Transformer Protection

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Director of Engineering

THREE-C ELECTRICAL COMPANY, INC.
Power Transformer Protection

1. Protection Philosophies
2. Overvoltage Protection
3. Overcurrent and Thermal Protection
   a. Transformer Damage Curve
   b. Fuse Protection
   c. Overcurrent Relay Protection
   d. Differential Protection
   e. Thermal Protection
   f. Gas Pressure
4. Monitoring and On-Line Diagnostics
Power Transformer Protection
Transformer Protection Philosophies

1. Reasons to provide transformer protection
   a. Detect and Isolate Faulty Equipment
   b. Maintain System Stability
   c. Limit Damage
   d. Minimize Fire Risk
   e. Minimize Risk to Personnel

2. Factors Affecting Transformer Protection
   a. Cost of Repair
   b. Cost of Down Time
   c. Affects on the Rest of the System
   d. Potential to Damage Adjacent Equipment
   e. Length of Time to Repair or Replace
Transformer Protection Philosophies

3. Basic Tenets of Protection
   a. Speed
   b. Sensitivity
   c. Reliability
   d. Security

4. Applicable Standards
   a. C57.12.00 – IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers
   d. C37.91 – IEEE Guide for Protecting Power Transformers
   e. C62.22 – IEEE Guide for the Application of Metal-Oxide Surge Arresters for Alternating-Current Systems
Transformer Overvoltage Protection

Types of Over Voltages

1. Temporary
   a. Power Frequency
   b. Relatively Long Duration (seconds to hours)
   c. Attributable to Ground Faults, Load Rejection, Low Frequency Resonance

2. Transient
   a. Fast Rate of Rise
   b. Short Duration (microseconds to milliseconds)
   c. Attributable to Lightning, Switching, Flashover and Restrike Phenomena
Transformer Overvoltage Protection

Considerations for Overvoltage Protection

Temporary Overvoltage Levels and Duration
Equipment BIL
System Grounding
Transformer Overcurrent Protection

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Data for Specific Arrester
Type and Model Should be
Obtained from Manufacturer

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Per Unit of MCOV Rating

Permissible Duration of Overvoltage (seconds)

- No Prior Energy
- Prior Energy
Transformer Overvoltage Protection

Equipment Overvoltage Withstand Ratings

<table>
<thead>
<tr>
<th>High-Voltage Ratings (V)</th>
<th>Basic Impulse Insulation Level (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Distribution Transformers</td>
</tr>
<tr>
<td>2 400</td>
<td>45</td>
</tr>
<tr>
<td>4 160</td>
<td>60</td>
</tr>
<tr>
<td>4 800</td>
<td>60</td>
</tr>
<tr>
<td>6 900</td>
<td>75</td>
</tr>
<tr>
<td>7 200</td>
<td>75</td>
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<tr>
<td>12 000</td>
<td>95</td>
</tr>
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<td>13 200</td>
<td>95</td>
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<td>13 800</td>
<td>95</td>
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<td>23 000</td>
<td>125</td>
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<tr>
<td>34 500</td>
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<tr>
<td>69 000</td>
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<td>115 000</td>
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<tr>
<td>138 000</td>
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<tr>
<td>161 000</td>
<td>–</td>
</tr>
<tr>
<td>230 000</td>
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</table>
Transformer Overvoltage Protection

Gapless Metal Oxide Arrester Characteristics

<table>
<thead>
<tr>
<th>Table 2a Polymer Station Arrester Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Voltage kVrms</td>
</tr>
<tr>
<td>---------------------</td>
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<tr>
<td></td>
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<tr>
<td>3</td>
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<td>6</td>
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<td>9</td>
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<tr>
<td>10</td>
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<td>15</td>
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<td>24</td>
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<td>27</td>
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<td>30</td>
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<td>36</td>
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<td>39</td>
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<tr>
<td>45</td>
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<tr>
<td>48</td>
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<tr>
<td>54</td>
</tr>
<tr>
<td>60</td>
</tr>
<tr>
<td>66</td>
</tr>
<tr>
<td>72</td>
</tr>
<tr>
<td>90</td>
</tr>
<tr>
<td>96</td>
</tr>
<tr>
<td>108</td>
</tr>
<tr>
<td>120</td>
</tr>
<tr>
<td>132</td>
</tr>
<tr>
<td>144</td>
</tr>
</tbody>
</table>
Transformer Overvoltage Protection

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**General Electric**

**Transformer**

*CAUTION! INSTRUCTION BOOK INSIDE BOX BEFORE INSTALLING OR OPERATING READ INSTRUCTIONS*

**VOLTAGE RATING 115000-138000V 79720**

KVA RATING: 33000 CONTINUOUS 65 C RISE SELF COOLED
KVA RATING: 44000 CONTINUOUS 65 C RISE FORCED AIR
KVA RATING: 55000 CONTINUOUS 65 C RISE FORCED OIL AIR

**IMPEDEANCE VOLTS (%) 115000-138000 VOLTS AT 33000KVA**

<table>
<thead>
<tr>
<th>VOLTS</th>
<th>TAP CHANGER POS</th>
<th>AMP AT 33000 KVA</th>
<th>AMP AT 44000 KVA</th>
<th>AMP AT 55000 KVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>120000</td>
<td>1</td>
<td>159</td>
<td>213</td>
<td>265</td>
</tr>
<tr>
<td>117500</td>
<td>2</td>
<td>162</td>
<td>216</td>
<td>270</td>
</tr>
<tr>
<td>115000</td>
<td>3</td>
<td>166</td>
<td>221</td>
<td>275</td>
</tr>
<tr>
<td>112500</td>
<td>4</td>
<td>169</td>
<td>225</td>
<td>282</td>
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<tr>
<td>110000</td>
<td>5</td>
<td>173</td>
<td>231</td>
<td>289</td>
</tr>
</tbody>
</table>

**FOR STEP DOWN OPERATION**

**APPROXIMATE WEIGHTS IN POUNDS**

- TOTAL: 165100
- UNTANKING: 95200
- TANK AND FITTINGS: 33200
- MAIN TANK TYPE: 11 OIL 6120 GAL 45600

**LIQUID LEVEL CHANGES 1.1 INCH PER 10 C CHANGE IN LIQUID TEMPERATURE.**

**LIQUID LEVEL BELOW TOP SURFACE OF THE HIGHEST POINT OF MANHOLE FLANGE AT 25 C IS 12.1 INCHES.**

**MAXIMUM OPERATING PRESSURE OF LIQUID PRESERVATION SYSTEM 7.5 POUNDS POSITIVE TO 5.0 POUNDS NEGATIVE.**

**TANK SUITABLE FOR 14.7 POUNDS VACUUM FILLING.**

**CT’S 1, 2, 3, 5, 6, 7, 9, 10, 11 ARE 1200/5 AMP. (ACCESS CLASS IEC800).**

**DATE OF MANUFACTURE**

**SOUND LEVEL GUARANTEED**

- OA = 61 DB
- FA = 65 DB
- FOA = 66 DB
Transformer Overvoltage Protection

Transformer Primary Rated Line to Ground Voltage:

\[ \frac{115kV}{\sqrt{3}} = 66.4kV \]

Transformer Secondary Rated Line to Ground Voltage:

\[ \frac{13.8kV}{\sqrt{3}} = 7.97kV \]

However – Note that the secondary neutral is reactor grounded
Transformer Overvoltage Protection

### Table 1: Typical Arrester Ratings for System Voltages

<table>
<thead>
<tr>
<th>Nominal System L-L Voltage (kV)</th>
<th>Grounded Neutral Circuits</th>
<th>High Impedance Grounded, Ungrounded, or Temporarily Ungrounded</th>
<th>Nominal System L-L Voltage (kV)</th>
<th>Grounded Neutral Circuits</th>
<th>High Impedance Grounded, Ungrounded, or Temporarily Ungrounded</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.4</td>
<td>2.7</td>
<td>3.0</td>
<td>69</td>
<td>54</td>
<td>--</td>
</tr>
<tr>
<td>4.16</td>
<td>3.0</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>4.5</td>
<td>4.5</td>
<td>5.1</td>
<td>72</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>4.8</td>
<td>4.5</td>
<td>5.1</td>
<td>--</td>
<td>108</td>
<td>108</td>
</tr>
<tr>
<td>6.9</td>
<td>6.0</td>
<td>--</td>
<td>138</td>
<td>108</td>
<td>--</td>
</tr>
<tr>
<td>12.47</td>
<td>--</td>
<td>7.5</td>
<td>161</td>
<td>120</td>
<td>--</td>
</tr>
<tr>
<td>13.2, 13.8</td>
<td>10</td>
<td>--</td>
<td>230</td>
<td>172</td>
<td>--</td>
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<tr>
<td>23.2, 24.94</td>
<td>18</td>
<td>--</td>
<td>345</td>
<td>238</td>
<td>240</td>
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<tr>
<td>34.5</td>
<td>--</td>
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<td>--</td>
<td>--</td>
<td>--</td>
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<tr>
<td>46</td>
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<td>--</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

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Transformer Overvoltage Protection

Table 2a: Polymer Station Arrester Characteristics

<table>
<thead>
<tr>
<th>Rated Voltage (kVrms)</th>
<th>MCOV (kVrms)</th>
<th>0.5 μsec 10 kA Max IR-kVcrest</th>
<th>Switching Surge Maximum IR-kVcrest</th>
<th>8/20 μs Maximum Discharge Voltage - kVcrest</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.5 kA</td>
</tr>
<tr>
<td>3</td>
<td>2.55</td>
<td>8.4</td>
<td>6.0</td>
<td>6.4</td>
</tr>
<tr>
<td>6</td>
<td>5.10</td>
<td>16.7</td>
<td>11.9</td>
<td>12.8</td>
</tr>
<tr>
<td>9</td>
<td>7.65</td>
<td>25.0</td>
<td>17.8</td>
<td>19.2</td>
</tr>
<tr>
<td>10</td>
<td>8.40</td>
<td>27.8</td>
<td>19.8</td>
<td>21.1</td>
</tr>
<tr>
<td>12</td>
<td>10.2</td>
<td>33.3</td>
<td>23.7</td>
<td>25.6</td>
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<td>15</td>
<td>12.7</td>
<td>41.7</td>
<td>29.7</td>
<td>32.0</td>
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<td>50.1</td>
<td>35.6</td>
<td>38.4</td>
</tr>
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<td>17.0</td>
<td>56.3</td>
<td>40.1</td>
<td>43.2</td>
</tr>
<tr>
<td>24</td>
<td>19.5</td>
<td>63.9</td>
<td>45.5</td>
<td>49.1</td>
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<tr>
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<td>22.0</td>
<td>72.9</td>
<td>51.9</td>
<td>56.0</td>
</tr>
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<td>30</td>
<td>24.4</td>
<td>80.4</td>
<td>57.2</td>
<td>61.7</td>
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<td>36</td>
<td>29.0</td>
<td>95.9</td>
<td>68.3</td>
<td>73.6</td>
</tr>
<tr>
<td>39</td>
<td>31.5</td>
<td>104.2</td>
<td>74.2</td>
<td>80.0</td>
</tr>
<tr>
<td>43</td>
<td>36.5</td>
<td>120.9</td>
<td>86.1</td>
<td>92.8</td>
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<tr>
<td>48</td>
<td>39.0</td>
<td>128.7</td>
<td>91.6</td>
<td>98.8</td>
</tr>
<tr>
<td>54</td>
<td>42.0</td>
<td>144.4</td>
<td>102.8</td>
<td>110.9</td>
</tr>
<tr>
<td>60</td>
<td>48.0</td>
<td>163.5</td>
<td>116.4</td>
<td>125.5</td>
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<tr>
<td>66</td>
<td>53.0</td>
<td>179.9</td>
<td>128.0</td>
<td>138.1</td>
</tr>
<tr>
<td>72</td>
<td>57.0</td>
<td>191.8</td>
<td>136.6</td>
<td>147.3</td>
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<tr>
<td>90</td>
<td>70.0</td>
<td>241.8</td>
<td>172.1</td>
<td>185.6</td>
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<tr>
<td>96</td>
<td>76.0</td>
<td>257.4</td>
<td>183.2</td>
<td>197.6</td>
</tr>
<tr>
<td>108</td>
<td>84.0</td>
<td>288.9</td>
<td>205.6</td>
<td>221.8</td>
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<tr>
<td>120</td>
<td>98.0</td>
<td>326.9</td>
<td>241.3</td>
<td>251.0</td>
</tr>
<tr>
<td>132</td>
<td>106.0</td>
<td>362.7</td>
<td>267.7</td>
<td>278.5</td>
</tr>
<tr>
<td>144</td>
<td>115.0</td>
<td>386.1</td>
<td>285.0</td>
<td>296.5</td>
</tr>
</tbody>
</table>
Transformer Overcurrent Protection

Protect Transformer from Overloads

*C57.91 - IEEE Guide for Loading Mineral-Oil-Immersed Transformers*

Protect Transformer from Internal Faults

Protect Transformer from Through Faults

*C57.109 - IEEE Guide for Liquid-Immersed Transformer Through-Fault-Current Duration*
Transformer Overcurrent Protection

![Diagram of transformer protection system]

13800.0 V

PRI FUSE

TRF T1

LS BUS

Size 3750.00 kVA
%Z 5.7500 %
4160.0 V

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Transformer Overcurrent Protection

- Rated Current
  
  \textit{Rated kVA and Voltage plus adjustments from C57.91}

- Inrush Current
  
  \textit{12x Rated Current for 0.1 sec}

- Short Circuit Currents
  
  \textit{From system fault study, available SCC on Primary, Sec based on Trf. Z}

- Transformer Damage Curve
  
  \textit{Calculated per C57.109}
Transformer Overcurrent Protection

Rated Transformer Primary Current:

\[
\frac{3750000}{\sqrt{3} \times 13800} = 157\ A
\]

Rated Transformer Secondary Current:

\[
\frac{3750000}{\sqrt{3} \times 4160} = 520\ A
\]

Transformer Inrush Current:

\[
157 \times 12 = 1884\ A
\]
Transformer Overcurrent Protection

Transformer Damage Curve – C57.109

Table 1—Transformer categories

<table>
<thead>
<tr>
<th>Category</th>
<th>Single phase (kVA)</th>
<th>Three phase (kVA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I*</td>
<td>5 to 500</td>
<td>15 to 500</td>
</tr>
<tr>
<td>II</td>
<td>501 to 1667</td>
<td>501 to 5000</td>
</tr>
<tr>
<td>III</td>
<td>1668 to 10 000</td>
<td>5001 to 30 000</td>
</tr>
<tr>
<td>IV</td>
<td>Above 10 000</td>
<td>Above 30 000</td>
</tr>
</tbody>
</table>

*Category I shall include distribution transformers manufactured in accordance with IEEE Std C57.12.20-1988 up through 500 kVA, single phase or three phase. In addition, autotransformers of 500 equivalent two-winding kilovoltamperes or less, which are manufactured as distribution transformers in accordance with IEEE Std C57.12.20-1988, shall be included in Category I, even though their nameplate kVA may exceed 500.

NOTE—All kilovoltampere ratings are minimum nameplate kVA for the principal windings.
Transformer Overcurrent Protection

Transformer Damage Curve – C57.109

Table 2 – Transformer short-time thermal load capability

<table>
<thead>
<tr>
<th>Time</th>
<th>Times rated current</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 s</td>
<td>25.0</td>
</tr>
<tr>
<td>10 s</td>
<td>11.3</td>
</tr>
<tr>
<td>30 s</td>
<td>6.3</td>
</tr>
<tr>
<td>60 s</td>
<td>4.75</td>
</tr>
<tr>
<td>5 min</td>
<td>3.0</td>
</tr>
<tr>
<td>30 min</td>
<td>2.0</td>
</tr>
</tbody>
</table>

\[ i^2t = 1250 \]
Transformer Overcurrent Protection

Transformer Damage Curve – C57.109

\[ i^2 t = K \]

\[ K = \frac{2}{Z_T^2} \]
Transformer Overcurrent Protection

Transformer Damage Curve – C57.109

Figure 3—Category III transformers
1668 to 10 000 kVA single-phase
5001 to 30 000 KVA three-phase

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

Transformer Damage Curve – C57.109
Transformer Overcurrent Protection
Transformer Overcurrent Protection

Unbalanced Fault Through Delta-Wye Transformer

\[ 0.58 \times I_f \times \frac{V_s}{V_p} \]

13800V

4160V

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Transformer Overcurrent Protection
Transformer Overcurrent Protection

HS BUS

52-T1

50/51-T1

TRF T1

LS BUS

13800.0 V

50/51-T1

Size 3750.00 kVA

%Z 5.7500 %

4160.0 V

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Transformer Overcurrent Protection

![Graph showing transformer overcurrent protection characteristics.](image)
Transformer Overcurrent Protection

Transformer Differential Protection

High Speed, Sensitive Protection for Internal Faults
Looks at current flowing into and out of zone
Unequal currents means fault in the zone
Transformer Overcurrent Protection

Special Considerations for Transformer Differential Relays

- Different Currents at Zone Boundaries
- Typically Have a 30° Phase Shift from Primary to Secondary
- Usually Have Mismatch in CT secondary currents, especially w/ LTC’s
- Primary and Secondary CT’s may have Different Saturation Characteristics
- Have to Worry About Transformer Inrush Current

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Transformer Overcurrent Protection

Dealing w/ Delta-Wye Phase Shift
Traditional Method w/ Wye-Delta Connected CT’s
Transformer Overcurrent Protection

Dealing w/ Delta-Wye Phase Shift
Traditional Method w/ Wye-Delta Connected CT’s

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Transformer Overcurrent Protection

Dealing w/ Delta-Wye Phase Shift
New Method w/ Wye Connected CT’s and Phase Shift in Relay
Transformer Overcurrent Protection

Current Mismatch, Restraint, and Slope

For Wye Connected CT's

\[ I_p = \frac{55000000}{115000 \times \sqrt{3}} = 276.1A \]

\[ I_{Prel} = 276.1A \times \frac{5}{300} = 4.61A \]

\[ I_s = \frac{55000000}{13800 \times \sqrt{3}} = 2301A \]

\[ I_{SRel} = 2301A \times \frac{5}{2500} = 4.60A \]

For Delta Connected CT's

\[ I_s = \frac{55000000}{13800 \times \sqrt{3}} = 2301A \]

\[ I_{SRel} = 2301A \times \frac{5}{2500} \times \sqrt{3} = 7.97A \]
Transformer Overcurrent Protection

Current Mismatch, Restraint, and Slope

- Older Style Relays Had Fixed Taps
- New Numerical Relays Have Wider Range of Tap Settings
- All bets off for LTC’s
- Quality and location of CT’s can affect saturation differently
- Transformer Differential Relays Use Restraint Coil to Compensate

- Slope: Ratio of Operating Current to Restraint Current
Transformer Overcurrent Protection

Inrush Current

- Caused by residual flux in transformer core
- Current Flows in One Set of Windings (typically the Primary) which could fool differential relays
- Characterized by DC offset and high 2\textsuperscript{nd} harmonic content.
- If unloaded or lightly loaded, can also have high 5\textsuperscript{th} harmonic content
- Transformer Differential Relays utilize Harmonic Filters to discriminate between Inrush Currents and Internal Faults
Transformer Overcurrent Protection

Ground Fault Sensing
Transformer Overcurrent Protection

Advantages of Newer Style Numerical Relays

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Transformer Overcurrent Protection

Advantages of Newer Style Numerical Relays

- Can use Wye Connected CT’s for All Winding Connections
- Low Burden – Minimize CT Saturation Issues
- Wide Range of Pickups Settings – Minimize CT Mismatch Problems
- Adjustable Slope Characteristics
- Restrained and Unrestrained Differential Elements
- Typically have other functions built in such as:
  - Primary and Secondary Time and Inst OC Functions
  - Restricted Earth Fault Element
  - Thermal Element (ANSI Device 49)
- Typically include metering, fault/event recording, and communications
Other Transformer Protection
Other Transformer Protection

ANSI Device 63
Sudden Pressure or Rate of Rise Relay

- Sudden Pressure or Rate of Rise Relay
  Applied on Sealed Tank Designs >5 MVA
- Detects rapid changes in tank pressure due to decomposition of transformer oil by an arc
- Designed to ignore slow changes in tank pressure due to thermal cycling.

Gas Accumulator (Buchholz) Relay

- Applied on Conservator Tank Designs
- Installed in Pipe connecting Main and Aux Tanks
- Trips for Rapid Gas Flow to Conservator Tank
- Alarms for Slow Flow
Transformer Monitoring

Standard Gauges and Indicators
- Liquid Level
- Tank Pressure
- Oil Temperature
- Hot Spot Temperature
- Gauges have contacts which can be brought back to SCADA

LTC Controls
- LTC Position
- LTC Malfunction

Fan/Pump Controls
- Fan/Pump Operating Stages
- Fan/Pump Malfunction
Transformer Monitoring

On-Line Water in Oil Monitoring
On-Line Dissolved Gas Monitoring
On-Line Acoustical and Partial Discharge Monitoring