PG&E 500 kV Protection
Standard Design and Development

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PG&E 500 kV System Overview

- Geographically central component of Pacific AC Intertie
- Twenty-three 500 kV transmission lines (2 terminal lines)
- Line lengths from 7 to 145 miles
- Most lines are series-compensated
- Single-pole tripping and reclosing
- Breaker-and-a-half (BAAH) and ring-bus topologies
2008 – PG&E Saw Need to Upgrade 500 kV Protection

- Several generations of relays (1970s–2008)
- 20 different protection designs for 23 lines
- Old relay models no longer supported and many relays out of service
- No continuous monitoring or alarming for most relays
- High misoperation rate
Double Line Outage and Close Call

- Simultaneous Los Banos-Midway 2 (LB-MW) and Gates-Midway (GT-MW) line outages
- 8 hours to restore corridor
- Discovery of hidden relay failures on Vaca Dixon–Tesla (VD–TS) line
Misoperation Rate

- High incorrect tripping (overtrip) rate for 500 kV line relays over prior 10 years
- 25% of all 500 kV line outages caused by relay misoperation (4.4 events per year)
- Benchmark study results – peer utilities average EHV misoperation rate was 10%
Root Cause of Overtripping – Relay Failures Caused 70% of Misoperations

- Many obsolete analog solid-state relays from 1970s
- Inaccurate fault responses
- Difficult to diagnose or repair – no event reports, rare spare parts, slow vendor support, and departed product experts
Making the Replacement Business Case

- Independent technical evaluation to secure executive management support for system-wide replacement project
- Industry-wide benchmark study
  - Collected detailed industry product demographics and field experience – reliability and misoperations
  - Cataloged protection standards and design principles
  - Surveyed relay replacement costs
  - Extracted list of best practices
Scope of 500 kV Transmission Line Protection Redesign

- Replace line relays and panels
- Replace channel interfaces and carrier sets including directional / current comparison and transfer tripping
- Replace breaker failure and reclosing relays with separate dedicated breaker relays
- Replace these components for 17 of 23 lines with highest priority and old relays
Ranking of Replacement Priority

- WECC / CAISO critical paths (Paths 15 and 66)
- Terminals with aged relays or history of poor performance
- Major generation outlet lines; lines to load-serving outlets
- Coordination with neighbors’ protection
- Clearance availability
Develop New 500 kV Design Standard

- Investigation of PG&E control buildings
  - Large 500 kV buildings well-suited to reuse
  - Contrast with drop-in MPAC building solution used for PG&E standard installations at 230 kV and below
- Internal PG&E field experience surveys
- Study of recent operating history
- Development of standard design philosophy (redundancy, mix of protection methods, panel layout and marking, and sustainability features)
- Relay product testing with PG&E system model (Real-Time Digital Simulator [RTDS®] closed-loop testing of candidate relays)
## Comparative Evaluation and Selection of Relays and Other Equipment

<table>
<thead>
<tr>
<th>Vendor</th>
<th>Relay</th>
<th>Operating Principle (subcycle)</th>
<th>Synchrophasors</th>
<th>Backup Distance With Series Caps</th>
<th>Adaptive Reach</th>
<th>Single-Pole Trip and Reclose</th>
<th>Ethernet Protocols</th>
<th>Protection Communications Interface</th>
<th>CT Inputs</th>
<th>Historical Relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vendor 1</td>
<td>Relay 1</td>
<td>Current</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes (phase selection not reliable)</td>
<td>61850 DNP3</td>
<td>Included</td>
<td>2</td>
<td>Yes</td>
</tr>
<tr>
<td>Vendor 1</td>
<td>Relay 2</td>
<td>Current</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>C37.118 61850 DNP3</td>
<td>Included</td>
<td>2</td>
<td>Yes</td>
</tr>
<tr>
<td>Vendor 1</td>
<td>Relay 3</td>
<td>Distance</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes (phase selection not reliable)</td>
<td>C37.118 61850 DNP3</td>
<td>Included</td>
<td>2</td>
<td>Yes</td>
</tr>
<tr>
<td>Vendor 2</td>
<td>Relay 1</td>
<td>Current</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>61850 DNP3 is serial</td>
<td>Included</td>
<td>1</td>
<td>Yes</td>
</tr>
<tr>
<td>Vendor 2</td>
<td>Relay 2</td>
<td>Distance</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes (except for instantaneous elements)</td>
<td>C37.118 61850 DNP3</td>
<td>Included</td>
<td>2</td>
<td>Yes</td>
</tr>
<tr>
<td>Vendor 3</td>
<td>Relay 1</td>
<td>Distance</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>61850 excludes serial DNP</td>
<td>Included</td>
<td>1</td>
<td>No</td>
</tr>
<tr>
<td>Vendor 4</td>
<td>Relay 1</td>
<td>Current</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>61850 excludes serial DNP</td>
<td>Requires C37.94 or other converters</td>
<td>1</td>
<td>No</td>
</tr>
</tbody>
</table>
Redesign Scope

• Line protection and control
  ◆ Line protection
  ◆ Direct transfer trip (DTT)

• Breaker protection and control
  ◆ Breaker failure
  ◆ Reclosing
  ◆ Pole disagreement
  ◆ Trip coil monitor
  ◆ Permissive closing

• Operator visibility (remote)
High-Level Standard Line Protection

- Two redundant electrically identical cabinets for each terminal
- Each cabinet has two isolated protection systems – different schemes and vendors
- Three diverse communications routes
- Consistent labeling
  - “Channel” for DTT
  - “Set” for relays
  - “System” for SPS / RAS schemes
High-Level Standard Line Protection

- No auxiliary relays
- NERC-compliant maintenance and outage flexibility
- Simple operation and maintenance
- End-of-life replacement with minimal line outage requirement
- 72 wires to trip coil and BFI
- Evaluated CTs, PTs, and control wiring
- Meets NERC Order No. 754 single-point-of-failure (SPF) immunity
- Continuous monitoring
SOE captures channel failure and channel normal conditions. Removed chattering elements so that channel availability data for several months is captured and maintained.

### Channel Availability

<table>
<thead>
<tr>
<th>TM Set A (TM-TS Line)</th>
<th>TM Set B (TM-TS Line)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Date Time of Channel Fail</strong></td>
<td><strong>Channel Fail time</strong></td>
</tr>
<tr>
<td>4/1/2011 3:38:01.255</td>
<td>87L CH FAIL</td>
</tr>
<tr>
<td>4/1/2011 1:17:37.958</td>
<td>87L CH FAIL</td>
</tr>
<tr>
<td>4/1/2011 23:51:55.046</td>
<td>87L CH FAIL</td>
</tr>
<tr>
<td>4/3/2011 19:56:02.208</td>
<td>87L CH FAIL</td>
</tr>
<tr>
<td>4/8/2011 18:19:01.974</td>
<td>87L CH FAIL</td>
</tr>
<tr>
<td>4/14/2011 22:45:09.823</td>
<td>87L CH FAIL</td>
</tr>
<tr>
<td>4/14/2011 22:45:09.927</td>
<td>87L CH FAIL</td>
</tr>
<tr>
<td>4/24/2011 14:41:59.035</td>
<td>87L CH FAIL</td>
</tr>
<tr>
<td>4/24/2011 14:42:07.878</td>
<td>87L CH FAIL</td>
</tr>
<tr>
<td>4/25/2011 7:22:00.978</td>
<td>87L CH FAIL</td>
</tr>
<tr>
<td>4/25/2011 7:22:00.800</td>
<td>87L CH FAIL</td>
</tr>
<tr>
<td>4/27/2011 0:15:45.124</td>
<td>87L CH FAIL</td>
</tr>
<tr>
<td>4/27/2011 0:15:48.365</td>
<td>87L CH FAIL</td>
</tr>
</tbody>
</table>

**Channel Availability**

<table>
<thead>
<tr>
<th>TM Set A (TM-TS Line)</th>
<th>TM Set B (TM-TS Line)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total Unavailability</strong></td>
<td><strong>Total Unavailability</strong></td>
</tr>
<tr>
<td>(h,m,s,fraction of s)</td>
<td>(h,m,s,fraction of s)</td>
</tr>
<tr>
<td>0:03:15.077</td>
<td>0:01:46.673</td>
</tr>
<tr>
<td>Unavailability Percentage</td>
<td>Unavailability Percentage</td>
</tr>
<tr>
<td>0.003303%</td>
<td>0.004166%</td>
</tr>
<tr>
<td><strong>Availability</strong></td>
<td><strong>Availability</strong></td>
</tr>
<tr>
<td>99.991697%</td>
<td>99.995634%</td>
</tr>
</tbody>
</table>
Integration – When?

- Protection feature integration thoroughly analyzed
- If more than one device requires this status, has to be standalone (NOT integrated into relay)
  - Example: Breaker maintenance cannot be pushbutton in relay – also needed by RAS / SPS schemes and cannot be dependent upon line relay
  - Example: Group selection in relay pushbutton and SCADA because only used by single device
Operator Interface Switches
Relay and Breaker Interface
Line Relaying and Bay Convention

Line Relaying / CB - Bay Convention

Bus 1

Line 1 Relaying

CB 1

Set A

D

C

B

Line 2 Relaying

CB 2

Set A

D

C

B

Bus 2

Line 1 Relaying

CB 1

CB 2

CB 3

LINE 1

LINE 2

CCVT-1

CCVT-2

CCVT-3

CCVT-4
Details of Line Relays

• Sets A and B are line differential
  - Enabled current differential, DTT, neutral instantaneous and time-delayed overcurrent, and SOTF
  - CCVTs not required for proper operation
  - Distance invoked on channel failure (PRC-23 exclusion)
  - Channel asymmetry not used in differential calculation (set to alarm only)

• Sets C and D are POTT (enabled POTT, DTT, neutral time-delayed overcurrent, distance elements, and SOTF)
Simplified Telecommunication and Relay Cabinet Design

- Replace CCVTs
- Utilize Second Tap
- Place With Shielded Wire

3000:5 C1200 CTs

Many CBs With 2 CTs
## Standard Group Setting Details

<table>
<thead>
<tr>
<th>Group Number</th>
<th>Group Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pilot and DTT (normal operating group)</td>
</tr>
<tr>
<td>2</td>
<td>Nonpilot (no DTT)</td>
</tr>
<tr>
<td>3</td>
<td>Stub bus</td>
</tr>
<tr>
<td>4</td>
<td>Nonpilot (extended Zone 1 distance)</td>
</tr>
</tbody>
</table>
DTT and POTT

- Three-pole trip (sends DTT to other end)
- Sends for breaker failure operation
- Design has DTT feature integrated into line relays (no longer uses external DTT equipment)
- Single-phase permissive algorithm (needed for double-circuit tower lines for cross-country faults)
DTT Custom Logic

- Relay Trip 3 Phase & BLAR
  1. Any Multiphase Fault
  2. Any Time Delayed Trip
  3. Trip during SPO
  4. NG HSR

Line Protection Relay
Station “X”
(Set A)

Line Protection Relay
Station “X”
(Set C)

Same as Set “A”

Line Protection Relay
Station “X”
(Set B)

Line Protection Relay
Station “X”
(Set D)

Same as Set “A”

Same as Set “A”

Same as Set “A”

Block Reclose
“A” phase DTT

Block Reclose
“B” phase DTT

Block Reclose
“C” phase DTT

Route 1

Route 2

Route 2

16 ms
0 s
10 ms
0 s
To Recloser

* Relay Trip 3 Phase & BLAR -
  1. Any Multiphase Fault
  2. Any Time Delayed Trip
  3. Trip during SPO
  4. NG HSR

Bidirectional Digital Communication
Custom Logic TT and Operator Interface

Microwave (MW) Select
PLC Select
To Compare Alarm
10 s
0 s
To Recloser
10 ms
0 s
CB 1 BF
CB 2 BF
SC Platform
DTT TX Enable
(Relay Cut-In)
Relay Trip 3 Phase *
Relay Z1 or POTT TRIP SLG (A-G)
Relay Z1 or POTT TRIP SLG (B-G)
Relay Z1 or POTT TRIP SLG (C-G)
MW Select (TX)
Sets C and D
MW Select (RX)
Sets C and D
Block Redose (RX)
Block Redose (TX)
A-Phase DTT (TX)
B-Phase DTT (TX)
C-Phase DTT (TX)
DTT Send
A-Phase PERM (TX)
B-Phase PERM (TX)
C-Phase PERM (TX)
A-Phase PERM (RX)
B-Phase PERM (RX)
C-Phase PERM (RX)
Custom Logic, Operator Interface, and Trip

- Line Three-Pole Select (Operator Select)
- DTT RX Enable (Tech TCO)
- CB 2 Parallel (Operator Select)
- CB 1 Parallel (Operator Select)

*Relay Trip*
1. Any Multiphase Fault
2. Any Time-Delayed Trip
3. Trip During SPO
4. NG HSR

- DTT Receive
- Route 1 Telecom
- A-Phase DTT (RX)
- B-Phase DTT (RX)
- C-Phase DTT (RX)
Breaker Control Design

• Breaker failure detection
• Previously external
  ♦ High-speed reclosing and time-delayed parallel
  ♦ Variable pole disagreement
  ♦ Trip coil monitor and dc health monitoring
  ♦ Remote manual close synchronism supervision
Breaker Protection and Control Design
One Relay Per Circuit Breaker

• Breaker failure must remain in service for CB to remain closed
• Uniform design (ring-bus and BAAH)
• Consistent interconnection (bus, line and transformer, and S&T)
• Not integrated in line relays
• Auxiliary device reduction
BAAH Breaker Relay Configuration

- I/O is designated as S (Bus 1 side of CB)
- I/O is designated as T (Bus 2 side of CB)
- Results in uniform standard I/O for each terminal
Breaker Failure Detection

- Independent pole breaker failure protection
- One algorithm for current detection
- One algorithm for breaker status detection
- Both algorithms work in parallel

Original logic with current supervision after BF Timer
High-Speed Reclosing (HSR)

- For single-line-to-ground faults only
- Terminal lead / follow selector switch
  - Lead – CB performs HSR
  - Follow – CB performs parallel
- 1-pole / 3-pole selector switch
  - HSR in 30 cycles for 3-pole
  - HSR in 60 cycles for 1-pole
High-Speed Reclosing

- Parallel in 12 seconds (meets synchronism requirements)
- Interlock for middle breaker when selected as lead
  - Only allowed if bus-side breaker associated with adjacent element is closed
  - Required because relay settings do not account for loss of station source
Variable Pole Disagreement

- Variable pole disagreement timer
  - Single-pole trip timer = 90 cycles
  - All other CB operations timer = 20 cycles

- Line Relay: Ground directional overcurrent element coordination
  - During single-pole trip line relay shifts time dial for ground directional overcurrent element
Integration and Monitoring for Complete Relaying Package

- Continuous monitoring with SCADA
  - HMI and EMS
  - DNP3 over TCP/IP

- Utilizes two Ethernet ports (one for failover)
- GOOSE between relays not implemented
Prototype: Pre-field Deployment

- Panels placed in laboratory
  - Complete line package for each terminal
  - Two breaker panels per BAAH terminal
- Contains all indoor equipment
- Breaker simulators (single pole)
- Channel impairment equipment, test sets
- Used for testing custom logic, setting templates, physical design, and validate new changes
- Used by technicians and engineers
- Training of operators and electricians
Real-Time Digital Simulation
Field Deployment

- One category of field deployment
- Develop accurate real-time model
- Interface model with relays
- Test relays with tens of thousands of faults
- Prove that settings, custom logic, and firmware will work
Transmission Line Protection Design

- One level of pilot-assisted protection must be in service
  - Needed for coordination because most lines are series-compensated
  - DTT required for clearing of all adjacent breakers
- Single-pole trip and reclose
Zone 1 Results

Fault Location (% of Line)
- Left
- Right

Percentage of Zone 1 Operations

0.00% 10.00% 20.00% 30.00% 40.00% 50.00% 60.00% 70.00% 80.00% 90.00% 100.00%

0.1% 5.0% 10.0% 15.0% 20.0% 25.0% 30.0% 35.0% 40.0% 45.0% 50.0% 55.0% 60.0% 65.0% 70.0% 75.0% 80.0% 85.0% 90.0% 95.0% 99.9%
Maximum Zone 2 Pickup

Fault Location (% of Line)
- Left
- Right

Seconds

Graph showing the pickup time for different fault locations on the line.
Lessons Learned and Setting Management

- Prototype implementation
  - Small differences with field installations
  - Setting template conversion process (prototype to RTDS to field)
- Relay firmware upgrades
  - Some by manufacturer recommendation
  - Some found during RTDS
- Nonassertion of reclose block for evolving faults
- Simplified DNP3 mapping (sluggish performance)
Lessons Learned and Setting Management

- Single-pole tripping for SOTF
- Additional zone when required line setting reaches through remote transformers
- Reclosing issue with existing breaker failure logic
- Pole disagreement lockout
- Additional items
## Nonassertion of Reclose Block for Evolving Faults During Open Pole

<table>
<thead>
<tr>
<th>Time to Evolve From Single-Phase-to-Ground Fault to Multiphase Fault</th>
<th>Single-Phase-to-Ground Trip Result</th>
<th>Multiphase Trip Result</th>
<th>Reclose Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 cycles</td>
<td>Single-Pole Trip</td>
<td>Three-Pole Trip</td>
<td>Reclose Block</td>
</tr>
<tr>
<td>3 cycles</td>
<td>Single-Pole Trip</td>
<td>Three-Pole Trip</td>
<td>No Reclose Block</td>
</tr>
<tr>
<td>12 cycles</td>
<td>Single-Pole Trip</td>
<td>Three-Pole Trip</td>
<td>No Reclose Block</td>
</tr>
</tbody>
</table>
Custom Logic Change for Nonassertion of Reclose Block for Evolving Faults During Open Pole

Trip 3-Pole
Open Pole OP
1-Pole Select
Bad Reclose
3-Pole Trippers
Trip Output OP
Setting Group 1 Active
87L Diff Blocked

Custom logic additions shown in yellow
Single-Pole Tripping for SOTF

- VT Fuse Failure
- Setting Group 1 Active
- 87L Block
- Line Pickup LEO PKP

Distance Block

Custom logic additions shown in yellow
**HSR / BF Issue**

- BF as individual system
- Line relaying as individual system
- Do not think of BF and Line Relaying as independent systems
New Breaker Failure Logic

BF Initiate → Current Supervision → BF Timer

BF Timer:
- Z
- 0

BF Output
Process Flow Chart
Questions?