Improving Transformer Protection

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Beckwith Electric’s 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 strategies, 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 and control seminars.
- Senior Member of IEEE, serving as a Main Committee Member of the Power System Relaying and Control Committee for more than 25 years.
- Chair Emeritus of the IEEE PSRCC Rotating Machinery Protection subcommittee (’07-’10).
- Contributed to numerous IEEE Standards, Guides, Reports, Tutorials and Transactions, delivered Tutorials IEEE Conferences, and authored and presented numerous technical papers at key industry conferences.
Abstract

• Power transformers play a critical role in process continuity

• Transformers are subject to:
  – Internal short circuits
  – External short circuits
  – Abnormal operating conditions

• Challenges:
  – CT remanence & high X/R ratio
  – Inrush
  – Overexcitation
  – Ground fault sensitivity
Transformers: T & D
Transformers: T & D
Transformers: T & D
Transformer: GSU Step Up
FAILURE!
FAILURE!
FAILURE!
Remanence & X/R Ratio: CT Saturation

• Remanent Flux
  – Magnetization left behind in CT iron after an external magnetic field is removed
  – Caused by current interruption with DC offset

• High X/R Ratio
  – Increases the time constant of CT saturation period

• CT saturation is increased by the above factors working alone or in combination with:
  – Large fault or through-fault current (causes high secondary CT voltage)
IEEE CT Saturation Calculator

• The IEEE Power System Relaying & Control Committee (PSRCC) developed a simplified model for CT saturation
  – Includes the major parameters that should be considered.

• Examples of saturation with a 2-node bus

Internal Fault

External Fault
CT Saturation [1]

400:5, C400, R=0.5, Offset = 0.5, 2000A
CT Saturation [2]

400:5, C400, R=0.5, Offset = 0.5, 4000A
CT Saturation [3]

### INPUT PARAMETERS:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Enter Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inverse of sat. curve slope</td>
<td>S = 22</td>
</tr>
<tr>
<td>RMS voltage at 10A exc. current</td>
<td>Vs = 400</td>
</tr>
<tr>
<td>Turns ratio = n2/1</td>
<td>N = 80</td>
</tr>
<tr>
<td>Winding resistance</td>
<td>Rw = 0.300</td>
</tr>
<tr>
<td>Burden resistance</td>
<td>Rb = 0.500</td>
</tr>
<tr>
<td>Burden reactance</td>
<td>Xb = 0.500</td>
</tr>
<tr>
<td>System X/R ratio</td>
<td>XoverR = 12.0</td>
</tr>
<tr>
<td>Per unit offset in primary current</td>
<td>Off = 0.500</td>
</tr>
<tr>
<td>Per unit remanence (based on Vs)</td>
<td>Irem = 0.500</td>
</tr>
<tr>
<td>Symmetrical primary fault current</td>
<td>Ip = 8000</td>
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</table>

### CALCULATED:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rt = Total burden resistance</td>
<td>0.800 ohms</td>
</tr>
<tr>
<td>pf = Total burden power factor</td>
<td>0.848</td>
</tr>
<tr>
<td>Zb = Total burden impedance</td>
<td>0.943 ohms</td>
</tr>
<tr>
<td>Tau1 = System time constant</td>
<td>0.032 seconds</td>
</tr>
<tr>
<td>Lamsat = Peak flux-linkages corresponding to Vs</td>
<td>1.501 Wb-turns</td>
</tr>
<tr>
<td>ω = Radian freq</td>
<td>376.99 rad/s</td>
</tr>
<tr>
<td>RP = Rms-to-peak ratio</td>
<td>0.34584</td>
</tr>
<tr>
<td>A = Coefficient in instantaneous ie</td>
<td>3.63E-03</td>
</tr>
<tr>
<td>dT = Time step</td>
<td>0.000083 seconds</td>
</tr>
<tr>
<td>Lb = Burden inductance</td>
<td>0.00133 henries</td>
</tr>
</tbody>
</table>

400:5, C400, R=0.5, Offset = 0.5, 8000A
CT Saturation [4]

400:5, C400, R=0.5, Offset = 0.75, 8000A
CT Saturation [5]

**INPUT PARAMETERS:**
- Inverse of sat. curve slope = \( S = 22 \)
- RMS voltage at 13A exc. current = \( V_s = 400 \) volts rms
- Turns ratio = \( n_{2/1} = 80 \)
- Winding resistance = \( R_w = 0.300 \) ohms
- Burden resistance = \( R_b = 0.500 \) ohms
- Burden reactance = \( X_b = 0.500 \) ohms
- System X/R ratio = \( X_{ov/1} = 12.0 \)
- Per unit offset in primary current = \( \text{Off} = 0.75 \) -1 < Off < 1
- Per unit remanence (based on \( V_s \)) = \( \lambda_{rem} = 0.75 \)
- Symmetrical primary fault current = \( I_p = 8.000 \) amps rms

**ENTER:**

**CALCULATED:**
- \( R_t = \text{Total burden resistance} = R_w + R_b = 0.800 \) ohms
- \( p_f = \text{Total burden power factor} = 0.848 \)
- \( Z_b = \text{Total burden impedance} = 0.943 \) ohms
- \( \tau_{11} = \text{System time constant} = 0.032 \) seconds
- \( \text{Lmsat} = \text{Peak flux-linkages corresponding to} V_s = 1.501 \) Wb-turns
- \( \omega = \text{Radian freq} = 376.99 \) rad/s
- \( R_p = \text{Rms-to-peak ratio} = 0.34584 \)
- \( A = \text{Coefficient in instantaneous i.e. versus lambda curve} = 3.83E-03 \)
- \( \Delta t = \text{Time step} = 0.000063 \) seconds
- \( L_b = \text{Burden inductance} = 0.00133 \) 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.

**Equation:**
400:5, C400, \( R=0.75 \), Offset = 0.75, 8000A
Differential Element Quantities

- Restraining versus Operating

\[ I_{RES} = \sum |I_{W1}| + |I_{W2}| / 2 \]

\[ I_{OP} = I_{W1} + I_{W2} \]

- Assumptions
  - Rated current (full load): 400A = 1 pu
  - Maximum through or internal fault current = 20X rated = 20pu

<table>
<thead>
<tr>
<th>Fig</th>
<th>Rated I</th>
<th>Test I</th>
<th>Rated/Test (pu)</th>
<th>% Diff (max)</th>
<th>EXT·Op</th>
<th>EXT·Res</th>
<th>INT·Op</th>
<th>INT·Res</th>
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<tbody>
<tr>
<td>2</td>
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<td>2000</td>
<td>5</td>
<td>0</td>
<td>0</td>
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<td>5</td>
</tr>
<tr>
<td>3</td>
<td>400</td>
<td>4000</td>
<td>10</td>
<td>5</td>
<td>0.5</td>
<td>9.75</td>
<td>20.5</td>
<td>9.75</td>
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<tr>
<td>4</td>
<td>400</td>
<td>8000</td>
<td>20</td>
<td>25</td>
<td>5</td>
<td>17.5</td>
<td>36</td>
<td>17.5</td>
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<tr>
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<td>400</td>
<td>8000</td>
<td>20</td>
<td>45</td>
<td>9</td>
<td>15.5</td>
<td>32</td>
<td>15.5</td>
</tr>
<tr>
<td>6</td>
<td>400</td>
<td>8000</td>
<td>20</td>
<td>50</td>
<td>10</td>
<td>15</td>
<td>31</td>
<td>15</td>
</tr>
</tbody>
</table>
Characteristic & Values Plot

- Pick Up: 0.35pu
- Slope 1 Breakpoint: 1.5pu
- Slope 1: 57%
- Slope 2 Breakpoint: 3.0pu
- Slope 2: 200%

- Relay elements from different manufacturers use different restraining and operating calculations
- Careful evaluation is recommended

\[ I_{RES} = \sum \left| I_{W1} \right| + \left| I_{W2} \right| \]

Modeled Test Plots
Coping with Transformer Inrush

• Initial energizing inrush that occurs when the transformer is energized from the completely deenergized state

• Sympathetic inrush that occurs when an energized transformer undergoes inrush after a neighboring transformer energizes

• Recovery inrush that occurs after a fault occurs and is cleared
Coping with Transformer Inrush

- Inrush current is distinguishable from fault current by the inclusion of harmonic components.
- 2nd harmonic restraint has traditionally been applied to prevent undesired tripping of differential elements.
- 2nd harmonic quantity depends upon the magnetizing characteristics of the transformer core and residual magnetism present in the core.
Coping with Transformer Inrush

- Modern transformers tend to have:
  - Low core losses
  - Step lap construction
  - Very steep magnetizing characteristics
  - Lower values of 2nd harmonic on inrush

- Fortunately, *even* order harmonics are generated during inrush, not only 2nd harmonic

- Use 2\textsuperscript{nd} and 4\textsuperscript{th} harmonic as a restraining quantity for inrush.

\[
I_{RES:2nd-4th} = \sqrt{(I_{RES:2nd}^2 + I_{RES:4th}^2)}
\]
Transformer Inrush Harmonics

Inrush Currents:
- Actual, Fundamental, 2nd Harmonic and 4th Harmonic Levels
- 2nd and 4th inrush harmonics are approximately 1/5 the value of the fundamental value.
Transformer Overexcitation
Creates Excess Flux

• Occurs whenever the ratio of V/Hz at the secondary terminals of a transformer exceeds:
  • Full Load: 1.05 per unit (PU) on transformer base, 0.8 power factor
  • No Load: 1.1 PU

- Localized overheating and breakdown
  • Core assembly
  • Winding insulation
Coping with Transformer Overexcitation

• Non-laminated components at the ends of the cores begin to heat up because of the higher losses induced in them

• This can cause severe localized overheating in the transformer and eventual breakdown in the core assembly or winding insulation
Overexcitation Causes

• May be caused by system events
Increased $V/Hz = \text{Overexcitation} = \text{Excess Current}$

Overexcitation Event Oscillograph
Overexcitation Harmonics: A Closer Look

Overexcitation Event Oscillograph

High 5th Harmonic Currents
Overexcitation

– Responds to overfluxing; excessive V/Hz
  • 120V/60Hz = 2 = 1pu

– Constant operational limits
  o ANSI C37.106 & C57.12
    • 1.05 loaded, 1.10 unloaded
  o 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)
➢ 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
  - The voltage excursion may be less than the prohibited dielectric limits (overvoltage limit)
  - Overfluxing causes heating
  - Time is not negotiable
  - The excess current cause excess heating
    - Causes cumulative damage the asset
    - If time/level limits violated, may cause a catastrophic failure
Protect Against Overexcitation

- V / Hz levels indicate flux
- V / Hz element for alarm and trip
- Use manufacturer’s level and time withstand curves
- Reset timer waits for cooling

Typical Overexcitation Protection Curves
Transformer Overexcitation: 87T Concerns

• For differential protection, 5th harmonic restraint has been used to prevent undesired tripping by blocking the differential element.

• Issue with blocking the differential element is if a single-phase fault or two-phase fault occurs in the transformer, and one phase remains unfaulted, the differential element remains blocked.
Transformer Overexcitation: 87T Concerns

• Overexcitation in T&D systems is typically caused by the voltage component of the V/Hz value

• The transformer is more inclined to fault during an overexcitation event as the voltage is higher than rated.
  – It is at this moment that the differential element should not be blocked
Transformer Overexcitation: 87T Concerns

• Improved strategy: Raise the pickup of the differential element during overexcitation
  – Keeps the element secure against undesired tripping
  – Allows the element to quickly respond to an internal fault that occurs during the overexcitation event.
Transformer Overexcitation: 87T Concerns

\[ I_d = \sum |I_{A1}| + |I_{A2}| + |I_{A3}| \]

5th Harmonic Used to Modify 87T Pickup
Ground Fault Security

- Low level ground fault current difficult to detect with phase differential
- Ground differential offers far greater sensitivity while remaining secure
Ground Fault Security

- Residual current ($3I_0$) calculated from individual phase currents
- Paralleled CTs shown to illustrate principle

$$-3I_o \times I_G \cos (180) = 3I_0 I_G$$

87GD with Internal Fault, Double Fed
Ground Fault Security

- Residual current ($3I_0$) calculated from individual phase currents
- Paralleled CTs shown to illustrate principle

$-3I_0 \times I_G \cos (180) = 3I_0I_G$

87GD with External Through Fault
Ground Fault Security

- Residual current (3I₀) calculated from individual phase currents
- Paralleled CTs shown to illustrate principle

\[-3I₀ \times I_G \cos(180) = 3I₀I_G\]
Through-Fault

- Provides protection against cumulative through fault damage
- Typically alarm function
Through-Fault

- A transformer is like a motor that does not spin
- There are still forces acting in it
- That is why we care about limiting through-faults
Through-Fault Monitoring

- Protection against heavy prolonged through-faults
- Transformer Categories
  - IEEE C57.109-2018 Curves

<table>
<thead>
<tr>
<th>Category</th>
<th>Single-Phase</th>
<th>Three-Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>5-500</td>
<td>15-500</td>
</tr>
<tr>
<td>II</td>
<td>501-1667</td>
<td>501-5000</td>
</tr>
<tr>
<td>III</td>
<td>1668-10,000</td>
<td>5001-30,000</td>
</tr>
<tr>
<td>IV</td>
<td>Above 10,000</td>
<td>Above 30,000</td>
</tr>
</tbody>
</table>
Through-Fault Damage Mechanisms

- Thermal Limits for prolonged through-faults typically 1-5X rated
  - Time limit of many seconds

- Mechanical Limits for shorter duration through-faults typically greater than 5X rated
  - Time limit of few seconds

- NOTE: Occurrence limits on each Transformer Class Graph
Through-Fault Category 1 (15 kVA – 500 kVA)

NOTE—Low current values of less than or equal to five times rated current do not follow the function \( T = \frac{1250}{I} \); rather the duration comes from Table 2.

Figure 1—Category I transformers: 5 kVA to 500 kVA single phase and 15 kVA to 500 kVA three phase

From IEEE C57.109-2018
Cat. 2 & 3
Fault Frequency Zones
(501 kVA - 30 MVA)

From IEEE C37.91
Through-Fault Category 2
(501 kVA – 5 MVA)

NOTE—Low current values of less than or equal to five times rated current may result from overloads rather than faults. An appropriate loading guide should be referred to for specific allowable time durations.

Figure 3—Category II transformers: 501 kVA to 1667 kVA single-phase and 501 kVA to 5000 kVA three phase
Through-Fault Category 2
(501 kVA – 5 MVA)

Through-Fault damage increases for a given amount of transformer Z%, as more I (I^2) through the Z results in higher energy (forces)

From IEEE C57.109-2018
THROUGH-FAULT PROTECTION CURVE FOR FAULTS THAT WILL OCCUR INFREQUENTLY (TYPICALLY NOT MORE THAN FIVE IN A TRANSFORMER’S LIFETIME)*

*This curve may also be used for backup protection where the transformer is exposed to frequent faults normally cleared by high-speed relaying.

NOTE—Low current values of less than or equal to five times rated current may result from overloads rather than faults. An appropriate loading guide should be referred to for specific allowable time durations.

From IEEE C57.109-2018
Through-Fault Category 3
5.001 MVA – 30 MVA

Through-Fault damage increases for a given amount of transformer $Z\%$, as more $I$ ($I^2$) through the $Z$ results in higher energy (forces)

From IEEE C57.109-2018
Through-Fault Category 4 (>30 MVA)

Through-Fault damage increases for a given amount of transformer Z%, as more I (I²) through the Z results in higher energy (forces).
Current Summing & Through-Fault
Through-Fault Function Settings (TF)

- Should have a **current threshold** to discriminate between mechanical and thermal damage areas
  - May ignore through-faults in the thermal damage zone that fail to meet recording criteria

- Should have a **minimum through-fault event time delay** to ignore short transient through-faults

- Should have a **through-fault operations counter**
  - Any through-fault that meets recording criteria increments counter

- Should have a **preset** for application on existing assets with through-fault history

- Should have **cumulative I^2t setting**
  - How total damage is tracked

- Should use **inrush restraint** to not record inrush periods
  - Inrush does not place the mechanical forces to the transformer as does a through-fault
Through-Fault Function Settings (TF)
Summary and Conclusions

• The operating principle and quantities for restraint and operate should be understood.

• Analysis of internal and external faults with various fault current levels, offset and remanent flux levels can help determine settings.
  – IEEE CT secondary circuit performance model.

• The use of 2nd and 4th harmonics restraint can provide improved security for all types of inrush phenomena versus use of 2nd harmonic alone.
Summary and Conclusions

• The use of 5th harmonic restraint can be improved by raising the pickup when 5th harmonic from overexcitation is encountered
  – This enhances dependability from the typical employment of 5th harmonic restraint that blocks the differential element

• Overexcitation protection (V/Hz) should be employed on transformers
  – Voltage inputs required
Summary and Conclusions

• The use of ground differential to supplement phase differential provides improved sensitivity and dependability to detect ground faults in transformers
  – Directional supervision helps improve security

• Through-fault protection helps quantify the events so something can be done about them
  – Should employ supervisions to ensure true through-fault events are logged
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Questions?