Protective Relaying

Daniel L. Ransom, PE
Principal Technical Application Engineer

March 16, 2015
Confidentiality Notice

Doble Engineering (Doble) hereby grants the recipient (you) the right to retain this presentation and materials included within (the Presentation) for private reference. No other rights, title, or interest, including, but not limited to, the rights to copy, make use of, distribute, transmit, display or perform in public (or to third parties), edit, translate, or reformat any portion of the Presentation are hereby or otherwise granted and shall remain expressly reserved by Doble. You acknowledge and agree that such limited license is expressly conditioned upon your acceptance of the terms herein. You further agree that, in the event of your breach, Doble will suffer irreparable damage and injury for which there is no adequate remedy at law. As such, Doble, in addition to any other rights and remedies available, shall be entitled to seek injunction by a tribunal of competent jurisdiction restricting you from committing or continuing any breach of these terms.
“The function of protective relaying is to cause prompt removal from service of any element of a power system when it suffers a short circuit, or when it starts to operate in an abnormal manner that might cause damage or otherwise interfere with the effective operation of the system.”

—Charles Mason

—The Art and Science of Protective Relaying, 1956
Why Do We Need Protective Relaying?

- Avoid faults and abnormal operating conditions
- Maintain equipment, personnel and system integrity
- Protection examples:
  - Overload
  - Out-of-step conditions
  - Phase-open conditions
  - Short circuits
Accidents Happen!

- “One never knows, do one?” –Fats Waller
"War of the Currents"

- Efficient distribution: AC wins
- Nicola Tesla (invented ac motor): “Electric power frees us from physical toil and drudgery”

DC
Thomas Edison

AC
George Westinghouse

Poly-phase AC
Nicola Tesla
• Widespread electric power is engine of modern life
• Allows us to achieve better lives
  – Civilizations created science and art when not all labor was for subsistence (food)
  – Electric power frees us for other pursuits

Left: Tesla at Chicago World’s Fair  Right: Frank Doble testing early apparatus
You Have an Important Job

- Economic delivery of power to homes and industry
- Optimize electrical system assets
- You provide a valuable service
What Do Relays Do?
Protection Prevents Damage

- Protection limits damage to power system
- Fast is good
Relays are Good For...

- Detecting faults
  - Prevent damage to equipment and power system
  - Caused by wind, lightning, ice, contamination, animals, birds, reptiles, etc.

- Sensing abnormal system conditions
  - Act before damage to equipment
  - Alarm for close calls that cause later faults

- Performing control and monitoring
  - Reclosing, sync check
  - Metering
  - Main-tie-main and remedial action schemes
The objective of a relay system is to provide fast protection as simply and economically as possible.

Protection costs should be evaluated in light of the much greater cost of the equipment or the process the relays are protecting. Consider, too, the cost of an outage or loss of the protected equipment from improper protection.
Speed Classifications

- Instantaneous
  - Operate ASAP
  - No intentional delay
- Delayed
  - Short time
  - Long-time
  - Inverse-time
  - Set with time dial
- High speed
  - 1 cycle and less (≤ 16.7 ms at 60 Hz)

ANSI/IEEE C37.1
Reliability, Dependability, and Security

- Reliability = Dependability + Security
  - Good balance
  - Like parallel and series
- Equipment performs as intended
- Degree of certainty
  - "Highly reliable"
  - "Does the job!"

[Diagram of OR and AND logic gates indicating very dependable and very secure.]
Dependability

- Equipment performs every time
- Relay operates correctly
  - For all faults
  - Per relay design

OR

Very dependable
Security

- Equipment does not perform incorrectly
- No false trips

AND

Very secure

TC
Which is Better—dependability or security?
Designers of our modern power system have decided that security is not as important as dependability. In other words, false tripping is preferred. In this manner, valuable system assets are protected from damage (in a most conservative way). This situation is acceptable because the power system has alternate paths to provide energy to a destination or load. There is reserve in the networked power system that supplies the need created by false tripping. However, as accountants look to optimize economic use of assets, the amount of reserve is much less than in the past. The system is becoming “brittle.”
• Selectivity—isolating only faulty part of system
Networked/Interconnected system
Time-coordination curves (TCC) from SKM software
Speed of Operation

- One second is an eternity in relaying
- Speed is very critical
Fast Avoids Damage

- Avoid thermal damage to cables, transmission lines, transformers, and generators

GEN A speeds up MW IN, but no MW out!

System starts going out of sync Need to Trip CB B fast
Hit target in center
Games manufacturers play with specifications
• Voltage
• Current
• Power
• Temperature

Be careful
Accuracy / Precision

- Reading relay specs
- Voltage examples
- Current examples
- Power examples
- Temperature examples
System Protection Design Considerations

- Reliability
- Speed of operation
- Selectivity
- Simplicity
  - Reliable
  - Easy to maintain
- Economics
  - Costs
  - Benefits
Primary Protection Zones
CTs on both sides of power-system equipment are protected when two zones overlap. The circuit breaker in this diagram is protected by both zones. If there was no overlap, then the circuit breaker would not be protected.
Primary and Backup
Different Vendors is Better

- Avoid mutual failures
- Overcome hardware weaknesses
- Catch faults using dissimilar algorithms
Backup Types

- Local backup
  - Uses common elements (batteries, breakers, cts)
  - Might fail to operate if common elements fail
- Remote backup
  - Completely independent
  - Difficult to sense all local faults
Circuit-Breaker Failure

- Special local backup
- Focused on particular circuit breaker
- Trips if
  - Current still there
  - Timer has elapsed
- Communications assisted
Typical BF Circuit
Resources You Should Have
Codes

- NEC, CEC
- NFPA
- OSHA
- NEMA
- EGSA
Standards

- ANSI/IEEE
- IEC
Guides / Recommended Practices

- ANSI/IEEE
- NEMA
- EGSA
- Manufacturers’ manuals and application guides
Per Unit and Percent

pu value = \frac{\text{actual value}}{\text{base value}}

% value = \frac{\text{actual value}}{\text{base value}} \times 100
Advantages of Per Unit

- Compare magnitudes easily between circuits
- Reduce range of equipment impedances
- Per-unit method good for computer simulations
- Driving or source voltage assumed at 1.0 pu
- Less confusion between single-phase and three-phase systems
Types of Protection
Device Numbers

- 24 Generator / transformer over-excitation
- 25 Synchronism check
- 32 Reverse power
- 40Q Loss-of-field (VAR sense)
- 21 Distance
- 52 Circuit breaker
- 52a Closed when breaker closed
- 52b Closed when breaker open
- 101 Control switch for breaker
- 43 Manual transfer switch
Device Numbers

- 50  Instantaneous overcurrent
- 51  Inverse-time overcurrent
- 59N Neutral overvoltage
- 59  Overvoltage
- 64F Field-ground detection
- 60  Voltage balance
- 78  Out-of-step, Vector jump
- 81  Over-/underfrequency
- 87  Differential
Non-Directional Overcurrent

- One input source—based solely on current
- Tripping is slow
- Economical: no potential transformer (pt) needed
Directional Overcurrent

- Two input sources
  - Current and voltage, or current and current
  - One is operate source (current) and one is directionality (polarizing voltage or current)
- Tripping is slow
- Economical
Distance: Impedance Protection

- Two input sources (typically three phase)
  - Current and voltage
  - Based on ratio of voltage and current
- Tripping is fast (depending on zone)
- More expensive than overcurrent protection
Differential

- Based solely on current
  - Two currents
  - One operate and one restraint
- Tripping is fast
- More expensive than overcurrent protection
- For generators and transformers
For protection of short transmission line

**Distance protection backup**
Pilot-Wire Distance Protection

- Relies on communication between two terminals
  - Microwave, fiber optic, Power line carrier
- POTT, PUTT, blocking, and unblocking schemes
- Tripping is fast
- PTs needed for distance 21 impedance protection
- For protection of short/long transmission line
Price of Protection

- Pilot protection
- Step distance
- Directional overcurrent
- Inverse-time overcurrent relays
- Instantaneous relays
- Sectionalizers
- Fuses
What are Electromechanical Relays?

- Simple construction, easy to understand
  - Work on electromagnetic principle
  - Since late 1800s—useful life 30 to 80 years
  - Plungers
  - AC induction disks and cylinders with contacts
  - Jeweled bearings
  - Motor timers and logic sequencers
  - Big telephone, clapper-type, auxiliary relays
- Microprocessor relays emulate EM concepts
Pros for Electromechanical

- 1 to 2 cycles tripping for HV line fault
- Long useful life
- Nuclear plants still use relays
- Easy to set
- Energy to operate relay elements comes from CTs and VTs
- No surge or RFI problems
Cons for Electromechanical

- Require appreciable maintenance
- Perceived as “slow” — speed was fine for 97% of applications
- No built-in logic
  - External logic
  - Auxiliary relays/timers, etc
- Assumed current and voltage signals were perfect sinusoids, even during fault
Plunger Unit

- One scalar operating quantity
- Cheap and simple
- Low accuracy
- Dropout ratio: 10–50% (large hysteresis)
- Sensitive to DC offsets (transient overshoot)
Clapper unit

- Coil pulls on flat armature with contact to close contacts
- Characteristics like plunger unit
- Familiar auxiliary relay
- Still provides output contact on modern relays
Induction Disc

- One scalar operating quantity with shading coil, or two operating quantities with phasors
- Slow–large turning inertia
- Moderately good accuracy, 5%
- Stable inverse time characteristic, with repeatable, long times
- Variety of inverse curve shapes via damping magnet, spring, and magnetic flux levels
Induction Disc Relays

- Inverse time-overcurrent relays and overvoltage relays
- Models apparatus heating
Induction cylinder unit

- Product / multiplying element optimum for two operating quantities with phase difference
- Fast acting–low inertia
- Fast resetting
- Large dropout ratio–98%
- Less sensitive to dc
- More accurate measurements
- Zone-distance and directional elements with operating times as small as 5 ms
- Fast overcurrent / fast overvoltage detectors
Polar Unit

- Toggling contact in magnetic structure moves rapidly in response to applied flux
- Fastest element for differential and pilot wire relays
Caveats for Using Electromechanical Relays

- Large burden on CTs and VTs
- Sensitive ground relay presents a high burden to its CT
- Major scheme engineering and setting effort
- Saturation and ratio error needed to find right setting
  (settings less than required pickup)
Delicate measuring element contacts need a seal-in and indicating plunger device to carry sustained trip current
EM Relay Panels

- Groups of single function, single-phase relays
- Custom design
- Takes lots of space
- Costly
- Long lead time
Drawout Cases

- Easy removal for calibration, repair, or contact cleaning
- Relay out of panel did not false trip
- Convenient opening of trip circuits
- Easy connection for meters and test sets
- Expensive
- Less common with modern relays
Solid-State Electronic Relays

- Analog sampling in use from 1967
- Discrete-transistor and op-amps
- Fast! (and somewhat insecure)
- Really expensive at first (more than electromechanical)
- Calibration stability problems with potentiometers
Troubles of Solid-State Relays

- Solid-state trip (thyristor)—triggered easily and false tripped
- New semiconductors might be better, but bad reputation of static tripping has not gone away
- We learned about electrical environment vulnerability
  - Oscillatory surges from disconnect switch arcing
  - Fast transients from secondary circuit inductive interruption
  - Radiated EMI from radio transceivers
- We learned about new CT/VT response problems (especially CVT transient response)
Microprocessor-Based Protection

- Panel-mount and rack-mount design
- Multifunction— one relay replaces a full panel
- Microprocessors execute high-speed digital sampling
- Complex measurement algorithms and logic
Microprocessor Relays: Reduced Power and Size

- Power: 3 A @ 125 Vdc
- Large CT/VT burden
- Big: 90" H x 72" W
- Power: 100 mA @ 125 Vdc
- Small CT/VT burden
- Small: 7" H x 19" W
Pros for Microprocessor Relays

- More functions than entire old panel
- Reduced wiring
- Communications ready
- System config. via settings
- All in one metering, relaying, local / remote control
- Standard, off-shelf product
Why Microprocessor Relays?

- Better accuracy and precision
- Minimal routine maintenance
- No calibration
- Self-monitoring
- Data by remote communication
- Remote settings management
- Network-based substation control
Configuration and Monitoring Advantages

- Standard products, configured via settings
- Intelligent, programmable functions and features
  - All zone functions in one package
  - One set of inputs, outputs
- Minimal custom system engineering or wiring
- Fault-waveform recording and information
- Non-fault monitoring and information
Less is More

- Less panel space, battery power, burden
- Short ordering cycles, under a week
- Reduced inventories
- Keep few maintenance spares
Relays Were Bigger Business

Delivery Weeks

1980 2014

Price

1980 2014

$25,000 $20,000 $15,000 $10,000 $5,000 $0

$25,000 $20,000 $15,000 $10,000 $5,000 $0

Protective Relaying ©2015 Doole Engineering Company. All Rights Reserved
Microprocessor-Based Relay Challenges

- Useful life 10–20 years
- Most use only 30–40 percent of features
- Main and backup?
- Software bugs
- Firmware and settings version management
- Flexibility brings complexity
  - Long list of settings
  - Some pretty obscure and technical
  - What is chance that some of are set wrongly?
Microprocessor Relay Performs Multiple Functions

- Many protection elements plus
- Control and automation plus
- Communication
Overcurrent Protection
Confidentiality Notice

Doble Engineering (Doble) hereby grants the recipient (you) the right to retain this presentation and materials included within (the Presentation) for private reference. No other rights, title, or interest, including, but not limited to, the rights to copy, make use of, distribute, transmit, display or perform in public (or to third parties), edit, translate, or reformat any portion of the Presentation are hereby or otherwise granted and shall remain expressly reserved by Doble. You acknowledge and agree that such limited license is expressly conditioned upon your acceptance of the terms herein. You further agree that, in the event of your breach, Doble will suffer irreparable damage and injury for which there is no adequate remedy at law. As such, Doble, in addition to any other rights and remedies available, shall be entitled to seek injunction by a tribunal of competent jurisdiction restricting you from committing or continuing any breach of these terms.
Most-Used Protection Type

- “Too much of a good thing is bad”
- Excess current causes rapid overheating and destruction
- Coordination important upstream and downstream
Not Pilot-Wire Protection

- No information from other end
- Devices rely on currents from local ct (current transformer)
- Protection design depends upon:
  - Line voltage
  - Importance of line
Non-Directional Overcurrent

- One input source—based solely on current
- Tripping is slow
- Economical: no potential transformer (pt) needed
Directional Overcurrent

- Two input sources
  - Current and voltage, or current and current
  - One is operate source (current) and one is directionality (polarizing voltage or current)
- Tripping is slow
- Economical
Coordination, Fault Isolation

- Device B should operate to isolate fault
- Coordinating interval, CI
  - Operation time between two related protective devices
  - Should have enough coordinating interval for selective fault isolation
Fault occurs at feeder B
Both relays at A and B pickup
Relay at B operates first
Breaker B opens
Relay at A stops timing and resets
Selective operation: adequate difference between time of two protective devices
Coordinating Interval Time

- Circuit breaker operating time + relay over-travel time + safety margin

<table>
<thead>
<tr>
<th></th>
<th>Electromechanical Relay</th>
<th>Numeric Relay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breaker Operating</td>
<td>3.3–10 ms</td>
<td>3.3–10 ms</td>
</tr>
<tr>
<td>Relay Over-travel</td>
<td>10 ms</td>
<td>0 ms</td>
</tr>
<tr>
<td>Safety Margin</td>
<td>10 ms</td>
<td>10 ms</td>
</tr>
<tr>
<td>Coordinating Time</td>
<td>20 ms</td>
<td>20 ms</td>
</tr>
</tbody>
</table>
- CT ratio: 600/5
- Relay Tap: 4
- Relay pickup: 480 A primary
- 480 A is (1 • tap)
- Time Dial is 2
- Fault current
  - 4800 A
  - 10 • tap
- Relay operate: 50 ms
Coordinate with Downstream Relay

Overcurrent Protection © 2015 Doble Engineering Company All Rights Reserved
Relays Coordinate for Max and Min Fault Currents

A

C

B

Time

Min Fault Current

Max Fault Current

Cl: Min Fault Current

Cl: Max Fault Current
Electromechanical Inverse-Time Overcurrent Settings

- Two main settings
  - Pickup
  - Delay (via Time Dial)
Numeric Inverse-Time Overcurrent Relay

- Three main settings:
  - Characteristic
  - Pickup
  - Delay (via Time Dial)
Choosing CT

- Minimum CT rating: maximum expected current
- Ideal CT rating: 15 times maximum expected current
- Minimum fault is usually an end-of-line fault
- Consider “minimum system stiffness” when calculating minimum
Choosing OC Relay Pickup Setting

- GREATER THAN full-load current
- LESS THAN minimum fault
- Set relay pickup between:
  - 1.5 times maximum expected load
  - 50% of calculated I minimum short-circuit value
Fault Current Increases Toward Source

- Clearing time near Source should be less than 1 s

Source A B C D

Increasing I fault Decreasing I fault

10,000 A
CB3 Relay Acts First

15 kA sym
5 kA sym
1.5 kA sym

Overcurrent Protection © 2016 Doble Engineering Company All Rights Reserved 22
Momentary DC Skews Waveform

DC  AC fault current  Unsymmetrical waveform
 Relay B inst should not operate for any fault seen by breakers downstream of B
Inst at B = 173 • 11 • maximum sym of 15 kA = 3 kA
if relay B is sensitive to DC offset
Inst at B = 135 • 11 • maximum sym current of 15 kA
if relay B is insensitive to DC offset
Cannot Apply Instantaneous for All Instances

- Need adequate difference between short-circuit levels for local and remote ends
- Required minimum factor: 1.35
- Ensures selectivity
- Larger factor—more effective instantaneous application
Ground Overcurrent Elements and Coordination

- Simpler coordination because of breaks in zero-sequence path (delta / wye transformers)
- Independent of load
- Set sensitively with dedicated IC ct
Cannot be set very sensitive. The three Cts are not identical and misoperations have been reported especially if this arrangement is applied at the primary of a transformer and set very sensitively.
Measure Ground Current w/ One CT

- Core-balance ct is very sensitive
- Size and voltage limitations
  - Restricted by cable and busbar dimensions
  - Medium voltage is maximum BIL

![Diagram of core-balance CT with 51G or 50G markings and label: Zero-sequence (core-balance) ct]
Iop is I operating: operating current

- Reference is to fixed, “polarizing” quantity
- Determines direction of current flow
- Phase directional reference: system voltage or V1
- Ground directional reference: 3I0 or 3V0
- Negative-sequence polarization is popular (easy to obtain in microprocessor relays)
# Maximum Torque Angle

<table>
<thead>
<tr>
<th>Connection</th>
<th>Phase A</th>
<th>Phase B</th>
<th>Phase C</th>
<th>Maximum Torque When</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30 degrees</td>
<td>la</td>
<td>Vbc</td>
<td>lb</td>
</tr>
<tr>
<td>2</td>
<td>60 degrees</td>
<td>la-lb</td>
<td>Vbc</td>
<td>lb-lc</td>
</tr>
<tr>
<td>3</td>
<td>90 degrees</td>
<td>la</td>
<td>-Vbc</td>
<td>lb</td>
</tr>
<tr>
<td>4</td>
<td>90 degrees</td>
<td>la</td>
<td>Vbc</td>
<td>lb</td>
</tr>
</tbody>
</table>

Overcurrent Protection  ©2016 Doble Engineering Company All Rights Reserved  35
Iop is I operating: operating current
30° Connection

- Vac flux is along Vb (Vac is Vpol)
- Ia flux is in phase with Ia (Iop)
- Torque product is sine of angle between two fluxes
- Max torque when Ia is in phase with Vac
- Operate boundary: Current lags Va voltage by 120°, or leads Va voltage by 60°
Iop is I operating: operating current
• Flux produced by Vac is along Vb (Vac is Vpol)
• Flux produced by Iab is in phase with Iab (Iop)
• Torque product is sine of angle between two fluxes
• Max torque when lab is in phase with Vac
• Operate boundary: Current lags Va voltage by 120°, or leads Va voltage by 60°

• Flux produced by Vac is along Vb
• Flux produced by Iab is in phase with Iab
• Torque is proportional to Sin of angle between two fluxes
• Hence, if Iab is in phase with Vac, max torque will occur
• Operating Boundary: Current lags voltage by 120° or leads by 60°
Iop is I operating: operating current
60° Connection (Wye)

- Vc flux is along Vba (-Vc is Vpol)
- Ia flux is in phase with Ia (Iop)
- Torque product is sine of angle between two fluxes
- Max torque when Ia is in phase with -Vc
- Operate boundary: current lags Va by 150° or leads Va by 30°
Iop is I operating: operating current
90° Connection, 30° Displacement

- \((V_{bc} + 30°)\) flux is along \(V_{ba}\)
- \(I_a\) flux is in phase with \(I_a\) (Iop)
- Torque product is sine of angle between two fluxes
- Max torque when \(I_a\) is in phase with shifted \(V_{bc}\)
- Operate Boundary: current lags voltage \(V_a\) by 150° or leads voltage \(V_a\) by 30°
Iop is I operating: operating current
90° Connection, 45° Displacement

- (Vbc +45°) flux is along Vba
- Ia flux is in phase with la (Iop)
- Torque product is sine of angle between two fluxes
- Max torque when Ia is in phase with shifted Vbc
- Operate Boundary: current lags voltage Va by 135° or leads voltage Va by 45°
Pros and Cons of Negative-Sequence Polarization

• Pros
  – Not affected by mutual coupling
  – Negative impedance is significantly less than zero-sequence
  – Present in good quantity for remote faults at end of long lines
  – No need for extra cts and pts

• Cons
  – Affected by power source levels
  – Affected by system unbalance
Directional Ground Overcurrent Protection
Advances in Directional Polarization

- Originally, zero-sequence directional ground relays were one-source only
  - 3I0 current polarization
  - 3V0 voltage polarization
- Today, you select 3I0, 3V0, and/or 3I2 (negative-sequence polarization)
- Modern relays detect available polarizing quantities
  - Make automatic decision of which to apply
  - Optimize for different operating situations
There are some very few cases where $3I_0$ is not in the same direction; these are rare.
There are some very few cases where 3I0 is not in the same direction; these are rare.
There are some very few cases where 3I0 is not in the same direction; these are rare.
Two-Source Ground-Directional Polarizing

- Ground relay measures $I_0$, operating quantity
- $V_0$ as polarizing quantity
- Problems with this method:
  - Large line $Z_0$ limits $I_0$
  - Small source $Z_0$ limits $V_0$
This is the connection for 45° displacement
Zero-Sequence Sources

- Ground directional requires constant zero-sequence source
  - Should not change with fault location
  - Should not reverse in direction
- Current from transformer-neutral ct
- Voltage from line pt
- Zero-sequence current sources
  - delta-wye transformers—OK
  - wye-wye transformers—probably OK
  - Autotransformers—usually not suitable
  - Current from delta-tertiary ct—perhaps
Obtaining 3V0

A
B
C

3V0
This is a 60° directional unit. Most ground-fault current angles range to 80°, so this 60° unit gives good torque output for fault angles in this region.
Guidelines for Zero-Sequence Polarization

- Strong-source stations: use 3I0 if adequate quality
- Good ground source (solidly grounded neutral): current polarization preferred
- Where V0 is strong: voltage polarization is okay
- Stations where 3I0 is not available: use 3V0
- Critical applications: consider dual polarization
Pros and Cons of Zero-Sequence Polarization

• Pros
  – Easy to set, understand, and visualize
  – Not effected by load levels
  – Provides excellent resistive fault coverage

• Cons
  – Parallel lines have zero-sequence mutual coupling
  – Generation level impacts source quality
Negative-Sequence Overcurrent Protection

- Negative-sequence relays monitor feeder unbalances
- Coordinate with phase and ground relay settings

Single-phase loads
Negative Sequence Overcurrent Protection

Traditional phase-overcurrent elements must be set greater than maximum load current. This limits the sensitivity of the phase relays and increases the operating times for line-end faults.

Because phase-to-phase fault current levels are lower than three-phase fault levels, the result is further increased fault-clearing time.

Consider a phase-to-phase fault at 75 percent of the protected feeder. The voltage at the relay location is 0.79 Vnom, and the phase inverse-time overcurrent relay operates in 0.71 s. For the same three-phase fault the voltage drop seen by the relay is 0.71 Vnom with an operating time of 0.53 s. Any unbalanced fault condition produces negative-sequence current. Therefore, a negative-sequence overcurrent element operates for both phase-to-phase and phase-to-ground faults. If a definite-time, negative-sequence overcurrent element is used, the selective (no-tripping) setting is lower than the equivalent phase-overcurrent relay. Therefore, the negative-sequence overcurrent element clears the same phase-to-phase fault in less than 0.3 s.

Pros and Cons of Negative-Sequence Protection

- Uses negative-sequence current 3I2
- Works only for phase-to-phase and phase-to-ground faults
- Faster than phase overcurrent on P-P and P-G faults
  - Lower setting, more sensitive
  - Responds only to unbalances
- Not affected by false operate on heavy load
- Coordinate carefully, observing equivalency with phase OC
Multiply the 50/51Q pickup value by the table factor. Then, plot the negative-sequence time-overcurrent characteristic on the same plot as the phase and ground elements.

The multiplier is the ratio of phase current to the negative-sequence current for the fault type.

For example, a downstream phase 51 element has a pickup of 400 A. The upstream 51Q element has a pickup of 250 A. Plot the phase-overcurrent element normally with a pickup at 400 A. The 51Q element is shifted to the right (multiplied) by the appropriate factor. Check the coordination between these two elements for a phase-to-phase fault. Thus, the negative-sequence 51Q characteristic is plotted on the coordination graph with pickup at: 250 A • 1.732 = 433 A, and is coordinated.

Generally, for coordination with downstream phase-overcurrent devices, phase-to-phase faults are the most critical consideration. All other fault types shift in an equal or greater amount to the right on the TCC plot.
Questions?
Voltage and Frequency Protection
Confidentiality Notice

Doble Engineering (Doble) hereby grants the recipient (you) the right to retain this presentation and materials included within (the Presentation) for private reference. No other rights, title, or interest, including, but not limited to, the rights to copy, make use of, distribute, transmit, display or perform in public (or to third parties), edit, translate, or reformat any portion of the Presentation are hereby or otherwise granted and shall remain expressly reserved by Doble. You acknowledge and agree that such limited license is expressly conditioned upon your acceptance of the terms herein. You further agree that, in the event of your breach, Doble will suffer irreparable damage and injury for which there is no adequate remedy at law. As such, Doble, in addition to any other rights and remedies available, shall be entitled to seek injunction by a tribunal of competent jurisdiction restricting you from committing or continuing any breach of these terms.
Voltage and Frequency Protection Used Often

- Assure proper operating voltage
- Determine if source or feeder is nominal
- Monitor manual- and automatic-closing switches
- Detect voltage unbalance
- Detect underfrequency and overfrequency conditions
V and F Protection Element Types

- Undervoltage—27
- Overvoltage—59
- Underfrequency—81U
- Overfrequency—810
- Rate of change of frequency—81ROCOF
- Measure line voltage and phase-to-neutral voltage
- Instantaneous and inverse-time operation
Undervoltage Protection

- Undervoltage relays (27) operate when voltage drops below set point
- Operation can be instantaneous, delayed, and inverse time
- Applied voltage greater than pickup—no operation
- Applied voltage less than pickup—element operates
- Instantaneous relay operating time $\approx 1$ cycle
- Inverse time depends on voltage level
Applications for Undervoltage Protection 27

- Bus protection
- Motor protection
- Transfer schemes
- Permissive functions
- Backup functions
- Remedial action schemes (RAS)
Overvoltage Protection

- Operates when voltage is greater than set value
- Operation instantaneous, delayed, and inverse time
- Applied voltage greater than pickup—element operates
- Applied voltage less than pickup—no operation
- Instantaneous relay operating time \( \approx 1 \) cycle
- Inverse time depends on voltage level
Applications for Overvoltage Protection

- Bus protection
- Earth-fault protection
- Wind farms
- Capacitor banks
- Motor protection
- Transfer schemes
- Remedial action schemes (RAS)
The last San Onofre Nuclear Plant trip was an overspeed generator trip picked up by an overfrequency relay.
Mechanics of Frequency Protection

- Instantaneous, delayed, and rate-of-change
- Count time between zero crossings
- Inhibit at minimum voltage prevents noise error
Applications for Underfrequency Protection

- Detect under-speed conditions for synchronous motors and synchronous condensers
- Load shedding from lost generation and excess load
- ROCOF faster than waiting for specific UF level
Applications for Overfrequency Protection

- Detect over-speed conditions for ac machines
  - No mechanical governor
  - Machine shaft linked to a prime mover or to another machine
  - Accelerate combination to a hazardous over-speed condition
- Load control
- Distributed-generation transfer
- ROCOF faster than waiting for specific OF level
Voltage Steady-State Tests

- Pickup
  - LRAMPV
  - CREEPV
  - BSRHOV
  - PRAMPV
  - INDPUV
  - DRAMPV
- Operating time
  - TIMEV
  - TOVPLT

Figure 5-37 PRAMPV Operation Graph

Figure 5-35 TIMEV Operation Graph
Voltage Transient Tests (TRANS)

- Load-loss simulation evaluates overvoltage protection
- Voltage-decay simulation evaluates undervoltage relays
Frequency Steady-State Tests

- Pickup
  - LRAMPF
  - CREEPF
  - LRMPFS
  - FRDRMP
- Operating time
  - TIMEF
  - FRRMPT

Figure 5-9  CREEPF Operation Graph
Frequency Dynamic Tests

- **TRANS**
  - Generation-loss simulation evaluates underfrequency protection
  - Overspeed simulation evaluates overfrequency protection
- **ROCOF**
  - Rate of change of frequency
  - Confirm fast tripping

![Chart showing frequency over time with labels 81 ROCOF trips sooner and 81U.](image)
Synchronism (Sync) Check 25

- Verify sync parameters
  - Voltages in sync window
  - Small phase-angle difference
  - Slip rate within specification

- Monitor voltage and frequency elements
  - Voltage magnitudes
  - Phase-angle difference
  - Slip frequency
Sync-Check Steady-State Tests

- Voltage pickup
  - LRAMPV
  - CREEPV
  - BSRHOV
  - PRAMPV
  - INDPUV
  - DRAMPV
- Operating time
  - TIMEV
  - TOVPLT

- Frequency pickup
  - LRAMPF
  - CREEPF
  - LRMPFS
  - FRDRMP)
- Operating time
  - TIMEF
  - FRRMPT
- Phase pickup—PHROTV
Sync-Check Dynamic Test

- ASYNC

![Diagram showing expected time, relay operate, and CB closing area with specific degrees and milliseconds.](image)
Questions?
Instrument Transformers
Confidentiality Notice

Doble Engineering (Doble) hereby grants the recipient (you) the right to retain this presentation and materials included within (the Presentation) for private reference. No other rights, title, or interest, including, but not limited to, the rights to copy, make use of, distribute, transmit, display or perform in public (or to third parties), edit, translate, or reformat any portion of the Presentation are hereby or otherwise granted and shall remain expressly reserved by Doble. You acknowledge and agree that such limited license is expressly conditioned upon your acceptance of the terms herein. You further agree that, in the event of your breach, Doble will suffer irreparable damage and injury for which there is no adequate remedy at law. As such, Doble, in addition to any other rights and remedies available, shall be entitled to seek injunction by a tribunal of competent jurisdiction restricting you from committing or continuing any breach of these terms.
Instrument Transformer Basics

- Instrument transformers reproduce primary quantities
  - Minimal errors
  - Under all system conditions
- Instrument transformers are critical to accurate protection
Current Transformer (CT)

- CT primary rating depends upon current flow in ct primary
- CT secondary currents are 1 A and 5 A in North America, standard is 5 A
- CT inaccuracy is very critical
  - Increases with increased current during faults
  - Whereas, voltage magnitudes decrease during faults
Potential Transformer (PT)

- PT primary rating depends upon system voltage
- PT secondary voltages are 67 V, 100 V, 120 V, and 240 V
Current Transformer Equivalent Circuit
Burden, Impedance, Voltage, and Current

- Voltage across Burden goes up
  - If current goes up
  - If burden impedance goes up

\[ V = I \cdot Z \]

\[ Z = \frac{V}{I} \]
Excitation Impedance Affects CT Output

- Excitation impedance, $Z_e$ goes down—$V_{\text{burden}}$ goes down

$V_{\text{across Burden}}$

$Z_e \propto V$
No Saturation—CT Voltage Output Nearly Ideal

- If $Z_e$ is very large, current $I$ through $Z_e$ is negligible
- No saturation
- $V_{burden}$ goes up

![Diagram showing current through a current transformer with $Z_e$ large and $I_e = 0$.](image)
Saturation—CT Voltage Output OFF!

- If Ze is very small, current I through Ze is nearly total
- CT is saturated
- Vburden goes to zero

V across Burden
CT is saturated; Ze becomes very small
Most current flows through Ze
Relay (burden) sees negligible or
Almost zero current
CT is saturated; Ze becomes very small
Most current flows through Ze
Relay (burden) sees negligible or
Almost zero current
If you don’t have a spec sheet, do this.
Find Knee Point

- **IEC Knee Point:**
  - A 10% increase in $E_s$ results in 50% increase in $I_e$
  - Slightly greater than equivalent IEEE knee point

- **Select CT for non-fault operation below knee point**
High V at open terminal

Current through high impedance branch produces high voltage at open secondary terminal
Current Transformer Classifications

- ANSI classifies CTs for metering and protection
- Protection
  - C indicates accuracy can be calculated
  - Window, bushing and bar type have small leakage reactance, are usually type C
  - T indicates accuracy has to be tested
  - Wound type have large leakage reactance, tend to be type T
Classification Examples

- C200 CT: error of less than 10% for 200 V or less developed across CT, when 20 times nominal current flows in secondary circuit of CT
- \( V_{ct} = M \cdot I_n \cdot R_{burden} = 20 \cdot 5 \ A \cdot 2 \ \Omega = 200 \ \text{V} \)
- Sometimes number placed before ‘C,’ such as 25 or 10
- 25C200 implies an error less than 25% when less than 200 V is developed across secondary terminals
- No number before letter: C assumed at 10%
CT Saturation Causes Inaccuracy

• Factors affecting saturation
  – Iron core cross section
  – Number of secondary turns
  – Burden
  – Current Magnitude
  – DC Offset
Current Transformers: Types

- Wound
- Bar
- Bushing
- High-voltage, free-standing
CT Accuracy Calculation

- ZL, lead impedance = 0.5 Ohms
- ZB, burden = 1.3 Ohms
- Es, output voltage = \(25,000 / [(1000 / 5) \times (0.5 + 1.3)]\)
- Es = 225 V (accuracy is guaranteed to 200 V)
- Therefore, error greater than 10%
Reduce Lead Impedance—Better Performance

- ZL, lead impedance = 0.25 Ohms
- ZB, burden = 1.3 Ohms
- Es, output voltage = \( \frac{25,000}{[(1000 / 5) \cdot (0.5 + 1.3)]} \)
- Es = 194 V (accuracy is guaranteed to 200 V)
- Error less than 10%—accurate
I have an application where my fault current is 10,000A (primary)
CT is 1000/5 total burden connected is 2 ohms
Is C100 a suitable CT class to use

Nominal secondary current is 5A
Isc on secondary is 10000/CT ratio=10000/200=50

50 is how many multiples of 5A—-is is 50/5=10

10 times of 5 =50 and this times burden is 100V
C100 is fine
Optimize CT Circuit for Good Accuracy

- New generation is added
- Fault current goes to 15,000 A
- Cannot change C100 CT
- What choices do you have?
  - Make sure lead resistance ZL is small
  - Use relay with large ZB Impedance
  - Calculate inaccuracy from manufacturer’s excitation curves, and decide if acceptable
CT Not Perfectly Matched to Load

- No outage / no money: must use installed ct
- Fault current levels are independent of load
  - Can be very large compared to load
  - Selecting ratio is more difficult
- Ratio too small—load currents greater than rating
  - Thermal damage to CT or connected relays and meters
  - Avoid for sustained operation
  - Check manufacturer’s advice
- Ratio too large—small currents at full load
  - Increased ratio errors, especially for currents below 10% of load (core-excitation loss)
  - Large ratio hurts metering
  - Protection effect can sometimes be calculated
Measure Small Ground Currents w/ Donut CT

- Flux-canceling, zero-sequence, or donut CT
- No problems with phase CT differences
- Widely used at MV / LV—Not practical for HV / EHV
- Maximum opening is 8 inches
- Normally 50/5 ratio
- Detects very small fault current
Measure Ground Current w/ One CT

- Core-balance ct is very sensitive
- Size and voltage limitations
  - Restricted by cable and busbar dimensions
  - Medium voltage maximum BIL

Zero-sequence
(core-balance) ct
Shield Routing Wrong

- Normally 70% of ground-fault current flows on shield
- Current on shield cancels current in faulted phase
- Relay might not operate
Shield Routing Correct

- Run shield back through zero-sequence CT
- Cancels current through shield
- Relay operates correctly
Ct Core Reaches Saturation Flux Density

- Large current through burden produces large secondary output voltage (compliance voltage)
- DC offset (decaying exponential) in fault current
- Worse with remnant flux in core

[Graph: Large current and DC offset]
Large-Current Saturation

- Flux increases to saturation: CT output suddenly decays to near zero
- Flux drops below saturation
  - CT recovers and reproduces current again
  - Often at next zero crossing
- Flux saturation occurs on multiple successive cycles
Relays Do Not Get Enough Current to Operate

- AC saturation (large currents and high burden) truncates every half cycle
- DC saturation influences only half-cycles with polarity of offset
- Extreme AC case - a bunch of alternating spikes
Differential (87) Protection: External Fault

- External fault: $I_{op} = 0$
- Polarities are correct
- Current goes into dot, then out of dot
Differential (87) Protection: Internal Fault

- Internal fault: $I_{op} = $ Operate!
- Current goes into dot, then out of dot
Voltage Transformer: Types and Ratings

- Iron core
- Capacitance coupled CCVT for high voltage
- Primary ratings
  - Line-line (L-L)
  - Line-neutral (L-N)
- North America secondary
  - L-L rating is 120 V
  - L-N rating is \(120 \text{ V} / \sqrt{3} = 69.3 \text{ V}\)
Voltage Transformer Accuracy

- Have to be careful of total burden
  - Phase angle error—not critical for relaying (except that error should not be large)
  - Ratio error
- Internal compensation makes this 1:1 at standard burden
- Review application at other burdens
- Appropriate Ratio Correction Factor (RCF) applied
These are the nominal line-to-line and line-to-neutral voltages in a power system with ABC rotation. These phasors are the result of three potential transformers, connected one to each of three power-system phases.

This is the “common-point” view of line-to-line voltages in the power system.
Delta voltages get the name from the triangular representation of the phasors. This is a more correct way of showing the phasors, because there is no neutral point in a delta system.

It is for convenience that the middle-point convention of representing line-to-line voltages is used.
Delta voltages get the name from the triangular representation of the phasors. This is a more correct way of showing the phasors, because there is no neutral point in a delta system.

It is for convenience that the middle-point convention of representing line-to-line voltages is used.
There are two ways to obtain delta-connected voltages from a power system. One uses signals from three potential transformers (pts). Another method employs only two transformers, thus saving initial investment and installation labor.

**Sinusoidal output**

The delta connection provides a closed path the flux-caused third-harmonic current component. Thus this harmonic is removed and the flux remains sinusoidal, which results in sinusoidal output.

**Carries load if one transformer is faulty (at less power)**

For a bank of single-phase transformers connected in delta, if one of the transformers is disabled, power continues to flow. The load must be reduced to 58 percent \((1/\sqrt{3})\).

**Economical for low voltage**

In a delta connection the phase voltage is the same as the line voltage. So the windings have the same number of turns. For a delta connection, phase current is 58 percent \((1/\sqrt{3})\) of the line current. You can use less copper, making the transformer less expensive—good for low-voltage applications.

**No third-harmonic output**
Because the delta is closed, third-harmonic voltages are consumed.
This is the phasor representation of connecting to PTs in the open-delta configuration. Note the 60-degree angle between the two phasors.
This is the phasor representation of connecting to PTs in the open-delta configuration. Note the 60-degree angle between the two phasors.
Here we see the result of configuring the output of a C-B connected transformer and an A-B connected transformer. The phase relationship between the two transformer outputs is 60 degrees.
The animation on this slide shows the relay calculations for making the line-to-line and line-to-neutral voltages (and subsequent sequence voltages from these). Microprocessor-based relays (numeric or digital relays) make these calculations easily.

Use two simple rules of combining vectors. Vector addition is from head to tail. When subtracting, reverse the vector direction.

Remember, that a two-pt, open-delta configuration is blind to phase B-to-ground voltage problems.
Apply in phase (at 0° difference):

\[ P_{\text{Total}} = 3 \cdot W_{\text{single}} \phi = 3 \cdot \left[ \frac{2}{3} \cdot V_L \cdot I_L \cdot \cos \angle (30°) \right] = 2 \cdot V_L \cdot I_L \cdot \cos \angle (30°) \]  
(1)

The factor of \( \frac{2}{3} \) is from two voltage elements across 3 current elements.

Apply at 30° MTA:

\[ P_{\text{Total}} = 3 \cdot W_{\text{single}} \phi = 3 \cdot \left( \frac{\sqrt{3}}{\sqrt{3}} \cdot I_L \right) = \sqrt{3} \cdot V_L \cdot I_L \]  
(2)

Multiply the single-phase test by three to get the total power in the system, provided that the voltage and current have the MTA of 30° difference when applied to the relay.

This test is for relays like the GE GGP53C and the Basler BE1-32 ‘C’ connection.
A Scott-T transformer (also called a “Scott connection”) relates two-phase power (2-φ, 90°) to three-phase power (3-φ, 120°) with center-tapped delta transformer connections. The Scott T distributes a balanced load evenly among the phases.

Westinghouse engineer, Charles F. Scott invented the Scott three-phase transformer in the late 1890s. This was the era of the War of the Currents that pitted Thomas Edison against George Westinghouse and Nikola Tesla. Scott’s invention allowed Westinghouse to avoid paying royalties to Edison to use Edison’s expensive rotary converter. With the Scott T, you could run Nikola Tesla’s three-phase motors from two-phase generator plants.

The equations for power are the following:

\[ W_1 = V_{ab} \cdot I_a \cdot \cos(\angle V_{ab}, I_a) = V_L \cdot I_L \cdot \cos(30° + \phi) \]  
(1)

\[ W_2 = V_{cb} \cdot I_c \cdot \cos(\angle V_{cb}, I_c) = V_L \cdot I_L \cdot \cos(30° - \phi) \]  
(2)

\[ P_{Total} = W_1 + W_2 = \sqrt{3} \cdot V_L \cdot I_L \cdot \cos(\phi) \]  
(3)
At $\varphi = 0$:

\[ W_1 = V_{ab} \cdot I_a \cdot \cos(\angle V_{ab}, I_a) = V_L \cdot I_L \cdot \cos(30^\circ) \]  
(4)

\[ W_2 = V_{cb} \cdot I_c \cdot \cos(\angle V_{cb}, I_c) = V_L \cdot I_L \cdot \cos(30^\circ) \]  
(5)

\[ P_{\text{Total}} = 2 \cdot W = \sqrt{3} \cdot V_L \cdot I_L \]  
(6)
Voltage Level Determines PT Type

- Dry-type, iron core to 36 kV
- Oil-filled, iron-core PTs to 132 kV
- Above 132 kV, iron core becomes expensive
- Capacitive-coupled voltage transformer (CCVT) at higher voltages
- Accuracy of CCVT is less than iron core, but costs less
Basically it is a voltage divider

Voltage across C2 is between 5-15 kV

L plus inductance of transformer cancels capacitive reactance to avoid phase shift between primary and secondary voltage
Capacitive Voltage Transformer

- Transformer tapped at 5 kV, typical
- $L$, $C_1 + C_2$ tuned to power freq.
- Insulation cheaper than EHV iron-core transformer
- Larger capacitance is more money
  - Better transient response
  - Heavier burden
  - Broader carrier tuning
- Convenient carrier signal line-tuner coupling (LT)
CVTTransientResponse

- CVT accurate for steady-state measurement as long as \( L, C_1 + C_2 \) tuned correctly
- For transient conditions, tuned circuit generates its own transient response
  - Subsidence transient
  - Can fool relays

- Dotted curve: Fault at voltage maximum
- Solid curve: Fault at zero voltage

CVT subsidence transient
CVT Ferroresonance Risk

- Combination of iron-core inductance and capacitance
- Ferroresonance produces large, damaging, distorted voltages
- Ferroresonance suppression circuit controls problem
- CVT must have adequate burden, approaching its rating
Questions?
Local / Remote Backup
Confidentiality Notice

Doble Engineering (Doble) hereby grants the recipient (you) the right to retain this presentation and materials included within (the Presentation) for private reference. No other rights, title, or interest, including, but not limited to, the rights to copy, make use of, distribute, transmit, display or perform in public (or to third parties), edit, translate, or reformat any portion of the Presentation are hereby or otherwise granted and shall remain expressly reserved by Doble. You acknowledge and agree that such limited license is expressly conditioned upon your acceptance of the terms herein. You further agree that, in the event of your breach, Doble will suffer irreparable damage and injury for which there is no adequate remedy at law. As such, Doble, in addition to any other rights and remedies available, shall be entitled to seek injunction by a tribunal of competent jurisdiction restricting you from committing or continuing any breach of these terms.
Three Types of Backup Protection

- Remote
- Local
- Beaker Failure
Overlapping Zones of Protection

Dead-tank circuit breakers

Live-tank circuit breakers
Backup Protection has Overlapping Zones
Zones of Protection Provide Remote Backup

- Remote Backup is inherent with overlapped zones
- Tripping occurs at remote station(s)
- Remote backup when primary protection is slow
- Large part of system has to be tripped to isolate fault
- Sometimes remote backup not sensitive

CB5 opens correctly
CB3 fails to open
Remote protection at CB1 and CB6 have to open and isolate fault
Tripping is not assured under all operating conditions
  Infeed effect
  Communications failures
Remote backup is already available because of overlapping zones of protection
Substation Topology Affects Backup

- Circuit-breaker arrangement affects tripping requirements
- Less impact on system with breaker-and-a-half
EHV is 700 kV and greater

System Reliability Requires New Philosophy

- Greater emphasis on local backup and breaker failure
- Remote backup remains as a second tier
- Combination of both clears some faults
- EHV increases concern for system reliability
Local Backup Protection

- Redundant relays: primary and secondary
  - Primary and secondary relays from different manufacturers
  - Different technologies for primary and secondary relaying
- Redundant CTs
- Redundant battery supplies
- Dual circuit-breaker trip

We do not usually provide dual PTs
Secondary Relays Clear Fault

- Primary relays fail
- Secondary relays (local backup) at CB6 and CB8 operate
Circuit-Breaker Failure

- Special local backup
- Focused on particular circuit breaker
- Trips if
  - Current still there
  - Timer has elapsed
- Communications assisted
Circuit-Breaker Failure Basic Logic

Fault detectors

52 aux relay

L1
L2
L3

OR

AND

62BF

Timer

86BF
Typical BF Circuit

52 Status

Phase PIU

Ground PIU

OK

AND

Timer

BFT

AND

BF Retri

AND

BF Alarm

External EFI

Qualify Timer

Block

Local / Remote Backup ©2015 Doble Engineering Company All Rights Reserved
What Causes Circuit Breaker Failure?

- Circuit breaker fails to trip to clear a fault
  - Control wiring problem (relays are good)
  - Trip coil is defective
  - Gas pressure low
  - Operating mechanism is jammed
Typical Breaker Timing

Normal clearing time
4 cy, 66.7 ms

16.7 ma

Relay

THIP
1 cy

CD

Operate
3 cy
Questions?
Transformer Protection
Confidentiality Notice

Doble Engineering (Doble) hereby grants the recipient (you) the right to retain this presentation and materials included within (the Presentation) for private reference. No other rights, title, or interest, including, but not limited to, the rights to copy, make use of, distribute, transmit, display or perform in public (or to third parties), edit, translate, or reformat any portion of the Presentation are hereby or otherwise granted and shall remain expressly reserved by Doble. You acknowledge and agree that such limited license is expressly conditioned upon your acceptance of the terms herein. You further agree that, in the event of your breach, Doble will suffer irreparable damage and injury for which there is no adequate remedy at law. As such, Doble, in addition to any other rights and remedies available, shall be entitled to seek injunction by a tribunal of competent jurisdiction restricting you from committing or continuing any breach of these terms.
Common Transformer Failures

- Winding failure most common fault
- Bushing failure
- Load-tap changer failure
- Core-insulation breakdown
Mechanical Problems

- Bushing current-transformer failure
- Liquid leakage from poor weld
- Tank damage
- Foreign material left in tank
Unit protection is the transformer and associated bus work; perhaps a generator, too.
Transformer Inrush Current Factors

- Iron type used in transformer
- Transformer size
- Source impedance
- L/R ratio—system and transformer
- System impedance and short-circuit capacity
- Moment of energization
Challenges for Transformer Differential

- Transformer energization looks like an internal fault
- Different voltage levels
- Phase shifts from delta-wye and wye-delta connections
- Variable ratio caused by tap changer (OLTC)
- Unequal ct saturation
Magnetizing Inrush Conditions Vary

- Initial inrush
  - Largest magnetizing effect
  - When transformer is energized from de-energized state
- Recovery inrush
  - Operating transformer energizes from fault or momentary glitch
  - Remnant flux affects inrush
  - Unpredictable effects
- Sympathetic inrush
Recovery Magnetizing Inrush

- During a fault or momentary voltage dip, an inrush can occur upon return of normal voltage
- This is “recovery inrush”
- Worst case: after solid, external, three-phase fault
- Magnitude is less than initial magnetization inrush
Sympathetic Magnetizing Inrush

- Energized transformer experiences inrush when a parallel or nearby transformer is energized
- Energized transformer gets saturated by dc portion of inrush current
- Inrush contains very small harmonics
Inrush Size and Duration

- Typical exciting current is 1–2% of rated current
- Inrush between 800–3000% times rated current
- Inrush can last from 150 ms cycles to 60 s
Although usually considered a result of energizing a transformer, magnetizing inrush may also be caused by:

- Switching a transformer
- External fault
- Evolving (changing) fault
- Out-of-phase synchronization—generator comes online out of phase
How do we differentiate between
an internal short circuit and energization
Harmonics Vary with Transformer Design

- Older transformer: inrush contains 15% and more of 2\textsuperscript{nd} harmonic
- Modern transformers: as little as 7% of 2nd harmonic
- Solution: use 5\textsuperscript{th} harmonic as well as 2\textsuperscript{nd} harmonic
Differential Protection

- Restrain elements R: restrains tripping
- Operate element: trips element
External Fault

- Current flows only through restrain elements
- No trip
Internal Fault

- Current flows through Restrain and operating elements
- Trip!
Correcting Amplitude and Phase

- Amplitude correction
  - Account for different voltage levels
  - Select ct ratio and tap
- Vector correction—more complicate
DY1 and DY11 Connections

- These are two very common connections

```
[Diagram showing DY1 and DY11 connections with ABC and abc phase relationships]
```

abc lags ABC by 30° OR ABC leads abc by 30°

abc leads ABC by 30° OR ABC lags abc by 30°
Close-up on DY1

- Also YD11
Before microprocessor relays, we had to create physical delta and wye connections
Look at the A-phase negative lead. If it is connected to C-phase ‘+’ terminal, it is DAC. If the A-phase negative lead is connected to the B-phase ‘+’ terminal, then it is DAB.
Wrong Delta on CT

DAC CT: wrong  Wye / Delta DAB  Wye CT

Diagram of transformer protection systems showing the connections and currents for different configurations.
Out-of-Zone Ground Faults—Pay Special Attention!

- Avoid tripping for out-of-zone ground fault
- Zero-sequence compensation required
Old Way and New Way

- Older relays—amplitude and vector corrections using interposing cts
- Numeric relays have amplitude and vector correction
- Interposing cts are not required for modern numeric relays
- Zero-sequence trap in modern numeric relays
Errors Increase with Larger Current Multiples

- Restraint Setting: sum of mismatches / errors, plus margin
- Usually 20–40%

Diagram:
- $I_{op}$
- $87U_{pu}$
- $87R_{min-pu}$
- $87U_{Unrestricted\ Operate}$
- $87R_{Operate}$
- Restraint Slope setting
- Margin
- OLTC
- CT Error
- CT Ratio Mismatch

Legend:
- Restrained Operate
- Restrain
Dual-Slope Restraint Characteristic

- Avoid tripping on large load current

Knee point: approximately 2 pu restraint current

Slope 1 setting

Slope 2 setting

Slope 2 around twice Slope 1

I_{op}

I_{pu}

I_{restrain}
Transformer Limits

- Continuous
  - 105% of rated secondary voltage
  - Delivering rated kVA
  - Lagging power factor of 80% and greater
- No load—110% of rated secondary voltage
- Overexcitation and off-frequency operation overheat transformer
Volts-per-Hertz Protection

- Volts-per-hertz (24) limits for off-frequency operation
- E is directly proportional to frequency • flux (f • Θ)
- E / f is proportional to flux Θ
- Transformer significantly overexcited?
  - Harmonic restraint stops working
  - Harmonic magnitudes start going down
The steady-state flux $\Theta$ at the instant of energization equals the residual flux $\Theta_{\text{residual}}$, so no $I_e$ energization current flows.
The steady-state flux at energization is at the negative peak. Combined with a positive remanence $\Theta$, this condition produces the maximum transient current $I_t$. 
Sudden Open CB Causes Overexcitation

Unit-connected generator isolated from system

Transformer connected to open end of long line

Interconnected system following load shedding
Harmonics Contribute to Overexcitation

Magnetizing Current vs Total Harmonic Content

Voltage (percent of Vnom)

I_1 (% of I_m)
I_2 (% of I_m)
I_3 (% of I_m)
I_4 (% of I_m)
I_5 (% of I_m)

Transforming Protection
© 2015 Doble Engineering Company. All Rights Reserved.
NEC and Transformers

- Transformers built to withstand overload
- National Electric Code (Section 450-3): guideline for setting overcurrent pickup
- Guidelines provide maximum allowable settings for time-overcurrent devices
- Primary objective of NEC: fire prevention
Need to consider both Thermal and Mechanical Stress under through fault condition

Time overcurrent and instantaneous settings must ensure that transformer will not be damaged

ANSI Standard C57109 has established very specific guidelines for through-fault protection
Each of these categories have a withstand curve that must coordinate with protection
### Through-Fault Withstand Curves

**Diagram:**
- Time axis.
- Current axis labeled as 'Tm' and 'Im1' and 'Im2' and 'It' with corresponding values.
- Two curves indicated: Thermal limitation and Mechanical limitation.

<table>
<thead>
<tr>
<th>Category</th>
<th>Three Phase kVA</th>
<th>It</th>
<th>Im1</th>
<th>Im2</th>
<th>Tm</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>15-500</td>
<td>25X</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>II</td>
<td>501-5000</td>
<td>25X</td>
<td>1/Zt</td>
<td>70%</td>
<td>4 sec</td>
</tr>
<tr>
<td>III</td>
<td>5001-30,000</td>
<td>25X</td>
<td>1/(Zt+Zs)</td>
<td>50%</td>
<td>8 sec</td>
</tr>
<tr>
<td>IV</td>
<td>&gt;30,000</td>
<td>25X</td>
<td>1/(Zt+Zs)</td>
<td>50%</td>
<td>8 sec</td>
</tr>
</tbody>
</table>

*Transformer Protection ©2015 Doble Engineering Company All Rights Reserved 40*
Factors Affect Transformer Through-Fault Level

- Source impedance
- Transformer impedance
- Neutral grounding method

Time

Transformer Damage Curve

A

I

Transformer Protection ©2016 Doble Engineering Company All Rights Reserved 41
Sudden-Pressure Relays

- Sudden pressure relays operate on gas rate of rise
- Sealed-tank design
- Differential relay still required for faults
  - Bushings
  - Areas outside tank
Sudden Pressure—Trip, or Alarm Only?

- Much more sensitive than differential relays
- Sometimes insecure misoperations
- Some utilities now use it for alarm only
- Some use it for trip, but supervise it with overcurrent relay
Bucholz Relays

- Pressure relays
- Gas-actuated relay
- Used on transformers with conservator
- Much less prone to misoperations
- Detects low-level and severe faults
Questions?
R-X Diagrams
Confidentiality Notice

Doble Engineering (Doble) hereby grants the recipient (you) the right to retain this presentation and materials included within (the Presentation) for private reference. No other rights, title, or interest, including, but not limited to, the rights to copy, make use of, distribute, transmit, display or perform in public (or to third parties), edit, translate, or reformat any portion of the Presentation are hereby or otherwise granted and shall remain expressly reserved by Doble. You acknowledge and agree that such limited license is expressly conditioned upon your acceptance of the terms herein. You further agree that, in the event of your breach, Doble will suffer irreparable damage and injury for which there is no adequate remedy at law. As such, Doble, in addition to any other rights and remedies available, shall be entitled to seek injunction by a tribunal of competent jurisdiction restricting you from committing or continuing any breach of these terms.
Why Do We Need RX Diagrams?

- R-X diagrams are an extremely helpful tool for analyzing operation of relays that operate on impedance
- Without a knowledge of this diagram, it is difficult to analyze and visualize relay performance
Loads and Angles in Four Quadrants

(Power into bus) (Power into line) Nominal line angle

(Load with lagging pf) Lagging load of 30°

(Load with leading pf)

Bus

Line
Effect of Totally Inductive Line

Nominal line angle

(Load with lagging pf)

(Load with leading pf)

Lagging load of 30°

Line charging with remote circuit breaker open

Bus

Line
Adding Impedance Vectors

Zr = 1∠85°
ZL1 = 3∠70°
ZL2 = 6∠70°

Relay Location
Bus 1 voltage is 132 kV: 132 ∠ 0°

Current flowing away from Bus 1 is 1200 A at -37°:
1200 ∠ -37°
Bus 1 voltage is 132 kV: 132°/0°

Current flowing away from Bus 1 is 1200 A at -37°

1200 A = 274 MVA (approx.)

\[ Z_{load} = kV \cdot kV / MVA = 63.59°/37° \]
Lagging, Leading, Into, Out of

- Leading Load into Bus
- Lagging Load into Bus
- Lagging Load out of Bus
- Leading Load out of Bus

Zs
ZL1
ZL2
1200°-37°
Relay

R

R-K Diagrams ©2015 Doble Engineering Company. All Rights Reserved
Load Positions

R-K Diagrams ©2015 Doble Engineering Company. All Rights Reserved
Fault Action on R-X Diagram

Faults on transmission line

Impedance seen by relay is OX

As fault location moves along line, point X moves along as well

Normal Load
Example 1/6

- Rated load of transmission line AB is 8 MVA at 0.8 pf
- Voltage is 20 kV
- This corresponds to load current of 400 A
Example 2/6

- 8 MVA at 20 kV is
  \[ \frac{20 \text{ kV}}{400} = 50 \, \Omega, \text{ primary} \]
- Or, kV \cdot kV / MVA
  \[ = 20 \cdot 20 / 8 = 50 \, \Omega, \text{ primary} \]
Or, $kV \cdot kV / \text{MVA} = 20 \cdot 20 / 8 = 50$, primary
Or, \( \text{kV} \cdot \text{kV} / \text{MVA} = 20 \cdot 20 / 8 = 50 \), primary
Or, kV • kV / MVA = 20 • 20 / 8 = 50, primary
Or, $kV \cdot kV / MVA = 20 \cdot 20 / 8 = 50$, primary
Questions?
High-Speed Protection
Confidentiality Notice

• Doble Engineering (Doble) hereby grants the recipient (you) the right to retain this presentation and materials included within (the Presentation) for private reference. No other rights, title, or interest, including, but not limited to, the rights to copy, make use of, distribute, transmit, display or perform in public (or to third parties), edit, translate, or reformat any portion of the Presentation are hereby or otherwise granted and shall remain expressly reserved by Doble. You acknowledge and agree that such limited license is expressly conditioned upon your acceptance of the terms herein. You further agree that, in the event of your breach, Doble will suffer irreparable damage and injury for which there is no adequate remedy at law. As such, Doble, in addition to any other rights and remedies available, shall be entitled to seek injunction by a tribunal of competent jurisdiction restricting you from committing or continuing any breach of these terms.
Pilot Protection Scheme

- What is pilot protection scheme?
- Types of pilot schemes
- Principles of operation
- Compare different schemes
End-Zone Faults

- Zone 1 setting at A and B = 80% of line length
- Fault at F1—fault sensed in Zone 1 at A and B: cleared instantaneously
- Fault at F2 cleared instantaneously at station B but cleared with Zone-2 delay from Station A
  - Fault remains on line for Zone-2 time
  - End-zone fault is not cleared instantaneously
Goals for High-Speed Protection

- Support continuity of supply
- Clear fault on protected line instantaneously
- Limit damage and shock to electrical system
- Keep system stable
- Minimize revenue loss
- Clear end-zone faults correctly (pilot scheme)
Ideal Solution—Differential Between Bus A and Bus B

- Three-phase line requires six pilot conductors
  - One for each phase, one for neutral
  - Two for (dc) tripping
- Costs too much for distances beyond 16 km (10 miles)
Adapt Differential for Distances

- Solution is high-speed pilot protection—also called “teleprotection”
- Adaptation of differential protection that avoids control cables between stations
What is Pilot Protection?

- "Pilot" refers to communications channel
  - Between two or more terminals
  - Provides instantaneous tripping for both ends of terminals
Communications Channels

- Power-line Carrier
- Microwave
- Fiber optic
- Leased lines
Power-Line Carrier

- Operate in ON/OFF mode
- Transmit radio frequency signals (10–490 kHz) over transmission lines
- Common form of channel in US—being challenged by newer technologies
Microwave

- Operate between 150 MHz and 20 GHz
- Large bandwidth
- Unaffected by problems on transmission lines
- Subject to atmospheric attenuation and distortion
- Transmission limited to line-of-sight path between stations
- Repeaters increase length of lines covered
- Use of repeaters increases cost and reduces reliability
- Is not cost effective, unless used by several lines
Fiber-Optic Cables

• Becoming extremely popular
• Unlimited channel capacity
• Immune to electric noise and magnetic fields
• Excellent transmission quality
• Is costly
Leased Lines

- Telephone cables insulated to 15 kV
- Shielded against power-line interference
- #19 AWG wires in twisted pair design to avoid cross talk
- Good for 10–15 miles of transmission lines
- Protect short lines
- By leasing, utilities do not have complete control
- Soon, no longer supplied
High-Speed Protection Schemes

• Directional-Comparison Blocking—DCB
• Direct Under-reaching Transfer Trip—DUTT
• Permissive Under-reaching Transfer—Trip PUTT
• Permissive Over-reaching Transfer Trip—POTT
Two Types of Schemes

- Blocking
- Tripping
Blocking Schemes

- When a signal is received from a remote terminal, tripping is NOT permitted (blocked) at local terminal
- Very dependable
- Not very secure
- Power-line carrier ideal for blocking scheme
Tripping Schemes

- When a signal is received from a remote terminal, tripping occurs at local terminal
- Very secure
Blocking Scheme—All Quiet

[Diagram of a blocking scheme with various components and labels such as Z3A, Z2A, Z3B, and Pilot Channel.]

High-Speed Protection ©2015 Doble Engineering Company. All Rights Reserved
POTT Tripping Scheme—All Quiet

A Z2A

1

2 B

Z2 B

TA

AND A

RA

Pilot Channel

Trip Signal To Breaker 1

Trip Signal To Breaker 2

RB

AND B

TB

Pilot Channel

Timer

Timer

Z2 A

©2015 Doble Engineering Company. All Rights Reserved
POTT Tripping Scheme—In-Zone Fault

TRIP both terminals
POTT Transfer Trip Operation -1

- Relay C senses Zone-2 fault, Relay B senses Zone-1 fault
- Fault current flows C-D-B
- D gets permission to trip from C, but D senses reverse fault
- CB B opens because Relay B senses fault in Zone 1
- Now, fault current reverses and flows through D-C-A
C senses Zone 2 fault, B senses zone 1 fault
Fault current flows C-D-B
D receives permission to trip from C but D senses reverse fault
Breaker B opens as it senses fault in Zone 1
Now fault current reverses and flows through D-C-A
D senses Zone 2 fault, C does not sense fault and zone 2 resets and stop sending permissive signal to D
If D Zone 2 picks up before Zone 2 at C resets, D can trip
If C Zone 2 is slow to reset it can trip for a fault on parallel line
• Reset blocking element at D must be delayed to ensure that Circuit Breaker D does not trip for fault on parallel line
POTT Scheme—Remote Circuit Breaker Open

- A senses Zone-2 fault, B does not sense fault (it is open)
- A cannot trip instantaneously—it does not receive permissive signal from B
- If local circuit breaker is open and receives permissive signal from remote end, permissive signal can be “echoed” back to remote relay
- Now, circuit breaker A can trip to clear fault on line
POTT Scheme with Weak Infeed

- Local terminal sensed fault near remote terminal as Zone 2
- Needs permissive trip signal from remote end to clear fault
- Remote end has a weak source contributing to fault
- Zone 2 at remote end does not pick up and no permissive signal is sent to local end
- Fault on line is not cleared instantaneously
PUTT Scheme—Remote Breaker-Open Logic

- Zone-end fault with remote breaker open not cleared instantaneously
- Use 52b contact to send continuous permissive signal to remote end for open breaker
Compare Blocking and Tripping Schemes

**Blocking**
- Signal Receive: blocks local instantaneous Z2 tripping
- Signaling channel normally OFF—only ON when Z3 picks up
- When Z2 picks up, it waits for a delayed time before issuing trip
- Ensures remote terminal has time to send block signal

**POTT Tripping**
- Signal Receive: trips Z2 instantaneously
- Signaling channel "ON;" always sending "Guard" frequency
- Changes to trip frequency if Z2 picks up
- No intentional delay for tripping if permissive signal is received
Chose Best for Your Application

Blocking

• Intentional delay added to avoid over tripping
• Failure of communications channel results in over tripping for an external fault
• Blocking scheme is more dependable
• Single on/off signaling channel, operating at single frequency in both directions

POTT Tripping

• No intentional delay on trip for fault on line
• Failure of communications channel results in a failure to trip for fault on line
• POTT scheme is more secure
• Separate signaling channel for each direction of signaling
Questions?