Protection Review

- Fault types
- Electrical equipment damage
- Time versus current plot
- Protection requirements
- Protection system elements
Power System Faults

• Short circuits

• Contacts with ground
  ♦ Isolated neutral systems
  ♦ High-impedance grounded systems

• Open phases
Typical Short-Circuit-Type Distribution

- Single-phase-to-ground: 70 – 80%
- Phase-to-phase-to-ground: 10 – 17%
- Phase-to-phase: 8 – 10%
- Three-phase: 2 – 3%
Faults in Electrical Systems Produce Current Increments

Distribution Substation

Wire
Temperature Rise From Current

\[ T(t) = (T_i - T_e) e^{-\frac{t}{\tau}} + T_e \]
Factors Influence Wire Heating

Current Magnitude

Wire Material Properties

Wire Size

Ambient Temperature and Other Environmental Factors
Insulated Conductor (Cable) Thermal Damage

- Insulation Damage
- Thermal Damage
- $T_e$
- $T_d$
- $T_i$
- $t_d$
- Graph showing temperature $T$ vs. time $t$
Insulated Conductor Thermal Damage

I = I_{md}
I = I_1
I = I_2 > I_1
I = I_3 > I_2

T_d
T_i

Damage Curve

I = I_1
I = I_2 > I_1
I = I_3 > I_2

T

t

I

I_{md}
I_1
I_2
I_3
Electrical Equipment Component
Thermal Damage Curve

Damage Curve

$\text{Rating}$

$I_n$, $I_{md}$
Mechanical forces \((f_1 \text{ and } f_2)\) produced by short-circuit currents cause instantaneous damage to busbars, insulators, supports, transformers, and machines.

\[ f_1(t) = k \cdot i_1(t) \cdot i_2(t) \]
Real-World Mechanical Damage
Power System Protection Requirements

• Reliability
  ♦ Dependability
  ♦ Security
• Selectivity
Power System Protection Requirements

- **Speed**
  - System stability
  - Equipment damage
  - Power quality

- **Sensitivity**
  - High-impedance faults
  - Dispersed generation
Protection Functions

- Fault detection
- Faulted element disconnection
- Fault indication
Protective Devices

- Fuses
- Automatic reclosers
- Sectionalizers
- Circuit breakers
- Protective relays
Relay Classification

- Protective
- Regulating
- Reclosing and synchronism check
- Monitoring
- Auxiliary
IEEE C37.2 Device Numbers

51  Time-overcurrent relay
50  Instantaneous-overcurrent relay
67  Directional-overcurrent relay
21  Distance relay
87  Differential relay
52  Circuit breaker
Protection System Elements

- Protective relays
- Circuit breakers
- CTs and VTs (instrument transformers)
- Communications channels
- DC supply system
- Control cables
Protection System Elements

- Protective relays
  - Monitor
  - Detect
  - Report
  - Trigger
- Circuit breakers
  - Interrupt
  - Isolate from abnormal condition
Instrument Transformers

- CTs
  - Current scaling
  - Isolation

- VTs
  - Voltage scaling
  - Isolation
Overcurrent Relay Connections

Diagram showing connections and currents:
- \( I_a \)
- \( I_b \)
- \( I_c \)
- 3\( I_0 \)

Components labeled:
- 50, 51
- 50N, 51N
- Residual Current
DC Tripping Circuit

(+)

DC Station Battery

SI

Relay Contact

52a

52 TC

Circuit Breaker

(−)
Overcurrent Relay Setting

- 51 elements
  - Pickup setting
  - Time-dial setting

- 50 elements
  - Pickup setting
  - Time delay
Review

• What is the function of power system protection?
• Name two protective devices
• For what purpose is IEEE device 52 is used?
• Why are seal-in and 52a contacts used in the dc control scheme?
• In a typical feeder OC protection scheme, what does the residual relay measure?
Questions?
Digital Relay Basics

SEL-751A Feeder Protection Relay
Simple Protective Relay

Auxiliary input (ac or dc)

Input

Current, voltage (I and V), or other quantities

Settings

Set relay thresholds and operation time

Output (dry contact)

Contact used to energize circuit breaker trip coil
Electromechanical Instantaneous Overcurrent Elements
Magnetic Attraction Unit
Instantaneous Element

Force of contact: $F = k \cdot I^2$
Pickup Current Setting

- Tap in relay current coil
- Adjust air gap
- Adjust spring
Electromechanical Inverse-Time Overcurrent Elements
Anatomy of Induction Disc Overcurrent Relays

- Time Dial
- Spring
- Disc
- Main Core
- Moving Contact
- Main Coil, $N_T$ Turns
- Permanent Magnet
- Main Core

---

-5 -6 -7 -8 -9 -10
Electromagnetic Induction Principle

Torque
Summary of Induction
51 Element Setting

• Pickup current setting – taps in relay current coil

• Time-current curve setting – controls initial disc position (time dial setting)
Microprocessor-Based Protection
Digital Relay I/O Scheme

Computer-based relay (digital)

- Analog inputs
- Discrete inputs
- Auxiliary inputs (ac or dc)
- Dry contact outputs (trip and alarm)
- "Live" outputs

Computer communications
Digital Relay Architecture

- Analog input subsystem
- Discrete input subsystem
- Analog-to-digital (A/D) conversion
- Microprocessor
- Discrete output subsystem
- Operation signalling
- Communications ports

- RAM
- ROM / PROM
- EEPROM

Tripping Outputs

...
Digital Relay Algorithm

- Read present sample k
- Digital filtering
- Phasor calculation
- Protection methods
- Relay logic
- Modify if required
- No trip
- Trip order
Relay Operation
Analog Inputs
Signal Path for Microprocessor-Based Relays

- Current transformer (CT)
- Potential transformer (PT)
- Analog low-pass filter
- A/D conversion
- Digital cosine filter and phasor
- Magnitude and impedance
A/D Conversion

Input | A/D | Output

Analog signal | Digital signal

00000001
00000101
00001001
00100100
10010000

...
Digital Filtering

Nonfiltered signal (samples)

Digital filtering

Filtered signal (samples)
Phasor Calculation

Filtered signal (samples) → Phasor calculation → Phasor samples: magnitude and angle versus reference.
Sinusoid-to-Phasor Conversion

\[ v(t) = A \sin(\omega t + \theta) \]

\[ \frac{A}{\sqrt{2}} \]

\[ \theta \]
Sinusoid to Phasors
Current Channels Are Sampled

\[ \frac{1}{8} \text{ cycles} \]

<table>
<thead>
<tr>
<th>IA</th>
<th>1559</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-69</td>
</tr>
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<td></td>
<td>-1656</td>
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<tr>
<td></td>
<td>-2274</td>
</tr>
<tr>
<td></td>
<td>-1558</td>
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<tr>
<td></td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>1656</td>
</tr>
<tr>
<td></td>
<td>2273</td>
</tr>
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</table>
Sinusoid to Phasors

- Pick quadrature samples (1/4 cycle apart)
- Pick current sample (x sample)
- Pick previous sample 1/4-cycle old (y sample)

<table>
<thead>
<tr>
<th>IA</th>
<th>1559</th>
<th>-69</th>
<th>-1656</th>
<th>-2274</th>
<th>y sample (1/4-cycle old)</th>
</tr>
</thead>
<tbody>
<tr>
<td>x sample (present)</td>
<td>70</td>
<td>1656</td>
<td>2273</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Sinusoid to Phasors

Magnitude = $\sqrt{x^2 + y^2}$

Magnitude = $\sqrt{70^2 + (-2274)^2}$

Angle = $\arctan\left(\frac{y}{x}\right)$

Angle = $\arctan\left(\frac{-2274}{70}\right)$

$IA = 2275 \angle -88.2^\circ$
Relay Operation
Relay Word Bits and Logic
Relay Word Bits

- Instantaneous overcurrent
- Time overcurrent
- Voltage elements
- Inputs
- Internal relay logic: SELOGIC® variable (SV) and latches
- Outputs

Assert to logical 1 when conditions are true, deassert to logical 0 when conditions are false
Instantaneous-Overcurrent Element

- $50P1P = \text{instantaneous phase-overcurrent setting}$
- $I_p = \text{measured current of maximum phase}$
- $50P1P = 1$ if $I_p > 50P1P$; $50P1P = 0$ if $I_p < 50P1P$

When $b$ (+) terminal is greater than $a$ (–) terminal, $c$ is logical 1
SEL-751A Protection System

Phase Time-Overcurrent Element

Settings

- 51P1P: Pickup
- 51P1C: Pickup Type
- 51P1TD: Time Dial
- 51P1RS: Electromechanical Reset? (Y/N)
- 51P1CT: Constant Time Adder
- 51P1MR: Minimum Response

Controls the Torque Control Switch

<table>
<thead>
<tr>
<th>Setting 51P1RS=</th>
<th>Reset Timing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
<td>Electromechanical 1 Cycle</td>
</tr>
<tr>
<td>N</td>
<td>1 Cycle</td>
</tr>
</tbody>
</table>

Torque Control Switch

- Setting 51P1R: Reset
- Setting 51P1T: Curve Timeout
- Setting 51P1P: Pickup

SELogic Setting

- 51P1TC: Torque Control

(From Figure 4.1)
SEL-751A Protection System
ORED – Overcurrent Elements

• Relay Word bit ORED50T is asserted if 50PnT, 50NnT, 50GnT, or 50QnT Relay Word bits are asserted

• Relay Word bit ORED51T is asserted if 51AT, 51BT, 51CT, 51P1T, 51P2T, 51N1T, 51N2T, 51G1T, 51G2T, or 51QT Relay Word bits are asserted
# Standard Time-Current Characteristics

**IEEE C37.112-1996**

<table>
<thead>
<tr>
<th>Curve Type</th>
<th>Operating Time</th>
<th>Reset Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>U1 (Moderately Inverse)</td>
<td>$t_p = TD \cdot \left( 0.0226 + \frac{0.0104}{M^{0.02}} \right)$</td>
<td>$t_r = TD \cdot \left( \frac{1.08}{1 - M^2} \right)$</td>
</tr>
<tr>
<td>U2 (Inverse)</td>
<td>$t_p = TD \cdot \left( 0.180 + \frac{5.95}{M^2 - 1} \right)$</td>
<td>$t_r = TD \cdot \left( \frac{5.95}{1 - M^2} \right)$</td>
</tr>
<tr>
<td>U3 (Very Inverse)</td>
<td>$t_p = TD \cdot \left( 0.0963 + \frac{3.88}{M^2 - 1} \right)$</td>
<td>$t_r = TD \cdot \left( \frac{3.88}{1 - M^2} \right)$</td>
</tr>
<tr>
<td>U4 (Extremely Inverse)</td>
<td>$t_p = TD \cdot \left( 0.0352 + \frac{5.67}{M^2 - 1} \right)$</td>
<td>$t_r = TD \cdot \left( \frac{5.67}{1 - M^2} \right)$</td>
</tr>
<tr>
<td>U5 (Short-Time Inverse)</td>
<td>$t_p = TD \cdot \left( 0.00262 + \frac{0.00342}{M^{0.02}} \right)$</td>
<td>$t_r = TD \cdot \left( \frac{0.323}{1 - M^2} \right)$</td>
</tr>
</tbody>
</table>
SEL-751A Voltage Calculation

Voltage Magnitude Calculation

- (Minimum Phase Voltage Magnitude) \( |VP|_{\text{min}} \)
- (Minimum Phase-to-Phase Voltage Magnitude) \( |VPP|_{\text{min}} \)
- (Maximum Phase Voltage Magnitude) \( |VP|_{\text{max}} \)
- (Maximum Phase-to-Phase Voltage Magnitude) \( |VPP|_{\text{max}} \)
- \( |VS| \)
SEL-751A Single- and Three-Phase Voltage Elements

When DELTA_Y := WYE

- |VPP| max
- 27P1P • Vnm
- |VP| min
- 27P2P • Vnm

Relay Word Bits

<table>
<thead>
<tr>
<th>Relay Word Bits</th>
</tr>
</thead>
<tbody>
<tr>
<td>3P27</td>
</tr>
<tr>
<td>27P1</td>
</tr>
<tr>
<td>27P1T</td>
</tr>
<tr>
<td>27P2</td>
</tr>
<tr>
<td>27P2T</td>
</tr>
<tr>
<td>Row</td>
</tr>
<tr>
<td>-----</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
</tbody>
</table>
Logic
Boolean Logic

- Mathematics of logical variables (Relay Word bits)
- Operators: AND, OR, NOT, rising and falling edge, parentheses
- SELogic control equations Boolean operators
  - Defined symbols
  - Application rules
<table>
<thead>
<tr>
<th>Operator</th>
<th>Symbol</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parentheses</td>
<td>( )</td>
<td>Group terms</td>
</tr>
<tr>
<td>Negation</td>
<td>-</td>
<td>Changes sign of numerical value</td>
</tr>
<tr>
<td>NOT</td>
<td>NOT</td>
<td>Invert the logic</td>
</tr>
<tr>
<td>Rising edge</td>
<td>R_TRIG</td>
<td>Output asserts for one processing interval on inputs rising-edge transition</td>
</tr>
<tr>
<td>Falling edge</td>
<td>F_TRIG</td>
<td>Output asserts for one processing interval on inputs falling-edge transition</td>
</tr>
<tr>
<td>Multiply</td>
<td>*</td>
<td>Multiply numerical values</td>
</tr>
</tbody>
</table>
# SELogic Control Equations Operators

<table>
<thead>
<tr>
<th>Operator</th>
<th>Symbol</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Divide</td>
<td>/</td>
<td>Divide numerical values</td>
</tr>
<tr>
<td>Add</td>
<td>+</td>
<td>Add numerical values</td>
</tr>
<tr>
<td>Subtract</td>
<td>–</td>
<td>Subtract numerical values</td>
</tr>
<tr>
<td>Comparison</td>
<td>&lt;, &gt;, &lt;=, &gt;=, =, &lt;&gt;</td>
<td>Compare numerical values</td>
</tr>
<tr>
<td>AND</td>
<td>AND</td>
<td>Multiply Boolean values</td>
</tr>
<tr>
<td>OR</td>
<td>OR</td>
<td>Add Boolean values</td>
</tr>
</tbody>
</table>
SELogic Control Equation Examples

C = A OR B

C = A AND B

C = A AND NOT B
Programmable Logic

Equation implemented

E = A \text{ AND } B \text{ OR } C \text{ OR } \neg D

Diagram:

- A
- B
- C
- D
- E

(+)

(−)

Logic block icon:

- A
- B
- C
- D

Output:

E

Equation implemented

E = A \text{ AND } B \text{ OR } C \text{ OR } \neg D
SELogic Control Equation Examples

TR = 50P1P AND 50G1

Out101 = TRIP

50P1P

50G1P

TR

TRIP

Out101

Normally open; closes when Out101 asserts

When the TR equation asserts, the TRIP Relay Word bit asserts
Typical Logic Settings for Trip

TR  Trip (SELogic)
ORED50T OR ORED51T OR 81D1T OR 81D2T OR 81D3T OR 81D4T OR 59P1T OR 59P

REMTRIP  Remote Trip (SELogic)
0

OUT103FS  OUT103 Fail-Safe
N  Select: Y, N

OUT103  (SELogic)
TRIP
CL = CC AND 3P59 AND 27S1

When CL equation asserts, CLOSE Relay Word bit asserts

OUT102 = CLOSE

Normally open; closes when OUT102 asserts
SELogic Example

OUT101 = (51P1T OR OUT101) AND NOT TRGTR
Optoisolated Inputs

- Relay Word bits IN101 and IN102 monitor physical state inputs
- Debounce timer is built in and settable

IN101 → de-energized → IN101 → logical 0

IN102 → energized → IN102 → logical 1
Latching Control Logic

SELogic Latch Equation

SET<sub>n</sub>  \rightarrow \text{OR} \rightarrow \text{AND} \rightarrow \text{NOT} \rightarrow \text{LT}<sub>n</sub>

RST<sub>n</sub>  \rightarrow \text{AND} \rightarrow \text{OR} \rightarrow \text{NOT} \rightarrow \text{LT}<sub>n</sub>

n = 1 – 32

SET01 = CLOSE RST01 = TRIP 52A = LT01
SV Timer

- Set as logic placeholder and timer
- Example settings
  - SV05 = 50P1P
  - SV05PU = 0.17 seconds
- Operation
  - SV05 asserts when 50P1P asserts
  - SV05T asserts 0.17 seconds after 50P1P asserts
• When OUT101 equation is true (logical 1), OUT101 closes
• Example setting: OUT301 = SV05T
• Operation: OUT301 closes after 50P1P has been asserted for 0.17 seconds
Track Relay Word Bit State Change With Sequential Events Report (SER)

Example: 50P1 = 4 A; CTR = 120; Primary PU = 480 A

<table>
<thead>
<tr>
<th>#</th>
<th>DATE</th>
<th>TIME</th>
<th>ELEMENT</th>
<th>STATE</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>05/31/2011</td>
<td>20:09:47.808</td>
<td>50P1P</td>
<td>Asserted</td>
</tr>
<tr>
<td>9</td>
<td>05/31/2011</td>
<td>20:09:47.808</td>
<td>TRIP</td>
<td>Asserted</td>
</tr>
<tr>
<td>8</td>
<td>05/31/2011</td>
<td>20:09:47.808</td>
<td>SV05</td>
<td>Asserted</td>
</tr>
<tr>
<td>7</td>
<td>05/31/2011</td>
<td>20:09:47.979</td>
<td>OUT301</td>
<td>Asserted</td>
</tr>
<tr>
<td>6</td>
<td>05/31/2011</td>
<td>20:09:47.979</td>
<td>SV05T</td>
<td>Asserted</td>
</tr>
<tr>
<td>5</td>
<td>05/31/2011</td>
<td>20:09:48.287</td>
<td>50P1P</td>
<td>Deasserted</td>
</tr>
<tr>
<td>4</td>
<td>05/31/2011</td>
<td>20:09:48.287</td>
<td>SV05</td>
<td>Deasserted</td>
</tr>
<tr>
<td>3</td>
<td>05/31/2011</td>
<td>20:09:48.316</td>
<td>TRIP</td>
<td>Deasserted</td>
</tr>
<tr>
<td>2</td>
<td>05/31/2011</td>
<td>20:09:48.458</td>
<td>OUT301</td>
<td>Deasserted</td>
</tr>
<tr>
<td>1</td>
<td>05/31/2011</td>
<td>20:09:48.458</td>
<td>SV05T</td>
<td>Deasserted</td>
</tr>
</tbody>
</table>
Event Reporting

- Helpful in fault analysis
- Relay collects 15-cycle event report when ER = R_TRIG 50P1P
- HIS command text

<table>
<thead>
<tr>
<th>#</th>
<th>DATE</th>
<th>TIME</th>
<th>EVENT</th>
<th>CURRENT</th>
<th>FREQ</th>
<th>TARGETS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>05/31/2011</td>
<td>20:09:47.808</td>
<td>Phase A1 50 Trip</td>
<td>501.5</td>
<td>60.0</td>
<td>11100000</td>
</tr>
<tr>
<td>2</td>
<td>05/31/2011</td>
<td>20:09:21.153</td>
<td>Trigger</td>
<td>6.1</td>
<td>60.0</td>
<td>10000000</td>
</tr>
<tr>
<td>3</td>
<td>05/31/2011</td>
<td>20:08:24.056</td>
<td>Phase A1 50 Trip</td>
<td>500.2</td>
<td>60.0</td>
<td>11100000</td>
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<tr>
<td>4</td>
<td>05/31/2011</td>
<td>20:05:45.806</td>
<td>Phase A1 50 Trip</td>
<td>501.2</td>
<td>60.4</td>
<td>11100000</td>
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<tr>
<td>5</td>
<td>05/31/2011</td>
<td>20:04:48.178</td>
<td>Phase A1 50 Trip</td>
<td>502.2</td>
<td>59.8</td>
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<tr>
<td>6</td>
<td>05/31/2011</td>
<td>20:04:15.681</td>
<td>Phase A1 50 Trip</td>
<td>503.3</td>
<td>60.4</td>
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<tr>
<td>7</td>
<td>05/31/2011</td>
<td>19:56:03.175</td>
<td>Phase A1 50 Trip</td>
<td>500.4</td>
<td>60.0</td>
<td>11100000</td>
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</tbody>
</table>

=>|
# FEEDER RELAY

Serial Number=2007254448  
FID=SEL-751A-R301-V0-Z005003-D20090504  
CID=3148

<table>
<thead>
<tr>
<th>Currents (A Pri)</th>
<th>Voltages (V Pri)</th>
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<tbody>
<tr>
<td>IA</td>
<td>IB</td>
</tr>
<tr>
<td>-49.8</td>
<td>68.4</td>
</tr>
<tr>
<td>-56.4</td>
<td>-17.4</td>
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<tr>
<td>48.0</td>
<td>-71.4</td>
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<tr>
<td>54.6</td>
<td>18.0</td>
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<td>-49.8</td>
<td>69.6</td>
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<td>-56.4</td>
<td>-20.4</td>
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<tr>
<td>48.0</td>
<td>-71.4</td>
</tr>
<tr>
<td>54.6</td>
<td>18.6</td>
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<tr>
<td>-51.0</td>
<td>67.2</td>
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<tr>
<td>-55.2</td>
<td>-19.2</td>
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<td>81.6</td>
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<td>167</td>
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<td>-232</td>
<td>69.6</td>
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<td>-321</td>
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<td>347</td>
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<td>-352</td>
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<td>-----</td>
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<tr>
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<td></td>
<td>347</td>
</tr>
</tbody>
</table>
Summary

- Microprocessor-based relays create phasors from sinusoid (waveform) input
- Relay Word bits control relay I/O
- Microprocessor-based relays offer many troubleshooting and fault analysis tools
- SELOGIC control equations provide programming flexibility to create virtual control circuits
Questions?
Protection Basics: Overcurrent Protection
Fast Protection Minimizes

• Temperature rise
• Mechanical damage from magnetic forces
• Voltage sag
• Transient stability issues
• Shock and arc-flash hazards
Understand Basic Protection Principles

- Overcurrent (50, 51, 50N, 51N)
- Directional overcurrent (67, 67N)
- Distance (21, 21N)
- Differential (87)
Overcurrent Relays Protect Radial Lines

\[ I_{LOAD} = \frac{E}{Z_{Source} + Z_{Line} + Z_{LOAD}} \]

\[ I_{FAULT} = \frac{E}{Z_{Source} + m \cdot Z_{Line}} \]

\[ I_{FAULT} >> I_{LOAD} \]
Relay Operates When Current Magnitude Rises Above Threshold

Overcurrent Relay

Circuit Breaker Trip Coil and Auxiliary Contact

125 Vdc

52a

TC
Evolving Protective Relay Designs

• Electromechanical relays

• Electronic analog relays – solid state (transistors, integrated circuits)

• Microprocessor-based relays – digital or numeric
How Do Instantaneous Relays Work?

- **Coil**
- **Contacts**
- **Armature**
- **Hinge**
- **Coil 1**
- **Magnetic Core**
- **Coil 2**
- **Electromagnet**
- **Contacts**
- **Iron Core**
- **Adjustable Stop**
- **Moving Cup or Cylinder**
Plotting Electromechanical 50 Elements

Time vs. Current Curve

$\text{Operate} < 1.5 \text{ Cycles}$
Digital Overcurrent Relay Block Diagram

- Analog Input Subsystem
- Discrete Input Subsystem
- Microprocessor
- A / D
- Discrete Output Subsystem
- Operation Signaling
- Communications Ports
- Tripping Outputs
- RAM
- ROM / PROM
- EEPROM
Digital Relays Use Sampled Signals

\[ \Delta t = \text{Sample Interval} \]
Advantages of Digital 50 Elements

• No contact chatter with alternating currents
• Not affected by dc offset
• Reset-to-pickup ratio close to one
• Resistant to misoperation due to mechanical shock
Anatomy of Induction Disc Overcurrent Relays

- Time Dial
- Spring
- Disc
- Main Core
- Permanent Magnet
- Main Coil, $N_T$ Turns
- Moving Contact
Induction Disc Operation Condition

Operating torque > spring torque

\[ K_e I^2 \geq T_s \]

Pickup condition

\[ K_e I_{pu}^2 \geq T_s \]

Pickup set by changing number of turns (TAP)

\[ I_{pu} = \sqrt{\frac{T_s}{K_e}} = \sqrt{\frac{T_s}{K'}} / N_T \]
Acceleration Torque

\[ T_a = T_{op} - T_{pm} - T_s - T_f \]
High Current Can Damage Equipment

Thermal Damage Curve

Time vs. Current Plot

Damage Curve

$t$

$I_{Rated}$ $I_{damage}$ $I$
Changing Induction Disc Operation

Time

Adjustment of Time Curve

- Displacement of moving contact is adjustable
- Time dial sets total movement required to close contact
Select Overcurrent Relay Curve

Curve shape not adjustable for induction disc relays
Time-Current Characteristics Become Standard

- IEEE C37.112-1996
  \[ t = TD \cdot \left( \frac{A}{M^P - 1} + B \right) \]

- IEC 225-4
  \[ t = TD \cdot \frac{A}{M^P - 1} \]
Family of IEEE Inverse Characteristics

U.S. inverse curve

\[ A = 5.95, \quad P = 2, \quad B = 0.18 \]

\[
t_{OP} = TD \cdot \left[ \frac{5.95}{M^2 - 1} + 0.18 \right]
\]
Increase Flexibility With Digital 51 Relays

Settings

- Pickup current (or tap)
- Time-dial setting (TD)
- Curve shape – inverse, very inverse, etc.
Connecting Electromechanical Overcurrent Relays

\[ \bar{I}_a, \bar{I}_b, \bar{I}_c \]

Residual Current

\[ 3\bar{I}_0 \]
Digital Relays Calculate Residual Current

Residual current for balanced load or three-phase faults:

\[ I_A + I_B + I_C = 3I_0 = I_G = 0 \]

Residual current for ground fault:

\[ I_A + I_B + I_C = 3I_0 = I_G \]
Using Zero-Sequence CT for Ground Fault Protection

Zero-sequence or core-balance CT

Photo courtesy of NEI Electric Power Engineering
High Residual Current Due to CT Saturation

- Residual settings must be higher than elements operating from zero-sequence CTs
- Residual elements may not be appropriate for motors
- Zero-sequence CTs not subject to this problem
15,000 HP Motor Trips on Start

Numerical Relay

50G 49

50N

800/5

50/5

IG

IN

IG

IN

Cycles
What Are Negative-Sequence Quantities?

- Unbalanced load
- Rolled phases
- Open phases
- Unbalanced faults

\[ 3I_2 = I_A + a^2 I_B + aI_C \]

where \( a = 1\angle120^\circ \)
Negative-Sequence Element Response

Three-Phase Faults

\[ I_A = 1\angle0^\circ \quad I_B = 1\angle-120^\circ \quad I_C = 1\angle120^\circ \]

\[ 3I_2 = I_A + a^2I_B + aI_C \]

\[ = 1\angle0^\circ + 1\angle240^\circ \cdot 1\angle-120^\circ + 1\angle120^\circ \cdot 1\angle120^\circ \]

\[ = 0 \]
Negative-Sequence Element Response
Phase-to-Phase Faults

\[ I_A = 0 \]
\[ I_B = 1 \angle 0^\circ \]
\[ I_C = 1 \angle 180^\circ \]

\[ 3I_2 = I_A + a^2 I_B + a I_C \]

\[ = 0 + 1 \angle 240^\circ \cdot 1 \angle 0^\circ + 1 \angle 120^\circ \cdot 1 \angle 180^\circ \]

\[ = 1.73 \angle -90^\circ \]
Maximum Load vs. Minimum Short Circuit

3-Phase Fault Current
Phase-to-Phase Fault Current
Phase Relay Maximum Reach

I
I_{PU}
I_{LOAD}
d

Relay
Sensitive Protection With Negative-Sequence Elements

Reach of Conventional Phase Relays
Reach of Negative-Sequence Element

b-c fault, 3I₂
b-c fault, phase current

I

ILOAD

3I₂ PU

R

Relay
Coordinating Negative-Sequence Elements

Bus

Feeder Relay
51F, 51QF

Feeder

Line Recloser
51R
Phase 51, no 51Q
Traditional Phase Coordination
Plus Negative Sequence

51EP

Equivalent Phase Element With Low Pickup

51R
51F

CURRENT (A)

I_R I_{PU-E} I_F
Set Negative-Sequence Element Pickup

$$51Q \text{ pickup} = \sqrt{3} \cdot (51EP \text{ pickup})$$

Negative-sequence element is faster and more sensitive than phase overcurrent element for phase-to-phase faults
Protection Plus …
Questions?
Transformer Protection Basics
Differential Protection Is Easy in Theory

Kirchhoff’s Current Law (KCL): \( \sum_{k=1}^{n} I_k = 0 \)
Current In = Current Out

Balanced CT Ratio

Protected Equipment

CT CT CT

External Fault

50

I_{OP} = 0

No Relay Operation if CTs Are Considered Ideal
Operate Current Flows

Protected Equipment

CT

Internal Fault

I_{OP} > I_{SETTING}

CT

Relay Operates
Differential Scheme Objective

• Provide security during through faults
• Operate fast for internal faults
What Makes Differential Protection Challenging?
Examine CT Saturation Challenges
Unequal CT Performance Problems

Protected Equipment

External Fault

\[ I_{OP} \neq 0 \]
Unequal CT Saturation

Differential Current

Current at Left
Current at Right

Secondary Amperes

Cycles

0 1 2 3 4 5 6
Possible Scheme – Percentage Differential Protection Principle

Compares:

\[
\begin{align*}
I_{OP} &= |I_S + I_R| \\
K \cdot I_{RT} &= K \cdot \frac{|I_S + I_R|}{2}
\end{align*}
\]
Differential Element
Differential Characteristic Basics

Relay Operates When:

\[ |I_{OP}| \geq k \cdot I_{RT} + I_{PU} \]

For External Fault With Saturated CT
Percentage Differential Relays

$I_{OP}$ Versus $I_{RT}$

CT$_1$ W1 W2 CT$_2$

W1 W2

Power Transformer

Differential Relay

I$_{W1}$ I$_{W2}$
Dual-Slope Characteristic

Unrestrained Pickup

Minimum Pickup

Slope 1–2 Transition

Operate Region

Slope 1

Slope 2

Restraint Region

(Multiples of Tap)

$I_{OP}$

$I_{RT}$
How to Set Slope Characteristic Settings

- Load tap changer (10%)
- No-load tap changer (5%)
- Measuring relay error (< 5%)
- CT errors (1 to 10%)
- Transformer excitation (3 to 4%)
SEL-387 / SEL-787 Logic

2nd and 4th
HR / HB

SEL-387 / SEL-787

O87P
DIFF
SEL-387 / SEL-787 Slope

\( I_{OP} (I_{RT}) \)

\( I_{RT} \)
Examine Transformer Compensation Challenges
### Transformer Connection Compensation

<table>
<thead>
<tr>
<th>Phase Shift (Degrees)</th>
<th>Connections</th>
</tr>
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<tbody>
<tr>
<td>0</td>
<td>Yy0</td>
</tr>
<tr>
<td>30 lag</td>
<td>Yd1</td>
</tr>
<tr>
<td>60 lag</td>
<td>Dd2</td>
</tr>
<tr>
<td>120 lag</td>
<td>Dd4</td>
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<tr>
<td>150 lag</td>
<td>Yd5</td>
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<tr>
<td>180 lag</td>
<td>Yy6</td>
</tr>
<tr>
<td>150 lead</td>
<td>Yd7</td>
</tr>
<tr>
<td>120 lead</td>
<td>Dd8</td>
</tr>
<tr>
<td>60 lead</td>
<td>Dd10</td>
</tr>
<tr>
<td>30 lead</td>
<td>Yd11</td>
</tr>
</tbody>
</table>
Traditional Compensation Method

CTR₁

\[(I_a - I_b) \frac{N_2}{N_1}\]

CTR₂

\[(I_c - I_a) \frac{N_2}{N_1}\]

CTR₁

\[(I_b - I_c) \frac{N_2}{N_1}\]

CTR₂

\[(I_b - I_c) \frac{N_2}{N_1}\]

CTR₁

\[(I_a - I_b) \frac{N_2}{N_1}\]

CTR₂

\[(I_a - I_b) \frac{N_2}{N_1}\]
Compensation With Digital Relays

• Current magnitude and phase shift compensation
• Set relay according to transformer characteristics
• Consider all possible connections
Tap Compensation

\[
TAP = \frac{MVA \cdot 1000 \cdot C}{\sqrt{3} \cdot KV_{LL} \cdot CTR}
\]

where:

\[C = 1\] for wye-connected CTs

\[C = \sqrt{3}\] for delta-connected CTs
DABY Transformer and CT Connection Compensation

DABY ≡ Dy1

$\frac{1}{\text{Tap1}}$

$\frac{1}{\text{Tap2}}$

Y

DAB

87
Wye Connection Compensation

\[
\begin{align*}
I_{1W1C} &= \frac{I_{AW1}}{\text{Tap1}} \\
I_{2W1C} &= \frac{I_{BW1}}{\text{Tap1}} \\
I_{3W1C} &= \frac{I_{CW1}}{\text{Tap1}}
\end{align*}
\]
DAB Connection Compensation

\[ I_{1W2C} = \frac{1}{\text{Tap}2} \left( \frac{I_{AW2} - I_{BW2}}{\sqrt{3}} \right) \]

\[ I_{2W2C} = \frac{1}{\text{Tap}2} \left( \frac{I_{BW2} - I_{CW2}}{\sqrt{3}} \right) \]

\[ I_{3W2C} = \frac{1}{\text{Tap}2} \left( \frac{I_{CW2} - I_{AW2}}{\sqrt{3}} \right) \]
Compensation Matrices

IAWnC

M1

M2

M3

M4

M5

M6

M7

M8

M9

M10

M11

M12
SEL-387 Compensation Method

- \([\text{IAWnC}] = [\text{CTC(m)}] \cdot [\text{IAWn}]\)
- \([\text{IBWnC}] = [\text{CTC(m)}] \cdot [\text{IBWn}]\)
- \([\text{ICWnC}] = [\text{CTC(m)}] \cdot [\text{ICWn}]\)

- \([\text{CTC(m)}]: 3 \times 3 \text{ matrix}\)
- \(m = 0, 1, \ldots, 12\)
  - \(m = 0: \text{identity matrix (no changes)}\)
  - \(m \neq 0: \text{remove I0; compensate angles}\)
  - \(m = 12: \text{remove I0; no angle compensation}\)
Differential Element Operate and Restraint Quantities

\[ \frac{1}{\text{Tap1}} \quad \text{IW1} \quad \text{IW1}' \]

Transformer / CT Connection Compensation

\[ \frac{1}{\text{Tap2}} \quad \text{IW2} \quad \text{IW2}' \]

Transformer / CT Connection Compensation

\[ \bar{I}_1 \]

\[ \bar{I}_2 \]

\[ \bar{I}_1 + \bar{I}_2 \]

\[ \frac{|\bar{I}_1 + \bar{I}_2|}{2} \]

\[ I_{OP} \]

(Multiples of Tap)

\[ I_{RT} \]

(Multiples of Tap)
Examine Transformer Inrush Challenges
Phase C Inrush Current Obtained From Transformer Testing
Inrush Current Has High Second Harmonic

![Graph showing inrush current with high second harmonic](image_url)

- **Fundamental Frequency Magnitude**
- **2nd Harmonic Magnitude**
- **Primary Current (A)**
- **Cycles**
- **Percentage of Fundamental**
- **2nd Harmonic Percentage**
- **2nd Harmonic Block Threshold**

The graph illustrates the high second harmonic content in inrush current over time.
Internal Faults Versus Inrush
Harmonic-Based Methods

- Harmonic blocking
- Harmonic restraint
Conclusions

- Apply differential element Slope 2 to compensate for CT saturation
- Set current compensation for phase and magnitude differences across transformers
- Use harmonic blocking and restraint to prevent differential element assertion during inrush
Questions?
Induction and Synchronous Motor Protection Recommendations
Induction Motor Protection

- Phase overcurrent (50 / 51)
- Ground overcurrent (50G / 50N / 51G / 51N)
- Voltage (27 / 59)
- Current unbalance (46)
- Differential (87)
Induction Motor Protection

- Phase sequence (47)
- Resistance temperature device (RTD) thermal (49R)
- Thermal overload (49)
- Load-loss / load-jam (37)
- Starts per hour, time between starts (66)
- Antibackspin
Synchronous Motor Protection

- Induction motor protection elements
- Loss-of-excitation (40)
- Loss-of-synchronism (78)
- Field ground fault (64F)
Phase Overcurrent Protection (50 / 51)

Ground Overcurrent Protection
(50G / 50N / 51G / 51N)
Phase Overcurrent Protection

• Phase overcurrent devices detect phase-to-phase and three-phase faults within motor windings and on feeder cables

• Failure to clear fault quickly causes
  ♦ Increased motor conductor or feeder cable damage
  ♦ Stator iron damage
  ♦ Prolonged system voltage dips
Settings Considerations

• Do not use relay phase fault protection with fused motor contactors

• Avoid tripping on motor inrush
  ♦ Symmetrical locked rotor current
  ♦ Subtransient component
  ♦ Asymmetrical (dc offset) component effectively removed from element by microprocessor-based relay

• Coordinate with upstream protection
Optimum Two-Level Phase Overcurrent Protection

• Level 1 settings
  ♦ Phase overcurrent pickup at 1.2 to 1.5 • LRA
  ♦ Overcurrent delay at 6 to 10 cycles to ride through subtransient inrush

• Level 2 settings
  ♦ Phase overcurrent pickup at 1.65 to 2.0 • LRA
  ♦ Phase overcurrent delay at 0
Ground Overcurrent Protection

- Ground overcurrent devices detect faults involving ground within motor windings and on feeder cables
- Failure to clear these faults quickly causes:
  - Increased motor conductor or feeder cable damage
  - Stator iron damage
  - Prolonged system voltage dips
Ground Fault Protection Depends on System Grounding Design

- Solidly grounded systems have high phase-to-ground fault currents
- Resistance-grounded systems limit phase-to-ground fault current
- Limiting current limits damage due to ground faults but requires increased relay sensitivity
CT Connections

(a) Solidly / Low-Resistance Grounded Source

(b) Solidly / Low-Resistance Grounded Source

(c) Low- / High-Resistance Grounded Source

MPR = motor protection relay
Solidly Grounded Systems

- Ground fault currents in solidly grounded systems can approach phase fault levels.
- Ground fault protection for these systems is usually provided by residual protection, either calculated by relay or by external CT residual connection to IN input.
Settings Considerations

• Residual protection set to coordinate with upstream devices
• False residual current can occur because of CT saturation
• Level 1 residual overcurrent pickup set at 0.4 to 0.6 • FLA
• Level 1 residual overcurrent delay set at 0.2 s to ride through false residuals
Low-Resistance Grounded Systems

• Ground fault currents limited to 100 to 1000 A
• Ground faults cleared in < 10 s
  ♦ Minimize fault arc damage
  ♦ Protect grounding resistors from thermal damage
• Ground fault protection for motors is usually instantaneous or definite-time
Settings Considerations

• Residual elements
  ♦ Set Level 1 residual overcurrent pickup at 0.4 to 0.6 • FLA
  ♦ Set Level 1 residual overcurrent delay at 0.2 s to ride through false residuals upon starting

• Ground elements with core-balance CT
  ♦ Set Level 1 neutral overcurrent pickup at 5 to 20 A primary current
  ♦ Set Level 1 neutral overcurrent delay at 0.1 s
High-Resistance Grounded Systems

- Typically found on low-voltage systems but sometimes used on medium-voltage systems
- Limit phase-to-ground fault currents to < 10 A
High-Resistance Grounded Systems

• Single-phase-to-ground fault produces an alarm only – ground can then be located and cleared in controlled manner

• This system requires core-balance CT for sensitivity
Settings Considerations

- Set Level 1 neutral overcurrent pickup at 25 to 50% of available ground fault current
- Set Level 1 neutral overcurrent delay at 2 to 5 s
- Program neutral overcurrent for alarm only
## Ground Overcurrent Settings Considerations

<table>
<thead>
<tr>
<th>Source Grounding</th>
<th>Available Ground Fault Current</th>
<th>CT Connections</th>
<th>Relay Function</th>
<th>Setting Considerations</th>
<th>Delay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solidly grounded</td>
<td>Can approach phase fault levels</td>
<td>a</td>
<td>50G</td>
<td>40 to 60% • FLA</td>
<td>0.2 s</td>
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<tr>
<td></td>
<td></td>
<td>b</td>
<td>50N</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low-resistance grounded</td>
<td>100 to 1000 A</td>
<td>a</td>
<td>50G</td>
<td>40 to 60% • FLA</td>
<td>0.2 s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b</td>
<td>50N</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>c</td>
<td>50N</td>
<td>5 to 20 A (primary)</td>
<td>0.1 s</td>
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<tr>
<td>High-resistance grounded</td>
<td>&lt; 10 A</td>
<td>c</td>
<td>50N</td>
<td>25 to 50% of available ground fault current</td>
<td>2 to 5 s</td>
</tr>
</tbody>
</table>
Undervoltage Protection (27)

Overvoltage Protection (59)
Undervoltage

- Running motors for prolonged periods at less than rated voltage can cause overheating.
- Undervoltage tripping can clear a bus after complete loss of voltage – prevents simultaneous restart of connected motors when voltage returns.
Settings Considerations

• Motor standards require motors capable of continuous operation at 90% of motor-rated voltage per motor specification

• Undervoltage protection should not trip motors because of voltage dips caused by faults or motor starts

• Undervoltage protection is not usually set to trip motors during fast bus transfers
Settings Considerations – Trip

- Set undervoltage trip pickup slightly under minimum rated operating voltage
- Set undervoltage trip delay longer than
  - Maximum time required for fast bus transfers
  - Maximum fault-clearing time for faults that would cause voltage to drop below pickup
  - Starting time for any motor on bus if motor starts will cause bus voltage to drop below undervoltage trip pickup
Settings Considerations – Alarm

• Set undervoltage alarm level at or slightly above motor minimum rated operating voltage

• Set undervoltage alarm delay longer than
  ♦ Maximum time required for normal bus transfers
  ♦ Maximum fault-clearing time for faults that would cause voltage to drop below pickup
Overvoltage

Running motors for prolonged periods at greater than rated voltage can cause loss of insulation life or insulation failure.
Settings Considerations

- Motor standards require that motors be capable of continuous operation at 110% of rated voltage.
- Overvoltage alarming is generally used in favor of overvoltage tripping.
- If overvoltage tripping is applied, consider using a time delay.
Current Unbalance Protection (46)
Current Unbalance

- Caused by
  - Unbalanced voltages
  - Single phasing

- Creates negative-sequence current flow in rotor
  - Heating effect at full load is same as locked rotor condition
  - Rotor overheats
Negative-Sequence Heating

- Negative-sequence current causes double-frequency flux in rotor
- Rotor current occupies one-sixth of cross-section area of bars, causing overheating at periphery
Current Unbalance

- Biases thermal overload element
- Is detected by
  - Thermal model under moderate conditions
  - Current unbalance elements under severe conditions
Settings Considerations

• Trip
  ♦ Set current unbalance trip pickup to 15%
  ♦ Set current unbalance trip delay to 5 s

• Alarm
  ♦ Set current unbalance alarm pickup to 10%
  ♦ Set current unbalance alarm delay to 10 s
Differential Protection (87)
Differential Protection

- Phase differential (large machines)
- Self-balancing (87M) differential (machines rated 1000 hp and up)
- Detection of phase faults and possibly phase-to-ground faults depending on system grounding
Phase Percentage Differential (87R)

O = operating coil
R = restraining coil
Percentage Restraint (87)
Differential Characteristic

I_{OP}

Unrestrained Pickup

(Multiples of TAP)

Minimum Pickup

Slope 1 25%

Slope 1 to 2 Transition

Slope 2 60%

Operate

Restrain

(Multiples of TAP)

I_{RT}
Self-Balancing (87M) Differential Protection

Core-balance CT

Neutral-side CT with IA, IB, and IC connected

Neutral-side CT with IA, IB, and IC not connected
Phase Sequence Protection (47)
Phase Sequence

- Also referred to as phase reversal
- Operates on voltage or current
- Checks that phase rotation signals applied to relay match phase rotation setting
RTD Thermal Protection (49R)
RTD Thermal Element Detects Loss-of-Cooling Efficiency

- Cooling pump failure
- Inlet air reduction
- Detection using direct temperature measurement (RTDs)
Thermal Overload Protection (49)
Thermal Protection

• Running overload
• Starting / stalling
• Running unbalance
Running Protection

- Load greater than service factor causes excessive $I^2R$ heating in stator windings
- Unbalance current causes excessive heating in rotor
Thermal Model Protection

- Electromechanical relays using bimetal and solder-pot elements do not match motor time constants.
- Microprocessor-based relays can match thermal properties identified by motor data and can monitor RTDs embedded in stator winding.
Integrated Motor Thermal Protection

- Provides locked rotor, overload, and unbalance protection
- Defines operating characteristics by motor characteristics
Bimetallic Overload Element

- $I^2R$ heating opens contacts to trip motor
- Reset characteristic not related to motor
- This element has
  - Uncertain response to unbalance
  - Sensitivity to cabinet ambient temperature
Motor First Order Thermal Model

\[ f(I_1, I_2) \]

\[ C_{th} = \text{equivalent thermal capacity} \]
\[ R_{th} = \text{equivalent thermal resistance} \]
\[ \theta = \text{temperature rise with respect to ambient} \]
Motor Thermal Image or Thermal Model Relays

- Use single-state model
- Use double-state model
  - Starting
  - Running
Single-State Thermal Model

Relay Principle

\[ \theta = a \cdot I^2 \]

\[ \theta_{\text{trip}} \]

Heating  \quad \text{Cooling}
For $I_1 > I_{LIM}$

Start / Stall State

$3 \cdot (I_1^2 + I_2^2)$

For $I_1 < I_{LIM}$

Running State

$(I_1^2 + 5 \cdot I_2^2)$
Thermal Model Relay
Starting State

- If $C_{th}$ is fixed, determine only one setting, $\theta_{trip}$
- Use locked rotor safe stall times
Thermal Model Relay
Running State

- Determine settings: $C_{th}$, $R_{th}$, $\theta_{trip}$
- Use motor damage curves to fit model
High-Inertia Starting

- High-inertia loads, such as induced draft fans, require long acceleration times.
- Starting time may exceed locked rotor limit.
Traditional Solution: Speed Switch
Proximity Probe and Rotating Disk

- Proximity probe is magnetic
- Rotating disc uses laser
- Safe stall time setting is increased to accommodate acceleration – supervised by detection of shaft rotation (25 to 35% of speed) within set time limit
Rotor Resistance Variation

Rotor Bar Cross Section

Skin effect

Deep bar effect

Starting slip = 1
Line frequency = 60 Hz

Operating slip = 0.03
Slip frequency = 1.8 Hz
Linear Approximation of Slip-Dependent Rotor Resistance and Reactance
Steinmetz Electrical Model

\[ V \rightarrow jX_s R_s I_s \]
\[ jX_r(S) R_r(S) I_r \]
\[ V \rightarrow jX_m \]
\[ \frac{1-S}{S} R_r(S) \]
Slip-Dependent Rotor Resistance

- Motor heating is caused by watt loss in rotor and stator resistance
- Rotor resistance decreases from high locked rotor value to low value at rated speed (shown in Steinmetz model)
Positive- and Negative-Sequence Rotor Resistances Are Linear Functions of Slip

\[
R_1 = \left[ (R_M - R_N) S \right] + R_N \\
R_2 = \left[ (R_M - R_N)(2 - S) \right] + R_N
\]

Where:

\[ R_M = \text{resistance at locked rotor} \]
\[ R_N = \text{rotor resistance at rated speed} \]
\[ S = \text{slip} \]
RM and RN Defined

• $R_M$ and $R_N$ are defined by
  ♦ Locked rotor current $I_L$
  ♦ Locked rotor torque LRQ
  ♦ Synchronous speed $\omega_{\text{syn}}$
  ♦ Rated speed $\omega_{\text{rated}}$

• In Steinmetz model, mechanical power $P_M$ is
  $$P_M = \frac{1 - S}{S} \cdot I^2 R_r$$
Solving for Rotor Resistance

Torque is power divided by speed

\[ Q_M = \frac{P_M}{\omega} = \frac{P_M}{1 - S} = I^2 \left( \frac{1 - S}{S} \right) R_r \left( \frac{1}{1 - S} \right) = \frac{I^2 R_r}{S} \]

Solving for rotor resistance \( R_r \)

\[ R_r = \frac{Q_M}{I^2} S \]
Substitute Known Values

At locked rotor, \( S = 1 \) and \( Q_M = LRQ \)

\[
R_r = R_M = \frac{LRQ}{I_L^2}
\]

S at rated speed is \( S_N \), \( I = 1 \) and \( Q_M = 1 \)

\[
R_N = S_N
\]

\[
R_N = \frac{\omega_{syn} - \omega_{rated}}{\omega_{syn}}
\]
Locked Rotor Case

I^2t Rotor Temperature

Motor Current

Temperature (U/UL), Rotor (R \cdot 0.01)

Motor Torque

Current (pu)

Time (s)

R_M = R_N
When $V_1$ and $I_1$ are monitored, apparent positive-sequence impedance looking into the motor is

$$Z = R + jX = \frac{V_1}{I_1}$$
Motor Impedance

From the Steinmetz model

\[ Z = R_S + jX_S + \left( \frac{R_r}{S} + jX_r \right) \cdot jX_m \]
Motor Impedance

Expanding the equation

\[ Z = R_S + jX_S + \frac{R_r}{S} X_m^2 + j \left[ X_m \left( \frac{R_r}{S} \right)^2 + X_r X_m (X_r + X_m) \right] \]

\[ \left( \frac{R_r}{S} \right)^2 + (X_r + X_m)^2 \]
Motor Impedance

The real part of $Z$ is

$$R = R_S + \frac{R_r}{S} X_m^2 \left( \frac{R_r}{S} \right)^2 + \left( X_r + X_m \right)^2$$
Motor Impedance

Divide numerator and denominator by \((X_m)^2\)

\[
R = R_S + \frac{R_r}{S} \left( \frac{R_r}{S} \right)^2 \frac{1}{X_m^2} + \frac{(X_r + X_m)^2}{X_m^2}
\]

But \(\left( \frac{R_r}{S} \right)^2 \frac{1}{X_m^2}\) is negligible
Motor Impedance

Let

\[ A = \left( \frac{X_r + X_m}{X_m} \right)^2 \]

Then

\[ R = R_s + \frac{R_r}{A \cdot S} \]
Derive Slip

Consider only the real part of motor impedance

\[ R = R_s + \frac{R_r}{A \cdot S} \]

Next, substitute the linear equation for \( R_{r+} \) in terms of slip, and solve for slip

\[ S = \frac{R_N}{A (R - R_s) - (R_M - R_N)} \]
Slip-Dependent Rotor Resistance

Positive-sequence rotor resistance

\[ R_1(s) = [(R_M - R_N)S] + R_N \]

Negative-sequence rotor resistance

\[ R_2(s) = [(R_M - R_N)(2 - S)] + R_N \]
Motor Current and Rotor Temperature

\[ R_r = (R_M - R_N)S + R_N \]
Constant Resistance Model Accuracy

- Motor Current
- Rotor Temperature
- \( I^2t \) Relay

![Graph showing Motor Current, Rotor Temperature, and \( I^2t \) Relay over time.]

*Time (s)*
Load-Loss / Load-Jam Protection

- Detects load loss on undercurrent or low power
- Trips for safety if load decouples
- Detects load jam using definite-time overcurrent (armed only when motor is running)
Frequent Starts

• Repetitive intermittent operation can cause mechanical stressing of stator or rotor end windings

• Microprocessor-based relays provide for fixed time intervals between starts or limit the number of starts per hour
Frequent Starts or Intermittent Operation

- Starts-per-hour protection limits the number of motor starts in any 60-minute period
- Minimum time between starts prevents immediate restart
- Settings developed using motor data sheet
Frequent Starts or Intermittent Operation

- Induction motors, initially at ambient, usually allow two successive starts – coasting to reset between starts
- One start occurs with motor initially at operating temperature
Antibackspin Protection

- Pump motors can spin backward for a short time after motor shutdown.
- Restart during backspin period is dangerous (prevent high torque with premature starts).
- Simple lockout delay follows trip.
Synchronous Motor Protection
Loss of Excitation

• Causes
  - Operator error
  - Excitation system failure
  - Flashover across slip rings
  - Incorrect tripping of rotor field breaker

• Consequences
  - Motor operates as induction motor
  - Motor draws reactive power from system
Loss-of-Excitation Detection

Elements detect excessive VAR flow into the motor

- Impedance
- Power factor
- VAR
Synchronous Motor Protection
Loss of Synchronism

• Causes
  ♦ Excessive load
  ♦ Reduced supply voltage
  ♦ Low motor excitation

• Consequences
  ♦ High current pulses may exceed three-phase faults at motor terminals
  ♦ Motor operates at different speed
  ♦ Watts flow out and VAR flows into motor
Loss-of-Synchronism Detection

- Element usually responds to variation on motor power factor angle or reactive power.
- Impedance relays available for loss-of-excitation detection may also detect loss of synchronism.
Importance of Field Ground Detection

- Single point-to-ground fault in field winding circuit does not affect motor operation
- Second point-to-ground fault can cause severe damage to machine
  - Excessive vibration
  - Rotor steel and/or copper melting
Rotor Ground Detection Methods

- Voltage divider
- DC injection
- AC injection
- Switched dc injection
Switched DC Injection Method

- Exciter
- Field Breaker
- Rotor and Field Winding
- Brushes
- Grounding Brush
- Measured Voltage
- Rs
- R1
- R2
Questions?