Transformer Differential Protection Setting Calculations
Objectives

- Examine CT performance
- Calculate winding “tap” values
- **Determine 87T pickup points**
  - Determine variable percentage slope breakpoints
  - Determine harmonic restraint values
- **Determine 87H pick up**
- **Determine 87GD pick up**
CT Performance

- Class “C” CTs have established secondary voltage/burden curves that are used to predict linear performance.

- Operating a CT at values above the “kneepoint” on the curve invite unfaithful replication of the primary waveform and saturation.

- Unfaithful replication (including saturation) between measurement CTs in a differential protection causes misoperation.
Class “C” CTs

- Class “C” CTs are designed to “faithfully” replicate primary currents to within +/- 10%

- Class designations designate maximum secondary CT circuit voltage at standard burden that can be applied to maintain accuracy
  - \( Z_{\text{rated}} = \frac{\text{Voltage Class}}{20} \times \text{Rated Secondary Current} \)
  - \( Z_{\text{rated}} = \frac{C800}{20} \times 5A = 8 \, \Omega \), \( \therefore \) 800V at 8\( \Omega \) burden
  - \( Z_{\text{rated}} = \frac{C200}{20} \times 5A = 2 \, \Omega \), \( \therefore \) 200V at 2\( \Omega \) burden
Class “C” CT Performance Curve

More than 100V secondary and you’re in trouble
CT Performance: +/- 10%

Accuracy curve for Class “C” 2000:5 multitap CT
CT Performance

Comparison of primary to secondary waveforms with saturation
CT Performance Calculation

Use with Class “C” CTs

- Determine maximum primary phase and ground fault current
- Calculate secondary current based on CTR and CT connection type (wye or delta)
- Determine secondary CT circuit burden
- Determine maximum secondary voltage produced from burden with secondary fault currents
- Check maximum secondary voltage against CT capability
Fault Types and Currents in Secondary Circuits

For WYE connected CTs, to obtain secondary current, use: \((1X) \frac{I_{PRI}}{CTR} = I_{SEC}\)
Fault Types and Currents in Secondary Circuits

For Delta connected CTs, to obtain secondary current, use:

\[(1.73) \frac{I_{PRI}}{CTR} = I_{SEC}\]
Burden Calculation

- Determine all device burdens in secondary circuit
  - Relays, meters, instrumentation

- Determine lead burden
  - Use wire tables (AWG @ ohms/ft)

- Determine CT impedance

- Use CT data sheet (typ. 0.4 ohm or less)
Equivalent circuit of the CT Secondary wiring

Where

- $R_{CT}$ is CT burden (internal)
- $R_W$ total resistance of the ct secondary wiring.
- $R_R$ is relay burden

$V_S = I (R_{CT} + R_W + R_R)$

Where $I$ is the fault current and $V_S$ is the ct secondary voltage. In order to make sure that the ct is in the linear range (to avoid ac saturation of the ct’s), $V_S$ should be less than the knee-point voltage of the ct excitation characteristics. (See IEEE Guide for the Application of Current Transformers Used for Protective Relaying Purposes C37.110-1996).
Burden Calculation

Example

- Relay = 0.5VA @ 5 A
  \[ R_R = \frac{VA}{A^2} \], \[ R_R = \frac{0.5}{25} = 0.02 \Omega \]

- \[ R_W = 2 \Omega \ (\text{round trip}) \]

- \[ R_{CT} = 0.20 \Omega \]

- Total = 2.22 \Omega
Secondary CT Circuit Voltage

- Assume maximum secondary current of 90A and wye CTs

\[ V_s = I (R_{CT} + R_W + R_R) \times (F_{\Delta-Y}) \]
- \( (F_{\Delta-Y}) \) = delta or wye CT factor
  - Use 1 for wye; use 1.73 for delta

\[ V_s = 90 \times 2.22 \times (1) = 199.8 \text{ V} \]

\[ V_s \times 2 = 199.8 \times 2 = 399.6 \text{ V} \]
- The 2X factor accounts for full DC offset

- Use at least a C400
Power-Current Conversion

- Used to determine current at rated transformer capacity
  - Normally pick highest rating of multiple MVA rated transformers

- Allows “nominalization” of the transformer windings

- Used to obtain “tap” that is digitally set

\[ I_{\text{tap}} = \frac{VA}{\sqrt{3} \cdot V_{LL}} \cdot \text{CTR} \]

- This accommodates:
  - Transformer winding ratios
  - CT ratios
Calculating “Tap”

Transformer Rating
392.8 MVA / 196.4 MVA / 196.4 MVA
161 kV / 17.1 kV / 17.1 kV
Wye

Dac CT 2000:5
Wye CT 8000:5
Wye CT 8000:5

Use highest rating as basis for tap calculations
Calculating “Tap”

\[
87 \text{ CT Tap}_{w1} = \frac{392.8 \text{ MVA} \times 10^3}{\sqrt{3} \times 17.1 \text{ kV} \times 1600} = 8.29
\]

\[
87 \text{ CT Tap}_{w2} = \frac{392.8 \text{ MVA} \times 10^3}{\sqrt{3} \times 17.1 \text{ kV} \times 1600} = 8.29
\]

\[
87 \text{ CT Tap}_{w3} = \frac{392.8 \text{ MVA} \times 10^3}{\sqrt{3} \times 161 \text{ kV} \times 400} = 3.52
\]

- This nominalizes the current flow with respect to transformation ratios and CT ratios
- Rated power passing through any winding would yield these currents to the protection system
Phase Shift Compensation

- From 3-Line Diagram, determine transformer and CT winding arrangements

- Example
  - $W1 = DAC$, wye CTs
  - $W2 = DAC$, wye CTs
  - $W3 = Wye$, wye CTs

Transformer Rating
392.8 MVA / 196.4 MVA / 196.4 MVA
161 kV / 17.1 kV / 17.1 kV
Trip Characteristic – 87T

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

\[ I_R = \frac{\sum |I_{AW1}| + |I_{AW2}| + |I_{AW3}|}{2} \]
Trip Characteristic – 87T

- **87T Pickup**
  - Set above the magnetizing current and other CT inaccuracies
  - 0.2 to 0.4 p.u. (typical setting)

- **Slope 1**
  - Set to accommodate +/- 10% CT inaccuracies
  - LTC adds another +/- 10%
  - Used for currents < 2X nominal
  - Typically set for 25% to 30% (can be set lower for non LTC transformers)

- **Slope 2 “breakpoint”**
  - Typically set at 2X rated current
  - This setting assumes that any current over 2X rated is a fault condition and is used to desensitize the element against unfaithful replication of currents due to CT saturation
Trip Characteristic – 87T

- **Slope 2**
  - Typically set at 50% to 70%
  - Prevents relay misoperation for though faults with CT saturation.

- **Inrush Restraint (2\textsuperscript{nd} and 4\textsuperscript{th} harmonic)**
  - Typically set from 10-20%
  - Employ cross phase averaging (harmonic sharing) blocking for security – especially for modern transformers where the harmonic content is low

- **Overexcitation Restraint (5\textsuperscript{th} harmonic)**
  - Typically set at 30%
  - Raise 87T pickup to 0.60 pu during overexcitation
  - No cross phase averaging is needed, as the magnetizing currents during overexcitation condition are symmetrical
Trip Characteristic – 87H

- **87H Pickup**
  - Typically set at 8 to 12 pu rated current
  - This value should be set to above the maximum possible inrush current.
  - Relay oscillograph analysis software can be used to determine the inrush current level and fine tune the setting.
  - Also, need to know if the high set element uses fundamental component of current (typically the case) or total RMS current and set the pickup appropriately.
Trip Characteristic – 87GD

- **87GD Pickup**

  - Element normally uses directional comparison between phase residual current ($3I_0$) and measured ground current ($I_G$). The element becomes non-directional when the $3I_0$ current is small (example < 140 ma).

  - Pickup of 0.2 to 0.5 A (5A rated CTs) can be applied when using same ratio CTs on both phase and ground circuits.

  - When CT correction factor higher than 1.0 is applied, the pickup needs to be increased to account for noise amplification due to high CT ratio correction.

  - Use 6 cycle time delay to provide security against misoperations during external phase-to-phase to ground faults with CT saturation. The time delay must not be set below 2 cycles.
**Improved Ground Fault Sensitivity**

Typical Pickup of 87T:
- 0.3 pu pickup
- Relay Tap set at Trans. Rating (45MVA)
  \[I_{FL138KV} = 4.71 \text{ A}\]
- PU = 4.71A x 0.3 = 1.41A

- WITHOUT GROUND DIFF. (87GD) THERE IS NO HIGHSPEED PROTECTION FOR SEC. GND FAULTS
DIGITAL TRANSFORMER
DIFFERENTIAL RELAY SETTING EXAMPLE
Sample Calculation – 87T

30/40/50 MVA
69/13 KV

NLT 70.350 KV
LTCN 13.80 KV

3 PT'S
14,400/120

3000/5

600/5
87T Sample Calculation

Calculating Differential Set Points and System Setup

- Transformer Size – MVA Rating
- Voltage Taps – No Load
- Transformer Connection
- Current Transformer Ratios
- Current Transformer Connection
- Voltage Transformer Ratios
- Voltage Transformer Connections — L-G or L-L
- LTC Tap Information
Data Required

MVA - 30/40/50
Voltage Taps - No load
Transformer Connections - US Standard Delta AB: Y-Δ CT’s
CT W-1 600/5 = 120/1
CT W-2 3000/5 = 600/1
VT Ratio 66.7/1
VT Connection Y-Y
LTC Tap Range +/-10%

87T Sample Calculation
87T Sample Calculation

**Communicates Phasing to Relay**

**Communicates Metering Data to Relay**
Differential Protection Setting Calculations

87T Sample Calculation W-2 Delta CT’S

- **Communicates Phasing to Relay**
  - Transformer Connection (W1): Dab
  - Transformer Connection (W2): Y
  - Transformer Connection (W3): Y
- **Communicates Metering Data to Relay**
  - V.T. Configuration: VVA, VVB, VVC, VAB, VBC, VCA, VGB
  - Phase Rotation: ABC, ACB
  - V.T. x Phase Ratio: 120.0
  - C.T. W1 Phase Ratio: 120
  - C.T. W2 Phase Ratio: 600
  - C.T. W3 Phase Ratio: 1
  - C.T. W2 Ground Ratio: 120
  - C.T. W3 Ground Ratio: 1

Input Active State:
- 6: Open, Close
- 5: Open, Close
- 4: Open, Close
- 3: Open, Close
- 2: Open, Close
- 1: Open, Close

Nominal Frequency: 60 Hz
CT. Secondary Rating: 5 A
Nominal Voltage: 120 V
Winding Selection:
- Three Windings
- Two Windings
- Disable Winding: W1, W2, W3
Transformer/CT Connection:
- Standard
- Custom
Zero Sequence Filter Enable: W1, W2, W3

Relay Sealin Time:
- OUT 1: 30 cycles
- OUT 2: 8160 cycles
- OUT 3: 30 cycles
- OUT 4: 30 cycles
- OUT 5: 30 cycles
- OUT 6: 30 cycles
- OUT 7: 30 cycles
- OUT 8: 30 cycles
- OUT 9: 2 cycles

Save | Cancel
87T Sample Calculation

Step 1 - Check CT and Relay Input Ratings
Sample Transformer Ratings:
OA/FA/FA = 30/40/50 MVA

Short Time Rating of this transformer is
1.35 x 50 MVA = 67.5 MVA

Relay current input is rated at 2X Nominal Rating
i.e. 5A relay = 10 AMPS continuous

\[ I_{67.5 \text{ MVA W-2 PRI}} = \frac{67,500 \text{ KVA}}{13.8 \text{KV}} \times \sqrt{3} = 2827 \text{A} \]
\[ I_{67.5 \text{ MVA W-2 SEC}} = \frac{2827}{600/1} = 4.71 \text{ A} \]

For Δ CTs relay gets
4.71 x √3 = 8.15A <10A Sec. Winding (W2) OK

\[ I_{67.5 \text{ MVA W-1 PRI}} = \frac{67,500 \text{ KVA}}{70.35 \text{KV}} \times \sqrt{3} = 554.6 \text{A} \]
\[ I_{67.5 \text{ MVA W-1 SEC}} = \frac{554.6}{120/1} = 4.62 \text{A} <10A \text{ Pri. Winding (W1) OK} \]
87T Sample Calculation

Step 2: Select W1 & W2 Tap Settings Balance at OA Rating

\[
87T \text{ W1 CT Tap} = \frac{\text{MVA} \times 10^3}{\sqrt{3} \cdot V_{W1-L-L} \cdot \text{CTR1}} = \frac{30000}{\sqrt{3} \cdot 70.35 \cdot 120/1} = 2.05 \text{ A}
\]

- W2

\[
87T \text{ W2 CT Tap} = \frac{\text{cal A} - \Delta \text{CTs}}{\sqrt{3} \cdot V_{W2} \cdot \text{CTR2}} \cdot \frac{\text{MVA} \times 10^3}{30000} \cdot \frac{\sqrt{3}}{\sqrt{3} \cdot 138 \text{KV} \cdot 600} = \frac{2.09 \text{ A}}{1}
\]

\[
\text{cal B} - \text{YCTs} \quad 87T \text{ W2 CT Tap} = \frac{\text{cal B} - \text{YCTs}}{\sqrt{3} \cdot V_{W2} \cdot \text{CTR2}} \cdot \frac{\text{MVA} \times 10^3}{30000} \cdot \frac{\sqrt{3}}{\sqrt{3} \cdot 138 \text{KV} \cdot 600} = \frac{2.09 \text{ A}}{1}
\]
87T Sample Calculation

Step 2: Select W1 & W2 Tap Settings Balance at OA Rating
87T Sample Calculation

Step 3: Select minimum pickup of 87T

- Pick up should be set to prevent operation of 87T due to transformer steady-state excitation current.
- Typical Transformer excitation current ~1% = .01 pu
- CT Error 10% = .10 pu
- LTC Error 10% = .10 pu
- Safety Margin Typical 5% = .05 pu
- 26% = .26 pu

- Typical setting is 0.26 to 0.35 p.u.

Select p.u. at 0.3
87T Sample Calculation

Step 3: Select minimum pickup of 87T

MINIMUM PICKUP
Step 4: Select Slope #1 Setting

Slope 1

The setting of Slope #1 should be set according to various possible errors:

1. Tapchanger operations in the power transformer (worst case $\pm 10\%$)

2. CT mismatch due to ratio errors. Errors can be as high as $\pm 10\%$

3. Transformer excitation current (typical current of 1%) $1\%$

4. Relay measurement error $5\%$

Set Slope #1 = 30\%
Step 4: Select Slope #1 Setting

SLOPE #1 SETTING

Percent Slope #1: 30%

Step 5: Select slope #2 Setting

• Provides security for high fault current levels outside the differential zone where CT inputs can saturate.

• Factors effecting CT saturation
  - Residual magnetism in CT core
  - CT characteristic mismatch
  - CT circuit burden

• CT Burden Check

\[ V_S = \frac{I_P}{N} \left[ R_{CT} + 2R_W + R_R \right] \]

\[ V_S < V_K \]
Step 5: Select Slope #2 Setting

Typical Slope #2 Settings is Twice Slope #2

60%
87T Sample Calculation

Step 5: Select Slope #2 Setting
87T Sample Calculation

Step 6: Select Break Point between Slope 1 and Slope 2

- Breakpoint is crossover from Slope 1 to Slope 2

Typical Breakpoint = 2.0
Step 6: Select Break Point between Slope 1 and Slope 2

BREAK POINT BETWEEN SLOPES 1 AND 2
87T Sample Calculation

Step 7: Select Inrush Harmonic Restraint

- Relay uses 2\textsuperscript{nd} and 4\textsuperscript{th} harmonics
- Percent harmonics defined as –
- Amount of 2\textsuperscript{nd} and 4\textsuperscript{th} harmonics depend on:
  - Magnetizing characteristics of transformer core
  - Residual magnetism in core
- Typical Settings
  - 15\% for most transformers
  - Can be 10\% or lower on new transformers with low core losses and steep magnetizing curves. Setting below 10\% risks blocking for internal faults.
87T Sample Calculation

Step 7: (continued)

Cross Phase Averaging (recommended)

- Inrush harmonic level different in each phase
- Cross phase averaging means each phase restrains on harmonics in other phases. For example:

\[ I_{d_{CPA24}} = \sqrt{I_{A_{d24}}^2 + I_{B_{d24}}^2 + I_{C_{d24}}^2} \]
### Differential Protection Setting Calculations

**Step 7: Select Inrush Harmonic Restraint**

![Inrush Harmonic Restraint](image)

- **Even Harmonics Restraint (2nd, 4th):** 5% Enable, Enable w/cross average
- **5th Harmonic Restraint:** 5% Enable, Enable w/cross average
- **Pickup at 5th H.R.:** 0.10 p.u. 50%

*WARNING: You have not selected an output!*

---

**Pickup:** 5.0 p.u. 20.0 p.u.
**Delay:** 1 Cycle 8160 Cycles

**Output:***
- 81, 71, 61, 51, 41, 31, 21, 11
- 61, 51, 41, 31, 21, 11

**W1 C.T. Tap:** 2.05
**W2 C.T. Tap:** 2.09
**W3 C.T. Tap:** 2.00
87T Sample Calculation

Step 8: Select Overexcitation Harmonic Restraint

- M-3311 uses 5\textsuperscript{th} harmonic.
- Overexcitation (V/Hz) produces high amounts of 5\textsuperscript{th} harmonic current.
- 87T in M-3311 shifts minimum pickup to higher value, typically 150 to 200\% of normal 87T p.u.

Typical setting is 200\% X 87T pickup, or 0.3 X 200\% = 0.6 p.u.
87T Sample Calculation

Step 8: (continued)

- Amount of 5th harmonic depends on transformer core magnetizing characteristics.

- No cross phase averaging – Overexcitation is symmetrical.

Typical setting is 30%
87T Sample Calculation

Step 8: Select Overexcitation Harmonic Restraint
Step 9: Setting 87H Unrestrained High Set Differential

- 87H function is not blocked by any harmonic restraint
- Pickup must be set above first peak of inrush current
- 87H is used in almost all transformer differentials to overcome restraint of 87T due to CT saturation for high internal transformer faults
- Typical pickup setting is 8 to 12 p.u.

Set at 10 p.u.
Set delay at 1 cycle
87T Sample Calculation

Step 9: Setting 87H Unrestrained High Set Differential