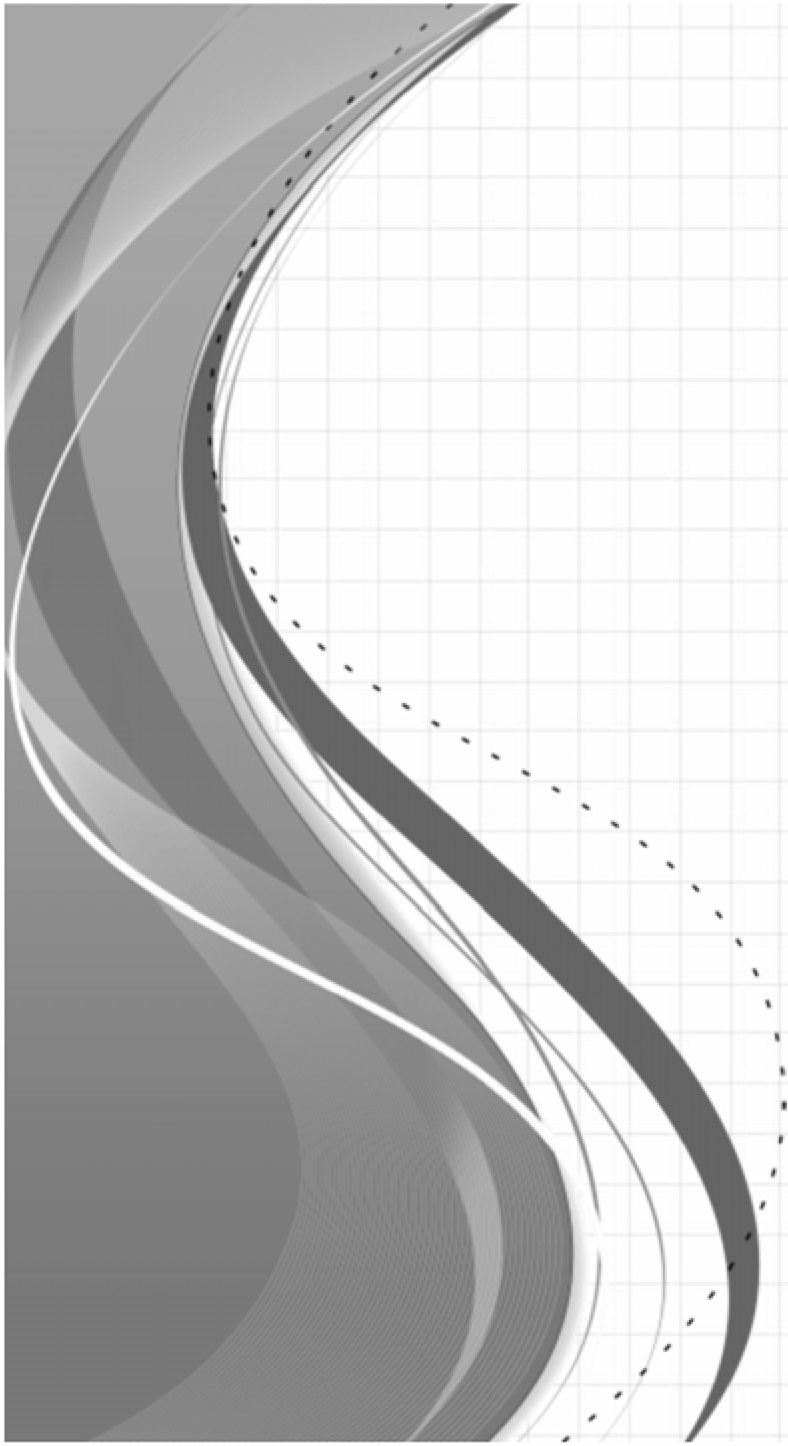


UNDERSTANDING POWER CONCEPTS BASIC COURSE

PARTS 1, 2, & 3

PART 4 WILL BE ADDED IN REV 1.

Continuing Education Course

Revision 0 (April 2013)

References

- IEEE, NFPA,
- Schneider Electric
- General Electric
- Chevron
- DuPont
- Phillips
- Allen Bradley
- Siemens
- Powell Electric
- Fluke
- SEL
- ABB
- Readily available power points on the internet.
- ExxonMobil
- ECM
- Baldor
- Toshiba
- Post Glover

Understanding Power Concepts

- This course was put together using readily available material from the internet, and from older IEEE presentations. It is for educational purposes only. The user of this material should consult a licensed professional engineer on all topics presented in this basic electrical power course.

- This material has not been checked for accuracy. It should be assumed to be out of date.

- This material is again for educational purposes only. No profits have been made in the making of this course or in its presentation. This course is solely to help educate our engineers and society on electrical power topics.

Understanding Power Concepts

- This REV 0 April 2013 course covers Parts 1, 2, and 3.

- Part 4 will be added at a later date, REV 1.

Understanding Power Concepts

- Part 1
  - Introduction
  - Formulas (AC/DC Basics)
  - Standards
  - Codes/Personal Safety
  - Grounding

Understanding Power Concepts

Part 2

- Electrical Studies
    - One lines
    - SC
    - LF
    - I2T
- Transfer Schemes
- Cable types
- Feeder Designs

Understanding Power Concepts

Part 3

- Motors
  - AC Induction Motors
  - Motor Efficiency and Assessment
  - Motor Controllers (VFD and Harmonics)
  - Application Considerations
- Transformers
- Substations
- Switchgear
- Panels (Lighting and Power)
- MCC
- DC/UPS Systems

Understanding Power Concepts

Part 4 ***(has not been added as of REV 0)***

- Protective Relaying
  - Bus
  - Feeders
  - Motors
  - Generators
  - Transformers

Understanding Power Concepts

Part 2

- ***Electrical Studies***
  - One lines
  - SC
  - LF
  - I2T
- Transfer Schemes
- Cable types
- Feeder Designs

TOPICS

- INTRODUCTION
- SOLUTION APPROACH
- IMPEDANCE DIAGRAMS
- STUDIES
  - LOAD FLOW
  - SHORT CIRCUIT
  - PROTECTIVE DEVICE COORDINATION

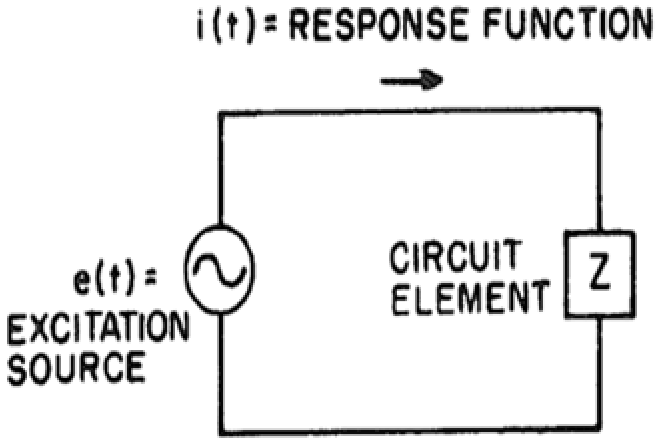
INTRODUCTION

- Load Flow Analysis
  - Determines Voltage, Current, Active and Reactive Power and Power Factor
- Short-Circuit Analysis
  - Determine magnitude of the current flowing throughout the power system at different times after a fault occurs.
- Protective Device Coordination
  - Utilized to achieve balance between equipment protection and selective fault isolation.

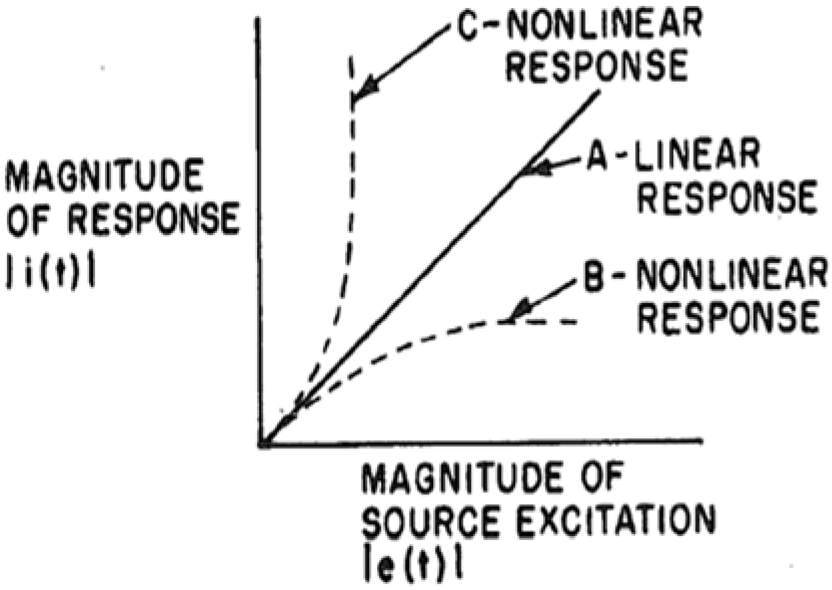
SOLUTION APPROACH

- LINEARITY
- SUPERPOSITION
- THEVENIN and NORTON EQUIVALENTS
- SYMMETRICAL COMPONENTS
- PER UNIT METHOD

LINEARITY



(a)

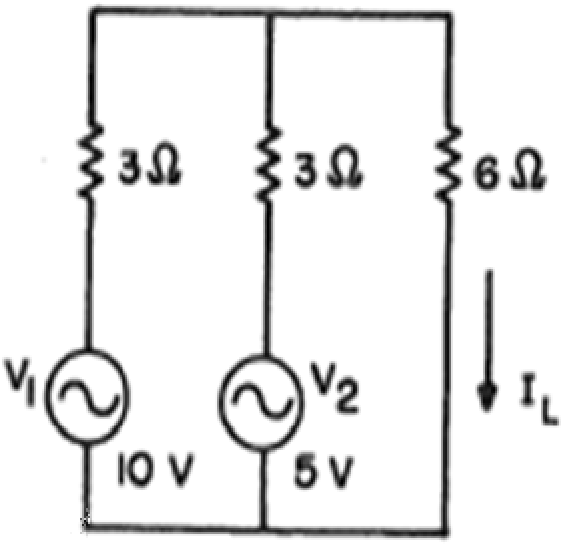


(b)

SUPERPOSITION

- LINEAR NETWORKS
- SEVERAL SOURCES (CURRENT and/or VOLTAGE)
- RESPONSE CALCULATED BY EACH INDEPENDENT SOURCE ACTING ALONE (VOLTAGE SOURCES SHORTED AND CURRENT SOURCES OPENED)

SUPERPOSITION (EXAMPLE)



$$I_L = I_{v_1} + I_{v_2}$$

$$= \frac{10}{\left(3+\frac{6\cdot 3}{6+3}\right)}\left(\frac{6\cdot 3}{6+3}\right)\cdot\frac{1}{6} + \frac{5}{\left(3+\frac{6\cdot 3}{6+3}\right)}\left(\frac{6\cdot 3}{6+3}\right)\cdot\frac{1}{6}$$

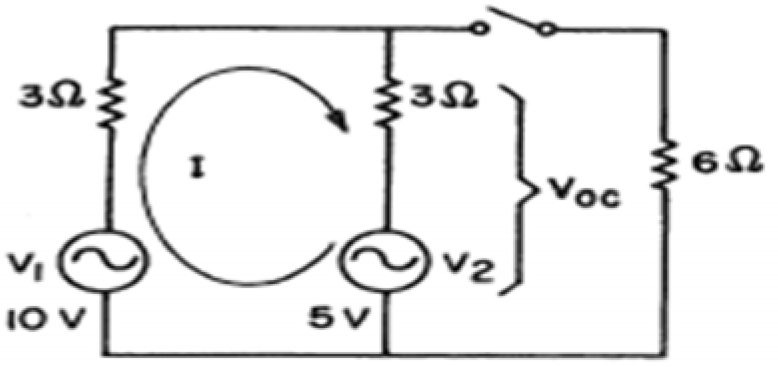
$$= \frac{10}{5}\cdot 2\cdot\frac{1}{6} + \frac{5}{5}\cdot 2\cdot\frac{1}{6}$$

$$= \frac{2\cdot 2}{6} + \frac{2}{6} = \frac{2}{3} + \frac{1}{3} = 1\text{ A}$$

THEVENIN EQUIVALENT

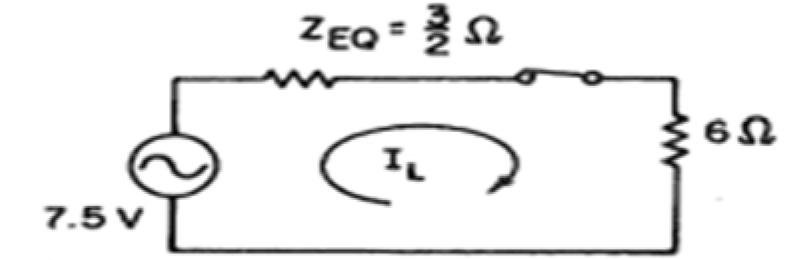
- Linear Network
- Voc = Open-Circuit Voltage
- Zeq = Equivalent Impedance
- Series Connected

THEVENIN EQUIVALENT



$$V_{OC} = I \cdot 3 + 5$$
$$= \frac{10-5}{6} \cdot 3 + 5$$
$$= \frac{5}{2} + 5 = \frac{15}{2}$$
$$= 7.5\ \mathrm{V}$$
$$Z_{EQ} = \frac{3 \cdot 3}{3+3} = \frac{9}{6} = \frac{3}{2}\ \Omega$$

(a)



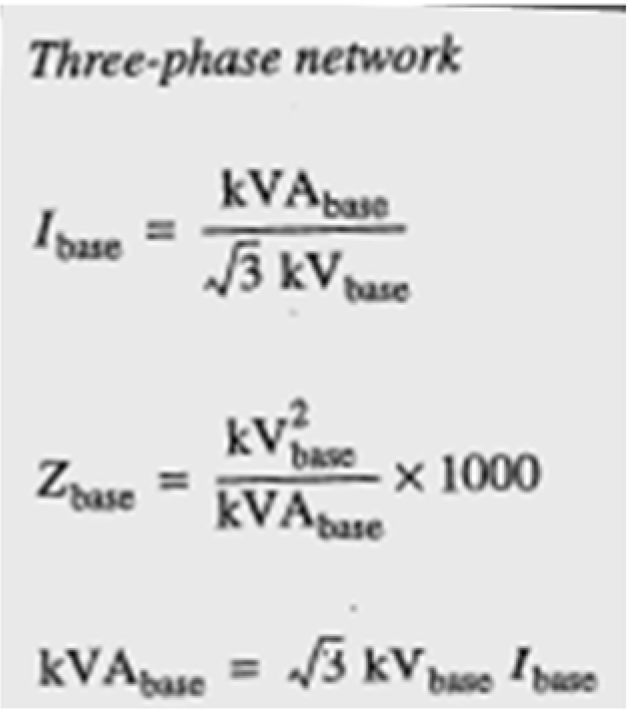
THEVENIN EQUIVALENT REPRESENTATION

$$I_L = 7.5 \cdot \frac{1}{6 + \frac{3}{2}}$$
$$= \frac{15}{2} \cdot \frac{2}{12+3}$$
$$= 15 \cdot \frac{1}{15} = 1\ \mathrm{A}$$

NORTON EQUIVALENT

- I = Voc/Zeq
- Zeq
- Connected in parallel

PER-UNIT METHOD

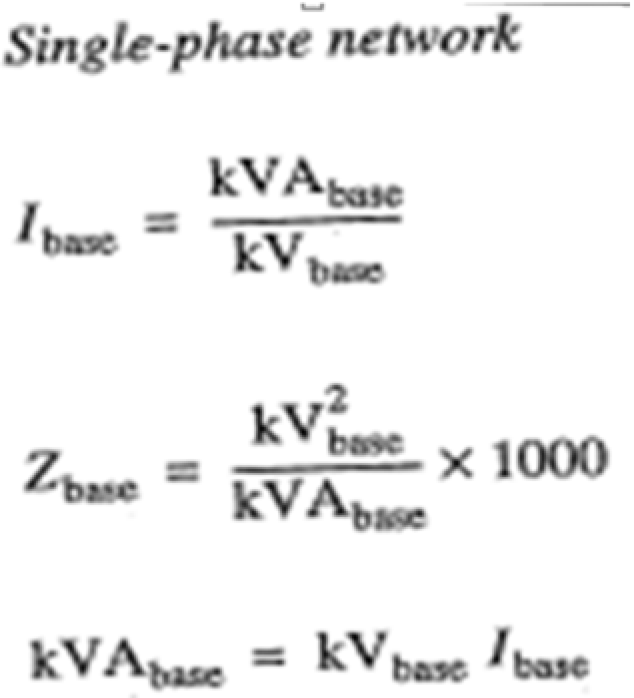


Three-phase network

$$I_{\text{base}} = \frac{\text{kVA}_{\text{base}}}{\sqrt{3}\,\text{kV}_{\text{base}}}$$

$$Z_{\text{base}} = \frac{\text{kV}^2_{\text{base}}}{\text{kVA}_{\text{base}}} \times 1000$$

$$\text{kVA}_{\text{base}} = \sqrt{3}\,\text{kV}_{\text{base}}\, I_{\text{base}}$$



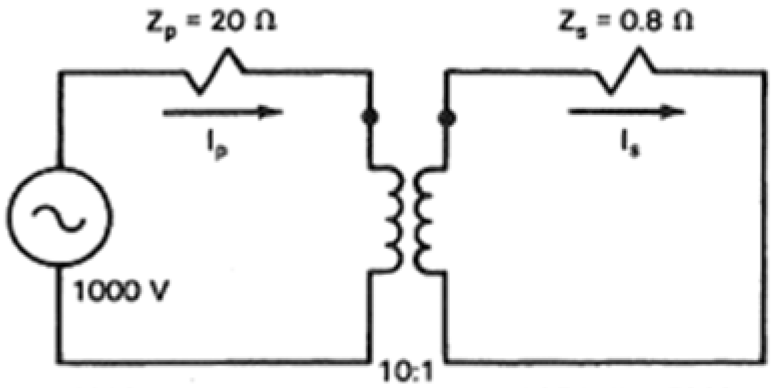
Single-phase network

$$I_{\text{base}} = \frac{\text{kVA}_{\text{base}}}{\text{kV}_{\text{base}}}$$

$$Z_{\text{base}} = \frac{\text{kV}^2_{\text{base}}}{\text{kVA}_{\text{base}}} \times 1000$$

$$\text{kVA}_{\text{base}} = \text{kV}_{\text{base}}\, I_{\text{base}}$$

PER-UNIT METHOD



BASE kVA = 5000

BASE kV = 1.0

$$\text{BASE Z} = \frac{1.0^2}{5000} \cdot 1000 = 0.2\ \Omega$$

$$Z_p = \frac{20\ \Omega}{0.2\ \Omega} = 100\ \text{PU}$$

$$V_p = \frac{1000\ \text{V}}{1.0\ \text{kV}} = 1.0\ \text{PU}$$

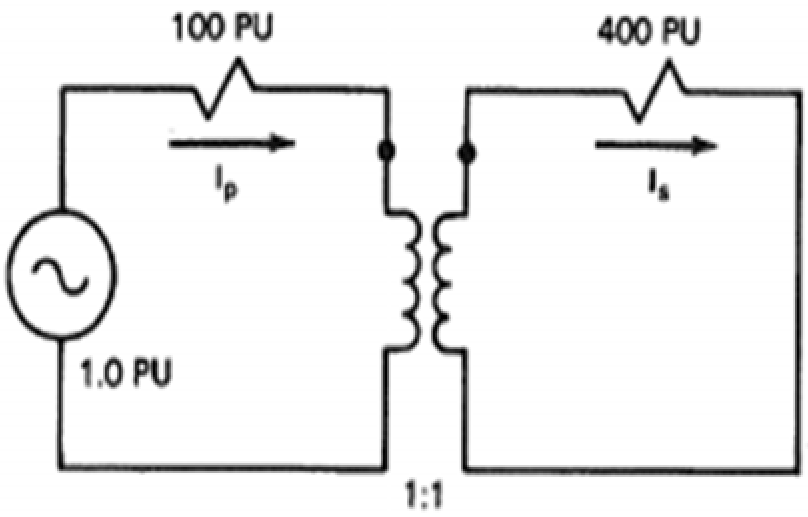
BASE kVA = 5000

BASE kV = 0.1

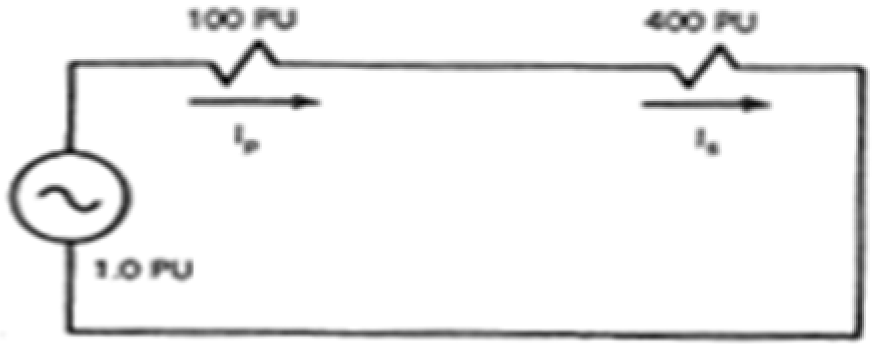
$$\text{BASE Z} = \frac{0.1^2}{5000} \cdot 1000 = 0.002\ \Omega$$

$$Z_s = \frac{0.8\ \Omega}{0.002\ \Omega} = 400\ \text{PU}$$

PER-UNIT METHOD



PER-UNIT METHOD



$$I_p = I_s = \frac{V}{Z} = \frac{1.0}{100 + 400} = 0.002 \text{ PU}$$

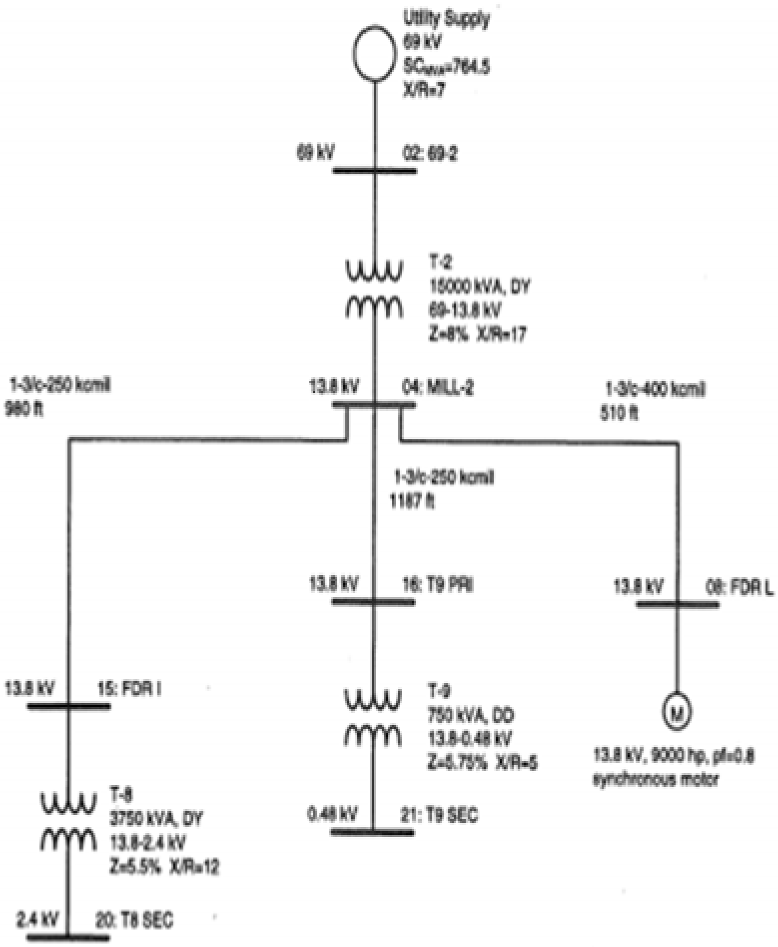
$$I_{BASE} \text{ (PRIMARY)} = \frac{5000}{1.0} = 5000 \text{ A}$$

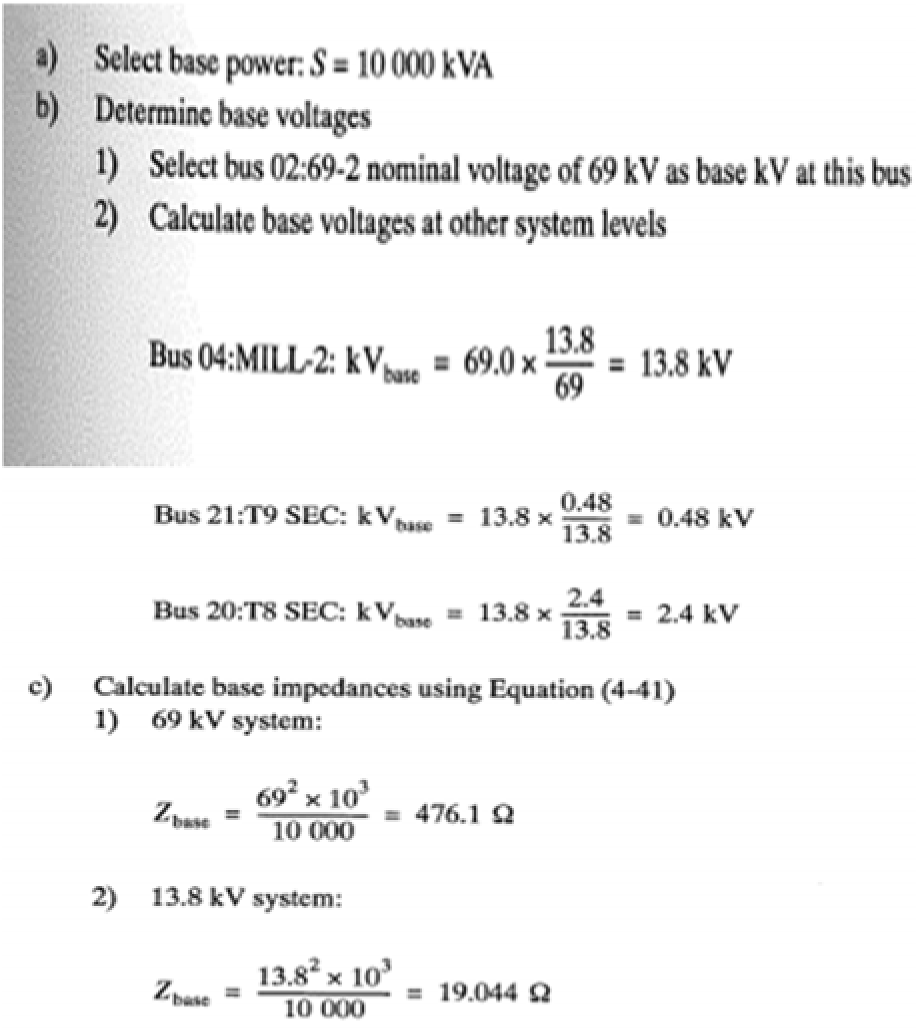
$$I_{BASE} \text{ (SECONDARY)} = \frac{5000}{0.1} = 50\,000 \text{ A}$$

$I_p = 0.002 \times 5000 = 10$ A

$I_s = 0.002 \times 50\,000 = 100$ A

EXAMPLE





a) Select base power: $S = 10\,000$ kVA

b) Determine base voltages

1) Select bus 02:69-2 nominal voltage of 69 kV as base kV at this bus

2) Calculate base voltages at other system levels

$$\text{Bus 04:MILL-2: } kV_{base} = 69.0 \times \frac{13.8}{69} = 13.8 \text{ kV}$$

$$\text{Bus 21:T9 SEC: } kV_{base} = 13.8 \times \frac{0.48}{13.8} = 0.48 \text{ kV}$$

$$\text{Bus 20:T8 SEC: } kV_{base} = 13.8 \times \frac{2.4}{13.8} = 2.4 \text{ kV}$$

c) Calculate base impedances using Equation (4-41)

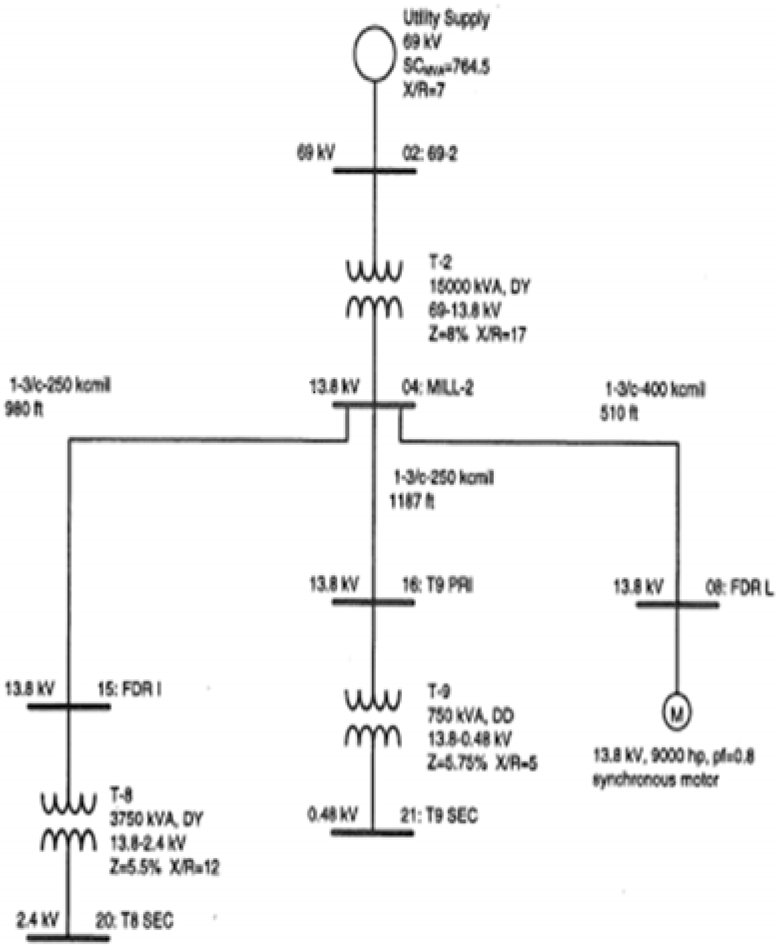
1) 69 kV system:

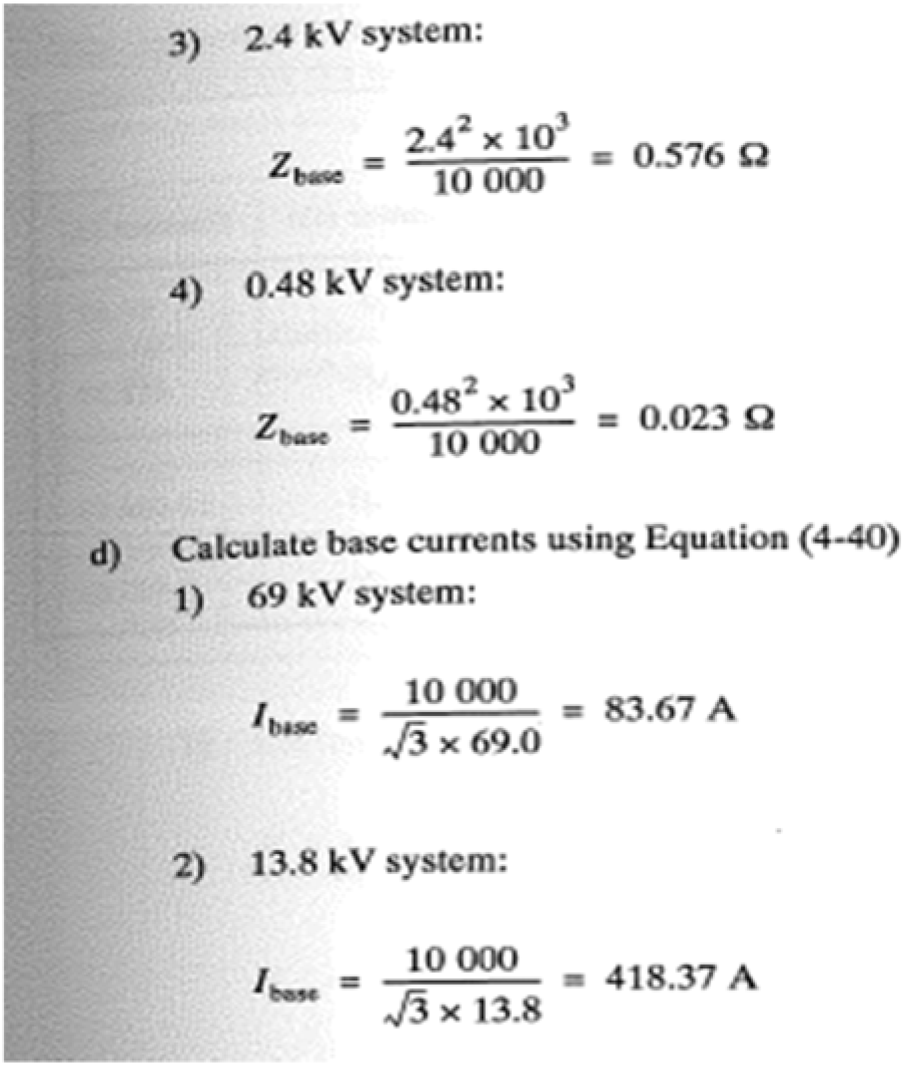
$$Z_{base} = \frac{69^2 \times 10^3}{10\,000} = 476.1\ \Omega$$

2) 13.8 kV system:

$$Z_{base} = \frac{13.8^2 \times 10^3}{10\,000} = 19.044\ \Omega$$

EXAMPLE





3) 2.4 kV system:

$$Z_{base} = \frac{2.4^2 \times 10^3}{10\,000} = 0.576\ \Omega$$

4) 0.48 kV system:

$$Z_{base} = \frac{0.48^2 \times 10^3}{10\,000} = 0.023\ \Omega$$

d) Calculate base currents using Equation (4-40)

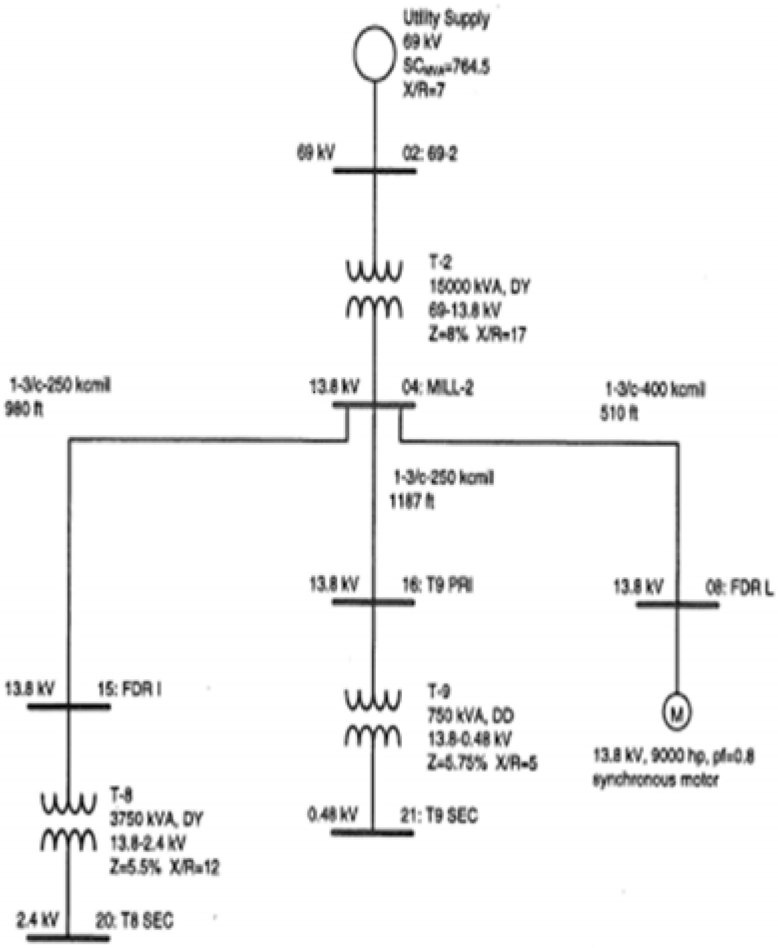
1) 69 kV system:

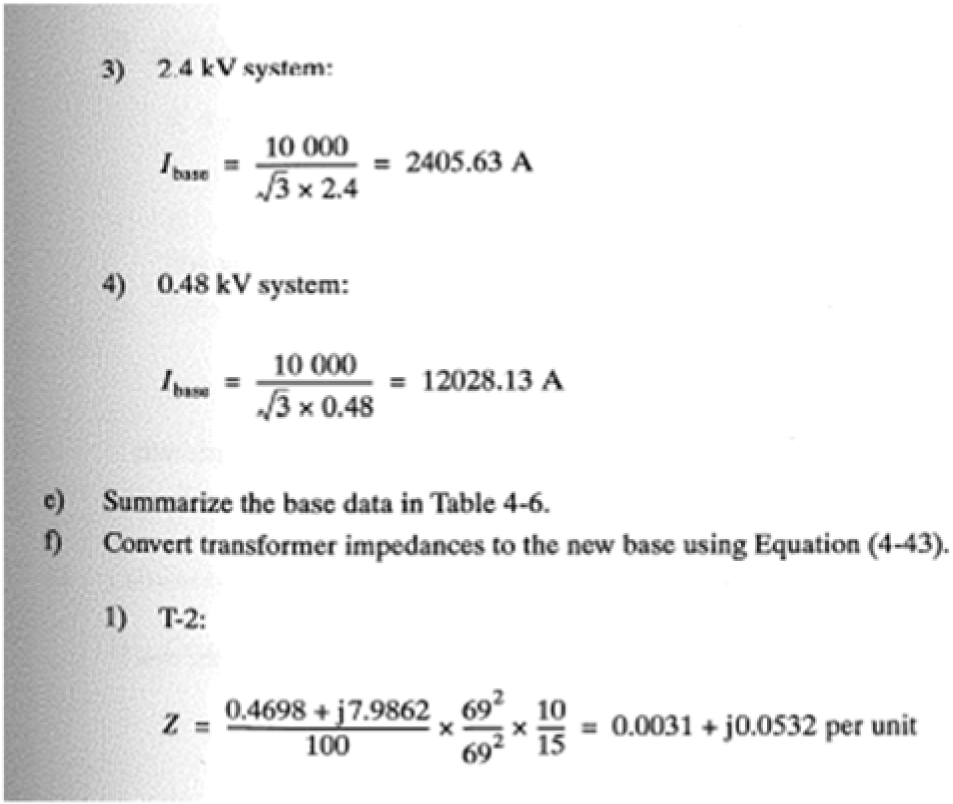
$$I_{base} = \frac{10\,000}{\sqrt{3} \times 69.0} = 83.67\ \text{A}$$

2) 13.8 kV system:

$$I_{base} = \frac{10\,000}{\sqrt{3} \times 13.8} = 418.37\ \text{A}$$

EXAMPLE





3) 2.4 kV system:

$$I_{\text{base}} = \frac{10\,000}{\sqrt{3} \times 2.4} = 2405.63 \text{ A}$$

4) 0.48 kV system:

$$I_{\text{base}} = \frac{10\,000}{\sqrt{3} \times 0.48} = 12028.13 \text{ A}$$

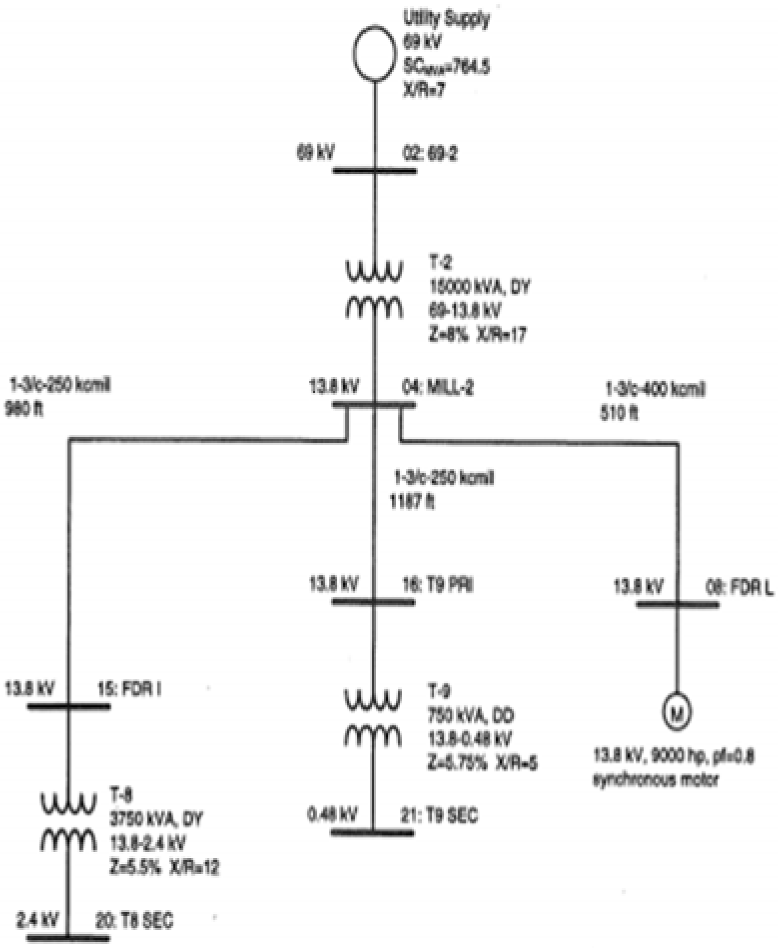
e) Summarize the base data in Table 4-6.

f) Convert transformer impedances to the new base using Equation (4-43).

1) T-2:

$$Z = \frac{0.4698 + j7.9862}{100} \times \frac{69^2}{69^2} \times \frac{10}{15} = 0.0031 + j0.0532 \text{ per unit}$$

EXAMPLE



or

$$Z = \frac{0.4698 + j7.9862}{100} \times \frac{13.8^2}{13.8^2} \times \frac{10}{15} = 0.0031 + j0.0532 \text{ per unit}$$

2) T-8:

$$Z = \frac{0.4568 + j5.481}{100} \times \frac{13.8^2}{13.8^2} \times \frac{10}{3.75} = 0.0122 + j0.1462 \text{ per unit}$$

or

$$Z = \frac{0.4568 + j5.481}{100} \times \frac{2.4^2}{2.4^2} \times \frac{10}{3.75} = 0.0122 + j0.1462 \text{ per unit}$$

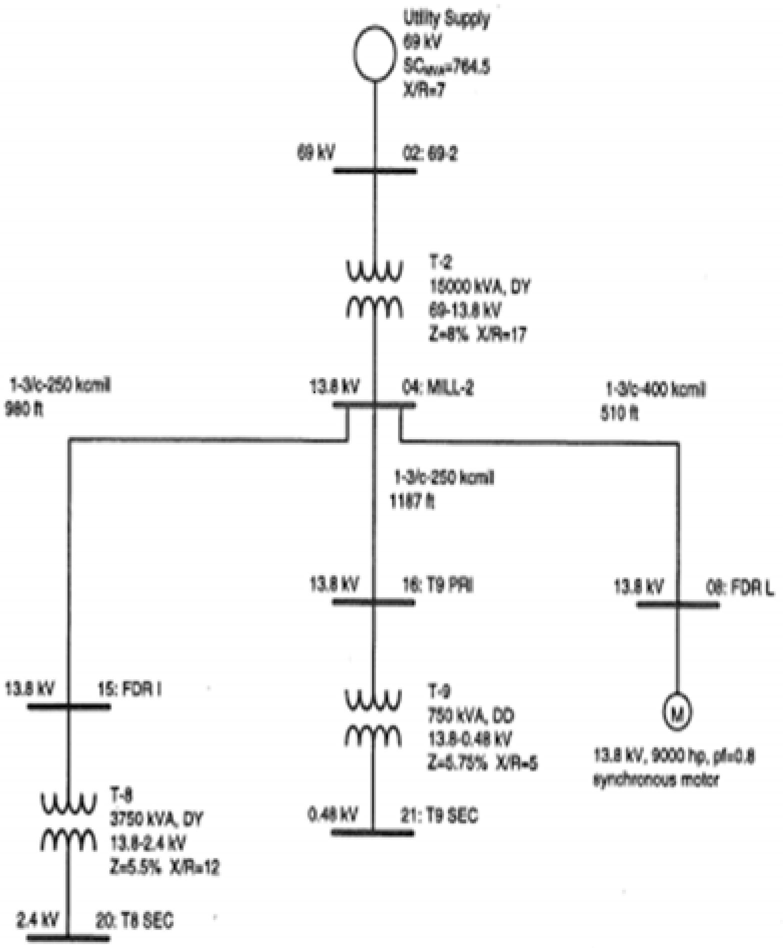
3) T-9:

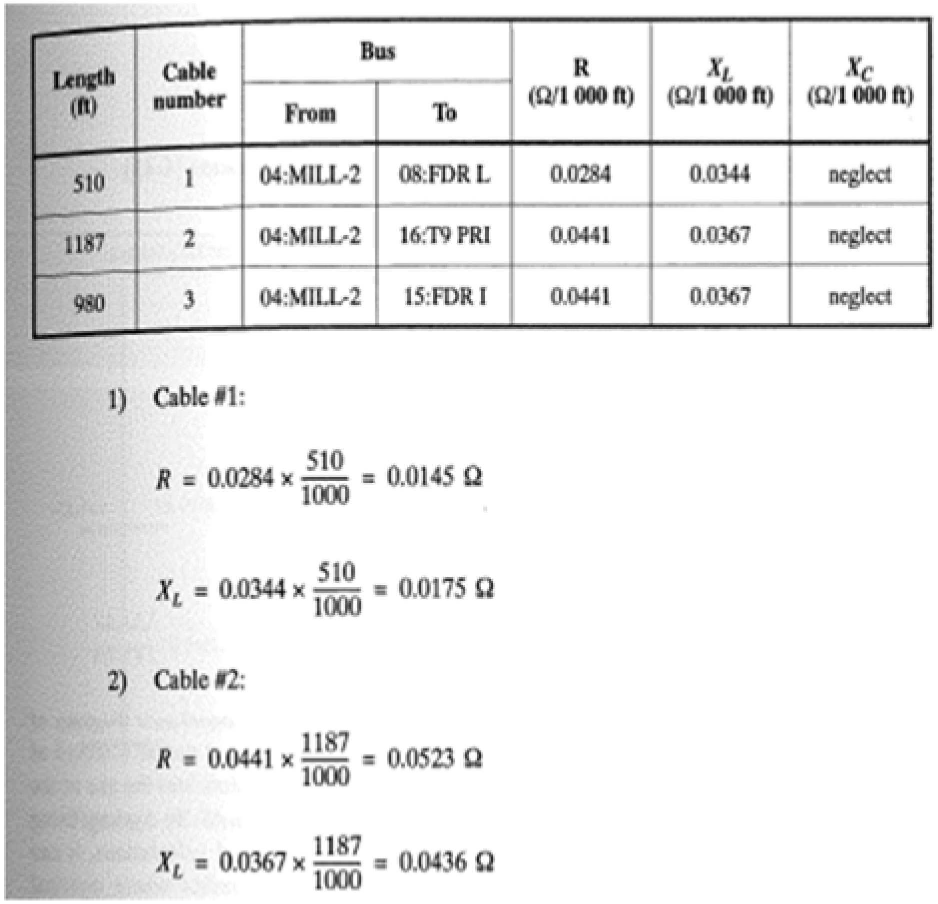
$$Z = \frac{1.1277 + j5.6383}{100} \times \frac{13.8^2}{13.8^2} \times \frac{10}{0.75} = 0.1504 + j0.7518 \text{ per unit}$$

or

$$Z = \frac{1.1277 + j5.6383}{100} \times \frac{0.48^2}{0.48^2} \times \frac{10}{0.75} = 0.1504 + j0.7518 \text{ per unit}$$

EXAMPLE





Length (ft)	Cable number	Bus		R (Ω/1 000 ft)	X_L (Ω/1 000 ft)	X_C (Ω/1 000 ft)
		From	To			
510	1	04:MILL-2	08:FDR L	0.0284	0.0344	neglect
1187	2	04:MILL-2	16:T9 PRI	0.0441	0.0367	neglect
980	3	04:MILL-2	15:FDR I	0.0441	0.0367	neglect

1) Cable #1:

$$R = 0.0284 \times \frac{510}{1000} = 0.0145\ \Omega$$

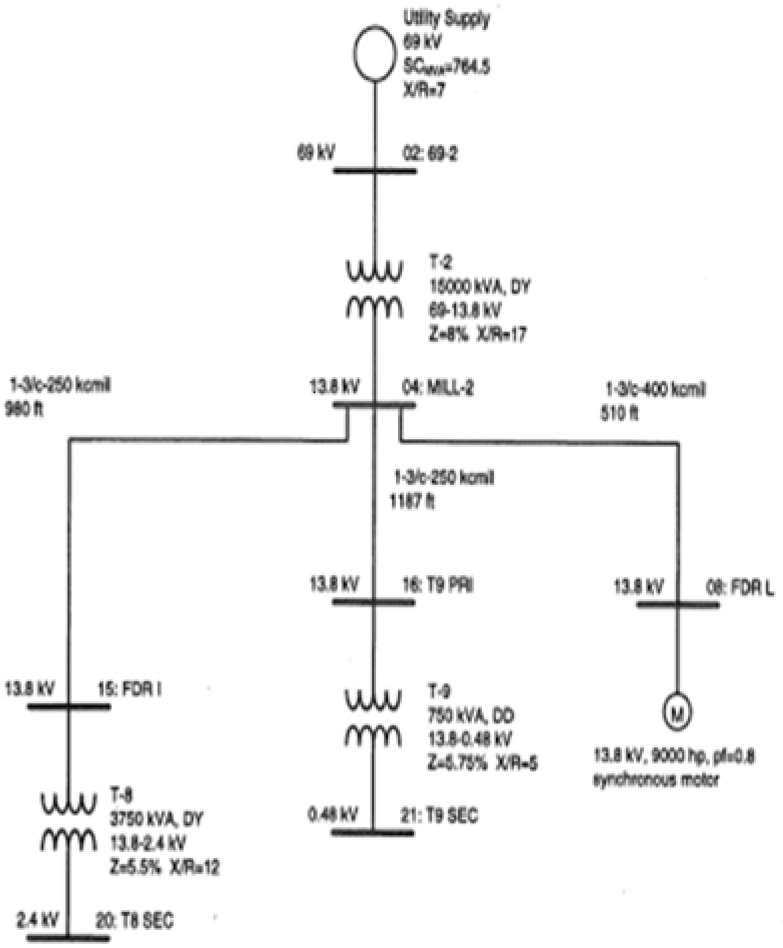
$$X_L = 0.0344 \times \frac{510}{1000} = 0.0175\ \Omega$$

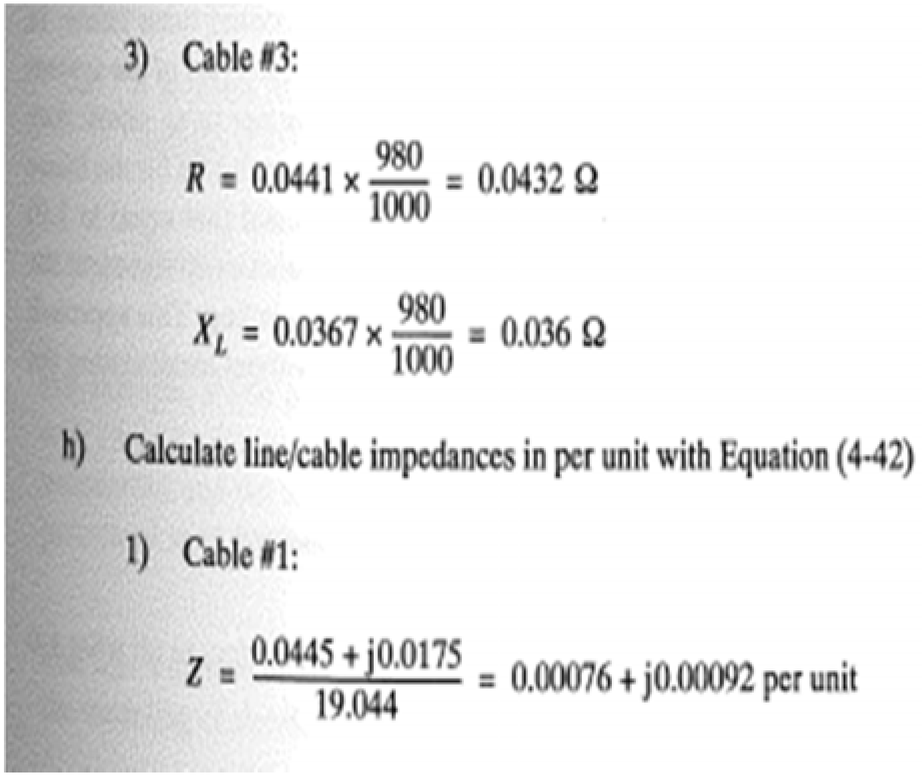
2) Cable #2:

$$R = 0.0441 \times \frac{1187}{1000} = 0.0523\ \Omega$$

$$X_L = 0.0367 \times \frac{1187}{1000} = 0.0436\ \Omega$$

EXAMPLE





3) Cable #3:

$$R = 0.0441 \times \frac{980}{1000} = 0.0432\ \Omega$$

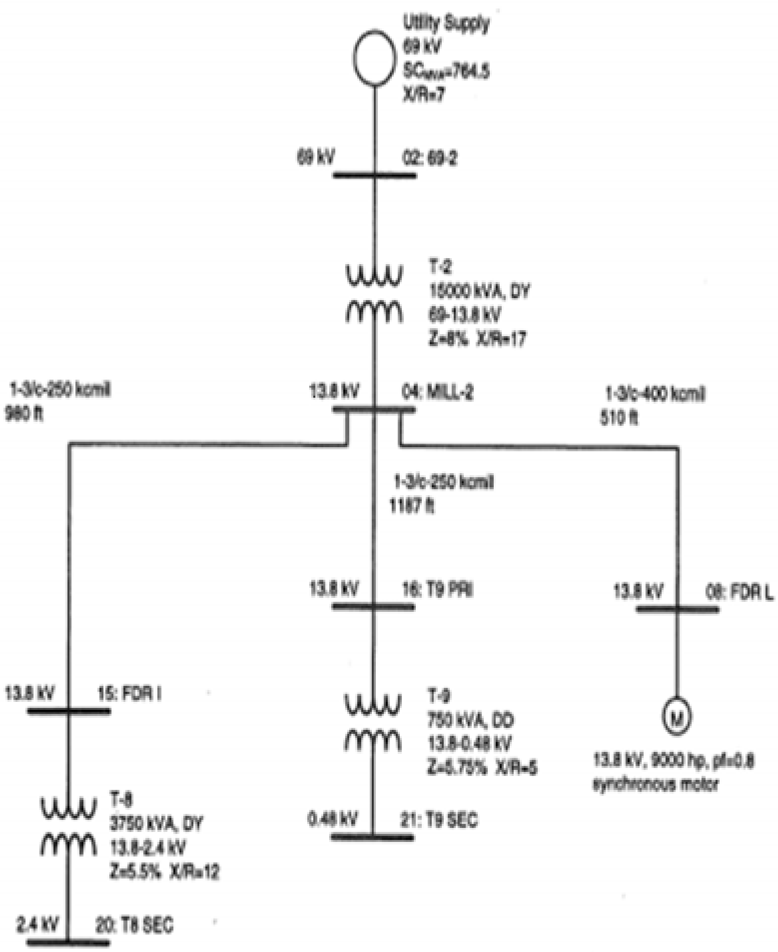
$$X_L = 0.0367 \times \frac{980}{1000} = 0.036\ \Omega$$

h) Calculate line/cable impedances in per unit with Equation (4-42)

1) Cable #1:

$$Z = \frac{0.0445 + j0.0175}{19.044} = 0.00076 + j0.00092 \text{ per unit}$$

EXAMPLE



2) Cable #2:

$$Z = \frac{0.0523 + j0.0436}{19.044} = 0.00275 + j0.00229 \text{ per unit}$$

3) Cable #3:

$$Z = \frac{0.0432 + j0.036}{19.044} = 0.00227 + j0.00189 \text{ per unit}$$

i) Calculate X'_d of the synchronous machine in per unit with Equation (4-43)

1) Synchronous motor on bus 08:FDR L:

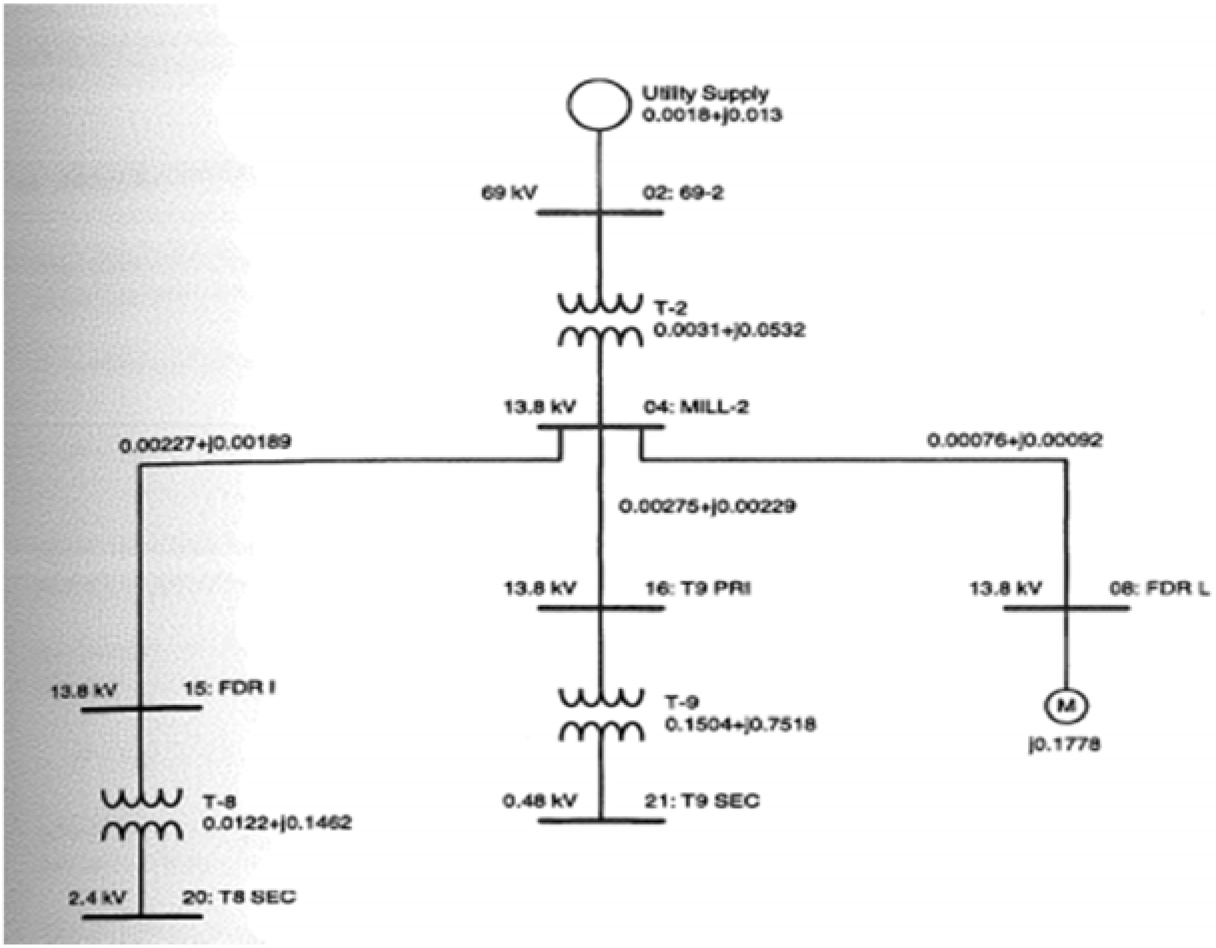
$$X'_d = j0.2 \times \frac{13.8^2}{13.8^2} \times \frac{10\,000}{9\,000/0.8} = j0.1778 \text{ per unit}$$

j) Calculate the utility system impedance in per unit

1) at bus 02: 69-2:

$$Z = (0.876 + j6.1655) \times \frac{10}{69^2} = 0.0018 + j0.013 \text{ per unit}$$

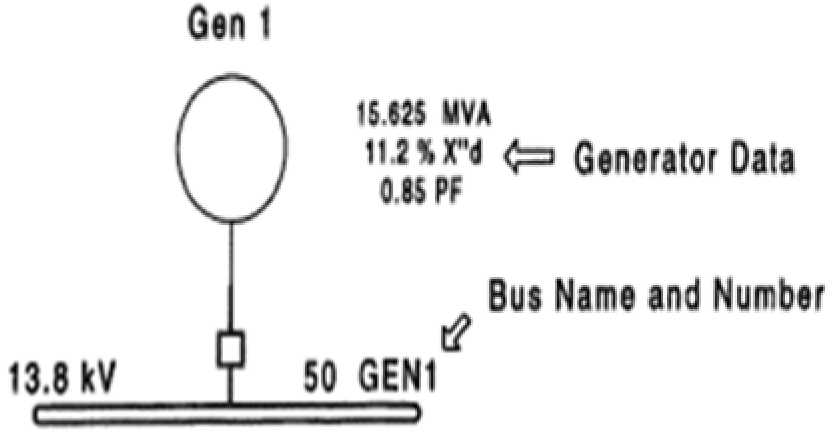
EXAMPLE


Utility Supply
0.0018+j0.013
69 kV
02: 69-2
T-2
0.0031+j0.0532
13.8 kV
04: MILL-2
0.00227+j0.00189
0.00076+j0.00092
0.00275+j0.00229
13.8 kV
16: T9 PRI
13.8 kV
08: FDR L
13.8 kV
15: FDR I
T-9
0.1504+j0.7518
M
j0.1778
0.48 kV
21: T9 SEC
T-8
0.0122+j0.1462
2.4 kV
20: T8 SEC

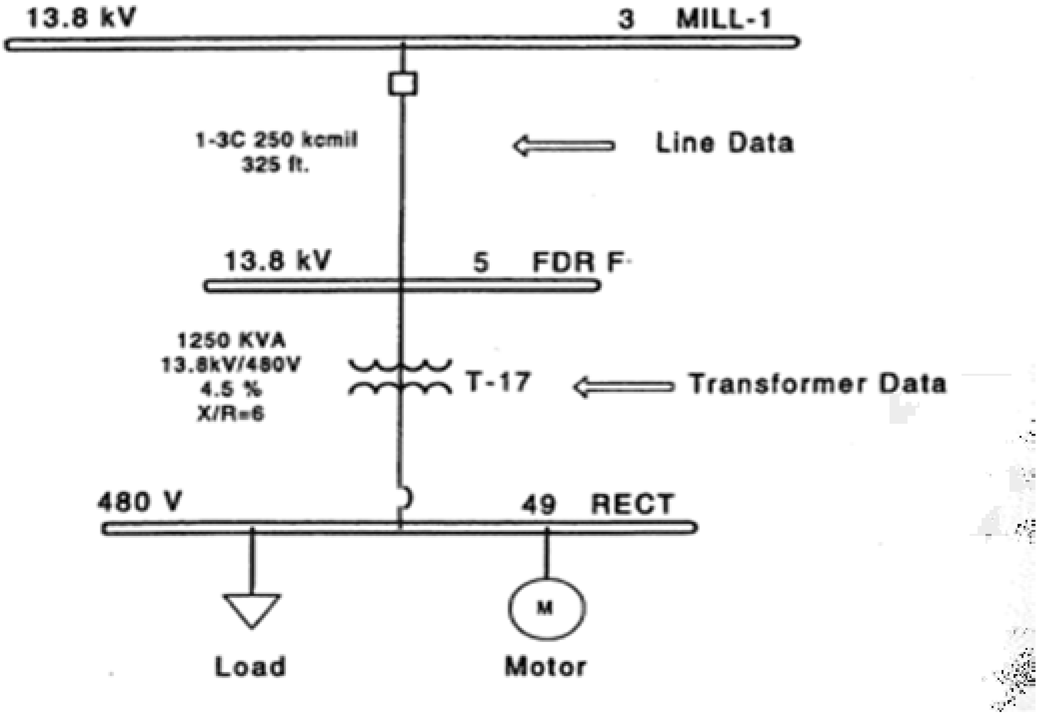
ELECTRICAL REPRESENTATIONS

- Swing Bus
  - accounts for losses in the system
- Load Buses
  - any bus without a generator
- Generator Buses
  - Can contain load and generators
- Disconnected Buses

ELECTRICAL REPRESENTATIONS



ELECTRICAL REPRESENTATIONS



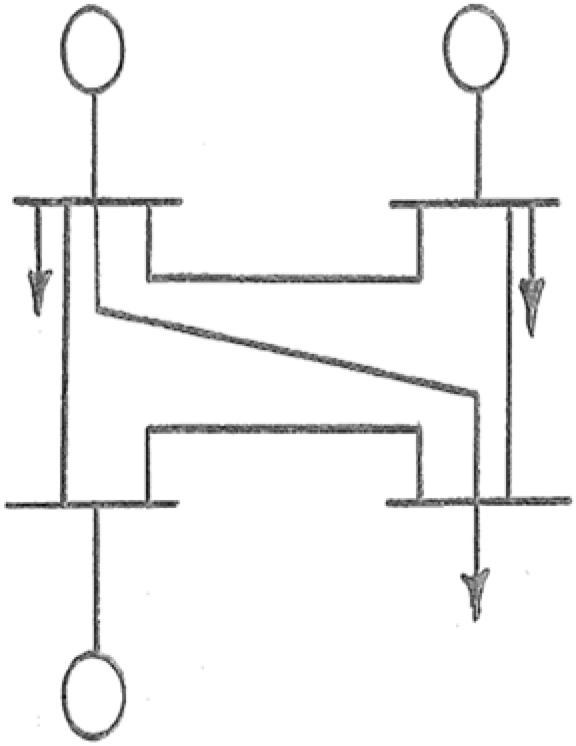
ELECTRICAL REPRESENTATIONS

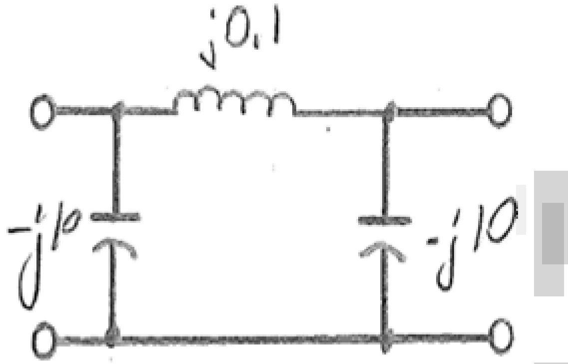
- Power Flow Equations:
  - $[\mathbf{I}] = [\mathbf{Y}] * [\mathbf{V}]$

- Bus Current
  - $I = (P + jQ)^*/V^*$

EXAMPLE

GIVEN:





ELEMENT VALUES ARE IMPEDANCES

REQUIRED: FIND Y_{BUS}

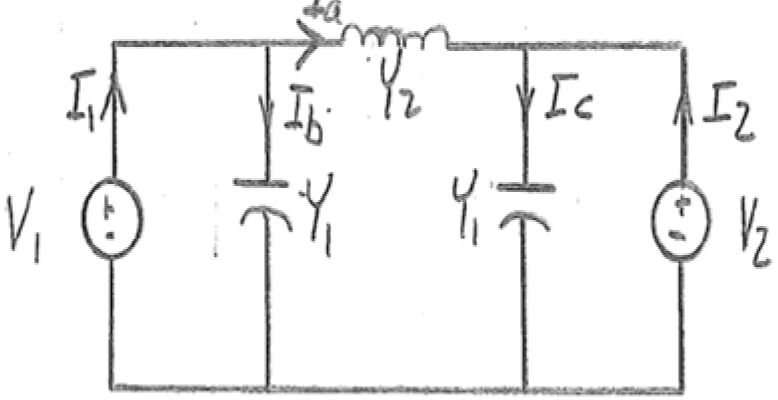
EXAMPLE

SOLUTION; CONSIDER BUS 1 - BUS 2:

$$Y_1 = 1/-j10 = j\,0.1$$

$$Y_2 = 1/j\,0.1 = -j10$$

(I)



KCL@BUS 1: $I_1 = I_a + I_b$

KCL@BUS 2: $I_2 = I_c - I_a$

$I_a = (V_1 - V_2)\,Y_2$ & $I_b = (V_1 - 0)\,Y_1$

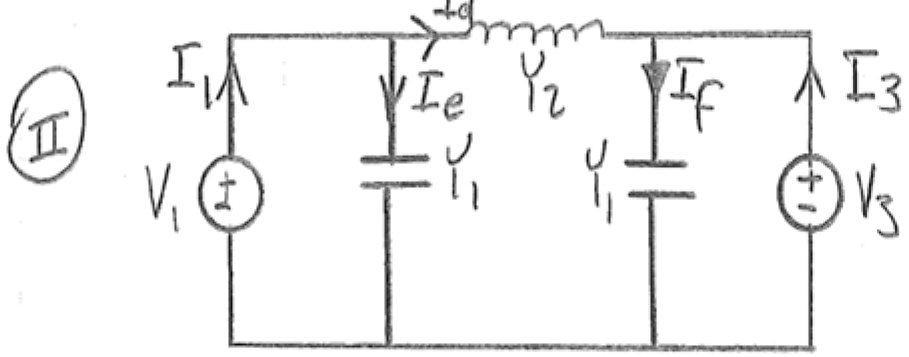
$I_c = (V_2 - 0)\,Y_1$

$$\boxed{\therefore I_1 = (Y_1 + Y_2)V_1 - Y_2 V_2}$$

$$\boxed{\therefore I_2 = -Y_2 V_1 + (Y_1 + Y_2)V_2}$$

EXAMPLE

CONSIDER BUS 1 – BUS 3:



KCL @ Bus 1: $I_1 = I_d + I_e$

$I_d = (V_1 - V_3)Y_2 \quad I_e = V_1 Y_1$

$$\therefore I_1 = (Y_1 + Y_2)V_1 - Y_2 V_3$$

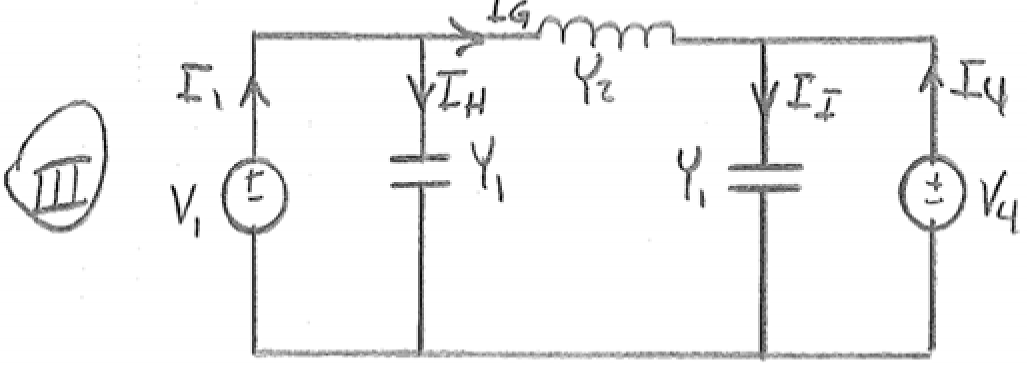
KCL @ Bus 3: $I_3 = I_f - I_d$

$I_f = Y_1 V_3$

$$\therefore I_3 = -Y_2 V_1 + (Y_1 + Y_2)V_3$$

EXAMPLE

SOLUTION: CONSIDER BUS 1 - BUS 4:



KCL @ BUS 1: $I_1 = I_G + I_H$

$I_G = (V_1 - V_4) Y_2$; $I_H = V_1 Y_1$

$$\therefore I_1 = (Y_1 + Y_2) V_1 - Y_2 V_4$$

KCL @ BUS 4: $I_4 = I_I - I_G$

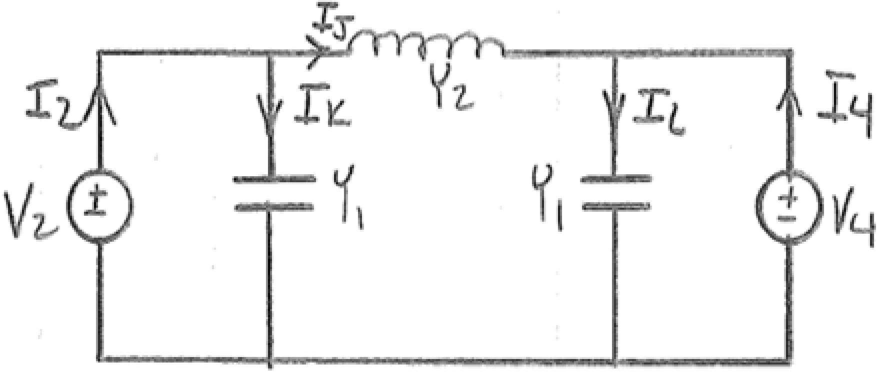
$I_I = Y_1 V_4$

$$\therefore I_4 = -Y_2 V_1 + (Y_1 + Y_2) V_4$$

EXAMPLE

CONSIDER BUS 2 - BUS 4:

IV



KCL @ BUS 2: $I_2 = I_J + I_K$

$I_J = (V_2 - V_4)Y_2$; $I_K = V_2 Y_1$

$$\boxed{\therefore I_2 = (Y_1 + Y_2)V_2 - Y_2 V_4}$$

KCL @ BUS 4: $I_4 = I_L - I_J$

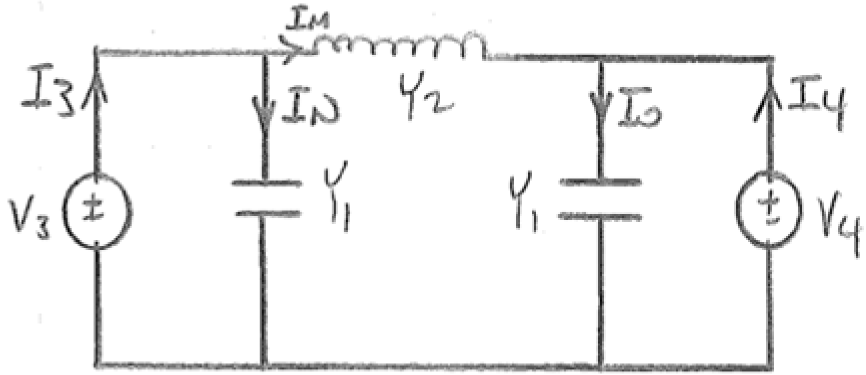
$I_L = Y_1 V_4$

$$\boxed{\therefore I_4 = -Y_2 V_2 + (Y_1 + Y_2)V_4}$$

EXAMPLE

Consider Bus 3 - Bus 4:

(V)



KCL @ Bus 3: $I_3 = I_M + I_N$

$I_M = (V_3 - V_4)Y_2$; $I_N = V_3 Y_1$

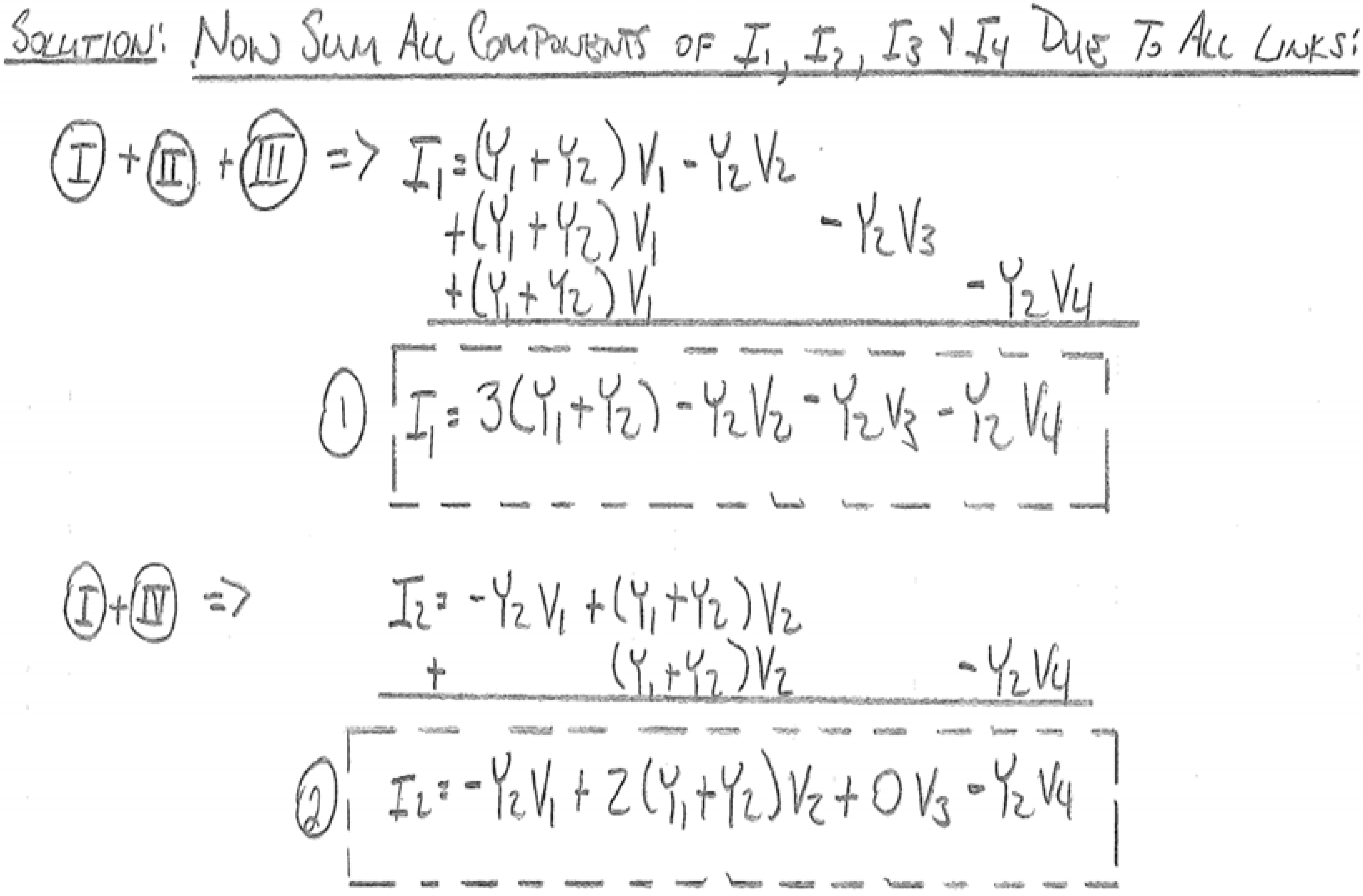
$$\boxed{\therefore I_3 = (Y_1 + Y_2)V_3 - Y_2 V_4}$$

KCL @ Bus 4: $I_4 = I_O - I_M$

$I_O = Y_1 V_4$

$$\boxed{\therefore I_4 = -Y_2 V_3 + (Y_1 + Y_2) V_4}$$

EXAMPLE



SOLUTION: NOW SUM ALL COMPONENTS OF I_1, I_2, I_3 Y I_4 DUE TO ALL LINKS:

$$
\text{Ⅰ} + \text{Ⅱ} + \text{Ⅲ} \Rightarrow \quad
\begin{array}{rl}
I_1 = & (Y_1+Y_2)V_1 - Y_2V_2 \\
& +(Y_1+Y_2)V_1 - Y_2V_3 \\
& +(Y_1+Y_2)V_1 - Y_2V_4 \\
\hline
\end{array}
$$

$$
① \quad \boxed{I_1 = 3(Y_1+Y_2) - Y_2V_2 - Y_2V_3 - Y_2V_4}
$$

$$
\text{Ⅰ} + \text{Ⅳ} \Rightarrow \quad
\begin{array}{rl}
I_2 = & -Y_2V_1 + (Y_1+Y_2)V_2 \\
+ & (Y_1+Y_2)V_2 - Y_2V_4 \\
\hline
\end{array}
$$

$$
② \quad \boxed{I_2 = -Y_2V_1 + 2(Y_1+Y_2)V_2 + 0V_3 - Y_2V_4}
$$

EXAMPLE

(II) + (V) ⇒

$$\begin{array}{rl} I_3 = -Y_2V_1 + & (Y_1+Y_2)V_3 \\ + & (Y_1+Y_2)V_3 - Y_2V_4 \\ \hline \end{array}$$

③ $$\boxed{I_3 = -Y_2V_1 + 0V_2 + 2(Y_1+Y_2)V_3 - Y_2V_4}$$

(III) + (IV) + (V) ⇒

$$\begin{array}{rrrr} I_4 = -Y_2V_1 & & & +(Y_1+Y_2)V_4 \\ + & -Y_2V_2 & & +(Y_1+Y_2)V_4 \\ + & & -Y_2V_3 & +(Y_1+Y_2)V_4 \\ \hline \end{array}$$

④ $$\boxed{I_4 = -Y_2V_1 - Y_2V_2 - Y_2V_3 + 3(Y_1+Y_2)V_4}$$

EXAMPLE

NOW INSERT CALCULATED VALUES OF APPROPRIATE ADMITTANCES!

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} = \underbrace{\begin{bmatrix} -j29.7 & j10 & j10 & j10 \\ j10 & -j19.8 & j0 & j10 \\ j10 & 0 & -j19.8 & j10 \\ j10 & j10 & j10 & -j29.7 \end{bmatrix}}_{Y_{BUS}} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix}$$

EXAMPLE

GIVEN:

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} = \begin{bmatrix} -j29.7 & j10 & j10 & j10 \\ j10 & -j19.8 & 0 & j10 \\ j10 & 0 & -j19.8 & j10 \\ j10 & j10 & j10 & -j29.7 \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix}$$

REQUIRED: WRITE THE GIVEN POWER FLOW EQUATIONS IN THE FORM: $S_i = V_i \left(\sum_{k=1}^{N} y_{ik} V_k \right)^*$

EXAMPLE

Solution: $I_1 = (-j29.7)V_1 + (j10)V_2 + (j10)V_3 + (j10)V_4$

$I_2 = (j10)V_1 - (j19.8)V_2 + (j10)V_4$

$I_3 = (j10)V_1 - (j19.8)V_3 + (j10)V_4$

$I_4 = (j10)V_1 + (j10)V_2 + (j10)V_3 - (j29.7)V_4$

EXAMPLE

NOW FIND I_1^*, I_2^*, I_3^* & I_4^*:

$$I_1^* = (j29.7)V_1^* - (j10)V_2^* - (j10)V_3^* - (j10)V_4^*$$

$$I_2^* = -(j10)V_1^* + (j19.8)V_2^* - (j10)V_4^*$$

$$I_3^* = -(j10)V_1^* + (j19.8)V_3^* - (j10)V_4^*$$

$$I_4^* = -(j10)V_1^* - (j10)V_2^* - (j10)V_3^* + (j29.7)V_4^*$$

EXAMPLE

NOW CALCULATE S_1, S_2, S_3 & S_4:

$$S_1 = V_1 I_1^* = \underbrace{V_1\{(j29.7)V_1}{}^* - (j10)V_2^* - (j10)V_3^* - (j10)V_4^*\}$$

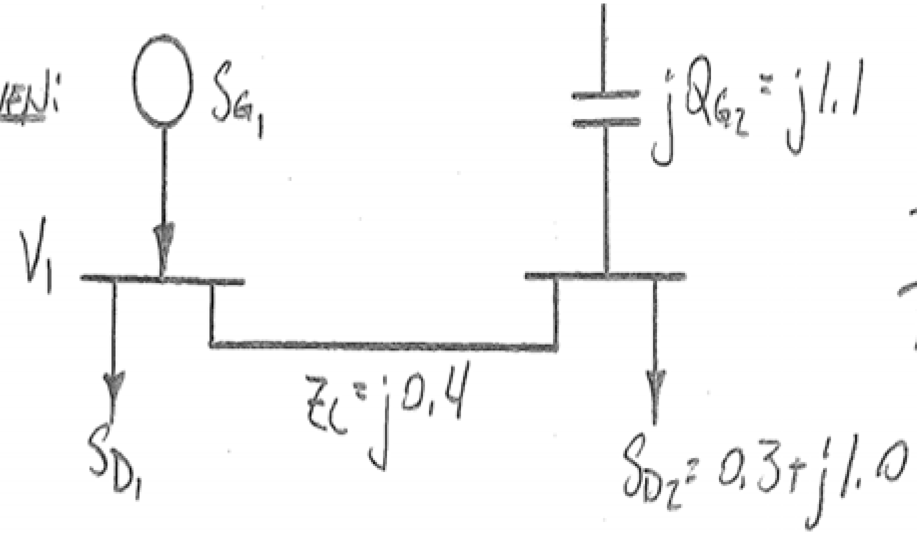
$$S_2 = V_2 I_2^* = V_2\{-(j10)V_1^* + (j19.8)V_2^* - (j10)V_4^*\}$$

$$S_3 = V_3 I_3^* = V_3\{-(j10)V_1^* + (j19.8)V_3^* - (j10)V_4^*\}$$

$$S_4 = V_4 I_4^* = V_4\{-(j10)V_1^* - (j10)V_2^* - (j10)V_3^* + (j29.7)V_4^*\}$$

EXAMPLE

GIVEN:



$V_1 = 1\angle 0^\circ$

BUS 1: $V_1 \angle \delta_1$ KNOWN ∴ SLACK BUS
BUS 2: P, Q KNOWN ∴ LOAD BUS

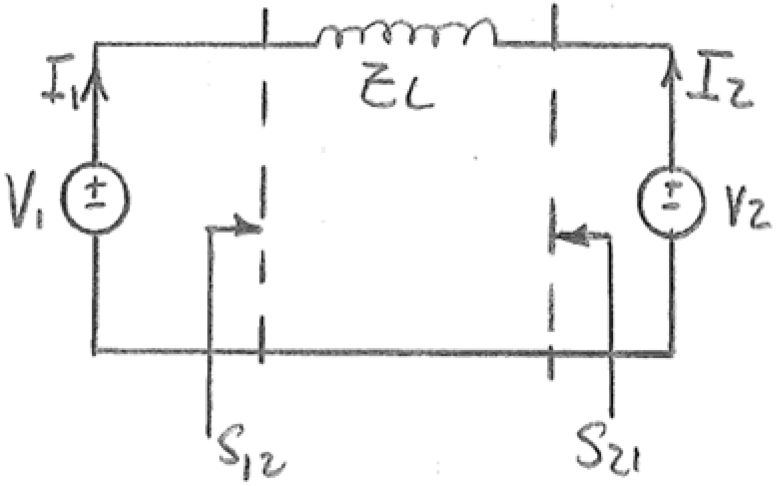
REQUIRED: (a) FIND V_2 EXACTLY (TAKE THE LARGER OF TWO POSSIBLE VALUES).
(b) FIND V_2 BY GAUSS ITERATION STARTING WITH $V_2^0 = 1\angle 0^\circ$. IF YOU USE HAND CALCULATION, STOP AFTER ONE ITERATION
(c) FIND $S_1 = S_{G_1} - S_{D_1}$

EXAMPLE

SOLUTION: (a) $S_2 = S_{G_2} - S_{D_2} = (0+j1.1)-(0.3+j1.0)$

$$\boxed{S_2 = -0.3 + j0.1}$$

EQUIVALENT MODEL:



$$Y_L = \frac{1}{Z_L} = \frac{1}{j0.4} = -j2.5$$

$$\begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} -j2.5 & j2.5 \\ j2.5 & -j2.5 \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix}$$

EXAMPLE

SOLVE FOR I_1 & I_2: (1) $I_1 = -j2.5V_1 + j2.5V_2$

(2) $I_2 = j2.5V_1 - j2.5V_2$

SOLVE FOR $S_1 = V_1 I_1^*$ & $S_2 = V_2 I_2^*$:

(3) $S_1 = V_1 \{ j2.5V_1^* - j2.5V_2^* \}$

(4) $S_2 = V_2 \{ -j2.5V_1^* + j2.5V_2^* \}$

$$S_1 = |V_1|^2 (2.5\angle 90^\circ) - |V_1||V_2|^* (2.5\angle 90^\circ)$$

$$= 2.5|V_1|^2 e^{j90^\circ} - |V_1||V_2|(2.5)e^{j(90-\delta_2)}$$

EXAMPLE

$$S_1 = 2.5|V_1|^2\{\cos(\cancelto{0}{90^\circ}) + j\sin(90^\circ)\} - |V_1||V_2|(2.5)\{\cos(90^\circ - \delta_2) + j\sin(90^\circ - \delta_2)\}$$

$$P_1 = -2.5|V_1||V_2|(-\sin\delta_2) \Rightarrow \boxed{P_1 = 2.5|V_1||V_2|\sin\delta_2}$$

$$\underline{Q_1 = 2.5|V_1|^2 - 2.5|V_1||V_2|\sin(90^\circ - \delta_2)}$$

$$\boxed{Q_1 = 2.5|V_1|^2 - 2.5|V_1||V_2|\cos\delta_2}$$

EXAMPLE

SOLUTION: (4) $S_2 = -|V_2||V_1|(2.5\angle +90^\circ)(\cancelto{0}{\angle -\delta_1})(\angle \delta_2) + (2.5\angle 90^\circ)|V_2|^2$

$$S_2 = 2.5|V_2|^2 e^{j90^\circ} - 2.5|V_2||V_1| e^{j(90+\delta_2)}$$

$$S_2 = 2.5|V_2|^2\{\cos\cancelto{0}{(90^\circ)} + j\,\cancelto{1}{\sin(90^\circ)}\} - 2.5|V_2||V_1|\{\cos(90^\circ+\delta_2) + j\sin(90^\circ+\delta_2)\}$$

$$P_2 = -2.5|V_2||V_1|(-\sin\delta_2)$$

$$\boxed{P_2 = 2.5|V_2||V_1|\sin\delta_2}$$

$$\boxed{Q_2 = 2.5|V_2|^2 - 2.5|V_2||V_1|\cos\delta_2}$$

EXAMPLE

$$P_2 = 2.5|V_2||1|\sin\delta_2 = -0.3$$

$$Q_2 = -2.5|V_2||1|\cos\delta_2 = -2.5|V_2|^2 + 0.1$$

$$P_2^2 + Q_2^2 = 6.25|V_2|^2\sin^2\delta_2 + 6.25|V_2|^2\cos^2\delta_2 = 0.10 + 6.25|V_2|^4 - 0.5|V_2|^2$$

$$P_2^2 + Q_2^2 = 6.25|V_2|^2\underbrace{\left\{\sin^2\delta_2 + \cos^2\delta_2\right\}}_{1} = 0.10 + 6.25|V_2|^4 - 0.5|V_2|^2$$

$$P_2^2 + Q_2^2 = 6.25|V_2|^4 - 6.75|V_2|^2 + 0.10 = 0$$

EXAMPLE

LET $x = |V_2|^2$

$$\therefore\ x^2 - 1.08x + 0.016 = 0$$

$$x = |V_2|^2 = \frac{-(-1.08) \pm \sqrt{(1.08)^2 - (4)(1)(0.016)}}{2(1)}$$

$$|V_2|^2 = 0.54 \pm 0.5\sqrt{1.10240}$$

$$|V_2| = \sqrt{1.06498} \Rightarrow \boxed{|V_2| = 1.032}$$

OR

$$|V_2| = \sqrt{0.01502} \Rightarrow |V_2| = 0.12257$$

EXAMPLE

FIND δ_2: $P_2 = 2.5 \, |1.032| \, |1| \sin\delta_2 = -0.3$

$$\delta_2 = \sin^{-1}(-0.11628)$$

$$\boxed{\delta_2 = -6.677^\circ} \qquad \therefore \boxed{V_2 = 1.032 \angle \underline{-6.677^\circ}}$$

EXAMPLE

SOLUTION: (b) $S_i = V_i \sum_{k=1}^{n} Y_{ik}^* V_k^* \Rightarrow \sum_{k=1}^{n} Y_{ik} V_k = \frac{S_i^*}{V_i^*} = Y_{ii} V_i + \sum_{\substack{k=1 \\ k \neq i}}^{n} Y_{ik} V_k$

$$V_i = \frac{1}{Y_{ii}} \left[\frac{S_i^*}{V_i^*} - \sum_{\substack{k=1 \\ k \neq i}}^{n} Y_{ik} V_k \right]$$

EXAMPLE

$S_2 = -0.3 + j0.1$ ASSUME $V_2 = 1\angle 0^\circ$

$$V_2 = j0.4\left[\frac{-0.3-j0.1}{1-j0} - j2.5\,(1\angle 0^\circ)\right]$$

$$V_2 = 0.4\angle 90^\circ\left[\frac{0.31623\angle -161.565^\circ}{1\angle 0^\circ} - 2.5\angle 90^\circ\right]$$

$$V_2 = 0.4\angle 90^\circ\left[0.31623\angle -161.565^\circ - 2.5\angle 90^\circ\right]$$

$$V_2 = (0.4\angle 90^\circ)(-0.3-j0.1 - j2.5)$$

EXAMPLE

$$V_2 = (0.4\angle 90^\circ)(-0.3 - j0.1 - j2.5)$$

$$V_2 = (0.4\angle 90^\circ)(-0.3 - j2.6) = (0.4\angle 90^\circ)(2.61725\angle -96.5819^\circ)$$

$$\boxed{V_2 = 1.0469\angle -6.582^\circ}$$

END OF ITERATION #1 ✓

(c) $S_1 = V_1 I_1^* = 2.5|V_1||V_2|\sin\delta_{12} + j\left(2.5|V_1|^2 - 2.5|V_1||V_2|\cos\delta_{12}\right)$

$$S_1 = S_{G_1} - S_{D_1} = (2.5)(|1|)(|1.032|)\sin(+6.677^\circ) + j\left((2.5)(|1|)^2 - (2.5)(1)(1.032)\cos(+6.677^\circ)\right)$$

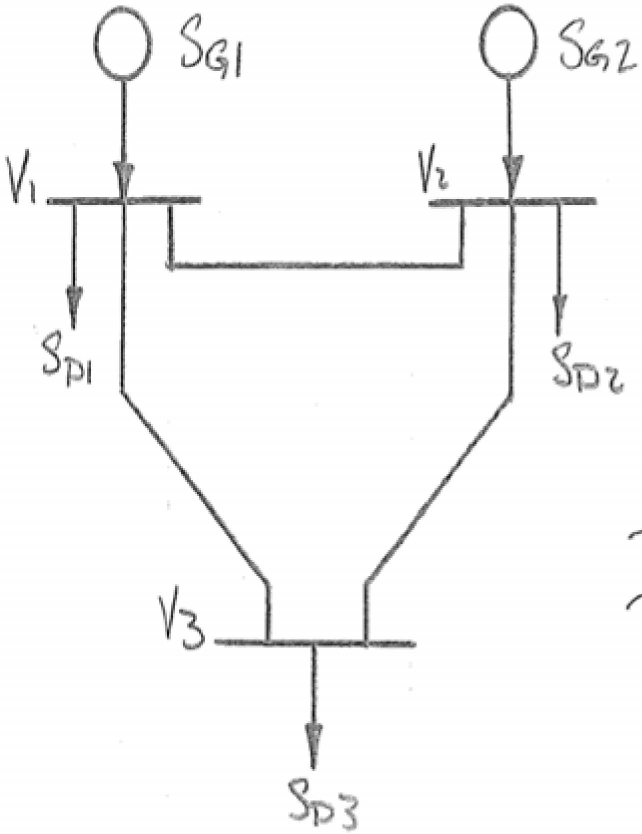
$$\boxed{S_1 = S_{G_1} - S_{D_1} = +0.30 - j\,0.0625}$$

USING V_2 RESULT IN PART (a)

✓

EXAMPLE

GIVEN:



$S_{D1} = 1.0$ $V_1 = 1\angle 0^\circ$
$S_{D2} = 1.0 - j0.8$ $V_2 = 1\angle\delta_2$
$S_{D3} = 1.0 + j0.6$ $P_{G2} = 0.8$

$Z_L = j0.4$; ALL LINES

BUS 1: SLACK BUS; $V_1\angle\delta_1$ KNOWN
BUS 2: GENERATOR BUS; P_2, $|V_2|$ KNOWN
BUS 3: LOAD BUS; P_3 & Q_3 KNOWN

REQUIRED: USE GAUSS ITERATION TO FIND $\angle\delta_2$, V_3 & V_2. ASSUME $V_2^0 = V_3^0 = 1\angle 0^\circ$. DO ONE ITERATION ONLY.

EXAMPLE

SOLUTION:

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \begin{bmatrix} -j5.0 & j2.5 & j2.5 \\ j2.5 & -j5.0 & j2.5 \\ j2.5 & j2.5 & -j5.0 \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix}$$

(1) $I_1 = (-j\,5.0\,V_1) + j(2.5\,V_2) + j(2.5\,V_3)$

(2) $I_2 = j\,2.5\,V_1 - j\,5.0\,V_2 + j\,2.5\,V_3$

(3) $I_3 = j\,2.5\,V_1 + j\,2.5\,V_2 - j\,5.0\,V_3$

EXAMPLE

$$Q_2^0 = \text{IMAGINARY}\left[V_2 \underline{\angle \delta_2} \left\{ -j2.5\,V_1^* + j5.0\,V_2^* - j2.5\,V_3^* \right\} \right]$$

$$Q_2^0 = \text{IMAGINARY}\left\{ +j2.5\,|V_1||V_2^0|e^{j(\delta_2-\delta_1)} + j5.0\,|V_2^0|^2 - j2.5\,|V_2^0||V_3^0|e^{j(\delta_2-\delta_3)} \right\}$$

$$Q_2^0 = \text{IMAGINARY}\{ -2.5\,|V_1||V_2^0|e^{j(90+\delta_2-\delta_1)} + 5.0\,|V_2^0|^2 e^{j(90^\circ)} - 2.5\,|V_2^0||V_3^0|e^{j(90^\circ+\delta_2-\delta_3)}$$

$$Q_2^0 = -2.5\,|V_1||V_2^0|\sin(90^\circ+\delta_2-\delta_1) + 5.0\,|V_2^0|^2 - 2.5\,|V_2^0||V_3^0|\sin(90^\circ+\delta_2-\delta_3)$$

EXAMPLE

ASSUMING: $V_2^0 = V_3^0 = 1\angle 0^\circ$

$$Q_2^0 = (-2.5)(1)(1)\sin(90^\circ) + 5.0(1)^2 - (2.5)(1)(1)\sin(90^\circ)$$

$$\boxed{Q_2^0 = -2.5 + 5.0 - 2.5 = 0}$$

EXAMPLE

SOLUTION: $S_i = V_i \sum_{k=1}^{n} Y_{ik}^{*} V_k^{*} \Rightarrow \frac{P_i - jQ_i}{V_i^{*}} = \sum_{k=1}^{n} Y_{ik} V_k$

$$V_i = \frac{1}{Y_{ii}}\left[\frac{P_i - jQ_i^{\nu}}{V_i^{\nu *}} - \sum_{\substack{k=1\\k\neq i}}^{n} Y_{ik} V_k\right]$$

$S_2 = S_{G2} - S_{D2} = 0.8 - (1.0 - j0.8)$

$\underline{\underline{S_2 = -0.2 + j0.8}}$

$$V_2^{(1)} = (j0.2)\left[\frac{-0.2 - j0.8}{1\angle 0^\circ} - (j2.5)(1\angle 0) - (j2.5)(1\angle 0^\circ)\right]$$

$$V_2^{(1)} = (0.2\angle 90^\circ)(-0.2 - j0.8 - j2.5 - j2.5)$$

$$V_2^{(1)} = (0.2\angle 90^\circ)(-0.2 - j5.8) = (0.2\angle 90^\circ)(5.80345\angle -91.9749^\circ)$$

EXAMPLE

$$V_2^{(1)} = 1.161\angle{-1.9749^\circ}$$

TO PROCEED I WOULD NEED TO CORRECT $V_2^{(1)}$ MAGNITUDE BACK TO 1.0

$$V_2^{(1)} = 1.00\angle{-1.9749^\circ}$$; CORRECTED

$$\underline{\underline{S_3 = -S_{D3} = -1.0 - j0.6}}$$

$$V_3^{(1)} = (j0.2)\left[\frac{-1.0 + j0.6}{1\angle 0^\circ} - j2.5(1\angle 0^\circ) - j2.5(1\angle 0^\circ)\right]$$

EXAMPLE

$$V_3^{(1)} = (0.2\angle 90^\circ)(-1 + j0.6 - j2.5 - j2.5)$$

$$V_3^{(1)} = (0.2\angle 90^\circ)(-1 - j4.4) = (0.2\angle 90^\circ)(4.51221\angle -102.804^\circ)$$

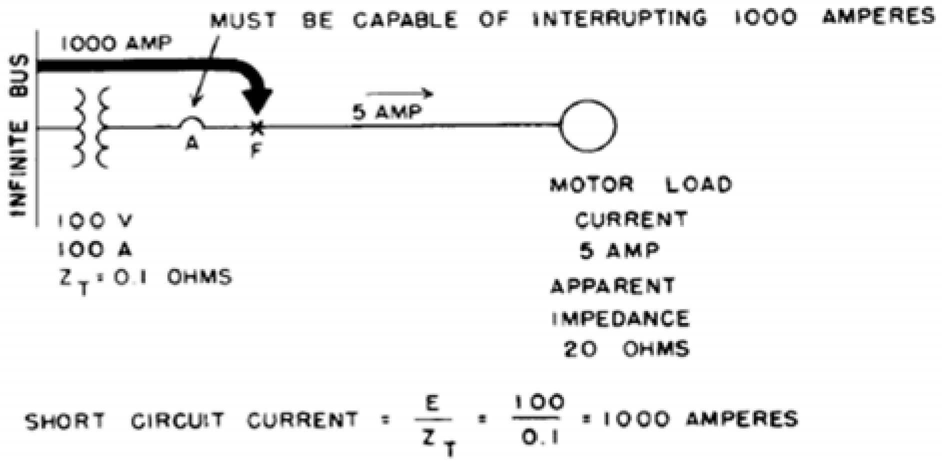
$$\boxed{V_3^{(1)} = 0.9024\angle -12.804^\circ} \quad \checkmark$$

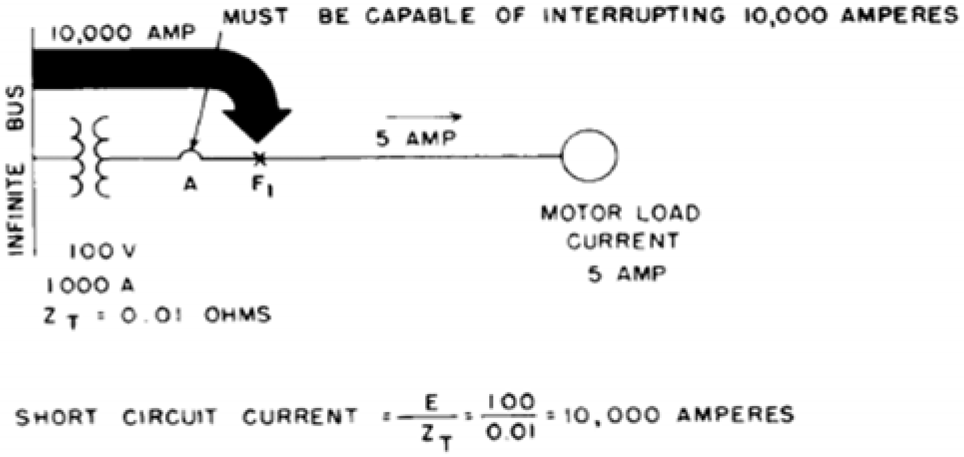
SHORT CIRCUIT

- Arcing and burning occurs
- Short circuit current flows from other locations to fault
- Equipment subjected to thermal and mechanical stresses due to I^2t heating
- System voltage drops in proportion to the magnitude of the short-circuit current

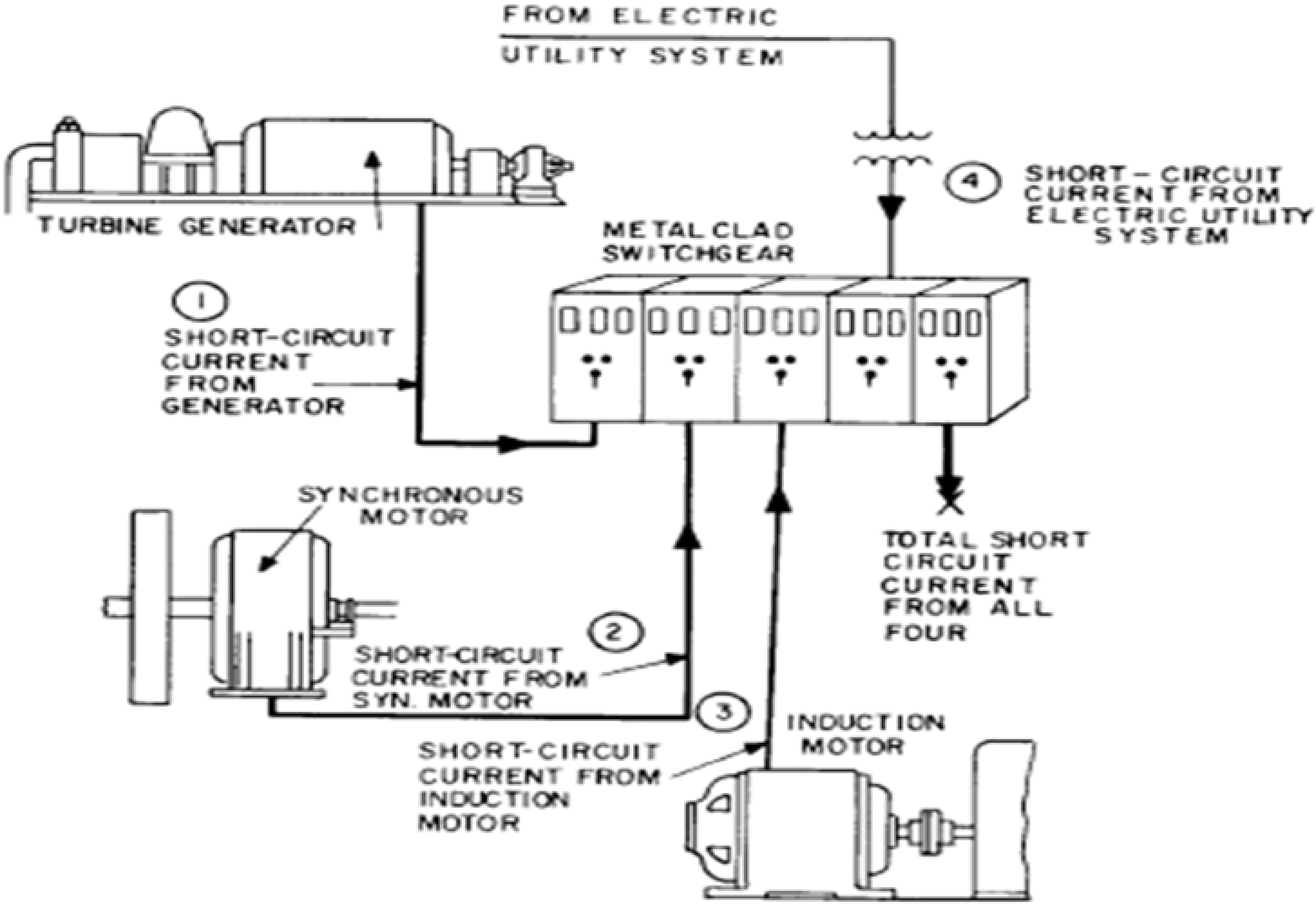
SHORT CIRCUIT

- **Available short circuit** current is also known as the **maximum** value of short circuit current.

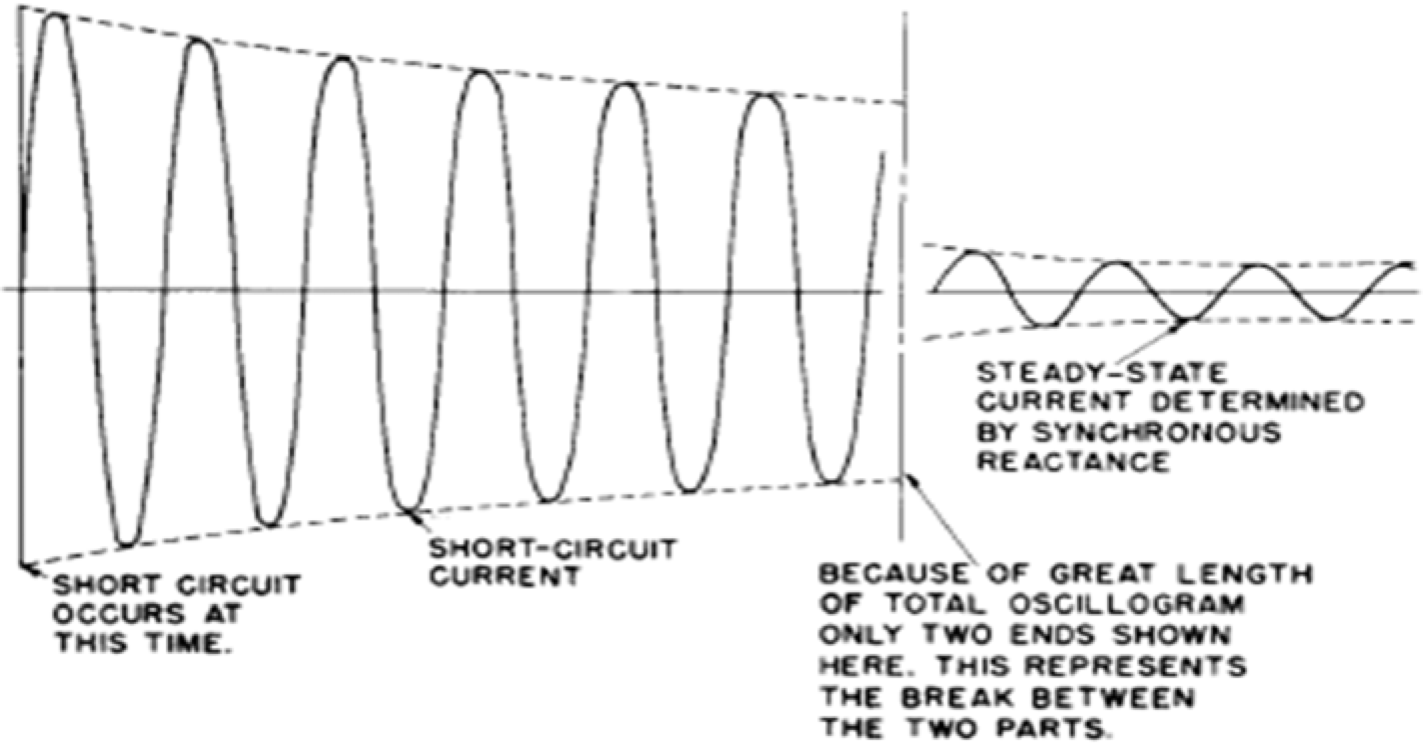




SHORT CIRCUIT



ROTATING MACHINES



ROTATING MACHINES

- Impedance of a rotating machine is primarily reactive.
- Impedance of a rotating machine changes with time
- Three values assigned to generators
  - Subtransient Reactance (X_d'')
  - Transient Reactance (X_d')
  - Synchronous Reactance (X_d)

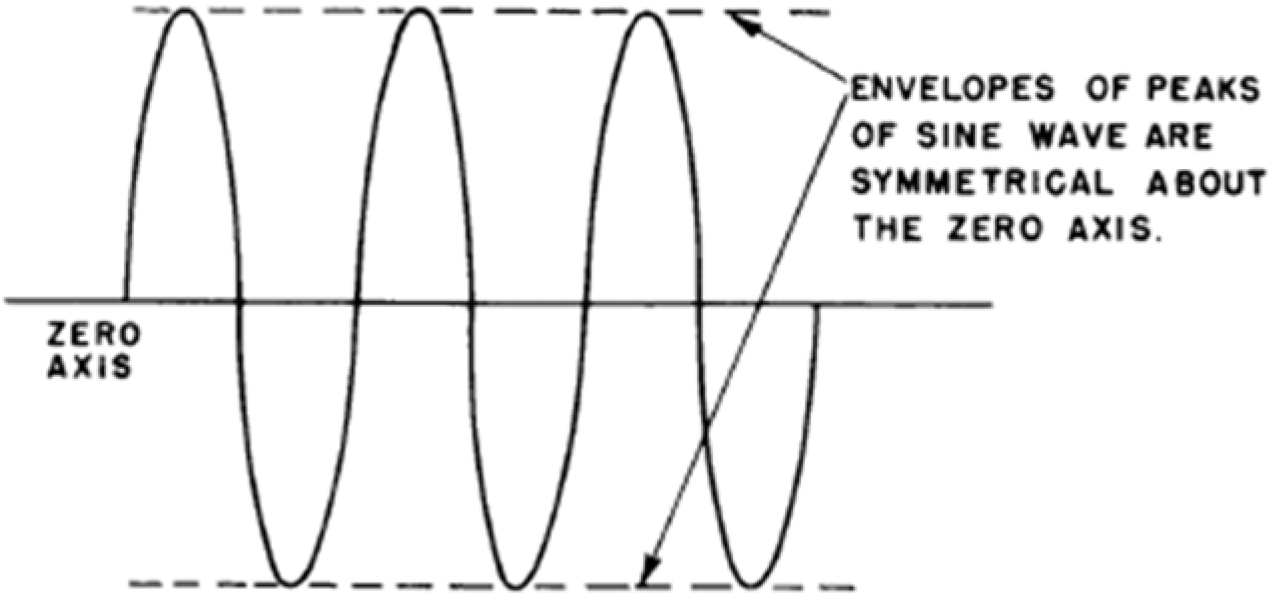
ROTATING MACHINES

- **Subtransient Reactance (X_d'')**
  - Apparent reactance of the stator winding at inception of a short-circuit for the first few cycles
- **Transient Reactance (X_d')**
  - Reactance of the stator that is used after the first few cycles to approximately 0.5 seconds
- **Synchronous Reactance (X_d)**
  - Reactance used for steady state solutions

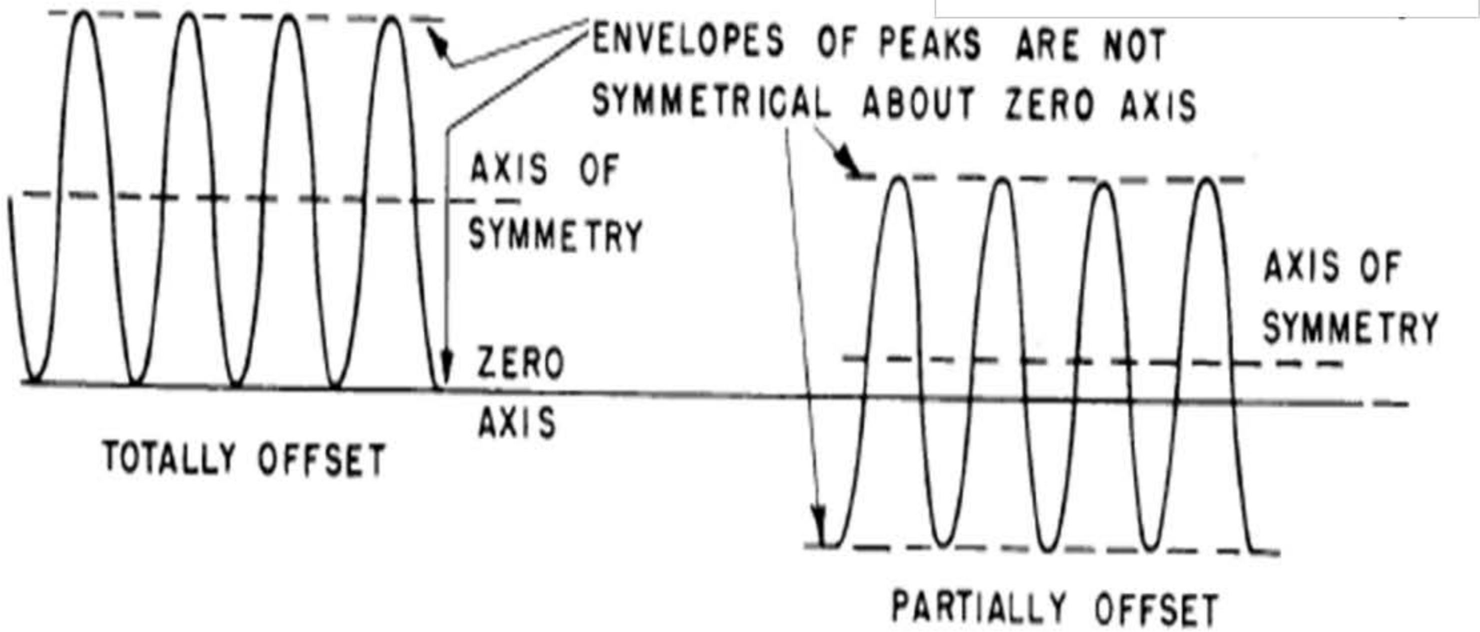
ROTATING MACHINES

- Synchronous motors and generators have similar reactance's for short circuit calculations.
- Induction motors have sub transient reactance only since there is no separate field to continue supplying current to the fault

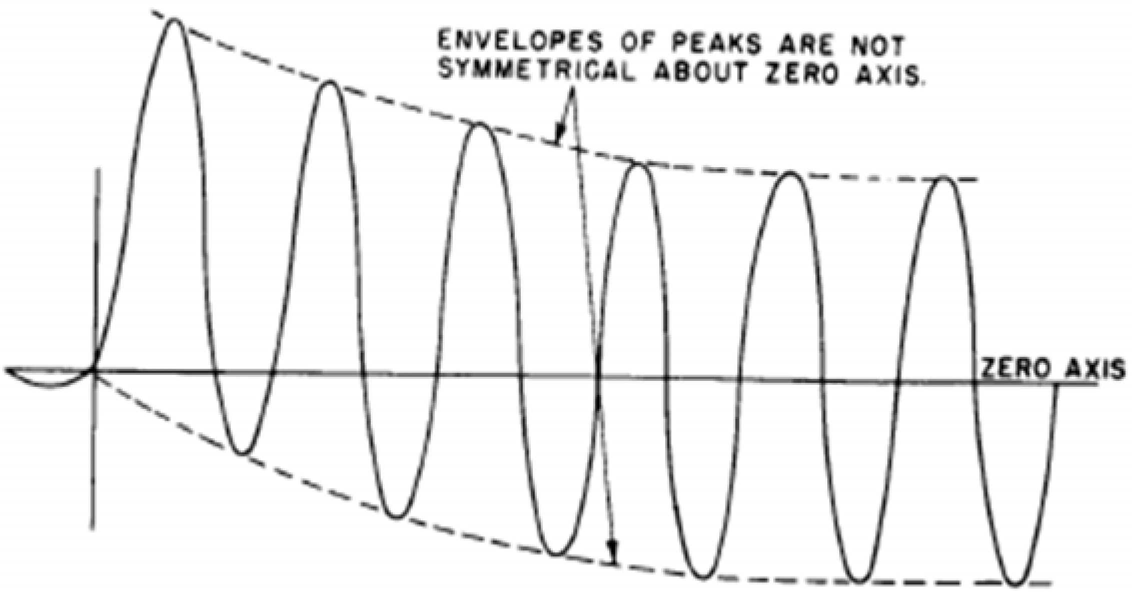
SYMMETRICAL CURRENT



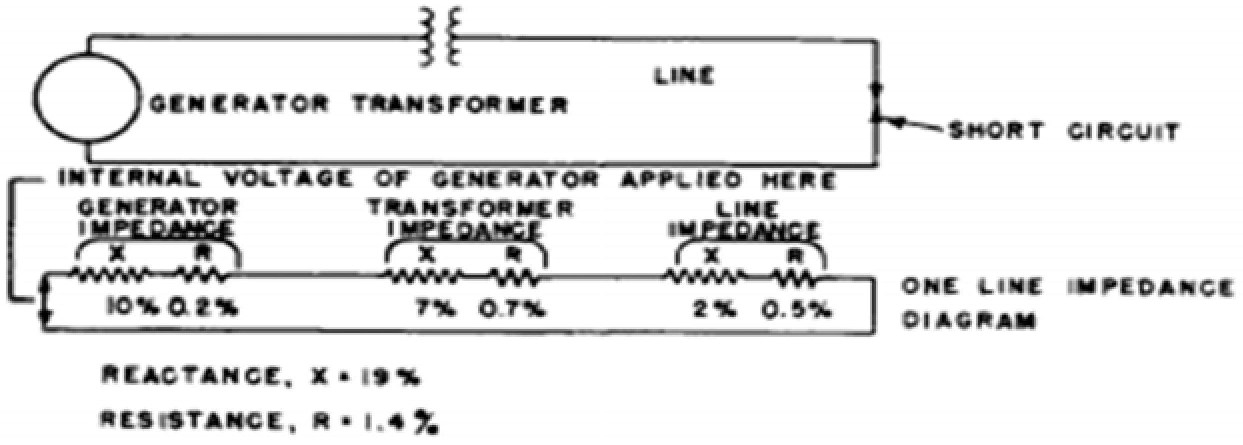
OFFSET CURRENT

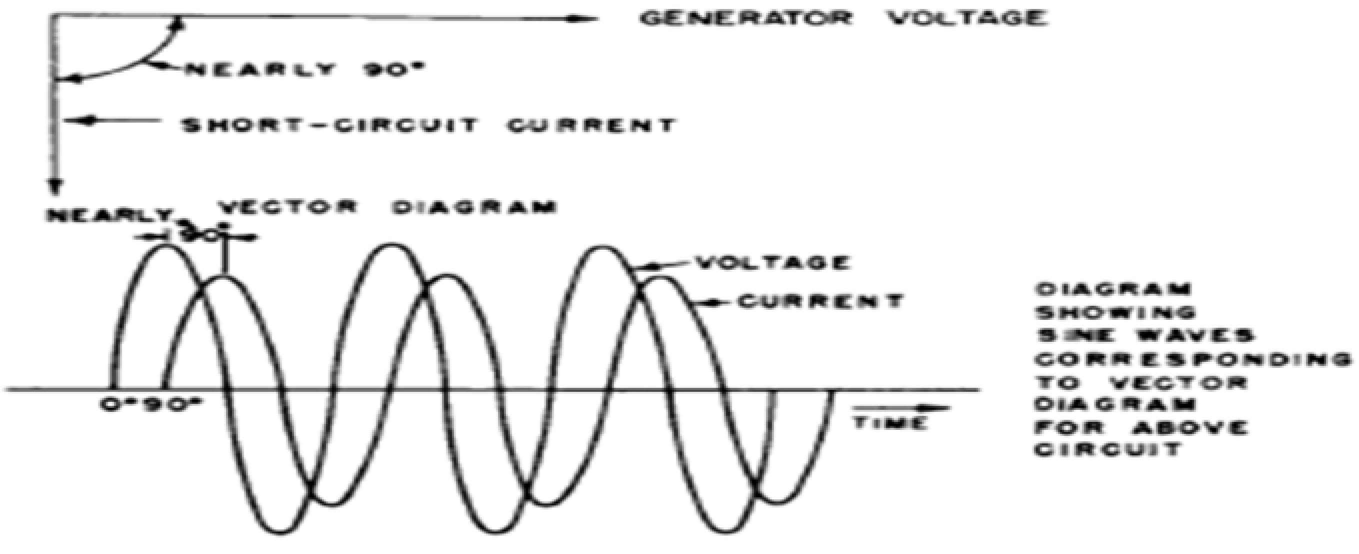


ASYMMETRICAL CURRENT

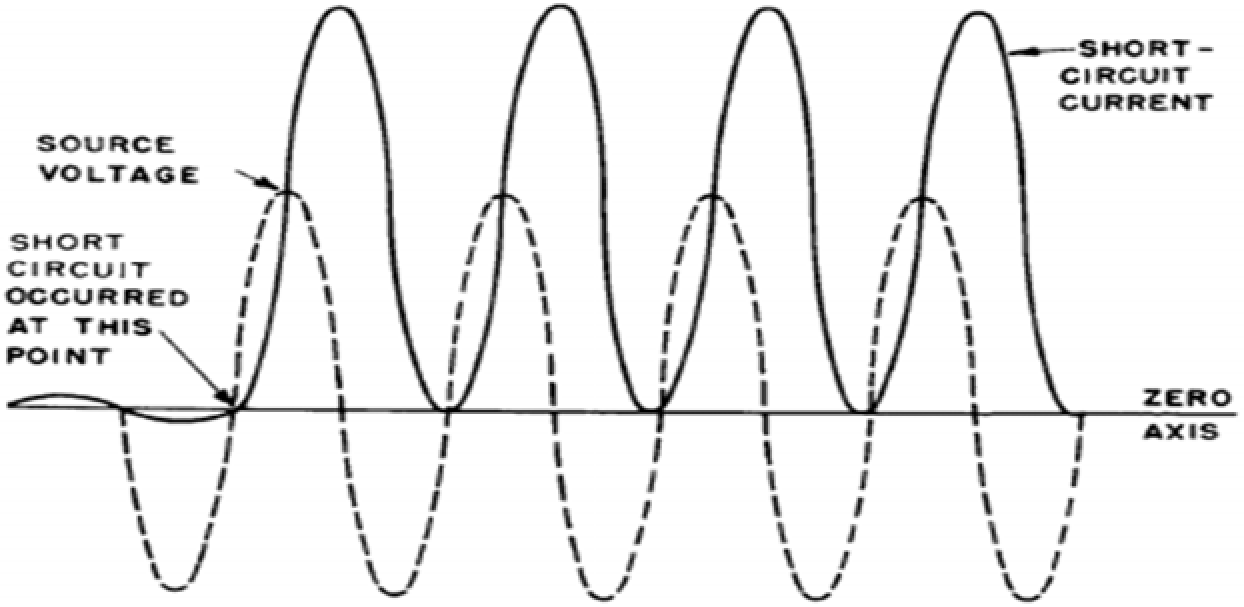


TYPICAL CIRCUIT

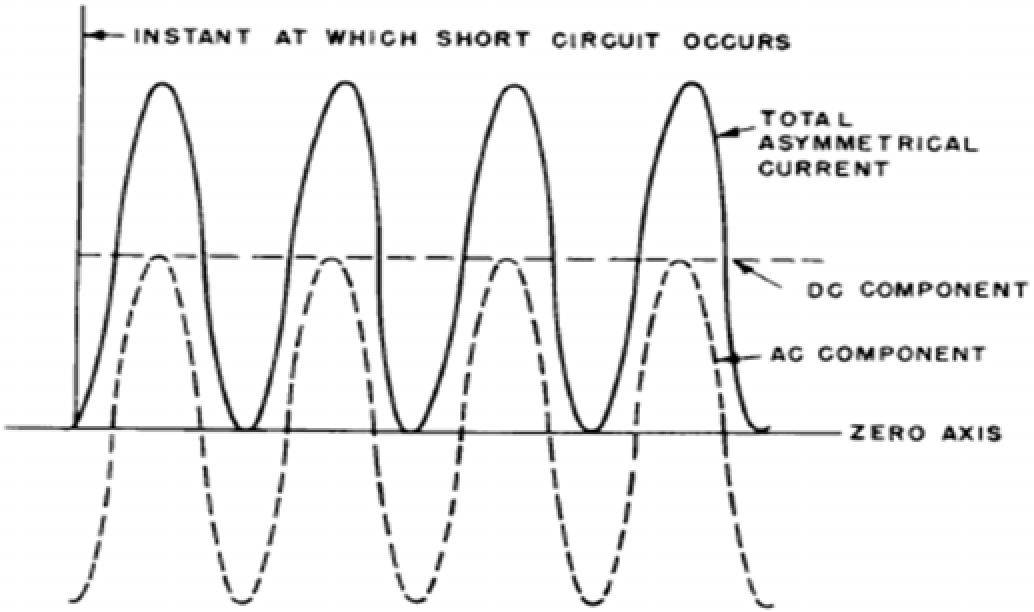




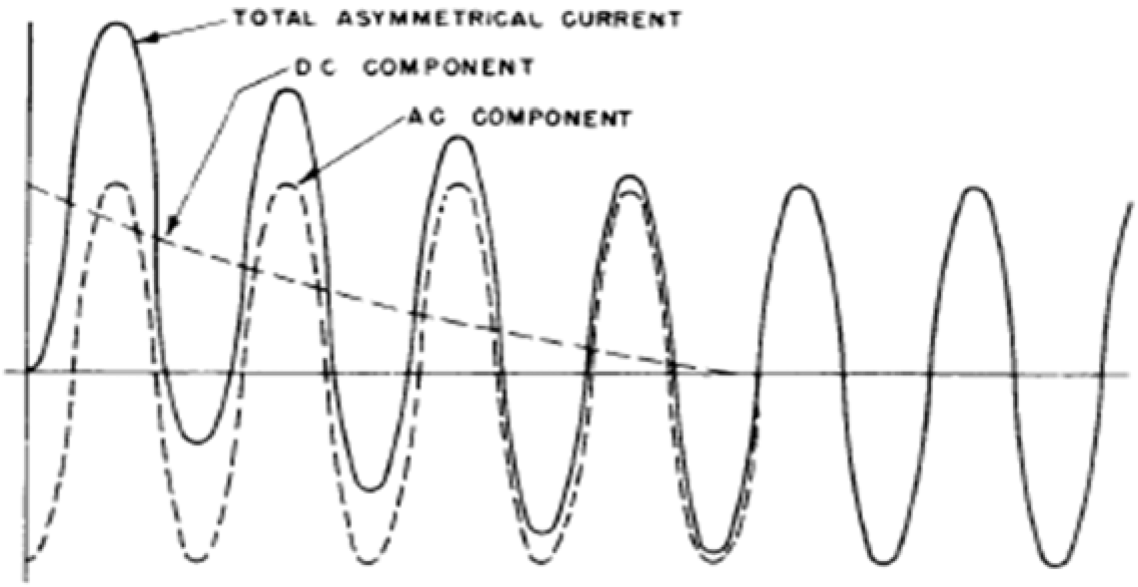
TYPICAL CIRCUIT



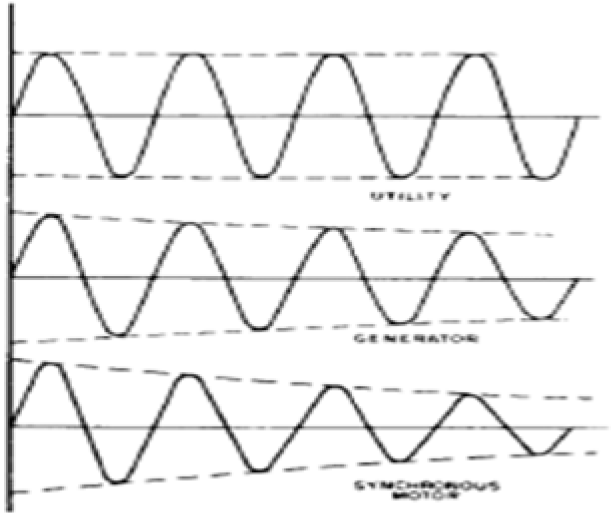
TYPICAL CIRCUIT

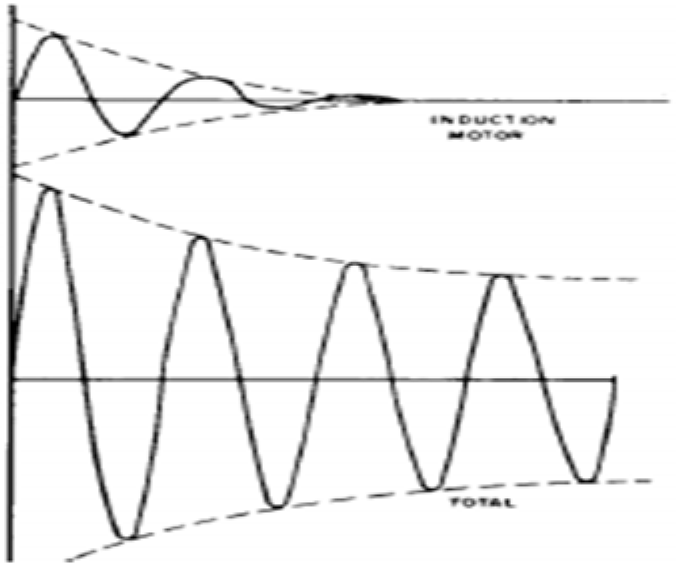


ASYMMETRICAL CURRENT



ASYMMETRICAL CURRENT





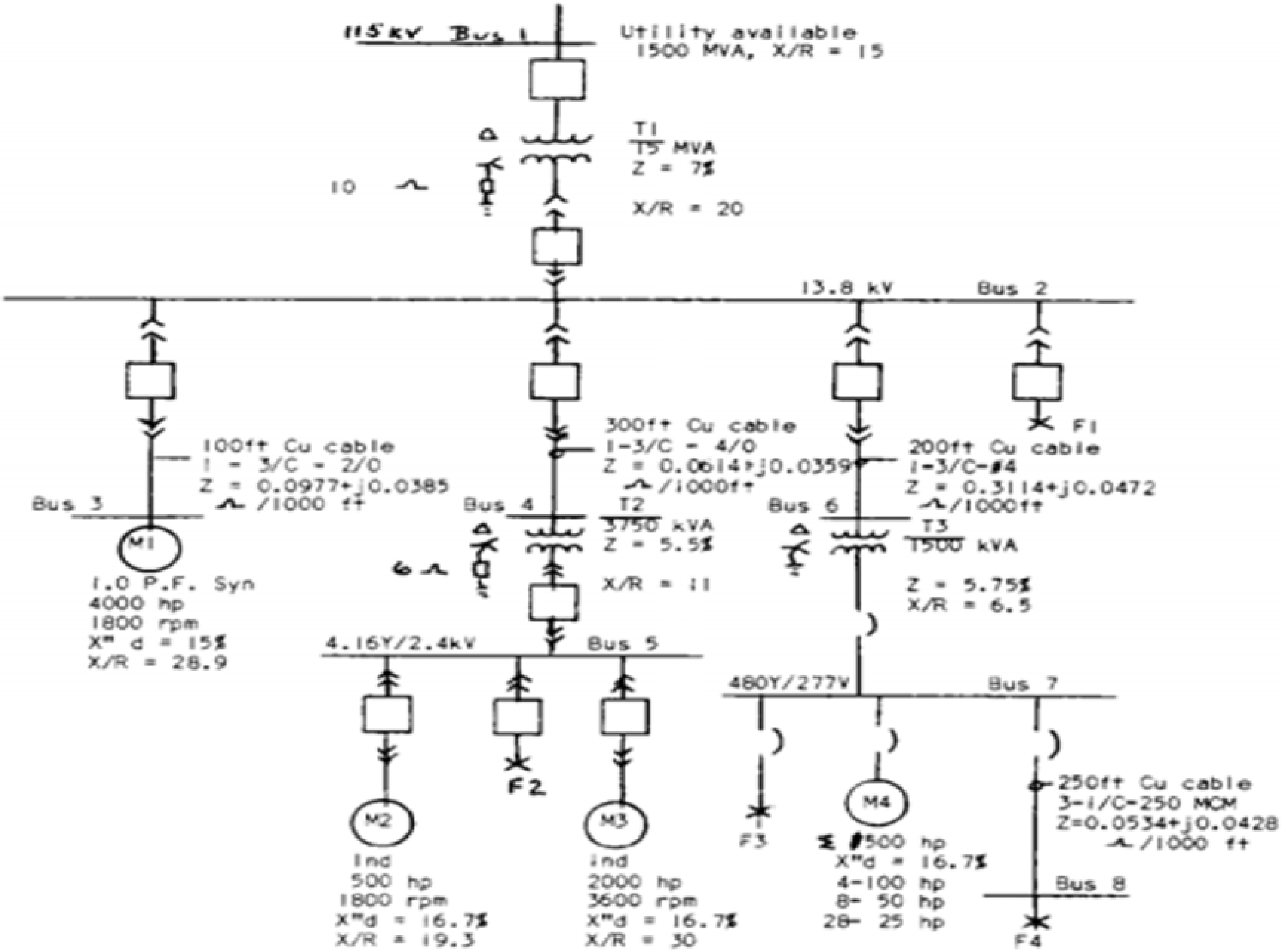
SHORT CIRCUIT CALCULATION

- Prepare one line diagram
- Decide on location of short circuit
- Prepare impedance diagram
- Interconnect networks correctly per type of fault
- Calculate symmetrical short circuit current at the buses of concern
- Apply multiplying factors to symmetrical short-circuit currents for asymmetry

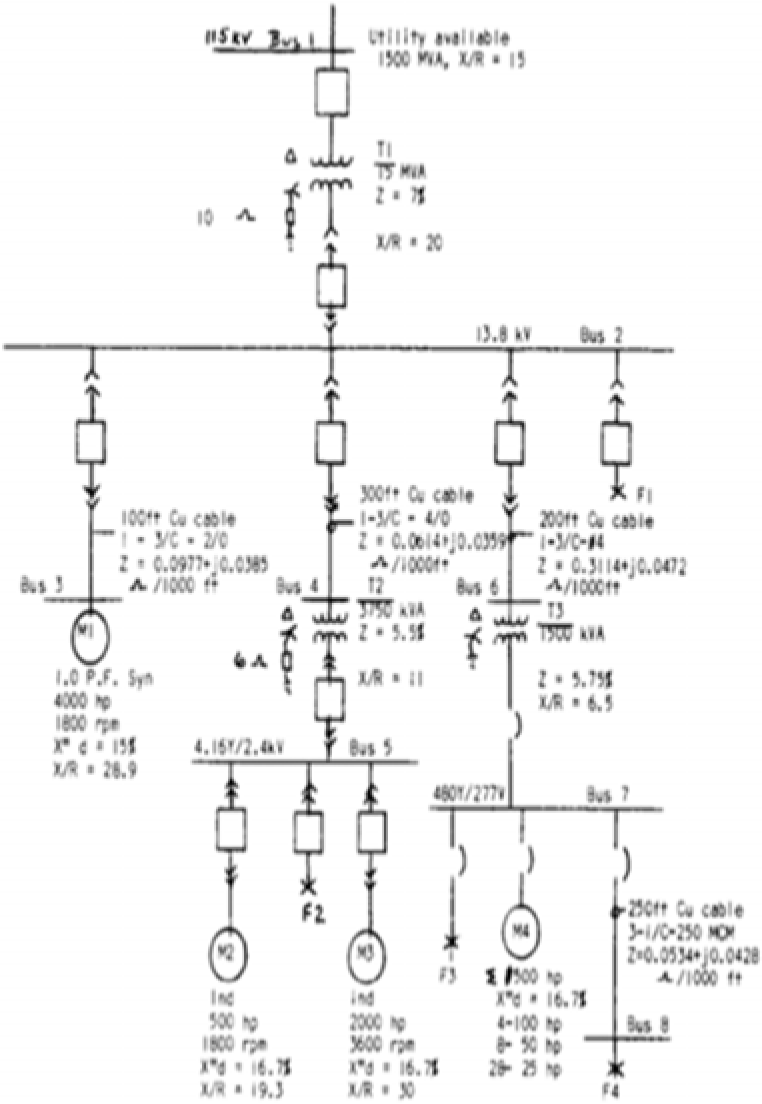
SHORT CIRCUIT CALCULATION

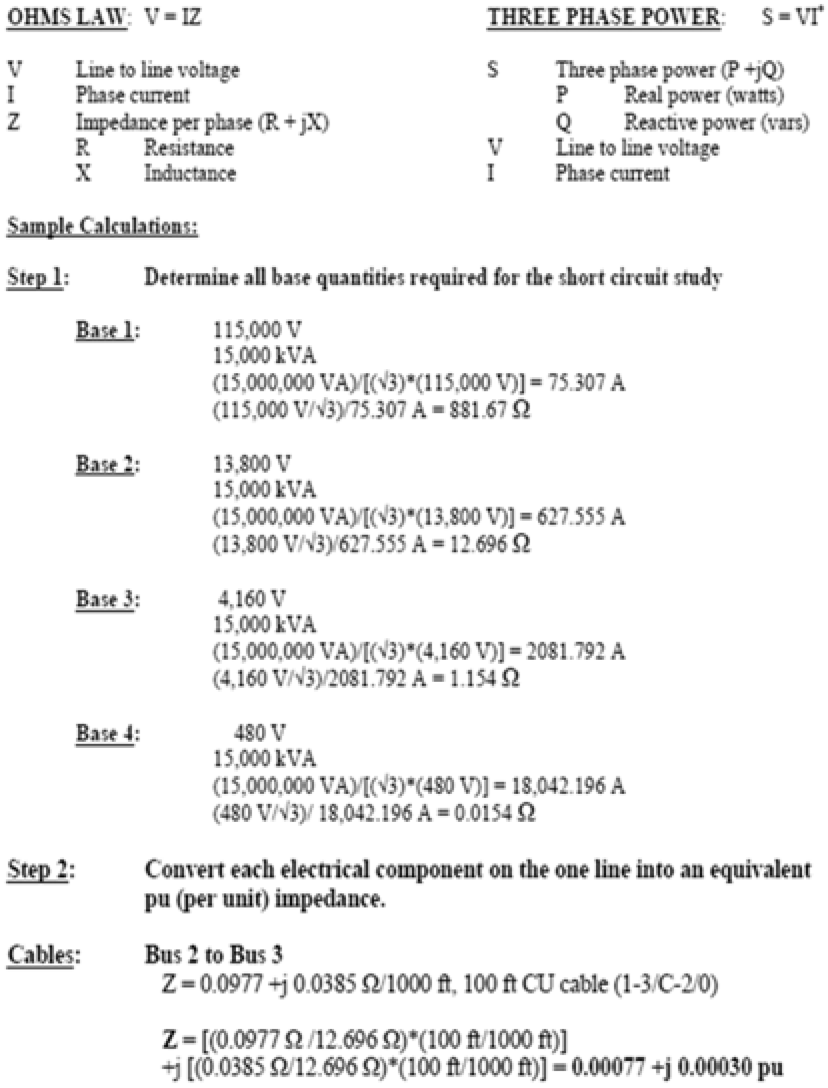
- Multiplying Factors
  - First Cycle Peak Calculation
    - Peak Multiplier = 2.6
    - Used for medium and high-voltage breakers > 1 kV
    - Assumes X/R=17 if X/R increases higher multipliers may result
  - First ½ Cycle Asymmetrical Calculation
    - Multiplier = 1.6
    - Assumes X/R = 25
    - Higher X/R may yield higher multipliers

3 PHASE FAULT EXAMPLE



3 PHASE FAULT EXAMPLE





<u>OHMS LAW</u>: $V = IZ$

V	Line to line voltage
I	Phase current
Z	Impedance per phase (R + jX)
R	Resistance
X	Inductance

<u>THREE PHASE POWER</u>: $S = VI^*$

S	Three phase power (P +jQ)
P	Real power (watts)
Q	Reactive power (vars)
V	Line to line voltage
I	Phase current

<u>Sample Calculations:</u>

<u>Step 1</u>: **Determine all base quantities required for the short circuit study**

<u>Base 1</u>:
115,000 V
15,000 kVA
(15,000,000 VA)/[(√3)*(115,000 V)] = 75.307 A
(115,000 V/√3)/75.307 A = 881.67 Ω

<u>Base 2</u>:
13,800 V
15,000 kVA
(15,000,000 VA)/[(√3)*(13,800 V)] = 627.555 A
(13,800 V/√3)/627.555 A = 12.696 Ω

<u>Base 3</u>:
4,160 V
15,000 kVA
(15,000,000 VA)/[(√3)*(4,160 V)] = 2081.792 A
(4,160 V/√3)/2081.792 A = 1.154 Ω

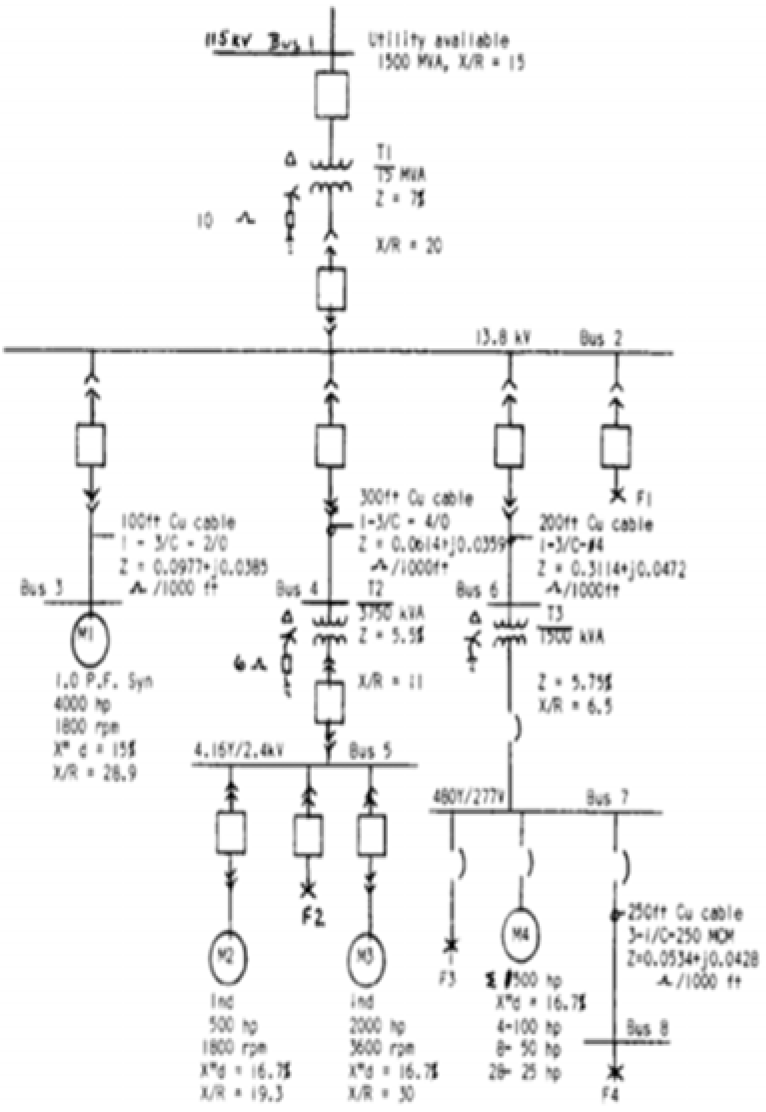
<u>Base 4</u>:
480 V
15,000 kVA
(15,000,000 VA)/[(√3)*(480 V)] = 18,042.196 A
(480 V/√3)/ 18,042.196 A = 0.0154 Ω

<u>Step 2</u>: **Convert each electrical component on the one line into an equivalent pu (per unit) impedance.**

<u>Cables</u>: Bus 2 to Bus 3
Z = 0.0977 +j 0.0385 Ω/1000 ft, 100 ft CU cable (1-3/C-2/0)

Z = [(0.0977 Ω /12.696 Ω)*(100 ft/1000 ft)]
+j [(0.0385 Ω/12.696 Ω)*(100 ft/1000 ft)] = **0.00077 +j 0.00030 pu**

3 PHASE FAULT EXAMPLE



Bus 2 to Bus 4

Z = 0.0614 +j 0.0359 Ω/1000 ft, 300 ft CU cable (1-3/C-4/0)

Z = [(0.0614 Ω /12.696 Ω)*(300 ft/1000 ft)]
+j [(0.0359 Ω/12.696 Ω)*(300 ft/1000 ft)] = **0.00145 +j 0.00085 pu**

Bus 2 to Bus 6

Z = 0.3114 +j 0.0472 Ω/1000 ft, 200 ft CU cable (1-3/C-#4)

Z = [(0.3114 Ω /12.696 Ω)*(200 ft/1000 ft)]
+j [(0.0472 Ω/12.696 Ω)*(200 ft/1000 ft)] = **0.0049 +j 0.00074 pu**

Bus 7 to Bus 8

Z = 0.0534 +j 0.0428 Ω/1000 ft, 250 ft CU cable (3-1/C-250 MCM)

Z = [(0.0534 Ω /0.0154 Ω)*(250 ft/1000 ft)]
+j [(0.0428 Ω/0.0154 Ω)*(250 ft/1000 ft)] = **0.867 +j 0.695 pu**

<u>Utility:</u>

115,000 V
1500 MVA
X/R = 15

I = (150,000,000 VA)/[(√3)*(115,000 V)] = 7530.656 A
Z = (115,000 V/√3)/7530.656 A = 8.817 Ω

Z = 8.817 Ω/881.67 Ω = **0.01 pu**
Z = 0.01*[(cos (tan^{-1}(15)) +j (sin (tan^{-1}(15))] = **0.000667 +j 0.0100 pu**

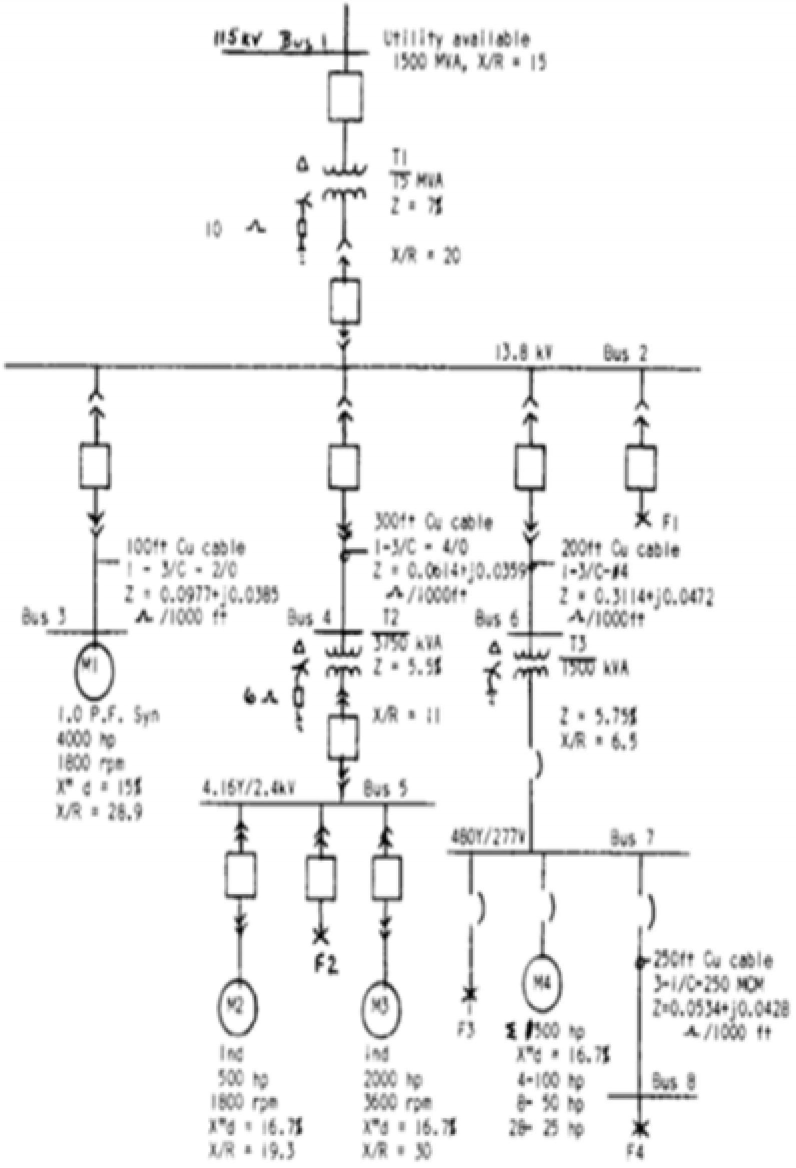
<u>Transformers:</u> **Bus 1 to Bus 2**

15 MVA; 115 kV/13.8 kV
X/R = 20
Z = 7%

I = (15,000,000 VA)/[(√3)*(13,800 V)] = 627.555 A
Z = (13,800 V/√3)/ 627.555 A = 12.696 Ω

Z = 12.696 Ω/12.696 Ω = 1.0 pu * 0.07 = **0.07 pu**
Z = 0.07*[(cos (tan^{-1}(20)) +j (sin (tan^{-1}(20))] = **0.0035 +j 0.0699 pu**

3 PHASE FAULT EXAMPLE



Bus 4 to Bus 5

3,750 kVA; 13.8 kV/4.16 kV
X/R = 11
Z = 5.5%

I = (3,750,000 VA)/[(√3)*(13,800 V)] = 156.889 A
Z = (13,800 V/√3)/ 156.889 A = 50.784 Ω

Z = 50.784 Ω /12.696 Ω = 4.0 pu * 0.055 = **0.22 pu**
Z = 0.22*[(cos $(\tan^{-1}(11))$ +j (sin $(\tan^{-1}(11))$] = **0.0199 +j 0.219 pu**

Bus 6 to Bus 7

1,500 kVA; 13.8 kV/0.48 kV
X/R = 6.5
Z = 5.75%

I = (1,500,000 VA)/[(√3)*(13,800 V)] = 62.755 A
Z = (13,800 V/√3)/ 62.755 A = 126.96 Ω

Z = 126.96 Ω /12.696 Ω = 10.0 pu * 0.0575 = **0.575 pu**
Z = 0.575*[(cos $(\tan^{-1}(6.5))$ +j (sin $(\tan^{-1}(6.5))$] = **0.0874 +j 0.568 pu**

Motors: **Bus 5**

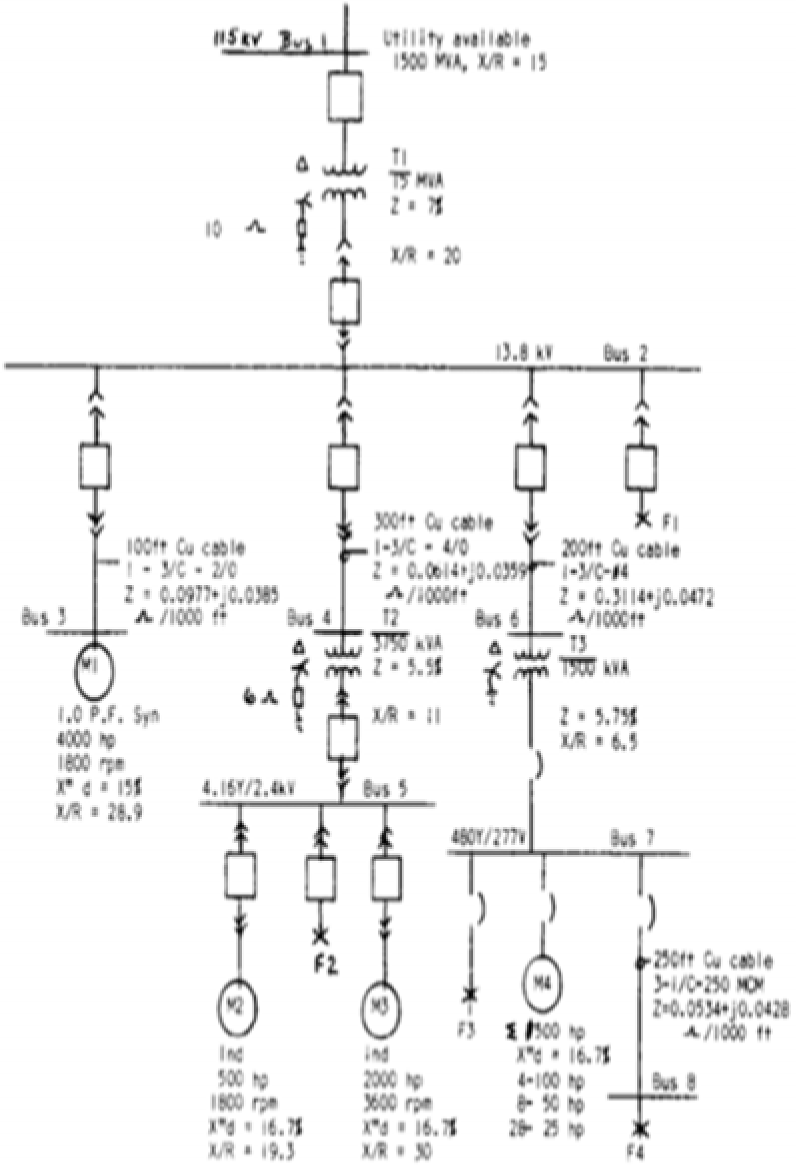
4.16 kV, 500 HP Induction, 1800 rpm
X"d = 16.7%
X/R = 19.3

S = 0.95 * (500 HP) = 475 kVA (approximation, see page 18)
I = (475,000 VA)/[(√3)*(4,160 V)] = 65.923 A
Z = (4,160 V/√3)/ 65.923 A = 36.433 Ω

Z = 36.433 Ω /1.154 Ω = 31.571 pu * 0.167 = **5.272 pu**
Z = 5.272*[(cos $(\tan^{-1}(19.3))$ +j (sin $(\tan^{-1}(19.3))$] = **0.273 +j 5.265 pu**

Z = 1.2*(0.273 +j 5.265 pu) = 0.328 +j 6.318 pu
(ANSI/IEEE Recommended Practice for Rotating Machines)

3 PHASE FAULT EXAMPLE



Bus 3

13.8 kV, 4000 HP 1.0PF SYNC, 1800 rpm

$X''d = 15.0\%$

$X/R = 28.9$

$S = 0.80 * (4000\text{ HP}) = 3200\text{ kVA}$ (approximation, see page 18)

$I = (3{,}200{,}000\text{ VA})/[(\sqrt{3})*(13{,}800\text{ V})] = 133.878\text{ A}$

$Z = (13{,}800\text{ V}/\sqrt{3})/\ 133.878\text{ A} = 59.513\ \Omega$

$Z = 59.513\ \Omega\ /12.696\ \Omega = 4.688\text{ pu} * 0.150 = \mathbf{0.703\ pu}$

$Z = 0.703*[(\cos(\tan^{-1}(28.9)) + j(\sin(\tan^{-1}(28.9))] = \mathbf{0.0243 + j\ 0.703pu}$

$\mathbf{Z = 1.0*(0.0243 + j\ 0.703\ pu) = 0.0243 + j\ 0.703\ pu}$

(ANSI/IEEE Recommended Practice for Rotating Machines)

Bus 5

4.16 kV, 2000 HP IND, 3600 rpm

$X''d = 16.7\%$

$X/R = 30$

$S = 0.90 * (2000\text{ HP}) = 1800\text{ kVA}$ (approximation, see page 18)

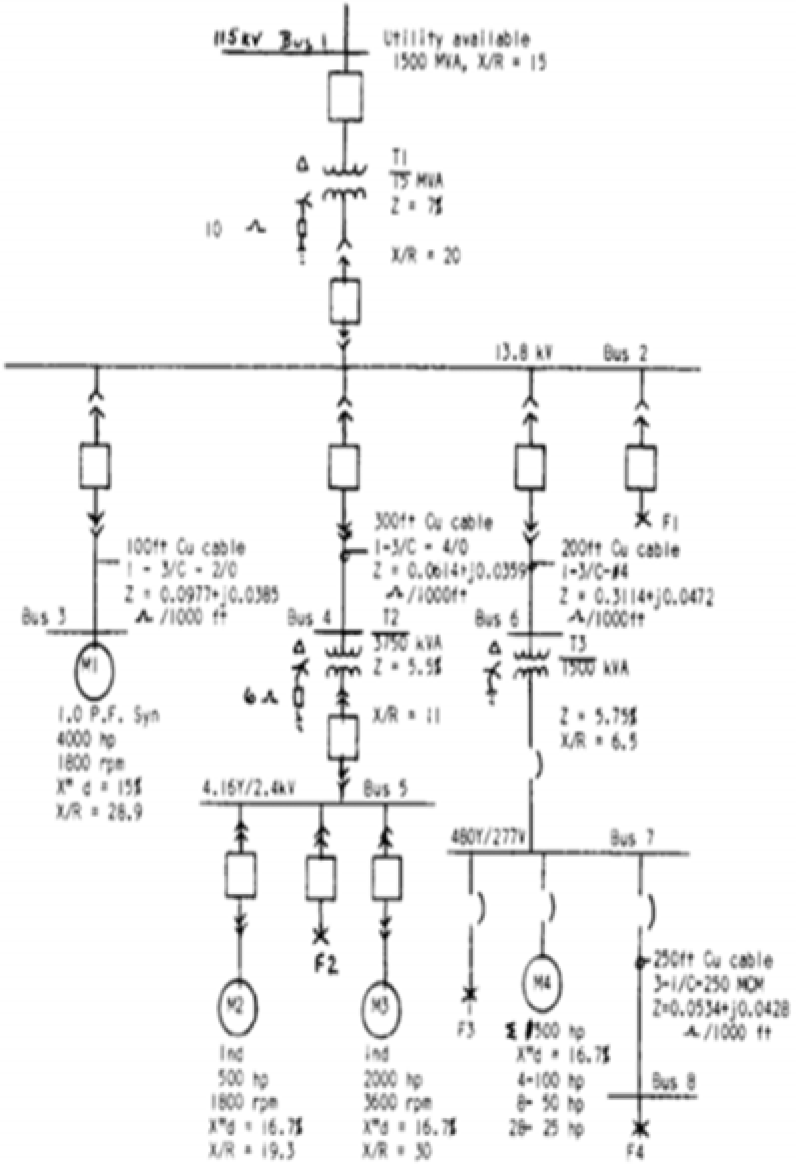
$I = (1{,}800{,}000\text{ VA})/[(\sqrt{3})*(4{,}160\text{ V})] = 249.815\text{ A}$

$Z = (4{,}160\text{ V}/\sqrt{3})/\ 249.815\text{ A} = 9.614\ \Omega$

Type Motors	Rated kVA =
All (exact)	$\frac{(\text{V rated})(\text{I rated})}{1000}$
Induction (approximate) 100 hp or less	Rated hp
>100, <1000 hp	0.95 rated hp
≥ 1000 hp	0.9 rated hp
Synchronous (approximate) 0.8 p.F	Rated hp
1.0 p.F	0.8 rated hp

TYPE OF ROTATING MACHINE	FIRST CYCLE (a)	1.5-4 CYCLES (b)
All turbine generators, all hydrogenerators with amortisseur windings, all condensers	$1.00\ X''_d$	$1.00\ X''_d$
Hydrogenerators with amortisseur windings	$0.75\ X'_d$	$0.75\ X'_d$
All synchronous motors	$1.00\ X''_d$	$1.50\ X''_d$
Induction motors		
above 1000 horsepower at 1800 rpm or less	$1.00\ X''_d$	$1.50\ X''_d$
above 250 horsepower at 3600 rpm	$1.00\ X''_d$	$1.50\ X''_d$
all others 50 horsepower and above	$1.20\ X''_d$	$3.00\ X''_d$
all smaller than 50 horsepower	$1.67\ X''_d$	neglect

3 PHASE FAULT EXAMPLE



$Z = 9.614\ \Omega / 1.154\ \Omega = 8.331\text{ pu} * 0.167 = \mathbf{1.391\ pu}$

$\mathbf{Z} = 1.391*[(\cos(\tan^{-1}(30)) + j(\sin(\tan^{-1}(30))] = \mathbf{0.0463 + j\,1.390\ pu}$

$\mathbf{Z = 1.0*(0.0463 + j\,1.390\ pu) = 0.0463 + j\,1.390\ pu}$

(ANSI/IEEE Recommended Practice for Rotating Machines)

Bus 7

480 V, 4 x 100 HP IND, X/R = 8.3
8 x 50 HP IND, X/R = 5.5 &
28 x 25 HP IND, X/R = 3.8
X"d = 16.7%

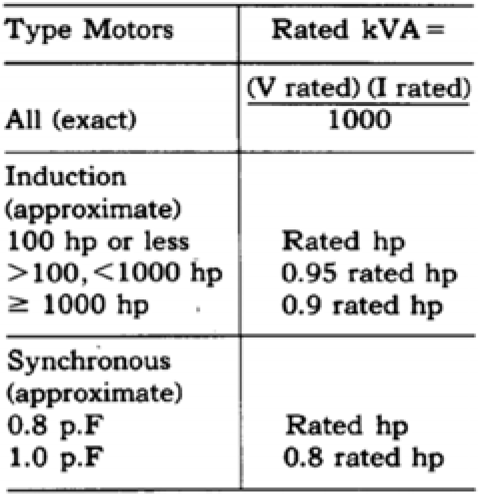
S = 1.00 * (4*100 HP) = 400 kVA (approximation, see page 18)
$I = (400{,}000\text{ VA})/[(\sqrt{3})*(480\text{ V})] = 481.125\text{ A}$
$Z = (480\text{ V}/\sqrt{3}) / 481.125\text{ A} = 0.576\ \Omega$

$Z = 0.576\ \Omega / 0.0154\ \Omega = 37.403\text{ pu} * 0.167 = \mathbf{6.246\ pu}$

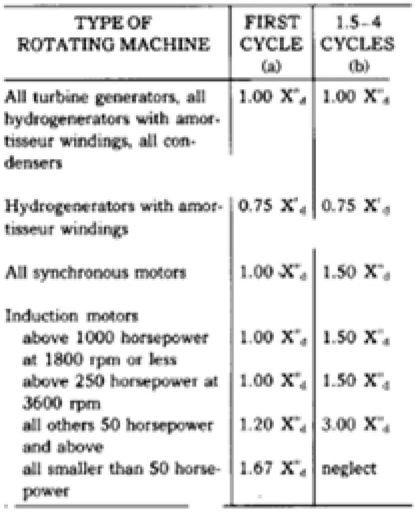
$\mathbf{Z} = 6.246*[(\cos(\tan^{-1}(8.3)) + j(\sin(\tan^{-1}(8.3))] = \mathbf{0.747 + j\,6.201\ pu}$

$\mathbf{Z = 1.2*(0.747 + j\,6.201\ pu) = 0.897 + j\,7.441\ pu}$

(ANSI/IEEE Recommended Practice for Rotating Machines)

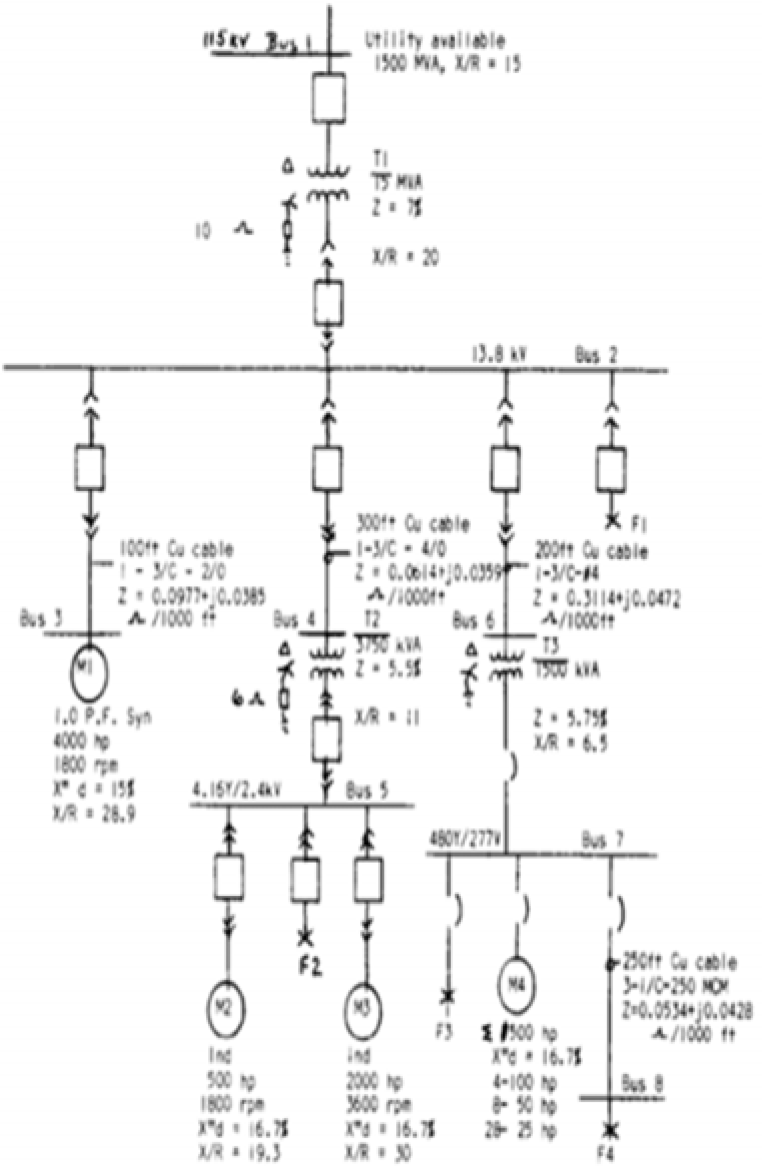


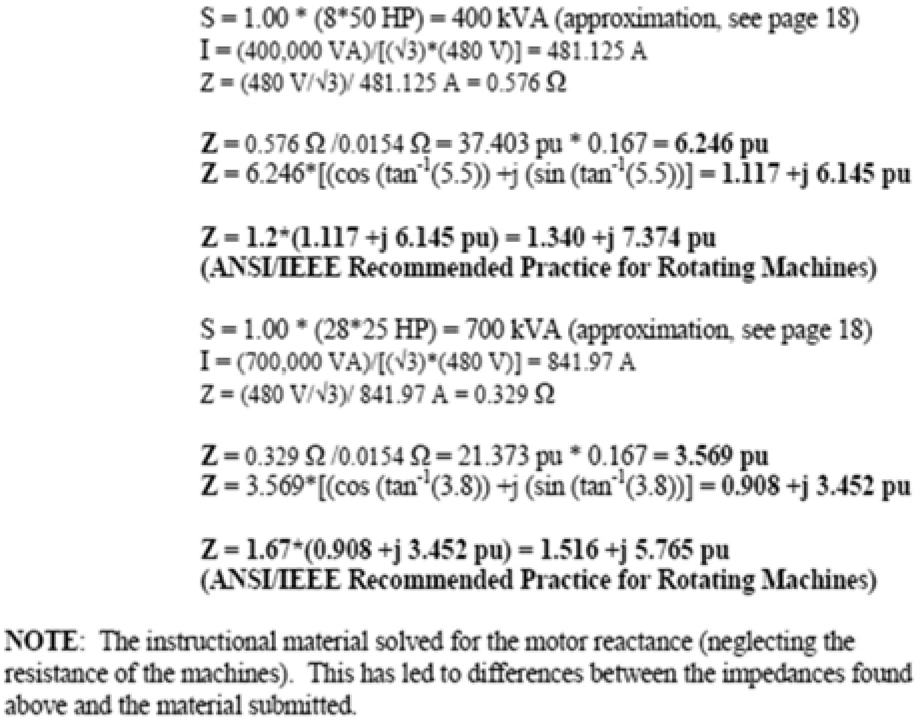
Type Motors	Rated kVA =
All (exact)	$\frac{(\text{V rated})(\text{I rated})}{1000}$
Induction (approximate) 100 hp or less >100, <1000 hp ≥ 1000 hp	 Rated hp 0.95 rated hp 0.9 rated hp
Synchronous (approximate) 0.8 p.F 1.0 p.F	 Rated hp 0.8 rated hp



TYPE OF ROTATING MACHINE	FIRST CYCLE (a)	1.5-4 CYCLES (b)
All turbine generators, all hydrogenerators with amortisseur windings, all condensers	1.00 X"_d	1.00 X"_d
Hydrogenerators with amortisseur windings	0.75 X'_d	0.75 X'_d
All synchronous motors	1.00 X"_d	1.50 X"_d
Induction motors		
above 1000 horsepower at 1800 rpm or less	1.00 X"_d	1.50 X"_d
above 250 horsepower at 3600 rpm	1.00 X"_d	1.50 X"_d
all others 50 horsepower and above	1.20 X"_d	3.00 X"_d
all smaller than 50 horsepower	1.67 X"_d	neglect

3 PHASE FAULT EXAMPLE





S = 1.00 * (8*50 HP) = 400 kVA (approximation, see page 18)
I = (400,000 VA)/[(√3)*(480 V)] = 481.125 A
Z = (480 V/√3)/ 481.125 A = 0.576 Ω

Z = 0.576 Ω /0.0154 Ω = 37.403 pu * 0.167 = **6.246 pu**
Z = 6.246*[(cos (tan^{-1}(5.5)) +j (sin (tan^{-1}(5.5))] = **1.117 +j 6.145 pu**

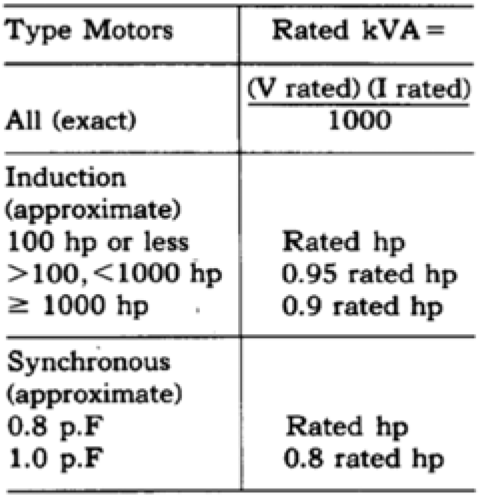
Z = 1.2*(1.117 +j 6.145 pu) = 1.340 +j 7.374 pu
(ANSI/IEEE Recommended Practice for Rotating Machines)

S = 1.00 * (28*25 HP) = 700 kVA (approximation, see page 18)
I = (700,000 VA)/[(√3)*(480 V)] = 841.97 A
Z = (480 V/√3)/ 841.97 A = 0.329 Ω

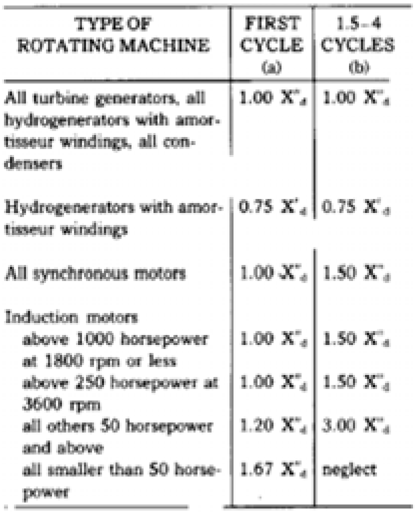
Z = 0.329 Ω /0.0154 Ω = 21.373 pu * 0.167 = **3.569 pu**
Z = 3.569*[(cos (tan^{-1}(3.8)) +j (sin (tan^{-1}(3.8))] = **0.908 +j 3.452 pu**

Z = 1.67*(0.908 +j 3.452 pu) = 1.516 +j 5.765 pu
(ANSI/IEEE Recommended Practice for Rotating Machines)

NOTE: The instructional material solved for the motor reactance (neglecting the resistance of the machines). This has led to differences between the impedances found above and the material submitted.

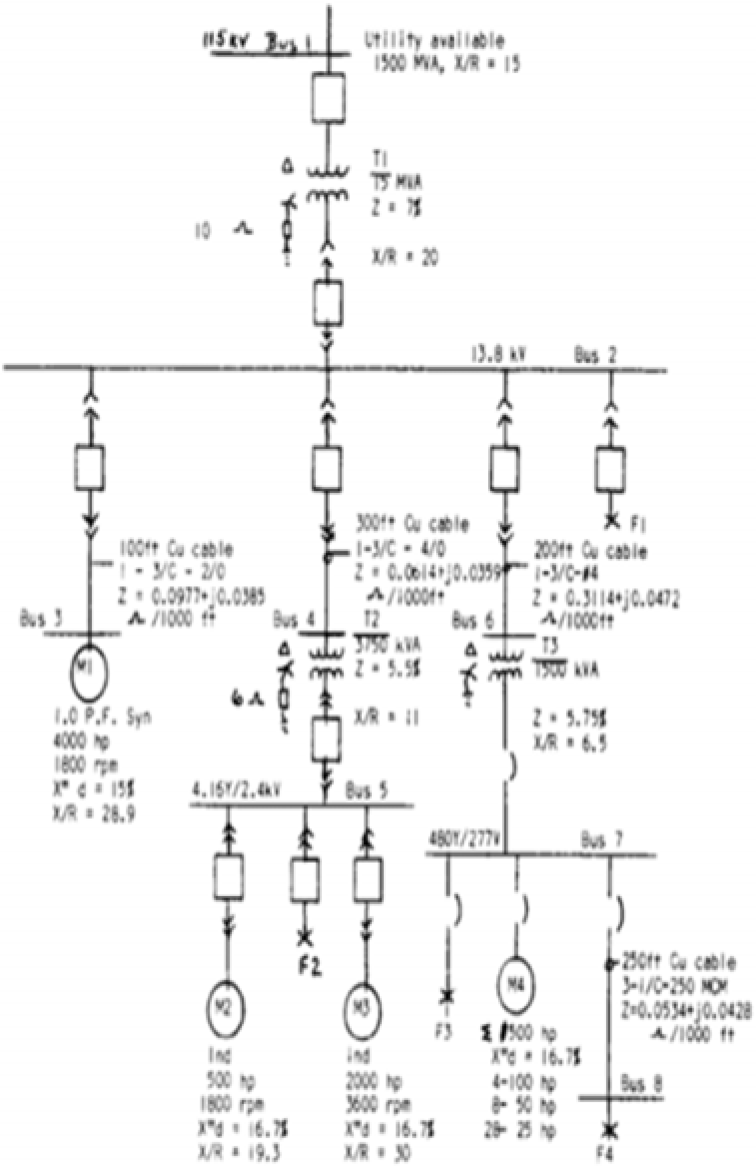


Type Motors	Rated kVA =
All (exact)	$\frac{(V\ rated)\ (I\ rated)}{1000}$
Induction (approximate)	
100 hp or less	Rated hp
>100, <1000 hp	0.95 rated hp
≥ 1000 hp	0.9 rated hp
Synchronous (approximate)	
0.8 p.F	Rated hp
1.0 p.F	0.8 rated hp



TYPE OF ROTATING MACHINE	FIRST CYCLE (a)	1.5-4 CYCLES (b)
All turbine generators, all hydrogenerators with amortisseur windings, all condensers	1.00 X''_d	1.00 X''_d
Hydrogenerators with amortisseur windings	0.75 X'_d	0.75 X'_d
All synchronous motors	1.00 X''_d	1.50 X''_d
Induction motors		
above 1000 horsepower at 1800 rpm or less	1.00 X''_d	1.50 X''_d
above 250 horsepower at 3600 rpm	1.00 X''_d	1.50 X''_d
all others 50 horsepower and above	1.20 X''_d	3.00 X''_d
all smaller than 50 horsepower	1.67 X''_d	neglect

3 PHASE FAULT EXAMPLE



Summary of Results:

Utility: Bus 1: Z_{UTIL} = 0.000667 +j 0.0100 pu

Cables:

Bus 2 to Bus 3: Z_{C1} = 0.00077 +j 0.00030 pu
Bus 2 to Bus 4: Z_{C2} = 0.00145 +j 0.00085 pu
Bus 2 to Bus 6: Z_{C3} = 0.0049 +j 0.00074 pu
Bus 7 to Bus 8: Z_{C4} = 0.867 +j 0.695 pu

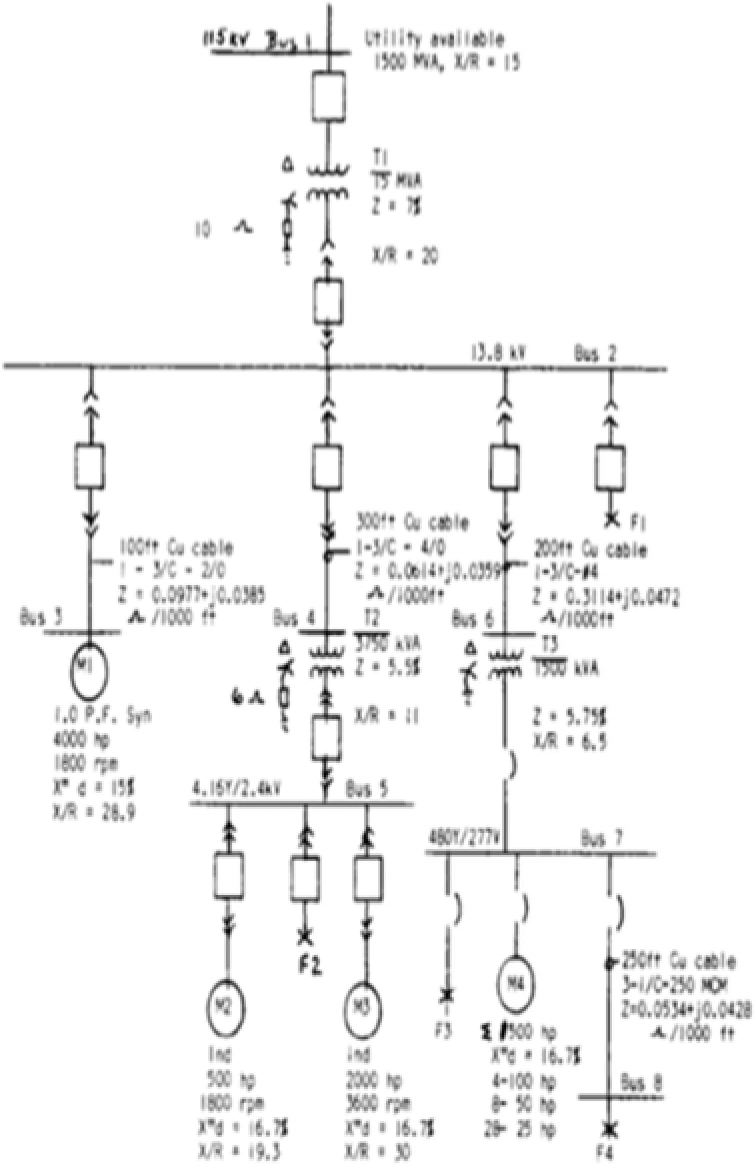
Transformers:

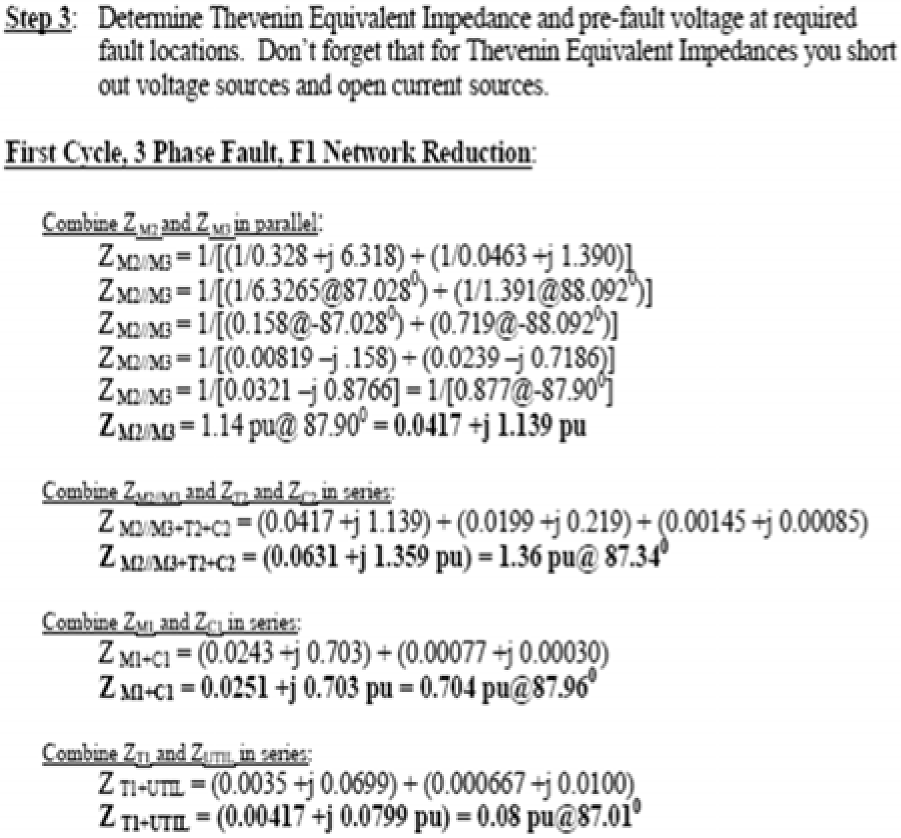
Bus 1 to Bus 2: Z_{T1} = 0.0035 +j 0.0699 pu
Bus 4 to Bus 5: Z_{T2} = 0.0199 +j 0.219 pu
Bus 6 to Bus 7: Z_{T3} = 0.0874 +j 0.568 pu

Motors:

Bus 3: Z_{M1} = 0.0243 +j 0.703 pu
Bus 5: Z_{M2} = 0.328 +j 6.318 pu
Z_{M3} = 0.0463 +j 1.390 pu
Bus 7: Z_{M4} = 0.897 +j 7.441 pu
Z_{M5} = 1.340 +j 7.374 pu
Z_{M6} = 1.516 +j 5.765 pu

3 PHASE FAULT EXAMPLE





Step 3: Determine Thevenin Equivalent Impedance and pre-fault voltage at required fault locations. Don't forget that for Thevenin Equivalent Impedances you short out voltage sources and open current sources.

First Cycle, 3 Phase Fault, F1 Network Reduction:

Combine Z_{M2} and Z_{M3} in parallel:

$Z_{M2//M3} = 1/[(1/0.328 + j\,6.318) + (1/0.0463 + j\,1.390)]$
$Z_{M2//M3} = 1/[(1/6.3265@87.028^0) + (1/1.391@88.092^0)]$
$Z_{M2//M3} = 1/[(0.158@{-87.028^0}) + (0.719@{-88.092^0})]$
$Z_{M2//M3} = 1/[(0.00819 - j\,.158) + (0.0239 - j\,0.7186)]$
$Z_{M2//M3} = 1/[0.0321 - j\,0.8766] = 1/[0.877@{-87.90^0}]$
$Z_{M2//M3} = 1.14\text{ pu}@\,87.90^0 = \mathbf{0.0417 + j\,1.139\text{ pu}}$

Combine $Z_{M2//M3}$ and Z_{T2} and Z_{C2} in series:

$Z_{M2//M3+T2+C2} = (0.0417 + j\,1.139) + (0.0199 + j\,0.219) + (0.00145 + j\,0.00085)$
$\mathbf{Z_{M2//M3+T2+C2} = (0.0631 + j\,1.359\text{ pu}) = 1.36\text{ pu}@\,87.34^0}$

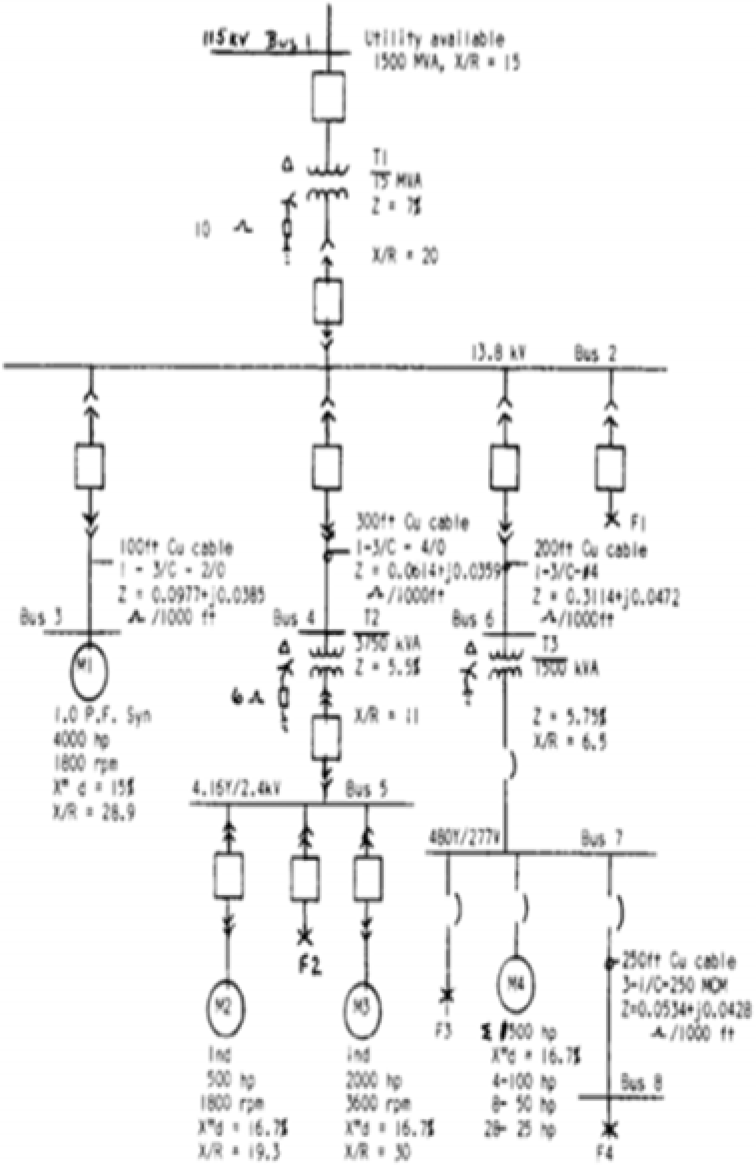
Combine Z_{M1} and Z_{C1} in series:

$Z_{M1+C1} = (0.0243 + j\,0.703) + (0.00077 + j\,0.00030)$
$\mathbf{Z_{M1+C1} = 0.0251 + j\,0.703\text{ pu} = 0.704\text{ pu}@87.96^0}$

Combine Z_{T1} and Z_{UTIL} in series:

$Z_{T1+UTIL} = (0.0035 + j\,0.0699) + (0.000667 + j\,0.0100)$
$\mathbf{Z_{T1+UTIL} = (0.00417 + j\,0.0799\text{ pu}) = 0.08\text{ pu}@87.01^0}$

3 PHASE FAULT EXAMPLE



Combine Z_{M4}, Z_{M5} and Z_{M6} in parallel:

$$Z_{M4//M5//M6} = 1/[(1/0.897 + j\,7.441) + (1/1.340 + j\,7.374) + (1/1.516 + j\,5.765)]$$

$$Z_{M4//M5//M6} = 1/[(0.0160 - j\,0.132) + (0.0239 - j\,0.131) + (0.043 - j\,0.162)]$$

$$\mathbf{Z_{M4//M5//M6} = 1/[(0.0829 - j\,0.425)] = 0.442 + j\,2.267\ pu = 2.309\ pu@78.96^0}$$

Combine $Z_{M4//M5//M6}$ and Z_{T3} and Z_{C3} in series:

$$Z_{M2//M3+T3+C3} = (0.442 + j\,2.267) + (0.0874 + j\,0.568) + (0.0049 + j\,0.00074)$$

$$\mathbf{Z_{M2//M3+T3+C3} = 0.534 + j\,2.836\ pu = 2.886\ pu@79.33^0}$$

Calculate the impedance at Fault F1:

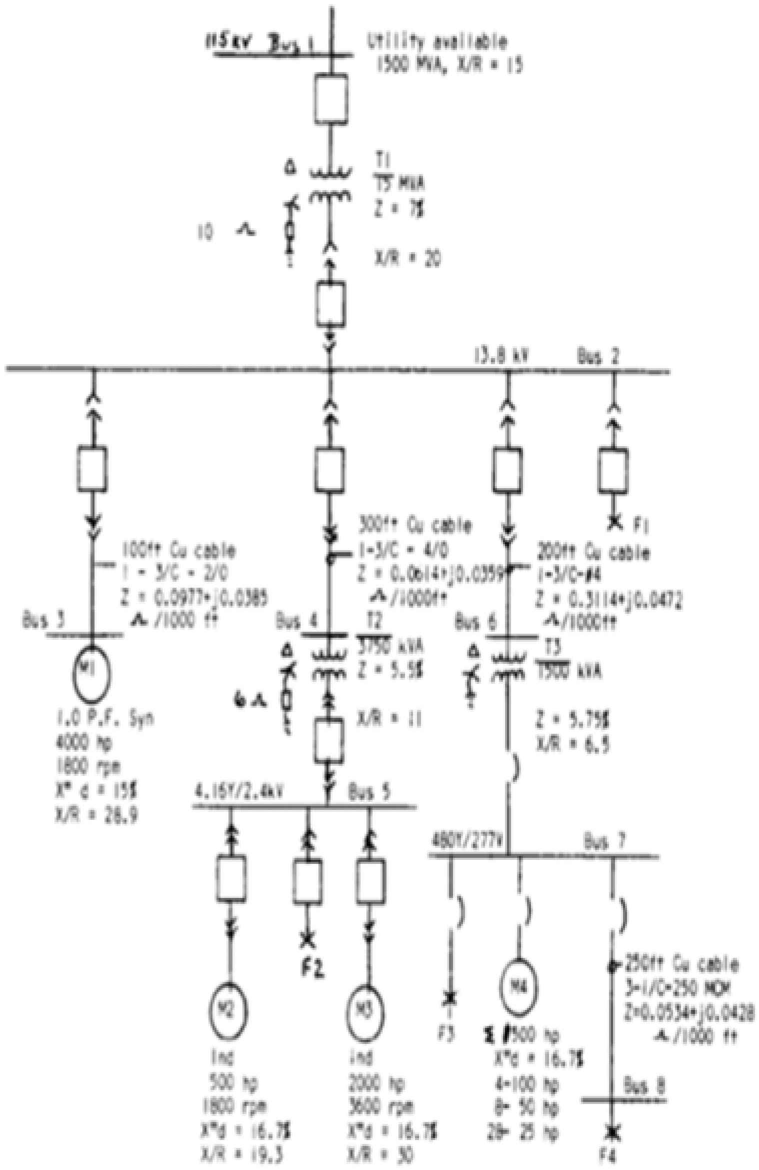
$$Z_{F1} = 1/[(1/1.36@\,87.34^0) + (1/0.704@87.96^0) + (1/0.08\,@87.01^0) + (1/2.886\,@79.33^0)]$$

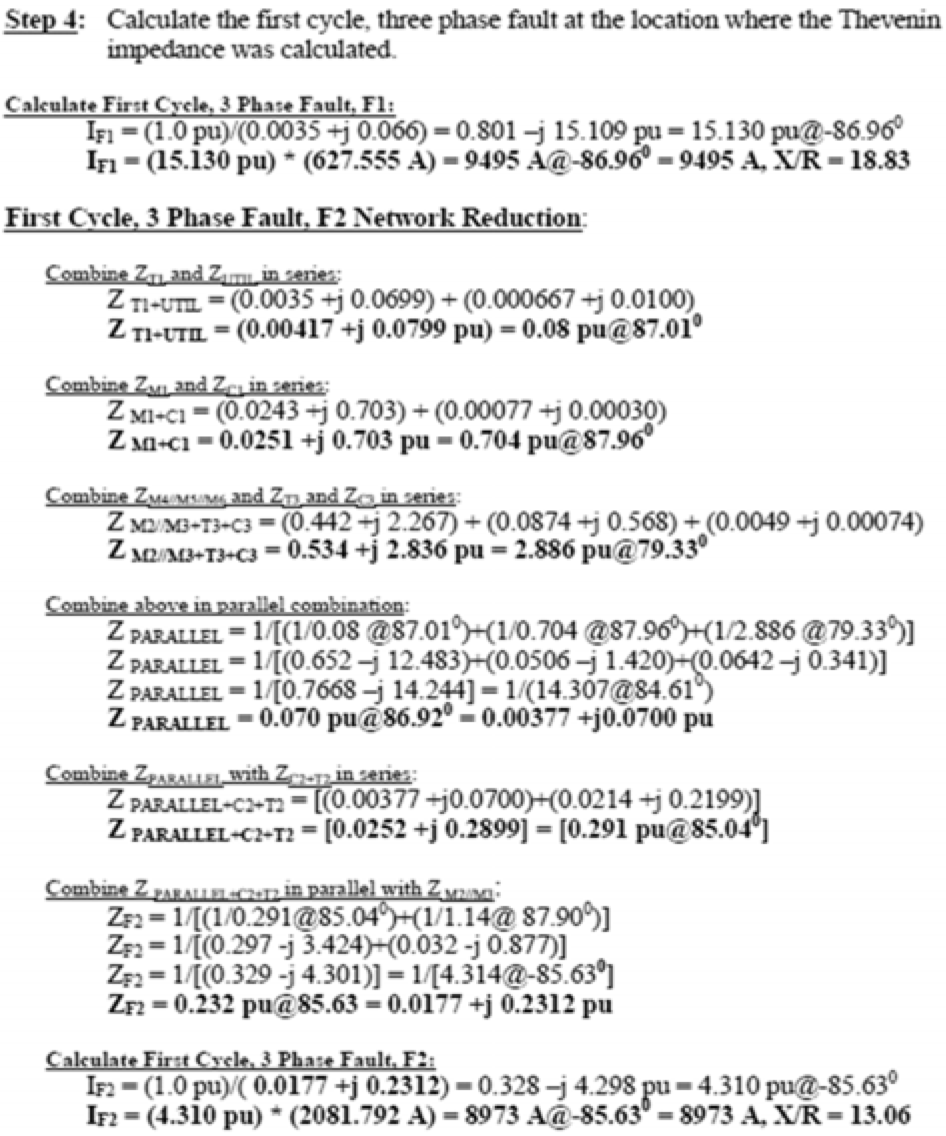
$$Z_{F1} = 1/[0.8803@\,-87.34^0) + (1.420@-87.96^0) + (12.5@-87.01^0) + (0.3465@-79.33^0)]$$

$$Z_{F1} = 1/[(0.0409 - j\,0.879) + (0.0506 - j\,1.419) + (0.652 - j12.483) + (0.0642 - j\,0.341)]$$

$$\mathbf{Z_{F1} = 1/[(0.8077 - j\,15.122)] = 0.0035 + j\,0.066\ pu}$$

3 PHASE FAULT EXAMPLE





Step 4: Calculate the first cycle, three phase fault at the location where the Thevenin impedance was calculated.

Calculate First Cycle, 3 Phase Fault, F1:

$I_{F1} = (1.0\ \text{pu})/(0.0035 + j\ 0.066) = 0.801 - j\ 15.109\ \text{pu} = 15.130\ \text{pu}@{-86.96}^{0}$

$I_{F1} = (15.130\ \text{pu}) * (627.555\ \text{A}) = 9495\ \text{A}@{-86.96}^{0} = 9495\ \text{A},\ X/R = 18.83$

First Cycle, 3 Phase Fault, F2 Network Reduction:

Combine Z_{T1} and Z_{UTIL} in series:

$Z_{T1+UTIL} = (0.0035 + j\ 0.0699) + (0.000667 + j\ 0.0100)$

$Z_{T1+UTIL} = (0.00417 + j\ 0.0799\ \text{pu}) = 0.08\ \text{pu}@87.01^{0}$

Combine Z_{M1} and Z_{C1} in series:

$Z_{M1+C1} = (0.0243 + j\ 0.703) + (0.00077 + j\ 0.00030)$

$Z_{M1+C1} = 0.0251 + j\ 0.703\ \text{pu} = 0.704\ \text{pu}@87.96^{0}$

Combine $Z_{M4//M5//M6}$ and Z_{T3} and Z_{C3} in series:

$Z_{M2//M3+T3+C3} = (0.442 + j\ 2.267) + (0.0874 + j\ 0.568) + (0.0049 + j\ 0.00074)$

$Z_{M2//M3+T3+C3} = 0.534 + j\ 2.836\ \text{pu} = 2.886\ \text{pu}@79.33^{0}$

Combine above in parallel combination:

$Z_{PARALLEL} = 1/[(1/0.08\ @87.01^{0}) + (1/0.704\ @87.96^{0}) + (1/2.886\ @79.33^{0})]$

$Z_{PARALLEL} = 1/[(0.652 - j\ 12.483) + (0.0506 - j\ 1.420) + (0.0642 - j\ 0.341)]$

$Z_{PARALLEL} = 1/[0.7668 - j\ 14.244] = 1/(14.307@84.61^{0})$

$Z_{PARALLEL} = 0.070\ \text{pu}@86.92^{0} = 0.00377 + j0.0700\ \text{pu}$

Combine $Z_{PARALLEL}$ with Z_{C2+T2} in series:

$Z_{PARALLEL+C2+T2} = [(0.00377 + j0.0700) + (0.0214 + j\ 0.2199)]$

$Z_{PARALLEL+C2+T2} = [0.0252 + j\ 0.2899] = [0.291\ \text{pu}@85.04^{0}]$

Combine $Z_{PARALLEL+C2+T2}$ in parallel with $Z_{M2//M3}$:

$Z_{F2} = 1/[(1/0.291@85.04^{0}) + (1/1.14@\ 87.90^{0})]$

$Z_{F2} = 1/[(0.297 - j\ 3.424) + (0.032 - j\ 0.877)]$

$Z_{F2} = 1/[(0.329 - j\ 4.301)] = 1/[4.314@{-85.63}^{0}]$

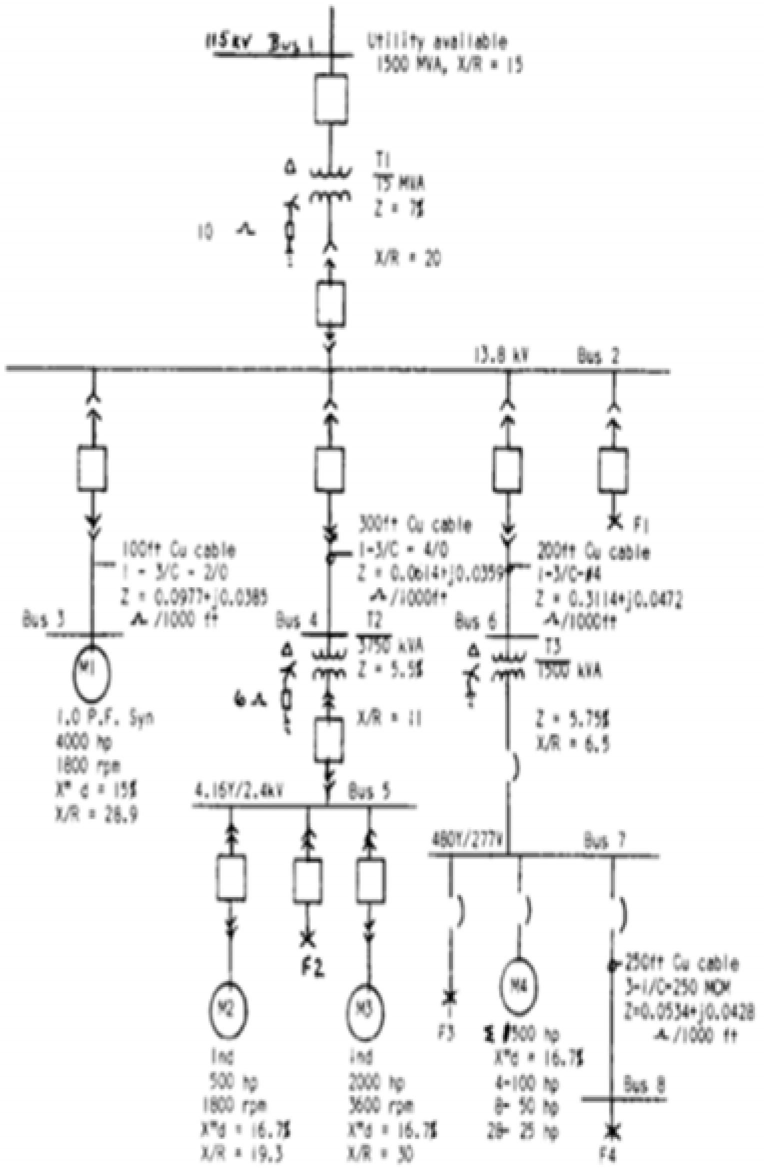
$Z_{F2} = 0.232\ \text{pu}@85.63 = 0.0177 + j\ 0.2312\ \text{pu}$

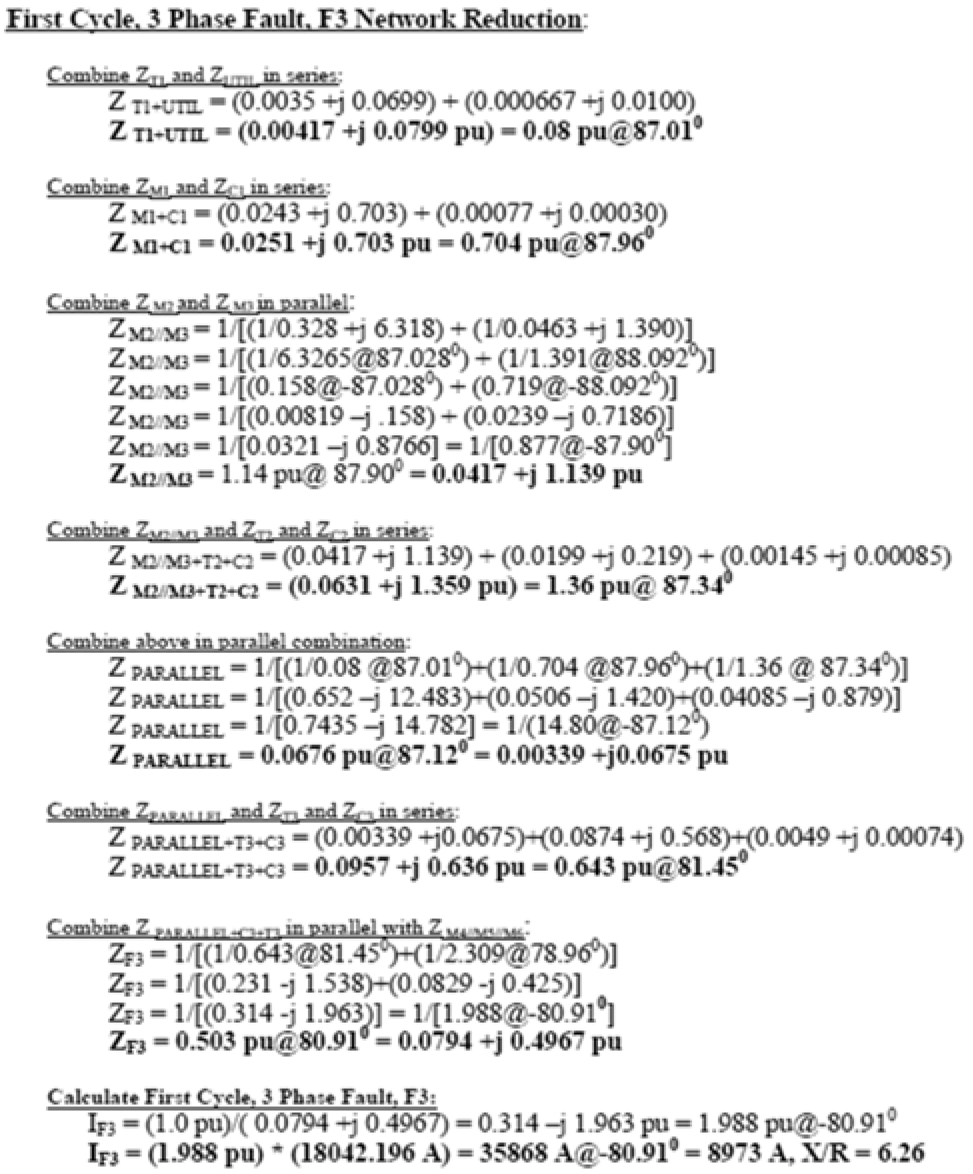
Calculate First Cycle, 3 Phase Fault, F2:

$I_{F2} = (1.0\ \text{pu})/(\ 0.0177 + j\ 0.2312) = 0.328 - j\ 4.298\ \text{pu} = 4.310\ \text{pu}@{-85.63}^{0}$

$I_{F2} = (4.310\ \text{pu}) * (2081.792\ \text{A}) = 8973\ \text{A}@{-85.63}^{0} = 8973\ \text{A},\ X/R = 13.06$

3 PHASE FAULT EXAMPLE





First Cycle, 3 Phase Fault, F3 Network Reduction:

Combine Z_{T1} and Z_{UTIL} in series:

$Z_{T1+UTIL} = (0.0035 +j\,0.0699) + (0.000667 +j\,0.0100)$

$Z_{T1+UTIL} = (0.00417 +j\,0.0799\text{ pu}) = 0.08\text{ pu}@87.01^{0}$

Combine Z_{M1} and Z_{C1} in series:

$Z_{M1+C1} = (0.0243 +j\,0.703) + (0.00077 +j\,0.00030)$

$Z_{M1+C1} = 0.0251 +j\,0.703\text{ pu} = 0.704\text{ pu}@87.96^{0}$

Combine Z_{M2} and Z_{M3} in parallel:

$Z_{M2//M3} = 1/[(1/0.328 +j\,6.318) + (1/0.0463 +j\,1.390)]$

$Z_{M2//M3} = 1/[(1/6.3265@87.028^{0}) + (1/1.391@88.092^{0})]$

$Z_{M2//M3} = 1/[(0.158@-87.028^{0}) + (0.719@-88.092^{0})]$

$Z_{M2//M3} = 1/[(0.00819 -j\,.158) + (0.0239 -j\,0.7186)]$

$Z_{M2//M3} = 1/[0.0321 -j\,0.8766] = 1/[0.877@-87.90^{0}]$

$Z_{M2//M3} = 1.14\text{ pu}@\,87.90^{0} = 0.0417 +j\,1.139\text{ pu}$

Combine $Z_{M2//M3}$ and Z_{T2} and Z_{C2} in series:

$Z_{M2//M3+T2+C2} = (0.0417 +j\,1.139) + (0.0199 +j\,0.219) + (0.00145 +j\,0.00085)$

$Z_{M2//M3+T2+C2} = (0.0631 +j\,1.359\text{ pu}) = 1.36\text{ pu}@\,87.34^{0}$

Combine above in parallel combination:

$Z_{PARALLEL} = 1/[(1/0.08\,@87.01^{0})+(1/0.704\,@87.96^{0})+(1/1.36\,@\,87.34^{0})]$

$Z_{PARALLEL} = 1/[(0.652 -j\,12.483)+(0.0506 -j\,1.420)+(0.04085 -j\,0.879)]$

$Z_{PARALLEL} = 1/[0.7435 -j\,14.782] = 1/(14.80@-87.12^{0})$

$Z_{PARALLEL} = 0.0676\text{ pu}@87.12^{0} = 0.00339 +j0.0675\text{ pu}$

Combine $Z_{PARALLEL}$ and Z_{T3} and Z_{C3} in series:

$Z_{PARALLEL+T3+C3} = (0.00339 +j0.0675)+(0.0874 +j\,0.568)+(0.0049 +j\,0.00074)$

$Z_{PARALLEL+T3+C3} =$ **$0.0957 +j\,0.636\text{ pu} = 0.643\text{ pu}@81.45^{0}$**

Combine $Z_{PARALLEL+C3+T3}$ in parallel with $Z_{M4//M5//M6}$:

$Z_{F3} = 1/[(1/0.643@81.45^{0})+(1/2.309@78.96^{0})]$

$Z_{F3} = 1/[(0.231 -j\,1.538)+(0.0829 -j\,0.425)]$

$Z_{F3} = 1/[(0.314 -j\,1.963)] = 1/[1.988@-80.91^{0}]$

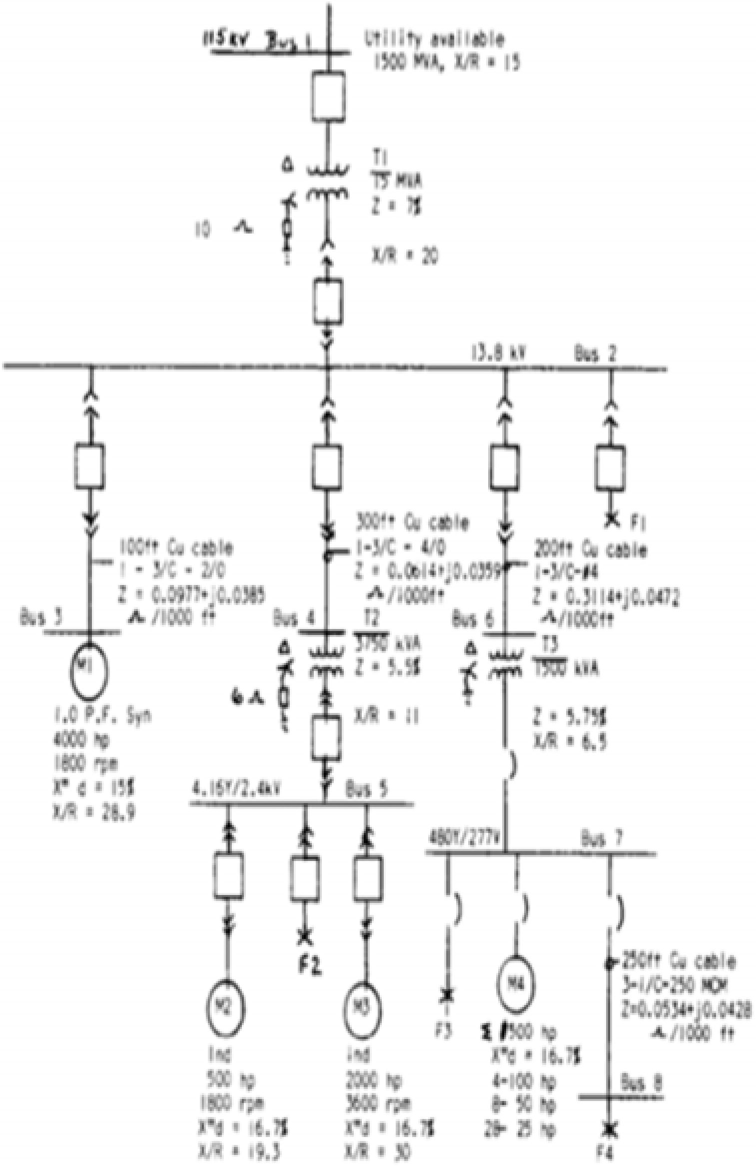
$Z_{F3} = 0.503\text{ pu}@80.91^{0} = 0.0794 +j\,0.4967\text{ pu}$

Calculate First Cycle, 3 Phase Fault, F3:

$I_{F3} = (1.0\text{ pu})/(\,0.0794 +j\,0.4967) = 0.314 -j\,1.963\text{ pu} = 1.988\text{ pu}@-80.91^{0}$

$I_{F3} = (1.988\text{ pu}) * (18042.196\text{ A}) = 35868\text{ A}@-80.91^{0} = 8973\text{ A}, X/R = 6.26$

3 PHASE FAULT EXAMPLE



First Cycle, 3 Phase Fault, F4 Network Reduction:

Combine Z_{T1} and Z_{UTIL} in series:

$Z_{T1+UTIL} = (0.0035 + j\,0.0699) + (0.000667 + j\,0.0100)$

$\mathbf{Z_{T1+UTIL} = (0.00417 + j\,0.0799\ pu) = 0.08\ pu@87.01^{0}}$

Combine Z_{M1} and Z_{C1} in series:

$Z_{M1+C1} = (0.0243 + j\,0.703) + (0.00077 + j\,0.00030)$

$\mathbf{Z_{M1+C1} = 0.0251 + j\,0.703\ pu = 0.704\ pu@87.96^{0}}$

Combine Z_{M2} and Z_{M3} in parallel:

$Z_{M2//M3} = 1/[(1/0.328 + j\,6.318) + (1/0.0463 + j\,1.390)]$

$Z_{M2//M3} = 1/[(1/6.3265@87.028^{0}) + (1/1.391@88.092^{0})]$

$Z_{M2//M3} = 1/[(0.158@-87.028^{0}) + (0.719@-88.092^{0})]$

$Z_{M2//M3} = 1/[(0.00819 - j\,.158) + (0.0239 - j\,0.7186)]$

$Z_{M2//M3} = 1/[0.0321 - j\,0.8766] = 1/[0.877@-87.90^{0}]$

$\mathbf{Z_{M2//M3}} = 1.14\ pu@\ 87.90^{0} = \mathbf{0.0417 + j\,1.139\ pu}$

Combine $Z_{M2//M3}$ and Z_{T2} and Z_{C2} in series:

$Z_{M2//M3+T2+C2} = (0.0417 + j\,1.139) + (0.0199 + j\,0.219) + (0.00145 + j\,0.00085)$

$\mathbf{Z_{M2//M3+T2+C2} = (0.0631 + j\,1.359\ pu) = 1.36\ pu@\ 87.34^{0}}$

Combine above in parallel combination:

$Z_{PARALLEL} = 1/[(1/0.08\ @87.01^{0}) + (1/0.704\ @87.96^{0}) + (1/1.36\ @\ 87.34^{0})]$

$Z_{PARALLEL} = 1/[(0.652 - j\,12.483) + (0.0506 - j\,1.420) + (0.04085 - j\,0.879)]$

$Z_{PARALLEL} = 1/[0.7435 - j\,14.782] = 1/(14.80@-87.12^{0})$

$\mathbf{Z_{PARALLEL} = 0.0676\ pu@87.12^{0} = 0.00339 + j0.0675\ pu}$

Combine $Z_{PARALLEL}$ and Z_{T3} and Z_{C3} in series:

$Z_{PARALLEL+T3+C3} = (0.00339 + j0.0675) + (0.0874 + j\,0.568) + (0.0049 + j\,0.00074)$

$Z_{PARALLEL+T3+C3} = \mathbf{0.0957 + j\,0.636\ pu = 0.643\ pu@81.45^{0}}$

Combine $Z_{PARALLEL+C3+T3}$ in parallel with $Z_{M4/M5/M6}$:

$Z_{F3} = 1/[(1/0.643@81.45^{0}) + (1/2.309@78.96^{0})]$

$Z_{F3} = 1/[(0.231 - j\,1.538) + (0.0829 - j\,0.425)]$

$Z_{F3} = 1/[(0.314 - j\,1.963)] = 1/[1.988@-80.91^{0}]$

$\mathbf{Z_{F3} = 0.503\ pu@80.91^{0} = 0.0794 + j\,0.4967\ pu}$

Combine Z_{F3} in series with Z_{C4}:

$Z_{F4} = (0.0794 + j\,0.4967) + (0.867 + j\,0.695)$

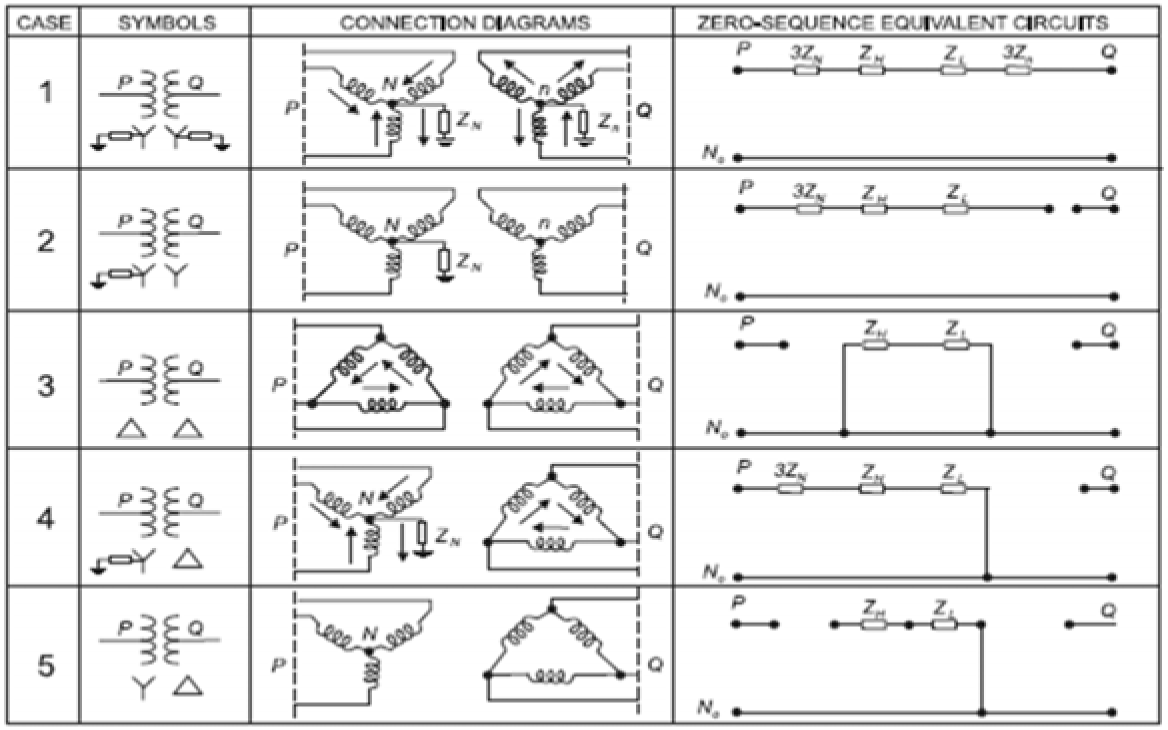
$\mathbf{Z_{F4} = 0.9464 + j\,1.192\ pu = 1.522\ pu@51.54^{0}}$

Calculate First Cycle, 3 Phase Fault, F4:

$I_{F4} = (1.0\ pu)/(\,0.9464 + j\,1.192) = 0.409 - j\,0.515\ pu = 0.657\ pu@-51.54^{0}$

$\mathbf{I_{F4} = (0.657\ pu) * (18042.196\ A) = 11856\ A@-51.54^{0} = 11856\ A,\ X/R = 1.26}$

SHORT CIRCUIT CALCULATION



CASE	SYMBOLS	CONNECTION DIAGRAMS	ZERO-SEQUENCE EQUIVALENT CIRCUITS
1	P Q	P N Z_N n Z_n Q	P $3Z_N$ Z_H Z_L $3Z_n$ Q N_o
2	P Q	P N Z_N n Q	P $3Z_N$ Z_H Z_L Q N_o
3	P Q	P Q	P Z_H Z_L Q N_o
4	P Q	P N Z_N Q	P $3Z_N$ Z_H Z_L Q N_o
5	P Q	P N Q	P Z_H Z_L Q N_o

OVERCURRENT COORDINATION

- Determine characteristics, ratings and settings that provide the following:
  - Minimize equipment damage
  - Interrupt short circuits as quickly as possible
  - Only minimum portion of the system is interrupted
  - Protection versus selectivity

OVERCURRENT COORDINATION

- Coordinating Time Intervals (CTIs)
  - – Time interval between protective device curves used to insure correct selective operation and to reduce nuisance tripping.

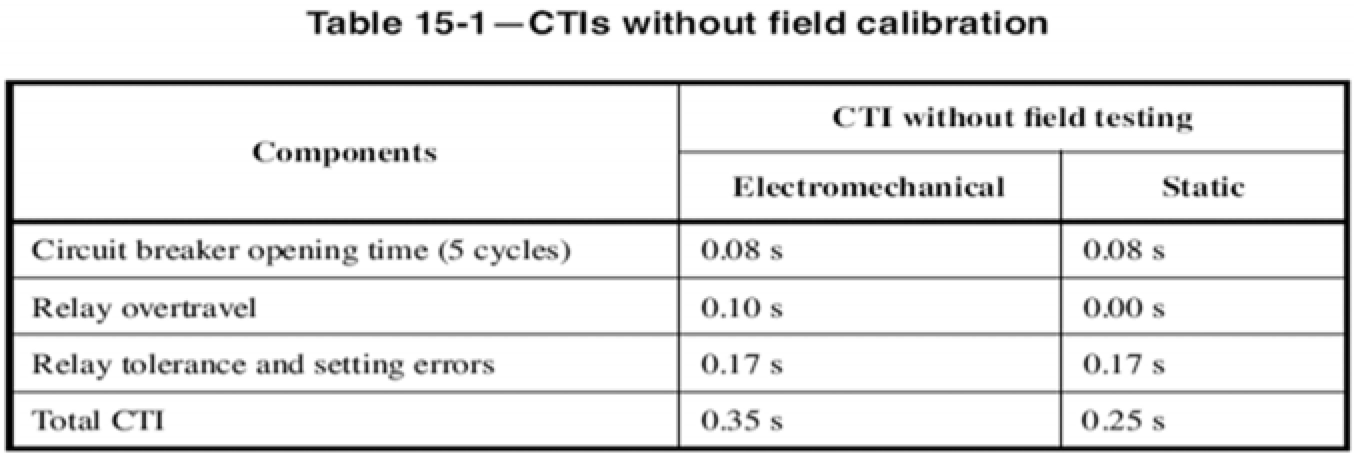


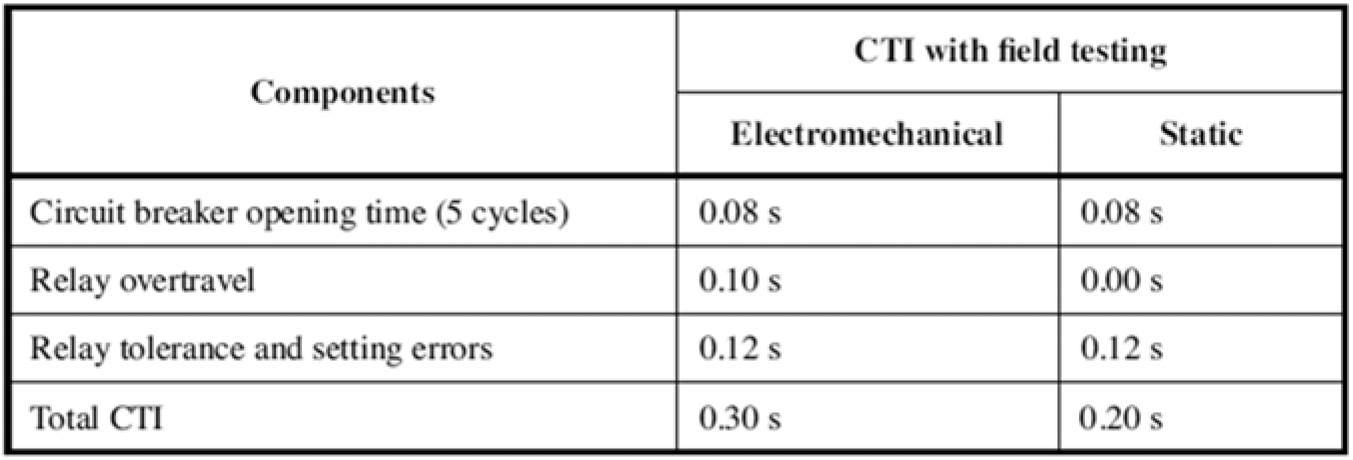
Table 15-1—CTIs without field calibration

Components	CTI without field testing	
	Electromechanical	Static
Circuit breaker opening time (5 cycles)	0.08 s	0.08 s
Relay overtravel	0.10 s	0.00 s
Relay tolerance and setting errors	0.17 s	0.17 s
Total CTI	0.35 s	0.25 s

OVERCURRENT COORDINATION

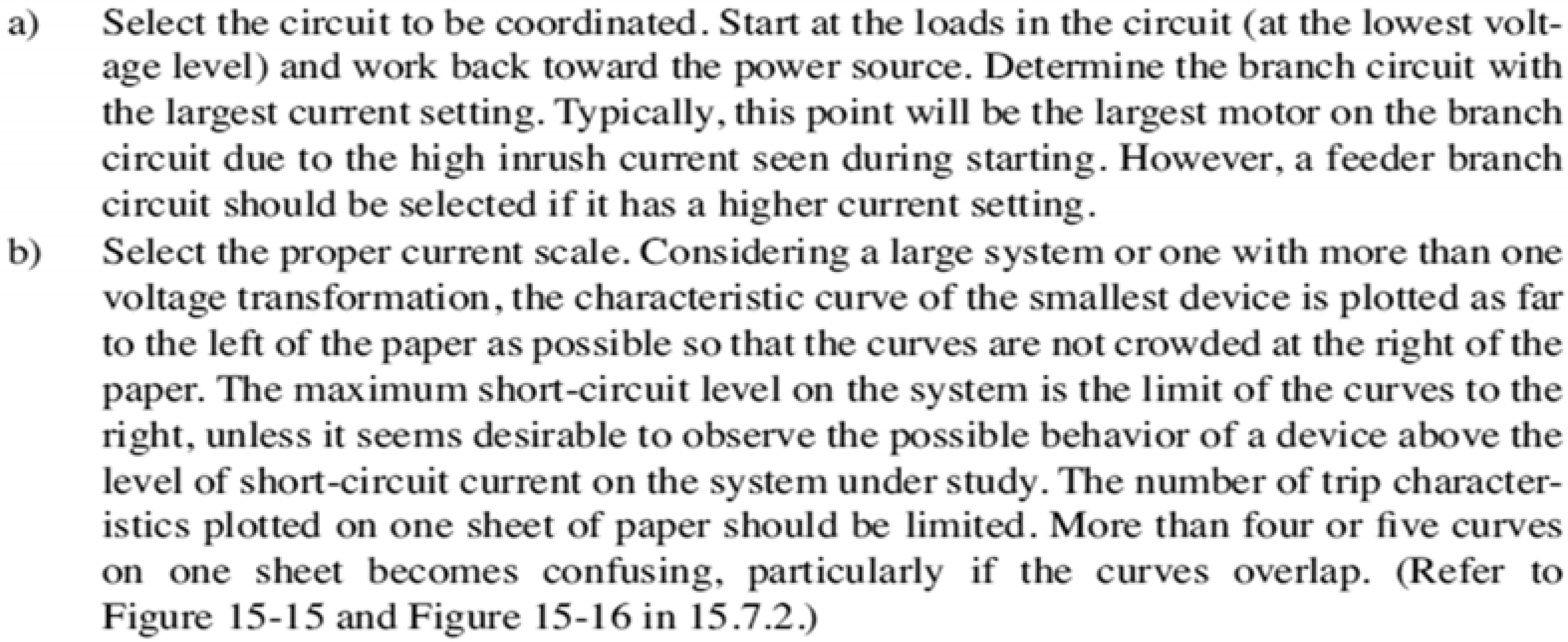
- Coordinating Time Intervals (CTIs)

Table 15-2—CTIs with field calibration



Components	CTI with field testing	
	Electromechanical	Static
Circuit breaker opening time (5 cycles)	0.08 s	0.08 s
Relay overtravel	0.10 s	0.00 s
Relay tolerance and setting errors	0.12 s	0.12 s
Total CTI	0.30 s	0.20 s

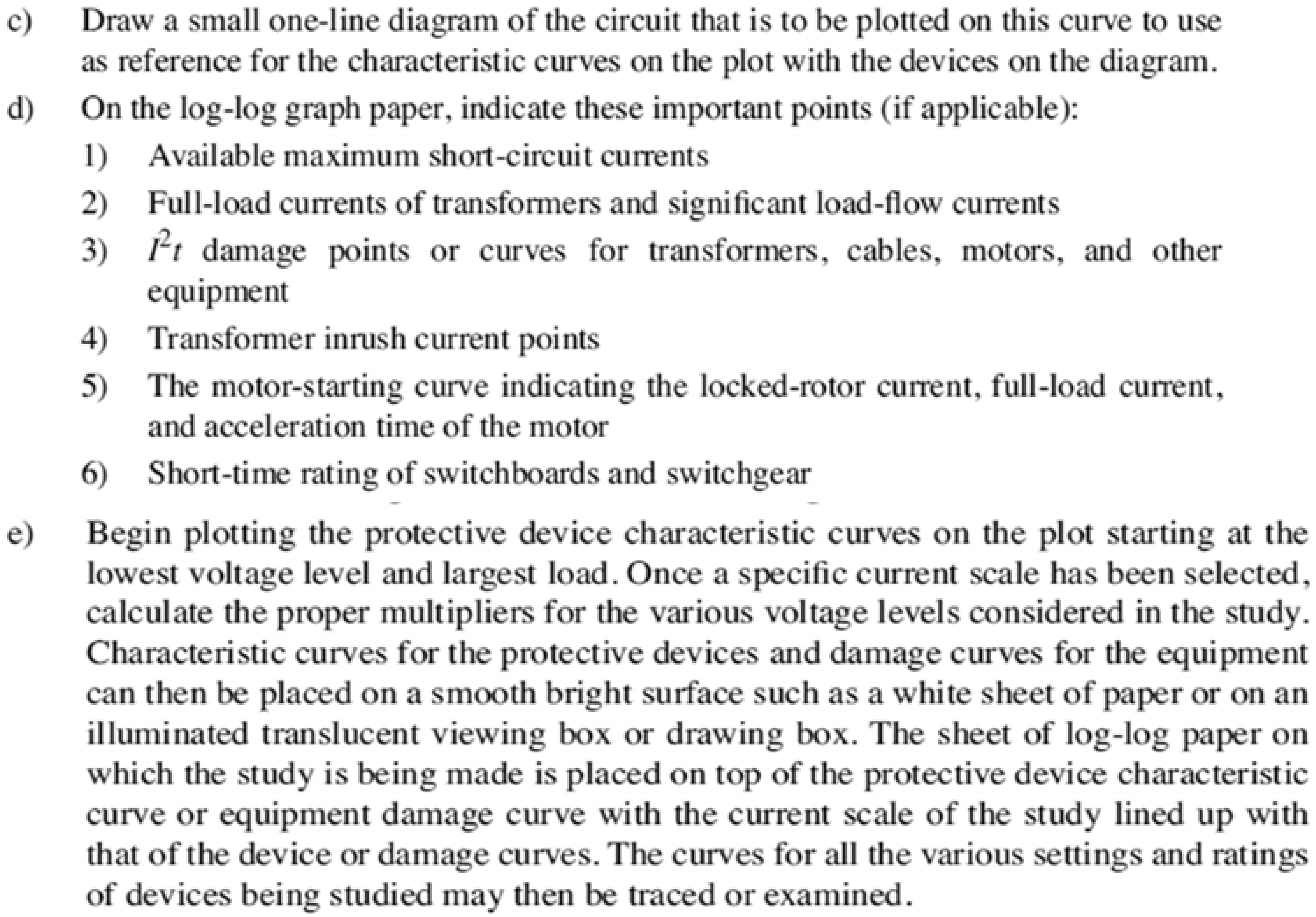
CONSTRUCTING TCCs



a) Select the circuit to be coordinated. Start at the loads in the circuit (at the lowest voltage level) and work back toward the power source. Determine the branch circuit with the largest current setting. Typically, this point will be the largest motor on the branch circuit due to the high inrush current seen during starting. However, a feeder branch circuit should be selected if it has a higher current setting.

b) Select the proper current scale. Considering a large system or one with more than one voltage transformation, the characteristic curve of the smallest device is plotted as far to the left of the paper as possible so that the curves are not crowded at the right of the paper. The maximum short-circuit level on the system is the limit of the curves to the right, unless it seems desirable to observe the possible behavior of a device above the level of short-circuit current on the system under study. The number of trip characteristics plotted on one sheet of paper should be limited. More than four or five curves on one sheet becomes confusing, particularly if the curves overlap. (Refer to Figure 15-15 and Figure 15-16 in 15.7.2.)

CONSTRUCTING TCCs



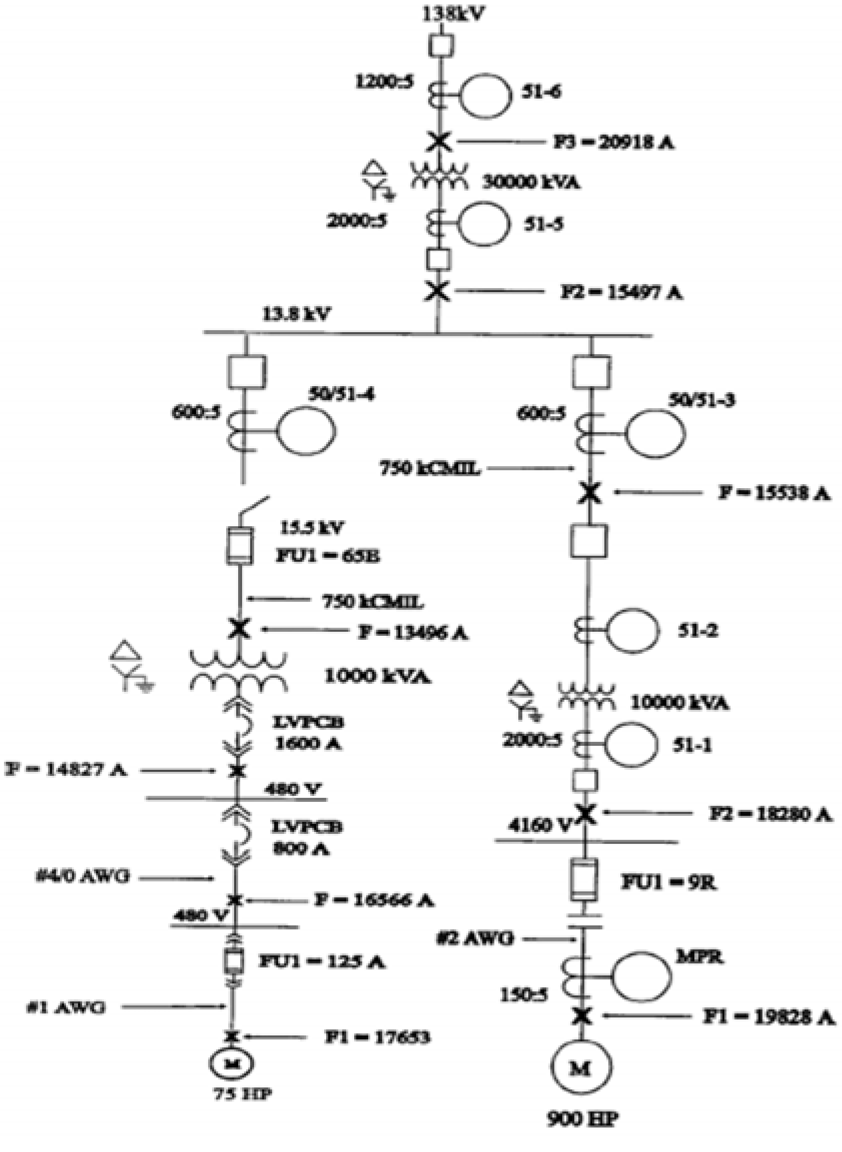
c) Draw a small one-line diagram of the circuit that is to be plotted on this curve to use as reference for the characteristic curves on the plot with the devices on the diagram.

d) On the log-log graph paper, indicate these important points (if applicable):

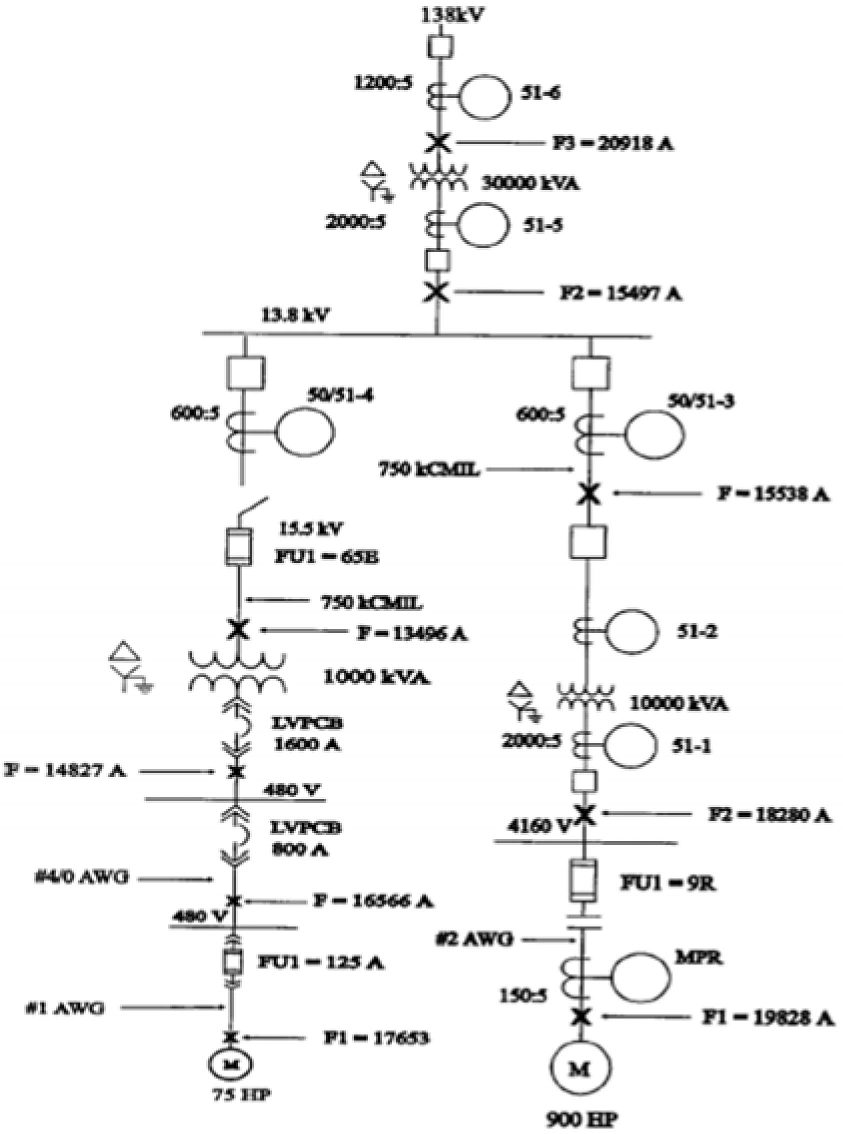
    1) Available maximum short-circuit currents
    2) Full-load currents of transformers and significant load-flow currents
    3) I^2t damage points or curves for transformers, cables, motors, and other equipment
    4) Transformer inrush current points
    5) The motor-starting curve indicating the locked-rotor current, full-load current, and acceleration time of the motor
    6) Short-time rating of switchboards and switchgear

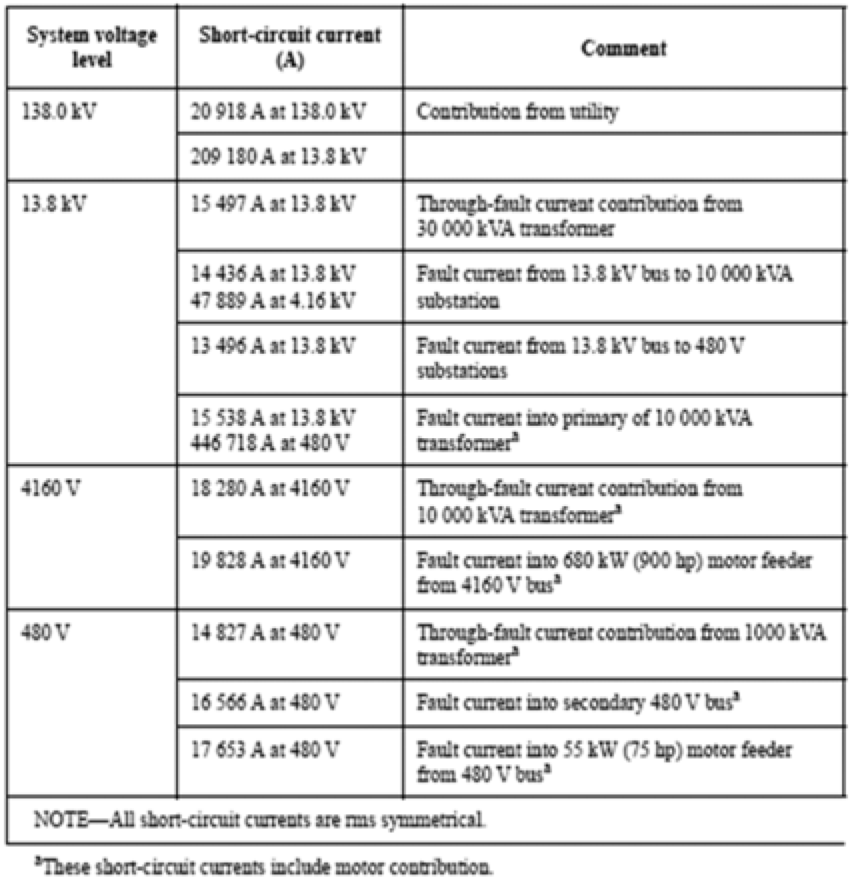
e) Begin plotting the protective device characteristic curves on the plot starting at the lowest voltage level and largest load. Once a specific current scale has been selected, calculate the proper multipliers for the various voltage levels considered in the study. Characteristic curves for the protective devices and damage curves for the equipment can then be placed on a smooth bright surface such as a white sheet of paper or on an illuminated translucent viewing box or drawing box. The sheet of log-log paper on which the study is being made is placed on top of the protective device characteristic curve or equipment damage curve with the current scale of the study lined up with that of the device or damage curves. The curves for all the various settings and ratings of devices being studied may then be traced or examined.

EXAMPLE CONSTRUCTING TCCs



EXAMPLE CONSTRUCTING TCCs

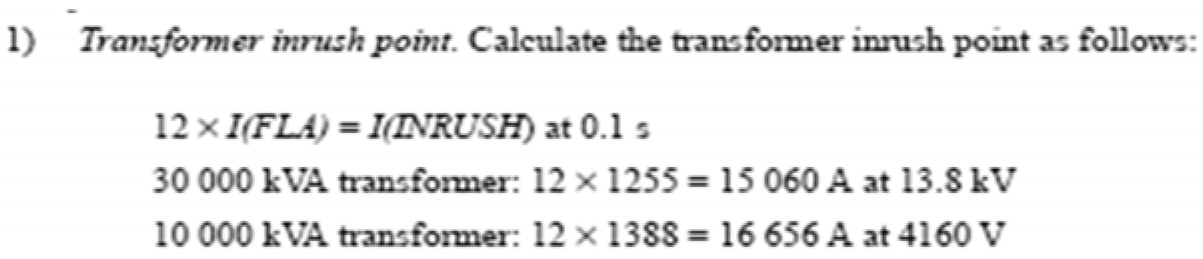




System voltage level	Short-circuit current (A)	Comment
138.0 kV	20 918 A at 138.0 kV	Contribution from utility
	209 180 A at 13.8 kV	
13.8 kV	15 497 A at 13.8 kV	Through-fault current contribution from 30 000 kVA transformer
	14 436 A at 13.8 kV 47 889 A at 4.16 kV	Fault current from 13.8 kV bus to 10 000 kVA substation
	13 496 A at 13.8 kV	Fault current from 13.8 kV bus to 480 V substations
	15 538 A at 13.8 kV 446 718 A at 480 V	Fault current into primary of 10 000 kVA transformer[a]
4160 V	18 280 A at 4160 V	Through-fault current contribution from 10 000 kVA transformer[a]
	19 828 A at 4160 V	Fault current into 680 kW (900 hp) motor feeder from 4160 V bus[a]
480 V	14 827 A at 480 V	Through-fault current contribution from 1000 kVA transformer[a]
	16 566 A at 480 V	Fault current into secondary 480 V bus[a]
	17 653 A at 480 V	Fault current into 55 kW (75 hp) motor feeder from 480 V bus[a]
NOTE—All short-circuit currents are rms symmetrical.		

[a] These short-circuit currents include motor contribution.

EXAMPLE CONSTRUCTING TCCs

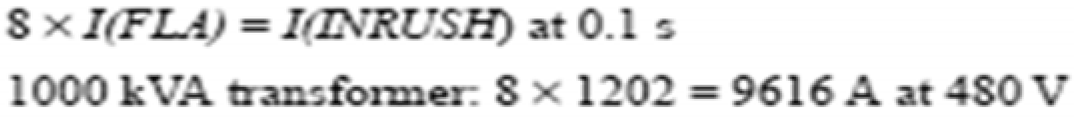


1) *Transformer inrush point*. Calculate the transformer inrush point as follows:

$12 \times I(FLA) = I(INRUSH)$ at 0.1 s

30 000 kVA transformer: $12 \times 1255 = 15\,060$ A at 13.8 kV

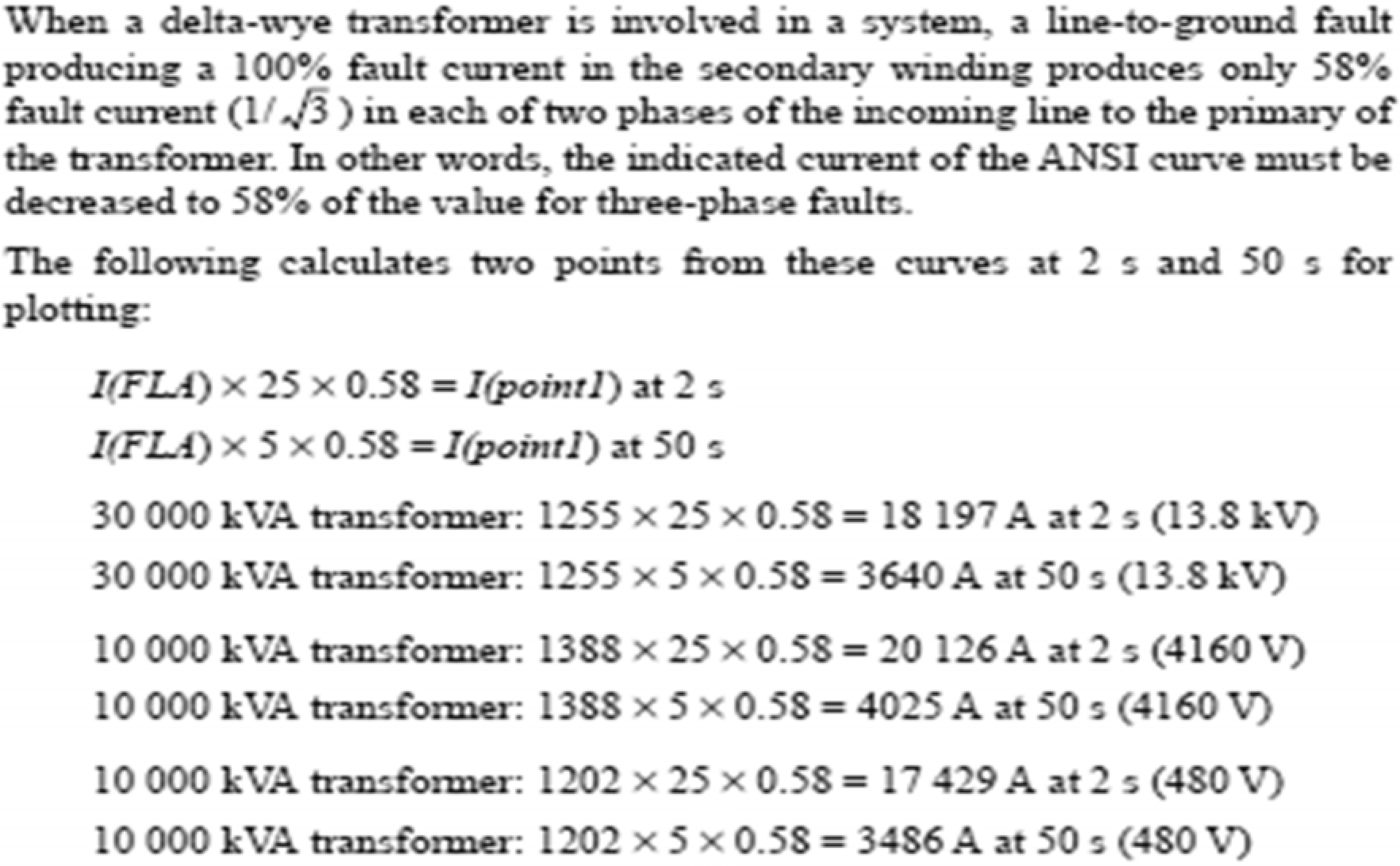
10 000 kVA transformer: $12 \times 1388 = 16\,656$ A at 4160 V



$8 \times I(FLA) = I(INRUSH)$ at 0.1 s

1000 kVA transformer: $8 \times 1202 = 9616$ A at 480 V

EXAMPLE CONSTRUCTING TCCs



When a delta-wye transformer is involved in a system, a line-to-ground fault producing a 100% fault current in the secondary winding produces only 58% fault current ($1/\sqrt{3}$) in each of two phases of the incoming line to the primary of the transformer. In other words, the indicated current of the ANSI curve must be decreased to 58% of the value for three-phase faults.

The following calculates two points from these curves at 2 s and 50 s for plotting:

$I(FLA) \times 25 \times 0.58 = I(point1)$ at 2 s

$I(FLA) \times 5 \times 0.58 = I(point1)$ at 50 s

30 000 kVA transformer: 1255 × 25 × 0.58 = 18 197 A at 2 s (13.8 kV)

30 000 kVA transformer: 1255 × 5 × 0.58 = 3640 A at 50 s (13.8 kV)

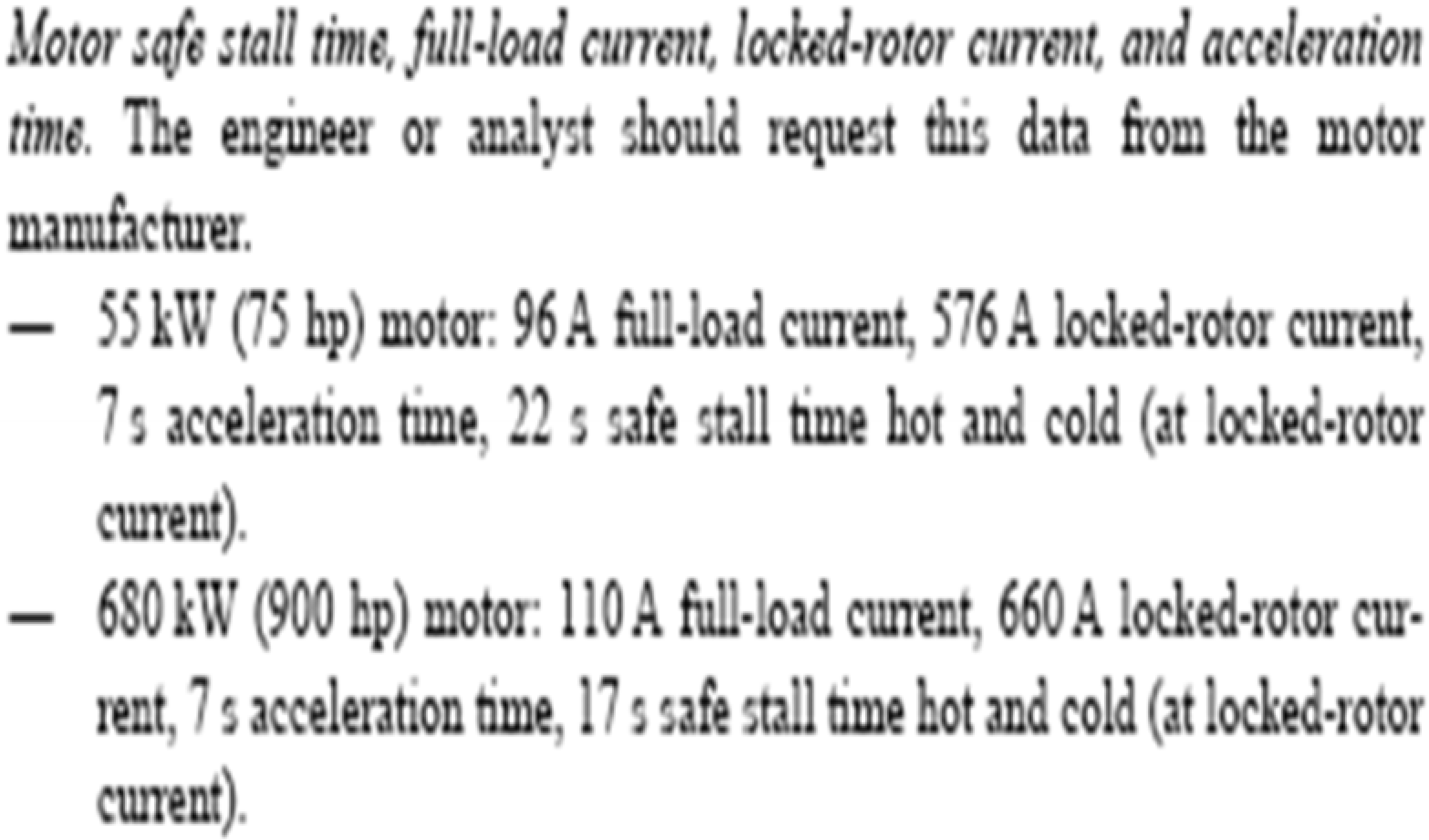
10 000 kVA transformer: 1388 × 25 × 0.58 = 20 126 A at 2 s (4160 V)

10 000 kVA transformer: 1388 × 5 × 0.58 = 4025 A at 50 s (4160 V)

10 000 kVA transformer: 1202 × 25 × 0.58 = 17 429 A at 2 s (480 V)

10 000 kVA transformer: 1202 × 5 × 0.58 = 3486 A at 50 s (480 V)

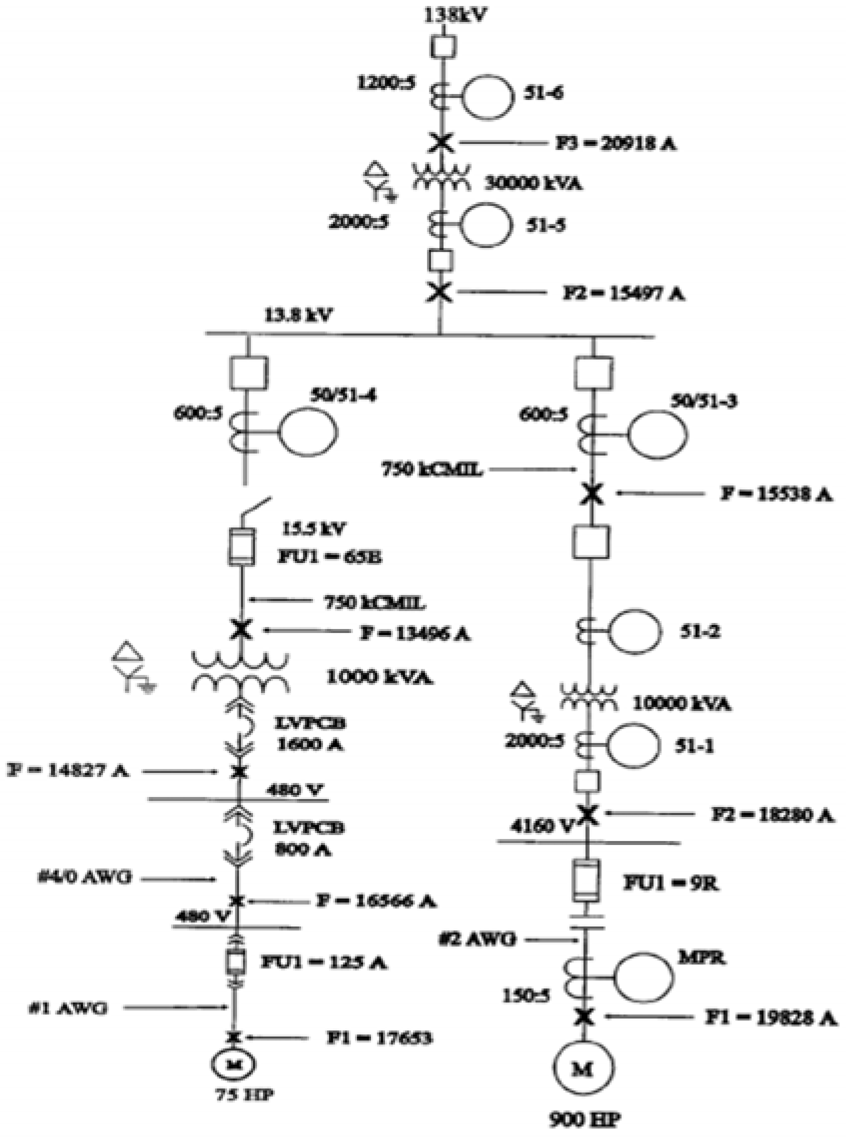
EXAMPLE CONSTRUCTING TCCs

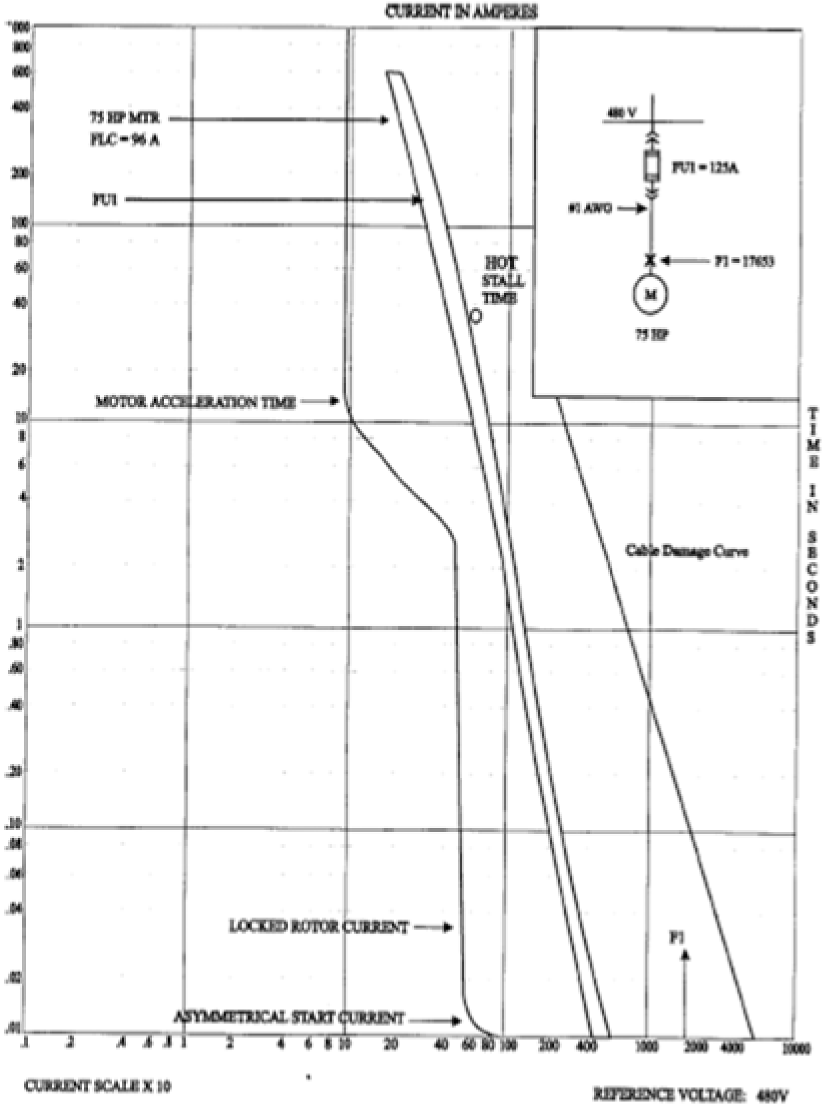


Motor safe stall time, full-load current, locked-rotor current, and acceleration time. The engineer or analyst should request this data from the motor manufacturer.

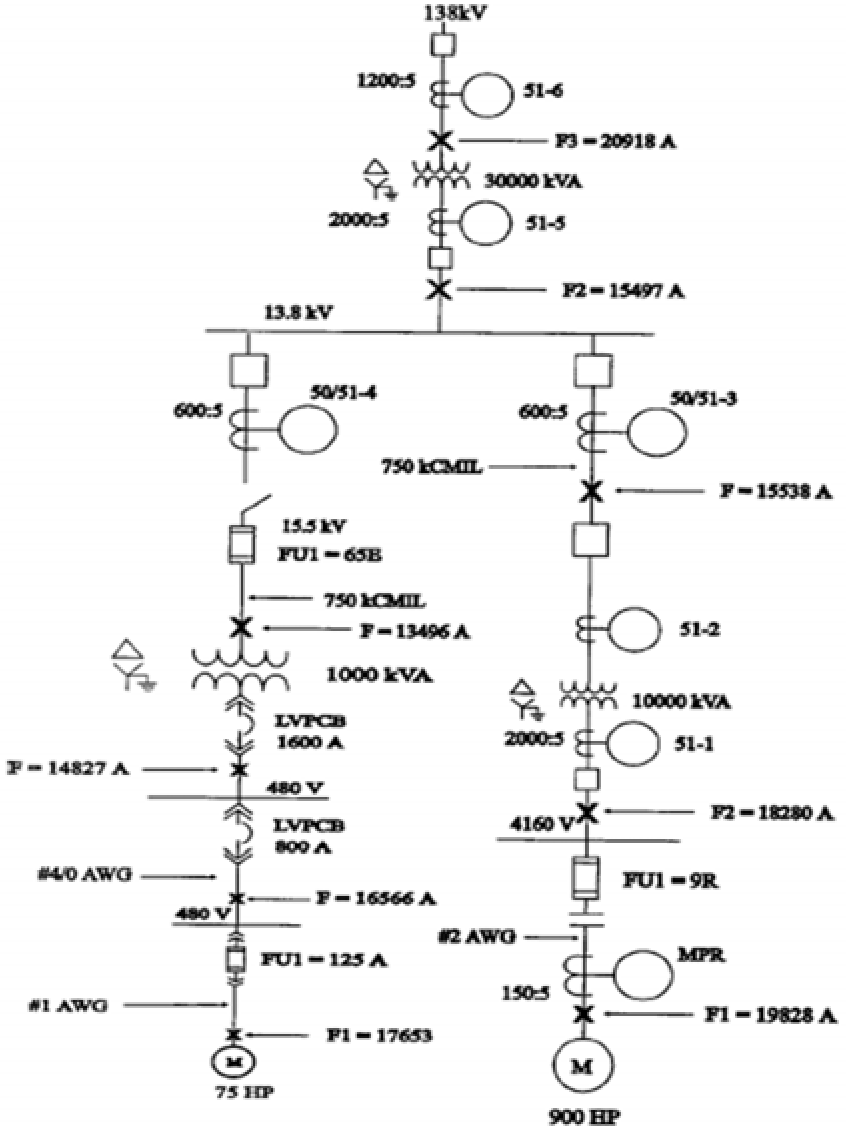
- 55 kW (75 hp) motor: 96 A full-load current, 576 A locked-rotor current, 7 s acceleration time, 22 s safe stall time hot and cold (at locked-rotor current).
- 680 kW (900 hp) motor: 110 A full-load current, 660 A locked-rotor current, 7 s acceleration time, 17 s safe stall time hot and cold (at locked-rotor current).

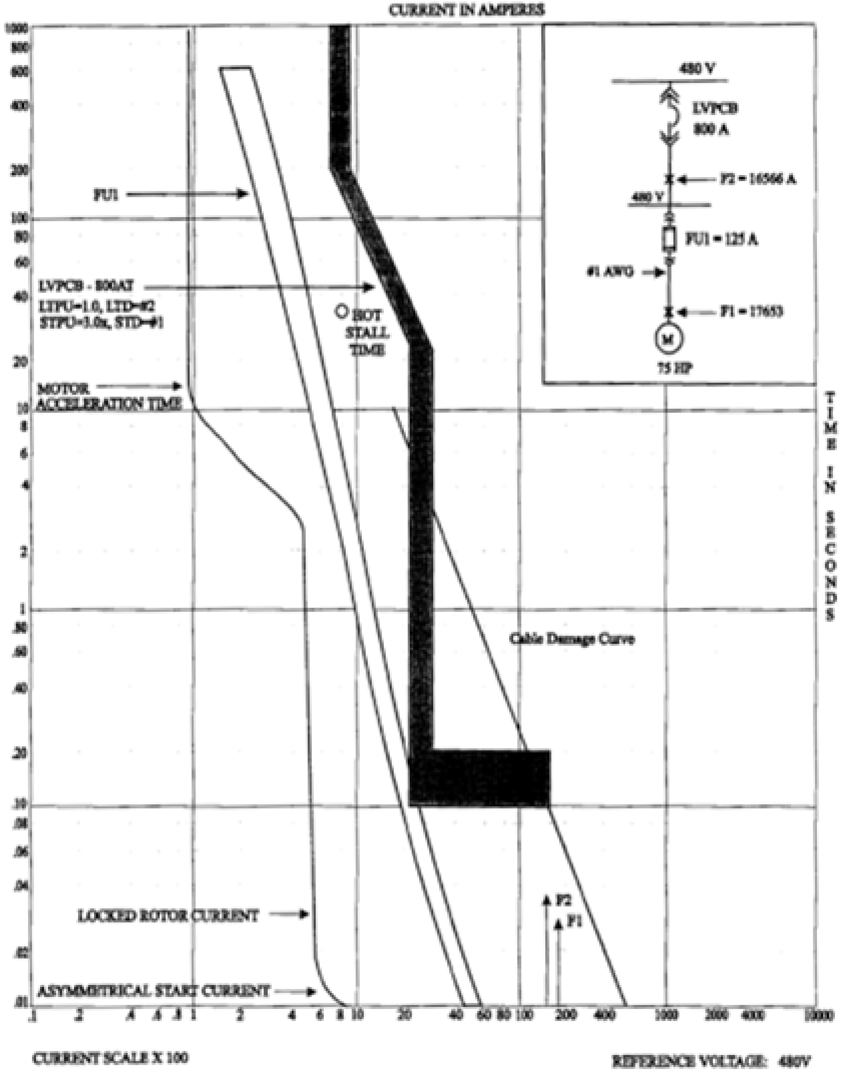
EXAMPLE CONSTRUCTING TCCs



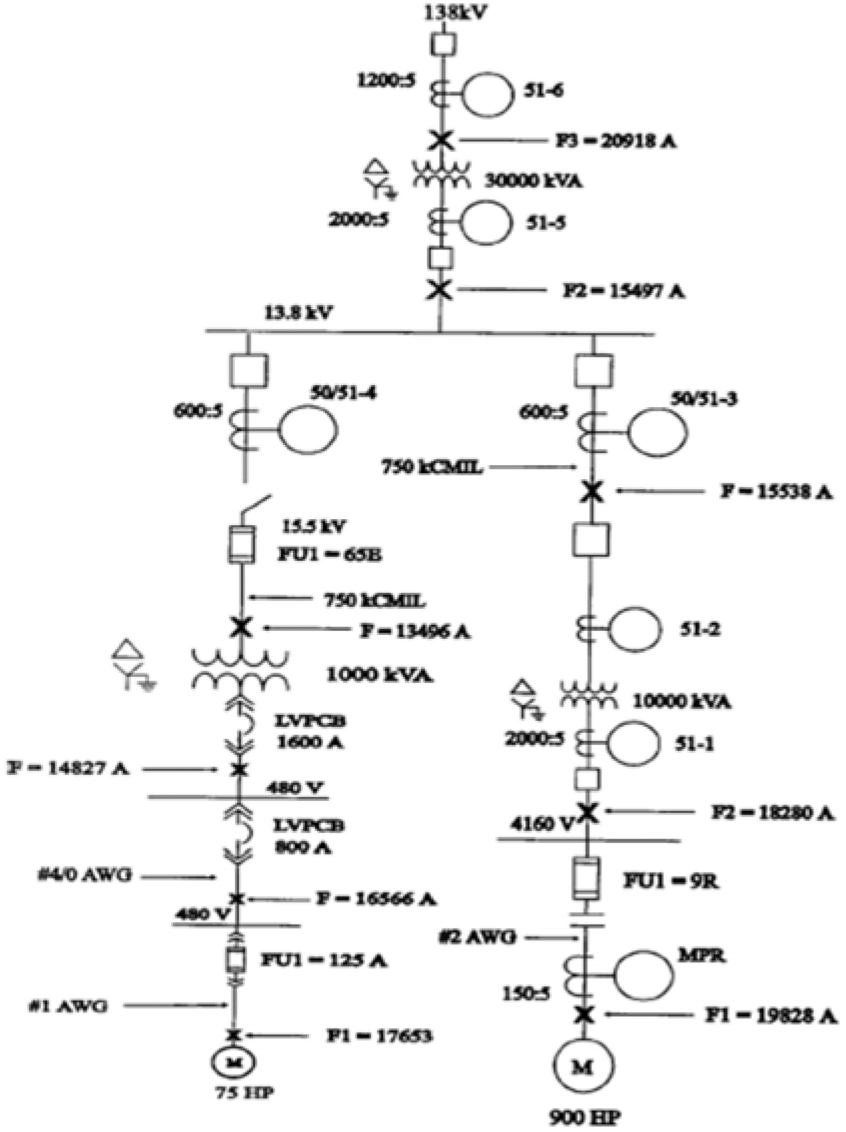


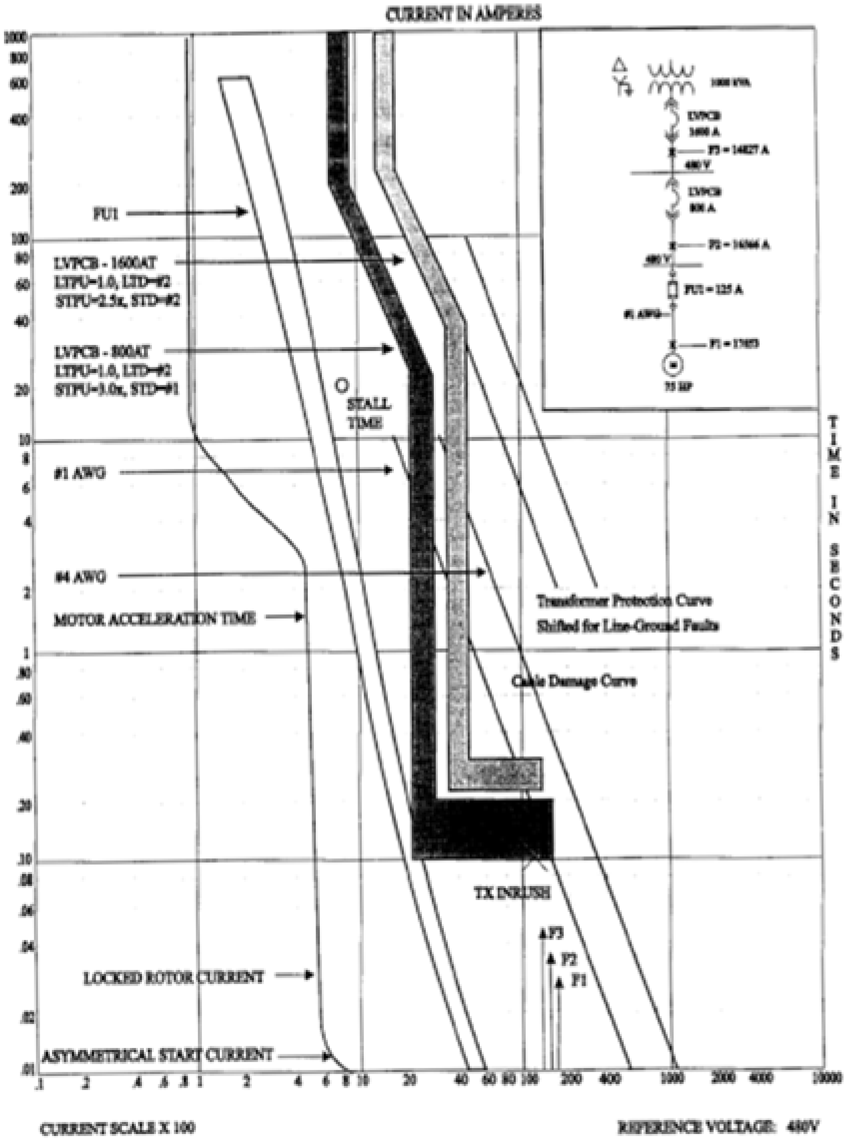
EXAMPLE CONSTRUCTING TCCs



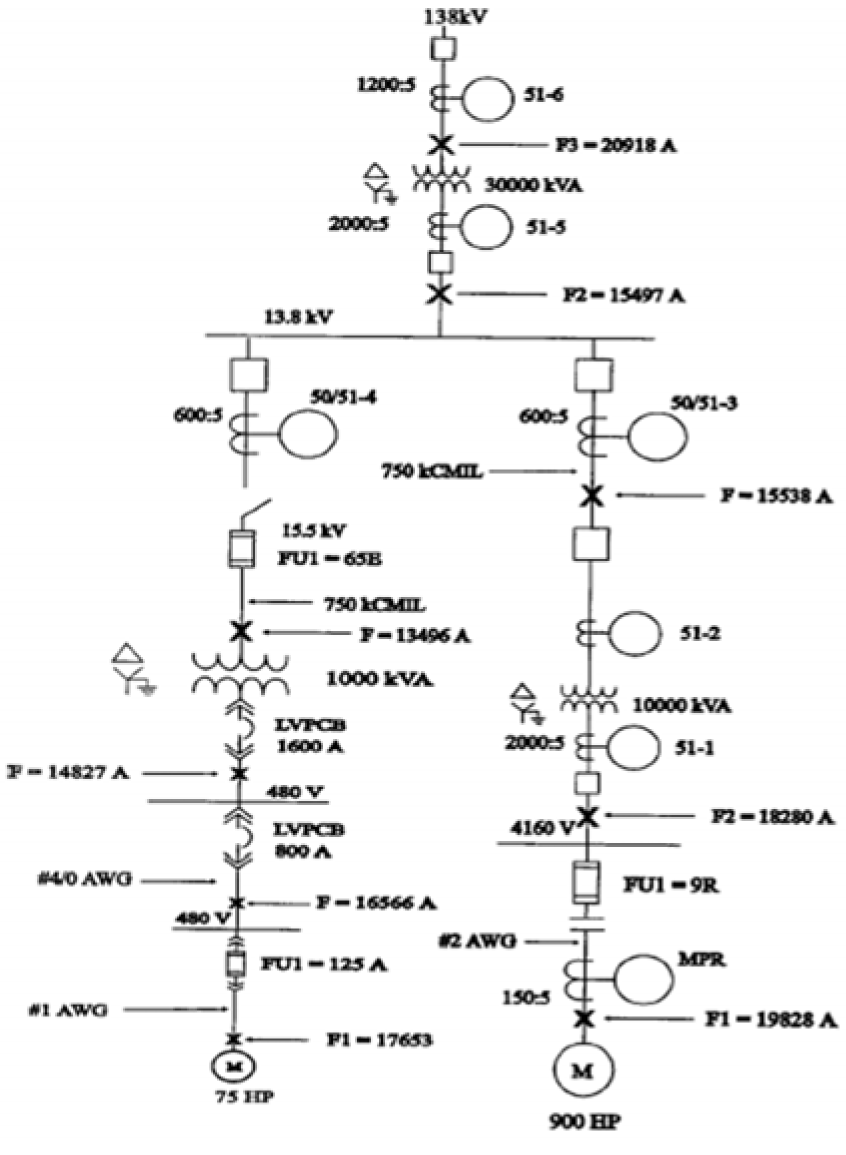


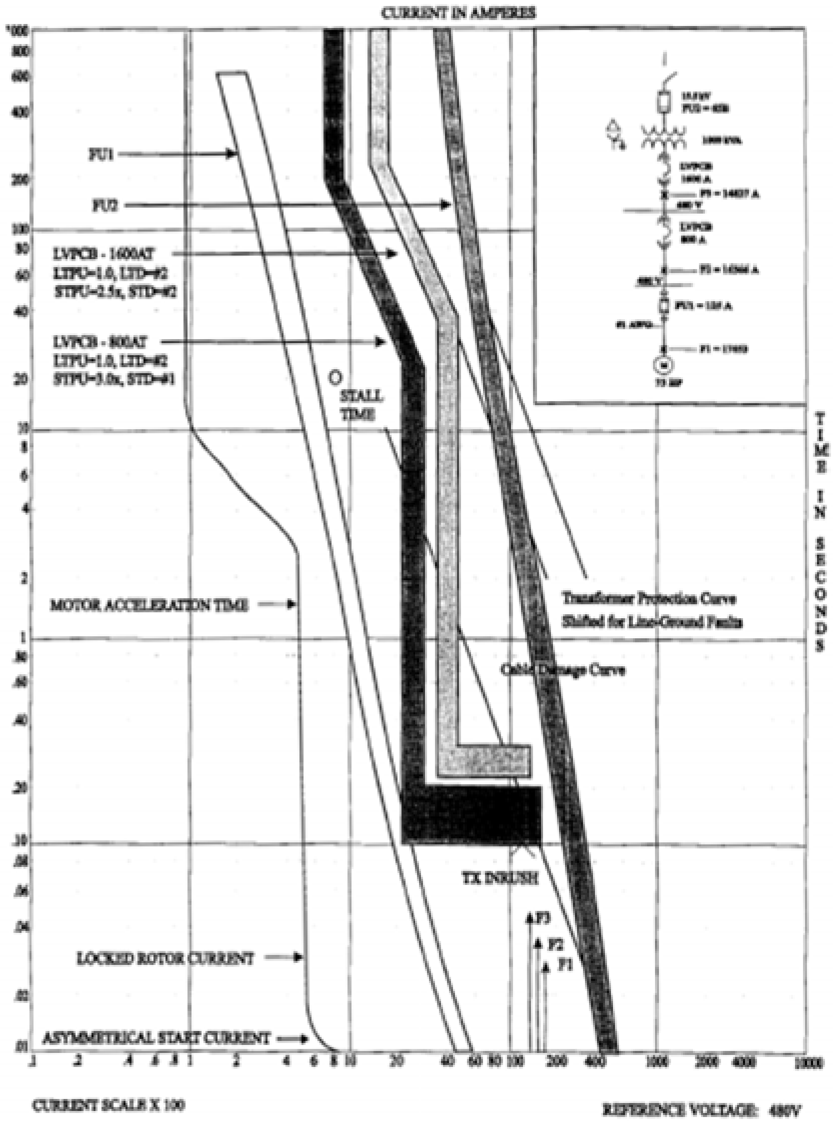
EXAMPLE CONSTRUCTING TCCs



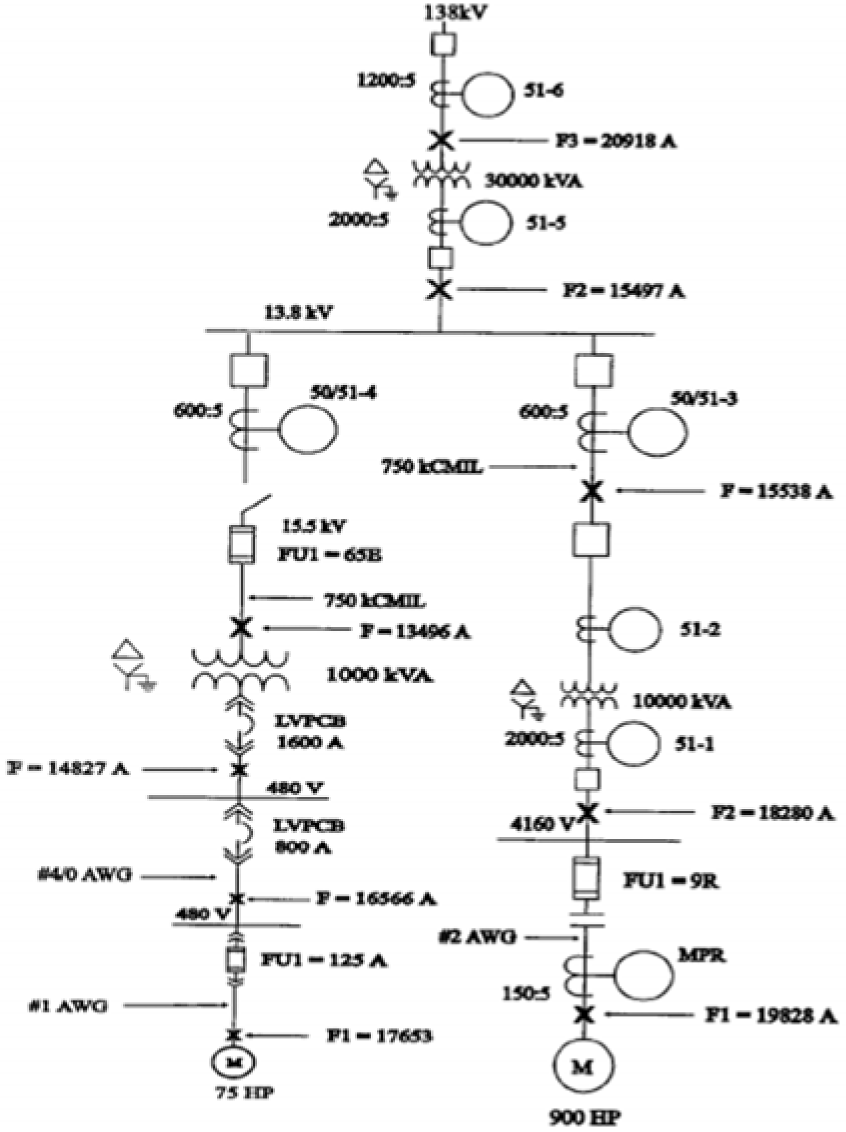


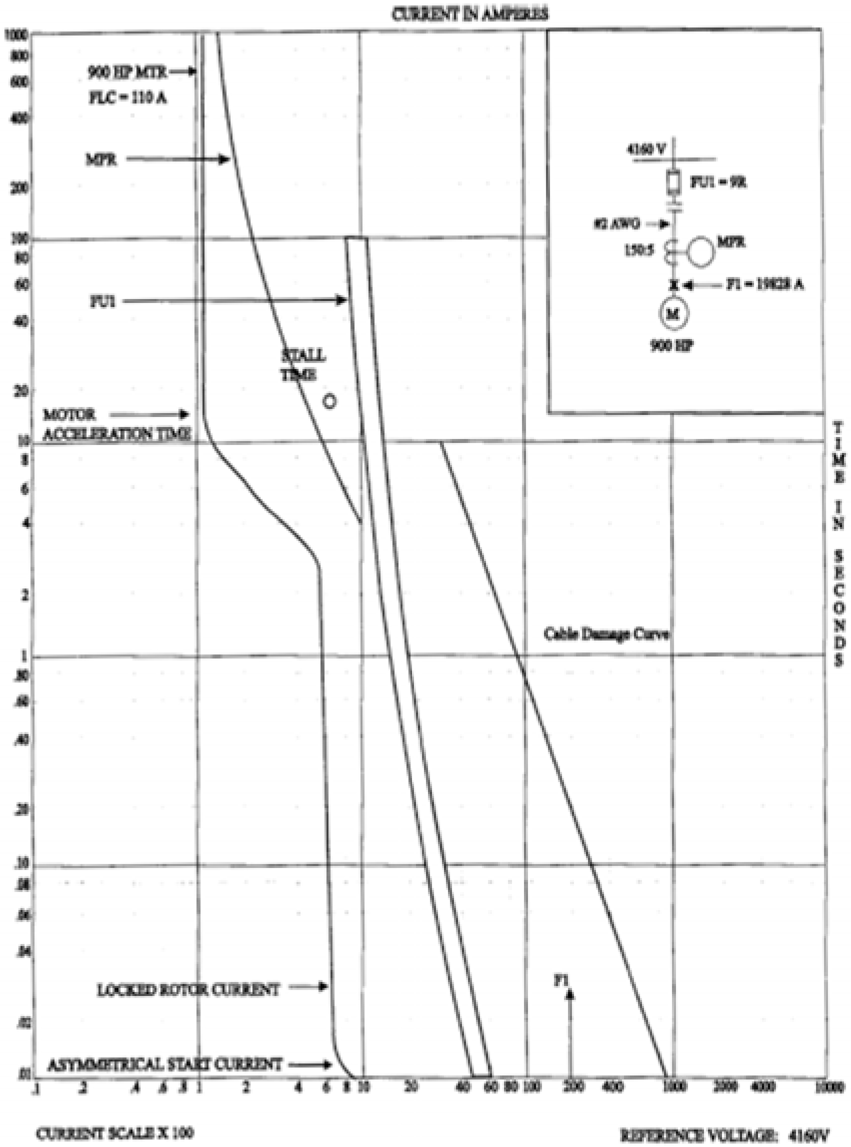
EXAMPLE CONSTRUCTING TCCs



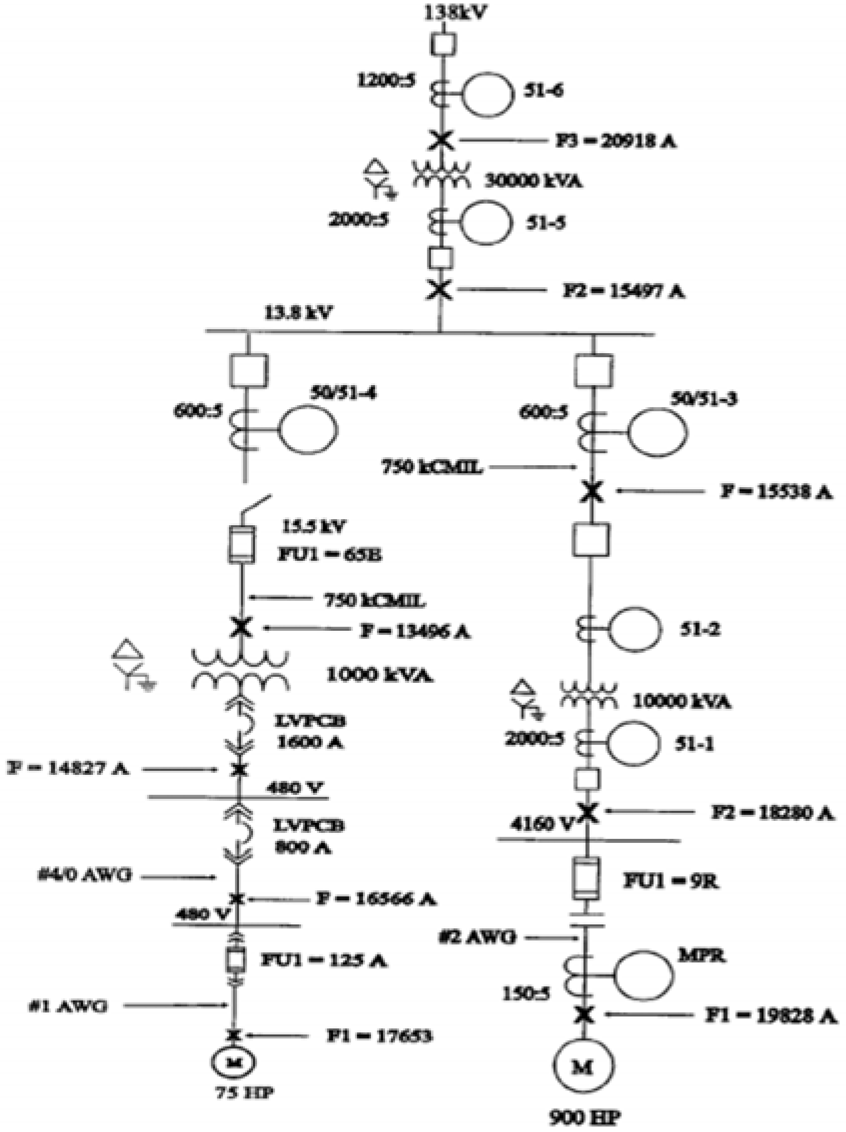


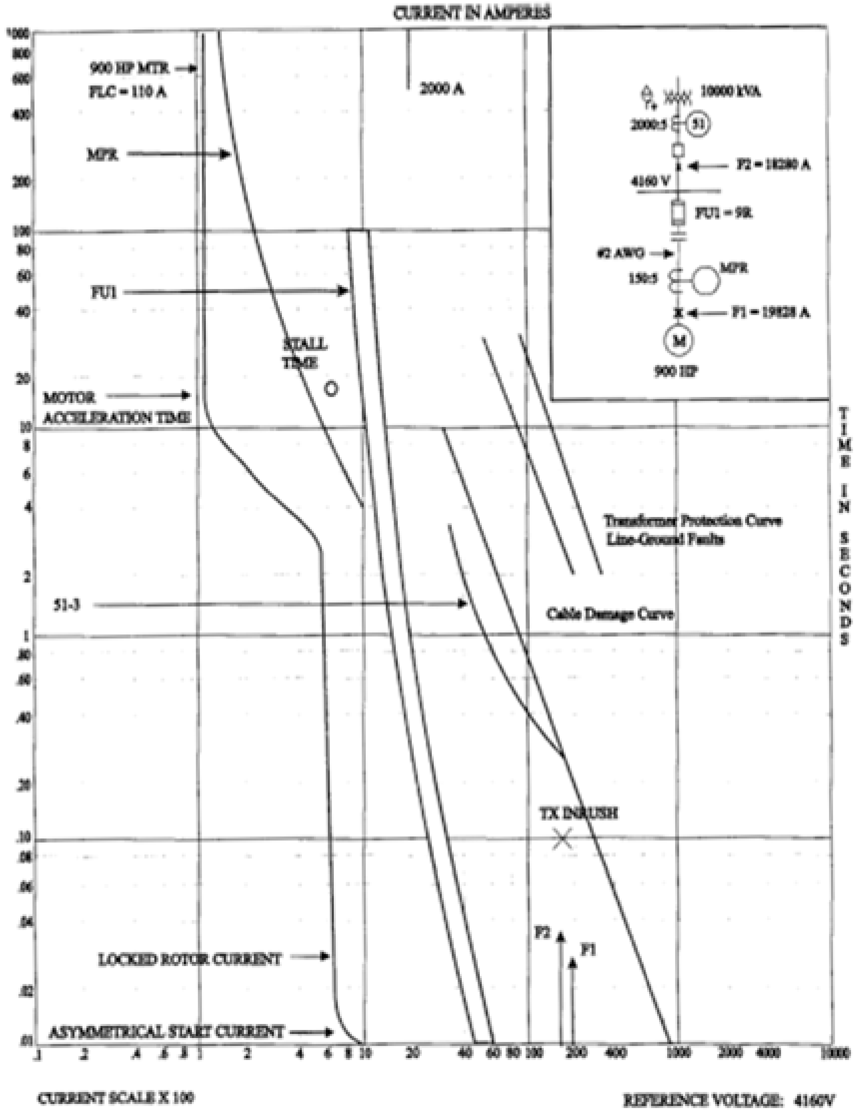
EXAMPLE CONSTRUCTING TCCs



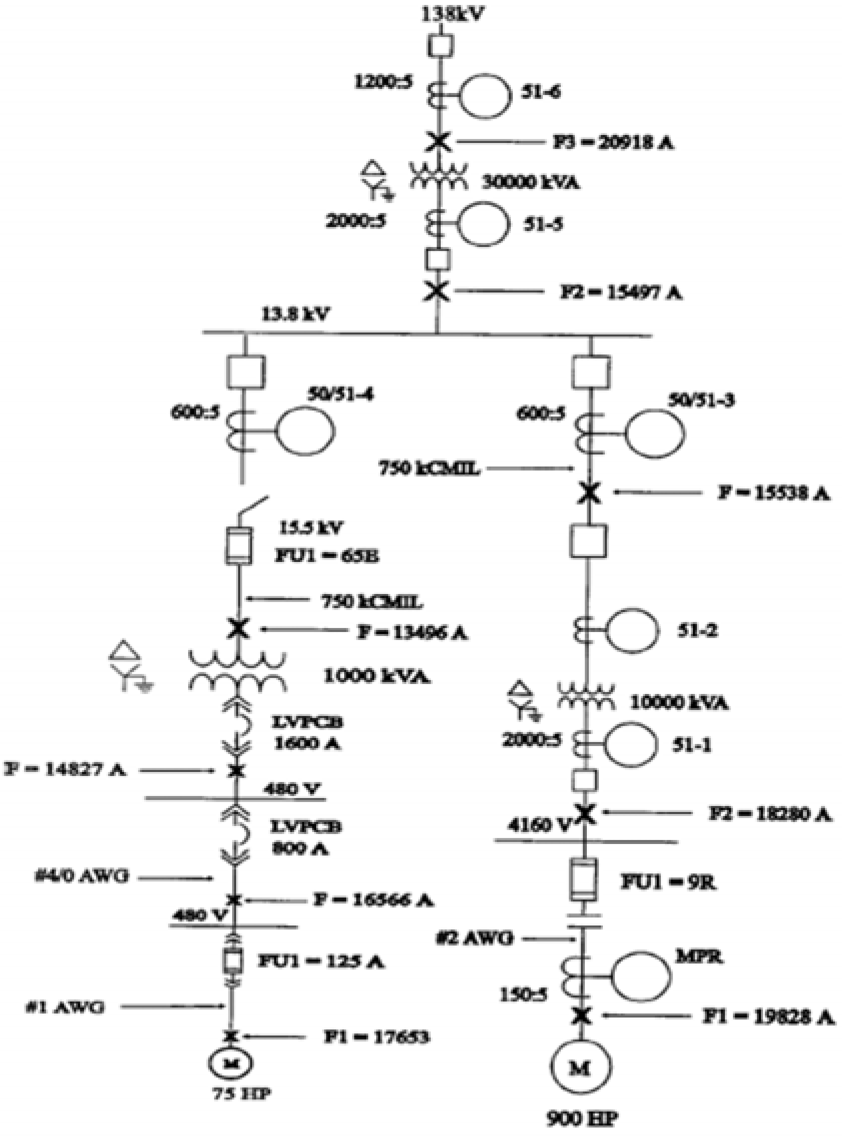


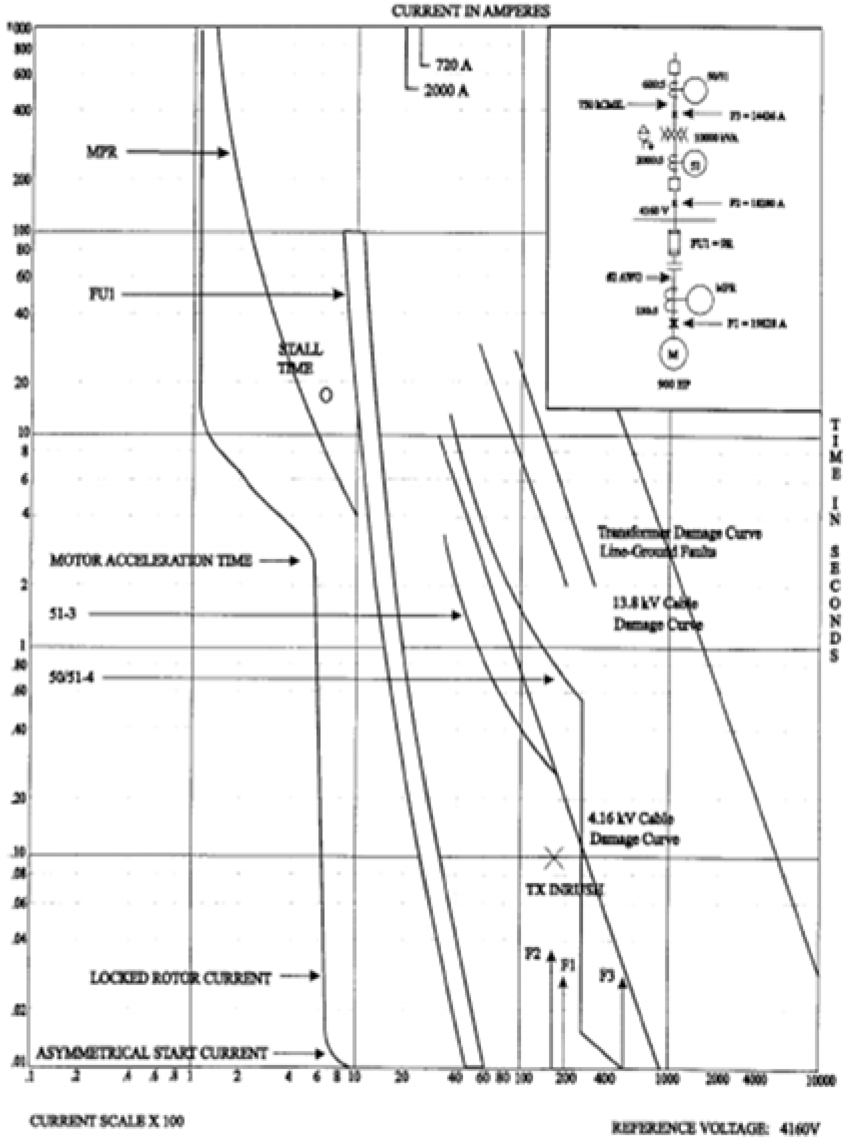
EXAMPLE CONSTRUCTING TCCs



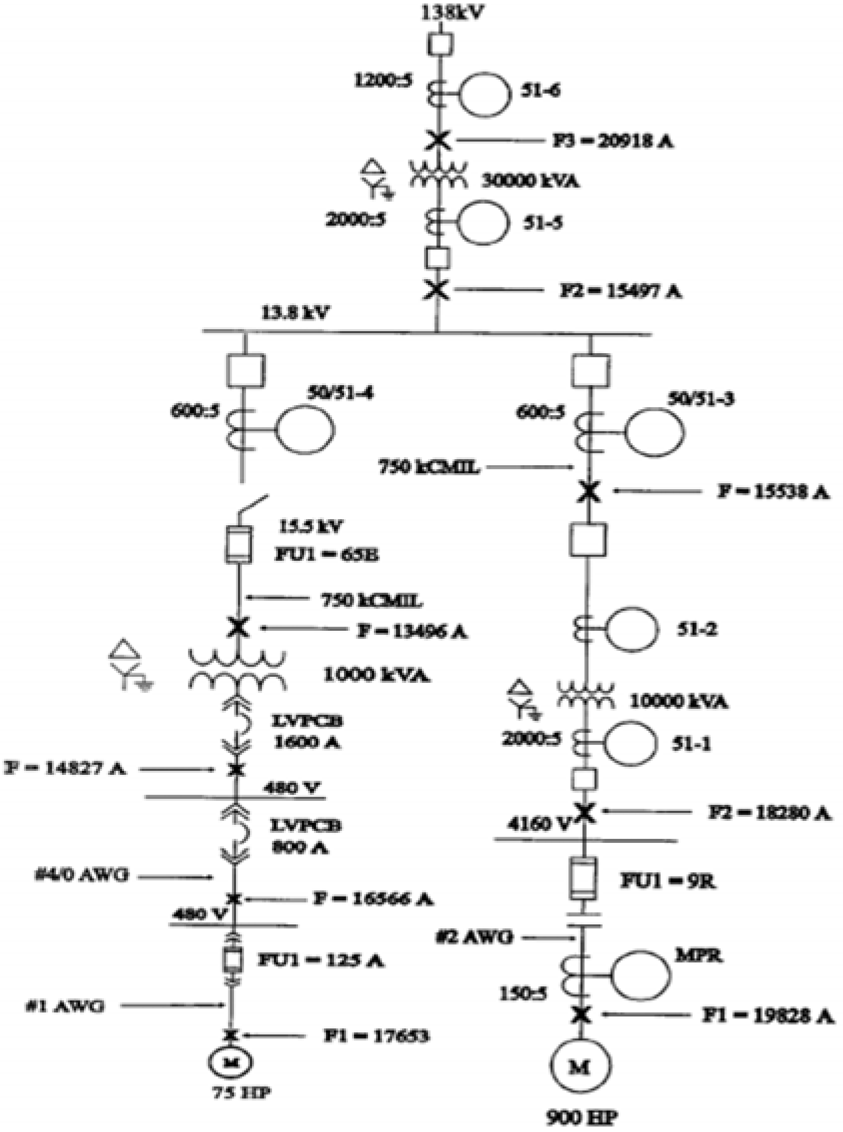


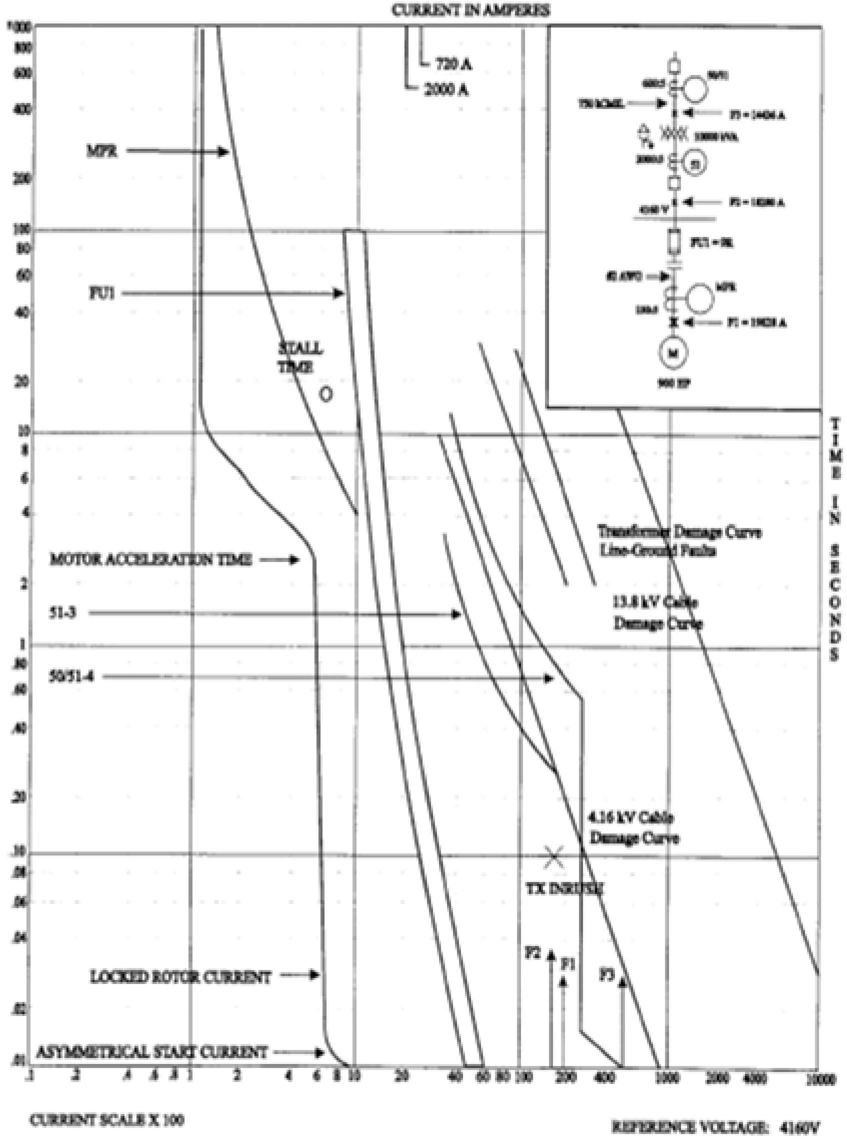
EXAMPLE CONSTRUCTING TCCs



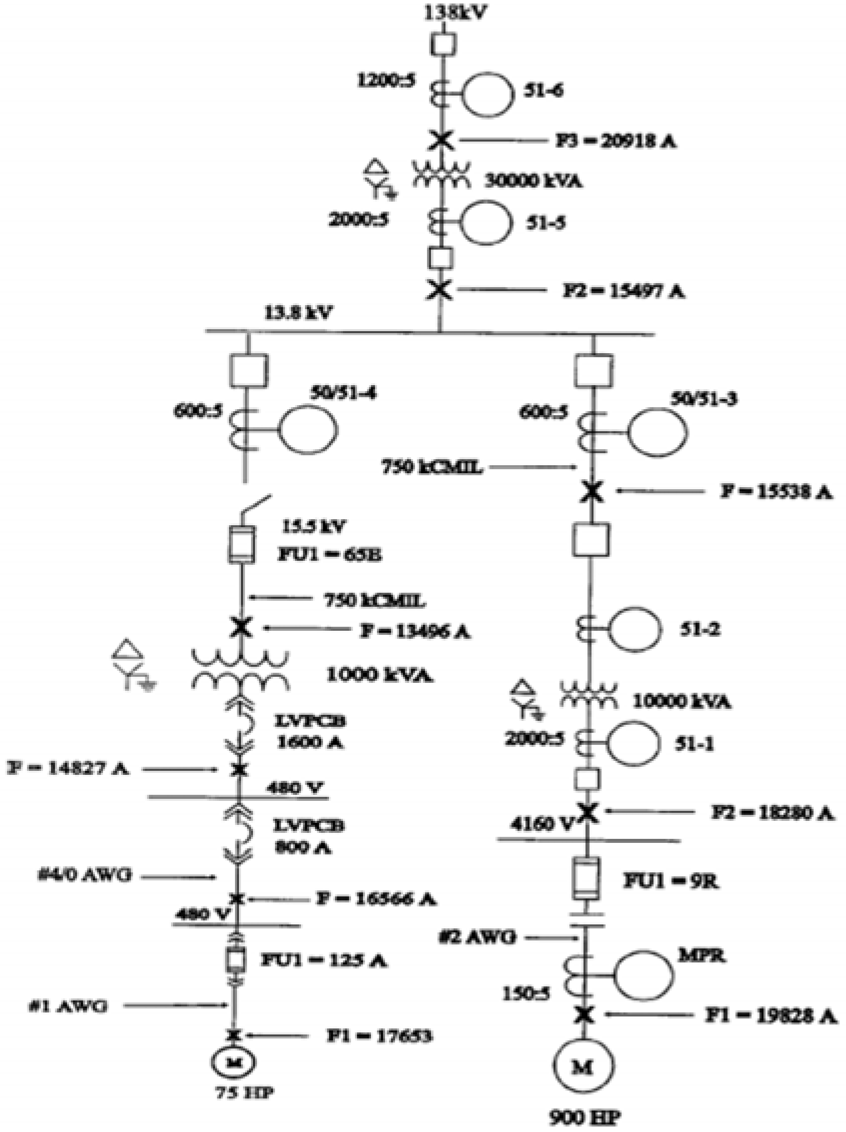


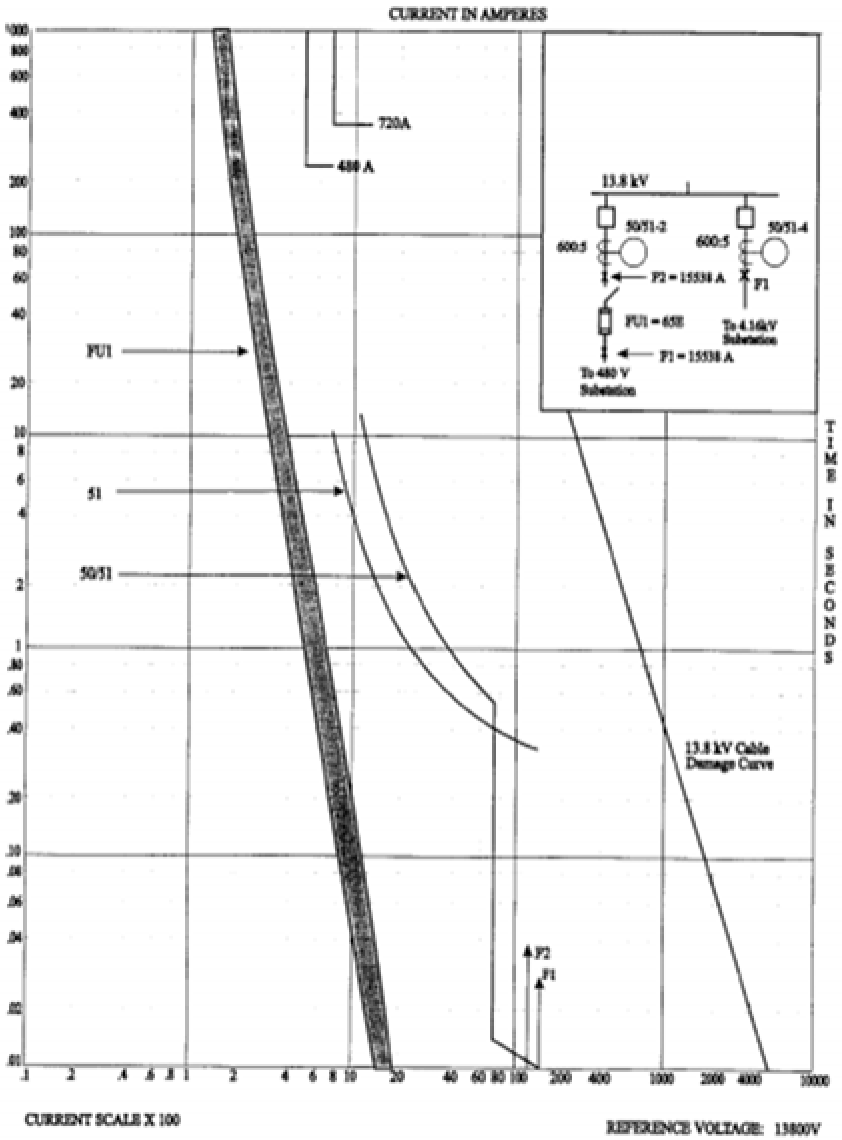
EXAMPLE CONSTRUCTING TCCs



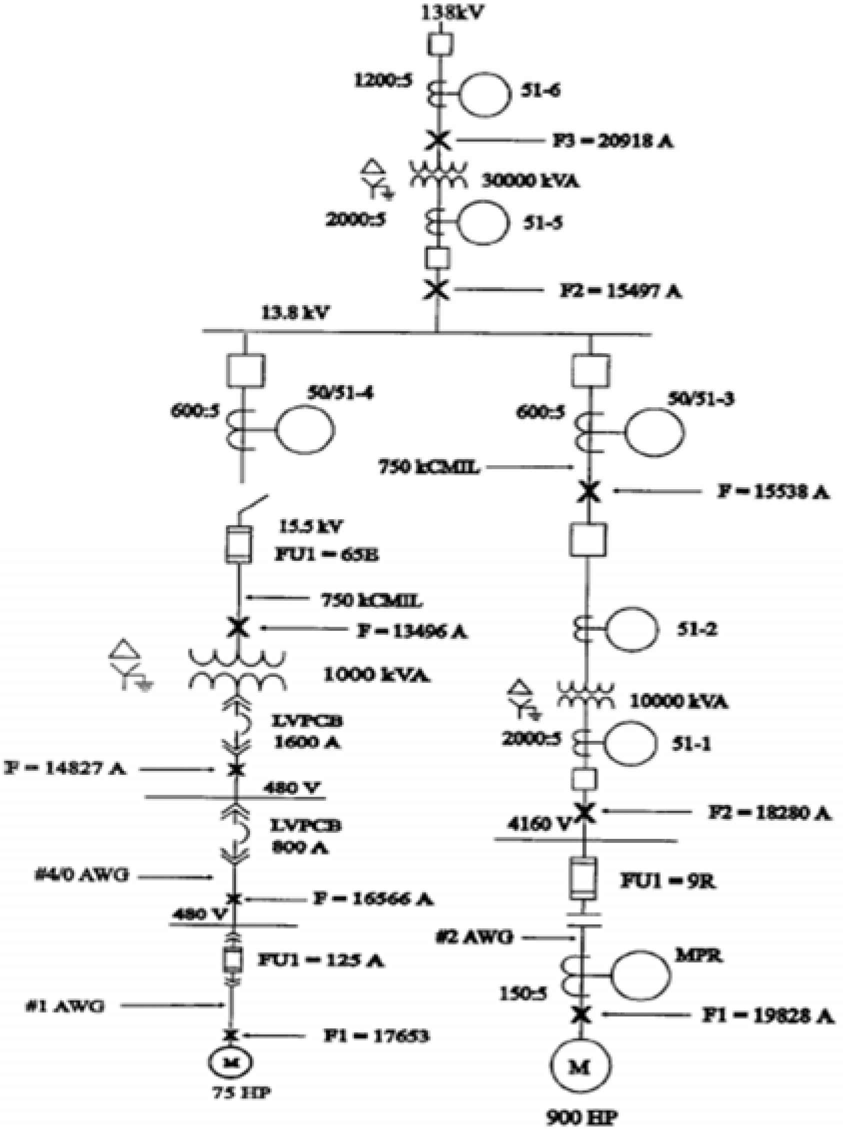


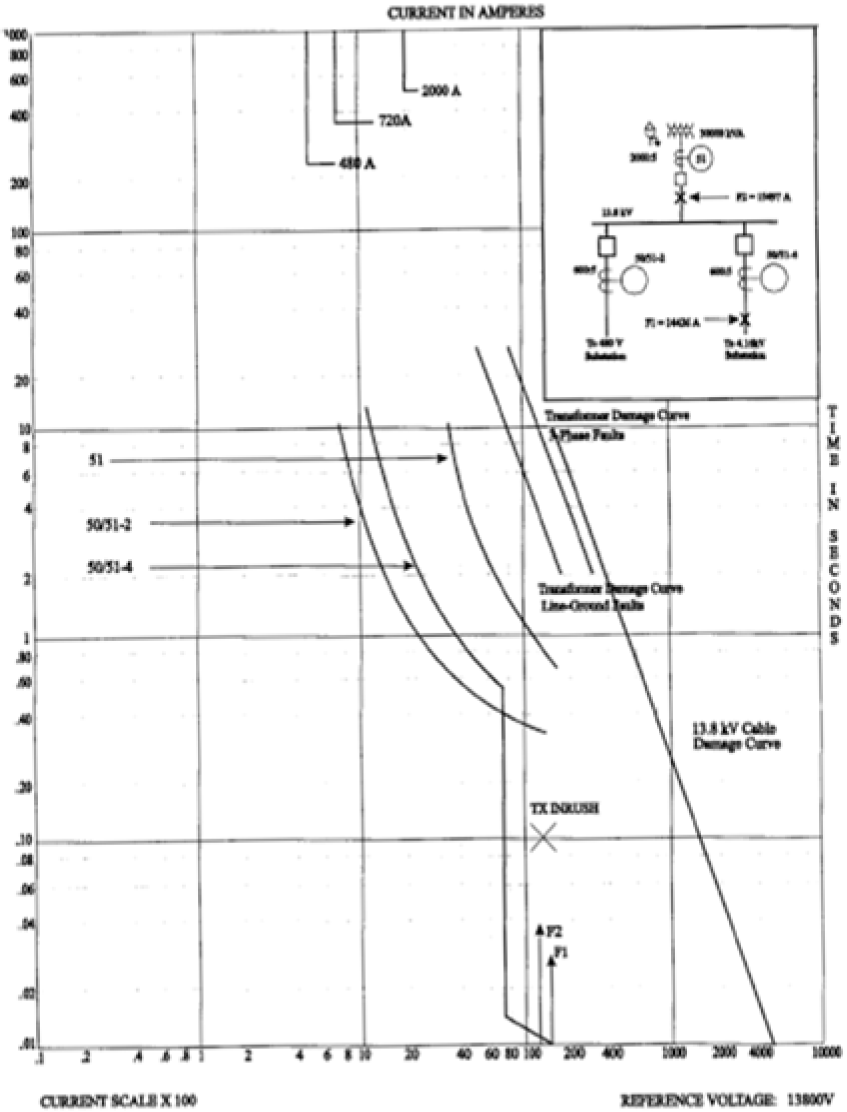
EXAMPLE CONSTRUCTING TCCs



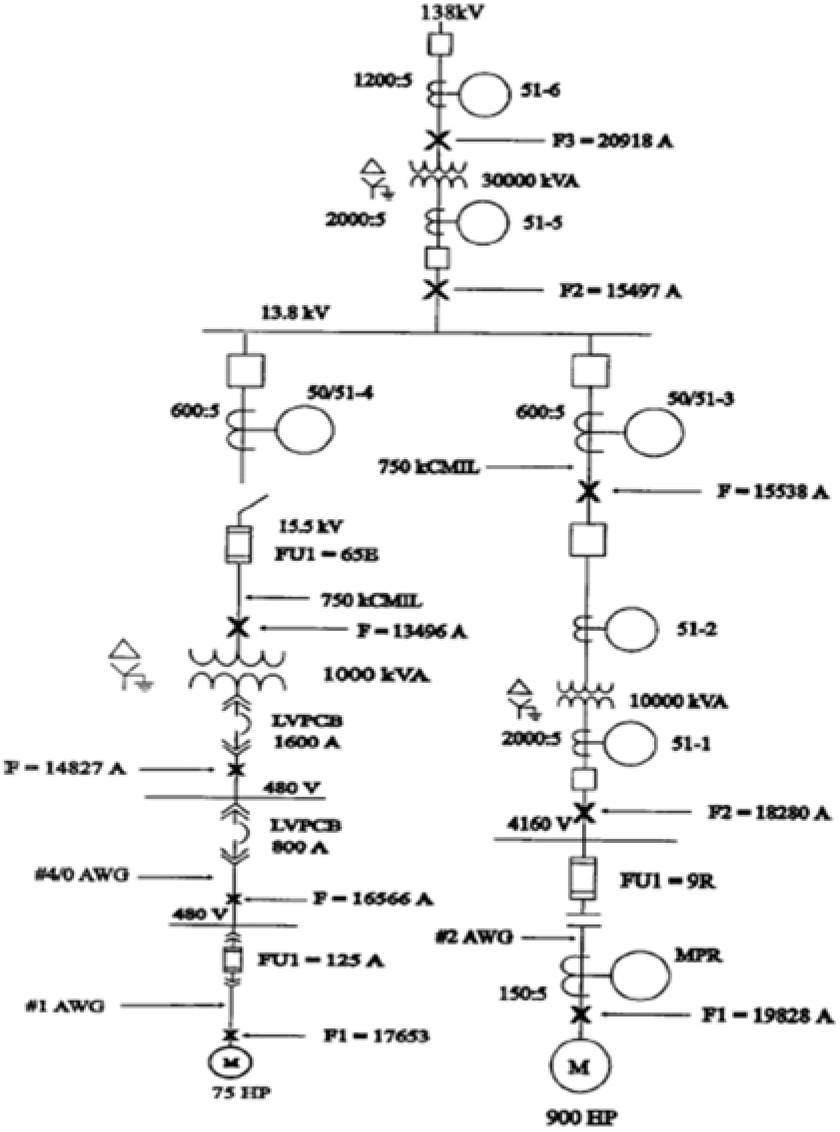


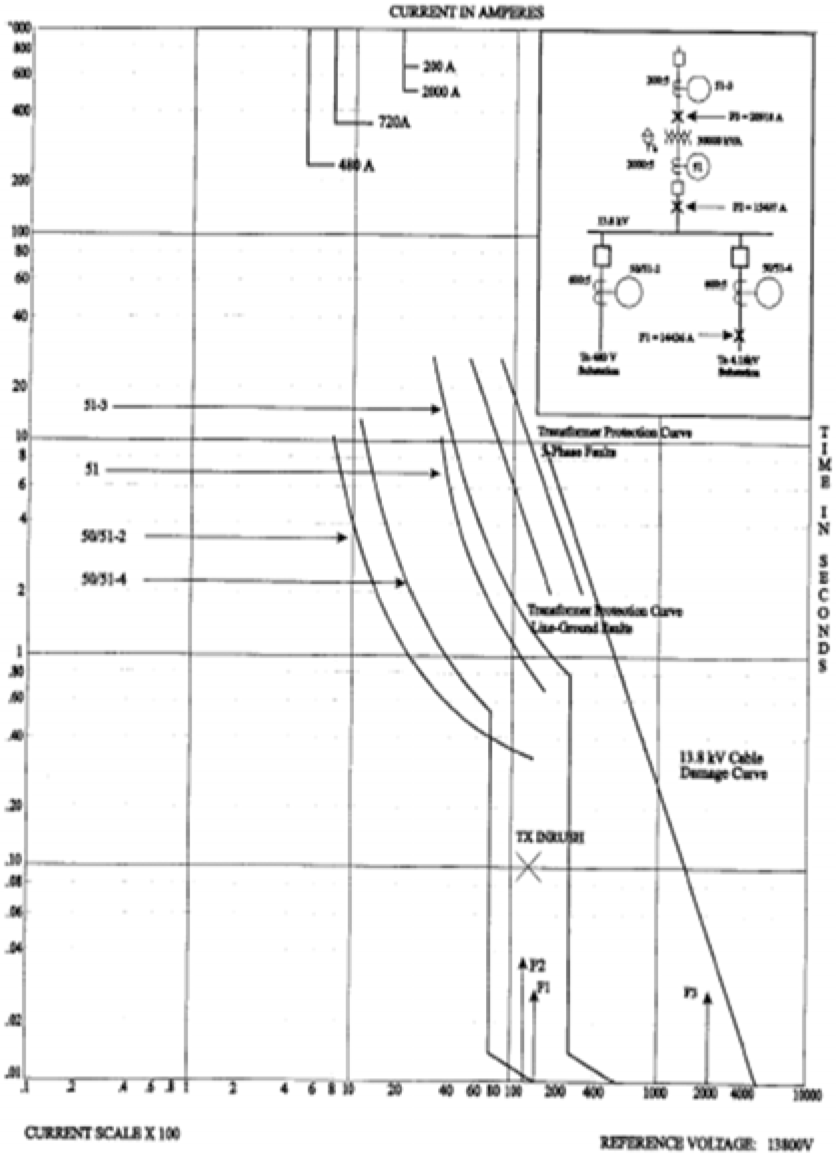
EXAMPLE CONSTRUCTING TCCs





EXAMPLE CONSTRUCTING TCCs





Understanding Power Concepts

Part 2

- Electrical Studies
  - One lines
  - SC
  - LF
  - I2T
- ***<u>Transfer Schemes</u>***
- Cable types
- Feeder Design

Presentation Outline

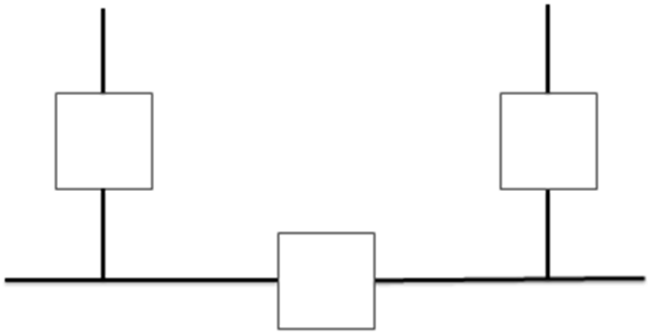
- Definition – Secondary Selective Substation
- Equipment Arrangement
- Discussion Topics – How do you design a transfer scheme?
- Existing System Description
  - Normal System Loading
  - Abnormal System Loading
- Final System Configuration
- Transfer Scheme Definitions
- Implementation

Definition

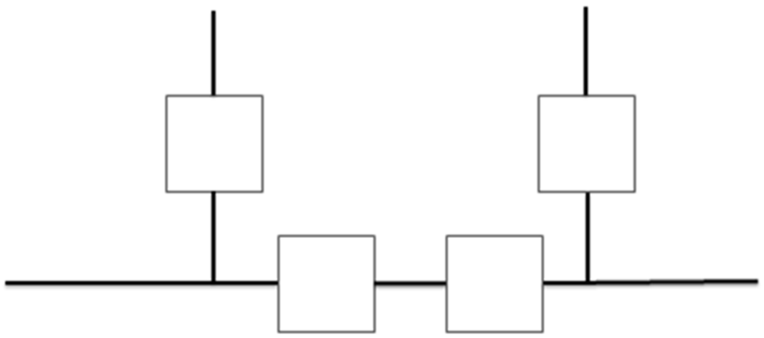
Secondary Selective Substation

- Substations having two busses, each supplied by a normally-closed incoming line circuit breaker and connected together by a normally-open bus tie circuit breaker.

Single Tie Arrangement



Double Tie Arrangement



Discussion Topics

<u>How do you design a transfer scheme?</u>

- What conditions are required for transfer?
  - Breaker positions?
  - Breaker status?
  - Voltage conditions?
  - Make before break or break before make?
  - Do we need to know about one side or both sides of switchgear to initiate transfer?
  - Flow Chart, Logic Chart or if then statements?
- What is the equipment arrangement?
  - Where are current transformers going to be placed? Why?
  - Where are potential transformers going to be placed? Why?

Discussion Topics

How do you design a transfer scheme?

- Safety concerns?
  - Electrical protection requirements?
  - Re-energizing bus with fault present?
  - What do I do with downstream power sources (i.e. generators or synchronous motors)?
  - Sources synchronized? How do you know?
    - Motor spin down complete
- How will the system be implemented?
  - Mechanical relays/hardwired
  - Electronic relays/hardwired
  - Electronic relays/communication

Discussion Topics

How do you design a transfer scheme?

- How do you recover from automatic transfer?
  - Automatic or Manual?
- If electronic relays, which ones?
  - Pros and Cons for each
  - Do you want to program the scheme or do you want to work within an existing framework?
  - Typical: SEL or MULTILIN
  - Does one give you an advantage in terms of end of project paperwork?
  - Will final implementation be “black box” approach or will there be certain outputs that can be checked to tell you where you are in the transfer initiation by technician?

Discussion Topics

How do you design a transfer scheme?

- Communication between team members?
  - No two engineers will design the system the same way.
  - What are common assumptions?
    - Single mode of failure or multiple?
    - Will additional failure modes be handled with internal programming or procedural changes to the operation of the equipment.
    - What ranges or setpoints will be utilized? Why?
    - What requires an alarm to be sent?
    - What requires the automatic system to be disabled?

Discussion Topics

How do you design a transfer scheme?

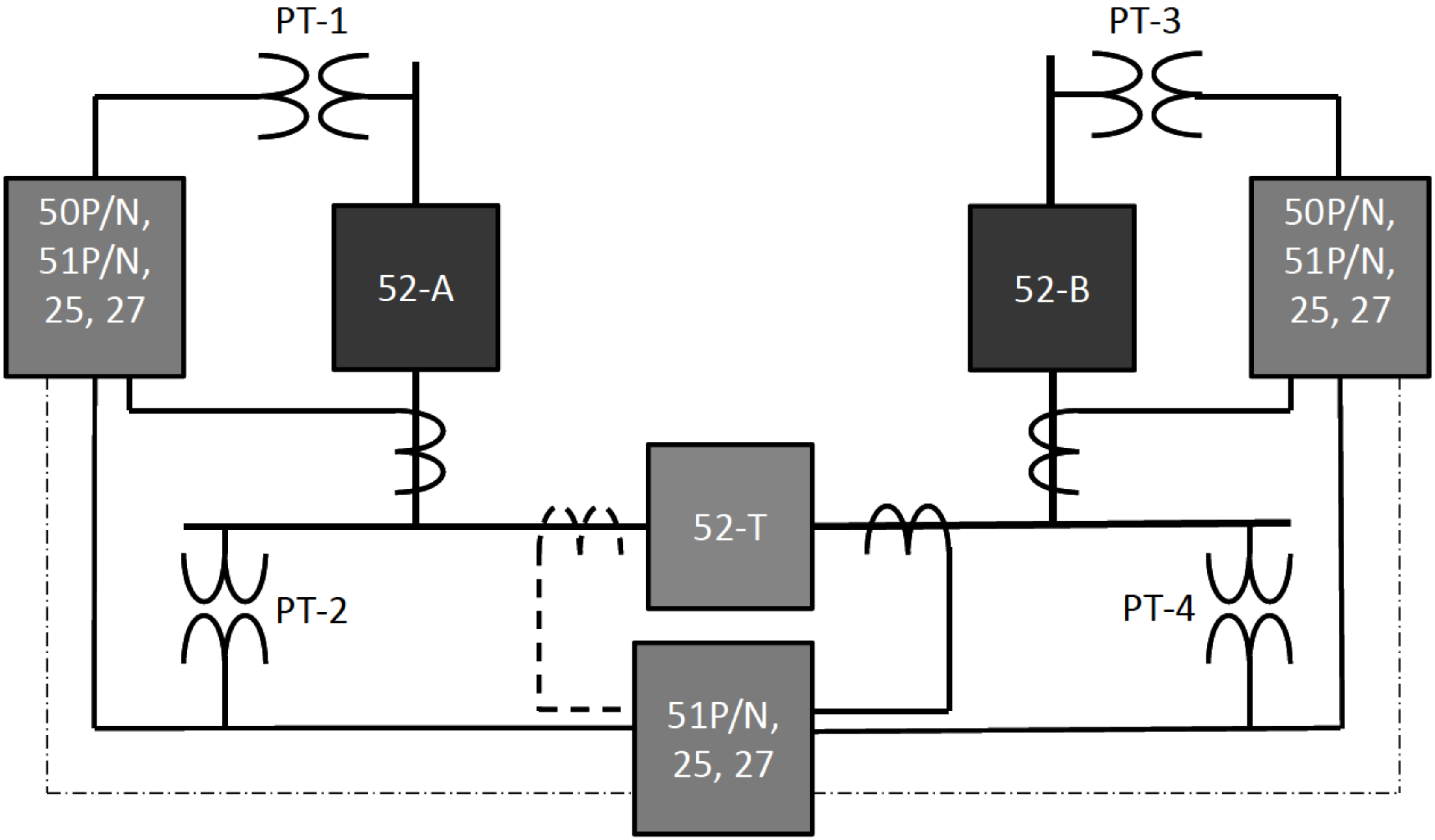
- How do you test the system?
  - What equipment is needed?
  - If doors are stand alone
- Where do you test the system?
  - Factory
  - Office/Lab
  - In the field
- Who should be involved in final testing?
- Who decides on final testing methodology?

Discussion Topics

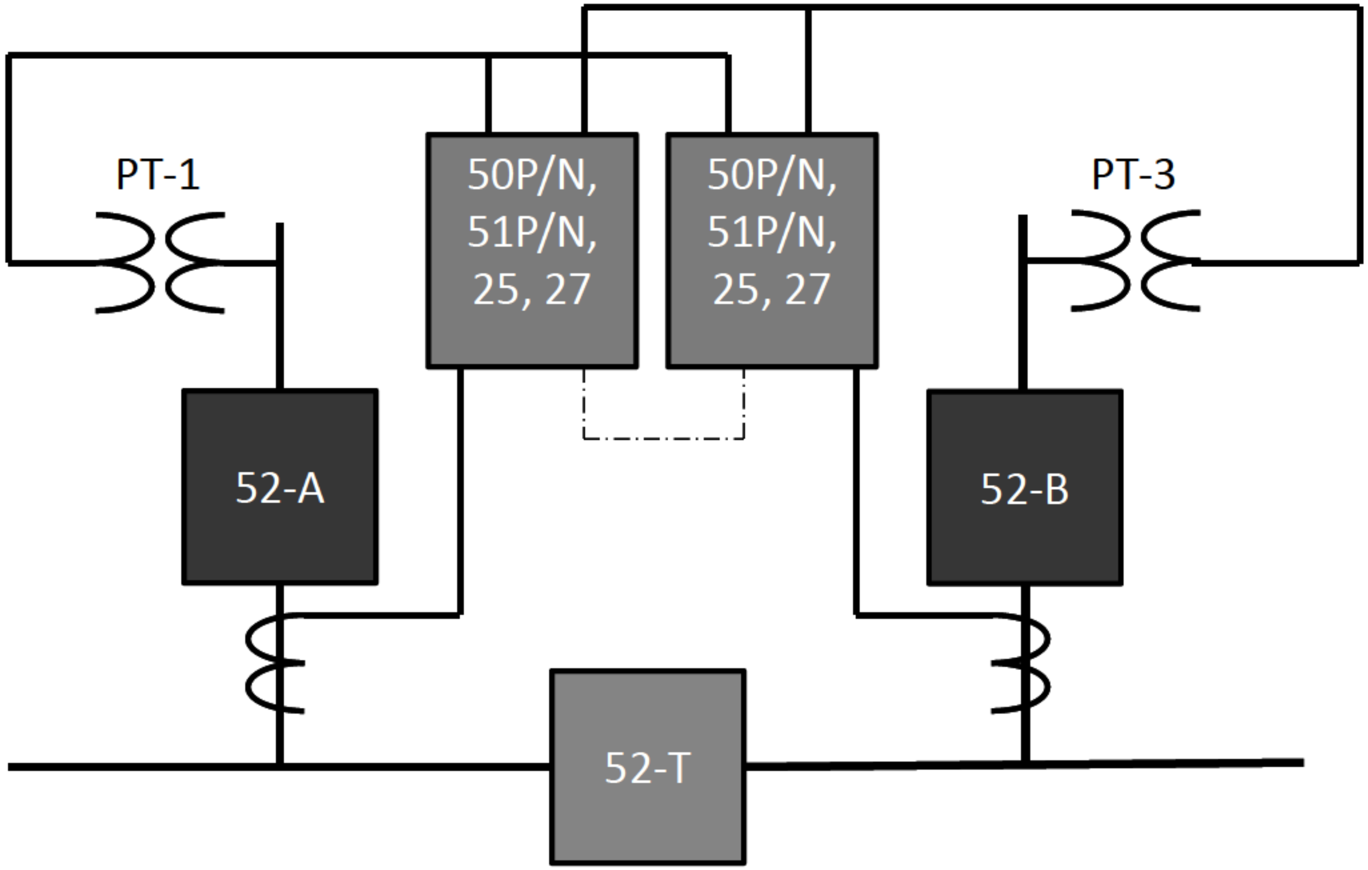
<u>How do you design a transfer scheme?</u>

- How do you know if your system is working properly?
- Maintenance
  - What needs to be done on a periodic basis?
    - Software updates, how do they effect the current system?
    - Who maintains programming files?
    - Standard breaker maintenance and time testing?
    - Relay testing to validate accuracy?
- Training
  - Who gets trained?
  - What material is provided to make that individual successful?

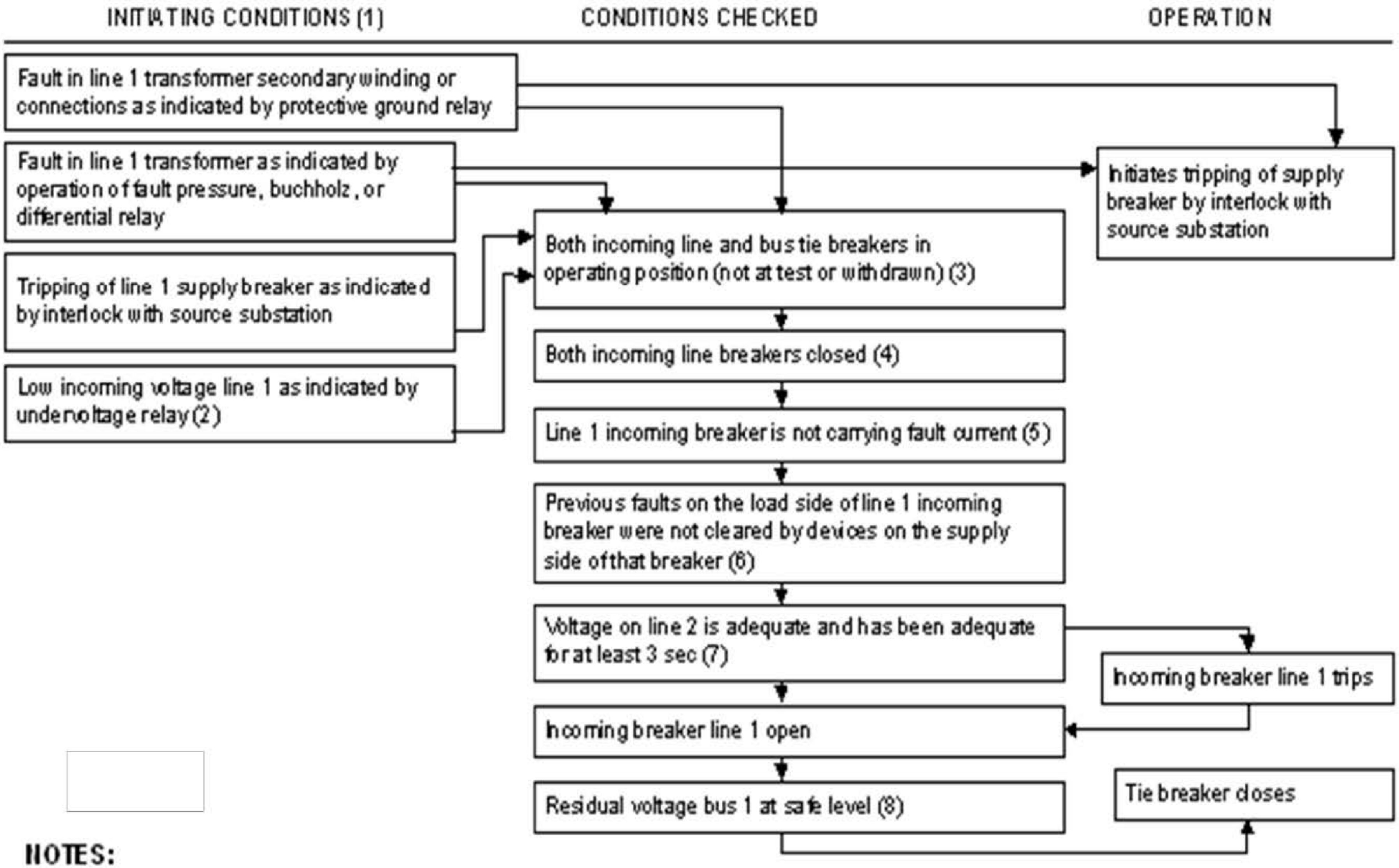
Single Tie Arrangement



Single Tie Arrangement



Flow Chart



INITIATING CONDITIONS (1)

CONDITIONS CHECKED

OPERATION

Fault in line 1 transformer secondary winding or connections as indicated by protective ground relay

Fault in line 1 transformer as indicated by operation of fault pressure, buchholz, or differential relay

Tripping of line 1 supply breaker as indicated by interlock with source substation

Low incoming voltage line 1 as indicated by undervoltage relay (2)

Both incoming line and bus tie breakers in operating position (not at test or withdrawn) (3)

Both incoming line breakers closed (4)

Line 1 incoming breaker is not carrying fault current (5)

Previous faults on the load side of line 1 incoming breaker were not cleared by devices on the supply side of that breaker (6)

Voltage on line 2 is adequate and has been adequate for at least 3 sec (7)

Incoming breaker line 1 open

Residual voltage bus 1 at safe level (8)

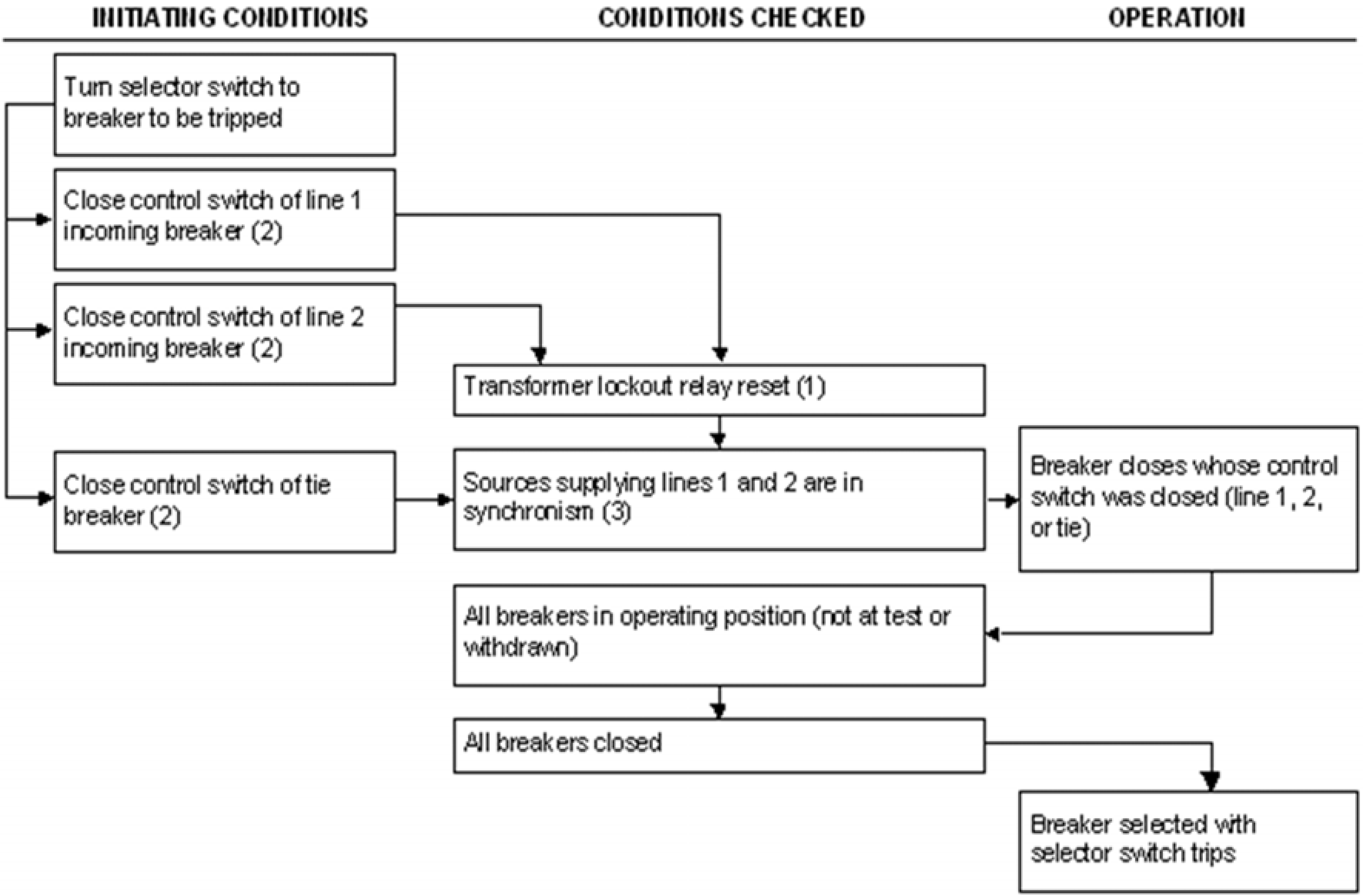
Initiates tripping of supply breaker by interlock with source substation

Incoming breaker line 1 trips

Tie breaker closes

NOTES:

Flow Chart



INITIATING CONDITIONS

CONDITIONS CHECKED

OPERATION

Turn selector switch to breaker to be tripped

Close control switch of line 1 incoming breaker (2)

Close control switch of line 2 incoming breaker (2)

Close control switch of tie breaker (2)

Transformer lockout relay reset (1)

Sources supplying lines 1 and 2 are in synchronism (3)

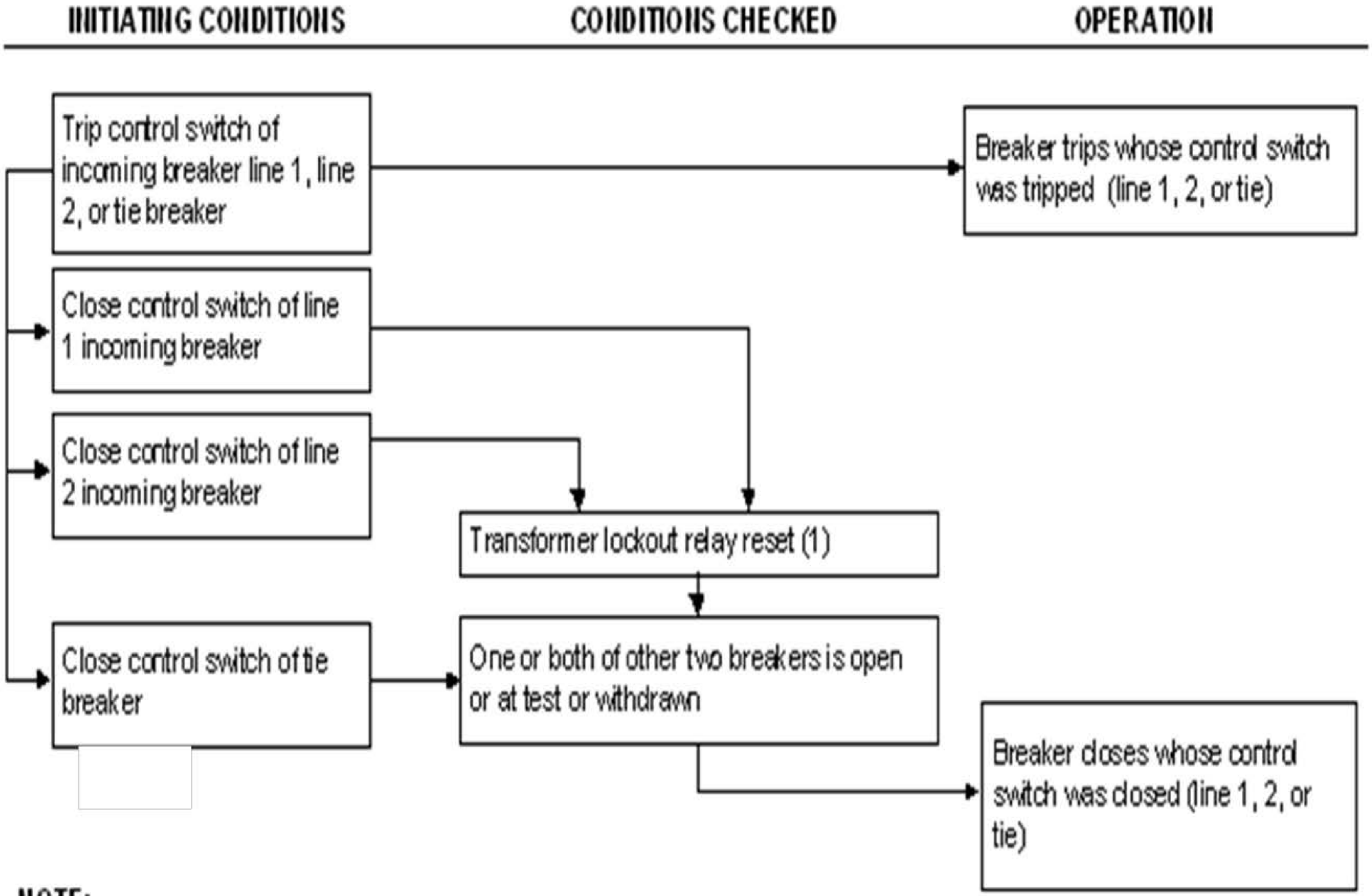
All breakers in operating position (not at test or withdrawn)

All breakers closed

Breaker closes whose control switch was closed (line 1, 2, or tie)

Breaker selected with selector switch trips

Flow Chart



INITIATING CONDITIONS

CONDITIONS CHECKED

OPERATION

Trip control switch of incoming breaker line 1, line 2, or tie breaker

Breaker trips whose control switch was tripped (line 1, 2, or tie)

Close control switch of line 1 incoming breaker

Close control switch of line 2 incoming breaker

Transformer lockout relay reset (1)

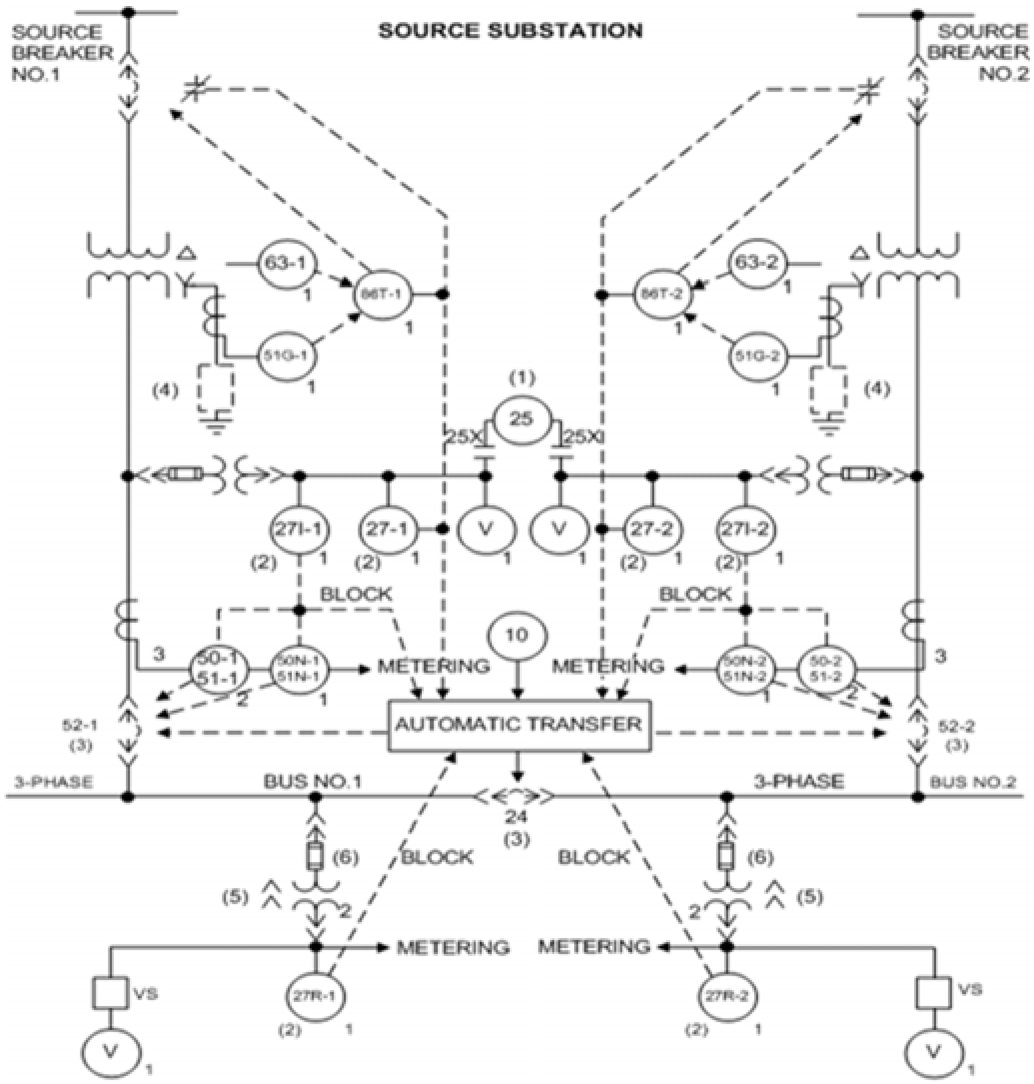
Close control switch of tie breaker

One or both of other two breakers is open or at test or withdrawn

Breaker closes whose control switch was closed (line 1, 2, or tie)

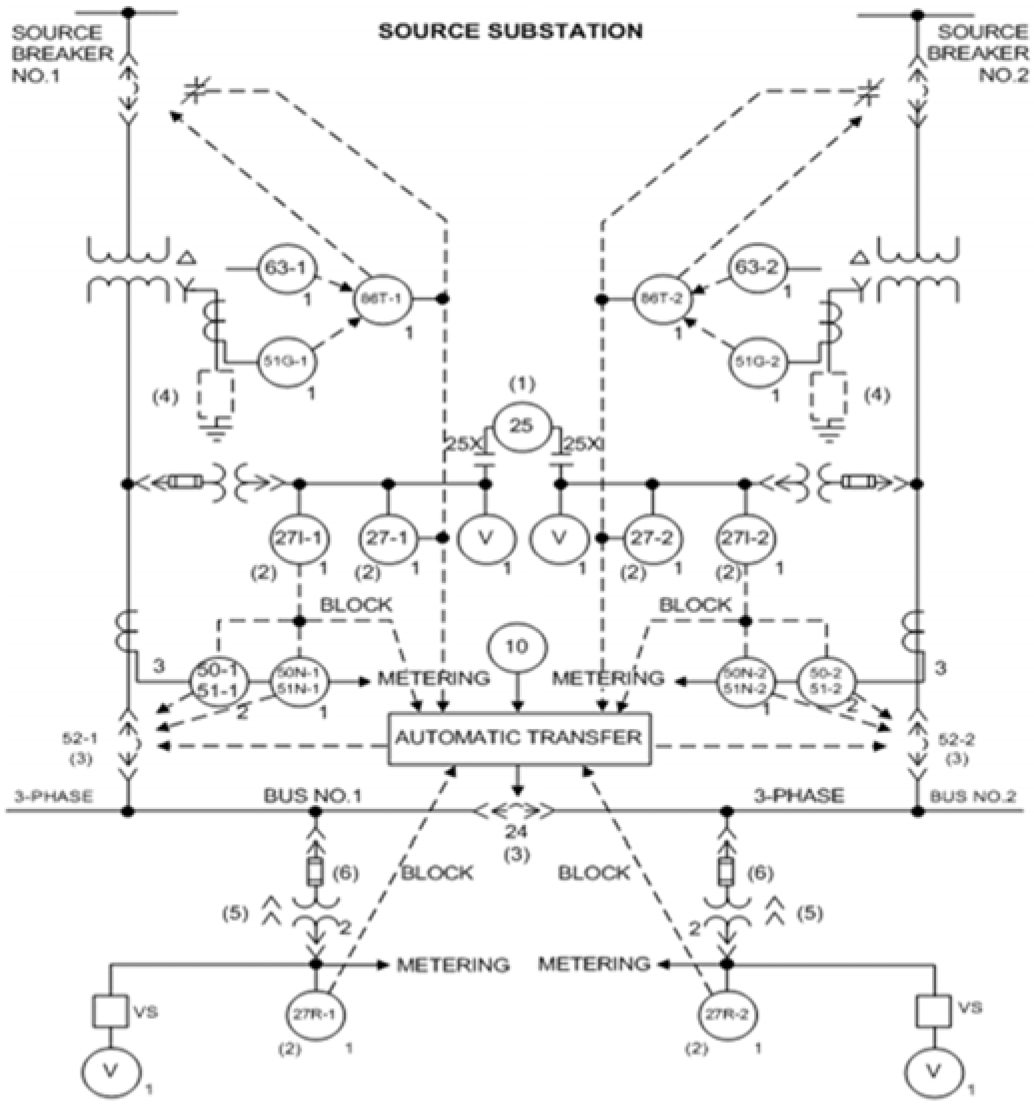
NOTE:

One-Line Depiction



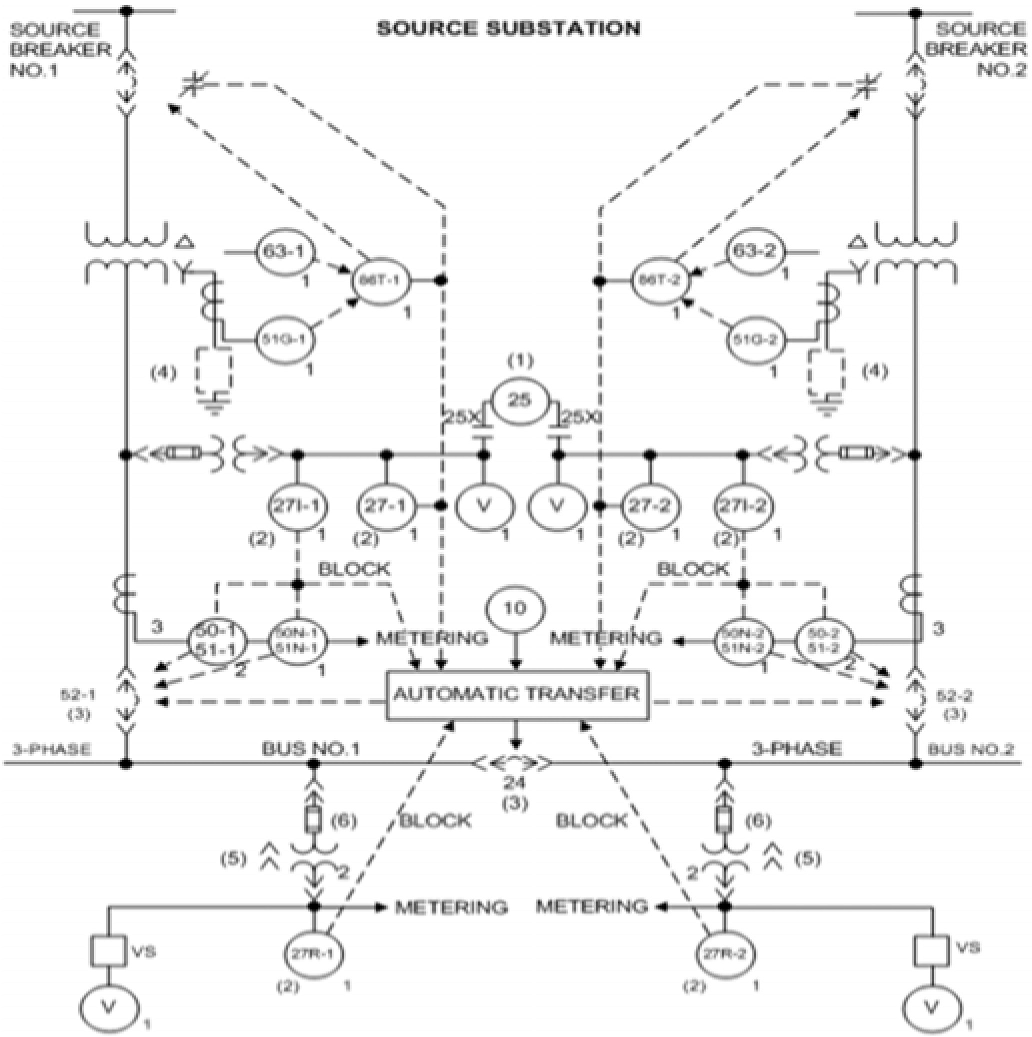
27I-1, 27I-2	Instantaneous under voltage relay
27R-1, 27R-2	Residual voltage relay, 3 phase
50/51-1, 2	Instantaneous and time overcurrent relay
50N/51N-1, 2	Residually connected instantaneous and time overcurrent relay
51G-1, 2	Transformer X0 connection overcurrent relay

One-Line Depiction



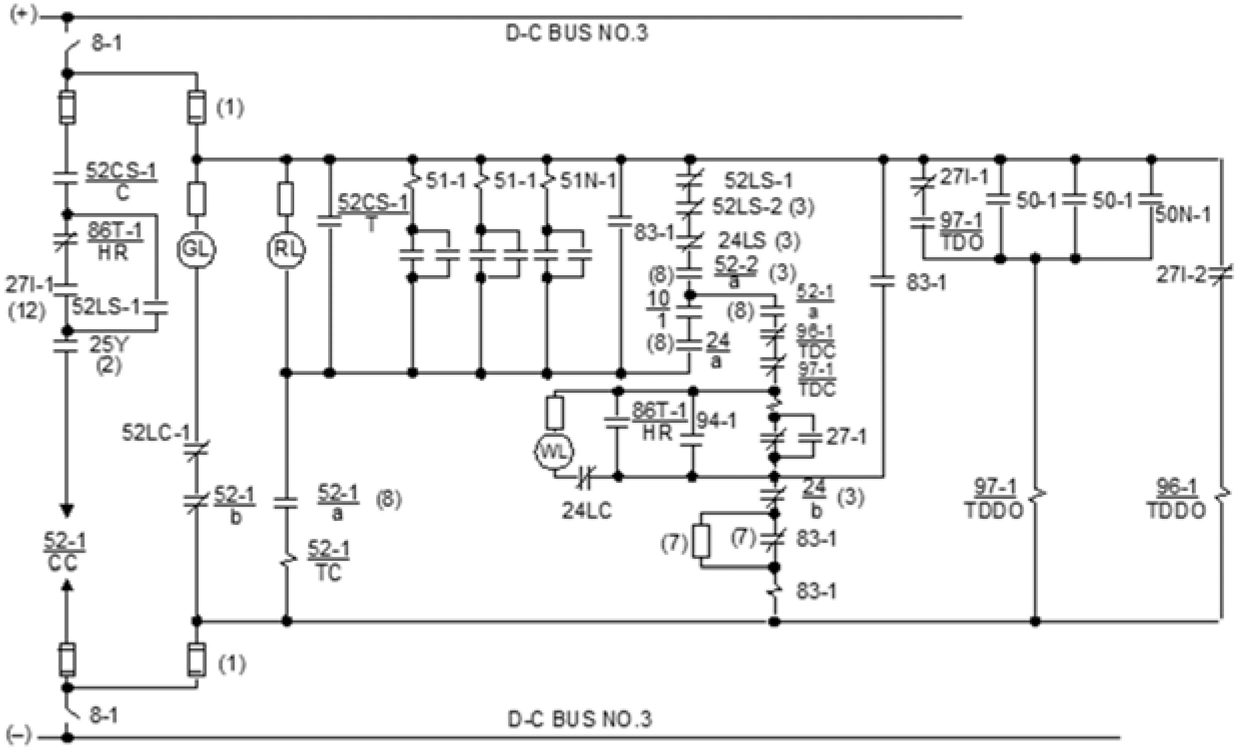
- 63 - Transformer fault pressure relay, rate-of-rise type or Buchholz relay
- 63X - Auxiliary seal in relay
- 86T- Hand reset transformer lockout relay
- 25- Synchronism check relay

One-Line Depiction



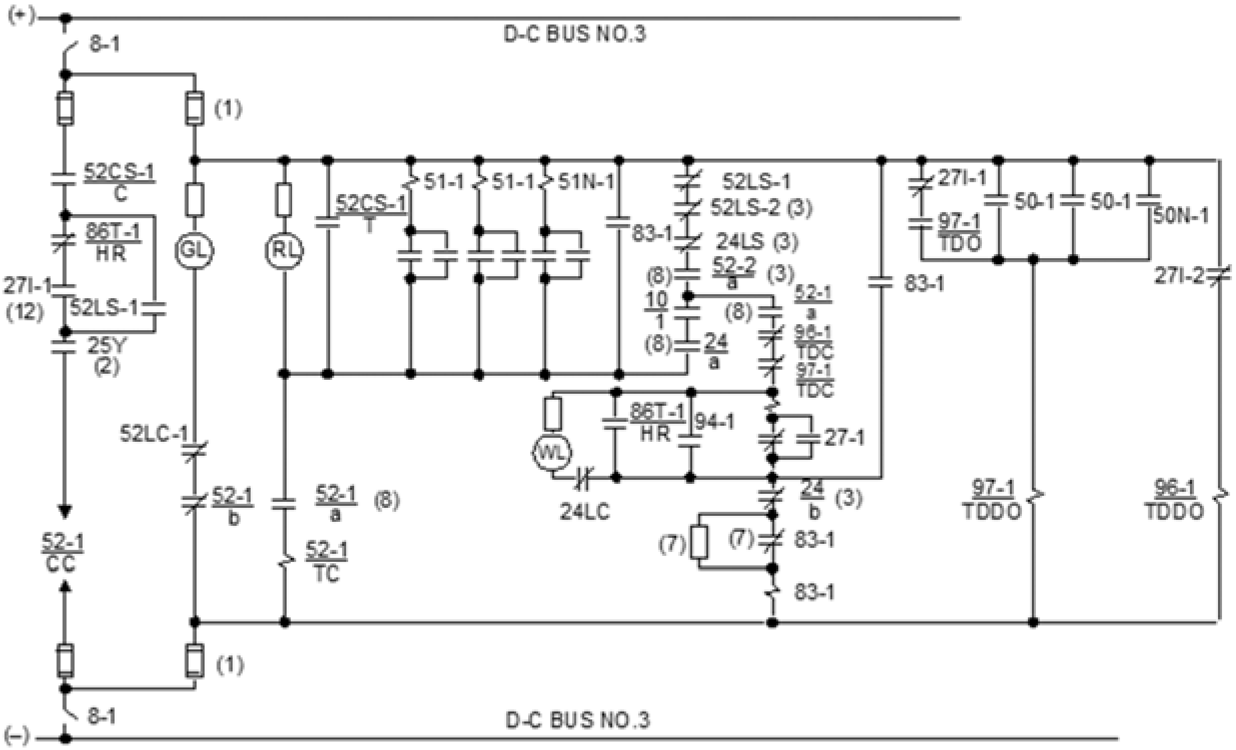
- 27I Relays 27I prevent an automatic transfer from occurring upon simultaneous loss of both sources, or loss of one source and low voltage on the other. Relays 27I operate through auxiliary relay 96. Because relays 96 are time delay type, an automatic transfer is also prevented upon simultaneous restoration of both sources after a double outage. Relays 27I also seal in relays 97 to prevent transfer if the supply breaker should trip first on overcurrent faults in the secondary selective substation.

Main Breaker Schematic



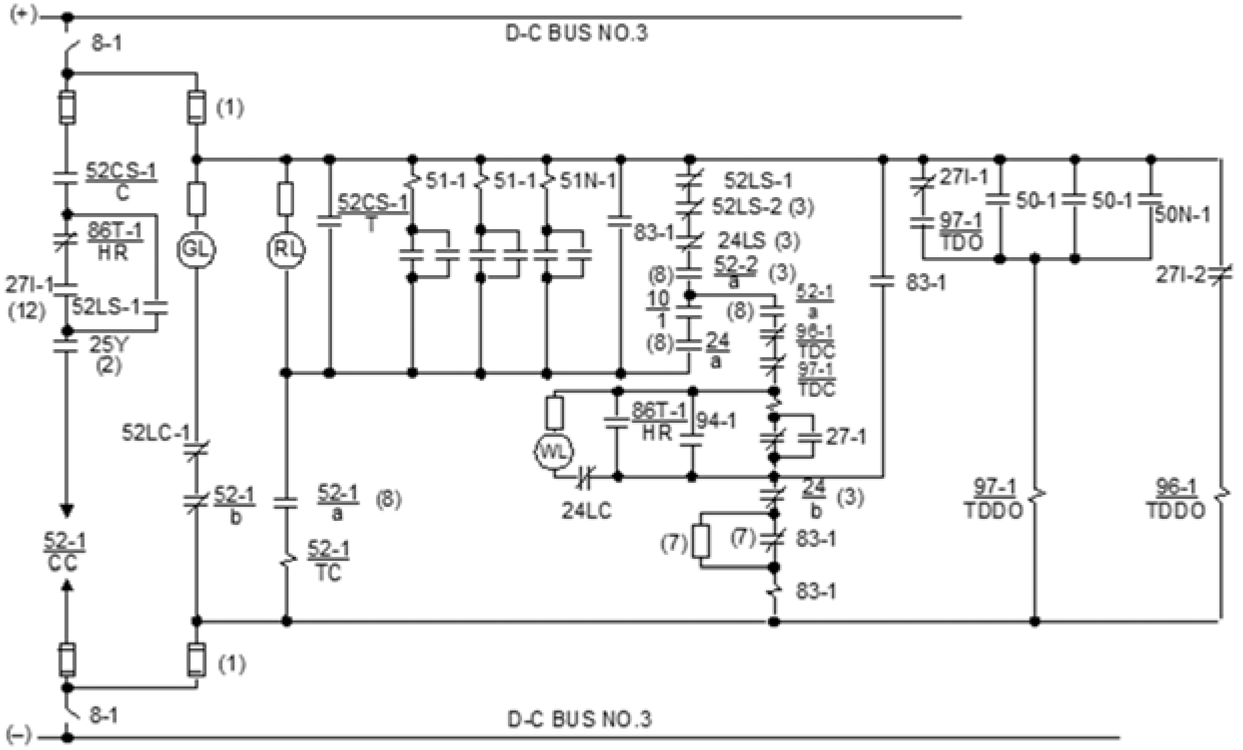
27I	Relays 27I prevent an automatic transfer from occurring upon simultaneous loss of both sources, or loss of one source and low voltage on the other. Relays 27I operate through auxiliary relay 96. Because relays 96 are time delay type, an automatic transfer is also prevented upon simultaneous restoration of both sources after a double outage. Relays 27I also seal in relays 97 to prevent transfer if the supply breaker should trip first on overcurrent faults in the secondary selective substation.

Main Breaker Schematic



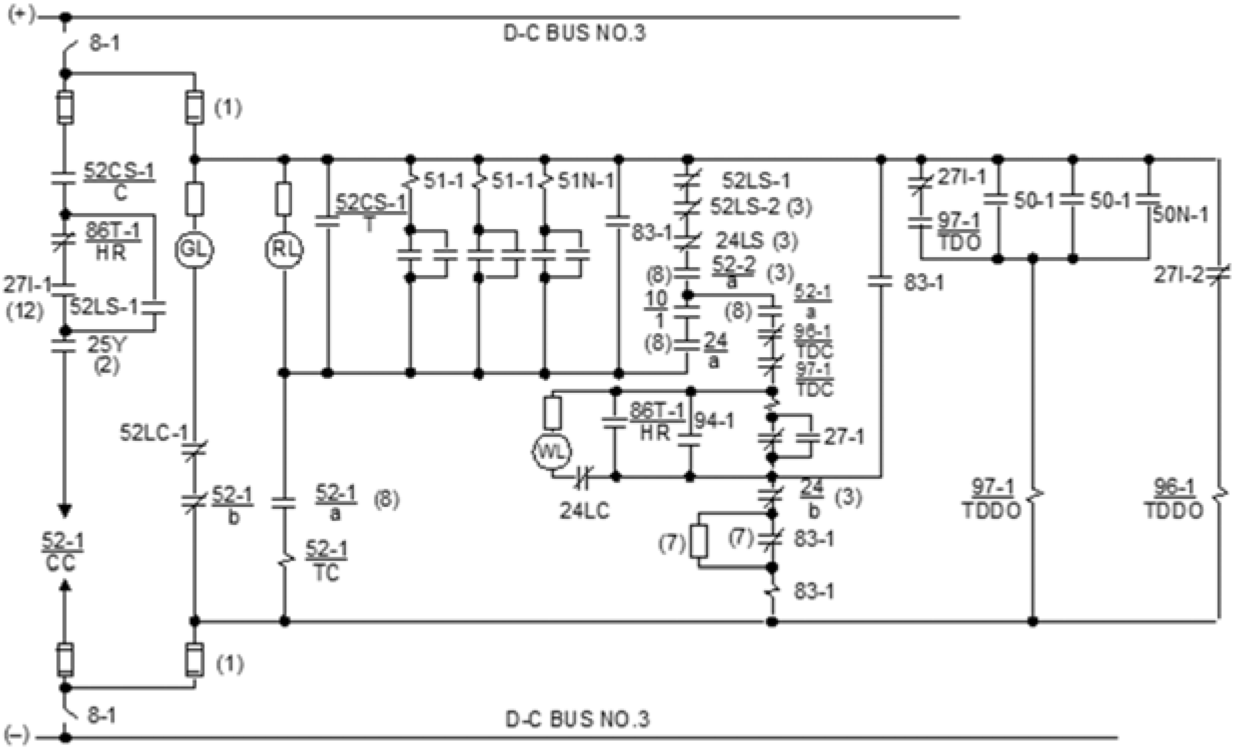
50/50N Relays 50 and 50N operate through the 97 relay, and are used to block transfer during overcurrent faults until the fault is cleared by the feeder breaker or incoming line breaker. When the settings are properly set they permit relay 27 to time out faster under fault conditions. The backup to this scheme includes time current/voltage coordination between the 51 overcurrent relay and the 27 undervoltage relay. The 51 relay should trip before the 27 sends the tripping signal.

Main Breaker Schematic



- 83- Auxiliary relay used in the transfer initiation from the main breaker to the tie breaker via the following functions:
  Trips the main breaker Closes the tie once the main breaker opens, and the bus voltage is 25% of it nominal value to prevent out of phase re-closer

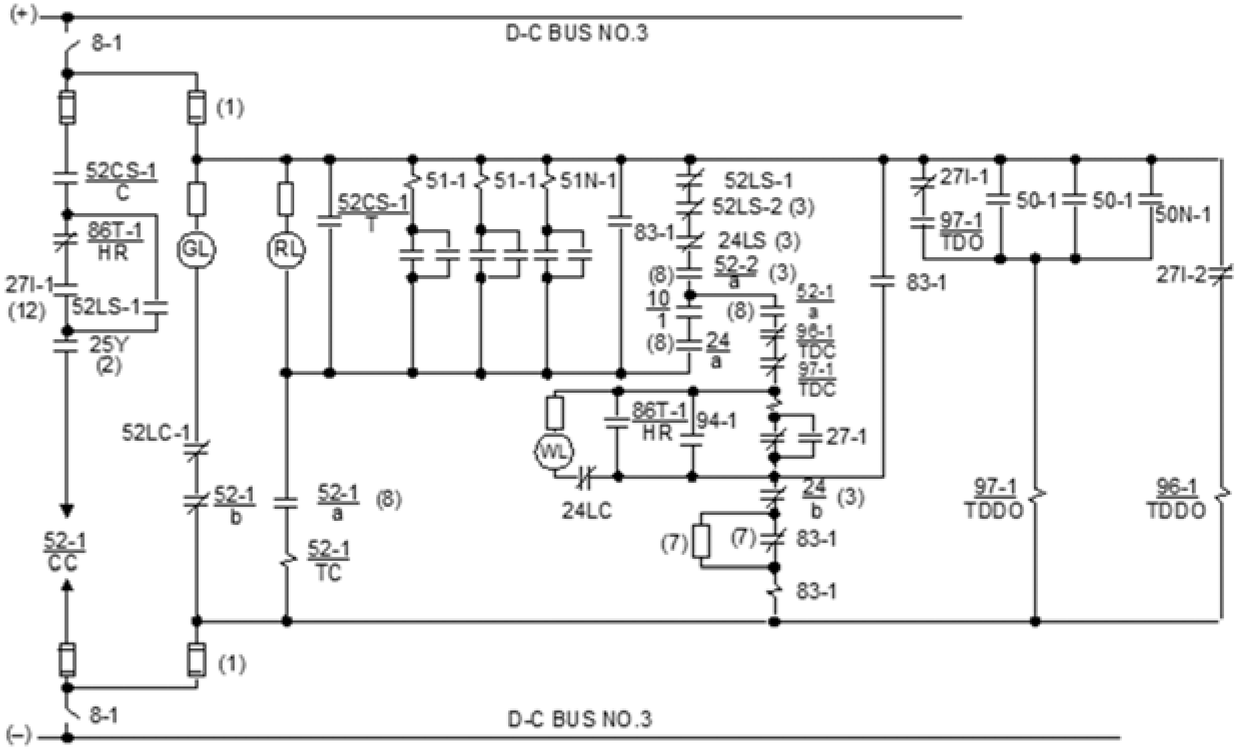
Main Breaker Schematic



- Auxiliary relay, instantaneous pickup, adjustable time delay drop out

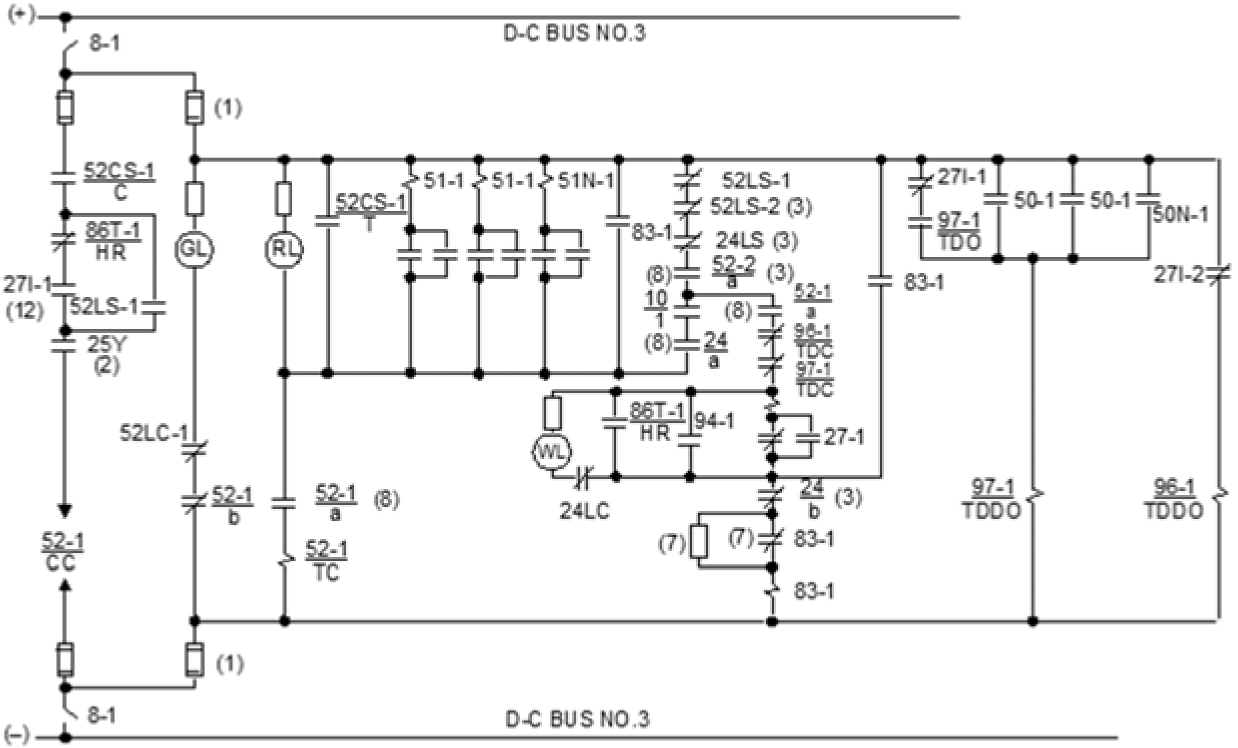
  TDDO- time delay dropout,
  TDC- time delay closing,
  TDO-time delay opening

Main Breaker Schematic



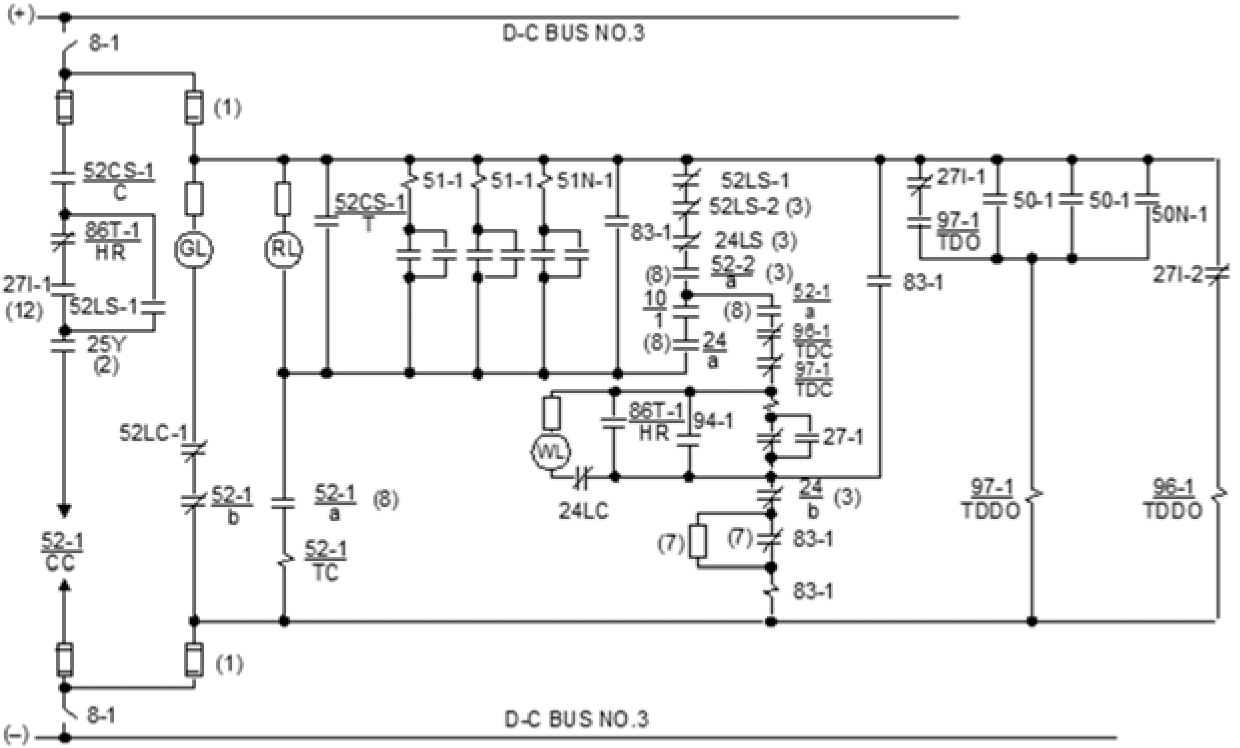
• 52LS-1	contact closes when incomer No. 1 is in the racked in position.
• 52LS-2	contact closes when incomer No. 2 is in the racked in position.
• 24LS	contact closes when the tie breaker is in the racked in position.
• 52-2/a	contact closes when incomer No. 2 breaker is closed.
• 10	trip selector switch used in manual transfers.

Main Breaker Schematic



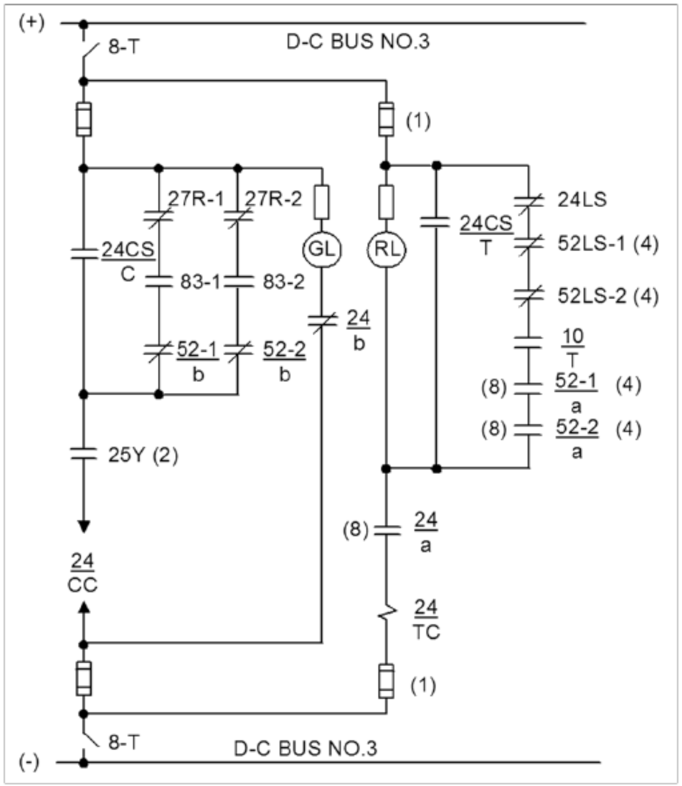
• 24/a	contact closes when the tie breaker is closed.
• 52-1/a	contact closes when incomer No. 1 breaker is closed.
• 96-1/TDC	blocks the automatic transfer if the incomer No. 2 bus voltage is not healthy.
• 97-1/TDC	blocks the automatic transfer if the 50 instantaneous current relay detects flow of fault current. The block doesn't clear until the 50 relay clears and there is no longer a depressed undervoltage condition caused by the fault condition.

Main Breaker Schematic



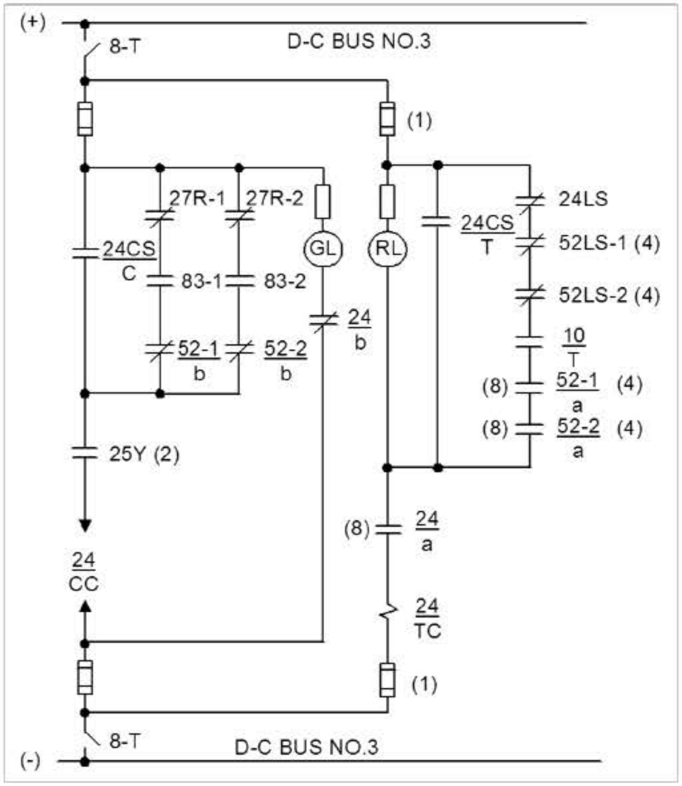
• 24/b	breaks the transfer system seal in rung when the tie breaker closes.
• 83-1	auxiliary relay that initiates the automatic transfer.

Tie Breaker Schematic



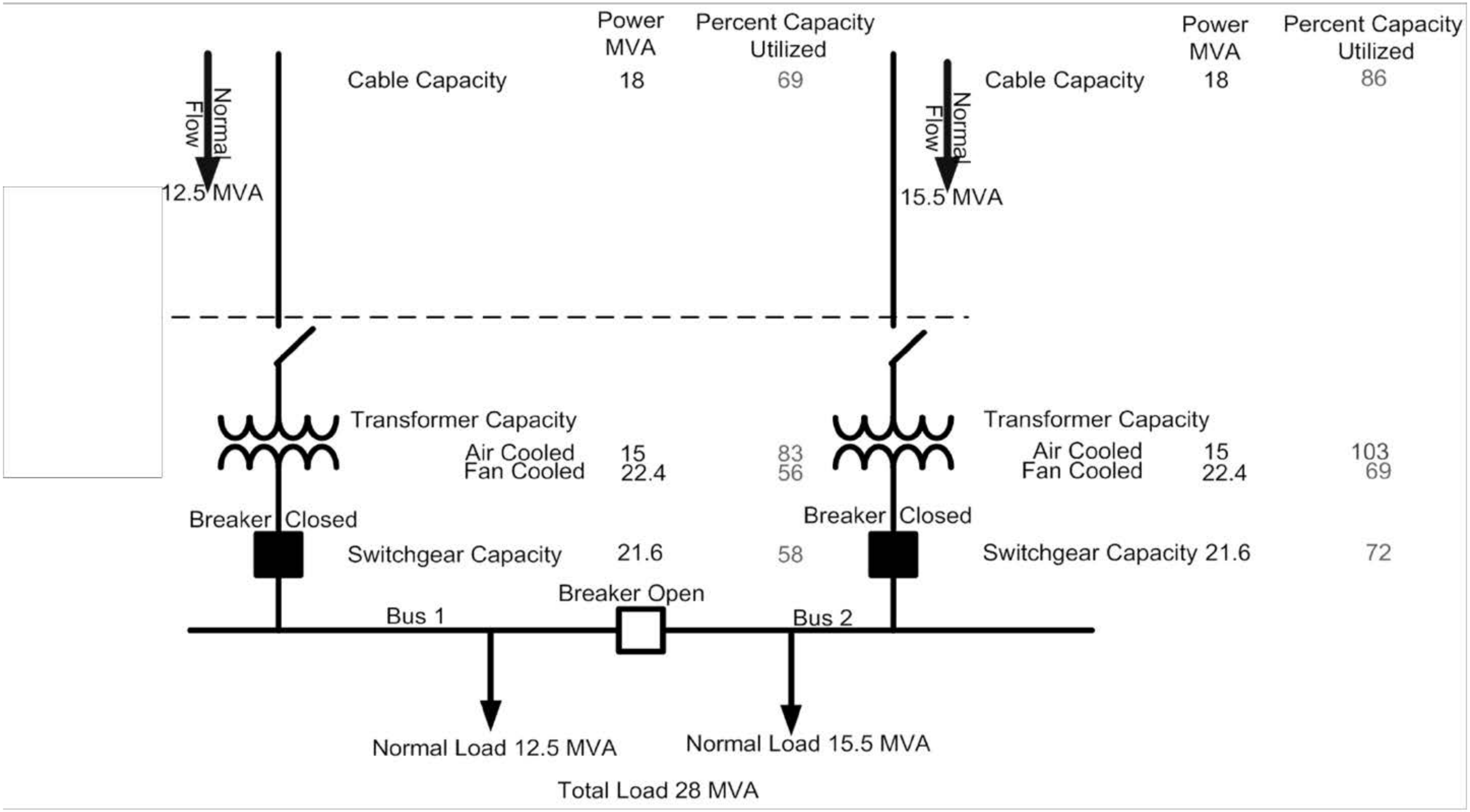
27R Relays protect the motors which carry through automatic transfer, against overvoltage and instantaneous tripping of their circuit breakers due to closing in out of phase with residual voltage. Protection is achieved by delaying transfer until residual voltage drops to a safe level. Motors will generate a decaying residual voltage if source power is interrupted under load with no fault to dissipate magnetic energy stored in the motors.

Tie Breaker Schematic

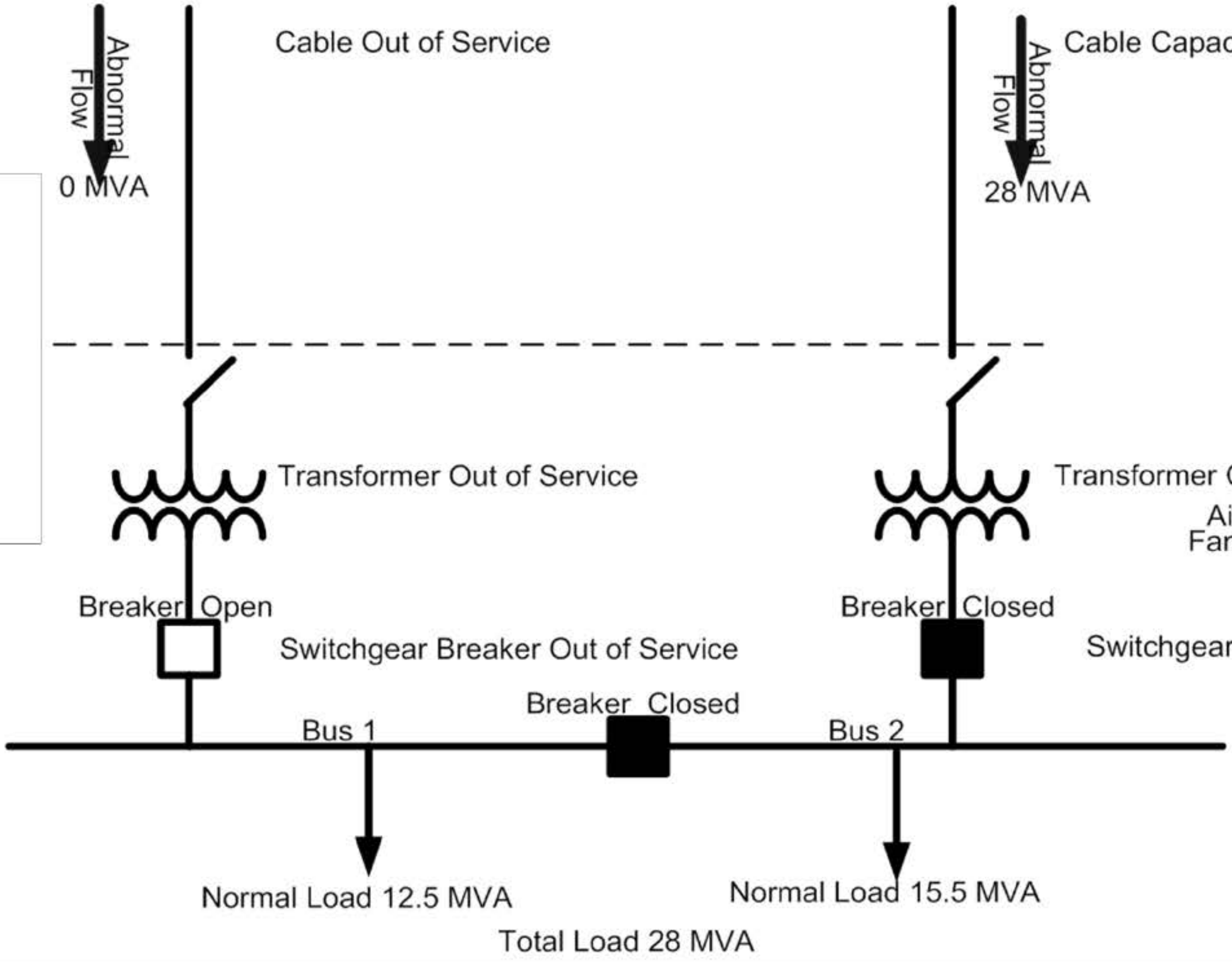


27R-1 contact closes when the residual bus voltage decays to 25% of the rated bus voltage in order to prevent an out of phase reclosure between the motor back emf and the new source voltage when the tie breaker is closed.

Normal Operating Condition



Abnormal Operating Condition



Abnormal Flow

0 MVA

Cable Out of Service

Abnormal Flow

28 MVA

Transformer Out of Service

Breaker Open

Switchgear Breaker Out of Service

Breaker Closed

Bus 1

Breaker Closed

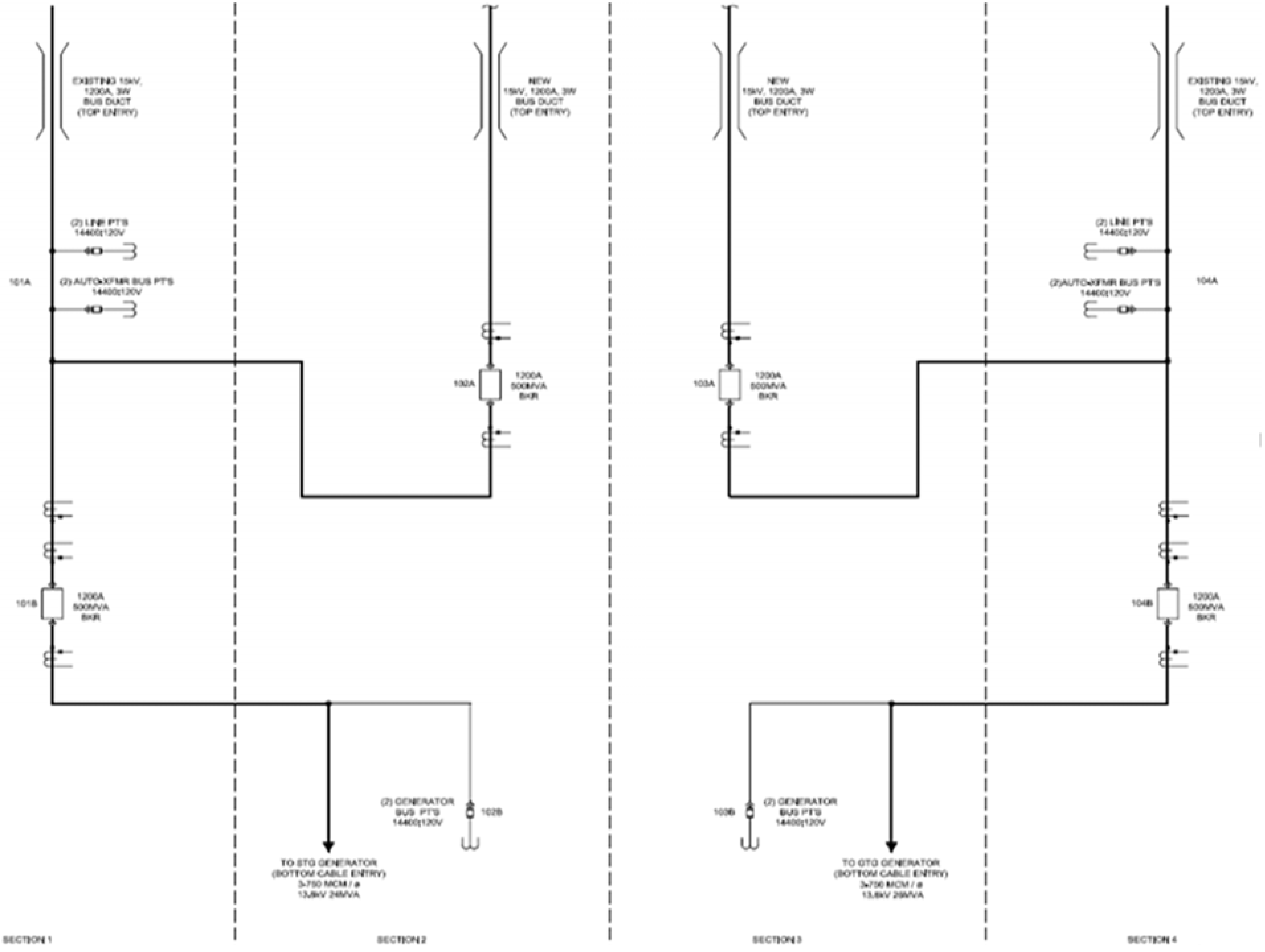
Bus 2

Normal Load 12.5 MVA

Normal Load 15.5 MVA

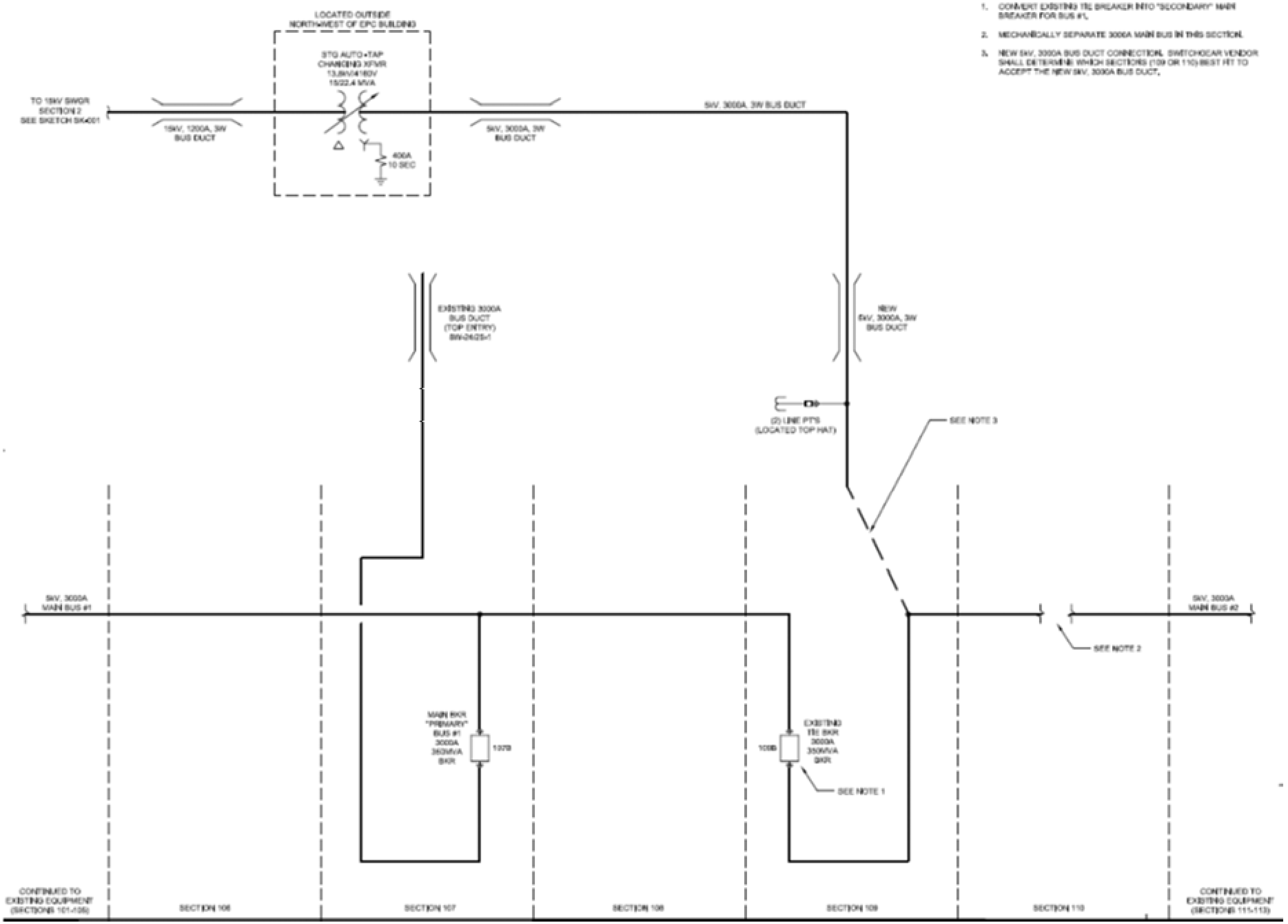
Total Load 28 MVA

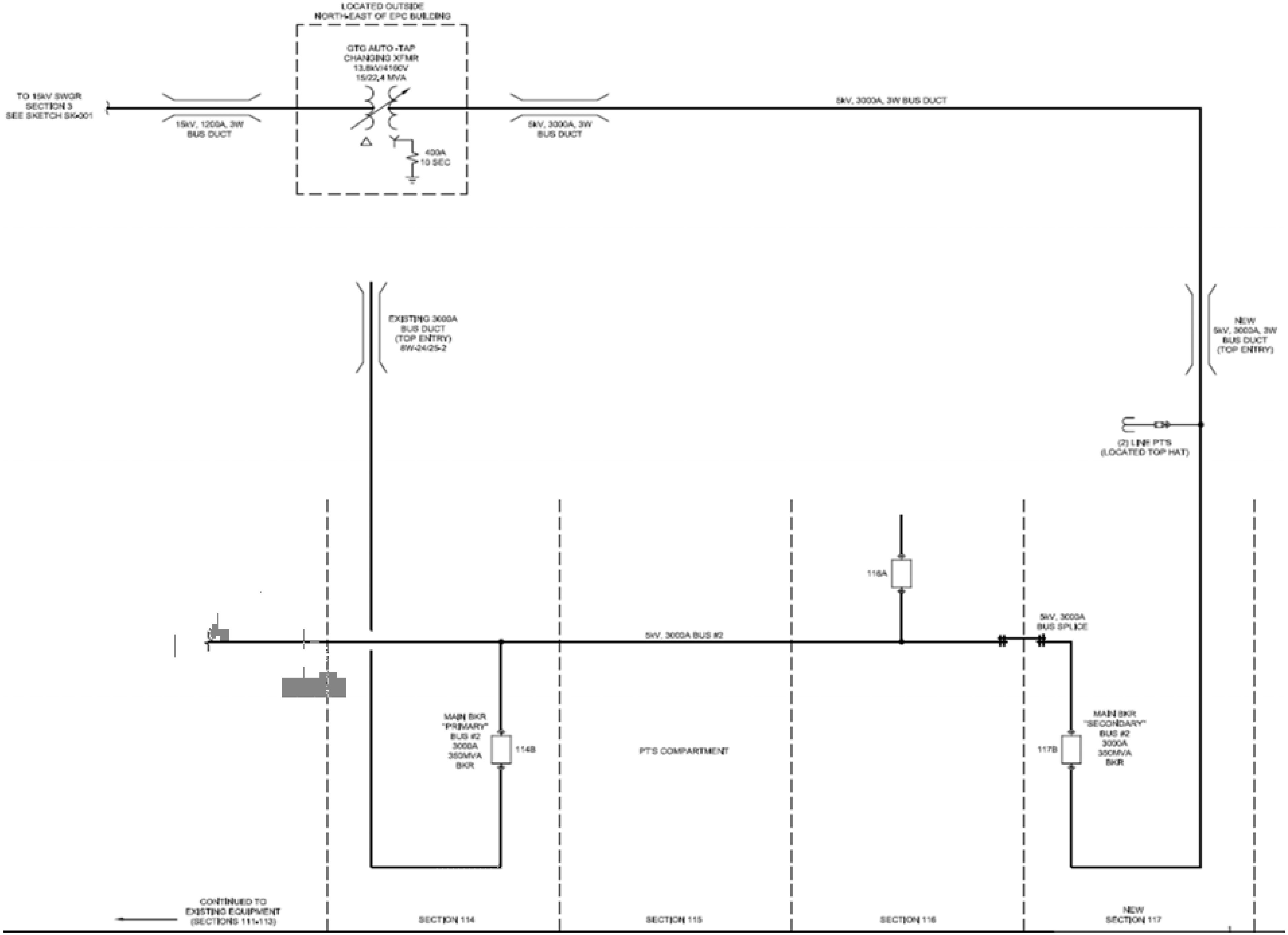
	Power MVA	Percent Capacity Utilized
Cable Capacity	18	156
Transformer Capacity		
Air Cooled	15	187
Fan Cooled	22.4	123
Switchgear Capacity	21.6	130

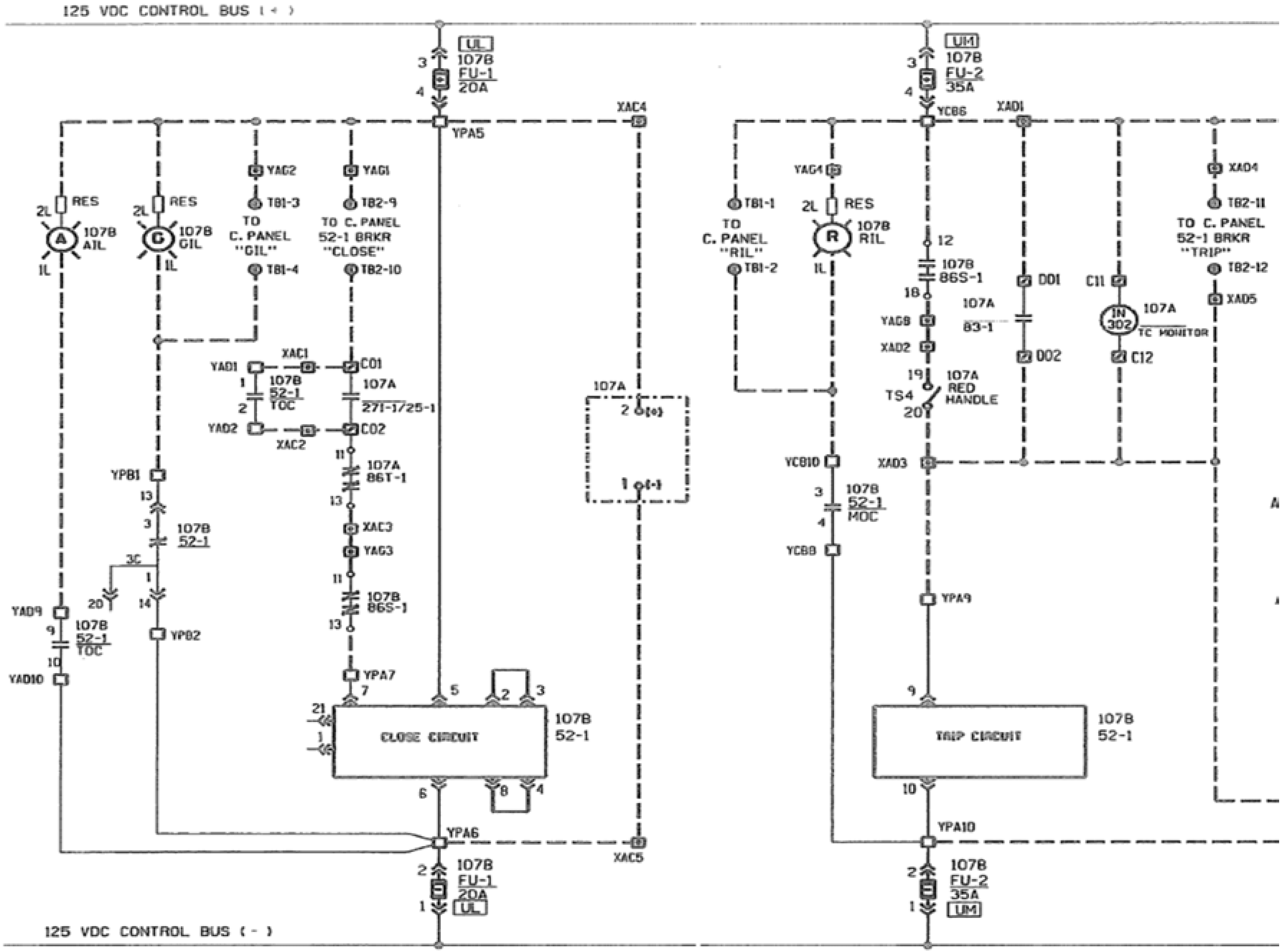

EXISTING 15kV, 1200A, 3W BUS DUCT (TOP ENTRY)
NEW 15kV, 1200A, 3W BUS DUCT (TOP ENTRY)
NEW 15kV, 1200A, 3W BUS DUCT (TOP ENTRY)
EXISTING 15kV, 1200A, 3W BUS DUCT (TOP ENTRY)
(2) LINE PT'S 14400:120V
101A
(2) AUTO-XFMR BUS PT'S 14400:120V
(2) LINE PT'S 14400:120V
(2)AUTO-XFMR BUS PT'S 14400:120V
104A
102A
1200A 500MVA BKR
103A
1200A 500MVA BKR
101B
1200A 500MVA BKR
104B
1200A 500MVA BKR
(2) GENERATOR BUS PT'S 14400:120V
102B
103B
(2) GENERATOR BUS PT'S 14400:120V
TO STG GENERATOR (BOTTOM CABLE ENTRY) 3-750 MCM / ø 13.8kV 24MVA
TO GTG GENERATOR (BOTTOM CABLE ENTRY) 3-750 MCM / ø 13.8kV 28MVA
SECTION 1
SECTION 2
SECTION 3
SECTION 4

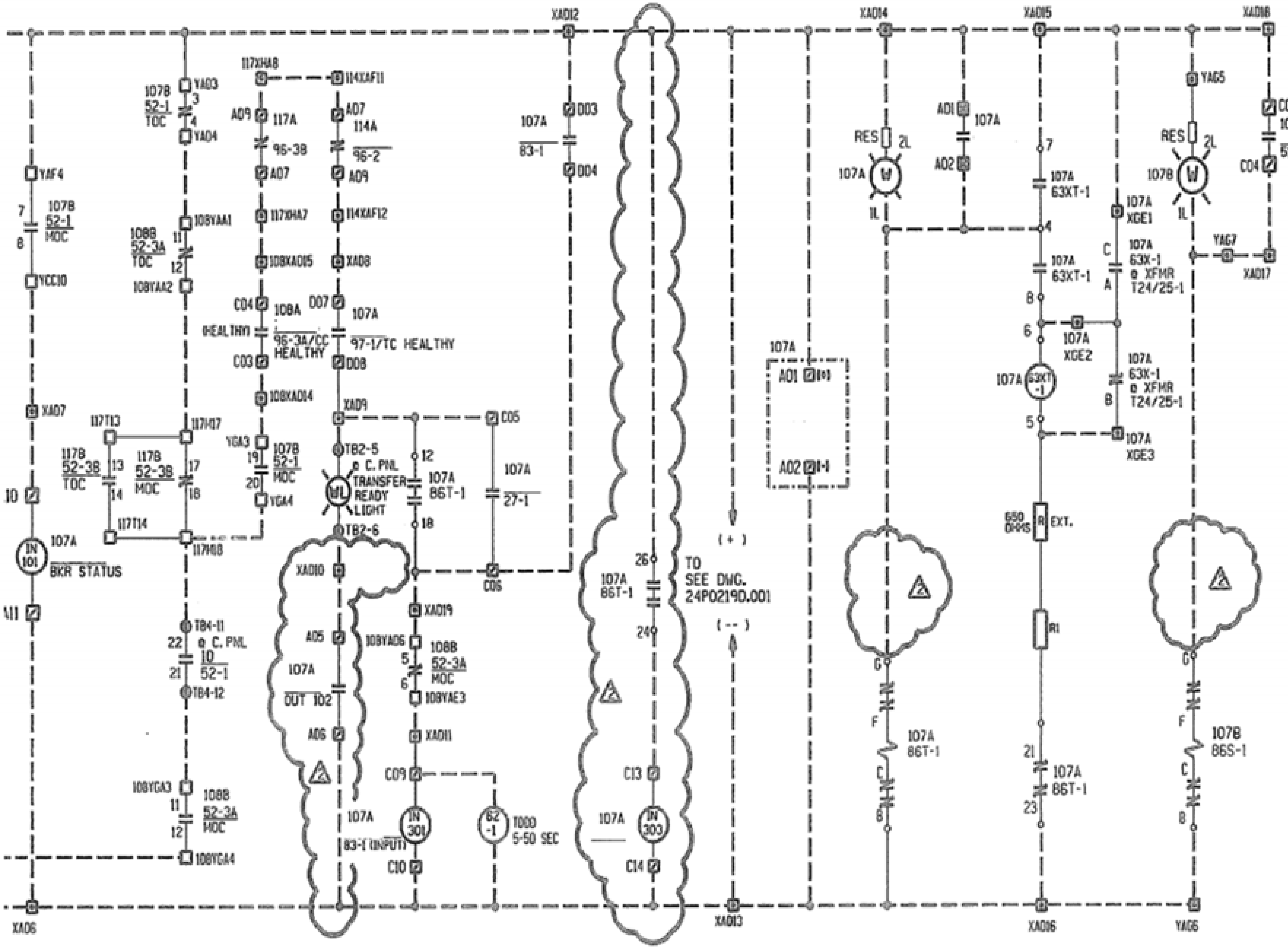
NOTES:

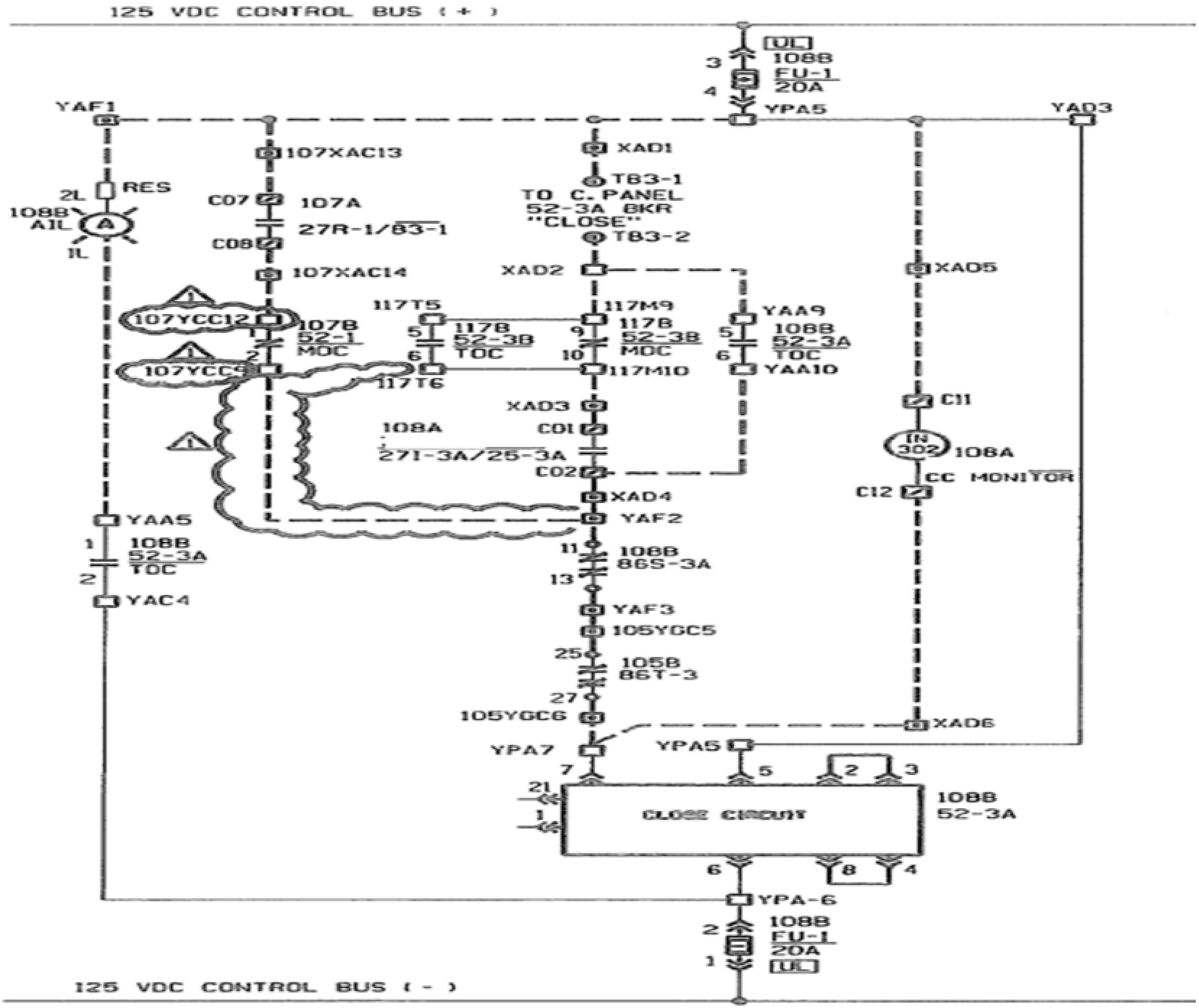
1. CONVERT EXISTING TIE BREAKER INTO "SECONDARY" MAIN BREAKER FOR BUS #1.
2. MECHANICALLY SEPARATE 3000A MAIN BUS IN THIS SECTION.
3. NEW 5KV, 3000A BUS DUCT CONNECTION. SWITCHGEAR VENDOR SHALL DETERMINE WHICH SECTIONS (109 OR 110) BEST FIT TO ACCEPT THE NEW 5KV, 3000A BUS DUCT.

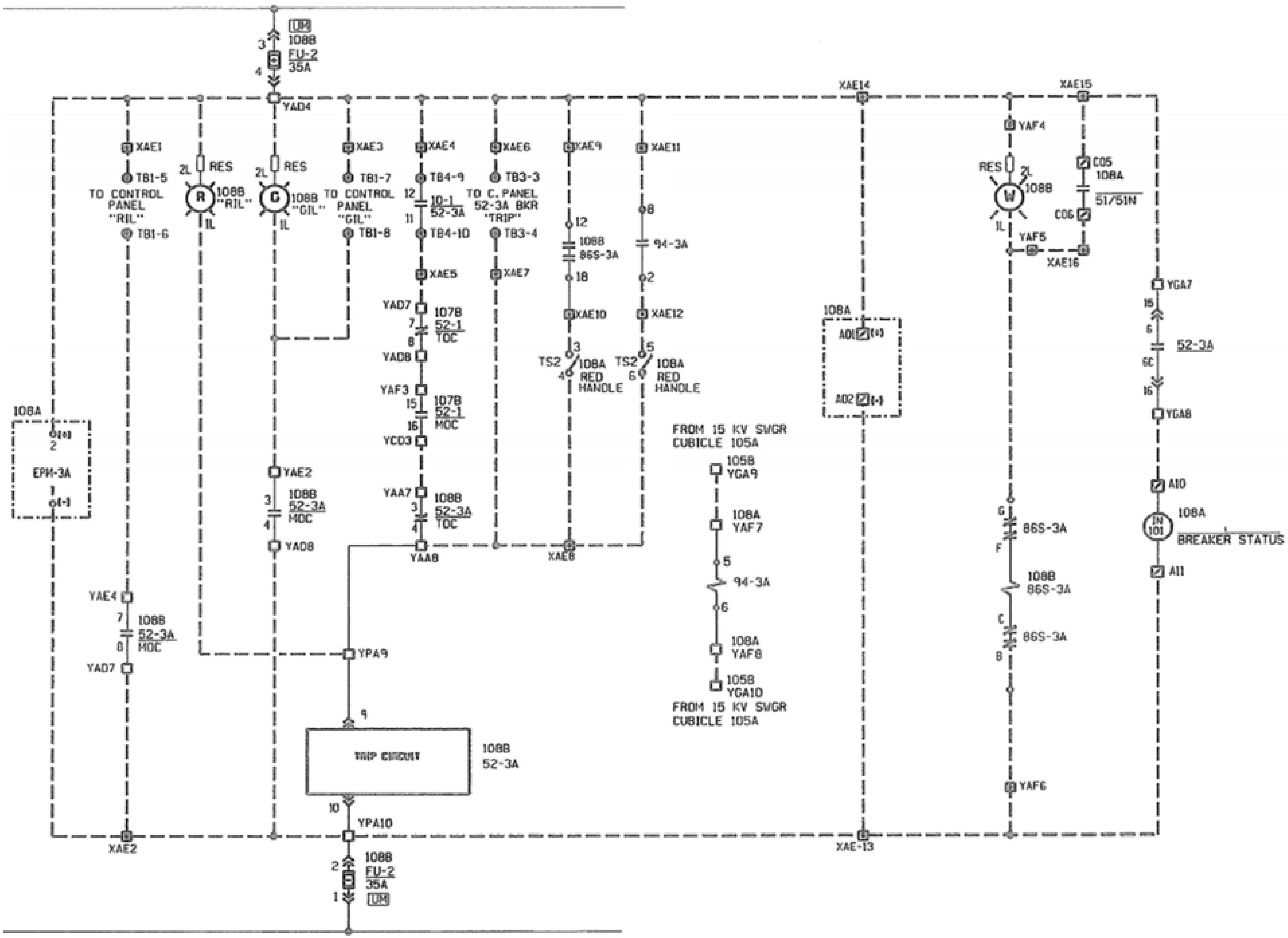



LOCATED OUTSIDE
NORTH-EAST OF EPC BUILDING
GTG AUTO-TAP
CHANGING XFMR
13.8kV/4160V
15/22.4 MVA
TO 15kV SWGR
SECTION 3
SEE SKETCH SK-001
15kV, 1200A, 3W
BUS DUCT
5kV, 3000A, 3W
BUS DUCT
5kV, 3000A, 3W BUS DUCT
400A
10 SEC
EXISTING 3000A
BUS DUCT
(TOP ENTRY)
8W-24/25-2
NEW
5kV, 3000A, 3W
BUS DUCT
(TOP ENTRY)
(2) LINE PTS
(LOCATED TOP HAT)
116A
5kV, 3000A BUS #2
5kV, 3000A
BUS SPLICE
MAIN BKR
"PRIMARY"
BUS #2
3000A
350MVA
BKR
114B
PTS COMPARTMENT
117B
MAIN BKR
"SECONDARY"
BUS #2
3000A
350MVA
BKR
CONTINUED TO
EXISTING EQUIPMENT
(SECTIONS 111-113)
SECTION 114
SECTION 115
SECTION 116
NEW
SECTION 117


125 VDC CONTROL BUS (+)
UL
107B
FU-1
20A
3
4
YPA5
XAC4
UM
107B
FU-2
35A
YCB6
XAD1
YAG2
YAG1
TB1-3
TB2-9
TO
C. PANEL
"GIL"
TO C. PANEL
52-1 BRKR
"CLOSE"
TB1-4
TB2-10
2L
RES
A
107B
AIL
1L
G
107B
GIL
XAC1
YAD1
C01
107B
52-1
TOC
107A
27I-1/25-1
YAD2
C02
XAC2
107A
86T-1
11
13
XAC3
YAG3
107B
86S-1
YPA7
7
YPB1
13
3
107B
52-1
3C
1
14
20
YPB2
YAD9
9
107B
52-1
TOC
10
YAD10
107A
2 (+)
1 (-)
5
2
3
21
1
CLOSE CIRCUIT
107B
52-1
6
8
4
YPA6
XAC5
107B
FU-1
20A
UL
125 VDC CONTROL BUS (-)
YAG4
TB1-1
TO
C. PANEL
"RIL"
TB1-2
R
107B
RIL
12
107B
86S-1
18
YAG8
XAD2
19
TS4
20
107A
RED
HANDLE
DD1
107A
83-1
DD2
C11
IN
302
107A
TC MONITOR
C12
XAD4
TB2-11
TO C. PANEL
52-1 BRKR
"TRIP"
TB2-12
XAD5
YCB10
XAD3
107B
52-1
MOC
YCB8
YPA9
9
TRIP CIRCUIT
107B
52-1
10
YPA10
107B
FU-2
35A
UM


XAD12
XAD14
XAD15
XAD18
YAF4
7
107B
52-1
MOC
8
YCC10
XAD7
ID
IN 101
107A
BKR STATUS
XI1
XAD6
YAD3
107B
52-1
TOC
3
4
YAD4
108YAA1
108B
52-3A
TOC
11
12
108YAA2
117T13
117B
52-3B
TOC
13
14
117B
52-3B
MOC
17
18
117H17
117T14
117H18
TB4-11
22
@ C. PNL
10
52-1
21
TB4-12
108YGA3
11
108B
52-3A
MOC
12
108YGA4
117XHA8
114XAF11
A09
117A
96-3B
A07
117XHA7
108XAD15
C04
108A
96-3A/CC HEALTHY
HEALTHY
C03
108XAD14
YGA3
107B
52-1
MOC
19
20
YGA4
A07
114A
96-2
A09
114XAF12
XAD8
D07
107A
97-1/TC HEALTHY
D08
XAD9
TB2-5
@ C. PNL
WL
TRANSFER READY LIGHT
TB2-6
XAD10
A05
107A
OUT 102
A06
107A
83-1 (INPUT)
12
107A
86T-1
18
XAD19
108YAD6
108B
52-3A
MOC
5
6
108YAE3
XAD11
C09
IN 301
C10
62 -1
TDDO
5-50 SEC
C05
107A
27-1
C06
107A
83-1
D03
D04
26
107A
86T-1
24
C13
107A
IN 303
C14
TO
SEE DWG.
24P0219D.001
(+)
(--)
XAD13
107A
A01
A02
RES
2L
107A
W
1L
A01
107A
A02
7
107A
63XT-1
4
107A
63XT-1
8
6
107A
XGE2
107A
63XT -1
5
107A
XGE1
C
107A
63X-1
@ XFMR
T24/25-1
A
107A
63X-1
@ XFMR
T24/25-1
B
107A
XGE3
650 OHMS
R
EXT.
R1
21
107A
86T-1
23
XAD16
G
F
107A
86T-1
C
B
YAG5
RES
2L
107B
W
1L
C03
107A
51/51N
C04
YAG7
XAD17
G
F
107B
86S-1
C
B
YAG6
2


125 VDC CONTROL BUS (+)
UL
3
108B
FU-1
20A
4
YPA5
YAF1
YAD3
107XAC13
XAD1
TB3-1
TO C. PANEL
52-3A BKR
"CLOSE"
TB3-2
2L
RES
108B
A1L
A
1L
C07
107A
27R-1/83-1
C08
107XAC14
XAD2
XAD5
1
107YCC12
107B
52-1
MOC
1
107YCC9
2
117T5
5
117B
52-3B
TOC
6
117T6
117M9
9
117B
52-3B
MOC
10
117M10
YAA9
5
108B
52-3A
TOC
6
YAA10
C11
XAD3
C01
108A
27I-3A/25-3A
C02
IN
302
108A
CC MONITOR
C12
1
XAD4
YAF2
YAA5
1
108B
52-3A
TOC
2
YAC4
11
108B
86S-3A
13
YAF3
105YGC5
25
105B
86T-3
27
105YGC6
XAD6
YPA7
YPA5
7
5
2
3
21
1
CLOSE CIRCUIT
108B
52-3A
6
8
4
YPA-6
2
108B
FU-1
20A
1
UL
125 VDC CONTROL BUS (-)



UM
1088
FU-2
35A
3
4
YAD4
XAE14
XAE15
XAE1
TB1-5
TO CONTROL PANEL "RIL"
TB1-6
2L
RES
R
1088 "RIL"
1L
G
1088 "GIL"
XAE3
TB1-7
TO CONTROL PANEL "GIL"
TB1-8
XAE4
TB4-9
12
10-1
52-3A
11
TB4-10
XAE5
YAD7
107B
52-1
TOC
7
8
YAD8
YAF3
15
16
107B
52-1
MOC
YCD3
YAA7
3
4
1088
52-3A
TOC
YAA8
XAE6
TB3-3
TO C. PANEL 52-3A BKR "TRIP"
TB3-4
XAE7
XAE9
12
1088
86S-3A
18
XAE10
3
TS2
4
108A
RED HANDLE
XAE8
XAE11
8
94-3A
2
XAE12
5
TS2
6
108A
RED HANDLE
108A
EPM-3A
2
(+)
(-)
YAE2
3
1088
52-3A
MOC
4
YAD8
YAE4
7
1088
52-3A
MOC
8
YAD7
YPA9
9
TRIP CIRCUIT
1088
52-3A
10
YPA10
XAE2
1088
FU-2
35A
2
1
UM
FROM 15 KV SWGR CUBICLE 105A
1058
YGA9
108A
YAF7
5
94-3A
6
108A
YAF8
1058
YGA10
FROM 15 KV SWGR CUBICLE 105A
108A
A01 (+)
A02 (-)
XAE-13
YAF4
RES
2L
W
1088
1L
YAF5
XAE16
C05
108A
51/51N
C06
G
86S-3A
F
1088
86S-3A
C
86S-3A
B
YAF6
YGA7
15
6
52-3A
6C
16
YGA8
A10
IN 101
108A
BREAKER STATUS
A11

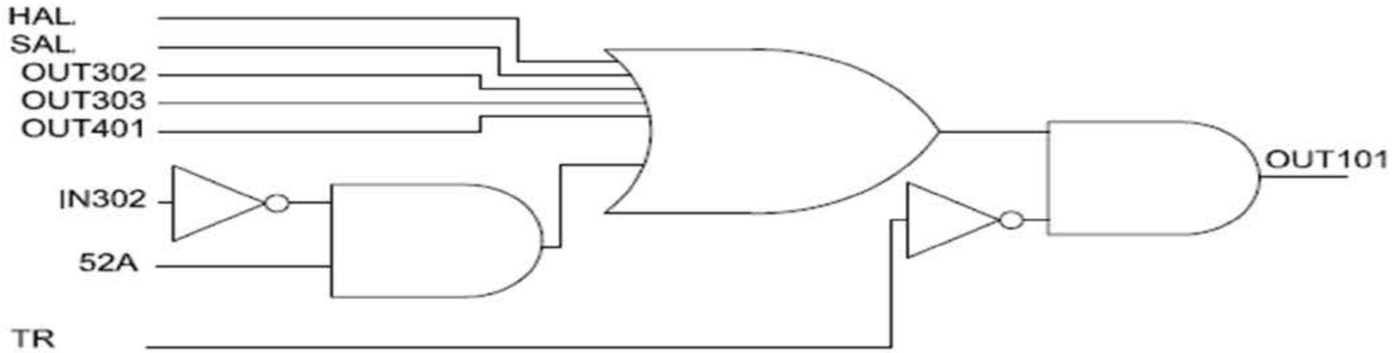
Final System Logic Diagrams

HAL - Hardware Alarm. Trigged by:
Relay disabled
RAM failure
Memory failure
Relay communications failure
Input card failure
Power supply failure

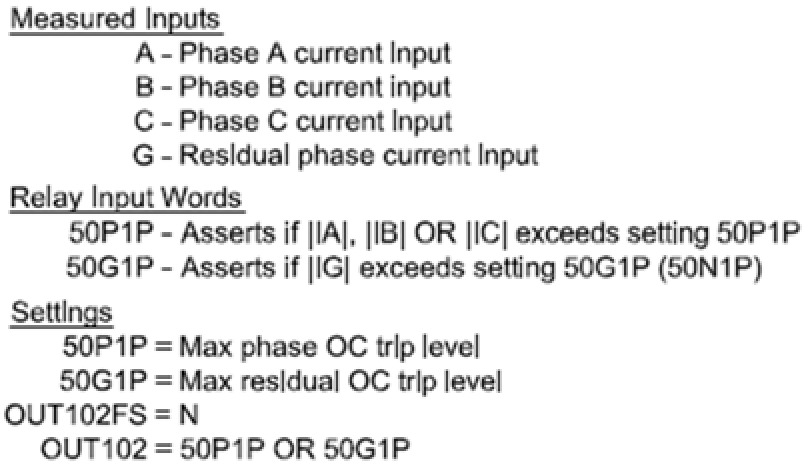
SAL - Relay settings alarm. Trigged by:
Settings changed
Access level changed
Three unsuccessful password entry attempts

OUT302 - 51P1T/51G1T (Time overcurrent) See 53228DL05
OUT303 - 27 (Phase undervoltage) See 53228DL07
OUT401 - 83 (Auto transfer initiated) See 53228DL09
IN302 - Trip coil healthy

Settings
OUT101FS = Y
OUT101 = (HAL OR SAL OR OUT302 OR OUT303 OR OUT401 OR (NOT IN302 AND 52A)) AND NOT TR



Final System Logic Diagrams



Measured Inputs

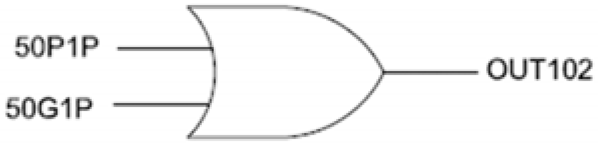
A - Phase A current Input
B - Phase B current input
C - Phase C current Input
G - Residual phase current Input

Relay Input Words

50P1P - Asserts if |IA|, |IB| OR |IC| exceeds setting 50P1P
50G1P - Asserts if |IG| exceeds setting 50G1P (50N1P)

Settings

50P1P = Max phase OC trip level
50G1P = Max residual OC trip level
OUT102FS = N
OUT102 = 50P1P OR 50G1P



Final System Logic Diagrams

Measured Inputs

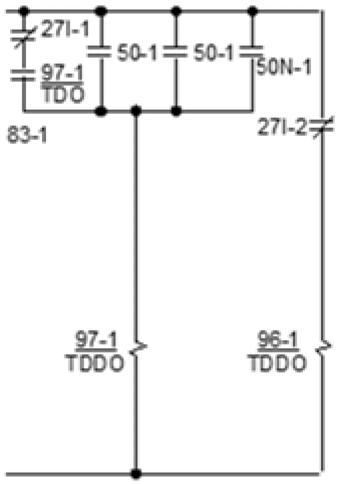
VAB - Voltage phase A to phase B
VBC - Voltage phase B to phase C
VAC - Voltage phase A to phase C
|VS| - Synchronism line voltage magnitude

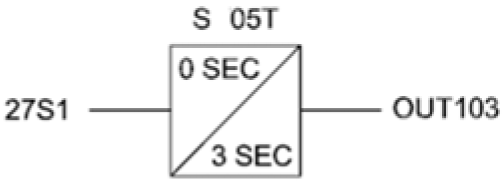
Relay Word Bits

27S1P - Asserts when |VS| voltage falls below 27S1P setting
SV05 - SEL variable to follow input setting
SV05T - SEL variable to follow SV05 pickup or dropout time delay setting

Settings

27S1P = 107V (Line undervoltage setting)
S 05 = Pickup: 0 sec.; Dropout: 3 sec.
50G1P = Residual ground instantaneous setting
OUT103FS = N
OUT103 = S 05T





Non-failsafe normally closed output contact stays closed under normal conditions. Opens to block auto transfer on undervoltage.

Final System Logic Diagrams

Measured Inputs

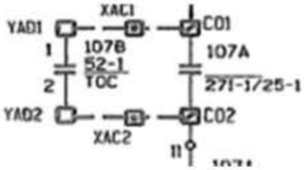
VAB - Voltage phase A to phase B
VBC - Voltage phase B to phase C
VAC - Voltage phase A to phase C
|VS| - Synchronism line voltage magnitude

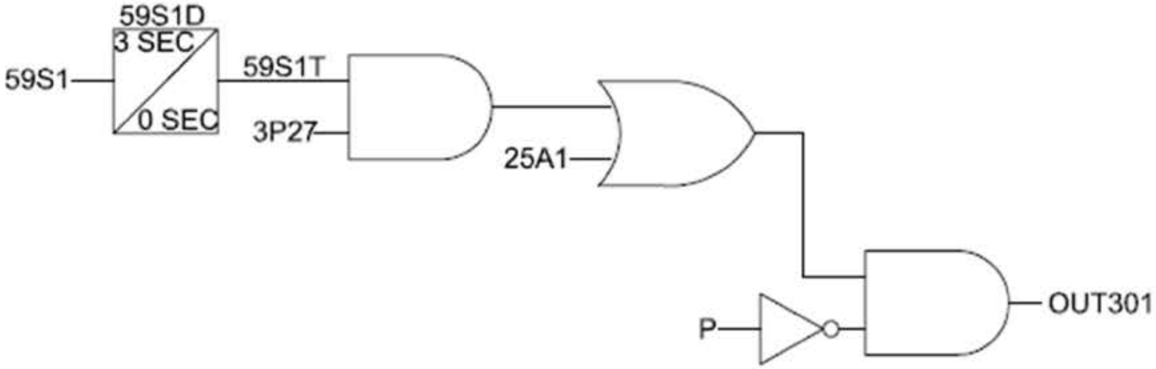
Relay Word Bits

59S1 - Asserted when |VS| voltage is above the 59S1P setting
59S1D - 59S1 time delay setting
59S1T - Asserts when 59S1D timed out
3P27 - Asserts when all residual voltages fall below the 27P1P setting (27R residual bus voltage)
25A1 - Sync. Check element asserts when synchronising parameters are met
3P27 - Loss of potential detection due to blown fuses or circuit breakers on
P - ac voltage sensing input

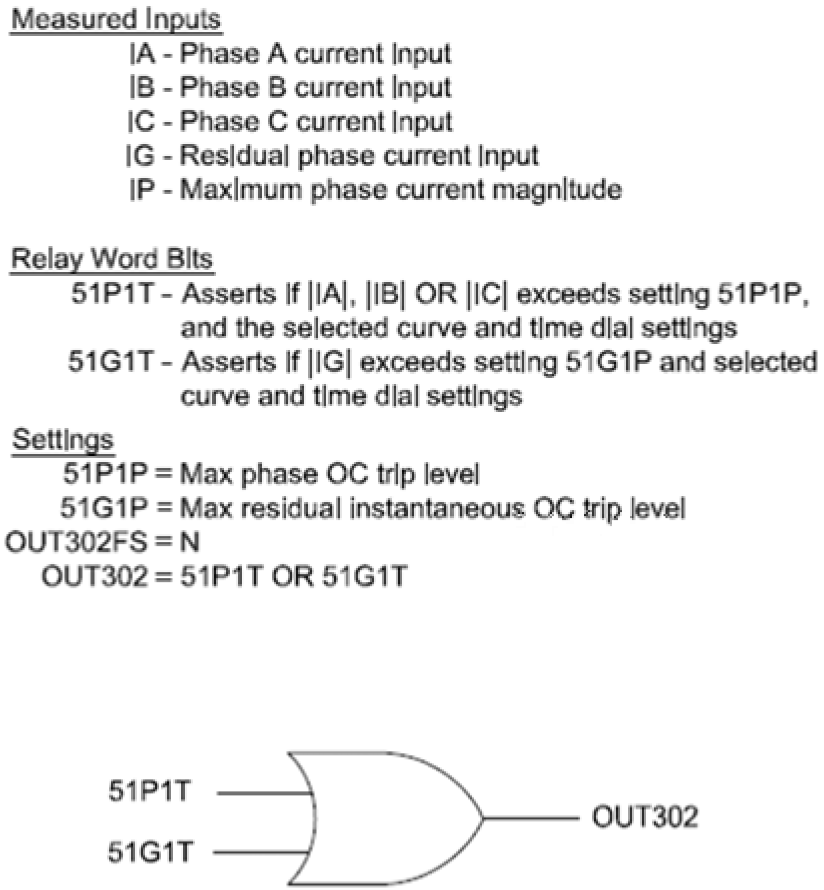
Settings

59S1 = 107V
27P1P = 0.25
E35 = Y (Enable Sync,Check)
25VLO = 105V
25VHI = 130V
25RCF = 1
25SF = 0.2
25ANG1 = 20
25ANG2 = 40
SYNCPH = VAB
BSYNCH = 52A (IN101)
TCLOSD = 83 msec (5 cycles)
OUT301FS = N
OUT301 = (59S1T AND 3P27 OR 25A1) AND NOT P





Final System Logic Diagrams



Measured Inputs

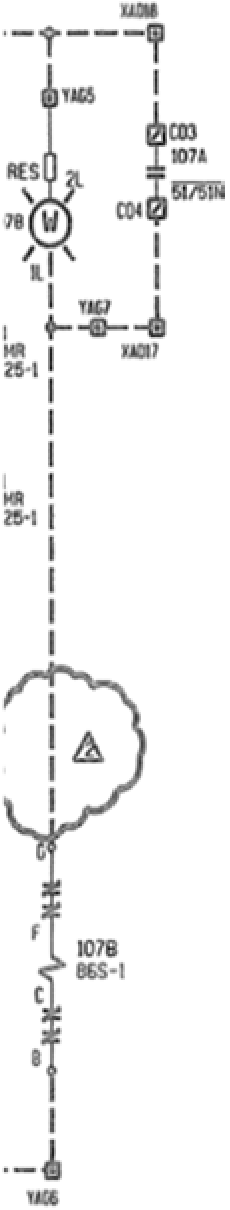
IA - Phase A current input
IB - Phase B current input
IC - Phase C current input
IG - Residual phase current input
IP - Maximum phase current magnitude

Relay Word Bits

51P1T - Asserts if |IA|, |IB| OR |IC| exceeds setting 51P1P, and the selected curve and time dial settings
51G1T - Asserts if |IG| exceeds setting 51G1P and selected curve and time dial settings

Settings

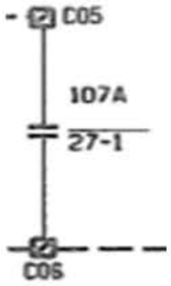
51P1P = Max phase OC trip level
51G1P = Max residual instantaneous OC trip level
OUT302FS = N
OUT302 = 51P1T OR 51G1T



Final System Logic Diagrams

Measured Inputs

IA - Phase A current input
IB - Phase B current input
IC - Phase C current input
IG - Residual phase current input
VAB - Voltage Phase A to Phase B
VBC - Voltage Phase B to Phase C
VAC - Voltage Phase A to Phase C

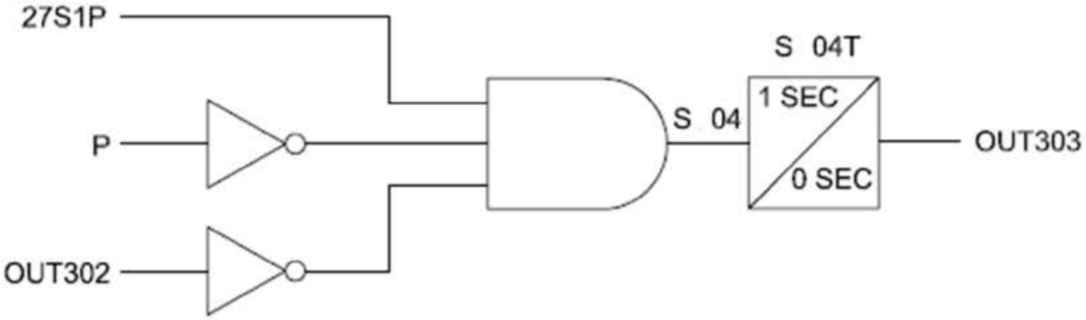


Relay Word Bits

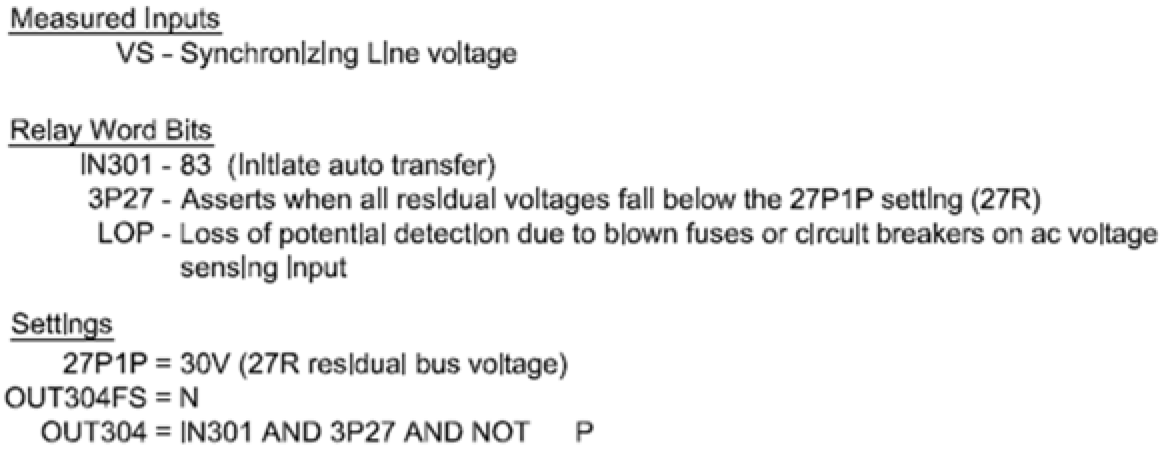
27S1P - Line undervoltage setting for phase VAB voltage
27S1D - Time delay on pickup
OUT302 - Trip on fault output
P - Loss of potential detection due to blown fuses or circuit breakers on ac voltage sensing Input

Settings

27S1P = 89V
27S1D = 0 SEC.
OUT302 = (51P1T OR 51G1T)
S 04 = 27S1P AND NOT P AND NOT OUT302
S 04T = PICKUP IS 1 SEC AND DROP OUT IS 0 SEC.
OUT303 = S 04T
OUT303FS = N



Final System Logic Diagrams



Measured Inputs

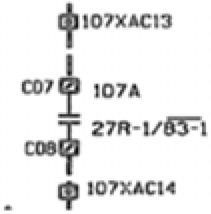
VS – Synchronizing Line voltage

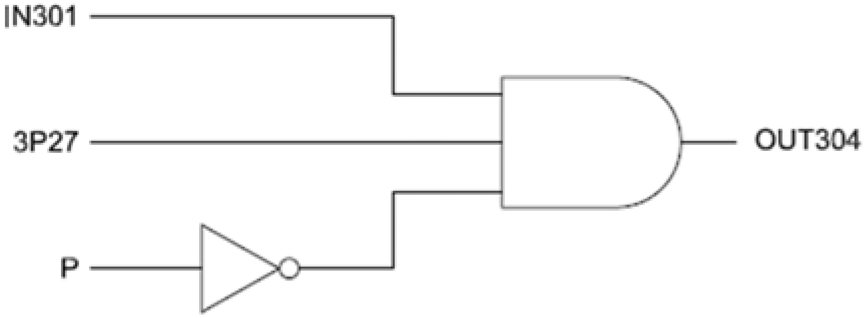
Relay Word Bits

IN301 - 83 (Initiate auto transfer)
3P27 - Asserts when all residual voltages fall below the 27P1P setting (27R)
LOP - Loss of potential detection due to blown fuses or circuit breakers on ac voltage sensing input

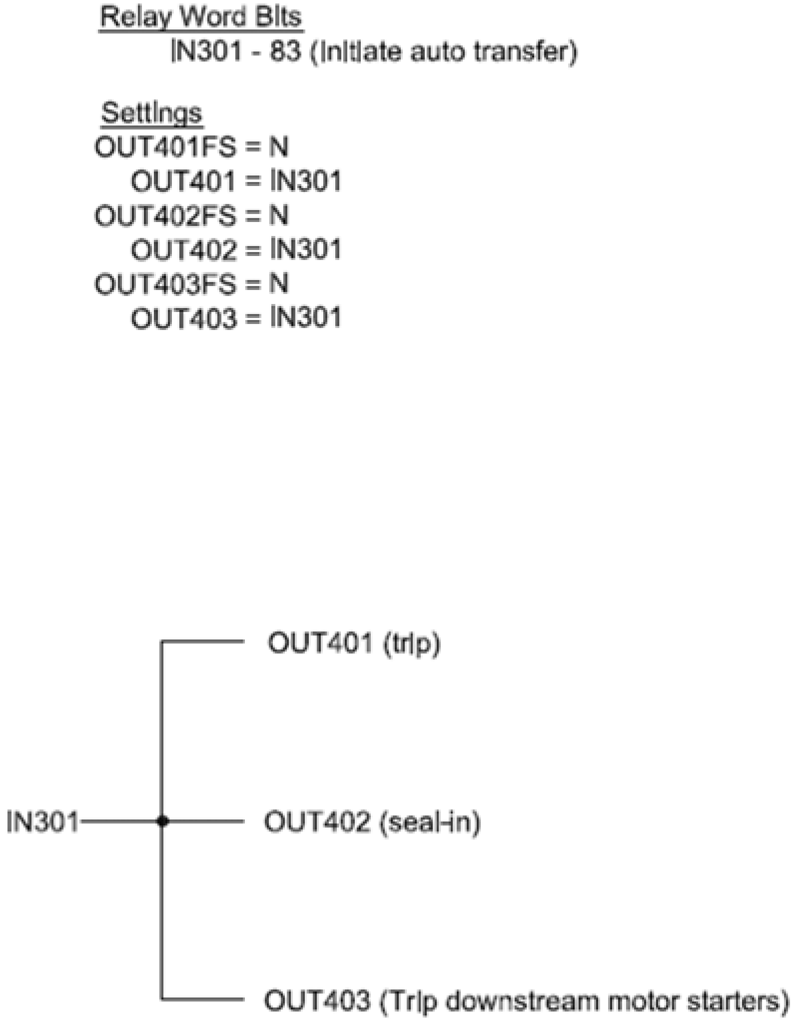
Settings

27P1P = 30V (27R residual bus voltage)
OUT304FS = N
OUT304 = IN301 AND 3P27 AND NOT P





Final System Logic Diagrams



Relay Word Bits

IN301 - 83 (Initiate auto transfer)

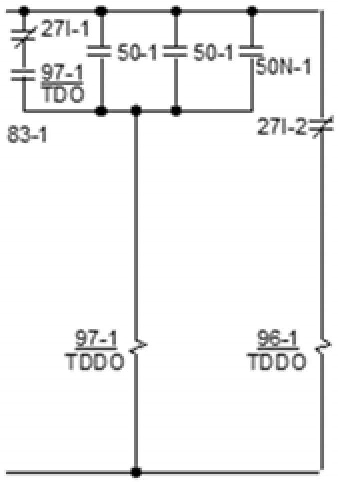
Settings

OUT401FS = N
OUT401 = IN301
OUT402FS = N
OUT402 = IN301
OUT403FS = N
OUT403 = IN301

Final System Logic Diagrams

Measured Inputs

VAB - Voltage Phase A to Phase B
VBC - Voltage Phase B to Phase C
VAC - Voltage Phase A to Phase C
VS - Synchronizing Line Voltage

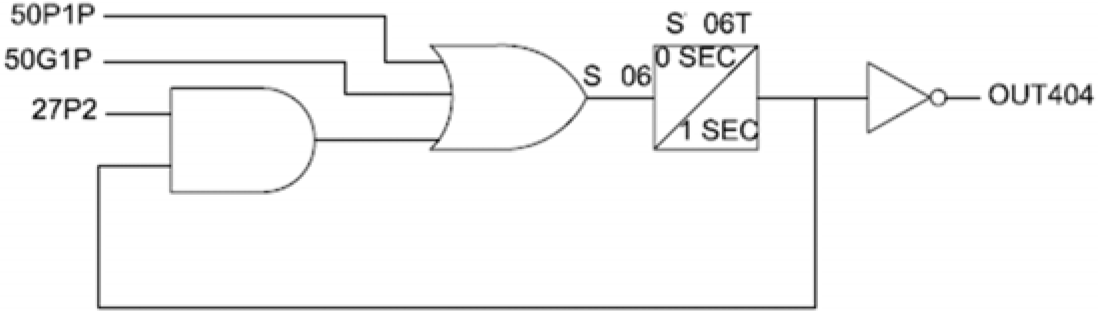


Relay Word Bits

50P1P/50G1P - Phase or ground current detection
27P2 - Line undervoltage condition

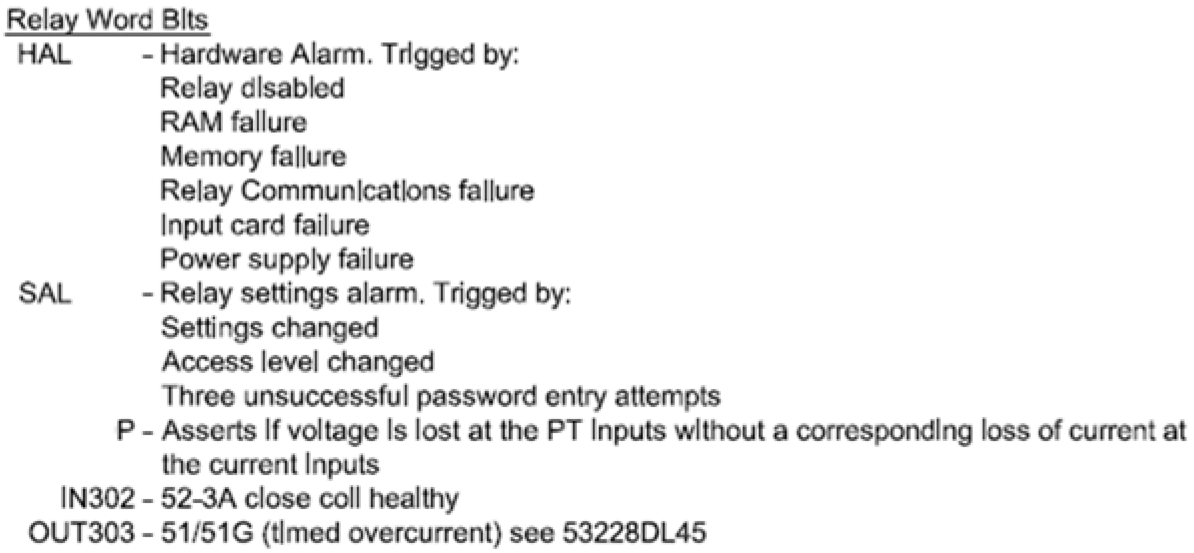
Settings

27P2P = 0.9 (27 phase undervoltage setting)
S 06 = SEL variable to follow Input setting
S 06T = SEL variable to follow S 06 pickup and dropout time delay setting
OUT404FS = N
OUT404 = NOT S 06T



Non-failsafe normally open output contact logic keeps the contact closed under normal conditions and opens the contact to block auto transfer (83).

Final System Logic Diagrams



Relay Word Bits

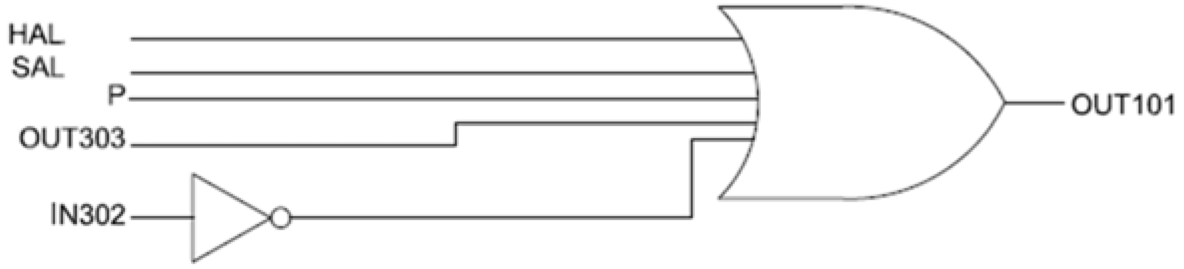
HAL - Hardware Alarm. Trigged by:
Relay disabled
RAM failure
Memory failure
Relay Communications failure
Input card failure
Power supply failure

SAL - Relay settings alarm. Trigged by:
Settings changed
Access level changed
Three unsuccessful password entry attempts

P - Asserts if voltage is lost at the PT inputs without a corresponding loss of current at the current inputs

IN302 - 52-3A close coil healthy

OUT303 - 51/51G (timed overcurrent) see 53228DL45



Final System Logic Diagrams

Measured Inputs

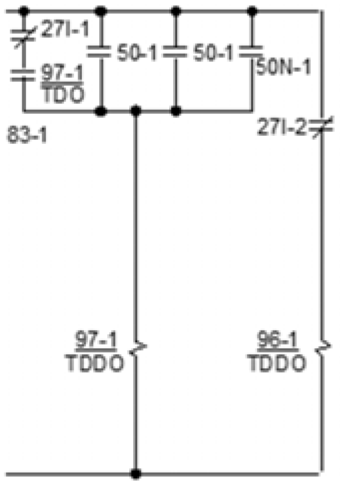
VAB - Voltage phase A to phase B
VBC - Voltage phase B to phase C
VAC - Voltage phase A to phase C
|VS| - Synchronism line voltage magnitude

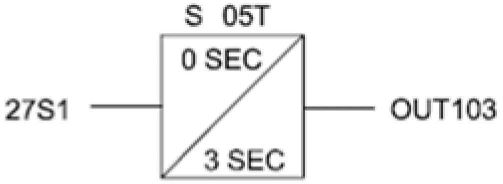
Relay Word Bits

27S1P - Asserts when |VS| voltage falls below 27S1P setting
SV05 - SEL variable to follow input setting
SV05T - SEL variable to follow SV05 pickup or dropout time delay setting

Settings

27S1P = 107V (Line undervoltage setting)
S 05 = Pickup: 0 sec.; Dropout: 3 sec.
OUT103FS= N
OUT103 = S 05T





Non-failsafe normally closed output contact stays closed under normal conditions. Opens to block auto transfer on undervoltage.

Final System Logic Diagrams

Measured Inputs

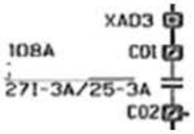
VAB - Voltage phase A to phase B
VBC - Voltage phase B to phase C
VAC - Voltage phase A to phase C
|VS| - Synchronism line voltage magnitude

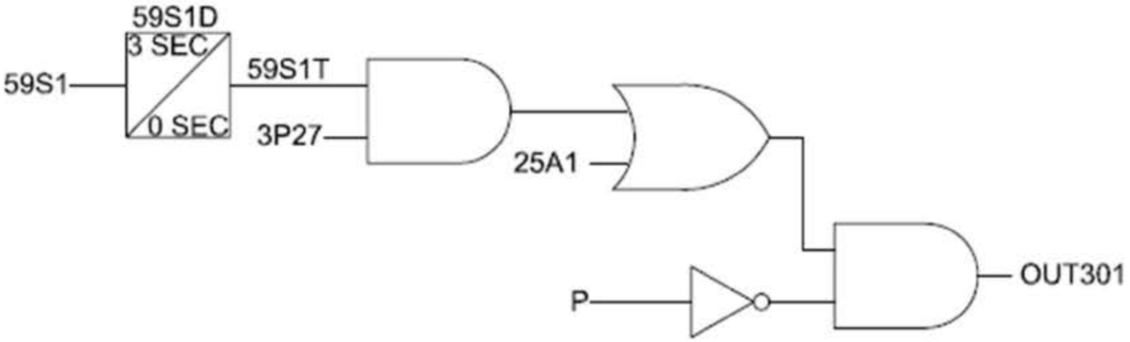
Relay Word Bits

59S1 - Asserted when |VS| voltage is above the 59S1P setting
59S1D - 59S1 time delay setting
59S1T - Asserts when 59S1D timed out
3P27 - Asserts when all residual voltages fall below the 27P1P setting (27R residual bus voltage)
25A1 - Sync. Check element asserts when synchronising parameters are met
P - Loss of potential detection due to blown fuses or circuit breakers on ac voltage sensing input

Settings

59S1 = 107V
27P1P = 0.25
E35 = Y (Enable Sync,Check)
25VLO = 105V
25VHI = 130V
25RCF = 1
25SF = 0.2
25ANG1 = 20
25ANG2 = 40
SYNCPH = VAB
BSYNCH = 52A (IN101)
TCLOSD = 83 msec (5 cycles)
OUT301FS = N
OUT301 = (59S1T AND 3P27 OR 25A1)
AND NOT P





Final System Logic Diagrams

Measured Inputs

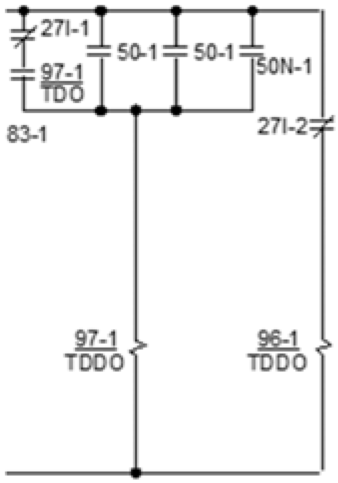
VAB - Voltage phase A to phase B
VBC - Voltage phase A to phase B
VAC - Voltage phase A to phase B
|VS| - Synchronism line voltage magnitude

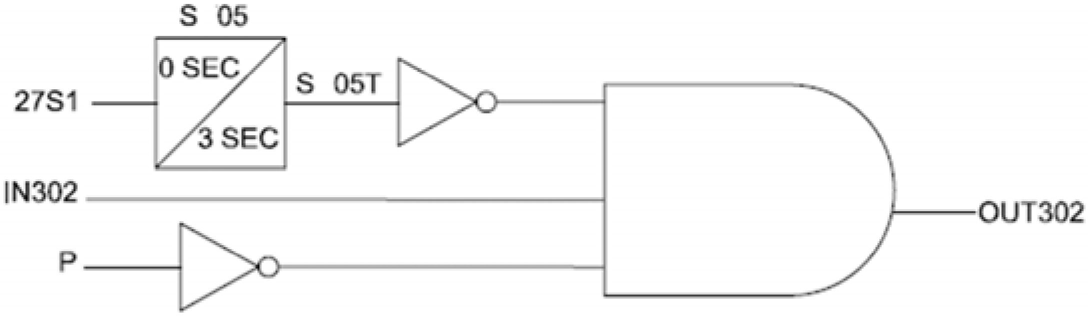
Relay Word Bits

27S1 - Asserts when |VS| voltage falls below 27S1P setting
IN302 - 52-1 close coil healthy
LOP - Loss of potential detection due to blown fuses or circuit breakers on ac voltage sensing input

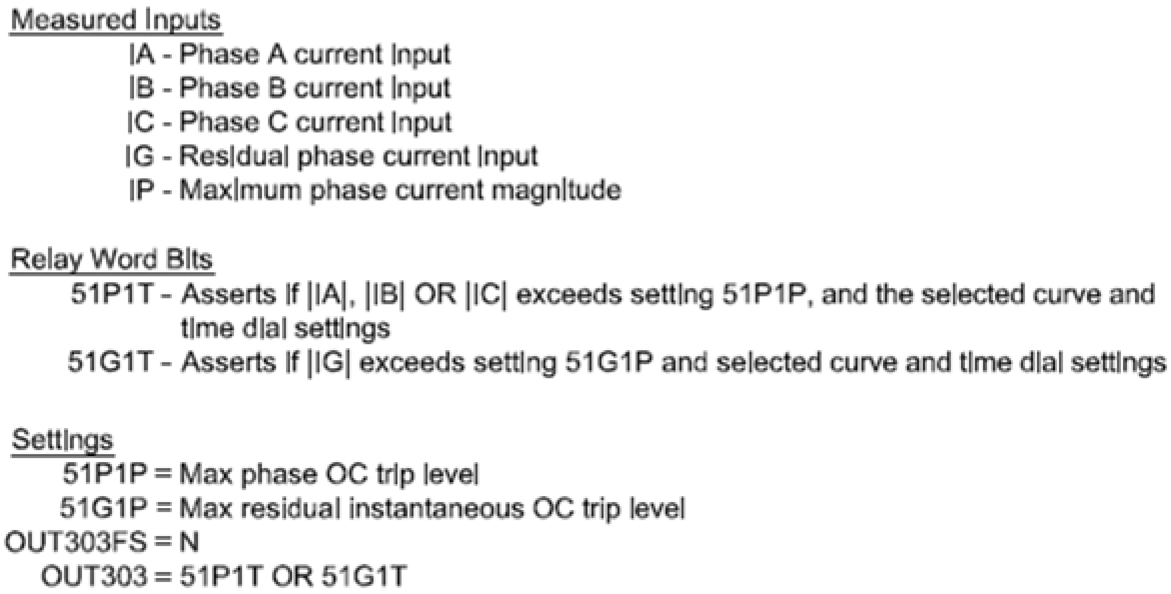
Settings

27S1P - 107V (Line undervoltage setting)
S 05 - 27S1
S 05DO - 3 SEC
OUT302FS - N
OUT 302 - NOT S 05T AND NOT P AND IN302





Final System Logic Diagrams



Measured Inputs

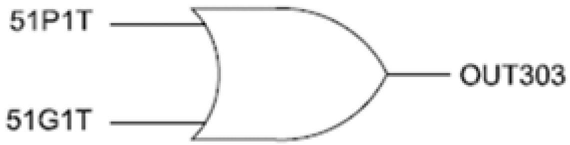
IA - Phase A current input
IB - Phase B current input
IC - Phase C current input
IG - Residual phase current input
IP - Maximum phase current magnitude

Relay Word Bits

51P1T - Asserts if |IA|, |IB| OR |IC| exceeds setting 51P1P, and the selected curve and time dial settings
51G1T - Asserts if |IG| exceeds setting 51G1P and selected curve and time dial settings

Settings

51P1P = Max phase OC trip level
51G1P = Max residual instantaneous OC trip level
OUT303FS = N
OUT303 = 51P1T OR 51G1T



Understanding Power Concepts

Part 2

- Electrical Studies
  - One lines
  - SC
  - LF
  - I2T
- Transfer Schemes
- ***<u>Cable Types</u>***
- Feeder Designs

Insulated Cable & Raceways

- For Substation Applications

Presentation Objectives

Understand the basics of cable construction

Know what are the usual cables used in a substation

Understand the basics of raceways in substations

Know what are the usual raceways used in substations

Importance

Cables

Cables are defined as the backbone of any substation. They connect the devices in the control building to various items in the field.

Raceways

Raceways are defined as the means of protecting the cables from physical damage as the cables go from the control building to the various devices in the field.

Cables

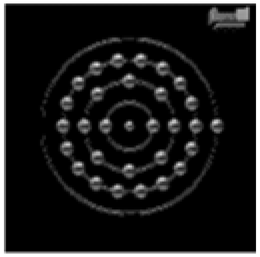
Cables follow the various voltage levels

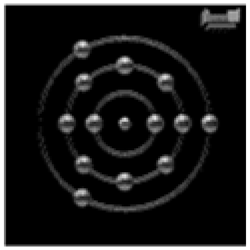
300 volts

600 volts

5,000 volts

15,000 volts





Per IEEE:-

Low voltage is under 1KV

Medium voltage is 1K through 99KV

High voltage is 100K through 250KV (?)

Extra high voltage is 250KV (?) and above

Cables

For instrumentation 300V cable is just fine.

For power and control in a substation, 600 V is the cable that we use.

5,000 V cable is used in a power line carrier (PLC) system.

If we are involved in power distribution then we could be using 15,000 V cables. Occasionally we may be at 35,000 V distribution, but I would expect that to be overhead bare and not insulated cable.

Of course there are exceptions such as obtaining station service power from a transformer tertiary, 0f from a distribution line. These exceptions are not major and will be defined early in the project.

600V Cables

Cables are needed for:

Transformers – power, control & status

Circuit breakers – power, control & status

Circuit switchers – power, control & status

Disconnect switches – status

Station service power – power

CT's & PT's – for heater, control

Lights – power

Cap Bank Regulation – power control & status

Substation security – mixture

Control building – power & status

Relay panels – power, control & status

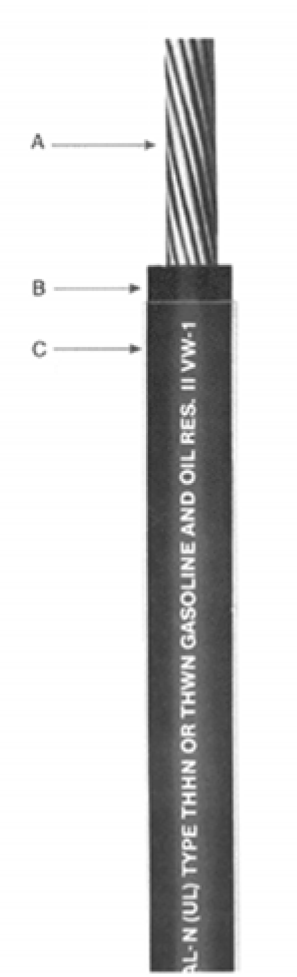
600V Cables

- **Not all substations are created equal. There are subtle differences, and for cable you need to know the following.**

  - **For a 138kV yard and below, power (AC & DC), control and status cables are not required to be shielded.**
  - **For a 345kV yard and above, control and status cables going out to the equipment are shielded. Control and status cabling within the control building do not need to be shielded.**
  - **Shielding is grounded at one end: the panel end.**

    Make sure your panel design has the vertical ground bus.
  - **345kV substations are physically large so voltage drop must be looked at. Therefore, cables may be larger at 345kV and above than a typical 138kV substation.**

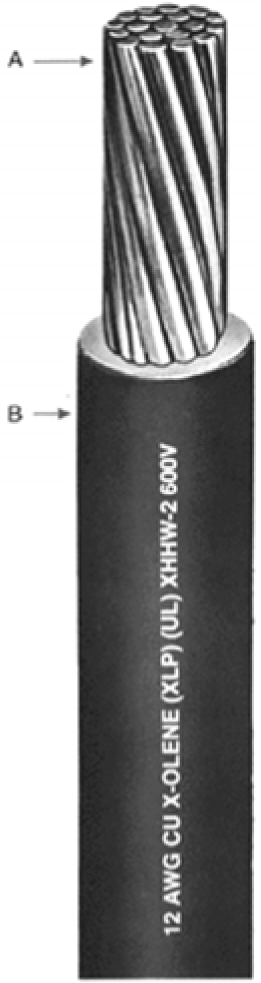
600V Cable – THHN/THWN



A. Bare, Stranded Copper Conductor
B. Insulation - Okoseal
C. Covering - Nylon

Insulation
Okoseal is Okonite's trade name for one of its PVC (polyvinyl chloride) insulating compounds with good electrical, mechanical and flame resistant properties.
Covering
The nylon covering provides excellent mechanical strength and resistance to oil, gasoline and chemicals.
Applications
Okoseal-N Type THHN or THWN 600 Volt Power Cables are recommended for use in branch circuits or feeders, as machine tool wire or appliance wire. Type THHN or THWN is rated at 90°C in dry locations and 75°C in wet locations in accordance with the National Electrical Code. These cables may be installed in wet or dry locations, indoors or outdoors, in raceways, underground ducts, or lashed to a messenger for aerial installation.
Okoseal-N is not recommended for dc operation in wet locations.
Listed by Underwriters Laboratories, Inc. as Type THHN or THWN, VW-1.

600V Cable - XHHW



A Bare, Solid or Stranded Copper Conductor
B X-Olene Insulation

Insulation

X-Olene is Okonite's trade name for its chemically cross-linked polyethylene insulating compound with outstanding electrical and physical properties. Its excellent chemical physical resistance permits X-Olene's use in areas exposed to alcohol, ketones and dilute acids and bases, without additional coverings.

Applications

X-Olene Type XHHW-2 600 Volt Cables are recommended for general low voltage power and control applications. Where the National Electrical Code applies, Type XHHW-2 may be used up to 90°C in wet or dry locations. These cables may be installed in wet or dry locations, indoors or outdoors, in raceways, underground ducts, or lashed to a messenger for aerial installation.

Specifications

Conductor: Bare, solid or stranded copper per ASTM B-3 or B-8.

Insulation: Meets or exceeds all requirements of ICEA S-95-658, NEMA WC-70, and UL Standards.

Listed by Underwriters Laboratories, Inc. as Type XHHW-2.

600V Power Cable

The difference between THWN/THHN & XHHW

1. Ampacity
   a. see NEC table 310-16 and there is none
2. Thickness of the insulation
   a. see NEC table 310-13 (NEC 2008) and XHHW is thicker
3. Roughness of surface – nylon is smooth XHHW is rough
4. Nylon can crack if mishandled and XHHW can split if soap is not used.

600V Power Cable

(NEC 2008) **NEC Table 310.16 (Partial)**		
	75C	90C
Size	RHW, THHN, THW, THWN, XHHW, USE,ZW	TBS, SA, SIS, FEP, FEBP, MI, RHH, RHW-2, THHN, THWN, THW-2, THWN-2, USE-2, XHH, XHHW, XHHW-2, ZW-2
Copper		
18	--	14
16	--	18
14*	20	25
12*	25	30
10*	35	40
8	50	55

* - See 240.4(D)

600V Power Cable

(NEC 2008) **NEC Table 310.13 (Partial)**

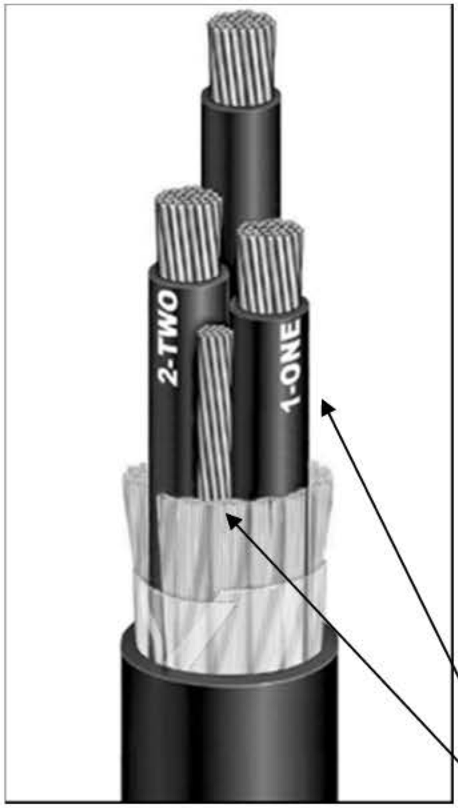
Type Letter	Max Op Temp	Applications	Size	Mils	Outer Covering
XHHW	90C 75C	Dry & Damp Locations Wet Locations	14 - 10 8 - 2 1 - 4/0	30 45 55	None
XHHW-2	90C	Dry & Wet Locations	14 - 10 8 - 2 1 - 4/0	30 45 55	None
THHN	90C	Dry & Damp Locations	14 - 10 8 - 2 1 - 4/0	15 20 30	Nylon Jacket or Equiv
THWN	90C	Dry & Wet Locations	14 - 10 8 - 2 1 - 4/0	15 20 30	Nylon Jacket or Equiv

See NEC Article 100 for definitions of dry, damp and wet locations

600V Power Cable

There is a specific way of stating the wire to be used. Simply put it is like this:-

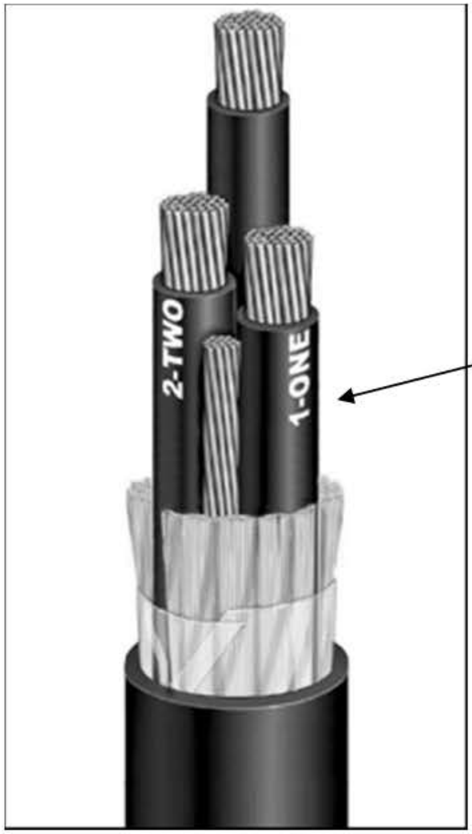
1-3/C #2 or 1-3/C #2 AWG
1-3/C 500 or 1-3/C 500 kcmil



Also remember small cables are in AWG and large cables are in kcmil. The designation MCM was discontinued by the NEC back in the 1980's when changing from the archaic Roman 'M' to the modern metric system.

Note the cable designation and the one ground wire.

What Cable to use for Power



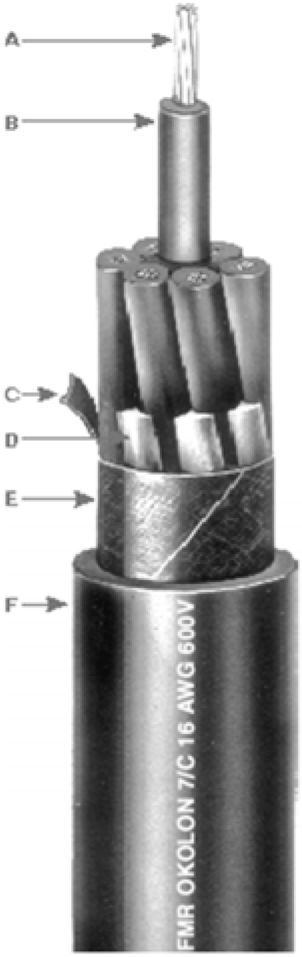
Do I go with:-

1-3/C 2/0 or

3-1/C 2/0

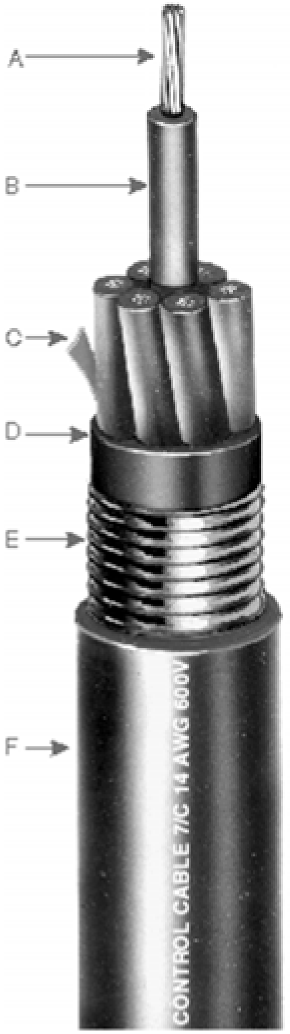
Which is better?

600V Control Cable (Shield)



A Coated, Stranded Copper Conductors
B Okonite-FMR Insulation
C Marker Strip
D Flame and Moisture Resistant Fillers
E Cable Tape
F Okolon Jacket

A Coated, Stranded Copper Conductors
B Okonite-FMR Insulation
C Marker Strip
D Extruded Fill and Belt
E 5 mil Longitudinal Corrugated Coated Copper Shield
F Okolon Jacket



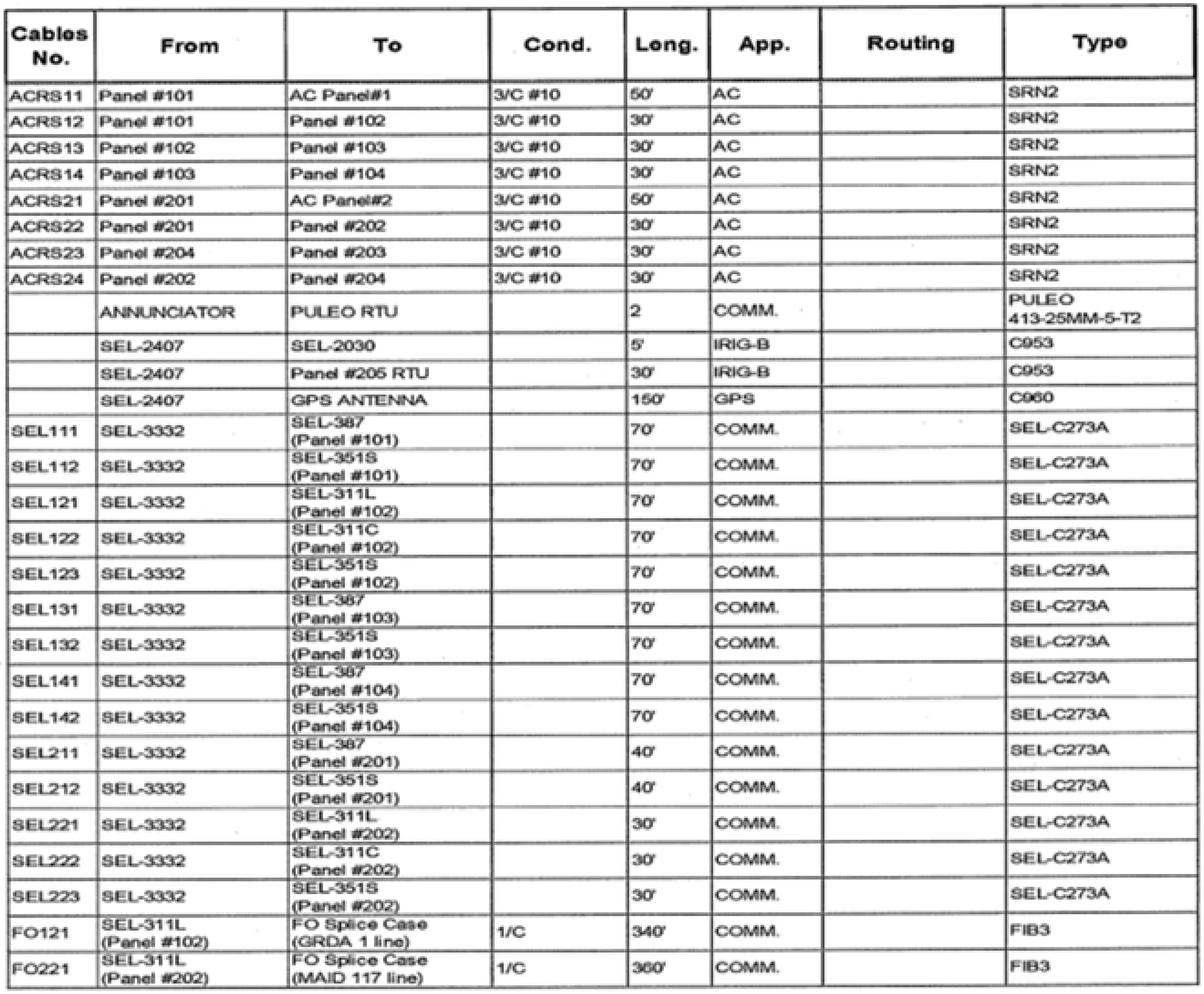
600V Control Cable – Color Coding

Do we go with ICEA Method 1 Table E-1
Or ICEA Method 1 Table E-2?

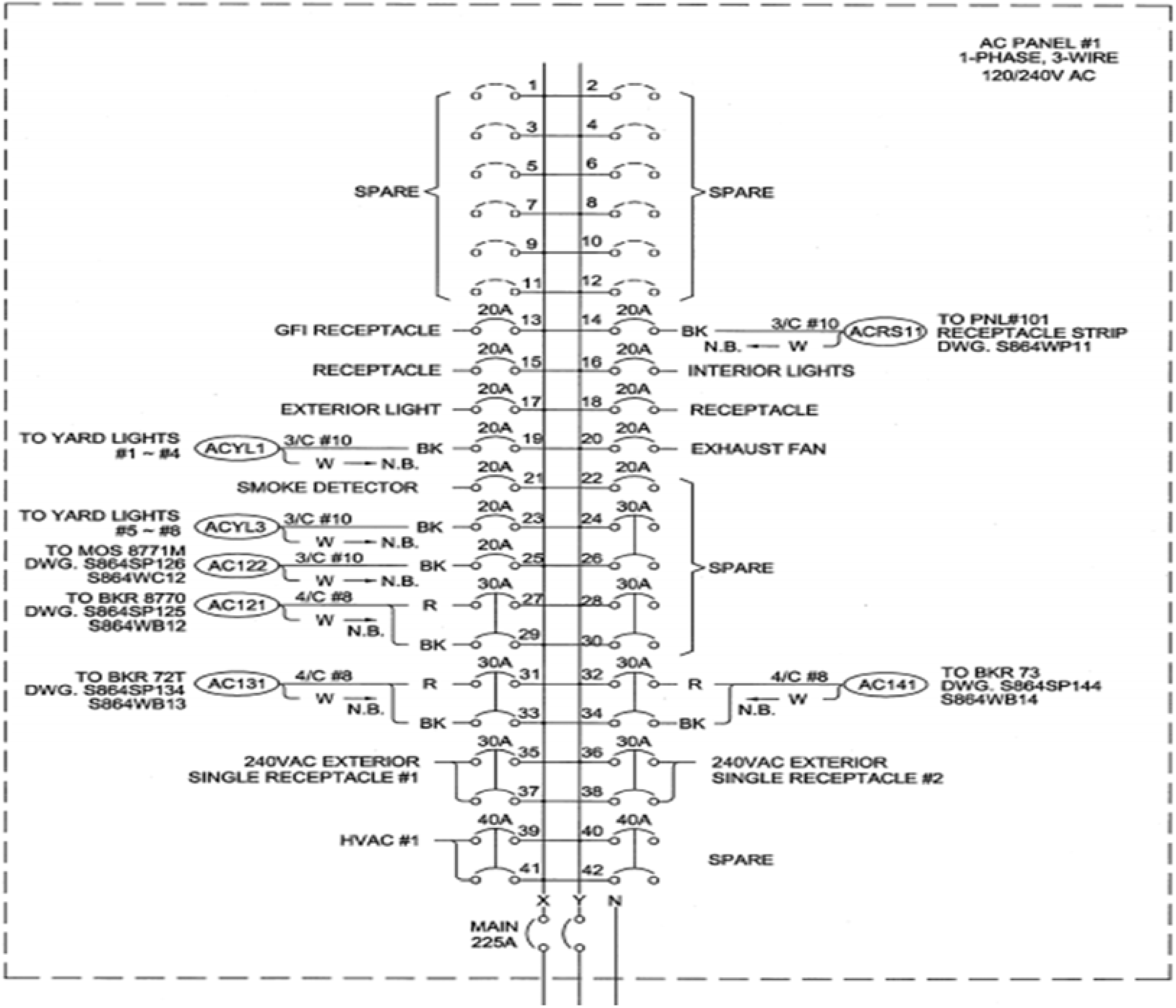
Cable per
Table E-1

Table E-1			Table E-2		
#	Base	Strip	Base	Strip	Abbrev'
1	Black		Black		BK
2	White		Red		R
3	Red		Blue		B
4	Green		Orange		O
5	Orange		Yellow		Y
6	Blue		Brown		BR
7	White	Black	Red	Black	R/BK
8	Red	Black	Blue	Black	B/BK
9	Green	Black	Orange	Black	O/BK
10	Orange	Black	Yellow	Black	Y/BK
11	Blue	Black	Brown	Black	BR/BK
12	Black	White	Black	Red	BK/R

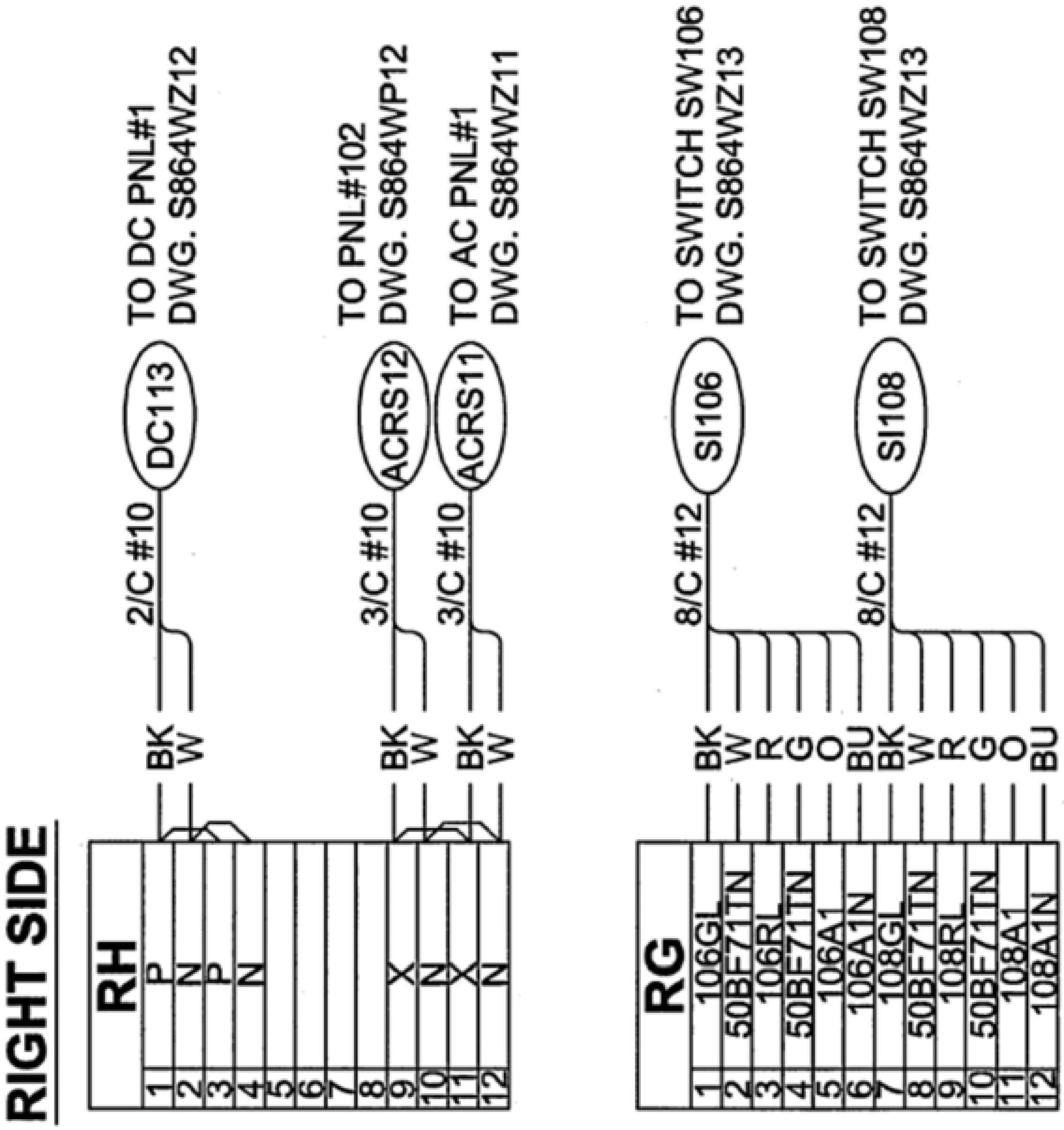
Cable List



Cables No.	From	To	Cond.	Long.	App.	Routing	Type
ACRS11	Panel #101	AC Panel#1	3/C #10	50'	AC		SRN2
ACRS12	Panel #101	Panel #102	3/C #10	30'	AC		SRN2
ACRS13	Panel #102	Panel #103	3/C #10	30'	AC		SRN2
ACRS14	Panel #103	Panel #104	3/C #10	30'	AC		SRN2
ACRS21	Panel #201	AC Panel#2	3/C #10	50'	AC		SRN2
ACRS22	Panel #201	Panel #202	3/C #10	30'	AC		SRN2
ACRS23	Panel #204	Panel #203	3/C #10	30'	AC		SRN2
ACRS24	Panel #202	Panel #204	3/C #10	30'	AC		SRN2
	ANNUNCIATOR	PULEO RTU		2	COMM.		PULEO 413-25MM-5-T2
	SEL-2407	SEL-2030		5'	IRIG-B		C953
	SEL-2407	Panel #205 RTU		30'	IRIG-B		C953
	SEL-2407	GPS ANTENNA		150'	GPS		C960
SEL111	SEL-3332	SEL-387 (Panel #101)		70'	COMM.		SEL-C273A
SEL112	SEL-3332	SEL-351S (Panel #101)		70'	COMM.		SEL-C273A
SEL121	SEL-3332	SEL-311L (Panel #102)		70'	COMM.		SEL-C273A
SEL122	SEL-3332	SEL-311C (Panel #102)		70'	COMM.		SEL-C273A
SEL123	SEL-3332	SEL-351S (Panel #102)		70'	COMM.		SEL-C273A
SEL131	SEL-3332	SEL-387 (Panel #103)		70'	COMM.		SEL-C273A
SEL132	SEL-3332	SEL-351S (Panel #103)		70'	COMM.		SEL-C273A
SEL141	SEL-3332	SEL-387 (Panel #104)		70'	COMM.		SEL-C273A
SEL142	SEL-3332	SEL-351S (Panel #104)		70'	COMM.		SEL-C273A
SEL211	SEL-3332	SEL-387 (Panel #201)		40'	COMM.		SEL-C273A
SEL212	SEL-3332	SEL-351S (Panel #201)		40'	COMM.		SEL-C273A
SEL221	SEL-3332	SEL-311L (Panel #202)		30'	COMM.		SEL-C273A
SEL222	SEL-3332	SEL-311C (Panel #202)		30'	COMM.		SEL-C273A
SEL223	SEL-3332	SEL-351S (Panel #202)		30'	COMM.		SEL-C273A
FO121	SEL-311L (Panel #102)	FO Splice Case (GRDA 1 line)	1/C	340'	COMM.		FIB3
FO221	SEL-311L (Panel #202)	FO Splice Case (MAID 117 line)	1/C	360'	COMM.		FIB3


AC PANEL #1
1-PHASE, 3-WIRE
120/240V AC
SPARE
SPARE
1
2
3
4
5
6
7
8
9
10
11
12
GFI RECEPTACLE
20A
13
14
20A
BK
3/C #10
ACRS11
N.B.
W
TO PNL#101
RECEPTACLE STRIP
DWG. S864WP11
RECEPTACLE
20A
15
16
20A
INTERIOR LIGHTS
EXTERIOR LIGHT
20A
17
18
20A
RECEPTACLE
TO YARD LIGHTS
#1 ~ #4
ACYL1
3/C #10
W
N.B.
BK
20A
19
20
20A
EXHAUST FAN
SMOKE DETECTOR
20A
21
22
20A
TO YARD LIGHTS
#5 ~ #8
ACYL3
3/C #10
W
N.B.
BK
20A
23
24
30A
TO MOS 8771M
DWG. S864SP126
S864WC12
AC122
3/C #10
W
N.B.
BK
20A
25
26
SPARE
TO BKR 8770
DWG. S864SP125
S864WB12
AC121
4/C #8
W
N.B.
R
BK
30A
27
28
30A
29
30
TO BKR 72T
DWG. S864SP134
S864WB13
AC131
4/C #8
W
N.B.
R
BK
30A
31
32
30A
33
34
R
BK
4/C #8
W
N.B.
AC141
TO BKR 73
DWG. S864SP144
S864WB14
240VAC EXTERIOR
SINGLE RECEPTACLE #1
30A
35
36
30A
37
38
240VAC EXTERIOR
SINGLE RECEPTACLE #2
HVAC #1
40A
39
40
40A
41
42
SPARE
X
Y
N
MAIN
225A

Cable List


RIGHT SIDE
RH
1 P
2 N
3 P
4 N
5
6
7
8
9 X
10 N
11 X
12 N
BK
W
2/C #10
DC113
TO DC PNL#1
DWG. S864WZ12
BK
W
3/C #10
ACRS12
TO PNL#102
DWG. S864WP12
BK
W
3/C #10
ACRS11
TO AC PNL#1
DWG. S864WZ11
RG
1 106GL
2 50BF71TN
3 106RL
4 50BF71TN
5 106A1
6 106A1N
7 108GL
8 50BF71TN
9 108RL
10 50BF71TN
11 108A1
12 108A1N
BK
W
R
G
O
BU
8/C #12
SI106
TO SWITCH SW106
DWG. S864WZ13
BK
W
R
G
O
BU
8/C #12
SI108
TO SWITCH SW108
DWG. S864WZ13

300V Communication Cable

A Bare Stranded Copper Conductor

B Okoseal Insulation

C Twisted Pair/Triad

D Aluminum/Synthetic Polymer Tape

E Tinned Stranded Copper Drain Wire

F Rip Cord

G Black Okoseal Jacket

Specifications

Conductors: Bare soft annealed copper, Class B, 7-strand concentric per ASTM B-8.

Insulation: Flame-retardant Okoseal® (PVC) per UL 13 and UL 2250, 15 mils nominal thickness, 105°C temperature rating.

Conductor Identification: Pigmented black and white in pairs, black, red and white in triads.

Assembly: Pair or triad assembled with left-hand lay.

Cable Shield: Aluminum/synthetic polymer tape overlapped to provide 100% coverage, and a 7-strand tinned copper drain wire, same size as conductor.

Jacket: Black, flame-retardant, low temperature Okoseal per UL 13 and UL 2250. A rip cord is laid longitudinally under the jacket to facilitate removal.

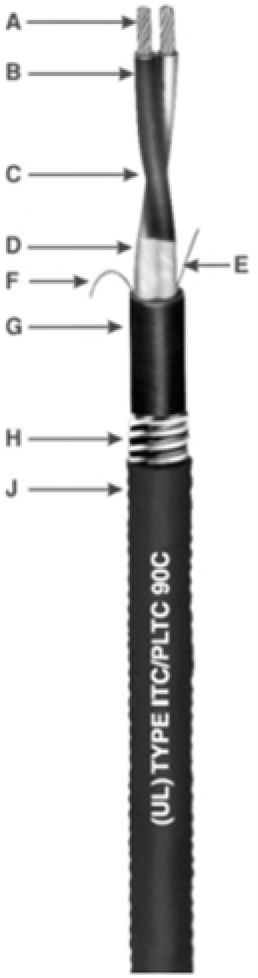
Classifications

UL Listed as ITC/PLTC — Instrument Tray Cable/Power Limited Tray Cable for use in accordance with Article 727 and Article 725 of the National Electrical Code.

The overall shield eliminates most of the static interference from the electric field radiated by power cables and other electrical equipment.

For dc service in wet locations, X-Olene® insulation is recommended.

300V Communication Cable - Pt1



A Bare Stranded Copper Conductor
B X-olene Insulation
C Twisted Pair/Triad
D Aluminum/Polyester Tape
E Tinned Stranded Copper Drain Wire
F Rip Cord
G Inner Black Okoseal Jacket
H Impervious, Continuous Corrugated Aluminum C-L-X Sheath
J Outer Black Okoseal Jacket

Specifications
Conductors: Bare soft annealed copper, Class B, 7-strand concentric per ASTM B-8.

Insulation: X-Olene (XLP), UL Standard 13 and 2250, 15 mils nominal thickness, 90°C temperature rating.

Conductor Identification: Pigmented black and white in pairs, black, red and white in triads.

Assembly: Pair or triad assembled with left-hand lay.

Communication Wire: 20 AWG solid copper conductor, 15 mils X-Olene, 90°C temperature rating.

Cable Shield: Aluminum/Polyester tape overlapped to provide
100% coverage, and a 7-strand tinned copper drain wire, same size as conductor.

Cont... Over →

300V Communication Cable – Pt2

Inner Jacket: Black, flame-retardant, low temperature Okoseal (PVC) per UL Standard 13 and 2250. A rip cord is laid longitudinally under the jacket to facilitate removal.

C-L-X Sheath: A close-fitting, impervious, continuously welded and corrugated aluminum sheath provides complete protection against moisture, liquids, and gases, has excellent mechanical strength and provides equipment grounding through the sheath.

Outer Jacket: Black, flame-retardant low temperature Okoseal per UL Standard 13 and 2250.

Classifications
UL Listed as ITC/PLTC — Instrument Tray Cable/Power Limited Tray Cable for use in accordance with Article 727 and Article 725 of the National Electrical Code.

These cables comply with UL 2250 and UL Standard 13 for PLTC, CL2 and CL3.

Applications
Okonite Type C-L-X P-OS (Pair/Triad - Overall Shield) instrumentation cables are designed for use as instrumentation, process control, and computer cables in ITC non-classified or labeled circuits up to 150 volts and 5 amps (750VA) and in Class 2 or 3 Power-Limited circuits where shielding against external interference is required, but shielding against interference among groups is not required; indoors or outdoors; in wet or dry locations with conductor operating temperatures up to 90°C; in cable trays; in raceways; supported by a messenger wire; under raised floors; for direct burial. Suitable Class I, Division 2, Class II, Division 2, or Class III, Division 2 hazardous locations. Also for use as Power-Limited fire protective signaling cable (FPL) per NEC Code 760.

The C-L-X sheath provides physical protection against mechanical damage. It may be installed in both exposed and concealed work, secured to supports not greater than 6 feet apart.

Raceways

There are several basic raceway methods

1. Direct buried cables encased in select back-fill
2. Conduit encased in select back-fill
3. Conduit encased in concrete
3. Concrete trench

The function of the raceway is to protect the cable as it travels from the panel through the control building, across the yard and up the equipment to the junction box. Therefore, the raceway can be the panduit, tray, conduit and flex.

Raceways

- Direct buried

  Direct buried is the cheapest method of routing cable between two points. You dig a trench, toss in or layer in the cables, add a tracer tape on top, and fill up the trench with selected back-fill –or not. But there are heavy drawbacks.

  a. Lack of flexibility to add or remove cable
  b. Lack of ability to access the cable if a problem happens
  c. Very risky to dig up the trench to add or remove cables
  d. Location drawings are usually not accurate

  This is not a recommended way to do business, unless the client specifically requests it.

Raceways

- Conduit encased in select back-fill

  This a better than direct buried but not as expensive as using concrete. You dig a trench, install the conduits using spacers, pour select back-fill or sand, add a tracer tape on top, and fill up the trench with selected back-fill –or not.

  Usually there is a main raceway that leaves the control building running through the yard. Throughout the length of the raceway conduits peal off to their respective equipment. The conduits that peal off are still encased in select back-fill

  a. This is a good design

  b. Need to install spare conduits of the right size

  c. May need man-holes depending on layout

Raceways

- Conduit encased in concrete

  This a much better way to do business but it is also the most expensive. You dig a trench, install the conduits using spacers, pour red concrete, add a tracer tape on top, and fill up the trench with selected back-fill –or not.

  Usually there is a main duct bank that leaves the control building running through the yard. Throughout the length of the duct bank conduits peal off to their respective equipment. The conduits that peal off are still encased in concrete.

  a. This is a robust design
  b. Need to install spare conduits of the right size
  c. May need man-holes depending on layout

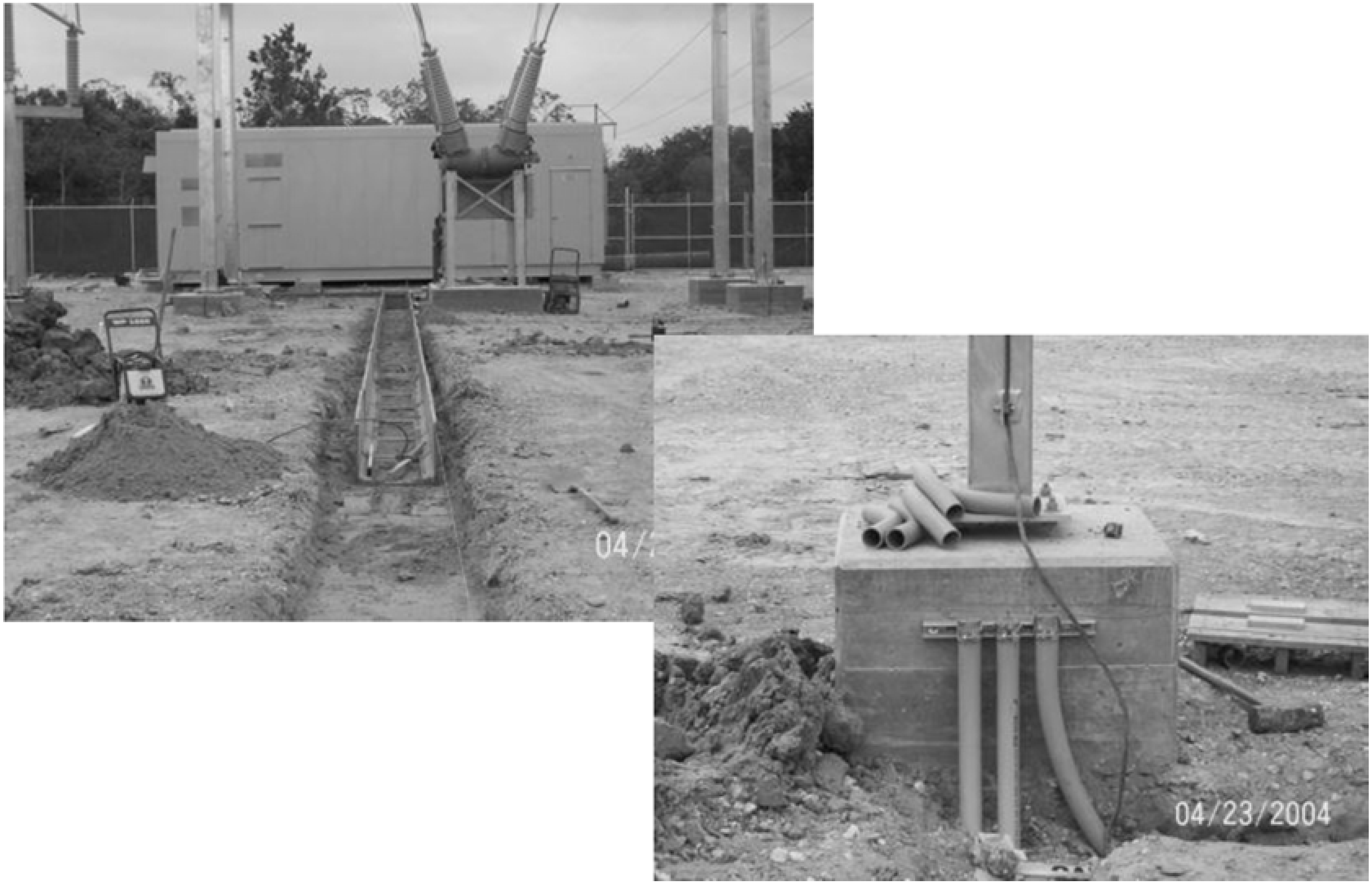
Raceways

Concrete trench

Raceways are better than direct buried, cheaper than duct banks, and more flexible than both. You dig a trench, install the concrete trench, back-fill about the trench with selected back-fill –or not, install the cables and put the lids on.

This photo illustrates a pedestrian trench & road crossing with steel checker plate lids

Raceways



Raceways

Raceways

The Field End

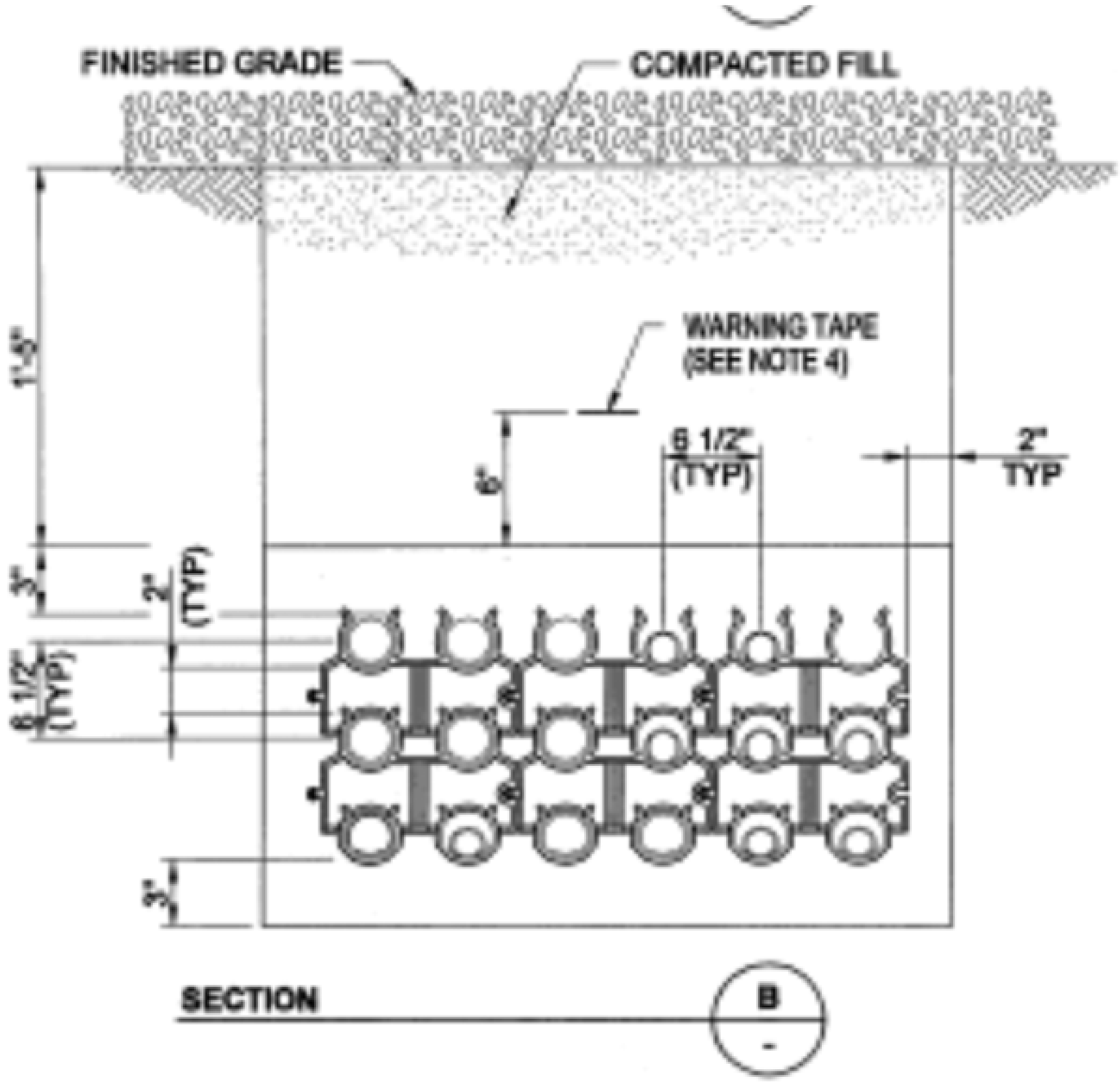
The CVT JB is a classic installation of the three CVT’s coming into the JB and the one main conduit out of the JB.

Raceways

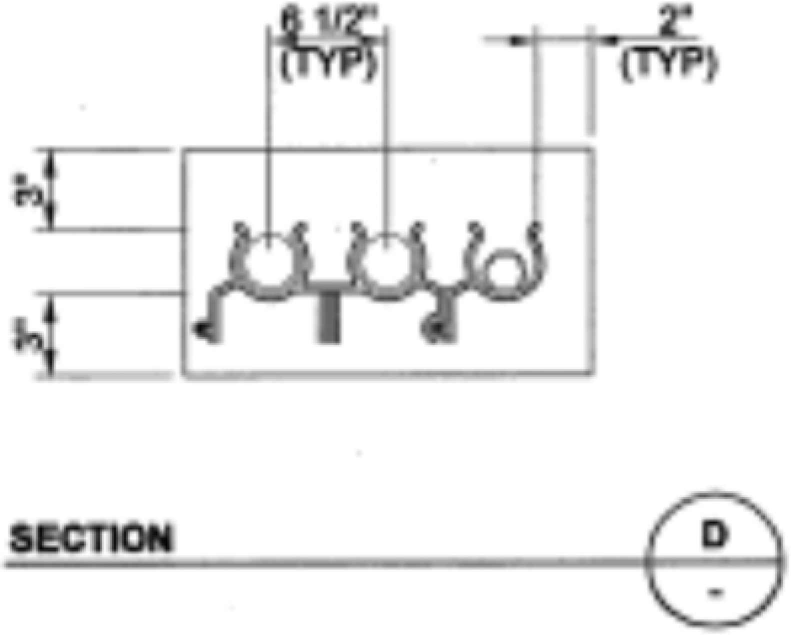
Control Room End

Overhead tray protecting the cables before they drop into the relay panels.

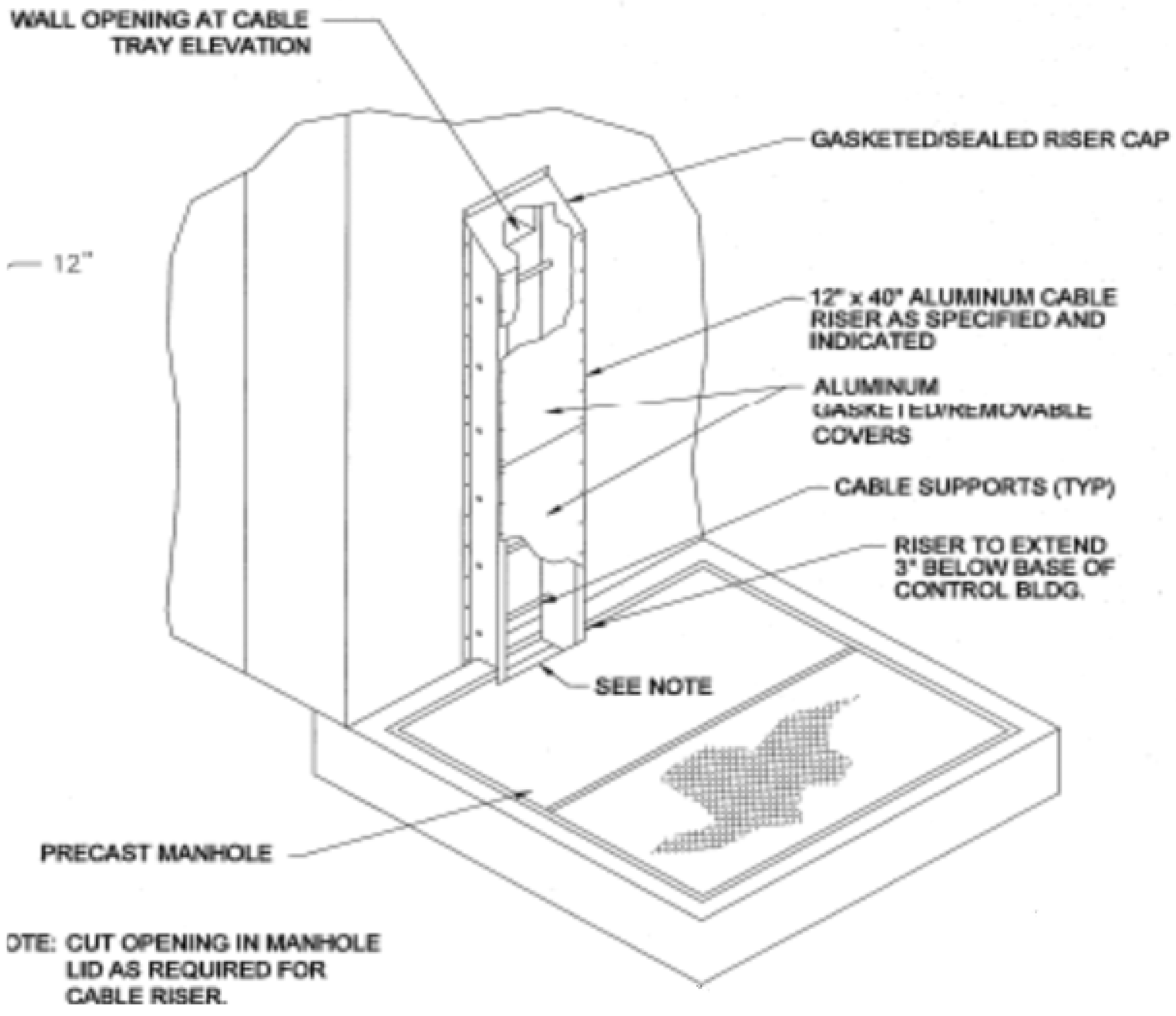
Raceways


FINISHED GRADE
COMPACTED FILL
WARNING TAPE
(SEE NOTE 4)
6 1/2"
(TYP)
2"
TYP
1'-5"
6"
3"
2"
(TYP)
6 1/2"
(TYP)
3"
SECTION
B
-

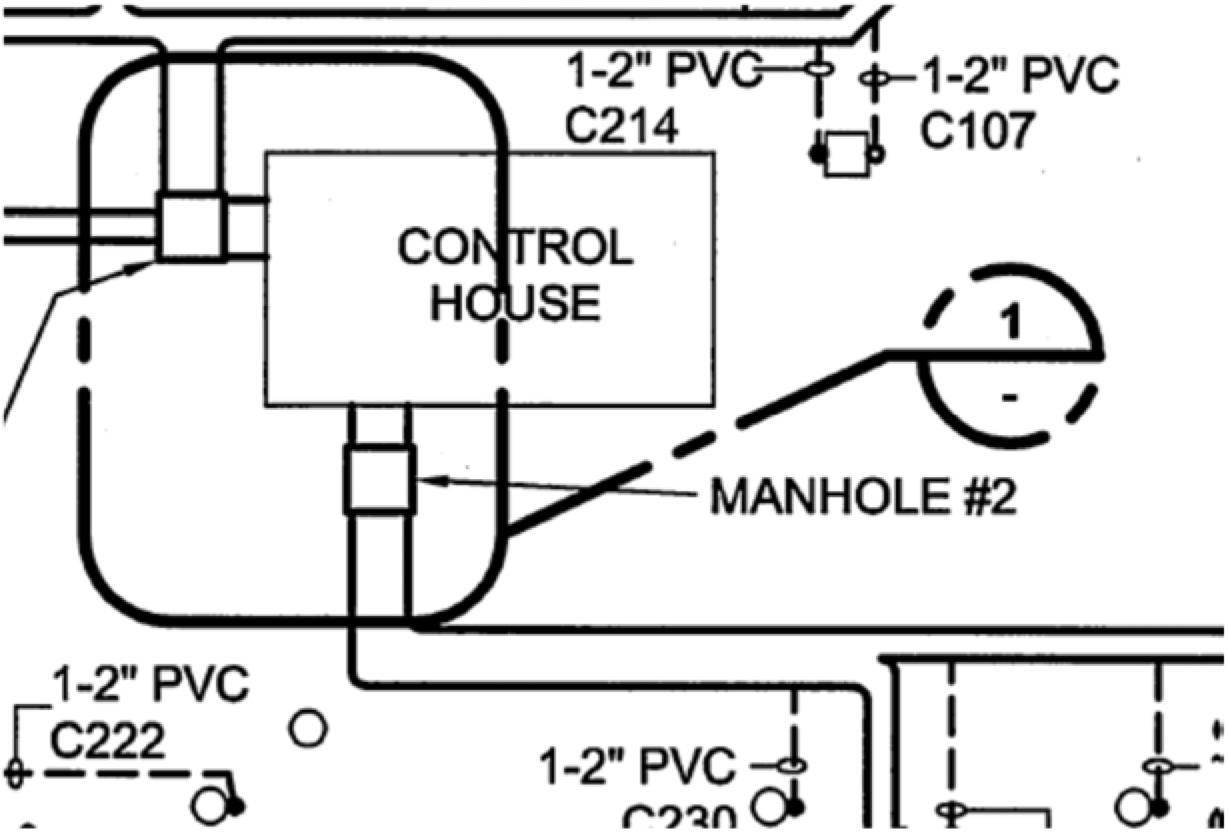
Raceways

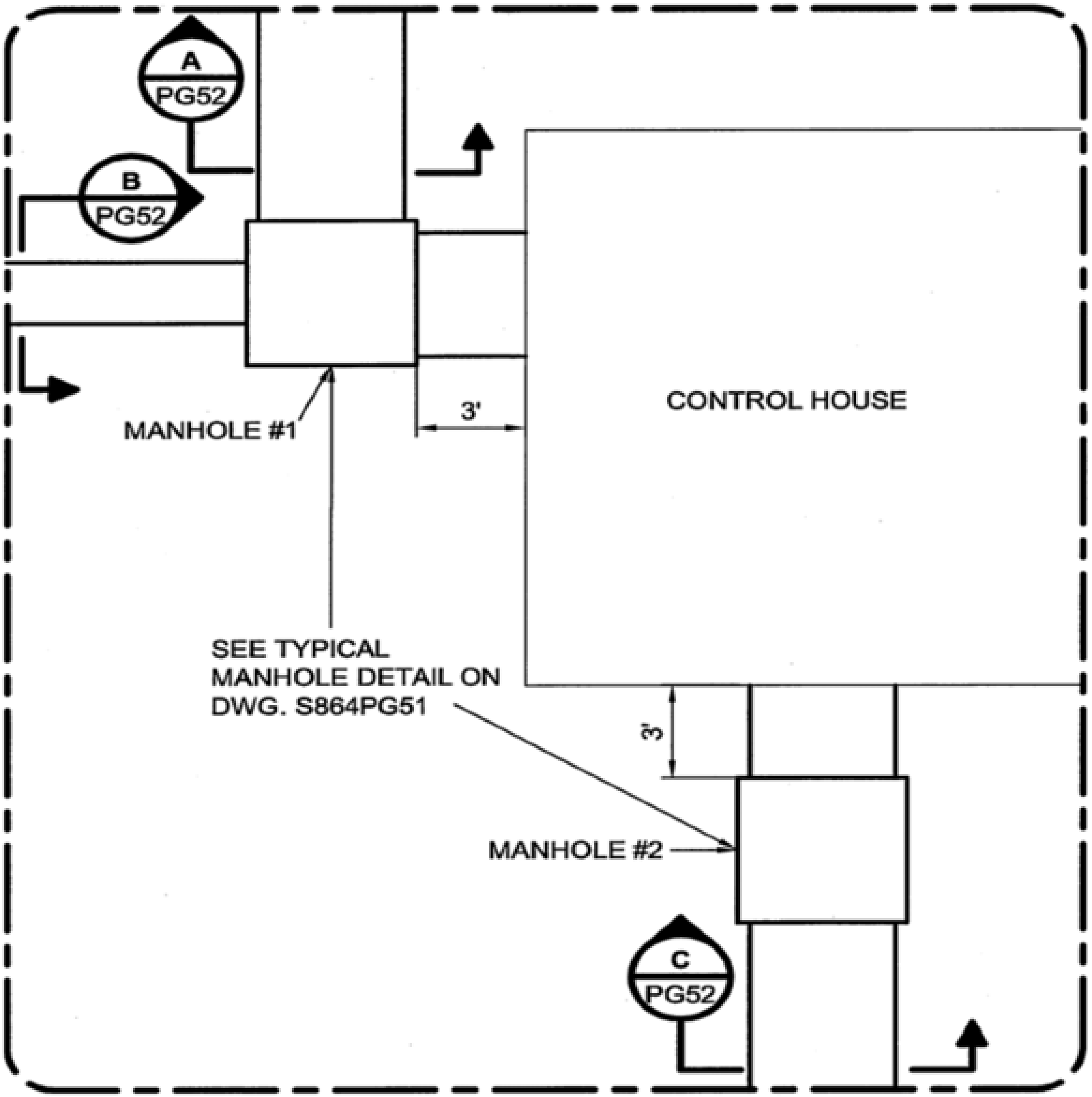


Raceways


WALL OPENING AT CABLE TRAY ELEVATION
GASKETED/SEALED RISER CAP
12"
12" x 40" ALUMINUM CABLE RISER AS SPECIFIED AND INDICATED
ALUMINUM GASKETED/REMOVABLE COVERS
CABLE SUPPORTS (TYP)
RISER TO EXTEND 3" BELOW BASE OF CONTROL BLDG.
SEE NOTE
PRECAST MANHOLE
OTE: CUT OPENING IN MANHOLE LID AS REQUIRED FOR CABLE RISER.

Raceways


1-2" PVC
C214
1-2" PVC
C107
CONTROL
HOUSE
1
-
MANHOLE #2
1-2" PVC
C222
1-2" PVC
C230

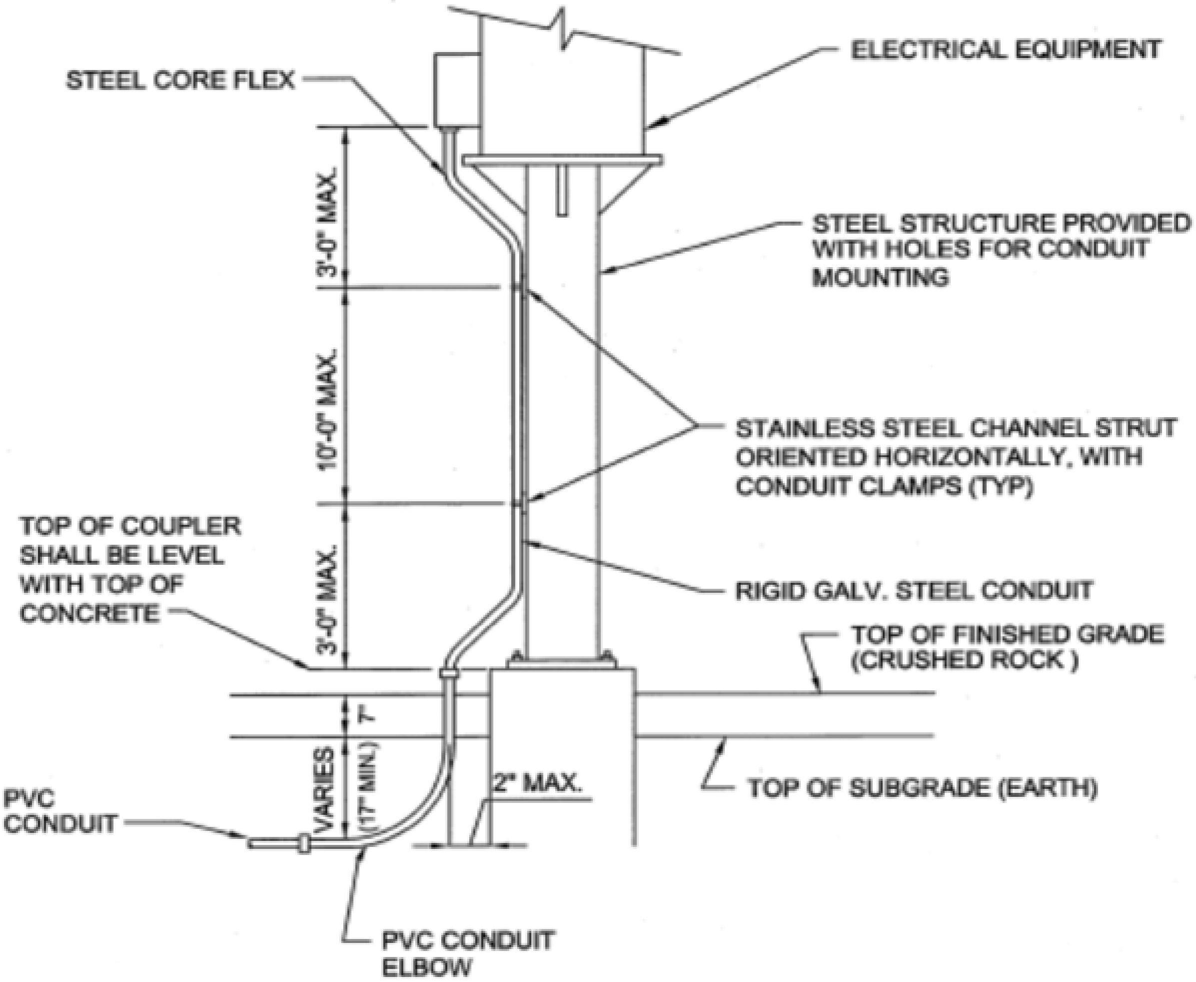


DETAIL 1 -

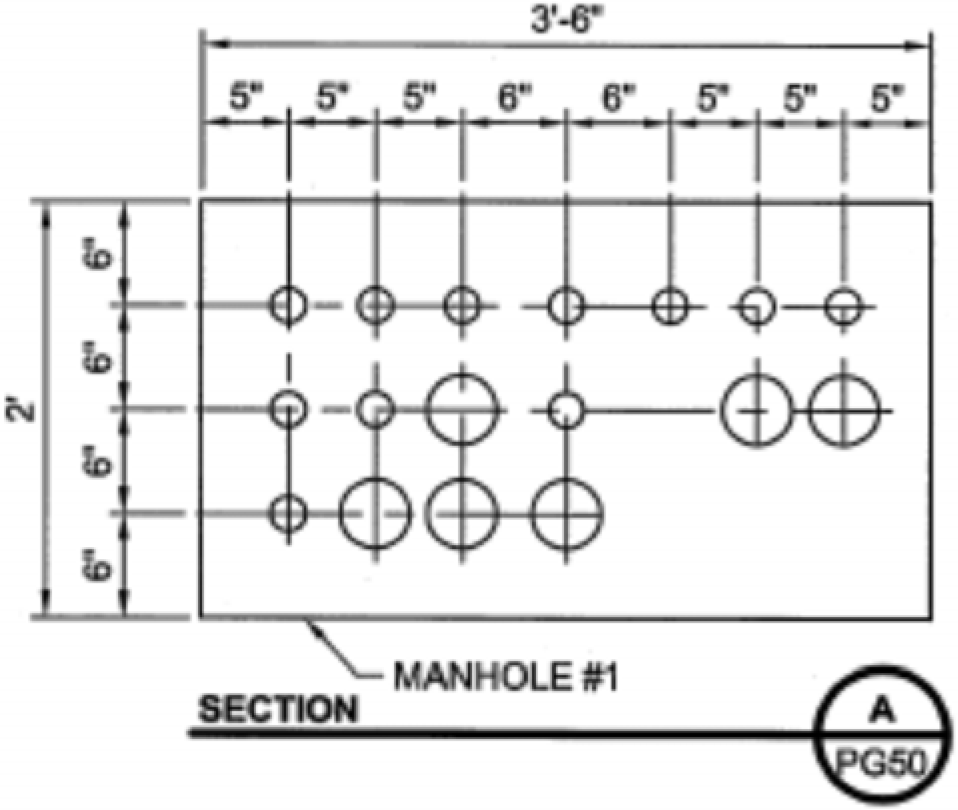
NOT TO SCALE

TYPICAL CONDUIT RISER

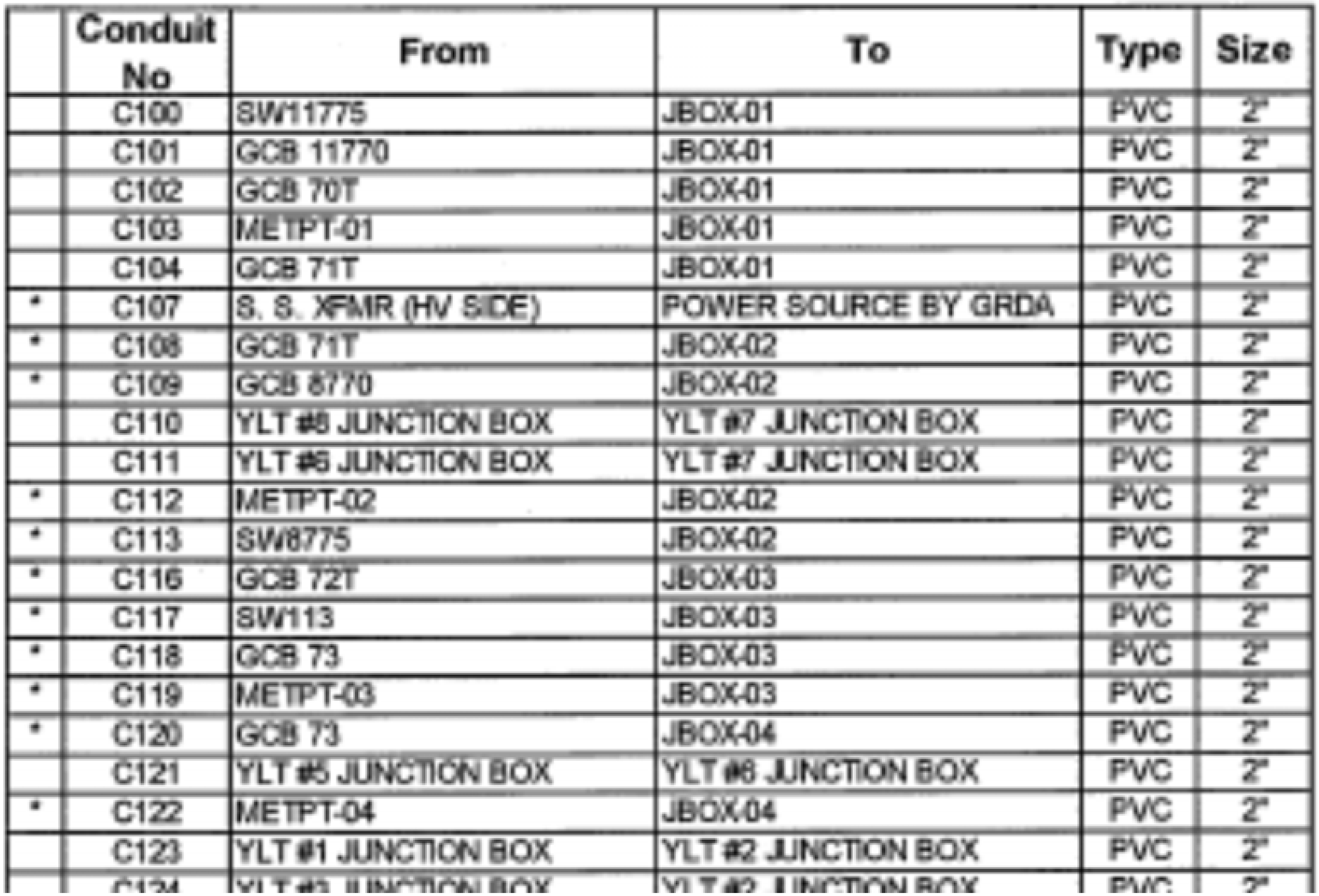
NOT TO SCALE



Raceways



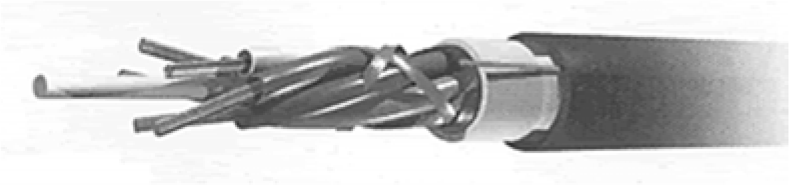
Raceways



	Conduit No	From	To	Type	Size
	C100	SW11775	JBOX-01	PVC	2"
	C101	GCB 11770	JBOX-01	PVC	2"
	C102	GCB 70T	JBOX-01	PVC	2"
	C103	METPT-01	JBOX-01	PVC	2"
	C104	GCB 71T	JBOX-01	PVC	2"
*	C107	S. S. XFMR (HV SIDE)	POWER SOURCE BY GRDA	PVC	2"
*	C108	GCB 71T	JBOX-02	PVC	2"
*	C109	GCB 8770	JBOX-02	PVC	2"
	C110	YLT #6 JUNCTION BOX	YLT #7 JUNCTION BOX	PVC	2"
	C111	YLT #6 JUNCTION BOX	YLT #7 JUNCTION BOX	PVC	2"
*	C112	METPT-02	JBOX-02	PVC	2"
*	C113	SW8775	JBOX-02	PVC	2"
*	C116	GCB 72T	JBOX-03	PVC	2"
*	C117	SW113	JBOX-03	PVC	2"
*	C118	GCB 73	JBOX-03	PVC	2"
*	C119	METPT-03	JBOX-03	PVC	2"
*	C120	GCB 73	JBOX-04	PVC	2"
	C121	YLT #5 JUNCTION BOX	YLT #6 JUNCTION BOX	PVC	2"
*	C122	METPT-04	JBOX-04	PVC	2"
	C123	YLT #1 JUNCTION BOX	YLT #2 JUNCTION BOX	PVC	2"
	C124	YLT #3 JUNCTION BOX	YLT #2 JUNCTION BOX	PVC	2"

Fiber Cable

ADSS MINI-SPAN® Series 484 Fiber



Fiber cable is used for communication between substations and back to the control center. The incoming cable interfaces with the substation fiber cable at the bottom of the incoming pole. Then the substation fiber cable is routed to the substation control building.

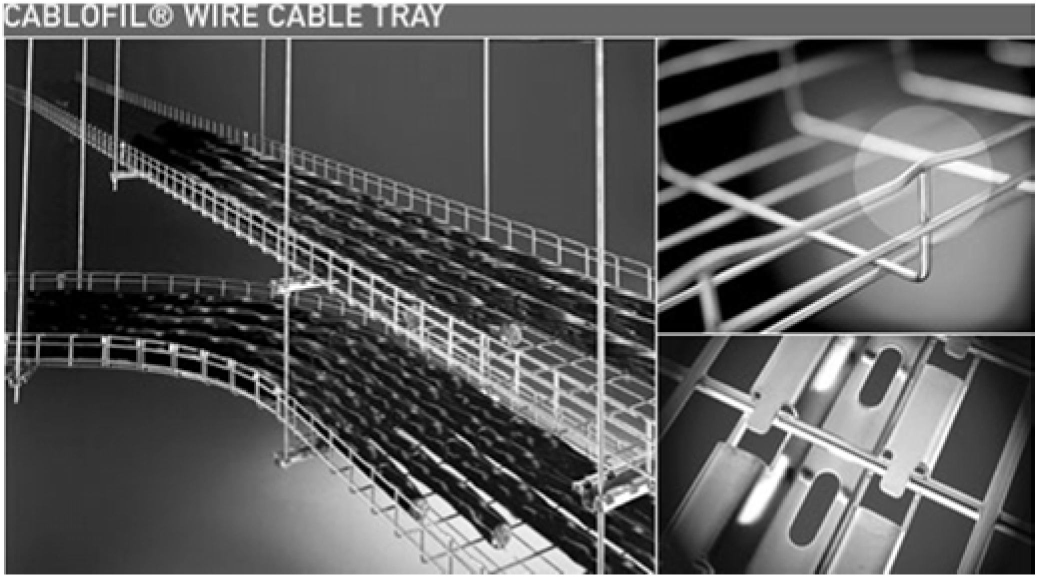
Fiber Cable

Cable Tray

- Article 392 – Cable Trays (Ampacity, Cable fill, Installation, Supports, grounding, separation of trays, uses not permitted and uses permitted.
- NEMA – VE1, FG1, VE2 and CTI – Cable Tray Institute

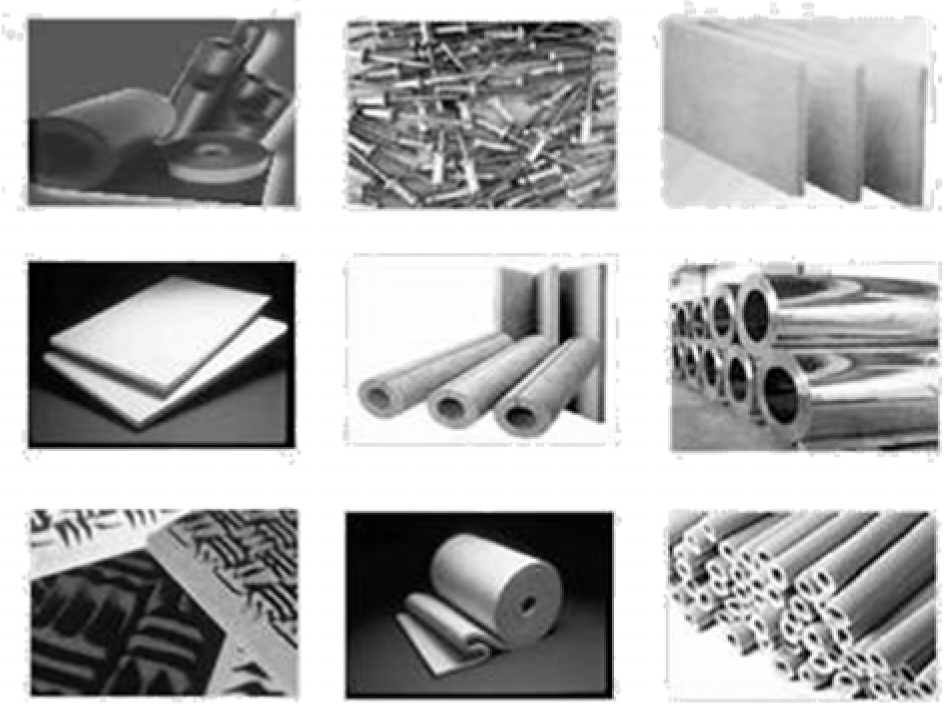
Cable Tray

Definition: A unit or assembly of units or sections and associated fittings forming a ridge structural system used to securely fasten or support cables and raceways. Cable trays are used to hold up and distribute cables



Materials Used

- Steel
- Stainless Steel
- Aluminum
- Fiberglass



Standard Length.

10’,12’,20’,& 24’

Rung Spacing

6”,9”,12” & 18”

Different Widths of Cable Tray

6”,9”,12”,18”,24”,30”,36”

Different Depths of Cable Tray

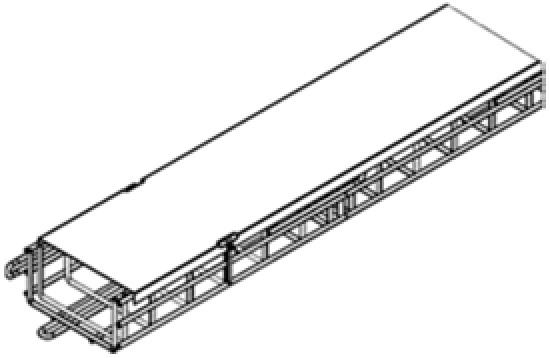
3”,4”,5”,6”,7”,8”

Different Types of Cable Tray

- Wire Basket
- Ladder-Different Variation of rung spacing
- Ventilated Trough. Non ventilated trough
- Solid
- Center Rail system

Different Types of Cable Tray Covers

- Solid Flat
- Solid Flanged
- Ventilated Flanged
- Peak Flanged
- Pitch Peak Flanged



Loads on cable Tray

- Wind
- Snow & Ice
- Seismic
- Concentrated loads converted to uniform load

Supporting Cable Tray

- Purlin, beam
- Pipe Rack
- Strut & threaded rod (trapeze)
- Custom Supports shop or field fabricated
- Adding support to existing system vs Heavier cable tray
- (Build 50 supports vs specifying Heavier tray)

Factors for selecting correct Cable Tray

- Inside bending radius minimum
- Spans
- Client Standards
- Fiberglass instead of steel or aluminum because of environment
- Weight of cable in tray
- Power vs Instrument cable
- Weight of cable & tray vs. Span Distance
- Type of cable being routed in the tray

Cost Comparison of cable tray vs. conduit

It costs the same amount of money to install 2-2” RGS conduits as is cost to install a 24” wide Cable tray

Fittings

There is a wide variety of fittings for cable tray.

Not all types of cable tray carry all of the same fittings. Don’t take this for granted, go and look up the parts you need to design your tray system.

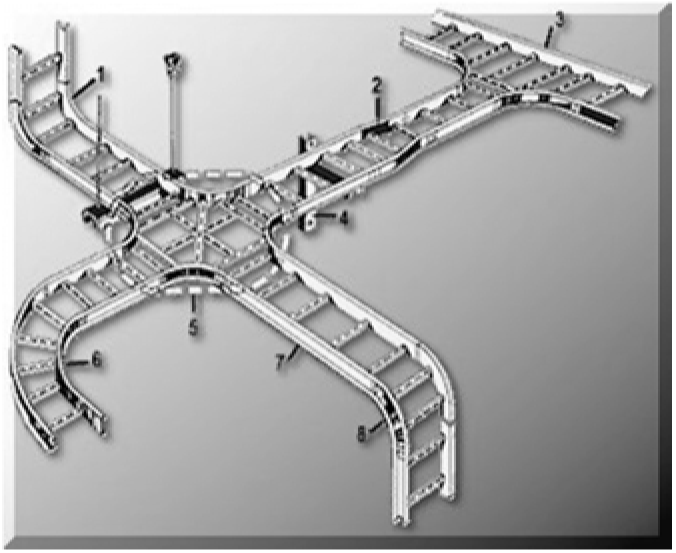
Design Cost Savings

- Save money and manpower Now & Later
- Requires less space
- Material cost savings-Installation
- Manpower savings – Installation
- Maintenance Savings – Less down time to possible no down time
- Enter & exit cable tray anywhere along the tray route

<u>Cost Factors</u>

- Less cable pulling cost
- Cheaper than conduit installation

Cable tray in some situations is not always the best solution, but most of the time it is.



Outdoor cable Tray

- Consider tray covers & clamps
- Space available in existing pipe rack
- Space available & location on new rack
- Clients specifications and minimum space allowances
- Cable identified as being sunlight resistant

Cable Tray Ground

Usually a bare cable or covered, is installed in the tray & secured to each section of tray as a continuous ground conductor

Cable Trays in Hazardous classified areas

Shall only contain certain permitted cable types

Cable Tray Code Issues

Article 500 – Classified areas
Article 392 – Cable Trays (Ampacity, Cable fill, Installation, Supports, grounding, separation of trays, uses not permitted and uses permitted.
Article 250 – Grounding and Bonding
NEMA – VE1, FG1, VE2 and CTI – Cable Tray Institute

Construction Checks and Quality Inspection Record

UNIT/LOCATION:________________________________
DRAWING NO:__________________________________ REVISION NO_______________

CABLE TRAY INSPECTION CHECKLIST

	DFD ENG / DATE		
1. Tray size in accordance with drawings.			
2. Expansion joints properly installed.			
3. All braces and supports located in accordance with drawings.			
4. Hold-downs properly installed. Tray is anchored only in location shown on drawings.			
5. No sharp edges to cut cable. Hardware assembled with bolt heads flush with inside of tray side rail.			
6. All nonconductive coatings removed at splice joints, ensuring continuity of electrical ground path, and fittings designed to make removal unnecessary.			
7. Field bends per modifications continue to provide electrical ground path and proper support for cables.			
8. Bonding jumpers installed in accordance with drawings.			
9. No obstruction to pulling cable.			
10. Tray grounded per drawings.			

Unit/Location ______________________________
Equipment/Tag Number ______________________

CABLE TRAY INSPECTION CHECKLIST

	DFD ENG/Date		
11. Spacing between power and instrument trays in accordance with project specifications.			
12. Spacing from hot (insulated) pipes in accordance with project specifications.			
13. All covers, fire stops, and partitions installed			
14. Correct metal dropouts installed for all cables exiting bottom of trays			
15. Any removal of supports, or loosening of hardware caused by cable pulling procedures is restored or corrected			

Inspection Completed and Accepted

ENG/ Date ____________________________________

Ductbank Definition:

A tube, pipe or channel for carrying electrical current carrying conductors.

Considerations Before Starting to Design a Ductbank

- Cost of above grade vs. below grade
- Soil Conditions
- Ground Contamination of Soil
- Seismic Zone

- Underground Interferences
- Manhole placement, hand hole placement
- Existing means to get conductors from Point “A” to Point “B”

- Size of overall ductbank
- Length of runs
- Bending Radius

- Conduit Type (RGS,PVC,PVC Coated RGS)
- Depth
- Spare Ducts
- Client Needs

Types of Ductbank

1) Precast Trench

2) Direct Buried

3) Cast in Place

Precast Trench

Trenwa
Tough Enough to Trust

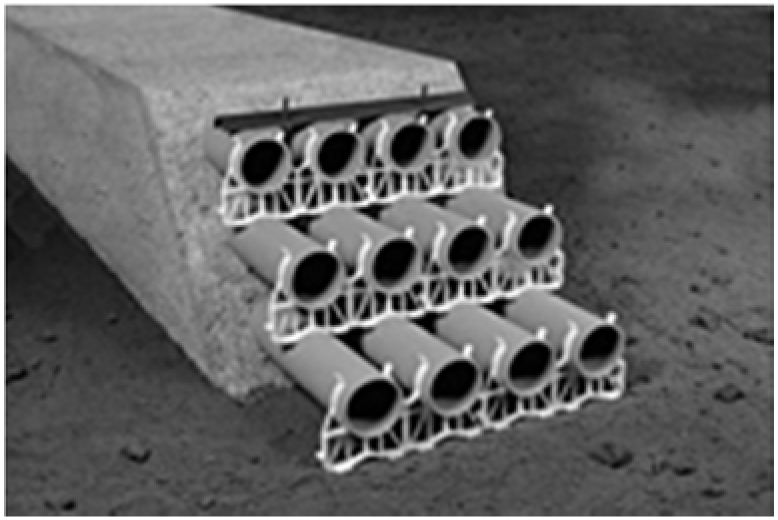
Precast Trench and Other Products

- Excavation is minimal
- Easy to install
- Derating cable necessary
- Cable pulling quick & easy
- Must consult Civil Engineer for drainage concerns
- Adding fixed spacers for more than one row of conductors
- Over/Under areas to keep voltage class separated that cross
- Work with vendor on site lay out

Direct Buried

- No concrete in ductbank but could be over the ductbank for protection
- Spacers 3'-6' on center or sand for spacer
- Backfill with sand /sandy soil mix
- Magnetic tape over top of duct bank 1'-0" below top of grade for warning
- Bury copper ground cable with conductors
- Don’t need man holes or hand holes
- Derating cables necessary

Concrete Encased Ductbank



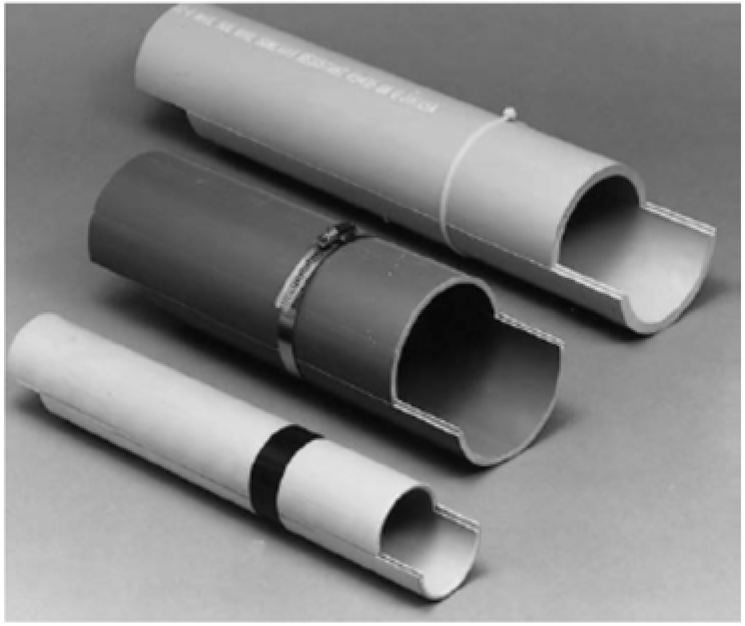
- Spacers 6‘ on center
- Rebar to reinforce & hold ducts down while concrete is poured
- Bare copper ground cable embedded at bottom of duct bank in concrete, usually #4/0 AWG.

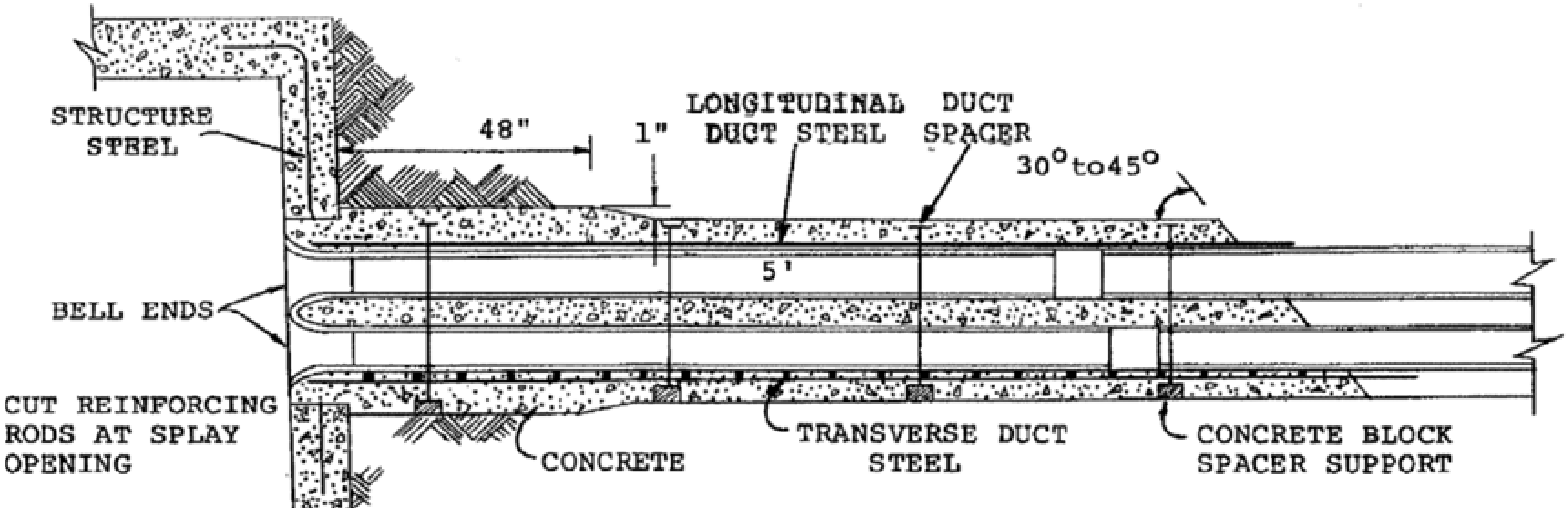
Concrete Encased Ductbank

- Connect ground cables in manhole w/ exothermic weld or certified compression connection
- Red Dye in concrete at top and or magnetic tape for warning

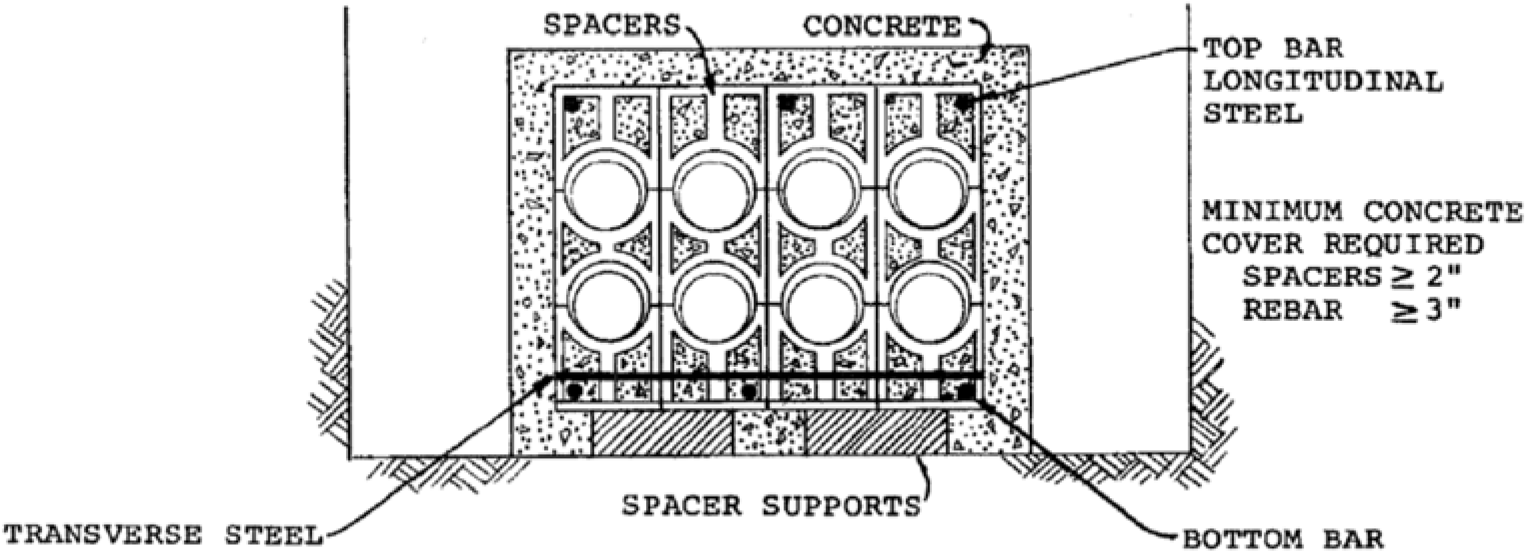
Manhole/ hand holes required

Minimum 3” concrete to cover duct bank on all 4 sides



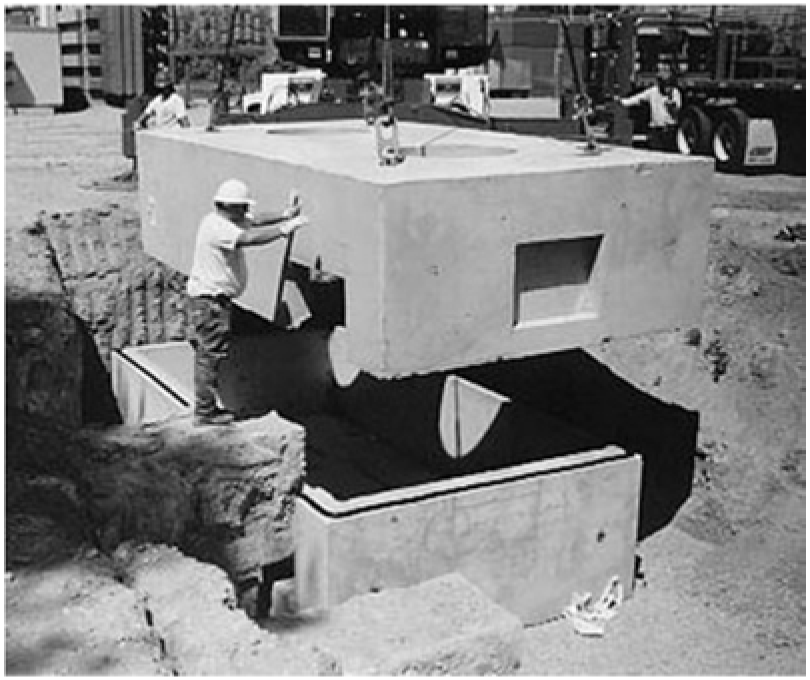


TYPICAL PROFILE SECTION ILLUSTRATING
DUCT TERMINATION & CONSTRUCTION JOINT DETAILS



TYPCIAL CROSS-SECTION ILLUSTRATING
PLACEMENT OF REINFORCING STEEL IN
RELATIONSHIP TO SPACERS

Manholes / Handholes



- Precast & delivered to site
- Cast in place
- Fiberglass handholes or concrete

Manholes / Handholes

- HS20 Cover- Highway rated manhole cover for vehicle traffic

- Coordinate with structural engineers to get the size and thickness of the pulling eyes, sump, rebar, embedded strut, etc. into the manhole

- Duct sealant, bushings at penetrations into the enclosure.

Manholes / Handholes

- Materials shall confirm to ASTM A48 – Standard spec for Gray Iron Castings
- Minimum clear opening through the frame will be 30 inches (man way opening)
- Provide lid lettering “Electric” for power manhole and “Telephone” for communication manhole
- Paint manhole ladder one coat of rust inhibiting primer & two coats of water based alkyd enamel safety yellow

Ductbank Risers

- Change in conduit type PVC to RGS
- Direct buried run thru RGS elbow & riser
- Concrete pad and duct spacing for ground rings and/or end bells

Ductbank Orientation

- High Voltage on top
- Medium Voltage Middle
- Low Voltage Bottom
- Instrumentation/ Control

Notes:

1. Before starting the design of the ductbank it is a good idea to get a site plan drawing and sketch the duct bank where you think it will go with hand holes/manholes. Also, your design will have to be coordinated with ditches, drains, footings, swells, marsh land, pipe racks, buildings, skids, right of ways, etc.

Notes:

2. Derating cable usually increases the size of the cable and causes more ducts to be incorporated into the design

3. Depth and size of ductbank must be coordinated with the structural and civil disciplines

4. NEC Tables for ductbank are based around 20°C earth ambient temperature

Ductbank Penetration Considerations

- Into Manholes
- Into Hand Holes
- Through basement or underground walls coordinate w/ structural for penetration size & details
- Smoke/Fire stop fittings (kits), water tight fittings
- Dimensions to ductbank stub-up from a common point
- Insulated bushings

Minimum Cover Requirements for Direct Buried Ductbank

- In state right of ways the minimum vertical clearance is 36” below top of pavement and 30” below the existing top of grade

- The direct buried ducts shall be no closer than two feet behind the curb and if buried under a sidewalk or bike path the minimum depth is 18” according to the NEC

Minimum Cover Requirements

- The 18” min depth below sidewalks may be reduced 6” for every 2” of concrete or equivalent above the conductors

- Areas subjected to heavy automobile traffic shall have a minimum cover of 24”

Ductbank Alignment:

- PVC Ducbank is flexible during normal weather conditions
- 4” duct can be bent cold to a 20’ radius and a 6” duct can be bent cold to a 40’ radius
- Any shorter radius bends must be done with a duct heater
- This duct shall be placed in spacers 6’ on center

Note

- The deeper the ductbank the wider the cutback needed into the earth

Ductbank Minimum Separations to Other Utilities

Water	36” Horizontal Separation	24” Perpendicular Crossing
Gravity Sewer….......	36” Horizontal Separation	24” Perpendicular Crossing
Force Main Sewer ….	36” Horizontal Separation	24” Perpendicular Crossing
Storm Drain…….	36” Horizontal Separation	24” Perpendicular Crossing
Natural Gas……..	60” Horizontal Separation	24” Perpendicular Crossing
Steam or Hot Water..	60” Horizontal Separation	24” Perpendicular Crossing
Open Communications..	24” Horizontal Separation	12” Perpendicular Crossing
Secure Communications..	36” Horizontal Separation	24” Perpendicular Crossing
Electrical	12” Horizontal Separation	12” Perpendicular Crossing

Code Requirements:

NEC & IEEE C2, NESC, NECA

(ex.) NEC, Article 110 Manholes
NEC, Article 310 Conductors & General Wiring
NEC, Article 725 Class 1, 2, & 3 circuits

*The NEC has no provision for determining the derating effects of multiple duct bank and/or direct buried cables in close proximity. We do have an in-house program that you can use.

Understanding Power Concepts

Part 2

- Electrical Studies
    - One lines
    - SC
    - LF
    - I2T
- Transfer Schemes
- Types of Cables
- ***Feeder Designs***

Feeder Design

- Identify the factors that affect ampacity ratings of conductors.
- Determine the ampacity ratings of conductors.
- Determine the short-circuit rating of conductors.
- Determine the voltage drop of a feeder.
- Identify types of cables.
- Recognize the uses of raceways.
- Select conduit sizes.
- Design feeders.
- Recognize the purpose for using cable trays and busways.

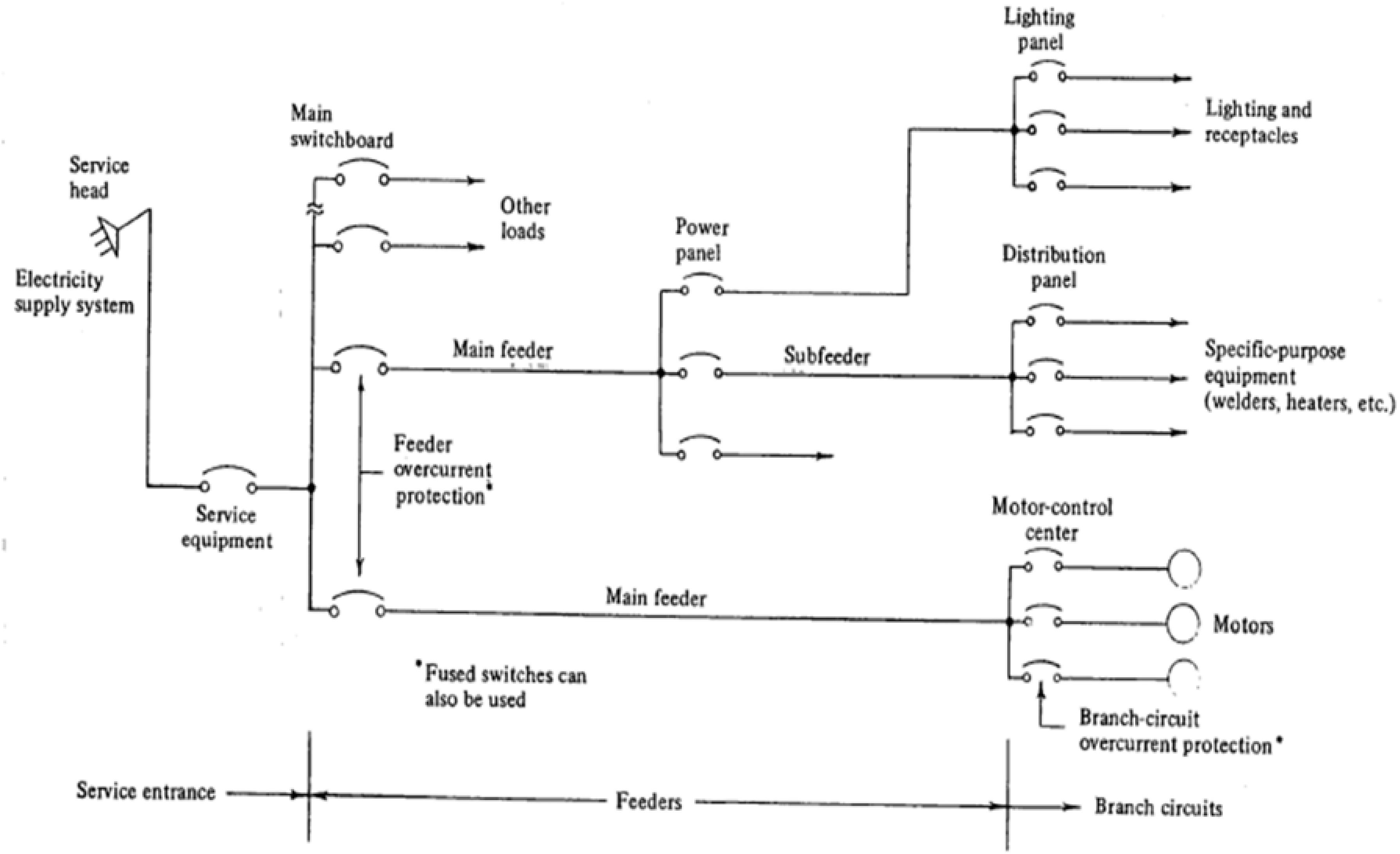
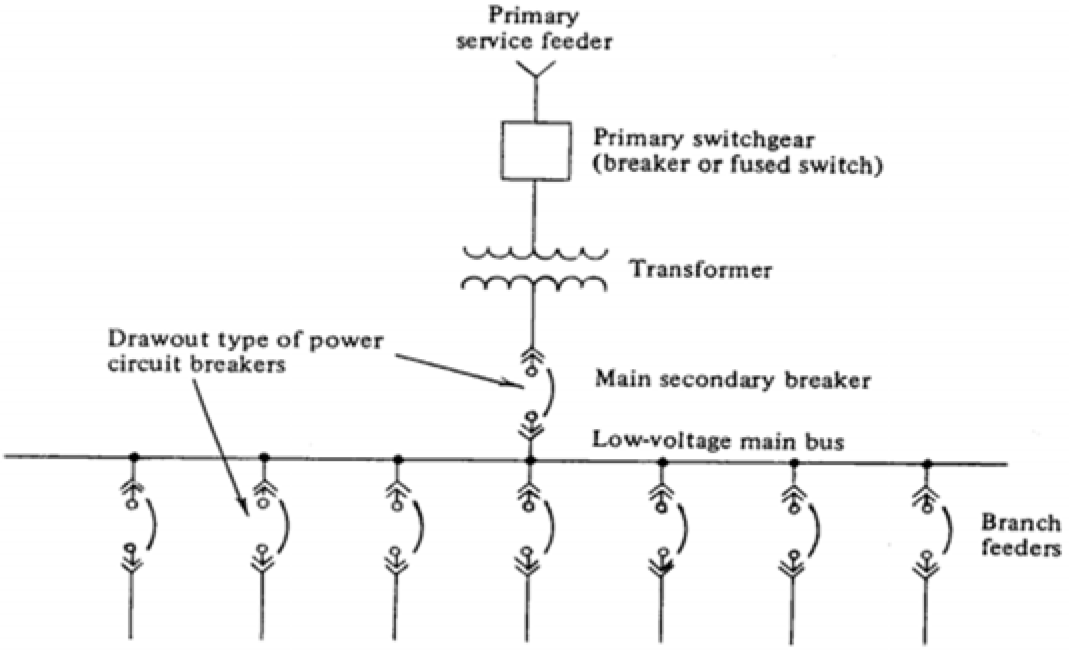


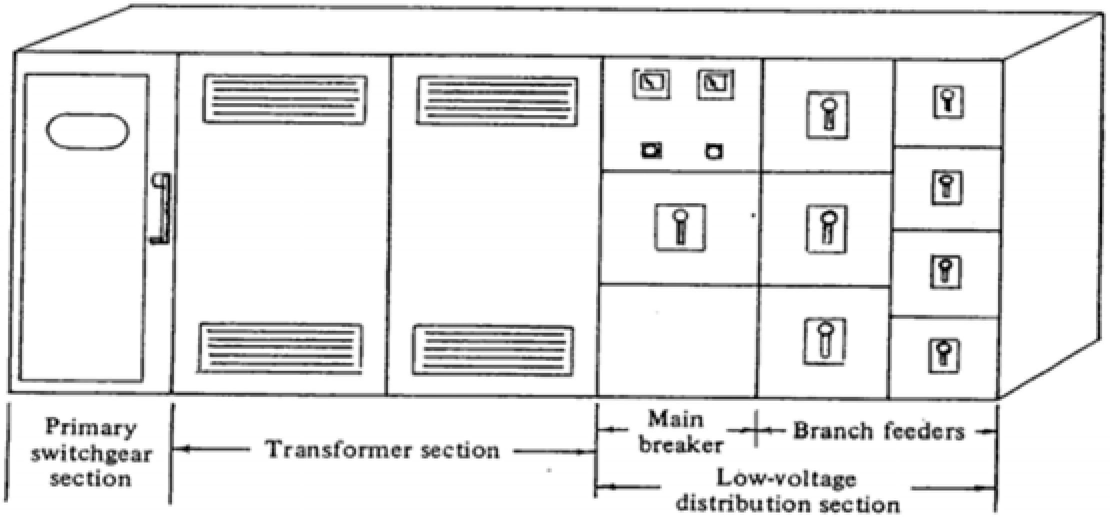
FIGURE 11.1

One-line diagram showing basic system components

Service entrance: These are the conductors for delivering energy from the electricity supply system to the premises being served. The conductors are terminated near their point of entrance into the building in the service equipment. The service equipment is the main control and means of cutoff for the supply. In the case of a large premise, the electric power is usually supplied by the electric utility at a medium-voltage level, requiring a transformer to step down the voltage to the utilization level. The typical one-line diagram for such an arrangement is shown in Figure 15.1.



(a) One-line diagram



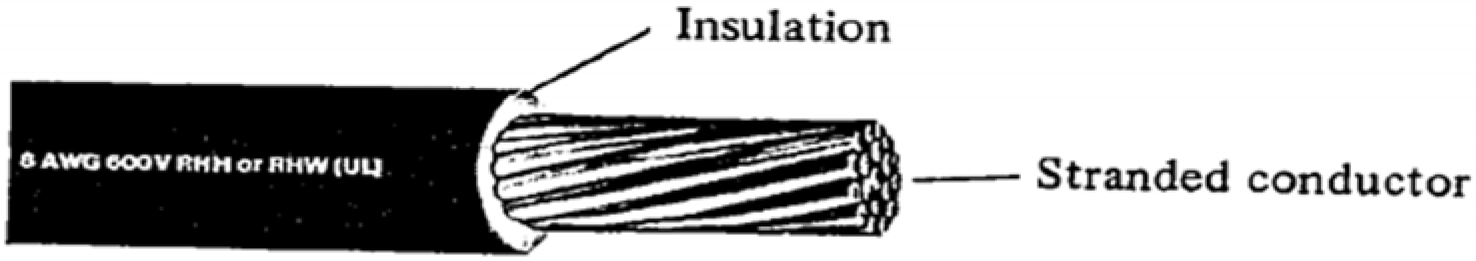
(b) Layout of single-ended unit substation

FIGURE 15.1

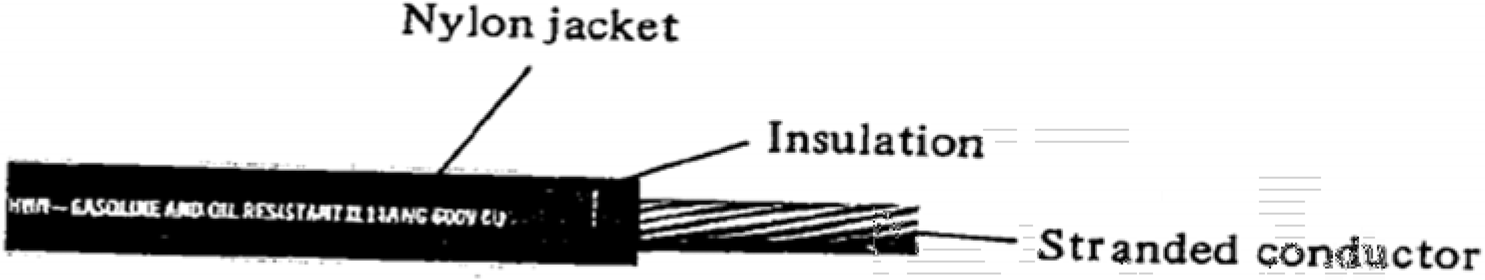
Typical radial system

Feeders: These are the conductors for delivering the energy from the service equipment location to the final branch-circuit overcurrent device protecting each piece of utilization equipment. Main feeders originate at the service equipment location, and subfeeders originate at panelboards or distribution centers at other than the service equipment location.

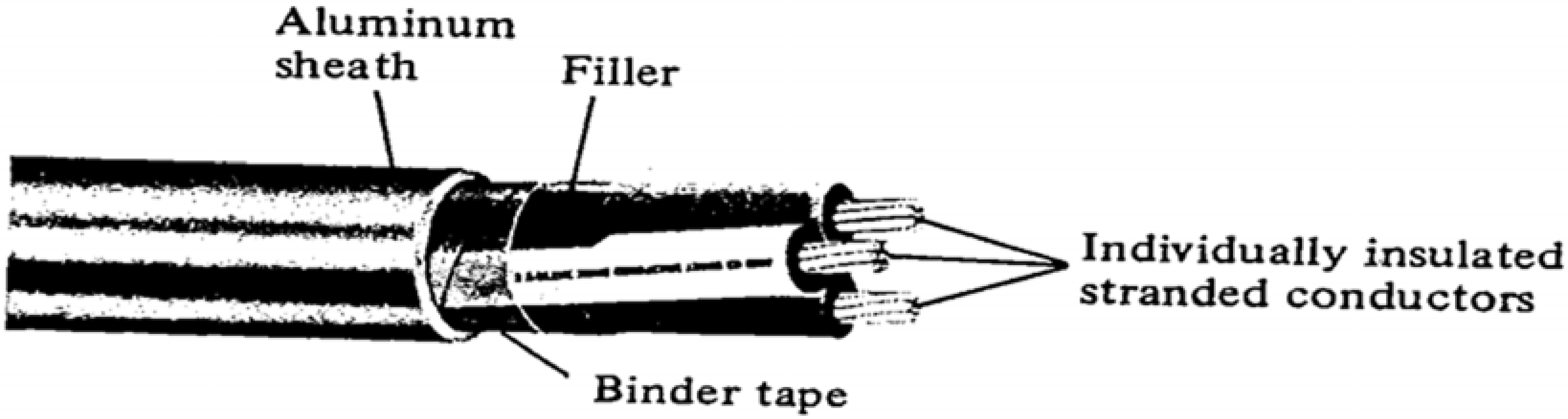
Branch circuits: These are the conductors for delivering the energy from the point of the final overcurrent device to the utilization equipment.



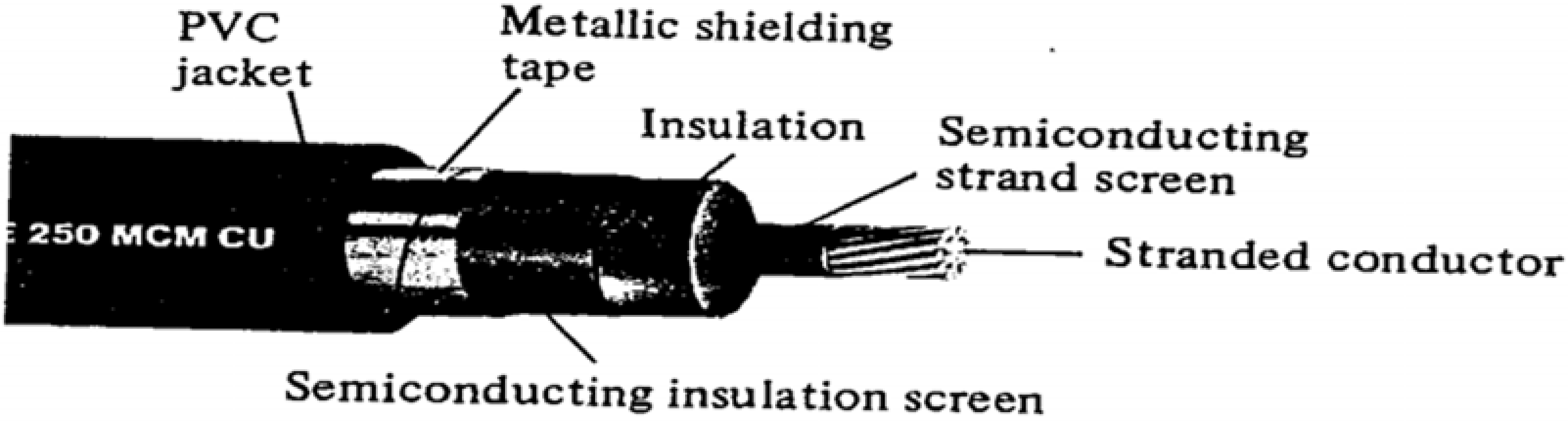
(a) 600 V, single-conductor cable



(b) 600 V, single-conductor cable with jacket



(c) 600 V, three-conductor, metal-clad cable



(d) 5000 V, single-conductor cable

Designing Feeders

- Solve for continuous current
- Solve for short circuit current rating
- Maximum allowable voltage drop

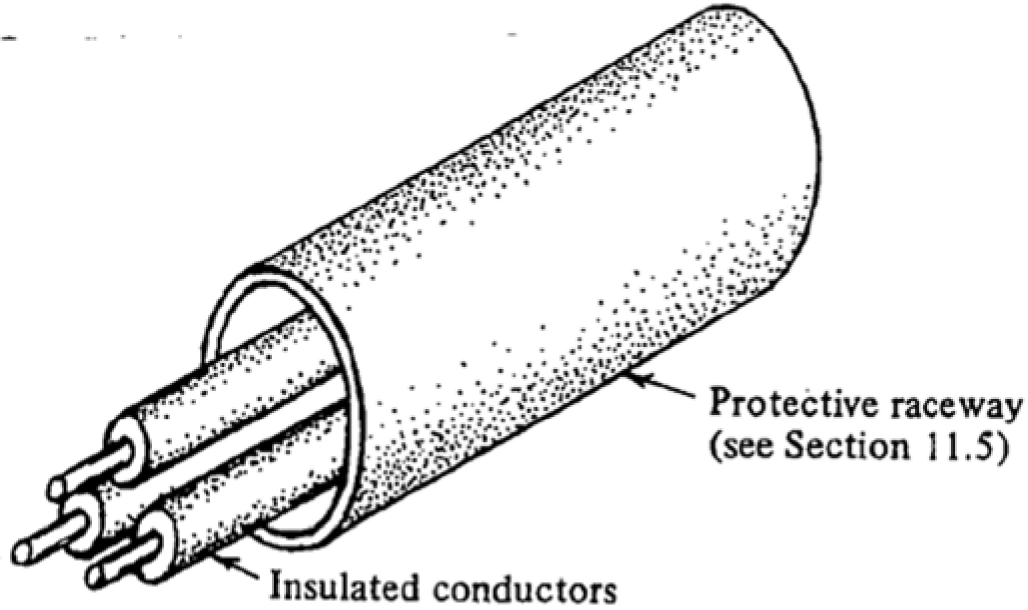

Protective raceway
(see Section 11.5)
Insulated conductors

Table 310.15(B)(16) (formerly Table 310.16) Allowable Ampacities of Insulated Conductors Rated Up to and Including 2000 Volts, 60°C Through 90°C (140°F Through 194°F), Not More Than Three Current-Carrying Conductors in Raceway, Cable, or Earth (Directly Buried), Based on Ambient Temperature of 30°C (86°F)*

	Temperature Rating of Conductor [See Table 310.104(A).]						
	60°C (140°F)	75°C (167°F)	90°C (194°F)	60°C (140°F)	75°C (167°F)	90°C (194°F)	
Size AWG or kcmil	Types TW, UF	Types RHW, THHW, THW, THWN, XHHW, USE, ZW	Types TBS, SA, SIS, FEP, FEPB, MI, RHH, RHW-2, THHN, THHW, THW-2, THWN-2, USE-2, XHH, XHHW, XHHW-2, ZW-2	Types TW, UF	Types RHW, THHW, THW, THWN, XHHW, USE	Types TBS, SA, SIS, THHN, THHW, THW-2, THWN-2, RHH, RHW-2, USE-2, XHH, XHHW, XHHW-2, ZW-2	
	COPPER			ALUMINUM OR COPPER-CLAD ALUMINUM			Size AWG or kcmil
18	—	—	14	—	—	—	—
16	—	—	18	—	—	—	—
14**	15	20	25	—	—	—	—
12**	20	25	30	15	20	25	12**
10**	30	35	40	25	30	35	10**
8	40	50	55	35	40	45	8
6	55	65	75	40	50	55	6
4	70	85	95	55	65	75	4
3	85	100	115	65	75	85	3
2	95	115	130	75	90	100	2
1	110	130	145	85	100	115	1
1/0	125	150	170	100	120	135	1/0
2/0	145	175	195	115	135	150	2/0
3/0	165	200	225	130	155	175	3/0
4/0	195	230	260	150	180	205	4/0
250	215	255	290	170	205	230	250
300	240	285	320	195	230	260	300
350	260	310	350	210	250	280	350
400	280	335	380	225	270	305	400
500	320	380	430	260	310	350	500
600	350	420	475	285	340	385	600
700	385	460	520	315	375	425	700
750	400	475	535	320	385	435	750
800	410	490	555	330	395	445	800
900	435	520	585	355	425	480	900
1000	455	545	615	375	445	500	1000
1250	495	590	665	405	485	545	1250
1500	525	625	705	435	520	585	1500
1750	545	650	735	455	545	615	1750
2000	555	665	750	470	560	630	2000

*Refer to 310.15(B)(2) for the ampacity correction factors where the ambient temperature is other than 30°C (86°F).

**Refer to 240.4(D) for conductor overcurrent protection limitations.

Table 310.15(B)(3)(a) Adjustment Factors for More Than Three Current-Carrying Conductors in a Raceway or Cable

Number of Conductors[1]	Percent of Values in Table 310.15(B)(16) through Table 310.15(B)(19) as Adjusted for Ambient Temperature if Necessary
4–6	80
7–9	70
10–20	50
21–30	45
31–40	40
41 and above	35

[1] Number of conductors is the total number of conductors in the raceway or cable adjusted in accordance with 310.15(B)(5) and (6).

Informational Note No. 2: See 366.23(A) for adjustment factors for conductors in sheet metal auxiliary gutters and 376.22(B) for adjustment factors for conductors in metal wireways.

(1) Where conductors are installed in cable trays, the provisions of 392.80 shall apply.

(2) Adjustment factors shall not apply to conductors in raceways having a length not exceeding 600 mm (24 in.).

(3) Adjustment factors shall not apply to underground conductors entering or leaving an outdoor trench if those conductors have physical protection in the form of rigid metal conduit, intermediate metal conduit, rigid polyvinyl chloride conduit (PVC), or reinforced thermosetting resin conduit (RTRC) having a length not exceeding 3.05 m (10 ft), and if the number of conductors does not exceed four.

(4) Adjustment factors shall not apply to Type AC cable or to Type MC cable under the following conditions:

a. The cables do not have an overall outer jacket.
b. Each cable has not more than three current-carrying conductors.
c. The conductors are 12 AWG copper.
d. Not more than 20 current-carrying conductors are installed without maintaining spacing, are stacked, or are supported on"bridle rings."

(5) An adjustment factor of 60 percent shall be applied to Type AC cable or Type MC cable under the following conditions:

a. The cables do not have an overall outer jacket.
b. The number of current carrying conductors exceeds 20.
c. The cables are stacked or bundled longer that 600 mm (24 in) without spacing being maintained.

(b) *More Than One Conduit, Tube, or Raceway.* Spacing between conduits, tubing, or raceways shall be maintained.

(c) *Circular Raceways Exposed to Sunlight on Rooftops.* Where conductors or cables are installed in circular raceways exposed to direct sunlight on or above rooftops, the adjustments shown in Table 310.15(B)(3)(c) shall be added to the outdoor temperature to determine the applicable ambient temperature for application of the correction factors in Table 310.15(B)(2)(a) or Table 310.15(B)(2)(b).

Informational Note: One source for the average ambient temperatures in various locations is the ASHRAE *Handbook — Fundamentals*.

Table 310.15(B)(3)(c) Ambient Temperature Adjustment for Circular Raceways Exposed to Sunlight on or Above Rooftops

Distance Above Roof to Bottom of Conduit	Temperature Adder °C	Temperature Adder °F
0–13 mm (½ in.)	33	60
Above 13 mm (½ in.)–90 mm (3½ in.)	22	40
Above 90 mm (3½ in.)–300 mm (12 in.)	17	30
Above 300 mm (12 in.)–900 mm (36 in.)	14	25

Informational Note to Table 310.15(B)(3)(c): The temperature adders in Table 310.15(B)(3)(c) are based on the results of averaging the ambient temperatures.

(4) Bare or Covered Conductors. Where bare or covered conductors are installed with insulated conductors, the temperature rating of the bare or covered conductor shall be equal to the lowest temperature rating of the insulated conductors for the purpose of determining ampacity.

(5) Neutral Conductor.

(a) A neutral conductor that carries only the unbalanced current from other conductors of the same circuit shall not be required to be counted when applying the provisions of 310.15(B)(3)(a).

(b) In a 3-wire circuit consisting of two phase conductors and the neutral conductor of a 4-wire, 3-phase, wye-connected system, a common conductor carries approximately the same current as the line-to-neutral load currents of the other conductors and shall be counted when applying the provisions of 310.15(B)(3)(a).

(c) On a 4-wire, 3-phase wye circuit where the major portion of the load consists of nonlinear loads, harmonic currents are present in the neutral conductor; the neutral conductor shall therefore be considered a current-carrying conductor.

(6) Grounding or Bonding Conductor. A grounding or bonding conductor shall not be counted when applying the provisions of 310.15(B)(3)(a).

(3) The rate at which generated heat dissipates into the ambient medium. Thermal insulation that covers or surrounds conductors affects the rate of heat dissipation.
(4) Adjacent load-carrying conductors — adjacent conductors have the dual effect of raising the ambient temperature and impeding heat dissipation.

Informational Note No. 2: Refer to 110.14(C) for the temperature limitation of terminations.

(B) Tables. Ampacities for conductors rated 0 to 2000 volts shall be as specified in the Allowable Ampacity Table 310.15(B)(16) through Table 310.15(B)(19), and Ampacity Table 310.15(B)(20) and Table 310.15(B)(21) as modified by 310.15(B)(1) through (B)(7).

The temperature correction and adjustment factors shall be permitted to be applied to the ampacity for the temperature rating of the conductor, if the corrected and adjusted ampacity does not exceed the ampacity for the temperature rating of the termination in accordance with the provisions of 110.14(C).

Informational Note: Table 310.15(B)(16) through Table 310.15(B)(19) are application tables for use in determining conductor sizes on loads calculated in accordance with Article 220. Allowable ampacities result from consideration of one or more of the following:

(1) Temperature compatibility with connected equipment, especially the connection points.
(2) Coordination with circuit and system overcurrent protection.
(3) Compliance with the requirements of product listings or certifications. See 110.3(B).
(4) Preservation of the safety benefits of established industry practices and standardized procedures.

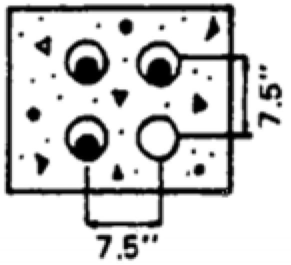
Table 310.15(B)(2)(a) Ambient Temperature Correction Factors Based on 30°C (86°F)

For ambient temperatures other than 30°C (86°F), multiply the allowable ampacities specified in the ampacity tables by the appropriate correction factor shown below.

Ambient Temperature (°C)	Temperature Rating of Conductor			Ambient Temperature (°F)
	60°C	75°C	90°C	
10 or less	1.29	1.20	1.15	50 or less
11–15	1.22	1.15	1.12	51–59
16–20	1.15	1.11	1.08	60–68
21–25	1.08	1.05	1.04	69–77
26–30	1.00	1.00	1.00	78–86
31–35	0.91	0.94	0.96	87–95
36–40	0.82	0.88	0.91	96–104
41–45	0.71	0.82	0.87	105–113
46–50	0.58	0.75	0.82	114–122
51–55	0.41	0.67	0.76	123–131
56–60	—	0.58	0.71	132–140
61–65	—	0.47	0.65	141–149
66–70	—	0.33	0.58	150–158
71–75	—	—	0.50	159–167
76–80	—	—	0.41	168–176
81–85	—	—	0.29	177–185

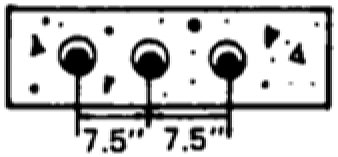
(1) General. For explanation of type letters used in tables

Detail 1
11.5" x 11.5"
Electrical duct bank
One electrical duct

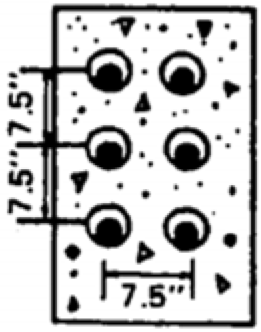


Detail 2
19" x 19"
Electrical duct bank
Three electrical ducts

OR

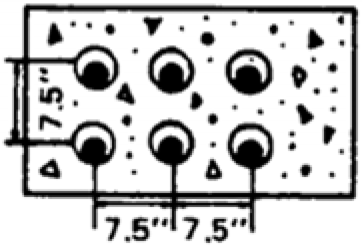


27" x 11.5"
Electrical duct bank
Three electrical ducts



Detail 3
19" x 27"
Electrical duct bank
Six electrical ducts

OR



27" x 19"
Electrical duct bank
Six electrical ducts

(i) For cables installed in two electrical ducts in one horizontal row, 7.5-inch center-to-center spacing, multiply ampacity shown for 1 electrical duct by 0.88.

(ii) For cables installed in four electrical ducts in one horizontal row, 7.5-inch center-to-center spacing, multiply ampacity shown for 3 electrical ducts by 0.94.

Determine the ampacity of a three-phase, four-wire feeder using 250 MCM copper conductors, 75°C insulation, installed in a raceway in free air, 40°C ambient temperature, and feeding an incandescent lighting load.

Based on Ambient Air Temperature of 30°C (86°F).

Size	Temperature Rating of Conductor. See Table 310-13.								Size
	60°C (140°F)	75°C (167°F)	85°C (185°F)	90°C (194°F)	60°C (140°F)	75°C (167°F)	85°C (185°F)	90°C (194°F)	
AWG MCM	TYPES †TW, †UF	TYPES †FEPW, †RH, †RHW, †THW, †THWN, †XHHW, †USE, †ZW	TYPE V	TYPES TA, TBS, SA, AVB, SIS, †FEP, †FEPB, †RHH, †THHN, †XHHW*	TYPES †TW, †UF	TYPES †RH, †RHW, †THW, †THWN, †XHHW †USE	TYPE V	TYPES TA, TBS, SA, AVB, SIS, †RHH, †THHN, †XHHW*	AWG MCM
	COPPER				ALUMINUM OR COPPER-CLAD ALUMINUM				
18	....	....	....	14	....	....	....	....	....
16	....	....	18	18	....	....	....	....	....
14	20†	20†	25	25†	....	....	....	....	....
12	25†	25†	30	30†	20†	20†	25	25†	12
10	30	35†	40	40†	25	30†	30	35†	10
8	40	50	55	55	30	40	40	45	8
6	55	65	70	75	40	50	55	60	6
4	70	85	95	95	55	65	75	75	4
3	85	100	110	110	65	75	85	85	3
2	95	115	125	130	75	90	100	100	2
1	110	130	145	150	85	100	110	115	1
1/0	125	150	165	170	100	120	130	135	1/0
2/0	145	175	190	195	115	135	145	150	2/0
3/0	165	200	215	225	130	155	170	175	3/0
4/0	195	230	250	260	150	180	195	205	4/0
250	215	255	275	290	170	205	220	230	250
300	240	285	310	320	190	230	250	255	300
350	260	310	340	350	210	250	270	280	350
400	280	335	365	380	225	270	295	305	400
500	320	380	415	430	260	310	335	350	500
600	355	420	460	475	285	340	370	385	600
700	385	460	500	520	310	375	405	420	700
750	400	475	515	535	320	385	420	435	750
800	410	490	535	555	330	395	430	450	800
900	435	520	565	585	355	425	465	480	900
1000	455	545	590	615	375	445	485	500	1000
1250	495	590	640	665	405	485	525	545	1250
1500	520	625	680	705	435	520	565	585	1500
1750	545	650	705	735	455	545	595	615	1750
2000	560	665	725	750	470	560	610	630	2000

AMPACITY CORRECTION FACTORS

Ambient Temp. °C	For ambient temperatures other than 30°C (86°F), multiply the ampacities shown above by the appropriate factor shown below.								Ambient Temp. °F
21-25	1.08	1.05	1.04	1.04	1.08	1.05	1.04	1.04	70-77
26-30	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	79-86
31-35	.91	.94	.95	.96	.91	.94	.95	.96	88-95
36-40	.82	.88	.90	.91	.82	.88	.90	.91	97-104
41-45	.71	.82	.85	.87	.71	.82	.85	.87	106-113
46-50	.58	.75	.80	.82	.58	.75	.80	.82	115-122
51-55	.41	.67	.74	.76	.41	.67	74	.76	124-131
56-60	....	.58	.67	.71	....	.58	.67	.71	133-140
61-70	....	.33	.52	.58	....	.33	.52	.58	142-158
71-80	....	....	.30	.41	....	....	.30	.41	160-176

† Unless otherwise specifically

(b) Ampacity adjustment factors for more than three conductors in a raceway or cable [from *NEC* Notes to Tables 310-16 through 310-31, No. 8(a)].

Number of Conductors	Percent of Values in Tables 11.1 and 11.2
4–6	80
7–9	70
10–24[a]	70
25–42[a]	60
43 and above[a]	50

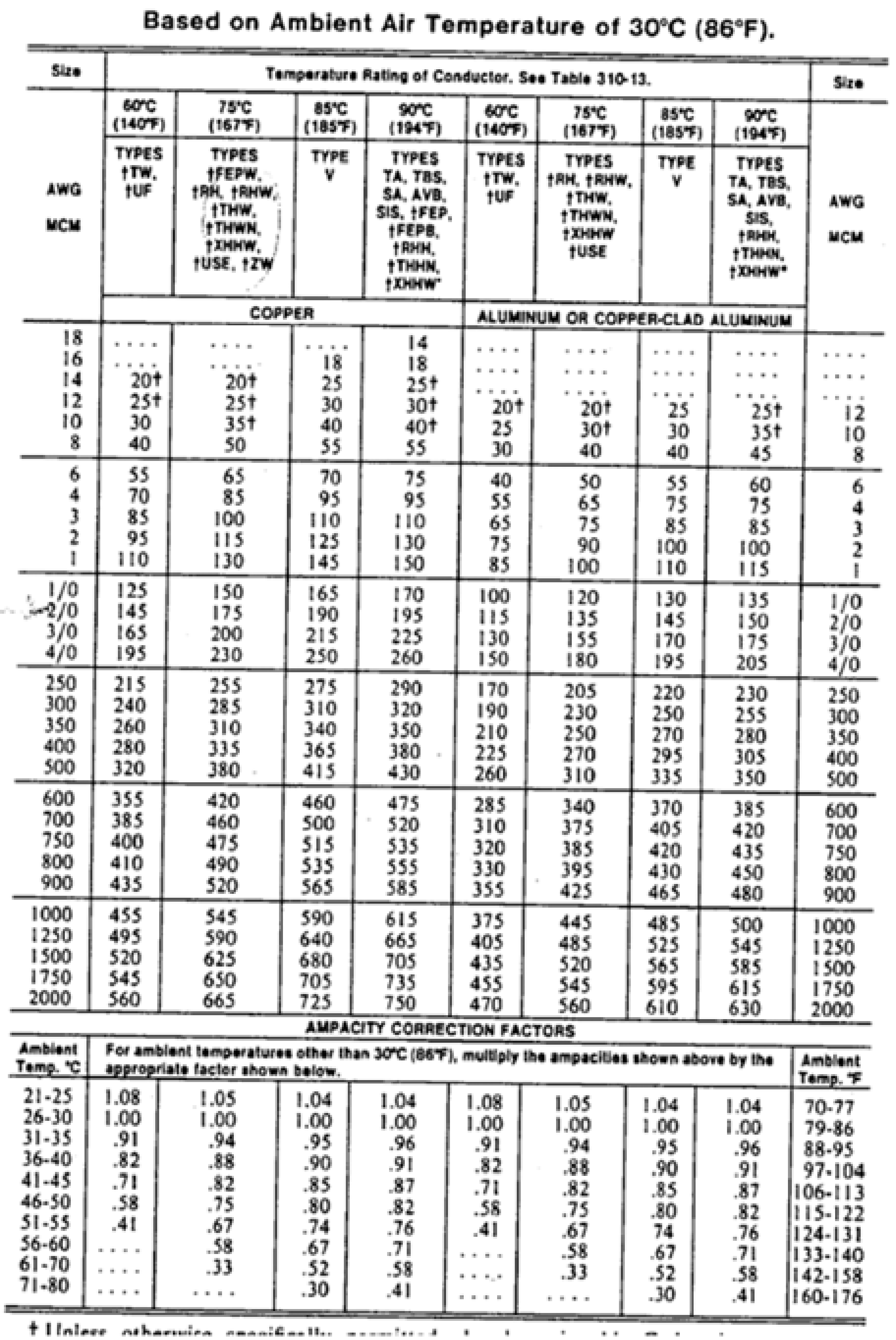
Determine the ampacity of a three-phase, four-wire feeder using 250 MCM copper conductors, 75°C insulation, installed in a raceway in free air, 40°C ambient temperature, and feeding an incandescent lighting load.

From Table 11.1, column 3, the rating for 250 MCM is 255 A. The correction factor for 40°C is 0.88:

$$\text{Ampacity} = 255 \times 0.88 = 224 \text{ A}$$

There is no need to derate for the neutral (the fourth wire) because there are no third harmonics with incandescent lighting.

Determine the ampacity of a three-phase, four-wire feeder using 400 MCM copper conductors, 90°C insulation, installed in a raceway in free air, 30°C ambient temperature, and feeding a fluorescent lighting load.



Based on Ambient Air Temperature of 30°C (86°F).

Size	Temperature Rating of Conductor. See Table 310-13.								Size
	60°C (140°F)	75°C (167°F)	85°C (185°F)	90°C (194°F)	60°C (140°F)	75°C (167°F)	85°C (185°F)	90°C (194°F)	
AWG MCM	TYPES †TW, †UF	TYPES †FEPW, †RH, †RHW, †THW, †THWN, †XHHW, †USE, †ZW	TYPE V	TYPES TA, TBS, SA, AVB, SIS, †FEP, †FEPB, †RHH, †THHN, †XHHW*	TYPES †TW, †UF	TYPES †RH, †RHW, †THW, †THWN, †XHHW †USE	TYPE V	TYPES TA, TBS, SA, AVB, SIS, †RHH, †THHN, †XHHW*	AWG MCM
	COPPER				ALUMINUM OR COPPER-CLAD ALUMINUM				
18	....	....	....	14	....	....	....	....	....
16	....	....	18	18	....	....	....	....	....
14	20†	20†	25	25†	....	....	....	....	....
12	25†	25†	30	30†	20†	20†	25	25†	12
10	30	35†	40	40†	25	30†	30	35†	10
8	40	50	55	55	30	40	40	45	8
6	55	65	70	75	40	50	55	60	6
4	70	85	95	95	55	65	75	75	4
3	85	100	110	110	65	75	85	85	3
2	95	115	125	130	75	90	100	100	2
1	110	130	145	150	85	100	110	115	1
1/0	125	150	165	170	100	120	130	135	1/0
2/0	145	175	190	195	115	135	145	150	2/0
3/0	165	200	215	225	130	155	170	175	3/0
4/0	195	230	250	260	150	180	195	205	4/0
250	215	255	275	290	170	205	220	230	250
300	240	285	310	320	190	230	250	255	300
350	260	310	340	350	210	250	270	280	350
400	280	335	365	380	225	270	295	305	400
500	320	380	415	430	260	310	335	350	500
600	355	420	460	475	285	340	370	385	600
700	385	460	500	520	310	375	405	420	700
750	400	475	515	535	320	385	420	435	750
800	410	490	535	555	330	395	430	450	800
900	435	520	565	585	355	425	465	480	900
1000	455	545	590	615	375	445	485	500	1000
1250	495	590	640	665	405	485	525	545	1250
1500	520	625	680	705	435	520	565	585	1500
1750	545	650	705	735	455	545	595	615	1750
2000	560	665	725	750	470	560	610	630	2000

AMPACITY CORRECTION FACTORS

Ambient Temp. °C	For ambient temperatures other than 30°C (86°F), multiply the ampacities shown above by the appropriate factor shown below.								Ambient Temp. °F
21-25	1.08	1.05	1.04	1.04	1.08	1.05	1.04	1.04	70-77
26-30	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	79-86
31-35	.91	.94	.95	.96	.91	.94	.95	.96	88-95
36-40	.82	.88	.90	.91	.82	.88	.90	.91	97-104
41-45	.71	.82	.85	.87	.71	.82	.85	.87	106-113
46-50	.58	.75	.80	.82	.58	.75	.80	.82	115-122
51-55	.41	.67	.74	.76	.41	.67	74	.76	124-131
56-60	....	.58	.67	.71	....	.58	.67	.71	133-140
61-70	....	.33	.52	.58	....	.33	.52	.58	142-158
71-80	....	....	.30	.41	....	....	.30	.41	160-176

† Unless otherwise specifically

(b) Ampacity adjustment factors for more than three conductors in a raceway or cable [from *NEC* Notes to Tables 310-16 through 310-31, No. 8(a)].

Number of Conductors	Percent of Values in Tables 11.1 and 11.2
4–6	80
7–9	70
10–24[a]	70
25–42[a]	60
43 and above[a]	50

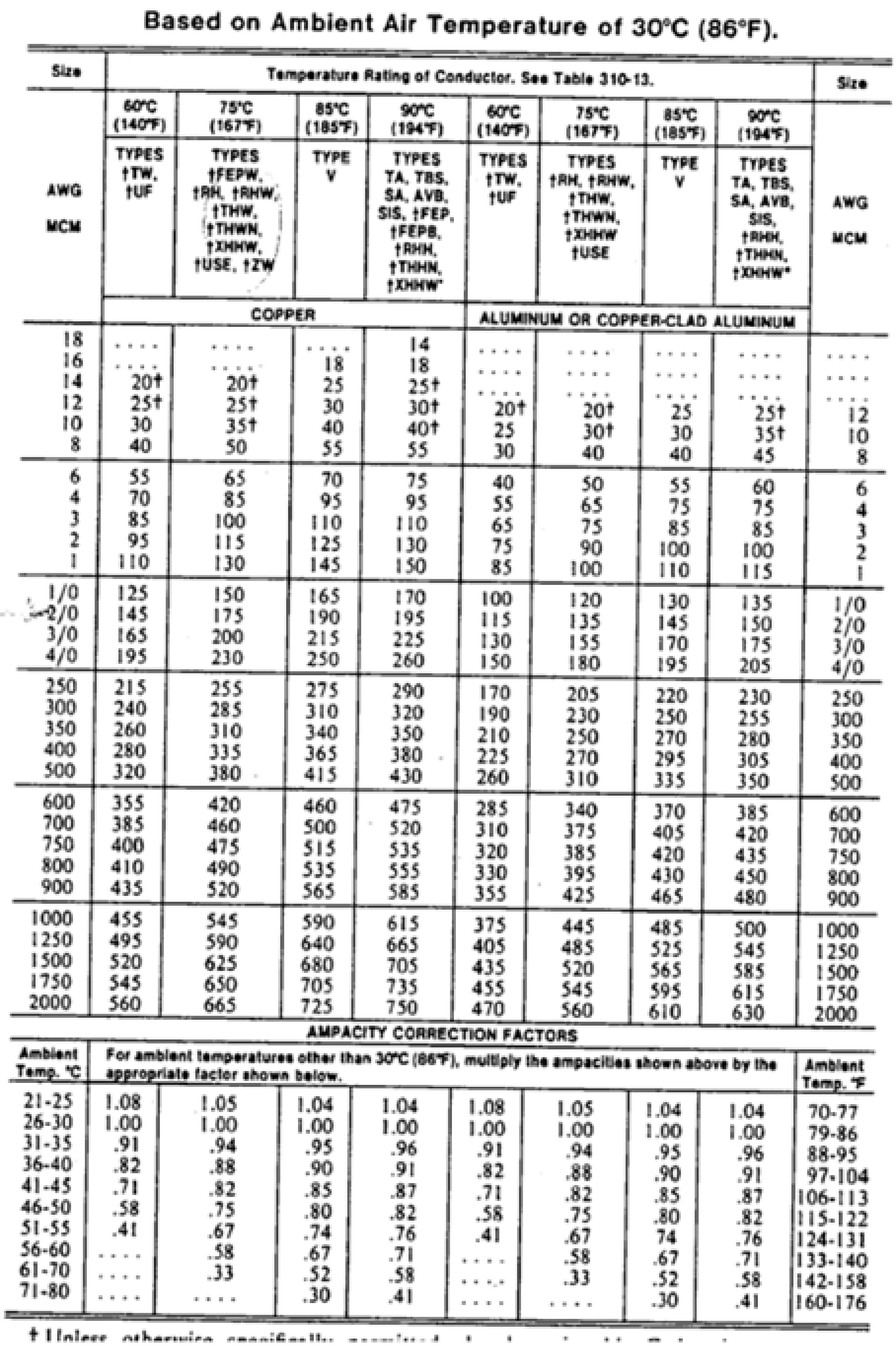
Determine the ampacity of a three-phase, four-wire feeder using 400 MCM copper conductors, 90°C insulation, installed in a raceway in free air, 30°C ambient temperature, and feeding a fluorescent lighting load.

Determine the ampacity of a three-phase, four-wire feeder using 400 MCM copper conductors, 90°C insulation, installed in a raceway in free air, 30°C ambient temperature, and feeding a fluorescent lighting load.

From Table 11.1, column 5, the rating for 400 MCM is 380 A. The neutral must be counted as the fourth current-carrying conductor because of the fluorescent lighting (which is an electric discharge type). From Table 11.3(b), the ampacity adjustment factor for four conductors is 0.80:

$$\text{Ampacity} = 380 \times 0.80 = 304 \text{ A}$$

Determine the ampacity of No. 6 aluminum conductors, 75°C insulation, eight current-carrying conductors in a raceway in free air, 45°C ambient temperature.



Based on Ambient Air Temperature of 30°C (86°F).

Size	Temperature Rating of Conductor. See Table 310-13.								Size
	60°C (140°F)	75°C (167°F)	85°C (185°F)	90°C (194°F)	60°C (140°F)	75°C (167°F)	85°C (185°F)	90°C (194°F)	
AWG MCM	TYPES †TW, †UF	TYPES †FEPW, †RH, †RHW, †THW, †THWN, †XHHW, †USE, †ZW	TYPE V	TYPES TA, TBS, SA, AVB, SIS, †FEP, †FEPB, †RHH, †THHN, †XHHW*	TYPES †TW, †UF	TYPES †RH, †RHW, †THW, †THWN, †XHHW †USE	TYPE V	TYPES TA, TBS, SA, AVB, SIS, †RHH, †THHN, †XHHW*	AWG MCM
	COPPER				ALUMINUM OR COPPER-CLAD ALUMINUM				
18	....	....	....	14	....	....	....	....	....
16	....	....	18	18	....	....	....	....	....
14	20†	20†	25	25†	....	....	....	....	....
12	25†	25†	30	30†	20†	20†	25	25†	12
10	30	35†	40	40†	25	30†	30	35†	10
8	40	50	55	55	30	40	40	45	8
6	55	65	70	75	40	50	55	60	6
4	70	85	95	95	55	65	75	75	4
3	85	100	110	110	65	75	85	85	3
2	95	115	125	130	75	90	100	100	2
1	110	130	145	150	85	100	110	115	1
1/0	125	150	165	170	100	120	130	135	1/0
2/0	145	175	190	195	115	135	145	150	2/0
3/0	165	200	215	225	130	155	170	175	3/0
4/0	195	230	250	260	150	180	195	205	4/0
250	215	255	275	290	170	205	220	230	250
300	240	285	310	320	190	230	250	255	300
350	260	310	340	350	210	250	270	280	350
400	280	335	365	380	225	270	295	305	400
500	320	380	415	430	260	310	335	350	500
600	355	420	460	475	285	340	370	385	600
700	385	460	500	520	310	375	405	420	700
750	400	475	515	535	320	385	420	435	750
800	410	490	535	555	330	395	430	450	800
900	435	520	565	585	355	425	465	480	900
1000	455	545	590	615	375	445	485	500	1000
1250	495	590	640	665	405	485	525	545	1250
1500	520	625	680	705	435	520	565	585	1500
1750	545	650	705	735	455	545	595	615	1750
2000	560	665	725	750	470	560	610	630	2000

AMPACITY CORRECTION FACTORS

Ambient Temp. °C	For ambient temperatures other than 30°C (86°F), multiply the ampacities shown above by the appropriate factor shown below.								Ambient Temp. °F
21-25	1.08	1.05	1.04	1.04	1.08	1.05	1.04	1.04	70-77
26-30	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	79-86
31-35	.91	.94	.95	.96	.91	.94	.95	.96	88-95
36-40	.82	.88	.90	.91	.82	.88	.90	.91	97-104
41-45	.71	.82	.85	.87	.71	.82	.85	.87	106-113
46-50	.58	.75	.80	.82	.58	.75	.80	.82	115-122
51-55	.41	.67	.74	.76	.41	.67	74	.76	124-131
56-60	....	.58	.67	.71	....	.58	.67	.71	133-140
61-70	....	.33	.52	.58	....	.33	.52	.58	142-158
71-80	....	....	.30	.41	....	....	.30	.41	160-176

† Unless otherwise specifically

(b) Ampacity adjustment factors for more than three conductors in a raceway or cable [from *NEC* Notes to Tables 310-16 through 310-31, No. 8(a)].

Number of Conductors	Percent of Values in Tables 11.1 and 11.2
4–6	80
7–9	70
10–24ª	70
25–42ª	60
43 and aboveª	50

Determine the ampacity of No. 6 aluminum conductors, 75°C insulation, eight current-carrying conductors in a raceway in free air, 45°C ambient temperature.

Determine the ampacity of No. 6 aluminum conductors, 75°C insulation, eight current-carrying conductors in a raceway in free air, 45°C ambient temperature.

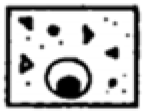
From Table 11.1, column 7, the rating for No. 6 is 50 A. The correction factor for 45°C is 0.82. From Table 11.3(b), the ampacity adjustment factor for eight conductors is 0.70:

Ampacity = $50 \times 0.82 \times 0.70 = 28.7$ A

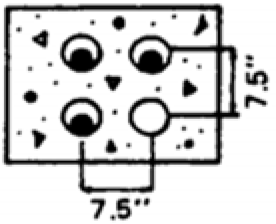
Determine the ampacity of a three-phase, three-wire feeder using 4/0 copper conductors, 75°C insulation, installed in an underground electrical duct, ambient earth temperature of 20°C. There is a second feeder installed in the same duct bank.

TABLE 11.3 Details and Adjustment Factors for Tables 11.1 and 11.2

(a) Electrical duct details for use with Table 11.2 (from *NEC* Figure 310-1 and Notes to Tables 310-25 through 310-27).

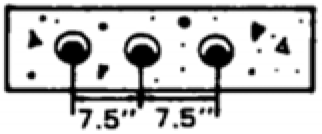


Detail 1
11.5" x 11.5"
Electrical duct bank
One electrical duct

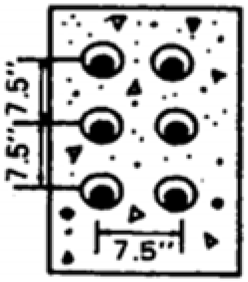


Detail 2
19" x 19"
Electrical duct bank
Three electrical ducts

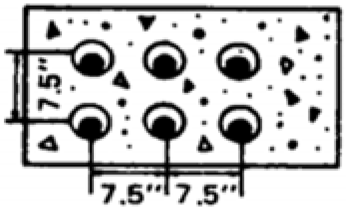
OR



27" x 11.5"
Electrical duct bank
Three electrical ducts



Detail 3
19" x 27"
Electrical duct bank
Six electrical ducts
OR



27" x 19"
Electrical duct bank
Six electrical ducts

(i) For cables installed in two electrical ducts in one horizontal row, 7.5-inch center-to-center spacing, multiply ampacity shown for 1 electrical duct by 0.88.

(ii) For cables installed in four electrical ducts in one horizontal row, 7.5-inch center-to-center spacing, multiply ampacity shown for 3 electrical ducts by 0.94.

TABLE 11.2 Ampacities of Three Single Insulated Conductors, Rated 0 through 2000 Volts, in Underground Electrical Ducts (from *NEC* Table 310-27)

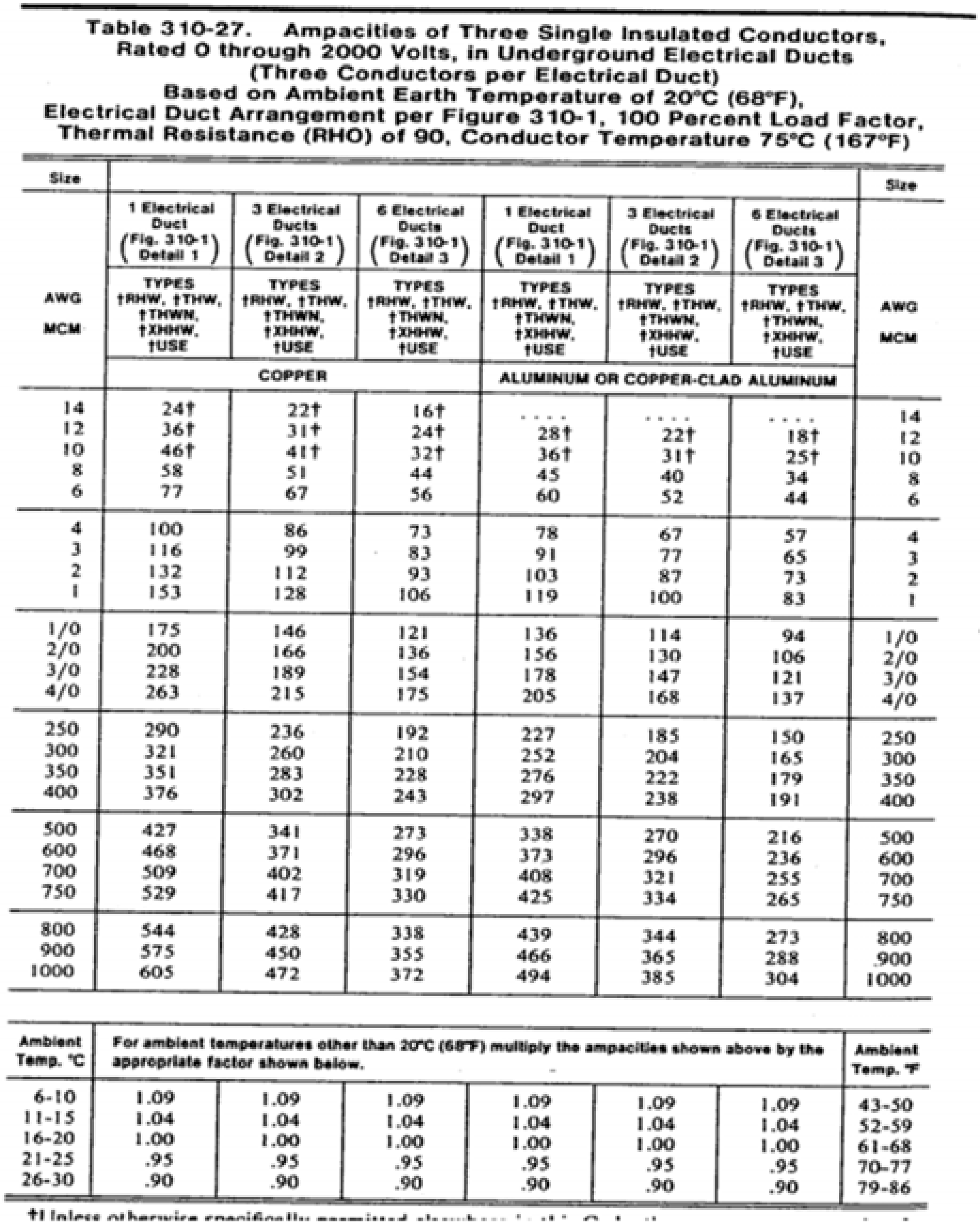


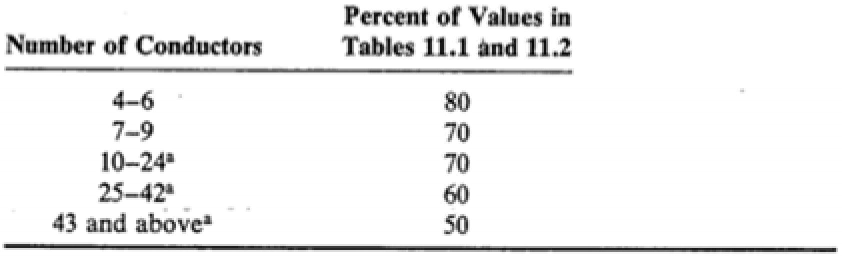
Table 310-27. Ampacities of Three Single Insulated Conductors, Rated 0 through 2000 Volts, in Underground Electrical Ducts (Three Conductors per Electrical Duct) Based on Ambient Earth Temperature of 20°C (68°F), Electrical Duct Arrangement per Figure 310-1, 100 Percent Load Factor, Thermal Resistance (RHO) of 90, Conductor Temperature 75°C (167°F)

Size AWG MCM	1 Electrical Duct (Fig. 310-1 Detail 1)	3 Electrical Ducts (Fig. 310-1 Detail 2)	6 Electrical Ducts (Fig. 310-1 Detail 3)	1 Electrical Duct (Fig. 310-1 Detail 1)	3 Electrical Ducts (Fig. 310-1 Detail 2)	6 Electrical Ducts (Fig. 310-1 Detail 3)	Size AWG MCM
	TYPES †RHW, †THW, †THWN, †XHHW, †USE	TYPES †RHW, †THW, †THWN, †XHHW, †USE	TYPES †RHW, †THW, †THWN, †XHHW, †USE	TYPES †RHW, †THW, †THWN, †XHHW, †USE	TYPES †RHW, †THW, †THWN, †XHHW, †USE	TYPES †RHW, †THW, †THWN, †XHHW, †USE	
	COPPER			ALUMINUM OR COPPER-CLAD ALUMINUM			
14	24†	22†	16†	....	....	....	14
12	36†	31†	24†	28†	22†	18†	12
10	46†	41†	32†	36†	31†	25†	10
8	58	51	44	45	40	34	8
6	77	67	56	60	52	44	6
4	100	86	73	78	67	57	4
3	116	99	83	91	77	65	3
2	132	112	93	103	87	73	2
1	153	128	106	119	100	83	1
1/0	175	146	121	136	114	94	1/0
2/0	200	166	136	156	130	106	2/0
3/0	228	189	154	178	147	121	3/0
4/0	263	215	175	205	168	137	4/0
250	290	236	192	227	185	150	250
300	321	260	210	252	204	165	300
350	351	283	228	276	222	179	350
400	376	302	243	297	238	191	400
500	427	341	273	338	270	216	500
600	468	371	296	373	296	236	600
700	509	402	319	408	321	255	700
750	529	417	330	425	334	265	750
800	544	428	338	439	344	273	800
900	575	450	355	466	365	288	900
1000	605	472	372	494	385	304	1000

Ambient Temp. °C	For ambient temperatures other than 20°C (68°F) multiply the ampacities shown above by the appropriate factor shown below.						Ambient Temp. °F
6-10	1.09	1.09	1.09	1.09	1.09	1.09	43-50
11-15	1.04	1.04	1.04	1.04	1.04	1.04	52-59
16-20	1.00	1.00	1.00	1.00	1.00	1.00	61-68
21-25	.95	.95	.95	.95	.95	.95	70-77
26-30	.90	.90	.90	.90	.90	.90	79-86

†Unless otherwise specifically permitted elsewhere in this Code

(b) Ampacity adjustment factors for more than three conductors in a raceway or cable [from *NEC* Notes to Tables 310-16 through 310-31, No. 8(a)].



Number of Conductors	Percent of Values in Tables 11.1 and 11.2
4–6	80
7–9	70
10–24[a]	70
25–42[a]	60
43 and above[a]	50

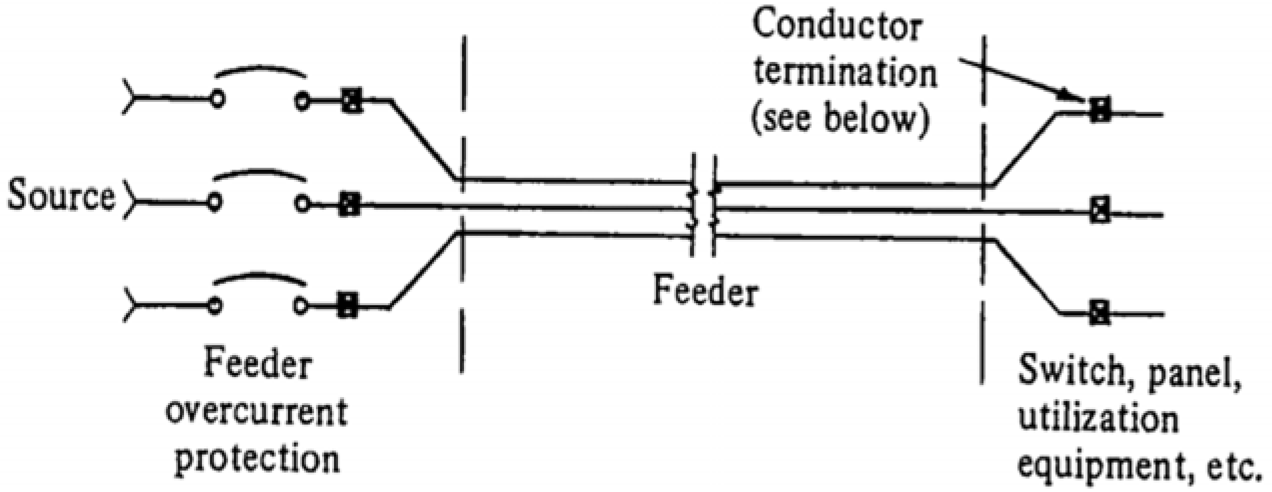
Determine the ampacity of a three-phase, three-wire feeder using 4/0 copper conductors, 75°C insulation, installed in an underground electrical duct, ambient earth temperature of 20°C. There is a second feeder installed in the same duct bank.

Determine the ampacity of a three-phase, three-wire feeder using 4/0 copper conductors, 75°C insulation, installed in an underground electrical duct, ambient earth temperature of 20°C. There is a second feeder installed in the same duct bank.

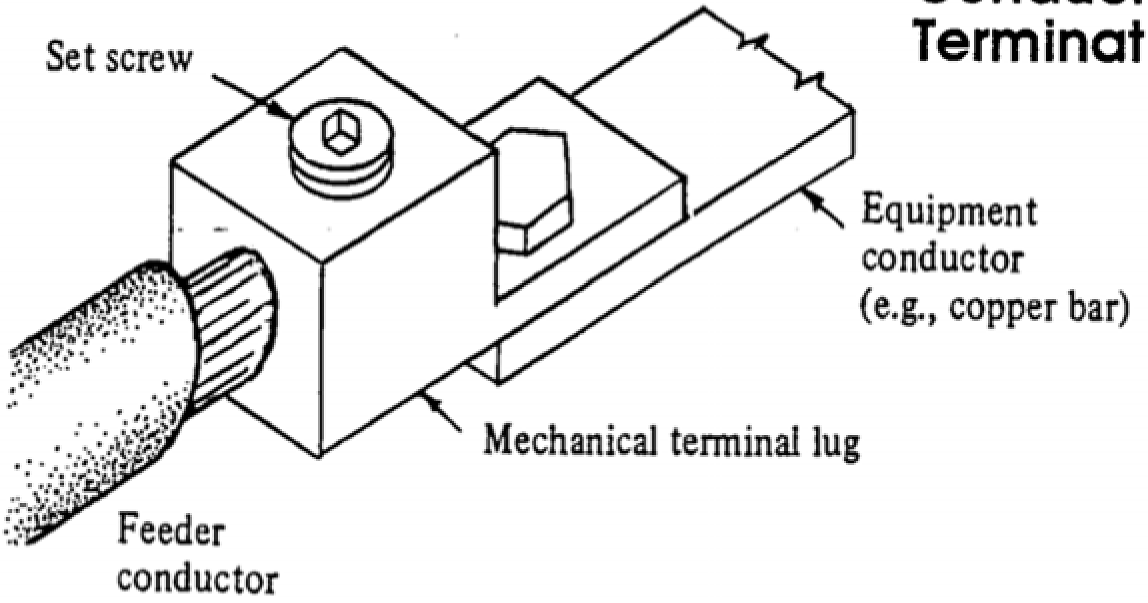
From Table 11.2, column 2, the rating for No. 4/0 is 263 A. From Table 11.3(a), the multiplying factor for two ducts is 0.88:

$$\text{Ampacity} = 263 \times 0.88 = 231\ \text{A}$$

Ampacity Limitations Imposed by Conductor Terminations



(a) Typical feeder connections



The termination provisions of the approved equipment are based on the use of 60°C insulated conductors in circuits rated 100 amperes or less and the use of 75°C insulated conductors in higher rated circuits. The 60°C ampacities for circuits rated 100 amperes or less and the 75°C ampacities for circuits rated over 100 amperes shall be based on Table 310-16 of the *National Electrical Code* [Table 11.1]. Conductors having a temperature rating higher than specified may be used if the size of the conductor is based on the 60°C ampacity for circuits 100 amperes and less and the 75°C ampacity for circuits over 100 amperes.

These temperature limitations are required to protect electrical equipment. A cable rated for 90°C, when loaded to its full ampacity rating, operates at a temperature of 90°C. If this cable is connected to an equipment terminal rated for 75°C, then the higher conductor temperature can eventually overheat the terminal, even though the load current does not exceed the rated current of the equipment. The excess heat can ultimately damage the equipment.

The foregoing would appear to eliminate the use of the 90°C insulated conductors for the majority of the feeders installed in a building, since most of the feeders and circuits are terminated in UL-approved equipment. However, this is not necessarily the case. The use of 90°C rated cables is justified where derating factors as previously discussed must be applied. To explain this, return to Example 11.2. Since the final ampacity of 304 amperes is less than the listed 75°C ampacity of 335 amperes for 400 MCM, there will be no problem at the terminations of this feeder. If 75°C rated conductors were to be used for this feeder, then one size larger (500 MCM) would have had to be selected to obtain the same ampacity rating of 304 amperes after the 80% derate factor is applied.

At this point we must return to Section 6.5 on asymmetrical fault currents and in particular to Figure 6.4. With an asymmetrical fault current, the heating of the conductors is greater than it would be if the fault current were symmetrical. Therefore, allowance must be made for this increased heating in selecting the correct size of conductor. The ratio between the asymmetrical and the symmetrical current is dependent on the rate of decay of the dc component after the fault occurs. If we let K_0 represent this ratio, then

$$I_{ASY} = K_0 \times I_{SYM} \tag{11.1}$$

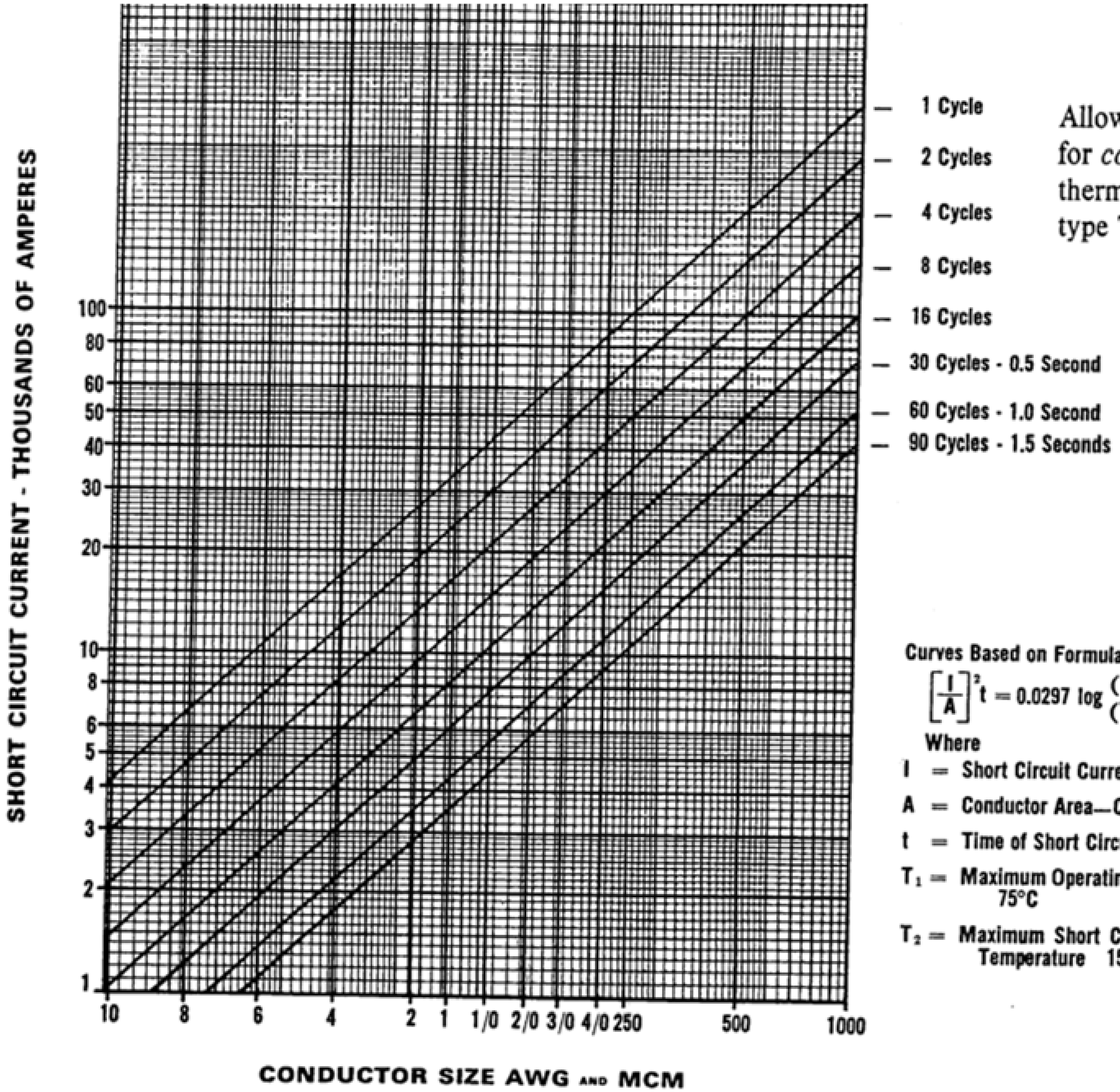
where I_{ASY} = asymmetrical short-circuit current used to size the conductor

I_{SYM} = available short-circuit symmetrical current

TABLE 11.4 Clearing Times and K_0 Factors

System Voltage	Feeder Overcurrent Device	Total Clearing Time (cycles)	K_0 Factor
Up to 1000 V	Circuit breaker[a]	2	1.3
	Current-limiting fuse	$\frac{1}{2}$	1.4
Above 1000 V	Air circuit breaker	5	1.15
	Oil circuit breaker	8	1.1
	Power fuse	1	1.6
	Current-limiting fuse	$\frac{1}{2}$	1.6

[a] Noncurrent-limiting type.



Allowable short-circuit currents for *copper* conductors with thermoplastic insulation (*NEC* type THW, CSA type TW75)

Curves Based on Formula

$$\left[\frac{I}{A}\right]^2 t = 0.0297 \log \frac{(T_2+234)}{(T_1+234)}$$

Where

I = Short Circuit Current—Amperes

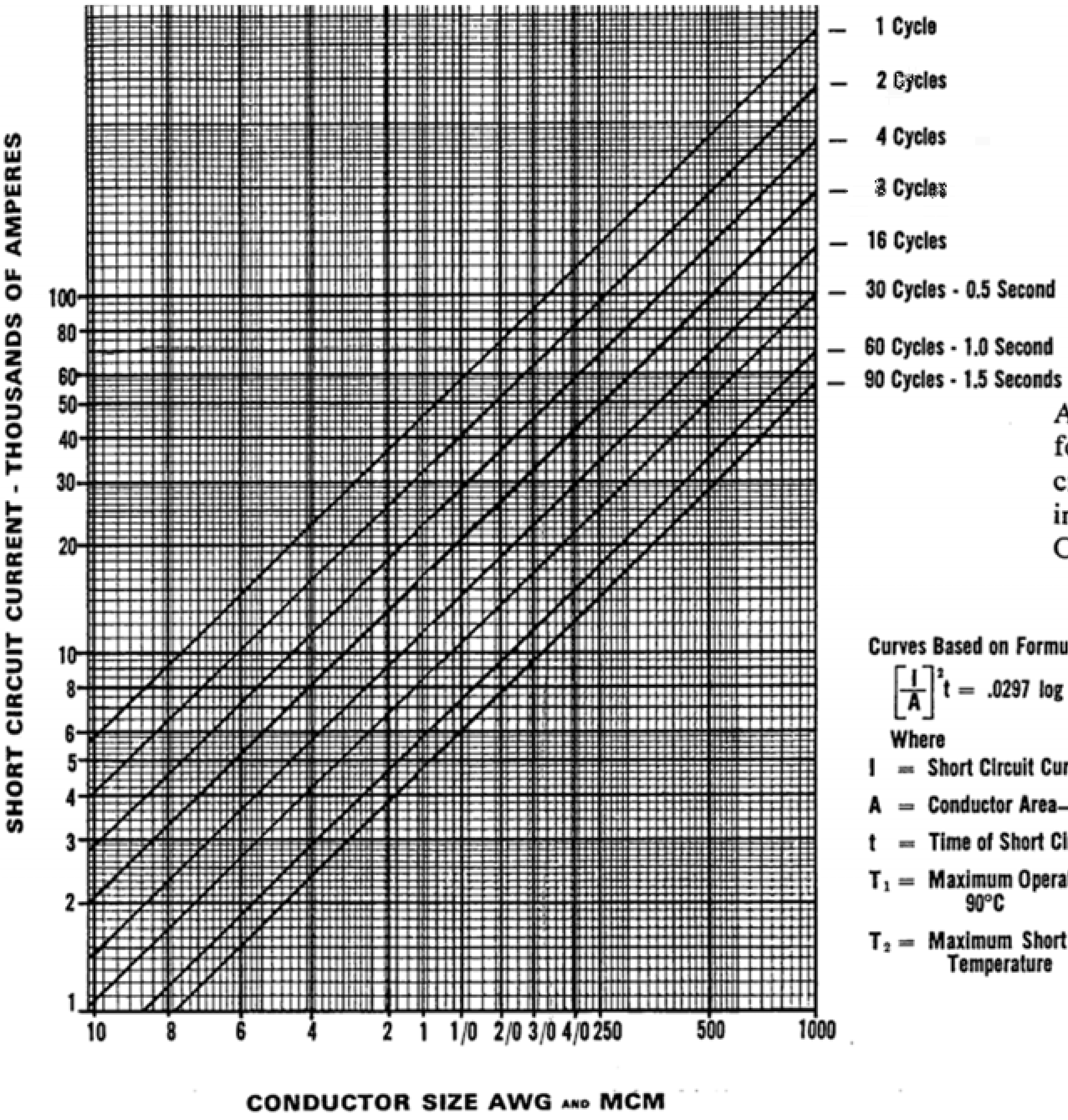
A = Conductor Area—Circular Mils

t = Time of Short Circuit—Seconds

T_1 = Maximum Operating Temperature 75°C

T_2 = Maximum Short Circuit Temperature 150°C

FIGURE 11.5



Allowable short-circuit currents for *copper* conductors with cross-linked synthetic polymer insulation [*NEC* type XHHW, CSA type RW90 (XLPE)]

Curves Based on Formula

$$\left[\frac{I}{A}\right]^2 t = .0297 \log \frac{(T_2+234)}{(T_1+234)}$$

Where

I = Short Circuit Current—Amperes

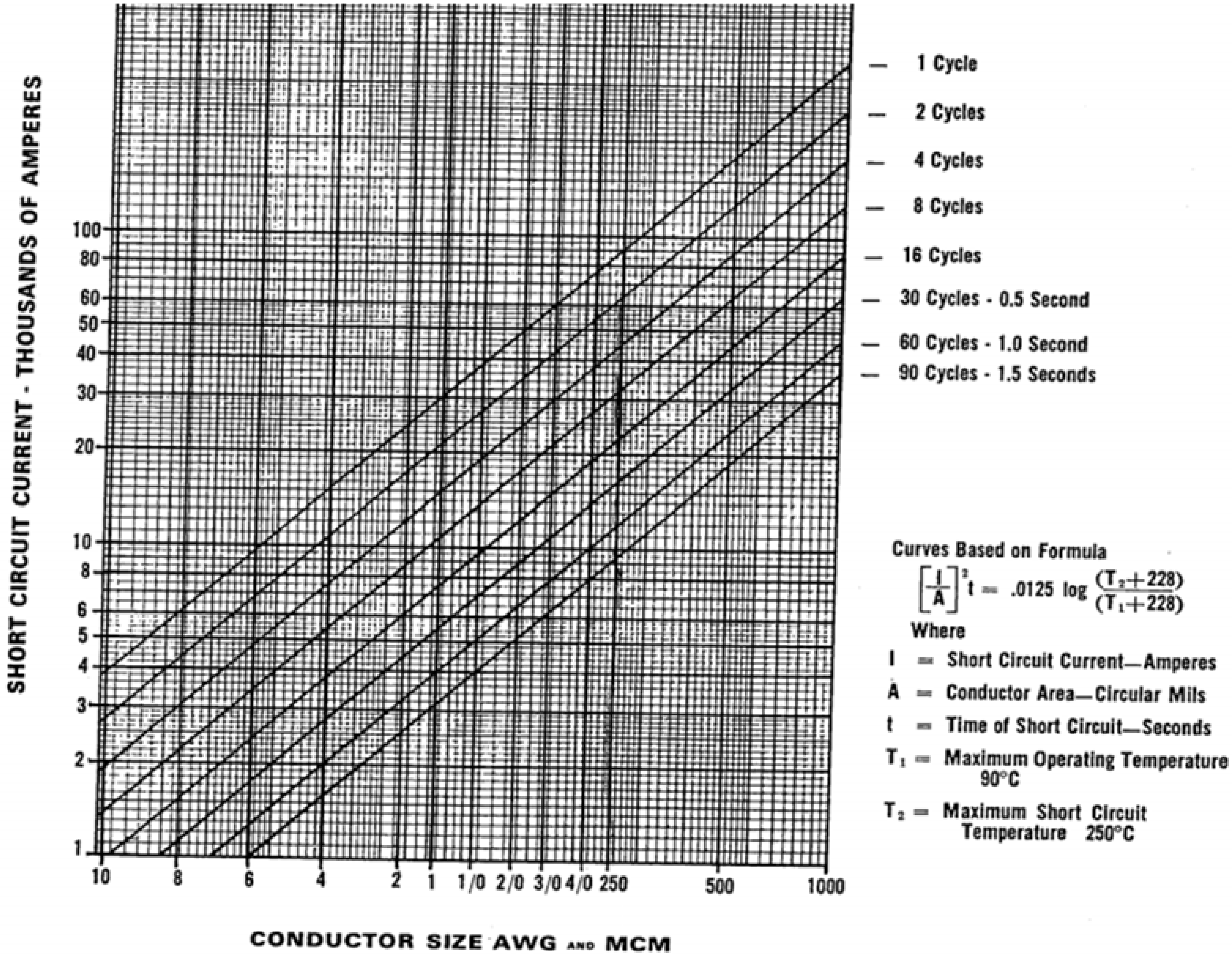
A = Conductor Area—Circular Mils

t = Time of Short Circuit—Seconds

T_1 = Maximum Operating Temperature 90°C

T_2 = Maximum Short Circuit Temperature 250°C

FIGURE 11.6



Curves Based on Formula

$$\left[\frac{I}{A}\right]^2 t = .0125 \log \frac{(T_2+228)}{(T_1+228)}$$

Where

I = Short Circuit Current—Amperes

A = Conductor Area—Circular Mils

t = Time of Short Circuit—Seconds

T_1 = Maximum Operating Temperature 90°C

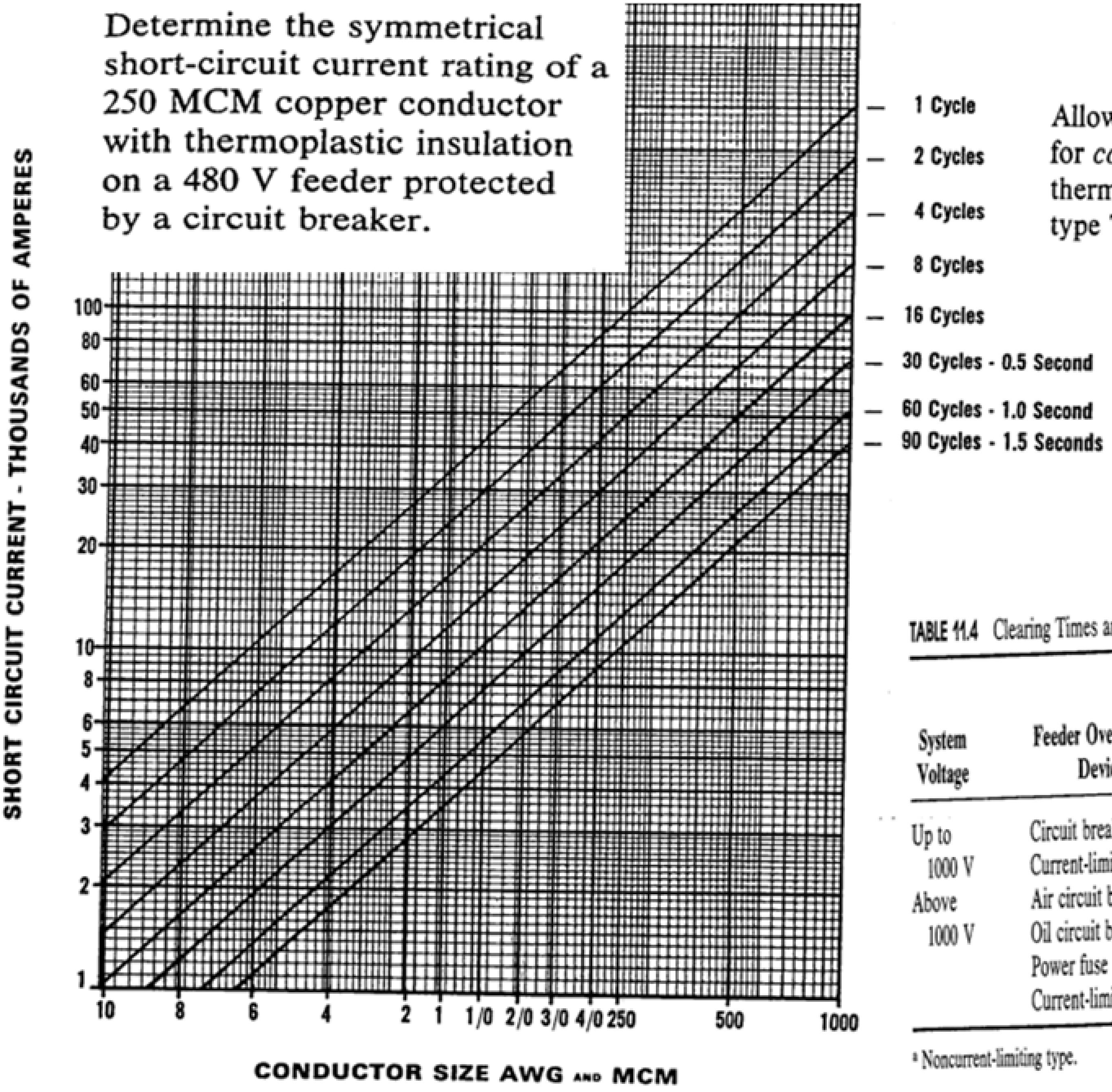
T_2 = Maximum Short Circuit Temperature 250°C

FIGURE 11.7

Allowable short-circuit currents for *aluminum* conductors with cross-linked synthetic polymer insulation [*NEC* type XHHW, CSA type RW90 (XLPE)]

Determine the symmetrical short-circuit current rating of a 250 MCM copper conductor with thermoplastic insulation on a 480 V feeder protected by a circuit breaker.

Determine the symmetrical short-circuit current rating of a 250 MCM copper conductor with thermoplastic insulation on a 480 V feeder protected by a circuit breaker.



Allowable short-circuit currents for *copper* conductors with thermoplastic insulation (*NEC* type THW, CSA type TW75)

FIGURE 11.5

TABLE 11.4 Clearing Times and K_0 Factors

System Voltage	Feeder Overcurrent Device	Total Clearing Time (cycles)	K_0 Factor
Up to 1000 V	Circuit breaker[a]	2	1.3
	Current-limiting fuse	½	1.4
Above 1000 V	Air circuit breaker	5	1.15
	Oil circuit breaker	8	1.1
	Power fuse	1	1.6
	Current-limiting fuse	¼	1.6

[a] Noncurrent-limiting type.

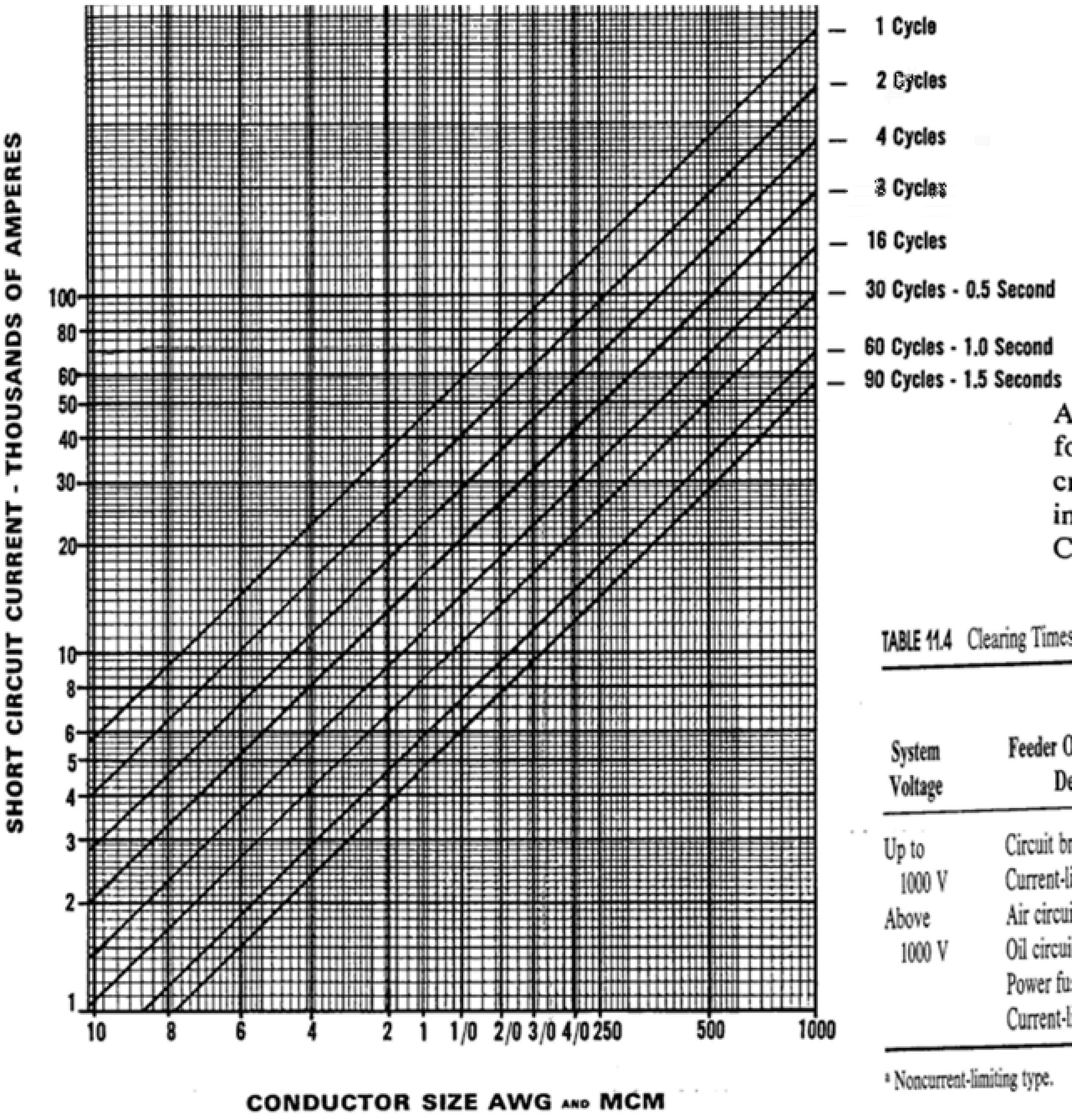
Determine the symmetrical short-circuit current rating of a 250 MCM copper conductor with thermoplastic insulation on a 480 V feeder protected by a circuit breaker.

From Table 11.4, the clearing time is 2 cycles and K_0 is 1.3. From Figure 11.5, the point of intersection of the vertical line for 250 MCM and the diagonal line for 2 cycles is 72 × 1000 A (I_{ASY}). Using Equation 11.1,

$$I_{SYM} = \frac{72{,}000}{1.3} = 55{,}400 \text{ A}$$

Repeat Example 11.5 except that the insulation is the cross-linked synthetic polymer type.

Determine the symmetrical short-circuit current rating of a 250 MCM copper conductor with thermoplastic insulation on a 480 V feeder protected by a circuit breaker.



Allowable short-circuit currents for *copper* conductors with cross-linked synthetic polymer insulation [*NEC* type XHHW, CSA type RW90 (XLPE)]

FIGURE 11.6

TABLE 11.4 Clearing Times and K_0 Factors

System Voltage	Feeder Overcurrent Device	Total Clearing Time (cycles)	K_0 Factor
Up to 1000 V	Circuit breaker[a]	2	1.3
	Current-limiting fuse	$\frac{1}{2}$	1.4
Above 1000 V	Air circuit breaker	5	1.15
	Oil circuit breaker	8	1.1
	Power fuse	1	1.6
	Current-limiting fuse	$\frac{1}{2}$	1.6

[a] Noncurrent-limiting type.

Repeat Example 11.5 except that the insulation is the cross-linked synthetic polymer type.

Determine the symmetrical short-circuit current rating of a 250 MCM copper conductor with thermoplastic insulation on a 480 V feeder protected by a circuit breaker.

From Figure 11.6, using the same values as in Example 11.5, the intersection of the lines gives 95 × 1000 A. Using Equation 11.1,

$$I_{SYM} = \frac{95{,}000}{1.3} = 73{,}100 \text{ A}$$

Determine the symmetrical short-circuit current rating of a No. 1/0 aluminum conductor with cross-linked synthetic polymer insulation on a 4160 V feeder protected by an oil circuit breaker.

Determine the symmetrical short-circuit current rating of a No. 1/0 aluminum conductor with cross-linked synthetic polymer insulation on a 4160 V feeder protected by an oil circuit breaker.

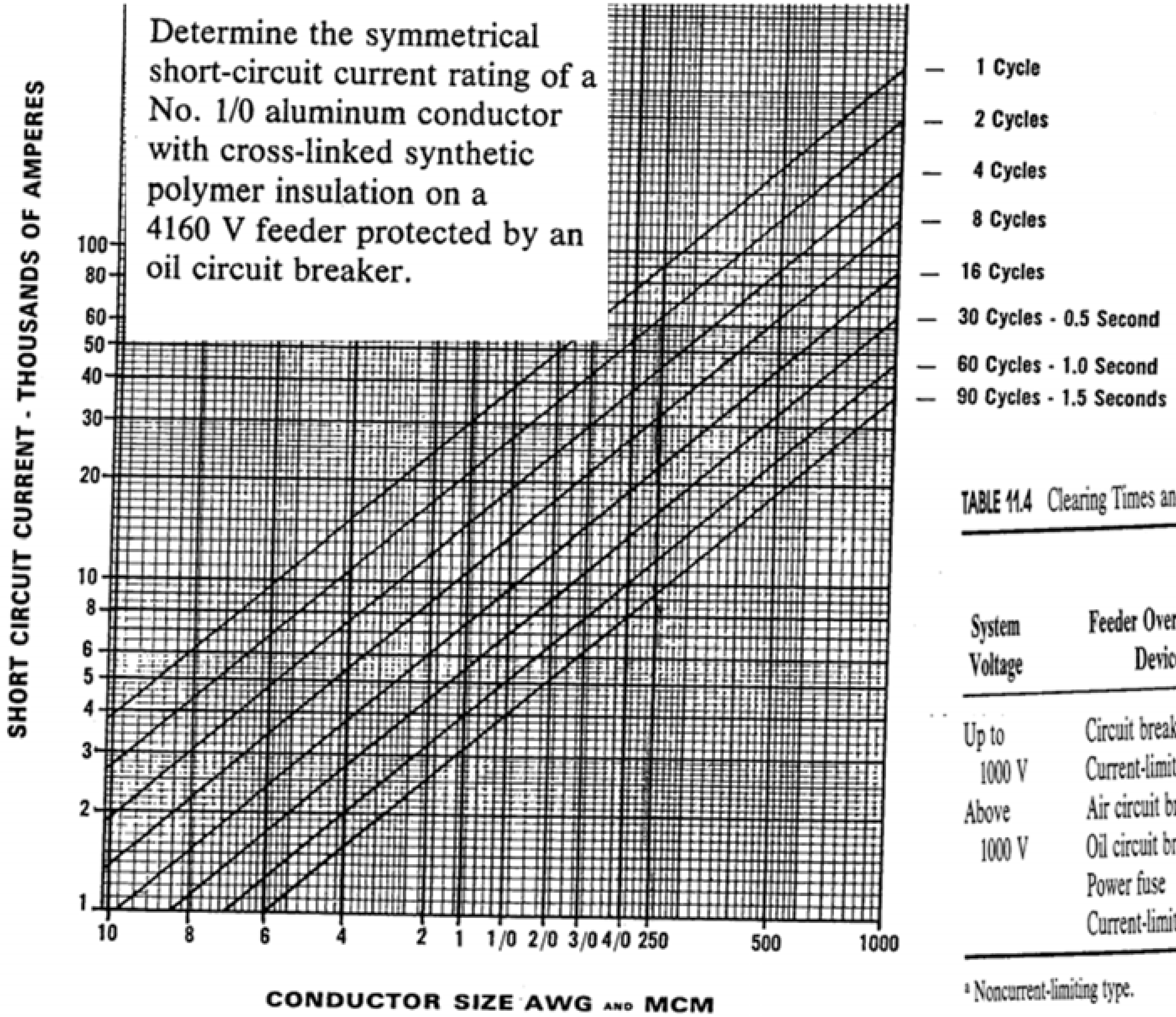


TABLE 11.4 Clearing Times and K_0 Factors

System Voltage	Feeder Overcurrent Device	Total Clearing Time (cycles)	K_0 Factor
Up to 1000 V	Circuit breaker[a]	2	1.3
	Current-limiting fuse	½	1.4
Above 1000 V	Air circuit breaker	5	1.15
	Oil circuit breaker	8	1.1
	Power fuse	1	1.6
	Current-limiting fuse	½	1.6

[a] Noncurrent-limiting type.

FIGURE 11.7

Allowable short-circuit currents for *aluminum* conductors with cross-linked synthetic polymer insulation [*NEC* type XHHW, CSA type RW90 (XLPE)]

Determine the symmetrical short-circuit current rating of a No. 1/0 aluminum conductor with cross-linked synthetic polymer insulation on a 4160 V feeder protected by an oil circuit breaker.

From Table 11.4, the clearing time is 8 cycles and K_0 is 1.1. From Figure 11.7, the point of intersection of the vertical line for No. 1/0 and the diagonal line for 8 cycles is 13.6 × 1000 A (I_{ASY}). Using Equation 11.1,

$$I_{SYM} = \frac{13,600}{1.1} = 12,400\text{ A}$$

MAXIMUM ALLOWABLE VOLTAGE DROP

It is very important to have the correct voltage at the outlet that serves a piece of utilization equipment. Most equipment is voltage sensitive, and an excessive voltage drop impairs the starting and operation of the equipment. See Section 2.9 with regard to motors and their rated voltages. See Chapter 4 with regard to light sources: Section 4.1.4 for incandescent lamps, Section 4.3.8 for fluorescent lamps, and Section 4.5.1 for mercury lamps. The *National Electrical Code* recommends a maximum voltage drop of 3% for any one branch circuit or feeder with a maximum voltage drop from the service entrance to the utilization outlet of 5% [*NEC* Sections 210-19(a) and 215-2(b)].

TABLE 11.5 Voltage Drops for 60 Hz Systems*

Size AWG or MCM	COPPER						ALUMINUM					
	Magnetic Conduit or Armour			Non-Mag. Conduit or Armour			Magnetic Conduit or Armour			Non-Mag. Conduit or Armour		
	80% P.F.	90%P.F.	100% P.F.	80% P.F.	90% P.F.	100% P.F.	80% P.F.	90% P.F.	100% P.F.	80% P.F.	90% P.F.	100% P.F.
14	2.540	2.790	3.067	2.535	2.780	3.060						
12	1.570	1.749	1.917	1.565	1.749	1.923	2.460	2.748	3.020	2.448	2.743	3.020
10	.993	1.103	1.200	.987	1.103	1.201	1.553	1.732	1.900	1.547	1.726	1.900
8	.635	.699	.750	.629	.693	.751	.993	1.103	1.195	.981	1.091	1.195
6	.421	.462	.485	.461	.456	.485	.647	.710	.762	.641	.710	.768
4	.277	.300	.306	.271	.294	.306	.421	.456	.491	.410	.450	.479
2	.185	.196	.196	.179	.191	.191	.271	.294	.300	.266	.289	.306
1	.150	.162	.150	.150	.156	.150	.225	.237	.242	.219	.231	.242
1/0	.127	.133	.121	.121	.127	.121	.185	.196	.191	.179	.191	.191
2/0	.109	.110	.098	.098	.104	.092	.150	.156	.150	.144	.150	.150
3/0	.092	.092	.081	.081	.087	.075	.127	.133	.121	.121	.127	.121
4/0	.081	.075	.064	.069	.069	.057	.104	.104	.098	.098	.104	.098
250	.070	.070	.054	.064	.064	.051	.092	.092	.081	.086	.087	.081
300	.064	.064	.045	.056	.055	.042	.081	.081	.069	.075	.075	.069
350	.058	.055	.039	.051	.049	.036	.075	.075	.058	.069	.069	.057
400	.055	.051	.035	.047	.044	.032	.069	.069	.053	.064	.064	.050
500	.049	.045	.029	.042	.039	.026	.058	.057	.043	.053	.051	.040
600	.046	.041	.024	.038	.034	.022	.055	.051	.036	.048	.046	.034
700	.043	.038	.021	.036	.032	.019	.051	.047	.032	.044	.041	.029
750	.042	.037	.020	.034	.031	.017	.049	.046	.030	.042	.039	.028
1000	.038	.032	.016	.029	.025	.013	.044	.040	.024	.039	.036	.024

* Values are per 1000 ampere-feet for three single conductors in conduit.

1. Values are based on three-phase, line-to-neutral voltages. For line-to-line voltage drops, multiply by a factor of 1.73. For single-phase circuits, multiply by a factor of

Calculate the percentage voltage drop on a 60 Hz, 480 V, three-phase feeder, load current 100 A, power factor of load 100%, length 300 ft, consisting of three No. 2 copper conductors rated for 75°C operation installed in steel conduit.

Calculate the percentage voltage drop on a 60 Hz, 480 V, three-phase feeder, load current 100 A, power factor of load 100%, length 300 ft, consisting of three No. 2 copper conductors rated for 75°C operation installed in steel conduit.

From Table 11.5, column 4 (copper, magnetic conduit, 100% P.F.), the voltage drop/1000 ampere-feet for No. 2 is 0.196. From note 2, no correction is needed for 75°C.

Ampere-feet = $100 \times 300 = 30{,}000 = 30 \times 1000$

Voltage drop (line to neutral) = $30 \times 0.196 = 5.88$ V

Voltage drop (line to line) = $1.73 \times 5.88 = 10.2$ V (note 1)

The 10.2 V represents the difference between V_S and V_L. Using Equation 11.2,

$$\% \text{ voltage drop} = \frac{10.2}{480} \times 100 = 2.1\%$$

Calculate the percentage voltage drop on a 60 Hz, 208 V, three-phase feeder, load current 290 A, power factor 90% lagging, length 150 ft, consisting of three 250 MCM copper conductors rated for 90°C operation installed in aluminum conduit.

Calculate the percentage voltage drop on a 60 Hz, 208 V, three-phase feeder, load current 290 A, power factor 90% lagging, length 150 ft, consisting of three 250 MCM copper conductors rated for 90°C operation installed in aluminum conduit.

From Table 11.5, column 6 (copper, nonmagnetic conduit, 90% P.F.), the voltage drop/1000 ampere-feet for 250 MCM is 0.064. From note 2, the correction for 90°C is 1.1 × 0.064 = 0.070.

Amperere-feet = 290 × 150 = 43,500 = 43.5 × 1000

Voltage drop (line to neutral) = 43.5 × 0.070 = 3.05 V

Voltage drop (line to line) = 1.73 × 3.05 = 5.3 V

Using Equation 11.2,

$$\% \text{ voltage drop} = \frac{5.3}{208} \times 100 = 2.5\%$$

LETTER DESIGNATION OF CABLES

According to the type of insulation material:
A, asbestos
MI, mineral insulation
R, rubber
SA, silicone asbestos (rubber)
T, thermoplastic
V, varnished cambric
X, cross-linked synthetic polymer
According to conditions of use:
H, heat resistant up to 75°C
HH, heat resistant up to 90°C (Note: no designation indicates 60°C)
UF, suitable for underground, direct burial
W, moisture resistant, suitable for use in wet locations

—THW: thermoplastic insulation, rated for maximum operating temperature of 75°C and suitable for use in wet locations (also dry locations).

—XHHW: cross-linked synthetic polymer insulation, rated for maximum operating temperature of 90°C and suitable for use in wet locations. However, see the asterisk (*) beside this type and the footnote in the table to the effect that the 90°C ampacity applies only in dry and damp locations and that the 75°C ampacity must be used in wet locations.

In addition to the insulation around the conductor, some types of cables have an outer jacket or sheath, either enclosing a single conductor or a group of individually insulated conductors, as shown in Figure 11.2. These outer coverings provide mechanical and/or corrosion protection. The following letters identify some of these types of cables:

—AC, armored cable (flexible metallic interlocked armor sheath)
—L, lead sheath
—MC, metal-clad cable (metallic sheath of interlocking tape or a smooth or corrugated tube)
—NM, nonmetallic sheath cable (moisture resistant, flame retardant)
—N, cables with nylon jacket

Care must be taken in identifying some of the letter combinations. For example, with type MI, the M stands for ‘‘mineral,’’ whereas with type MC, the M stands for ‘‘metal.’’ For a full description of all types of insulated conductors and their uses, refer to the *National Electrical Code*, Article 310 and Table 310-13.

RACEWAYS

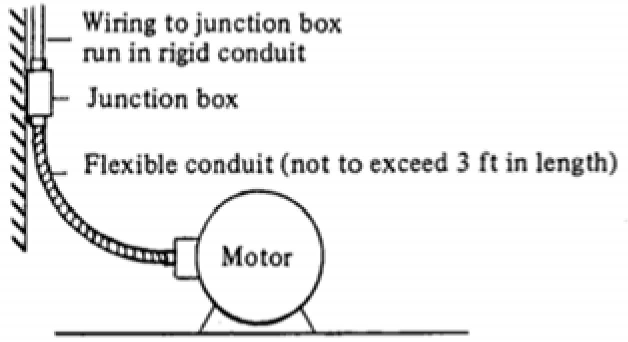
The *NEC* defines a *raceway* as *an enclosed channel designed expressly for holding wires, cables, or busbars*. Raceways may be constructed from metal or insulating material. Raceways may be rigid or flexible conduit, tubing, underfloor raceways, cellular floor raceways, wireways, and busways. The most common type of raceway for general wiring is the conduit, which in effect is a pipe or tube through which the insulated conductors are pulled, as shown in Figure 11.3.

Types of Conduit

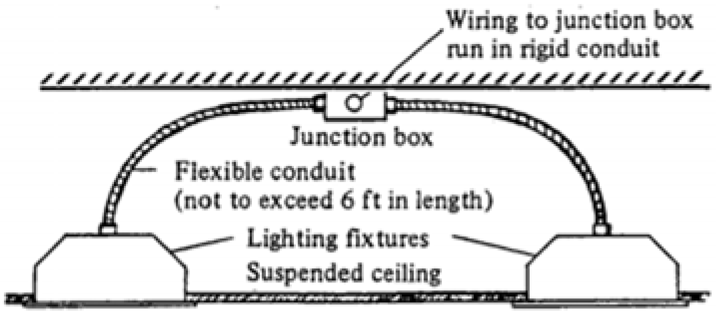
1. *Rigid metal conduit* (either steel or aluminum) has the thickest wall of all types and can be threaded so that joints can be made very secure and tight.
2. *Intermediate metal conduit* is a thinner-walled rigid metal conduit and may be used the same as rigid metal conduit.
3. *Electrical metallic tubing* (EMT) is a metal conduit with much thinner walls. In fact it is also referred to as thin-wall conduit. Connections are simplified by using threadless components of the compression, indentation, or set-screw type. The lighter weight of EMT is also a decided advantage during installation. However, its thin-wall construction makes it less able to withstand punishment. The *NEC* therefore restricts the use of EMT to areas where it will not be subjected to severe physical damage during installation or after installation.

4. *Rigid nonmetallic conduit* is made of nonmetallic material such as fiber, asbestos cement, and rigid polyvinyl chloride (PVC). Only PVC, however, is permitted to be used both underground and above ground. Rigid nonmetallic conduit cannot be used where subject to physical damage unless approved for such use.
5. *Electrical nonmetallic tubing* is a pliable corrugated raceway of circular cross section that can be bent by hand with a reasonable force. This type can be concealed within walls, ceilings, and floors where the floor, wall, or ceiling provides a thermal barrier of material that has at least a 15-minute fire rating.

6. *Flexible conduit* is constructed so that it can be readily flexed and therefore is not affected by vibration. A common application is for the final connection to a motor, as shown in Figure 11.9(a). The flexible conduit isolates the rigid conduit distribution system from the vibrations and movement of the motor. Another use is for the final connections to recessed lighting fixtures, as shown in Figure 11.9(b). The flexible conduit can be either metallic or nonmetallic. Liquid-tight flexible metal conduit is a special form that allows it to be used where protection from liquids or vapors is required. The *NEC* restricts the use of flexible metal conduit as an equipment grounding conductor, often requiring that an additional grounding jumper be installed (see *NEC* Sections 350-5 and 351-9).



(a) Connection to motor



(b) Connections to lighting fixtures

A three-phase, four-wire feeder requires No. 4/0 type THW conductors. Determine the trade size of conduit required for the feeder.

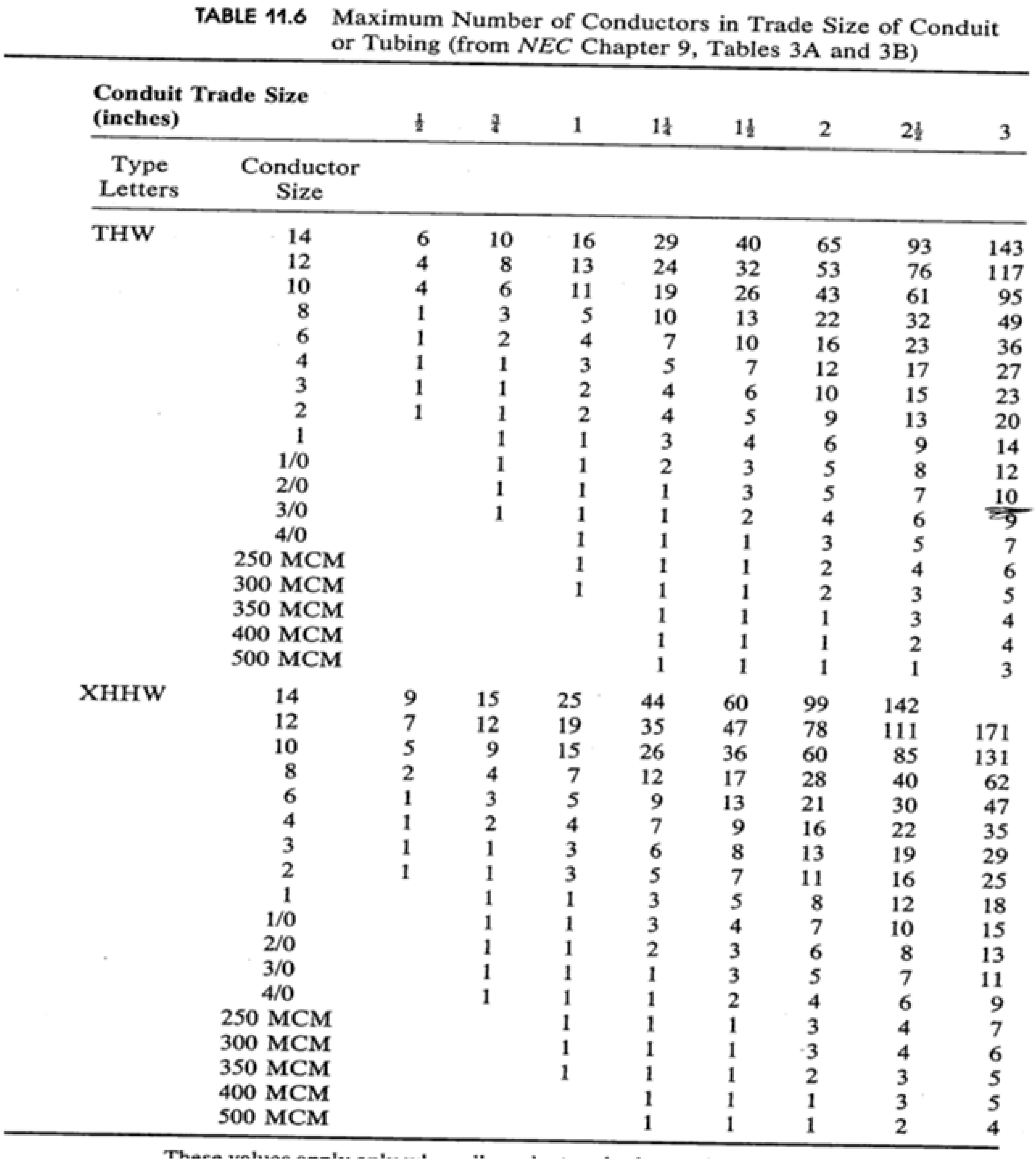


TABLE 11.6 Maximum Number of Conductors in Trade Size of Conduit or Tubing (from *NEC* Chapter 9, Tables 3A and 3B)

Conduit Trade Size (inches)		½	¾	1	1¼	1½	2	2½	3
Type Letters	Conductor Size								
THW	14	6	10	16	29	40	65	93	143
	12	4	8	13	24	32	53	76	117
	10	4	6	11	19	26	43	61	95
	8	1	3	5	10	13	22	32	49
	6	1	2	4	7	10	16	23	36
	4	1	1	3	5	7	12	17	27
	3	1	1	2	4	6	10	15	23
	2	1	1	2	4	5	9	13	20
	1		1	1	3	4	6	9	14
	1/0		1	1	2	3	5	8	12
	2/0		1	1	1	3	5	7	10
	3/0		1	1	1	2	4	6	9
	4/0			1	1	1	3	5	7
	250 MCM			1	1	1	2	4	6
	300 MCM			1	1	1	2	3	5
	350 MCM				1	1	1	3	4
	400 MCM				1	1	1	2	4
	500 MCM				1	1	1	1	3
XHHW	14	9	15	25	44	60	99	142	
	12	7	12	19	35	47	78	111	171
	10	5	9	15	26	36	60	85	131
	8	2	4	7	12	17	28	40	62
	6	1	3	5	9	13	21	30	47
	4	1	2	4	7	9	16	22	35
	3	1	1	3	6	8	13	19	29
	2	1	1	3	5	7	11	16	25
	1		1	1	3	5	8	12	18
	1/0		1	1	3	4	7	10	15
	2/0		1	1	2	3	6	8	13
	3/0		1	1	1	3	5	7	11
	4/0		1	1	1	2	4	6	9
	250 MCM			1	1	1	3	4	7
	300 MCM			1	1	1	3	4	6
	350 MCM			1	1	1	2	3	5
	400 MCM				1	1	1	3	5
	500 MCM				1	1	1	2	4

A three-phase, four-wire feeder requires No. 4/0 type THW conductors. Determine the trade size of conduit required for the feeder.

A three-phase, four-wire feeder requires No. 4/0 type THW conductors. Determine the trade size of conduit required for the feeder.

Four conductors have to be installed in the conduit (the neutral must be counted). From Table 11.6, for type THW, size 4/0, a 2 in. conduit can only accommodate three conductors; therefore, a $2\frac{1}{2}$ in. conduit (maximum of 5) is required. A common method of indicating the above feeder on a one-line diagram is as follows: $\underline{2\frac{1}{2}\text{" C, 4 -\#4/0, THW}}$

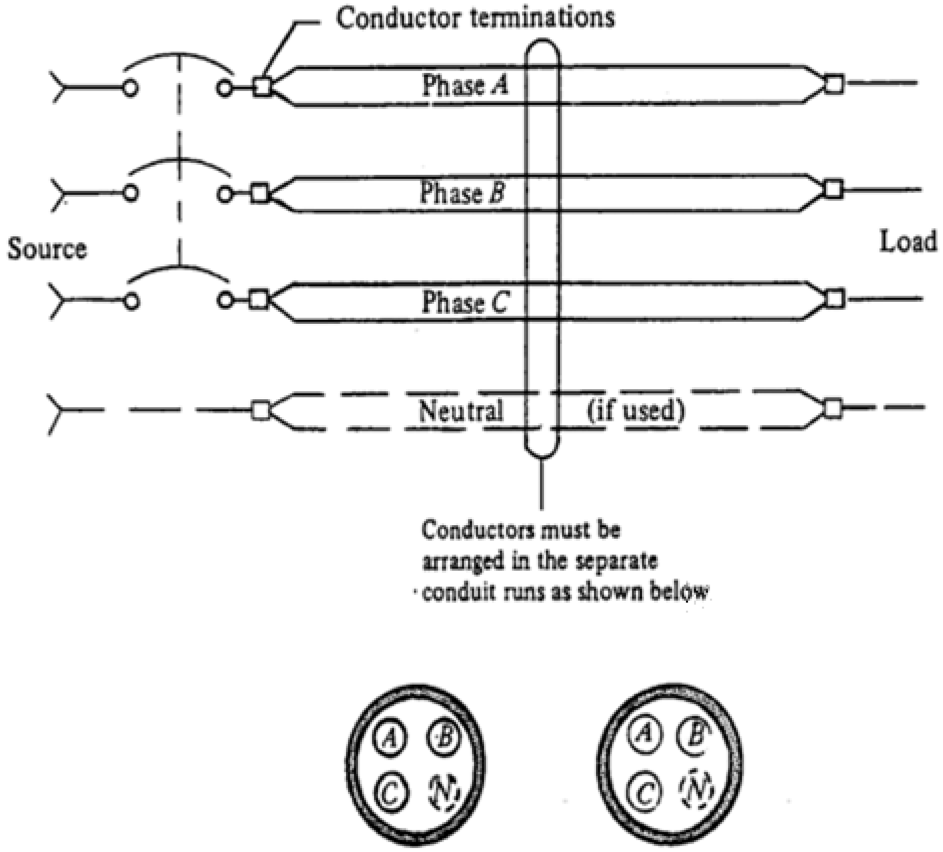


FIGURE 11.11

Conductors run in parallel

circuit breaker responds to heat, no matter how it is generated, the protective device may no longer be able to continuously carry its rated current. Therefore, *NEC* Section 220-10(b) requires that the rating of the overcurrent device for a feeder supplying a continuous load shall not be less than 125% of the continuous load current. Continuous loads are discussed in Section 11.7. This in effect means that the protective device cannot be continuously loaded beyond 80% of its rating. The *NEC* allows an exception to this 80% derating rule:

> That where the assembly, including the overcurrent devices protecting the feeder, are listed [that is, approved] for continuous operation at 100% of their rating, then the feeder can be loaded to 100% of its ampacity rating.

However, to date the only fusible equipment that has UL approval for 100% continuous operation is some large bolted-pressure switches rated above 600 amperes and using class L fuses. Also, only low-voltage power and encased-type circuit breakers (Sections 8.5 and 8.8) have UL approval for 100% continuous operation. This is an area that requires a lot more attention by manufacturers and the standards agencies. The 80% derating causes extra costs for electrical systems in requiring oversized feeders, switches, fuses, circuit breakers, panelboards, and the like, when supplying continuous loads.

EXAMPLE 11.11

Select the size of the conductors and conduit for the feeder required for the following:

- Load is 100 kW at 90% power factor and is noncontinuous.
- Load is less than 50% ballast-type lighting and there are no other loads that cause third harmonics.
- Supply is three-phase, four-wire, 480Y/277 V.
- Length of feeder is 250 ft and it is to be run above grade.
- Available short-circuit current is 17,000 A symmetrical.
- Feeder overcurrent protection is a molded-case breaker.
- Maximum allowable voltage drop is to be 2%.
- Conductors to be copper, type THW in steel conduit.

Using Equation 1.12,

$$I_L \text{ (of load)} = \frac{100 \times 1000}{(1.73)(480)(0.9)} = 134 \text{ A}$$

(a) Minimum size required for ampacity:

- Minimum ampacity for noncontinuous load is 100%: 134 A.
- Neutral does not count as a fourth current-carrying conductor.
- From Table 11.1, minimum size is No. 1/0 (rated for 150 A).

(b) Minimum size required for short-circuit current:

- From Table 11.4, K_0 factor is 1.3, clearing time is 2 cycles.
- Using Equation 11.1,

$$I_{ASY} = 1.3 \times 17{,}000 = 22{,}100 \text{ A}$$

- From Figure 11.5, minimum size is No. 1 (see Figure 11.12 for method of reading the short-circuit graph).

(c) Minimum size required for voltage drop:

- Maximum allowable = 2% of 277 = 5.54 V (line-to-neutral).
- Ampere-feet = 134 × 250 = 33,500 = 33.5 × 1000.
- Maximum voltage drop/1000 AF = 5.54/33.5 = 0.165.
- From Table 11.5, minimum size is No. 1 with value of 0.162.

(d) Therefore, the ampacity requires the largest size: No. 1/0.

(e) From Table 11.6, the size of conduit is 2 in. for four conductors.

Feeder designation: 2″ C, 4 -#1/0, THW (Cu)

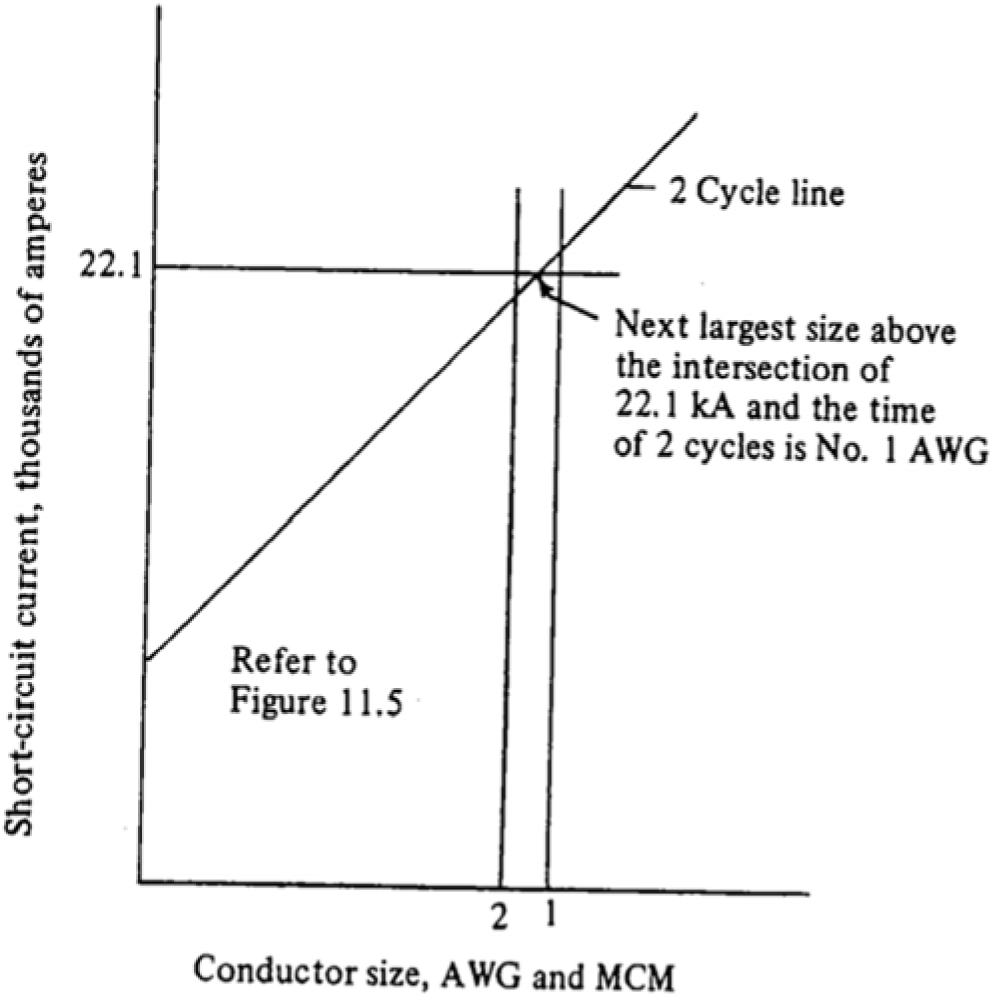
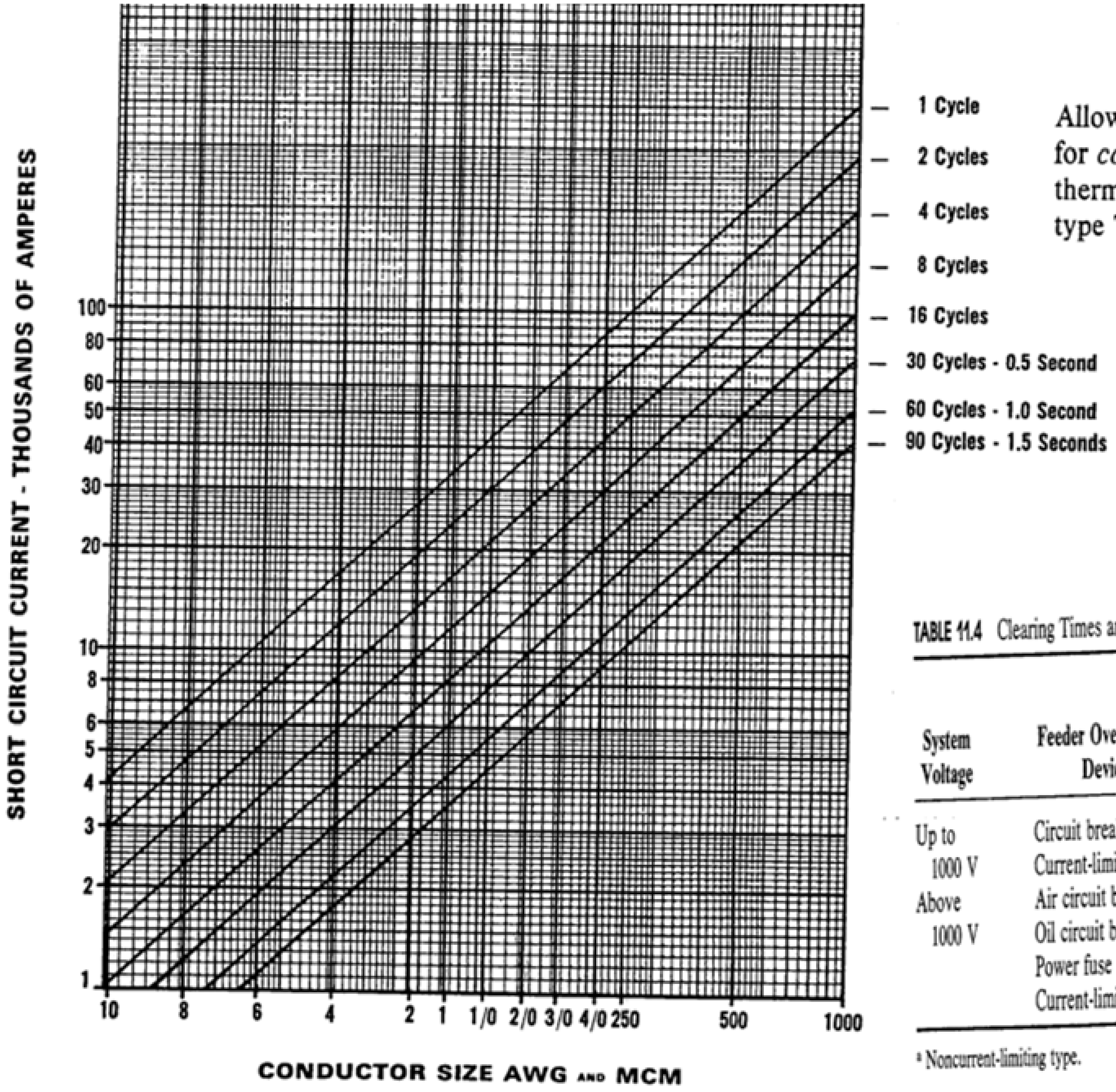


FIGURE 11.12

Determining the minimum conductor size for the short-circuit current in Example 11.11



Allowable short-circuit currents for *copper* conductors with thermoplastic insulation (*NEC* type THW, CSA type TW75)

FIGURE 11.5

TABLE 11.4 Clearing Times and K_0 Factors

System Voltage	Feeder Overcurrent Device	Total Clearing Time (cycles)	K_0 Factor
Up to 1000 V	Circuit breaker[a]	2	1.3
	Current-limiting fuse	$\frac{1}{2}$	1.4
Above 1000 V	Air circuit breaker	5	1.15
	Oil circuit breaker	8	1.1
	Power fuse	1	1.6
	Current-limiting fuse	$\frac{1}{2}$	1.6

[a] Noncurrent-limiting type.

EXAMPLE 11.12

Repeat Example 11.11, except the available short-circuit current is 35,000 A symmetrical.

Solution

(a) Minimum size for ampacity same as in Example 11.11: No. 1/0.

(b) Minimum size required for short-circuit current:

— K_0 factor and clearing time same as in Example 11.11.
— Using Equation 11.1,

$$I_{ASY} = 1.3 \times 35{,}000 = 45{,}500 \text{ A}$$

— From Figure 11.5, minimum size is No. 3/0.

(c) Minimum size for voltage drop same as in Example 11.11: No. 1.

(d) Therefore, short-circuit current requires largest size: No. 3/0.

(e) From Table 11.6, the size of conduit is 2 in. for four conductors.

Feeder designation: 2″ C, 4 -#3/0 THW (Cu)

Select the molded-case circuit breaker ratings for overcurrent protection of the feeder in Example 11.15. Note that molded-case breakers are not normally UL listed for 100% continuous operation.

EXAMPLE 11.15

Repeat Example 11.11, except that the 100 kW load is continuous and consists of more than 50% electric discharge type of lighting. Consider both types THW and XHHW conductors (dry location).

Solution

The load has same full-load current of 134 A.

(a) Minimum size required for ampacity:

- Minimum ampacity for continuous load = 125% of 134 = 167.5 A.
- Neutral must be counted as fourth current-carrying conductor.
- From Table 11.3(b), the ampacity adjustment factor is 80% (0.80).
- Rating to select from Table 11.1 is 167.5/0.80 = 209 A.
- THW minimum size is No. 4/0 (rating in table of 230 A).
- XHHW minimum size is No. 3/0 (rating in table of 225 A) (satisfactory for equipment terminals; see Section 11.1.7).

(b) Minimum size required for short-circuit current:

- I_{ASY} = 22,000 A, same as in Example 11.11.
- THW from Figure 11.5, minimum size is No. 1, same as in Example 11.11.
- XHHW from figure 11.6, minimum size is No. 2.

(c) Minimum size required for voltage drop (still based on actual load current of 134 A):

- Maximum voltage drop/1000 AF = 0.165, same as in Example 11.11.
- THW minimum size is No. 1, same as in Example 11.11.
- XHHW correction factor for 90°C is 1.1 (note 2, Table 11.5). The value for use in Table 11.5 = 0.165/1.1 = 0.150. The minimum size is No. 1/0 with a value of 0.133.

(d) Summary

	THW	XHHW
Ampacity	4/0	3/0
Short circuit	1	2
Voltage drop	1	1/0

Therefore, the preferred selection is No. 3/0 XHHW.

(e) From Table 11.6, the conduit size is 2 in. for four conductors.

Feeder designation: 2″ C, 4 -#3/0 XHHW (Cu)

EXAMPLE 11.17

Select the molded-case circuit breaker ratings for overcurrent protection of the feeder in Example 11.15. Note that molded-case breakers are not normally UL listed for 100% continuous operation.

Solution

- — The minimum trip rating for the breaker is 125% of 134 = 167.5 A.
- — From Table 8.1, the next highest standard trip rating is 175 A (the ampacity of the four #3/0 XHHW in conduit is 0.80 × 225 = 180 A).
- — The frame size required for the 175 A trip is 225 A, which has an interrupting rating of 22,000 A symmetrical at 480 V (Table 8.1), which is satisfactory for the available short-circuit current of 17,000 A symmetrical (from Example 11.11).

Standard trip ratings: 15, 20, 25, 30, 35, 40, 50, 60, 70, 80, 90, 100, 125, 150, 175, 200, 225, 250, 300, 350, 400, 450, 500, 600, 800, 1000, and 1200 amperes.

Manufacturers should be consulted for confirmed ratings.

TABLE 8.1 Frame Sizes and Typical Ratings for Industrial-Type Molded-Case Circuit Breakers

Frame Size (A)	Rated Voltage (V)	Range of Trip Ratings (A)	Dimensions (in.)			Interrupting Ratings (rms symmetrical amperes)		
			W	*H*	*D*	240 V[a]	480 V[a]	600 V[a]
100 Std 100 HIC	240	15–100	4⅛	6	3⅜	10,000 65,000	— —	— —
100 Std	480	15–100	4⅛	6	3⅜	18,000	14,000	—
150 Std 150 HIC	600	15–150	4⅛	6	3⅜	18,000 65,000	14,000 25,000	14,000 18,000
225 Std 225 HIC	600	70–225	4⅛	10	4 1/16	25,000 65,000	22,000 25,000	18,000 22,000
400 Std 400 HIC	600	125–400	5½	10⅛	4 1/16	42,000 65,000	30,000 35,000	22,000 25,000
600 Std 600 HIC	600	250–600	8¼	10¾	4 1/16	42,000 65,000	30,000 35,000	22,000 25,000
800 Std 800 HIC	600	400–800	8¼	16	4 1/16	42,000 65,000	30,000 50,000	22,000 25,000