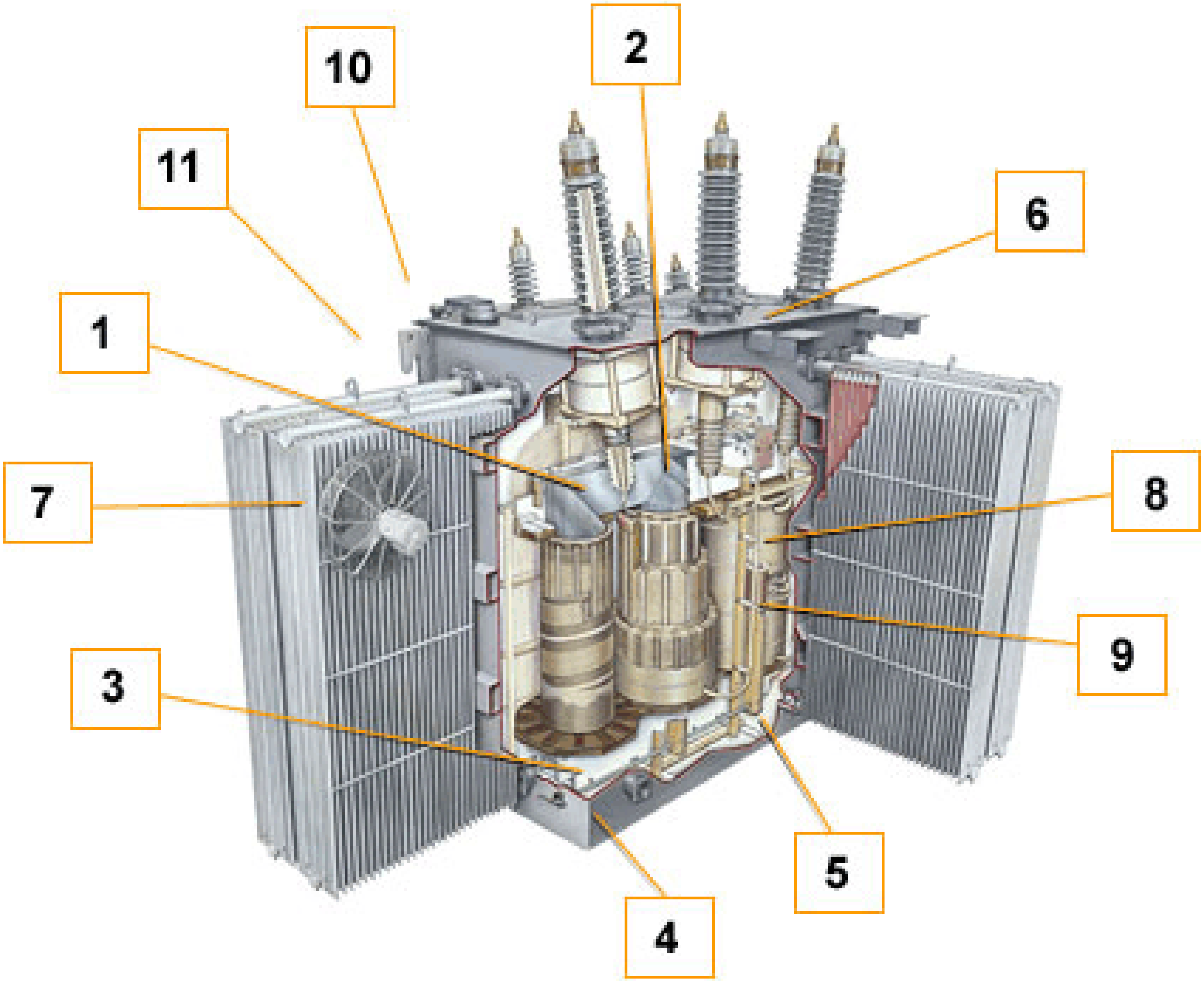
EE 5223 - Lecture 30 Fri Mar 21, 2025

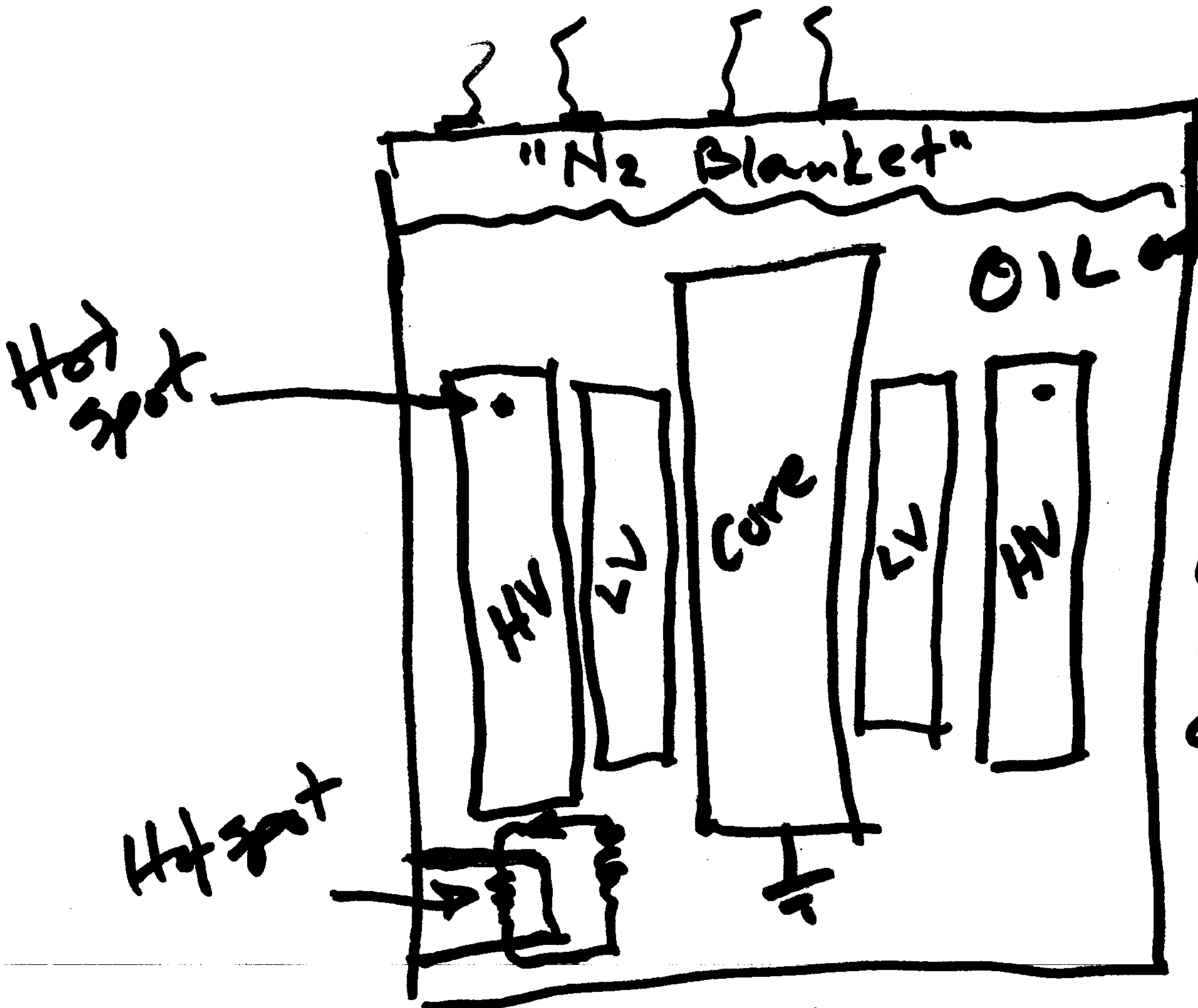
Ongoing List of Topics:

- URL: https://pages.mtu.edu/~bamork/EE5223/index.htm
- Term Project - Follow posted Guidelines!
  - Working prototype/basecase - goal by end of Week 12!
- Assn#10: Probs 4.2, 4.3 a,b,c and 4.4 (View tutorial videos)
  - Problems due Tues Mar 25th 9am. Use e-mail discussion!
- Transformer Fundamentals
  - Correct connection of CT secondaries to relays (Lecture 29)
  - Physical design, protection/control needs, issues
  - IEEE C57 stds
  - Design, operation, specs
  - Thermal issues, cooling
  - Load tap changer
  - Field tests - insulation PF tests, TTR, oil dielectric levels
  - Gas in oil analysis
  - Other alarm and protection systems
  - Next lecture: Return to details of 87T relay - CT ratios, tap settings, mismatch, CT saturation, etc.


10
2
11
6
1
7
8
9
3
5
4

Test your knowledge: How many of the key features on the previous page could you identify? Source: Waukesha Electric, http://www.waukeshaelectric.com/peg-T1.shtml

1. Core (no-load) losses minimized by utilizing laser-scribed, super-grain-oriented steel.
2. Lamination width customized to achieve a near perfect-circle core cross section, resulting in the efficient use of materials plus a lighter, more compact, high performance transformer.
3. Coil assembly rigidly braced in a high-strength frame that distributes clamping forces around the full circumference of the windings.
4. Submerged-arc welding process produces deep penetration welds, virtually eliminating leakage from welded tank joints.
5. Inside tank surfaces are painted white to facilitate internal inspection.
6. Transformer exterior coated to a minimum thickness of 3 mils; this coating has superior endurance characteristics and meets the ANSI C57.12.28 standard.
7. Galvanized radiators provide excellent corrosion resistance and require minimal maintenance (fan guards and blades also galvanized).
8. Material-stabilized coils are pressure-fit within the core frame.
9. Patented DETC (De-Energized Tap Changer) features simple and compact in-line contact arrangement (Patent Number: 5,744,764)
10. Waukesha® Type UZD Load Tap Changer designed to withstand up to a half-million operations without the need for contact replacement.
11. Worldbox® Control Enclosure features IEC standard components and is easy to maintain and service in the field.



Top Oil Temp

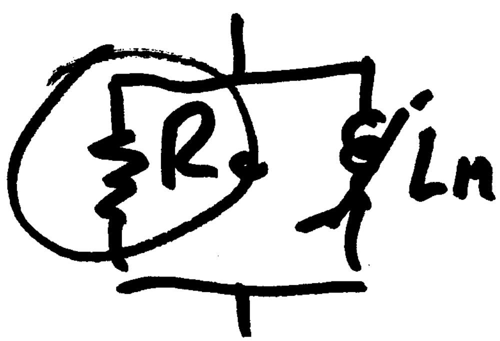
Alarm - 26H
Trip - 26HH

Bank 1 - 49-1
Bank 2 - 49-2
alarm - 49H
trip - 49HH

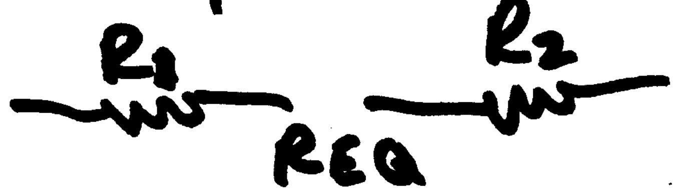
$$P_{core} \propto \frac{V^2}{R_c} = P_{NL}$$

Heat:

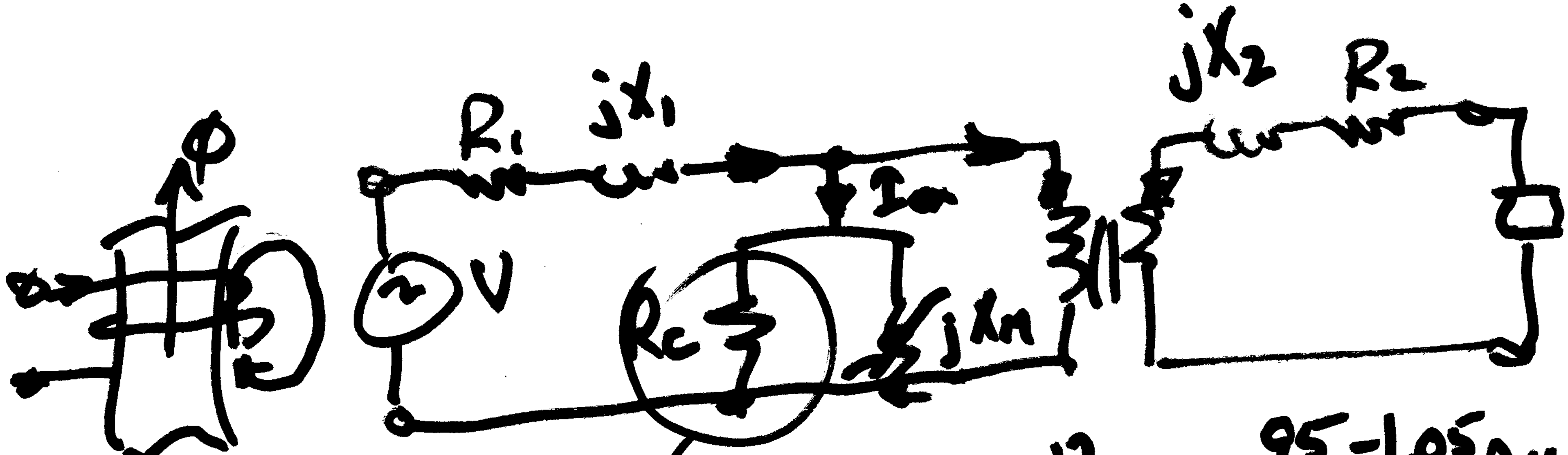
Core:



Coils:



$$P_{coil} \propto I^2 R_{EQ} = P_{LOAD}$$



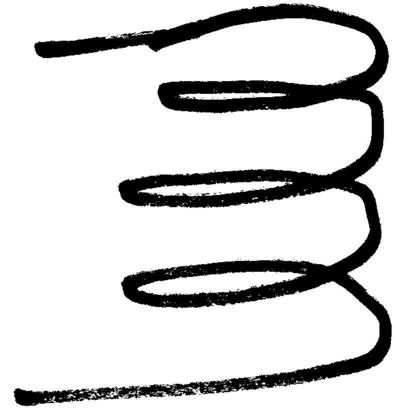
$P_{NL} = P_{CORE} \propto V^2$

.95 - 1.05 p.u

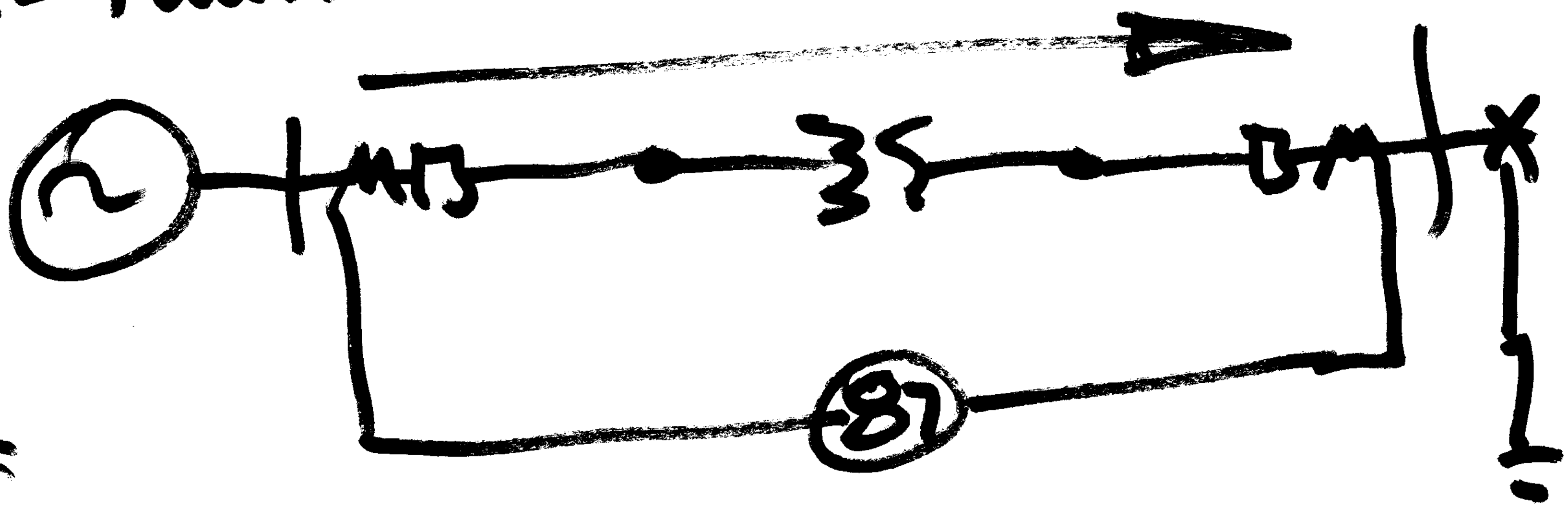
$\Rightarrow \pm 10\%$

- Internal Faults
  - Turn-turn
  - Layer-to-Layer
  - Coil-to-tank
  - Coil-to-core

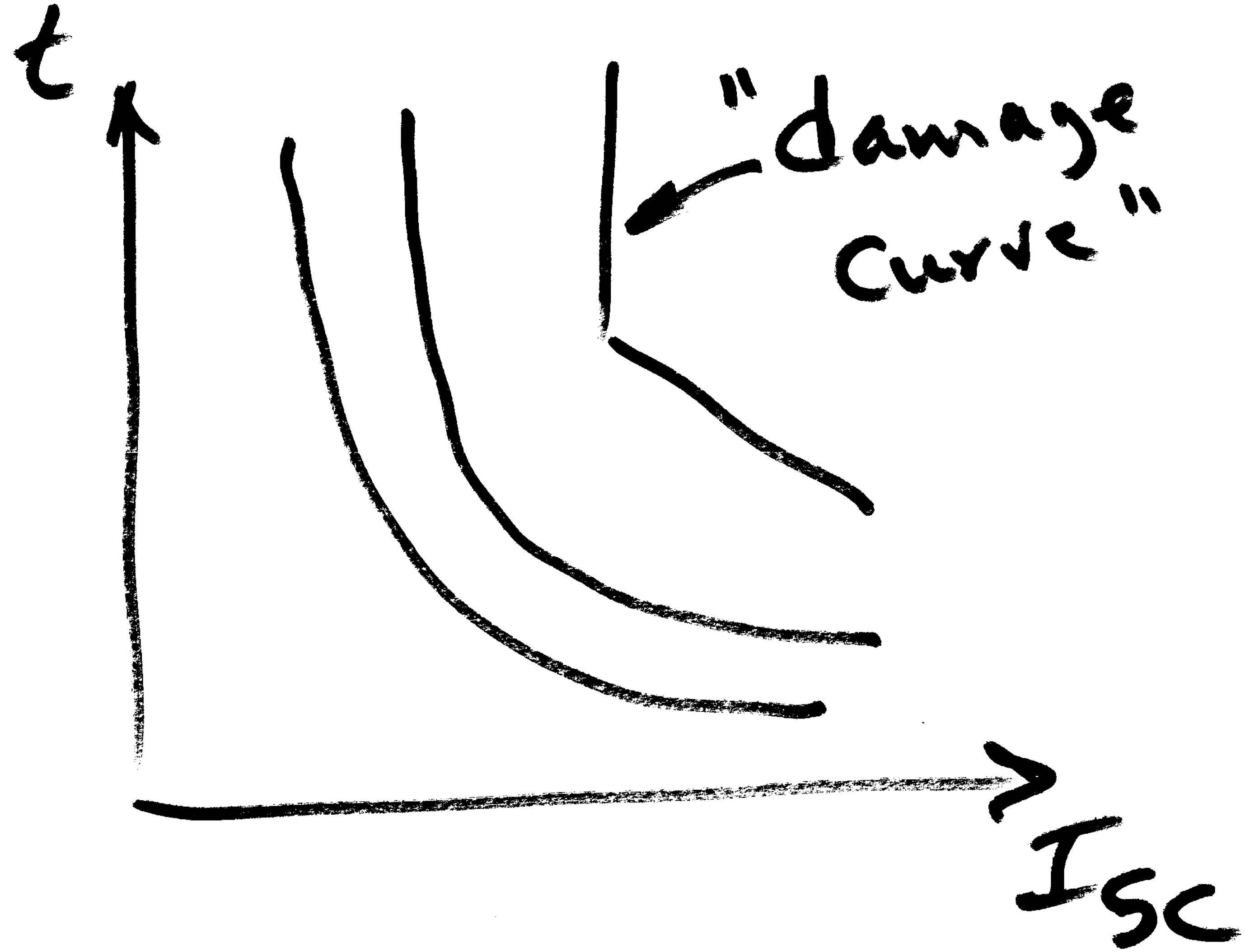
induced force

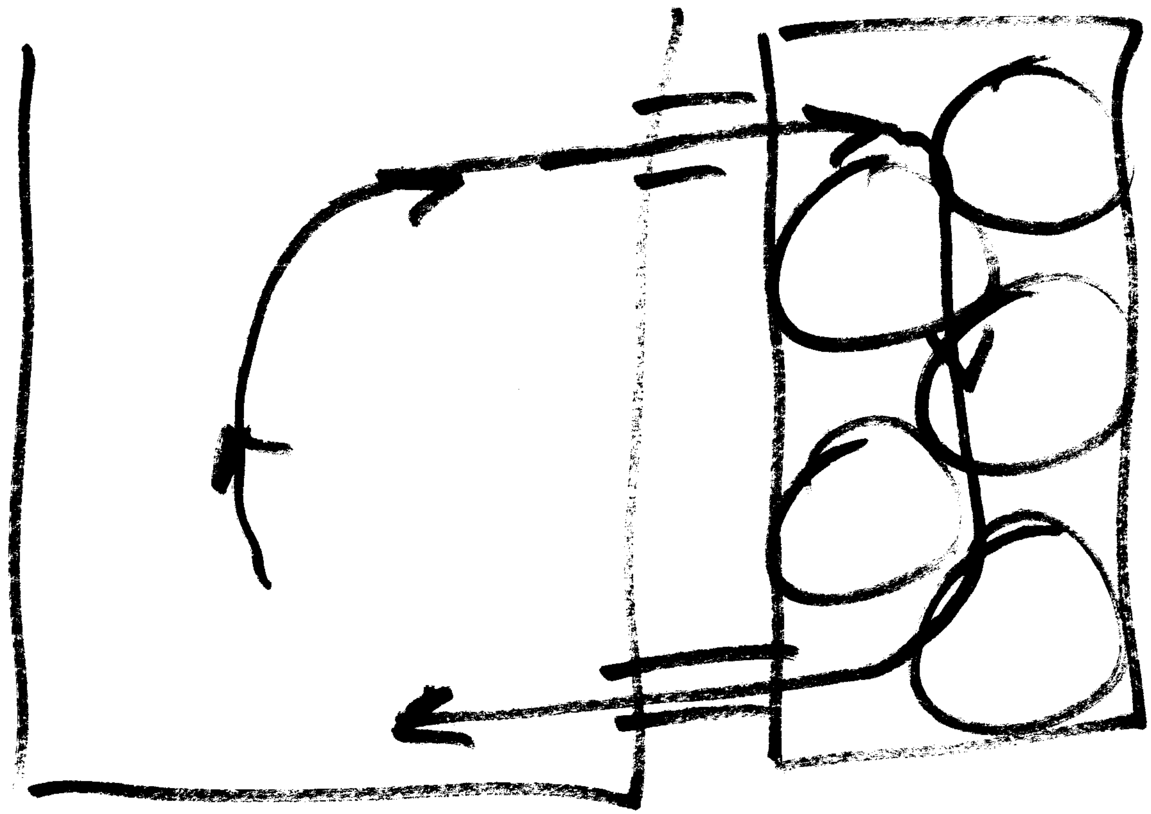


- Thru-faults



C57


t
"damage
curve"
I_{SC}



OA/FA/FA

XFMR.pdf

"Other" conditions monitored / alarm points

- Sudden Pressure
  - "Bucholtz Relay" → 63X → 86T
- Oil Level -71L, 71LL
  - 71L: Alarm SCADA
  - 71LL: Trip
- N_2 Pressure (2000 psi when full)
  - High Pressure Low
  - Low / Tank Press

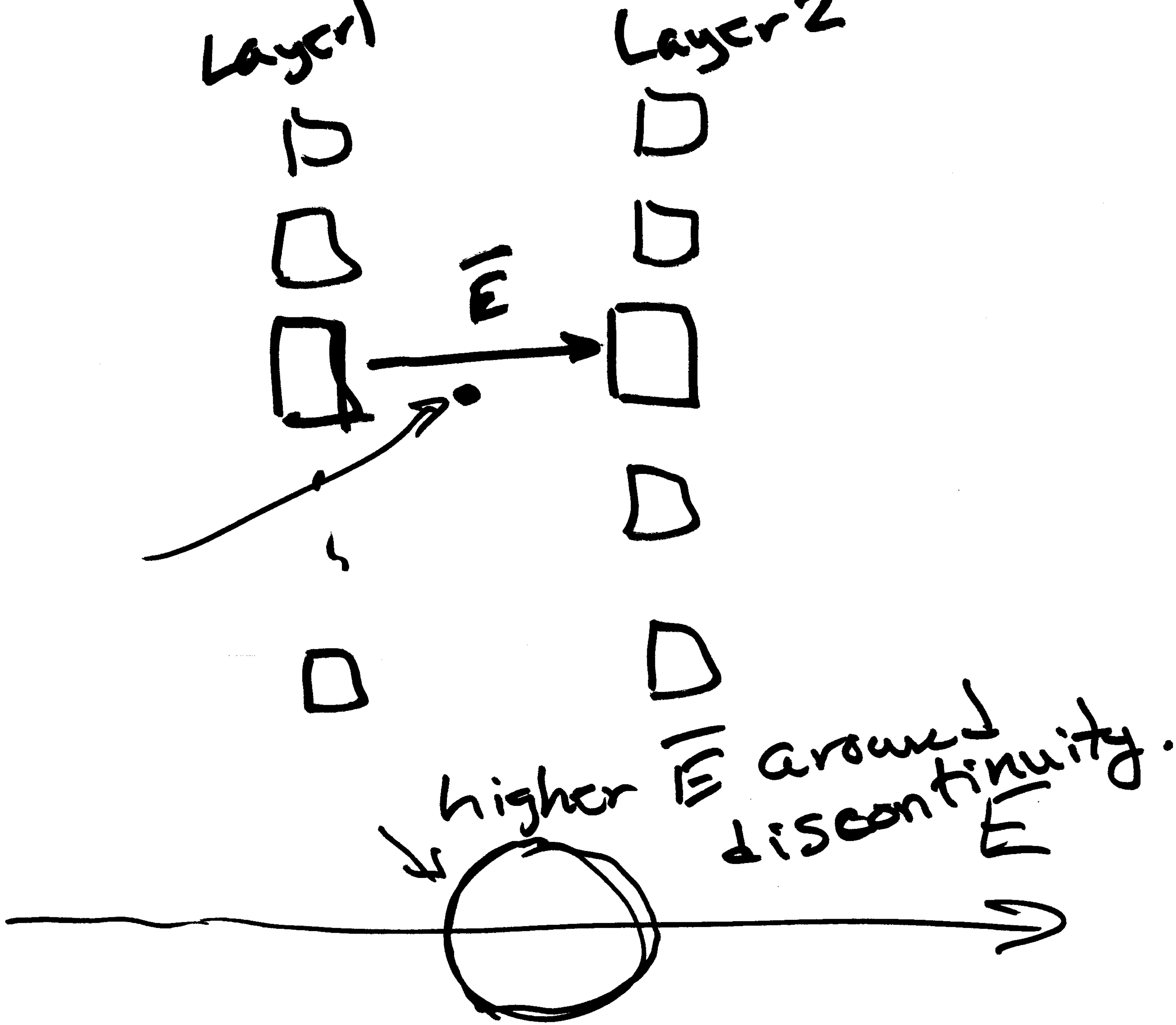
high — 20-40 psi
low — 4-8 psi

Other Alarms (Con't)

- Pressure Relief Valve – SCADA
- Loss of Power to AC "loads"
    - Cooling Fans / Pumps
    - Controls

<u>Annunciator</u> – Monitor / Group Alarm Points. Pass on to SCADA.

(in control cabinet on transformer)


Layer1
Layer2
$\bar{E}$
higher $\bar{E}$ around discontinuity.
$\underline{E}$

MODERN POWER TRANSFORMER PRACTICE

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M

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2.2.7 Load loss and resistance voltage

From standard specifications the load loss is the power absorbed on short-circuit test related to the reference temperature. It therefore consists of the I^2R loss and eddy current loss in the copper and the stray losses; the iron loss is negligible at the very low voltage of the test. If P_{Cu} is the copper loss per phase, then for a three-phase transformer the load loss P_l is

$$P_l = 3P_{Cu} + \text{stray losses} \tag{2.10}$$

where

$$P_{Cu} = (1 + \%P_{i1}/100)I_1^2R_1 + (1 + \%P_{i2}/100)I_2^2R_2 \tag{2.11}$$

The subscripts 1 and 2 denote quantities related to the low- and high-voltage windings, respectively, and the values of resistance and percentage eddy current loss are at 75 °C.

The resistance voltage is the component of the impedance voltage in phase with the current. Its value is related to the reference temperature and is equal to IR, where I is rated current and R is the effective ac phase resistance at 75 °C, including an allowance for the effects of eddy current and stray losses.

Expressed as a percentage, the resistance voltage is

$$\%R = 100 \times IR/V \tag{2.12}$$

where V is rated phase voltage referred to the same side of the transformer as I and R. Thus,

$$\%R = \frac{I^2R}{VI} \times 100 \doteq \frac{\text{load loss per phase in watts}}{\text{voltamperes per phase}} \times 100$$

or, for a three-phase transformer, with equation 2.10

$$\%R = 10^{-4} \times P_l/3S \tag{2.13}$$

where P_l is in watts and S is the rating per phase in megavoltamperes.

2.3 GENERAL CONSIDERATIONS: TRANSFORMER WINDINGS AND INSULATION

The subject of transformer windings and insulation is presented in chapter 5. Additional information, contained in subsequent chapters, is listed in sub-section 1.8.3.

Figure 2.2 illustrates the principles of the arrangement of winding insulation in one type of distribution transformer.

The ultimate limit to the life of a transformer is imposed by the life of its insulation which decreases with increase in operating temperature. To ensure an economic life, upper limits of temperature have been set for the various classes of insulation, for example, 105 °C for class A materials[G1.9]. Such limits relate to the

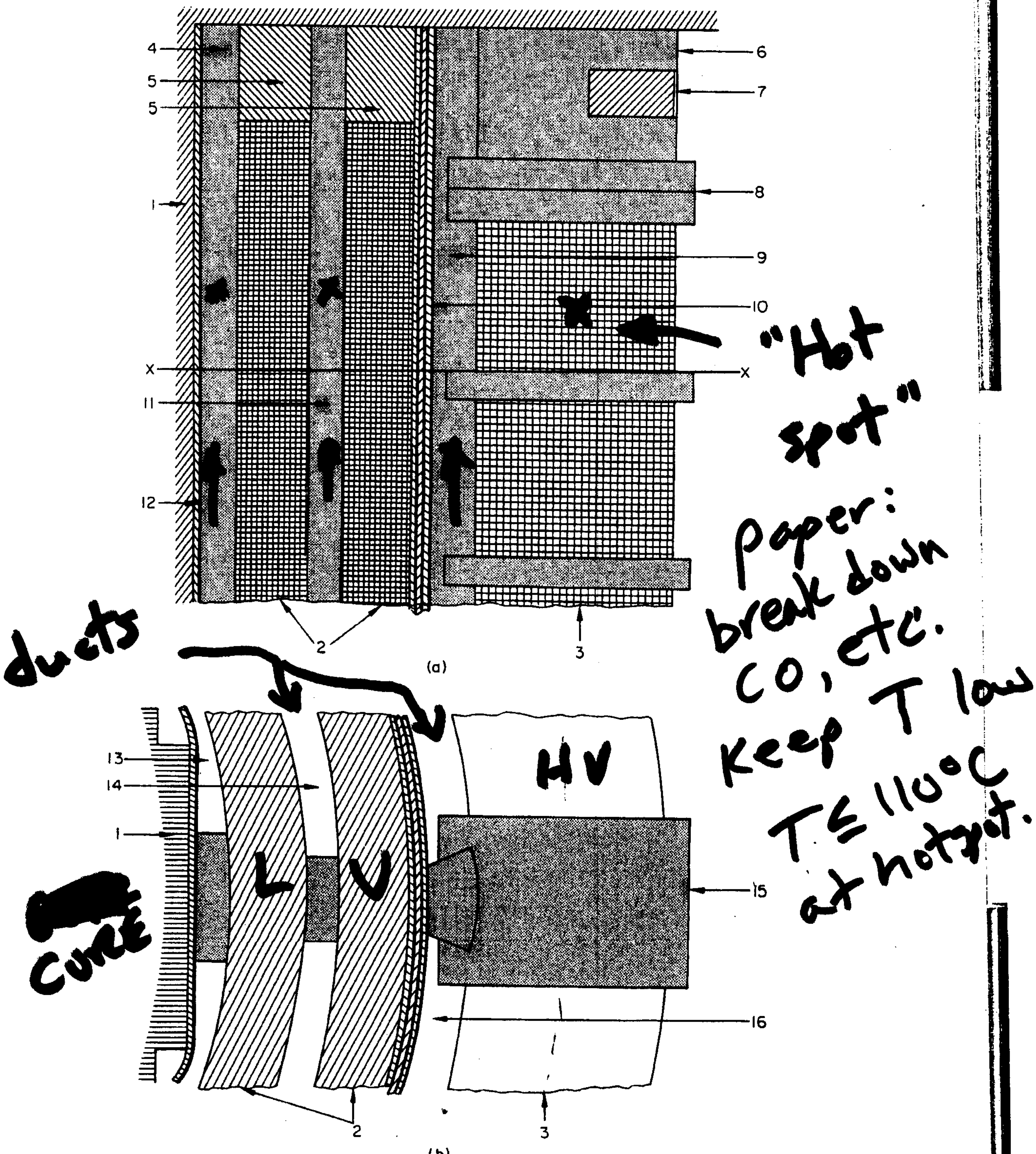


Figure 2.2 Typical distribution transformer insulation: (a) vertical section; (b) horizontal section on X–X: 1, core leg; 2, low-voltage winding; 3, high-voltage winding; 4, spacing strip; 5, edge block; 6, insulation end block; 7, end washer; 8, spacers; 9, spacing strip; 10, paper insulation; 11, spacing strip; 12, paper insulation; 13, duct; 14, cooling duct; 15, spacer; 16, duct

hottest part of the windings and are implicit in the definitions of continuous rating in standard specifications.

2.4 GENERAL CONSIDERATIONS: COOLING OF ONAN TRANSFORMERS

2.4.1 Temperature distribution in core, windings and oil

Figure 2.3 indicates the approximate temperature distribution. Figure 2.3(a) represents conditions near the top of the windings where the maximum temperatures occur. All the oil above the transformer is assumed to have the same temperature, irrespective of whether it has ascended through the ducts or past the external winding surfaces. Since the thermal resistivity of copper is negligible in comparison with that of insulation, the high-voltage winding is the most difficult to cool and usually contains the hot spot.

The core material has a greater thermal resistivity than that of copper but much less than that of paper insulation or of the insulation between laminations. A path of comparatively high thermal conductivity is thus provided to the edge of the laminations. This generally limits the temperature of the core to a value less than that of the windings when the transformer is operating at full-load condition.

Figure 2.3(b) shows the temperature distribution across the high-voltage winding to an enlarged scale. Internally, the heat passes by conduction through the layers of insulation and the curve is approximately parabolic. The coil surfaces, however, cool by convection, and this results in the characteristically steep surface temperature drops shown. The difference between the hot-spot temperature and the oil temperature is called the maximum winding temperature gradient $\Delta\theta_{wom}$. Similarly the difference between the mean coil temperature and that of the oil is the mean gradient $\Delta\theta_{wo}$. The term gradient is used merely to indicate a difference in temperature and not in the strict sense of temperature difference per unit length.

At the tank surfaces, there are also steep drops in temperature, as shown in figure 2.3(a). The external temperature drop, however, does not take place entirely at the surface. Cooling by both radiation and convection is involved, and the air temperature remains above the ambient value for some distance from the tank wall.

Figure 2.3(c) indicates approximately the temperature distribution vertically through the windings. The oil temperature may be considered to increase linearly with height up the coil stack, reaching a maximum at the top of the windings. The temperature then remains constant to the surface and is referred to as the top oil temperature. Over the full height of the windings the graph of copper temperature is parallel with that of the oil, since the temperature gradients in the body of the winding are assumed independent of vertical position, as shown. In fact, the hot spot does not occur at the very top of the windings owing to cooling

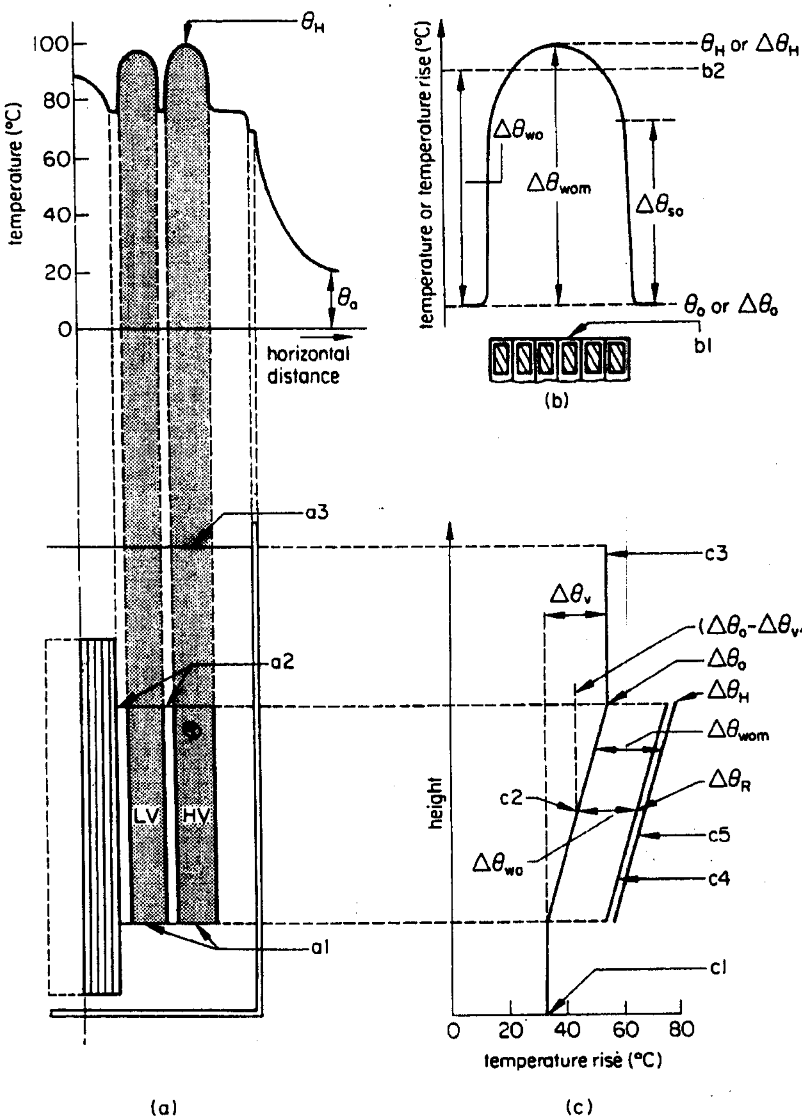


Figure 2.3 Temperature distribution in an ONAN transformer: (a) typical temperature profile on horizontal plane through winding hot spot; (b) temperature gradients in high-voltage winding to enlarged scale; (c) simplified temperature rise diagram in vertical plane: a1, sections of windings to enlarged horizontal scale; a2, ducts; a3, oil level; b1, top of high-voltage winding; c1, approximate oil temperature rise at tank bottom; c2, average duct oil temperature rise; c3, approximate oil temperature rise at tank top; c4, mean oil temperature rise; c5, maximum oil temperature rise; θ_H, hot-spot temperature; θ_a, ambient temperature; $\Delta\theta_{wom}$, maximum winding temperature gradient; $\Delta\theta_{wo}$, mean winding temperature gradient; $\Delta\theta_{so}$, surface temperature drop; $\Delta\theta_o$, temperature rise of top oil; $\Delta\theta_v$, difference in oil temperature rise between tank top and bottom; $\Delta\theta_R$, mean winding temperature rise

from the upper surface. Its vertical position is very difficult to determine, however, and the approximation implicit in the graph is accepted in calculating the winding temperature.

2.4.2 Specified limits of temperature rise

Although the hot-spot temperature is of critical importance, it can only be measured directly by a thermocouple embedded in the winding, which is obviously impracticable. Standard specifications, therefore, give limits of temperature rise above ambient temperature which, although related only indirectly to the hot-spot temperature rise, are easily measured on test. These are the mean temperature rise of the windings as measured by the increase $\Delta\theta_R$ in resistance, and the temperature rise $\Delta\theta_0$ of the top oil measured by thermometer.

2.4.3 Tank configuration and winding temperature gradients

The specified limits of temperature rise considered in conjunction with the design of the tank imply maximum values for the winding temperature gradient $\Delta\theta_{wo}$, and the windings should be formed in such a way that these values are not normally exceeded.

In figure 2.3(c), the difference in temperature rise between the oil at the top and bottom of the tank is denoted by $\Delta\theta_v$. This depends upon the tank design, and a low value is preferable as the slope of the graphs is then increased. Thus the maximum copper temperature rise at the top of the windings is reduced for the same specified mean temperature rise, which, for the linear graphs assumed, occurs at half the winding height. A lower value of $\Delta\theta_v$ corresponds to a more vigorous rate of oil circulation, resulting in an increased rate of heat transfer at the coil and tank surfaces and thus reducing the surface temperature drops.

In ON-type transformers the rate of circulation of oil depends upon the difference in densities between the hot oil, which rises through and above the transformer, and the cool oil which descends at the tank surfaces. Ideal conditions for ON-type cooling are thus obtained by placing the transformer in a relatively tall plain tank. The bulk of the ascending oil then has the maximum temperature rise $\Delta\theta_o$, corresponding to the lowest possible density and thus giving the most vigorous rate of oil circulation. Furthermore, a plain surface is the most efficient for heat dissipation.

Except for transformers rated at less than about 50 kVA, however, such an arrangement is uneconomical, as the tank would have to be very large relative to the size of transformer to provide sufficient cooling surface area. Radiators or tubes are, therefore, provided to increase the cooling area without a corresponding increase in oil quantity but at the expense of some loss in cooling efficiency.

The relationship between $\Delta\theta_v$ and $\Delta\theta_o$ may be expressed in the form

$$\Delta\theta_v = k_v\Delta\theta_o \qquad ^\circ\mathrm{C} \tag{2.14}$$

where the factor k_v has values ranging from about 0.3 for plain tanks or for tanks equipped with radiators to 0.5 for three-row tubular tanks. From figure 2.3(c), the mean duct oil temperature rise is $\Delta\theta_o - \Delta\theta_v/2$; thus the mean winding temperature rise is

$$\Delta\theta_R = (\Delta\theta_o - \tfrac{1}{2}\Delta\theta_v) + \Delta\theta_{wo} \qquad ^\circ\mathrm{C} \tag{2.15}$$

Substituting for $\Delta\theta_v$ and rearranging, we obtain

$$\Delta\theta_{wo} = \Delta\theta_R - \Delta\theta_o(1 - \tfrac{1}{2}k_v) \qquad {}^\circ\mathrm{C} \tag{2.16}$$

Thus values of $\Delta\theta_{wo}$ compatible with the specified limits of temperature rise may be calculated.

It may be assumed[1] that

$$\Delta\theta_{wom} = 1.1\Delta\theta_{wo} \qquad {}^\circ\mathrm{C} \tag{2.17}$$

thus the hot-spot temperature rise is given by

$$\Delta\theta_H = \Delta\theta_o + \Delta\theta_{wom} = \Delta\theta_o + 1.1\Delta\theta_{wom} \qquad {}^\circ\mathrm{C} \tag{2.18}$$

and the hot-spot temperature is

$$\theta_H = \Delta\theta_H + \theta_a \qquad {}^\circ\mathrm{C} \tag{2.19}$$

where θ_a is the ambient temperature in degrees Celsius.

2.5 PRACTICAL CONSTRAINTS ON THE DESIGN

2.5.1 Specific electric and magnetic loadings

Equation 2.4 indicates that the specific I^2R loss is directly proportional to J^2 and figure 2.1 relates the specific iron loss at 50 Hz to B_m for a given core material and type of construction. For these reasons, the values of current density J and flux density B_m are often termed the specific electric and magnetic loadings, respectively. The choice of specific loadings is commonly regarded as the starting point for preliminary design work on a transformer. Provided the losses and reactance are not specified, the highest acceptable values may be chosen for both J and B_m, thus reducing the cost of materials to a minimum.

The cooling method determines the maximum value of current density, which in class A insulated transformers varies from about 3.2 A mm^{-2} for distribution transformers to 5.5 A mm^{-2} for large transformers with forced cooling.

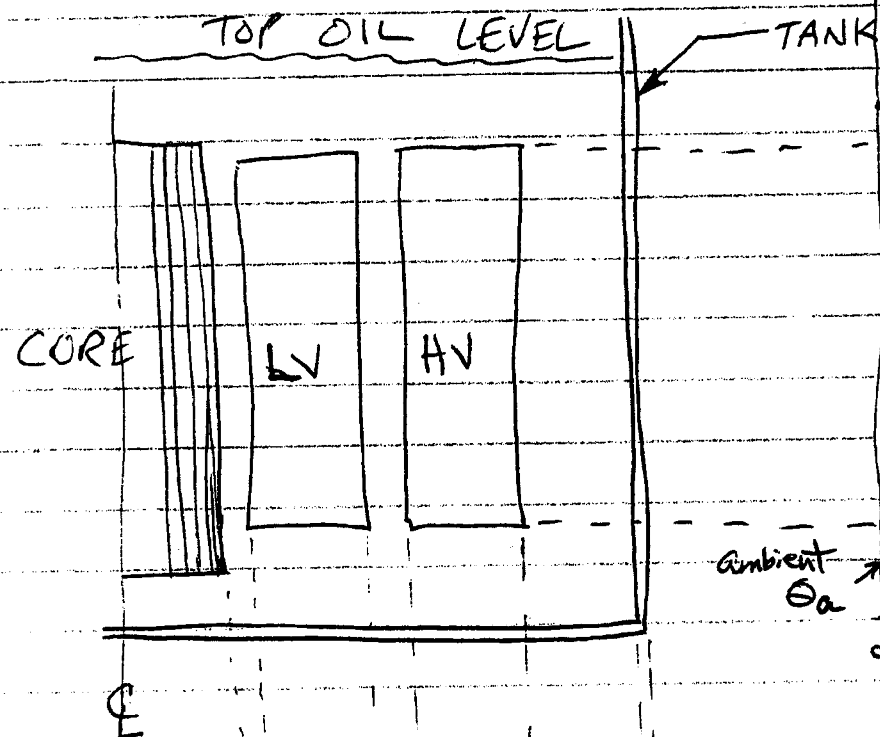
The limit on the value of B_m is imposed by distortion of the magnetising current and generation of noise, as described in sub-section 1.2.4 and section 1.9, respectively. For generator transformers, these factors are relatively unimportant, and flux densities as high as 1.8 T have been used. In other cases, however, it is considered good practice to keep B_m below 1.6 T.

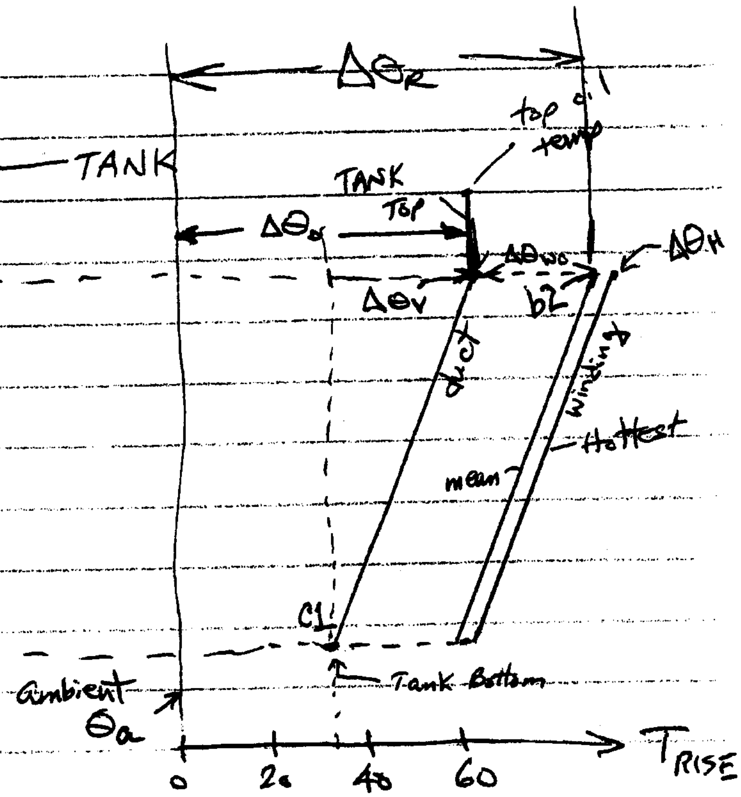
2.5.2 Relationship between current density and flux density

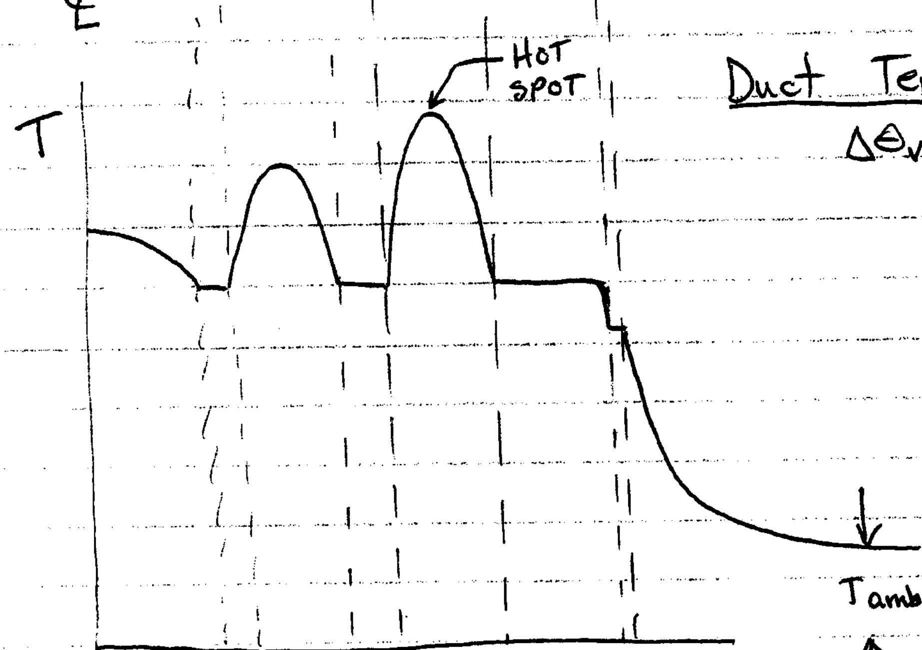
If we assume that the percentage eddy current losses in the low-voltage and high-voltage windings on normal tapping, $\%P_{i1}$ and $\%P_{i2}$, may be taken as each approximately equal to the average percentage eddy current loss $\%P_i$,

$$1 + \%P_{i1}/100 \approx 1 + \%P_{i2}/100 \approx 1 + \%P_i/100 = k_i$$

Transformer Cooling –







Tambient

Duct Temp Rise

$$\Delta\Theta_v = K_v\,\Delta\Theta_o$$

$K_v = 0.3$

$\Delta\Theta_o$ = Top oil Temp Rise

$\Delta\Theta_{wo}$ = mean winding ~~temp~~ rise from duct

$\Delta\Theta_R$ = mean temp rise from ambient

$\Delta\Theta_{wom} = 1.1\,\Delta\Theta_{wo}$ @ Hot spot rise from duct

Comparatively:

Cu – Nearly perfect thermal cond

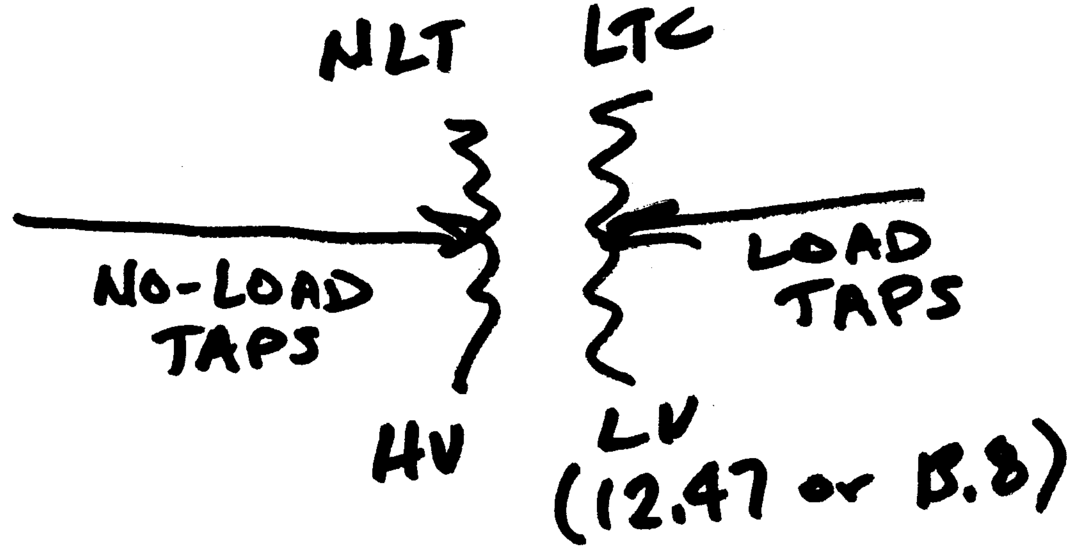
Fe – Also very good

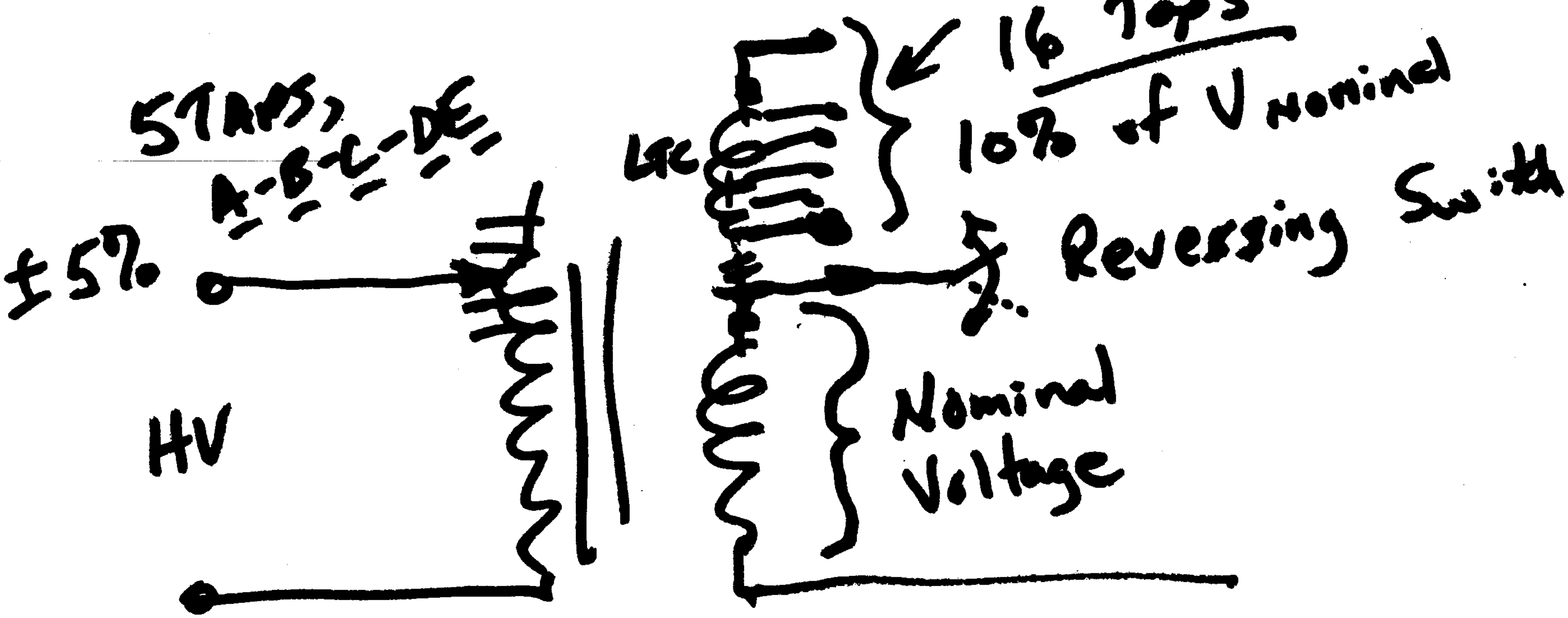
Paper – Terrible

Oil – Fairly good.

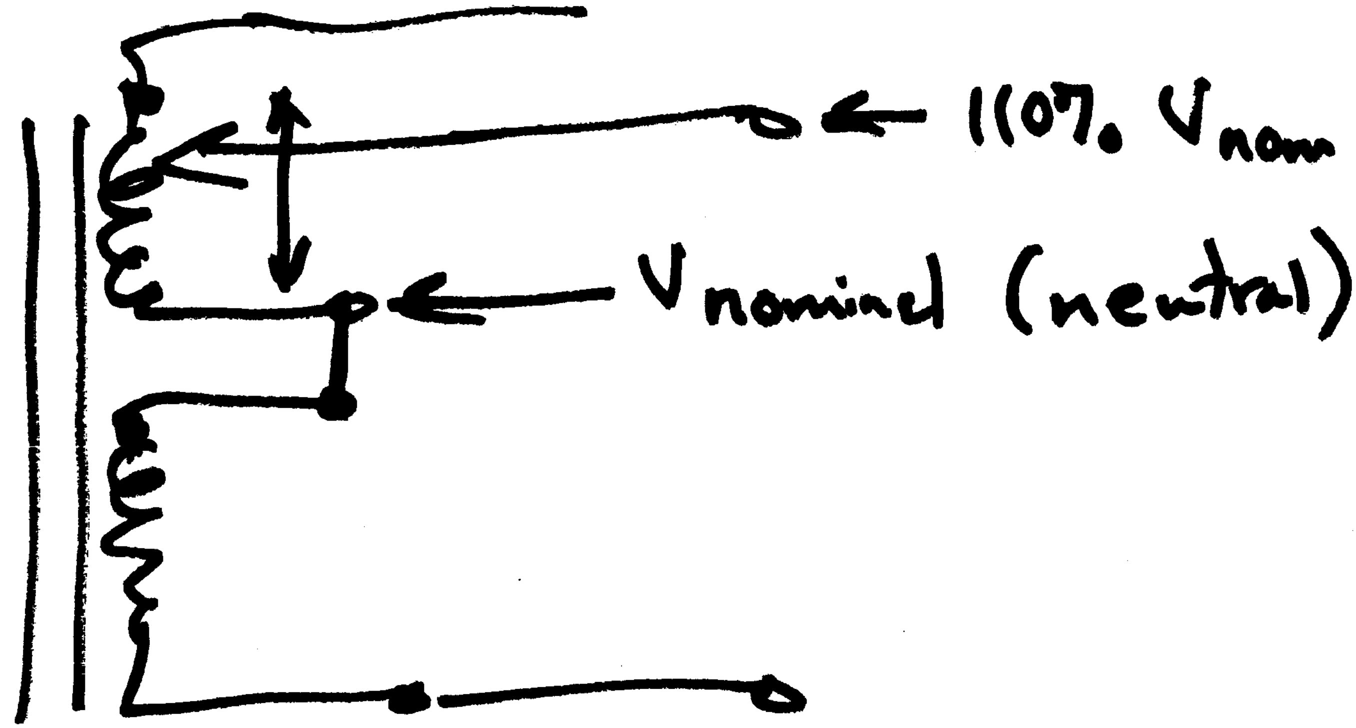
} oil-impregnated paper is ~~good~~. better.

- LTC min/max position

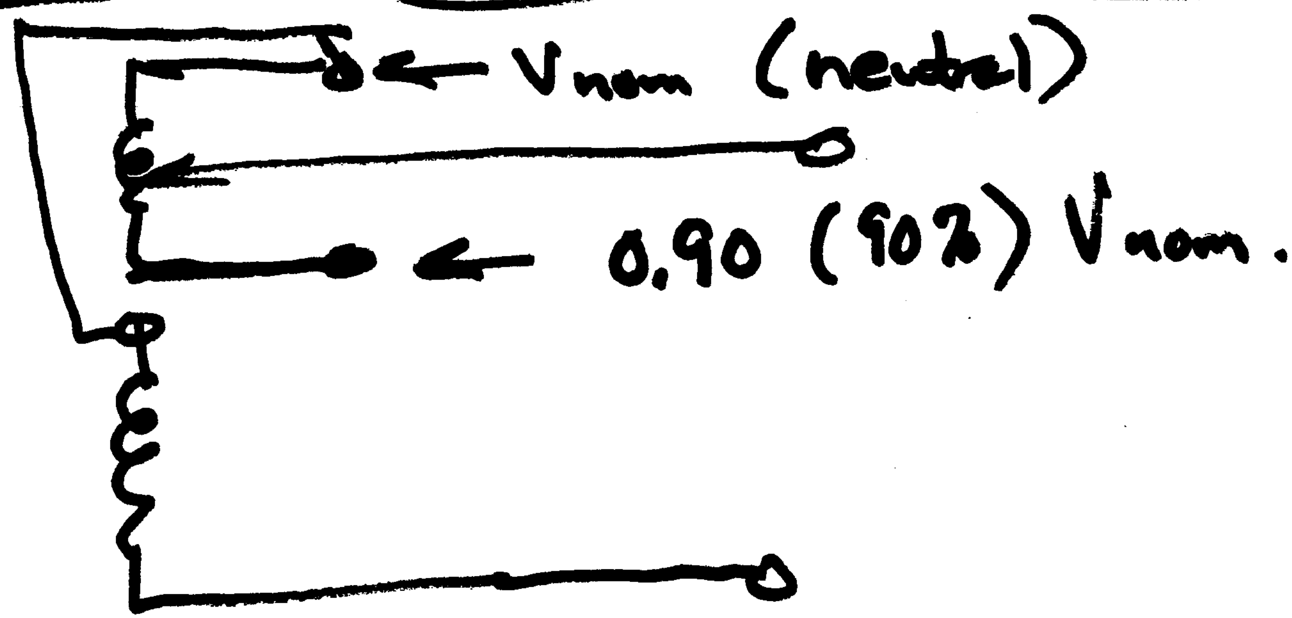


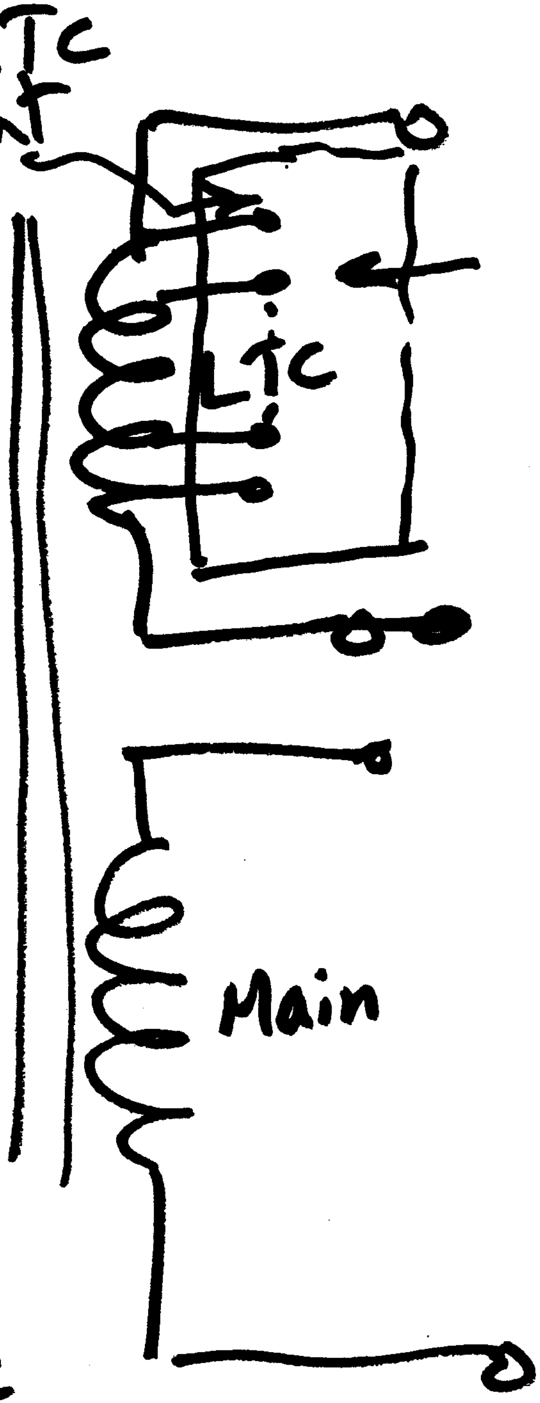


"Boost"



"Buck"





17 total Tap Points

⇒

Neutral and ±16 taps

33 total positions

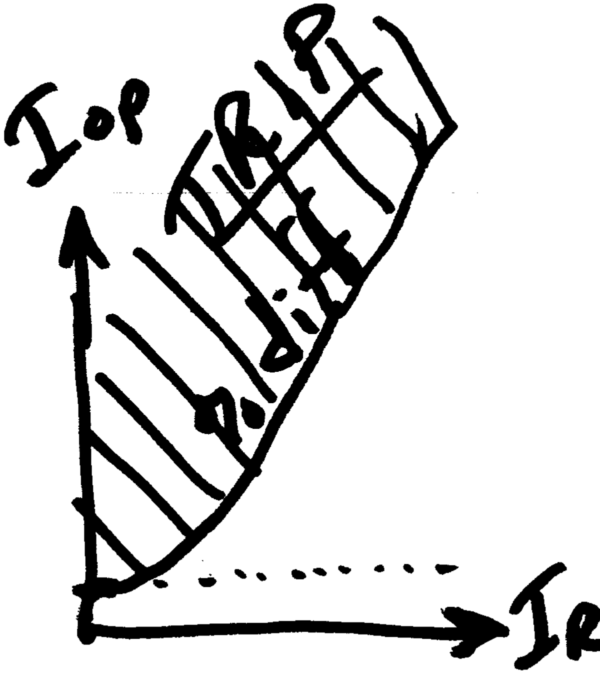
16H (+10%)

Boost

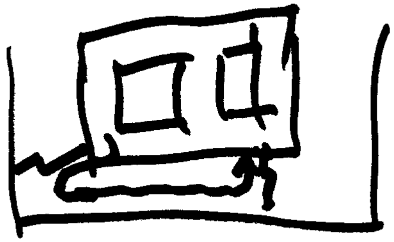
Neutral

Buck

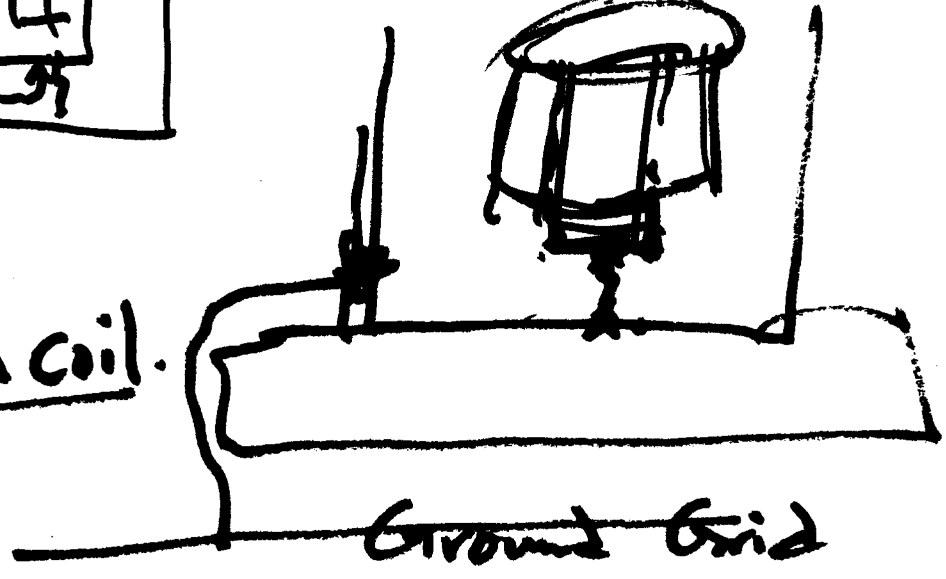
16L (-10%)



Testing:



- Megger the core
- Also: R_{dc} of each coil.
- TTR
  - meas V ratio
    ($\propto$ Turns Ratio)



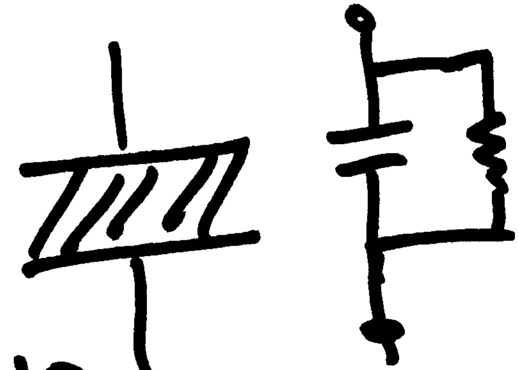
- "Doble Test" – Insulation Power Factor

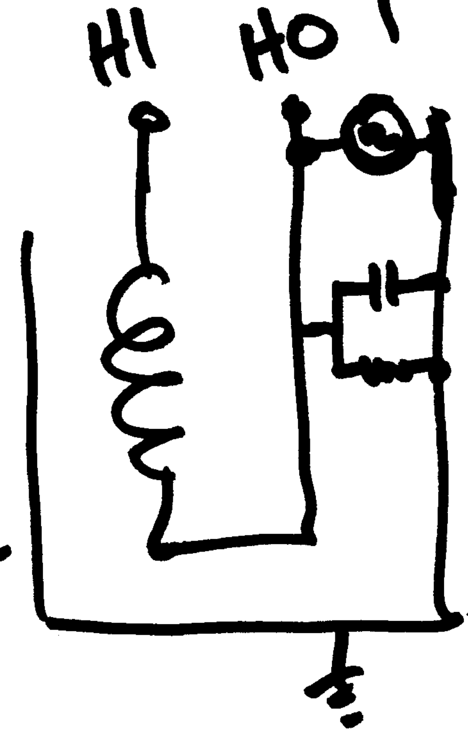
Typically $PF < .01$

$PF = 0.3\%$ (typical)

- Diagnostic Tests
  - "Doble" Test (Insulation PF)
    ((Capacitance Diss Factor)

$PF \cong 0.3\%$
($< 1\%$ typ)



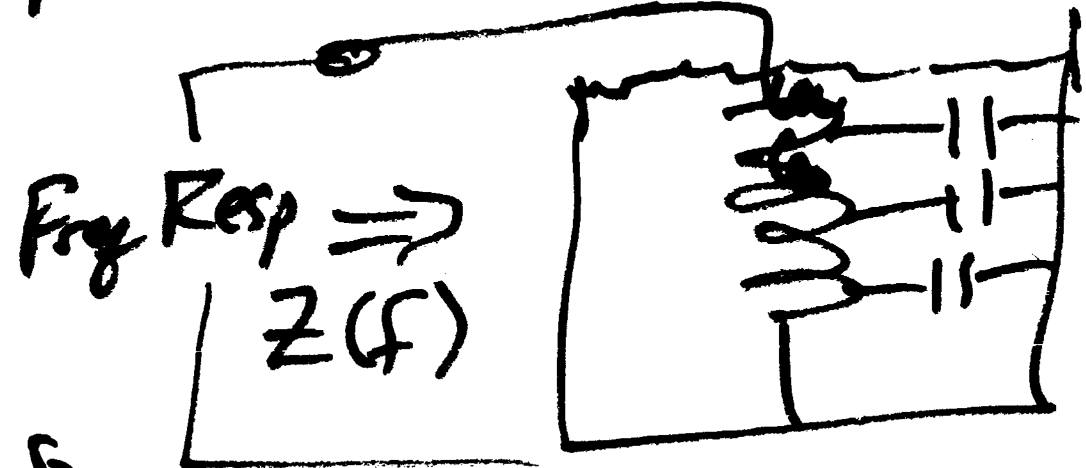


<u>Tip-Up Test</u>

Deterioration:
- Water
- Carbon

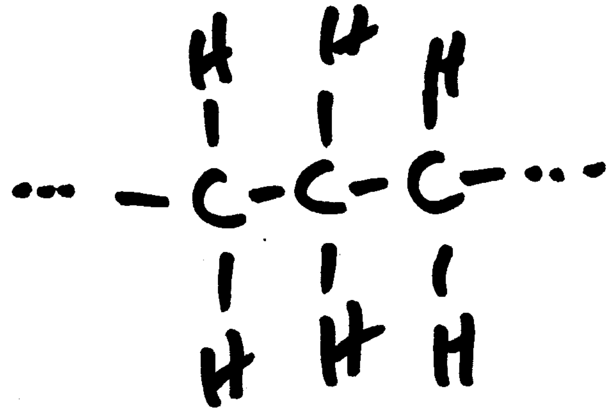
Gradually Increase V_{TEST}
- If $PF = \text{const} \Rightarrow$ moisture
- If PF increases $\Rightarrow$ carbon.

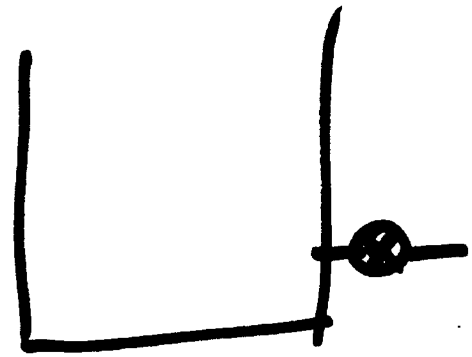
- Freq Response Test



- Gas-in-Oil
  - "Pull a sample" of oil from tank.
  - Use syringe to extract.

arcing
- H_2
- CH_4
- C_2H_4
- C_2H_2





- CO - Heating, deterioration of paper
- CO_2 - Oxidation / "burning" paper

LOL

IEEE C57 - Stds
- Thru faults
- Gas in oil
- etc.

XFMR.pdf

"Other" conditions monitored / alarm points

- Sudden Pressure
  - "Bucholtz Relay" → 63X → 86T
- Oil Level - 71L, 71LL
  - 71L: Alarm SCADA
  - 71LL: Trip
- N_2 Pressure (2000 psi when full)
  - High Pressure Low
  - Low / Tank Press

high - 20-40 psi
low - 4-8 psi

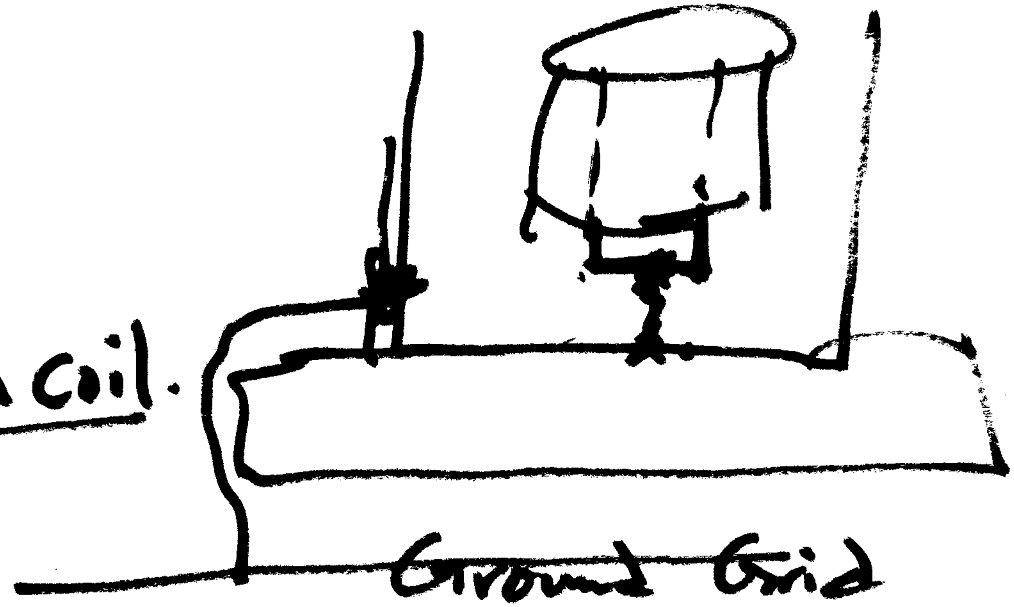
Other Alarms (Con't)

- Pressure Relief Valve – SCADA
- Loss of ~~E~~ Power to AC "loads"
  - Cooling Fans/Pumps
  - Controls

<u>Annunciator</u> – Monitor / Group Alarm Points. Pass on to SCADA.
(in control cabinet on transformer)

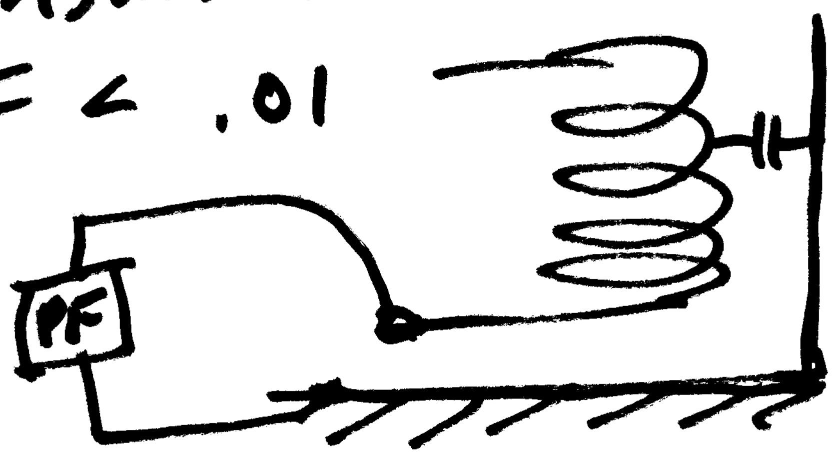
Testing:

- Megger the core
- Also: R_{dc} of each coil.
- TTR
  - Meas V ratio
    ($\propto$ Turns Ratio)



- "Doble Test" - Insulation Power Factor
  Typically PF < .01

PF = 0.3% (typical)



- Freq Response Test