Introduction to System Protection

Protection Basics and Terminology

30th Annual
Hands-On Relay School

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BPA (Retired)
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Relays for DUMMIES

A Reference for the Rest of Us!

4th Edition

Your guide to System Protection

Hands-On Relay School
March 12, 2013
Purpose of Protective Relays

Transmission line fault protection
Detect and isolate equipment failures
Improve system stability
Protect against overloading
Protect against abnormal conditions
  Voltage, frequency, current
Protect public
Fault Causes

- Lightning
- Wind and ice
- Vandalism
- Contamination
- External forces
  - Cars, tractors, balloons, airplanes, trees, critters, flying saucers, etc.
- Equipment failures
- System disturbances
  - Overloads, system swings
Fault Types

One line to ground (most common)
Three phase (rare but most severe)
Phase to phase
Phase to phase to ground
Single Line to Ground Fault
Three Phase Fault

\[ I_a \quad I_b \quad I_c \]
\[ V_a \quad V_b \quad V_c \]
Phase to Phase Fault

\[ V_a \quad V_b \quad V_c \]

\[ I_a \quad I_b \quad I_c \]
Two Phase to Ground Fault

\[ V_a \quad V_b \quad V_c \]

\[ I_b \quad I_c \]
Balanced & Unbalanced Systems
# Balanced & Unbalanced Systems

<table>
<thead>
<tr>
<th>Balanced System:</th>
<th>Unbalanced System:</th>
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<tbody>
<tr>
<td>3 Phase load</td>
<td>Phase to phase fault</td>
</tr>
<tr>
<td>3 Phase fault</td>
<td>One line to ground fault</td>
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<tr>
<td></td>
<td>Phase to phase to ground fault</td>
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<tr>
<td></td>
<td>Open pole or conductor</td>
</tr>
<tr>
<td></td>
<td>Unbalanced load</td>
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</tbody>
</table>
# Sequence Quantities

*(Symmetrical Components)*

<table>
<thead>
<tr>
<th>Condition</th>
<th>+</th>
<th>-</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 Phase load</td>
<td>✓</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3 Phase fault</td>
<td>✓</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Phase to phase fault</td>
<td>✓</td>
<td>✓</td>
<td>-</td>
</tr>
<tr>
<td>One line to ground fault</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Two phase to ground fault</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Open pole or conductor</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Unbalanced load</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
Relay Types

Non-directional

Detect fault in any direction
- Operate when quantity exceeds pickup value
- Used on distribution lines
- Can be used on radial systems

Directional

Only trip for faults in front of relay (on line)
- Use voltages, currents, angles to determine fault direction
- Operate when quantities exceed pickup value and correct direction is determined
- Relay of choice for HV and EHV transmission
Relay Types

Current, voltage, frequency

Operates if input meets setting

Distance

Uses voltage and current to measure impedance to fault

Differential

Looks at imbalance between inputs

Common for power transformers and generators

Can be used for transmission lines
Relay Types

Recloser
Relay to automatically reclose circuit breaker following a relay operation to restore circuit

Pilot scheme
Uses communications to transmit relay information or trip to remote terminal
Provides high speed tripping for entire protection zone
Radio, fiber optics, hard wire, carrier current can be used for pilot channel
Most common on HV, EHV lines
Relay Types

Phase relay
Relay measures phase current or voltage quantities

Ground relay
Relay measures ground current or voltage quantity (zero sequence values)
Protects for one line to ground and phase to phase to ground faults

Sequence relay
Relay measures symmetrical component sequence quantity (+, -, 0)
Relay Trip Times

Instantaneous
Relay operates as soon as operating value is met

Time delay
Relay operating time is delayed
  Fixed delay determined by separate timing element (62)
  Inverse delay determined by magnitude of operating quantity and relay operating curve
    Delay decreases as operating value increases

Actual clearing time includes relay operate time plus circuit breaker opening time
Relay Construction

Electromechanical

Several individual relays required for complete fault protection

Static or electronic

One or more relays required for complete fault protection

Digital or microprocessor

Single device provides complete fault protection

Device may include additional features not available with electromechanical or electronic relays
Relay Basics

Component relay
Individual boxes that provide phase or ground protection, reclosing, etc.

Relay system
Bunch of single components designed to do a task
A multifunction device to do the same task or several tasks
Digital Relays

Digital relays were introduced in early 1980’s

Additional digital relay features

- Fault information and location
  - Voltage and current inputs required to locate fault
- Remote communications
- Self testing
- Circuit breaker history and monitoring
- Metering
- Time tagging (GPS clock input)

Concerns

- Complicated to apply (many elements)
- Single point of failure
- Limited life expectancy
IEEE Device Numbers

Numbers 1 - 97 used

21  Distance relay
25  Synchronizing or synchronism check device
27  Undervoltage relay
32  Directional power relay
43  Manual transfer or selector device
46  Reverse or phase balance current relay
50  Instantaneous overcurrent or rate of rise relay (fixed time overcurrent)

(IEEE C37.2)
IEEE Device Numbers

51  AC time overcurrent relay
52  AC circuit breaker
59  Overvoltage relay
62  Time delay stopping or opening relay
63  Pressure switch
67  AC directional overcurrent relay
79  AC reclosing relay
81  Frequency relay
86  Lock out relay
87  Differential relay

(IEEE C37.2)
Overlapping & Redundant Systems
Relay Reliability

Overlapping protection
  Relay systems are designed with a high level of dependability
  This includes redundant relays
Overlapping protection zones
We will trip no line before its time
  Relay system security is also very important
Every effort is made to avoid false trips
Relay Reliability

Relay dependability (trip when required)
- Redundant relays
- Remote backup
- Dual trip coils in circuit breaker
- Dual batteries
- Digital relay self testing
- Thorough installation testing
- Routine testing and maintenance
- Review of relay operations
Relay Reliability

Relay security (no false trip)

Relay security failures have increased the impact of numerous system disturbances

Careful evaluation before purchase

Right relay for right application

Voting

2 of 3 relays must agree before a trip

Thorough installation testing

Routine testing and maintenance

Review of relay operations
Protection Zone

Portion of system protected by relay
Usually determined by location of current transformers
Common protection zones
  Substation bus
  Transmission line
    May have multiple protection zones
  Power transformer
  Generator
Common to have backup protection for zone
Instrument Transformers

Used to transform line currents and voltages to relay values
  Voltage and current transformers
Transformer types
  Magnetic
  Capacitive
    Capacitor voltage divider to measure voltages
  Optical
Instrument Transformers

Transmission Lines

\[ Z_{\text{secondary}} = Z_{\text{primary}} \times \frac{\text{CTR}}{\text{VTR}} \]

For distance relays

The PT location determines the point from which impedance is measured.

The CT location determines the fault direction.

CT location generally determines zone of protection
CT Selection

C800 Current Transformer

Will support 800 volts @ 100 amps on CT secondary before saturation (20 times rated secondary current)

Consider burden of relays and cable impedance

CT Accuracy decreases when less than full winding used

At half ratio, CT is C400

CT Saturation:

Saturation most severe with high magnitude faults
Saturated Current
Overcurrent Relays
Distribution Protection (50/51)
Protective Devices

Circuit Breaker with relays
Pole mounted reclosers
Fuses
Overcurrent Relays (50/51)

Non directional
3 Phase and ground relays
Time overcurrent elements (51)
Instantaneous elements (50)
50/51 Relays

\[ I_r = I_a + I_b + I_c \]
Time Overcurrent (51)

Operate time inversely proportional to current
Select operating characteristic
  Inverse, very inverse, extremely inverse
Select pickup current (tap)
Select operate time (time lever or time dial)
Usually coordinated with next downstream device
51 Time Overcurrent Curves

Time, Seconds

Multiples of PU Current

Substation Bus Protection
Simple Bus Differential Scheme

CTs in parallel
Must have common CTR
Extremely inverse 50/51 relay used
  50 Element may have to be disabled
CT Saturation for external faults can cause misoperation
Need GOOD CTs! (C800)
Used for main & auxiliary bus, breaker & half configurations
Bus Protection Zone

Bus Protection

Line Protection

21

51

Line Protection
Bus Differential Scheme with Overcurrent Relays

External Fault

Internal Fault

I = 0

50/51  86LOR

Trip

Close Block

86LOR

Trip

Close Block
Power Transformer Protection
Fault Protection

Prevent thermal damage
\[ I^2 t = k \]

Prevent mechanical damage
Core shifts for through faults

No trip for normal or emergency loads
NERC Loading criteria
  - 150% of Nameplate rating
  - 115% of Emergency rating

Coordinate with other relays, fuses
Overcurrent Protection

115 kV / 13.8 kV

Relay(s) 50/51 50/51

Relay(s) 50/51N 50/51N
Transformer Differentials (87)

Detect faults within differential zone
   Between CTs (within protective zone)
   Immune to external faults
Will not see turn to turn fault
CT Connections
   Delta for wye winding
   Wye for delta winding
   Compensate for transformer phase shift
Use good quality CTs
External Fault

\[ I_{11} \quad I_{11}' \quad I_{22} \quad I_{22}' \]

\[ I_{Op} \sim 0 \]
Internal Fault

\[ I_{Op} = I_{1}' + I_{2}' \]
Transmission Line Protection
Typical Line Protection

52 Circuit Breaker
21 Distance Relay
50BF Breaker Failure
67N Directional Ground
Overcurrent Relay
79 Automatic Recloser
CT Current Transformer
PT Voltage Transformer
PTs on bus, main/transfer bus
PTs on line side, ring or breaker and half
Distance Relays
(21, 21G)
Typical Reaches

21 Zone 1  85-90%
21 Zone 2  125-180%, Time Delay Trip
21 Zone 3  150-200%, Time Delay Trip

67 Ground Instantaneous Overcurrent
67 Ground Time Overcurrent
67 Ground Time Permissive Transfer Trip Overcurrent

Typical Relay Protection Zones
Ground Fault Protection (21G, 67N)
Ground Faults

Ground distance relays (21G)
Directional ground overcurrent relays (67N)
Ground overcurrent relays
  Time overcurrent ground (51)
  Instantaneous overcurrent (50)
Measure zero sequence currents
Automatic Reclosing (79)

First reclose ~ 80% success rate
Second reclose ~ 5% success rate
Must delay long enough for arc to deionize
\[ t = 10.5 + \frac{kV}{34.5} \text{ cycles} \]
14 cycles for 115 kV; 25 cycles for 500 kV
Must delay long enough for remote terminal to clear
1LG Faults have a higher success rate than 3 phase faults
Automatic Reclosing (79)

Most often single shot for line protection
Multishot most often used on distribution
Delay of 30 to 60 cycles following line trip is common

Checking:
- Hot bus & dead line
- Hot line & dead bus
- Sync check
Generator Protection
Generator Protection

Amount of protection based on generator size and type

Common protection for larger units:
- Differential relays
- Reverse power relays
- Frequency
- Ground fault
- Over voltage
- Los of excitation
- Negative sequence
Differential Protection (87)

Generator differential
Step up transformer differential
Overall differential
    Generator and transformer

Diagram: [Diagram of differential protection system]
Frequency Protection (81)

Overfrequency/overspeed
Underfrequency
Must coordinate with load shedding
WSCC Requirement
Ground Fault Protection

Voltage relay across generator neutral (59N)
Generators usually grounded through a resistor to limit ground fault currents
Unbalanced Fault Protection

Negative sequence overcurrent relay (46)

$I_2$ Generates twice-rated frequency rotor currents; generates lots of heat
Balanced Fault Protection

Distance relay (21)
Voltage restrained overcurrent (51V)
Reverse Power (32)

Generators don’t make good motors
Similar to watt meter
Loss of Excitation

Loss of Excitation (40)

Similar to distance relay
  Mho characteristic @ -90 degrees
Alarm and trip levels
Multiple zones available
UFOs vs. Power Outages


Number of FPC Reports

Number of USAF UFO Reports
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