Ongoing List of Topics:

- URL: https://pages.mtu.edu/~bamork/EE5223/index.htm
- Term Project -
    - Follow timeline, see Term Project Guidelines on web page.
- Wrap-up on Transformer differential, CT saturation
- Ch.10: Bus protection - 87B (print out "Bus Prot" at Week 11)
    - Review of Bus configurations, Sections 10.1 thru 10,10.
    - Low, Medium, and High-Impedance relays
    - Partial bus protection using 51 relay (distribution bus w/radial feeders)
- Next: Protection of Shunt Capacitor Banks (print out "Cap Bank Prot" at Week 12)
    - Basic application, reason for using shunt cap banks
    - Cap bank configurations, methods of protection

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:

$$\% \text{ mismatch} = 100 \frac{(I_{RL}/I_{RH}) - (T_L/T_H)}{S} \quad (1)$$

   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:

$$[N_p V_{cl} - (I_{ext} - 100) R_s] / I_{ext}$$
is greater than Z_T (2)

Note: let $I_{ext} = 100$
if maximum external fault current is less than 100A.

For wye-connected ct:

$Z_T = $ lead resistance + relay burden + Z_A

$$= 1.13 R_L + \frac{0.15}{T} + Z_A \text{ ohms} \quad (3)$$

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

For delta-connected ct:

$$Z_T = 3 (1.13 R_L + \frac{0.15}{R} + Z_A) \text{ ohms}$$

$$= 3.4 R_L + \frac{0.45}{T} + 3 Z_A \quad (4)$$

*(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

HU Relay Tap Ratios

	2.9	3.2	3.5	3.8	4.2	4.6	5.0	8.7
2.9	1.000	1.103	1.207	1.310	1.448	1.586	1.724	3.000
3.2		1.000	1.094	1.188	1.313	1.438	1.563	2.719
3.5			1.000	1.086	1.200	1.314	1.429	2.486
3.8				1.000	1.105	1.211	1.316	2.289
4.2					1.000	1.095	1.190	2.071
4.6						1.000	1.087	1.890
5.0							1.000	1.740
8.7								1.000

INSTALLATION

The relays should be mounted on switchboard panels or their equivalent in a location free from
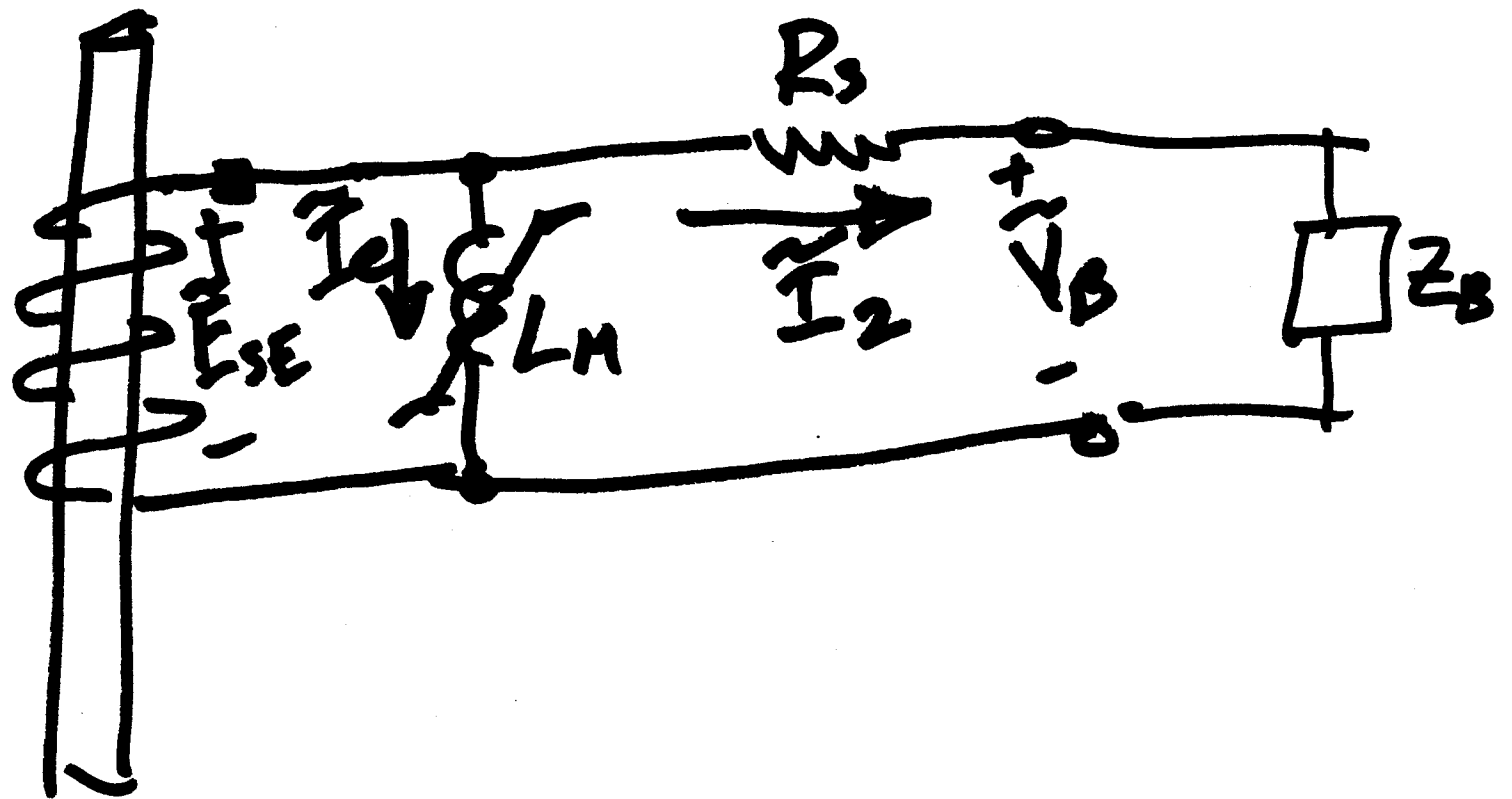
CT ERROR

MR CT

I_{ext} $+$ $I_{ext} R_s$ $-$

$+$

$400V$

$N_p V_{c1}$ $-$

V_B $+$ Z_T $-$

N
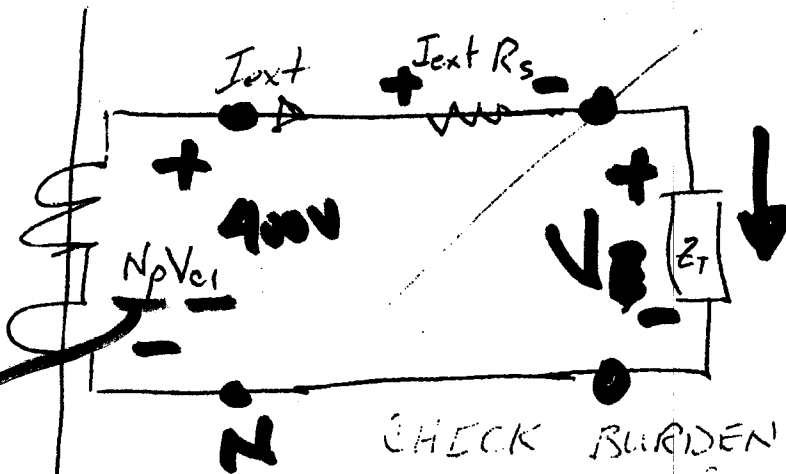
$\frac{300I5}{600I5}$

CHECK BURDEN ON CT!
(Page 3 of IL)

Check: $V_{CT \, CAPABLE \atop OF} - V_{DRIP \atop R_w} \overset{?}{>} I_{EXT} Z_B$

Condition Check:

$$\left[N_p V_{cl} - (I_{ext} - 100) \not{R_s} \right] / I_{ext} > \boxed{\underset{}{Z_T}}$$

V_{capab}

Valid for Y-conn
CT sec

Circuit diagram showing a transformer secondary winding with EMF E_{SE} (+ top, − bottom) and current I_1 flowing through a magnetizing branch L_M with current I_ϕ, then through resistance R_3 with current I_2 to a load with voltage V_B (+ top, − bottom) across burden impedance Z_B.

$20 \times I_{Rated}$

$I_2 \cong 100A$

I_2'

$800V$

$B-8$

$10 \, C \, 800$

8

$\theta = 60°$
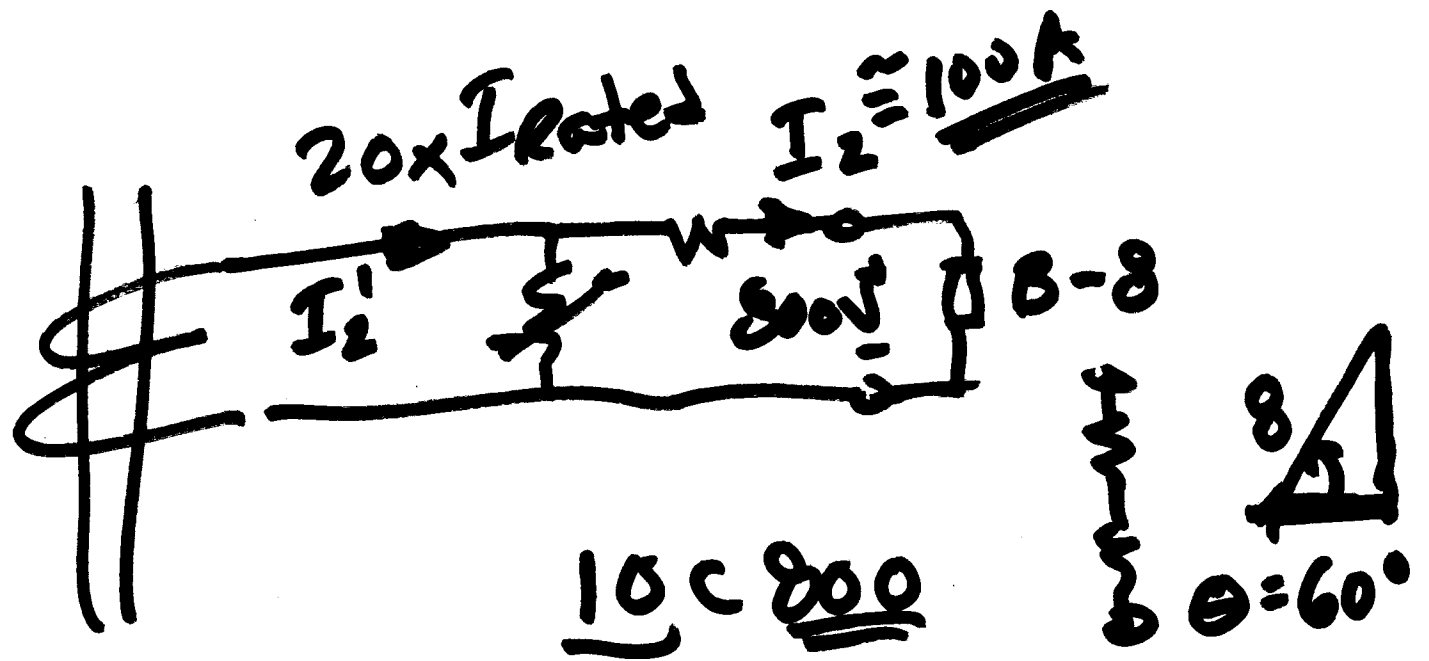
$\underline{I_2 \text{ is within } \pm 10\% \text{ of } I_2'.}$

$$\underbrace{N_p V_{cl} - (I_{ext} - 100) \cdot R_s}_{V \text{ cap at CT terms.}} > \underbrace{Z_T I_{ext}}_{V_{Total}}$$
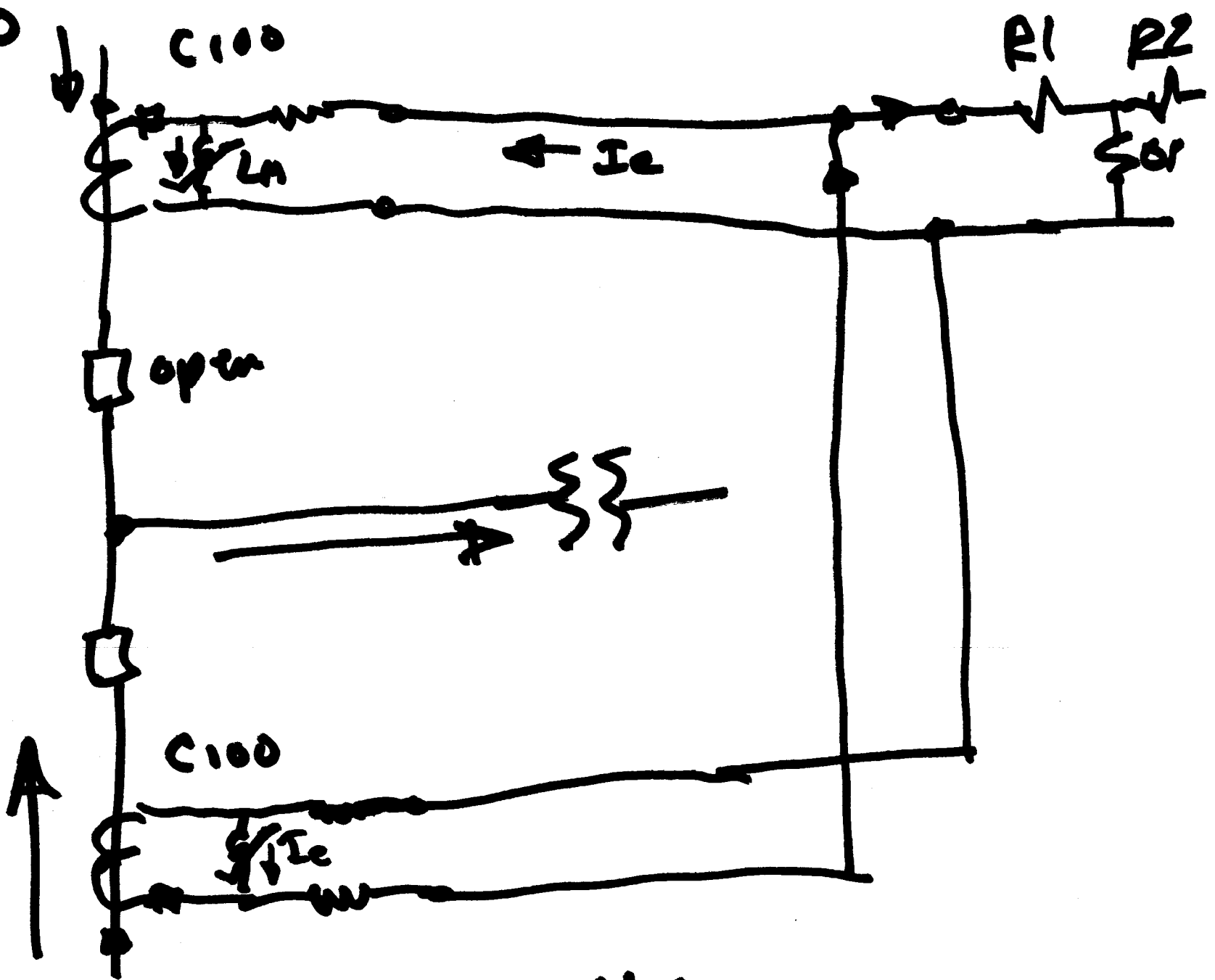
$$P = \frac{V^2}{R} = \frac{\tilde{V}_{LN}^2}{R_Y} = \frac{V_{LL}^2}{3R_Y}$$

$$= \frac{V_{LL}^2}{R_D}$$

$$\frac{Z_T}{V_{LL}} = 3\left(1.13R_L + \underbrace{\frac{0.15}{T} + R_A}_{V_{LN}}\right)$$

$I = 0$ C100   R1   R2

I_n I_e or

open

C100 I_e
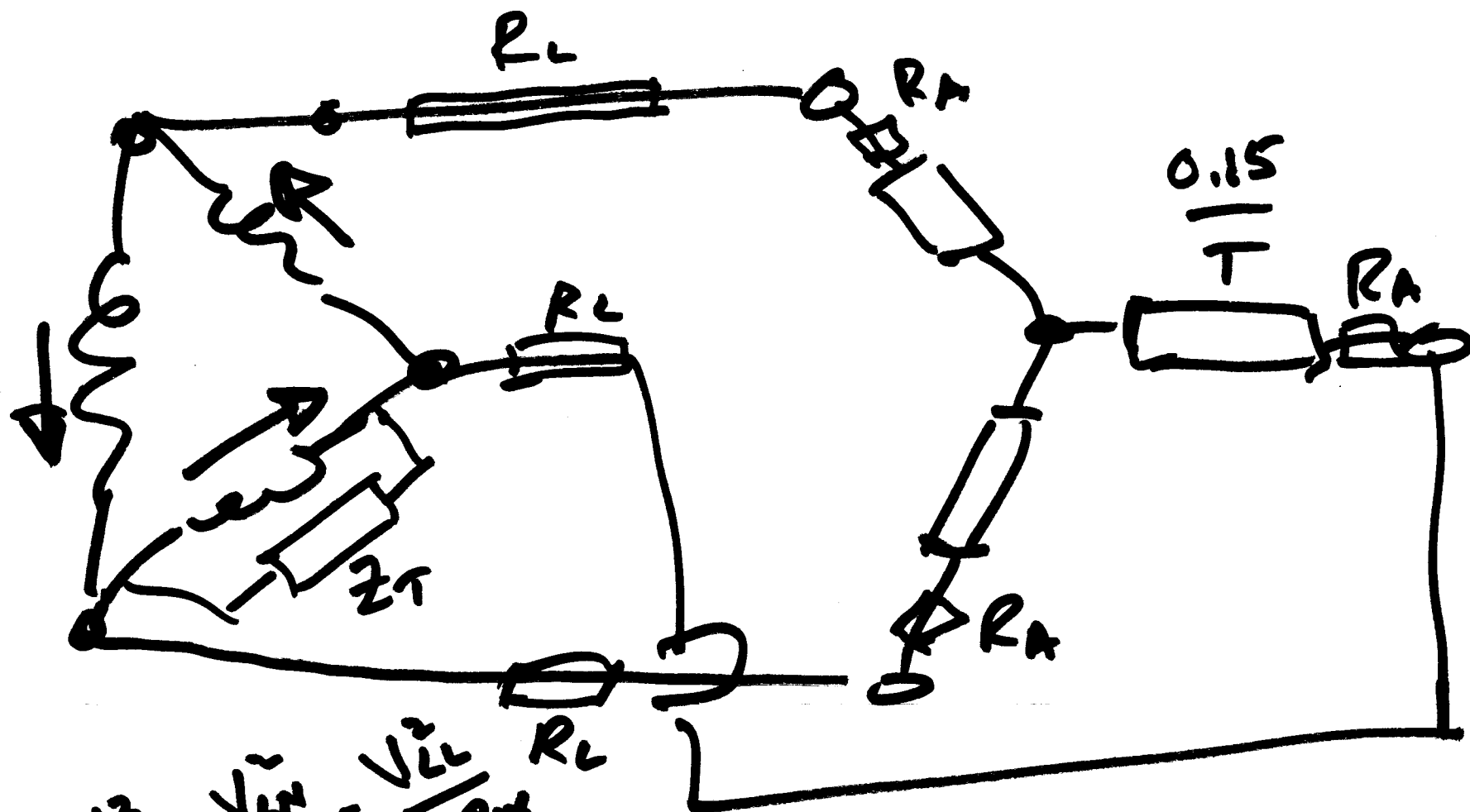
NpVcl

→ SELECTING CTS TO OPTIMIZE RELAY PERFORMANCE

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ABSTRACT

Although there is an abiding interest in the application of current transformers for relaying, few written rules exist for selecting ratings. For example, the PSRC document C37.110 "IEEE Guide to the Application of Current Transformers for Relaying Purposes" contains selection rules for differential relay applications. However, it offers no guidance for other applications where these rules do not apply. Small cores, long leads, high burdens, high currents, and offset lead to saturated cts. Saturation affects virtually all relay elements that use current. This paper examines the effects of saturation on various elements, and gives application guidelines that eliminate or minimize the risk of ct saturation.

KEY WORDS:

Ct Selection, Ct Saturation Effects, Ct Application.

INTRODUCTION

To introduce the subject of ct selection we first review the relation between the excitation curve and the standard burden and voltage ratings of a ct. We then examine the relation between the flux density and the time integral of the voltage. Using this information, we relate the fault current, the ct burden, and the system X/R ratio in an expression which ultimately determines the useful range in any ct. The paper then identifies the effects of degrees of saturation on various relay elements, and gives application guidelines which eliminate or minimize the risk of ct saturation.

CT RATINGS AND THE EXCITATION CURVE

A finite amount of ampere-turns are required to establish flux in a ct core and can be expressed as magnetizing current measured at the secondary terminals. The excitation current, which is subtracted from the ratio current, has definite values for each value of voltage as shown in Figure 1. This curve depicts steady-state voltage versus excitation current where the voltage is measured with an average reading voltmeter calibrated rms. It is actually a plot of flux versus magnetizing current since the average voltage is the volt-time integral averaged over the period of the sine wave.

The excitation curve, shown in Figure 1 for a C400, 2000:5 multi-ratio bushing ct, is a measure of ct performance and can be used to determine ratio correction factors at various levels of steady-state excitation. While the excitation curve has a well-defined knee-point [1], it has no discernible point of saturation. For this reason relaying accuracy ratings are based on a ratio correction not exceeding 10 percent and ratings are designated by classification and secondary

1

voltage. The secondary voltage rating is the voltage the ct will support across a standard burden with 20 times rated current without exceeding 10 percent ratio correction.
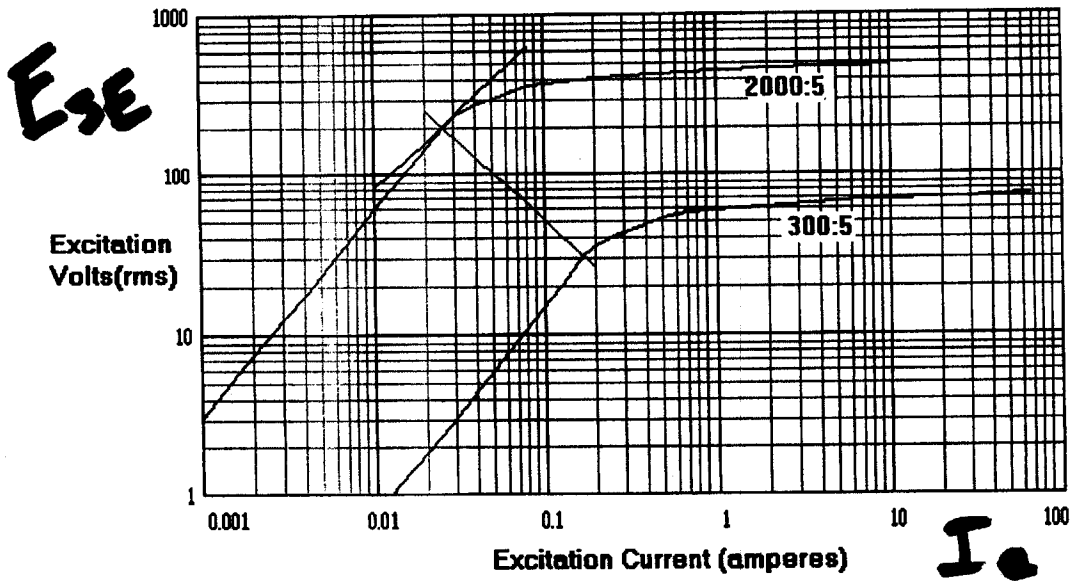
Figure 1: 2000:5 Ct Excitation Curve and its 300:5 Tap Shown With Knee-Point Tangents and Normal Lines

The standard burdens for relaying are 1, 2, 4, and 8 ohms, all with an impedance angle of 60°. Consequently, at 20 times the 5 ampere rated secondary current, the standard ratings are 100, 200, 400, and 800 volts. Since the ct rating occurs with 100 amps of secondary current at a 10 percent ratio correction factor, the voltage rating can be read from the excitation curve at 10 amperes of excitation current. We must first subtract the internal voltage drop due to the dc resistance of the winding. For the 2000:5 ratio winding in Figure 1, the voltage read the from curve at 10 amperes is 496 volts. In this case the voltage is less than the 800 rating and greater than 400. Therefore the rating is C400 provided the 400 turn winding has less than a 0.0024 ohms per turn dc resistance to guarantee an internal voltage drop less than 96 volts.

THE VOLT-TIME AREA

The burden voltage v is related to core turn N and the rate of change of the core flux ϕ by the induction equation:

$$v = N \cdot \frac{d\phi}{dt} \tag{1}$$

We can integrate Equation (1) to show that the flux density in the core is represented by the area under the voltage waveform. Therefore the flux linkages in the core are given by integral Equation (2) where the flux is expressed as flux density B times the core cross sectional area A.

2

$$\phi \cdot N = B \cdot A \cdot N = \int_0^t v \cdot dt \qquad (2)$$

We can now recognize the significance of the ANSI voltage rating because the area under the sine wave of that magnitude represents the saturated flux density B_S. That volt-time area signifies the threshold of saturation and marks the boundary of saturation-free operation.

Figure 2 shows the shaded volt-time area produced by asymmetrical fault current. Here I_F is the magnitude of the fault current in the secondary, Z_B is the burden impedance, and L/R is the time constant of the primary fault circuit. The sine wave and exponential components of the wave are shown dashed for comparison. The plot emphasizes the fact that although we think of the C-rating as a sine wave, we in fact must consider the increased volt-time area of the asymmetrical fault when selecting a ct.

$$v := I_F \cdot Z_B \cdot \left(e^{-\frac{R}{L} \cdot t} - \cos(\omega \cdot t) \right)$$
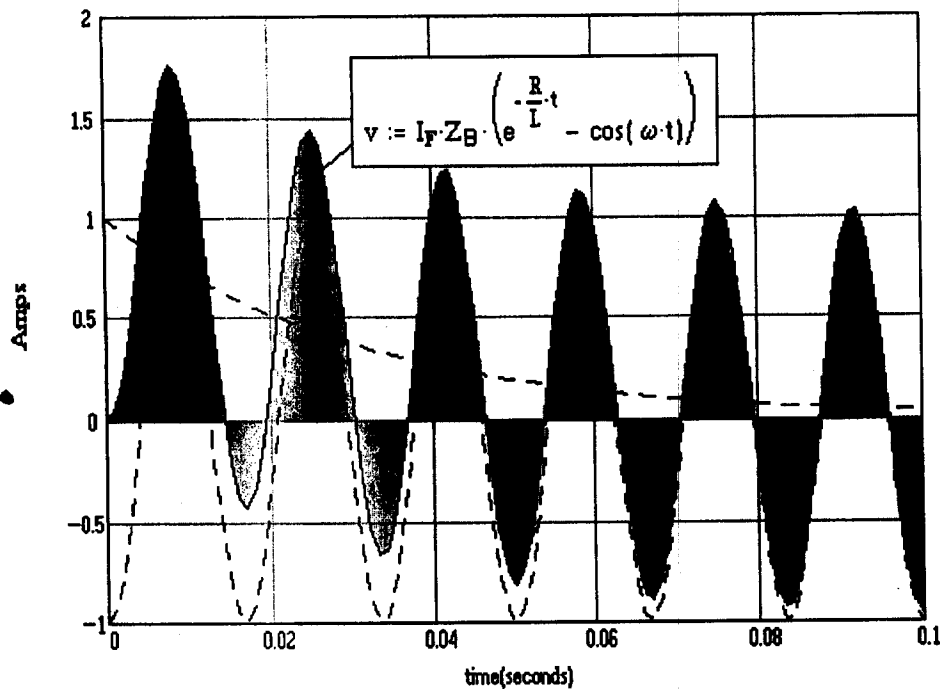
Figure 2: Burden Voltage for Asymmetrical Fault Current

Using the asymmetrical voltage in Equation (2) we can write:

$$B_S \cdot N \cdot A \cdot \omega = I_F Z_B \left[-\frac{\omega L}{R} \; e^{-\frac{R}{L}t} \Big|_0^t \; -\frac{R}{L} dt \Big| - \int_0^t \cos(\omega t)(\omega dt) \, \Big| \right] \qquad (3)$$

3

In Equation (3), the limit of the integral of the exponential term is the X/R ratio of the primary circuit. Since the limit integral of the cosine term is unity we can write the equation:

$$B_S \cdot N \cdot A \cdot \omega = \left| \frac{X}{R} + 1 \right| \cdot I_F Z_B \tag{4}$$

Equation (4) expresses the C-rating voltage in terms of the physical parameters of the ct, namely the saturated flux density B_S, the turns ratio N, the core cross-sectional area A, and the system frequency ω. Moreover, it determines the saturation-free operation range of the ct in terms of the system X/R ratio, the maximum fault current I_F, and the ct burden Z_B.

THE CRITERION TO AVOID SATURATION

We can derive a more versatile form of Equation (4) by recognizing that the rating voltage is 20 times the voltage across the standard burden at rated current. If we then express the fault current I_F in per unit of the rated current and the burden Z_B in per unit of the standard burden, Equation (4) becomes the simple criterion to avoid saturation:

$$20 \geq \left| \frac{X}{R} + 1 \right| \cdot I_f \cdot Z_b \tag{5}$$

where : I_f is the maximum fault current in per unit of ct rating
Z_b is the ct burden in per unit of standard burden
X/R   is the X/R ratio of the primary fault circuit

Here is an example of how the criterion is used: A transmission line has an 85.24° impedance angle (i.e., the X/R ratio is 12). The maximum fault current is 4 times the rated current of the C800 ct. Equation (5) is satisfied when Z_b is equal to or less than 0.38 per unit of the standard 8 ohm burden. Therefore saturation is avoided by keeping the ct burden at 3.02 ohms or less.

SELECTING CTS FOR LINE PROTECTION

In practice, modern line relays clear faults in cycles to preserve stability, accurately identify fault type for single-pole reclosing applications, and determine an accurate fault location. To do this, line relays require undistorted ct secondary current to perform phasor measurement in the presents of the dc offset. How well are ct rated for line protection? The criterion stated in Equation (5) can be used to check any given application.

For example, the line relaying for a 4.5 mile 138 kV transmission uses a vt ratio of 1200:1 and a ct ratio of 300:1. The ct is C800, 2000:5 multi-ratio on the 1500:5 tap. The maximum fault is 4625 MVA or 19349 amps and the line and source impedance angle is 74°. The parameters for Equation (5):

$$I_f = \frac{19349A}{1500A} = 12.9 \qquad \frac{X}{R} = \tan(74) = 3.48 \tag{6}$$

4
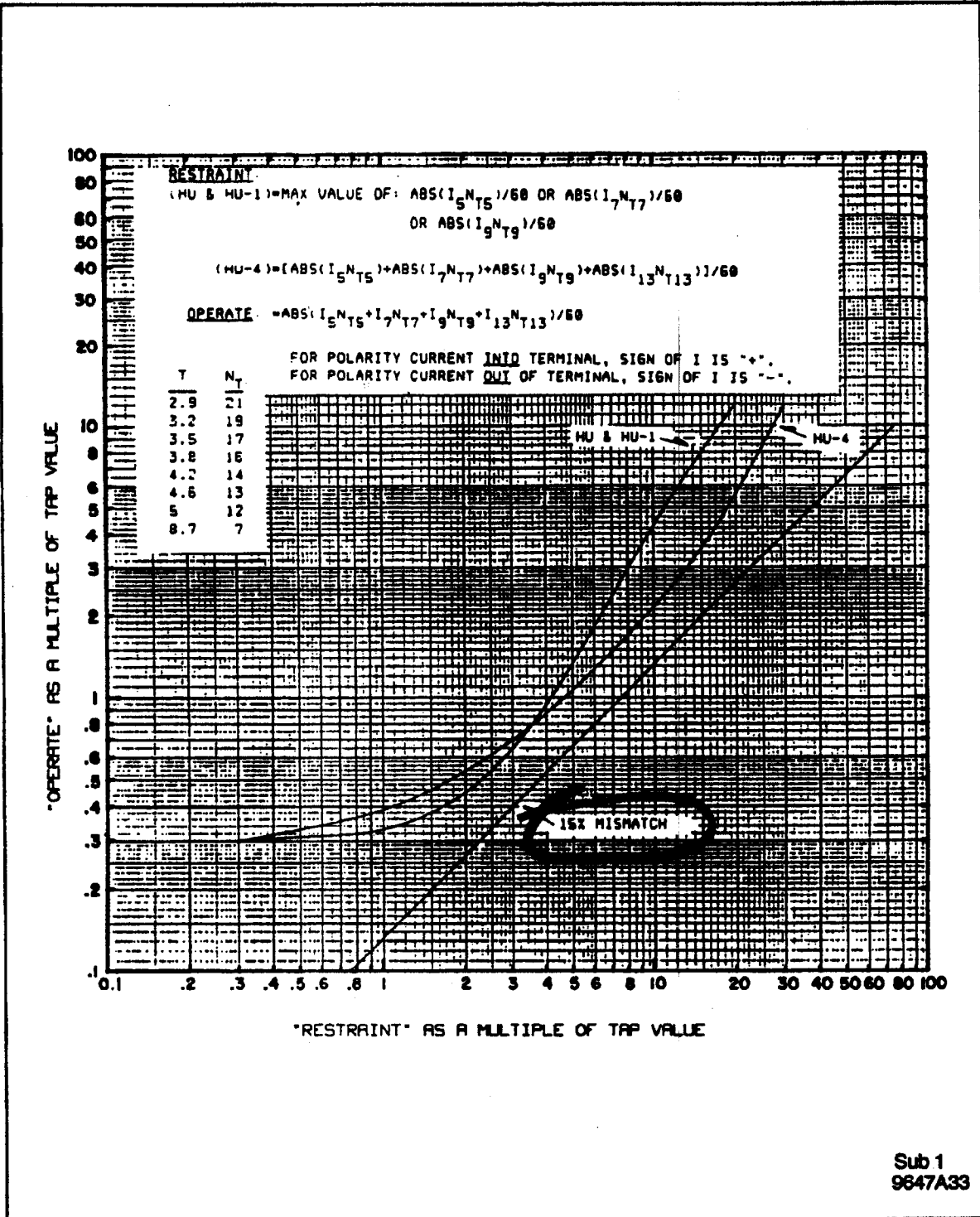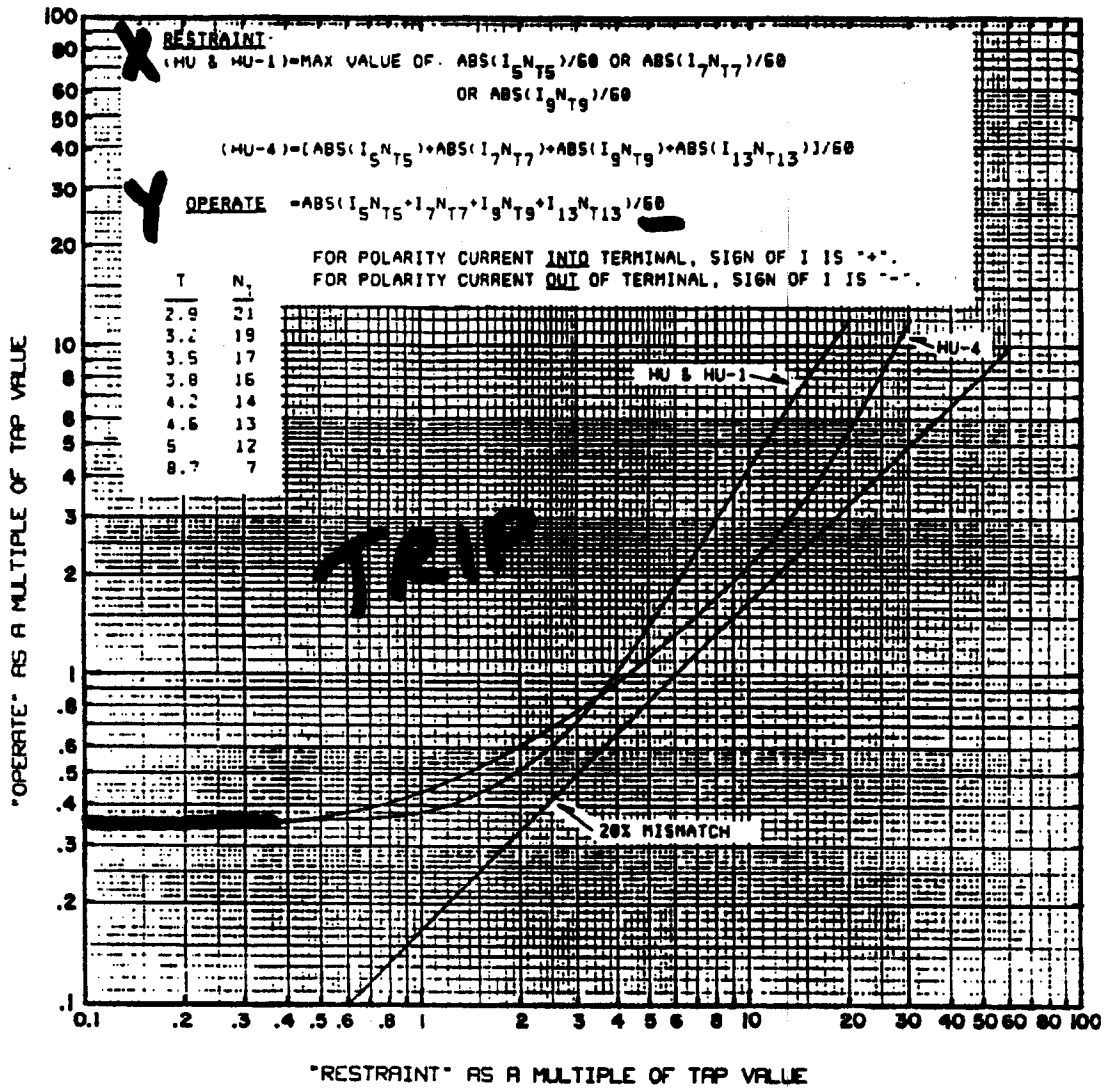
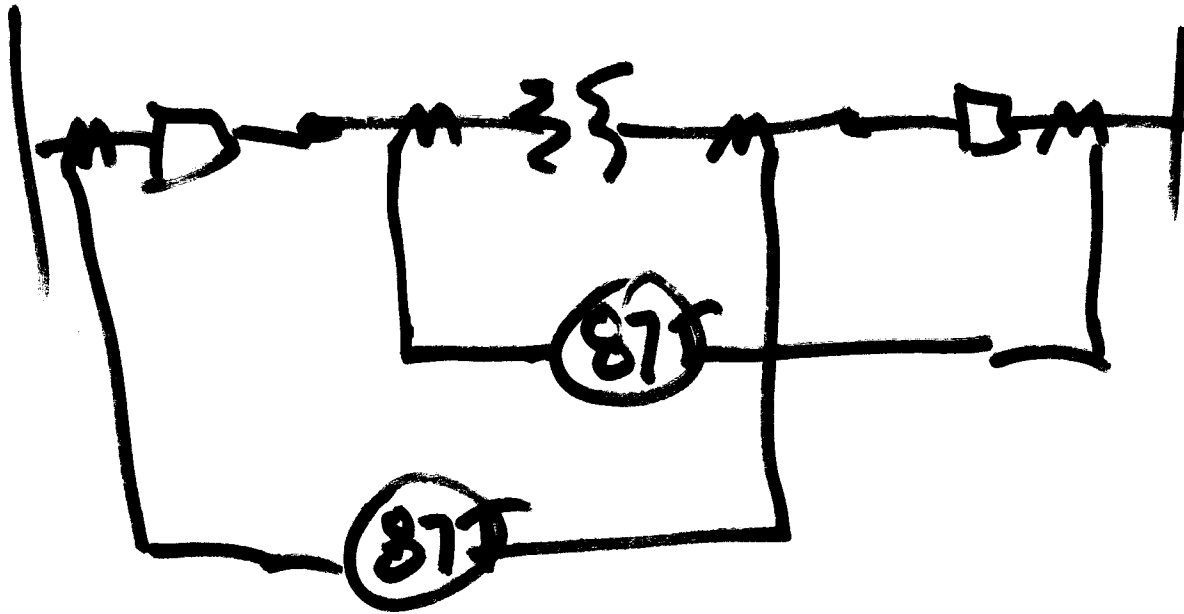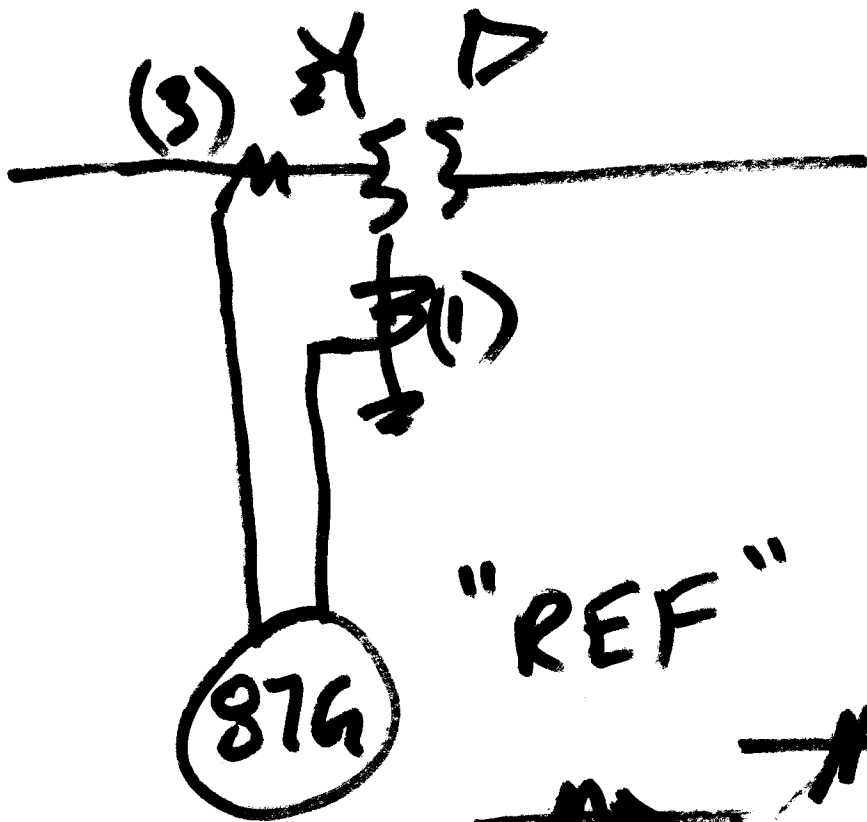Figure 13. HU, HU-1 and HU-4 Differential Characteristics (30% Sensitivity).

Sub 1
9647A33

Figure 14. HU, HU-1 and HU-4 Differential Characteristics (35% Sensitivity).

(3)

(1)

87G

"REF"

V / Hz

$3I_{A0}$
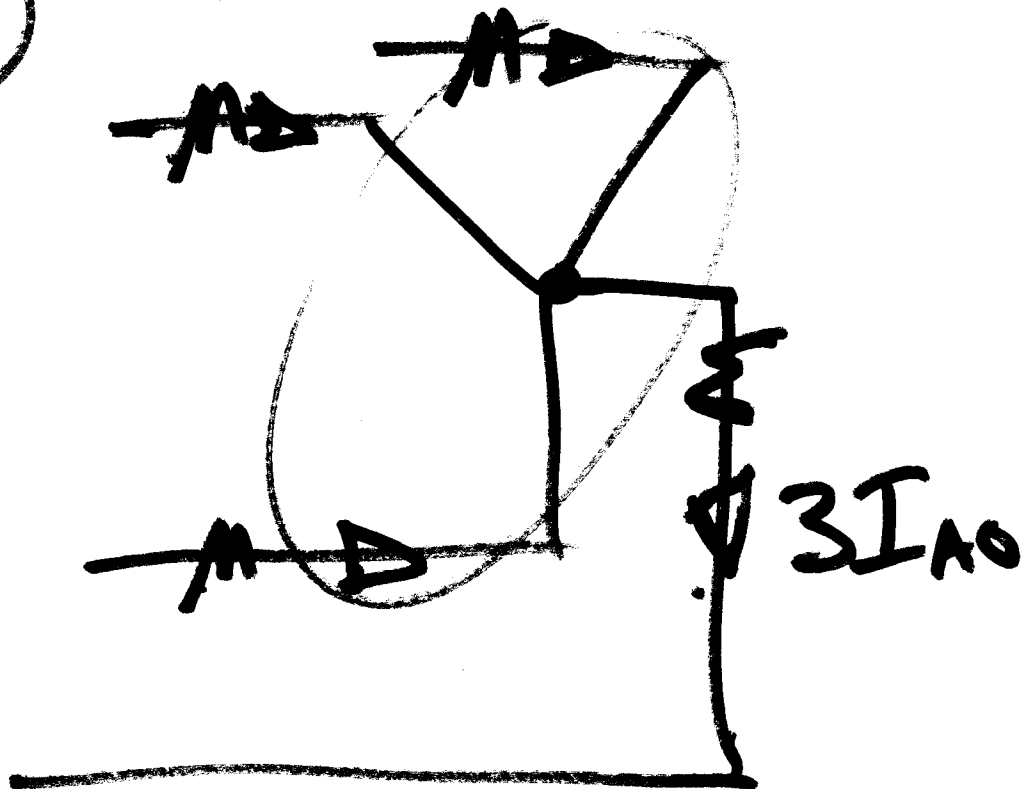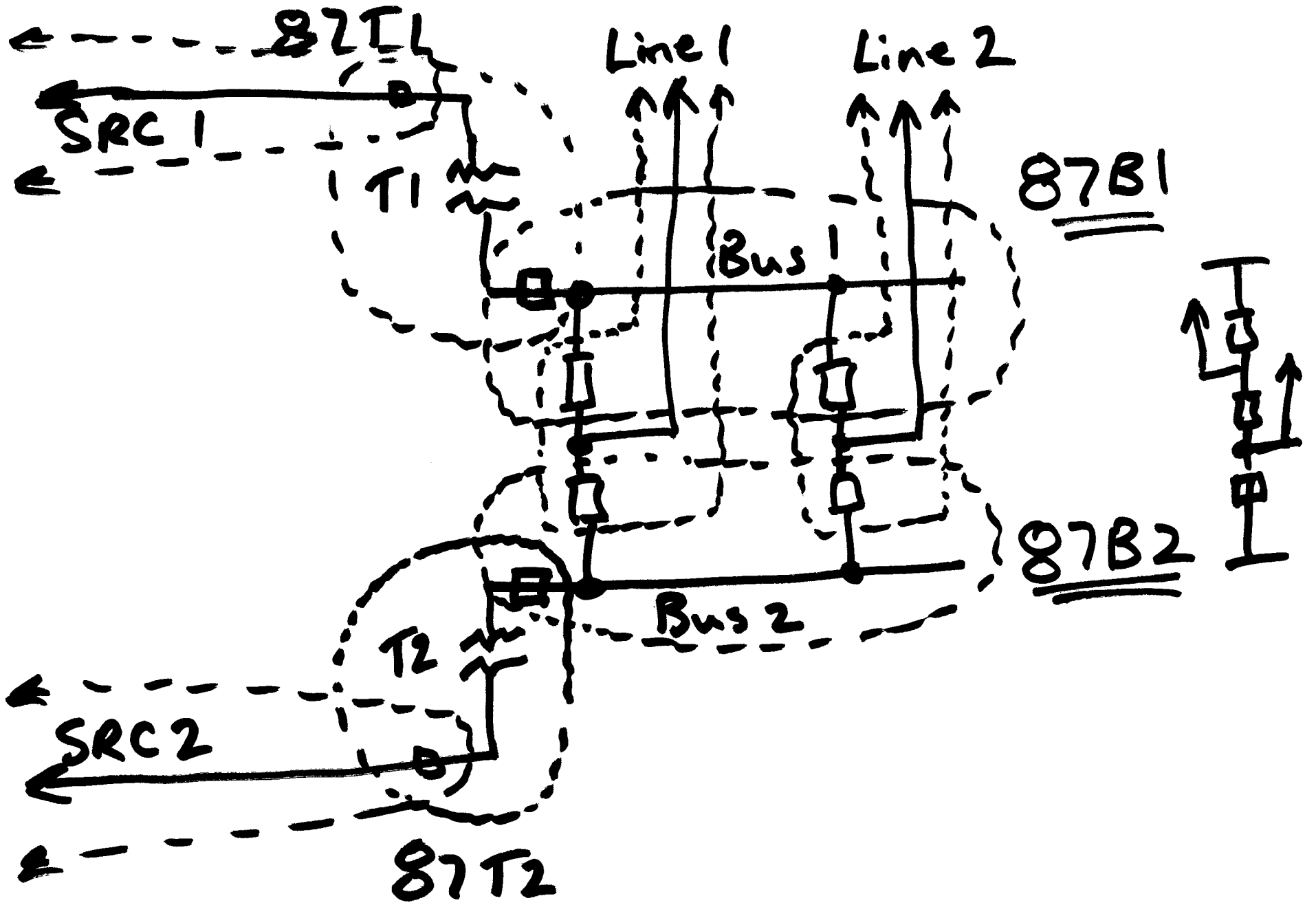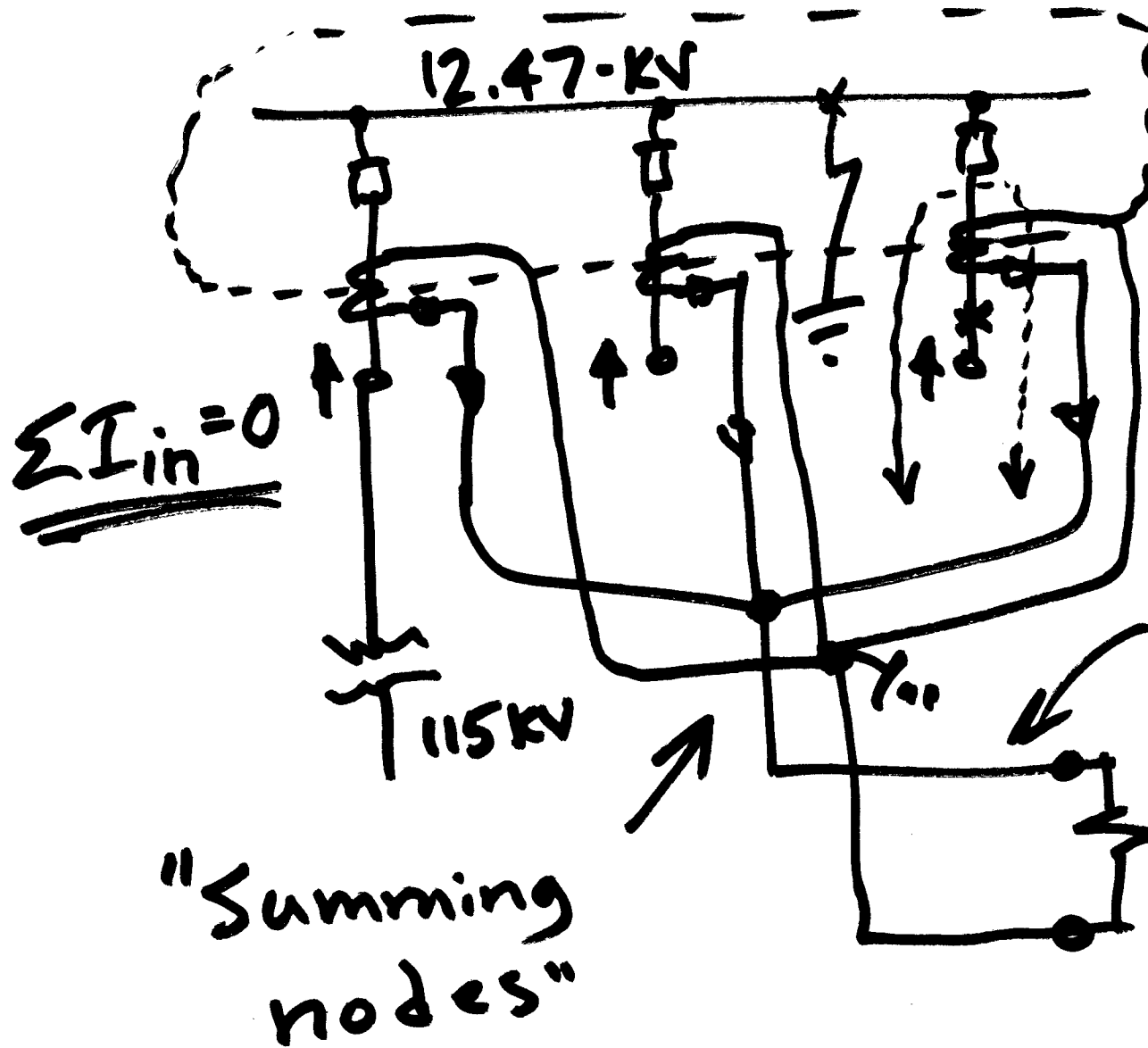
- XFMR Prot. — 87T
- Bus Diff. — ~~87~~ 87B
    - Low Z
    - Mod Z
    - High Z
- Gen Diff., Gen Prot. — 87G
- Cap Bank (Shunt)
    - O.C.
    - Volt Diff.

87T1

Line 1   Line 2

SRC 1

T1

87B1

Bus 1

87B2

T2

Bus 2

SRC 2

87T2

Single Bus, Single Breaker

12.47·KV

$\Sigma I_{in} = 0$

115KV

"Summing nodes"

$I \equiv 0$ normally.
$I >> 0$ for fault.

87B

Low Z ~ 0.1Ω
Med Z ~ 5-15Ω
High Z ~ 2600Ω

ABB/Ⓦ KAB

For MR CTs:
- All CTs at same ratio.
- use <u>Full</u> (max) ratio for best results
- CTs should be 10Cxxx, i.e. uniformly distributed secondary windings.