Transformer Protection: M-3311A
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Drew Welton is the Vice President of Sales & Creative Technical Solutions for Beckwith Electric and provides strategic leadership to the sales management team as well as creative technical solutions to our customers. Mr. Welton joined Beckwith Electric in 2016 as Director of Sales to provide strategic sales leadership and to further develop and execute sales channels.

- North American Regional Manager for OMICRON starting in 1997.
- Regional Sales Manager with Beckwith Electric. He also served as National Sales Director for Substation Automation with AREVA T&D.
- Written numerous articles on substation maintenance testing, and has conducted numerous training sessions for substation technicians and engineers at utilities and universities across North America.
- 20 year Senior Member of IEEE-PES, has been a contributor on a number of PSRC working groups, and presented at a number of industry conferences specific to power system protection and control.
- Graduate of Fort Lewis College, Durango, CO, with a Bachelor’s degree in Business Administration.
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Wayne is the top strategist for delivering innovative technology messages to the Electric Power Industry through technical forums and industry standard development.

- Before joining Beckwith Electric, performed in Application, Sales and Marketing Management capacities at PowerSecure, General Electric, Siemens Power T&D and Alstom T&D.
- Provides training and mentoring to Beckwith Electric personnel in Sales, Marketing, Creative Technical Solutions and Engineering.
- Key contributor to product ideation and holds a leadership role in the development of course structure and presentation materials for annual and regional Protection & Control Seminars.
- Senior Member of IEEE, serving as a Main Committee Member of the Power System Relaying and Control Committee for over 25 years.
  - Chair Emeritus of the IEEE PSRCC Rotating Machinery Subcommittee (‘07-‘10).
  - Contributed to numerous IEEE Standards, Guides, Reports, Tutorials and Transactions, delivered Tutorials IEEE Conferences, and authored and presented numerous technical papers at key industry conferences.
This function is available as a standard protective function.

This function is available in the Optional Voltage Protection Package.

M-3311A Typical Connection Diagram

Two Winding Model

Winding 1 (W1)

Winding 2 (W2)

M-3311A Targets (Optional)
Integral HMI (Optional)
Metering
Sequence Of Events
Waveform Capture
IRIG-B
Front RS232 Communication
Rear RS-232/485 Communication
Multiple Setting Groups
Programmable I/O
Programmable Logic
Self Diagnostics
Dual Power Supply (Optional)

2 Winding
Standard

Expanded
Normal Operation - No Targets

- Power supply fail contact = energized
  - Note: On relays with 2 power supplies installed, both must be powered up to energize this contact.

- Diagnostic Contact = coils energized, “OK” state

Display dark if there are no active targets
Tripped

• One or more “OUTPUT” LEDs illuminated
Trip Cleared and Target Present

• All “OUTPUT” LEDs Extinguished
• If the “Relay OK LED” is extinguished, the relay is not in service.
  • Contact the factory if a “System Halt” message is displayed or the “Relay OK” LED is extinguished.

• Resetting the relay may temporarily remove the error but may result in a false trip or no trip operation.

• Do not press any HMI buttons while the relay is in diagnostic mode.
Other front panel indicators

- **Breaker Closed:** Normally “ON” when Input 1 is Open
- **PS 1 and PS2:** “ON” when the associated power supply is on
- **Time Sync:** “ON” when IRIG-B signal is applied. No setting required.
- **Target:** “ON” when most recent event is not reset
Front panel controls

Target Reset Button:

- **Button Released:** Target module and HMI display the most recent event information.

- **Button Pressed and Released:** LED test then targets are reset *IF ALL TRIPPED FUNCTIONS ARE RESET.*

- **Button Pressed and Held:** Target module displays functions that are currently picked up.

*Note: Output LED’s always display real time status of output contacts.*
Front Panel Controls:  
HMI Operation

- Access by pressing any button after the Power On Self Test terminates.
- The selected menu item appears in capital letters.
- Press the **RIGHT** and **LEFT** arrows to move between menu items.
- Press **ENTER** to move into a submenu or item.
- Press **EXIT** move out of a submenu.
- The **UP** and **DOWN** arrows are used to change values.
PC Software
See Annex for Detailed Views
For a new Setting file:
  • Select File\New
  • Set Unit type, frequency, CT secondary rating
• For and Existing File:
  • Select File\Open
  • Pick the file to be opened
• To Save, use the Save or Save As commands

Working Offline
• Used to create, view, or modify relay setting files
Working Online

- Used to communicate directly with a relay via 232, 485, modem, or TCP/IP

- **PC Port - Serial port on the PC**

- The following must be set to match the relay settings:
  - Baud Rate: 9600 standard
  - Access Code: Defaults disabled
  - Address: 232/485 network address

- For Modem or TCP/IP communications, press the appropriate buttons and set the parameters
Periodic Maintenance: General

All our relays incorporate self diagnostic hardware and continuously run a number of self diagnostic routines.

We highly recommend the relay self test contact as well as the power supply fail contact be connected as your application dictates.

Our minimum recommended periodic maintenance focuses on those components that cannot be checked by the internal diagnostic routines:
Periodic Maintenance: Critical Checks

Each Maintenance Outage:
1) **Relay Trip Test**: Use the diagnostic feature to force a trip. Verify the breaker opens.

2) **Relay Diagnostics**: Perform relay diagnostic checks which check the operation of the status inputs and outputs.

3) **Breaker Position Sensing**: Verify the breaker's position contact is working correctly.
Digital Relay Self-Diagnostics

What it covers:

• Microprocessor hand-shaking
• ADC
• Power supply
• Communication failures
• Watchdogs
• Firmware flash failures

What it does not cover:

• Relay contacts
• Internal CT PT circuits
• Improper wiring
• Misapplied logic
• Incorrect settings

➢ In all cases, relay failures covered by self-diagnostics can alert operators through an alarm contact.
➢ The relay can then take itself out of service to avoid misoperations.

⇒ W
Transformer Phase Differential
87T, 87HS
Differential Protection

Advantages

- Provides high speed detection of faults that can reduce damage due to the flow of fault currents
- Offers high speed isolation of the faulted transformer, preserving stability and decreasing momentary sag duration
- No need to coordinate with other protections
- The location of the fault is determined more precisely
  - Within the zone of differential protection as demarked by CT location
Differential Protection

- What goes into a “unit” comes out of a “unit”

- Kirchoff’s Law: The sum of the currents entering and leaving a junction is zero

- Straight forward concept, but not that simple in practice with transformers

- A host of issues challenges security and reliability of transformer differential protection
Differential Relay Principle

![Differential Relay Diagram]

- Transformer
- Relay
- Restraint W-1
- Restraint W-2
- TAP W-1
- TAP W-2

Operate
Differential Relay Principle: External Fault
Differential Relay Principle:
External Fault
Transformer Phase Differential

- Applied with variable percentage slopes to accommodate CT saturation and CT ratio errors

- Applied with inrush and overexcitation restraints

- Pickup/slope setting should consider: magnetizing current, turns ratio errors due to fixed taps and +/-10% variation due to LTC

- May not be sensitive enough for all faults (low level, ground faults near neutral)
Typical Phase Differential Characteristic

\[ I_d = \sum \overline{I_{AW1}} + \overline{I_{AW2}} + \overline{I_{AW3}} \]

\[ I_R = \frac{\sum \left| I_{AW1} \right| + \left| I_{AW2} \right| + \left| I_{AW3} \right|}{2} \]

\[ I_1 + I_2 + I_3 = 0 \]
Through Current: Perfect Replication

\[ I_b = I_1 + I_2 \]

\[ I_R = |I_1| + |I_2| \]
Through Current: Imperfect Replication

\[ I_D = I_1 + I_2 \]

\[ I_R = |I_1| + |I_2| \]

2 Node Bus

TRIP

RESTRAIN

A (0,0)

B (2, -2)

C (1, -3)
Internal Fault: Perfect Replication

\[ I_D = I_1 + I_2 \]

\[ I_R = |I_1| + |I_2| \]
Internal Fault: Imperfect Replication

\[ I_0 = I_1 + I_2 \]

\[ I_R = |I_1| + |I_2| \]
Unique Issues Applying to Transformer Differential Protection

- CT ratio caused current mismatch
- Transformation ratio caused current mismatch (fixed taps)
- LTC induced current mismatch
- Delta-wye transformation of currents
  - Vector group and current derivation issues
- Zero-sequence current elimination for external ground faults on wye windings
- Inrush phenomena and its resultant current mismatch
Unique Issues Applying to Transformer Differential Protection

- Harmonic content available during inrush period due to point-on-wave switching
  - Especially with newer transformers with step-lap core construction
- Overexcitation phenomena and its resultant current mismatch
- Internal ground fault sensitivity concerns
- Switch onto fault concerns
- CT saturation, remanance and tolerance
CT Performance:
200:5, C200, R=0.5, Offset = 0.5, 1000A

Input Parameters:
- Inverse of sat. curve slope = S = 22
- RMS voltage at 10A exc. current = V_s = 200 volts rms
- Turns ratio = n2/1 = N = 40
- Winding resistance = R_w = 0.200 ohms
- Burden resistance = R_b = 0.500 ohms
- Burden reactance = X_b = 0.500 ohms
- System X/R ratio = X/R = 12.0
- Per unit offset in primary current = Off = 0.50
- Per unit reactance (based on Vs) = X/1 = 0.50
- Symmetrical primary fault current = I_p = 1.000 amps rms

Calculated:
- Total burden resistance = R_w + R_b = 0.800 ohms
- Total burden power factor = 0.848
- Total burden impedance = 0.943 ohms
- System time constant = 0.032 seconds
- Peak flux-linkages corresponding to V_s = 0.750 Wb-turns
- Radians freq = 376.99 radians
- Rms-to-peak ratio = 0.34594
- Coefficient in instantaneous le versus lambda curve, le = A * fS = 1.61E+04
- Time step = 0.000083 seconds
- Burden inductance = 0.00133 henries

http://www.pes-psrc.org/Reports/CT_SAT%2010-01-03.zip
CT Performance:
200:5, C200, R=0.5, Offset = 0.5, 2000A

INPUT PARAMETERS:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inverse of sat. curve slope</td>
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</tr>
<tr>
<td>RMS voltage at 10A exc. current</td>
<td>200 volts</td>
</tr>
<tr>
<td>Turns ratio = n/2 =</td>
<td>40</td>
</tr>
<tr>
<td>Winding resistance = R_w =</td>
<td>0.30 ohms</td>
</tr>
<tr>
<td>Burden resistance = R_b =</td>
<td>0.50 ohms</td>
</tr>
<tr>
<td>Burden reactance = X_b =</td>
<td>0.50 ohms</td>
</tr>
<tr>
<td>System XCR ratio = X/overR =</td>
<td>12.0</td>
</tr>
<tr>
<td>Per unit offset in primary current = Off =</td>
<td>0.50</td>
</tr>
<tr>
<td>Per unit remanence (based on V_s) = I_r =</td>
<td>0.50</td>
</tr>
<tr>
<td>Symmetrical primary fault current = I_p =</td>
<td>2.000 amps</td>
</tr>
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</table>

CALCULATED:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total burden resistance = R_w + R_b =</td>
<td>0.300 ohms</td>
</tr>
<tr>
<td>Total burden power factor = f_p =</td>
<td>0.848</td>
</tr>
<tr>
<td>Total burden impedance = Z_b =</td>
<td>0.943 ohms</td>
</tr>
<tr>
<td>System time constant = T_au1 =</td>
<td>0.032 s</td>
</tr>
<tr>
<td>Peak flux-linkages corresponding to V_s =</td>
<td>0.750 Wb-turns</td>
</tr>
<tr>
<td>Radian freq = ω =</td>
<td>378.99 rad/s</td>
</tr>
<tr>
<td>Rms-to-peak ratio = RP =</td>
<td>0.34584</td>
</tr>
<tr>
<td>Coefficient in instantaneous ie versus lambda curve = A = A + f_p's = 1.61E+04</td>
<td></td>
</tr>
<tr>
<td>Time step = t =</td>
<td>0.000083 s</td>
</tr>
<tr>
<td>Burden inductance = L_b =</td>
<td>0.00133 h</td>
</tr>
</tbody>
</table>

Thick lines: **ideal (blue)** and **actual (black)** secondary current in amps vs time in seconds.
Thin lines: **ideal (blue)** and **actual (black)** secondary current extracted fundamental rms value, using a simple DFT with a one-cycle window.

http://www.pes-psrc.org/Reports/CT_SAT%2010-01-03.zip
CT Performance:
200:5, C200, R=0.5, Offset = 0.75, 2000A

INPUT PARAMETERS:
- Inverse of sat. curve slope = S = 22
- RMS voltage at 10A exc. current = Vs = 200volts rms
- Turns ratio = n2/n1 = N = 40
- Winding resistance = Rw = 0.300 ohms
- Burden resistance = Rb = 0.500 ohms
- Burden reactance = Xb = 0.500 ohms
- System X/R ratio = XoverR = 12.0
- Per unit offset in primary current = Off = 0.75
- Per unit remanence (based on Vs) = Jrev = 0.50
- Symmetrical primary fault current = Ip = 2,000amps rms

CALCULATED:
- Rt = Total burden resistance = Rw + Rb = 0.600 ohms
- pf = Total burden power factor = 0.848
- Zb = Total burden impedance = 0.943 ohms
- Tau1 = System time constant = 0.032 seconds
- Lamsat = Peak flux-linkages corresponding to Vs = 0.750 Wb-turns
- ω = Radian freq = 376.99 rad/s
- RP = Rms-to-peak ratio = 0.34584
- A = Coefficient in instantaneous ie versus lambda curve: ie = A * PS = 1.61E+04
- dt = Time step = 0.000083 seconds
- Lb = Burden inductance = 0.00133 henries

Thickness lines: Ideal (blue) and actual (black) secondary current in amps vs. time in seconds. Thin lines: Ideal (blue) and actual (black) secondary current extracted fundamental rms value, using a simple DFT with a one-cycle window.

http://www.pes-psrc.org/Reports/CT_SAT%2010-01-03.zip
CT Performance:
200:5, C200, R=0.75, Offset = 0.75, 2000A

http://www.pes-psrc.org/Reports/CT_SAT%2010-01-03.zip
CT Performance:
400:5, C400, R=0.5, Offset = 0.5, 2000A

http://www.pes-psrc.org/Reports/CT_SAT%2010-01-03.zip
CT Performance:
400:5, C400, R=0.5, Offset = 0.5, 4000A

http://www.pes-psrc.org/Reports/CT_SAT%2010-01-03.zip
CT Performance:
400:5, C400, R=0.5, Offset = 0.5, 8000A

http://www.pes-psrc.org/Reports/CT_SAT%2010-01-03.zip
CT Performance:
400:5, C400, R=0.5, Offset = 0.75, 8000A

INPUT PARAMETERS:

- Inverse of sel. curve slope = 22
- RMS voltage at 10A exc. current = 400
- Turns ratio = n2/1 = 80
- Winding resistance = Rw = 0.300 ohms
- Burden resistance = Rb = 0.500 ohms
- Burden reactance = Xb = 0.500 ohms
- System X/R ratio = XoverR = 12.0
- Per unit offset in primary current = Off = 0.75
- Per unit remanence (based on Vs) = Vrem = 0.50
- Symmetrical primary fault current = Ip = 8.000

ENTER:

- Vp = Volts rms
- Ip = Amps rms

CALCULATED:

- Rs = Total burden resistance = Rw + Rb = 0.800 ohms
- Zb = Total burden impedance = 0.943 ohms
- Tau1 = System time constant = 0.032 seconds
- Lamsat = Peak flux-linkages corresponding to Vs = 1.591 Wb-turns
- @ = Radian freq = 376.99 rad/s
- RP = Rms-to-peak ratio = 0.34584
- A = Coefficient in instantaneous e
  versus lambda curve: ie = A * e^S = 3.63E-03
- dt = Time step = 0.000083 seconds
- Lb = Burden inductance = 0.00133 henries

**Graph:**

- Thick lines: Ideal (blue) and actual (black) secondary current in amps vs. time in seconds.
- Thin lines: Ideal (blue) and actual (black) secondary current extracted fundamental rms value, using a simple DFT with a one-cycle window.

http://www.pes-psrc.org/Reports/CT_SAT%2010-01-03.zip
CT Performance:
400:5, C400, R=0.75, Offset = 0.75, 8000A

**INPUT PARAMETERS:**
- Inverse of sat. curve slope = S = 22
- RMS voltage at 10A exc. current = V_s = 400 volts rms
- Turns ratio = n2/1 = N = 80
- Winding resistance = R_w = 0.300 ohms
- Burden resistance = R_b = 0.500 ohms
- Burden reactance = X_b = 0.500 ohms
- System X/R ratio = X_over_R = 12.0
- Per unit offset in primary current = Offset = 0.75
- Per unit remanence (based on V_s) = I_r = 8.000
- Symmetrical primary fault current = I_p = 8000 amps rms

**CALCULATED:**
- Total burden resistance = R_w + R_b = 0.800 ohms
- Total burden power factor = 0.848
- Total burden impedance = 0.943 ohms
- System time constant = 0.032 seconds
- Lamset = Peak flux-linkages corresponding to V_s = 1.501 Wb-turns
- R = Rms-to-peak ratio = 0.34584
- A = Coefficient in instantaneous ie versus lambda curve: ie = A \* \lambda_s = 3.83E-03
- T = Time step = 0.000083 seconds
- L_b = Burden inductance = 0.00133 henries

Thick lines: ideal (blue) and actual (black) secondary current in amps vs. time in seconds. Thin lines: ideal (blue) and actual (black) secondary current extracted fundamental rms value, using a simple DFT with a one-cycle window.

[http://www.pes-psrc.org/Reports/CT_SAT%2010-01-03.zip](http://www.pes-psrc.org/Reports/CT_SAT%2010-01-03.zip)
Application Considerations: Paralleling Sources

- When paralleling sources for differential protection, *beware!*
- Paralleled sources (not load, specifically sources) have different saturation characteristics and present the differential element input with corrupt values.

- Consider through-fault on bus section
  - One CT saturates, the other does not
  - Result: Input is presented with “false difference” due to combining of CTs from different sources outside of relay.
The problem with external faults is the possibility of CT saturation making an external fault “look” internal to the differential relay element.
Classical Differential Compensation

- CT ratios must be selected to account for:
  - Transformer ratios
  - If delta or wye connected CTs are applied
  - Delta increases ratio by 1.73

- Delta CTs must be used to filter zero-sequence current on wye transformer windings
“Dab” as polarity of “A” connected to non-polarity of “B”
Bushing Nomenclature

- H1, H2, H3
  - Primary Bushings
- X1, X2, X3
  - Secondary Bushings

Transformer

- Wye-Wye: H1 and X1 at zero degrees
- Delta-Delta: H1 and X1 at zero degrees
- Delta-Wye: H1 lead X1 by 30 degrees
- Wye-Delta: H1 lead X1 by 30 degrees

ANSI Standard
Angular Displacement

- ANSI Y-Y & Δ-Δ @ 0°
- ANSI Y-Δ & Δ-Y @ H1 lead X1 by 30° or X1 lag H1 by 30°
Winding Types and Impacts

- **Wye-Wye**
  - Cheaper than 2 winding if autobank
  - Conduct zero-sequence between circuits
  - Provides ground source for secondary circuit

- **Delta-Delta**
  - Blocks zero-sequence between circuits
  - Does not provide a ground source

- **Delta-Wye**
  - Blocks zero-sequence between circuits
  - Provides ground source for secondary circuit

- **Wye-Delta**
  - Blocks zero-sequence between circuits
  - Does not provide a ground source for secondary circuit
Wye-Wye
Winding Types

- Delta-Delta
Delta-Wye Winding Types

\[ I_A = I_a - I_b = I_a \times \sqrt{3} / 30^\circ \]
\[ I_B = I_b - I_c = I_b \times \sqrt{3} / 30^\circ \]
\[ I_C = I_c - I_a = I_c \times \sqrt{3} / 30^\circ \]
Winding Types

- Wye-Delta

![Diagram of Wye-Delta winding types]

Mathematical equations:

\[ I_a = I_A - I_C = I_A \times \sqrt{3} / -30^\circ \]
\[ I_b = I_B - I_A = I_B \times \sqrt{3} / -30^\circ \]
\[ I_c = I_C - I_B = I_C \times \sqrt{3} / -30^\circ \]
Compensation in Digital Relays

- Transformer ratio
- CT ratio
- Phase angle shift and √3 factor due to delta/wye connection
- Zero-sequence current filtering for wye windings so the differential quantities do not occur from external ground faults
Phase Angle Compensation in Numerical Relays

- Phase angle shift due to transformer connection in electromechanical and static relays is accomplished using appropriate connection of the CTs.

- The phase angle shift in Numerical Relays can be compensated in software for any transformer with zero or 30° increments.

- All CTs may be connected in WYE which allows the same CTs to be used for both metering and backup overcurrent functions.

- Some numerical relays will allow for delta CTs to accommodate legacy upgrade applications.
- Delta High Side, Wye Low Side
- High Lead Low by 30°
- Delta-Wye
- Delta (ab)
- Dy1
  - Dyn1
- Wye High Side, Delta Low Side
- High Lead Low by 30°
- Wye-Delta
- Delta (ac)
- Yd1
  - YNd1
Transformer Connection  Bushing Nomenclature

<table>
<thead>
<tr>
<th>IEC Connection Description Symbol</th>
<th>Description</th>
<th>Symbol</th>
<th>Input Value</th>
<th>Symbol</th>
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<td>Yy0</td>
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<td>Y Y 0 0</td>
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<tr>
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<td>Dac Dac</td>
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<td>Y Dac</td>
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<td>Yd11</td>
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<td></td>
<td>Y Dab 0 11</td>
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<td>Dy1</td>
<td>Dab Y</td>
<td></td>
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<td>Dz2</td>
<td>Dab Custom</td>
<td></td>
<td>Dab Wye 11 1</td>
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</table>

- **Y-Y ANSI**
- **Δ-Δ ANSI**
- **Y-Δ ANSI**
- **Δ-Y ANSI**

- ANSI follows “zero phase shift”, or “high lead low by 30°”
- IEC designations use “low lags high by increments of 30° phase shift
- IEC uses various phase shifts in 30° increments
  - 30, 60, 90, 180, etc.
Digital Relay Application

All WYE CTs shown
Benefits of Wye CTs

- Phase segregated line currents
  - Individual line current oscillography
  - Currents may be easily used for overcurrent protection and metering
  - Easier to commission and troubleshoot
  - Zero sequence elimination performed by calculation

**NOTE:**
- For protection upgrade applications where one wants to keep the existing wiring, the relay must:
  - Accept either delta or wye CTs
  - For delta CTs, recalculate the phase currents for overcurrent functions
Application Adaptation

- **Challenge:** To be able to handle **ANY** combination of transformer winding arrangements and CT connection arrangements

- **Strategy:** Use a menu that contains **EVERY** possible combination

  - Set W1’s transformer winding configuration and CT configuration
  - Set W2’s transformer winding configuration and CT configuration
  - Set W3’s transformer winding configuration and CT configuration
  - Set W4’s transformer winding configuration and CT configuration

- Standard or Custom Selection
  - Standard handles most arrangements, including all ANSI standard type
  - Custom allows any possible connections to be accommodated (Non-ANSI and legacy delta CTs)

- Relay selects the proper currents to use, directly or through vector subtraction
- Relay applies \( \sqrt{3} \) factor if required
- Relay applies zero sequence filtering if required
Compensation: Base Model

1:1, Y-Y

IA, IB, IC  →  IA', IB', IC'

1:1, 3Y

Ia, Ib, Ic  →  Ia', Ib', Ic'

IA' = Ia'
IB' = Ib'
IC' = Ic'
Compensation: Change in CT Ratio

1:1, Y-Y

IA, IB, IC
IA', IB', IC'

4:1, 3Y

1:1, 3Y
Ia, Ib, Ic
Ia', Ib', Ic'

IA' = Ia' / 4
IB' = Ib' / 4
IC' = Ic' / 4
Compensation: Transformer Ratio

2:1, Y-Y

IA, IB, IC

IA', IB', IC'

Ia, Ib, Ic

IA' = Ia' / 2
IB' = Ib' / 2
IC' = Ic' / 2
Compensation: Delta – Wye Transformation

1:1, Δ-Y

IA, IB, IC  1:1, 3Y  1:1, 3Y  Ia, Ib, Ic

IA', IB', IC'  Ia', Ib', Ic'

ANSI standard, high lead low by 30,
Current pairs are: IA-IB, IB-IC, IC-IA

IA' = Ia' * 1.73
IB' = Ib' * 1.73
IC' = Ic' * 1.73
Standard Application

• Set winding types
• 6 choices of configuration for windings and CTs
Custom Application:
Accommodates any CTs and Windings

[Image of software interface with options for Transformer/CT Phase Compensation and Winding selection]
Custom Application: Accommodates any CTs and Windings
Custom Application: Accommodates any CTs

- Legacy Application
- Need to keep Delta CTs on WYE side of transformer
Custom Application: Accommodates any CTs

- Legacy Application
- Need to keep Delta CTs on WYE side of transformer
Unit transformer with Three-Legged Core

- With a 3 legged core, the zero-sequence current contribution of the transformer case may contribute as much as 20% to 25% zero-sequence current.
  - This is true regardless of if there is delta winding involved
  - Use $3I_0$ restraint on wye CTs even on the delta CT winding!!!
  - Use $3I_0$ restraint on wye CTs with wye windings!!!
Compensation: Zero-Sequence Elimination

\[ 3I_0 = [I_a + I_b + I_c] \]
\[ I_0 = \frac{1}{3} \times [I_a + I_b + I_c] \]

Used where filtering is required (Ex: Y/Y transformer).
 Relay Custom Application

\[ I_0 = 0 \]

Delta

[Diagram of an electrical circuit showing a ground fault with labels indicating currents and a device labeled M-3311.]
Winding Types

- Zig-Zag
  - Provides Ground Source for Ungrounded systems
Wye-Delta Ground Bank

- Provides Ground Source for Ungrounded Systems
Inrush Detection and Restraint

- Characterized by current into one winding of transformer, and not out of the other winding(s)
  - This causes a differential element to pickup

- Use **inrush restraint** to block differential element during inrush period
  - **Initial inrush** occurs during transformer energizing as the core magnetizes
  - **Sympathy inrush** occurs from adjacent transformer(s) energizing, fault removal, allowing the transformer to undergo a low level inrush
  - **Recovery Inrush** occurs after an out-of-zone fault is cleared and the fault induced depressed voltage suddenly rises to rated.
Classical Inrush Detection

- 2nd harmonic restraint has been employed for years
- “Gap” detection has also been employed
- As transformers are designed to closer tolerances, the incidence of both 2nd harmonic and low current gaps in waveform have decreased
- If 2nd harmonic restraint level is set too low, differential element may be blocked for internal faults with CT saturation (with associated harmonics generated)
Advanced Inrush Detection

- 4\textsuperscript{th} harmonic is also generated during inrush
  - Even harmonics are more prevalent than odd harmonics during inrush
  - Odd harmonics are more prevalent during CT saturation

- Use 4\textsuperscript{th} harmonic and 2\textsuperscript{nd} harmonic together
  - Use RMS sum of the 2\textsuperscript{nd} and 4\textsuperscript{th} harmonic as inrush restraint

- Result: Improved security while not sacrificing reliability
Inrush Oscillograph

Typical Transformer Inrush Waveform

2nd and 4th Harmonics During Inrush
Inrush Oscillograph

Typical Transformer Inrush Waveform
Overexcitation Restraint

- Overexcitation occurs when volts per hertz level rises (V/Hz) above the rated value
- This may occur from:
  - Load rejection (generator transformers)
  - Malfunctioning of voltage and reactive support elements
  - Malfunctioning of breakers and line protection (including transfer trip communication equipment schemes)
  - Malfunctioning of generator AVRs
- The voltage rise at nominal frequency causes the V/Hz to rise
- This causes the transformer core to saturate and thereby increase the magnetizing current.
- The increased magnetizing current contains 5th harmonic component
- This magnetizing current causes the differential element to pickup
  - Current into transformer that does not come out
Trip Characteristic – 87T

\[ I_d = \sum |I_{\text{AW1}}| + |I_{\text{AW2}}| + |I_{\text{AW3}}| \]

\[ I_R = \frac{\sum |I_{\text{AW1}}| + |I_{\text{AW2}}| + |I_{\text{AW3}}|}{2} \]
Testing the 87 Elements

1. Review setting calculations
2. Testing Minimum Pick-up, both windings of 87 element
3. Testing slope segment 1
4. Testing slope segment 2
5. Testing the high set
6. Testing 20% harmonic restraint

But first, a few scary stories!
Testing Rules of the Road!!

1. Minimum 6 phase currents, essential for accurate slope tests
2. NEVER change tap settings for testing purposes
3. NEVER change logic of relay for testing
4. NEVER close the trip circuits before checking for a relay trip indication
5. ALWAYS try to verify the correct settings

“Thinking logically as to how a relay responds in a faulted condition helps to visualize a proper test sequence”

--Drew Welton
Today’s Transformer Model

1. Y-Y Connected
2. Y Connected CT’s
3. 40 MVA
4. Primary L-L Voltage of 30KV
5. Secondary L-L Voltage of 240K
6. CT Ratios of 240:1 on Primary, 50:1 on Secondary
Relay Systems Settings for Today
Setting Calculations for Tap Wdg 1 and 2
(Math Class!)

Translated for a Sales Guy!

\[ 87 \text{ CT Tap}_{wn} = \frac{\text{MVA} \times 10^3}{\sqrt{3} \times \text{kVL-L} \times \text{CTR}_{wn}} \]

\[ 40 \times 1000 / 1.732 / 30 / 240 = \boxed{3.2} \text{ Tap wdg 1} \]

\[ 40 \times 1000 / 1.732 / 240 / 50 = \boxed{1.94} \text{ Tap wdg 2} \]
Settings for the 87 Element
Wiring Check

Apply tap setting values on both windings.

Relay should not trip, Pos. Seq. Currents for both windings.

No Differential Current
Testing Minimum Pick Up

(Tap Wdg 1) 3.2 X .3 = .96 Amps

(Tap Wdg 2) 1.94 X .3 = .58 Amps
Testing the 25% Slope, First Quiz:

When verifying the slope, the initials P.U. refer to:

1) Something really smelly
2) Pick up
3) Per unit
4) None of the above, or we started too early and I’m still asleep!

How do we convert to per unit values?

Tap setting of 3.2 Amps=1 P.U. wdg 1
Tap setting of 1.94 Amps = 1 P.U. wdg 2

How do we use this information to verify a 25% Slope?
Verifying the 25% Slope

1. Start with balance currents, same as meter check
2. Ramp the wdg 1-3 phase currents up in 100mA increments
3. Record the values at the point of tripping
4. View the 87 Dual Slope graphic in the IPScom Monitor menu
25% Slope Math Equations

Wdg 1 Pick Up / Wdg 1 Nominal

4.1/3.2 = 1.28

1.28 – 1 (pu value of Wdg 2) = .28

1 + 1.28 = 2.28/2 = 1.14 (pu value of Wdg. 1+2)

.28/1.14 = @25%
25% Slope - Doubled Values

Same out come, further up the slope!
60% Slope 2 Math Equations

\[ W_{1pu} = \frac{W_1 \text{ actual value}}{W_1 \text{ Nominal}} = \frac{13}{3.2} = 4.06 \text{ pu} \]
\[ W_{2pu} = \frac{W_2 \text{ actual value}}{W_2 \text{ Nominal}} = \frac{5.82}{1.94} = 3 \text{ pu} \]

\[ \text{Diff} = W_{1pu} - W_{2pu} = 4.06 - 3 = 1.06 \text{ pu} \]

\[ \text{Restraint} = \frac{(W_{1pu} + W_{2pu})}{2} = 3.53 \text{ pu} \]

\[ y = mx + b \]
\[ \text{Diff} = m \times \text{Restraint} + b \]
\[ b = \text{Diff} - m \times \text{Restraint} = 1.06 - 0.60 \times 3.53 = -1 \]

\[ m = \frac{(y + b)}{x} = \frac{(1.06 + 1)}{3.53} = 0.60 \]

\[ \text{Slope 2} = m \times 100 = 0.60 \times 100 = 60\% \]
Test the 87 High Set (Unrestrained)

Current magnitudes are too high for most test sets to apply both windings! We are set to only a pick up of 5X, some are 10X, and this would double these values.
Test the 87 High Set
(Unrestrained)

Add additional output contact for assessment

Ramp 3 phase currents as such:
- Wdg 1 tap $3.2A \times 5 = 16$
- Wdg 2 tap $1.94 \times 5 = 9.7$

Corresponding windings set to zero
Testing 20% Harmonic Restraint

Set Wdg 1 to 110%, of tap at 60 Hz to trip the 87 relay
Change 1 or all 3 phases to 120Hz, target should clear.
(4th is 240Hz, 5th is 300Hz)

⇒W
Overexcitation (V/Hz)
24
Overexcitation

- Responds to overfluxing; excessive V/Hz
  - 120V/60Hz = 2 = 1pu

- Constant operational limits
  - ANSI C37.106 & C57.12
    - 1.05 loaded, 1.10 unloaded
  - Inverse time curves typically available for values over the constant allowable level

- Overfluxing is a **voltage** and **frequency** based issue
- Overfluxing protection needs to be voltage and frequency based (V/Hz)
- Although 5th harmonic is generated during an overfluxing event, there is no correlation between levels of 5th harmonic and severity of overfluxing
- Apparatus (transformers and generators) is rated with V/Hz withstand curves and limits – *not* 5th harmonic withstand limits
Overexcitation vs. Overvoltage

- Overvoltage protection reacts to dielectric limits.
  - Exceed those limits and risk punching a hole in the insulation
  - Time is not negotiable

- Overexcitation protection reacts to overfluxing
  - Overfluxing causes heating
  - The voltage excursion may be less than the prohibited dielectric limits (overvoltage limit)
  - Time is not negotiable
  - The excess current cause excess heating which will cumulatively damage the asset, and if left long enough, will cause a catastrophic failure
Causes of Overexcitation

- **Generating Plants**
  - Excitation system runaway
  - Sudden loss of load
  - Operational issues (reduced frequency)
    - Static starts
    - Pumped hydro starting
    - Rotor warming

- **Transmission Systems**
  - Voltage and Reactive Support Control Failures
    - Capacitor banks ON when they should be OFF
    - Shunt reactors OFF when they should be ON
    - Near-end breaker failures resulting in voltage rise on line
      - Ferranti Effect
    - Runaway LTCs
    - Load Loss on Long Lines (Capacitive Charging Voltage Rise)
System Control Issues:

Overvoltage and Overexcitation

Caps **ON** When They Should Be Off
System Control Issues:
*Overvoltage and Overexcitation*

Reactors **OFF** When They Should Be On
System Control Issues: 
*Overvoltage and Overexcitation*
System Control Issues:
*Overvoltage and Overexcitation*
System Control Issues: 
*Overvoltage and Overexcitation*

**Small Load Trasport (Load Rejection at Remote Area)**

1996 WECC Load Rejection Event
Overexcitation Event

[Diagram showing voltage and current graphs with annotations:
- Voltage
- Current
- Rated Voltage
- Overvoltage Voltage
- Current into Transformer due to Overfluxing
- Transformer Magnetizing Current
- 24 Elements Tripping]
Overexcitation Curves

This is typically how the apparatus manufacturer specifies the V/Hz curves.
Overexcitation Curves

This is typically how the apparatus manufacturer specifies the V/Hz curves.
This is how protection engineers enter the v/Hz curve into a protective device
Overexcitation (24)

Percent, not volts!

Test Settings
Output 1=trip, Output 2=alarm
Testing Overexcitation Volts/Hz-(24)

Setting is in percentage, $V_{nom} / F_{nom} = 100\%$

- Nominal Voltage
- Nominal Freq= 100% V/Hz

Single Phase Voltage Input
Def. Time Overexcitation Volts/Hz-(24)

69 $\times$ 1.05$=$72.45 Alarm out 2 @ 600Cycles
69 $\times$ 1.20$=$82.8 Trip out 1 @ 30 Cycles

Trip time validation for alarm setting

Start with pre-fault
Apply faulted value
Validate trip time
Def. Time Overexcitation Volts/Hz-(24)

69 X 1.05=72.45 Alarm out 2 @ 600 Cycles
69 X 1.20=82.8 Trip out 1 @ 30 Cycles

Trip time validation for trip setting

Start with pre-fault
Apply faulted value
Validate trip time
Def. Time Overexcitation Volts/Hz-(24)

Testing with constant voltage, vary the frequency:

60 X 1.05=63Hz  Alarm out 2 @ 600Cycles
60 X 1.20=72Hz Trip out 1 @ 30 Cycles

Rule of thumb when verifying a pick up value:

1. Time between each incremental state > time delay
2. Incremental state should be< tolerance of the element
Questions???