

# Industrial Systems

- Problem Example
- Basic System Overview
- Complex System
- Fine Detail

(c) 2.4 KV system:

$$I = 10,000 / (1.732 * 2.623)$$

$$= 2201 \text{ A}$$

(d) 0.48 KV system:

$$I = 10,000 / (1.732 * 0.525)$$

$$= 11,000 \text{ A}$$

(5) Summarize the base data in table

## SUMMARY

System Base Values  
(Base Power 10 000 kVA)

Bus	Base kV	Base Z	Base I
2	69.00	476.1	83.67
4	14.427	20.82	400.2
8	14.427	20.82	400.2
24	14.427	20.82	400.2
31	14.427	20.82	400.2
32	14.427	20.82	2201.0
36	2.623	0.688	11 000.0
37	0.525	0.027 56	

(6) Convert transformer impedances to per unit using

$$Z_2 = Z_1 * ((\text{base KV}_1)^2 / (\text{base KV}_2)^2) * (\text{base KVA}_2) / (\text{base kVA}_1)$$

(a) T2:

$$Z = ((1.0 + j8.0) / 100) * (66^2 / 69^2) * (10 / 15)$$

$$= 0.00610 + j0.04880$$

(b) T13:

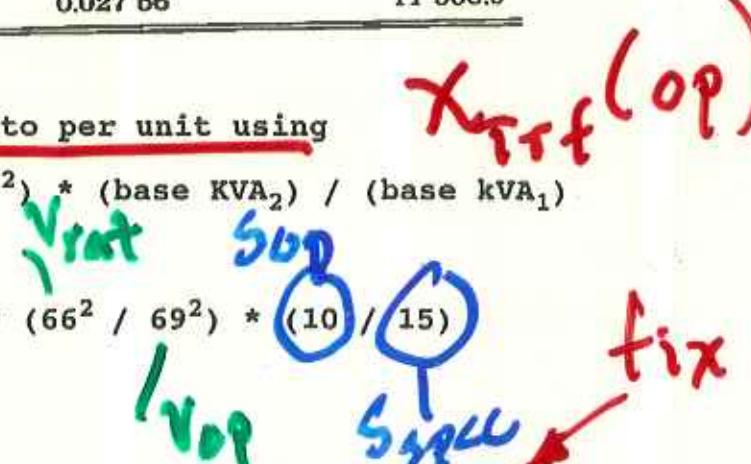
$$Z = ((0.8 + j5.75) / 100) * (2.4^2 / 2.623^2) * (10 / 15)$$

$$= 0.02679 + j0.19255$$

(c) T14:

$$Z = ((0.8 + j5.75) / 100) * (13.2^2 / 14.427^2) * (10 / 1)$$

$$= 0.06697 + j0.48135$$



next page more

# ① Operating Voltages

Each Section: Use  $V_{op}$  &  $\frac{V_o}{V_{IN}}$

$$\text{Bus 4: KV} = 69.0 * \frac{13.8 / 66}{T_2} \quad \text{where } 13.8 / 66 \text{ equals turns ratio of T2}$$

$$= 14.427 \text{ KV}$$

$$\text{Bus 36: KV} = 14.427 * \frac{2.4 / 13.2}{T_3} \quad \text{turns ratio of T13}$$

$$= 2.623 \text{ KV}$$

$$\text{Bus 37: KV} = 14.427 * (0.48 / 13.2) \quad \text{turns ratio of T14}$$

$$= 0.525 \text{ KV}$$

## ② Base impedance each section

$$(3) \text{ Calculate base impedances} = (\text{base KV})^2 / \text{base MVA}$$

$$(a) 69 \text{ KV system:} \\ Z = (69^2 * 10^3) / (10,000)$$

$$= 476.1 \Omega$$

$$(b) 13.8 \text{ KV system:} \\ Z = (14.427^2 * 10^3) / (10,000)$$

$$= 20.82 \Omega$$

$$(c) 2.4 \text{ KV system:} \\ Z = (2.623^2 * 10^3) / (10,000)$$

$$= 0.688 \Omega$$

$$(d) 0.48 \text{ KV system:} \\ Z = (0.525^2 * 10^3) / (10,000)$$

$$= 0.02756 \Omega$$

$$(4) \text{ Calculate base currents} = \text{base KVA} / (\sqrt{3} * \text{base KV})$$

$$(a) 69 \text{ KV system:}$$

$$I = 10,000 / (1.732 * 69.0)$$

$$= 83.67 \text{ A}$$

$$(b) 13.8 \text{ KV system:}$$

$$I = 10,000 / (1.732 * 14.427)$$

$$= 400.2 \text{ A}$$

## ③ Operating Base Currents

$I_B^{op}$

Look at each trf.

Get rated values

1.  $X_{pu}^R$

2.  $V^R$  primary

3.  $S^R$  from V-A values

Calculate operating values

1.  $V^{OP}$  for all buses

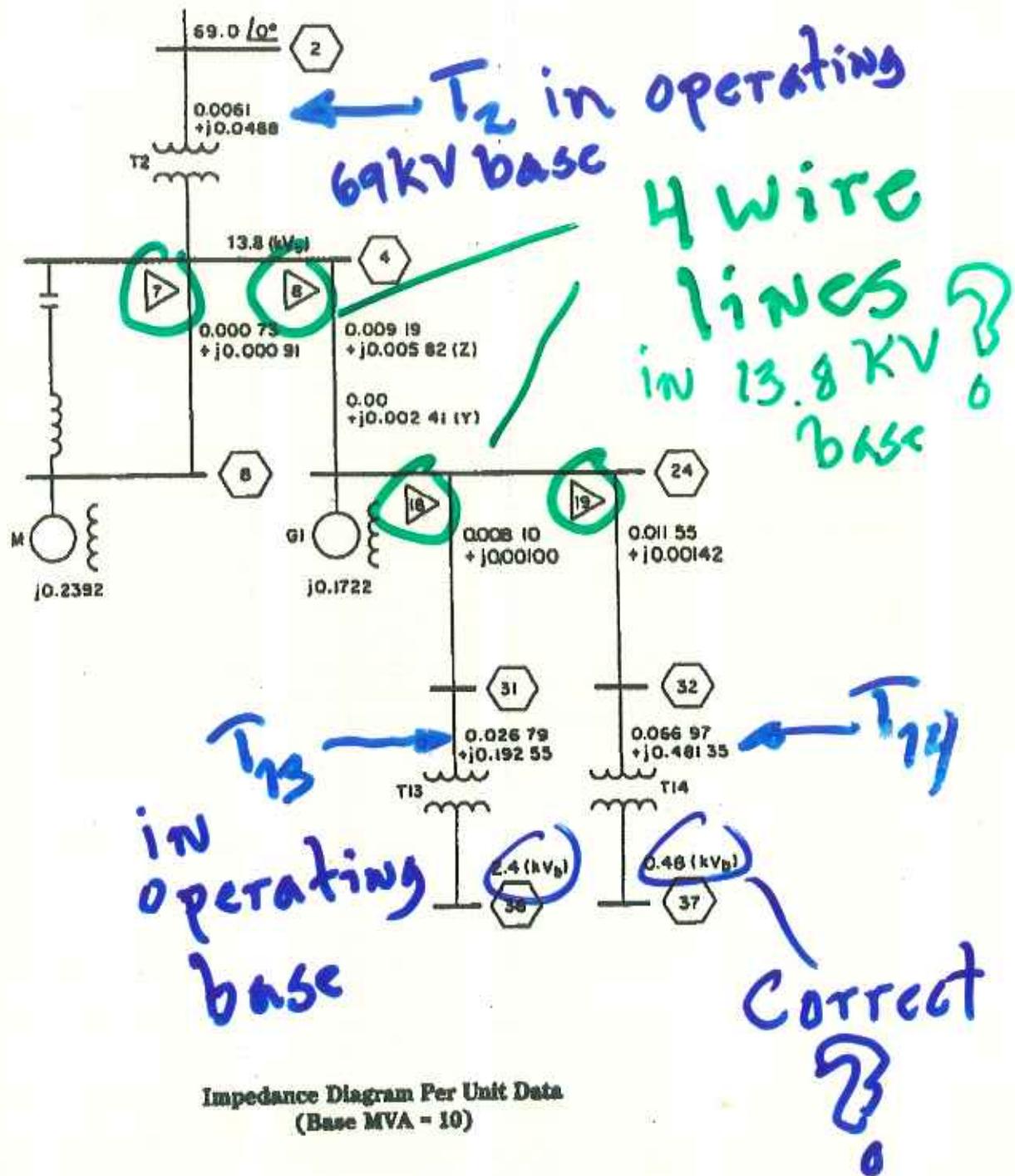
from given  $V^{OP} \approx 69\text{kV}$

2. Given  $S^{OP} \equiv 10\text{MVA}$

Change  $X_{pu}^R \rightarrow X_{pu}^{OP}$

# Per Unit with 1-line diagram

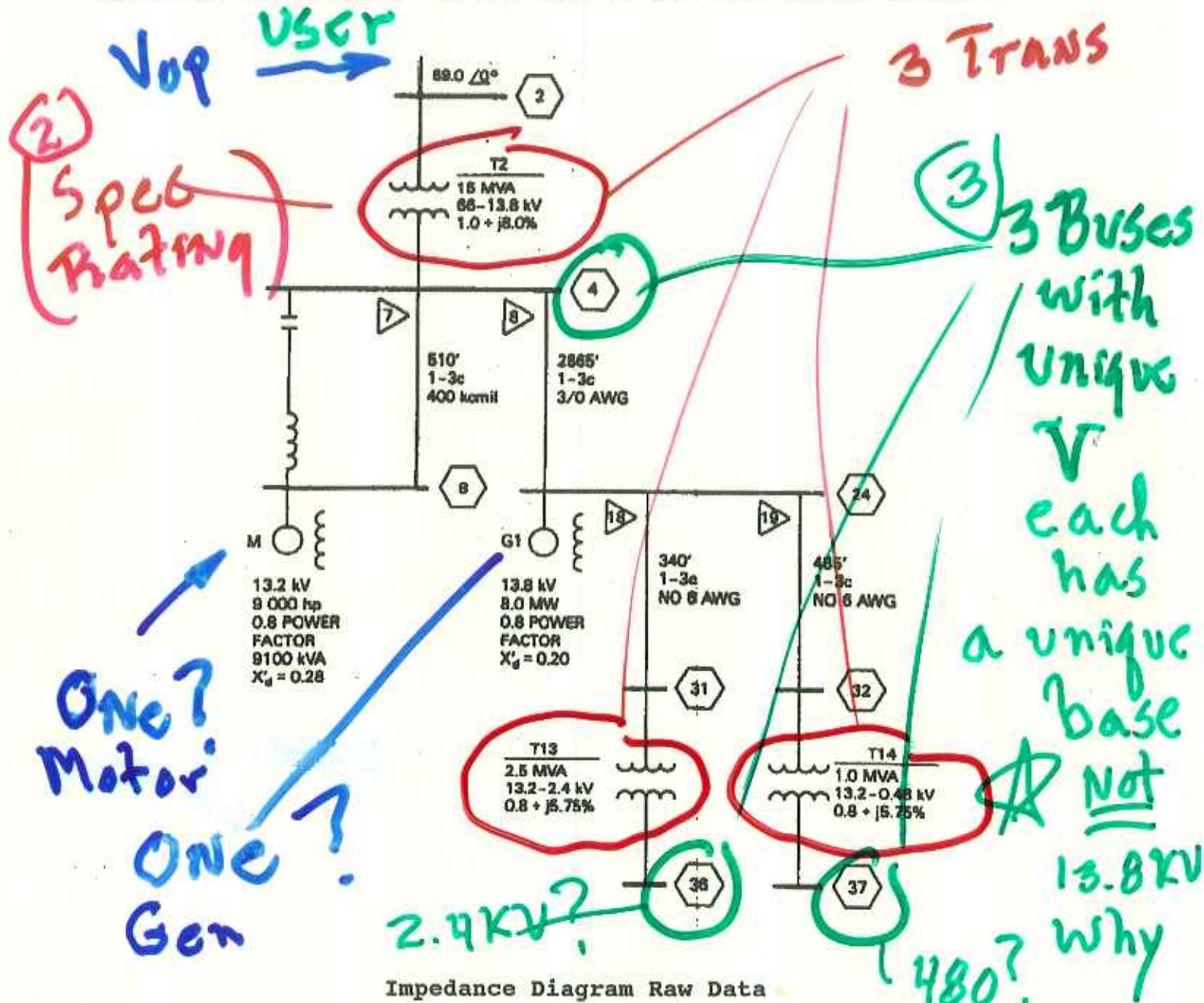
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# ① One line diagram with Ratings will simplify!

Problem #1

The steps in reducing the raw data to per unit are as follows:



(1) Select base power:  $S = 10,000 \text{ KVA}$

(2) Determine base voltages

(a) Select bus 2 nominal voltage of 69 KV as base

(b) Calculate base voltages at other system levels

Constant in system

Type wires: 1-3c, various diameters!  
various lengths!

# Handout $T_{13}$ Ratings

$\text{MVA}$  ratings provided

$$S_R = 2.5 \text{ MVA}$$

$$V_R = 13.2 \text{ KV} / 2.4 \text{ KV}$$

$$\text{prim sec}$$

$$Z_R^P (trf) = 0.8 + j 5.75 \Omega$$

## (2) Operating conditions

USC rules

Operation in System:  $S_{op} \neq S_R$

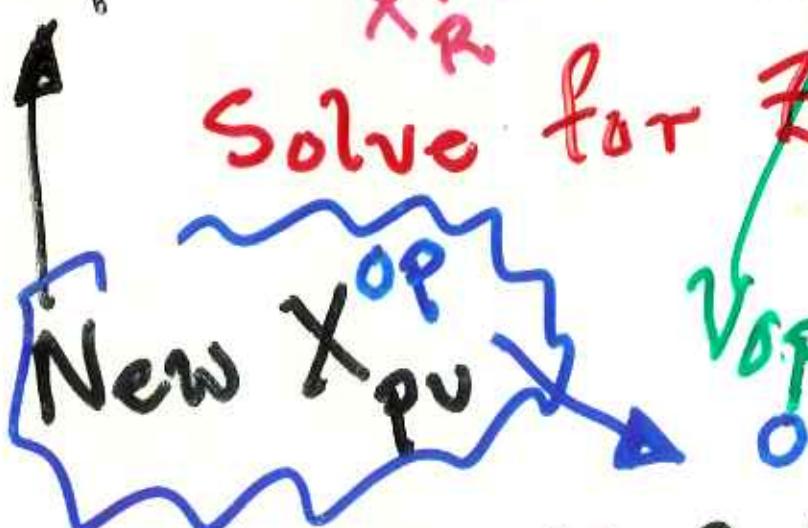
$$S_{op} = 2.5 \text{ MVA} 10$$

$$V_{op} = 2.62 \text{ KV sec}$$

$$24.427 \text{ KV pri } \frac{S_{op}}{V_R}$$

Section 6.6, Pg 4

$$Z_{op}^{pu} = \left( 0.8 + j 5.75 \right) \times \left( \frac{2.4}{2.6} \right)^2 \left( \frac{10}{2.5} \right) = ?$$



$$0.027 + j 0.19$$

Same method for other trf

Handout has  
E5  
Final  
Exam  
Key

Wire impedances P.V.  
assume  $T = 20^\circ C$  std spacing

$$Z_{pu}^{\text{wire}} = \frac{\text{Actual } Z_{\text{wire}} \text{ from tables and length}}{\text{two lines and } 10} \quad \left. \begin{array}{l} \text{look up} \\ \text{and length} \end{array} \right\}$$

$\rightarrow$

$Z_{\text{appropriate}}$

$$Z_{\text{op}}^{\text{base}} \equiv \frac{V_{\text{op}}^2}{S_{\text{op}}} = \frac{(14.4 \text{ kV})^2}{10 \text{ MVA}} = 20.8 \Omega$$

Bus

line  $\Delta$   
510' 1-3c  
400 Kcmil

$$Z_{\text{wire}}^t = 0.15 + j0.19$$

$$(Z_{pu})_{\text{op}} = \frac{0.15 + j0.19}{20.8}$$

line  $\Delta$   
2865' 1-3c  
3/0 AWG

$$Z_{\text{wire}}^s = 0.19 + j0.12$$

$$(Z_{pu})_{\text{op}} = ?$$

1

$z_0$  (w/o)  
 $z$  (able) given here

5

(7) Calculate line impedance in ohms:  $z = \text{actual ohms} / \text{base ohms}$

Lines 7, 8, 18, and 19 are 3/C, copper cables, paper

insulated, shielded conductors; dielectric constant: 3.7

(a) Line 7:

$$z = (0.01515 + j0.01887) / 20.82 \\ = 0.000728 + j0.000906 \text{ per unit}$$

(b) Line 8:

$$z = (0.19138 + j0.12119) / 20.82 \\ = 0.0009192 + j0.005821 \text{ per unit}$$
$$Y = z_c / -jX_c = 20.82 / -j8630 \\ = 0 + j0.002413 \text{ per unit}$$

(c) Line 18:

$$z = (0.16864 + j0.02074) / 20.82 \\ = 0.00810 + j0.001 \text{ per unit}$$

(d) Line 19:

$$z = (0.24056 + j0.02959) / 20.82 \\ = 0.01155 + j0.00142 \text{ per unit}$$

(8) Calculate  $X_d'$  of two synchronous machines in per unit using equation from (6)

(a) Synchronous motor on bus 8:

$$X_d' = j0.28 * ((13.2^2) / (14.427^2)) * (10,000 / 9,800) \\ = j0.2392$$

(b) Generator G1:

$$X_d' = j0.20 * ((13.8^2) / (14.427^2)) * (10,000 / (8500/0.8)) \\ = j0.1722$$

done  
print  
page

rest

$z_3$  Bus 36

fix  
 $S_R$

fix  
 $S_R$

# Generator Rating : G<sub>1</sub>

$$V_R = 13.8 \text{ kV} , \quad \text{PF} = .8$$

$$P_R = 8 \text{ MW}$$

$$S_R = \frac{8}{.8} = 10 \text{ MVA} \quad X_2^{\text{pu}} = 0.20 \quad \} \text{rated}$$

# Generator Operation

$$V_A = 14.427 \text{ kV}$$

$$S_{\text{A}}^{\text{op}} = 10,000 \text{ kVA} = 10 \text{ MVA}$$

$$X_2^{\text{op}}(\text{operation}) = j 0.2 \left( \frac{13.8}{14.42} \right) \left( \frac{10}{\frac{8}{80}} \right)$$

Section 8b, Pg 5

$$\underbrace{X_2^{\text{op}}}_{G_1} = j 0.17 \quad V_{\text{op}} \quad S_R$$

fix in  
handout

Motor Ratings : M,

$$V_R = 13.2 \text{ KV}$$

$$S_R = 9100 \text{ KVA}$$

$$X_2' = 0.28 \text{ pu rated}$$

Motor Operation

$$V_{OP} = 14.42 \text{ KV}$$

$$S_{OP} = 10,000 \text{ KVA}$$

Section 8a, Page 5

$$X_2' (OP) = X_2' (\text{rating}) \left( \frac{V_R}{V_{OP}} \right)^2 \left( \frac{S_{OP}}{S_R} \right)$$

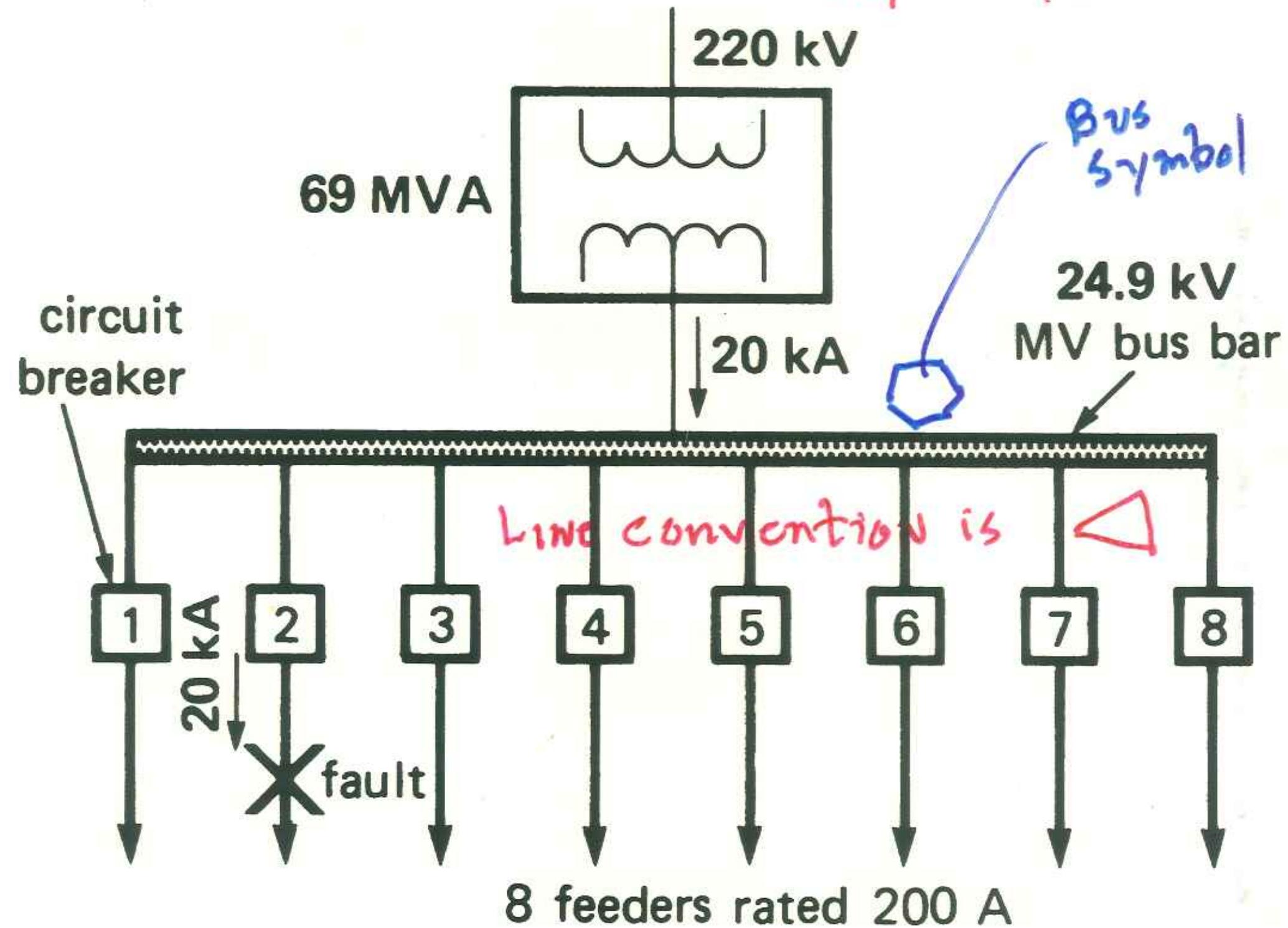
$$= j0.28 \left( \frac{13.2}{14.42} \right)^2 \left( \frac{10,000}{9100} \right)$$

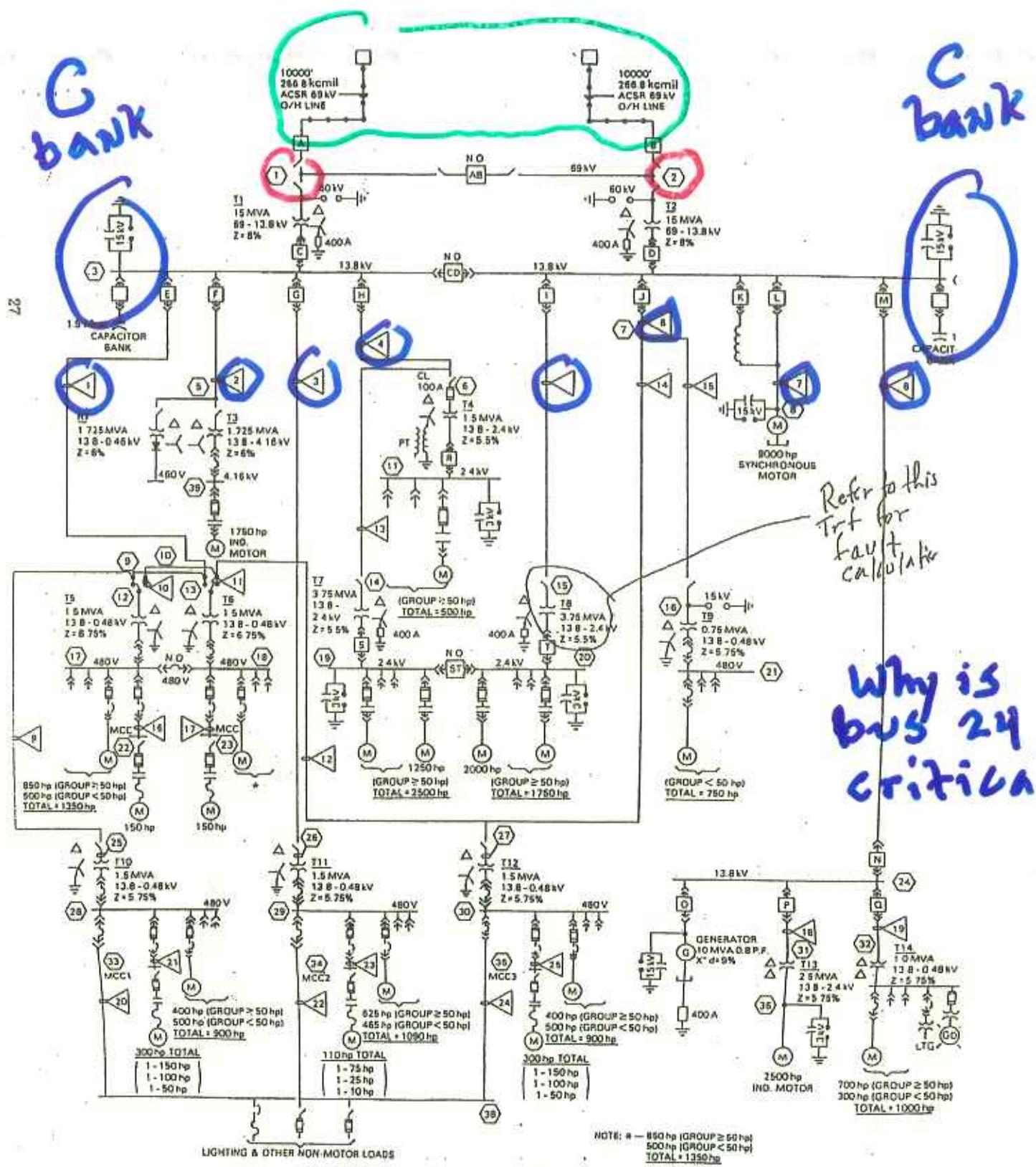
$$\underline{X_{PU}^{OP}} = j0.239 \quad V_{OP} \quad S_R$$

for HW

MOTOR 1 Non simplify 1 line diagram with pu

Fig 26.10 Q750



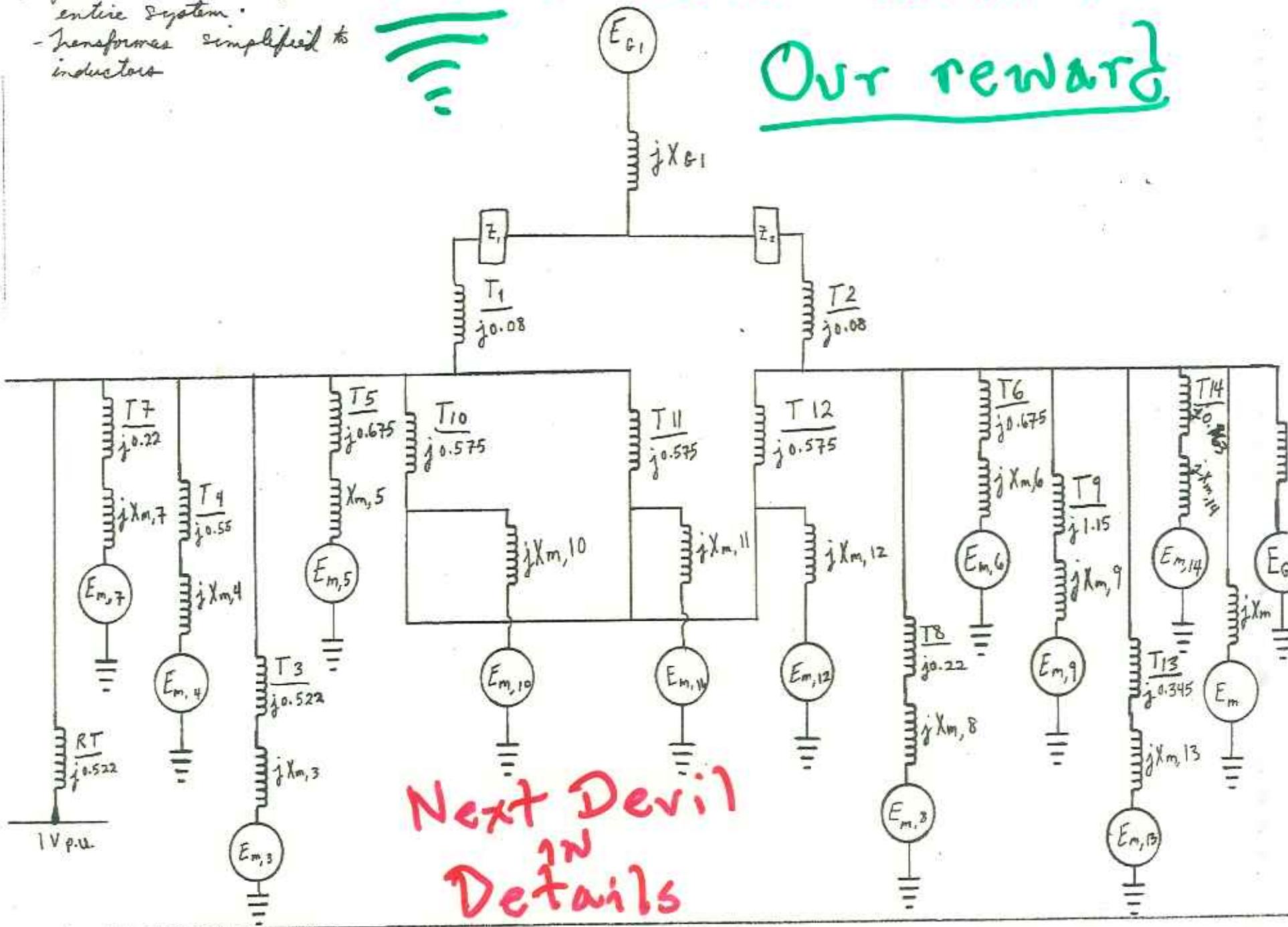


Composite Single-Line Diagram for Typical Large Industrial Power System

\* Equivalent circuit for entire system.  
- Transformers simplified to inductors

# P.U. Solution Format

Our reward



# Large Industrial Power System

- redundant / failsafe approach  
Dual Back-up
- Two 69 KV lines with individual breakers wcb
  - lines 10,000' 2.67 Kmi } 461 e-utility rec book

## Parallel buses ① & ②

connected by normally open air circuit breaker } NO brkr  
for redundancy if one 69KV fails       $T_1 \Delta-\gamma$   
→ Two transformers  $T_2 \Delta-\gamma$   
69 - 13.8 KV

60 KV surge arrestors  
find it on what bus?  
Y 100A line to ground  
rated impedance

# Redo for HW

## Symbol Definitions

—||— surge arrester (used for 3rd Harmonic)

—||— surge capacitor

—||— rectifier bank

—mm— reactor non-magnetic core

—Y— 3-Φ, neutral ungrounded

—X— 3-Φ, neutral grounded  
(allows to test for balance)

↔↔□↔ Air circuit breaker,  
removable type DH

—□— circuit breaker,  
nonremovable (oil or vacuum)

↔↔ Air circuit breaker,  
draw out type

—□/— disconnecting fuse, nonremovable

—□— fuse      ↔↔□↔ drawout  
                  fuse

✓— switch

—3E— Potential Transformer

—||— ground

—mm— Two Winding Power  
Transformer

Δ Three phase, three wire delta connection

◇ PMS indicator

◻ line flag

○ AC machine (generator or motor)

~ circuit breaker

↑— capacitor bank  
(used to compensate reactive load)

1. Top of page Cap Bank: Role?  
Look at 13.8 KV bus



2. lots of fuses



disconnected  
fuse  
on All motors

3. Circuit Breakers:  air breaker



oil, SF<sub>6</sub> breaker

4.

Allows for?



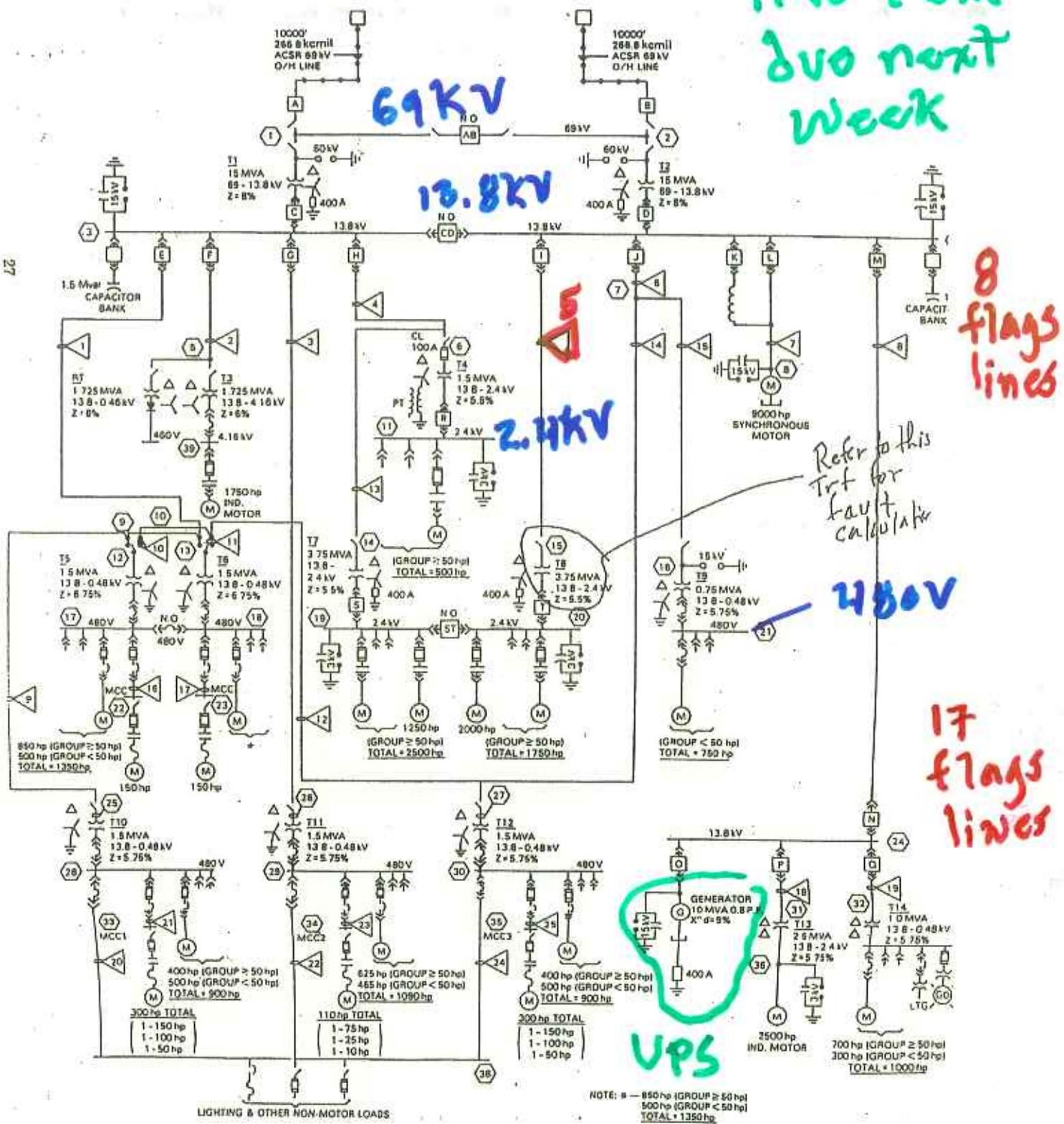
5.



surge spark gap  
e.g. 15 KV on 13.8 KV line  
60 KV on 69 KV line  
surge CAP

b.

HW Pbm  
due next  
week



Composite Single-Line Diagram for Typical Large Industrial Power System

## Large Industrial Power System

- Redundant/failsafe approach – Dual backup
- Two 69 KV lines with individual breakers

→ Lines 10,000 ft of 267 kMil

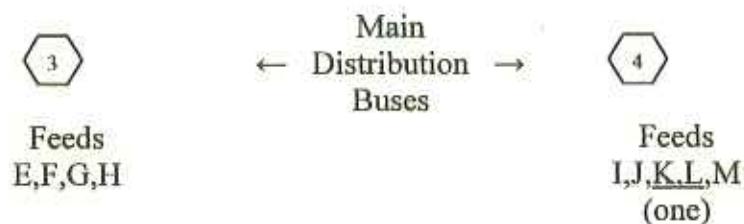
→ Parallel Buses & connected by normally open air circuit breaker for redundancy if one 69kV fails

→ Two transformers T<sub>1</sub>: Δ - Y & T<sub>2</sub>: Δ - Y 69 – 13.8 kV w/60 kV surge arrestors

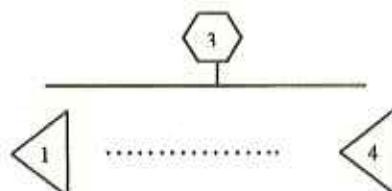
→ 400A line to ground rated impedance

Two redundant 13.8kV busses, and

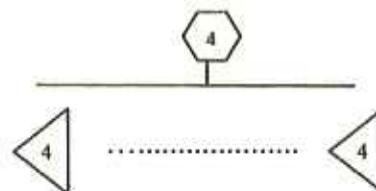
Normally open switch air circuit breaker



Both and have 1.5 MVAR "C" compensation due to 17 motors downline to reduce  $I_{in}$  and  $pF \uparrow$



Lines @ 13.8 kV  
Each has air circuit breaker



Lines @ 13.8 kV  
Each has air circuit breaker

Total of 8 13.8 kV lines

Throughout the system there are 25 lines



17 lines @13.8 kV

8 lines @ 480 V

There are 15 Transformers

There are 16 Motors at various HP

Throughout the system are  
25  <sup>flag</sup> lines Can you find?

17 lines @ 13.8 KV

8 lines @ 480 V

There are 15 Transformers

There are 16 Motors at  
various HP

Reality begins need for  
PSSE

There are 40 Busses 

2 @ 69 KV

19 @ 13.8 KV

4 @ 2.4 KV

1 @ 4.16 KV

13 @ 480 V

1 @ 460 V

Note:

Bus #38  
dedicated to  
lighting

What next?

Line	First Connection Bus Number	Protection First Connection has	Second Connection Bus Number	Protection Second Connection has	Line Voltage
24	30	Air circuit breaker, drawout type	38	X	0.480
25	30	Drawout fuse and Air circuit breaker, drawout type	35	X	0.480

You are able to see that Buses 17,18,19,20 and 21 and others in this system services a numerous number of motors. There are many different number of motors in this one line diagram, which operate at different hp and have different ratings. This table shows all the motors in this system.

**Motors**

Buss Number	Group > 51 hp	Group < 50 hp	Any thing else	Total
8	X	X	9000hp Synchronous	9000hp
11	500hp	X	X	500hp
17	850hp	500hp	X	1350hp
18	850hp	500hp	X	1350hp
19	2500hp	X	1250hp	3750hp
20	1750hp	X	2000hp	3750hp
21	X	750hp	X	750hp
22	X	X	150hp	150hp
23	X	X	150hp	150hp
28	400hp	500hp	X	900hp
29	625hp	465hp	X	1090hp
30	400hp	500hp	X	900hp
33	300hp	X	X	300hp
34	75hp	35hp	X	110hp
35	300hp	X	X	300hp
36	X	X	2500hp IND. Motor	2500hp
37	700hp	300hp	X	1000hp

Each one of these motors might be connected to a protection device or transformer but will start at a bus some where. There are 40 buses though out the system. The following table shows all the voltages of each Bus.

### Buses

Bus	Voltage on the Bus in (kV)	Bus	Voltage on the Bus in (kV)	Bus	Voltage on the Bus in (kV)
1	69	15	13.8	29	0.480
2	69	16	13.8	30	0.480
3	13.8	17	0.480	31	13.8
4	13.8	18	0.480	32	13.8
5	13.8	19	2.4	33	0.480
6	13.8	20	2.4	34	0.480
7	13.8	21	0.480	35	0.480
8	13.8	22	0.480	36	2.4
9	13.8	23	0.480	37	0.480
10	13.8	24	13.8	38	0.480
11	2.4	25	13.8	39	4.16
12	13.8	26	13.8	Not labeled	0.460
13	13.8	27	13.8		
14	13.8	28	0.480		

With out transformers the power industry would probably not exist. This leads me to my next table transformers. Transforms help us with transporting electricity because higher the voltage the less loss we will have.  $P=(V^2)/R$  You can see that there are a total of 15 transformers in this system.

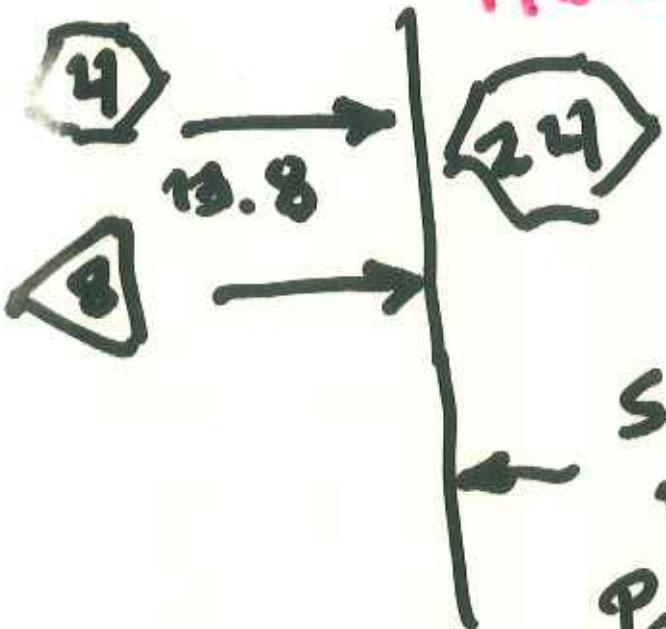
### Transformer Data

	Old MVA Base	New MVA Base	Primary Windings	Primary Voltage	Primary Connection	Secondary Windings	Secondary Voltage	Secondary Connection	Old (PU) Z
T1	15	15	Δ	69kV	Bus 1	Y	13.8kV	Bus 3	j0.08
T2	15	15	Δ	69kV	Bus 2	Y	13.8kV	Bus 4	j0.08
T3	1.725	15	Δ	13.8kV	Bus 5	Y	4.16kV	Bus 39	j0.06
T4	1.5	15	Δ	13.8kV	Bus 6	Y	2.4kV	Bus 11	j0.055
T5	1.5	15	Δ	13.8kV	Bus 12	Y	480V	Bus 17	j0.0675
T6	1.5	15	Δ	13.8kV	Bus 13	Y	480V	Bus 18	j0.0675
T7	3.75	15	Δ	13.8kV	Bus 14	Y	2.4kV	Bus 19	j0.055
T8	3.75	15	Δ	13.8kV	Bus 15	Y	2.4kv	Bus 20	j0.055
T9	0.75	15	Δ	13.8kV	Bus 16	Y	480V	Bus 21	j0.0575
T10	1.5	15	Δ	13.8kV	Bus 25	Y	480V	Bus 28	j0.0575
T11	1.5	15	Δ	13.8kV	Bus 26	Y	480V	Bus 29	j0.0575
T12	1.5	15	Δ	13.8kV	Bus 27	Y	480V	Bus 30	j0.0575
T13	2.5	15	Δ	13.8kV	Bus 31	Δ	2.4kV	Bus 36	j0.0575
T14	1	15	Δ	13.8kV	Bus 32	Δ	480V	Bus 37	j0.0575
RT	1.725	15	Δ	13.8kV	Bus 5	Y	480V	Not Stated	j0.06

The following table is the per unit diagram of this whole system and you can see how easily per unit can convert a one line diagram.

Drawin  
Circuit

Bus 24 is critical  
How can you tell?



$\rho F = .8$   
 $X_d = 9\%$

Separate [10 MVA]  
UPS Generator  
Protected by 15kV  
Surge Capacitor

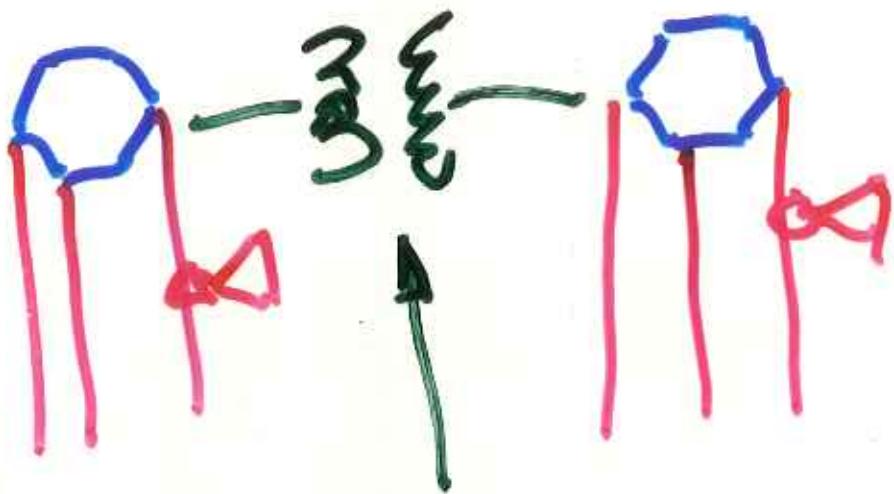
## Substantial Protection

Backup }  
Surge } ON all flag  
Fault } lines  
25 lines (each) connect two buses  
Each bus is protected!

e.g. 69 KV (2) TOP  
 13.8 KV (1)  
 4.16 KV (3) down  
 2.4 KV (4)  
 .48 KV (5)  
 .46 KV (6) down

○ - Bus

∞ - Line flag



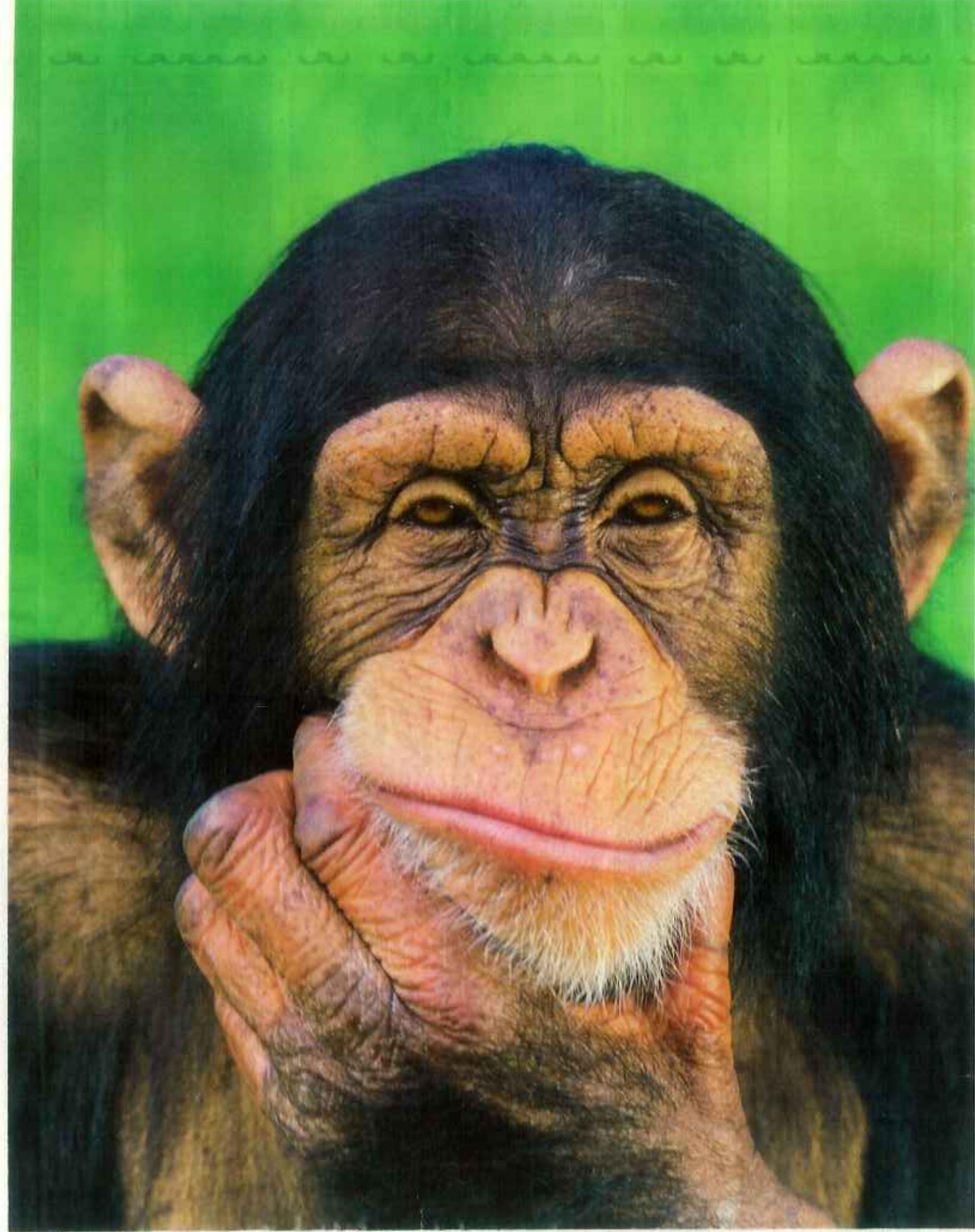
Lots of transformers (15)

Many motor loads (16)

One lighting load @ 480

One UPS generator: Find it!

Redundancy Points: Where?  
Why?



19 @ 13.8 kV

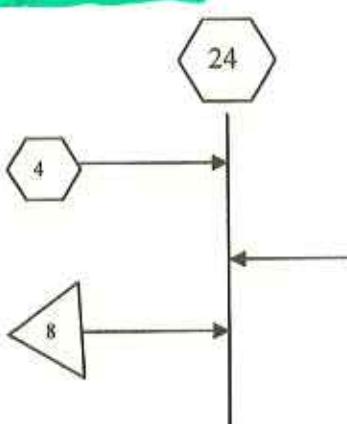
There are 40 busses



2 @ 69 kV  
19 @ 13.8 kV  
4 @ 2.4 kV  
1 @ 4.16 kV  
13 @ 480 V  
1 @ 460 V

Note:  
Bus #38  
Dedicated to  
"lighting"

Bus 24 is critical



pF = 0.8  
 $X_d = 9\%$   
10 MVA

Substantial Protection  
Backup  
Surge  
Fault

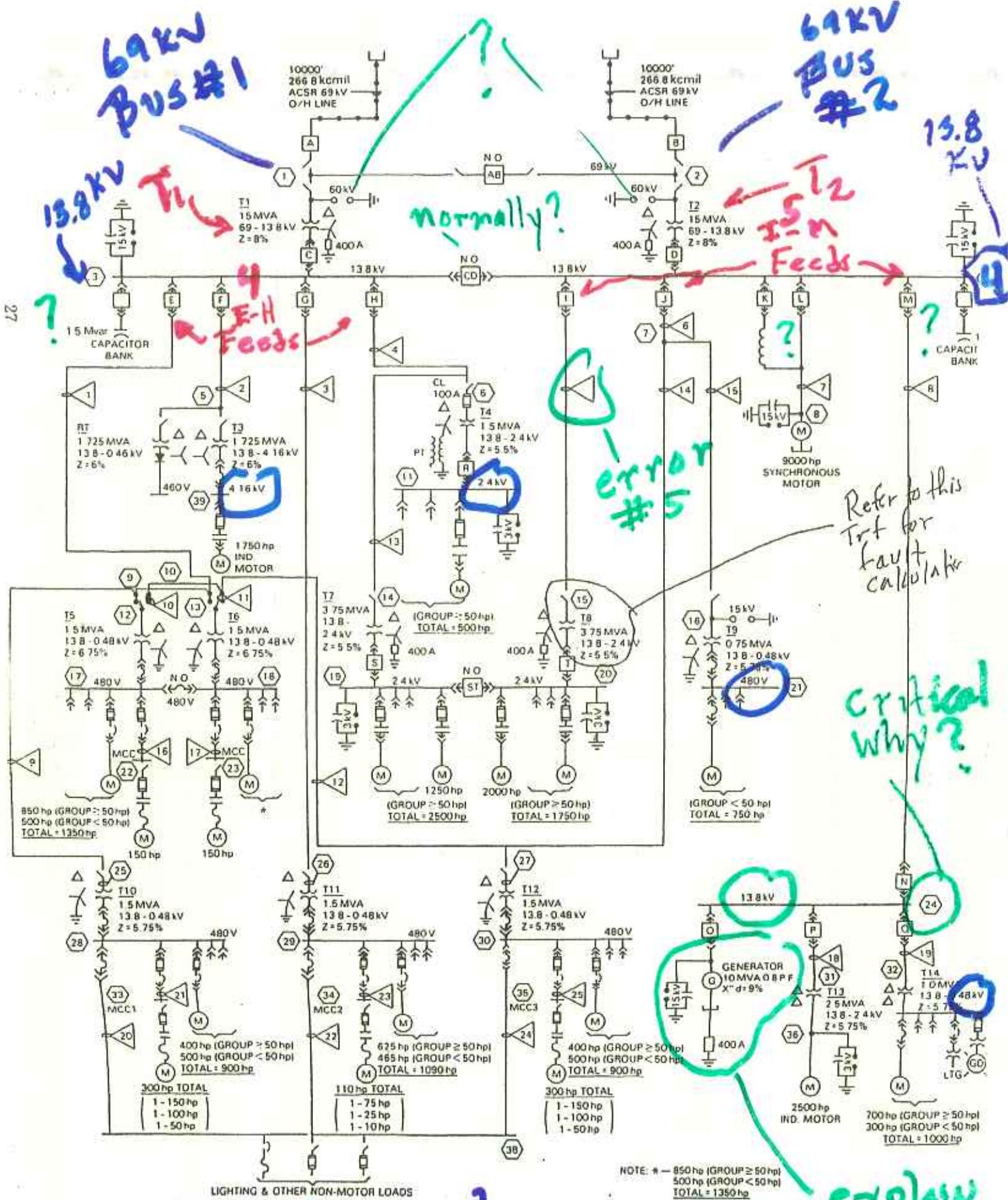
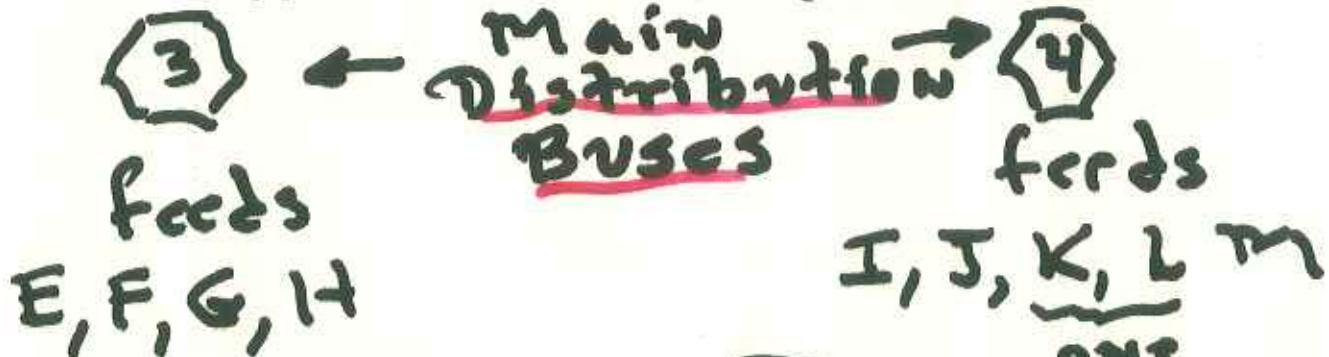


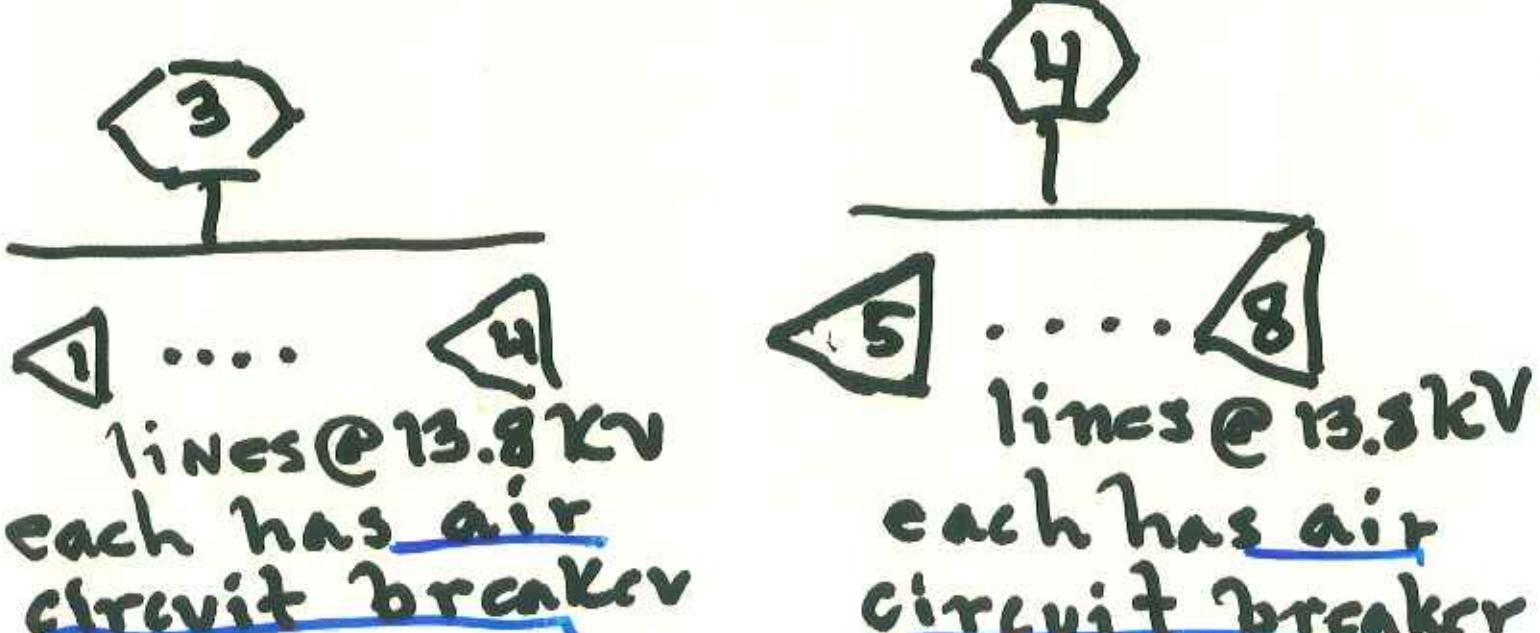
Fig 1  
Composite Single-Line Diagram for Typical Large Industrial Power System

Two redundant 13.8kV   Buses

Normally open switch  
Air circuit breaker



Both  and  have  
1.5 MVAR "C" Compensation  
due to 17 Motors downline  
to reduce  $I_{in}$  and  $PF \uparrow$



Total of 8 13.8kV lines

Kaz in parallel

### Line Data

Line	First Connection Bus Number	Protection First Connection has	Second Connection Bus Number	Protection Second Connection has	Line Voltage (kV)
1	3	Air circuit breaker, removable type DH	13	X	13.8
2	3	Air circuit breaker, removable type DH	5	X	13.8
3	3	Air circuit breaker, removable type DH	26	Disconnecting switch, nondrawout	13.8
4	3	Air circuit breaker, removable type DH	6	Disconnecting switch, nondrawout	13.8
5	4	Air circuit breaker, removable type DH	15	Disconnecting switch, nondrawout	13.8
6	4	Air circuit breaker, removable type DH	7	X	13.8
7	4	Air circuit breaker, removable type DH	8	15kV surge capacitor	13.8
8	4	Air circuit breaker, removable type DH	24	Air circuit breaker, removable type DH	13.8
9	9	X	25	Disconnecting switch, nondrawout	13.8
10	10	X	12	Disconnecting switch, nondrawout	13.8
11	10	X	13	Disconnecting switch, nondrawout	13.8
12	10	X	27	Disconnecting switch, nondrawout	13.8
13	6	Switch	14	Disconnecting switch, nondrawout	13.8
14	7	X	27	Disconnecting switch, nondrawout	13.8
15	7	X	16	Disconnecting switch, nondrawout	13.8
16	17	Drawout fuse and Air circuit breaker, drawout type	22	X	0.480
17	18	Drawout fuse and Air circuit breaker, drawout type	23	X	0.480
18	24	Air circuit breaker, removable type DH	31	X	13.8
19	24	Air circuit breaker, removable type DH	32	X	13.8
20	28	Air circuit breaker, drawout type	38	X	0.480
21	28	Drawout fuse and Air circuit breaker, drawout type	33	X	0.480
22	29	Air circuit breaker, drawout type	38	X	0.480
23	29	Drawout fuse and Air circuit breaker, drawout	34	X	0.480

A young girl with dark hair and glasses is looking up at a bookshelf filled with colorful books. She is holding a book in front of her chest. The book has a dark cover with the words "ROCKET SCIENCE" written in large, light-colored letters. There are also some small blue squares and a grid pattern on the book cover.

ROCKET  
SCIENCE

# Summary

## Large Industrial Power System

- Redundant/failsafe approach – Dual backup
- Two 69 KV lines with individual breakers

→ Lines 10,000 ft of 267 kMil

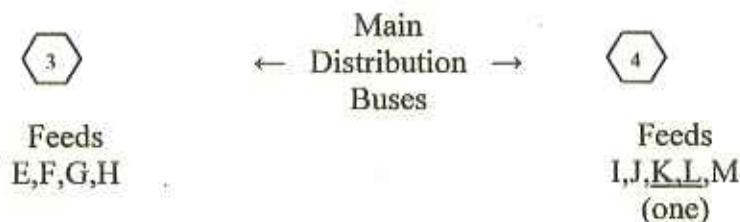
→ Parallel Buses & connected by normally open air circuit breaker for redundancy if one 69kV fails

→ Two transformers  $T_1$ :  $\Delta - Y$  &  $T_2$ :  $\Delta - Y$  69 – 13.8 kV w/60 kV surge arrestors

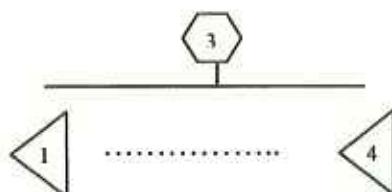
→ 400A line to ground rated impedance

Two redundant 13.8kV busses, and

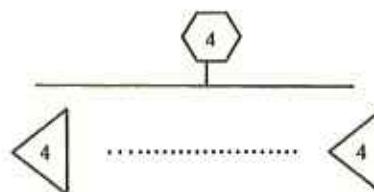
Normally open switch air circuit breaker



Both and have 1.5 MVAR "C" compensation due to 17 motors downline to reduce  $I_{in}$  and  $pF \uparrow$



Lines @ 13.8 kV  
Each has air circuit breaker



Lines @ 13.8 kV  
Each has air circuit breaker

Total of 8 13.8 kV lines

Throughout the system there are 25 lines

17 lines @13.8 kV

8 lines @ 480 V

There are 15 Transformers

There are 16 Motors at various HP

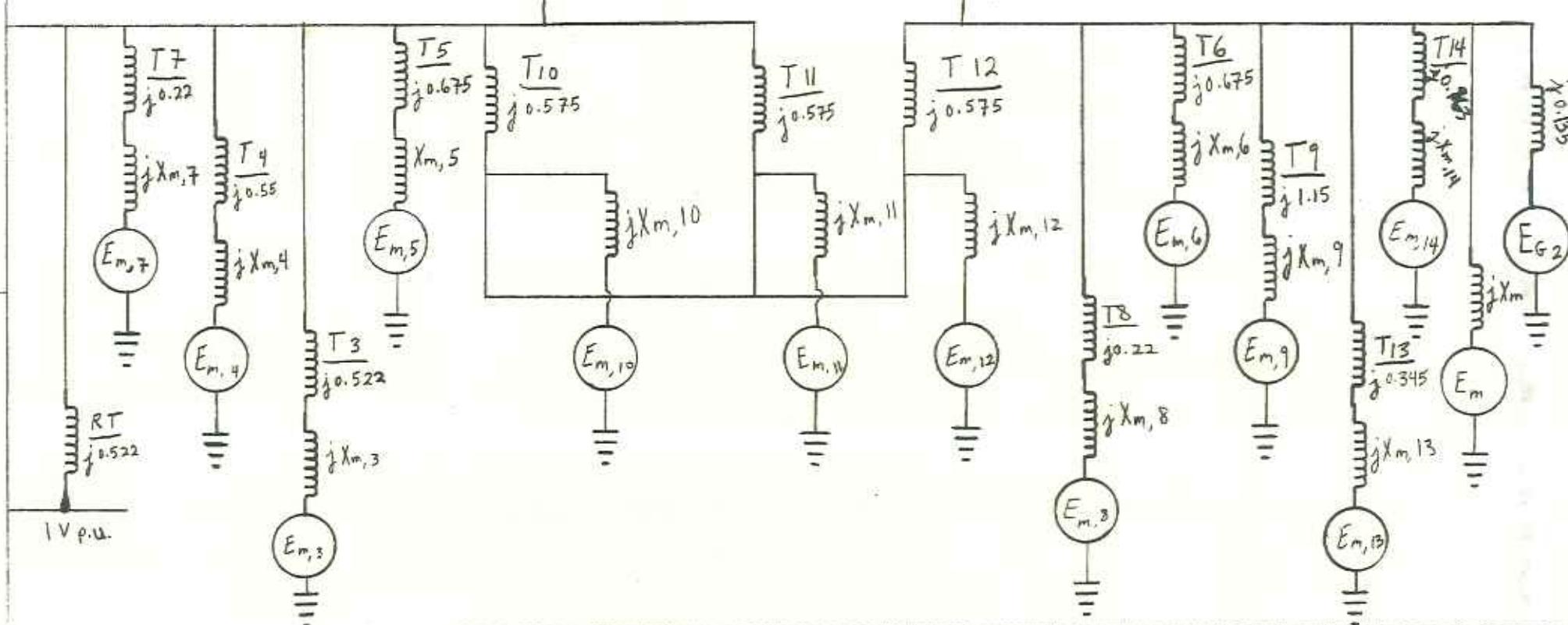
Use PSSE for  
what if system  
modeling



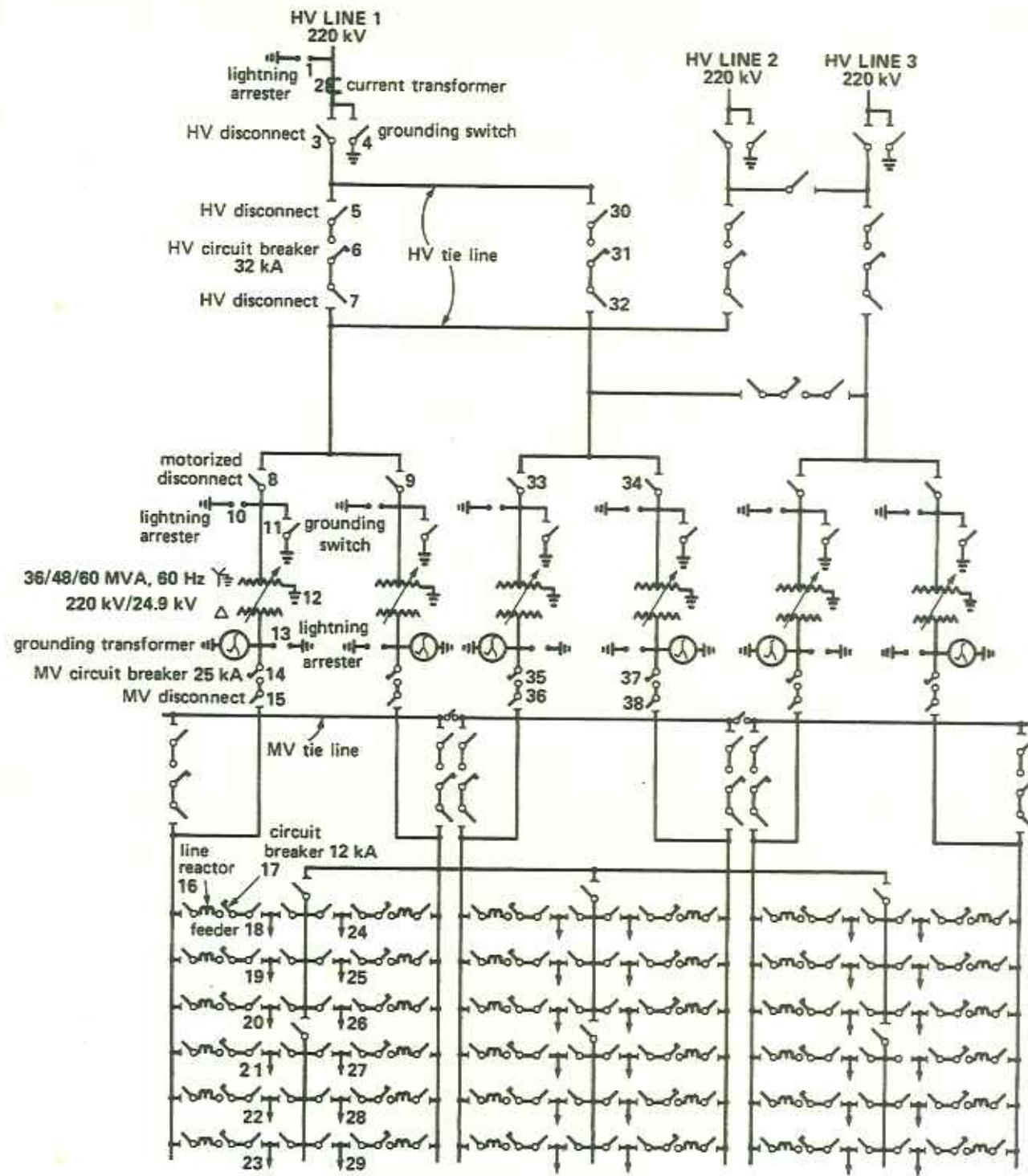
Put on PSEE lab b

- \* Equivalent circuit for entire system.
- Transformers simplified to inductors

? HW } group  
1. ex. cr. } show  
all work



# Another?



24.9 kV FEEDERS LEADING TO SUBURB