M-3311A
TRANSFORMER PROTECTION
TEST PLAN

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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 PSRC: Rotating Machinery Subcommittee (2007-10).
  - Contributed to numerous IEEE Standards, Guides, Reports, Tutorials and Transactions, delivered Tutorials IEEE Conference, 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

- Standard
- Expanded
Normal Operation - No Targets

Display dark if there are no active 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

Tripped

Target, Time, Outputs, Function, Phase

- One or more "OUTPUT" LEDs illuminated
Trip Cleared and Target Present

- All "OUTPUT" LEDs Extinguished

Relay failed internal self diagnostics

- 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

Working Offline

• Used to create, view, or modify relay setting files

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 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.
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 Principle Diagram](image)
Differential Relay Principle:
External Fault

TRANSFORMER

RELAY

TAP W-1

Restraint W-1

Operate = 0

Restraint W-2

TAP W-2

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)
Through Current: Perfect Replication

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

\[ ID = I_1 + I_2 \]

Through Current: Imperfect Replication

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

\[ ID = I_1 + I_2 \]
Internal Fault: Perfect Replication

\[ I_n = I_1 + I_2 \]

Internal Fault: Imperfect Replication

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

http://www.pes-psrc.org/Reports/CT_SAT%2010-01-03.zip

CT Performance:
200:5, C200, R=0.5, Offset = 0.5, 2000A

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:**
- Primary of hard curve slope = $S_y$
- Ratio of hard curve slope = $S_y$
- Turn ratio = $D$
- Winding resistance = $R_w$
- Birreg resistance = $R_b$
- System X/R ratio = $X/R$
- Per unit offset in primary current = $I_{off,p}$
- Per unit resistance based on Vp = $I_{res,p}$

**CALCULATED:**
- Total burden resistance = $R_b + R_w$
- Total burden inductive reactance = $X_b$
- System X/R ratio = $X/R$
- Total shunt inductive reactance = $X_{sh}$
- Transformer (primary) current = $I_{p}$
- Transformer (secondary) current = $I_{s}$

**Graphs:**
- Graphs showing the transformer's performance under different conditions.

**Links:**
- [http://www.pes-psrc.org/Reports/CT_SAT%2010-01-03.zip](http://www.pes-psrc.org/Reports/CT_SAT%2010-01-03.zip)

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CT Performance:
200:5, C200, R=0.75, Offset = 0.75, 2000A

**INPUT PARAMETERS:**
- Primary of hard curve slope = $S_y$
- Ratio of hard curve slope = $S_y$
- Turn ratio = $D$
- Winding resistance = $R_w$
- Birreg resistance = $R_b$
- System X/R ratio = $X/R$
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CT Performance:
400:5, C400, R=0.5, Offset = 0.5, 2000A

Input Parameters:
- Transformer ratio: 400:5
- Core type: C400
- Ratio accuracy: R=0.5
- Offset accuracy: Offset = 0.5
- Nominal current: 2000A

Output Parameters:
- Nominal primary current: 2000A
- Nominal secondary current: 5A
- Core loss: 0.5W
- Magnetic material: Silicon steel
- Core design: Eddy current design

Deterministic System Response:
- Total burden resistance: R
- Total burden inductance: L
- Total burden capacity: C
- Transformer leakage inductance: L_t
- Transformer leakage resistance: R_t
- Transformer leakage capacity: C_t

Performance Characteristics:
- Saturation curve
- Harmonic distortion
- Magnetic flux density
- Core loss (W)
- Eddy current loss (W)

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

Input Parameters:
- Inverse of set curve slope = \( S \)
- RMS voltage of TA exc. current = \( V_A \)
- Transformer ratio = \( K_t \)
- Winding resistance = \( R_w \)
- Burden resistance = \( R_b \)
- Total burden resistance = \( R_b + R_w \)
- System X/R ratio = \( X/R \)
- Per unit current = \( I_p \)
- Per unit current (based on X) = \( I_p(X) \)

Calculated:
- \( R_b \) = Total burden resistance
- \( P_b \) = Total burden power factor
- \( \delta \) = Time delay
- \( A \) = Coefficient of inrush
- \( \delta_{lb} \) = Time delay for leakage

Thin lines: Ideal (blue) and actual (black) secondary current in amp vs. time in seconds.

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:
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CT Performance:
400:5, C400, R=0.75, Offset = 0.75, 8000A

- 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.

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.
Classical Differential Compensation

"Dab" as polarity of “A” connected to non-polarity of “B”

Bushing Nomenclature

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

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 Winding Types
Delta-Wye

Winding Types

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

Wye-Delta

Winding Types

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

- Transformer ratio
- CT ratio
- Phase angle shift and $\sqrt{3}$ 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
### Transformer Connection Bushing Nomenclature

<table>
<thead>
<tr>
<th>IEC Connection Description</th>
<th>Symbol</th>
<th>Input Value</th>
<th>Symbol</th>
</tr>
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<tbody>
<tr>
<td>Yy0</td>
<td><img src="#" alt="Yy0" /></td>
<td>Y Y</td>
<td><img src="#" alt="Yy0" /></td>
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<tr>
<td>Dd0</td>
<td><img src="#" alt="Dd0" /></td>
<td>Y y Dec</td>
<td><img src="#" alt="Dd0" /></td>
</tr>
<tr>
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<td><img src="#" alt="Yd1" /></td>
<td>Y Dec</td>
<td><img src="#" alt="Yd1" /></td>
</tr>
<tr>
<td>Yd11</td>
<td><img src="#" alt="Yd11" /></td>
<td>Y Dec y</td>
<td><img src="#" alt="Yd11" /></td>
</tr>
<tr>
<td>Dy1</td>
<td><img src="#" alt="Dy1" /></td>
<td>Dab Y</td>
<td><img src="#" alt="Dy1" /></td>
</tr>
<tr>
<td>Dy11</td>
<td><img src="#" alt="Dy11" /></td>
<td>Dab y</td>
<td><img src="#" alt="Dy11" /></td>
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<tr>
<td>Yd5</td>
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<td>Y Inverse Dab</td>
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<tr>
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<td>Y Inverse Dab y</td>
<td><img src="#" alt="Dy5" /></td>
</tr>
<tr>
<td>Dy10</td>
<td><img src="#" alt="Dy10" /></td>
<td>Dab Dab</td>
<td><img src="#" alt="Dy10" /></td>
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<tr>
<td>Dy2</td>
<td><img src="#" alt="Dy2" /></td>
<td>Dab Wye</td>
<td><img src="#" alt="Dy2" /></td>
</tr>
</tbody>
</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

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

![Diagram of 1:1, Y-Y compensation]

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

1:1, Y-Y

\[ IA' = \frac{Ia'}{4} \]
\[ IB' = \frac{Ib'}{4} \]
\[ IC' = \frac{Ic'}{4} \]

Compensation: Transformer Ratio

2:1, Y-Y

\[ IA' = \frac{Ia'}{2} \]
\[ IB' = \frac{Ib'}{2} \]
\[ IC' = \frac{Ic'}{2} \]
Compensation: Delta – Wye Transformation

1:1, Δ-Y

IA, IB, IC

1:1, 3Y

IA', IB', IC'

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

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

Standard Application

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

### Core Construction and $3I_0$ Current

$$3I_0 = [I_a + I_b + I_c ]$$

$$I_0 = 1/3 *[I_a + I_b + I_c]$$

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

- \( I_0 = 0 \)
- Delta
- \( I_0 \)
- M-3311
- Ground Fault

Winding Types

- Zig-Zag
  - Provides Ground Source for Ungrounded systems

- Diagrams showing Zig-Zag winding configurations
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

- 4th 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 4th harmonic and 2nd harmonic together
  - Use RMS sum of the 2nd and 4th harmonic as inrush restraint
- Result: Improved security while not sacrificing reliability
2nd and 4th Harmonics During Inrush
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

\[ I_g = \frac{\sum |I_{AW1}| + |I_{AW2}| + |I_{AW3}|}{2} \]

TRIP

87T Pick Up

with 5th Harmonic Restraint

Slope 1

Slope 2

Breakpoint

RESTRAIN
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. Yg-Yg Connected
2. Y Connected CTs
3. 40 MVA
4. Primary L-L Voltage of 30KV (W1)
5. Primary CT Ratio is 1200/5 (240:1)
6. Secondary L-L Voltage of 240K (W2)
7. Secondary CT Ratio is 250/5 (50:1)

Test Set Connections

- Test Set with Internally Commoned Neutrals
- Test Set with Externally Commoned Neutrals
Relay Systems Settings for Today

Setting Calculations for Tap Winding 1 and 2 (Math Class!)

**Translated for a Sales Guy!**

Tap Winding 1 = \( \frac{40 \text{MVA} \times 1000}{1.732 \times 30 \text{kV} \times 240} = 3.2 \text{ Tap} \)

Tap Winding 2 = \( \frac{40 \text{MVA} \times 1000}{1.732 \times 240 \text{kV} \times 50} = 1.94 \text{ Tap} \)
Settings for the 87 Element

Wiring Check

Apply tap setting currents on both windings
- All 3 phases identical magnitude, 120° apart
- Relay should not trip
- Positive Sequence (I₁) Currents for both windings
  - No I₂ or I₀ should be observed
Differential Current should NOT be observed
Testing Minimum Pick Up

Minimum Pickup = 0.3A

(Tap W1) 3.2 X .3 = .96 Amps

(Tap W 2) 1.94 X .3 = .58 Amps

Winding 1 Tap = 3.2

Winding 2 Tap = 1.94

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. W1
Tap setting of 1.94 Amps = 1 P.U. W2

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

W1 Pick Up / W1 Nominal
• \( \frac{4.1}{3.2} = 1.28 \)

\( 1.28 - 1 \) (pu value of W2) = 0.28

\( 1 + 1.28 = 2.28 / 2 = 1.14 \) (pu value of W[1+2])

\( \frac{0.28}{1.14} = @25\% \)
25% Slope - Doubled Values

Same outcome, further up the slope!

60% Slope 2 Math Equations

\[ W1_{pu} = \frac{W1 \text{ actual value}}{W1 \text{ Nominal}} = \frac{13}{3.2} = 4.06 \text{ pu} \]

\[ W2_{pu} = \frac{W2 \text{ actual value}}{W2 \text{ Nominal}} = \frac{5.82}{1.94} = 3 \text{ pu} \]

\[ \text{Diff} = W1_{pu} - W2_{pu} = 4.06 - 3 = 1.06 \text{ pu} \]

\[ \text{Restraint} = \frac{(W1_{pu} + W2_{pu})}{2} = 3.53 \text{ pu} \]

\[ y = mx + b \]

\[ \text{Diff} = m \cdot \text{Restraint} + b \]

\[ b = \text{Diff} - m \cdot \text{Restraint} = 1.06 - 0.60 \cdot 3.53 = -1 \]

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

\[ \text{Slope 2} = m \cdot 100 = 0.60 \cdot 100 = 60\% \]
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.

Ramp 3 phase currents as such:
- W1 tap 3.2A X 5 = 16
- W2 tap 1.94 X 5 = 9.7

Corresponding windings set to zero

Add additional output contact for assessment
Testing 20% Harmonic Restraint

Set W1 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)

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*

![Diagram showing system control issues](image)

**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

Ferranti Effect
System Control Issues:
Overvoltage and Overexcitation

Run-Away LTC

30-40 MVAR

10-20 MVAR

System Control Issues:
Overvoltage and Overexcitation

Generation

Load

Small Load Transport (Load Rejection at Remote Area)

1996 WECC Load Rejection Event
Overexcitation Event

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.

Overexcitation Relay Curves

This is how protection engineers enter the v/Hz curve into a protective device.
Overexcitation (24)

Test Settings
Output 1=trip, Output 2=alarm

Percent, not volts!

Testing Overexcitation Volts/Hz-(24)

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

Nominal Voltage

Single Phase Voltage Input

Nominal Freq= 100\% V/Hz
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 alarm setting

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<thead>
<tr>
<th>Set Mode</th>
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<td>69.28 V, 0.00 °, 60,000 Hz</td>
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Start with pre-fault

Apply faulted value

Validate trip time

Def. Time Overexcitation Volts/Hz-(24)

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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???