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

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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**

\[ Z_1 = 0.05 + j0.58 = 0.58 \angle 85^\circ \text{ ohms/mile} \]
\[ Z_0 = 0.44 + j2.13 = 2.17 \angle 78^\circ \text{ ohms/mile} \]

**Underground**

\[ Z_1 = 0.02 + j0.31 = 0.31 \angle 86^\circ \text{ ohms/mile} \]
\[ Z_0 = 0.20 + j0.13 = 0.24 \angle 33^\circ \text{ ohms/mile} \]
• Phase conductors induce voltage in ground wire
• Induced voltage leads to circulating current and losses
• Segmenting ground wires prevents circulating current
Line Impedance Calculation

\[ \text{VA}_{\text{DROP}} = Z_{\text{AA}} \cdot I_A + Z_{\text{AB}} \cdot I_B + Z_{\text{AC}} \cdot I_C + \ldots \]
\[ Z_{\text{AA}'} \cdot I_A' + Z_{\text{AB}'} \cdot I_B' + Z_{\text{AC}'} \cdot I_C' \]

Where:

- \( Z_{\text{AA}} \) = Self impedance
- \( Z_{\text{AB}} \) and \( Z_{\text{BC}} \) = Mutual impedance between phases
- \( Z_{\text{AA}'} \), \( Z_{\text{AB}'} \), and \( Z_{\text{AC}'} \) = Mutual impedance between the A-phase conductor Line 1 and \( \phi \)-phase conductor Line 2
Put in Matrix Form...

\[
\begin{pmatrix}
V_{A}\text{DROP} \\
V_{B}\text{DROP} \\
V_{C}\text{DROP} \\
V_{A}'\text{DROP} \\
V_{B}'\text{DROP} \\
V_{C}'\text{DROP}
\end{pmatrix}
= 
\begin{pmatrix}
Z_{AA} & Z_{AB} & Z_{AC} & Z_{AA'} & Z_{AB'} & Z_{AC'} \\
Z_{BA} & Z_{BB} & Z_{BC} & Z_{BA'} & Z_{BB'} & Z_{BC'} \\
Z_{CA} & Z_{CB} & Z_{CC} & Z_{CA'} & Z_{CB'} & Z_{CC'} \\
Z_{A'A} & Z_{A'B} & Z_{A'C} & Z_{A'A'} & Z_{A'B'} & Z_{A'C'} \\
Z_{B'A} & Z_{B'B} & Z_{B'C} & Z_{B'A'} & Z_{B'B'} & Z_{B'C'} \\
Z_{C'A} & Z_{C'B} & Z_{C'C} & Z_{C'A'} & Z_{C'B'} & Z_{C'C'}
\end{pmatrix}
\begin{pmatrix}
IA \\
IB \\
IC \\
IA' \\
IB' \\
IC'
\end{pmatrix}
\]
…Then Sequence Domain

\[
(Z_{012}) = \begin{pmatrix}
Z_0 & w & x \\
Z_1 & y & Z_2 \\
Z_{0M} & w_m & x_m \\
w_m & Z_{1m} & y_m \\
x_m & y_m & Z_{2m}
\end{pmatrix}
\]
Parallel Line Apparent Impedance

\[ Z_{S\_TERM} = m \cdot Z_{L1} \left(1 - \frac{1}{2} m\right) \]

\[ Z_{T\_TERM} = \frac{1}{2} \cdot Z_{L1} \cdot (1 - m^2) \]
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

\[ I_{1\_CHRG} = j\omega C_1 \frac{V_{Ph-Ph}}{\sqrt{3}} \approx 2 \text{ amperes per mile overhead} \]
\[ \approx 40 \text{ amperes per mile underground} \]
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

Measured Impedance (Ohms)

Theoretical Impedance (Ohms)

Vincent

Mira Loma

Measured Impedance (Ohms) vs. Theoretical Impedance (Ohms) graph.
Zone 1 Performance
Manufacturer A
How Did the Other Relay Do?

Manufacturer B
Manufacturer A Distance Performance

![Graph showing operating time (cycles) vs. fault location for Manufacturer A. The graph indicates a relatively stable performance across different fault locations, with a slight decrease towards the end.]
Manufacturer B Differential Performance

Operating Time (Cycles) vs. Fault Location

0% 20% 40% 60% 80% 100%

0.0 0.8 1.5 2.3 3.0

Fault Location
Impedance-Based Fault Locator
Manufacturer A

Fault Location Error (Miles)

Fault Location (Miles)
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

Closed

$LL_1, V_1$
$LL_2, V_2$
$LL_3, V_3$
$LL_4, V_4$

Open

$t_0$
$t_1$
$t_2$
$t_3$
$t_4$

Diagram showing incident and reflected signals at different junctions and times.
Traveling-Wave Waveform

Current Magnitude (Amperes Secondary) vs. Time (Cycles)
Traveling-Wave Measurements

Traveling-Wave Magnitude (Amperes) vs. Time (Microseconds)

- $t_0$
- $t_1$
- $t_2$
- $t_3$
- $t_4$
Traveling-Wave Fault Locator Accuracy

Fault Locator Error (Miles) vs. Line Length (Miles)
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?