DDS300-2

DESIGN DATA SHEET

FAULT CURRENT CALCULATIONS AND PROTECTIVE DEVICE COORDINATIONS FOR 60 AND 400 HZ POWER SYSTEMS SUPPLIED BY ROTATING MACHINERY

DEPARTMENT OF THE NAVY
NAVAL SEA SYSTEMS COMMAND
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DDS 300-2: CALCULATION OF FAULT CURRENTS AND COORDINATION OF PROTECTIVE DEVICES FOR 60 AND 400 HZ POWER SYSTEMS SUPPLIED BY ROTATING MACHINERY

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300-2-a. References.

(a) American National Standards Institute, ANSI C37.010(1979) Application Guide for AC High Voltage Circuit Breakers Rated on a Total Current Basis.

(b) DDS 314-1 - Calculations of Fault Currents and Coordinations of Protective Devices for 400 Hz Power Systems Supplied by Solid State Frequency Changers

(c) MIL-C-17587(SH) - Circuit Breakers, Air, Electric, Open Frame (Shipboard Use)

(d) MIL-C-17361(SH) - Circuit Breakers, Air, Electric, Insulated housing, (Shipboard Use)

(e) MIL-C-17588(SH) - Circuit Breaker (Automatic - ALB-1) and Switch, Toggle (Circuit Breaker, Non-automatic - NLB-1) Air, Insulated Housing, 125 Volts and Below, AC and DC (Naval Shipboard Use), General Specification for

(f) MIL-F-15160 - Fuses, Instrument, Power, and Telephone

(g) MIL-G-3124 - Generator, Alternating Current, 60 Cycle (Naval Shipboard Use)

(h) MIL-M-17060 - Motors, 60 Hz, Alternating-current, Integral Horsepower

(i) MIL-M-19633(SH) - Motor-Generator, 60 Cycle, AC to 400 Cycle, AC (Voltage and Frequency Regulated) Ship Service

(j) MIL-HDBK-299(SH) - Cable Comparison Handbook, Data Pertaining to Electric Shipboard Cables

(k) MIL-T-15108(SH) - Transformer, Power, 60 Hertz, Dry-Type, general Specification for

(l) Bureau of Ships Plan No. 94000-S6100-554762 - Short-circuit Characteristics, Ship's Service and Emergency Service Generators

(m) MIL-T-17221(SH) - Transformers, Power, Distribution; Single Phase, 400 Hertz, Insulation System Class 200° C, Dry, (Air Cooled) (Naval Shipboard Use)

(n) Ship Specifications of the US Navy, Section 303

(o) Insulated Power Cable Engineers Association - Short-circuit Characteristics of Insulated Cable

(p) IEEE STD 399-1980 - Industrial And Commercial Power System analysis

300-2-b. Scope.

This Design Data Sheet covers methods for fault current calculations and protective device coordinations for 60 and 400 Hz systems powered by rotating machinery. For 400 Hz systems supplied by Solid State Frequency Changers, use reference (b).

300-2-c. Definitions.

Average Fault Current - The average rms value of the three phase currents at the first 1/2 cycle after fault inception (calculated with maximum fault current conditions).

Bus - A conductor or group of conductors, that serves as a common connection for two or more circuits.

Coordination - The selection and setting of protective devices such as circuit breakers, fuses, etc., so that damage due to fault currents is minimized, and the minimum amount of equipment will be removed from service during the fault.

Fault - The condition at which a relatively low impedance occurs between two points of different voltage potential.

Fault Impedance - The vectorial combination of component impedances from a fault location to a power source.

Instantaneous Rating (INST) - Current value which initiates tripping of a circuit breaker without intentional delay.

Interrupting Rating (INTR) - The maximum rms value of current at rated voltage and frequency, that a protective device can safely interrupt and continue to safely carry rated current.

K_1 - Ratio of the average fault current (I_{avg}) to the symmetrical current (I_{sym}).

K_2 - Ratio of the maximum fault current (I_{max}) to the symmetrical current (I_{sym}).

Long Time Delay (LTD) - The time that a circuit breaker trips in the overload current region.

Long Time Pickup Current (LTPU) - Minimum current at which the circuit breaker trip element will operate.

Maximum Fault Current (I_{max}) - Maximum asymmetrical current in rms generated at the first 1/2 cycle after the fault inception.

Maximum Generator Short-Circuit Current (I_T") - Maximum available rms short-circuit current of a ship service generator at a switchboard at the first 1/2 cycle after the fault inception in a phase having the maximum asymmetrical current.

Minimum Fault Current (I_{min}) - Symmetrical rms current on a circuit generated by a minimum source (one generator) at the first 1/2 cycle after fault inception.

Miscoordination - A lack of coordination in a protective system as evidenced by an overlapping of the time-current curves of two or more protective devices in series.

Resultant Load Current - The product of the total connected load currents and a demand factor applicable to each connected load.

Short-Circuit - A zero-impedance fault.

Short Time Delay (STD) - The minimum elapsed time by which a circuit breaker trip is delayed for a specific current setting.

Short Time Pickup Current (STPU) - The rms current setting at which a protective device will initiate for a specified delay time.

Sustained Generator Short-Circuit Current (I_s) - The value of the steady-state short-circuit current shall be determined on the assumed condition of a three-phase fault at the line terminal of the generator circuit breaker, and shall include the effect of the generator voltage regulator, using the value of field resistance with a hot field.

Symmetrical Fault Current (I_{sym}) - Symmetrical rms current generated at the first 1/2 cycle after fault inception. This current does not include the dc component of the fault current.

300-2-d. Symbols and Abbreviations.

Symbols	Description	Unit
CONT	Circuit breaker or fuse continuous current rating	A
E_C	Generator or ship service switchboard terminal voltage (line-to-line)	V
G	Ship service generator (G1, G2, G3,...)	-
I_L	Load current	A
I_{lr}	Motor locked rotor current	A
I_n	Generator or equipment full load current	A
M	Grouped motors (M1, M2, M3,...)	-
MG	Motor generator set (MG1, MG2, MG3,...)	-
P	Equipment power rating (P_G, P_{MG}, P_M)	kW
R_a	Generator armature resistance per phase	Ω
kVA_{base}	System or equipment complex power base rating	kVA
TRE	Circuit breaker trip element	-
kV_{base}	System base line-to-line voltage	kV
X_d''	Generator direct axis subtransient reactance per phase	Ω
Z_{base}	System base impedance per phase	Ω
Z_C	Cable impedance (Z_{C1}, Z_{C2}, Z_{C3},...) per phase	Ω
Z_F	Equivalent impedance (Z_{F1}, Z_{F2}, Z_{F3},...) from the source to the fault location	Ω

Z_M	Grouped motor impedance per phase (Z_{M1}, Z_{M2}, Z_{M3}...)	Ω
Z_{pu}	Per unit impedance	-
Z_G	Generator impedance per phase (Z_{G1}, Z_{G2}, Z_{G3}, ...)	Ω
Z_T	Transformer impedance per phase	Ω

300-2-e. General.

Fault currents are generated when an unintentionally low or zero impedance path between phases occurs due to equipment or cable failures in the power distribution system. If not isolated quickly, the over-current from the fault or short-circuit may damage the power generation and distribution system. The fault current is mainly limited by the internal impedances of the generators or motors and the impedance of the system components. Fault current calculations are required to determine the type, rating, and tripping characteristics of protective devices in the power system. The fault current calculations are also required to determine the short-circuit rating of bus transfer switches, the interrupting rating of fuses, and the short time rating and mechanical strength of switches, cables, and bus work.

In calculating the fault currents on ships' power distribution systems, it is necessary to determine not only the contribution of generating equipment, but also that of induction and synchronous motors. The motor contribution must also be considered due to high speed operation of certain protective devices.

The power system impedance modeling procedure and fault current calculations that follow are consistent with the format of most commercially available fault current calculation computer programs.

300-2-f. Fault Current Calculations.

Fault current calculations are made to determine the magnitude of currents I_{min}, I_{sym}, I_{avg}, and I_{max} at any fault location in the system under the following conditions of fault generation:

1. Minimum Fault Generation.

The fault current I_{min} is calculated under conditions which generate the minimum fault current, and include the following assumptions:

- One generator having the lowest rating is connected to the system.
- The motor contribution is negligible.
- A line-to-line fault is located on the line side of the next protective device beyond the protective device in question or at the end of the cable supplied from the protective device in question.

2. Maximum Fault Generation.

The available fault currents I_{sym}, I_{avg}, and I_{max} are calculated under conditions which generate the maximum fault current, and include the following assumptions:

- A three-phase zero-impedance fault is located on the line terminal of the protective device in question.
- The maximum permissible number of generators having the largest total capacity and operating in parallel are connected to the system.
- The generators are operating at rated output and rated power factor before the fault inception.
- The maximum motor load contribution.

The following steps should be applied for the fault calculations:

Step 1: System Impedance Development.

1. System Impedance Diagram.

The impedances of system components (generators, motors, cables, transformers, etc.) are included in the system impedance diagram. The impedance for each component in the diagram is expressed in ohms per phase. Frequently, the system impedance and circuit components are expressed in percent or per unit associated with the system base kVA_{base} and the system line-to-line voltage base kV_{base}. To convert these quantities to ohmic values use the following equations:

$$Z_{\Omega} = Z_{pu} \times Z_{base} \qquad (1)$$

$$Z_{base} = \left(\frac{kV_{base}^2}{kVA_{base}} \right) \times 1000 \qquad (2)$$

$$Z_{\Omega} = Z_{pu} \left(\frac{kV_{base}^2}{kVA_{base}} \right) \times 1000 \qquad (3)$$

$$X_{\Omega} = Z_{\Omega} \sin(\tan^{-1}(X/R)) \qquad (4)$$

$$R_{\Omega} = Z_{\Omega} \cos(\tan^{-1}(X/R)) \qquad (5)$$

Notes: The (X/R) ratio is based on the rated voltage, power, and current of the equipment.

2. Component Impedance Calculations.

2.1 Generators & Synchronous Motors.

The impedance of a generator or synchronous motor is the vectorial combination of its armature resistance R_a and the subtransient reactance X_d''. The subtransient reactance and the ratio (X_d''/R_a) values listed in Tables I and II may be used to estimate the 60 and 400 Hz generators impedance when the actual values of X_d'' are not available. The reactance X_d'' is the most significant impedance in the fault analysis. The reactance values in Tables I and II are developed from references (g) and (h) based on the kVA rating of the machine having a power factor of 0.8.

TABLE I. Typical 60 Hz Generator Subtransient Reactance

Generator Rating		X_d'' (pu)		X_d''/R_a
kW	kVA	Minimum	Typical	
0-100	0-125	0.080	0.100	
101-500	126-625	0.100	0.130	1
501-850	626-1062	0.120	0.130	31
851-1500	1064-1852	0.126	0.150	31
1501-over	1876-over	0.132	0.170	31

TABLE II. Typical 400 Hz Generator Subtransient Reactance

Generator Rating			X_d''	X_d''	R_a	X_d''/R_a
kW	A	kVA	pu	Ω	Ω	
15	24	18.75	0.11	1.190	0.319	3.73
30	48	37.5	0.14	0.758	0.081	9.36
60	96	75	0.11	0.298	0.025	11.92
100	160	125	0.15	0.244	0.019	12.84
200	320	250	0.11	0.089	0.008	11.13
300	480	375	0.12	0.065	0.005	13.00

2.2 Induction Motors.

The operating induction motors in a distribution system are represented in the impedance diagram by assuming that the actual fault current contribution of the motors can be modeled by grouping the motors powered by each generator into one equivalent motor on the generator switchboard. The grouped motors for every operating 60 Hz generator switchboard is assumed to have ⅔ kVA of the generator kVA. This assumption is based on typical load analysis data which shows that under ship maximum power consumption, the connected kVA of operating motors represented approximately ⅔ of the rated kVA of the operating generator. A different percentage of assumed group-motor load may be used if adequately supported by load analysis data. The grouped motors are then assumed to have an impedance of 0.28 per unit on the grouped motors' kVA base with the ratio (X/R) of 8. Individual motors of specific interest may be represented separately if their connected kVA is subtracted from the assumed group-motor load kVA. Due to rarity and small horsepower ratings, 400 Hz motors may be omitted or modeled separately.

2.3 Cables.

Cable impedances may be obtained from reference (j).

2.4 Transformers.

In the fault calculation, the use of actual transformer impedance is recommended. Typical transformer impedances range from 2 to 7 percent. The transformer impedances may be available from reference (k) or 1(m). If not available, an estimated impedance of 2 percent and a (X/R) ratio of 3 may be used.

2.5 Circuit Breakers & Bus Work.

Typical circuit breaker and bus work impedances are listed in Table III. Note that the impedances of circuit breakers and switchboards are negligible compared to the impedances of sources, cables, and transformers. Rarely are the impedances of generators, motors, transformers, and cable lengths known to an accuracy which makes consideration of circuit breaker and switchboard impedances valid.

TABLE III - Typical Circuit Breaker Impedances for 60 Hz System

Circuit Breakers		Resistance	Reactance
Types	Rating (A)	(Ω)	(Ω)
ACB	All	0.000040	0.000100
AQB	250-600	0.000200	0.000050
AQB	125-225	0.000500	0.000100
AQB	75-100	0.000900	0.000100
AQB	> 50	0.001600	0.000150
AQB	< 50	0.008000	0.000300
ALB	35-50	0.002800	0.000010
ALB	< 35	0.010000	0.000010

Note: The reactance of bus work can be assumed to be equal to 0.000042Ω/ft and the resistance is negligible.

2.6 System Impedance Conversion.

The component impedances in the 120V system base should be converted to the 450V base by the following equation:

$$Z_{450} = Z_{120}\left(\frac{450}{120}\right)^2 \tag{6}$$

Step 2: Fault Calculations.

After the system impedance diagram is developed, the equivalent impedance between the source(s) and fault location is calculated. The equivalent impedance or fault impedance, Z_F, will determine the fault currents.

1. Calculations Under Minimum Generation.

1.1 Fault Impedance.

The fault impedance Z_F for minimum fault generation should include the following:

- Internal impedance of one of the lowest kW rating generators.
- Cable and transformer impedances from the source to the line side of the first protective device beyond the protective device in question, or to the end of cable supplied from the protective device in question.
- Impedances of protective devices and bus work are typically negligible, but may be included if known accuracy of other data or magnitude of impedance warrants.

The impedance Z_F for each fault location is calculated by combining all the component impedances in the fault circuit.

1.2 Minimum Fault Current.

The available minimum fault current, I_{min}, is used to determine the trip settings of protective devices. The protective devices should operate under the minimum fault condition.

The line-to-line fault current I_{min} is related to a three-phase fault current, $I_{3\phi}$, by the following equation:

$$\begin{aligned} I_{min} &= \left(\frac{\sqrt{3}}{2}\right) I_{3\phi} \\ &= \left(\frac{\sqrt{3}}{2}\right)\left(\frac{E_G/\sqrt{3}}{Z_F}\right) \\ &= (1/2)\left(\frac{E_G}{Z_F}\right) \end{aligned} \tag{7}$$

2. Calculations Under Maximum Fault Generation.

2.1 Fault Impedance.

The fault impedance Z_F (used for calculation of I_{sym}, I_{avg} and I_{max}) for maximum generation should include the following:

- Internal impedance of generators permitted to operate in parallel.
- Internal impedance of maximum number of synchronous motors.
- Internal impedance of grouped-motors with maximum kVA or assumed ⅔ kVA of the generator.
- Cable and transformer impedances from the sources to the load side of the protective device in question.
- Protective device and bus work impedances are generally negligible, but may be included if they are more than one percent of the fault impedance calculated without them.

2.2 K_1 & K_2 Determination.

The constants K_1 and K_2 are used to determine currents I_{avg} and I_{max} respectively. The factors K_1 and K_2 are also used to factor in the dc component of the fault current to check interrupting ratings of the circuit breakers. Once, the equivalent impedance Z_F for I_{sym} calculation is obtained, the ratio (X/R) is determined by taking the ratio (X_F/R_F) of Z_F.

The applicable K_1 and K_2 are then determined from the (X/R) ratios as shown in Table IV.

TABLE IV. **Conversion Factors for Symmetrical Currents to Asymmetrical Currents**

X/R	K_1	K_2	X/R	K_1	K_2
<1.0	1.000	1.000	10.0	1.230	1.438
1.0	1.001	1.002	10.2	1.232	1.442
1.2	1.003	1.005	10.4	1.235	1.447
1.4	1.006	1.011	10.6	1.237	1.451
1.6	1.010	1.020	10.8	1.239	1.455
1.8	1.015	1.030	11.0	1.241	1.459
2.0	1.021	1.042	11.2	1.244	1.463
2.2	1.028	1.056	11.4	1.246	1.467
2.4	1.036	1.070	11.6	1.248	1.471
2.6	1.043	1.086	11.8	1.250	1.475
2.8	1.051	1.101	12.0	1.252	1.478
3.0	1.059	1.116	12.2	1.254	1.482
3.2	1.067	1.132	12.4	1.255	1.485
3.4	1.075	1.147	12.6	1.257	1.488
3.6	1.082	1.162	12.8	1.259	1.491
3.8	1.090	1.176	13.0	1.261	1.494
4.0	1.097	1.190	13.2	1.262	1.498
4.2	1.104	1.203	13.4	1.264	1.500
4.4	1.111	1.216	13.6	1.266	1.503
4.6	1.118	2.229	13.8	1.267	1.506
4.8	1.124	1.241	14.0	1.269	1.509
5.0	1.130	1.253	14.2	1.270	1.512
5.2	1.136	1.264	14.4	1.272	1.514
5.4	1.142	1.275	14.6	1.273	1.517
5.6	1.147	1.285	14.8	1.274	1.519
5.8	1.153	1.295	15.0	1.276	1.522
6.0	1.158	1.305	15.2	1.277	1.524
6.2	1.163	1.314	15.4	1.278	1.526
6.4	1.167	1.323	15.6	1.280	1.529
6.6	1.172	1.331	15.8	1.281	1.531
6.8	1.176	1.339	16.0	1.282	1.533
7.0	1.181	1.347	16.2	1.283	1.535
7.2	1.185	1.355	16.4	1.284	1.537
7.4	1.189	1.362	16.6	1.286	1.539
7.6	1.192	1.369	16.8	1.287	1.541
7.8	1.196	1.376	17.0	1.288	1.543
8.0	1.200	1.383	17.2	1.289	1.545
8.2	1.203	1.389	17.4	1.290	1.547
8.4	1.206	1.395	17.6	1.291	1.549
8.6	1.210	1.401	17.8	1.292	1.551
8.8	1.213	1.407	18.0	1.293	1.553
9.0	1.216	1.412	19.0	1.297	1.560
9.2	1.219	1.418	20.0	1.301	1.568
9.4	1.222	1.423	25.0	1.318	1.598
9.6	1.224	1.428	30.0	1.336	1.630
9.8	1.227	1.433	35.0	1.339	1.634

The above data are developed from reference (a).

2.3 Symmetrical Fault Current.

The symmetrical fault current I_{sym} is required to determine the protective device trip settings and to calculate I_{avg} and I_{max}. I_{sym} is calculated as follows:

$$I_{sym} = \frac{1}{\sqrt{3}}\left(\frac{E_G}{Z_F}\right) \qquad (8)$$

2.4 Average Fault Current.

The average fault current I_{avg} is used to determine the interrupting rating of a circuit breaker and the short-circuit current rating of a bus transfer switch under maximum fault generation. As the calculation progresses, I_{avg} should be compared frequently with the maximum ratings of the devices selected to ensure a fully rated system. Once I_{sym} and K_1 are obtained, I_{avg} is calculated as follows:

$$I_{avg} = K_1 I_{sym} \qquad (9)$$

2.5 Maximum Fault Current.

The maximum fault current I_{max} is used to determine the required interrupting rating of fuses and the short time rating and mechanical strength of switches, cables and bus work under maximum fault generation. As the calculation progresses I_{max} should be compared with the maximum ratings of the devices selected to ensure a fully rated system. Once K_2 and I_{sym} are obtained, I_{max} is calculated as follows:

$$I_{max} = K_2 I_{sym} \qquad (10)$$

Step 3: Generator Short-Circuit Current Calculations.

Generally, the minimum and maximum generator short-circuit currents are specified by the manufacturer. These currents may also be estimated from the generator specifications.

1. Sustained generator short-circuit current.

The sustained generator short-circuit current I_C is required to establish the short time pickup current (STPU) setting for a generator circuit breaker. For a generator with static exciter, I_C may be estimated from the generator rating as follows:

$$I_G = (3.2/\sqrt{3})\left(\frac{P_G}{(pf)E_G}\right) \qquad (11)$$

For 400 Hz generator, I_G may be estimated from the following equation:

$$I_G = \sqrt{3}\left(\frac{P_{MG}}{(pf)E_{MG}}\right) \qquad (12)$$

Because of their impact on the overall accuracy of the fault calculations, any estimated values for X_d'' and I_G of a generator must be verified with data and decrement curves obtained from the manufacturer.

2. <u>Maximum Generator short-circuit current</u>.

The maximum generator short-circuit current I_G'' is required to determine the instantaneous pickup current setting (INST) of a generator circuit breaker. Since the cable impedance from the generator terminals to the line side of the circuit breaker is negligible when compared to the generator impedance, I_G'' can be estimated by the following equation:

$$I_G'' = \frac{(K_2)}{\sqrt{3}}\left(\frac{E_G}{X_d''}\right) \tag{13}$$

3. <u>Generator Rated Current</u>.

The generator rated or full load current I_n is required to determine the continuous current rating of a generator circuit breaker. The I_n is calculated as follows:

$$I_{fl} = \frac{\sqrt{3}}{3}\left(\frac{P_G}{(pf)E_G}\right) \tag{14}$$

300-2-g. <u>Example of Fault Current Calculations for 60 Hz System</u>.

Consider a 60 Hz power distribution system supplied by three 2,500kW, 450V generators as shown in Figure 1. The fault currents will be calculated at the selected locations F0 through F6 which are respectively at the switchboards 3S, 3SA, 1SA, 1SB, load center LC 41, power panel PP 01-143-1, and the load. The following steps will be followed for the calculations:

<u>Step 1</u>: <u>System Impedance Development</u>.

1. <u>System Impedance Diagram</u>.

The system one-line diagram is shown as in Figure 1. The system impedance in Figures 2 and 3 are developed from the information in Figure 1. All the component impedances are expressed in ohms per phase.

2. <u>Component Impedance Calculations</u>.

2.1 <u>Generator Impedances</u>.

Assume all generators (G1, G2, and G3) have the same characteristics: $P_G = 2{,}500$kW ==> $kVA_{base} = 3{,}125$kVA, $E_G = 450$V, pf = 0.8, $X_d'' = 19\% = 0.19$pu, $X_d''/R = 31$.

Use equation (3) to calculate X_d'' in ohm:

$$X_d'' = (0.19)\{(0.450\text{kV})^2/3{,}125\text{kVA}\}10^3$$
$$= 0.012312\Omega$$

For $X/R = X_d''/R = 31$, the value of R in ohm is:

$$R = X/31$$
$$= 0.000397\Omega$$

The impedance for each generator is:

$$Z_C = 0.000397 + j0.012312$$

2.2 Grouped Motors Impedance.

$P_G = 2{,}500\text{kW}$, $E_G = 450\text{V}$. Assume P_M (P_{M1}, P_{M2}, or P_{M3}) is equal to ⅔ of the P_G. The grouped motor kVA is:

$$\begin{aligned} \text{kVA}_{base} &= (2/3)(2{,}500/0.8)\text{kVA} \\ &= 2{,}083.333\text{kVA} \end{aligned}$$

Assume also the X_{pu} and (X/R) of the grouped motors are equal to 0.28 and 8 respectively.

Use equation (3) to calculate X in ohm:

$$\begin{aligned} X &= (0.28)\{(0.450\text{kV})^2/2{,}083.333\text{kVA}\}\text{x}10^3\Omega \\ &= 0.027216\Omega \end{aligned}$$

For $X/R = 8$, $R = 0.003402\Omega$

Then, the impedance of each grouped motor (M1, M2, or M3) is equal to:

$$\begin{aligned} Z_M &= 0.003402 + j0.027216 \\ &= 0.027428\Omega\angle 82.87° \end{aligned}$$

3. Transformer Impedance.

A three-phase transformer having $\text{kVA}_{base} = (3)(7.5\text{kVA}) = 22.5\text{kVA}$. Terminal voltage = (450/120)V, $Z_T = 2\%$, $(X/R) = 3$

Use equation (3) to calculate Z_T in ohm:

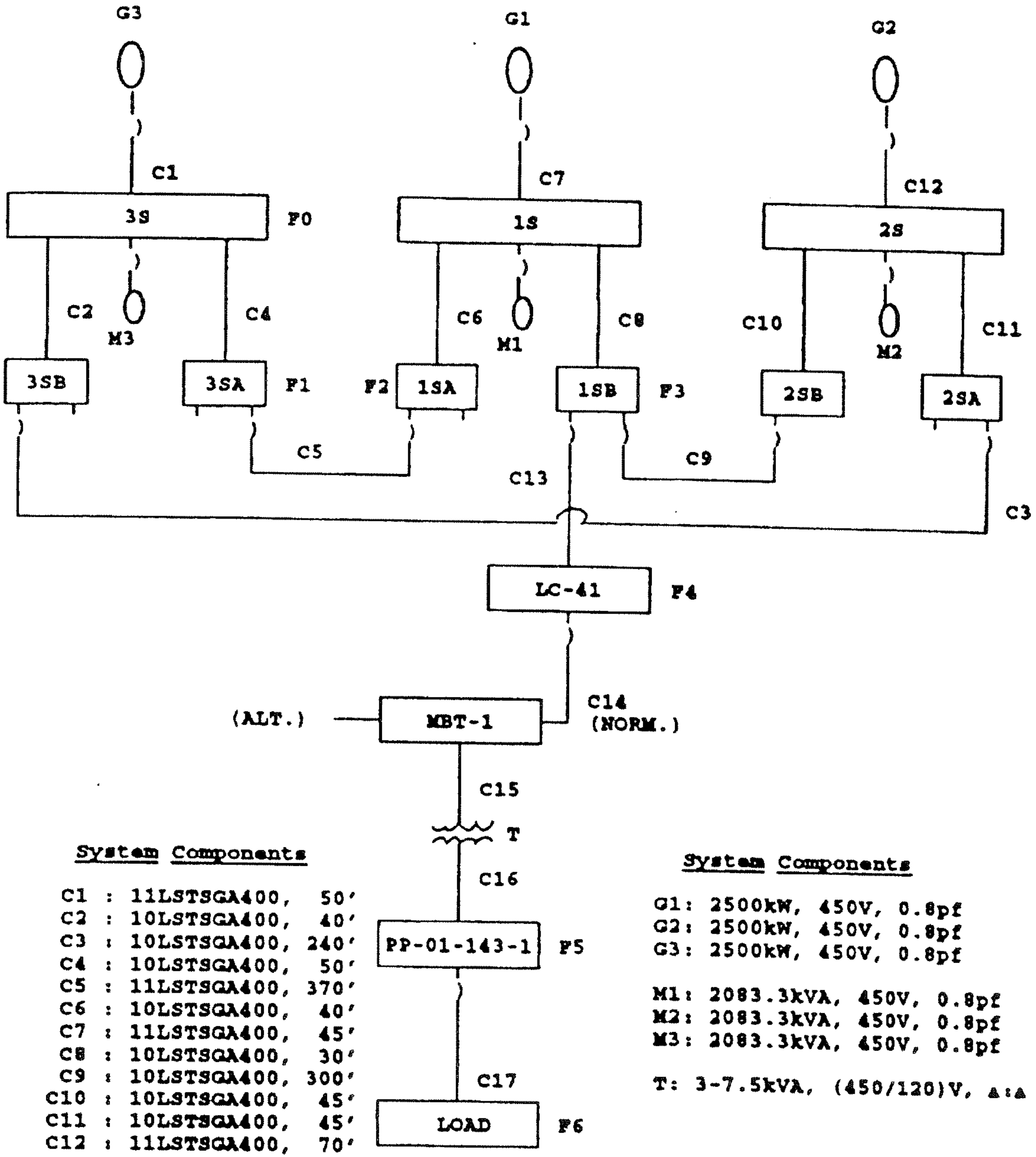
$$\begin{aligned} Z_T &= (0.02)\{(0.450\text{kV})^2/22.5\text{kVA}\}\text{x}10^3\Omega \\ &= 0.18\Omega \end{aligned}$$

Use equations (4) and (5) to calculate X in ohm:

$$\begin{aligned} X &= 0.18\{\sin[\tan^{-1}(3)]\}\Omega \\ &= 0.170763\Omega \end{aligned}$$

$$\begin{aligned} R &= 0.18\{\cos[\tan^{-1}(3)]\}\Omega \\ &= 0.056921\Omega \end{aligned}$$

$$Z_T = 0.056921 + j0.170763$$



System Components

C1 : 11LSTSGA400, 50'
C2 : 10LSTSGA400, 40'
C3 : 10LSTSGA400, 240'
C4 : 10LSTSGA400, 50'
C5 : 11LSTSGA400, 370'
C6 : 10LSTSGA400, 40'
C7 : 11LSTSGA400, 45'
C8 : 10LSTSGA400, 30'
C9 : 10LSTSGA400, 300'
C10 : 10LSTSGA400, 45'
C11 : 10LSTSGA400, 45'
C12 : 11LSTSGA400, 70'
C13 : 4LSTSGA400, 190'
C14 : LSTSGA9, 115'
C15 : LSTSGA9, 50'
C16 : LSTSGA75, 40'
C17 : LSTSGA14, 25'

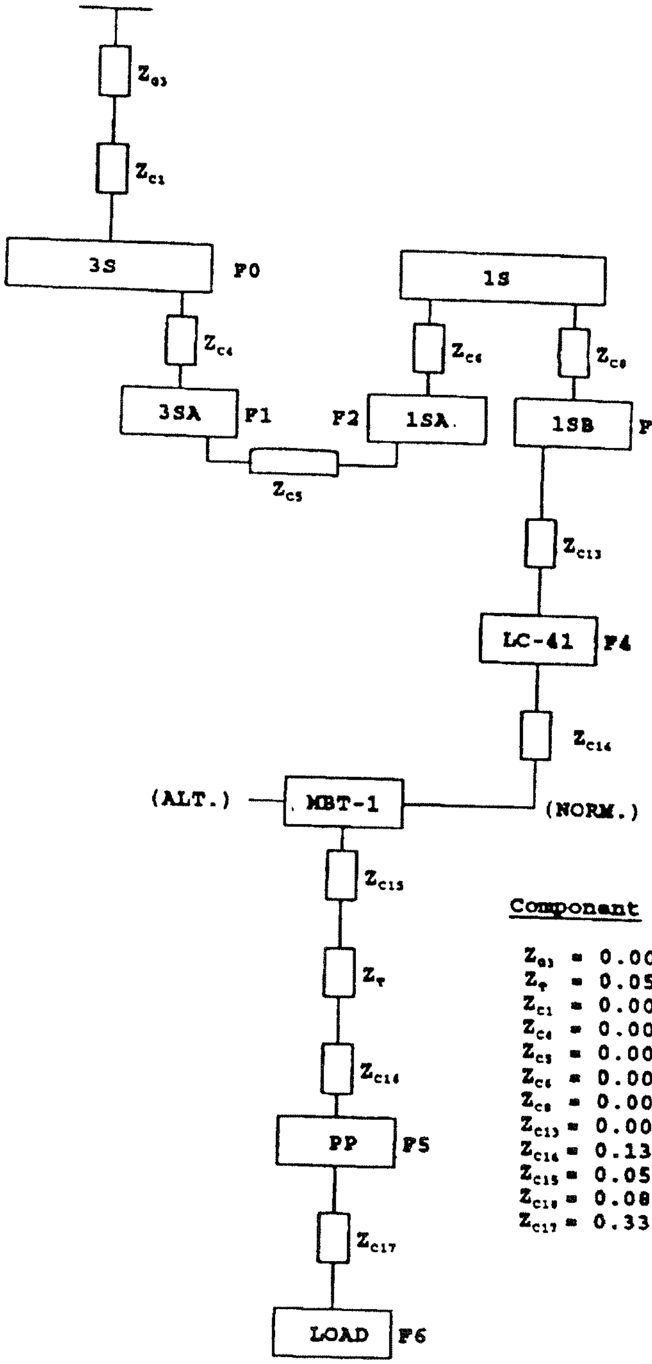
System Components

G1: 2500kW, 450V, 0.8pf
G2: 2500kW, 450V, 0.8pf
G3: 2500kW, 450V, 0.8pf

M1: 2083.3kVA, 450V, 0.8pf
M2: 2083.3kVA, 450V, 0.8pf
M3: 2083.3kVA, 450V, 0.8pf

T: 3-7.5kVA, (450/120)V, Δ:Δ

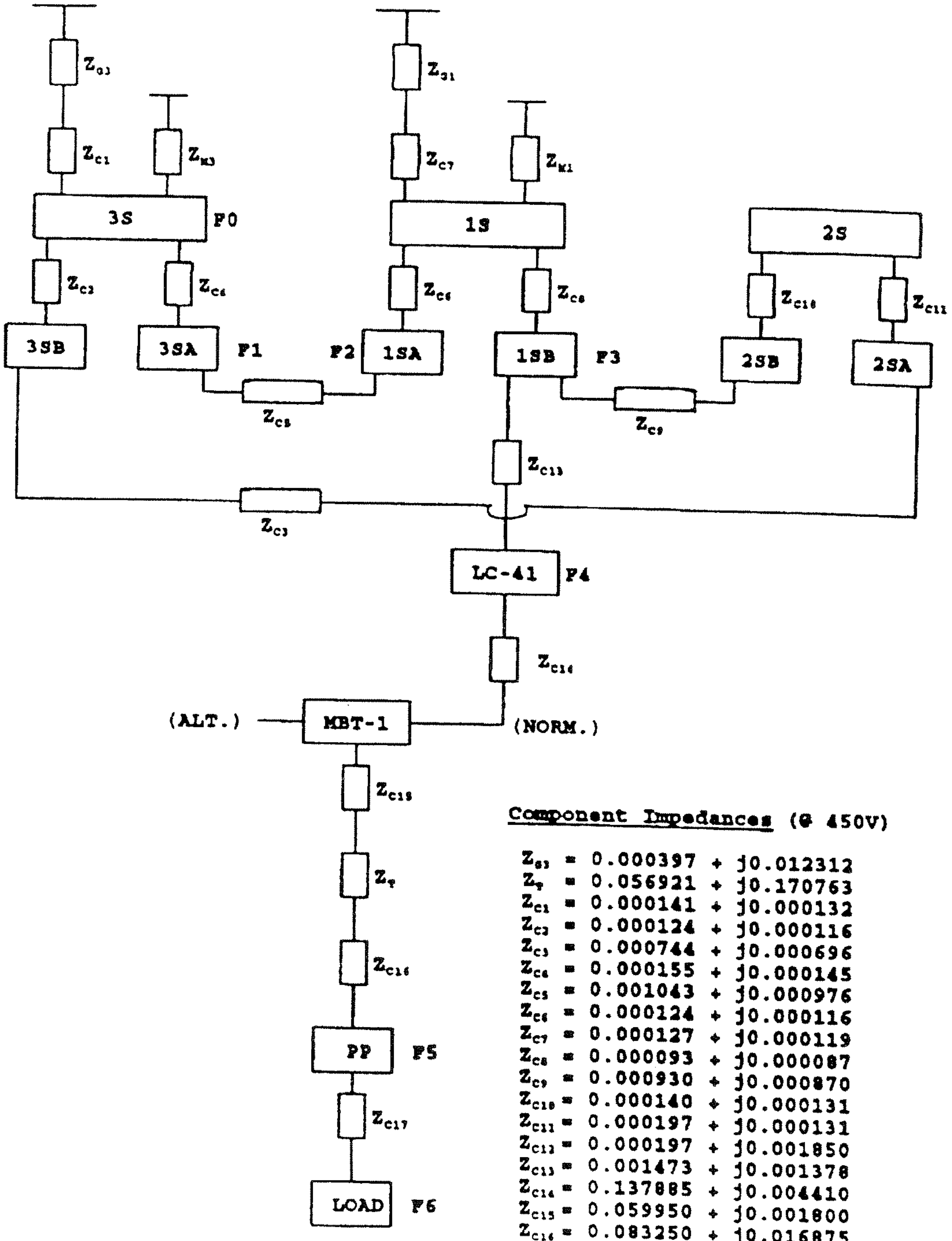
FIGURE 1. Typical 60 Hz Power system One-Line Diagram



<u>Component</u> <u>Impedances</u> (@ 450V)

Z_{e3} = 0.000397 + j0.012312
Z_{T} = 0.056921 + j0.170763
Z_{c1} = 0.000141 + j0.000132
Z_{c4} = 0.000155 + j0.000145
Z_{c5} = 0.001043 + j0.000976
Z_{c6} = 0.000124 + j0.000116
Z_{c8} = 0.000093 + j0.000087
Z_{c13} = 0.001473 + j0.001378
Z_{c14} = 0.137885 + j0.004140
Z_{c15} = 0.059950 + j0.001800
Z_{c16} = 0.083250 + j0.016875
Z_{c17} = 0.334336 + j0.014414

FIGURE 2. 60 Hz System Impedance Diagram for Minimum Fault Generation



Component Impedances (@ 450V)

Z_{G3} = 0.000397 + j0.012312
Z_T = 0.056921 + j0.170763
Z_{C1} = 0.000141 + j0.000132
Z_{C2} = 0.000124 + j0.000116
Z_{C3} = 0.000744 + j0.000696
Z_{C4} = 0.000155 + j0.000145
Z_{C5} = 0.001043 + j0.000976
Z_{C6} = 0.000124 + j0.000116
Z_{C7} = 0.000127 + j0.000119
Z_{C8} = 0.000093 + j0.000087
Z_{C9} = 0.000930 + j0.000870
Z_{C10} = 0.000140 + j0.000131
Z_{C11} = 0.000197 + j0.000131
Z_{C12} = 0.000197 + j0.001850
Z_{C13} = 0.001473 + j0.001378
Z_{C14} = 0.137885 + j0.004410
Z_{C15} = 0.059950 + j0.001800
Z_{C16} = 0.083250 + j0.016875
Z_{C17} = 0.334336 + j0.014414
$Z_{G1} = Z_{G2}$, $Z_{M1} = Z_{M2}$

FIGURE 3. 60 Hz System Impedance Diagram for Maximum Fault Generation

4. **Cable Impedance.**

The characteristics and impedance of cables are shown in Figures 1 and 2. The sample calculation of cable C1 is as follows:

The C1 cable is a combination of 11 cables in parallel. From reference (j), its impedance is:

$$R = (0.031\Omega/10^3ft)(50ft)/(11)$$
$$= 0.000141\Omega$$

$$X = (0.029\Omega/10^3ft)(50ft)/(11)$$
$$= 0.000132\Omega$$

Then,

$$Z_{C1} = 0.000141 + j0.000132$$

Note: Use equation (6) to convert the cable and other component impedances in the 120V to 450V base before incorporating into the impedance diagram.

Step 2: Fault Calculations.

1. Fault Calculations Under Minimum Fault Generation.

1.1 Z_F & I_{min}.

The impedances required to calculate I_{min} for the selected protective locations are shown in Figure 2. The generator G3 is selected as the sole source of power since it has the highest impedance path to the selected fault locations F0 through F6.

Location F0.

The impedance from G3 to F0 consists of Z_{G3} and Z_{C1} in series:

$$Z_{F0} = Z_{G3} + Z_{C1}$$

$$= (0.397 + j12.312 + 0.141 + j0.132)10^{-3}\Omega$$
$$= 0.000538 + j0.012444$$
$$= 0.012456\angle 87.52°$$

Use Equation (7) to calculate I_{min}:

$$I_{min} = (1/2)(450V)/0.012456\Omega$$
$$= 18{,}064A$$

Notice that the fault current calculations at F0 are optional since this system configuration does not require feeder circuit breaker for switchboard 3S.

Location F1.

The impedance from G3 to F1 consists of Z_{F0} and Z_{C4} in series:

$$Z_{F1} = Z_{F0} + Z_{C4}$$

$$= 0.000538 + j0.012444 + 0.000155 + j0.000145$$
$$= 0.000693 + j0.012589$$
$$= 0.012608\angle 86.85°$$

Use Equation (7) to calculate I_{min}:

$$\begin{aligned} I_{min} &= (1/2)(450V)/0.012608\Omega \\ &= 17{,}846A \end{aligned}$$

Location F2.

The impedance from G3 to F2 consists of Z_{F1} and Z_{C3} in series:

$$\begin{aligned} Z_{F2} &= Z_{F1} + Z_{C3} \\ &= 0.000693 + j0.012589 + 0.001043 + j0.000976 \\ &= 0.001736 + j0.013565 \\ &= 0.013676\angle 82.71° \end{aligned}$$

Use Equation (7) to calculate I_{min}:

$$\begin{aligned} I_{min} &= (1/2)(450V)/0.013676\Omega \\ &= 16{,}452A \end{aligned}$$

Location F3.

The impedances from G3 to 1SB are in series and their equivalent is:

$$\begin{aligned} Z_{F3} &= Z_{F2} + Z_{C6} + Z_{C8} \\ &= 0.001736 + j0.013565 + 0.000124 + j0.000116 \\ &\quad + 0.000093 + j0.000087 \\ &= 0.001953 + j0.013768 \\ &= 0.013906\angle 81.93° \end{aligned}$$

$$\begin{aligned} I_{min} &= (1/2)(450V)/13.906\text{x}10^{-3}\Omega \\ &= 16{,}180A \end{aligned}$$

Location F4.

The component impedances from G3 to LC-41 are in series:

$$\begin{aligned} Z_{F4} &= Z_{F3} + Z_{C13} \\ &= 0.001953 + j0.013768 + 0.001473 + j0.001378 \\ &= 0.003426 + j0.015146 \\ &= 0.015529\angle 77.25° \end{aligned}$$

$$\begin{aligned} I_{min} &= (1/2)(450V)/0.015529\Omega \\ &= 14{,}489A \end{aligned}$$

Location F5.

The fault impedance at location F5 is:

$$\begin{aligned} Z_{F5} &= Z_{F4} + Z_{C14} + Z_{C15} + Z_T + Z_{C16} \\ &= 0.003426 + j0.015146 + 0.137885 + j0.004140 \\ &\quad + 0.059950 + j0.001800 + 0.056921 + j0.170763 \\ &\quad + 0.083250 + j0.016875 \\ &= 0.341432 + j0.208724 \\ &= 0.400177\angle 31.44° \end{aligned}$$

$$\begin{aligned} I_{min} &= (1/2)(450V)/0.400177\Omega \\ &= 562A \\ &= 2{,}108A \text{ @ } 120V \end{aligned}$$

Location F6.

Z_{F6} is the series combination of Z_{F5} and Z_{C17}:

$$
\begin{aligned}
Z_{F6} &= Z_{F5} + Z_{C17} \\
&= 0.341432 + j0.208724 + 0.334336 + j0.014414 \\
&= 0.675768 + j0.223138 \\
&= 0.711655\angle 18.27^\circ
\end{aligned}
$$

$$
\begin{aligned}
I_{min} &= (1/2)(450V)/0.711655\Omega \\
&= 316A \\
&= 1{,}185A \ @ \ 120V
\end{aligned}
$$

2. Fault Calculations Under Maximum Fault Generation.

2.1 Z_F, I_{sym}, I_{asy}, & I_{mom}.

Let assume only two generators G3 and G1 are on the line. Therefore, the grouped motor load M2 should be reduced or disconnected. For this example, the M2 is not included. The equivalent fault impedance, Z_F, at each fault location (F0 through F6) is calculated as follows:

Location F0.

The impedance in the path 3S-3SA-1SA-1S is:

$$
\begin{aligned}
(a) &= Z_{C4} + Z_{C5} + Z_{C6} \\
&= 0.000155 + j0.000145 + 0.001043 + j0.000976 \\
&\quad + 0.000124 + j0.000116 \\
&= 0.001322 + j0.001237 \\
&= 0.001810\angle 43.10^\circ
\end{aligned}
$$

The impedances in the path 1S-1SB-2SB-2S-2SA-3SB-3S are in series:

$$
\begin{aligned}
(b) &= Z_{C8} + Z_{C9} + Z_{C10} + Z_{C11} + Z_{C3} + Z_{C2} \\
&= 0.000093 + j0.000087 + 0.000930 + j0.000870 \\
&\quad + 0.000140 + j0.000131 + 0.000140 + j0.000131 \\
&\quad + 0.000744 + j0.000696 + 0.000124 + j0.000116 \\
&= 0.002171 + j0.002031 \\
&= 0.002973\angle 43.09^\circ
\end{aligned}
$$

The parallel combination of (a) and (b) gives:

$$
\begin{aligned}
(a)//(b) &= (a)(b)/\{(a) + (b)\} \\
&= \{(1.810\angle 43.10^\circ)(2.973\angle 43.09^\circ)/(3.493 + j3.268)\}10^{-3} \\
&= 0.005381\angle 86.19^\circ/(0.003493 + j0.003268) \\
&= 0.001125\angle 43.10^\circ \\
&= 0.000822 + j0.000769 = (c)
\end{aligned}
$$

The impedance from G1 to 1S is:

$$
\begin{aligned}
(d) &= Z_{C1} + Z_{C7} \\
&= 0.000397 + j0.012312 + 0.000127 + j0.000119 \\
&= 0.000524 + j0.012431 \\
&= 0.012442\angle 87.59^\circ
\end{aligned}
$$

The parallel combination of (d) and Z_{M1} gives:

$(e) = (d)(Z_{M1})/\{(d) + Z_{M1}\}$

$= (0.012442\angle 87.59°)(0.027428\angle 82.87°)/0.003926 + j0.039647$
$= 0.000580 + j0.008546$
$= 0.008565\angle 86.12°$

The series combination of (e) and (c) gives:

$(e) + (c) = 0.000580 + j0.008546 + 0.000822 + j0.000769$
$= 0.001402 + j0.009315$
$= 0.009420\angle 81.44° = (f)$

As before, the impedance from G3 to 3S is:

$(g) = Z_{G3} + Z_{C1}$

$= 0.000397 + j0.012312 + 0.000141 + j0.000132$
$= 0.000538 + j0.012444$
$= 0.012456\angle 87.52°$

The parallel combination of (g) and Z_{M3} gives:

$(h) = (g)(Z_{M3})/\{(g) + Z_{M3}\}$

$= \{(12.456\angle 87.52°)(27.428\angle 82.87°)/(0.538 + j12.444$
$+ 3.402 + j27.216)\}\text{x}10^{-3}$
$= 0.341643\angle 170.39°/0.039855\angle 84.32°$
$= 0.008572\angle 86.07°$
$= 0.000588 + j0.008552$

Finally, the fault impedance at F0 is the parallel combination of (f) and (h):

$Z_{F0} = (f)//(h)$
$= (f)(h)/\{(f) + (h)\}$

$= \{(9.420\angle 81.44°)(8.572\angle 86.07°)/(1.990 + j17.867)\}\text{x}10^{-3}$
$= 0.080748\angle 167.51°/0.017977\angle 83.64°$
$= 0.004492\angle 83.87°$
$= 0.000480 + j0.004466, \quad X/R = 9.3$

Use Table IV to determine K_1 and K_2:

$K_1 = 1.221, \qquad K_2 = 1.421$

Use equation (8) to calculate I_{sym}:

$I_{SYM} = (450V/\sqrt{3})/4.492\text{x}10^{-3}\Omega$
$= 57{,}838A$

Use equations (9) and (10) to calculate I_{avg} and I_{max}:

$I_{avg} = K_1 I_{sym}$

$= (1.221)(57{,}838A)$
$= 70{,}620A$

$I_{max} = K_2 I_{sym}$

$= (1.421)(57{,}838A)$
$= 82{,}188A$

Location F1.

As above, the impedances in the path 1S-1SB-2SB-2S-2SA-3SB-3S are in series:

$$\begin{aligned}(b) &= Z_{c8} + Z_{c9} + Z_{c10} + Z_{c11} + Z_{c3} + Z_{c2} \\ &= 0.002171 + j0.002031 \\ &= 0.002973\angle 43.09^\circ\end{aligned}$$

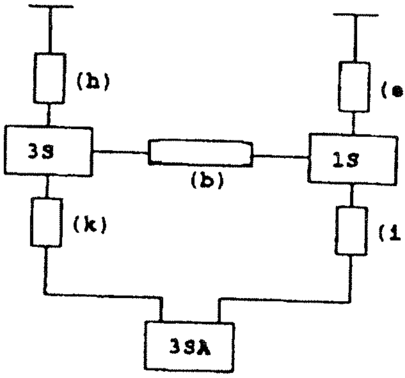
The impedances in the path 1S-1SA-3SA are in series:

$$\begin{aligned}(i) &= Z_{c5} + Z_{c6} \\ &= 0.001043 + j0.000976 + 0.000124 + j0.000116 \\ &= 0.001167 + j0.001092 \\ &= 0.001598\angle 43.10^\circ\end{aligned}$$

The impedance from 3S to 3SA is:

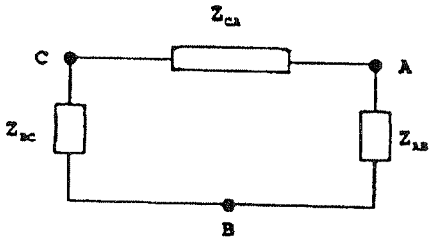
$$\begin{aligned}(k) &= Z_{c4} \\ &= 0.000155 + j0.000145 \\ &= 0.000212\angle 43.09^\circ\end{aligned}$$

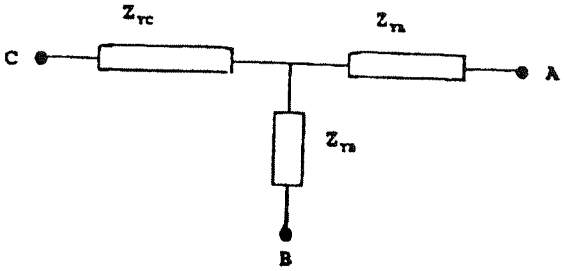
From the fault location F1 (3SA) back to the two sources, G3 and G1, the impedances (b), (i), and (k) are in Delta configuration:



Let the switchboards 3S, 1S, and 3SA be node C, node A, and node B respectively.

The Delta-Wye transformation gives:





$$Z_{YA} = (Z_{AB}Z_{CA})/(Z_{AB} + Z_{BC} + Z_{CA})$$

$$Z_{YB} = (Z_{AB}Z_{BC})/(Z_{AB} + Z_{BC} + Z_{CA})$$

$$Z_{YC} = (Z_{BC}Z_{CA})/(Z_{AB} + Z_{BC} + Z_{CA})$$

Applying the above formula:

$$Z_{YA} = (i)(b)/\{(i) + (k) + (b)\}$$

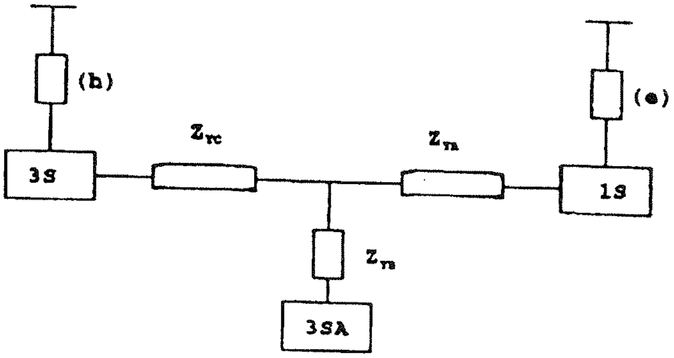
$$= ((1.1598\angle 43.10°)(2.973\angle 43.09°)/(1.167 + j1.092 + 0.155 + j0.145 + 2.171 + j2.031))10^{-3}$$
$$= \{(1.598\angle 43.10°)(2.973\angle 43.09°)/4.783\angle 43.09°\}10^{-3}$$
$$= 0.000993\angle 43.10°$$
$$= 0.000725 + j0.000678$$

$$Z_{YB} = (i)(k)/\{(i) + (k) + (b)\}$$

$$= ((1.598\angle 43.10°)(0.212\angle 43.09°)/4.783\angle 43.09°\}10^{-3}$$
$$= 0.000071\angle 43.10°$$
$$= 0.000052 + j0.000049$$

$$Z_{YC} = (k)(b)/\{(i) + (k) + (b)\}$$
$$= \{(0.212\angle 43.09°)(2.973\angle 43.09°)/4.783\angle 43.09°\}10^{-3}$$
$$= 0.000132\angle 43.09°$$
$$= 0.000096 + j0.000090$$

The new impedance network is as follows



The impedances (h) and Z_{YC} are in series:

$$(m) = (h) + Z_{YC}$$

$$
\begin{aligned}
(m) &= 0.000587 + j0.008552 + 0.000096 + j0.000090 \\
&= 0.000683 + j0.008642 \\
&= 0.008669\angle 85.48^\circ
\end{aligned}
$$

The impedances (e) and Z_{YA} are in series:

$$
\begin{aligned}
(n) &= (e) + Z_{YA} \\
&= 0.000580 + j0.008546 + 0.000725 + j0.000679 \\
&= 0.001305 + j0.009225 \\
&= 0.009317\angle 81.95^\circ
\end{aligned}
$$

The parallel combination of (m) and (n) gives:

$$
\begin{aligned}
(p) &= (m)(n)/\{(m) + (n)\} \\
&= \{(8.669\angle 85.48^\circ)(9.317\angle 81.95^\circ)/(1.988 + j17.867)\}10^{-3} \\
&= 0.004493\angle 85.48^\circ \\
&= (0.487 + j4.466)10^{-3}\Omega
\end{aligned}
$$

Finally, the fault impedance at F1 (3SA) is:

$$
\begin{aligned}
Z_{F1} &= (p) + Z_{YB} \\
&= 0.000052 + j0.000048 + 0.000487 + j0.004514 \\
&= 0.000539 + j0.004562 \\
&= 0.004546\angle 83.19^\circ, \quad X/R = 8.4
\end{aligned}
$$

From Table IV, the constants K_1 and K_2 are determined:

$K_1 = 1.206, \qquad K_2 = 1.395$

Use equation (8) to compute I_{sym} at F1:

$$
\begin{aligned}
I_{SYM} &= (450V/\sqrt{3})/4.546x10^{-3}\Omega \\
&= 57{,}151A
\end{aligned}
$$

Use equations (9) and (10) to compute I_{avg} and I_{max}:

$$
\begin{aligned}
I_{avg} &= (1.206)(57{,}151A) \\
&= 68{,}924A
\end{aligned}
$$

$$
\begin{aligned}
I_{max} &= (1.395)(57{,}151A) \\
&= 79{,}725A
\end{aligned}
$$

<u>Location</u> <u>F2</u>.

The fault impedances at switchboards 3SA (@ F1) and 1SA (@ F2) looking back to the sources G1 and G3 are approximately the same. Therefore, use the fault currents calculated at F1 to coordinate the bus tie circuit breakers.

<u>Location</u> <u>F3</u>.

The impedance from 3S to 1S via 3SA-3SB is:

$$
\begin{aligned}
(r) &= Z_{C4} + Z_{C5} + Z_{C6} \\
&= 0.000155 + j0.000145 + 0.001043 + j0.000976 \\
&\quad + 0.000124 + j0.000116 \\
&= 0.001322 + j0.001237
\end{aligned}
$$

$$(r) = 0.001810\angle 43.10^\circ$$

The impedance from 1S to 1SB is:

$$\begin{aligned}(q) &= Z_{C8}\\ &= 0.000093 + j0.000087\\ &= 0.000127\angle 43.09^\circ\end{aligned}$$

From 1SB to 3S via 2SB-2S-2SA-3SB, the impedances are in series:

$$\begin{aligned}(s) &= Z_{C9} + Z_{C10} + Z_{C11} + Z_{C3} + Z_{C2}\\ &= 0.002078 + j0.001944\\ &= 0.002846\angle 43.09^\circ\end{aligned}$$

For fault at location F3 (1SB) looking back to the two sources, G3 and G1, the impedances (r), (q), and (s) are in Delta configuration.

Another Delta-Wye transformation. Let the switchboard 3S be node C, 1S be node A, and 1SB be node B.

$$Z_{CA} = (r), \quad Z_{AB} = (q), \quad Z_{BC} = (s)$$

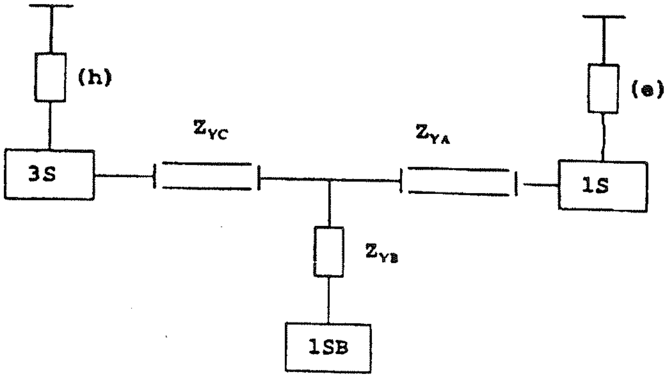
Then,

$$\begin{aligned}Z_{YA} &= (q)(r)/\{(r) + (q) + (s)\}\\ &= \{(0.127\angle 43.09^\circ)(1.810\angle 43.10^\circ)/(1.322 + j1.137\\ &\quad + 0.093 + j0.087 + 2.078 + j1.944)\}10^{-3}\\ &= \{(0.127\angle 43.09^\circ)(1.810\angle 43.10^\circ)/4.716\angle 42.21^\circ\}10^{-3}\\ &= 0.049\text{x}10^{-3}\angle 43.98^\circ\\ &= 0.000035 + j0.000033\end{aligned}$$

$$\begin{aligned}Z_{YB} &= (q)(s)/\{(r) + (q) + (s)\}\\ &= \{(0.127\angle 43.09^\circ)(2.846\angle 43.09^\circ)^\circ/4.716\angle 42.21^\circ\}10^{-3}\\ &= 0.077\text{x}10^{-3}\angle 43.97^\circ\\ &= 0.000055 + j0.000053\end{aligned}$$

$$\begin{aligned}Z_{YC} &= (s)(r)/\{(r) + (q) + (s)\}\\ &= \{(2.846\angle 43.09^\circ)(1.810\angle 43.10^\circ)/4.716\angle 42.21^\circ\}10^{-3}\\ &= 1.092\text{x}10^{-3}\angle 43.98^\circ\\ &= 0.000786 + j0.000758\end{aligned}$$

The new impedance network is:



The impedances (h) and Z_{YC} are in series:

$$\begin{aligned}(u) &= (h) + Z_{YC} \\ &= 0.000587 + j0.008552 + 0.000786 + j0.000758 \\ &= 0.001373 + j0.009310 \\ &= 0.009411\angle 81.61^{\circ}\end{aligned}$$

The impedances (e) and Z_{YA} are in series:

$$\begin{aligned}(v) &= (e) + Z_{YA} \\ &= 0.000580 + j0.008546 + 0.000035 + j0.000033 \\ &= 0.000615 + j0.008579 \\ &= 0.008601\angle 85.90^{\circ}\end{aligned}$$

The parallel combination of (u) and (v) gives:

$$\begin{aligned}(w) &= (u)(v)/\{(u) + (v)\} \\ &= \{(9.411\angle 81.61^{\circ})(8.601\angle 85.90^{\circ})/(1.373 + j9.310 \\ &\quad + 0.615 + j8.579)\}10^{-3} \\ &= 0.004497\angle 83.85^{\circ} \\ &= 0.000482 + j0.004471\end{aligned}$$

Finally, the fault impedance at F3 (1SB) is:

$$\begin{aligned}Z_{F3} &= (w) + Z_{YB} \\ &= 0.000482 + j0.004471 + 0.000055 + j0.000053 \\ &= 0.000537 + j0.004524 \\ &= 0.004556\angle 83.23^{\circ}, \qquad X/R = 8.4\end{aligned}$$

Use Table IV to obtain K_1 and K_2:

$$K_1 = 1.206 \qquad K_2 = 1.395$$

Use equation (8) to calculate I_{sym}:

$$\begin{aligned}I_{SYM} &= (450/\sqrt{3})/4.556\text{x}10^{-3}\Omega \\ &= 57{,}025\text{A}\end{aligned}$$

Use equations (9) and (10) to calculate I_{avg} and I_{max}:

$$\begin{aligned}I_{avg} &= (1.206)(57{,}025\text{A}) \\ &= 68{,}773\text{A}\end{aligned}$$

$$\begin{aligned}I_{max} &= (1.395)(57{,}025\text{A}) \\ &= 79{,}550\text{A}\end{aligned}$$

<u>Location F4</u>.

The fault impedance at F4 (LC-41) is the series combination of Z_{F3} and Z_{C14}:

$$\begin{aligned}Z_{F4} &= Z_{F3} + Z_{C13} \\ &= (0.000537 + j0.004524 + 0.001473 + j0.001378 \\ &= 0.002010 + j0.005902 \\ &= 0.006235\angle 71.19^{\circ}, \qquad X/R = 2.9\end{aligned}$$

Use Table IV to obtain K_1 and K_2:

$$K_1 = 1.056 \qquad K_2 = 1.111$$

Use equation (8) to calculate I_{sym}:

$$I_{SYM} = (450V/\sqrt{3})/6.235\times10^{-3}\Omega$$
$$= 41{,}669A$$

Use equations (9) and (10) to calculate I_{avg} and I_{max}:

$$I_{avg} = (1.056)(41{,}669A)$$
$$= 44{,}003A$$

$$I_{max} = (1.111)(41{,}669A)$$
$$= 46{,}294A$$

Location F5.

The impedance Z_{F5} is the series combination of Z_{F4}, Z_{C15}, Z_T, and Z_{C16}:

$$Z_{F5} = Z_{F4} + Z_{C14} + Z_{C15} + Z_T + Z_{C16}$$

$$= 0.002010 + j0.005902 + 0.137885 + j0.004140$$
$$+ 0.059950 + j0.001800 + 0.056921 + j0.170763$$
$$+ 0.083250 + j0.016875$$
$$= 0.340016 + j0.199480$$
$$= 0.394212\angle 30.4°, \quad X/R = 0.587$$

From Table IV, the constants K_1 and K_2 are:

$$K_1 = K_2 = 1.000$$

Use equations (8) to calculate I_{sym}:

$$I_{SYM} = (450V/\sqrt{3})/394.212\times10^{-3}\Omega$$
$$= 659A, \; [= 2471A \text{ @ } 120V]$$

Use equations (9) and (10) to calculate I_{avg} and I_{max}:

$$I_{avg} = I_{max} = 659A, \quad [\,= 2471A \text{ @ } 120V\,]$$

Step 3: Generator Output Current Calculations.

1. I_C Calculation.

Use equation (11) to calculate the minimum short-circuit current supplied by the generator to the switchboard:

$$I_g = (3.2/\sqrt{3})\,[P_g/(pf)(E_g)]$$
$$= (3.2/\sqrt{3})\,[2{,}500kW/(0.8)(0.45kV)]$$
$$= 12{,}829A$$

2. I_C'' **Calculation.**

Use equation (13) to calculate the maximum short-circuit current supplied by the generator to the switchboard:

$$\begin{aligned} I_g'' &= (1/\sqrt{3})K_2E_g/X_d'' \\ &= (1/\sqrt{3})(1.631)(450V/12.312\times10^{-3}\Omega) \\ &= 34{,}417A \end{aligned}$$

3. I_n **Calculation.**

Use equation (14) to determine the generator full load current:

$$\begin{aligned} I_{fl} &= (1/\sqrt{3})\,[P_g/(pf)(E_g)] \\ &= (1/\sqrt{3})\,[2{,}500kW/(0.8)(0.45kV)] \\ &= 4{,}009A \end{aligned}$$

The results of the fault calculation are summarized in Table V.

TABLE V. Fault Current Analysis Data for 60 Hz System

Circuit Breaker Locations	I_{min}	I_{sym}	I_{avg}	I_{max}	I_n	I_G	I_G''
	A	A	A	A	A	A	A
Gen-3S	18,064*	57,838*	70,620*	82,188*	4,009	12,829	34,413
Gen-3SA	17,846	57,151	68,924	79,725	-	-	-
3SA-1SA	16,452	57,151	68,924	79,725	-	-	-
1SB-LC41	14,491	41,669	44,003	46,294	-	-	-
LC-PP	562	659	659	659	-	-	-
LC-PP (@ 120V)	2,108	2,471	2,471	2,471	-	-	-
PP-LOAD	316	367	367	367	-	-	-
PP-LOAD (@ 120V)	1,185	1,376	1,376	1,376	-	-	-

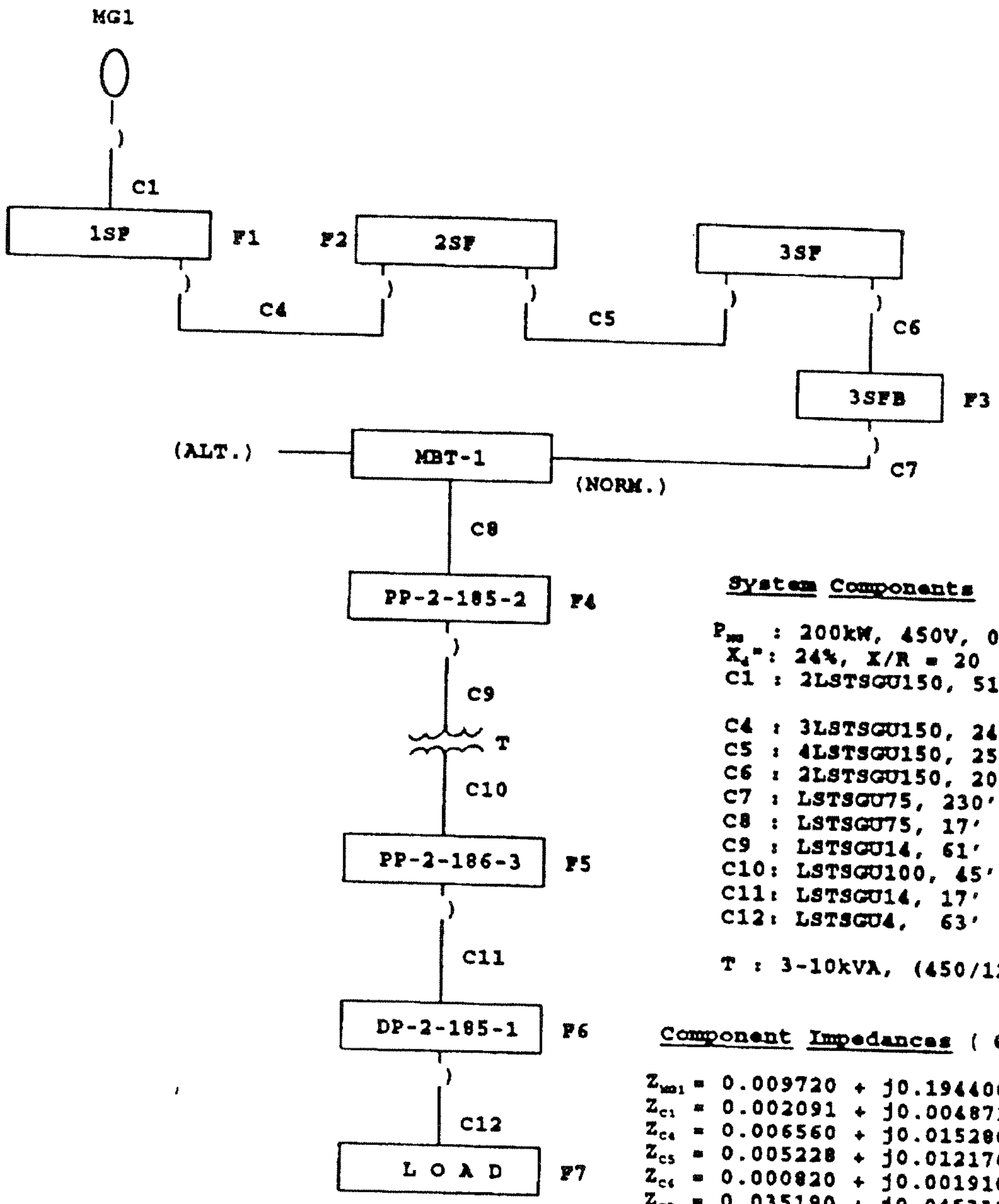
*: These fault current values at location F0 (3S SWBD) are only used to coordinate the generator circuit breaker if a feeder circuit breaker for 3S switchboard were installed.

300-2-h. Example of Fault Current Calculations for 400 Hz System.

Similar methods can be used for the fault calculation of the 400 Hz system. The one-line diagrams for the maximum and minimum fault current generation are shown in Figures 4 and 5 respectively. For I_{min} calculations, the MG1 is chosen as the source. For I_{max} calculation, only MG2 and MG3 are selected. Since the steps and methods are the same, detailed calculations of fault currents are omitted and only the results are summarized in Table VI.

TABLE VI. Fault Current Analysis Data for 400 Hz System

Circuit Breaker Locations	I_{min}	I_{sym}	I_{avg}	I_{max}	I_n	I_G	I_G'
	A	A	A	A	A	A	A
MG1-1SF	1,127	-	-	-	321	963	2096
MG2-2SF	-	2,603	3,357	4,000	321	963	2096
MG3-3SF	-	-	-	-	321	963	2096
1SF-2SF	1,045	-	-	-	321	-	-
3SF-3SFB	979	2526	3193	3825	321	-	-
3SFB to PP 2-185-2	792	2479	3126	3703	321	-	-
PP 2-185-2 to PP 2-186-3	377	1625	1747	1864	-	-	-
PP 2-186-3 to DP 2-185-1 (@ 120V)	292	544	555	566	-	-	-
	109	2040	2081	2123	-	-	-
DP 2-185-1 to Load (@ 120V)	69	391	391	391	-	-	-
	259	1466	1466	1466	-	-	-



System Components

P_{MG} : 200kW, 450V, 0.8pf,
X_d'': 24%, X/R = 20
C1 : 2LSTSGU150, 51'

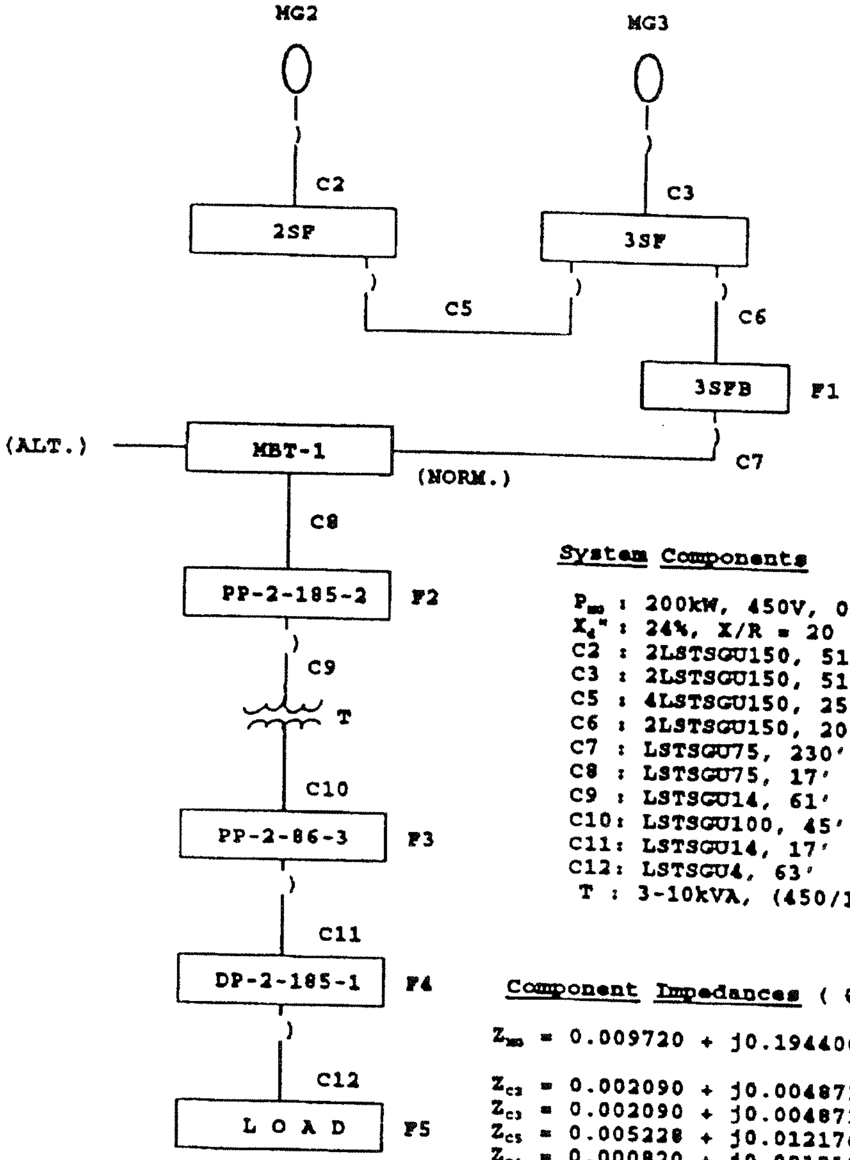
C4 : 3LSTSGU150, 240'
C5 : 4LSTSGU150, 255'
C6 : 2LSTSGU150, 20'
C7 : LSTSGU75, 230'
C8 : LSTSGU75, 17'
C9 : LSTSGU14, 61'
C10: LSTSGU100, 45'
C11: LSTSGU14, 17'
C12: LSTSGU4, 63'

T : 3-10kVA, (450/120)V, Δ:Δ

Component Impedances (@ 450V)

$Z_{MG1} = 0.009720 + j0.194400$
$Z_{C1} = 0.002091 + j0.004871$
$Z_{C4} = 0.006560 + j0.015280$
$Z_{C5} = 0.005228 + j0.012176$
$Z_{C6} = 0.000820 + j0.001910$
$Z_{C7} = 0.035190 + j0.045310$
$Z_{C8} = 0.002601 + j0.003349$
$Z_{C9} = 0.058011 + j0.016531$
$Z_{C10} = 0.078469 + j0.123398$
$Z_{C11} = 0.227348 + j0.064786$
$Z_{C12} = 2.682619 + j0.236545$
$Z_{T} = 0.042700 + j0.128000$

FIGURE 4. 400 Hz System One -Line Diagram for Minimum Fault generation.



System Components

P_{mg} : 200kW, 450V, 0.8pf,
X_d'' : 24%, X/R = 20
C2 : 2LSTSGU150, 51'
C3 : 2LSTSGU150, 51'
C5 : 4LSTSGU150, 255'
C6 : 2LSTSGU150, 20'
C7 : LSTSGU75, 230'
C8 : LSTSGU75, 17'
C9 : LSTSGU14, 61'
C10: LSTSGU100, 45'
C11: LSTSGU14, 17'
C12: LSTSGU4, 63'
T : 3-10kVA, (450/120)V, Δ:Δ

Component Impedances (@ 450V)

$Z_{mg} = 0.009720 + j0.194400$

$Z_{c2} = 0.002090 + j0.004871$
$Z_{c3} = 0.002090 + j0.004871$
$Z_{c5} = 0.005228 + j0.012176$
$Z_{c6} = 0.000820 + j0.001910$
$Z_{c7} = 0.035190 + j0.045310$
$Z_{c8} = 0.002601 + j0.003349$
$Z_{c9} = 0.058011 + j0.016531$
$Z_{c10} = 0.078469 + j0.123398$
$Z_{c11} = 0.227348 + j0.064786$
$Z_{c12} = 2.682619 + j0.236545$
$Z_T = 0.042700 + j0.128000$

FIGURE 5. 400 Hz System One-Line Diagram for Maximum Fault Generation

300-2-i. Protective Device Coordination.

After the fault calculation is complete, the next step is to do the fault protection coordination.

A completely coordinated fault system protection should have the following characteristics:

- High speed clearing of all low impedance faults.
- Maximum continuity of service under fault conditions to be achieved by the selective operation of the various protective devices.
- Maximum protection of electric apparatus and circuits under any fault conditions by coordinating of the thermal characteristics of the circuit interrupting characteristics of the protective devices.
- Adequate interrupting capacity in all circuit interrupting devices (fully rated system).
- Adequate thermal rating in all of the various circuit protective and switching devices for operation under all service conditions.
- Short-circuit current carrying capacity of circuit breakers and bus transfer equipment in excess of the maximum fault current at the point of application within the maximum time limitations of circuit opening.

The coordination and application of protective devices can be designed for one of the following systems:

1. Fully Rated System.

In a fully rated system, all circuit breakers have current interrupting capacity equal to or greater than the fault current at the point of application. This permits a selective tripping of protection system. The selective tripping systems are those in which the trip settings of the circuit breakers are such that the breaker nearest the fault operates first so that only the faulted portion of the system is de-energized.

2. Cascaded System.

In a cascaded system, circuit breakers may be used, under certain conditions, beyond their interrupting ratings. This applies where the interrupting capacity of the main circuit breaker is equal to or greater than the fault duty at the point of application. In this case, feeder breakers may be used to double their interrupting rating provided the following additional conditions are met:

- The instantaneous trip of the main circuit breaker is set to operate when the current through the feeder breaker is 80 percent of the interrupting rating of the feeder breaker. This ensures that the main circuit breaker as well as the feeder breaker will operate whenever the fault current exceeds the interrupting rating of the feeder breaker.

- The fault current must include the motor contribution and should not exceed twice the feeder breaker interrupting rating. All the motor contribution may not flow through the main breaker. Therefore, the instantaneous trip of the main breaker may have to be set less than 80 percent of the interrupting rating of the feeder circuit breaker, since the main breaker must still trip for this magnitude of fault current flowing through the feeder circuit breaker.

- Circuit breakers must have similar tripping characteristics. Electrical operation of the feeder circuit breaker is desirable since the force developed when closing into a fault in excess of the interrupting rating of the circuit breaker may prevent successfully manual closing.

- Circuit breakers must be inspected after each tripping initiated by the fault current and may require more than normal maintenance or replacement.

The operation of circuit breakers in a cascaded system is a means of lowering the cost of fault protection. In the cascaded system, smaller feeder breakers are used than may be required in a fully rated system. This favors a cascaded system from an economic standpoint. It must be recognized, however, that continuity of service is poorer in the cascaded system because, whenever a feeder fault current exceeds 80 percent of the feeder breaker interrupting rating, the main circuit breaker is also tripped and all feeders supplied by that main breaker are lost. The cascaded systems may be satisfactory for some applications. However, where vital loads are involved, a fully rated system should be used.

3. Protective Device Applications and Coordinations.

The method for applications and coordinations of protective devices may be summarized into the following steps:

- Collection of supporting data.

- Selection of protective devices.

- Initial selection of trip element ratings and trip settings of protective devices.

- Development of time-current coordination (TCC) curves.

- Final selection and trip setting of protective devices.

This step procedure is illustrated in the following examples using the circuits of Figure 1 for the 60 Hz system and Figure 4 for the 400 Hz system.

Step 1: Collection of Supporting Data.

The following information is required for the coordination study:

- A system one-line diagram showing system power source, system loads, circuit components and protective device locations.

- Resultant load current for the circuit being protected.
- A fault analysis providing the values of symmetrical, average, maximum, and minimum fault currents expected to flow through each protective device.
- The maximum starting, inrush, and locked rotor currents for equipment within the system.
- Time-current characteristic curve of each protective device within the system.

Step 2: Selection of Protective Devices.

The type, rating, and size of the protective devices are selected to satisfy the continuous load current of the circuit and fault protection requirements. The circuit breaker types and fuses are selected from references (c) through (e), and (f) respectively to satisfy the following conditions:

- The circuit breaker or fuse continuous rating shall be greater than or equal to the resultant load current of the circuit being protected.
- The circuit breaker interrupting rating shall be greater than or equal to the average fault current, I_{avg}, at the fault location where it is applied.

The circuit breakers with trip elements in all 3 poles should be provided for 4-wire grounded system. Therefore AQB-A50 type circuit breakers shall not be used for wye connected 4-wire grounded-neutral system.

To avoid the necessity of using backup type ACB circuit breakers with type AQB circuit breakers of inadequate interrupting capacity, type AQB-L, AQB-LL or AQB-LF circuit breakers should be used. The type AQB-L and AQB-LL circuit breakers have the interrupting rating of 100,000A asymmetrical. The type AQB-LF circuit breaker combines the standard type AQB circuit breaker with a current limiting fuse that interrupts all values of fault currents in excess of the interrupting rating of the circuit breaker. Thus the interrupting rating of type AQB circuit breaker is extended to 100,000A asymmetrical.

The protective device coordination is such that the circuit breaker overload and short-circuit trip elements perform their normal functions unless the magnitude of fault current reaches the fusing band of the current limiting fuses. For most types of Navy circuit breakers, the thermal and magnetic trip devices protect against overload and short-circuit currents up to the region of the interrupting rating of the circuit breaker.

The peak let-through currents of fused AQB circuit breakers are shown in Table VII.

In applying type AQB-LF circuit breakers, the time-current characteristics of the fuses are not to be considered, and no attempt should be made to coordinate two sets of these fuses. When two type AQB circuit breakers, fused or un-fused, are applied in series in a circuit, selectivity cannot be assured for faults on the output side of the downstream circuit breaker, having magnitudes of fault current in excess of the highest instantaneous pickup current setting of the magnetic trip element. Consequently, there is no advantage from the coordination of the fuses above the circuit breaker interrupting ratings when coordination cannot be achieved for some values of current below the interrupting ratings. In addition, the time-current characteristics of the fuses have not been defined with sufficient accuracy to permit coordination. Therefore, in a circuit having fault current in excess of the interrupting ratings of un-fused type AQB circuit breakers, only the circuit breaker nearest the source should be fused. This single unit will act to protect the other downstream type AQB circuit breakers in series.

TABLE VII. Peak Let-through Currents for Fused AQB Circuit Breakers

Fused AQB Circuit Breakers	Fuse Peak Let-through Current
AQB-F101A	20,000A
AQB-F101B	35,000A
AQB-A102F	32,800A
AQB-LF250	30,000A
AQB-LF252	30,000A
AQB-LF400	45,000A
AQB-LF402	45,000A

Step 3: Initial Selection of Trip Elements and Trip Settings.

The trip elements (TRE) and trip settings of protective devices chosen in step 2 should be selected in accordance with the guidelines in Tables I and II of reference (n).

Step 4: Development of Time-Current Curves.

In setting over-current protective devices, two competing system requirements must be reconciled. The continuity of electric service requires that the protective devices operate selectively. This normally means, for a given fault current, the protective devices have successively slower interrupting times or longer time delays the nearer they are to the source. On the other hand, the necessity for maximum safety to personnel and equipment requires the fastest isolation of faulted circuits.

The time-current curves (TCC) of protective devices provide a graphical solution for optimizing the competitive objectives of selectivity and protection systems. This method of analysis is applicable for designing the protection for a new system, or analyzing the protection of an existing system. The plot of time-current curves on a graph paper helps visualizing the tripping relationship between the protective devices. Any overlapping areas of the TCC curves show a miscoordination between the protective devices in the system. The adjustments in the protection system should be made.

Step 5: Final Selection and Setting of Protective Devices.

If the overlapping areas of the time-current curves of protective devices in series exist, the adjustments in protective device types, trip elements, and trip settings should be made to minimize the miscoordination.

The types, sizes, and adjustments of protective devices used in Navy shipboard electrical systems are defined in references (c), (d), (e), and (f). The adjustments of the circuit breakers are discussed in the following paragraphs with associated illustrations:

- Type ACB circuit breakers of reference (c) have the most adjustments among the Navy circuit breakers. These circuit breakers have LTPU, STPU, STD, and INST trip settings. Figure 7 illustrates the adjustments of these circuit breakers.

- Type AQB circuit breakers of reference (d), with thermal magnetic trip elements, have only the INST settings. The effect of changing this setting on the tripping characteristics of the AQB circuit breakers is shown in Figure 8.

- Type AQB circuit breakers with solid-state trip elements are more versatile and have STD and INST adjustments. Figure 9 illustrates the effects of changes in these settings.

- Non-adjustable protective devices such as type AQB-A50 and ALB-1 circuit breakers and fuses of references (d), (e) and (f) respectively, have fixed operating characteristics. Only the change in device rating will alter their relationship with other protective devices.

A number of changes can be made in order to improve the coordination:

- Increase the instantaneous setting of the upstream circuit breaker.

- Change the trip element rating of one of the miscoordinated circuit breakers.

- Change the type of circuit breaker which causes the miscoordination. Notice that the circuit breakers of different types with similar settings often do not coordinate.

- Reassign the circuits feeding any large loads to panels with larger upstream circuit breakers.

- Rearrange the distribution system, if necessary, to eliminate a level (or tier) of protective devices.

- If changes in the protective devices and settings have been made and the miscoordination still exists, restrict the miscoordination to the lowest tier of protection as much as possible.

300-2-j. Example of Protective Device Coordination for 60 Hz System.

Step 1: Collection of Supporting Data.

- A system one-line diagram is shown in Figure 1.

- The grouped motor impedance, transformer impedance, and cable impedance are shown in Figures 2 and 3.

- Fault current calculations are shown in section 300-2-g and summarized in Table V.

Step 2: Selection of Protective Devices.

The protective devices are selected to meet the following conditions:

Generator Circuit Breaker.

CONT: Greater than or equal to the generator full load current I_n.

The generator rated current is 4,009A which is within 4000 ± 2%.

INTR: Greater than or equal to the available fault current I_{avg} between the generator circuit breaker and the first downstream circuit breaker.

The fault current I_{avg} between the generator circuit breaker and next downstream circuit breaker (@ F1) is 68,924A asymmetrical or 57,151A symmetrical.

Select ACB-4000HR. This circuit breaker has a continuous rating of 4,000A and the interrupting rating of 85,000A symmetrical. The next greater continuous rating is 6,400A which is too conservative and would mean selecting a circuit breaker having a larger frame size.

Bus-Tie Circuit Breaker.

CONT: Greater than or equal to the resultant load current flowing through the bus tie circuit.

The maximum bus-tie load current is the output of one generator which is 4000A (also the continuous current rating of the bus-tie cable).

INTR: Greater than or equal to the available fault current I_{avg} at the assumed fault locations (I_{avg} @ F1 or F2).

The fault currents (for G3 and G1 sources) at the 3SA and 1SA bus-tie switchboards are approximately the same. The I_{avg} at location F1 (@ 3SA) or F2 (@ 1SA) is 68,924 asymmetrical or 57,151A symmetrical.

Select ACB-4000HR. This circuit breaker has a continuous rating of 4,000A and the interrupting rating of 85,000A symmetrical.

Switchboard Feeder Circuit Breaker.

CONT: Greater than or equal to the resultant load current of the circuit being protected.

The resultant load current of the switchboard feeder circuit is 1,600A.

INTR: Greater than or equal to the available fault current I_{avg} at the very nearest fault downstream.

The fault current I_{avg} at the load center switchboard (@ F4) is 44,003A asymmetrical or 41,709A symmetrical.

Select ACB-1600HR. This circuit breaker has the continuous rating of 1,600A and the interrupting rating of 85,000A symmetrical.

Load Center Feeder Circuit Breaker.

CONT: Greater than or equal to the resultant load current of the circuit being protected.

The load current is equal to the transformer rated current:

$$I_L = [(3)(7.5\text{kVA})/(\sqrt{3})(0.45\text{kV})] = 29\text{A}$$

INTR: Greater than or equal to the fault current I_{avg} between the load center feeder circuit breaker and the next downstream circuit breaker (I_{avg} @ F5).

The I_{avg} at the fault location F5 is 659A asymmetrical (2471A @ 120V).

Select AQB-A101 With Fuse. The continuous rating of this circuit breaker should be 50A along with the interrupting rating of 15,000A asymmetrical. The addition of a current limiting fuse extends its interrupting rating to 100,000A asymmetrical.

Power Panel Feeder Circuit Breaker.

CONT: Greater than or equal to the resultant load current of the circuit being protected.

The resultant load current of this feeder circuit is 50A.

INTR: Greater than or equal to the fault current between the power panel feeder circuit breaker and the load (I_{avg} @ F6).

The fault current I_{avg} at the load is 1,376A at 120V.

Select AQB-A50. This breaker has the continuous rating of 50A and the interrupting rating of 5,000A asymmetrical.

The results of circuit breaker selection are summarized in Table VIII.

TABLE VIII. Circuit Breaker Selection for 60 Hz System

Circuit Breaker Locations	System Voltage	Load Current	Circuit Breakers		
	V	A	Types	CONT	INTR
Generator (Gen-3SA)	450	4,009	ACB-4000HR	4,000A	85,000A
Bus-Tie (3SA-1SA)	450	4,009	ACB-4000HR	4,000A	85,000A
SWBD Feeder (1SB-LC41)	450	1,600	ACB-1600HR	1,600A	85,000A
LC Feeder (LC41-PP)	450	29	AQB-A101*	50A	100,000A
PP Feeder (PP-LOAD)	120	50	AQB-A50	50A	5,000A

* : With Current Limiting Fuse.

Step 3: Initial Circuit Breaker Settings.

Generator Circuit Breaker.

TRE: Equal to, or next above, generator full load current:

The generator rated current is 4,009A which is within the 4000A ± 2%.

Select TRE = 4000A. The next larger trip element is 4,800A, which is too conservative and would require the ACB-6400 circuit breaker.

INST: Greater than or equal to 120 percent of the maximum generator short-circuit current $I_C{}^*$:

$I_C{}^* = 34,417A$

$$\begin{aligned} \text{INST} &\geq (1.2)(34,417A) \\ &\geq 41,300A \end{aligned}$$

Set INST = 42,000A.

STPU: Less than or equal to 80 percent of the generator sustained short-circuit current I_C:

$I_C = 12,829A$

$$\begin{aligned} \text{STPU} &\leq 0.8(12,829A) \\ &\leq 10,263A \end{aligned}$$

Set STPU = 10,000A.

STD: Greater than the sum of the STD and the interrupting time of any downstream circuit breakers.

Set STD to Time Band = 4. This is the longest STD.

LTD: Greater than or equal to 150 percent of the generator full load current:

$$\begin{aligned} \text{LTD} &\geq (1.5)(4,009A) \\ &\geq 6,013A \end{aligned}$$

Set LTD = 6,000A. The next available setting is 8,000A which is not adequate to protect the generator from overloading.

Bus Tie Circuit Breaker.

TRE: Equal to, or next above, bus tie circuit resultant load current:

The resultant load current is equal the rated current of a single generator, which is 4,000A.

Select TRE = 4,000A. The next larger element rating is 4,800A, which is too conservative and would require the ACB-6400 circuit breaker.

INST: Not required, but if the circuit breaker is equipped with an INST trip device, the setting shall be the maximum available.

STPU: For single generator switchboard group, the STPU should be less than or equal to 80 percent of the generator circuit breaker STPU:

$$\begin{aligned} \text{STPU} &\le (0.8)(10{,}000\text{A}) \\ &\le 8{,}000\text{A} \end{aligned}$$

Set STPU = 8,000A.

STD: Greater than the sum of the STD and the interrupting time of any downstream bus or feeder circuit breaker.

This STD must also be less than that of the generator circuit breaker.

Set STD to Time Band = 3. This is the next shorter time delay setting from the generator circuit breaker time delay.

LTD: For single generator switchboard group, the LTD should be set as follows:

- Greater than or equal to 150 percent of bus tie resultant load current:

  $$\begin{aligned} \text{LTD} &\ge (1.5)(4{,}000\text{A}) \\ &\ge 6{,}000\text{A} \end{aligned}$$

- Less than 80 percent of the generator circuit breaker LTD:

  $$\begin{aligned} \text{LTD} &< (0.80)(6{,}000\text{A}) \\ &< 4{,}800\text{A} \end{aligned}$$
  , but the minimum LTD of ACB-4000HR circuit breaker is 6000A.

Set LTD = 6,000A.

Switchboard Feeder Circuit Breaker.

TRE: Equal to, or next above, resultant load current of the circuit being protected:

The circuit resultant load current is 1,600A.

Select TRE = 1,600A.

INST: Not required. But if the circuit breaker equipped with an INST trip device, the setting should be the maximum available.

STPU: Should be set:

- Less than or equal 80 percent of the bus tie circuit breaker STPU:

  $STPU \leq (0.8)(8{,}000A)$
  $\leq 6{,}400A$

- Greater than 120 percent of largest downstream feeder circuit breaker INST setting. Not known at this point, but certainly less than 4,000A [= 4,800A/1.2]. Therefore,

<u>Set</u> <u>STPU</u> = 6,000A.

STD: Greater than the sum of the STD and the interrupting time of any downstream circuit breakers. This STD must also be less than the bus-tie circuit breaker STD.

<u>Set</u> <u>STD</u> <u>to</u> <u>Time</u> <u>Band</u> = 2. This is the next shorter STD setting from the bus-tie circuit breaker short time delay.

LTD: Should be set:

- Greater than or equal to 150 percent of the resultant load current of the circuit being protected:

  $LTD \geq (1.5)(1{,}600A)$
  $\geq 2{,}400A$

- Less than 80 percent of the bus-tie circuit breaker LTD: Not applicable.

- Greater than 120 percent of the largest LTD of any downstream circuit breakers: The largest LTD of downstream circuit breakers is not known at this point, but certainly less than 1,920A [= (2,400A)(0.8)]. Therefore,

<u>Set</u> <u>LTD</u> = 2,400A.

<u>Load Center Feeder Circuit Breaker</u>.

TRE: Equal to, or next above, resultant load current of the circuit being protected.

The circuit resultant load current is equal to the transformer full load current which is equal to 29A.

<u>Select</u> <u>TRE</u> = 50A.

INST: Should be set:

- Greater than the sum of the maximum inrush current of the load producing the largest inrush and the full load current of the remaining loads: Not applicable.

- Less than 80 percent of the minimum fault current:

  $I_{min} = 562A$

INST ≤ (0.8)(562A)
≤ 450A

- Greater than 1200 percent of the trip element if supplying only a transformer:

INST ≥ (12)(50A)
≥ 600A

Set INST = 600A. This is a compromise setting which does not satisfy the above requirements. The setting protects against nuisance tripping, and I_{mu} falls within the - 15% tolerance of the instantaneous setting (510A = 600A x 0.85).

Power Panel Feeder Circuit Breaker.

TRE: Greater than or equal to the resultant load current of the circuit being protected.

The resultant load current is 50A.

Select TRE = 50A.

The initial settings are summarized in Table IX.

TABLE IX. Initial Circuit Breaker Settings for 60 Hz System

Circuit Breaker Locations	Circuit Breaker Types	Trip Elements (A)	Initial Settings			
			LTD	STPU	STD	INST
Generator	ACB-4000HR	4,000	6,000A	10,000A	TB4	42,000A
Bus-Tie SWBD	ACB-4000HR	4,000	6,000A	8,000A	TB3	--
SWBD Feeder	ACB-1600HR	1,600	2,400A	6,000A	TB2	--
LC Feeder	AQB-A101*	50	--	--	--	600A
PP Feeder	AQB-A50	50	--	--	--	--

* : With Current Limiting Fuse.

Step 4: Development of Time-Current Curves.

The initial settings of the protective devices and the available fault currents at each location are plotted as shown in Figure 6.

Step 5: Final Selection and Setting of Protective Devices.

This will minimize the number of loads affected by the miscoordination. In the example, the overlap of time-current characteristics can be seen in Figure 6. A number of changes in the protection can be investigated to improve coordination. The miscoordination is because the 600A instantaneous trip setting of the load center feeder circuit breaker will operate for the three-phase fault current of 659A at the power panel. It will also operate for a line-to-line fault current of 571A (= (659A)($\sqrt{3}/2$)) at the power panel since 571A falls within the ± 15% tolerance of the instantaneous setting. The most obvious change is to increase the instantaneous trip setting of the load center feeder circuit breaker. However, the instantaneous trip setting of this circuit breaker cannot be increased to a value greater than the three-phase fault current at the power panel since it would then not protect for a minimum fault of 562A as seen from the load center.

The trip elements of neither of the circuit breakers can be changed to improve coordination. In the case of the load center feeder circuit breaker, the next lower AQB-A101 element rating is 25A which is less than the full load current of the transformer it feeds. No change made in the trip element of the AQB-A50 circuit breaker at the power panel will effect the value of current for faults at the power panel.

As discussed above, the trip setting of the load center feeder circuit breaker must protect for a minimum fault as seen from the load center, and the value of current for a fault at the power panel will not be effected by changes in the Power Panel breaker. However, changing the AQB-A101F to an AQB-A102F and the AQB-A50 to AQB-A51, can improve the coordination. The AQB-A102F is equipped with short time pickup (STPU) and short time delay (STD) settings as well as an instantaneous trip (INST). These features allow the circuit breaker to be set to protect for the minimum fault condition and delay its operation until the power panel circuit breaker can clear a fault at its location. The instantaneous trip can be set higher and still protect for closer faults. The AQB-A51 allows smaller time bands for the AQB-A102. The final settings for the example system are summarized in Table X and the TCC is plotted in Figure 10.

TABLE X. Final Circuit Breaker Settings for 60 Hz System

Circuit Breaker Locations	Circuit Breaker Types	Trip Settings	Final Settings			
			LTD	STPU	STD	INST
Generator	ACB-4000HR	4,000A	6,000A	10,000A	TB4	42,000A
Bus Tie SWBD	ACB-4000HR	4,000A	6,000A	8,000A	TB3	--
SWBD Feeder	ACB-1600HR	1,600A	2,400A	6,000A	TB2	--
LC Feeder	AQB-A102F	50A	75A	400A	0.075s	1,000A
PP Feeder	AQB-A51	50A	--	--	--	--

As illustrated in Figure 10, the protective devices for the example are now satisfactorily coordinated. If no alternate circuit breaker were available to achieve coordination, the miscoordination must be restricted to the lowest tier of protection possible to minimize the number of loads affected by the miscoordination. In such a case, the instantaneous trip of the load center circuit breaker would have to be set to operate at a current greater than that for a three-phase fault at the power panel. For a minimum fault condition at the load center circuit breaker, clearing of the fault would be accomplished by operation of the thermal overload element of the load center circuit breaker.

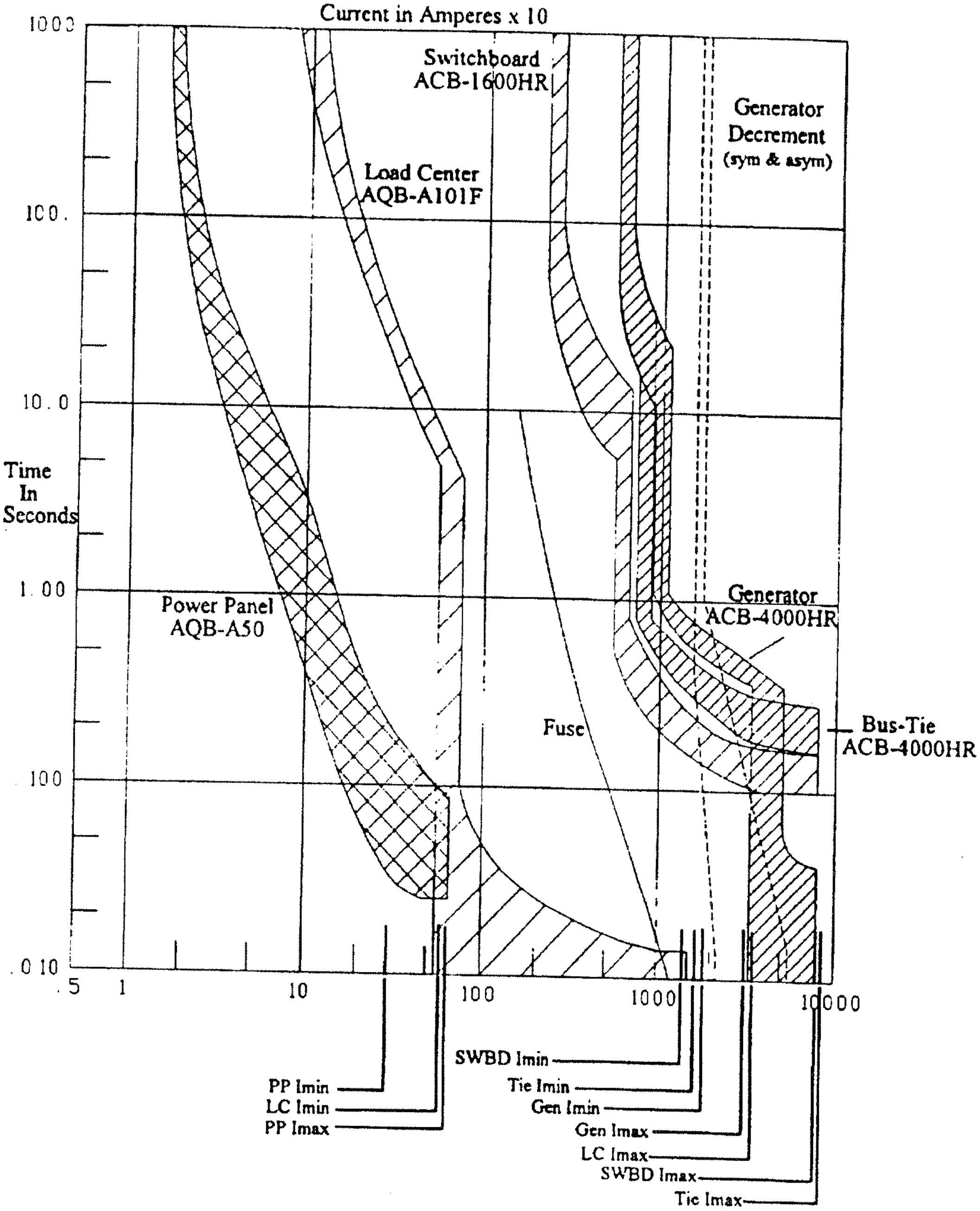


Figure 6. Initial 60 Hz Protective Device Settings

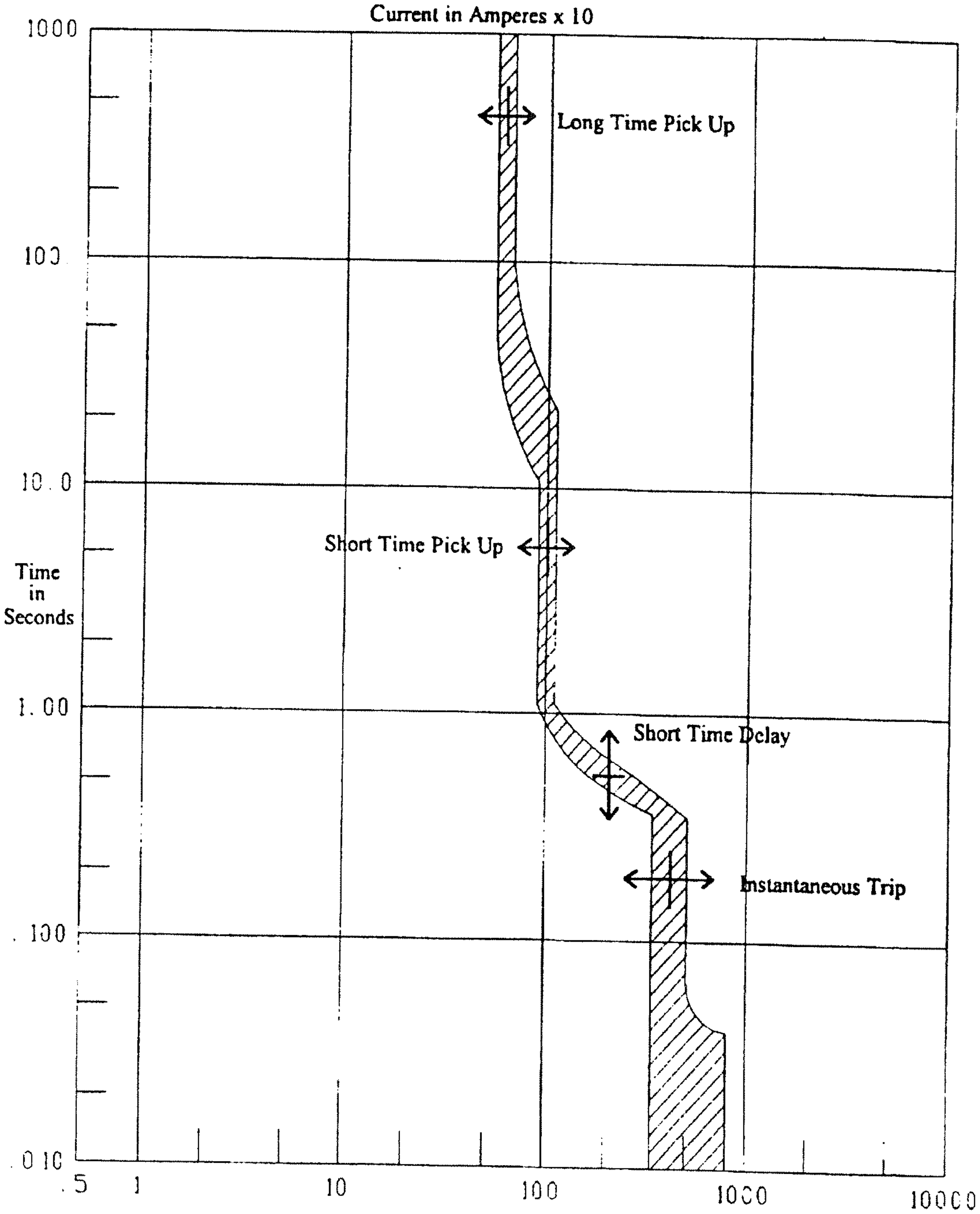


Figure 7. Type ACB Circuit Breaker Adjustments

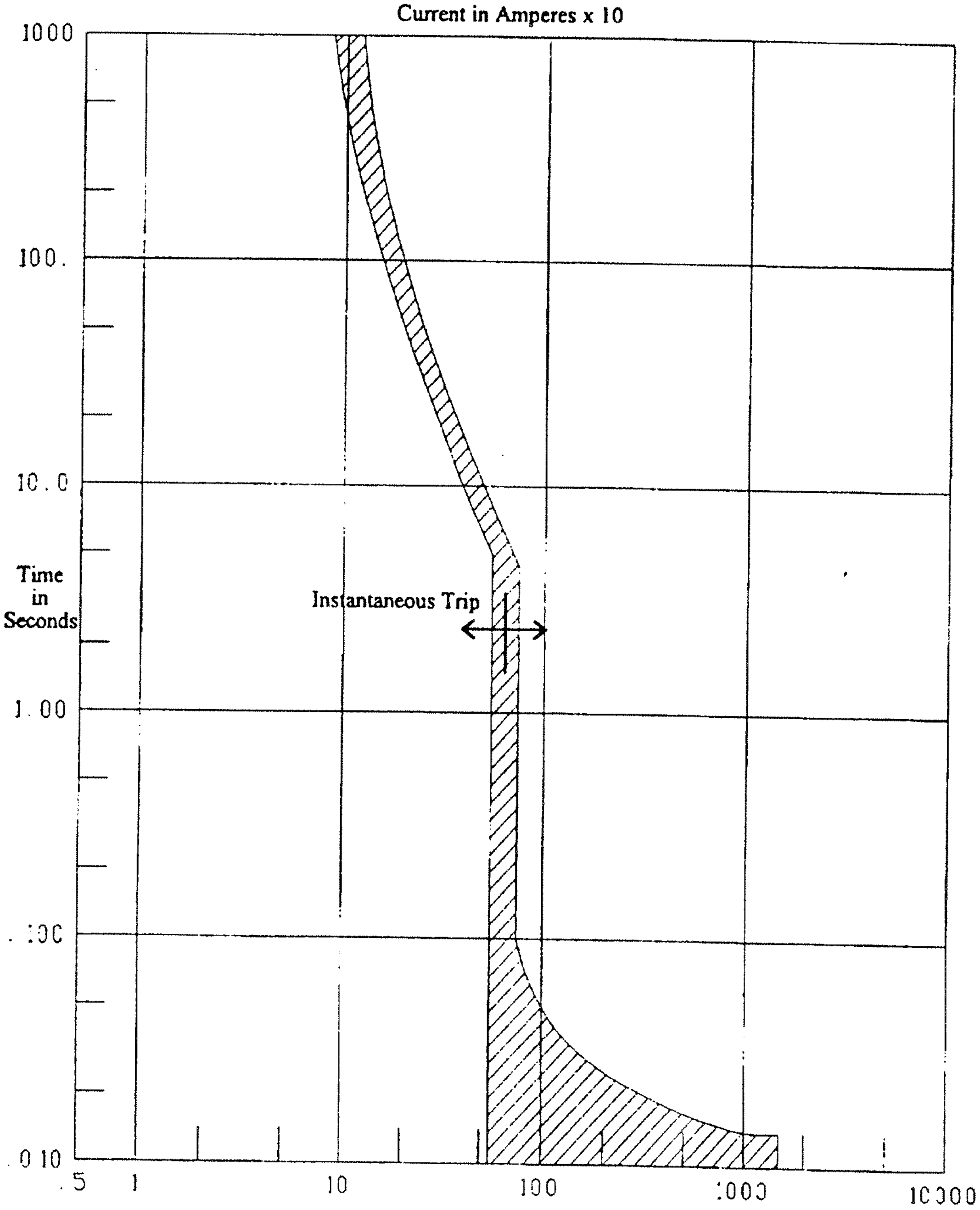


Figure 8. Type AQB Circuit Breaker (with Thermal-Magnetic Tripping Element) Adjustments

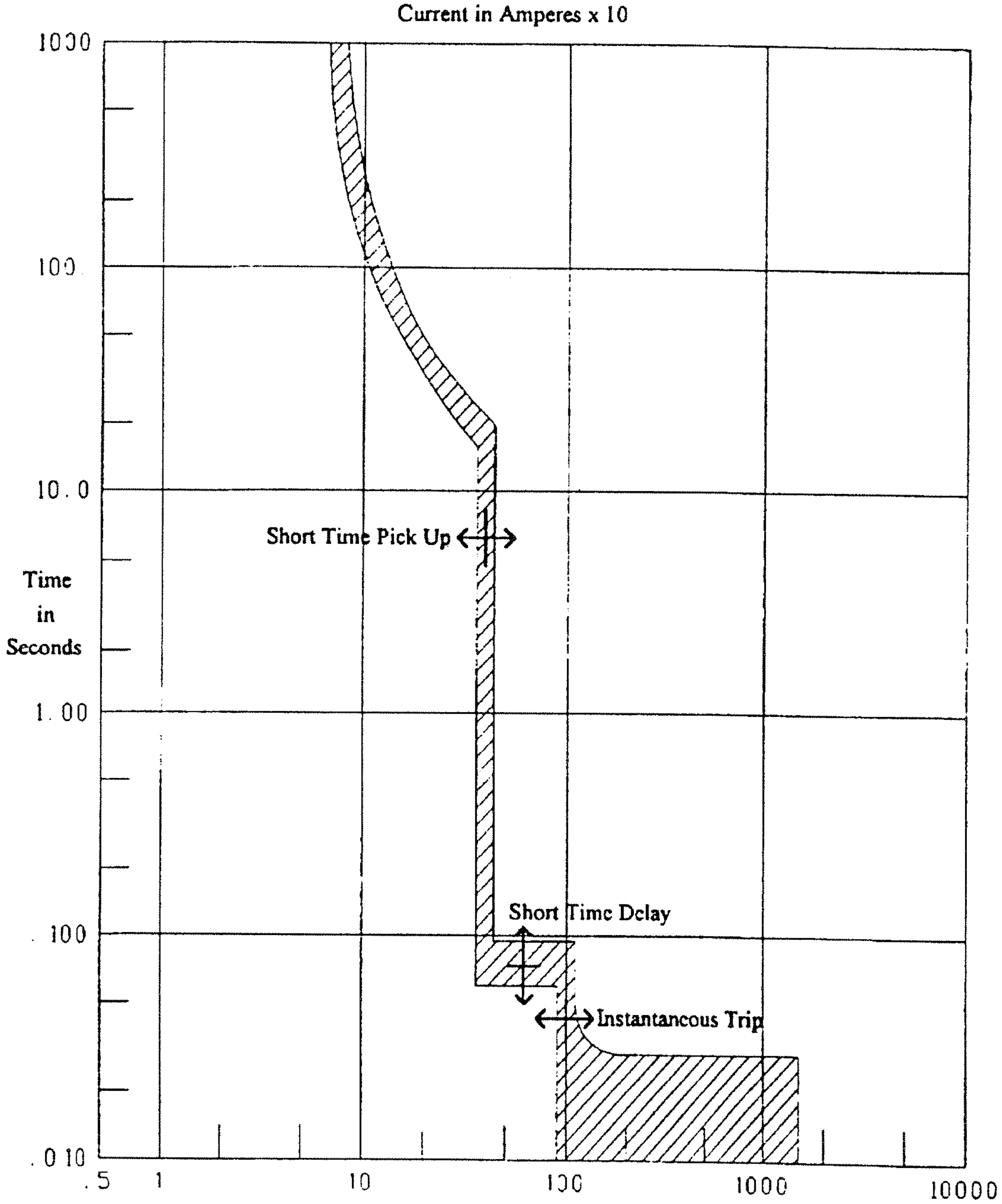


Figure 9. Type AQB Circuit Breaker (with Solid State Tripping Element) Adjustments

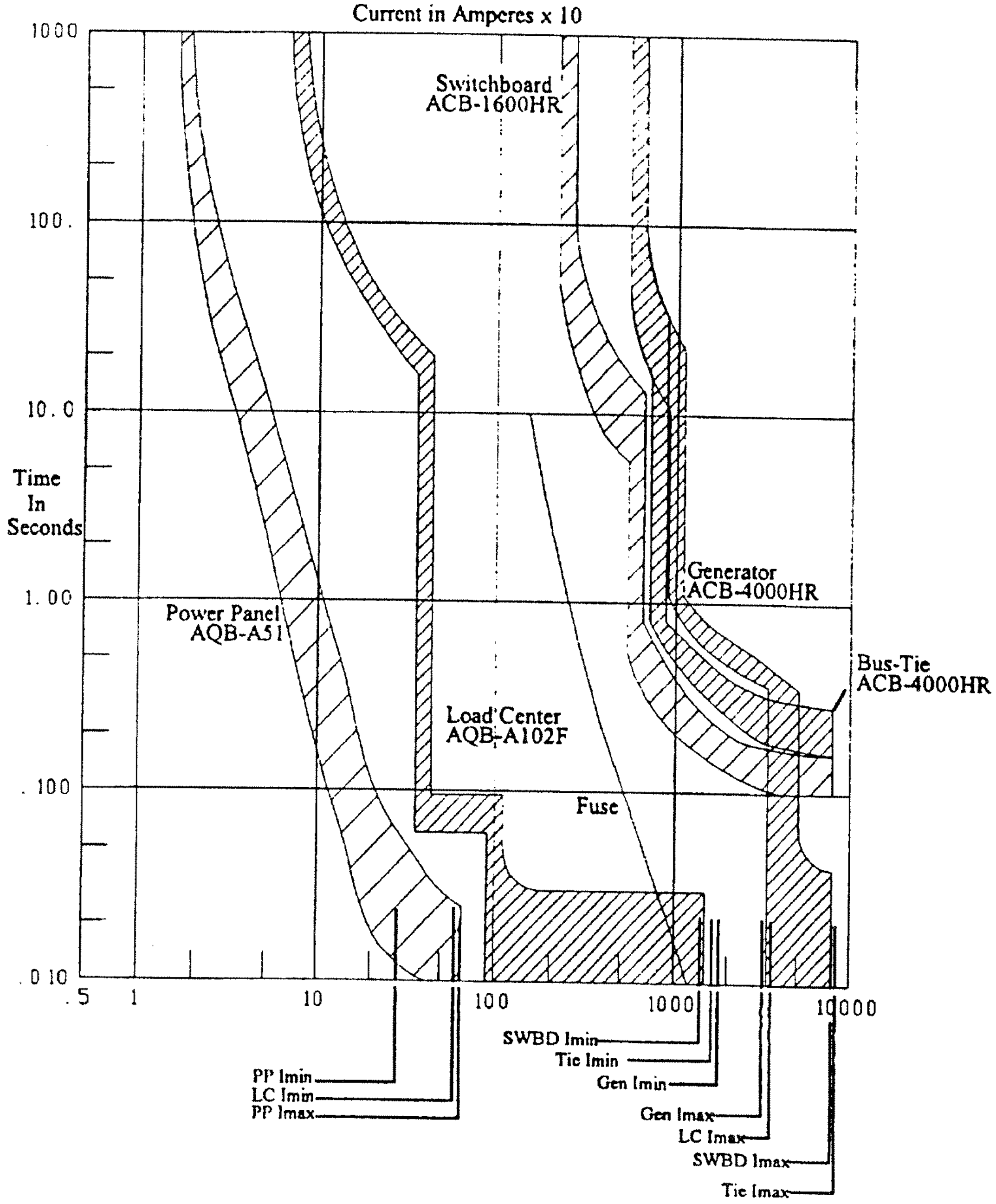


Figure 10. Final 60 Hz Protective Device Settings

300-2-k. <u>Example of Protective Device Coordination for 400 Hz System</u>.

Follow the same procedure of the previous example.

<u>Step 1</u>: <u>Collection of Supporting Data</u>.

The same information is needed for the 400 Hz system coordination as listed under step 1 of the 60 Hz example.

<u>Step 2</u>: <u>Selection of Type and Rating of Protective Devices</u>.

The types and ratings of protective devices shown in Figure 4 are selected as follows:

<u>Generator Circuit Breaker</u>.

CONT: Greater than or equal to the generator rated current: The generator rated current is 321A.

INTR: Greater than or equal to the fault current I_{avg} at the fault location F1.

The average fault current I_{avg} at the generator circuit breaker location is about 3,357A

<u>Select AQB-A400</u>. This circuit breaker has a continuous rating of 400A and an interrupting rating of 30,000A asymmetrical.

<u>Bus Tie Circuit Breaker</u>.

CONT: Greater than or equal to the maximum load current flowing in the bus tie circuit:

The maximum load current through the bus tie is the output current of one generator, which is equal to 321A (also the continuous current rating of the 400 Hz generator).

INTR: Greater than or equal to the fault current I_{avg} at the fault location F1:

The I_{avg} at the bus-tie circuit breaker is 3,357A (at switchboard 3SF).

<u>Select AQB-A400</u>. This circuit breaker has a continuous rating of 400A and an interrupting rating of 30,000A asymmetrical.

<u>Switchboard Feeder Circuit Breaker</u>.

CONT: Greater than or equal to the maximum load current of the circuit being protected:

The maximum load current of the switchboard feeder circuit is 150A.

INTR: Greater than or equal to the fault current I_{avg} flowing into this circuit breaker location:

The I_{avg} for this breaker location is 3,126A.

Select AQB-A101. The circuit breaker has a continuous rating of 100A and an interrupting rating of 10,000A asymmetrical.

Power Panel 2-185-2 Feeder Circuit Breaker.

CONT: Greater than or equal to the resultant load current of the circuit being protected:

The circuit load current is the transformer rated current which is:

$$I_L = [(3)(10\text{kVA})/(\sqrt{3})(0.45\text{kV})]$$
$$= 39\text{A}$$

INTR: Greater than or equal to the fault current I_{avg} at the assumed fault location (F3):

The average fault current at PP 2-185-2 is 1,747A.

Select AQB-A101. This circuit breaker has the continuous rating of 100A and the interrupting capacity of 10,000A asymmetrical.

Power Panel 2-186-3 Feeder Circuit Breaker.

CONT: Greater than or equal to the maximum load current of the circuit being protected:

The load current of this feeder circuit is 50A or less (the continuous rating of the cable from this feeder).

INTR: Greater than or equal to available fault current I_{avg} at the assumed fault location F4:

The average fault current I_{avg} is 555A or 2,081A at 120V.

Select AQB-A50. This circuit breaker has a continuous rating of 50A and the interrupting rating of 5,000A asymmetrical.

Power Panel 2-185-1 Feeder Circuit Breaker.

CONT: Greater than or equal to the maximum load current of the protected circuit:

The load current of this feeder circuit is 18A or less (the continuous rating of the cable from this feeder).

INTR: Greater than or equal to the maximum of fault current I_{avg} at the fault location (F5).

The fault current I_{avg} is 391A or 1,466A at 120V.

Select ALB-1. This circuit breaker has a continuous rating of 50A and the interrupting capacity of 5,000A asymmetrical.

The result of circuit breaker selection are summarized in table XI.

TABLE XI. Circuit Breaker Selection for 400 Hz System

Circuit Breaker Locations	System Voltage	Load Current	Circuit Breakers		
	(V)	(A)	Types	CONT	INTR
Gen - 3SF	450	321	AQB-A400	400A	30,000A
Bus Tie (2SF-3SF)	450	321	AQB-A400	400A	30,000A
SWBD 3SFB Feeder	450	77	AQB-A250	150A	20,000A
PP-2-185-2 Feeder	450	39	AQB-A100	50A	15,000A
PP-2-186-3 Feeder	120	50	AQB-A50	50A	5,000A
PP-2-185-1 Feeder	120	18	ALB-1	20A	5,000A

Note: The circuit breakers applied in the 400 Hz system of this example are types AQB or ALB-1 which do not have LTD or STD settings.

Step 3: Initial Selection of Trip Elements and Trip Settings.

The trip elements and trip settings of protective devices chosen in step 2 are initially selected and set as follows:

Generator Circuit Breaker.

TRE: Greater than or equal to the generator rated current:

The generator rated current is 321A.

Select TRE = 350KG.

INST: Greater than or equal to 120 percent of the generator maximum short-circuit current:

$$\text{INST} \geq (1.2)(2{,}096\text{A})$$
$$\geq 2{,}515\text{A}$$

Set INST = 3,190A, which is about 9.1 times of its trip element rating.

Bus Tie Circuit Breaker.

TRE: Greater than or equal to the bus-tie circuit load current:

The load current is equal to the rated current of a single generator, which is 321A.

Select TRE = 350KG.

INST: Not required, but it can be set at High (5,825A).

Switchboard Feeder Circuit Breaker.

TRE: Greater than or equal to the rated current of the circuit being protected:

The circuit rated current is 150A.

Select TRE = 150A.

INST: Less than or equal to 80 percent of the minimum fault current:

$$\begin{aligned} \text{INST} &\leq (0.8)(979\text{A}) \\ &\leq 783\text{A} \end{aligned}$$

Set INST = 650A.

Power Panel 2-185-2 Feeder Circuit Breaker.

TRE: Equal to or next above the resultant load current of the circuit being protected:

The resultant load current is equal to the transformer rated current:

$$\begin{aligned} I_L &= [(3)(10\text{kVA})/(\sqrt{3})(0.45\text{kV})] \\ &= 39\text{A} \end{aligned}$$

Select TRE = 50A.

INST: Should be set:

- Greater than or equal to the sum of 1.6 times the steady state starting current of the largest motor and the full load current of the remaining loads:

  Not applicable (assume no motor here).

- Less than or equal to 80 percent of the minimum fault current:

  $$\begin{aligned} \text{INST} &\leq (0.8)(377\text{A}) \\ &\leq 302\text{A} \end{aligned}$$

- Greater than or equal to 12 times of trip element if supplying only a transformer:

  $$\begin{aligned} \text{INST} &\geq (12)(50\text{A}) \\ &\geq 600\text{A} \end{aligned}$$

Set INST = 470A. This is a compromise setting and does not satisfy all the above requirements. The setting is the middle of the adjustable instantaneous range of the circuit breaker.

Power Panel 2-186-3 Feeder Circuit Breaker.

TRE: Equal to or next above the resultant load current of the circuit being protected:

The resultant load current is approximately equal to 50A.

Select TRE = 50A. This is a non-adjustable circuit breaker. No further settings are required.

Distribution Panel 2-185-1 Feeder Circuit Breaker.

TRE: Equal to or next above the resultant load current of the circuit being protected:

The resultant load current is equal to 18A.

Select TRE = 20A. This is a non-adjustable circuit breaker. No further settings are required.

The initial settings of the selected circuit breakers are summarized in Table XII.

TABLE XII. Initial Circuit Breaker Settings for 400 Hz System

Circuit Breaker Locations	Circuit Breaker Types	Trip Elements (A)	Initial Settings			
			LTD	STPU	STD	INST
Gen SWBD	AQB-A400	350	--	--	--	3,190A
Bus Tie SWBD	AQB-A400	350	--	--	--	5,825A
SWBD Feeder	AQB-A250	150	--	--	--	650A
PP 2-185-2 Feeder	AQB-A101	50	--	--	--	470A
PP 2-186-3 Feeder	AQB-A50	50	--	--	--	--
DP 2-185-1 Feeder	ALB-1	20	--	--	--	--

Step 4: Development of Time-Current Curves.

In setting over-current protective devices, two competing system requirements must be reconciled. The continuity of electric service requires that the protective devices operate selectively. This normally means, for a given fault current, the protective devices have successively slower interrupting times or longer time delays the nearer they are to the source. On the other hand, the necessity for maximum safety to personnel and equipment requires the fastest isolation of faulted circuits.

The time-current coordination curves (TCC) of protective devices provide a graphical solution for optimizing the competitive objectives of selectivity and protection systems. This method of analysis is applicable for designing the protection for a new system, or analyzing the protection of an existing system. The plot of time-current curves on a graph paper helps visualizing the tripping relationship between the protective devices. Any overlapping areas of the TCC curves show a miscoordination between the protective devices in the system. The adjustments in the protection system will be made.

The initial settings of the protective devices and the available fault currents at each location are plotted as shown in Figure 11.

Step 5: Final Selection and Setting of Protective Devices.

Any overlapping areas of the time-current characteristic curves of protective devices in series represent a potential lack of selectivity. If such areas exist, the following adjustments in protective device types, trip elements, and trip settings should be made to minimize the miscoordination:

- Increase the instantaneous setting of the upstream circuit breaker.
- Change the trip element (TRE) of one of the miscoordinated circuit breakers.
- Change the type of circuit breaker which causes the miscoordination. The circuit breakers of different types with similar settings often do not coordinate.
- Reassign the circuits which feed any large loads to panels with larger upstream circuit breakers.
- Rearrange the distribution system to eliminate a tier of protective devices.

If after the changes in the protective devices and settings, the overlapping area between the TCC curves still exists, restrict the miscoordination to the lowest tier of protection as much as possible. This will minimize the number of loads affected by the miscoordination. In this example, the overlap of time-current characteristics can be seen in Figure 11. A number of adjustments in the protection will be made to improve coordination. The miscoordinations are due to the instantaneous trip of the switchboard feeder circuit breaker will operate for a three-phase fault of 1,864A at PP 2-185-2, and the power panel feeder circuit breaker at PP 2-185-2 will operate for a three-phase fault current of 566A (2,801A @ 120V) at PP- 2-186-3. The most obvious change is to increase the instantaneous trip settings of the switchboard and power panel feeder circuit breakers. However, the instantaneous trip setting of the switchboard circuit breaker cannot be increased since it would then not protect for a minimum fault of 792A as seen from the switchboard. The same holds for the feeder circuit breaker at power panel PP 2-186-2. What is needed is some time delay in the operation of these circuit breakers to allow the downstream circuit breakers time to clear faults at their locations.

The AQB-A250 circuit breakers at the switchboard and the AQB-A101 at power panel PP 2-185-2 can be replaced with AQB-A252 and AQB-A102 circuit breakers respectively. The AQB-A252 is equipped with short time pickup (STPU) and short time delay (STD) settings as well as a wider range of instantaneous trip settings. These features allow the to be set to protect for the minimum fault condition but operation of the circuit breaker can be delayed until the downstream circuit breaker can clear the fault nearer its location. The INST trip can be set higher and still protect for closer faults. Also, replacing the AQB-A50 with an AQB-A51 allows a shorter time-band for the AQB-A102. The final settings for the circuit breakers are summarized in Table XIII and plotted as shown in Figure 12.

The miscoordination is restricted to the lowest tier of protection possible to minimize the number of loads affected by the miscoordination.

The final settings of circuit breakers are summarized in Table XIII.

TABLE XIII. Final Circuit Breaker Settings for 400 Hz System

Circuit Breaker Locations	Circuit Breaker Types	Trip Elements (A)	Final Settings			
			LTD	STPU	STD	INST
Generator	AQB-A400	350	--	--	--	1,750A
Bus Tie SWBD	AQB-A400	350	--	--	--	max
SWBD Feeder	AQB-A252	150	150	450	max	2,500A
PP 2-185-2 Feeder	AQB-A102	50	75	300	max	1,000A
PP 2-186-3 Feeder	AQB-A51	50	--	--	--	--
DP 2-185-1 Feeder	ALB-1	20	--	--	--	--

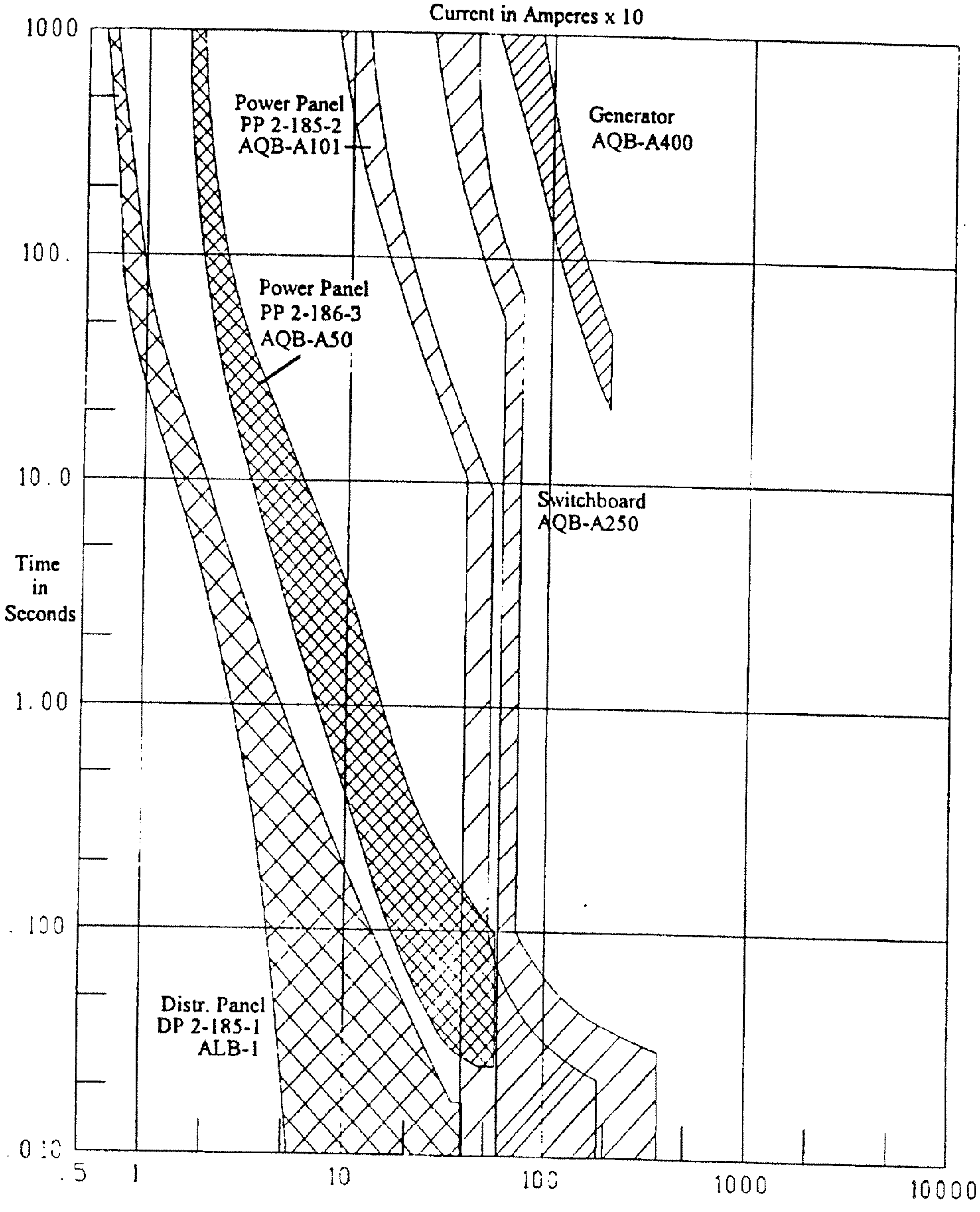


Figure 11. Initial 400 Hz Protective Device Settings

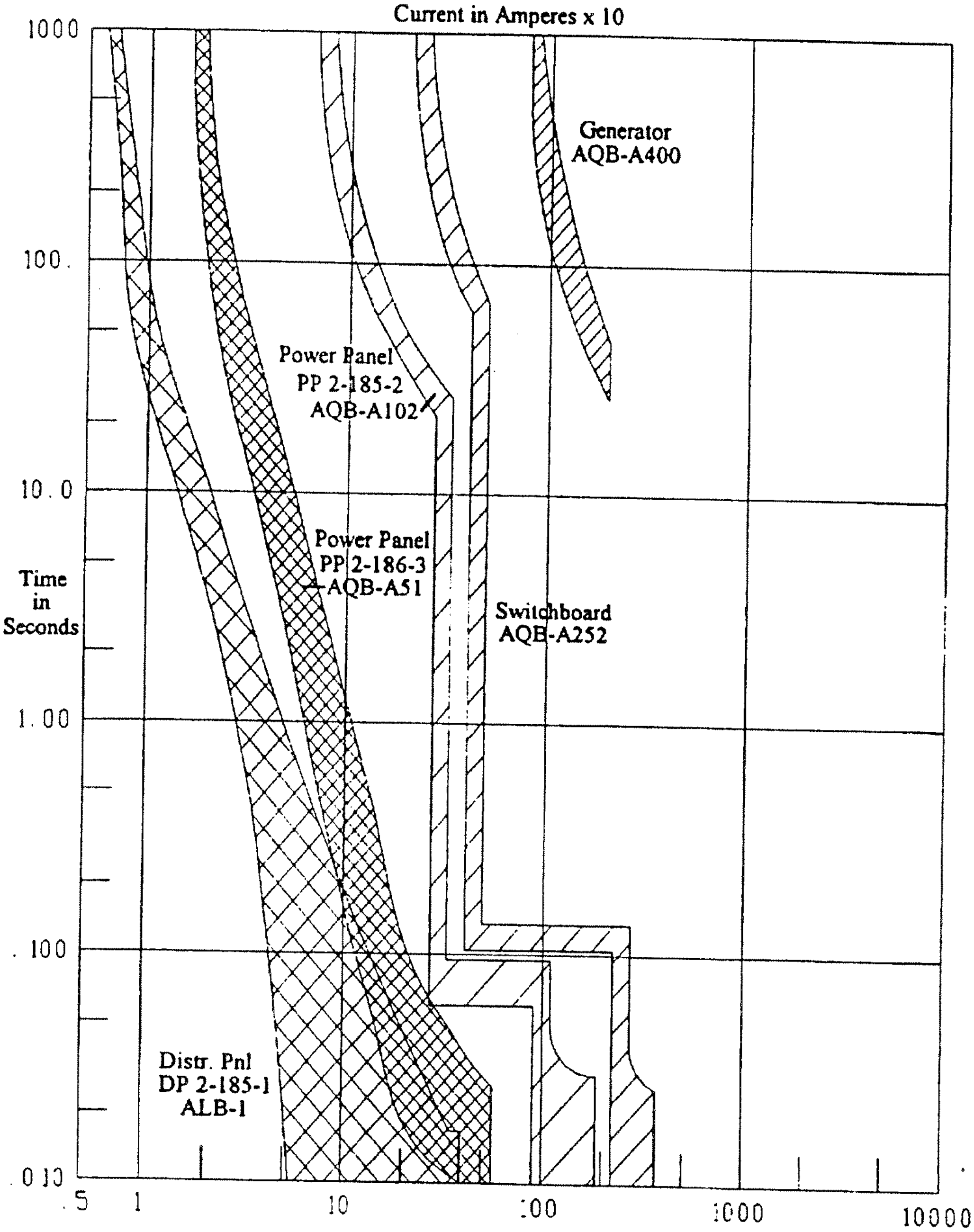


Figure 12. Final 400 Hz Protective Device Settings

300-2-1. Protective Device Coordination for Cable Protection.

Shipboard electrical cables must be protected from insulation damage due to high conductor temperatures during fault conditions. The conductors must be large enough to carry the fault current for a sufficient length of time to allow circuit breakers to interrupt the fault before the conductor temperature rises to the point where it damages the cable insulation.

Industrial users of power cable follow the recommendations of reference (o) for cable insulation protection. These recommendations are based on industrial studies and present an analytical approach to determine the maximum time that a cable may be subjected to a particular current without damage to its insulation. The problem is reduced to an ideal heat balance equation which is in function of time, current, temperature and conductor size.

For copper conductors:

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

Where:

I: Fault current in amperes.
CA: Conductor cross-sectional area in circular mils.
t: Duration of the fault in seconds.
T_1: Maximum operating temperature of the insulation in °C.
T_2: Maximum temperature of the insulation before the damage in °C.

This equation assumes that, prior to the fault, the cable is operating at rated current and at the maximum operating temperature T_1 of the insulation. The duration of the fault is assumed to be so short that the heat developed is contained in the conductor with minimum losses to the surrounding environment. This last assumption gives a conservative estimate since, in reality, some heat would be dissipated and the rise of conductor temperature would be slower. The values for T_1 and T_2 are:

Cable Types	Operating temperatures	
	T_1	T_2
Non-flexing cable	95°	250°
Flexing cable	75°	200°

The tripping characteristics of the circuit breaker that supplies power through the cable should be such that the circuit breaker operates before the maximum insulation temperature is reached. Figure 13 illustrates circuit breaker settings that satisfy this requirement Figures 14 and 15 show the damage curves for non-flexing TSGU cables.

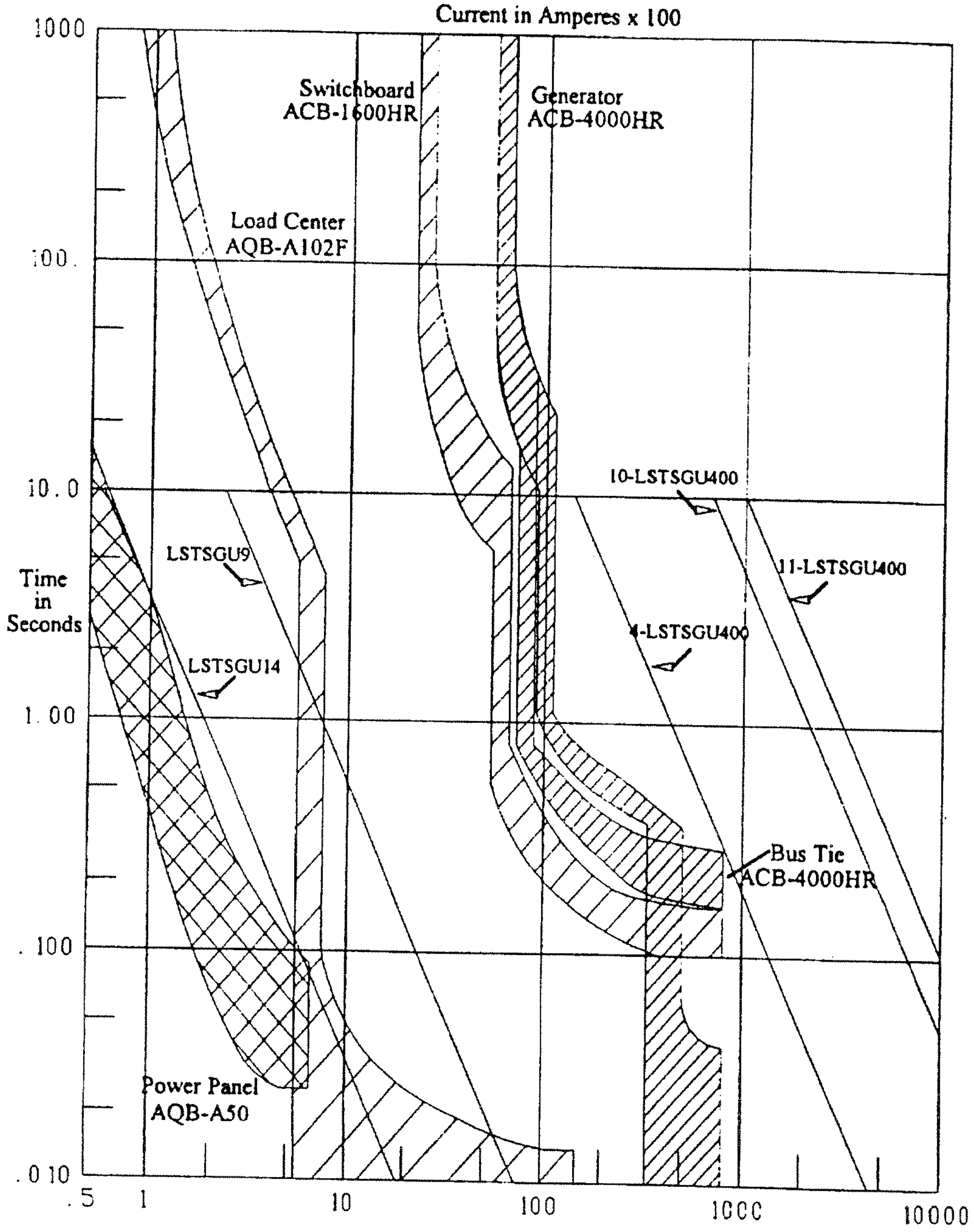


Figure 13. Time-Current Curves of Protective Devices for Cable Thermal Protection

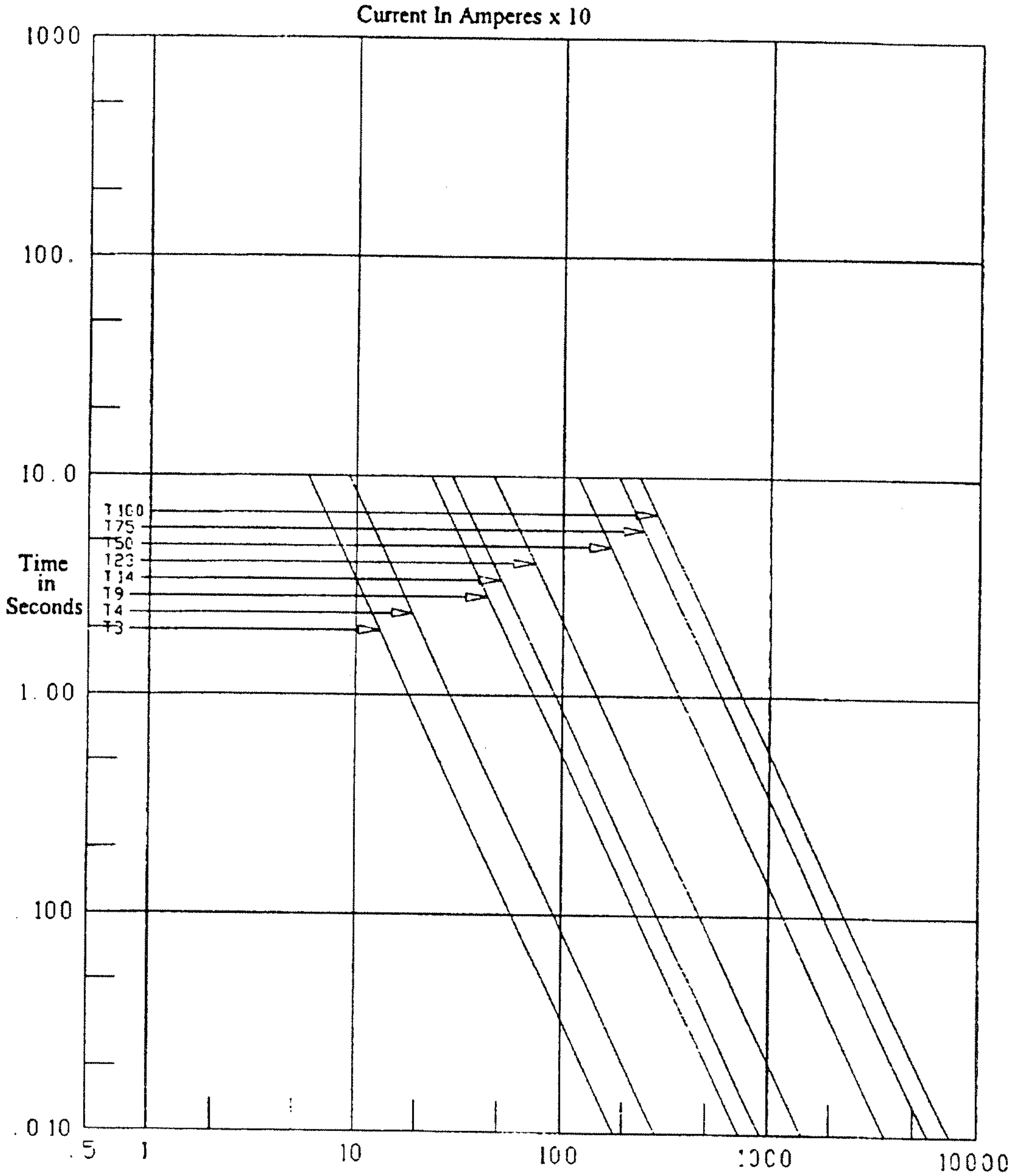


Figure 14. Cable Damage Curves for LSTSGU3 through LSTSGU100

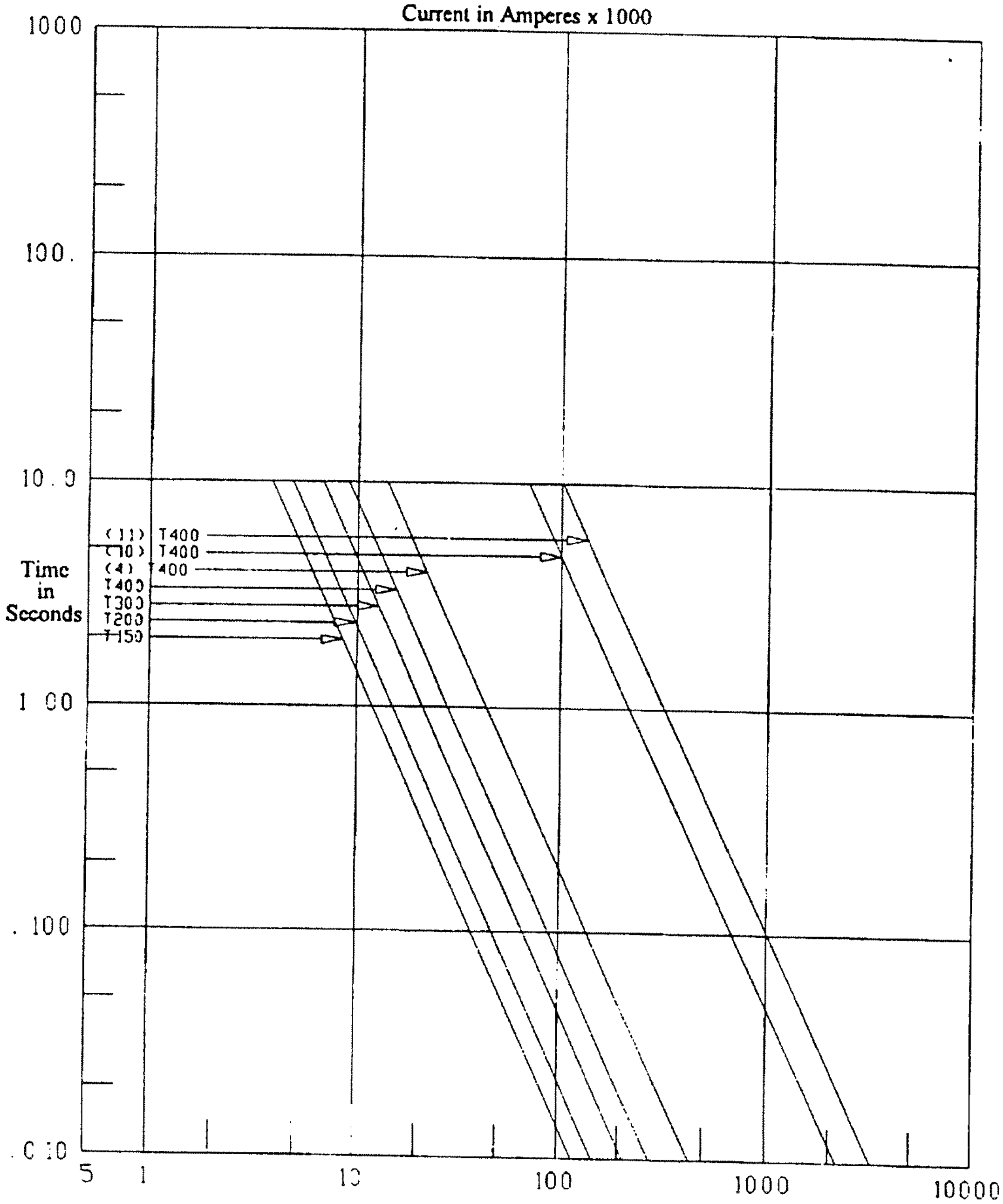


Figure 15. Cable Damage Curves for LSTSGU150 through 11-LSTSGU400

300-2-m. Protective Device Coordination for Transformer Protection.

From a protective device coordination point of view, there is a single concern for setting circuit breakers supplying transformers. The inrush current occurring on first energizing the transformer may cause operation of circuit breaker instantaneous trips or fuses. The magnitude of the inrush current depends on the transformer rating, the residual magnetism in the transformer, and the point on the voltage wave at which energizing occurs. For typical transformers found on ship power system, the maximum inrush current is in the range of 12 to 21 times of rated current (see transformer characteristic of reference (k)). On the time-current curves, the transformer inrush current is usually represented as a point with magnitude equal to the peak inrush current at 0.1 second.

The guidelines in reference (n) suggest that the instantaneous trip of a circuit breaker supplying a transformer be set at maximum 12 times the trip element and that the continuous rating of the fuses be no less than 125 percent of the transformer full load current.

Consider three 7.5kVA, single-phase, (450/120)V transformers in a delta-delta connection. The rated current is:

$$I_{f1} = (3)(7.5\text{kVA})/(\sqrt{3})(0.45\text{kV})$$
$$= 29\text{A}$$

From reference (k), the peak inrush current is 500A, so the rms inrush current will be approximately 375A or 12 times of the transformer rated current I_n.

Using the guidelines from Tables I and II of reference (n), the coordination of either of the two protective devices is possible to meet the following conditions:

- The circuit breaker supplying this transformer should be an AQB-A101 type having a continuous rating of 50A. The instantaneous trip should be set on HI (13 times the circuit breaker continuous current rating).
- The fuse supplying the transformer should have a continuous rating of 40A (the fuse rating not less than 125 percent of the transformer rated current).

The circuit breaker time-current characteristics and the transformer inrush current curves, are plotted in Figure 16.

300-2-n. Protective Device Coordination for Motor Starting.

The current drawn at the starting of an induction motor varies over a wide range of values. On energization, the locked rotor current is drawn during the motor acceleration. When the motor has reached full speed, the current drops to the rated current.

A number of coordination points should be examined to ensure that the branch circuit breaker does not trip during a normal starting. These points are:

- Locked rotor current.
- Acceleration time.

- Maximum withstand time of locked rotor current (stalled time).
- Rated current.

The locked rotor current for standard ratings of induction motors can be obtained from in reference (h). The dripproof induction motors are by far the most commonly used in Navy power system. The average of locked rotor currents for standard ratings of this type motor, in multiples of motor full load current, for motors rated 10hp and above, is 6.03 with a maximum variation of less than 0.4. This value for locked rotor current can be used if the actual locked rotor current is not available.

Usually, the acceleration of the motor is not known for every operation. However, the maximum withstand time for locked rotor current for all Navy motors is given in reference (h) as 20 seconds may be used as the coordination point in place of motor acceleration time. This represents an extreme but possible condition. The final motor characteristic to be considered is its full load current. This can be obtained from the motor nameplate. If this information is not available, it can be approximated using 1 hp equals 1 kVA in the equation:

$$I_{fl} = \left(\frac{kVA}{\sqrt{3}E_G}\right)$$

Where,

E_G : Terminal line-to-line voltage.

As an example, a 100hp motor is supplied from an AQB circuit breaker. The rated current is:

$$I_{fl} = 100kVA/(\sqrt{3})(0.45kV)$$
$$= 128A$$

Based on the average locked rotor current for Navy motors discussed above, the locked rotor current is:

$$I_{lr} = (6.03)(128.3A)$$
$$= 774A$$

The starting time for the motor is 20 seconds and assumed to be the maximum withstand time locked rotor current from reference (h). With these characteristics, the starting curve for the motor can be plotted as shown in Figure 17. The over-current protection should be selected so as not to trip when the motor is operating at rated load with enough time delay to allow the motor to start, but not so much that the maximum withstand time at locked rotor current is exceeded.

The AQB circuit breaker trip element for the motor is equal to the motor full load current (or the next higher rated element). The circuit breaker is thus an AQB-A250, since I_n of the motor is greater than 100A. From Table V of reference (d), the trip element is 150A. The guidelines in Table II of reference (n) suggest that the instantaneous trip setting for the circuit breaker be set at 12 times the trip element rating. This setting will be:

INST = (12)(150A)
= 1,800A

This value is above the maximum setting for a standard AQB-A250 instantaneous trip, so a trip element designed especially for motor applications must be selected. From Table V of reference (d), the instantaneous trip setting nearest the calculated value is 1,950A. The time-current characteristic curve of this circuit breaker is shown in Figure 17.

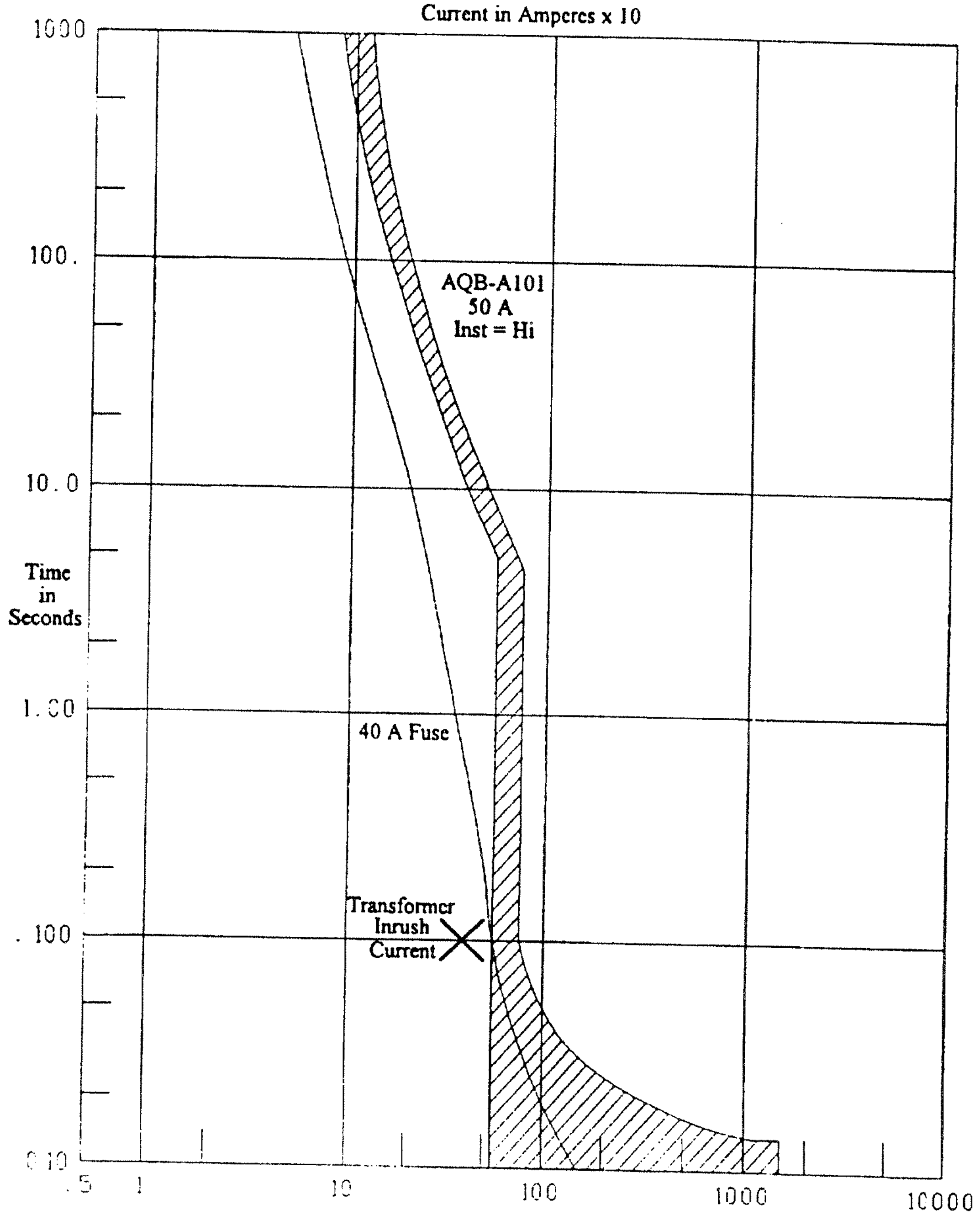


Figure 16. Time-Current Curves of Protective Devices for Transformer Inrush Current Protection

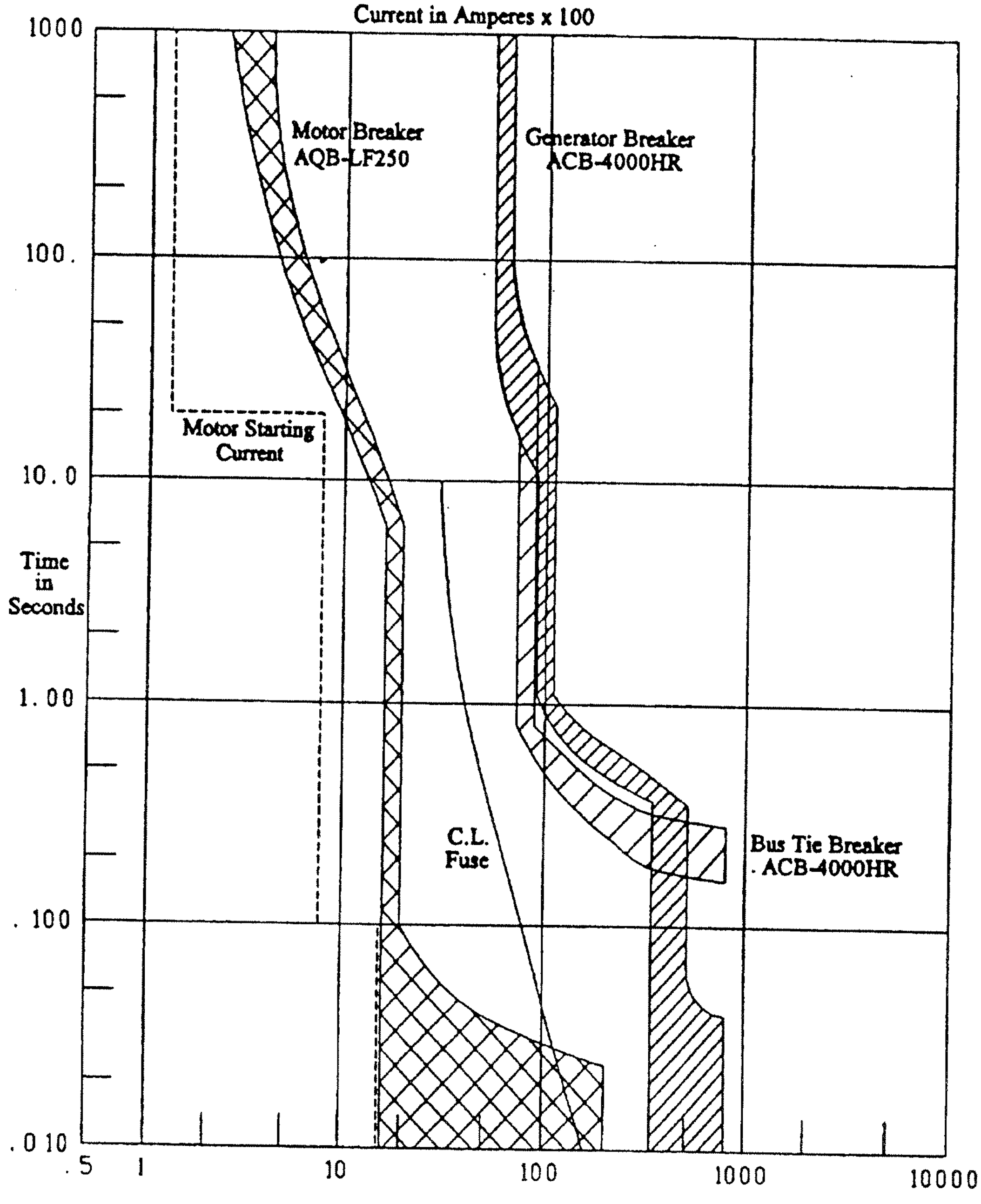


FIGURE 17. Time-Current Curves of Protective Devices for Motor Starting