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F-10 HOUSE PHASE SHIFT TRANSFORMER SHORT CIRCUIT TESTS

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Technical Note

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Abstract

This report documents the theory, testing, and modeling of the phase shift transformer internal 60Hz impedances. The internal impedances are used to help predict the commutation angle and ripple characteristics of rectifier loads and to determine available short circuit currents. The results of these tests were used on a per unit basis in the design of the AGS Booster main magnet power supply.

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1.0 INTRODUCTION

1.1 Purpose

The purpose of this test was to develop a one-line phase shifter transformer model for the AGS Booster main magnet power supply. This model will help determine commutation angles for various Booster loads. Specifically it was the per unit reactances based on the circuit kVA that were required. The per unit reactances were obtained by performing short circuit tests on the H20PBLW P.S. +/-7.5 degree phase shifter in the F-10 House. These per unit values were used as rough estimates or as "bench marks" for initial studies of the AGS Booster 13.8kV phase shift transformers.

1.2 Transformer Rating

The transformer connection diagram is shown in Fig. 1 with rated currents and voltages. Its circuit ratings are:

460V, 400kVA (2 X 200kVA) 3-phase 60Hz
+/- 7.5 degree phase shift

The transformer has one 3-phase input (A,B,C) and two 3-phase outputs (D,G,I) and (E,F,H). Each input phase is connected with two shift windings (+7.5 and -7.5 degree). The delta current is determined by the difference of MMF's in these two shift windings. This means that the delta current can vary as the relative power factors of the two output circuits change even though the circuit kVA loading remains constant. The transformer's rating is given as its circuit rating, i.e., what the transformer can actually delever from its terminals at the rated temperature rises (400kVA). This is in contrast to its "magnetic kVA" rating or "parts kVA" as referred to by some authors and is given by [1]:

$$S = (1/2) \sum_{1}^{n} S_i$$

where

S = magnetic kVA of transformer
S_i = volt-ampere rating of each winding
n = number of windings

The magnetic kVA is the volt-amperes that are transformed through actual magnetic coupling rather than by direct electrical conduction. Both of these processes occur in autotransformers. The physical size and weight of the transformer is dependent on its magnetic kVA, not its circuit kVA rating even though by convention it is the circuit kVA rating that appears on the nameplate. For this reason autotransformers are generally smaller and lighter than conventional 2-winding transformers of the same circuit kVA rating. In the case of the phase shifter only a small portion of the circuit kVA is transformed magnetically. Refering to Fig. 1 the magnetic kVA is:

$$S = 3(1/2)[(70)(249)+(460)(4.95)]$$

$$S = 29.56\text{kVA magnetic}$$

$$= 7.4\% \text{ of rated circuit kVA } (400)$$

With one 3-phase output open circuited the magnetic kVA is calculated from Fig. 2 as:

$$S = 3(1/2)[(460)(18.9)+(35)(249)]$$

$$= 26.1 \text{ kVA magnetic}$$

$$= 13\% \text{ of circuit kVA rating } (200)$$

2.0 ONE-LINE CIRCUIT MODEL

2.1 Three Winding Representation

The phase shift transformer is classified as a 3-winding transformer because it has three independent sets of 3-phase terminals (ABC), (DGH), and (EFI). The one line circuit representation is shown in Fig. 3 [2],[3]. The per unit reactances of each pair of windings is shown as a function of the reactances xp and xs in the circuit. Winding resistances and magnetizing reactances are neglected. This representation is a special case where the reactance between the primary and each of the secondaries is equal. This was intended in the design of the phase shifter and the short circuit tests showed that the two secondary impedances were different by 5.5%.

2.2 Commutation Effects in Rectifiers

The one-line model in Fig. 3 helps determine the SCR commutation angle because it gives the reactance contribution of the phase shifter. The model also indicates that the reactance xp will appear as 2xp to each rectifier on either secondary if both rectifiers are commutating at the same time. The reactances xs are not scaled as long as they drive only one rectifier circuit each. In complex rectifier circuits the pulse number and the commutation angle determine when and how much more xp is to be weighted than xs with respect to each rectifier. Because these two reactances are not weighted equally the sum xp+xs and the ratio xp/xs are required to determine the commutation angles in phase-shifted rectifier circuits. These reactances are found through short circuit tests.

3.0 SHORT CIRCUIT TESTS

3.1 Procedure

The most direct method used to measure impedance per phase of a transformer is to connect a short circuit to the secondary and to drive the primary with a voltage source. Usually the current is increased to its rated value at which point the resulting voltage is defined as the impedance voltage. For the unit under test the rated current with one secondary shorted is 251A. If the impedance is roughly 2% then the voltage required is (.02)(460) = 9.2V. This ratio of voltage to current is very awkward in terms of fine voltage control in available electrical equipment. An alternative procedure is to measure the impedance of one phase winding based on the magnetic kVA (or winding kVA) rather than on the circuit kVA rating. Since the magnetic kVA is much smaller than the circuit kVA of the transformer the effective ohmic impedance of the primary and secondary windings is much higher as compared to a standard 3-phase short circuit on one or both outputs. The connection for measuring impedance based on magnetic kVA is shown in Fig. 4. A 120V, 10A variac single phase source is sufficient to drive short circuit current through this connection.

The advantage of this method is that the current requirment for the source is smaller by a factor of 6.5 or 13 for the same winding short circuit current depending on whether one secondary or both secondaries are shorted. The kVA requirment is also reduced because the test is single phase. Voltage and current control is improved because of the increased ohmic impedance.

The disadvantage of this method is that the ohmic impedances measured are not the values that represent the phase shifter in a one-line diagram as shown in Fig. 3. However, the required values can be obtained from the test values by mathematical transformations as shown in Section 3.3.

In summary, this procedure measures the impedances of the individual pairs of transformer windings and then the characterictics of the phase shifter as a single unit are calculated based on circuit analysis and mathematical transformations. The approach is based on the premise that the impedance characteristics of any transformer connection regardless of complexity can be determined entirely if all the individual pairs of winding impedances are known.

3.2 Test Results

3.2.1 Test Measurements

Short circuit test measurements are shown in Fig. 5. The voltages and currents refer to the circuit diagram in

Fig. 4. The three phases are assumed to be identical so that only one phase is tested. Three short circuit tests were run: primary to secondary 1, primary to secondary 2, and primary to secondaries 1 and 2. The primary is defined as the delta AB winding. The two secondaries are the two shift windings DC and EC. Note in Fig. 4 that the current in delta windings BC and CA is zero for all three short circuit tests. Several voltage and current levels were used for each short circuit connection to confirm the linearity of the circuit.

3.2.2 Single Phase Equivalent Circuit

The windings that were energized for the test measurements as shown in Fig. 4 (AB, DC, and EC) constitute a single phase 3-winding transformer. The purpose of this section is to determine the impedances of the equivalent circuit for the transformer as shown in Fig. 6. In order to simplify the calculations the winding resistances are neglected, however, the procedure is unchanged if the resistances are included. In the latter case the winding impedances would become complex numbers but the form of all equations and matrix transformations would remain unchanged. The impedances are treated as being equal to the reactances in the following calculations although it is known that this is not true.

As seen from terminals AB in Fig. 4 the impedance of the transformer with winding CE shorted was

$$x = j(15.13/10)$$

$$x = j1.51 \text{ ohm}$$

With windings CE and DC shorted the impedance was

$$x = j(4.57/10)$$

$$x = j.457 \text{ ohm}$$

From circuit analysis the transformation equations are:

$$xp + xs = j1.51 \text{ ohm}$$

$$xp + (1/2)xs = j.457 \text{ ohm}$$

The solution is:

$$xp = -j.6 \text{ ohm}$$

$$xs = j2.11 \text{ ohm}$$

These reactances are referred to winding AB. It is noted that the impedance values in 3-winding transformers are allowed to be zero or negative as long as the net impedance between any pair of windings is positive [4].

The turns ratio between AB and CD was measured as 12.8 and calculated as 13.156 for a 7.50 degree phase shift. A value of 13.000 is used as the turns ratio throughout this analysis.

The impedance of winding CD and EC referred to 35V is

xs = j(1/13)**2(2.11)

xs = j.0125 ohm

3.3 Short Circuit Calculations

The purpose of this section is to compute the symmetrical rms 3-phase fault currents supplied from the lines when a 3-phase fault occurs at rated voltage. Three cases are computed: primary to secondary, primary to both secondaries, and secondary to secondary. In the last case the primary is open circuited and the source is connected to one of the secondaries with the remaining secondary shorted. These current magnitudes yield the impedances for the phase shifter one line diagram shown in Fig. 3. The 3-phase currents are calculated by using circuit analysis and the single phase equivalent circuit developed in Section 3.2.2.

3.3.1 Primary to Secondary

The 3-phase output on one secondary is shorted and a 3-phase 480V source is connected to the primary terminals. Since a 3-phase fault is a symmetrical fault the conditions in all three phases of the transformer are identical and displaced by 120 degrees from each other. By the same principle the voltage at the fault bus must be zero and coincident with the system neutral on a phasor diagram. Because of the balanced 3-phase condition the fault bus voltage must be zero regardless of whether this bus is grounded or whether the system is grounded or ungrounded.

The voltage on windings AB, CD, and EC therefore appear as in Fig. 7. The 3-phase short circuit is actually on terminals (DGI) in Fig. 1. The conditions on each phase are shown in Fig. 7. Since terminals D, G, and I are all at zero potential the terminal D in Fig. 7 is labeled (0). The supply voltages are VA/120 degrees, VB/240 degrees, and VC/0 degrees in sequence A-C-B. Terminal C is therefore at 277/0 volts/degrees with respect to the system neutral. Terminals A and B are at 277/120 and 277/240 volts/degrees with respect to the neutral. The voltage between A and B is therefore:

$$VAB = 277\underline{/120^\circ} - 277\underline{/240^\circ} \ \ V$$

$$VAB = 480\underline{/90^\circ}\ V$$

These voltages are shown in Fig. 7. Since winding CE is not involved the problem is a conventional 2-winding transformer circuit and is reduced as shown in Fig. 7. The current in winding CD is:

$$ICD = (277\underline{/0^\circ} + 37\underline{/90^\circ})/(j.0125 - j.00355)$$

$$ICD = 31.28\underline{/-82.4^\circ}\ \text{kA}$$

By the turns ratio law the current in the delta winding must be:

$$IAB = (1/13)*ICD$$

$$IAB = 2393\underline{/-82.4^\circ}\ \text{A}$$

The line current is determined by the KCL at node C in Fig. 8 as:

$$IL = 31.56\underline{/-90^\circ}\ \text{kA}$$

Therefore the 3-phase 480V fault current supplied from the lines when one secondary is shorted is 31.6kA sym rms.

3.3.2 Primary to Both Secondaries

In this section the line currents are calculated for (2) 3-phase short circuits on (DGI) and (EFH) as shown in Fig. 10. The single phase model developed from test results in Section 3.2 is shown in Fig. 9 with voltage conditions during a double 3-phase fault. Nodes D and E are coincident with the system neutral on a phasor diagram since they are both on a short circuit bus. The voltage accross AB is 480V and is 90 degrees out of phase with the phase C to neutral voltage as illustrated in Section 3.3.1. The equivalent circuit manipulations shown in Fig. 9 give rise to the following system of equations:

$$\begin{Bmatrix} 1 & -1 & -1 \\ j.00355 & -j.0125 & 0 \\ j.00355 & 0 & -j.0125 \end{Bmatrix} \begin{Bmatrix} I1 \\ I2 \\ I3 \end{Bmatrix} = \begin{Bmatrix} 0 \\ 280\underline{/-172.4^\circ} \\ 280\underline{/-7.6^\circ} \end{Bmatrix}$$

The solution is:

$$I1 = 13703.7\angle 0^\circ \text{ A}$$

$$I2 = 23195\angle -72.8^\circ \text{ A}$$

$$I3 = 23195\angle 72.8^\circ \text{ A}$$

Referred to winding AB the delta current is:

$$I1 = (1/13)(13703.7)$$

$$I1 = 1054 \text{ A}$$

The KCL equation at node C in Fig. 10 gives the total short circuit line current as:

$$IL = 46.14\angle -90^\circ \text{ kA sym rms}$$

Therefore the 3-phase 480V fault current supplied from the lines when both secondaries are shorted is 46.1kA sym rms.

3.3.3 Secondary to Secondary

The primary is open circuited and the fault current is driven from the source on one secondary to a 3-phase short circuit on the other secondary. The 3-phase circuit is shown in Fig. 12 with the single phase development and basis for calculation shown in Fig. 11. This situation is unlike the previous cases in Sections 3.3.1 and 3.3.2 in that the voltage at node C is unknown. This nessecitates a fourth equation to solve for the four unknowns VC, I1, I2, and I3.

The first two equations can be formed from the turns ratio law for currents. Referring to Fig. 11:

$$V_p = \sqrt{3}\, V_c e^{j\pi/2} + j.6\, I_1$$

$$V_{s1} = j.0125\, I_2 + (-V_c)$$

$$V_{s2} = j.0125\, I_3 + (V_c - 277)$$

$$V_{s1} = \left(\frac{1}{13}\right) V_p \qquad V_{s2} = \left(\frac{1}{13}\right) V_p$$

$$\therefore\ \frac{\sqrt{3}}{13} V_c e^{j\pi/2} + j\,\frac{.6}{13}\, I_1 - j.0125\, I_2 - (-V_c) = 0$$

This equation can be written as:

$$(1 + j.1332)V_c + j.04615 I_1 - j.0125 I_2 = 0$$

The other loop equation is:

$$\frac{\sqrt{3}}{13} V_c e^{j\pi/2} + j\frac{.6}{13} I_1 - j.0125 I_3 - (V_c - 277) = 0$$

This second equation is written as:

$$(-1 + j.1332)V_c + j.04615 I_1 - j.0125 I_3 = -277$$

The KCL at node C is:

$$I_1 e^{j2\pi/3} - I_1 e^{j4\pi/3} - (I_2 - I_3) = 0$$

$$\sqrt{3} I_1 e^{j\pi/2} - I_2 + I_3 = 0$$

The fourth equation is given by the law of balanced transformer MMFs that demands that the sum of all the winding MMFs on each core leg be zero:

$$13 I_1 - I_2 - I_3 = 0$$

In matrix format these equations become:

$$\left\{ \begin{matrix} 1+j.1332 & j.04615 & -j.0125 & 0 \\ -1+j.1332 & j.04615 & 0 & -j.0125 \\ 0 & 13 & -1 & -1 \\ 0 & j1.732 & -1 & 1 \end{matrix} \right\} \left\{ \begin{matrix} VC \\ I1 \\ I2 \\ I3 \end{matrix} \right\} = \left\{ \begin{matrix} 0 \\ -277 \\ 0 \\ 0 \end{matrix} \right\}$$

The solution was obtained by calling the fortran IMSL routine LINCG on the Vax computer:

$$\left\{ \begin{matrix} VC \\ I1 \\ I2 \\ I3 \end{matrix} \right\} = \left\{ \begin{matrix} 133 + j41 \\ 505 - j3790 \\ 6564 - j24200 \\ 0 \quad -j25073 \end{matrix} \right\} \begin{matrix} V \\ A \\ A \\ A \end{matrix}$$

The fault current is therefore 25.1kA symmetrical rms. The fact that I3 has zero as a real component is significant. The transformer model was assumed to be purely inductive. This means that regardless of the complexity of the connections, phase shifting, or any other aspect of circuit topology the final fault current must be 90 degrees out of phase with the supply voltage at node D. If the computer had returned any result where I3 had a nonzero real component outside of computer accuracy this would be indicative of an error in the matrix equations. This principle also applies to the two previous cases in Sections 3.3.1 and 3.3.2.

The final solution for the winding currents is shown in Fig. 12.

4.0 FINAL ONE LINE EQUIVALENT CIRCUIT

4.1 Mathematical Tests

The results of the 3-phase short circuit calculations at 480V gave the following results from Section 3.3.

Short Circuit Calculation Results

	Line current from source (sym rms A)	Delta current (sym rms A)
Primary to secondary	31560	2393
Primary to both secondaries	46145	1056
Secondary to secondary	25073	3823

Table 1: Short Circuit Magnitudes on the 400kVA, 460V, 3-phase +/-7.5 degree phase shifter from 480V source.

The transformer one line model in Fig. 3 is shown with the two secondary reactances equal. This means there are only two unknowns (xp and xs) and only two of the three short circuit results from Table 1 are required. The third test serves as a mathematical check since it should be in accordance with the one line model developed from the first two short circuit tests.

The solution for xp and xs based on the short circuit results from Table 1 are shown in Fig. 13. A mathematical test for this model is described as follows. The model in Fig. 13 predicts that the secondary to secondary short circuit current will be:

IL = 277/(2*.00554*(1.00863)**2)

IL = 24574 A sym rms

The value calculated in Section 3.3.3 based on the single phase model was

IL = 25073 A sym rms

This represents an error of:

$$\text{error} = (25073 - 24574)/25073 * 100$$

$$= 2.0\%$$

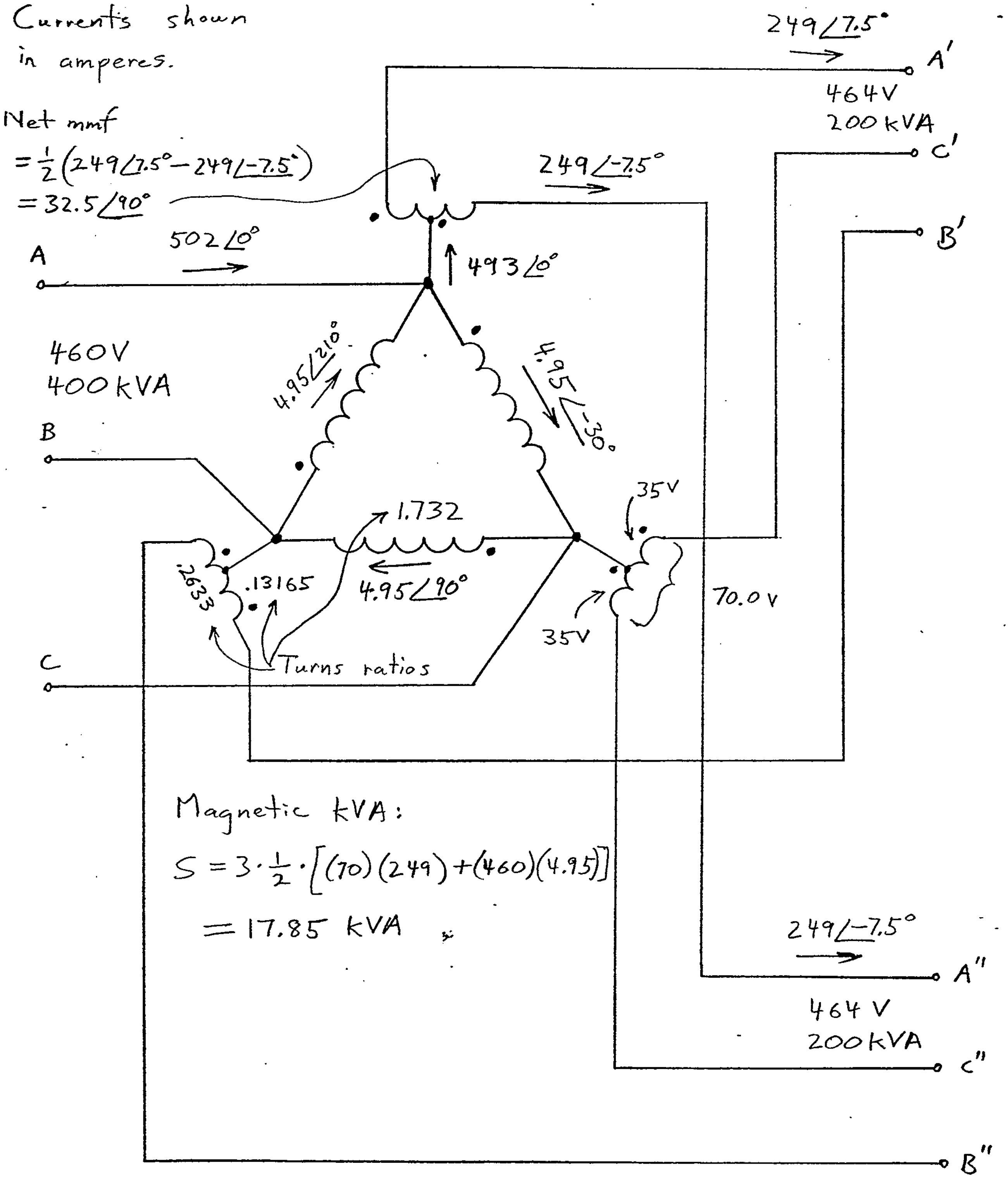
Theoretically this error should be zero. It is not known why this error exits. If the fault current of 24574A is multiplied by the square of the effective turns ratio in Fig. 13 (1.00863)**2 the error is almost eliminated but it is not clear why this would be a valid procedure. There seems to be no basis for introducing the turns ratio in this manner.

4.2 Conclusions

A test procedure has been presented that describes how the phase shift transformer impedances can be measured using short circuit currents that are smaller by an order of magnitude as compared to the transformer rated current. This procedure requires only a single phase source that operates at roughly one half of the kVA that is required by a standard three phase short circuit test. The final model of the phase shifting transformer can be used to predict the available short circuit current at full voltage and the relative effect on the commutation angle for phase shifted rectifier loads.

The method presented was mathematically checked in the following way. The final transformer model was used to predict the value of secondary-to-secondary short circuit current. The same current was calculated using the procedure shown in Section 3.3.3. The two results were in agreement to within 2.0%. Although a 2.0% accuracy in short circuit current calculations is sufficient for most practical purposes it is not clear why any error should exist at all. If a numerical or procedural error does exist it was missed during extensive mathematical checks.

5.0 FIGURES



Currents shown in amperes.

Net mmf

$$= \frac{1}{2}\left(249\angle 7.5^\circ - 249\angle -7.5^\circ\right)$$

$$= 32.5\angle 90^\circ$$

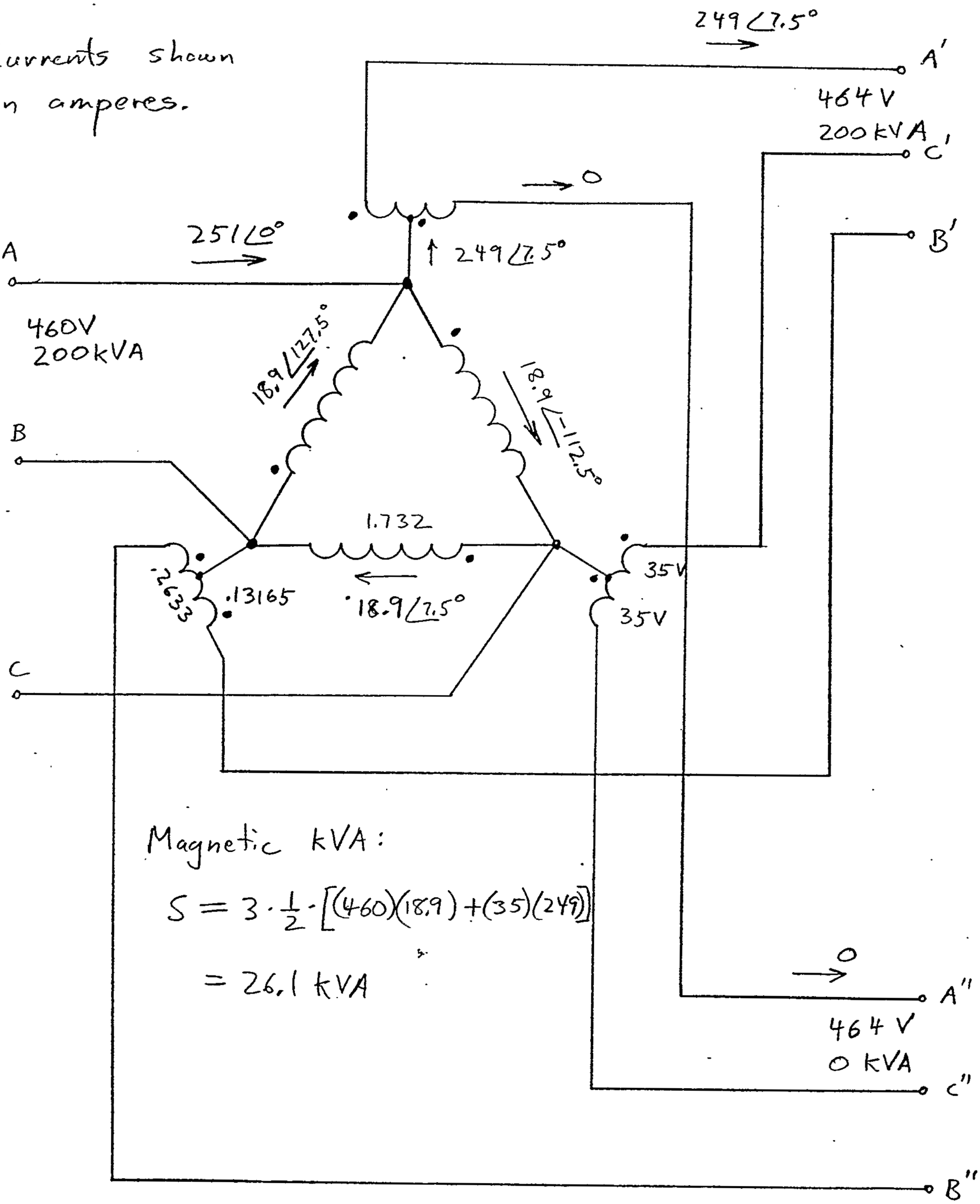
Magnetic kVA:

$$S = 3 \cdot \frac{1}{2} \cdot \left[(70)(249) + (460)(4.95)\right]$$

$$= 17.85 \text{ kVA}$$

Fig. 1 -- Transformer Connection Diagram With Rated Voltages and Currents

Currents shown in amperes.



Magnetic kVA:

$$S = 3 \cdot \frac{1}{2} \cdot \left[(460)(18.9) + (35)(249)\right]$$

$$= 26.1 \text{ kVA}$$

Fig. 2 -- Voltage and Current Solutions With One Output Open-Circuited

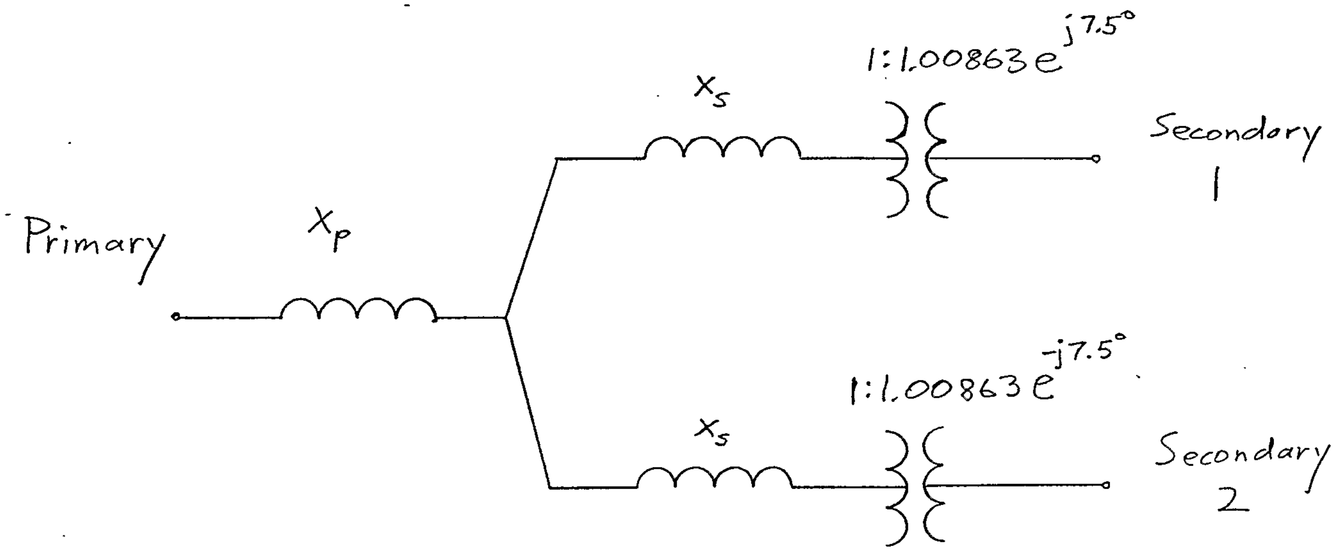
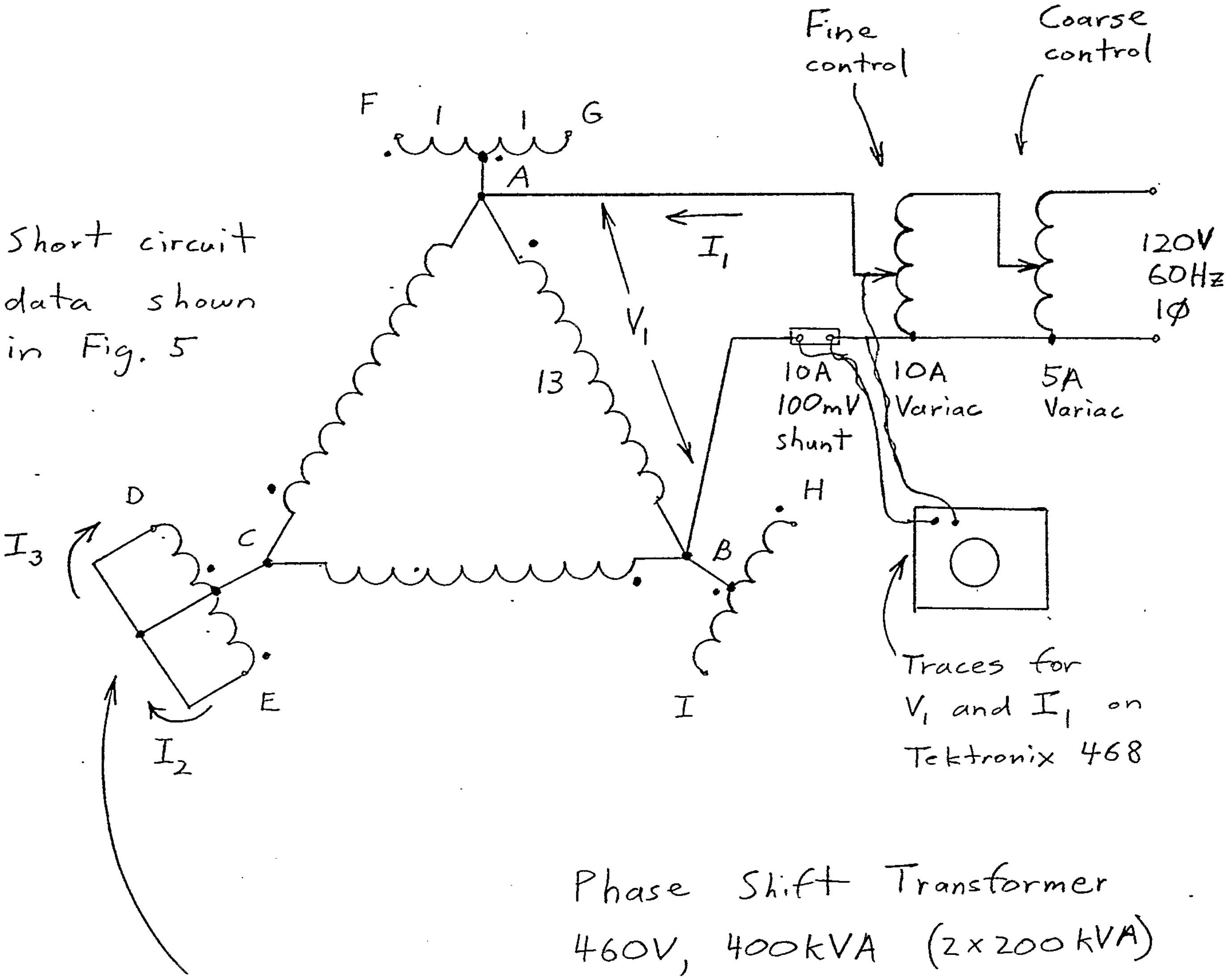


Fig. 3 -- Transformer One Line Equivalent Circuit



Short circuit data shown in Fig. 5

Traces for V_1 and I_1 on Tektronix 468

Phase Shift Transformer
460V, 400kVA (2×200 kVA)
±7.5° phase shift

Secondary coils EC and DC are short circuited in order to measure winding AB–CD/CE impedances.

Fig. 4 -- Connections For Short Circuit Tests

Phase Shift Transformer Test Data
H20 PBLW P.S. F-10 House
460V, 400kVA ±7.5° 3-phase 60Hz

Turns ratio: $V_{AB}/V_{CE} = (30.0/2.33) = 12.88$
(Test circuit shown in Fig. 4)

V_1 Primary volts	I_1 Primary Amps	I_2 Secondary Amps	I_3 Secondary Amps	Δt(ms) time between voltage and current zeros
Windings CD and CE Shorted: (taken 7/1/88)				
2,63	4,0	26	28	2.1
3,00	6.0	37	39	1.9
3,78	8.0	50	52	2.1
4,17	9,0	58	59	2.1
4.57	10.0	64	66	2.1
5,00	11.0	70	70	2.1
Winding CE shorted: (taken 7/1/88)				
6.58	4.0	52	0	2.8
9.36	6.0	79	0	3.0
12,24	8.0	105	0	3.1
13,71	9.0	118	0	3.3
15.13	10.0	133	0	3.3
16,58	11.0	144	0	3.3
Winding CD shorted: (taken 8/18/88)				
6.1	4.0	0	52	2.8
8,6	6.0	0	79	3.1
11.4	8,0	0	105	3.2
12.8	9.0	0	119	3.2
14,3	10,0	0	133	3.3
15,6	11.0	0	146	3.2

Fig. 5 -- Short Circuit Test Measurements

Equivalent circuit of one phase of phase shifting transformer.

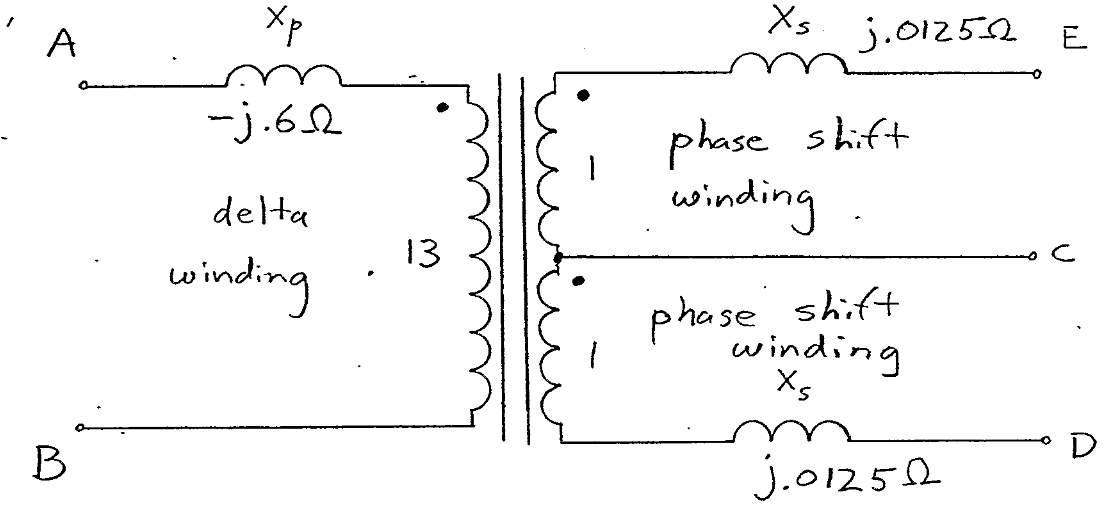
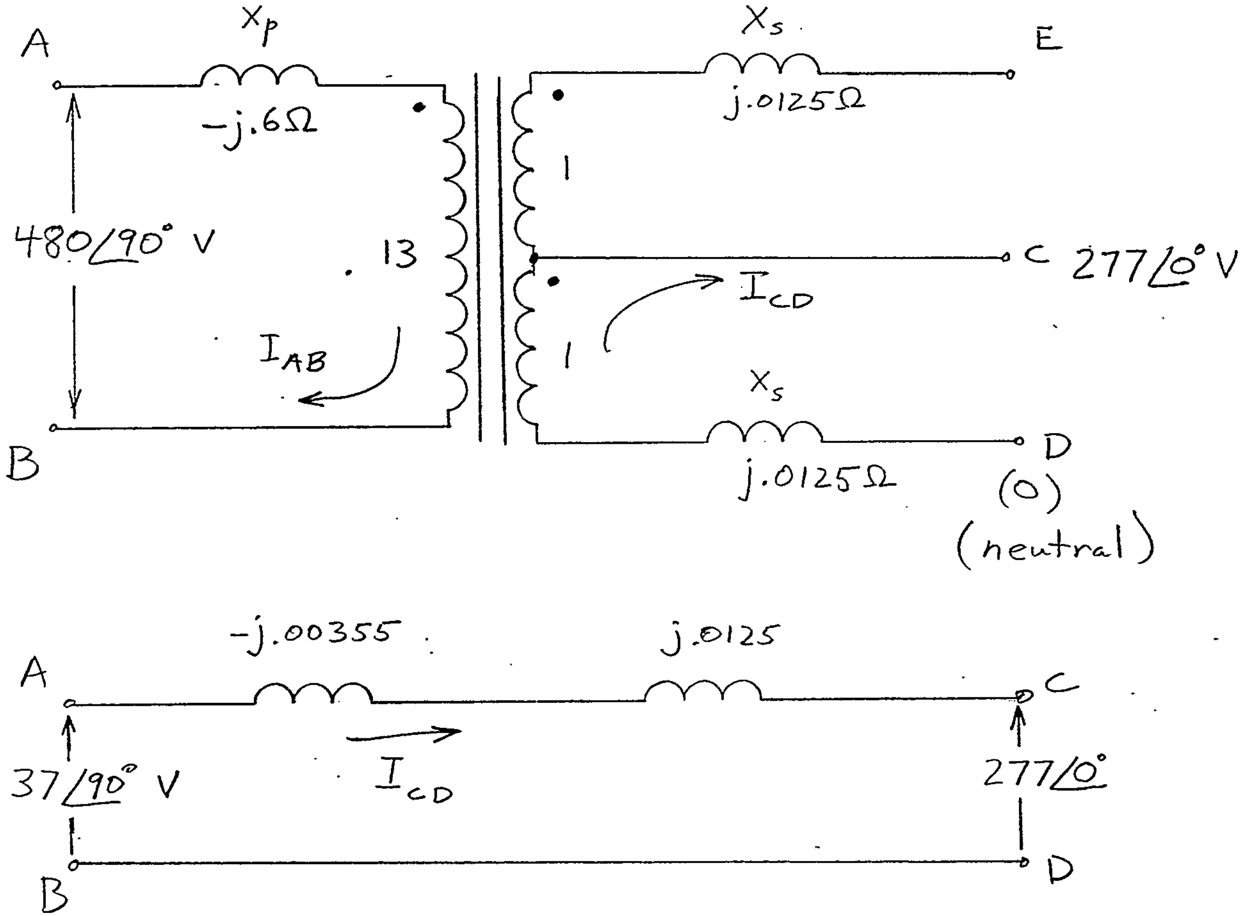


Fig. 6 -- Single Phase 3-Winding Transformer Equivalent Circuit

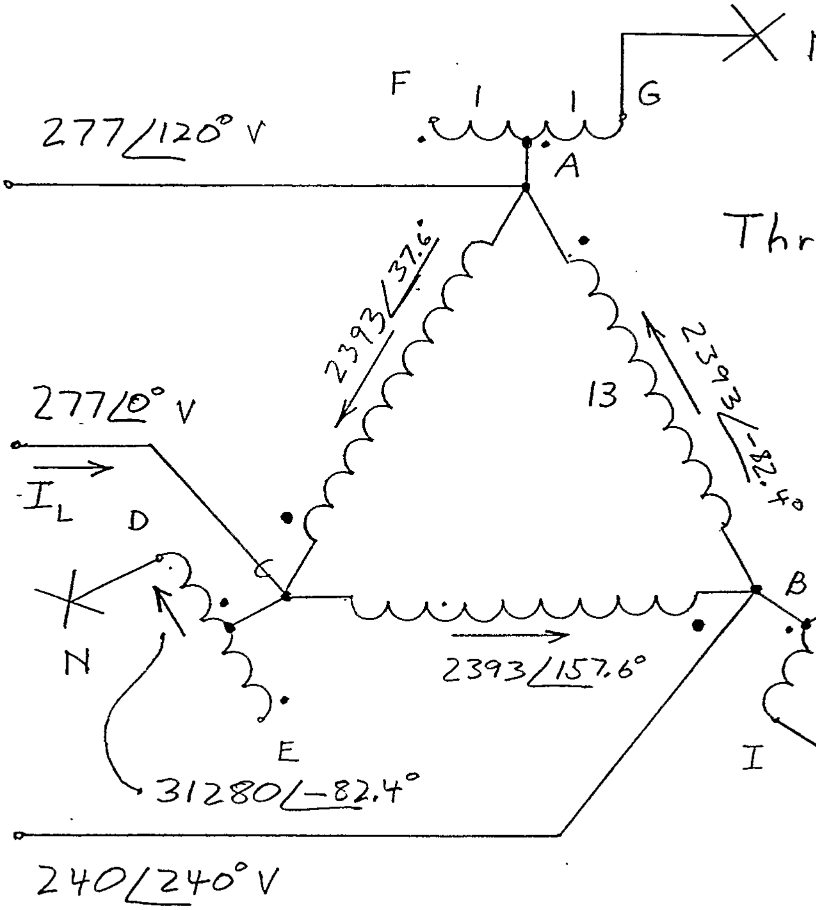
Voltage constraints for primary to secondary fault:



$$I_{CD} = \frac{277\angle 0^\circ + 37\angle 90^\circ}{j.0125 - j.00355} = 31280\angle -82.4^\circ \text{ A}$$

$$I_{AB} = \frac{1}{13} I_{CD} = 2406\angle -82.4^\circ \text{ A}$$

Fig. 7 -- Primary to Secondary Short Circuit Model

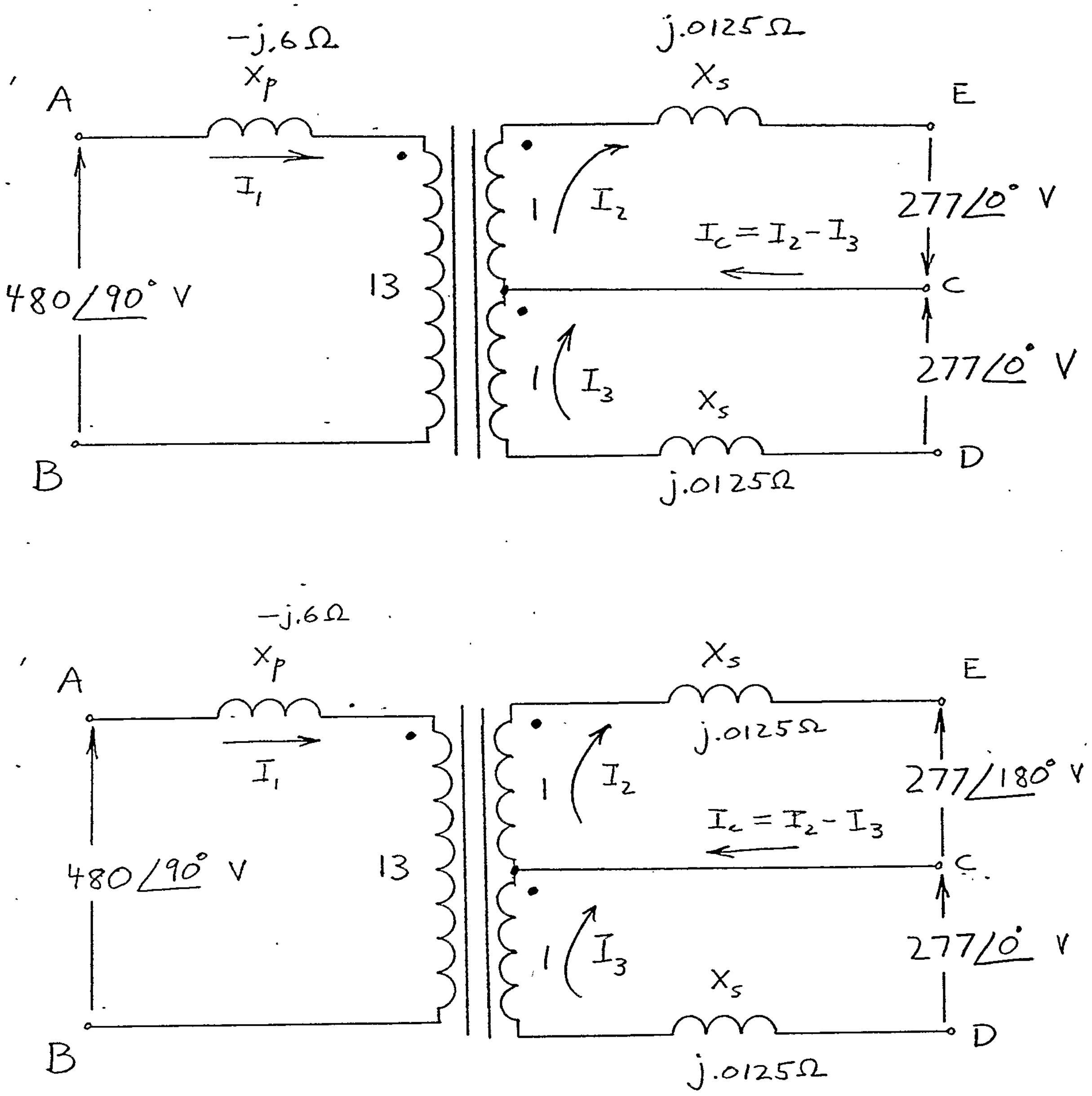


Three Phase Fault on DGI

$$I_L = 31280\angle{-82.4^\circ} - 2406\angle{37.6^\circ} + 2406\angle{157.6^\circ}$$

$$I_L = 31.56\angle{-90^\circ}\ \text{kA} \quad \text{rms} \quad \text{sym}$$

Fig. 8 -- Primary to Secondary 3-Phase Short Circuit Solution



One line referred to secondary:

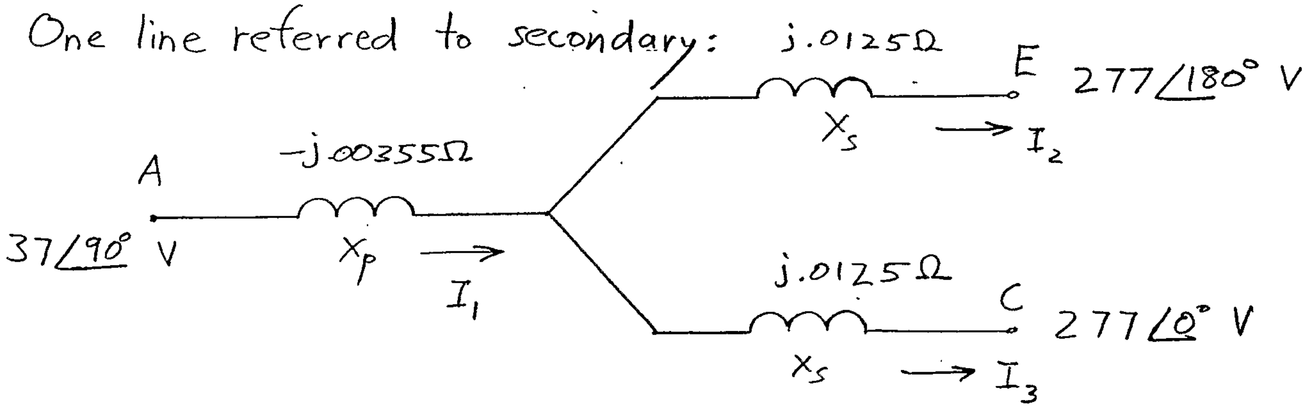
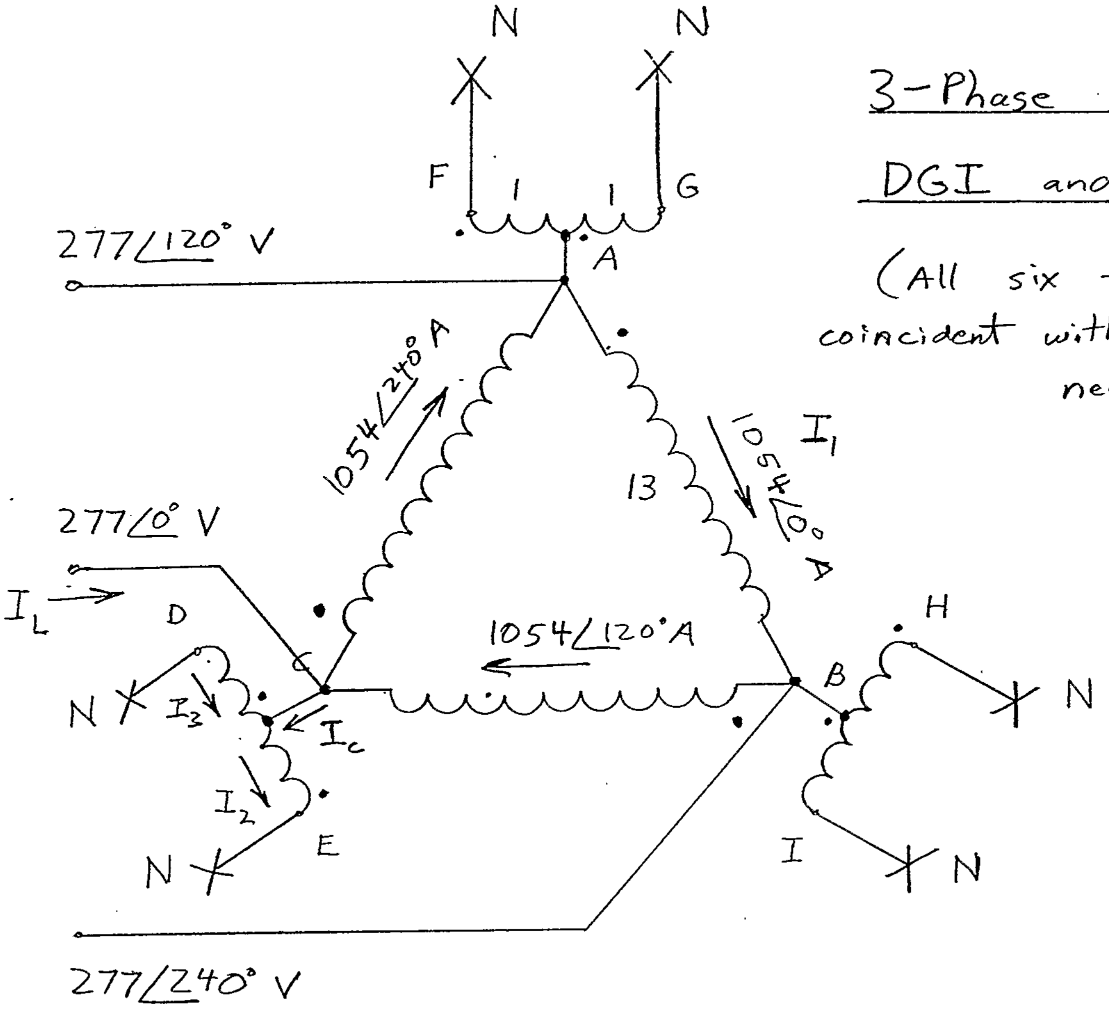


Fig. 9 -- Primary to Both Secondaries Short Circuit Model

3-Phase Faults on DGI and EFH

(All six terminals coincident with system neutral)



$$I_1 = 1054\angle 0^\circ \text{ A}$$

$$I_2 = 23195\angle -72.82^\circ \text{ A}$$

$$I_3 = 23195\angle 72.82^\circ \text{ A}$$

$$I_c = I_2 - I_3 = 44320\angle -90^\circ \text{ A}$$

KCL at node C:

$$I_L = 44320\angle -90^\circ + 1054\angle 240^\circ - 1054\angle 120^\circ \text{ A}$$

$$I_L = 46.14\angle -90^\circ \text{ kA sym rms}$$

Fig. 10 -- Primary to Both Secondaries 3-Phase Short Circuit Solution

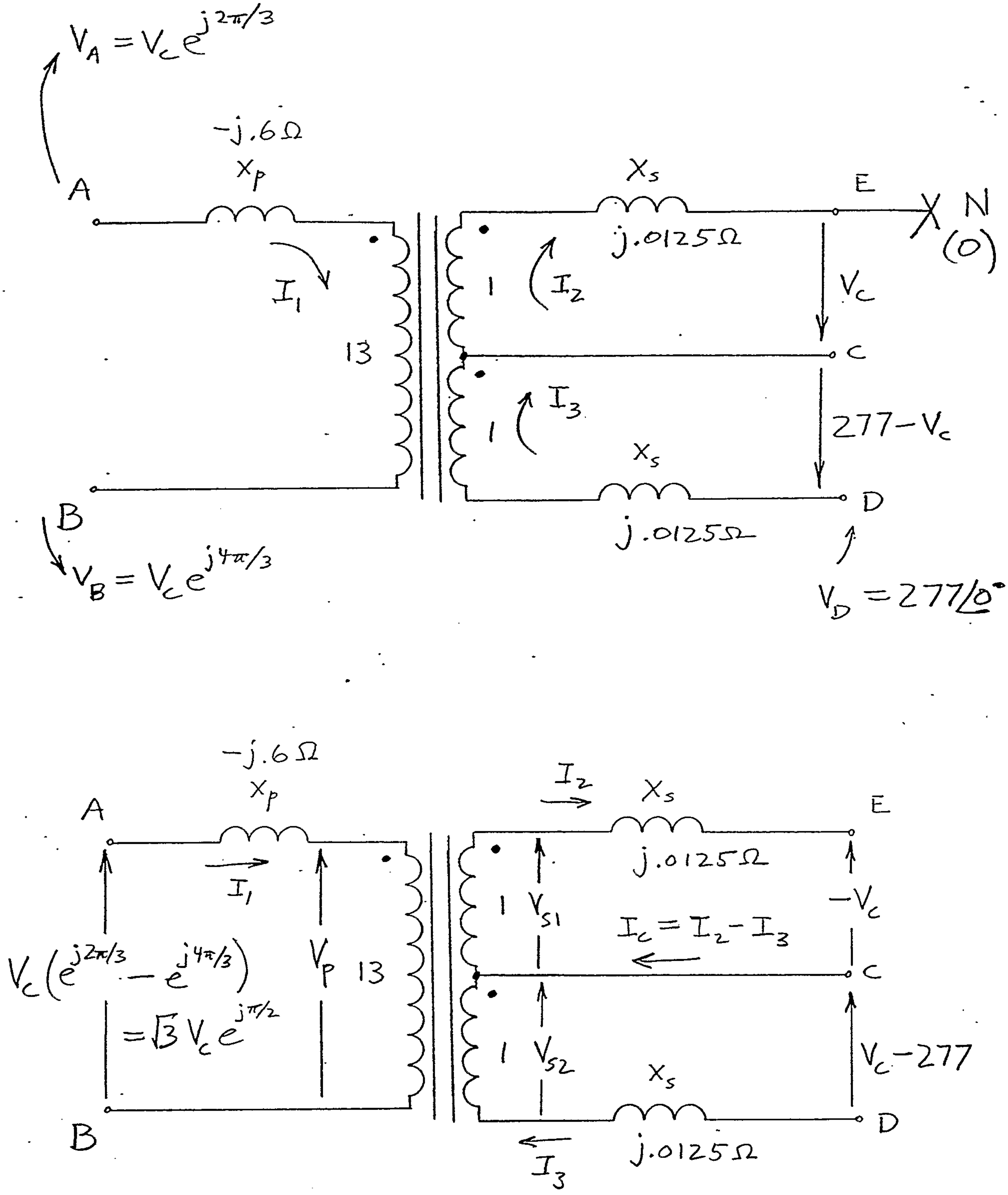
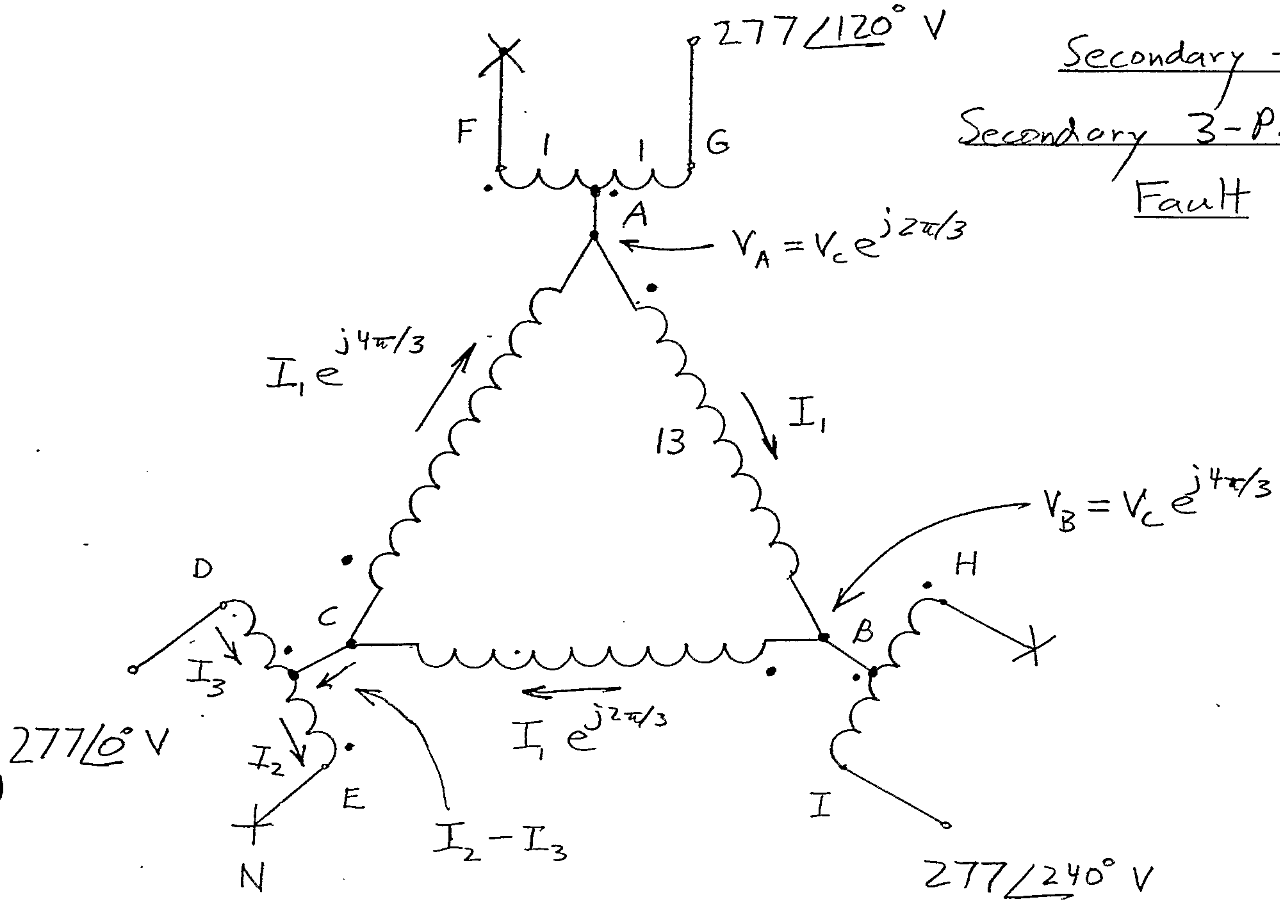


Fig. 11 -- Secondary to Secondary 3-Phase Short Circuit Model

Secondary-to-Secondary 3-Phase Fault



Fault current $I_L = I_3$

$$I_L = 25.1\angle{-90^\circ}\ \text{kA sym rms}$$

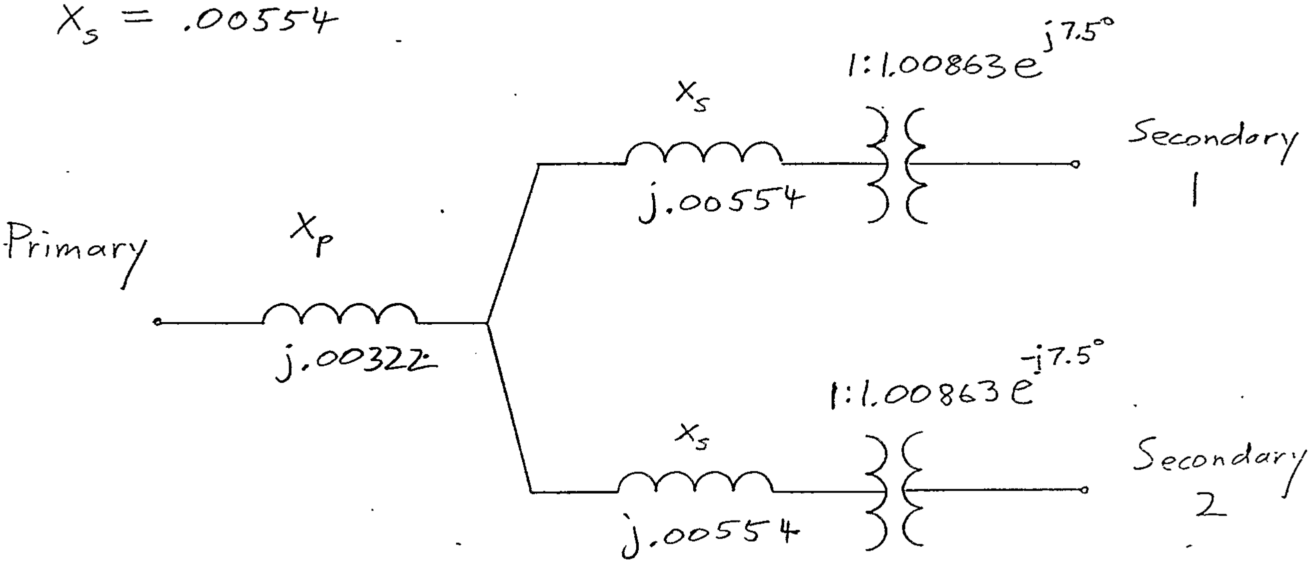
Fig. 12 -- Secondary to Secondary 3-Phase Short Circuit Solution

$$X_p + X_s = \frac{277}{31560} = .008777$$

$$X_p + \frac{1}{2} X_s = \frac{277}{46145} = .006$$

$X_p = .00322$

$X_s = .00554$



One Line Model For 460V, 400kVA ±7.5° Phase Shift Transformer

Fig. 13 -- Final One Line Equivalent Circuit Solution

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