EE 5223 - Lecture 22 Mon Feb 27, 2023

Ongoing List of Topics:

- URL: https://pages.mtu.edu/~bamork/EE5223/index.htm
- Term Project - project topics approved.
  - Follow timeline, see posting on web page
  - Weeks 6 thru 9 - develop formal outline w/complete reference list

- Protection fundamentals (cont'd):
  - Again — overview of bus diff, xfmr diff, synch check, capacitor banks, generators, motors, etc. (take a quick run through Ch.6, also Glover & Sarma, Ch.10).
  - Sequence networks, fault calcs
    - Transformers: Y-Δ, Δ-Y, Auto-Δ
    - Overall network calculations

- Protection fundamentals in preparation for next EE5224 relaying labs:
  - Gen diff 87G - quite simple, connect CTs so current flows in “do-nothing” loop through Restraint elements (resulting in near-zero current through Operate element). Use equal (preferably full) ratio with all CTs. Differential slope of trip characteristic is rather flat compared to 87T below. Example shown of how not to connect CT secondaries.
  - Xfmr diff 87T - a) must connect CT secondaries to provide proper phase shift so that restraint currents flowing through restraint elements are in phase; b) relay settings are used to compensate for pri voltage ratio and CT ratios. CT accuracy problems can be a big concern due to having 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% to allow for mismatch (measurement error) due to CT accuracy problems.

EE 5223 Term Project (updated: Feb 26, 2023) Spring 2023

A term project shall be done in lieu of a final exam. Teams shall be of 3. **Team requirement: min of 1 MS and 1 BS student/team.** The objective is to actively figure out and explain the underlying concepts, key relationships and equations, and then design, develop, implement, test, and document the engineering details. Goal of report: a tutorial to document technical background, get another engineer up to speed on what you have done, explain the implementation, and present the results.

The project you choose:

- must be of topical interest,
- must relate to course material of EE5223.
- must demonstrate level of mastery and application of the related concepts and theories, at the level of the EE5223 course.
- includes a detailed literature search (applications magazines, standards, and journal papers) and Reference List, with salient concepts summarized in Background section of report. You'll also need to do a technical review of the journal paper that is most related to their project.
- length of body of report: approximately 10 pages of text (not including figures, tables, equations, or appendices).

Time line and required submissions are as follows. All deliverables contribute to the grade of your term project. Approximate schedule is:

- Week 6 (Friday): submit short e-mail with idea(s) requesting instructor feedback. *
- Week 7 (Friday): submit formal outline of project and list of key references.
- Week 9: submit updated outline of project and complete reference list. *
- Week 12: Submit rough draft of project report including a working initial model/system. *
- Week 14: Submit final report/deliverable.
- Finals week: be prepared to present/demonstrate project. * Major milestones

Report Outline/Table of Contents (copy and paste this to start your Table of Contents):

- Title Page - Include project title, course name, authors' names, revision date
- Executive Summary (not needed for initial draft)
- Table of Contents (use as "working outline")
- Statement of contributions by each team member, signed in agreement by all.
- Introduction (brief overview of project: problem area, motivation, overview of project)
- Background
  - literature search, most important references
  - Presentation of key concepts connected with project
  - Identification of existing voids or weaknesses, and resulting opportunity
- Proposed Approach and Application
  - Overview of basic idea that you will develop and implement
  - Development and implementation details
- Implementation (may not be complete in draft versions)
- Results and Performance (in earlier draft reports, this can be the Expected Results)
- Conclusion
- Recommendations for Continued Work
- Reference List (IEEE format, numbered [1], [2], etc, in order of first author's last name)
- Appendices as required to document details. Include journal paper & review as one appendix.

Page layout:

- Font: 11-pt CG Times w/1.25-1.5 line spacing; or 10-pt comic or ariel w/1.0-1.25 line space
- Page layout: 1" margins, include page numbering

associated system. The wye point has no physical meaning. Quite often, one of the values will be negative and should be used as such in the network. It does not represent a capacitor.

The positive- and negative-sequence connections are all the same and independent of the actual bank connections. However, the connections for the zero-sequence network are all different and depend on the transformer bank connections. If the neutrals are solidly grounded, then the Z_N and $3Z_N$ components shown are shorted-out in the system and sequence circuits.

APPENDIX 4.3 SEQUENCE PHASE SHIFTS THROUGH WYE–DELTA TRANSFORMER BANKS

As has been indicated, positive and negative sequences pass through the transformer bank, and in the sequence networks, the impedance is the same independently of the bank connection. This is shown in Figs. A4.2-1 and A4.2-3. In these networks the phase shift is ignored, but if currents and voltages are transferred from one side of the transformer bank to the other, these phase shifts must be taken into account. This appendix will document these relations. For this the standard ANSI connections are shown in Fig. A4.3-1.

From Fig. A4.3-1a, all quantities are phase-to-neutral values, and in amperes or volts; for per unit, $N = 1$, $n = 1/\sqrt{3}$.

$$I_A = n(I_a - I_c) \qquad \text{and} \qquad V_a = n(V_A - V_B)$$

For positive sequence [see Eq. (4.2)],

$$I_{A1} = n(I_{a1} - aI_{a1}) = n(1 - a)I_{a1} \tag{A4.3-1}$$
$$= \sqrt{3}nI_{a1}\angle -30^\circ = NI_{a1}\angle -30^\circ$$

$$V_{a1} = n(V_{A1} - a^2V_{A1}) = n(1 - a^2)V_{A1} \tag{A4.3-2}$$
$$= \sqrt{3}nV_{A1}\angle +30^\circ = NV_{A1}\angle +30^\circ$$

For negative sequence [see Eq. (4.3)],

$$I_{A2} = n(I_{a1} - a^2I_{a1}) = n(1 - a^2)I_{a2} \tag{A4.3-3}$$
$$= \sqrt{3}nI_{a2}\angle +30^\circ = NI_{a2}\angle +30^\circ$$

$$V_{a2} = n(V_{A2} - aV_{A2}) = n(1 - a)V_{A2} \tag{A4.3-4}$$
$$= \sqrt{3}nV_{A2}\angle -30^\circ = NV_{A2}\angle -30^\circ \tag{A4.3-5}$$

"Through-Fault"

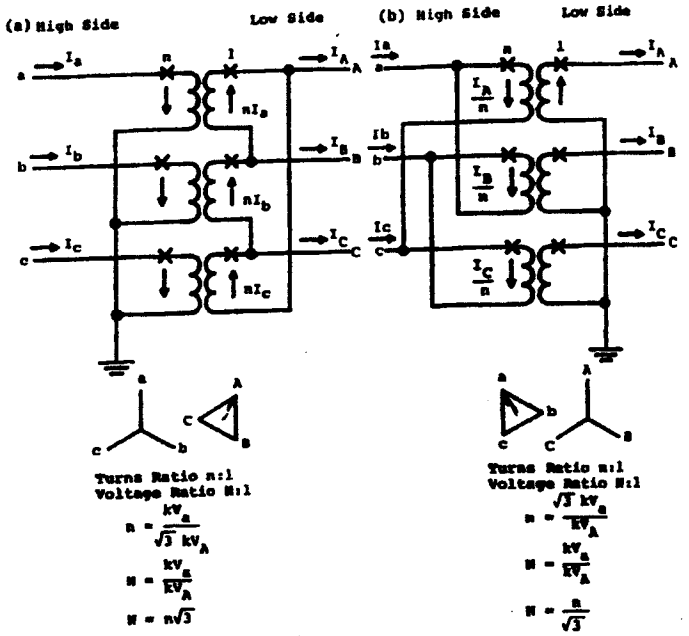


FIGURE A4.3-1 ANSI-connected wye–delta transformer banks: The high-voltage side phase *a* leads the low-voltage side phase *a* for both connections illustrated: (a) wye (star) on high side; (b) delta on high side.

Now consider the connections in Fig. A4.3-1b. Again all values are in phase-to-neutral amperes or volts; for per unit, $N = 1$, $n = \sqrt{3}$.

$$I_a = \frac{1}{n}(I_A - I_B) \qquad \text{and} \qquad V_A = \frac{1}{n}(V_a - V_c)$$

For positive sequence [see Eq. (4.2)],

$$I_{a1} = \frac{1}{n}(I_{A1} - a^2I_{A1}) = \frac{1}{n}(1 - a^2)I_{A1} \tag{A4.3-6}$$
$$= \frac{\sqrt{3}}{n}I_{A1}\angle +30^\circ = \frac{1}{N}I_{A1}\angle +30^\circ$$

$$V_{A1} = \frac{1}{n}(V_{a1} - aV_{a1}) = \frac{1}{n}(1 - a)V_{a1} \qquad \text{(A4.3-7)}$$
$$= \frac{\sqrt{3}}{n} V_{a1}\angle -30^\circ = \frac{1}{N} V_{a1}\angle -30^\circ$$

For negative sequence [see Eq. (4.3)],

$$I_{a2} = \frac{1}{n}(I_{A2} - aI_{A2}) = \frac{1}{n}(1 - a)I_{A2} \qquad \text{(A4.3-8)}$$
$$= \frac{\sqrt{3}}{n} I_{A2}\angle -30^\circ = \frac{1}{N} I_{A2}\angle -30^\circ$$

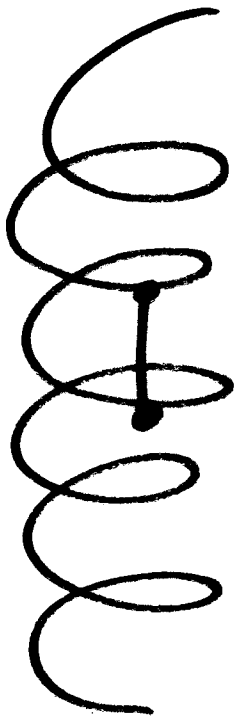
$$V_{A2} = \frac{1}{n}(V_{a2} - a^2V_{a2}) = \frac{1}{n}(1 - a^2)V_{a2} \qquad \text{(A4.3-9)}$$
$$= \frac{\sqrt{3}}{n} V_{a2}\angle +30^\circ = \frac{1}{N} V_{a2}\angle +30^\circ$$

Summary

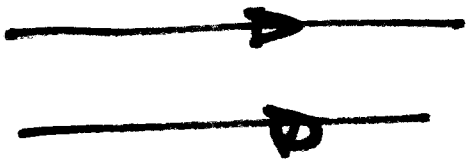
An examination of the foregoing equations shows that for ANSI standard connected wye–delta transformer banks: (1) if both the positive-sequence current and voltage on one side lead the positive-sequence current and voltage on the other side by 30°, the negative-sequence current and voltage correspondingly will both lag by 30°; and (2) similarly, if the positive-sequence quantities lag in passing through the bank, the negative-sequence quantities correspondingly will lead 30°. This fundamental is useful in transferring currents and voltages through these banks.

Zero sequence is not phase-shifted *if* it can pass through and flow in the transformer bank. The zero-sequence circuits for various transformer banks are shown in Figs. A4.2-1 and A4.2-3.

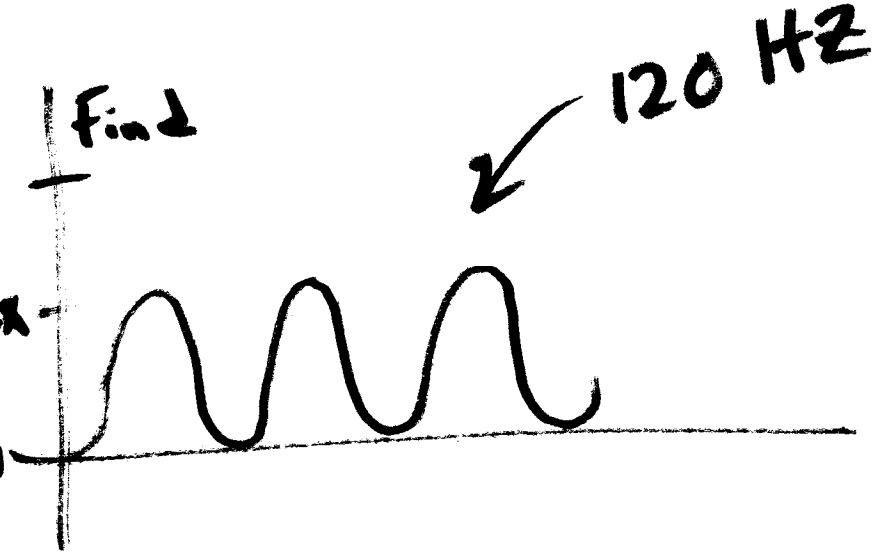
Find



N-1
turns



Find is attraction



- turn-turn faults
- Layer-layer faults
- Coil-core faults
- Coil-tank faults

From: Glover & Sarma. 3rd Ed.

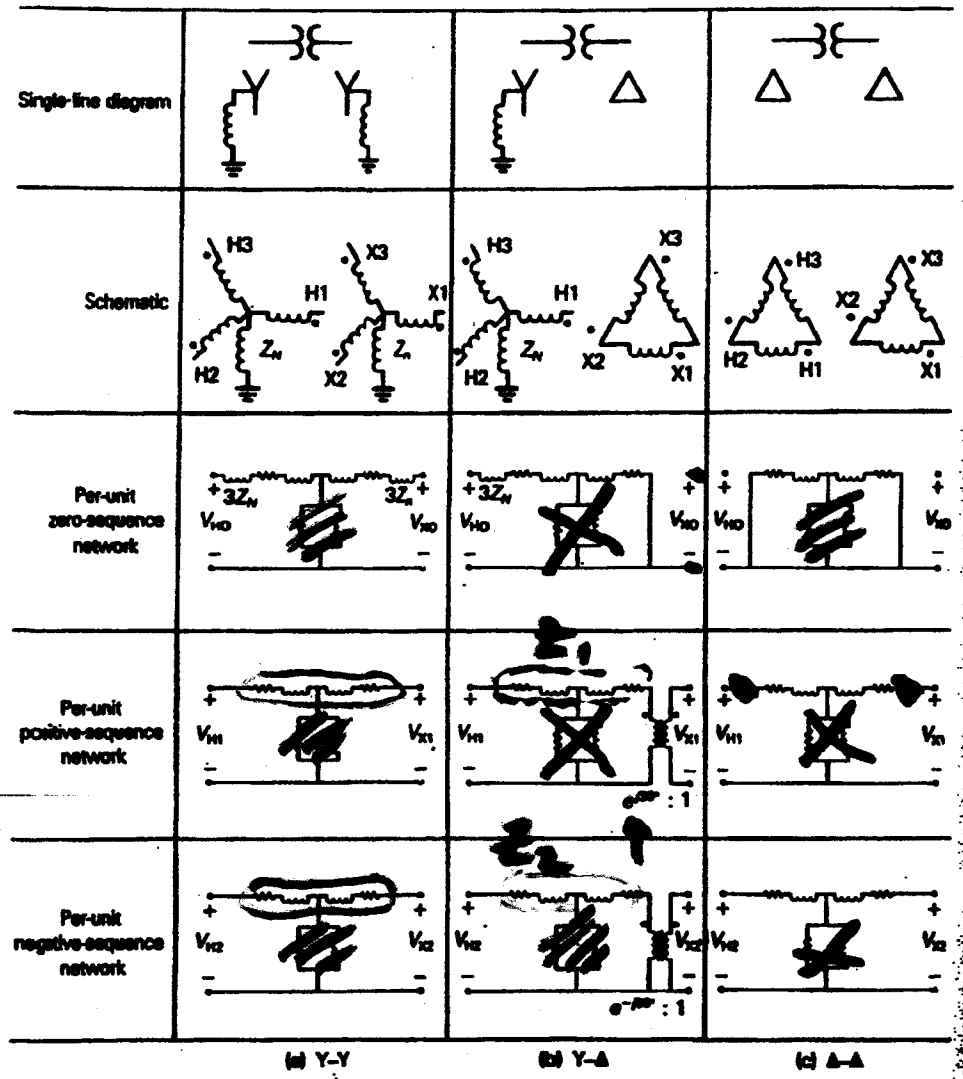


FIGURE 8.19 Per-unit sequence networks of practical Y–Y, Y–Δ, and Δ–Δ transformers

branches are also shown in Figure 8.19(a). Note that $(3Z_N)$ and $(3Z_n)$ have already been included in the zero-sequence network.

The per-unit positive- and negative-sequence transformer impedances of the practical Y–Y transformer in Figure 8.19(a) are identical, which is always true for nonrotating equipment. The per-unit zero-sequence network, how-

The per-unit sequence network
ure 8.19(b), have the following featu

1. The per-unit impedances do
That is, the per-unit imped
Y–Y, Y–Δ, Δ–Y, or Δ–Δ a
do depend on the winding c

2. A phase shift is included
sequence networks. For the
voltages and currents on t
former lead the correspondi
30°. For negative sequence,

3. Zero-sequence currents can
connection, and correspon
the Δ winding. However, n
the Δ winding.

The phase shifts in the positi
Figure 8.19(b) are represented by t
3.4. Also, the zero-sequence network
Y side for zero-sequence current to
enter or leave the Δ side.

The per-unit sequence network
ure 8.19(c), have the following featu

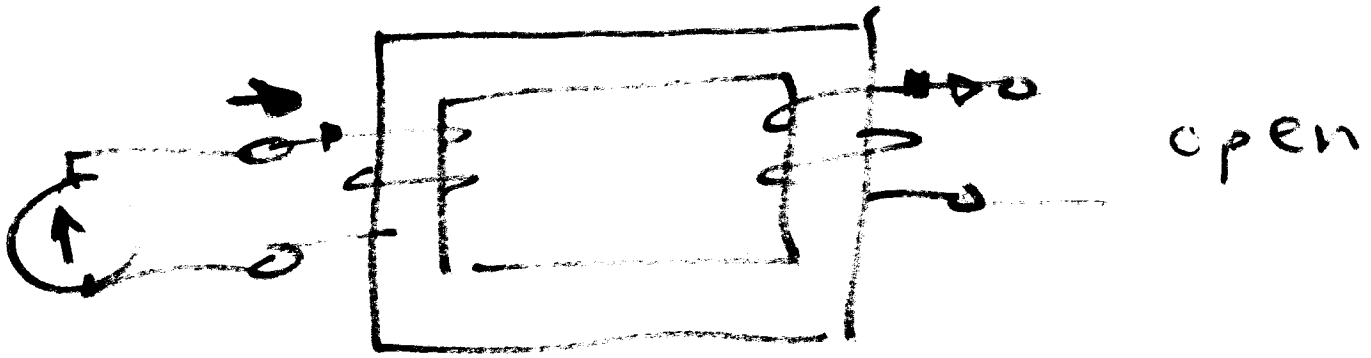
1. The positive- and negative-
are the same as those for the
windings are labeled so then
pedances do not depend or
voltages do.

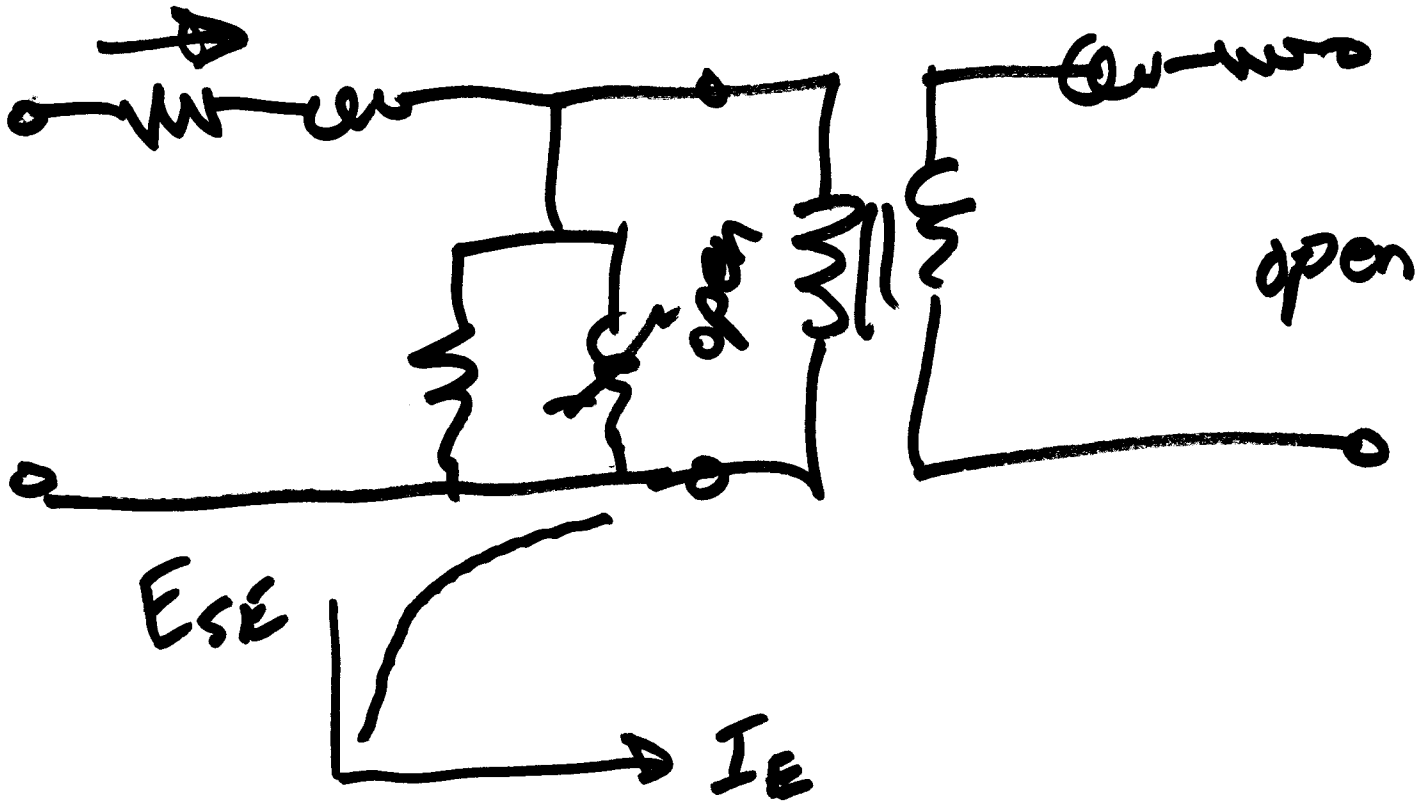
2. Zero-sequence currents *can*
though they can circulate wi

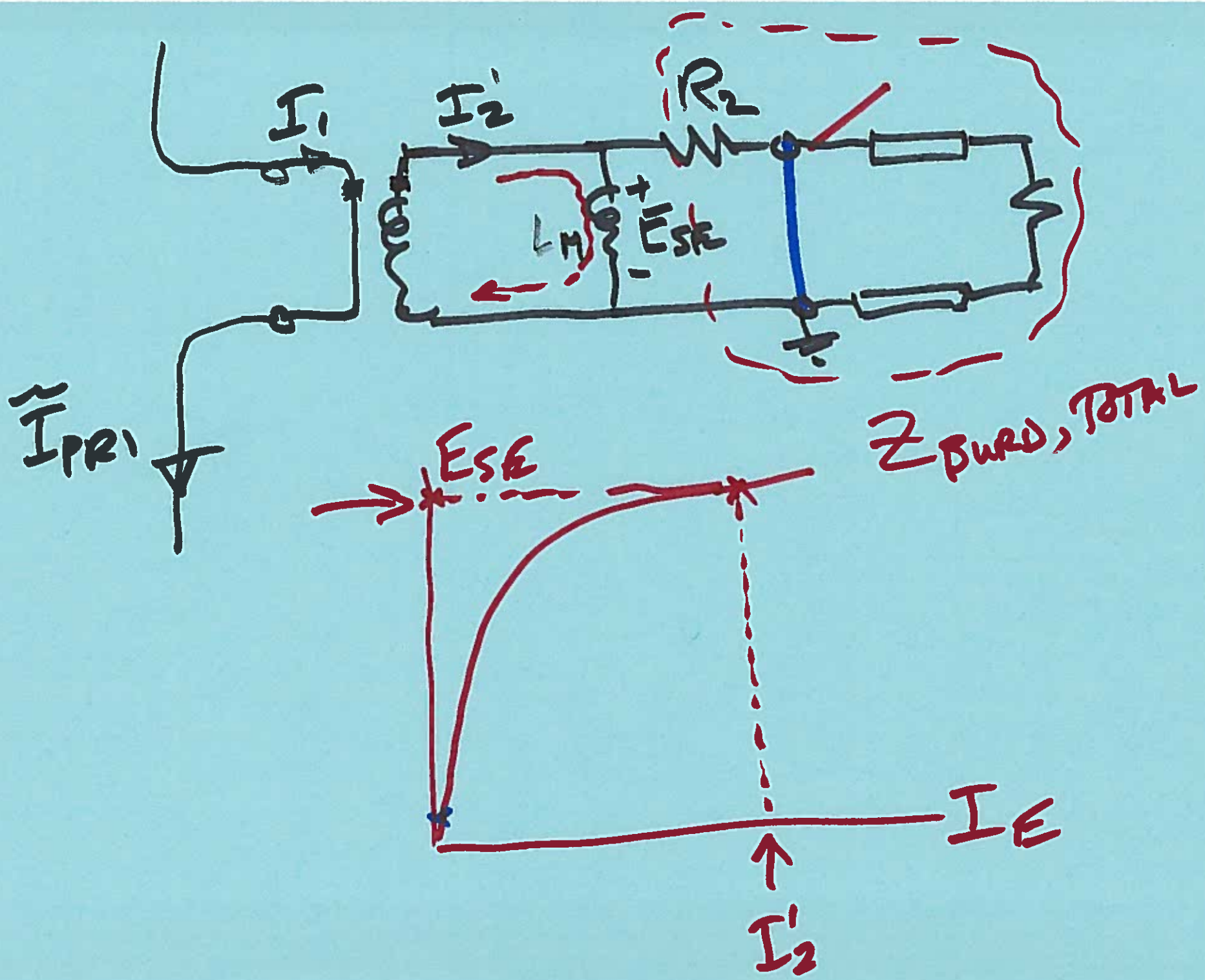
EXAMPLE 8.7 **Solving unbalanced three-phase n
using per-unit sequence compone**

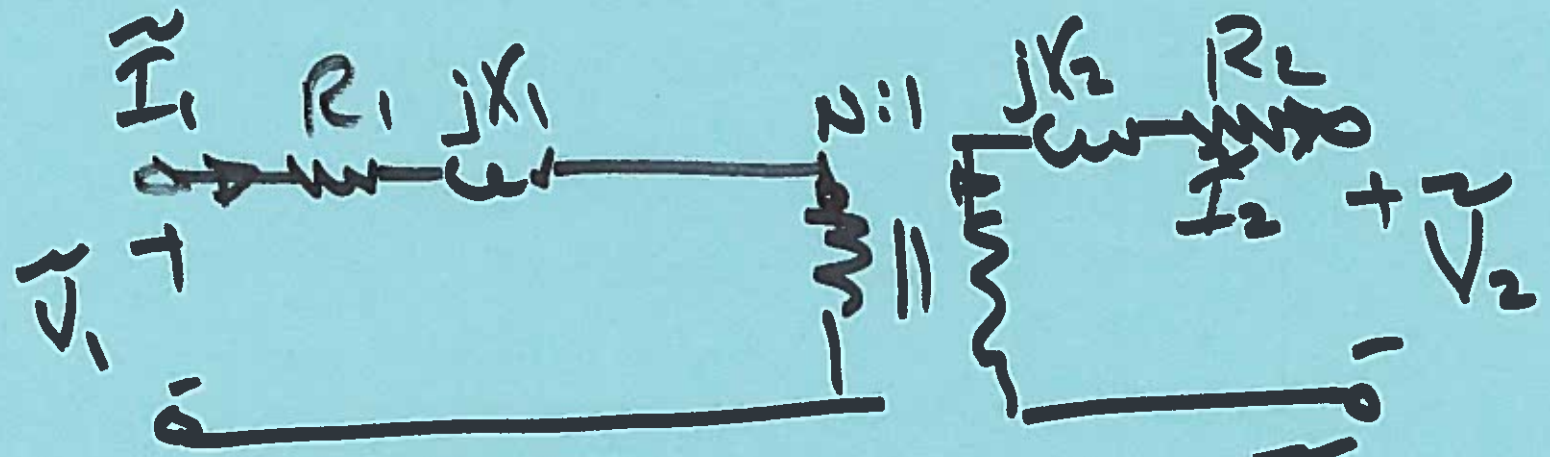
A 75-kVA, 480-volt Δ/208-volt Y tra
is connected between the source an
leakage reactance is $X_{eq} = 0.10$ pe
current are neglected. Using the tra
the per-unit sequence networks and

SOLUTION The base quantities an


open

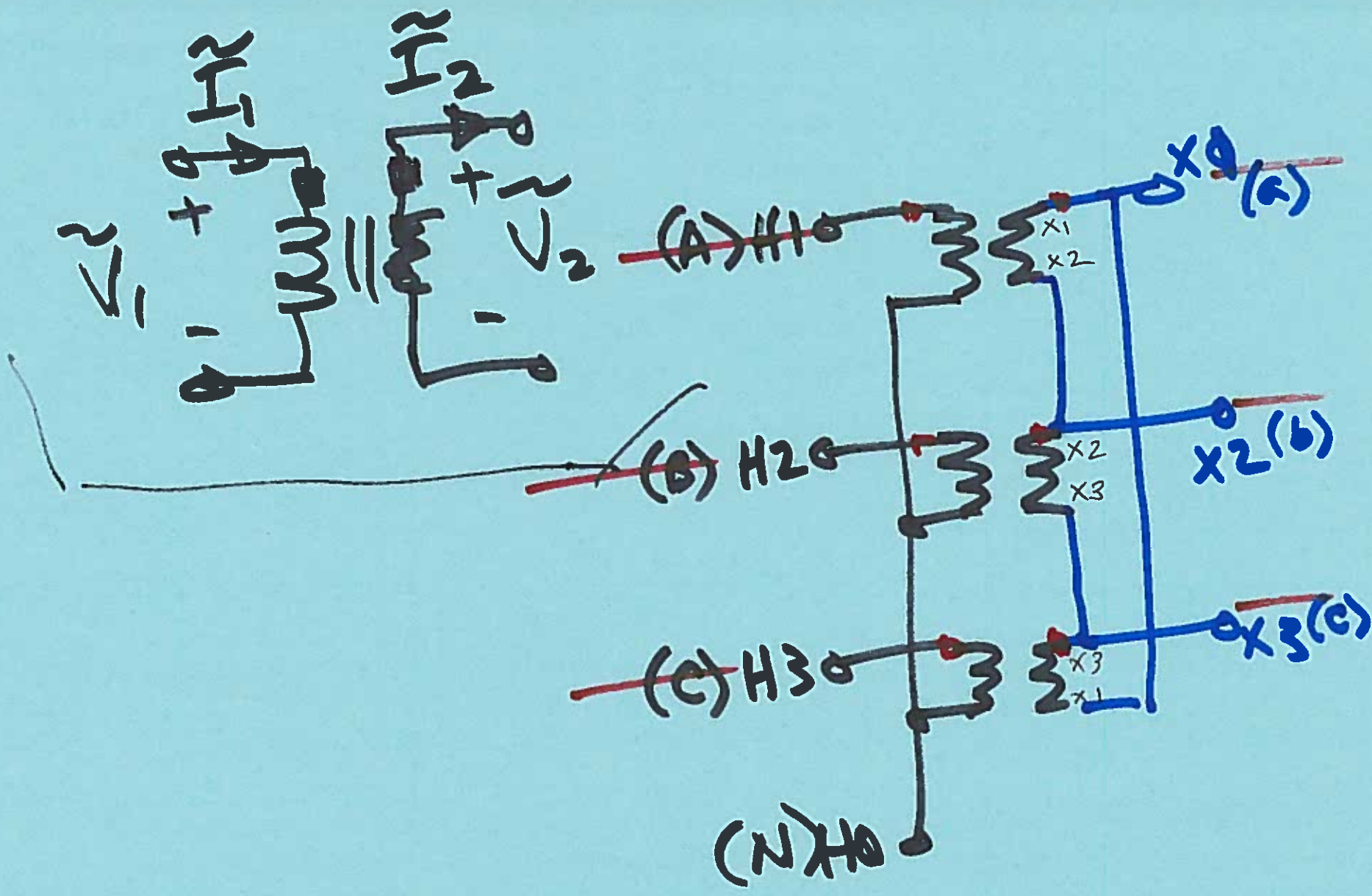

open
E_{SE}
I_E


I_1
I_2'
R_2
L_M
E_{SE}
$\tilde{I}_{PRI}$
E_{SE}
$Z_{BURD,TOTAL}$
I_E
I_2'

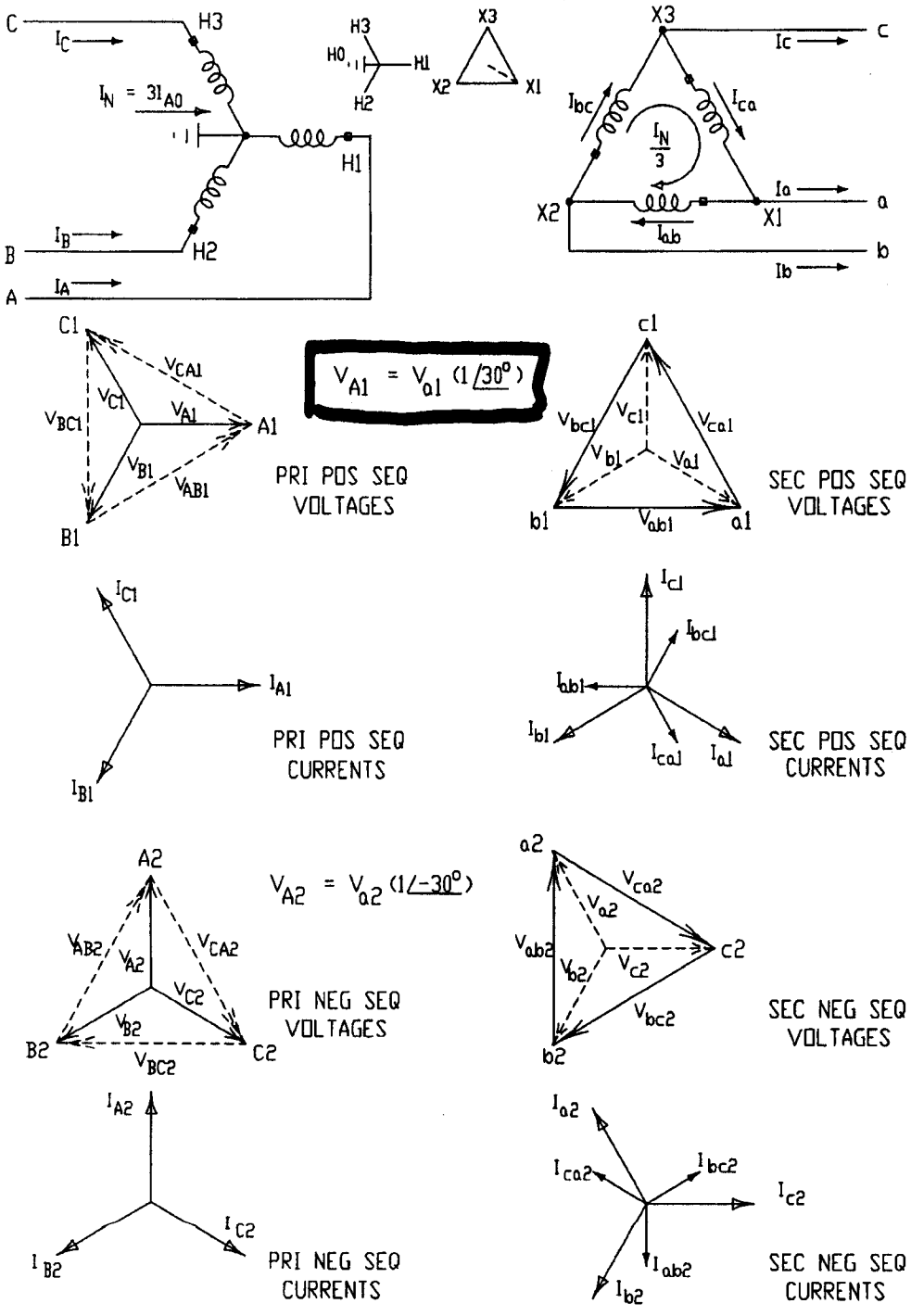

$\tilde{I}_1$
R_1
jX_1
N:1
jX_2
R_2
$\tilde{I}_2$
+
$\tilde{V}_2$
-
$\tilde{V}_1$

$\tilde{I}_1$
R_{EQ}
jX_{EQ}
$\tilde{I}_2$
+
$\tilde{V}_2$
-
$\tilde{V}_1$
0

P.U.

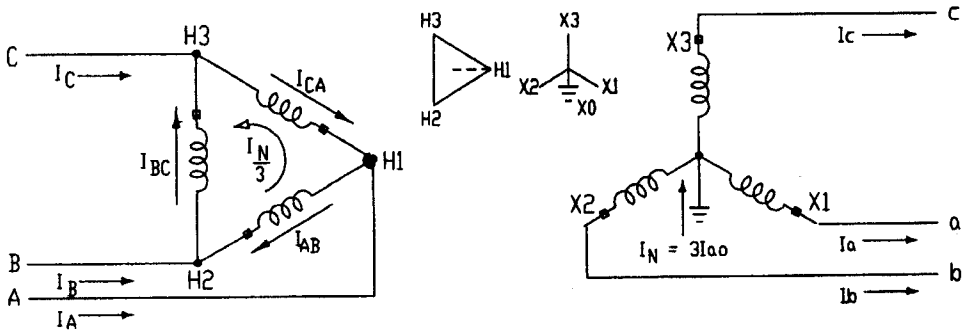

$\tilde{I}_1$
$\tilde{I}_2$
$\tilde{V}_1$
$\tilde{V}_2$
+
-
+
-
(A) H1
(B) H2
(C) H3
(N) H0
X1
X2
X2
X3
X3
X1
X1 (a)
X2 (b)
X3 (c)

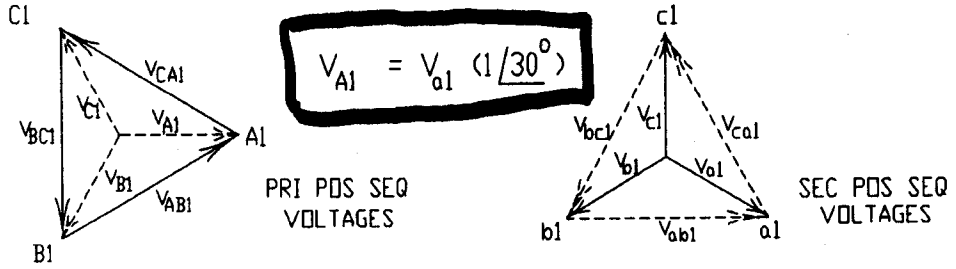
MORK

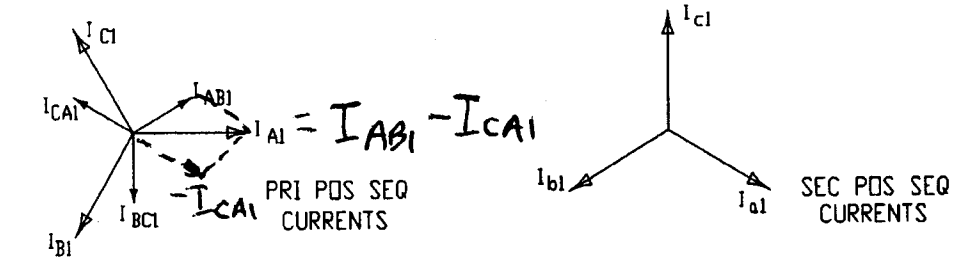


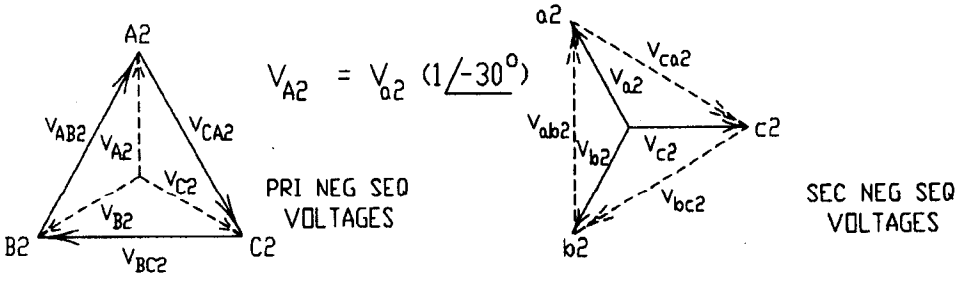
ANSI STANDARD 30-DEGREE SHIFT WYE-DELTA

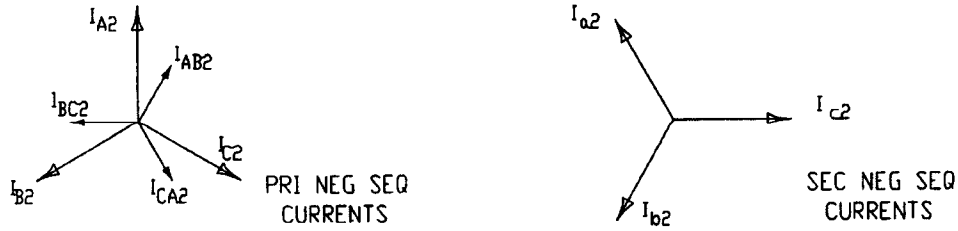
MARK



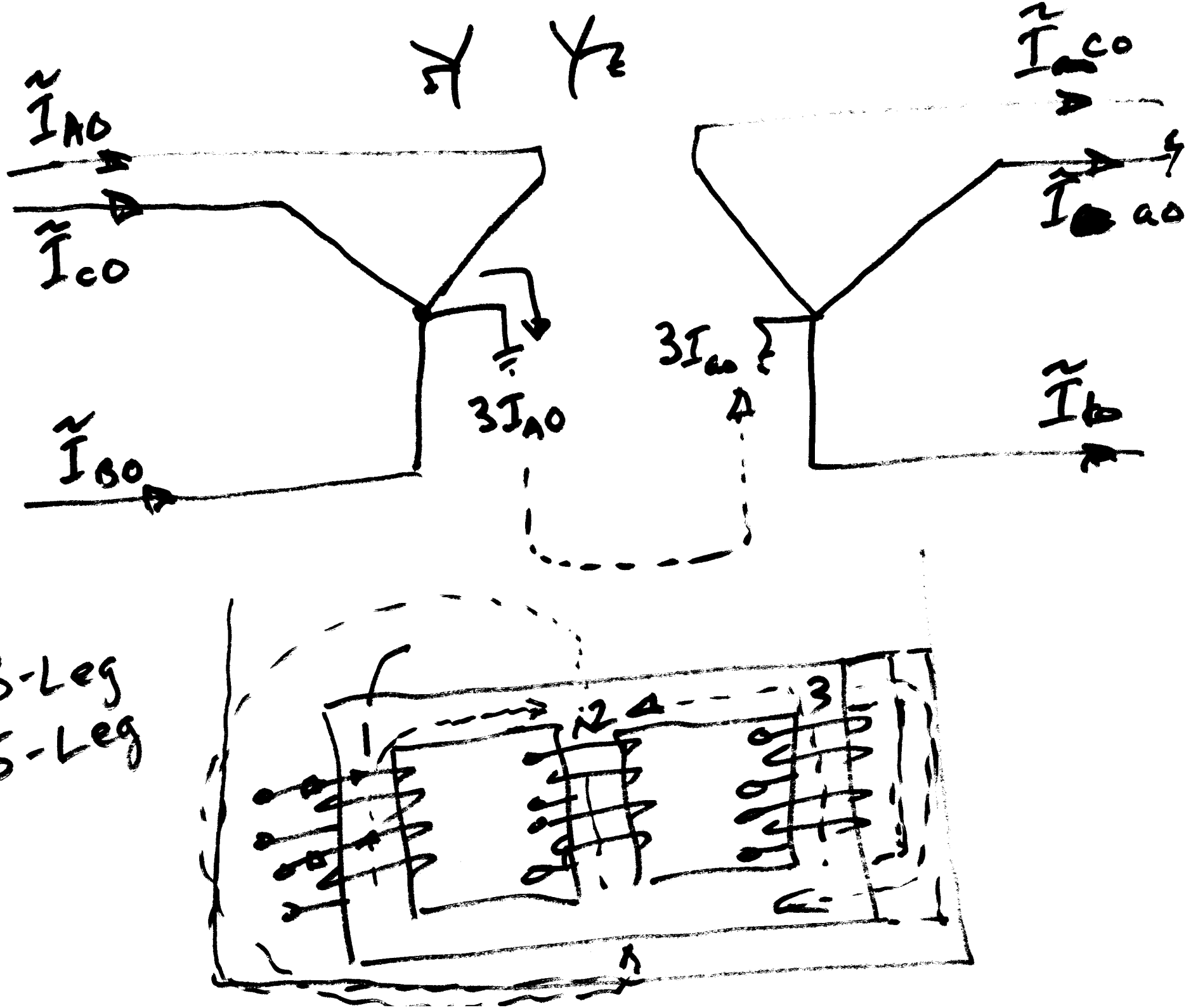


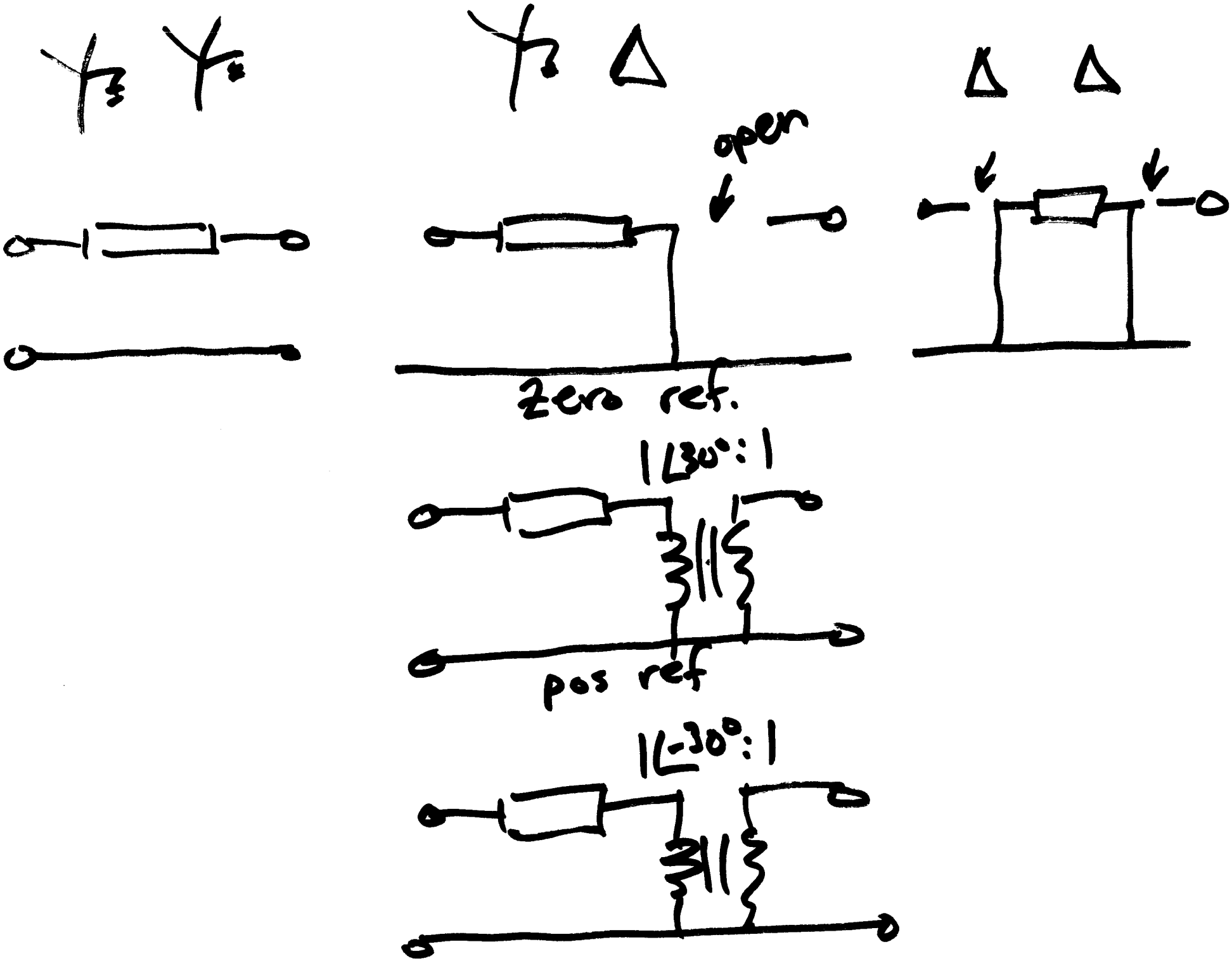




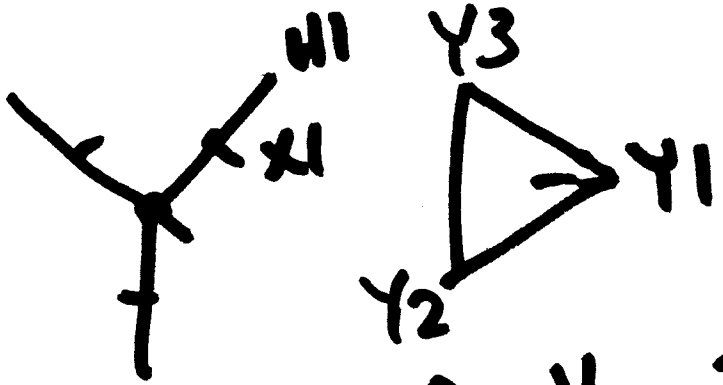


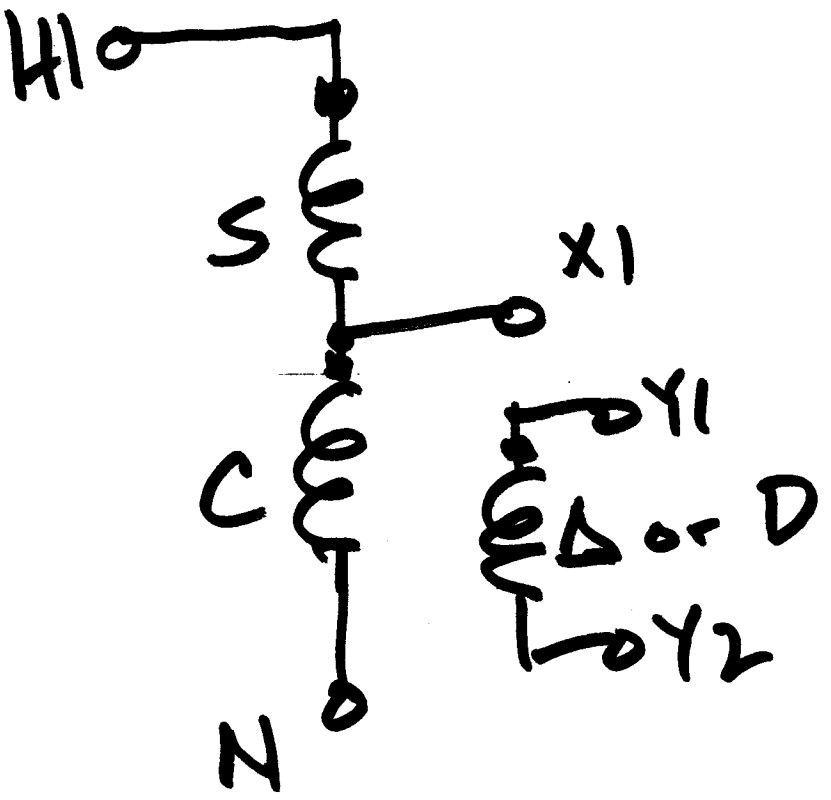
ANSI STANDARD 30-DEGREE SHIFT DELTA-WYE


$\tilde{I}_{AO}$
$\tilde{I}_{CO}$
$\tilde{I}_{BO}$
$3I_{AO}$
$3I_{aO}$
$\tilde{I}_{CO}$
$\tilde{I}_{aO}$
$\tilde{I}_{bO}$
3-Leg
5-Leg
1
2
3


open
Zero ref.
1∠30°:1
pos ref
1∠-30°:1

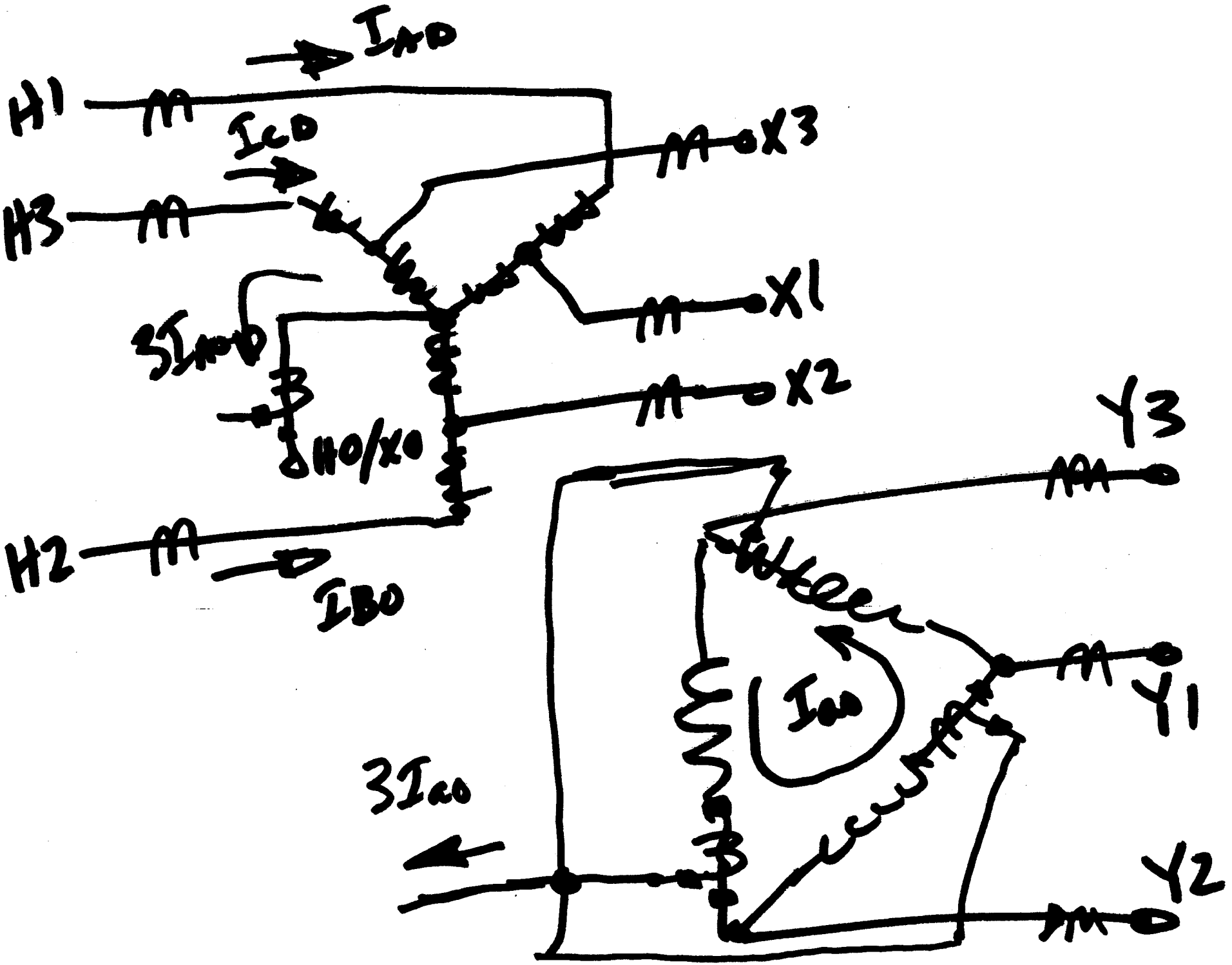
Auto

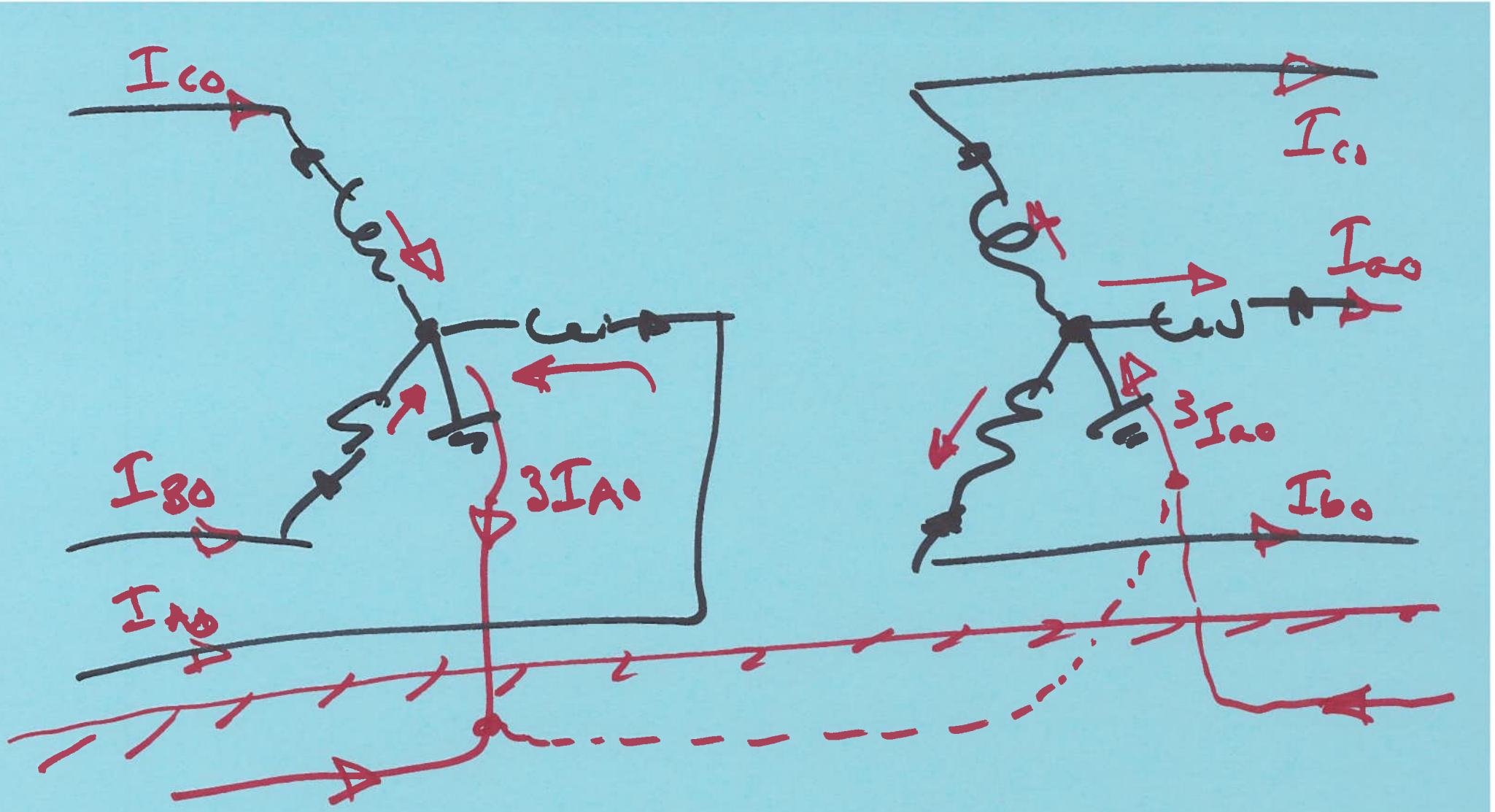


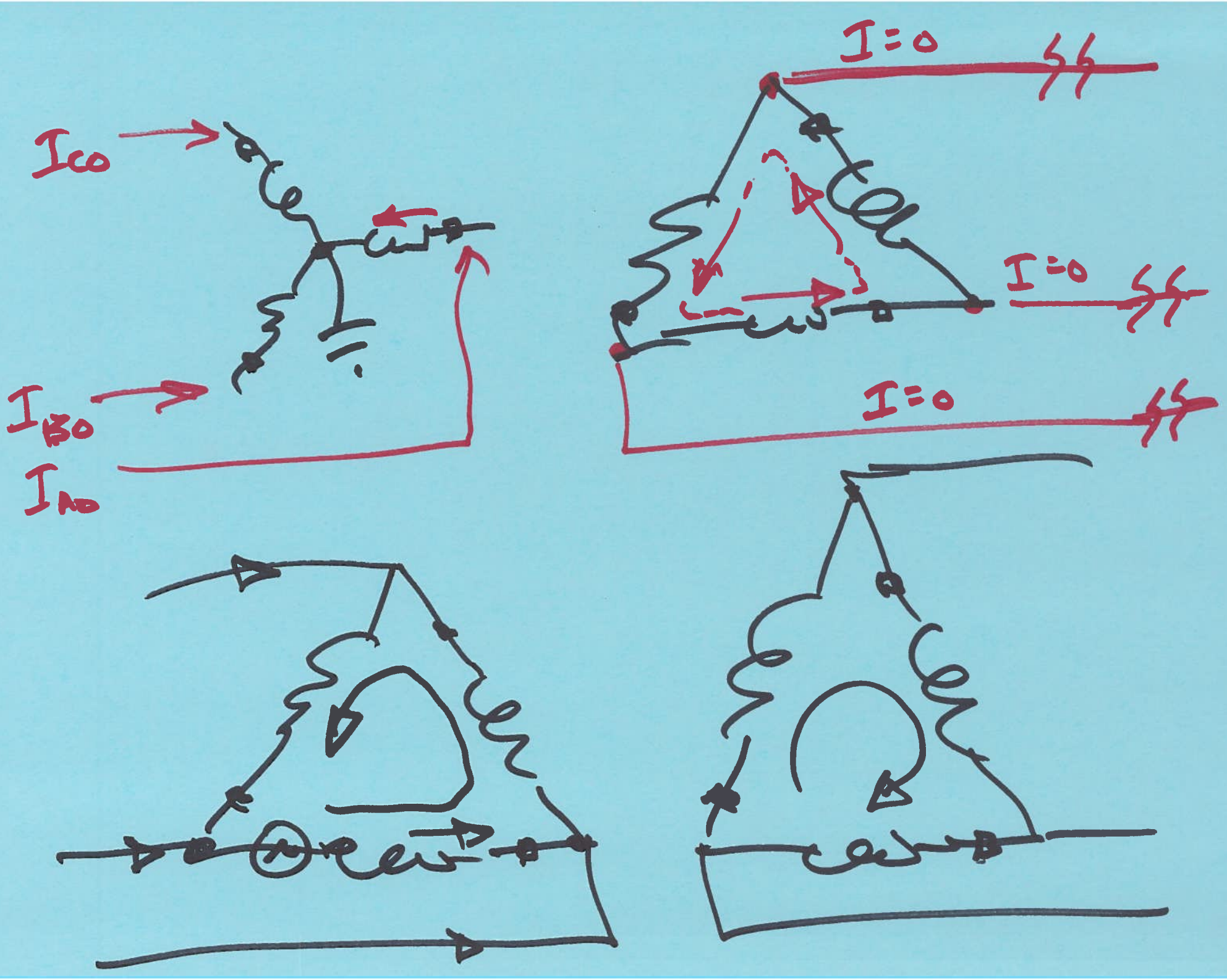


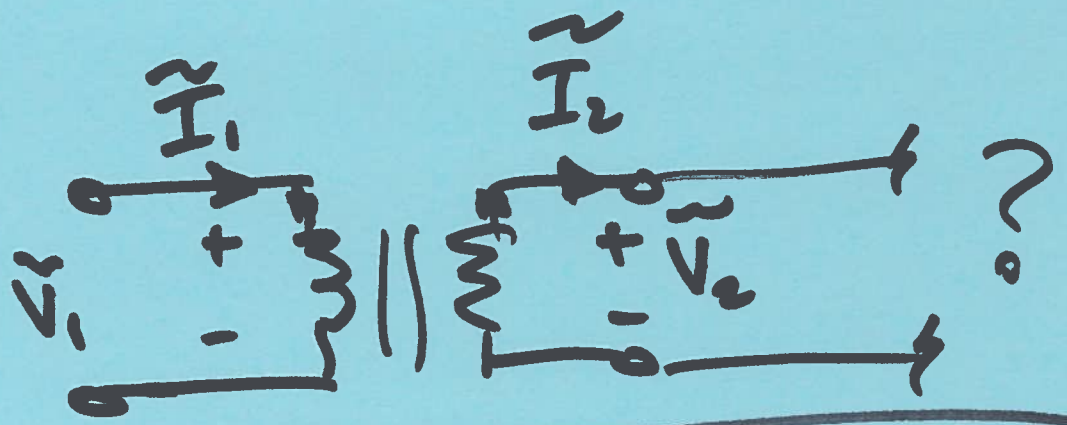
Delta Tertiary?

- Zero-seq circ.
- Harmonic "Containment"
  - "triplen" Harmonics
    - eg. 3rd, 6th, 9th...
  - ...like Z-seq, in phase.
- Relaying Conn.
- Station Service
- Local dist.


H1
H3
H2
X3
X1
X2
H0/X0
Y3
Y1
Y2


I_{C0}
I_{B0}
$3I_{A0}$
I_{C1}
I_{a0}
$3I_{a0}$
I_{b0}

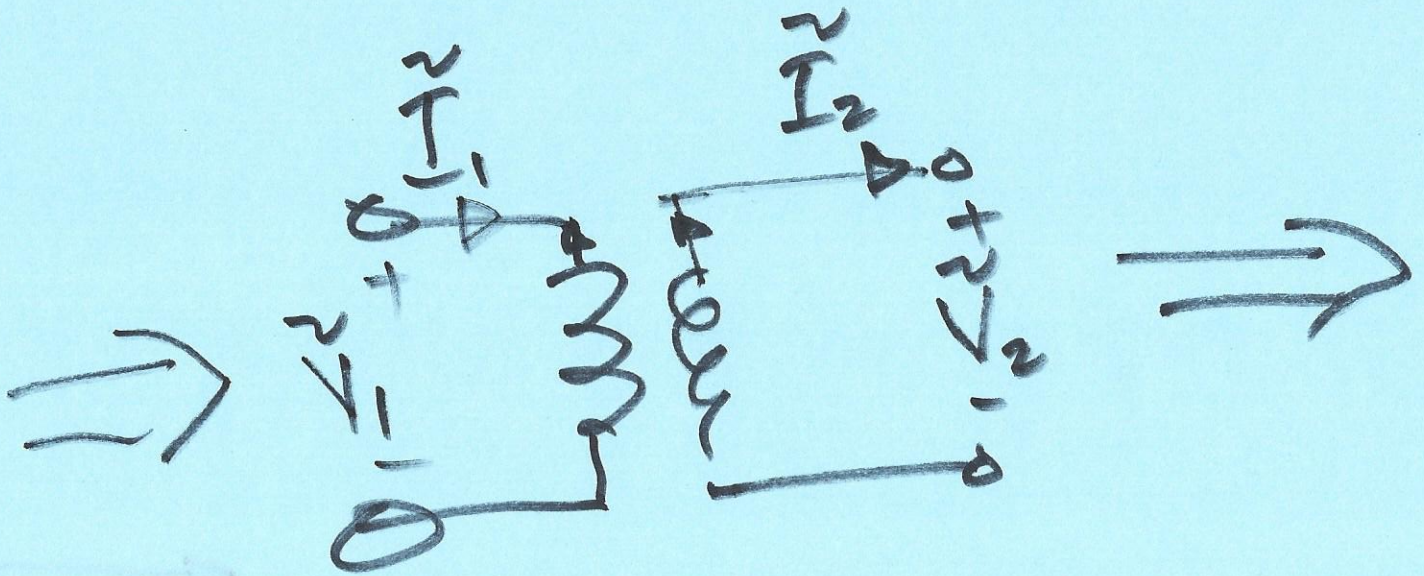

I_{CO}
I_{BO}
I_{AO}
I=0
I=0
I=0



No I_1 w/o I_2 !

No I_2 w/o I_1 !

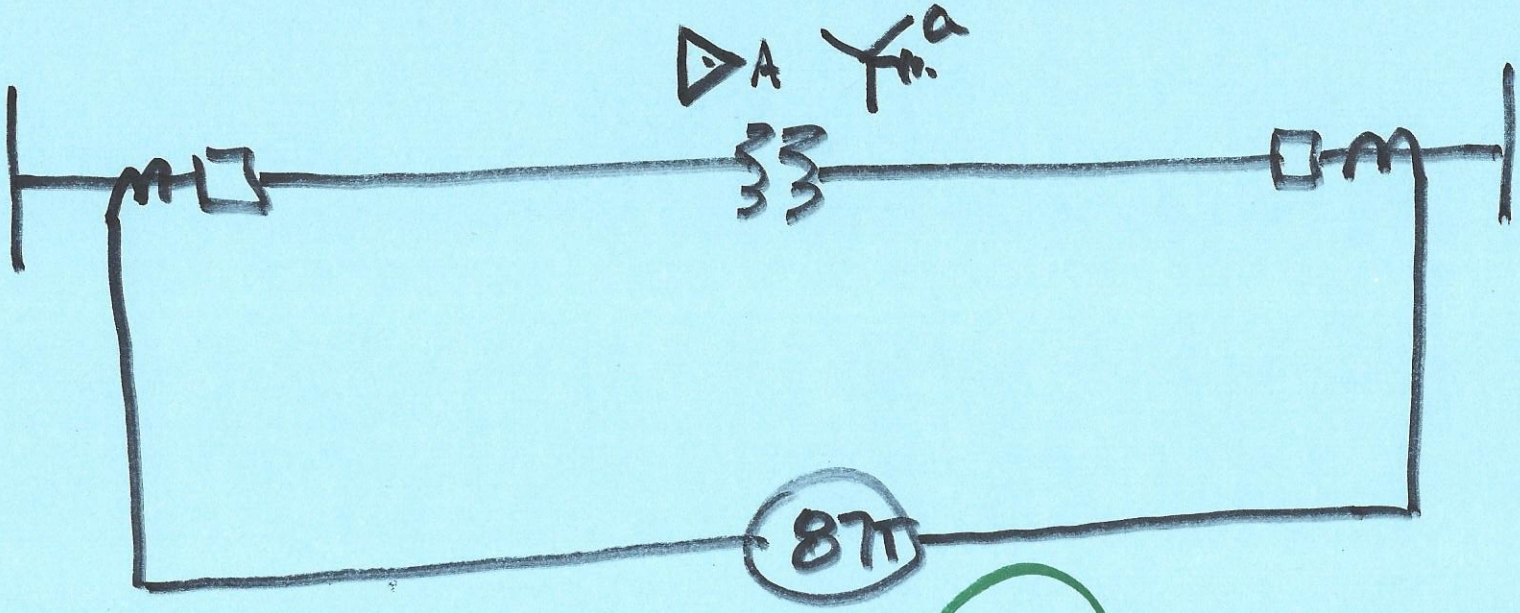
L22



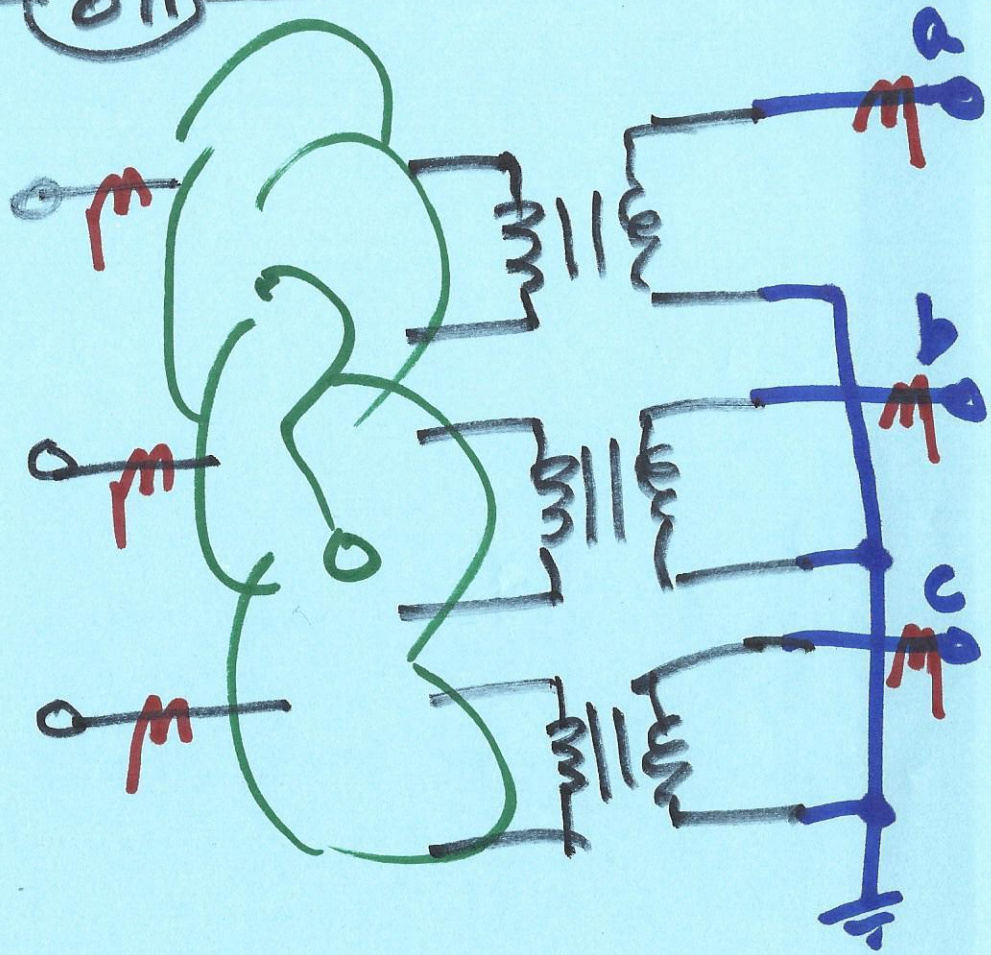
$$\tilde{V}_1 \tilde{I}_1^* = \tilde{V}_2 \tilde{I}_2^*$$

$$MVA_{IN} = MVA_{OUT}$$

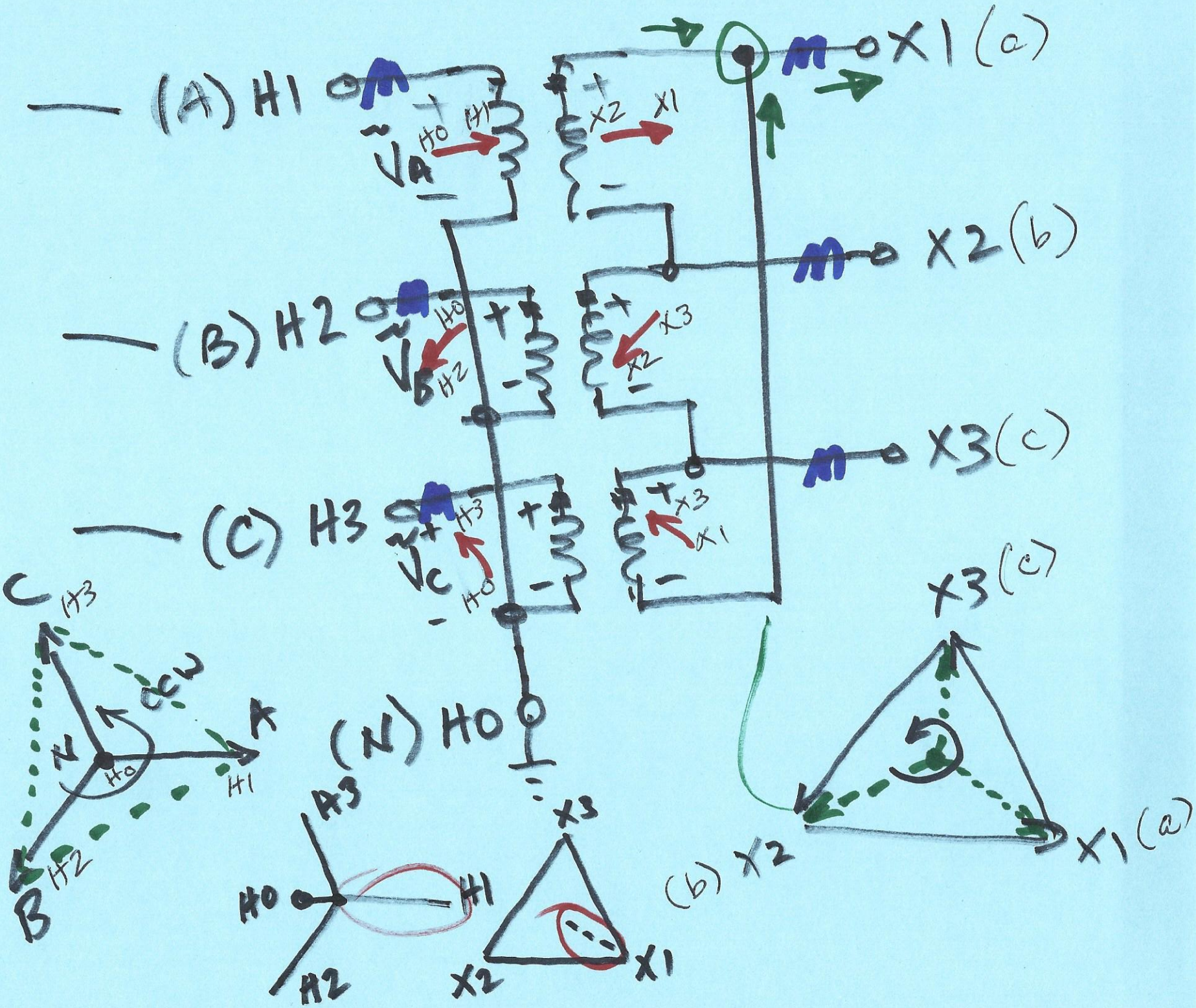
L22



- Voltage Ratio of XFMR
- Phase Shift
- Current Ratio of CTS.



L22



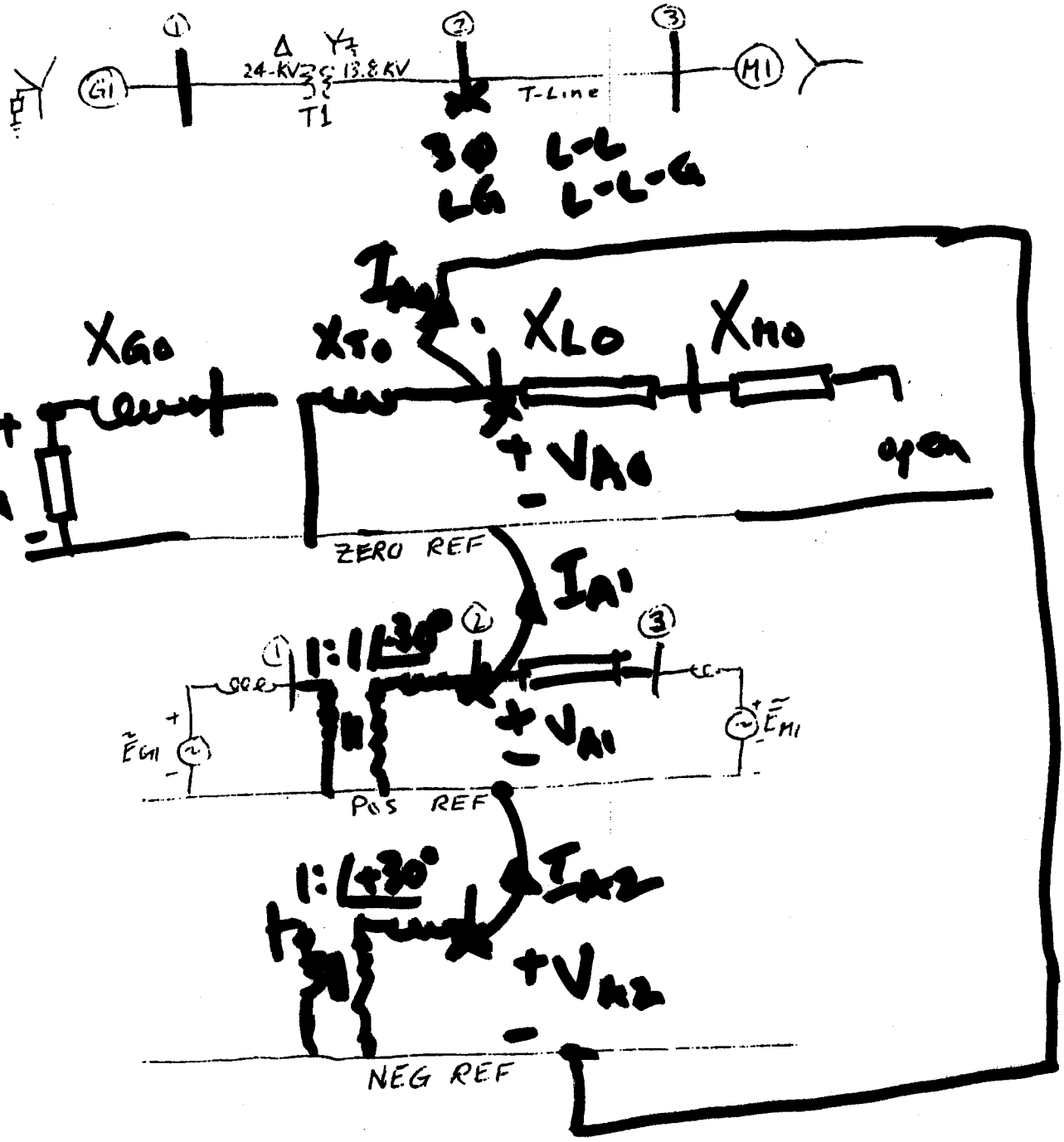
6) [30 pts] A simple 3ϕ power system consists of a generator, a transformer, a transmission line, and a large synchronous motor. Nameplate data for each piece of equipment is given below. The transformer has ANSI standard phase shift (high-voltage LN voltages lead the low-voltage LN voltages by 30°).

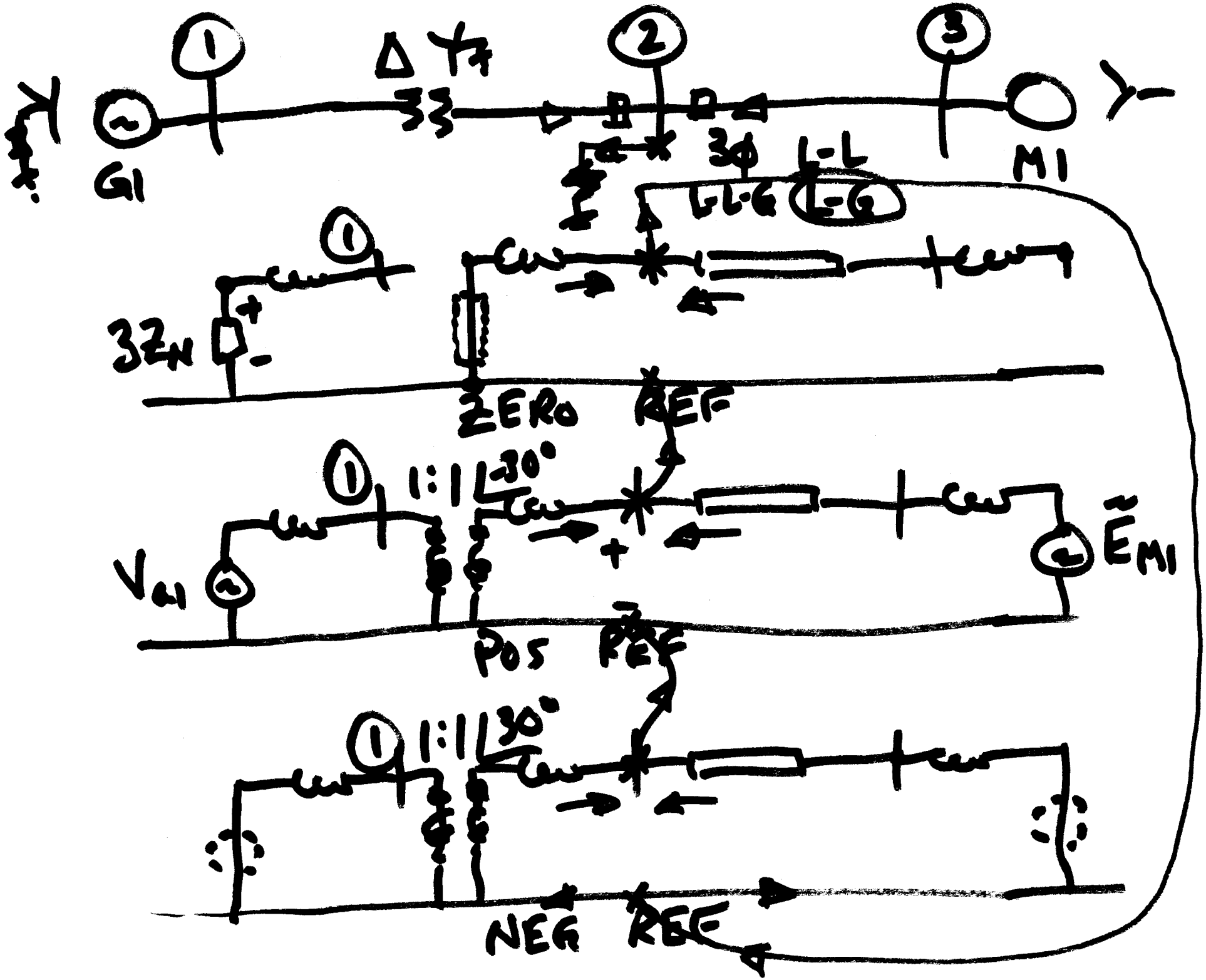
G1: 50MVA, 24kV, $X_0 = 5\%$, $X_1 = 20\%$, $X_2 = 10\%$, $X_N = 0.4\Omega$
T1: 100MVA, 24-13.8kV, $X_0 = 5\%$, $X_1 = X_2 = 10\%$
M1: 50MVA, 13.2kV, $X_0 = 5\%$, $X_1 = X_2 = 20\%$
T-Line: $X_0 = 1\Omega$, $X_1 = X_2 = 0.5\Omega$

$$\bar{Z}_{new} = \bar{Z}_{old}\left(\frac{V_{B\,old}}{V_{B\,new}}\right)^2\left(\frac{S_{B\,new}}{S_{B\,old}}\right)$$

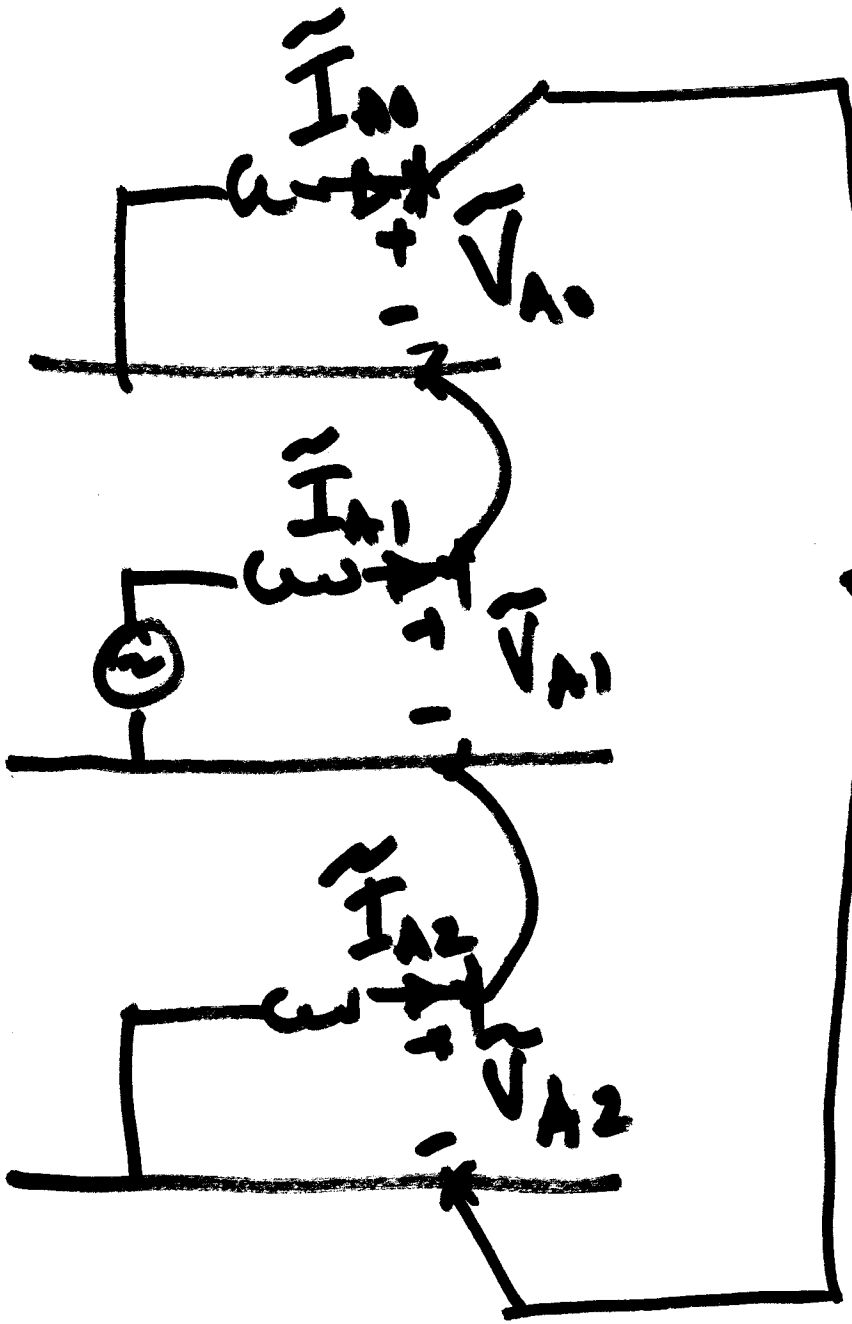
a) [15 pts] Using a system base of 100MVA and 24kV at bus 1, determine the base impedance for both sections of the system and convert all impedances to per unit values on the common system base.

b) [15 pts] Construct the zero, positive and negative sequence impedance diagrams. Label all impedances with their correct values in per unit. Include the effects of positive and negative sequence phase shift.





1
2
3
ΔY
G1
M1
3φ L-L
L-L-G
L-G
3Z_N
ZERO REF
1:1∠-30°
V_G1
Ẽ_M1
POS REF
1:1∠30°
NEG REF

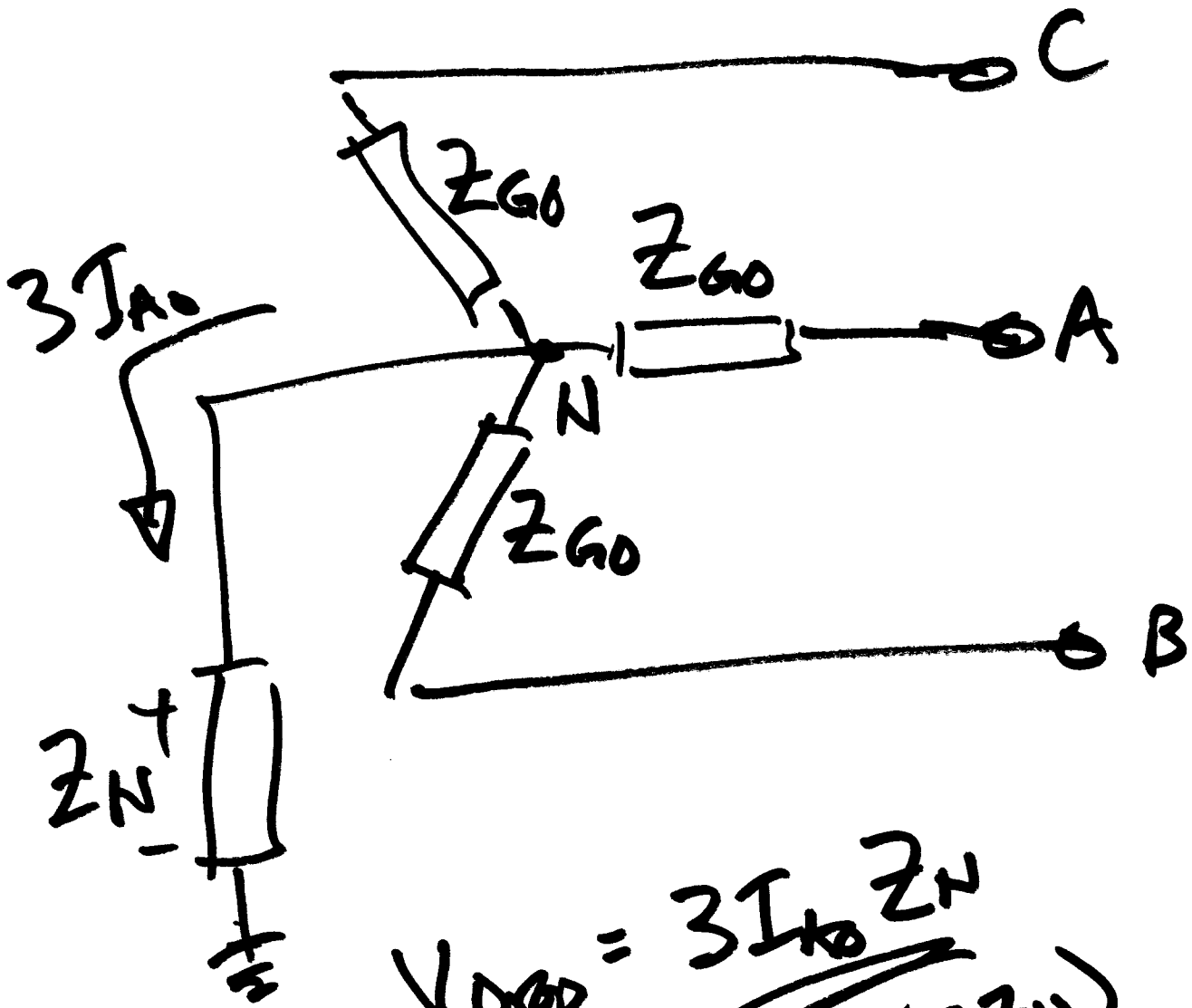


$$\tilde{I}_{A0} = \tilde{I}_{A1} = \tilde{I}_{A2}$$

$$\tilde{I}_A = 3\tilde{I}_{A0}$$

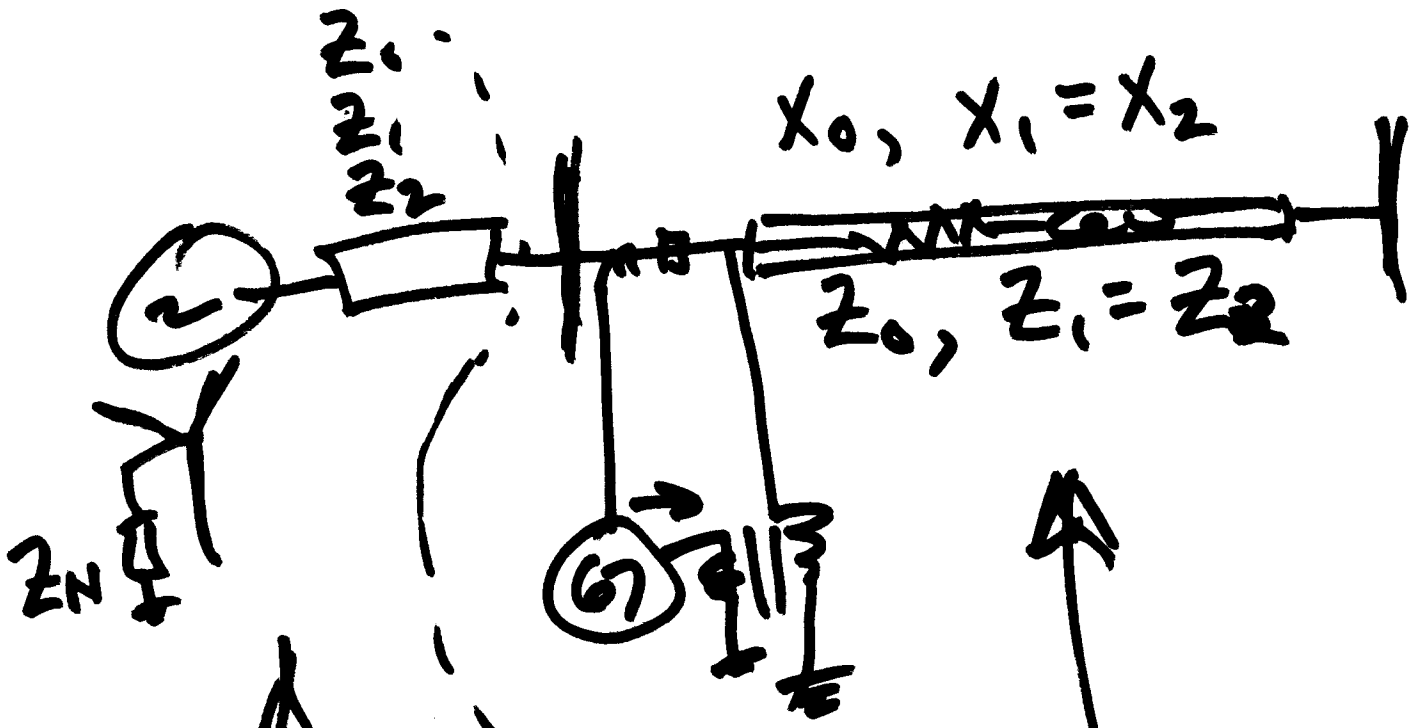
$$\tilde{I}_B = 0$$

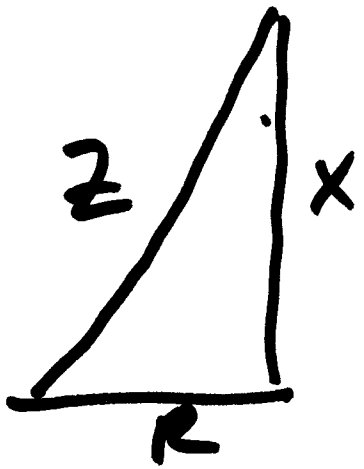
$$\tilde{I}_C = 0$$



$$V_{Drop} = 3I_{A0}Z_N$$

$$= I_{A0}(3Z_N)$$





$Z_1 = j.03$ p.u.

$Z_2 = j.03$ p.u.

$Z_0 = j.05$ p.u.

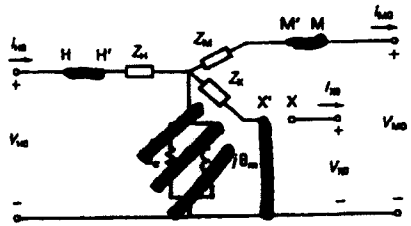
$Z_N = j.5\Omega$

$Z_0 =$ [redacted] 0.10 p.u.

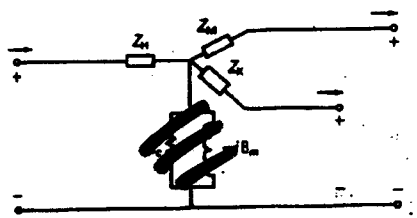
$Z_1 = Z_2 = .05$ p.u.

$X/R \cong 10$

FIGURE 8.21
Per-unit sequence networks of a three-phase three-winding transformer



(a) Per-unit zero-sequence network



(b) Per-unit positive- or negative-sequence network (phase shift not shown)

For the general zero-sequence network, Figure 8.21(a), the connection between terminals H and H′ depends on how the high-voltage windings are connected, as follows:

1. Solidly grounded Y—Short H to H′.
2. Grounded Y through Z_N—Connect ($3Z_N$) from H to H′.
3. Ungrounded Y—Leave H–H′ open as shown.
4. Δ—Short H′ to the reference bus.

Terminals X–X′ and M–M′ are connected in a similar manner.

The impedances of the per-unit negative-sequence network are the same as those of the per-unit positive-sequence network, which is always true for nonrotating equipment. Phase-shifting transformers, not shown in Figure 8.21(b), can be included to model phase shift between Δ and Y windings.

EXAMPLE 8.8 Three-winding three-phase transformer: per-unit sequence networks

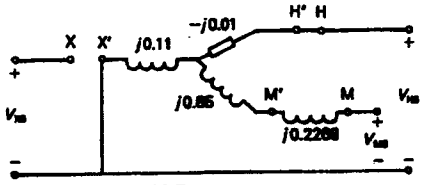
Three transformers, each identical to that described in Example 3.9, are connected as a three-phase bank in order to feed power from a 900-MVA, 13.8-kV generator to a 345-kV transmission line and to a 34.5-kV distribution line. The transformer windings are connected as follows:

13.8-kV windings (X):	Δ, to generator
199.2-kV windings (H):	solidly grounded Y, to 345-kV line
19.92-kV windings (M):	grounded Y through $Z_n = j0.10\ \Omega$, to 34.5-kV line

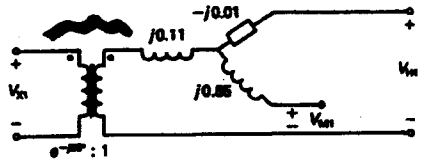
The positive-sequence voltages and currents of the high- and medium-voltage Y windings lead the corresponding quantities of the low-voltage Δ winding by 30°. Draw the per-unit sequence networks, using a three-phase base of 900 MVA and 13.8 kV for terminal X.

SOLUTION The per-unit sequence networks are shown in Figure 8.22. Since $V_{baseX} = 13.8$ kV is the rated line-to-line voltage of terminal X, $V_{baseX} =$

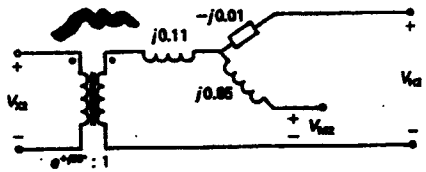
FIGURE 8.22
Per-unit sequence networks for Example 8.8



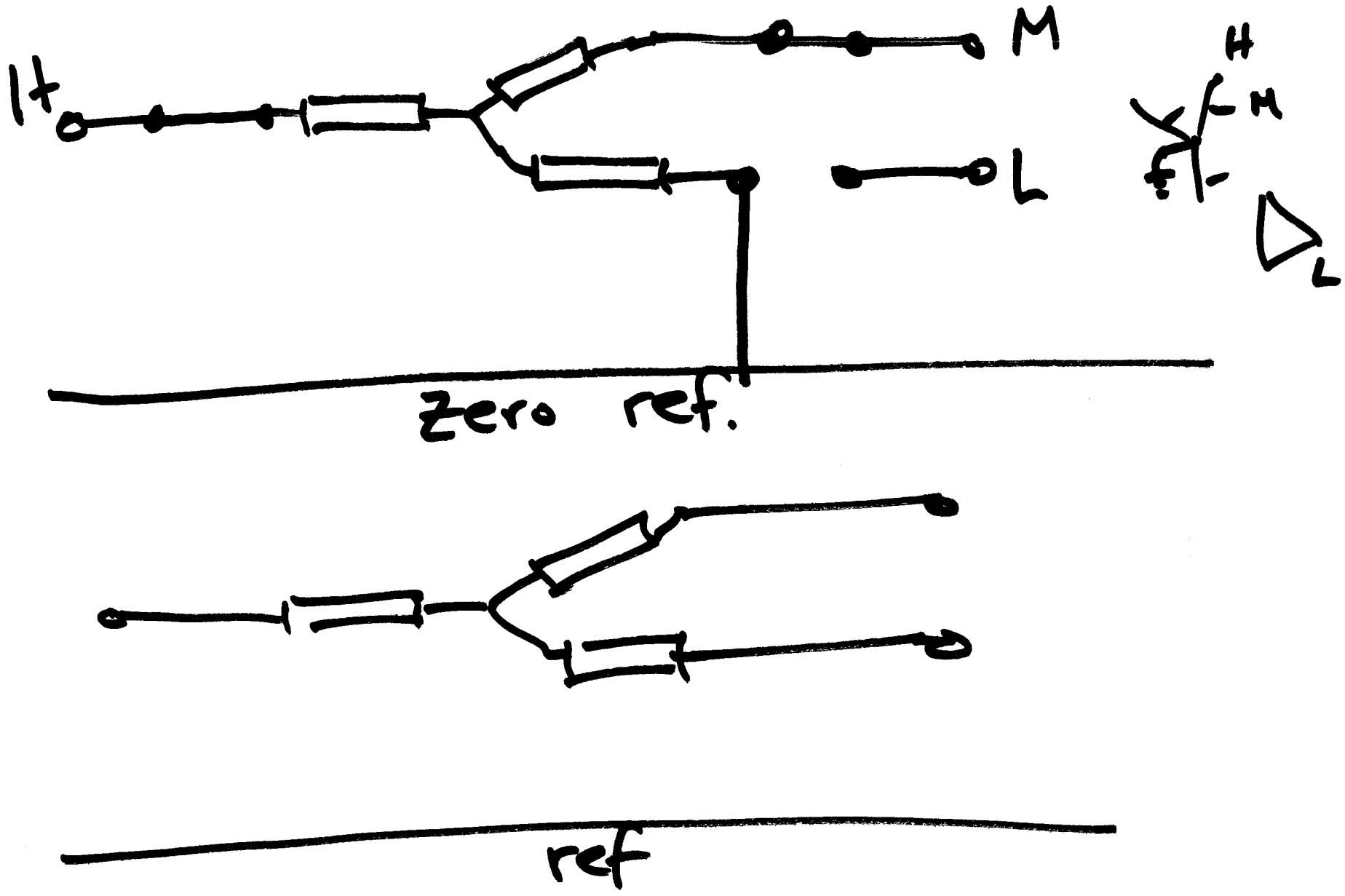
(a) Zero sequence



(b) Positive sequence



(c) Negative sequence


M
H
L
Zero ref.
ref