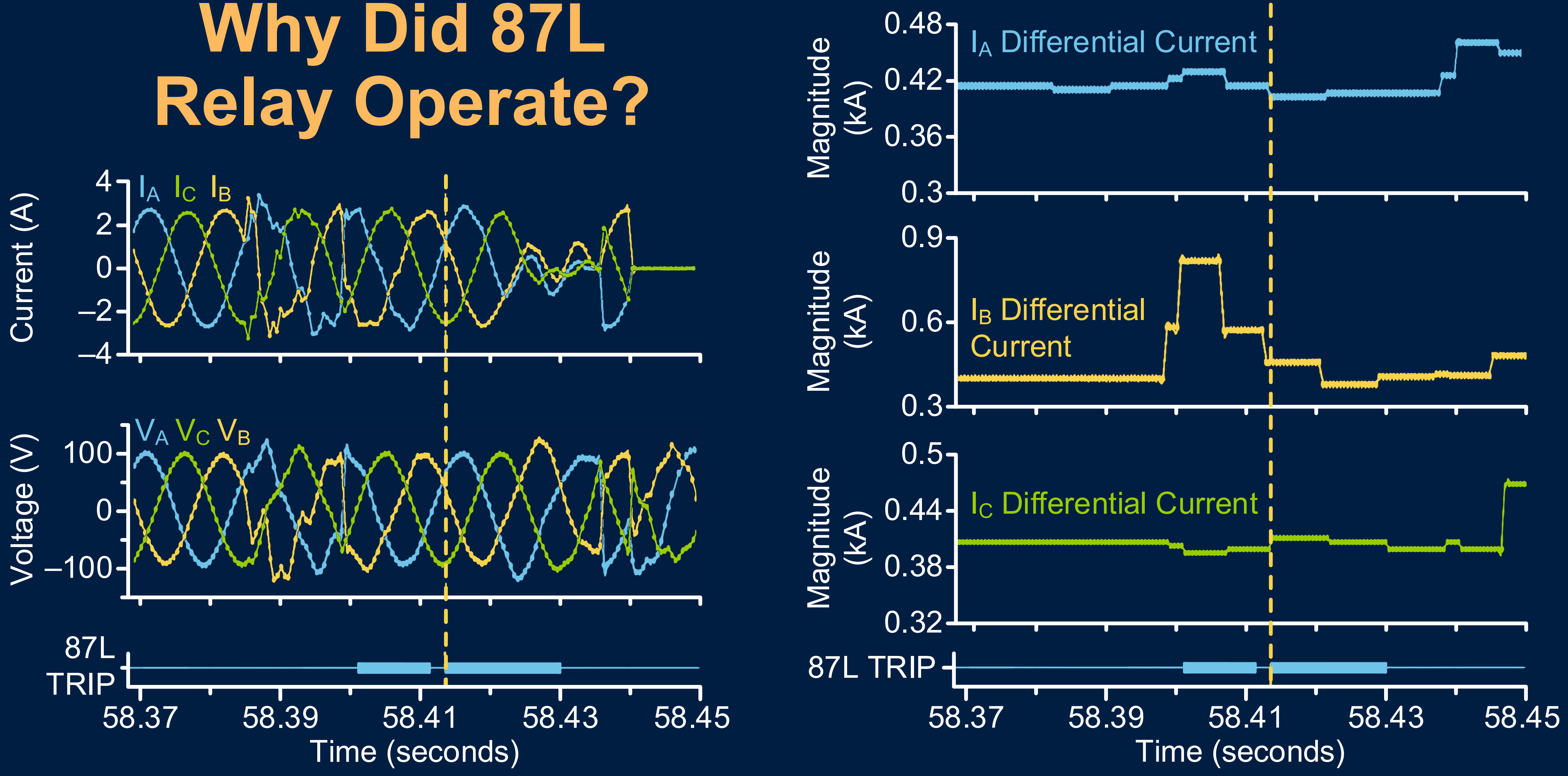
Excluding line-side reactors is recommended; compensation should be set based on full line susceptance

87L Relay Misoperation – Case 1

Charging Current Compensation Enabled When Line Reactors Present

- Line was 525 kV, 215 mi
- Three shunt reactors were included in differential protection zone
- 87L scheme operated but no fault was present
- Relays were using voltage-based compensation method

Why Did 87L Relay Operate?



Standing Differential Current Provides a Clue

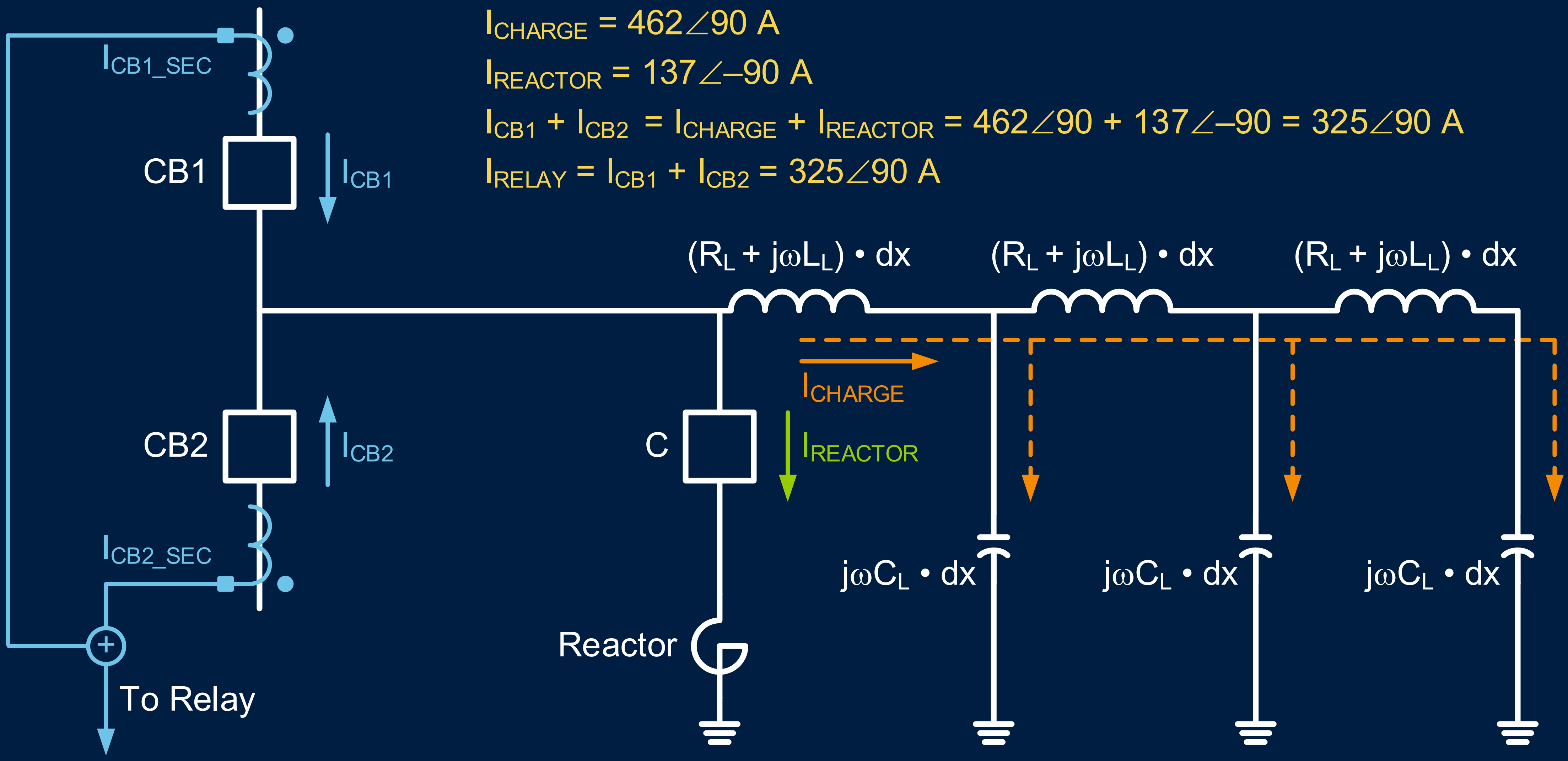
87L Scheme With Shunt Reactor Included

$I_{CHARGE} = 462\angle 90$ A

$I_{REACTOR} = 137\angle -90$ A

$I_{CB1} + I_{CB2} = I_{CHARGE} + I_{REACTOR} = 462\angle 90 + 137\angle -90 = 325\angle 90$ A

$I_{RELAY} = I_{CB1} + I_{CB2} = 325\angle 90$ A



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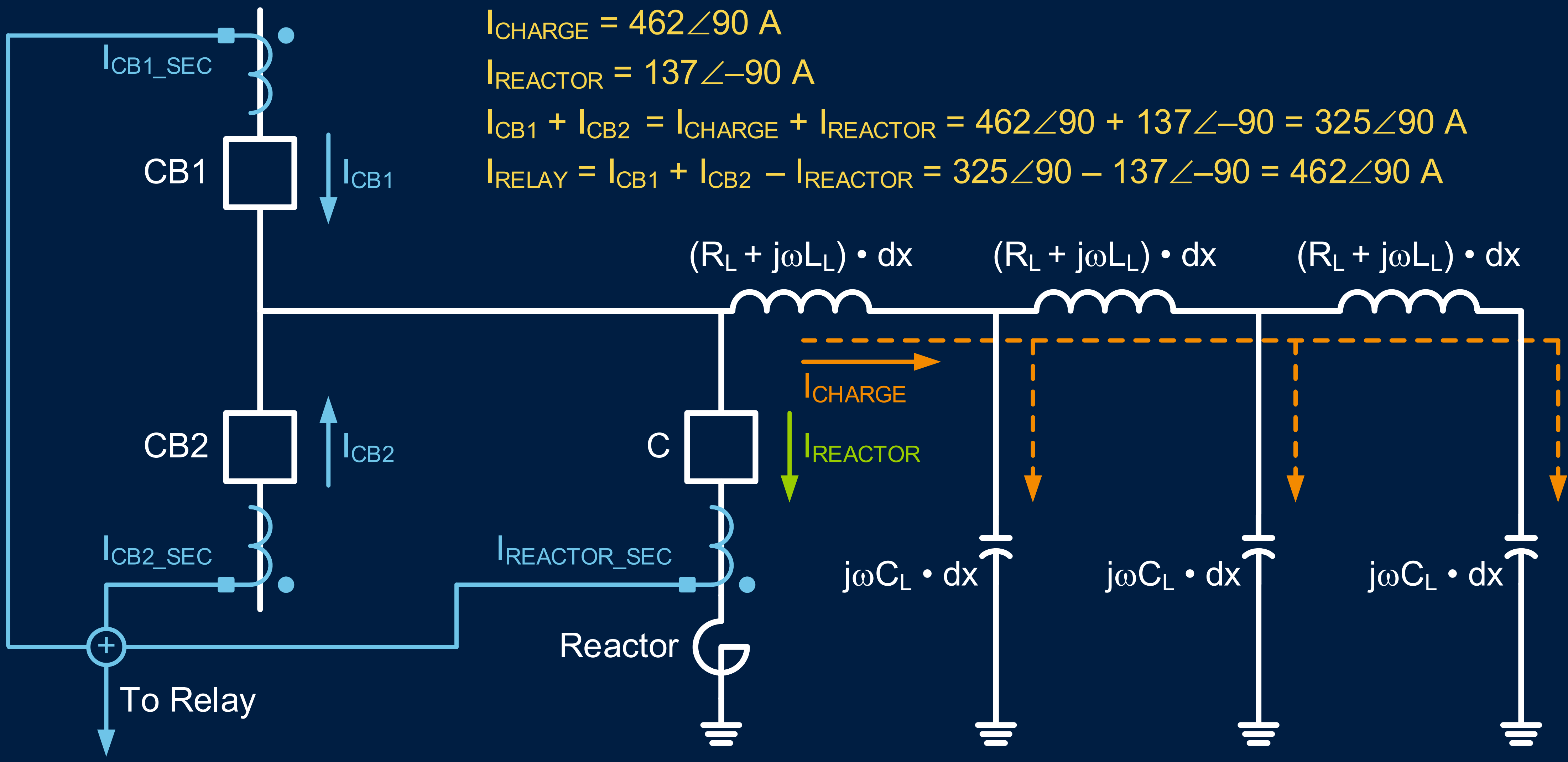
$I_{RELAY} = I_{CB1} + I_{CB2} - I_{REACTOR} = 325\angle 90 - 137\angle -90 = 462\angle 90$ A



Compensation Based on Reactor Configuration

Excluded

Settings are configured using full line susceptance to compensate for full charging current

$B_1 = 1.53$ mS

$B_0 = 0.83$ mS

Included

Settings are configured using partial line susceptance to compensate for remaining charging current that reactor does not compensate for

$B_1 = 0.62$ mS

$B_0 = 0.34$ mS

87L Relay Misoperation – Case 2

Incorrect Charging Current Relay Settings

- Line was 220 kV
- Relay tripped on energization
- There was correct phase current metering, but significant standing differential current

- Relays were using voltage-based compensation method
- Line susceptance values were obtained from software program
  - B_0 = 138.53 µS primary
  - B_1 = 237.24 µS primary

87L Relay Misoperation – Case 2
Incorrect Charging Current Relay Settings

Correct relay settings for line susceptance required conversion of primary μs to secondary mS

Ex: B_1 = 237.24 μS • (PTR / CTR)

= 593.1 μS

= 0.591 mS

87L Relay Misoperation – Case 2
Incorrect Charging Current Relay Settings

- Values were incorrectly converted from primary to secondary
- Units were also not converted from mS to µS

Ex: B_1 = 237.24 µS • (CTR / PTR)

= 94.9 µS

= 0.0949 mS

- Setting of 160 times correct value led to incorrect charging current calculation (6 A secondary; 4.8 kA primary)

87L Relay Misoperation – Case 2

- Expected charging current was approximately 30 A primary, but relays compensated for approximately 4,800 A
- Misoperation would have been avoided with correct settings

Was charging current compensation necessary?

Assume CTBASE = 4,000 and 87L pickup = 1.0 pu

$$I_{CHPU} = \frac{30\ \text{A}}{4{,}000\ \text{A}} = 0.0075\ \text{pu}$$

$$\frac{I_{CHPU}}{\text{87L pickup}} \cdot 100\% = 0.75\%$$

Summary

- Charging current exists on all lines and depends largely on line length, voltage level, and whether line is overhead or underground
- Settings engineer must evaluate impact of charging current on protection scheme and determine if compensation is necessary
- Settings engineer must understand compensation method used and apply correct settings to avoid misoperations