PNM Approach to Protecting Overcompensated High-Voltage Lines

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Introduction

- Overview of PNM system
- Cabezon project summary
- PNM protection standards
- Series-compensated lines and protection challenges
- PNM protection scheme
- Laboratory tests and field events
- Conclusion
- 14,388 mi of transmission lines
- 69–230 kV primary voltage
- 46 kV subtransmission
- Large generation at San Juan, Four Corners substations

PNM System

- Rio Puerco
- Cabezon
- San Juan
- Four Corners
- McKinley
- Springerville
- Greenlee

Legend:
- 115 kV
- 230 kV
- 345 kV
- HVDC Tie
- SPP
Cabezon Project Summary

- Compensation for Cabezon–Rio Puerco line is 170%
- Typical PNM compensation is 40–50%
- Shunt reactor provides reactive compensation

WW = San Juan–Cabezon
CZ = Cabezon–Rio Puerco
FW = Four Corners–Rio Puerco
PNM Line Protection Standards

- Two relays at 115 kV and 230 kV and three relays at 345 kV
- Line current differential, POTT, and step-distance protection with backup overcurrent protection
- Quadrilateral distance protection for phase and ground
  - $Z_1 = 70-80\%$ of line impedance
  - $Z_2 = \text{POTT forward direction, step-distance delay of 20 cycles}$
  - $Z_3 = \text{POTT reverse direction}$
  - $Z_4 = \text{Breaker failure, forward direction, delay of 60 cycles}$
PNM Line Protection Standards

- Backup instantaneous overcurrent element (phase and ground) at 15–20% of line
- Remote bus ground fault delay of 0.3–0.5 seconds
- Three-pole tripping for most applications
• Differential protection uses positive-, negative-, and zero-sequence elements

• 115 kV lines use tapped load and do not use negative-sequence differential elements

• Future protection will include breakers at tapped substations, allowing system to be restored once transformer fault is cleared
CB1 BF (line and bus)
1. Line 1 R1, R2, R3
2. Bus 1 RX1, RX2

Line R1
1. Re-Trip CB1
2. Trip CB2
3. DTT R2, R3 Line 1
4. TTR Remote End
5. DTT RX1, RX2 Bus 1
6. Assert 86BF/CB1

Bus 1 R1
1. Re-Trip CB1
2. DTT RX2 Bus 1
3. DTT R1, R2, R3 Line 1
4. Assert 86BF/CB1
Fault Description:
Bus Fault On: 0 RIO PUERCO 345 kV 3LG

Phase A: 0.0 + j -32.1 Ω
Phase B: 0.0 + j -32.1 Ω
Phase C: 0.0 + j -32.1 Ω

EQUIVALENT IMPEDANCE OF MOV-PROTECTED SERIES CAPACITORS THAT FIRED [CHM]:
- CAP PW 345.0 kV - RIO PUERTO 345.0 kV
- CAP WW 345.0 kV - RIO PUERTO 345.0 kV

Relay Response:
Zone 2 Tripped. Delay = 0.33 s.
✓ B-C UNIT: Zone 2 Tripped.
✓ C-A UNIT: Zone 2 Tripped.
✓ A-B UNIT: Zone 2 Tripped.

More details in TTY window.

Fault Current Through Capacitor = 2.87 kA
Z = 20.03 - 32.1 = ~ -12.0 Ω

Capacitor Bank Set = 4 kA

Compensated Lines and Challenges

- Current and voltage inversion
- Impedance estimation
- Differential protection
## Phasor and Time-Domain Principles

### Similarities and Differences

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Phasors</th>
<th>Incremental Quantities</th>
<th>Traveling Waves</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal spectrum</td>
<td>40–70 Hz</td>
<td>0.5 kHz</td>
<td>100 kHz</td>
</tr>
<tr>
<td>of interest</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Filtering</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sampling</td>
<td>16 s/c</td>
<td>10 kHz</td>
<td>1 MHz</td>
</tr>
<tr>
<td>Line theory</td>
<td>VF = V – ZI</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operating time</td>
<td>1 cycle</td>
<td>A few milliseconds</td>
<td>1–2 ms</td>
</tr>
<tr>
<td>Elements</td>
<td>Z1P, Z1G, 32G, 32Q, and more</td>
<td>TD21, TD32</td>
<td>TW87, TW32</td>
</tr>
</tbody>
</table>
• Phasor-based protection
• Four quadrilateral zones
• POTT

Reach Selection

• Line current differential settings
  ▪ Positive-sequence current = 600 A
  ▪ Maximum line loading 1,004 MVA = 1,680 A (600 A / 2,000 A = 0.3 pu)
  ▪ Zero-sequence element = 10–15% unbalance (10% • 2,000 = 200 A = 0.1 pu)
  ▪ Negative-sequence element = 25% of 500 A = 0.25 pu
Reach Selection – UHS Time Domain

• TD21
  ▪ Phase and ground elements set to 75% and 70%, respectively
  ▪ External series compensation = Y

• TD32
  ▪ TD32ZF = 0.3 • strongest impedance for fault at remote bus
  ▪ TD32ZR = 0.3 • line impedance including series capacitor
Reach Selection – UHS Time Domain

- **POTT – TP67P and TP67G** selected based on maximum incremental current caused by series capacitor switching.

- **TW87 – TP50P** set above line charging current and below minimum remote bus fault current (select margin of 50–75%).

The reach selection formula is:

\[ TP67G = \frac{1.25 \cdot \sqrt{3} \cdot V_{NOM}}{|Z_{S1} + Z_{L1} + Z_{T1}|} \]

where:
- \( Z_{S1} \) = strongest local source impedance
- \( Z_{L1} \) = line impedance
- \( Z_{T1} \) = strongest equivalent remote source impedance

And the relation between TP67P and TP67G is:

\[ TP67P = \sqrt{3} \cdot TP67G \]
Lab Testing

- Model system
- Test internal and external faults
Lab Testing

- Phasor-based
- Time domain
Results Summary

Average Trip Time (ms)

Fault Location (% of line)

Phasor-Based

UHS-Based

Rio Puerco

Cabezon
External Faults – Cabezon

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<thead>
<tr>
<th>Date</th>
<th>Fault Type</th>
<th>Location</th>
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<tbody>
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<td>CG</td>
<td>Behind San Juan terminal</td>
</tr>
<tr>
<td>10/3/2018</td>
<td>CG</td>
<td>Behind San Juan terminal</td>
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<td>8/13/2018</td>
<td>CG</td>
<td>Four Corners–Rio Puerco line</td>
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External Faults – Cabezon

Δ Voltage (V)

Δ Replica Current (A)

TD32F

Operating
Forward Restraining
Reverse Restraining

Integrated Torque (VA)

Reverse Restraining
External Faults – Rio Puerco

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External Faults – Rio Puerco
Conclusion

• 170% series-compensated line
• Protection challenges for series-compensated lines
• Phasor- and UHS-based relays
• PNM protection standards and set point selection
• Laboratory tests to validate set points
• Phasor-based relay operating time ~16 ms, UHS relay operating time ~2–4 ms
• Field event analysis verifying performance
Questions?