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 & control Seminars.
- Senior Member of IEEE, serving as a Main Committee Member of the Power System Relaying and Control Committee for over 25 years.
- Chair Emeritus of the IEEE PSRCC Rotating Machinery 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

• Remenant 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 the 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

Fig. 1A: Internal Fault

Fig. 1B: External Fault
CT Saturation [1]

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

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

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

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

**INPUT PARAMETERS:**

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<tbody>
<tr>
<td>Inverse of sat. curve slope</td>
<td>S = 22</td>
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<tr>
<td>RMS voltage at 10A exc. current</td>
<td>Vs = 400</td>
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<tr>
<td>Turns ratio = n2/l1</td>
<td>N = 80</td>
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<tr>
<td>Winding resistance</td>
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<td>Burden resistance</td>
<td>Rb = 0.500</td>
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<td>Burden reactance</td>
<td>Xb = 0.500</td>
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<tr>
<td>System X/R ratio</td>
<td>XoverR = 12.0</td>
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<td>Per unit offset in primary current</td>
<td>Off = 0.75</td>
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<td>Per unit remanence (based on Vs)</td>
<td>1/rem = 0.75</td>
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<td>Symmetrical primary fault current</td>
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**ENTER:**

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<td>Amps rms</td>
<td>I_e</td>
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<td>Slope</td>
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<td>Total burden resistance</td>
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<td>Total burden impedance</td>
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<td>System time constant</td>
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<td>Peak flux-linkages corresponding to Vs</td>
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<td>Radian freq</td>
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<td>Rms-to-peak ratio</td>
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<tr>
<td>Burden inductance</td>
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**Fig. 6:** 400:5, C400, R=0.75, Offset = 0.75, 8000A

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.
Differential Element Quantities

• Restraining versus Operating

\[ I_{RES} = \frac{\sum |I_{W1}| + |I_{W2}|}{2} \quad I_{OP} = \frac{I_{W1} + I_{W2}}{2} \]

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

![Characteristic & Values Plot](image-url)

Fig. 7 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
  • Very steep magnetizing characteristics
  • Exhibit lower values of 2nd harmonic

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

• Use $2^{\text{nd}}$ and $4^{\text{th}}$ harmonic as a restraining quantity for inrush.

$$I_{\text{RES: } 2-4} = \sqrt{(I_{\text{RES: } 2^2} + I_{\text{RES: } 4^2})}$$
Transformer Inrush Harmonics

Figs. 8a, b, c, d 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

Figs. 9a, b, c, d Overexcitation
Increased V/Hz = Overexcitation = Excess Current

Fig. 10, Overexcitation Event Oscillograph
Overexcitation Harmonics: A Closer Look

Fig. 11, Overexcitation Event Oscillograph
Overexcitation

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

- Constant operational limits
  - ANSI C37.106 & C57.12
    - 1.05 loaded, 1.10 unloaded
  - 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
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
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

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

\[ I_R = \frac{\sum |I_{AW1}| + |I_{AW2}| + |I_{AW3}|}{2} \]

Fig. 12, Overexcitation Event Oscillograph
Ground Fault Security

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

Fig. 13, Ground Differential Protection Application
Ground Fault Security

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

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

Fig. 14, 87GD with Internal Fault, Double Fed
Ground Fault Security

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

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

Fig. 15, 87GD with External Through Fault
Ground Fault Security

Fig. 16, 87GD with Internal Fault, Single Feed

- $-3I_0 \times I_G \cos (180) = 3I_0 I_G$
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 Category
  - IEEE Std. C57.109-1985 Curves

<table>
<thead>
<tr>
<th>Category</th>
<th>Single-Phase</th>
<th>Three-Phase</th>
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<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>
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<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>
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</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)

From IEEE C37.91
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)
Cat. 2 & 3
Fault Frequency Zones
(501 kVA - 30 MVA)

From IEEE C37.91
Through-Fault damage increases for a given amount of transformer Z%, as more I (I²) through the Z results in higher energy (forces)

From IEEE C37.91
Through-Fault Category 4 (>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).
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 I²t 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