Best Practices for Protection and Control Applications for Transmission Substations

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Objectives

- Provide basic understanding of protection and controls for transmission substations
- Provide guidance on specifying protective relaying
- Provide guidance on executing protection and control scope
Outline of Discussion

• Protection and control basics
  ♦ Protection fundamentals
  ♦ Transmission line protection

• Robust protective relaying scheme design
  ♦ Substation configuration
  ♦ Power system
  ♦ NERC requirements

• Real-world examples
Protection Fundamentals

• Overall purpose of a protective relaying scheme is to isolate any fault with minimum amount of system disturbance

• Protection engineers characterize scheme based on its reliability and performance
  ♦ Reliability objectives – dependability, security
  ♦ Performance objectives – selectivity, speed, sensitivity
The Art of Relaying

- Rules to live by
  - Set them fast but not too fast
  - Set them sensitive but not too sensitive
- Translation – every setting generally has two limits (dependability and security)
- Modern practice – prioritize dependability over security
Reliability of a Scheme
IEEE C37.100-1992

• Dependability – “The facet of reliability that relates to the degree of certainty that a relay or relay system will operate correctly”

• Security – “That facet of reliability that relates to the degree of certainty that a relay or relay system will not operate incorrectly”
Contingencies

• Power system operates 24 / 7
  ♦ Designed to survive loss of any single element or component (N-1)
  ♦ Designed to survive high probability double contingency conditions (N-2)

• Protection must be reliable for all N-1 and high probability N-2 conditions
Line Protection

Autotransformer Protection
Common Substation Configurations

- Single bus or straight bus
- Transfer bus
- Ring bus
- Breaker-and-a-half
- Double-breaker, double-bus
Single Bus

- Arrangement is simple
- Arrangement is economical (1 breaker per line)
- Breaker maintenance requires line outage
- Breaker failure results in entire substation outage
Transfer Bus

- Arrangement is complex
- Additional substation equipment is needed
- Breaker maintenance does not require line outage
- Breaker failure results in entire substation outage
Ring Bus

- Arrangement is slightly complex
- Arrangement is economical (1 breaker per line)
- Breaker maintenance does not require line outage
- Bus protection is not required
- Breaker failure results in partial substation outage
Breaker-and-a-Half Configuration

- Arrangement is very complex
- Arrangement is expensive (1.5 breakers per line)
- Breaker maintenance does not require line outage
- Breaker failure of middle breaker only results in outage of additional line
Double-Breaker, Double-Bus Configuration

- Arrangement is complex
- Arrangement is very expensive (2 breakers per line)
- Breaker maintenance does not require line outage
- Breaker failure does not result in any additional outages
Substation Configuration

- Substation configuration can greatly affect protection choices
- Substation physical design engineers must be in full agreement with protection and control engineers, even for temporary substation configurations
Understanding the Power System

• Weak or strong source behind line?
• Short or long line?
• Tapped loads along line?
• Line loadability (NERC PRC-023)?
• Contingencies to consider?
• Accurate power system modeling?
  ♦ Mutual coupling
  ♦ Zero-sequence sources
Verifying Power System Model

- To fully understand power system, we must work with accurate power system model

- For each substation project, power system model must be validated at local substation and all remote adjacent substations
Source Impedance

Radial lines have no source on other end and usually dead-end to distribution transformer
Source Impedance

- Consider use of weak-infeed logic for weak sources
- Consider single contingency when evaluating weak and strong sources
- If generator is in close proximity, consider generator terminal as follow terminal in reclosing scheme
Tapped Loads

- Line protection must protect for faults on high side of each distribution transformer that is tapped off of line.
- Infeed must be considered.

Diagram:
- Oklahoma City
- Houston
Contingencies to Consider for Power System

- Line out of service
- Transformer out of service
- Generator out of service
- Breaker out of service
- Breaker failure
- Line protection failure
Breaker Failure Contingency

Kansas City

Oklahoma City

Houston

New Orleans

Time (cycles)

Zone 1

Zone 2

Zone 3
After large investment by plant and utility partnership, disregarding importance of mutual coupling severely impacted reliability of service.
Zero-Sequence Sources

- Autotransformer model
- Transformers with wye-grounded connection on high side
NERC Requirements

• Following NERC requirements improves reliability of protective relaying scheme

• Protection and control standards include
  ♦ PRC-001
  ♦ PRC-005
  ♦ PRC-023

• Standards are applicable to ≥100 kV systems that are part of bulk electric system
NERC PRC-001

• All relay settings must be coordinated with remote substations to prevent cascading blackouts
• All coordination studies and relay settings report documentation must be retained for records
• All correspondence with neighboring utilities must be retained
NERC PRC-005

- Inventory list – provides listing of all protection components in substation
  - Maintenance interval
  - Last maintenance date
- Maintenance procedures – written procedures for performing periodic, in-service, functional verification of each protection component
NERC PRC-023

• Protective relaying scheme must **not** compromise on loadability of equipment

• If existing scheme dependability is compromised due to NERC PRC-023 requirements, scheme must be improved
  ♦ Add pilot scheme (POTT, DCB, 87L)
  ♦ Add weak-infeed logic

• NERC PRC-023 focuses on security
NERC Standards Drive Design

- Less maintenance is required for self-alarming relays that can be monitored via SCADA (12-year maintenance interval)
- NERC requirements drive protective relaying scheme upgrades
- Virtual lockout relays (LORs) programmed via other relays are recommended over physical LORs (as long as operators are trained)
SCADA Requirements

- Monitor binary quantities
- Monitor analog quantities
- Implement controls
SCADA Should Monitor Binary Quantities

- Breaker status and alarms
- Disconnect switch status and alarms
- LOR status
- Relay alarms
- Trip coil, LOR, control house alarms

- Scheme statuses
- Fault identification
- Fuse failure or LOP alarm
- High unbalance (I2 / I1) alarm
SCADA Should Monitor Analog Quantities

- Three-phase currents ($I_A, I_B, I_C$)
- Three-phase voltages ($V_A, V_B, V_C$)
- Three-phase power ($MW, MVAR, PF$)
- Frequency
- Fault location
SCADA Should Have Controls

- Breaker control
- Line and bypass switch control
- Scheme controls (reclosing enabled / disabled)
Performance of Scheme

Oklahoma City

16 miles

5 miles

1.5 miles

25 miles

Houston

4 miles
Reliability of Scheme

Oklahoma City

16 miles

5 miles

1.5 miles

25 miles

4 miles

Houston
Performance of Scheme Upgrade
Reliability of Scheme Upgrade

Oklahoma City

16 miles

5 miles

1.5 miles

Dallas

25 miles

4 miles

Houston
Protective Relaying Scheme Breakdown

- **Local Discrete Inputs**
  - Hard-Wired
  - Fiber

- **Local Analog Inputs**
  - Hard-Wired

- **SCADA Controls**
  - Communications Media

- **Remote Discrete Inputs**

- **Remote Analog Inputs**
  - Fiber

**Relay**

- Computation of Signals
- Determination of Power System State (faulted vs. normal)

- **Remote Discrete Outputs**
  - Hard-Wired

- **Remote Analog Outputs**
  - Hard-Wired

- **Local Discrete Outputs**
  - Fiber

- **SCADA Monitoring**
  - Communications Media

- **Protective Relaying**
  - Hard-Wired
Local Discrete Inputs

- Breaker Alarms
- Breaker Statuses
- Disconnect Switch Statuses
- LOR Statuses
- Breaker Failure Initiate (BFI) Inputs
- Reclose Initiate Inputs
- Transfer Trip Inputs

- Local Discrete Inputs

- Hard-Wired

- Relay
  - Computation of Signals
  - Determination of Power System State (faulted vs. normal)

- Fiber

- Local Discrete Inputs

- LOR Statuses
- BFI Inputs
- Reclose Initiate Inputs
- Transfer Trip Inputs
Remote Discrete Inputs

SCADA Controls
- Breaker Trip / Close
- Disconnect Switch
- Trip / Close
- Scheme Enable / Disable

Relay
- Computation of Signals
- Determination of Power System State (faulted vs. normal)

Remote Discrete Inputs
- Key Permissive Inputs
- Carrier Start Inputs
- Transfer Trip Inputs

Communications Medium
- Fiber
- PLC
- Microwave
Protective Relaying Discrete Outputs

Relay

- Computation of Signals
- Determination of Power System State (faulted vs. normal)

Local Discrete Outputs
- Breaker Trips
- LOR Trips
- BFI Outputs
- Reclose Initiate Outputs
- Transfer Trip Outputs

remote Discrete Outputs
- Carrier Start / Stop Outputs
- Key Permissive Outputs
- Transfer Trip Outputs

Hard-Wired

Protective Relaying

Communications Medium
- PLC
- Microwave
- Fiber
Scheme Design
Relay I/O Considerations

- Redundancy is important
- Failure of critical I/O results in “safe” (fail-safe) condition
- Operator error results in minimal system outage
- Maintenance does not require system outage
Scheme Design

Relay I/O Considerations

• During commissioning, verify that
  ♦ Each I/O is properly wired and configured in relay
  ♦ Test switches function as designed

• During power system operation, verify discrete inputs periodically through SCADA

• Verify through maintenance procedures that critical input signals are wired correctly through relay (NERC PRC-005)
Local Analog Signals

Local Analog Inputs
- CT Inputs
- PT Inputs

Hard-Wired

Relay
- Computation of Signals
- Determination of Power System State (faulted vs. normal)

Remote Analog Inputs
- CT Inputs

Fiber
Verification of Analog Signals

• Pre-energization
  ♦ Apply secondary injection
  ♦ Apply primary injection (when possible)

• Energization
  ♦ Energize substation under no-load condition – monitor voltage metering
  ♦ Energize substation under low-load condition
    ▪ Monitor voltage and current metering
    ▪ Monitor metering data seen by SCADA
Safety

• For any commissioning testing, make safety top priority

• Wear proper PPE

• Ensure all equipment is de-energized by verifying breaker and disconnect switch statuses

• Ensure all metering values show equipment is de-energized
Secondary Injection Connections

C-Phase
B-Phase
A-Phase

PT Cabinet

Relay Panel
Relay
Secondary Injection Benefits

- PT / CT circuits are wired correctly
- Circuits are grounded properly
- Leakage current is minimized
- Test switches function as designed
- Scaling for SCADA values is correct
SCADA Metering Benefits

• SCADA group should verify that apparent power (MW and MVAR) going into substation equals apparent power going out of substation

• Any discrepancy indicates problem
  ♦ Wiring problems
  ♦ Relay settings problems
Incorrect Protection Set Points

- Simple mistake is typographical error – peer reviews used to catch these
- Power system model has inaccurate data
  - Line impedances are inaccurate
  - Remote settings are inaccurate
- Contingencies are not evaluated
Verification of Relay Settings

• Relay testing of each protection element
• Functional testing of logic
  ♦ Reclosing and synchronization schemes
  ♦ Breaker failure schemes
  ♦ Pilot protection schemes
Real-World Examples

• Because power systems are really only tested when fault occurs, some systems may never get tested

• We cannot solve a problem we do not know about

• During commissioning, we can test security of scheme once substation is energized and loaded
Incorrect Configuration Settings

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Undependable Protection Scheme

ARK (562 / 662)

AUTO (462 / 562)

SUN (362 / 462)

662

562

462

362

162

262

CAN (662 / 162)

FAM (162 / 262)

SAM (262 / 362)
Undependable Protection Scheme

• When ARK line is out of service, ARK line protection must protect stub bus without voltages.

• Settings must accommodate contingency.
Substation Configuration Contingency

Breaker maintenance compromises transformer differential protection and line protection.
When bypass switch is closed, how can we provide reliable protection for 69 kV line?

Entire line must be protected for any single contingency condition.
Substation Configuration Contingency

- Old 138 kV transmission substation has no breaker failure relaying
- If line fault occurs and breaker fails, how can we ensure protection clears fault?
Example System One-Line Diagram

- Oklahoma City
- F1: First Fault
- F2: Second Fault
- F3: Third Fault
- Houston
- New Orleans
- Infeed
- Time (cycles)
  - Zone 1: 0
  - Zone 2: 20–30
  - Zone 3: 60–100
Construction Sequencing Issues

Protection schemes must be evaluated even for temporary substation configurations.
Construction Sites Are Prone to Problems
Intermediary Substation Configurations

- Engineers must develop good commissioning plan based on construction sequencing.
- Substation physical engineers and protection engineers must work together.
- When upgrading substation, it is best to isolate old protective relaying scheme from new protective relaying scheme.
Incorrect Wiring

During secondary injection, wiring appeared to be correct based on metering results.

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Incorrect Wiring

- After energization, C-phase current shows up incorrectly
- Wiring mistake was made after secondary injection testing

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Reliability of Protective Relaying Scheme

• Ensure protection is dependable and secure under ALL power system and substation configuration contingencies.

• Verify security against NERC PRC-001 and PRC-023 standards when applicable.
Reliability of Protective Relaying Scheme

- Utilize SCADA benefits

- Ensure installation matches design through thorough commissioning procedures.
Questions?
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