Case study: Analysis of 138/13.8 kV Transformer Differential Misoperation points to Faulty CT

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• 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
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)
History of Transformer Percentage Differential

- First Transformer Differential was Overcurrent only

- External Faults

- Internal Faults
History of Transformer Percentage Differential

• First Transformer Differential with Restraint:

• Coils Connected

• Operating Characteristic
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 unlikely, due to DC offset

  **Region 2 (DIF₂)**
  - High current magnitudes ⇒ Quick CT saturation likely
  - CT saturation easy to detect
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 2nd/fundamental magnitude to restrain (block) percentage differential

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

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

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

External Fault Conditions

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

Internal Fault Conditions

\[ \text{imag} \left( \frac{I_p}{I_D - I_p} \right) \]
Securing Percentage Differential With CT Saturation

- CTs provide typically 2-4 ms unsaturated current
- Fault starts at $t_0$, CT starts to saturate at $t_1$, fully saturated at $t_2$
Settings of Percentage Differential

- 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, eg. for 30deg lag:

<table>
<thead>
<tr>
<th>$Q_{\text{comp}}[w]$</th>
<th>Grounding[$w$] = &quot;Not within zone&quot;</th>
<th>Grounding[$w$] = &quot;Within zone&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>30° lag</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$i_a^p[w] = \frac{1}{\sqrt{3}}i_a[w] - \frac{1}{\sqrt{3}}i_c[w]$</td>
<td>$i_a^p[w] = \frac{1}{\sqrt{3}}i_a[w] - \frac{1}{\sqrt{3}}i_c[w]$</td>
<td></td>
</tr>
<tr>
<td>$i_b^p[w] = \frac{1}{\sqrt{3}}i_b[w] - \frac{1}{\sqrt{3}}i_c[w]$</td>
<td>$i_b^p[w] = \frac{1}{\sqrt{3}}i_b[w] - \frac{1}{\sqrt{3}}i_c[w]$</td>
<td></td>
</tr>
<tr>
<td>$i_c^p[w] = \frac{1}{\sqrt{3}}i_c[w] - \frac{1}{\sqrt{3}}i_a[w]$</td>
<td>$i_c^p[w] = \frac{1}{\sqrt{3}}i_c[w] - \frac{1}{\sqrt{3}}i_a[w]$</td>
<td></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
CT Saturation Calculator

**CONTENTS**

Sheet 1: CALCULATOR (this sheet)
Sheet 2: INSTRUCTIONS
Sheet 3: BACKGROUND

**ASSUMPTIONS:**
- CT core losses and secy reactance zero (thru-hole primary).
- Frequency 60 Hz
- CT primary current is zero for t<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 = Of
- Per unit remanence (based on Vs) = irm
- Symmetrical primary fault current = Ip

**CALCULATED:**
- Rl = Total burden resistance = Rw + Rb
- pfl = Total burden power factor = 0.894
- Zb = Total burden impedance = 4.472 ohms
- Tau = System time constant = 0.022 seconds
- Lambda = rms flux-linkages corresponding to Vs = 1.501 Wb-turns
- omega = Radian freq = 376.99 rad/s
- RP = Rms-to-peak ratio = 0.34584
- A = Coefficient in instantaneous ie versus lambda curve: ie = A * Ia * K:
  - dp = Time step = 0.000003 seconds
  - Db = Burden inductance = 0.00031 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.
Analysis of 138/13.8kV Diff Incorrect Operation

- 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

I_{ad} = I_{bd} = 0, I_{cd} = 0.472pu ???
Investigation

• Setting error?

Doesn’t look like…
• Relay algorithm error?

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

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

\[
\begin{align*}
\Phi_{comp}[w] & = 0^\circ \\
\text{Grounding}[w] & = \text{“Not within zone”} \\
I_A^p[w] & = I_A[w] \\
I_B^p[w] & = I_B[w] \\
I_C^p[w] & = I_C[w]
\end{align*}
\]

\[
\begin{align*}
I_A^p[w] & = \frac{1}{\sqrt{3}}I_A[w] - \frac{1}{\sqrt{3}}I_B[w] \\
I_B^p[w] & = \frac{1}{\sqrt{3}}I_B[w] - \frac{1}{\sqrt{3}}I_C[w] \\
I_C^p[w] & = \frac{1}{\sqrt{3}}I_C[w] - \frac{1}{\sqrt{3}}I_A[w]
\end{align*}
\]
Investigation

- Relay algorithm error?

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

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

For phase C, where high differential current was observed.

Pre-fault:

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

\[ = 0.14A \text{ or } 0.029pu \]

Fault:

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

\[ = 2.374A \text{ or } 0.476pu \]
• 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!

\[ I_d = m_1 \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} + m_2 \cdot \begin{bmatrix} \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{3}} & 0 \\ 0 & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{3}} \\ -\frac{1}{\sqrt{3}} & 0 & \frac{1}{\sqrt{3}} \end{bmatrix} \cdot \begin{bmatrix} I_{A_2} \\ I_{B_2} \\ I_{C_2} \end{bmatrix} = \begin{bmatrix} 0.02 \text{pu} \\ 0.006 \text{pu} \\ 0.475 \text{pu} \end{bmatrix} \]

• Only Differential phase C is high, out of 6 currents, incorrect \( I_{C_1} \) 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.
Investigation

\[ IC'_1 = (IA_{1F} - IA_{1L}) \cdot 1e^{j180^\circ} + IC_{1L} = (3.309e^{-j306.6^\circ} - 0.6e^{-j241.9^\circ}) \cdot 1e^{j180^\circ} + 0.572e^{-j116.5^\circ} = 3.643e^{-j133.6^\circ} \]

\( IC_{1L} \) 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

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

\[ = 0.496A \text{ or } 0.099pu \]
Investigation

• 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!!!
Testing

**Phase A Test**

**Phase B Test**

**Phase C Test**

<table>
<thead>
<tr>
<th>Connection</th>
<th>Ratio</th>
<th>Metering</th>
<th>Relaying</th>
<th>Secondary Resistance (ohms) @ 76°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>X1-X2</td>
<td>1000-5</td>
<td></td>
<td></td>
<td>C200</td>
</tr>
<tr>
<td>X1-X3</td>
<td>2200-5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X1-X4</td>
<td>2500-5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X1-X5</td>
<td>3000-5</td>
<td></td>
<td></td>
<td>0.851</td>
</tr>
</tbody>
</table>

**CT Excitation Curve**

**CT Excitation Plot**
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?