SEL
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New Techniques and Improved Methods for Fault Location

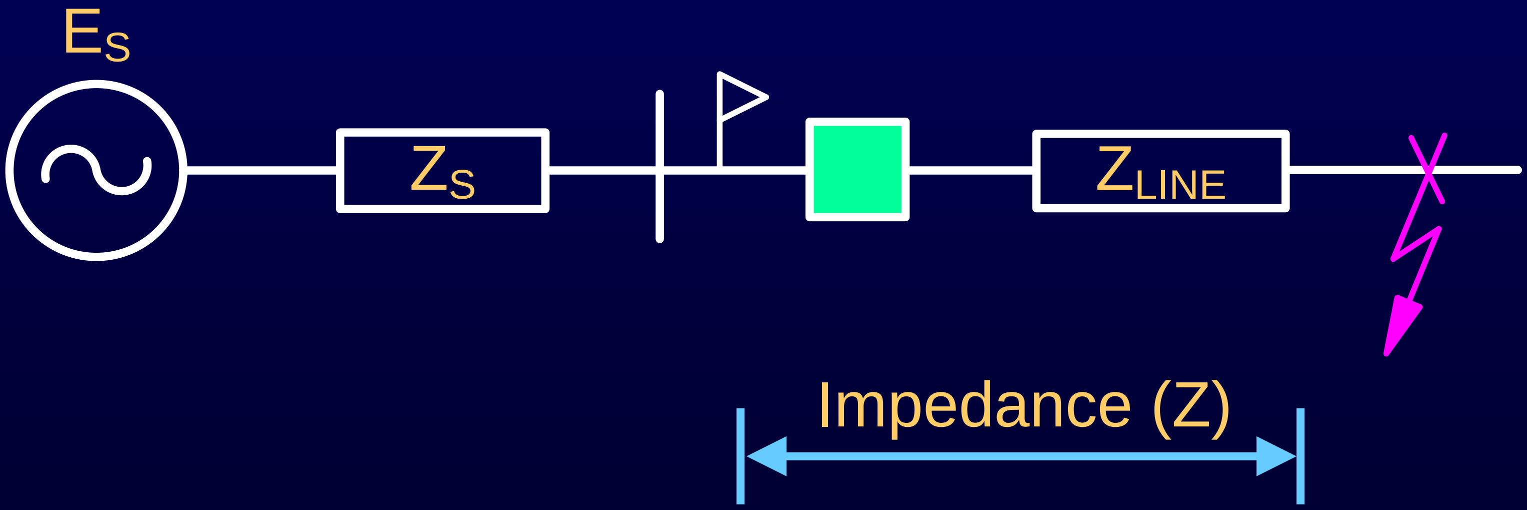
Making Electric Power Safer, More Reliable, and More Economical®

Fault Location (FL) Methods

- Impedance-based methods
  - Single-ended method
  - Multi-ended method
    - Real-time calculations in relays
    - Offline software tools
- Traveling wave (TW) method

Impedance-Based FL

What Is Impedance-Based Fault Location?

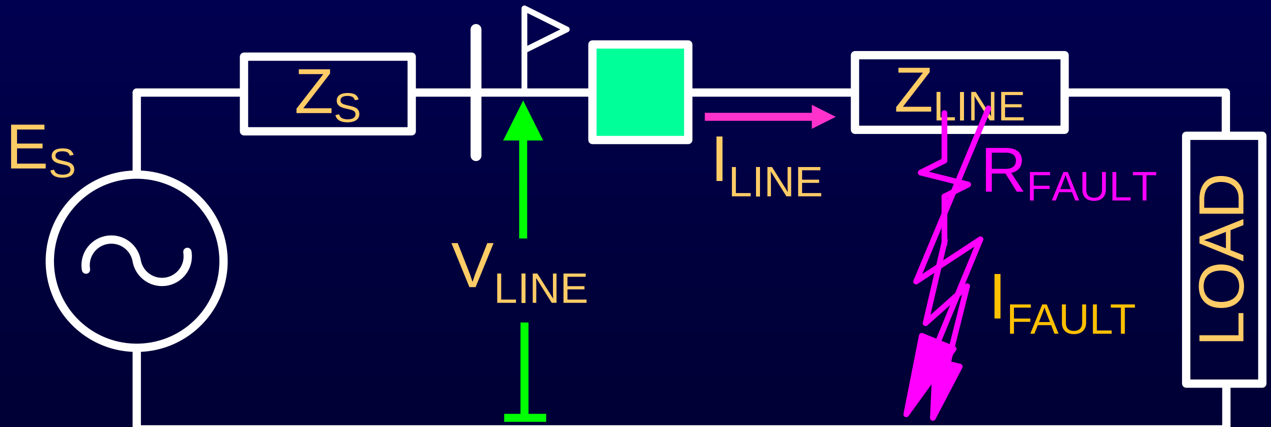


Impedance → Distance

$$\text{Distance} = \frac{\text{Im}(V_L \cdot I_{FLT}^*)}{\text{Im}(I_L \cdot Z_L \cdot I_{FLT}^*)} \cdot \text{Line Length}$$

Single-Ended Method

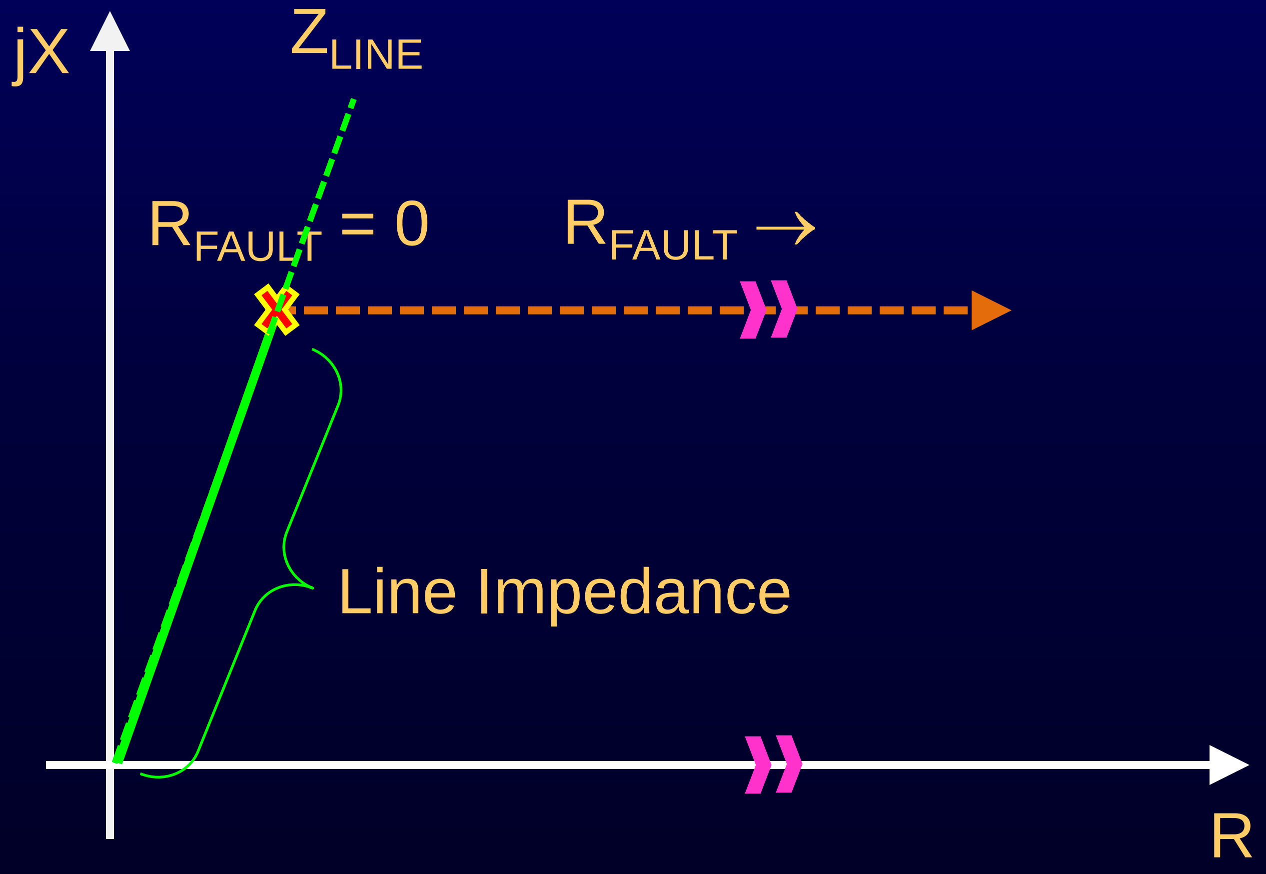
Uses Only Local Current and Voltage



$I_{LINE} = I_{FAULT}$

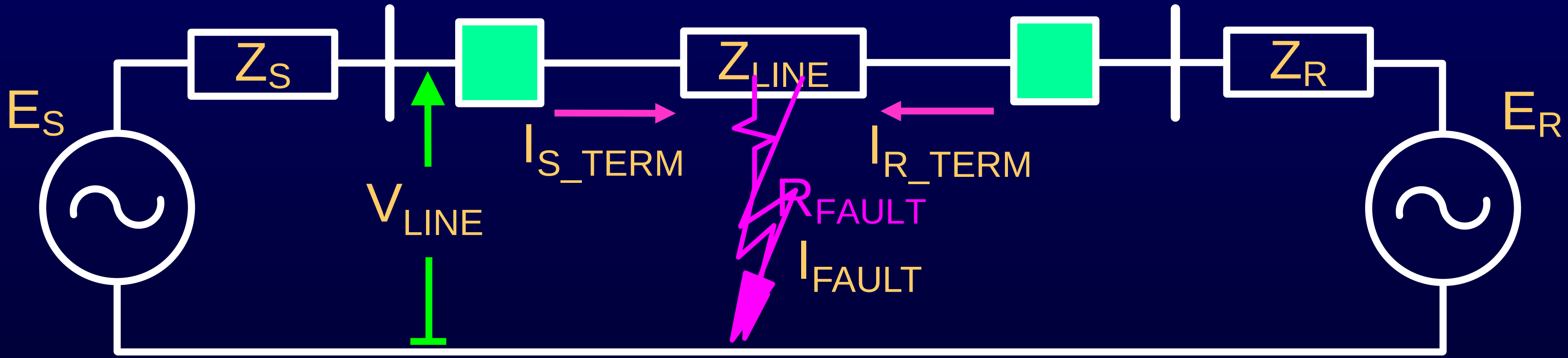
∴ Radial System → Single-Ended Method

Single-Ended Method



Single-Ended Method

Multisource System



$R_{FAULT} = 0$

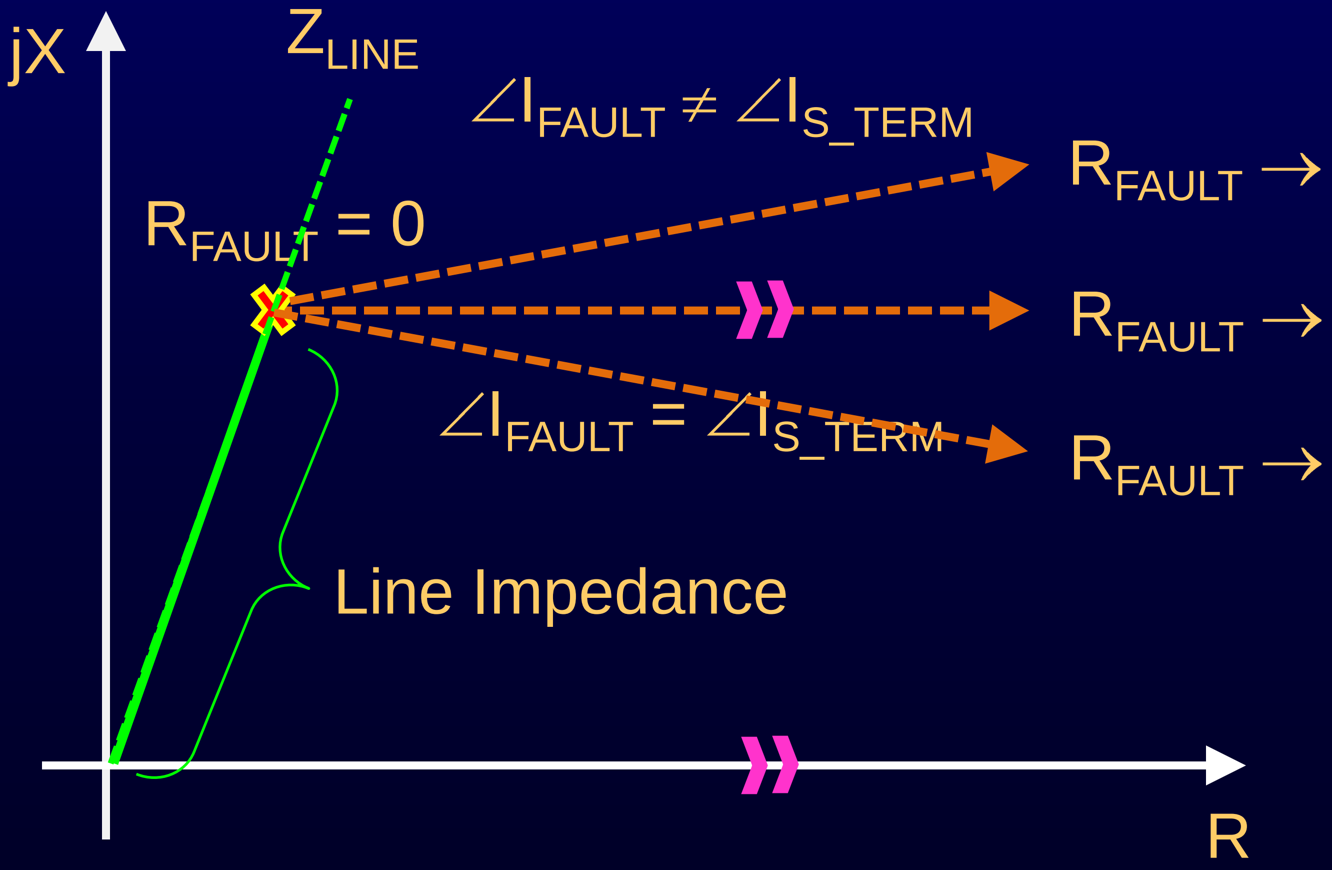
$I_{FAULT} \neq I_{S\_TERM}$ No Problem

$R_{FAULT} \neq 0$

$\angle I_{FAULT} = \angle I_{S\_TERM}$ No Problem

$\angle I_{FAULT} \neq \angle I_{S\_TERM}$ Problem!

Single-Ended Method



Multi-Ended Fault Location
Requires Communications

- Real time

  Between devices (relays)

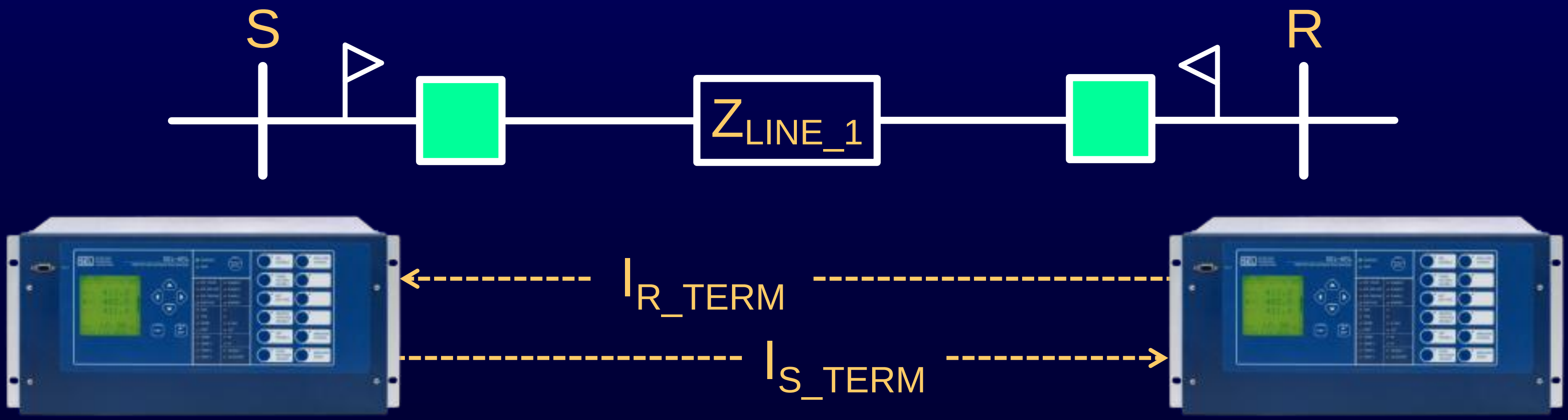
  Natural for line differential

- Offline

  Between devices and data concentrator (central unit)

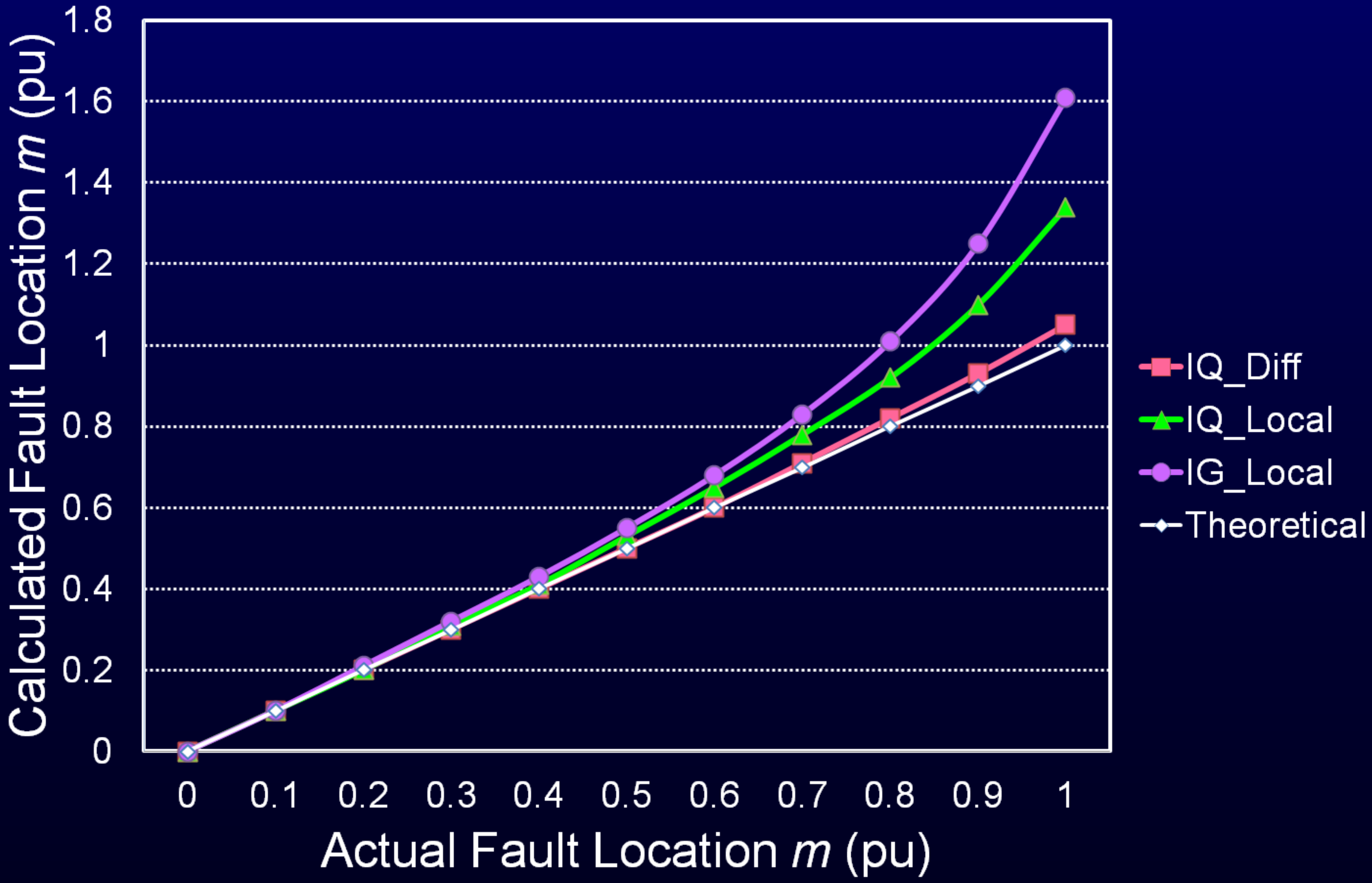
Multi-Ended Fault Location

Real Time

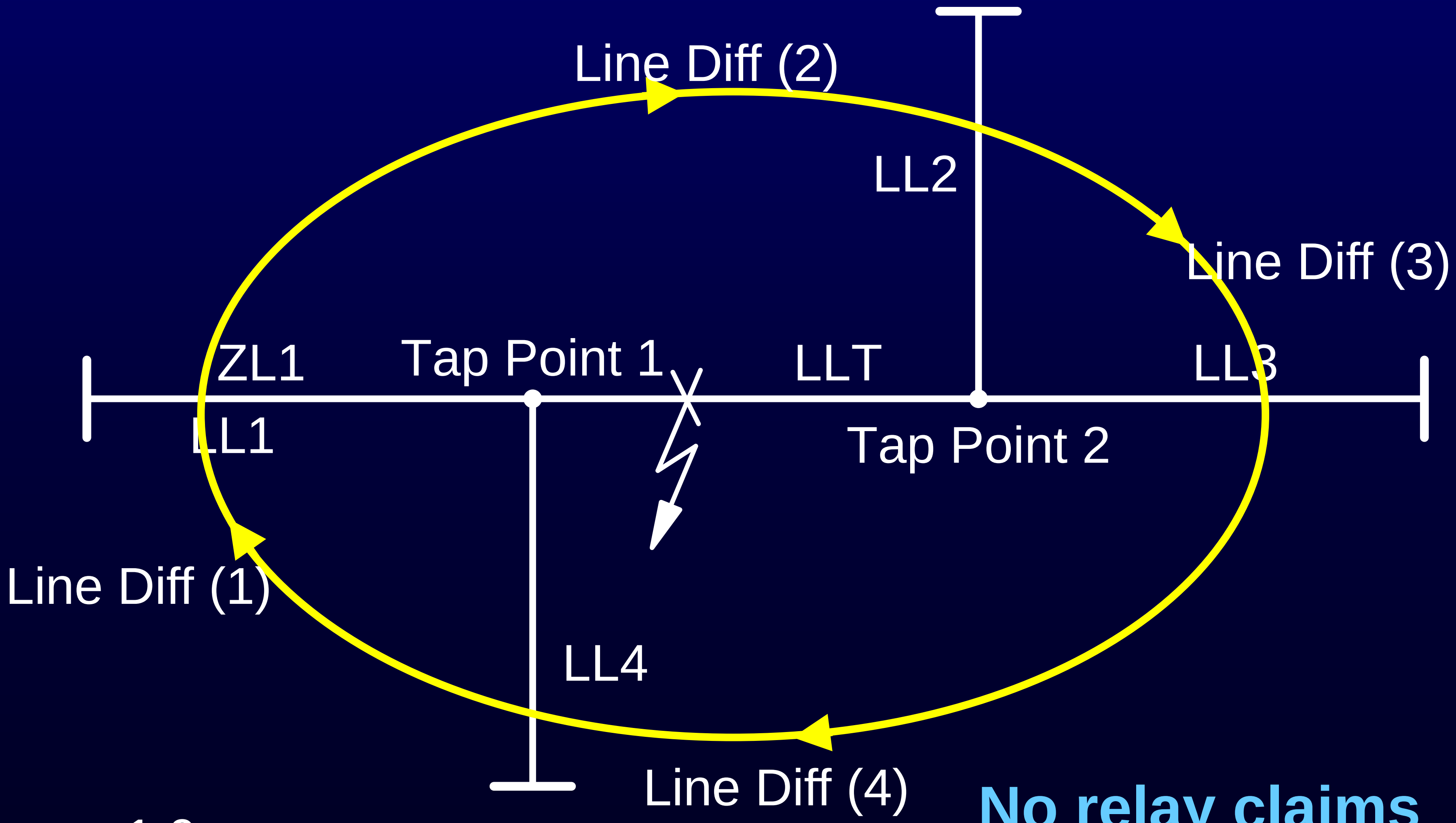


$$\text{Distance} = \frac{\mathrm{Im}\{V_L \bullet (I_{R\_TERM} + I_{S\_TERM})^{*}\}}{\mathrm{Im}\{I_L \bullet Z_L \bullet (I_{R\_TERM} + I_{S\_TERM})^{*}\}} \bullet \text{Line Length}$$

Impact of Polarizing Quantities



Four-Terminal FL Between Taps



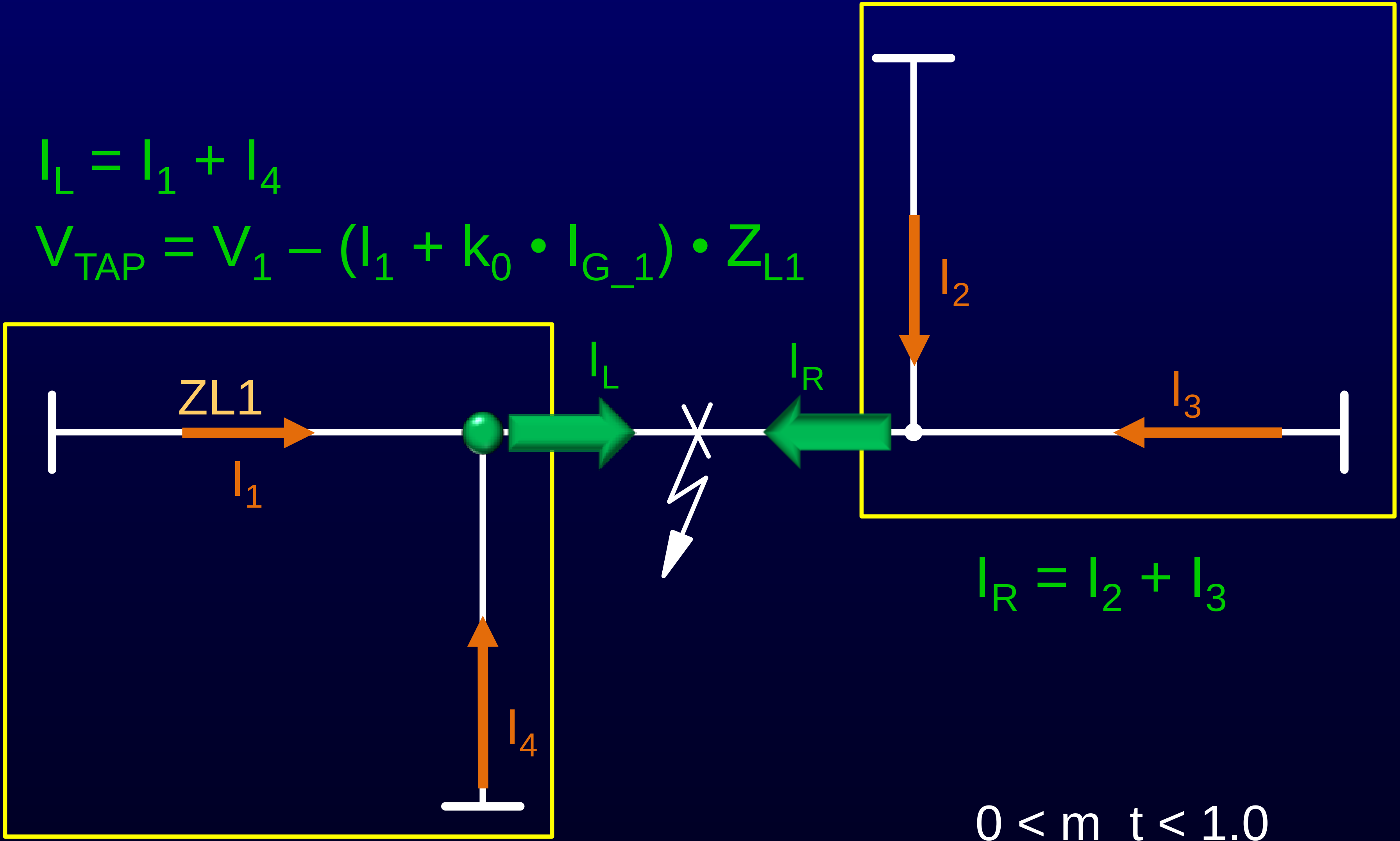
m > 1.0
Fault not in my section

No relay claims fault in own section!

Four-Terminal FL Between Taps

$I_L = I_1 + I_4$

$V_{TAP} = V_1 – (I_1 + k_0 \cdot I_{G\_1}) \cdot Z_{L1}$



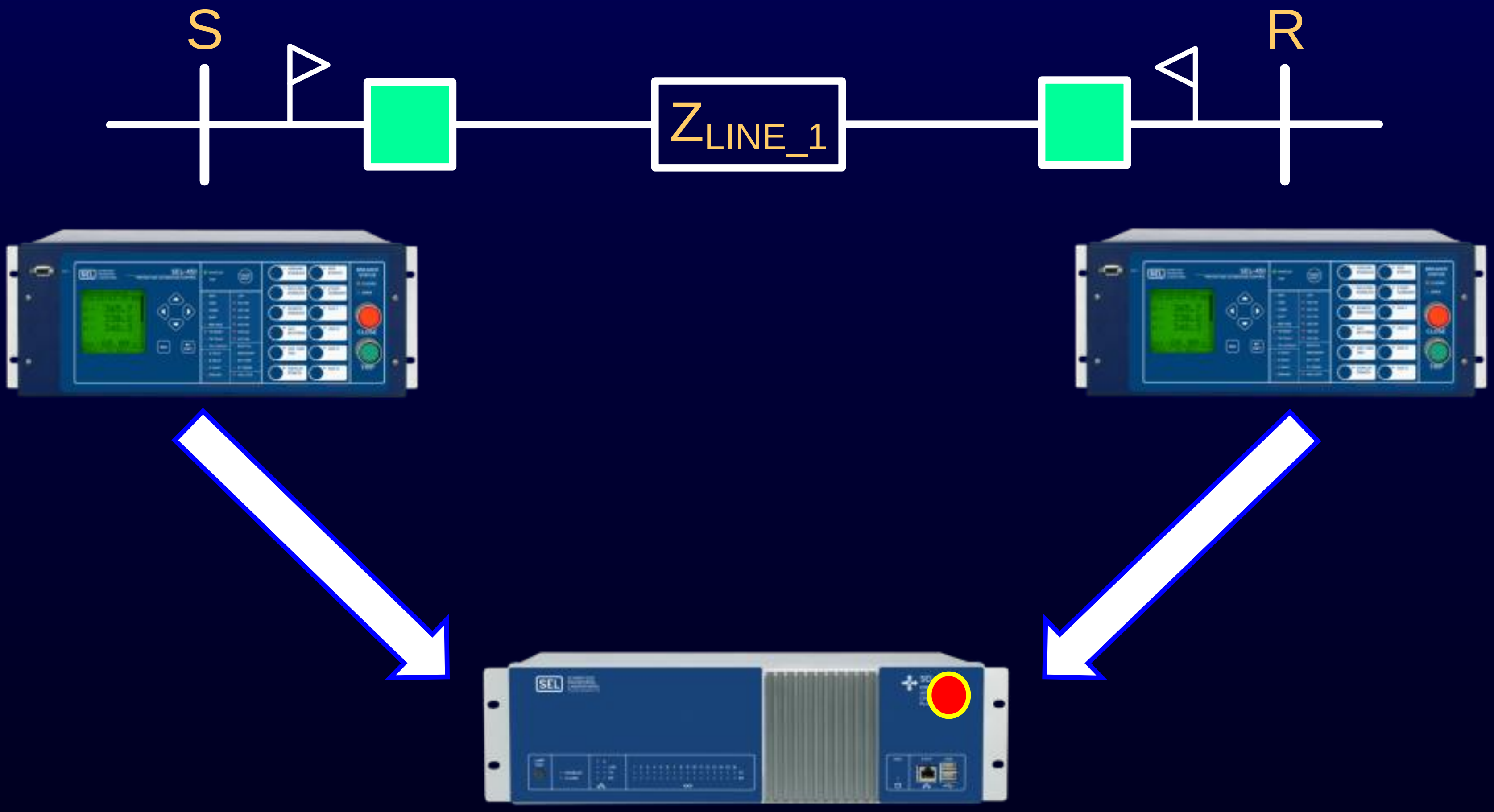
$I_R = I_2 + I_3$

0 < m_t < 1.0

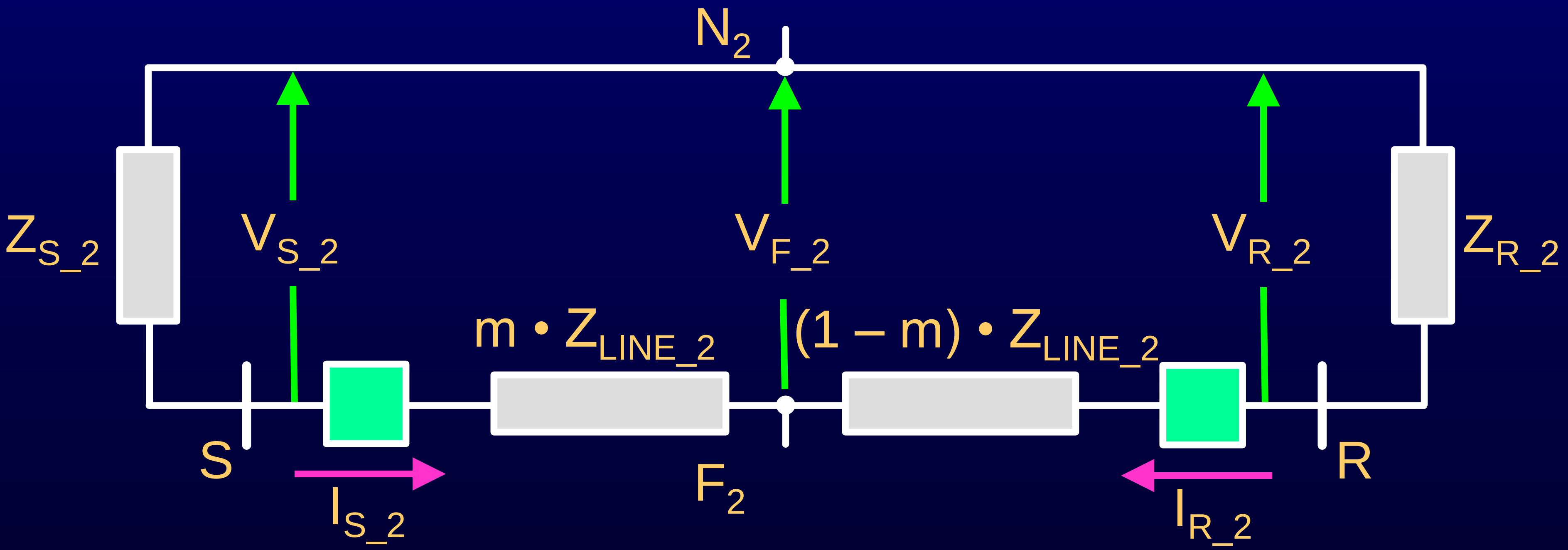
Fault in middle section

Multi-Ended Fault Location

Offline



Use Negative Sequence



Terminal S:

$$V_{2\_F} = V_{S\_2} + m \cdot Z_{LINE\_2} \cdot I_{S\_2}$$

Terminal R:

$$V_{2\_F} = V_{R\_2} + (1 - m) \cdot Z_{LINE\_2} \cdot I_{R\_2}$$

Solve for *m*

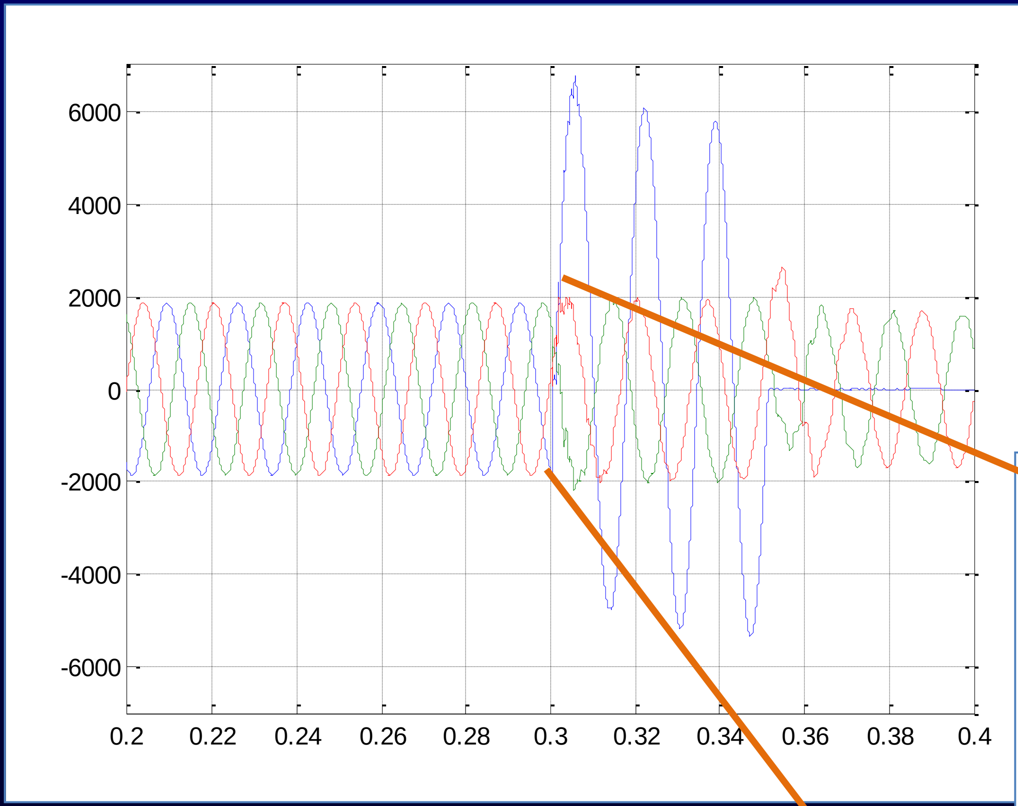
$$m = \frac{V_{R\_2} - V_{S\_2} + Z_{LINE\_2} \bullet I_{R\_2}}{Z_{LINE\_2} \bullet (I_{R\_2} + I_{R\_2})}$$

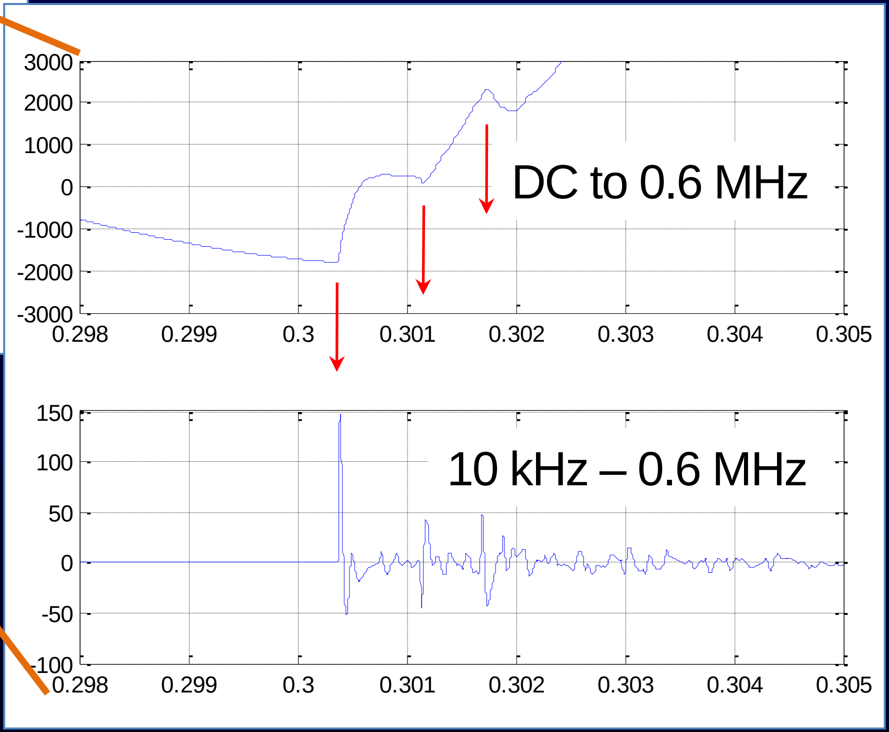
Traveling Wave

- Can locate faults within 300 m (0.2 miles)
- Works great for series-compensated and parallel lines
- Keeps high resolution regardless of line length

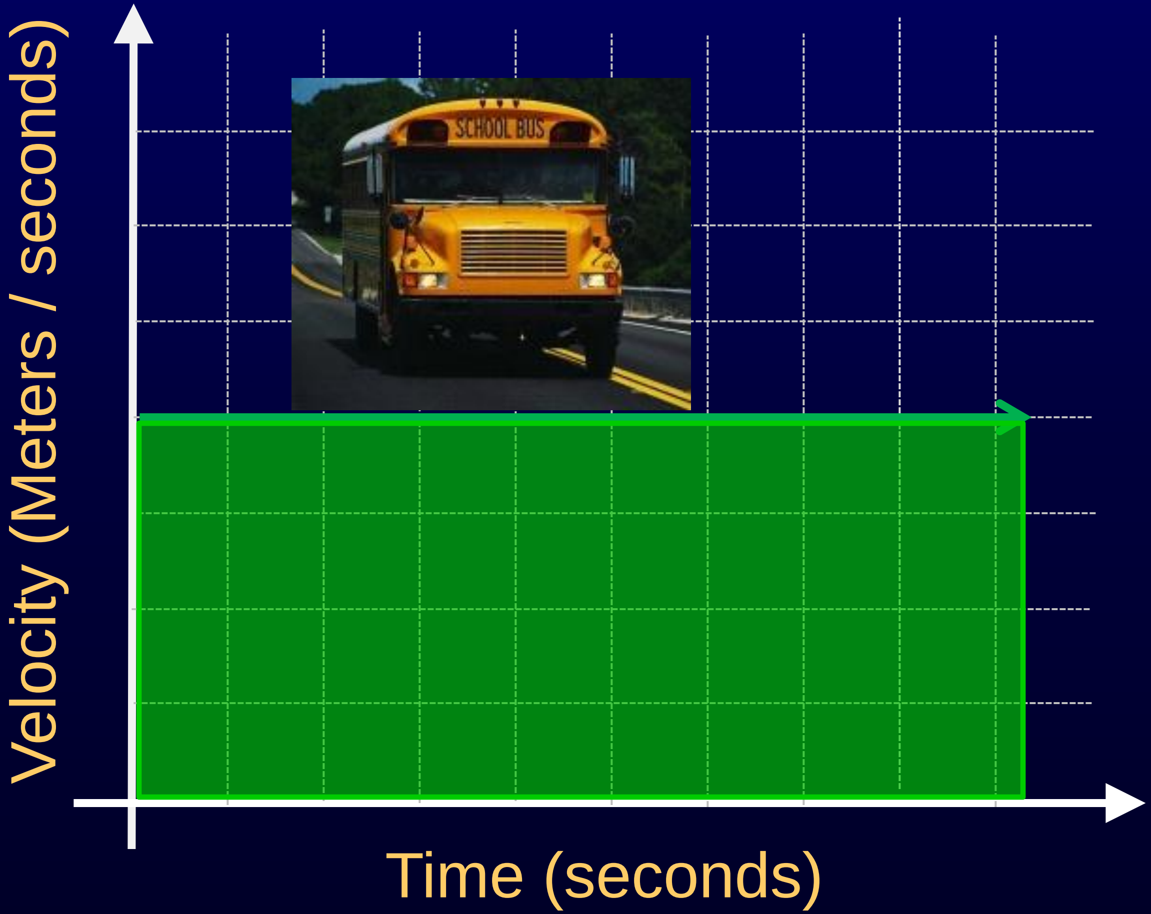
Transients Contain FL Information

High-frequency transients contain precise information about location of the fault





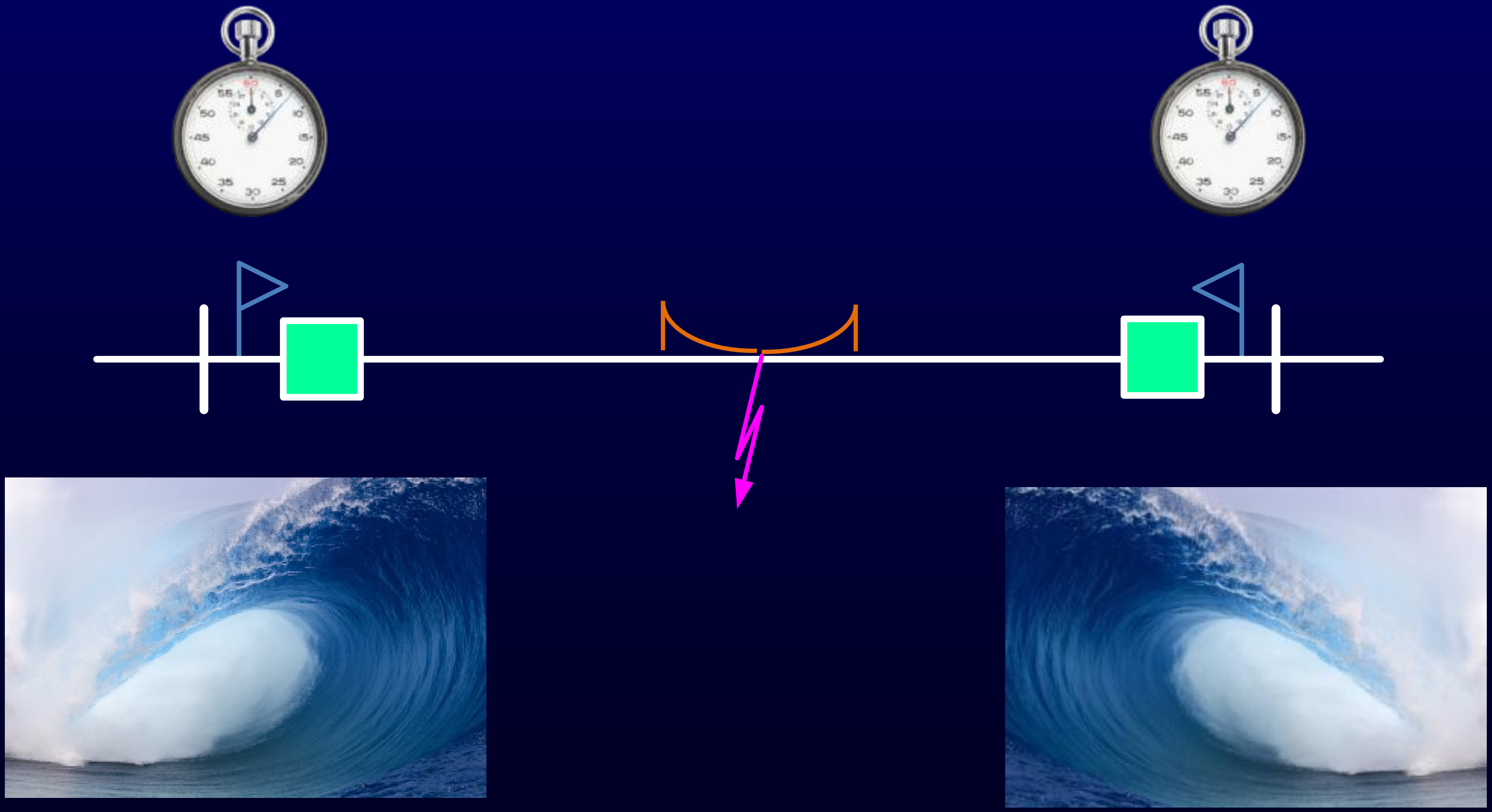
Basic Physics Revisited



Distance =
Velocity • Time

$$s = u \cdot t$$

Theory of Traveling Wave



Calculating the Fault Distance

Find the phase velocity (ν_p) of the TW

$$\nu_p = \frac{1}{\sqrt{\mu_0 \varepsilon_0 \varepsilon_r}} \qquad \varepsilon_r \cong 1 \qquad \nu_p \cong 300{,}000\ \text{km / s}$$

(186,000 miles / s)

Calculate the travel time of the wave in the line

$$\tau_{\text{Line}} = \frac{\text{Line Length}}{\nu_p}$$

Calculate the distance to the fault

$$F_{\text{LOCATION}} = \frac{L_{\text{LENGTH}}}{2} + \frac{(t_{\text{S\_TERM}} - t_{\text{R\_TERM}})}{\tau_{\text{LINE}}} \bullet \frac{L_{\text{LENGTH}}}{2}$$

Example – What Is the Distance to the Fault?

Line = 300 km (186 mi)

ν_p = 300,000 km / s

τ_{LINE} = 0.001 s or 1 ms

10:00.000,334,560

10:00.000,665,440

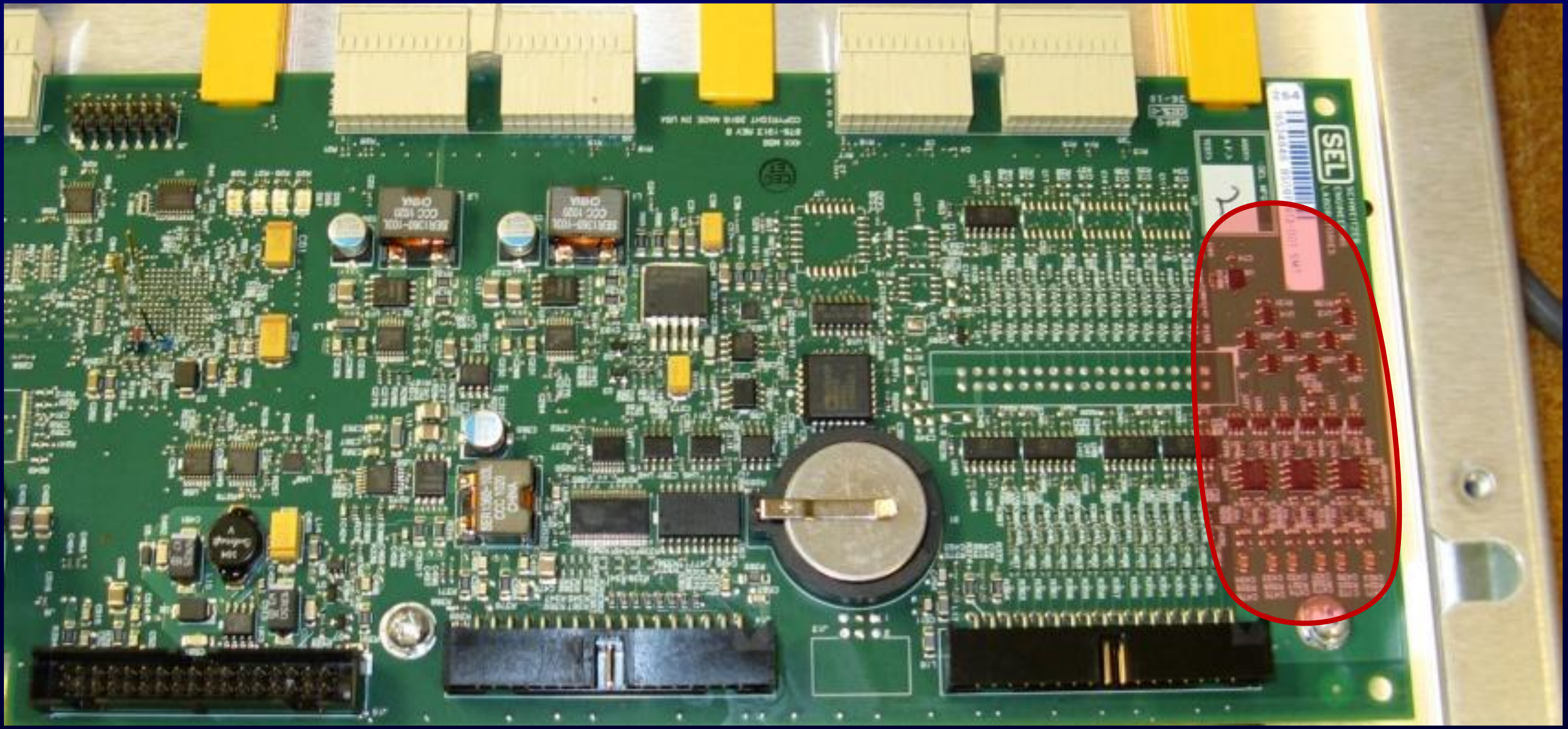
Distance From Terminal S

$$F_{LOCATION} = \frac{L_{LENGTH}}{2} + \frac{(t_{S\_TERM} - t_{R\_TERM})}{\tau_{LINE}} \bullet \frac{L_{LENGTH}}{2}$$

$$= 150 + \frac{(334{,}560 - 665{,}440)}{1{,}000{,}000} \bullet 150$$

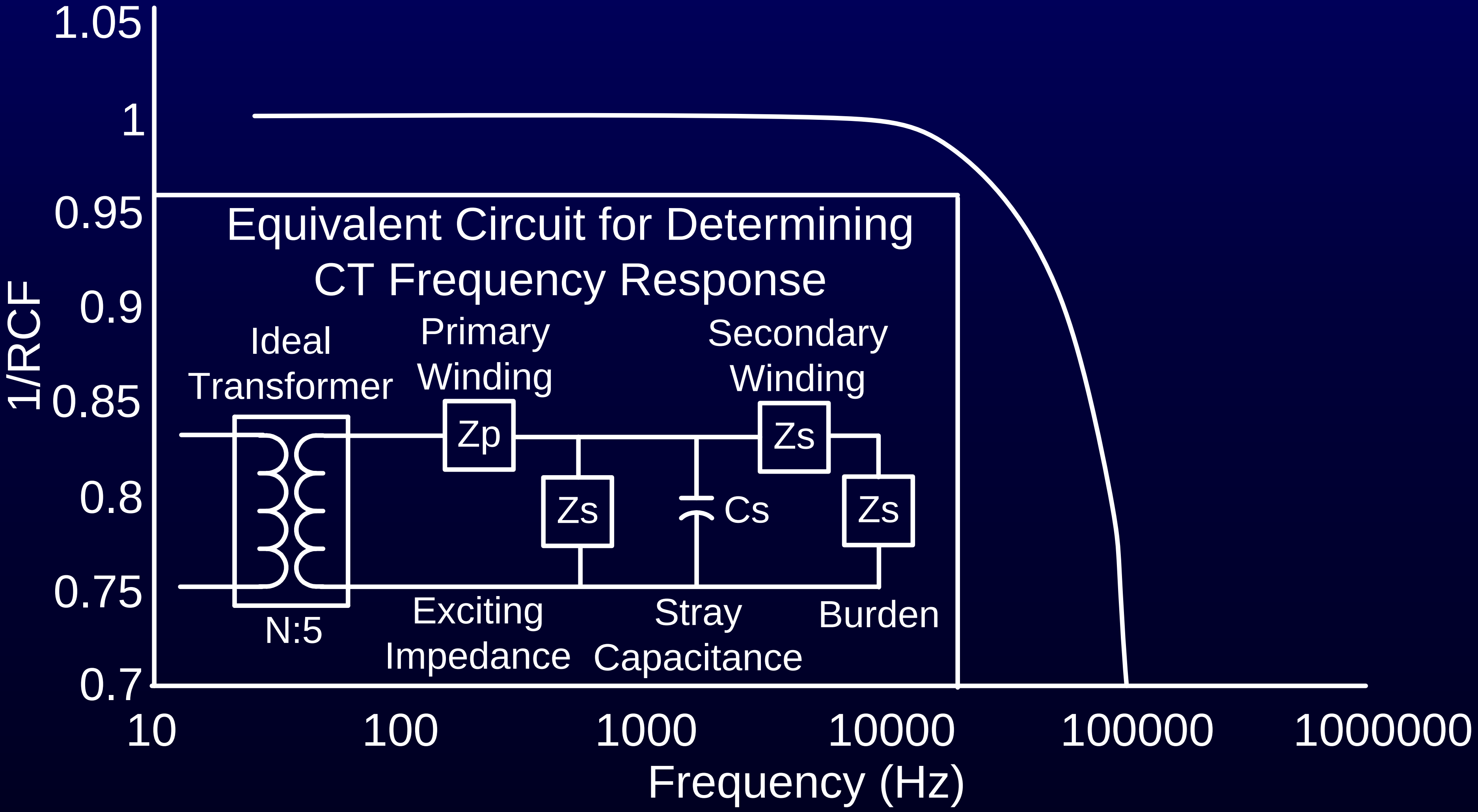
$$= 100.368 \text{ km}$$

Realizing the TW

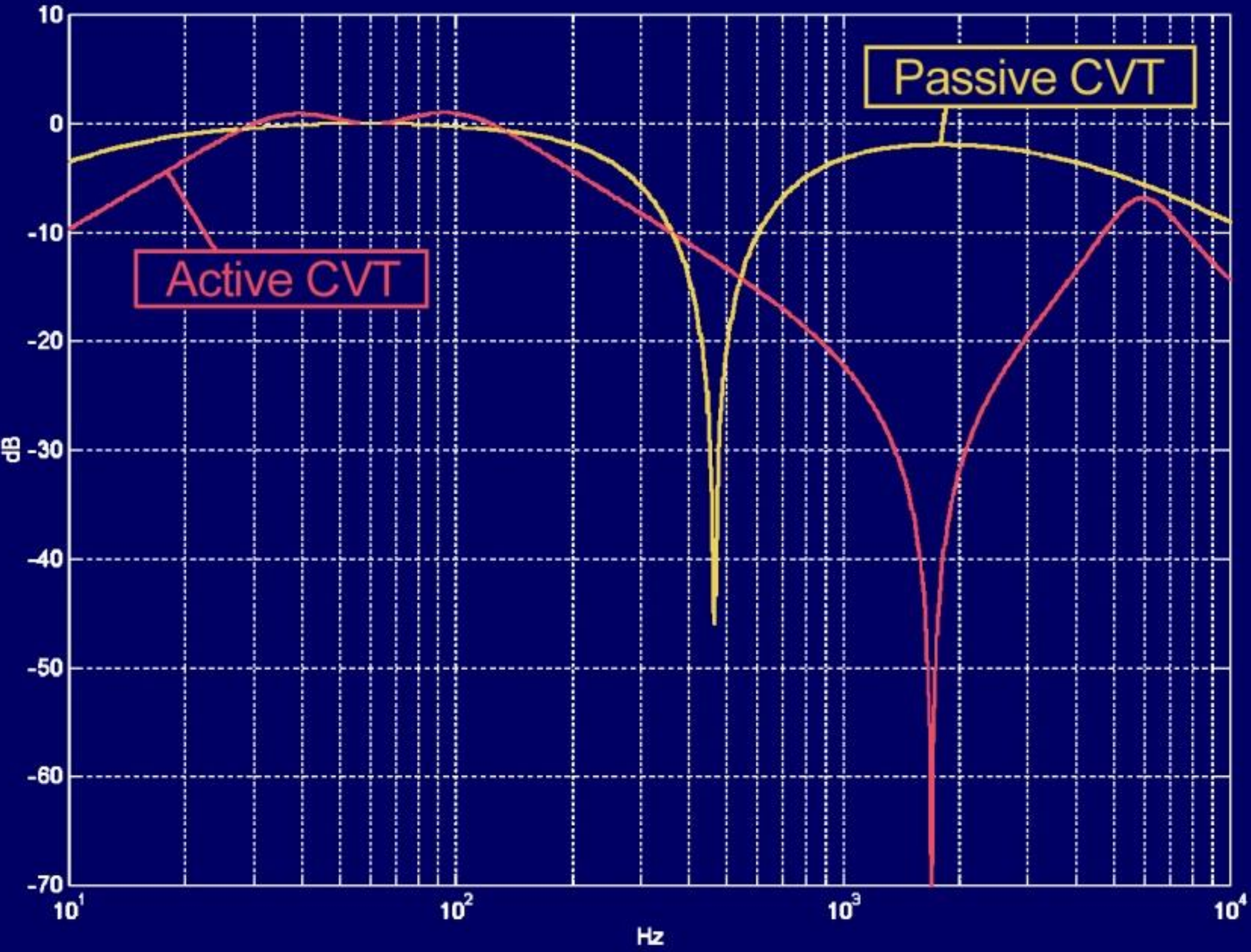


- Six current channels
- Sampling at 1.5625 MHz each
- 12-bit A/D converter

CT Bandwidth Is Adequate to Detect Traveling Waves



Frequency Response of CVT



Clarke Modal Transformations of TW

$$\begin{bmatrix} \mathrm{I0TW} \\ \mathrm{I\alpha TW} \\ \mathrm{I\beta TW} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 2 & -1 & -1 \\ 0 & \sqrt{3} & \sqrt{3} \end{bmatrix} \begin{bmatrix} \mathrm{IATW} \\ \mathrm{IBTW} \\ \mathrm{ICTW} \end{bmatrix}$$

Extract the aerial mode:

$\mathrm{I\alpha TW} = 1/3 \bullet (2 \bullet \mathrm{IATW} - \mathrm{IBTW} - \mathrm{ICTW})$

ν_p of aerial mode is $\cong$ c (speed of light)

TW Fault Locator Is Easy to Configure

Enable TW Fault Location (ETWFL)

TWLL	• Line Length
LLUNIT	• Units (miles, km)
SCBL	• Secondary Cable Length
LPVEL	• Line Propagation Velocity
TWATI	• Alternate TW Currents

Determine Line Propagation Velocity (LPVEL)

$$\nu_p = \frac{1}{\sqrt{\mu_0 \varepsilon_0 \varepsilon_r}} = \frac{1}{\sqrt{LC}}$$

For a 500 kV line:

$L_1 = 8.852 \bullet 10^{-7}$ H / m

$C_1 = 1.302 \bullet 10^{-11}$ F / m

$$\nu_{p1} = 2.946 \bullet 10^{8} \text{ m / s}$$

$$= 0.982 \text{ c}$$

Questions?