Protection Challenges for North America’s First Combined Cable / Overhead Double-Circuit 500 kV Transmission Line With Mutual Coupling

Denis Bucco, Curtis Sanden, Arturo Torres, and Edward Wong
Southern California Edison

Jordan Bell, Normann Fischer, and John Thompson
Schweitzer Engineering Laboratories, Inc.

Project Background

- New 75-mile 500 kV transmission line
- Single-circuit and double-circuit construction
- Protection package
  - System A – Line current differential
  - System B – Directional comparison blocking
  - System C – Permissive overreaching transfer trip

Decreasing Land Availability…

From Overhead…

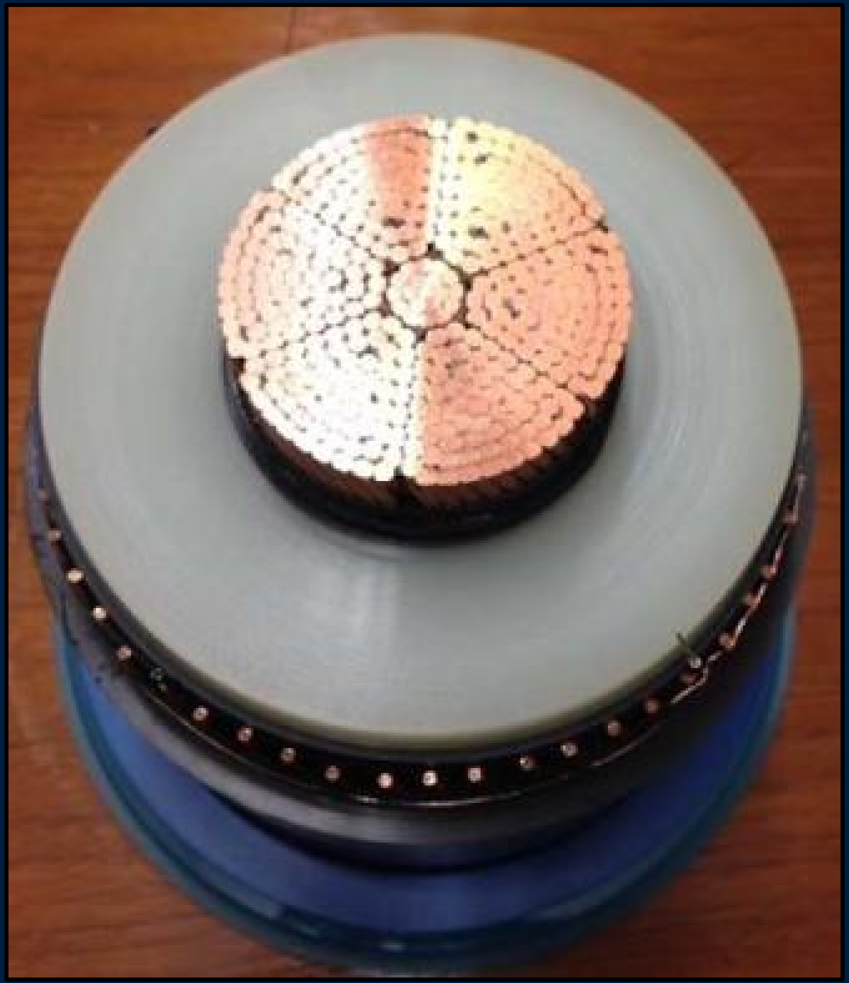
To Underground

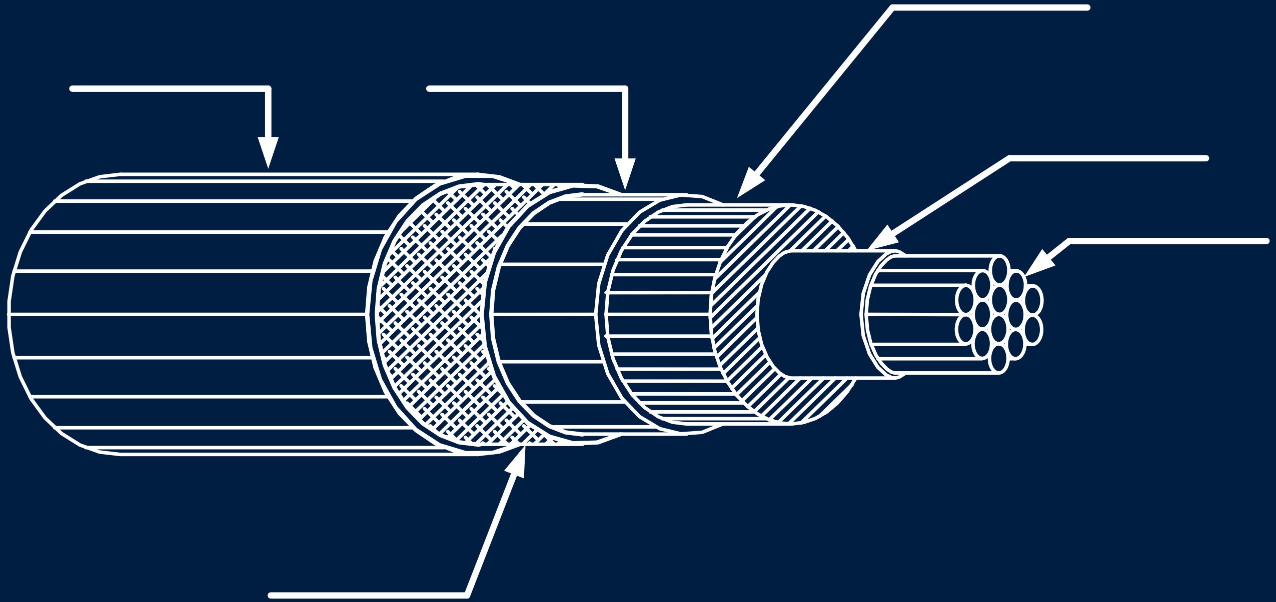
Transition Towers

West

East

Cable Layout





Vaults and Terminations

Overall Line Composition

Line Section 1: 33 Miles

- Two conductors per phase
- Segmented ground wires

Line Section 2: 28 Miles

- Two conductors per phase
- Segmented ground wires

Line Section 3: 4 Miles

- Underground
- Two cables per phase

Line Section 4: 8 Miles

- Line 1: 500 kV line
- Line 2: Future 500 kV line

Impedance Comparison

Overhead

$Z_1 = 0.05 + j0.58 = 0.58 \angle 85°$ ohms / mile

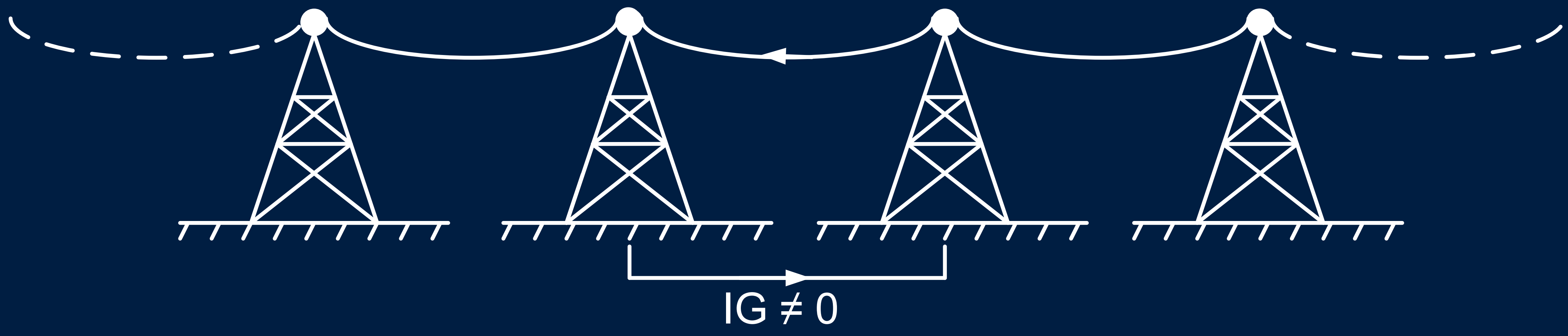
$Z_0 = 0.44 + j2.13 = 2.17 \angle 78°$ ohms / mile

Underground

$Z_1 = 0.02 + j0.31 = 0.31 \angle 86°$ ohms / mile

$Z_0 = 0.20 + j0.13 = 0.24 \angle 33°$ ohms / mile

Ground Wire Segmentation



- Phase conductors induce voltage in ground wire
- Induced voltage leads to circulating current and losses
- Segmenting ground wires prevents circulating current

Line Impedance Calculation

$$VA_{DROP} = Z_{AA} \bullet IA + Z_{AB} \bullet IB + Z_{AC} \bullet IC + \ldots$$
$$Z_{AA'} \bullet IA' + Z_{AB'} \bullet IB' + Z_{AC'} \bullet IC'$$

Where:

Z_{AA} = Self impedance

Z_{AB} and Z_{BC} = Mutual impedance between phases

$Z_{AA'}$, $Z_{AB'}$, and $Z_{AC'}$ = Mutual impedance between the A-phase conductor Line 1 and ϕ-phase conductor Line 2

Put in Matrix Form...

$$\begin{pmatrix} VA_{DROP} \\ VB_{DROP} \\ VC_{DROP} \\ VA'_{DROP} \\ VB'_{DROP} \\ VC'_{DROP} \end{pmatrix} = \begin{pmatrix} Z_{AA} & Z_{AB} & Z_{AC} & Z_{AA'} & Z_{AB'} & Z_{AC'} \\ Z_{BA} & Z_{BB} & Z_{BC} & Z_{BA'} & Z_{BB'} & Z_{BC'} \\ Z_{CA} & Z_{CB} & Z_{CC} & Z_{CA'} & Z_{CB'} & Z_{CC'} \\ Z_{A'A} & Z_{A'B} & Z_{A'C} & Z_{A'A'} & Z_{A'B'} & Z_{A'C'} \\ Z_{B'A} & Z_{B'B} & Z_{B'C} & Z_{B'A'} & Z_{B'B'} & Z_{B'C'} \\ Z_{C'A} & Z_{C'B} & Z_{C'C} & Z_{C'A'} & Z_{C'B'} & Z_{C'C} \end{pmatrix} \cdot \begin{pmatrix} IA \\ IB \\ IC \\ IA' \\ IB' \\ IC' \end{pmatrix}$$

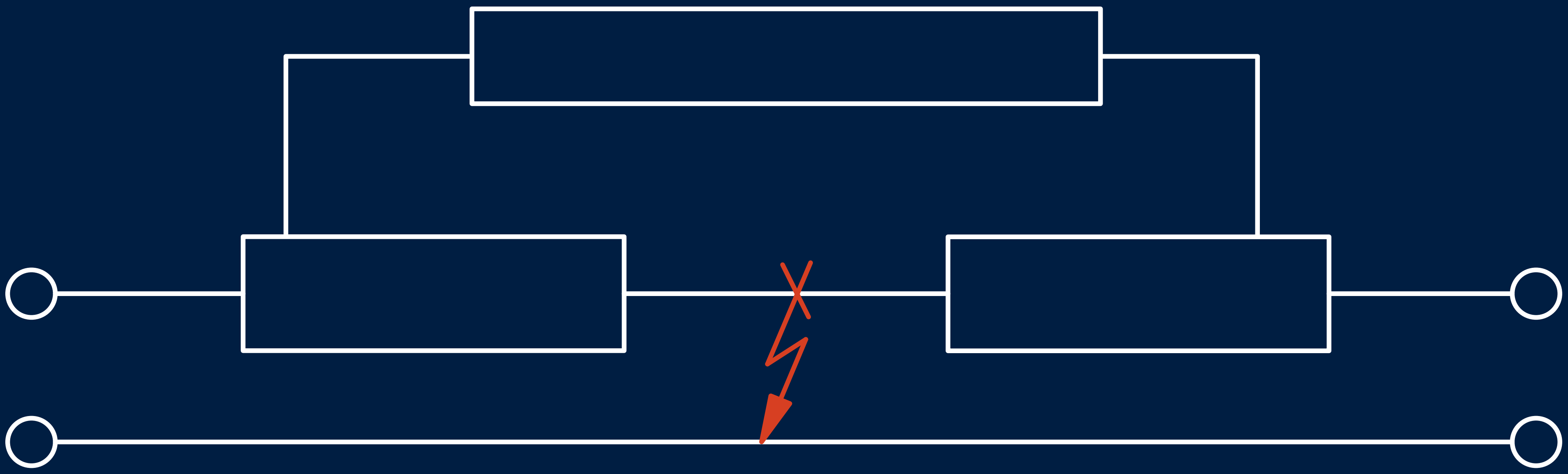
...Then Sequence Domain

Line 1 | Mutual

$$(Z_{012}) = \left(\begin{array}{ccc|ccc} Z_0 & w & x & Z_{0M} & w_m & x_m \\ w & Z_1 & y & w_m & Z_{1m} & y_m \\ x & y & Z_2 & x_m & y_m & Z_{2m} \\ \hline Z_{0M} & w_m & x_m & Z_{0'} & x' & y' \\ w_m & Z_{1m} & y_m & x' & Z_{1'} & z' \\ x_m & y_m & Z_{2m} & y' & z' & Z_{2'} \end{array}\right)$$

Mutual | Line 2

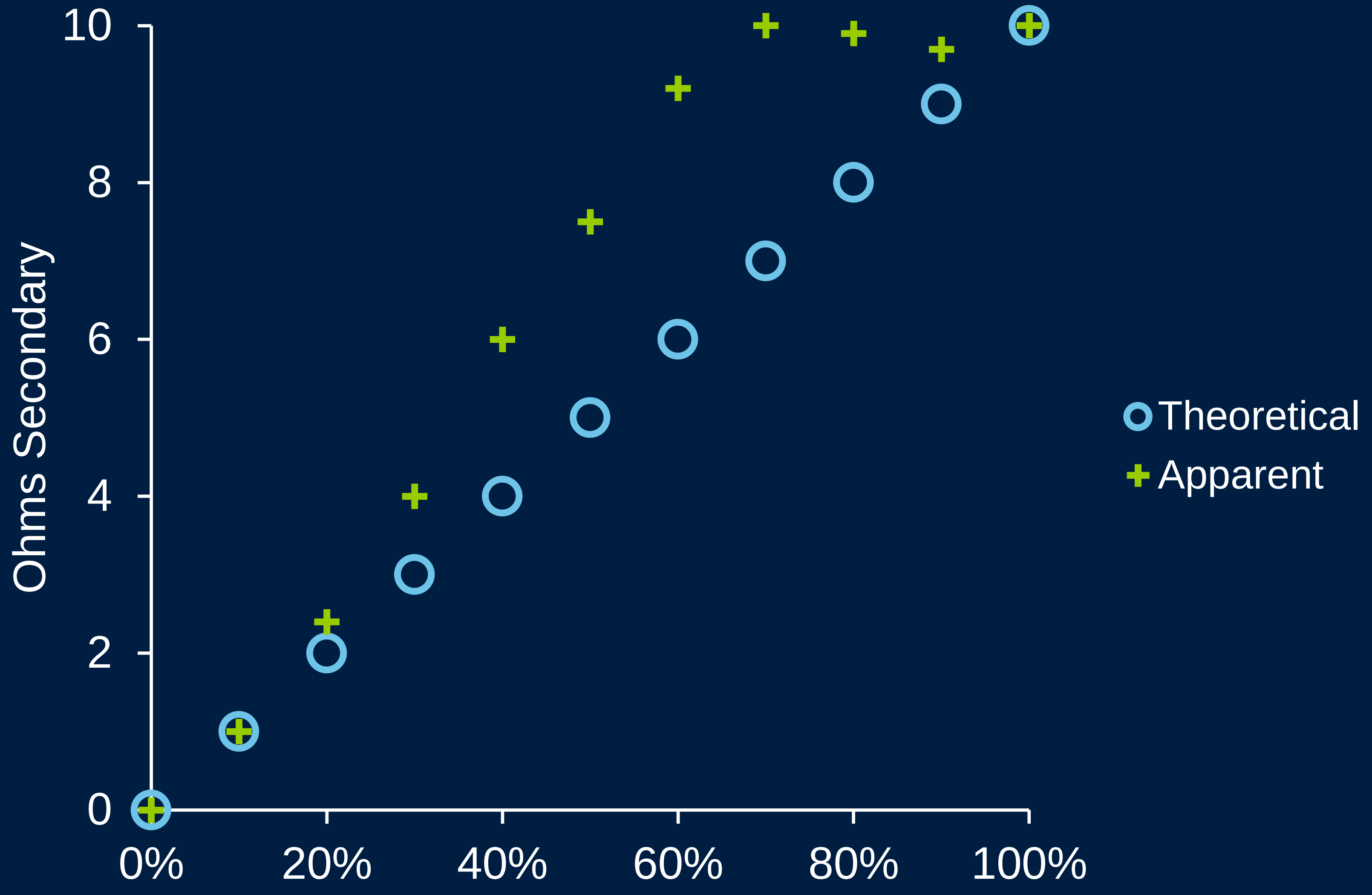
Parallel Line Apparent Impedance



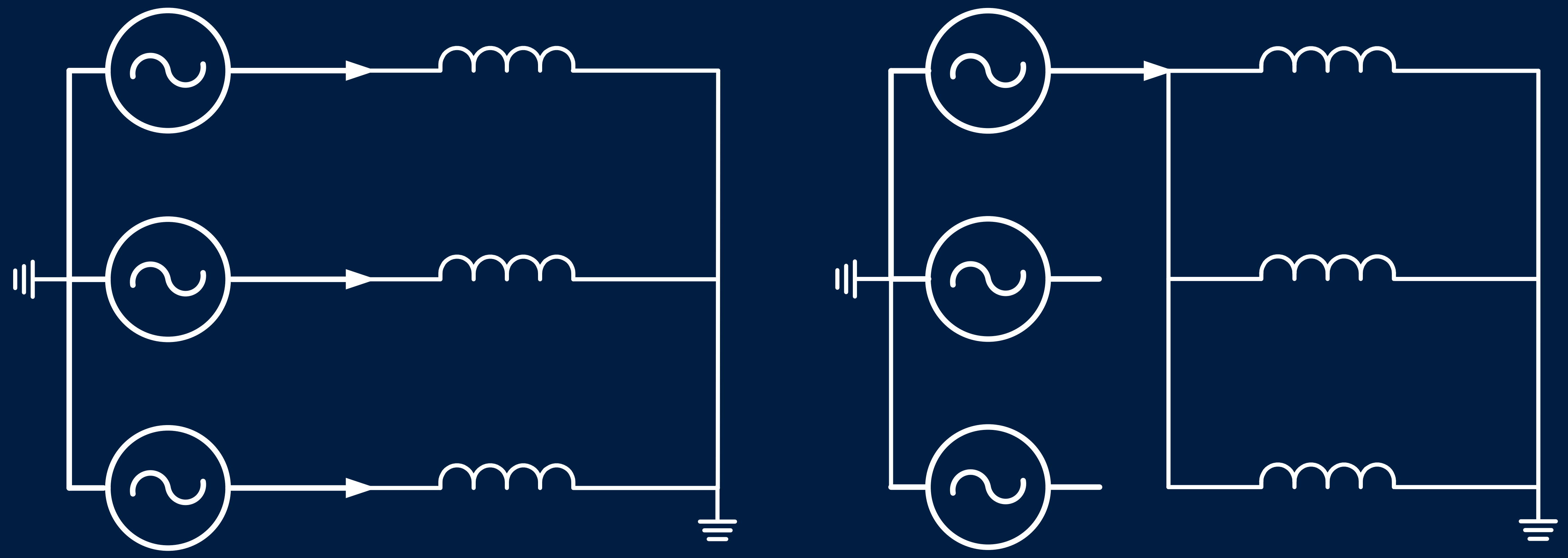
$$Z_{S\_TERM} = m \bullet Z_{L1} (1 - \tfrac{1}{2} m)$$

$$Z_{T\_TERM} = \tfrac{1}{2} \bullet Z_{L1} \bullet (1 - m^2)$$

Double-Circuit Apparent Impedance



Sequence Impedance Through Energization



Positive-sequence

Zero-sequence

Impedance Calculation

Matrix calculation

$Z_1 = 3.26 + j33.32\ \Omega$

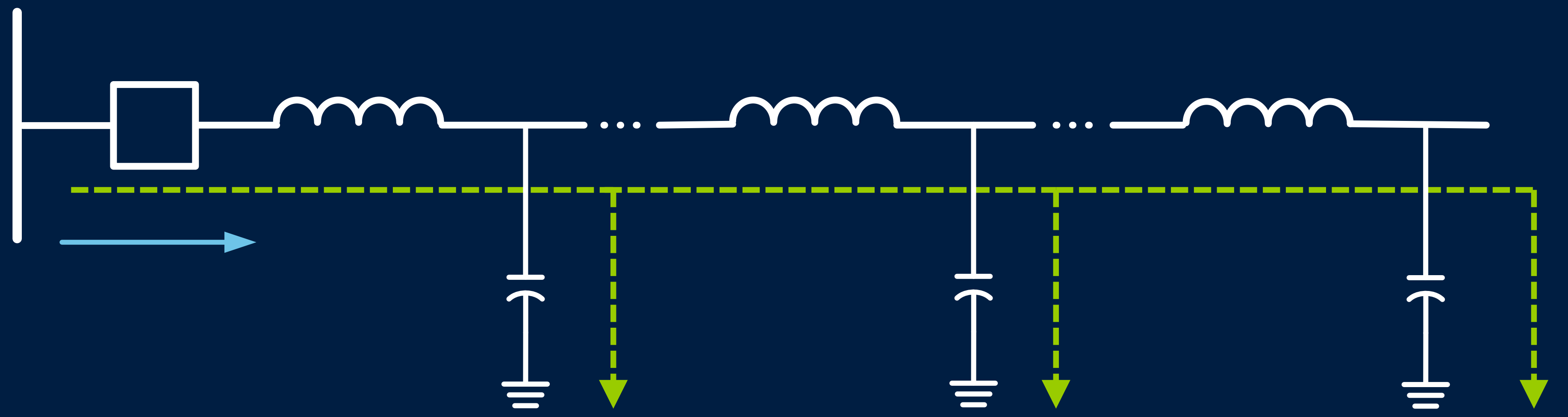
$Z_0 = 24.73 + j142.65\ \Omega$

Energization

$Z_1 = 3.56 + j33.92\ \Omega$

$Z_0 = 25.30 + j144.80\ \Omega$

Charging Current Leads to High Voltage



Voltage rise

Distributed capacitance charging current

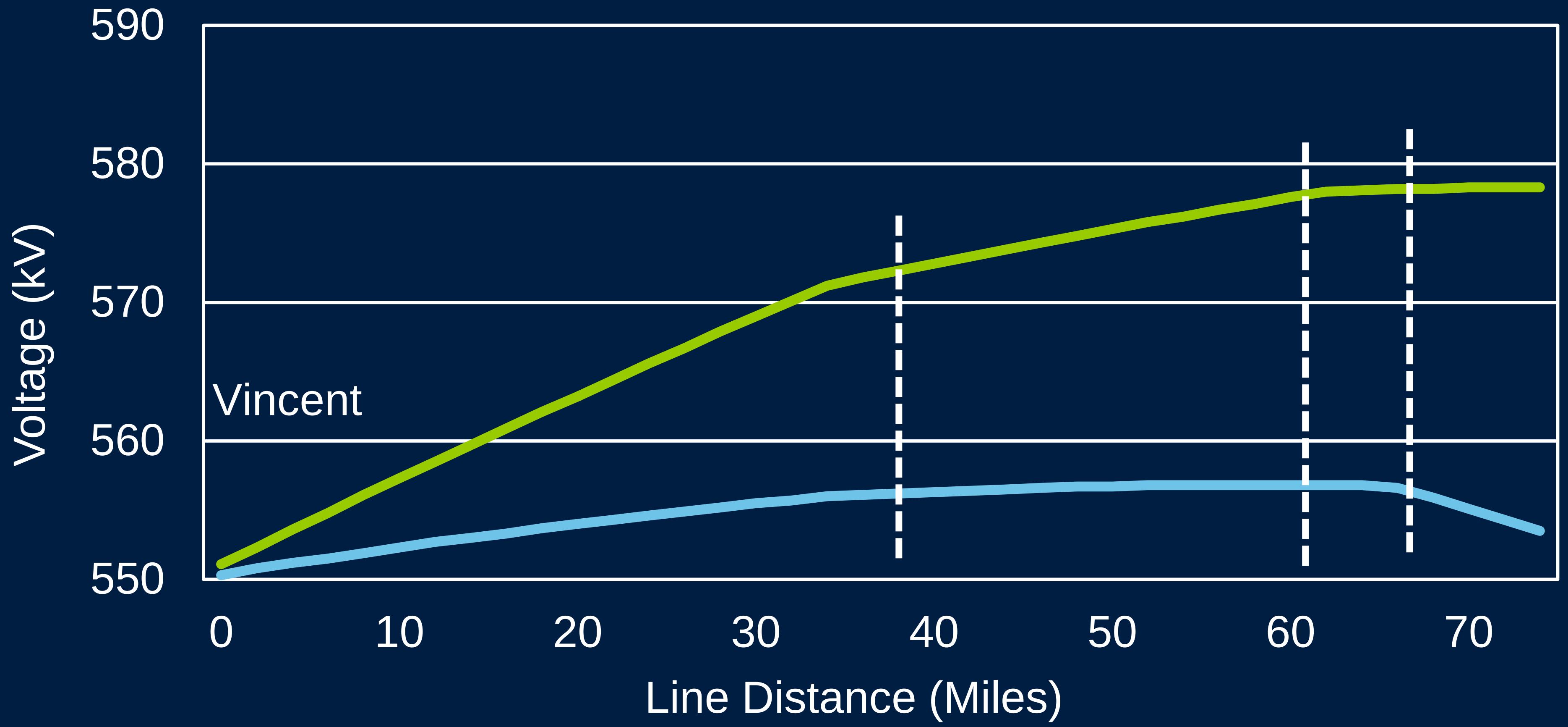
Total charging current

Charging Current Leads to High Voltage

$$I_{1\_CHRG} = j\omega C_1 \frac{V_{Ph-Ph}}{\sqrt{3}}$$

≈ 2 amperes per mile overhead

≈ 40 amperes per mile underground



Protection System Validation

- Reduce short-circuit model to area of interest
- Maintain 500 kV system with boundary equivalents
- Build model in real-time digital simulator
- Choose realistic operating conditions
- Integrate physical relays with simulation

Protection System Validation

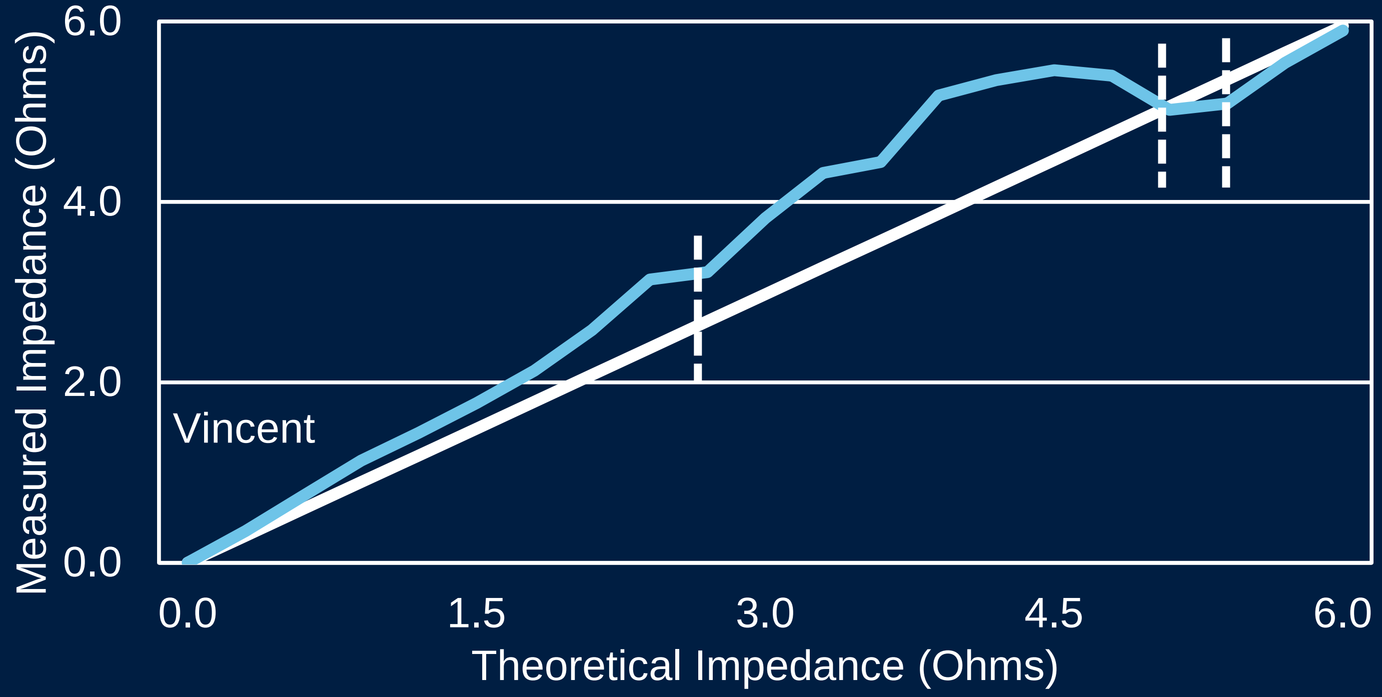
Test Plan

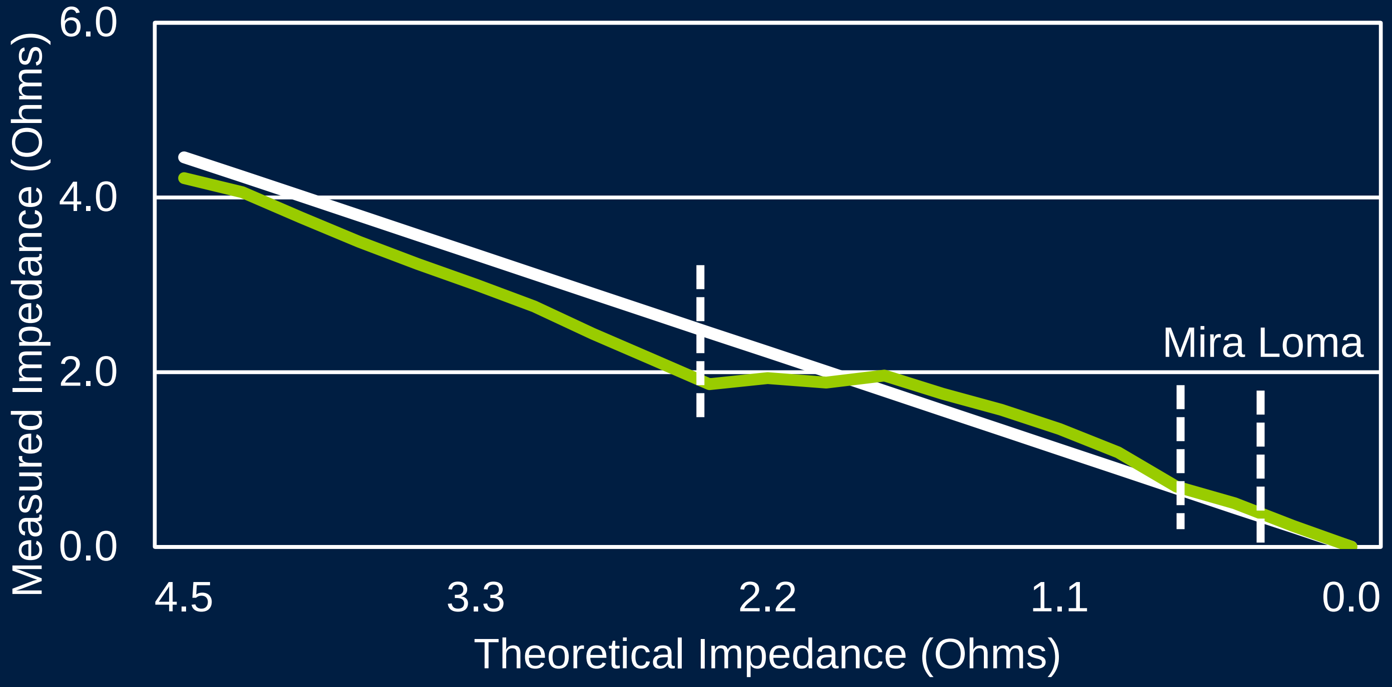
- Basic internal and external faults
- Line energization and load pickup
- Zone 1 margin
- High-impedance faults
- Batch tests

Batch Tests

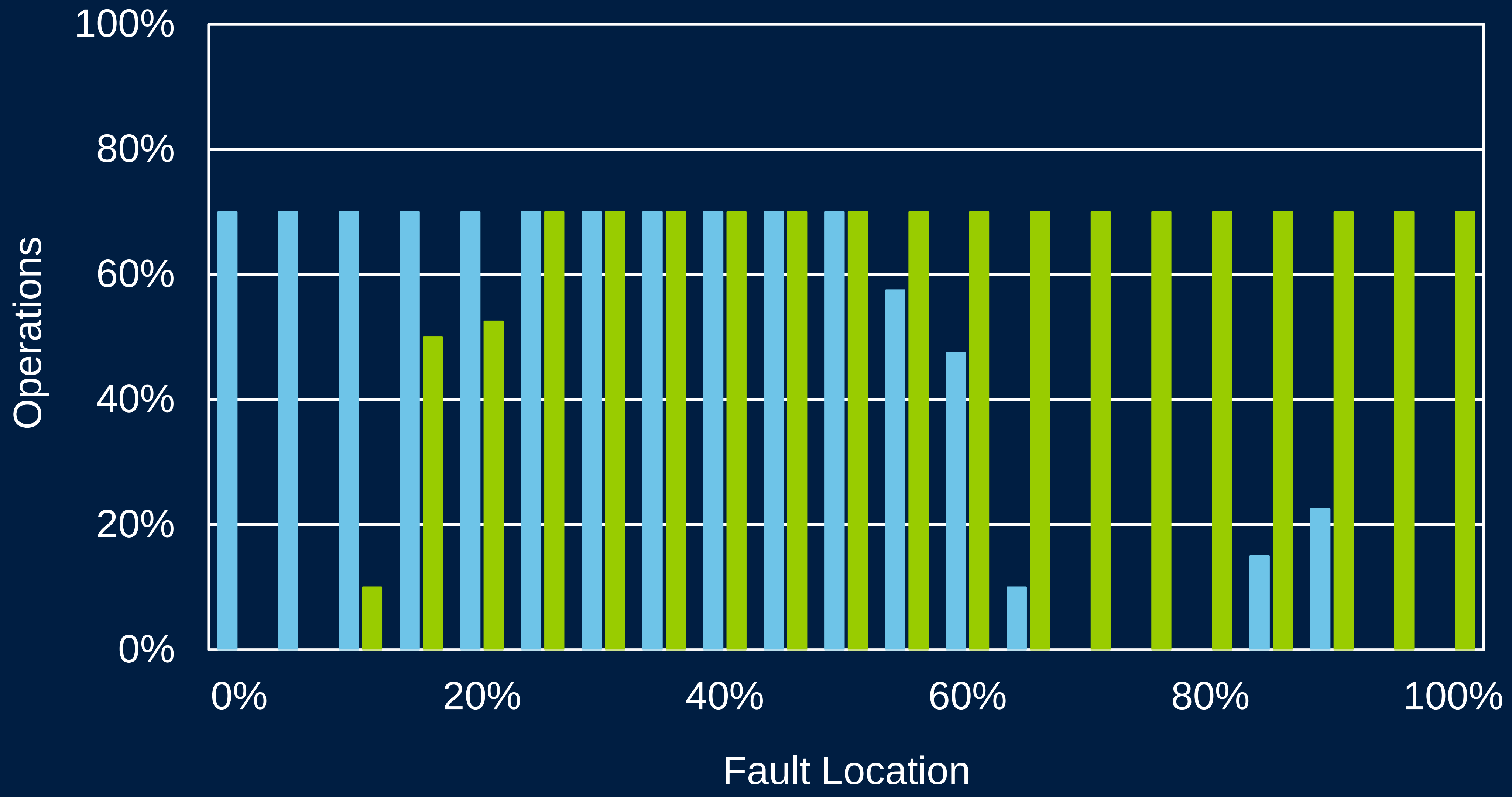
- All internal and external fault locations (21 internal and 10 external)
- Ten fault types (AG, BG, CG, ABG, BCG, CAG, AB, BC, CA, and ABCG)
- Four fault inception angles (0, 30, 60, and 90 degrees)
- All load flow cases

Distance Element Performance

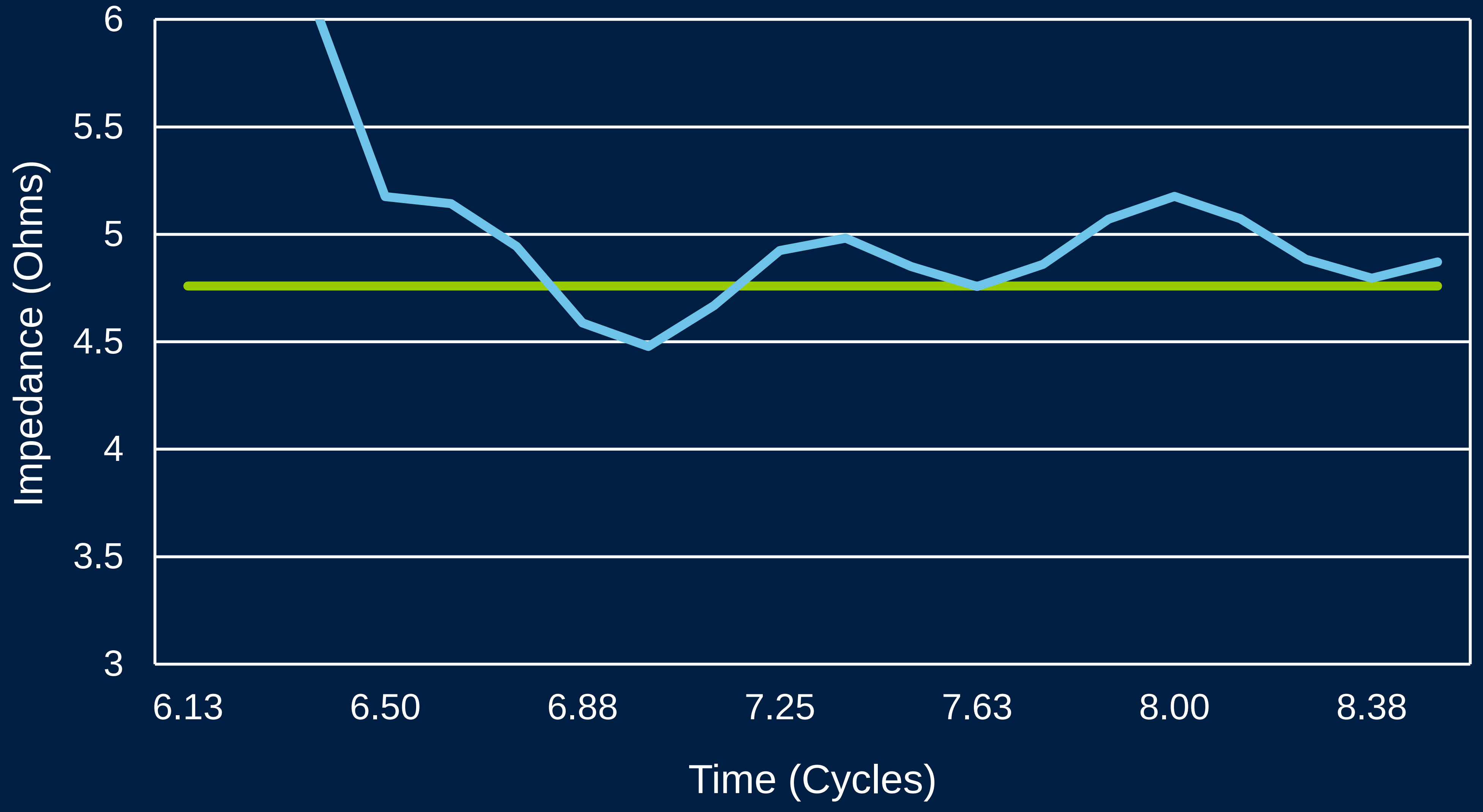




Zone 1 Performance
Manufacturer A

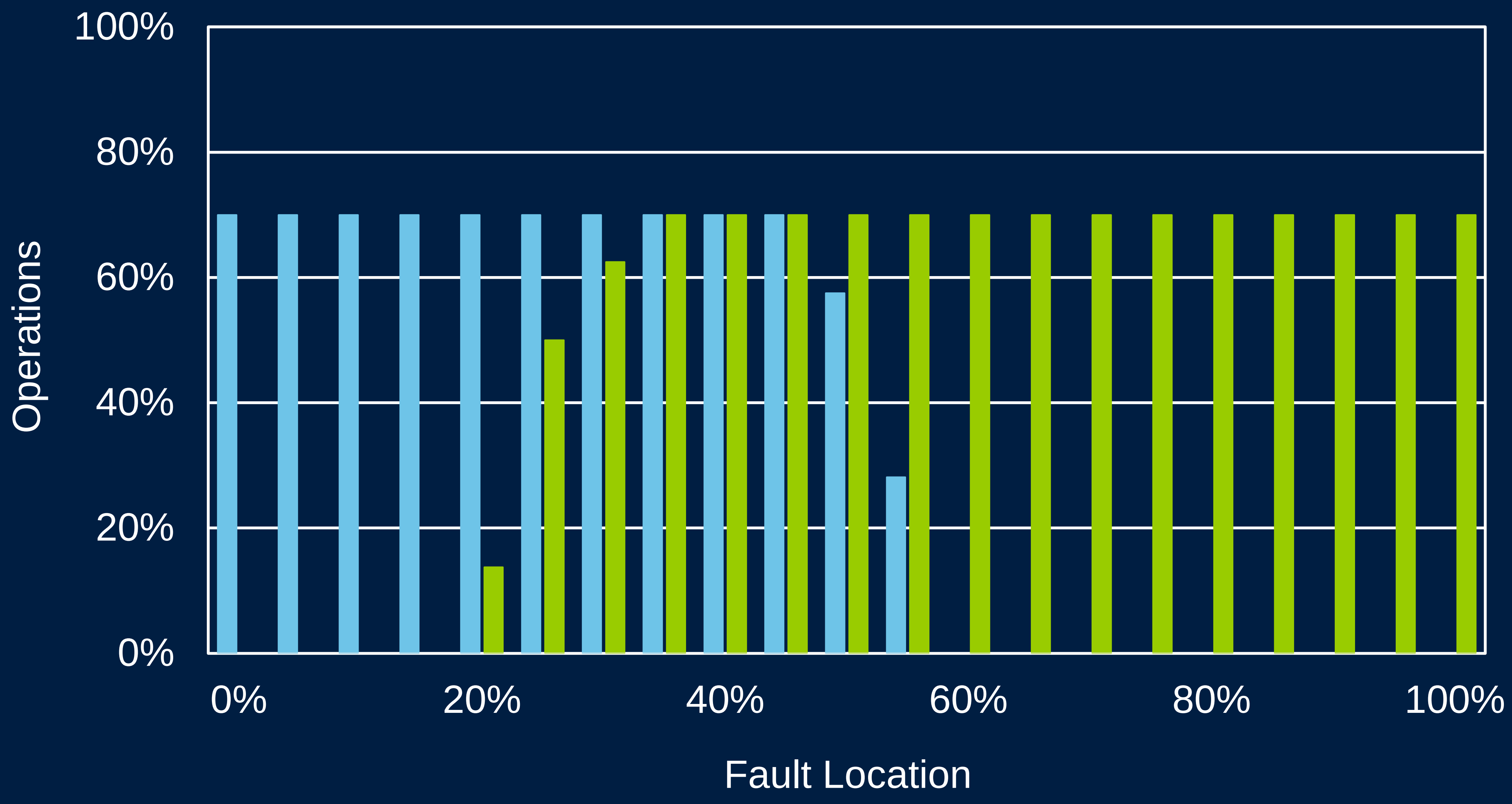


Zone 1 Performance
Manufacturer A



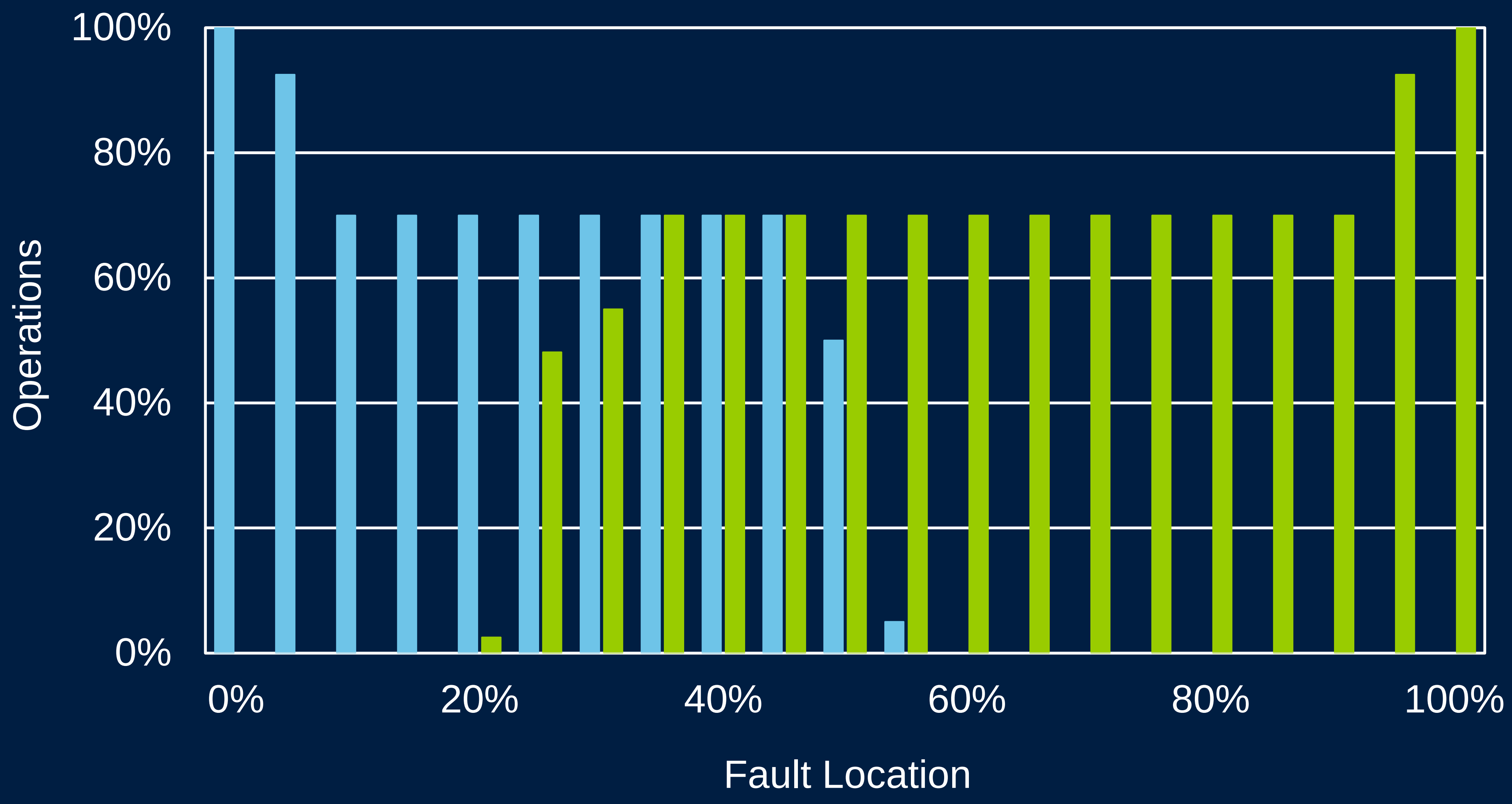
Modify Settings and Repeat

Manufacturer A

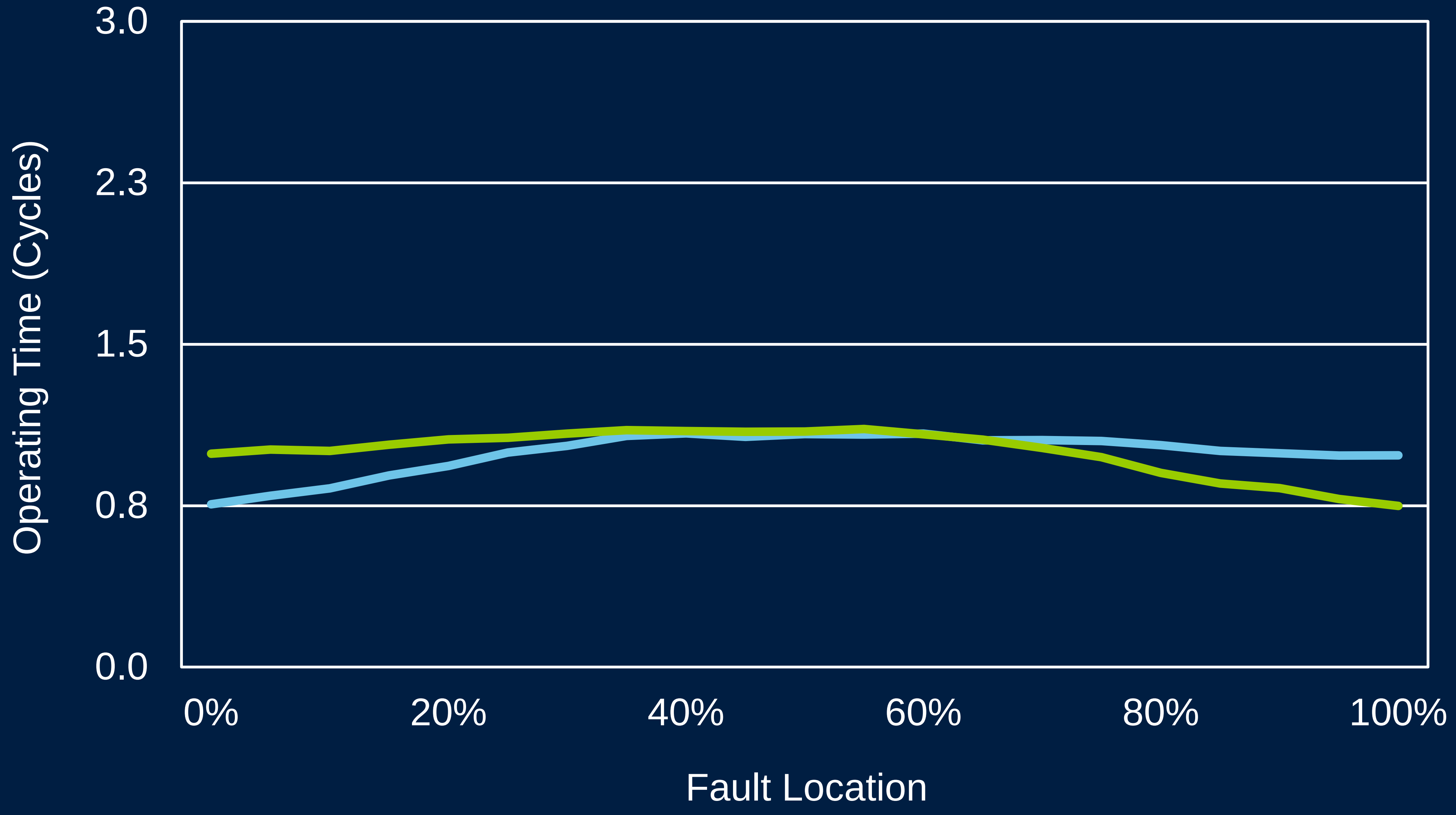


How Did the Other Relay Do?

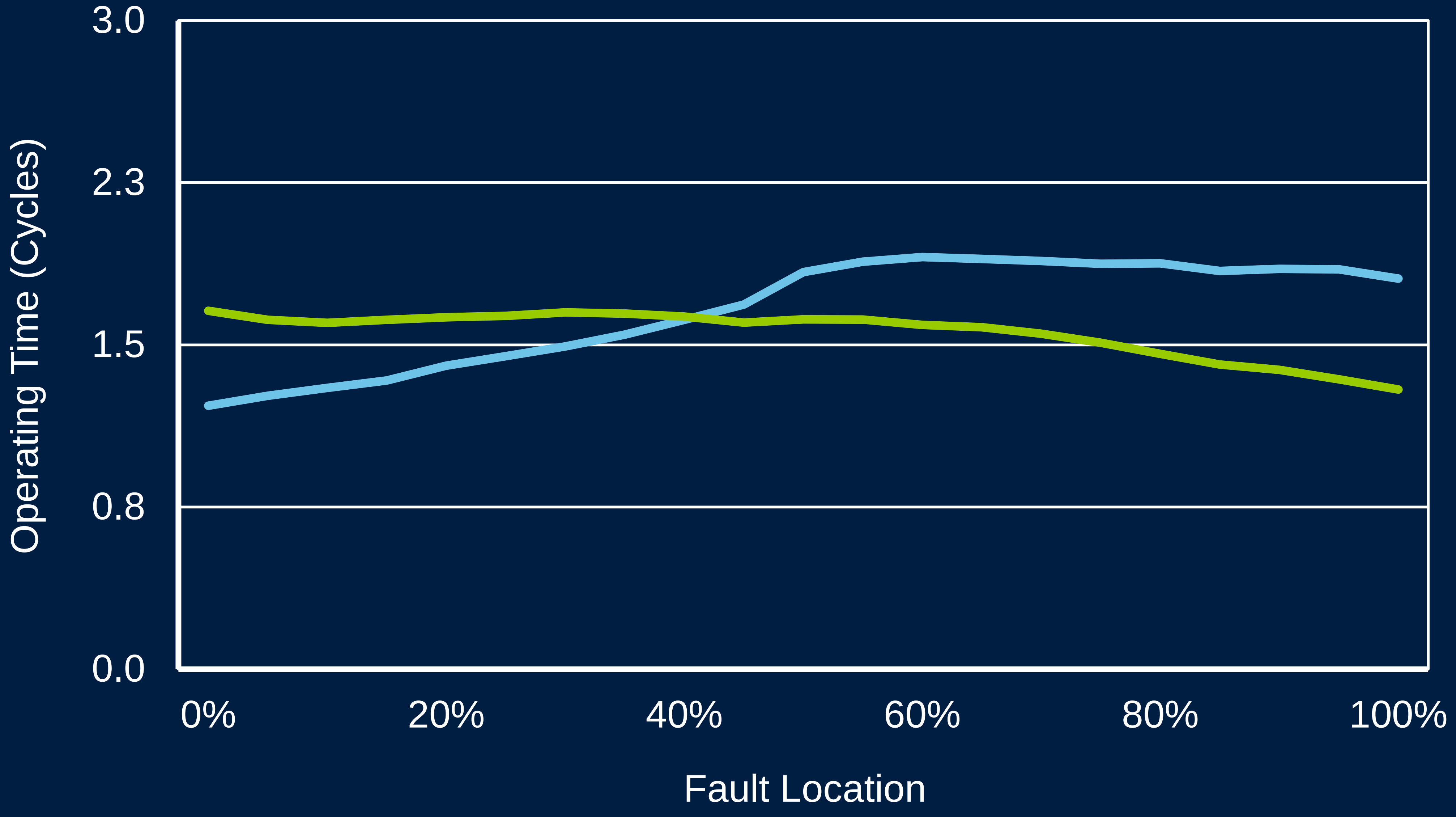
Manufacturer B



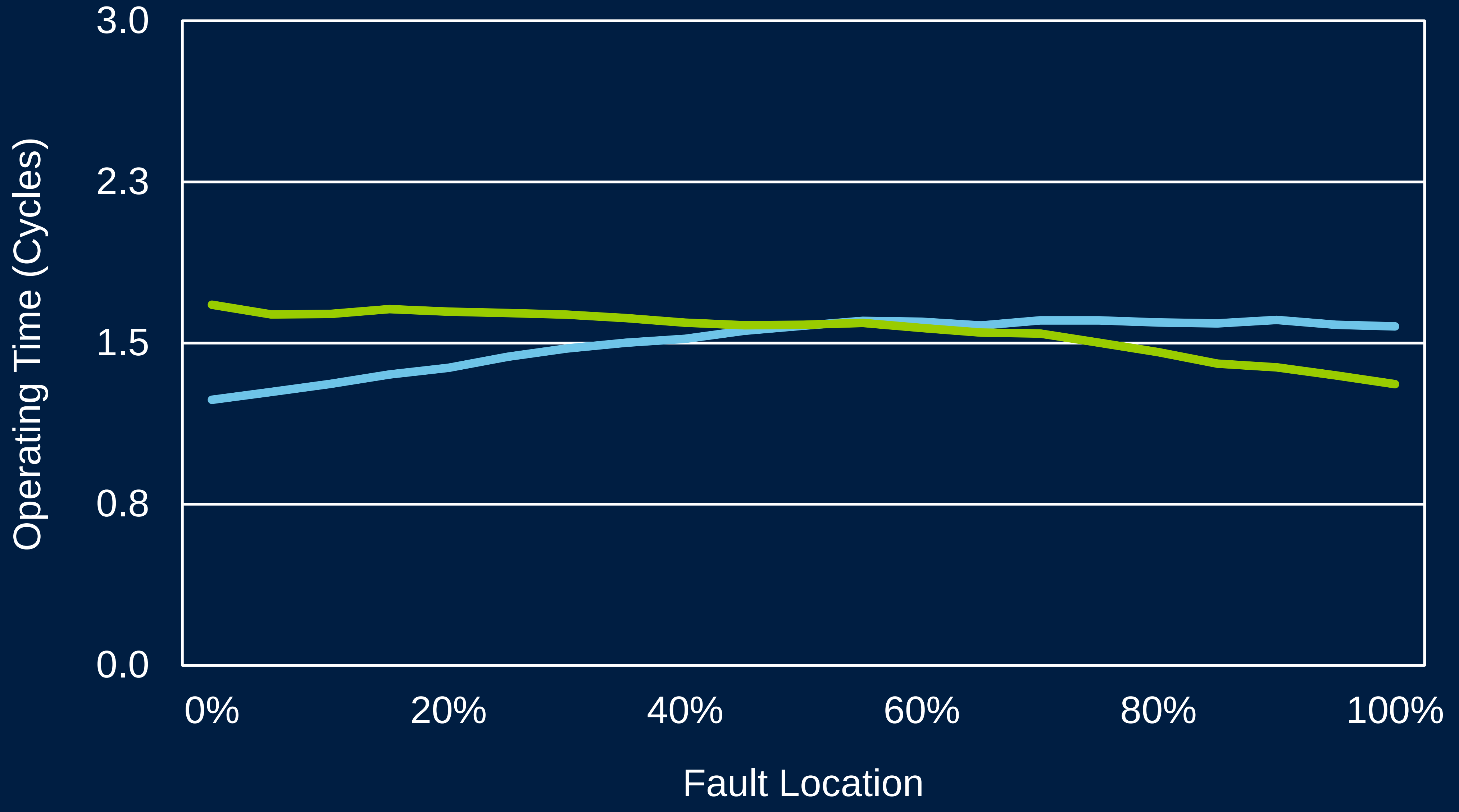
Manufacturer A Distance Performance



Manufacturer B Distance Performance

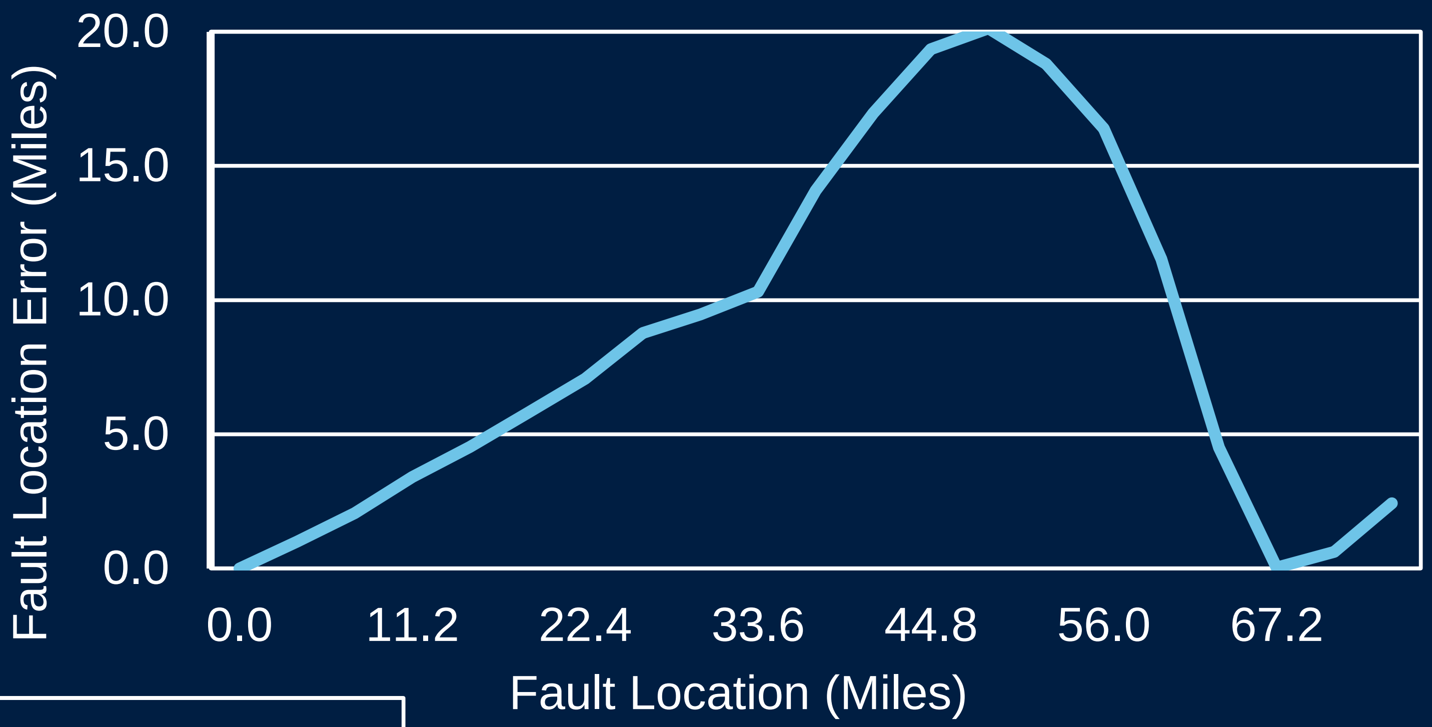


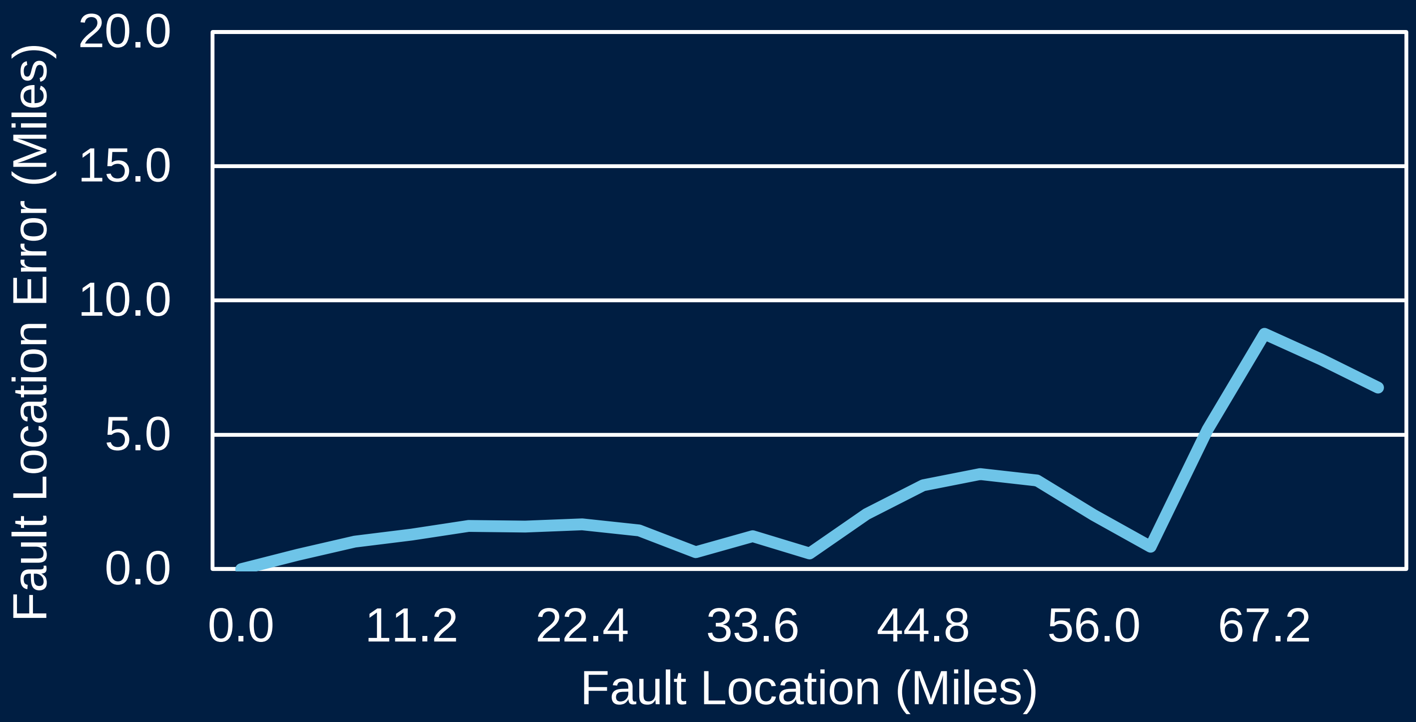
Manufacturer B Differential Performance



Impedance-Based Fault Locator

Manufacturer A

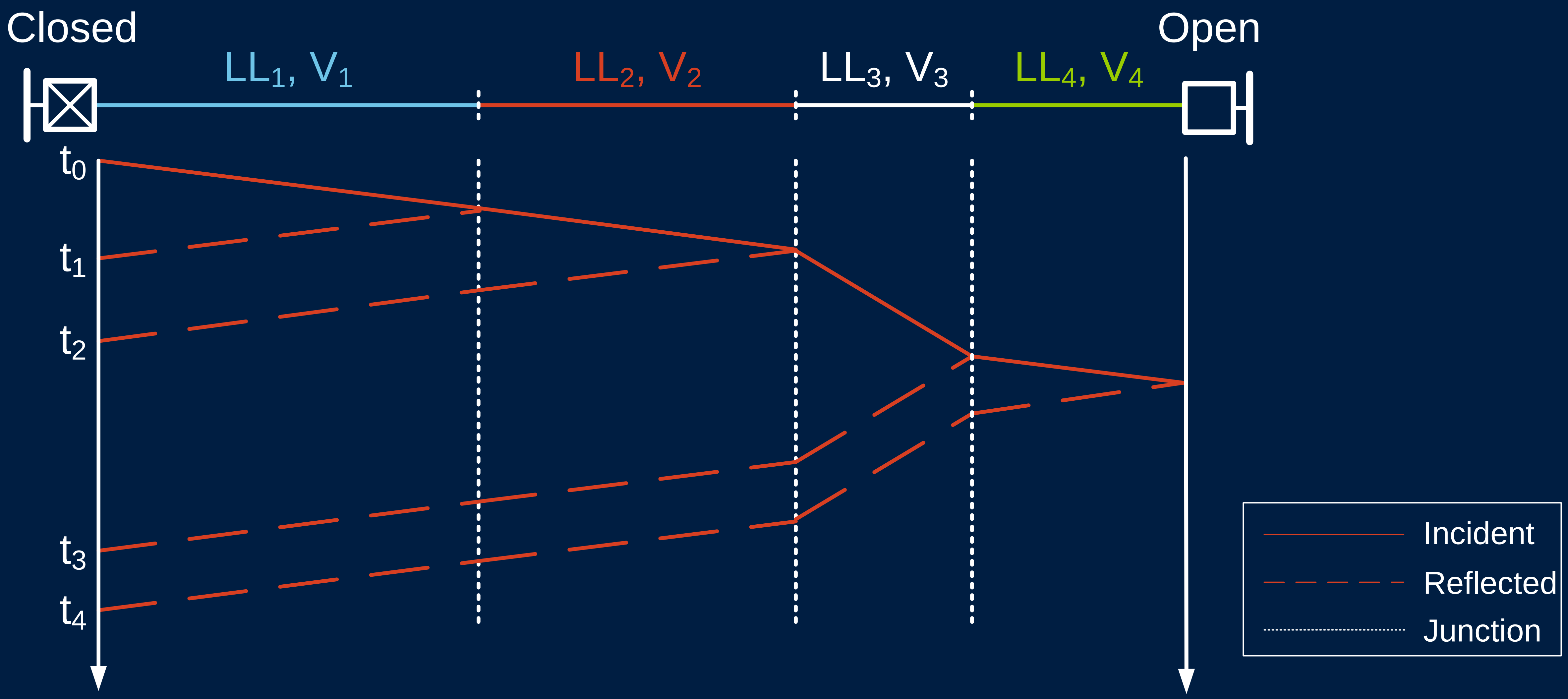




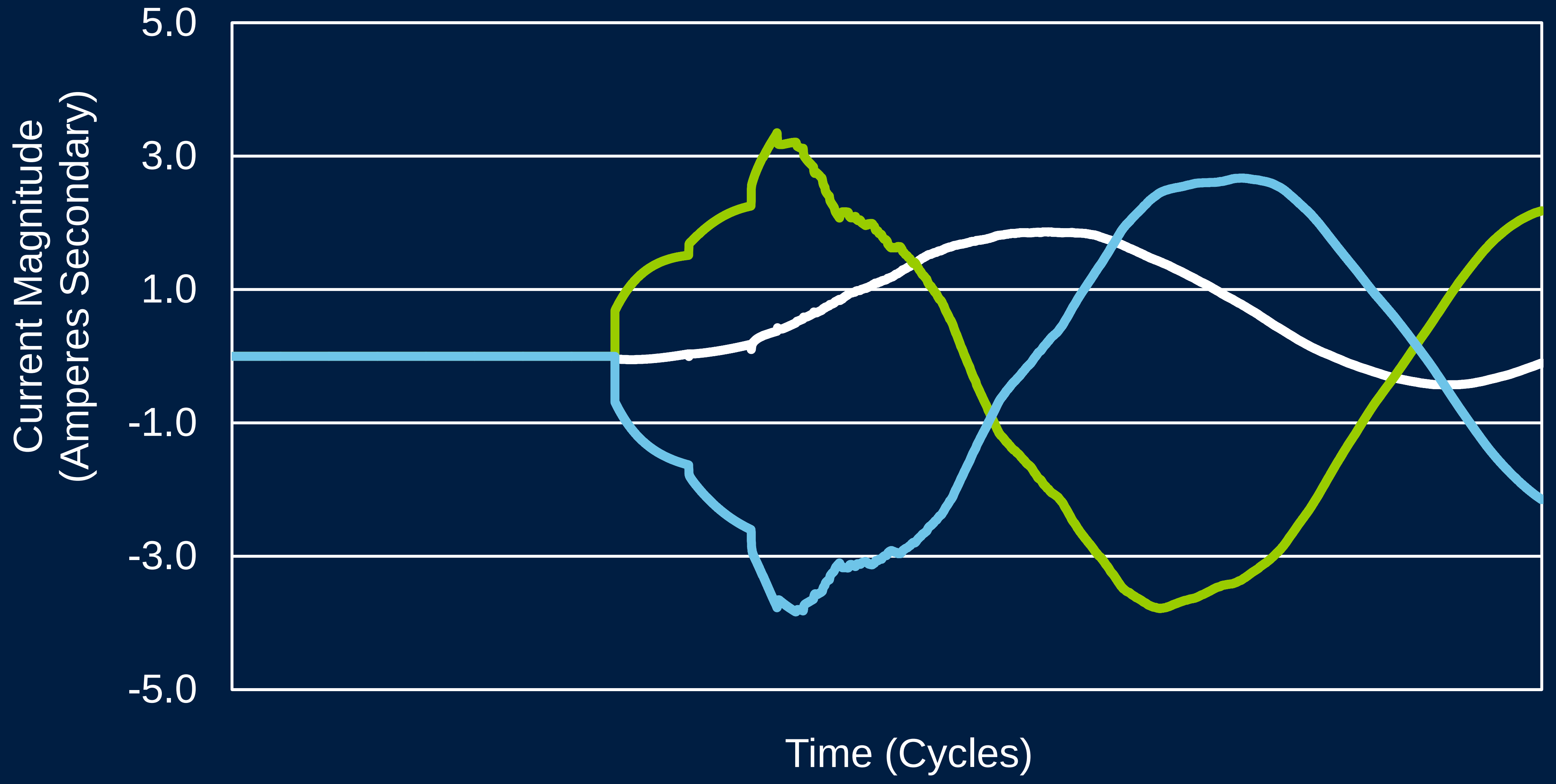
Traveling-Wave Fault Locator

- Explored to evaluate functionality on this composite line
- Simulated in non-real time
- Saved waveforms and replayed into the relays
- Evaluated the relay response

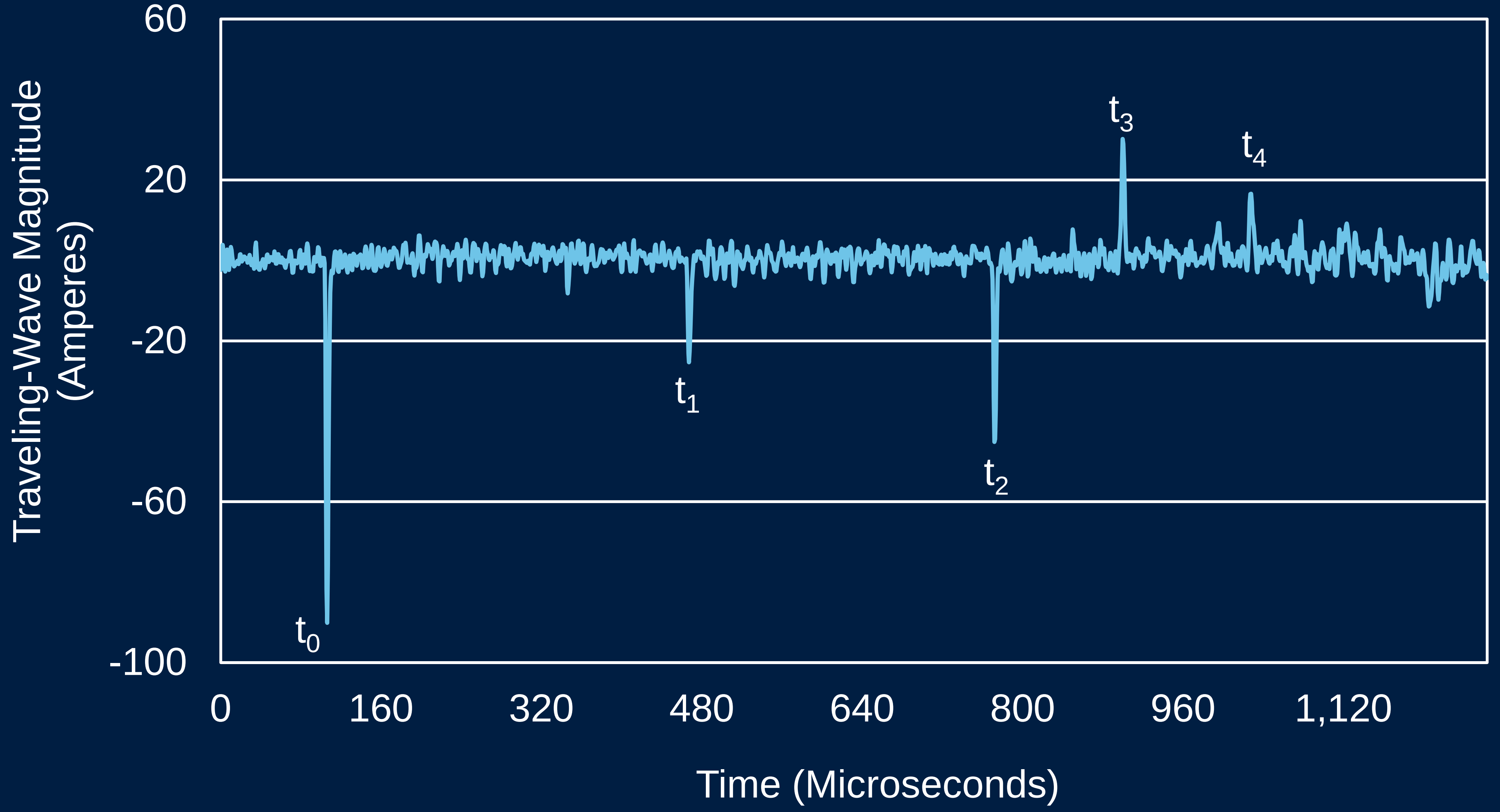
Traveling-Wave Reflections



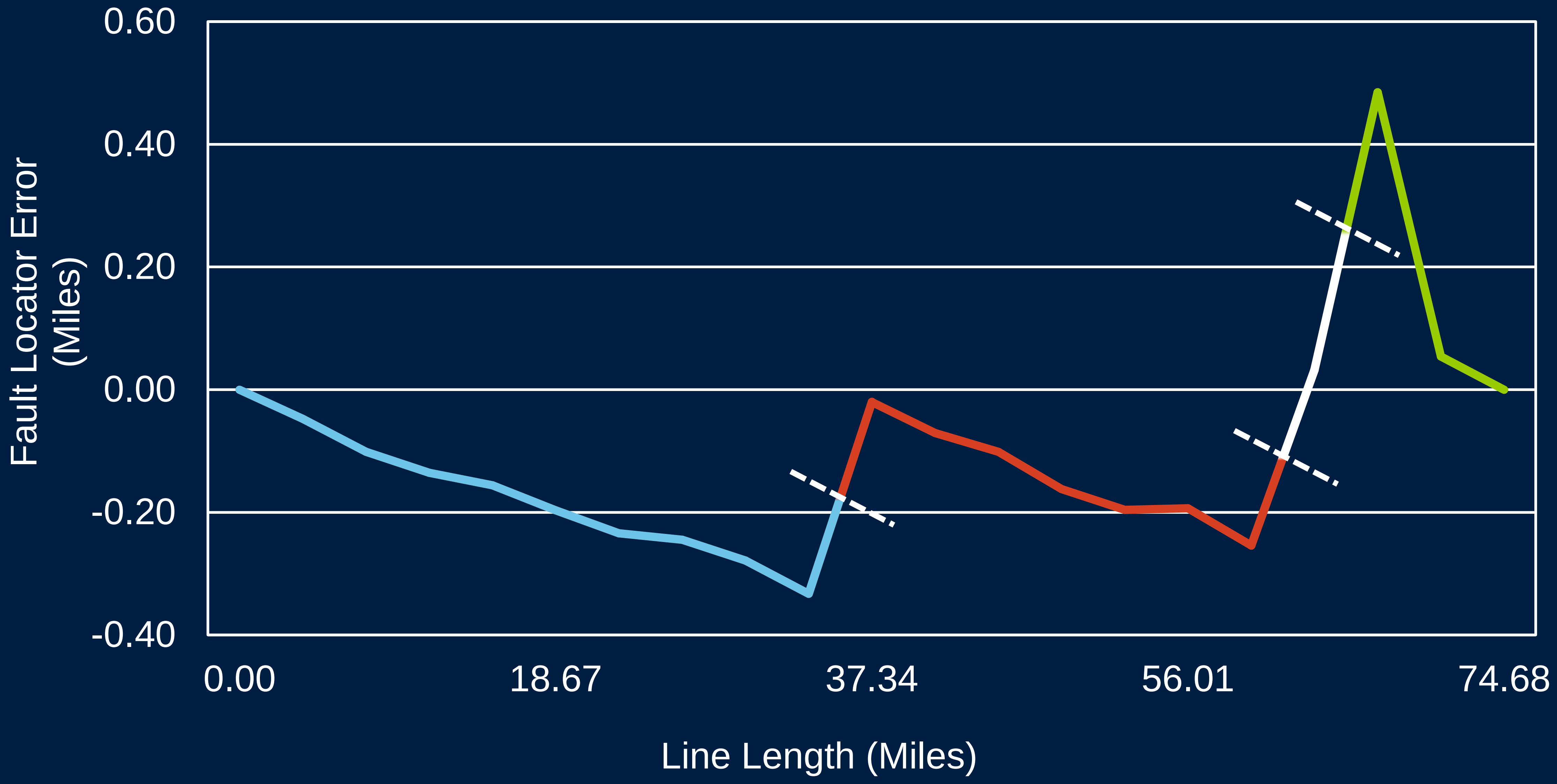
Traveling-Wave Waveform



Traveling-Wave Measurements



Traveling-Wave Fault Locator Accuracy



Summary

- Transmission line incorporated underground cables
- Protection scheme needed reevaluation to include multiple line current differential relays
- Real-time digital simulation validated relay performance

Questions?