Testing Numerical Transformer Differential Relays

Steve Turner

Beckwith Electric Co., Inc.
Power Transformers
INTRODUCTION

Commissioning versus Maintenance Testing

Main Transformer Protection:
- Restrained Phase Differential
- High Set Phase Differential
- Ground Differential
INTRODUCTION

Topics:

- *Transformer Differential Boundary Test* (Commissioning)
- *Ground Differential Sensitivity Test* (Commissioning/Maintenance)
- Secondary Transformer Protection
- *Harmonic Restraint for Transformer Inrush* (Maintenance)
## Failure Statistics of Transformers

<table>
<thead>
<tr>
<th>Failure Type</th>
<th>1955-1965</th>
<th>% of Total</th>
<th>1975-1982</th>
<th>% of Total</th>
<th>1983-1988</th>
<th>% of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winding failures</td>
<td>134</td>
<td>51</td>
<td>615</td>
<td>55</td>
<td>144</td>
<td>37</td>
</tr>
<tr>
<td>Tap changer failures</td>
<td>49</td>
<td>19</td>
<td>231</td>
<td>21</td>
<td>85</td>
<td>22</td>
</tr>
<tr>
<td>Bushing failures</td>
<td>41</td>
<td>15</td>
<td>114</td>
<td>10</td>
<td>42</td>
<td>11</td>
</tr>
<tr>
<td>Terminal board failures</td>
<td>19</td>
<td>7</td>
<td>71</td>
<td>6</td>
<td>13</td>
<td>3</td>
</tr>
<tr>
<td>Core failures</td>
<td>7</td>
<td>3</td>
<td>24</td>
<td>2</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>12</td>
<td>4</td>
<td>72</td>
<td>6</td>
<td>101</td>
<td>26</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>262</strong></td>
<td><strong>100</strong></td>
<td><strong>1127</strong></td>
<td><strong>100</strong></td>
<td><strong>389</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

Source: IEEE C37.91
Commissioning

Common Practice:

- Test all numerical relay settings – verify settings properly entered
- Easily facilitated using computer – automate test set & store results
- Hundreds of tests are possible – numerical relays have many settings
Commissioning

**Final Goal**

- Ensure the transformer is properly protected for the *particular* application
Typical Distribution Transformer

46: Negative-Sequence Overcurrent Element
(sees ground faults through bank)

R_G: Grounding Resistor
(Industrial Load)
Sensitive setting for ground fault - overreach for phase-to-phase fault
Transformer Differential Characteristic

Boundary Test

\[ I_1 = \text{Winding 1 per unit current (A, B or C-phase)} \]
\[ I_2 = \text{Winding 2 per unit current (A, B or C-phase)} \]

3 elements per function (A, B & C-phase)
Differential Characteristic

Operating Equations

\[ I_d = |I_1 - I_2|, \quad \text{Differential Current} \]

\[ I_r = \frac{|I_1| + |I_2|}{2}, \quad \text{Restraint Current} \]
Differential Characteristic

\[ \% = \frac{Y}{X} \times 100\% \]

Diagram showing the relationship between \( I_d \) and \( I_r \) with the formula for calculating the percent (%). The diagram includes labels for minimum pickup (per unit) and a slope indicating the relationship between current values.
Differential Characteristic

Diagram:
- **Id** vs **Ir**
- **Minimum Pickup**
- **Trip Region**
- **Block Region**
- **Percent Slope**
Matrix

\[
\begin{bmatrix}
I_d \\
I_r
\end{bmatrix}
= 
\begin{bmatrix}
1 & -1 \\
\frac{1}{2} & \frac{1}{2}
\end{bmatrix}
\times
\begin{bmatrix}
I_1 \\
I_2
\end{bmatrix}
\]
Inverted Matrix

\[
\begin{bmatrix}
I_1 \\
I_2
\end{bmatrix} = \begin{bmatrix}
\frac{1}{2} & 1 \\
-\frac{1}{2} & 1
\end{bmatrix} \times \begin{bmatrix}
I_d \\
I_r
\end{bmatrix}
\]
Differential Characteristic

Test Current Equations

\[ I_1 = 0.5I_d + I_r, \text{ Winding 1 Test Current (per unit)} \]

\[ I_2 = -0.5I_d + I_r, \text{ Winding 2 Test Current (per unit)} \]
Differential Characteristic

Test Points

Minimum Pickup = 0.2 per unit
Slope = 28.6%

Minimum Pickup

\[ I_d \]

\[ I_r \]
# Differential Characteristic

**Test Points (Per Unit)**

<table>
<thead>
<tr>
<th></th>
<th>$I_d$</th>
<th>$I_r$</th>
<th>$I_1$</th>
<th>$I_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.2</td>
<td>0.3</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>2</td>
<td>0.2</td>
<td>0.7</td>
<td>0.8</td>
<td>0.6</td>
</tr>
<tr>
<td>3</td>
<td>0.4</td>
<td>1.4</td>
<td>1.6</td>
<td>1.2</td>
</tr>
<tr>
<td>4</td>
<td>0.6</td>
<td>2.0</td>
<td>2.3</td>
<td>1.7</td>
</tr>
</tbody>
</table>

**TABLE 1**
Delta-Wye Differential Characteristic

*I Simulate Through Current*

$I_1 = \text{Winding 1 per unit current (A, B or C-phase)}$

$I_2 = \text{Winding 2 per unit current (A, B or C-phase)}$

3 elements per relay (A, B & C-phase)
Delta-Wye Differential Characteristic
( Relay Internally Compensates Test Currents )

**DAB WINDING**

\[
I_{A1}^{\text{relay}} = \frac{I_{A1}}{TAP1} \\
I_{B1}^{\text{relay}} = \frac{I_{B1}}{TAP1} \\
I_{C1}^{\text{relay}} = \frac{I_{B1}}{TAP1}
\]

**WYE WINDING**

\[
I_{A2}^{\text{relay}} = \frac{(I_{A2} - I_{B2})}{(TAP2 \times \sqrt{3})} \\
I_{B2}^{\text{relay}} = \frac{(I_{B2} - I_{C2})}{(TAP2 \times \sqrt{3})} \\
I_{C2}^{\text{relay}} = \frac{(I_{C2} - I_{A2})}{(TAP2 \times \sqrt{3})}
\]

\[
TAP# = \frac{MVA#}{kV#_{LL} \times CTR# \times \sqrt{3}}
\]
Delta-Wye Differential Characteristic

(Single-Phase Test for A-Phase Element)

\[ I_{A1} = I_1 \times TAP1 \]
\[ I_{A2} = I_2 \times TAP2 \times \sqrt{3} \]

From TABLE 1:

<table>
<thead>
<tr>
<th>( I_d )</th>
<th>( I_r )</th>
<th>( I_1 )</th>
<th>( I_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>0.7</td>
<td>0.8</td>
<td>0.6</td>
</tr>
</tbody>
</table>

\[ I_{A1}^{\text{test}} = 0.8 \times TAP1 \]
\[ I_{A2}^{\text{test}} = 0.6 \times TAP2 \times \sqrt{3} \]
As an example, if we have a two winding transformer with Y/Delta-AC connection (or YD1) with Y-Y cts. This will be equivalent to case 2 with a 30° phase shift.

\[
I'_{ABC} = \begin{bmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 1
\end{bmatrix} I_{ABC}
\]

\[
I'_{ABC} = \frac{1}{\sqrt{3}} \begin{bmatrix}
1 & -1 & 0 \\
0 & 1 & -1 \\
-1 & 0 & 1
\end{bmatrix} I_{ABC}
\]

\[
I'_{ABC} = \frac{1}{\sqrt{3}} \begin{bmatrix}
0 & -1 & 1 \\
1 & 0 & -1 \\
-1 & 1 & 0
\end{bmatrix} I_{ABC}
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-1 & 1 & 0
\end{bmatrix} I_{ABC}
\]

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I'_{ABC} = \frac{1}{\sqrt{3}} \begin{bmatrix}
1 & 0 & -1 \\
-1 & 1 & 0 \\
1 & 0 & 1
\end{bmatrix} I_{ABC}
\]
Ground Differential Element

Sensitivity Test

Directionality

(I₀ vs. I₆)

Ground Fault Location along Windings
Testing Numerical Transformer Differential Relays

Ground Differential Element

Directional Element

Disabled if $|3I_0|$ less than 140 mA
(Improves Security for CT saturation during external faults)
Ground Differential Element

Pickup

Operate When:

\[ |3I_0 - I_G| > \text{Pickup} \]
Ground Differential Element

Sensitivity Test

Power System Parameters:

• Source Impedance (Varies)
• $X_T = 10\%$
• $R_F$ (Varies)
• Ground Fault Location (5% from Transformer Neutral)
Ground Differential Element

$R_F$ Coverage vs. Source Strength

87GD Sensitivity

Source Impedance vs. Fault Resistance

- IG = 200 mA
- IG = 500 mA
- IG = 1 Amp
Ground Differential Element

*Pickup Setting*

\[ I_G \]

**Cold Load Pickup**
Reclosing into Single-Phase Load

**Pickup > Unbalance**
*Directional Element Disabled if 3I_0 Low*
\[ I_{G2} = 0.3 \text{ Amps } @ \ 177^\circ \]

\[ 3I_0^{(2)} = 0.136 \text{ Amps } @ \ 58^\circ \ (\text{Threshold} = 0.14 \text{ Amps}) \]

\[ |\text{CTCF} \times 3I_0^{(2)} - I_{G2}| = 0.75 \text{ Amps} \]

Original Pickup = 0.3 Amps
Directional Element

INTERNAL

EXTERNAL

CTCF*3I_0^{(2)}

I_{G2}

I_{OP}

New Pickup = 1.0 Amps
Other Transformer Protection

- 24 – Overexcitation (V/Hz)
- 46 – Negative-Sequence Overcurrent
- 49 – Winding Overload
- 50 – Instantaneous Phase Overcurrent (per winding)
- 50G – Instantaneous Ground Overcurrent (per winding)
- 50N – Instantaneous Neutral Overcurrent (per winding)
- 51 – Inverse Time Phase Overcurrent (per winding)
- 51G – Inverse Time Ground Overcurrent (per winding)
- 51N – Inverse Time Neutral Overcurrent (per winding)
- 59G – Ground Overvoltage (Ungrounded Windings)
- 63 – Sudden Pressure
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
System Control Issues: Overvoltage and Overexcitation

Reactors are off but should be on
Overexcitation Curves
Through Fault Monitoring

**TF: Through Fault**

- Through Fault Current Threshold: 5.0
- Through Fault Current Time Delay: 30
- Pickup Operation Limit: 1000
- Cumulative FT Limit: 10000
- Current Selection: Sum1, Sum2, W1, W2, W3
- Inrush Block by Even Harmonics: Disable, Enable
- Preset Cumulative FT: 0.00
- Blocking Inputs: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18

**Outputs**

- 1, 2, 3, 4, 5, 6, 7, 8
- 9, 10, 11, 12, 13, 14, 15, 16

**Blocking Inputs**

- 1, 2, 3, 4, 5, 6, 7, 8, 9
- 10, 11, 12, 13, 14, 15, 16, 17, 18

**Threshold Values**

- 1.0, 8160 (Cycles)
- 1.0, 65535 (Operations)
- 1.0, 1000000 (kAFCycles)

**Limit Values**

- 100.0 (A)
- 1000000 (kAFCycles)
## Through Fault Monitoring

### Harmonic Differential Currents (pu)

<table>
<thead>
<tr>
<th></th>
<th>Second</th>
<th>Fourth</th>
<th>Fifth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase A</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Phase B</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Phase C</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

### Thermal Currents (A)

<table>
<thead>
<tr>
<th></th>
<th>Summing 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase A</td>
<td>0</td>
</tr>
<tr>
<td>Phase B</td>
<td>0</td>
</tr>
<tr>
<td>Phase C</td>
<td>0</td>
</tr>
</tbody>
</table>

### Breaker Monitor Accumulators

<table>
<thead>
<tr>
<th></th>
<th>W1 (kA Cycles)</th>
<th>W2 (kA Cycles)</th>
<th>W3 (kA Cycles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase A</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Phase B</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Phase C</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

### Demand Currents (A)

<table>
<thead>
<tr>
<th></th>
<th>W1</th>
<th>W2</th>
<th>W3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase A</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Phase B</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Phase C</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

### Through Fault

<table>
<thead>
<tr>
<th></th>
<th>Counter</th>
<th>Cumulative Currents (kA^2 Cycles)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Even Harmonic Restraint during Inrush

**COMTRADE PLAYBACK**

Waveform Sources:
- Events from Numerical Relays
- Events from Digital Fault Recorders
- Simulate using Transient Software
Even Harmonic Restraint during Inrush

Traditional Approach

• 2nd Harmonic Restraint
• Cross Phase Blocking
Even Harmonic Restraint during Inrush

Auto-Transformer Model

13.2 kV

W3

delta

W1  W2

wye  wye

345 kV  230 kV

600 MVA Auto-Transformer (Tertiary Winding DAC)
Even Harmonic Restraint during Inrush

Auto-Transformer Model

Auto-transformer Characteristics

- \( Z_{HM} = 0.01073 \) per unit
- \( Z_{HL} = 0.04777 \) per unit
- \( Z_{ML} = 0.03123 \) per unit

\[
Z_{H} = \frac{Z_{HM} + Z_{HL} - Z_{ML}}{2} = 0.0140 \text{ per unit}
\]

\[
Z_{M} = \frac{Z_{HM} + Z_{ML} - Z_{HL}}{2} = -0.0029 \text{ per unit}
\]

\[
Z_{L} = \frac{Z_{HL} + Z_{ML} - Z_{HM}}{2} = 0.0340 \text{ per unit}
\]

- \( CTR_{W1} = 1200:5 \) (wye connected)
- \( CTR_{W2} = 2000:5 \) (wye connected)
Even Harmonic Restraint during Inrush

Auto-Transformer Model

\[
\begin{align*}
\text{TAP1} &= \frac{600 \text{ MVA}}{345 \text{ kV} \times 240 \times \sqrt{3}} = 4.18 \\
\text{TAP2} &= \frac{600 \text{ MVA}}{230 \text{ kV} \times 400 \times \sqrt{3}} = 3.77 \\
\text{Minimum Pickup}^* &= 0.5 \text{ per unit} \\
\text{Slope} &= 25\% \\
\text{*Original Pickup} &= 0.45 \text{ per unit}
\end{align*}
\]
Even Harmonic Restraint during Inrush

Energize Bank with Heavy A-Phase Residual Flux
Even Harmonic Restraint during Inrush

Energize Bank with Heavy A-Phase Residual Flux

2nd Harmonic Phase Current
Even Harmonic Restraint

\[ I_{\text{even}} = (I_2^2 + I_4^2)^{1/2} \]
Cross Phase Averaging

- Provides security if any phase has low harmonic content during inrush

- Cross phase averaging uses the sum of harmonics on all three phases as the restraint value

\[ I_{d_{CPA24}} = \sqrt{I_{Ad_{24}}^2 + I_{Bd_{24}}^2 + I_{Cd_{24}}^2} \]
Even Harmonic Restraint during Inrush

Energize Bank with Heavy A-Phase Residual Flux

4th Harmonic Phase Current
Even Harmonic Restraint during Inrush

A-Phase Current (Winding 2)
CONCLUSIONS
CONCLUSIONS

- Transformer Differential Boundary Test (Commissioning)
- Ground Differential Sensitivity Test (Commissioning/Maintenance)
- Harmonic Restraint for Transformer Inrush (Maintenance)
QUESTIONS