Case study: analysis of 138/13.8 kV transformer differential misoperation points to faulty CT

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2019 Texas A&M Protective Relaying Conference
Agenda

• Introduction
• History of Transformer Percentage Differential
• Enhancements to Percentage Differential
• Harmonic Restraint (Blocking) of Percentage Differential
• Securing Percentage Differential using Directionality Check and CT Saturation Detection
• Settings of Percentage Differential
• Analysis of 138/13.8 kV Transformer Differential Incorrect Operation
• Conclusion
Introduction

- Transformer Protection Original fuses, later Overcurrent
- Not very selective; Current/Time used for Coordination – Internal Faults NOT Instantaneous
- Transformer Protection Evolved, Schemes can include:

1. Percentage Differential
2. Instantaneous/Unrestraint Differential
3. Restricted Ground Fault
4. Sudden Pressure (Buchholz)
5. Oil/Winding Temperature
6. Phase/Neutral/Ground/Neg Seq Inst & Timed OC
7. Phase/Neutral/Ground/Neg Seq Dir OC
8. Breaker Fail
9. Phase and Ground Distance
10. Volts per Hertz (Over Fluxing)
11. Phase Under/Over Voltage
12. Neutral/Neg Seq Overvoltage
13. Tank Ground Fault
14. Dissolved Gas in Oil (DGA)
First Transformer Differential was Overcurrent only

- External Faults
- Internal Faults

External load or fault

Internal fault
History of Transformer Percentage Differential

• First Transformer Differential with Restraint:

- Coils Connected

• Operating Characteristic

- Positive–torque region
- Negative–torque region
Enhancements to Percentage Differential

- Percentage Differential Enhanced in IEDs for added Sensitivity:

- Two Regions of Percentage Differential

  **Region 1 (DIF₁)**
  - Low current magnitudes
  - CT saturation likely
  - CT saturation easy to detect

  **Region 2 (DIF₂)**
  - High current magnitudes ⇒ Quick CT saturation unlikely, due to DC offset
Harmonic Restraint of Percentage Differential

- Percentage Differential still challenged during Transformer Energization

- Multiple event types can cause Inrush/Harmonics:
  1. External Fault
  2. Voltage Recover after Ext Fault
  3. Fault Change eg. PG to PPG
  4. Out-of-phase Gen Synch
  5. CT Saturation during Inrush
  6. Inrush during Fault Removal
  7. Sympathetic Inrush

- Electromechanicals & early IEDs used fixed 20% of 2\textsuperscript{nd}/fundamental magnitude to restrain (block) percentage differential

- Modern Transformers much lower 2\textsuperscript{nd} harmonics (7-10%) – due to improvements

- Improvements to Harmonic Restraint:
  1. Adjustable levels of 2\textsuperscript{nd} Harm
  2. Account for 2\textsuperscript{nd} Harm Phase Angle
  3. 1-of-3, 2-of-3, 3-of-3 Inhibit
  4. 5\textsuperscript{th} Harm Restraint added
Securing Percentage Differential With Dir Chec

- Directionality Check of Current Phase Angles: (No Voltages Used)

**External Fault Conditions**

\[
\text{imag} \left( \frac{I_p}{I_D - I_p} \right) \quad \text{BLOCK}
\]

\[
I_D - I_p \quad I_p
\]

**Internal Fault Conditions**

\[
\text{imag} \left( \frac{I_p}{I_D - I_p} \right) \quad \text{BLOCK}
\]

\[
I_D - I_p \quad I_p
\]
Securing Percentage Differential With CT Satur.

- CTs provide typically 2-4 ms unsaturated current
- Fault starts at $t_0$, CT starts to saturate at $t_1$, fully saturated at $t_2$
• Electromechanical relays needed secondary currents to be same phase and magnitude, hence Wye-winding CTs connected in Delta and Aux CTs needed

• All CTs on IEDs Wye-connected; magnitude and phase angle compensated numerically

• Compensated currents calculated based on Magnitude and Phase, e.g. for 30° lag:

<table>
<thead>
<tr>
<th>$Q_{\text{comp}}[w]$</th>
<th>Grounding[w] = “Not within zone”</th>
<th>Grounding[w] = “Within zone”</th>
</tr>
</thead>
<tbody>
<tr>
<td>30° lag</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$i_a^P[w]$</td>
<td>$\frac{1}{\sqrt{3}}i_a[w] - \frac{1}{\sqrt{3}}i_c[w]$</td>
<td>$i_a^P[w] = \frac{1}{\sqrt{3}}i_a[w] - \frac{1}{\sqrt{3}}i_c[w]$</td>
</tr>
<tr>
<td>$i_b^P[w]$</td>
<td>$\frac{1}{\sqrt{3}}i_c[w] - \frac{1}{\sqrt{3}}i_a[w]$</td>
<td>$i_b^P[w] = \frac{1}{\sqrt{3}}i_c[w] - \frac{1}{\sqrt{3}}i_a[w]$</td>
</tr>
<tr>
<td>$i_c^P[w]$</td>
<td>$\frac{1}{\sqrt{3}}i_a[w] - \frac{1}{\sqrt{3}}i_c[w]$</td>
<td>$i_c^P[w] = \frac{1}{\sqrt{3}}i_a[w] - \frac{1}{\sqrt{3}}i_c[w]$</td>
</tr>
</tbody>
</table>

• Differential current calculated as: $I_d = \overrightarrow{i_{1(\text{comp})}} + \overrightarrow{i_{2(\text{comp})}}$

• Restraint can be: Sum of, scaled sum of, geometrical average, maximum of

• Most commonly used: “Max Of”
The Following Setting must be calculated:

**Minimum Pickup**
1. Defines Minimum Differential Pickup at 0 Restraint
2. Compensates for CT Errors at low currents
3. Must be above leakage current not zoned

**Low Slope**
1. Defines Percent Bias for Restraint A0 to Low Breakpt
2. Determines Sensitivity at Low-current Int Faults
3. Must be above CT Errors in Linear Operating Mode
4. Include errors due to Tap Changers
5. Based on CT performance in Linear Operating mode:

\[
\text{Slope} = \frac{\Delta I_d}{\Delta I_r} \times 100\% \text{ (in pu)}
\]

**Maximum Differential Current** can be calculated based on CT Performance using IEEE PSRC CT Saturation Calculator.
• **Low Breakpoint**
  1. Defines Upper Limit of Diff/Restraint of Low Slope
  2. Must be above Max Load and all CTs still Linear (including Remanence Flux)
  3. CTs Must be Linear with up to 80% Remanence Flux up to Low Breakpoint

• **High Breakpoint**
  1. Defines Min Limit of Diff/Restraint of High Slope
  2. Must be Minimum A where weakest CT Saturates with no Remanence Flux

• **High Slope**
  1. Defines Percent Bias for Restraint A above High Breakpoint
  2. Determines Stability of Diff at High External Faults
  3. Must be high to tolerate Spurious Diff CT Sat on Ext F
  4. Can be relaxed if Dir Check and CT Sat Detect used

• **Maximum Differential Current** can be calculated based on CT Performance using IEEE PSRC CT Saturation Calculator
Settings of Percentage Differential (4)

- CT Saturation Calculator

### CT Saturation Calculator

**Contents**
- Sheet 1: CALCULATOR (this sheet)
- Sheet 2: INSTRUCTIONS
- Sheet 4: BACKGROUND

**Excel Spreadsheet**

- Sheet 1: CALCULATOR
- Sheet 2: INSTRUCTIONS
- Sheet 4: BACKGROUND

**Assumptions:**
- CT core losses and secy reactance zero (thru-hole primary).
- Frequency 60 Hz
- CT primary current is zero for k<0
- CT is 5 amp nominal
- Time step = 1/12,000 second

**Input Parameters:**
- Inverse of sat. curve slope = S
- RMS voltage at 10A exc. current = Vs
- Turns ratio = N
- Winding resistance = Rw
- Burden resistance = Rb
- Burden reactance = Xb
- System X/R ratio = XoverR
- Per unit offset in primary current = Off
- Per unit remonence (based on Vs) = Irem
- Symmetrical primary fault current = Ip

**Calculated:**
- \( R_t \) = Total burden resistance = Rw + Rb
- \( p_f \) = Total burden power factor = 0.894
- \( Z_b \) = Total burden impedance = 4.472 ohms
- \( \tau_s \) = System time constant = 0.032 seconds
- Lamia = Pass flux-linkages corresponding to Vs = 1.501 Wb-turns
- \( \omega \) = Radian freq = 376.99 rad/s
- \( R_p \) = Rms-to-peak ratio = 0.34584
- A = Coefficient in instantaneous ie vs. lambda curve: ic = A * PS = 3.83E-03
- \( dt \) = Time step = 0.000083 seconds
- \( L_b \) = Burden inductance = 0.00531 henries

**Graphical Representation:**

- 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.
• Percentage differential operated incorrectly during an external AG fault on the 13.8kV side of the 30MVA, 138kV/13.8kV Dy-1 transformer.

• Differential operation happened in phase C, 140ms into the fault when external fault was cleared and restraint became smaller than differential.

• Other transformer protection relays (OC and B-Protection) did not operate.

• Both windings waveforms looked perfect, however differential current built very rapidly.

• No CT saturation observed

• Directional Check and CT Saturation Detection NOT used

• Why did it happened and what may be wrong?
Introduction

lad=Ibd=0, lcd=0.472pu ???
**TRANSFORMER SETTINGS AND CTs**

<table>
<thead>
<tr>
<th>Number of Windings</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>W2</td>
</tr>
<tr>
<td>Rated(MVA)</td>
<td>30</td>
</tr>
<tr>
<td>Nom. (KV)</td>
<td>138</td>
</tr>
<tr>
<td>Connection</td>
<td>DELTA</td>
</tr>
<tr>
<td>Grounding</td>
<td>NO</td>
</tr>
<tr>
<td>Angle WRT</td>
<td>0</td>
</tr>
<tr>
<td>CT primary</td>
<td>600</td>
</tr>
<tr>
<td>CT sec. tap</td>
<td>5</td>
</tr>
<tr>
<td>Inhom. Prim.</td>
<td>125.5</td>
</tr>
<tr>
<td>Inhom. Sec.</td>
<td>1.046</td>
</tr>
<tr>
<td>Rotations</td>
<td>ABC</td>
</tr>
</tbody>
</table>

**DIFF / RSTR CHARACTERISTIC**

**DIFFERENTIAL - RESTRAINT GRAPH**

| Diff. min., PKP | 0.35 | Slope1 | 25.0 |
| Kneepoint 1 | 1.30 |
| Kneepoint 2 | 2.00 | Slope2 | 75.0 |

**Pre-calculated graph points**

<table>
<thead>
<tr>
<th>idlr, (%)</th>
<th>Ph A</th>
<th>Ph B</th>
<th>Ph C</th>
</tr>
</thead>
<tbody>
<tr>
<td>25.0</td>
<td>25.0</td>
<td>25.0</td>
<td></td>
</tr>
</tbody>
</table>

**ACTUAL VALUES**

| Magnitude Ref. Winding #: | 2 |

**DIFFERENTIAL CURRENTS**

<table>
<thead>
<tr>
<th>lad</th>
<th>lbr</th>
<th>lcd</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02</td>
<td>0.06</td>
<td>0.37</td>
</tr>
<tr>
<td>-55.3</td>
<td>-75.0</td>
<td>-194.0</td>
</tr>
</tbody>
</table>

**RESTRAINT CURRENTS**

<table>
<thead>
<tr>
<th>lar</th>
<th>lbr</th>
<th>lcr</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.77</td>
<td>0.20</td>
<td>0.96</td>
</tr>
</tbody>
</table>

**Actual Differential/Restraint Ratio**

<table>
<thead>
<tr>
<th>ph A %</th>
<th>ph B %</th>
<th>ph C %</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.7</td>
<td>1.3</td>
<td>38.3</td>
</tr>
</tbody>
</table>

**DIFF. OPERATION**

<table>
<thead>
<tr>
<th>No Trip</th>
<th>No Trip</th>
<th>Trip</th>
</tr>
</thead>
</table>
• Setting error?

Doesn’t look like…
Investigation

- Relay algorithm error?

<table>
<thead>
<tr>
<th>Phase</th>
<th>Pre-fault</th>
<th></th>
<th>Fault</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Delta 138kV</td>
<td>Wye 13.8kV</td>
<td>Delta 138kV</td>
</tr>
<tr>
<td>A</td>
<td>0.600A∠-241.9°</td>
<td>1.222A∠-91.8°</td>
<td>3.309A∠-306.6°</td>
</tr>
<tr>
<td>B</td>
<td>0.603A∠0°</td>
<td>1.157A∠-212.1°</td>
<td>0.769A∠0°</td>
</tr>
<tr>
<td>C</td>
<td>0.572A∠-116.5°</td>
<td>1.234A∠-332.7°</td>
<td>3.866A∠-118.9°</td>
</tr>
</tbody>
</table>

We can verify relay response to these phasors. For given transformer group D/Yg-1, compensation currents are calculated:

**Delta**

$$\Phi_{\text{comp}}[w] = \text{"Not within zone"}$$

- $$I_A^P[w] = I_A[w]$$
- $$I_B^P[w] = I_B[w]$$
- $$I_C^P[w] = I_C[w]$$

**Wye-grounded**

$$330\degree$$

- $$I_A^P[w] = \frac{1}{\sqrt{3}}I_A[w] - \frac{1}{\sqrt{3}}I_B[w]$$
- $$I_B^P[w] = \frac{1}{\sqrt{3}}I_B[w] - \frac{1}{\sqrt{3}}I_C[w]$$
- $$I_C^P[w] = \frac{1}{\sqrt{3}}I_C[w] - \frac{1}{\sqrt{3}}I_A[w]$$
Relay algorithm error?

\[ I_d = m_1 \cdot \begin{bmatrix} IA_{1c} \\ IB_{1c} \\ IC_{1c} \end{bmatrix} + m_2 \cdot \begin{bmatrix} IA_{2c} \\ IB_{2c} \\ IC_{2c} \end{bmatrix} \]

\[ m_1 = 2 \text{ and } m_2 = 1 \] are magnitude compensation factors for each winding.

For phase C, where high differential current was observed. Pre-fault:

\[ IC_d = 2 \cdot IC_1 + 1 \cdot \left[ IA_2 \frac{1}{\sqrt{3}} + IC_2 \frac{1}{\sqrt{3}} \right] = 2 \cdot \left[ 0.572e^{-j116.5^\circ} + 1 \cdot \left[ 1.222e^{-j91.8^\circ} \cdot \frac{1}{\sqrt{3}} + 1.234e^{-j332.7^\circ} \cdot \frac{1}{\sqrt{3}} \right] \right] \]

= 0.14A or 0.029pu

Fault:

\[ IC_d = 2 \cdot IC_1 + 1 \cdot \left[ IA_2 \frac{1}{\sqrt{3}} + IC_2 \frac{1}{\sqrt{3}} \right] = 2 \cdot \left[ 3.866e^{-j118.9^\circ} + 1 \cdot \left[ 12.045e^{-j133.6^\circ} \cdot \frac{1}{\sqrt{3}} + 1.265e^{-j347.8^\circ} \cdot \frac{1}{\sqrt{3}} \right] \right] \]

= 2.374A or 0.476pu
Investigation

• Time out! Time to think where we are…
• Settings seems correct
• Waveforms look credible (No CT saturation)
• Differential current relay calculated from waveforms and settings seems correct as well.
• Let’s dig in…something must be wrong!

\[ I_d = m_1 \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} + m_2 \cdot \begin{bmatrix} \frac{1}{\sqrt{3}} & \frac{-1}{\sqrt{3}} & 0 \\ 0 & \frac{-1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \\ \frac{-1}{\sqrt{3}} & 0 & \frac{1}{\sqrt{3}} \end{bmatrix} \]

\[ \begin{bmatrix} IA_1 \\ IB_1 \\ IC_1 \end{bmatrix} + \begin{bmatrix} IA_2 \\ IB_2 \\ IC_2 \end{bmatrix} = \begin{bmatrix} 0.02pu \\ 0.006pu \\ 0.475pu \end{bmatrix} \]

• Only Differential phase C is high, out of 6 currents, incorrect \( IC_1 \) only from delta side can cause high phase C differential without affecting other phases.
• Can we prove that delta side $I_{C_1}$ is erroneous?

• We know that for unloaded transformer (ignoring magnetizing current), delta currents should be $180^\circ$ apart for P-G fault on Wye.

If we remove load current and rotate delta side phase A current by $180^\circ$, we should get “correct” phase C current.
\[ IC'_1 = (IA_{1F} - IA_{1L}) \cdot 1e^{j180°} + IC_{1L} = (3.309 e^{-j306.6°} - 0.6 e^{-j241.9°}) \cdot 1e^{j180°} + 0.572 e^{-j116.5°}\]

\[ = 3.643 e^{-j133.6°}\]

\( IC_{1L} \) is highlighted because as we suspect CT or CT wiring problem, we cannot 100% trust even pre-fault value.

Again differential calculation with assumed delta phase C current fault value

\[ IC_d = 2 \cdot IC_1 + 1 \cdot \left[ IA_2 \frac{-1}{\sqrt{3}} + IC_2 \frac{1}{\sqrt{3}} \right] = 2 \cdot 3.643 e^{-j133.6°} + 1 \cdot \left[ 12.045 e^{-j133.6°} \cdot \frac{-1}{\sqrt{3}} + 1.265 e^{-j347.8°} \cdot \frac{1}{\sqrt{3}} \right] \]

\[ = 0.496A \text{ or } 0.099pu \]
We proved that differential reduced from 0.476pu to 0.099pu by using assumed IC current derived from healthy IA current.

Differential is not reduced to zero, because we still use untrusted IC pre-fault value and ignore magnetizing current.

Now we have reasonable confidence that CT or CT wiring of the C phase is faulty.

CT Testing will reveal the truth!!!
Conclusions

• Percentage Differential is fast, dependable and secure; forms important part of Transformer Protection Scheme

• This function was enhanced with added sensitivity (changes to characteristic) and security (CT saturation detection and Directionality check)

• When investigating suspicious relay operation, don’t take anything for granted; consider settings errors, wiring errors, instrument transformers errors and relay h/w or s/w issues.

• Use analytical skills, literature, s/w analytical programs to identify possible causes and prove these possible causes right or wrong.

• Consult with colleagues, equipment manufacturers and Industry Experts.

• Don’t rush to blame the relay h/w or s/w, as we learnt from this case, even unlikely, but CT failure can happen as well.
Thank You

Questions?