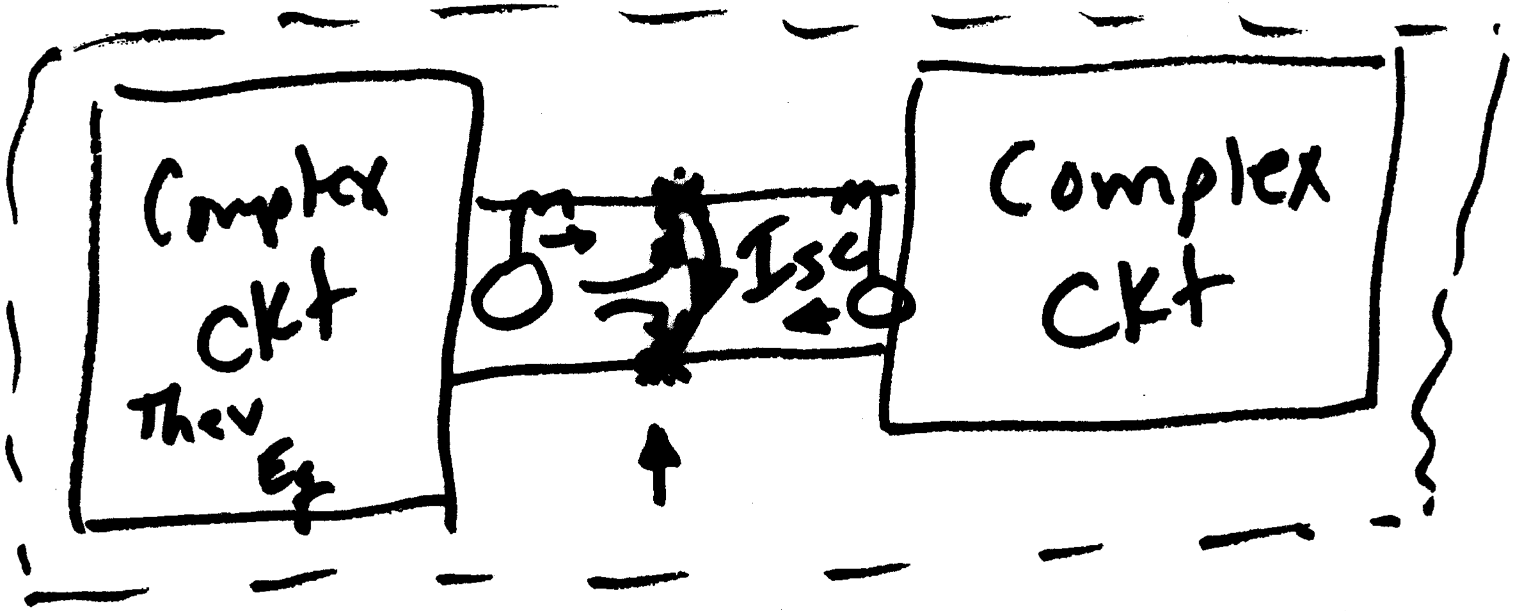
EE 5223 - Lecture 23 Wed Mar 1, 2023

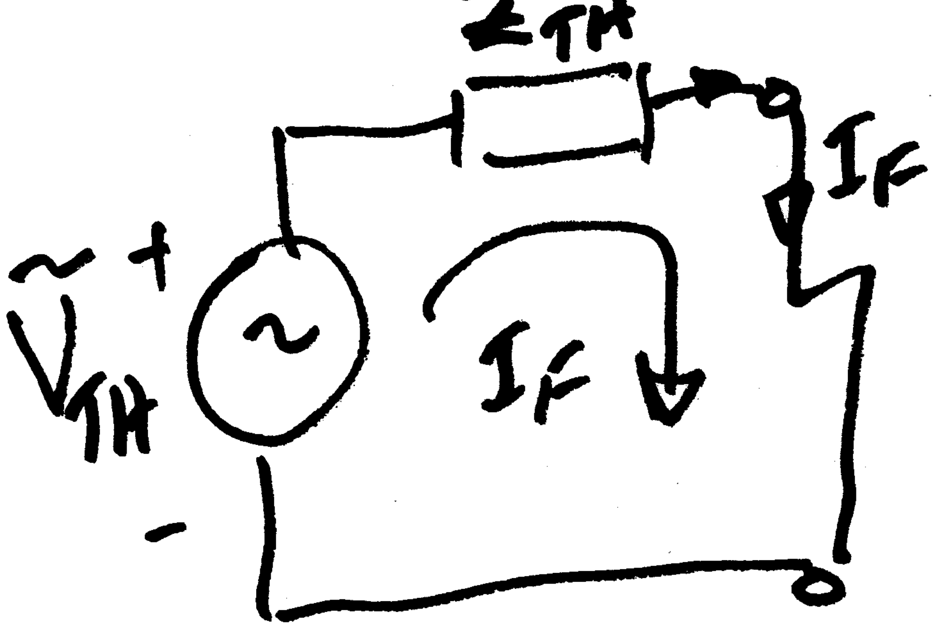
Ongoing List of Topics:

- URL: https://pages.mtu.edu/~bamork/EE5223/index.htm
- Term Project - last few proj/teams being firmed up and getting moving.
    - 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 lab:
  - 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.

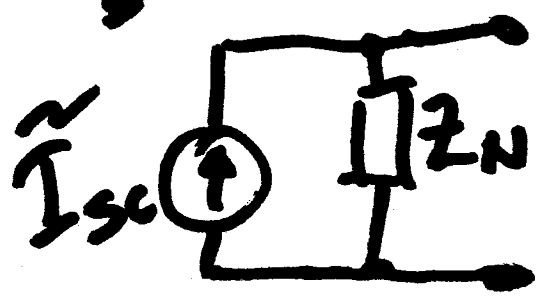


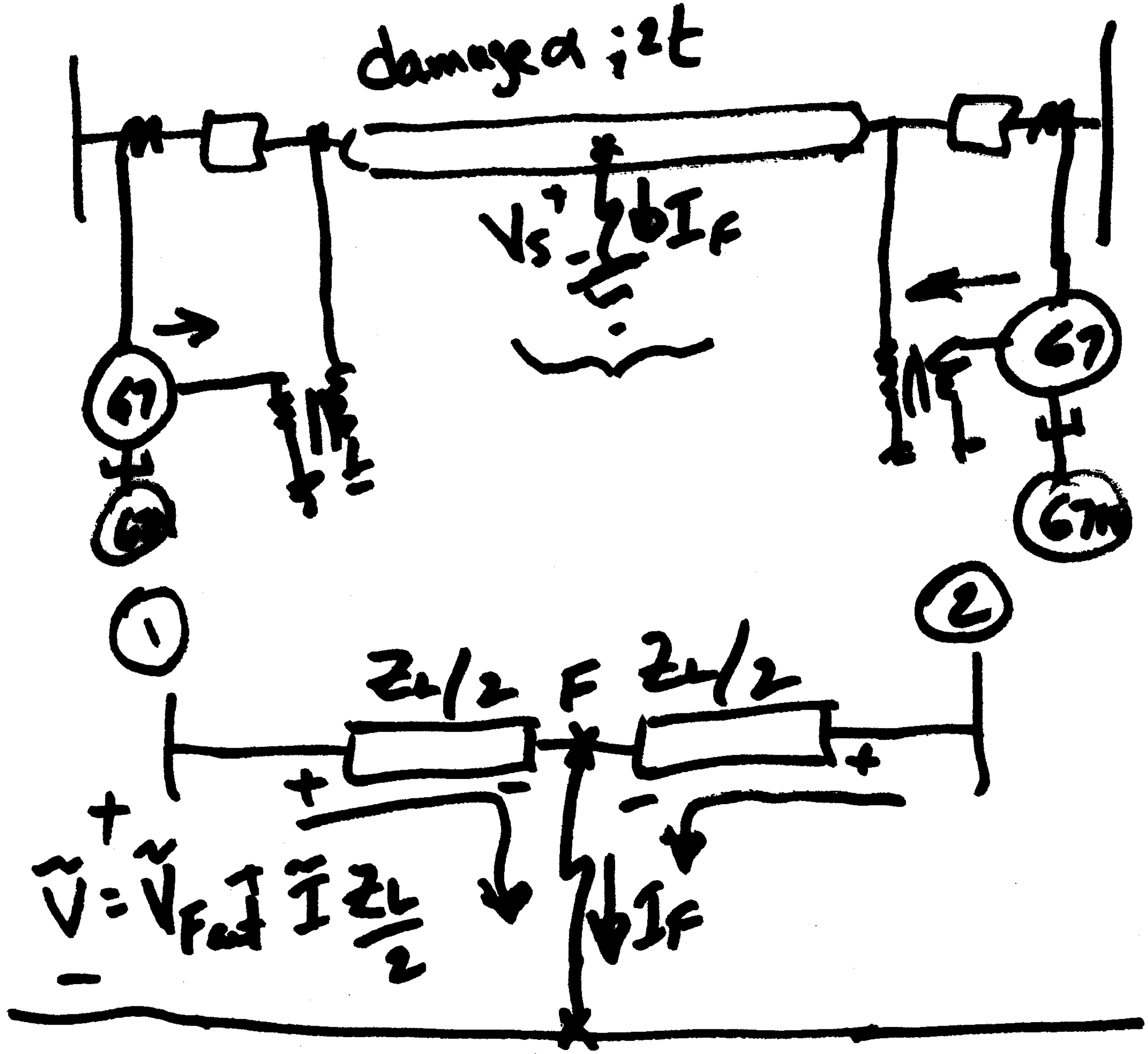


$$\tilde{V}_{TH} = \tilde{V}_{oc}$$

$$\tilde{Z}_{TH} = \tilde{V}_{oc}/\tilde{I}_{sc}$$

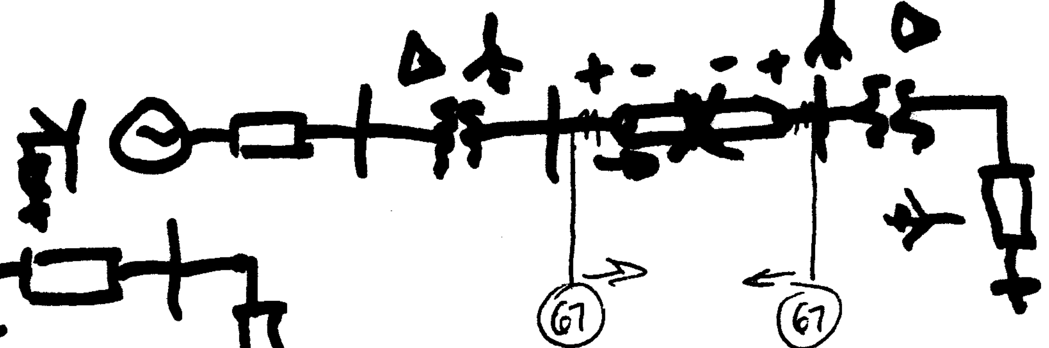
$$\tilde{I}_{sc} = \tilde{I}_N$$



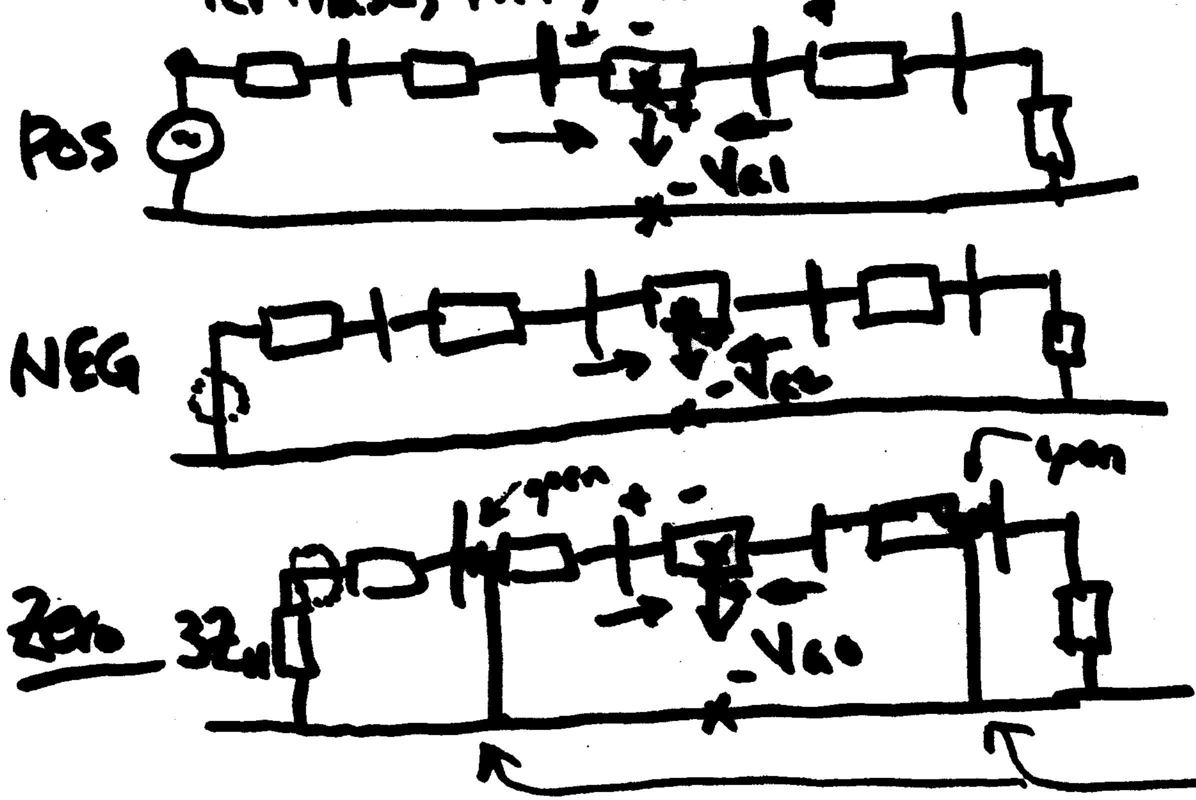

damage α i²t
Vs
I_F
67
67N
67
67N
1
2
Z_L/2
F
Z_L/2
Ṽ = Ṽ_Fault ± Ĩ Z_L/2
I_F

i.e.
$$\begin{bmatrix} \tilde{V}_{a0} \\ \tilde{V}_{a1} \\ \tilde{V}_{a2} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} \tilde{V}_a \\ \tilde{V}_b \\ \tilde{V}_c \end{bmatrix}$$

<u>Sequence Networks</u>

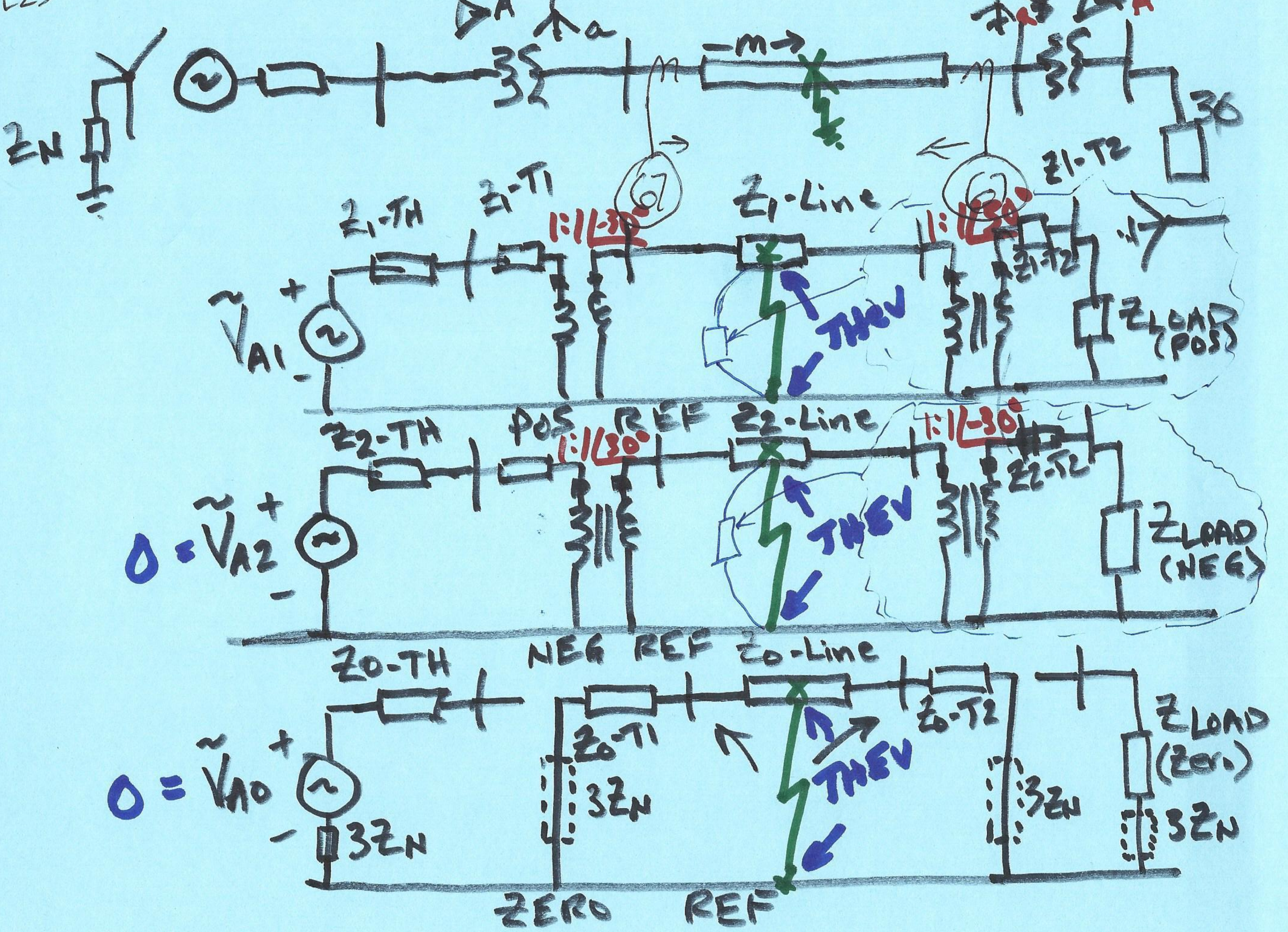


Per Phase, φA-N, P.U.



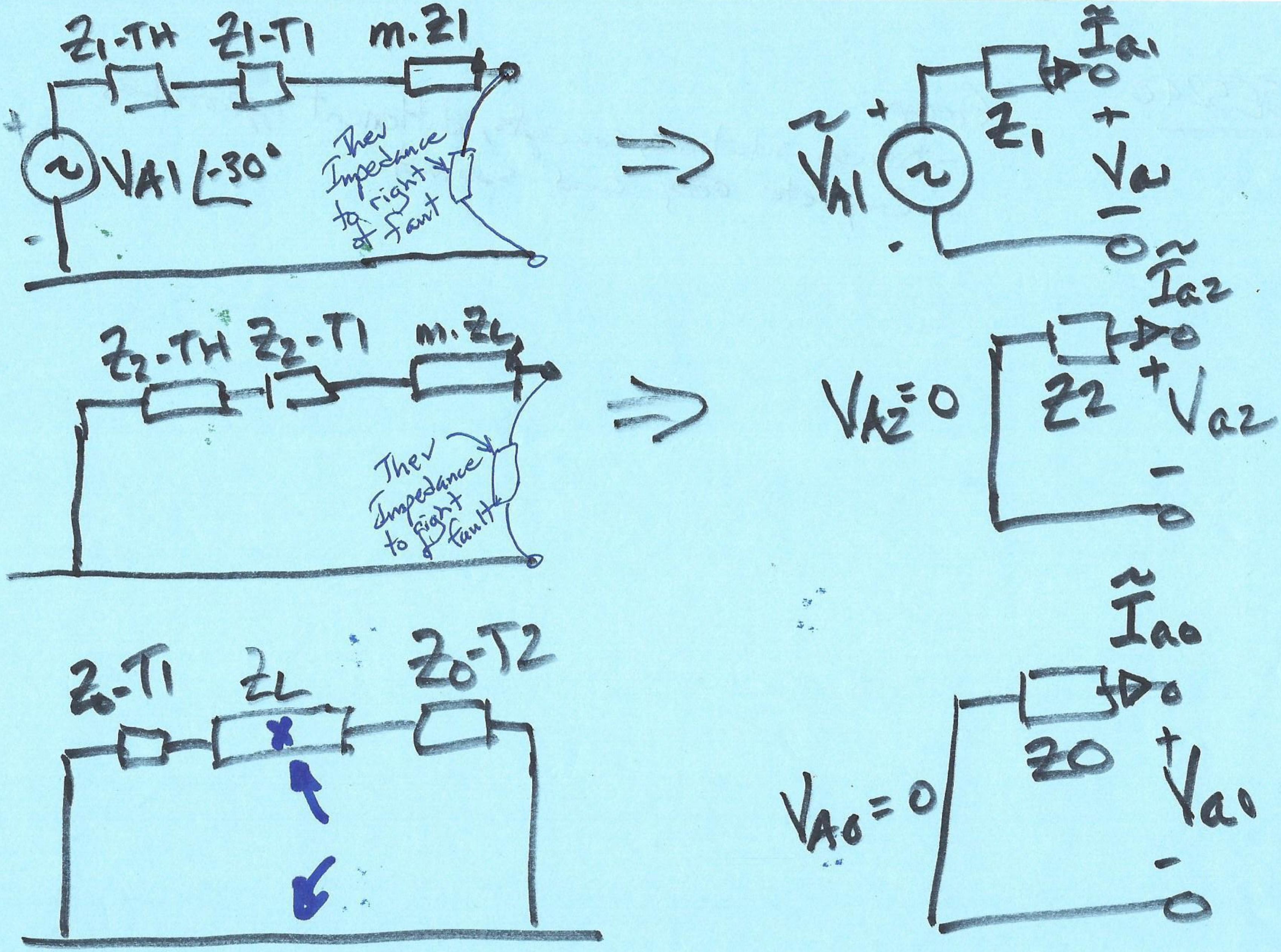
See details on next page.

L23



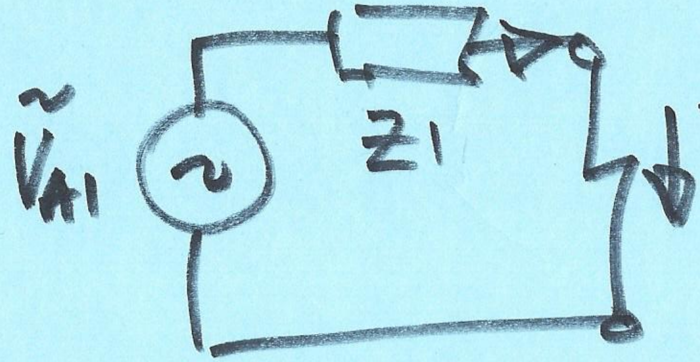
ΔA
Y a
—m→
Y a
ΔA
Z N
3Ø
67
67
Z1-TH
Z1-T1
1:1∠-30°
Z1-Line
1:1∠30°
Z1-T2
~
V A1
+
-
THEV
Z LOAD (POS)
POS REF
Z2-TH
1:1∠30°
Z2-Line
1:1∠-30°
Z2-T2
0 = ~V A2
THEV
Z LOAD (NEG)
NEG REF
Z0-TH
Z0-Line
Z0-T1
Z0-T2
0 = ~V A0
3Z N
THEV
Z LOAD (Zero)
ZERO REF

L23


Z1-TH
Z1-T1
m.Z1
VA1 ∠-30°
Thev Impedance to right of fault
Ia1
Z1
VA1
Va1
Ia2
Z2-TH
Z2-T1
m.ZL
Thev Impedance to right fault
VA2=0
Z2
Va2
Ia0
Z0-T1
ZL
Z0-T2
VA0=0
Z0
Va0

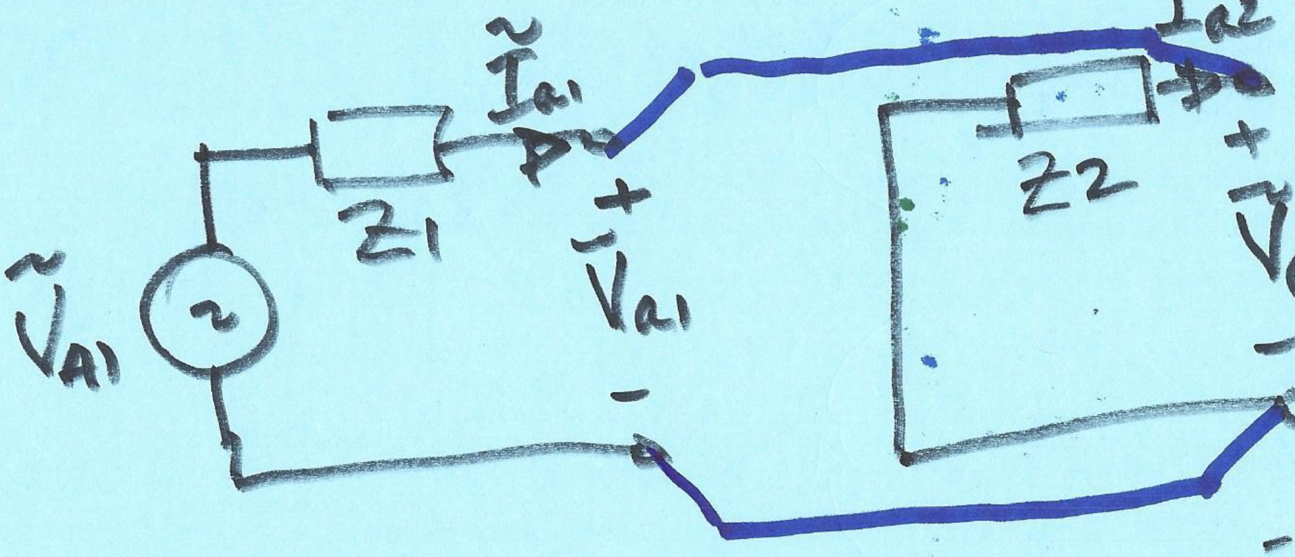
L23

$\underline{3\phi}$



$$I_{F,A1} = \frac{\tilde{V}_{A1}}{Z_1}$$

$\underline{L\text{-}L}$



$$\tilde{I}_{a1} = \frac{\tilde{V}_{A1}}{Z_1 + Z_2}$$

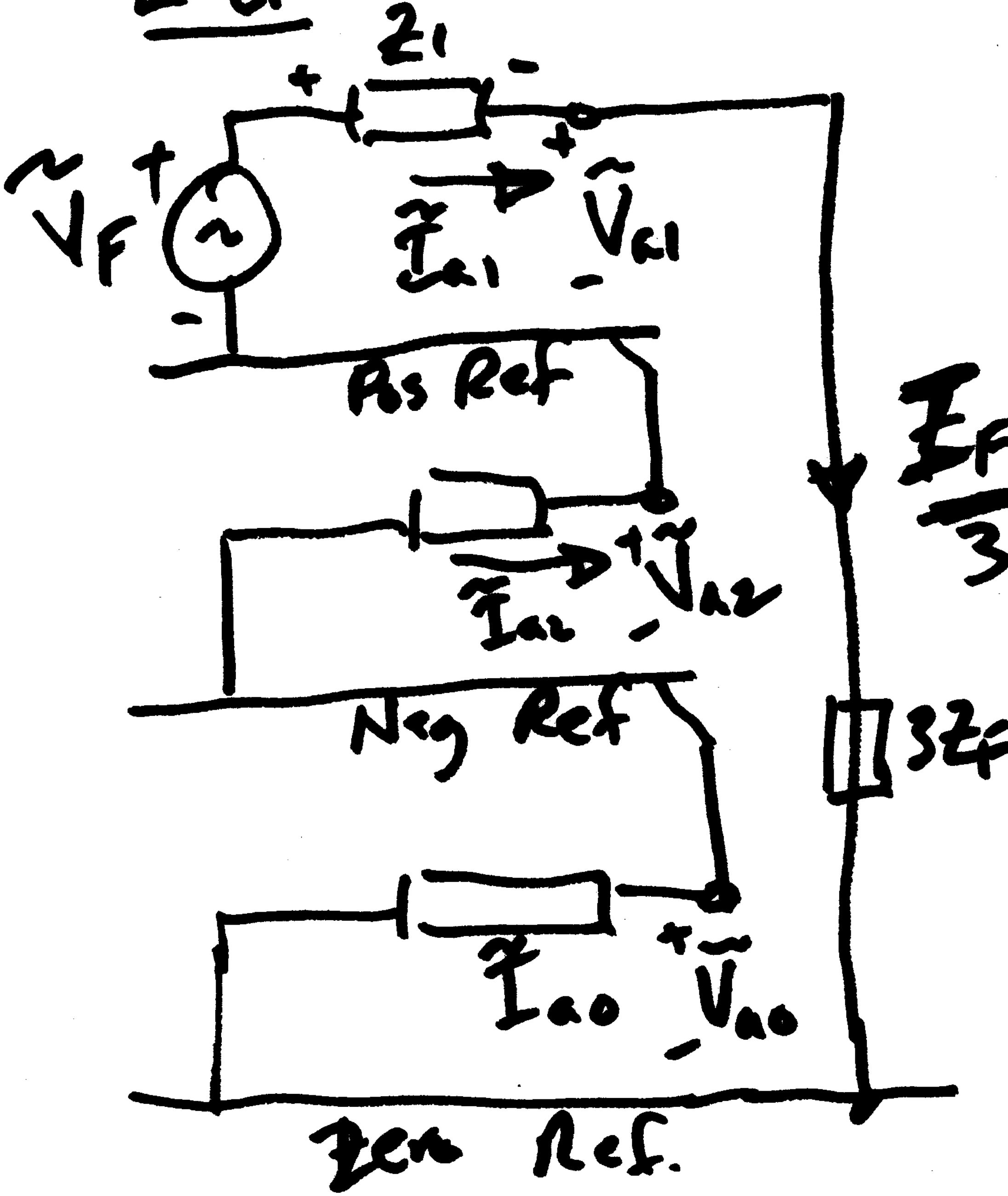
$$\tilde{I}_{a2} = -\tilde{I}_{a1}$$

$$\tilde{V}_{a1} = \tilde{V}_{a2}$$

$$= \tilde{I}_{a1} Z_2$$

$$= -\tilde{I}_{a2} Z_2$$

L-G

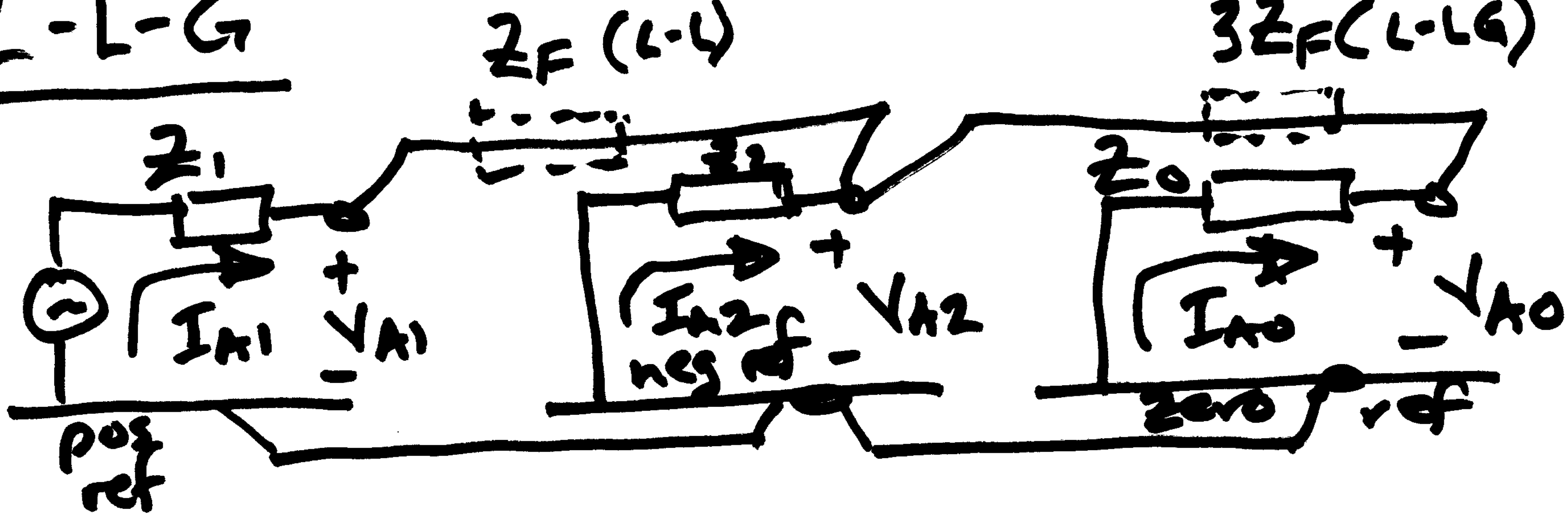


$$\tilde{I}_{a1} = \tilde{I}_{a2} = \underline{\tilde{I}_{a0}}$$

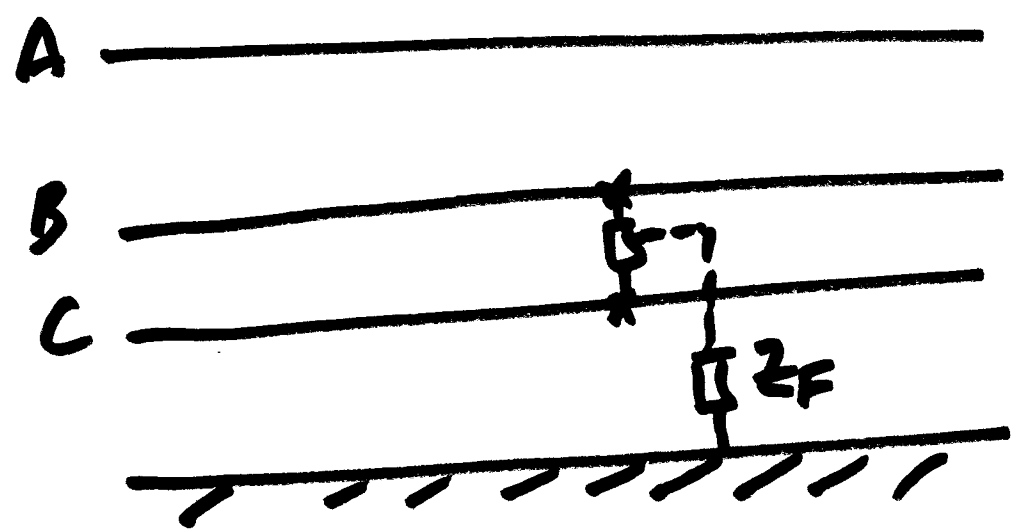
$$\frac{\tilde{I}_F}{3} = \tilde{I}_{a1} = \tilde{I}_{a2} = \tilde{I}_{a0}$$

$$[V_p] = [A][V_s]$$

L-L-G



L-L : Reduced case, $Z_0 \approx \infty$



Fault Impedance

Z_F:

- LG
- LL
- LLG
- 3ϕ

Pos:

Bus1: $V_{a1,1} = V_{a1,fault} + \tilde{I}^{a1}_{1F}\,\bar{Z}'_{L,1F}$

Bus2: $V_{a1,2} = V_{a1,fault} + \tilde{I}^{a1}_{2F}\,\bar{Z}'_{L,2F}$

NEG:

Bus 1 $\tilde{V}_{a2,1} = \tilde{V}_{a2,fault} + \tilde{I}_{a2,1F}\,\bar{Z}^{2}_{L,1F}$

Bus 2 $\tilde{V}_{a2,2} = \tilde{V}_{a2,fault} + \tilde{I}_{a2,2F}\,\bar{Z}^{2}_{L,2F}$

Zero:

$\tilde{V}_{a0,1} = \tilde{V}_{a0,fault} + \tilde{I}_{a0,1F}\,\bar{Z}^{0}_{L,1F}$

$\tilde{V}_{a0,2} = \tilde{V}_{a0,fault} + \tilde{I}_{a0,2F}\,\bar{Z}^{2}_{L,2F}$

Then you'll have $[I_s]$ & $[V_s]$ at each bus.

Then can "apply" relay.
i.e. do settings.

<u>Phase Qtys</u>: $\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} A \end{bmatrix} \begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix}$

67 relays: Phase Qtys (i.e. A, B, C

21 relays : Seq Qtys (i.e. pos, neg, zer

$$\bar{Z}(\omega) = \frac{V(\omega)}{\tilde{I}(\omega)}$$

<u>For Relays</u>:

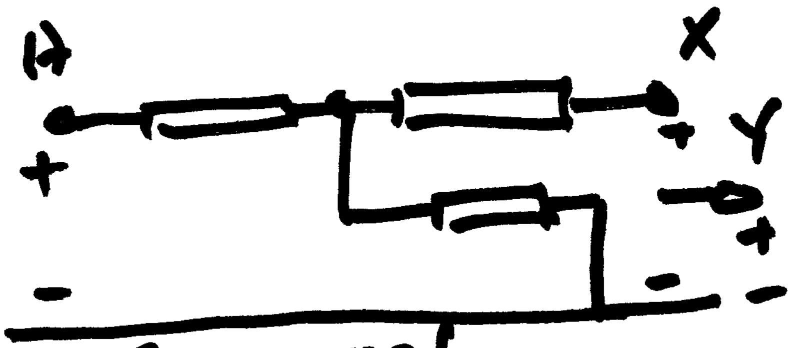
$$\left.\begin{aligned} \bar{Z}_0 &= \frac{\tilde{V}_{a0}}{\tilde{I}_{a0}} \\ \bar{Z}_1 &= \frac{\tilde{V}_{a1}}{\tilde{I}_{a1}} \end{aligned}\right] \text{Simplest case}$$

$$\bar{Z}_A = \frac{\tilde{V}_{AN}}{\tilde{I}_a}$$

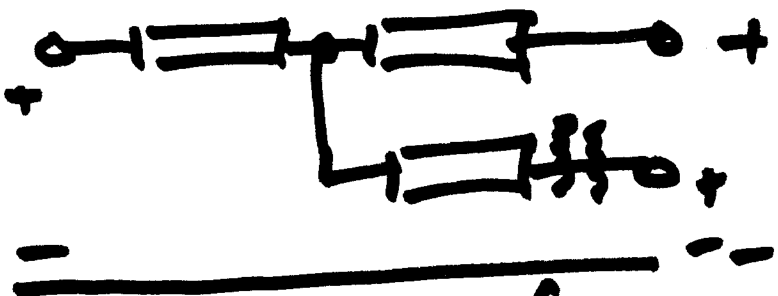
If you use V_{LL}

$$\bar{Z}_{AB} = \frac{\tilde{V}_{AB}}{\tilde{I}_{AB}} = \frac{\tilde{V}_A - \tilde{V}_B}{\underbrace{\tilde{I}_A - \tilde{I}_B}_{\text{"delta currents"}}}$$

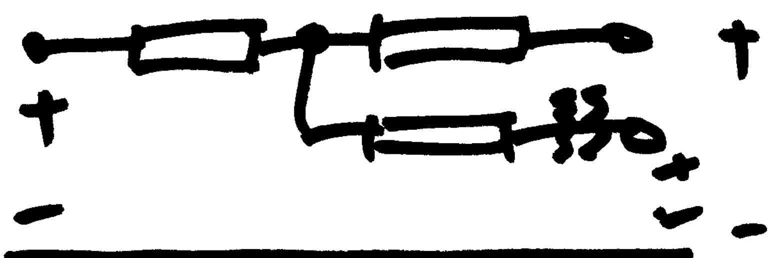
3-Winding XFMR



zero ref

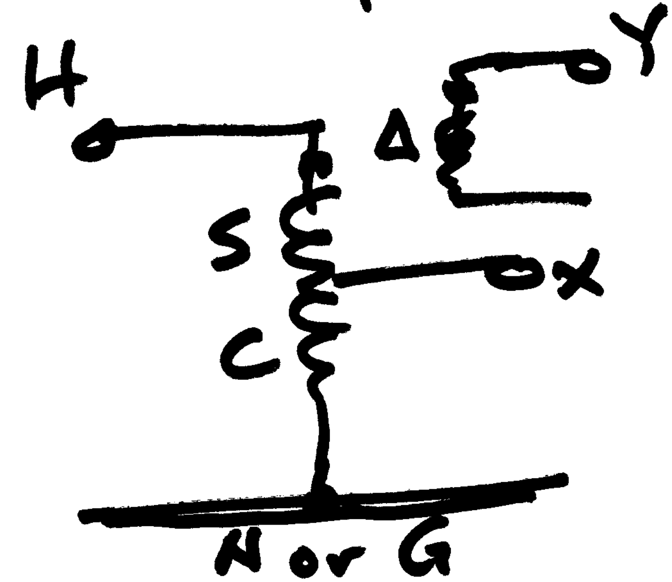


pos ref



neg ref

– Auto w/Δ tert.



Key: External fault:
It's enough to
know line currents
and voltages
at the bushings.

What about internal
fault?

Also: How can we calculate I_{A0} in neu or inside Δ for ground polarization?

Thus: need to reconcile line currents into xfmr, with internal currents thru coils.

See last page of L21!

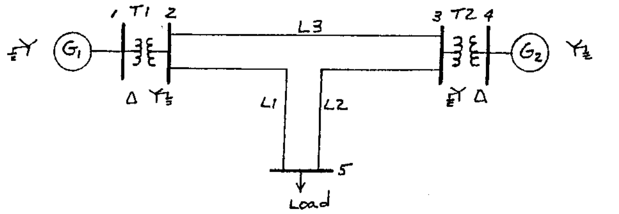
Objective: obtain CT currents of neutral and Δ for ground polarization.

EE 4222 - Homework Set 3
Due: March 1, 2006 Name Key No.____

1. In the 3-phase system below, the elements have the following values:

G1: 250 MVA, 15.0 kV, X_0 = .05, X_1 = .25, X_2 = .20
G2: 500 MVA, 15.0 kV, X_0 = .05, X_1 = .25, X_2 = .20
T1: three single-phase units, high voltage side connected wye, low voltage side connected delta, Each unit is 15 kV:200 kV, 300 MVA, with a reactance of .10
T2: A three-phase transformer, 345 kV wye:15 kV delta, 500 MVA, with a reactance of .10.
L1: Z_0 = j40 ohms/phase, Z_1 = Z_2 = j20 ohms/phase
L2: Z_0 = j20 ohms/phase, Z_1 = Z_2 = j10 ohms/phase
L3: Z_0 = j30 ohms/phase, Z_1 = Z_2 = j15 ohms/phase

Choose a base of 345 kV, 1,000 MVA at the load and draw the per unit zero, positive, and negative impedance diagrams. Show all the impedance values on the diagrams. Assume all pre-fault bus voltages are 1.0 per unit. Neglect the load.



2. Construct the Thevenin equivalent zero, positive, and negative sequence networks for the system of problem 1 looking into the network at bus 3.

3. For a L-G fault with an impedance of j.1 per unit on bus 3 in the problem above, find the a-b-c line currents flowing toward the fault:
A. Coming from line L2
B. Coming from generator G1

4. Repeat problem 3 for a solid L-L fault on bus 3

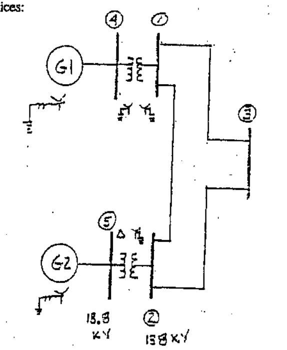
5. Repeat problem 3 for a solid 2L-G fault on bus 3

6. The 5-bus system shown below has the bus impedance matrices:

$$Z_0 = j\begin{bmatrix} .12847 & .02431 & .06597 & .10278 & .00000 \\ .02431 & .04514 & .03681 & .01944 & .00000 \\ .06597 & .03681 & .22847 & .05278 & .00000 \\ .10278 & .01944 & .05278 & .12222 & .00000 \\ .00000 & .00000 & .00000 & .00000 & .20000 \end{bmatrix}$$

$$Z_1 = j\begin{bmatrix} .13014 & .09589 & .10959 & .10411 & .07192 \\ .09589 & .12329 & .11233 & .07671 & .09247 \\ .10959 & .11233 & .17123 & .08767 & .08425 \\ .10411 & .07671 & .08767 & .12329 & .05753 \\ .07192 & .09247 & .08425 & .05753 & .10685 \end{bmatrix}$$

$$Z_2 = j\begin{bmatrix} .15517 & .12069 & .13448 & .12931 & .09655 \\ .12069 & .14943 & .13793 & .10057 & .11954 \\ .13448 & .13793 & .19655 & .11207 & .11034 \\ .12931 & .10057 & .11207 & .14943 & .08046 \\ .09655 & .11954 & .11034 & .08046 & .13563 \end{bmatrix}$$



Ignore pre-fault currents and assume a pre-fault voltage of 1.0. For a line-to-ground fault with an impedance of j.06792 on bus 3, find the a-b-c per unit line currents:

A. In the fault itself
B. From generator 2, which has: X_0 = .05, X_1 = .15, X_2 = .20, X_n = .05
C. In line 1-3, which has: X_1 = X_2 = .15, X_0 = .45

7. Repeat problem 6 for a line-to-line fault on bus 3 with an impedance of j .13222

8. Find the a-b-c fault current for a solid two-line-to-ground fault at bus 3 of the systme of problem 6.

1

1.] FINDING New Base Voltages:

V_{Base} @ 2, 3, 5 = 345 kV; V_{Base} @ 4 = $\frac{15}{345} \times 345$ = 15 kV;

V_{Base} @ 1 = $\frac{15}{200\sqrt{3}}(345) = \left(\frac{15}{346.41}\right)(345)$ = 14.93894 kV

FINDING Per Unit Values on new 1,000 MVA base.

G1: $X_0 = .05\left(\frac{15}{14.939}\right)^2\left(\frac{1000}{250}\right) = .20164$; $X_1 = .25\left(\frac{15}{14.939}\right)^2\left(\frac{1000}{250}\right) = 1.00819$; $X_2 = .8X_1 = .80655$

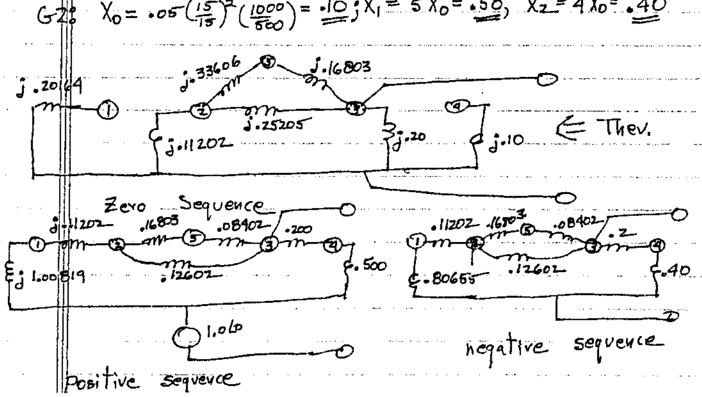
T1: $X = .10\left(\frac{15}{14.939}\right)^2\left(\frac{1000}{900}\right) = .11202$; L_1: $X_0 = \frac{40}{\frac{(345\times10^3)^2}{1{,}000\times10^6}} = .33606$

L_1: $X_1 = X_2 = \frac{1}{2}X_0 = .16803$ | L_2: $X_0 = X_1$ of L_1 = .16803, $X_1 = X_2 = \frac{1}{2}X_0 = .08402$

L_3: $X_0 = \frac{30}{\frac{(345\times10^3)^2}{1000\times10^6}} = .25205$; $X_1 = X_2 = \frac{15}{\frac{(345)^2}{1000}} = .12602$

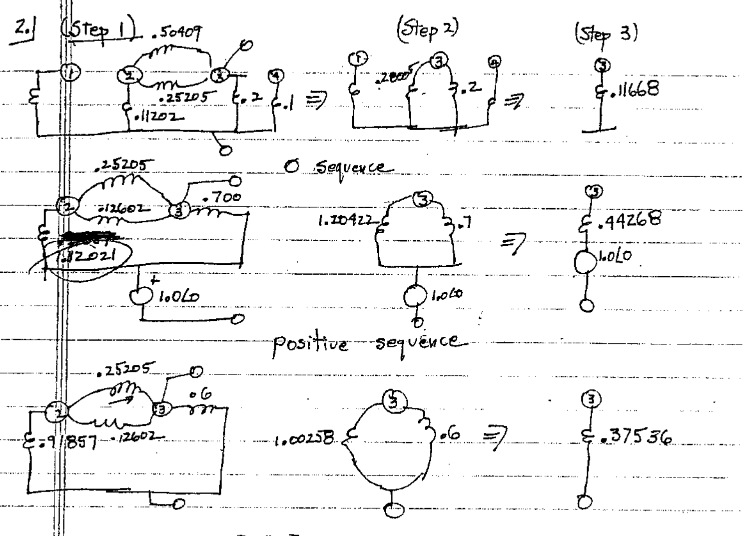
T2: $X = .10\left(\frac{1000}{500}\right) = .20$

G2: $X_0 = .05\left(\frac{15}{15}\right)^2\left(\frac{1000}{500}\right) = .10$; $X_1 = 5X_0 = .50$, $X_2 = 4X_0 = .40$

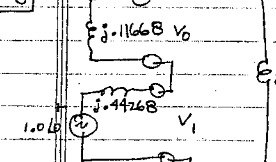


2

2.]



3.]



$I_1 = \frac{1.0\angle 0}{j(.11668 + .44268 + .37536 + .3)}$

$= .80990\angle{-90}$

From bus 2 (Gen 1 pos & neg)

$I_0 = \left(\frac{.2}{.28005 + .2}\right)(.80990\angle{-90}) = .33742\angle{-90}$

$I_1 = \left(\frac{.7}{.7 + 1.20422}\right)(.80990\angle{-90}) = .29778\angle{-90}$

$I_2 = \left(\frac{.6}{.6 + 1.00258}\right)(.80990\angle{-90}) = .30322\angle{-90}$

3

From Line 2:

$I_0 = \left(\frac{.25205}{.25205+.50409}\right).33742\angle-90 = .11247\angle-90$

$I_1 = \left(\frac{.12602}{.12602+.25205}\right).29772\angle-90 = .09924\angle-90$

$I_2 = \left(\frac{.12602}{.12602+.25205}\right)(.30328\angle-90) = .10108\angle-90$

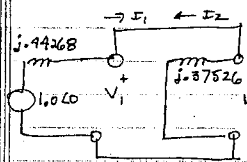
3-A)

$I_{a,b,c} = [A]\begin{bmatrix}.11247\angle-90\\ .09924\angle-90\\ .10108\angle-90\end{bmatrix} = \begin{matrix}.31278\angle-90\\ .01242\angle-82.667\\ .01242\angle-97.333\end{matrix}$

3-B)

$I_{a,b,c} = [A]\begin{bmatrix}0\\ .29772\angle-120\\ .30328\angle-60\end{bmatrix} = \begin{matrix}.52044\angle-89.697\\ .52044\angle86.697\\ .00550\angle180.00\end{matrix}$

4)



$I_1 = -I_2 = \frac{1.0\angle0}{j(.44268+.37526)} = 1.22258\angle-90;\ I_0 = 0$

From Bus 2: $I_1 = \left(\frac{.7}{.7+1.20422}\right)(1.22258\angle-90) = .44943\angle-90$

$I_2 = \left(\frac{.6}{.6+1.00258}\right)(1.22258\angle90) = .45773\angle90$

From Line 2: $I_1 = \left(\frac{.12602}{.12602+.25205}\right).44943\angle-90 = .14981\angle-90$

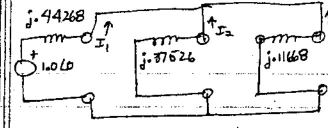
$I_2 = \left(\frac{.12602}{.12602+.25205}\right)(.45773\angle90) = .15257\angle90$ 2

A) $I_{a,b,c} = [A]\begin{bmatrix}0\\ .14981\angle90\\ .15257\angle90\end{bmatrix} = \begin{matrix}.00276\angle90\\ .26187\angle-179.70\\ .26187\angle-.30\end{matrix}$

B) $I_{a,b,c} = [A]\begin{bmatrix}0\\ .44943\angle-120\\ .45773\angle120\end{bmatrix} = \begin{matrix}.45364\angle179.09\\ .45364\angle-179.09\\ .90716\angle0\end{matrix}$

4

5.



$I_1 = \frac{1.0\angle0}{j(.44268+(.37526\|.11668))} = 1.8081\angle-90$

$I_2 = 1.8081\angle90\left(\frac{.11668}{.11668+.37526}\right) = .44601\angle90;\ I_0 = -(I_1+I_2) = 1.43471\angle90$

$I_{a,b,c} = [A]\begin{bmatrix}1.43471\angle90\\ 1.88081\angle-90\\ .44610\angle90\end{bmatrix} = \begin{matrix}0\\ 2.94826\angle133.118\\ 2.94826\angle46.882\end{matrix}$

6.

$I_{F(0)} = I_{F(1)} = I_{F(2)} = \frac{1.0\angle0}{j(.22847+.17123+.19655+3(.06792))} = 1.25\angle-90$

A) $I_{A,B,C} = [A]\begin{bmatrix}1.25\angle-90\\ 1.25\angle-90\\ 1.25\angle-90\end{bmatrix} = \begin{bmatrix}3.75\angle-90\\ 0\\ 0\end{bmatrix}$

B) $V_{5(0)} = 0;\ V_{5(1)} = 1.0-(1.25\angle-90)(.08425\angle90) = .89469;\ V_{5(2)} = (1.25\angle90)(.11034\angle90) = -.13793$

$I_{g(0)} = 0,\ I_{g(1)} = \frac{1-.89469}{.15\angle90} = .70208\angle-90;\ I_{g(2)} = \frac{0-(-.13793)}{j.2} = .68963\angle-90$

$I_{a,b,c\ g2} = [A]\begin{bmatrix}0\\ .70208\angle-120\\ .68963\angle-60\end{bmatrix} = \begin{bmatrix}1.2053\angle-90.296\\ 1.2053\angle90.296\\ .01245\angle0\end{bmatrix}$

C) $I_{1-3(0)} = \frac{V_{1(0)}-V_{3(0)}}{Z_{line(0)}} = \frac{1.25\angle-90(.22847\angle90-.06597\angle90)}{.45\angle90} = .45139\angle-90$

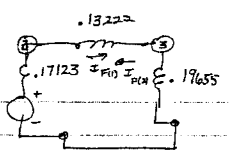
$I_{1-3(1)} = \frac{V_{1(1)}-V_{3(1)}}{Z_{line(1)}} = \frac{(.17123\angle90-.10959\angle90)(1.25\angle-90)}{.15\angle90} = .51367\angle-90$

$I_{1-3(2)} = \frac{V_{1(2)}-V_{3(2)}}{Z_{line(2)}} = \frac{(.19655\angle90-.13448\angle90)1.25\angle-90}{.15\angle90} = .51725\angle-90$

$I_{a,b,c} = [A]\begin{bmatrix}.45139\angle-90\\ .51367\angle-90\\ .51725\angle-90\end{bmatrix} = \begin{bmatrix}1.48231\angle-90\\ .06414\angle87.2296\\ .06414\angle92.7704\end{bmatrix}$

5

7)



$I_{F(1)} = -I_{F(2)} = \frac{1.0}{j(.17123+.13222+.19655)} = 2\angle-90°$

$I_{a,b,c\ Fault} = [A]\begin{bmatrix}0\\ 2\angle-90\\ 2\angle90\end{bmatrix} = \begin{bmatrix}0\\ 3.4641\angle180\\ 3.4641\angle0\end{bmatrix}$

$I_{g2(1)} = \frac{+.08425\angle90(2\angle-90)}{.15\angle90} = 1.12333\angle-90$

$I_{g2(2)} = \frac{(+.11034\angle90)(2\angle90)}{.20\angle90} = 1.10340\angle90$

$I_{A,B,C} = [A]\begin{bmatrix}0\\ 1.12333\angle-120\\ 1.10340\angle+120\end{bmatrix}$

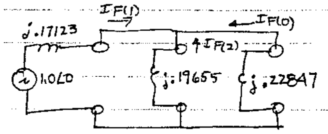
$I_{A,B,C} = \begin{bmatrix}1.1135\angle-179.1\\ 1.1135\angle+179.1\\ 2.22673\angle0\end{bmatrix}$

$I_{1-3(1)} = \frac{2\angle-90(.17123\angle90-.10959\angle90)}{.15\angle90} = .82187\angle-90$

$I_{1-3(2)} = \frac{2\angle90(.19655\angle90-.13448\angle90)}{.15\angle90} = .82760\angle90$

$I_{A,B,C} = [A]\begin{bmatrix}0\\ .82187\angle-90\\ .82760\angle+90\end{bmatrix} = \begin{matrix}.00573\angle90\\ 1.42849\angle-179.895\\ 1.42849\angle-.115\end{matrix}$

8)



$I_{F(1)} = \frac{1.0\angle0}{j\left[.17123+\frac{(.19655)(.22847)}{.19655+.22847}\right]}$

$I_{F(1)} = 3.61160\angle-90$

$I_{F(2)} = -I_{F(1)}\left(\frac{.22847}{.22847+.19655}\right) = 1.94142\angle90$

$I_{F(0)} = -(I_{F(1)}+I_{F(2)}) = 1.67018\angle90°$

$I_{a,b,c\ fault} = [A]\begin{bmatrix}1.67018\angle90\\ 3.61160\angle-90\\ 1.94142\angle90\end{bmatrix} = \begin{bmatrix}0\\ 5.42249\angle152.48\\ 5.42249\angle27.52\end{bmatrix}$