Ongoing List of Topics:

- URL: [http://www.ece.mtu.edu/faculty/bamork/EE5223/index.htm](http://www.ece.mtu.edu/faculty/bamork/EE5223/index.htm)
- Term Project - Follow posted Guidelines!
  - Formal outline w/complete references complete, get/keep cranking...
- Homework set for Ch.4
  - Problems due Tuesday 5pm. Use e-mail forum!
- Protection fundamentals for 87T, cont’d –
  - a) correct connection of CT secondaries to relays (Lecture 29)
  - b) relay settings, to compensate for pri voltage ratio and CT ratios.
  - c) Mismatch problems - due to being forced to use less than full CT ratio, and having Pri and Sec CTs with different accuracy levels. Differential slope of trip characteristic can be 10%, 15%, 25%, etc, to allow for mismatch. Refer to XFMR.pdf!
- Next: Bus protection - 87B
  - Low Impedance relays
  - High-Impedance relays
  - Partial bus protection using 51 relay (distribution bus w/radial feeders)
TABLE A.1
Typical range of transformer reactances†
Power transformers 25,000 kVA and larger

<table>
<thead>
<tr>
<th>Nominal system voltage, kV</th>
<th>Forced-air-cooled, %</th>
<th>Forced-oil-cooled, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>34.5</td>
<td>5–8</td>
<td>9–14</td>
</tr>
<tr>
<td>69</td>
<td>6–10</td>
<td>10–16</td>
</tr>
<tr>
<td>115</td>
<td>6–11</td>
<td>10–20</td>
</tr>
<tr>
<td>138</td>
<td>6–13</td>
<td>10–22</td>
</tr>
<tr>
<td>161</td>
<td>6–14</td>
<td>11–25</td>
</tr>
<tr>
<td>230</td>
<td>7–16</td>
<td>12–27</td>
</tr>
<tr>
<td>345</td>
<td>8–17</td>
<td>13–28</td>
</tr>
<tr>
<td>500</td>
<td>10–20</td>
<td>16–34</td>
</tr>
<tr>
<td>700</td>
<td>11–21</td>
<td>19–35</td>
</tr>
</tbody>
</table>

† Percent on rated kilovoltampere base. Typical transformers are now designed for the minimum reactance value shown. Distribution transformers have considerably lower reactance. Resistances of transformers are usually lower than 1%.

\[ X_0 = X'_d \]

\[ X_q = 1.66 \quad 1.63-1.69 \quad 1.7 \]

\[ X'_d = 0.21 \quad 0.18-0.23 \quad 0.2 \]

\[ X''_d = 0.13 \quad 0.11-0.14 \quad 0.2 \]

\[ X_2 = X'_d \]

\[ X_0 \] varies so critically with armature from 0.1 to 0.7 of \( X'_d \).
### TABLE A.2
Typical reactances of three-phase synchronous machines†
Values are per unit. For each reactance a range of values is listed below the typical value‡

<table>
<thead>
<tr>
<th>Turbine-generators</th>
<th>2-pole</th>
<th>4-pole</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Conventional cooled</td>
<td>Conductor cooled</td>
</tr>
<tr>
<td>$X_d$</td>
<td>1.76</td>
<td>1.95</td>
</tr>
<tr>
<td></td>
<td>1.7–1.82</td>
<td>1.72–2.17</td>
</tr>
<tr>
<td>$X_q$</td>
<td>1.66</td>
<td>1.93</td>
</tr>
<tr>
<td></td>
<td>1.63–1.69</td>
<td>1.71–2.14</td>
</tr>
<tr>
<td>$X'_d$</td>
<td>0.21</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>0.18–0.23</td>
<td>0.264–0.387</td>
</tr>
<tr>
<td>$X''_d$</td>
<td>0.13</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td>0.11–0.14</td>
<td>0.23–0.323</td>
</tr>
<tr>
<td>$X_2$</td>
<td>$=X''_d$</td>
<td>$=X'_d$</td>
</tr>
<tr>
<td>$X_0$§</td>
<td>0.13–0.32</td>
<td>0.30–0.45</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Salient-pole generators</th>
<th>With dampers</th>
<th>Without dampers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.6–1.5</td>
<td>0.6–1.5</td>
</tr>
<tr>
<td></td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>0.4–0.8</td>
<td>0.4–0.8</td>
</tr>
<tr>
<td></td>
<td>0.32</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td>0.25–0.5</td>
<td>0.25–0.5</td>
</tr>
<tr>
<td></td>
<td>0.13–0.32</td>
<td>0.2–0.5</td>
</tr>
<tr>
<td></td>
<td>0.2</td>
<td>0.30</td>
</tr>
</tbody>
</table>

†Data furnished by ABB Power T & D Company, Inc.
‡Reactances of older machines will generally be close to minimum values.
§$X_0$ varies so critically with armature winding pitch that an average value can hardly be given. Variation is from 0.1 to 0.7 of $X''_d$. 

Forced-oil-cooled, %

- Aging transformers: 25-40 yr, 40+
  - Aging - LOL
  - Thru-faults
  - Lightning

[ ] =

> Failure Mechanism.

- Grid bottlenecks
  - Energy contracts
  - System Security, contingency

- Time to deliver: 2+ yrs.
- Shipping transport: huge issues.
Load Tap Changer is designed to withstand up to a half-million operations without need for contact replacement.

Lamination width customized to achieve a near perfect-circle core cross section, resulting in the most efficient use of materials plus a lighter, more compact high-performance transformer.

Inside tank surfaces are painted white to facilitate internal inspection.

Coil assembly is rigidly braced in a high-strength frame that distributes clamping forces around the full circumference of the windings.

Submerged-arc process produces deep weld penetration, virtually eliminating leakage from welded tank joints.

De-energized tap changer features simple and compact in-line contact arrangement.

Galvanized radiators provide excellent corrosion resistance and minimal maintenance.

Material-stabilized coils are pressure-fit within the core frame.

Transformer exterior is coated to a minimum thickness of 3 mils. This coating has superior endurance characteristics and meets the ANSI C57.12.28 standard.

Low no-load losses result from use of laser-scribed, super-grain-oriented steel.

Waukesha Electric Systems offers component parts for transformer upgrades and repair, as well as extensive field service support that includes transformer moving, hauling and rigging, vacuum filling and oil processing, inspection, testing and customer training.

Waukesha Quality Inside
Means Reliability Is On Your Side

Transformers energy solutions...to power your future
Mismatch - - Thrn - Currents
- CT ratios
- Tap Settings

$M_{H_{ul}} = 82T$

$I_{e1} \rightarrow OP \rightarrow I_{e2}$
The diagram illustrates a transformer with two coils, $N_1$ and $N_2$, and two currents, $I_{e1}$ and $I_{e2}$. The slope of the curve represents the mismatch between $I_{e1}$ and $I_{e2}$, with the maximum value marked as $\max(I_{e1}, I_{e2})$. The graph shows the relationship between $I_{e}$ and $I_{e}$, with a trip point indicated at the maximum value.
Figure 13. HU, HU-1 and HU-4 Differential Characteristics (30% Sensitivity).
Figure 14. HU, HU-1 and HU-4 Differential Characteristics (35% Sensitivity).
$\Rightarrow 55^\circ$ rise (self-cooled) "OA" or "ONAN"

Base MVA for S.C. Calcns.

\[ \Delta T \]

\[ \frac{55^\circ \text{rise}}{65^\circ \text{rise}} = \frac{18}{20.2} / \frac{24}{26.9} / \frac{30}{35.6} \text{ MVA} \]

12.5%

(Refer to p. 5 of XFMR Prot notes posted in week 10)

↑ "passive" half of active cooling
↑ self-cooled all of active cooling
You are an applications engineer. You are given the spec of a new transformer that has just been ordered, and told to develop the protective relaying scheme.

The transformer rating is given as:

- 18/24/30-MVA @ 55°C rise
- 20.2/26.9/33.6-MVA @ 65°C rise
- Two-winding
- 69,000 volts Grounded Wye to 12,470 volts Delta
- Nonstandard phase shift: Wye leads by 150°
- LTC on secondary (±10% in 5/8% steps)

High side CTs are 600:5 multi-ratio, C800, 3 sets of three
Low side CTs are 2000:5 multi-ratio, C800, 2 sets of three
Neutral CT is 1200:5 multi-ratio, C800.

Low side CTs to be used for the 87T scheme are on the LV switchgear. They are 1200:5 single ratio, C100. LV interruption is provided by the switchgear breaker; HV interruption by sending a transfer trip to the other end of the 69-kV line.

Also specified with the transformer are a sudden pressure relay, a low-low oil level trip contact, a high-high winding hot spot contact, and a high-high top oil temperature contact.

- Draw a one-line of the transformer. Show the transformer and the connected LV switchgear. Show all CTs and ratios. Show 87T connections. Show trip contacts from alarm devices. Provide correct ANSI device designation numbers.
- Draw out a three-line, showing correct phase connections of the 87T relays.
- Determine the ratios for the multi-ratio CTs, assuming max load current for 65°C operation.
- Select tap settings for the relays. Use the Westinghouse relays that are described in the handout you were given in class.
- Calculate the mismatch, including the effects of the load tap changer. Come up with at least an acceptable combination of CT ratios and tap settings. You may want to try various combinations, but make sure that the load current does not exceed the CT ratio you use.
- Do the burden calculations to confirm that the CTs are within their accuracy range? Assume the source impedance for faults from the 69-kV side is 0.2 per unit on a 100 MVA base and that there is no fault source on the low voltage side. Ignore the impedance of the connecting cables. Is the C100 CT within its operating range?
Transformer Diff Relay

a) One-Line of XFMRe & Relaying

b) Three-Line is given on separate sheet.

Based on I_{load},

\[ I_H = \frac{33.6 \text{ MVA}}{\sqrt{3} \times (69.4 \text{ kV})} = 281 \text{ A} \]

\[ I_L = \frac{33.6 \text{ MVA}}{\sqrt{3} \times (12.47 \text{ kV})} = 1555 \text{ A} \]

CTR = 300:5

CTR = Fixed (2 - 1200:5 CTs) (paralleled)

c) @ 33.6 MVA,

\[ I_{RH} = \sqrt{3} (281) \left( \frac{5}{500} \right) = 8.11 \text{ A} \]

\[ I_{RX} = 1555 \frac{5}{1200} = 6.48 \text{ A} \]

Current Ratio = \[ \frac{8.11}{6.48} = 1.25 \]

d) \[ \frac{T_H}{T_L} = \frac{4.6}{5.8} = 1.21 \] (One Possible Choice)

\[ \frac{T_H}{T_L} = \frac{8.7}{8.7} = 1.000 \] (another choice)
c) Mismatch = \( \frac{1.25 - 1.211}{1.211} = 0.0322 \) (3.2%)

Mismatch (\( T_H = T_L = 8.7 \)) = \( \frac{1.25 - 1}{1} = 25\% \) (Too High!)

Use \( T_H = 4.6 \) (Assume not greater than energy requirement)
\( T_L = 3.8 \)

Total Mismatch, including LTC is 13.2%.
Better choose 30% diff slope.

f) Thru-Fault:

\[
I_F = \frac{1.0}{j0.2 \ p.u.} = -j5 \ p.u.
\]

\[
I_{BASE} = \frac{100 \ M}{15 \ 69K} = 8.69 \ A
\]

\[
I_{BASE} = \frac{100 \ M}{12 \ 47K} = 4.63 \ A
\]

\[
I_{RH} = 5 \times 8.69 = 43.45 \ A
\]

Assume

\[
I_{EXT} = 100
\]

\[
I_{RL} = \frac{5 \times 4.63 \times 1200}{1200} = 96.5 \ A
\]

Burdens:

\[
NPV_{11} = (I_{EXT} - 100)R_S \geq I_{EXT} Z_t
\]

HV: \( Z_t = \frac{45}{1.46} \Rightarrow (1.5)(800) \geq (100)(.45) \) Yes!

HV is OK.

LV: \( Z_t = \frac{15}{3.8} \Rightarrow 100 \geq (100)(\frac{15}{3.8}) \) Yes!

Assume only one set of CTs. Actually 2 in parallel.
Indicating Contactor Switch (ICS)

No setting is required on the ICS unit except the selection of the 0.2 or 2.0 amperes tape setting. This selection is made by connecting the lead located in front of the tape block to the desired setting by means of the connecting screw. When the relay energizes a 125-or 250-volt dc type WL relay switch, or equivalent, use the 0.2-ampere tape; for 48 volt DC applications set relay in 2 tape and use Type WL Relay coil S#304C209G01 or equivalent.

Indicating Instantaneous Trip (IIT)

No setting is required on the indicating instantaneous trip unit. This unit is set at the factory to pickup as follows:

HU/HU-1 Relays 10 times tap value current
HU-4 Relay 15 times tap value current

SETTING CALCULATIONS

Select the ratio matching taps. There are no other settings. In order to calculate the required tap settings and check current transformer performance the following information is required.

Required Information

1. Maximum transformer power rating (KVA)M
2. Maximum external fault currents
3. Line-to-Line voltage ratings of power transformer (VH, VL, VL)
4. Current transformer ratios, full tap (NT)
5. Current transformer "C" accuracy class voltage, (or excitation or ratio correction factor curve)
6. One way current transformer lead resistance at 25°C (RL) (when using excitation curve, include ct winding resistance)
7. Current transformer connections (wye or delta)
8. ct secondary winding resistance, R_S

Definitions of Terms

IP = Primary current at (KVA)M
IR = Relay input current at (KVA)M
IRH, IRL, IR1 are same as IR except for high, low and intermediate voltage sides respectively.
1. \( I_R \) should not exceed relay continuous rating as defined in Energy Requirement Table.

5. **Check IIT operation.** The IIT pickup is ten times the relay tap value for the HU and HU-1, or 15 times tap value for the HU-4. Therefore, the maximum symmetrical error current which is flowing in the differential circuit on external fault current due to dissimilar ct saturation should not exceed 10 or 15 times relay tap.

6. **Determine Mismatch**

For 2 winding banks:

\[
\% \text{mismatch} = 100 \frac{(I_{RL}/I_{RH})-(T_{L}/T_{H})}{S} \tag{1}
\]

where \( S \) is the smaller of the two terms, \( (I_{RL}/I_{RH}) \) or \( (T_{L}/T_{H}) \)

For 3 winding banks:

Repeat calculation of equation (1) and apply similar equations to calculate mismatch from the intermediate to high and from the intermediate to low voltage windings.

Where tap changing under load is performed the relays should be set on the basis of the middle or neutral tap position. The total mismatch, including the automatic tap change should not exceed 15% with a 30% sensitivity relay, and 20% with a 35% sensitivity relay. Note from Fig. 11 that an ample safety margin exists at these levels of mismatch.

7. **Check current transformer performance.**

Ratio error should not exceed 10% with maximum symmetrical external fault current flowing. An accurate method of determining ratio error is to use ratio-correction-factor curves (RCF). A less accurate, but satisfactory method is to utilize the ANSI relaying accuracy classification. If the "C" accuracy is used, performance will be adequate if:

\[
\begin{align*}
  [N_p V_c l - (I_{ext} - 100)(R_s)] / I_{ext} &\text{ is greater than } Z_T \\
  \text{Note: let } I_{ext} = 100 \\
  \text{where maximum external fault current is less than 100A.}
\end{align*}
\]

For wye-connected ct:

\[
Z_T = \text{lead resistance} + \text{relay burden} + Z_A
\]

\[
= 1.13 R_L + \frac{0.15}{T} + Z_A \text{ ohms} \tag{3}
\]

(RL multiplier, 1.13, is used to account for temperature rise during faults \( 0.15 \) \( \frac{T}{R} \) is an approximation. Use 2 way lead resistance for single phase to ground fault.)

For delta-connected ct:

\[
Z_T = 3 \left(1.13 R_L + \frac{0.15}{R} + Z_A\right) \text{ ohms}
\]

\[
= 3.4 R_L + \frac{0.45}{T} + 3Z_A \tag{4}
\]

*(The factor of 3 accounts for conditions existing during a phase fault.)*

8. **Examples**

Refer to pages 19, 20 and 21 and figure 21 for setting examples.

**TABLE 1**

<table>
<thead>
<tr>
<th>HU Relay Tap Ratios</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.9</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>1.000</td>
</tr>
<tr>
<td>1.000</td>
</tr>
<tr>
<td>1.000</td>
</tr>
<tr>
<td>1.000</td>
</tr>
<tr>
<td>1.000</td>
</tr>
<tr>
<td>1.000</td>
</tr>
<tr>
<td>1.000</td>
</tr>
</tbody>
</table>

**INSTALLATION**

The relays should be mounted on switchboard panels or their equivalent in a location free from
TWO-WINDING TRANSFORMER CALCULATIONS  (See Figure 21)

1. Select ct Ratio
\[ I_p = \frac{(KVA)_M}{(KV)\sqrt{3}} = \]

Select Ratio

2. Calculate Relay Current:
\[ I_S = \frac{I_p}{N} = \]
\[ I_R = \]

3. Calculate Current Ratio:

4. Select Tap Ratio from Table 1:
\[ I_R > \text{relay continuous rating} \]

5. Check IIT Operation
Max. Symmetrical error current > 10 times relay tap.

6. Determine Mismatch:
\[ \% \text{Mismatch} = 100 \left( \frac{I_{LR}/I_{RH}}{T_L/T_H} - (8.05/4.18) \right) = \]
\[ \frac{(8.05/4.18) - (8.7/4.6)}{8.7/4.6} = \]
\[ 100 \frac{1.92 - 1.89}{1.89} = 1.6\% \]

7. Check ct Performance
\[ Z_T = \]
\[ 3.4 R_L + \frac{0.45}{T} = \]
\[ 3.4 \times 0.4 + \frac{0.45}{8.7} = 1.36 + 0.05 = 1.41 \text{ ohms} \]
\[ 1.13 R_L + \frac{0.15}{T} = \]
\[ 1.13 \times 0.4 + \frac{0.15}{4.6} = 0.45 + 0.03 = 0.48 \text{ ohms} \]

\[ N_p = \frac{N}{N_T} = \]
\[ (N_pV_{CL}) = \]
\[ \frac{0.833 \times 200}{100} = 1.67 \]
\[ \frac{0.333 \times 200}{100} = 0.67 \]

Conclusion:
\[ T_L = 8.7 \]
Yes
\[ T_H = 4.6 \]
Yes

30% sensitivity Relay is adequate
TWO WINDING BANK

12.4KV

Y2

69KV

1200/5
MR
C200

16/20 MVA

600/5
MR
C200

THREE WINDING BANK

161KV

Y2

69KV

1200/5
MR
C800

30/40 MVA

75/10 MVA

600/5
MR
C200

1200/5
MR
10L200

12.4KV

HIGH

(kVA)_M = 20,000

(kVA)_S = 16,000

V_L = 12,400 VOLTS

N_T = 240 TURNS

V_CL = 200 VOLTS

R_L = 0.4 OHMS

DELTA CT

I_{ext} \leq 100A

HIGH

(kVA)_M = 40,000

(kVA)_S = 30,000

V_H = 16,000

N_T = 240

V_CL = 800

R_L = 0.5

DELTA CT

I_{ext} \leq 100A

INTERMEDIATE

(kVA)_M = 40,000

(kVA)_S = 30,000

V_T = 69,000

N_T = 120

V_CL = 200

R_L = 0.5

DELTA CT

LOW

(kVA)_M = 10,000

(kVA)_S = 7,500

V_L = 12,400

N_T = 240

V_CL = 200

R_L = 0.5

WYE CT

Sub. 2
2898412

Fig. 21. Example for Setting Calculations.