DDS 314-1

DESIGN DATA SHEET

CALCULATION OF FAULT CURRENTS AND COORDINATION OF PROTECTIVE DEVICES FOR 400 HZ POWER SYSTEMS SUPPLIED BY SOLID STATE FREQUENCY CHANGERS

DEPARTMENT OF THE NAVY
NAVAL SEA SYSTEMS COMMAND
WASHINGTON, D.C. 20362-5101

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314-1-a. References

(a) Design Data Sheet DDS 311-3. Ship Service Electric Power System, Application and Coordination of Protective Devices

(b) MIL-F-24638(SH). Frequency Changer, Solid State, Air Cooled (Naval Shipboard)

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

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

(e) MIL-C-17588(SH). Circuit Breakers (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-C-17361(SH). Circuit Breakers, Air, Electric, Insulated Housing (Shipboard Use), General Specification For

(g) MIL-F-15160. Fuses: Instrument, Power, and Telephone

(h) MIL-S-24561(SH). Sensing and Signaling Device, Current Time (CTS), (Naval Shipboard Use)

(i) MIL-M-24116. Monitors, Voltage and Frequency, 400 Hertz Electric Power

314-1-b. Scope

This design data sheet describes the procedure for calculating the available fault currents and coordinating the protective devices in a 400 Hz power distribution system which is supplied by solid state frequency changers (SSFC).

314-1-c. Definitions

ALB, AQB - Circuit breakers built in accordance with MIL-C-17588(SH) & MIL-C-17361(SH). Typical frame sizes are AQB-A250, AQB-A101, AQB-A102, and ALB-1.

Bus - A conductor serves as a common connection for two or more circuits.

Coordination - The selection and setting of protective devices, such as fuses and circuit breakers, so that damage from fault current is minimized, and a minimum number of equipments is removed from service when a fault occurs.

Time-Current Curve - A graph of time versus current characteristics of a power source or protective device.

Current-Time Sensing and Signaling Device - A device consisting of current transformer and control modules which provides functions as specified in MIL-S-24561 (SH).

Current Limiting Device - A protective device consisting of a solid state switch and current-limiting reactance. In the event of a large current which is over its threshold current, the CLD will activate the solid-state switch and thereby insert a current-limiting reactance in the circuit to reduce the current to a specified value.

Current Limit Mode - The condition at which a SSFC output is regulated to a constant current instead of a constant voltage for a predetermined period of time before the shut down.

Fault - The condition when a relatively low impedance occurs between two points of difference voltage potential.

Fault Impedance - The equivalent impedance from a fault location to the power source.

Full Load Current - Rated load current or maximum continuous current supplied by a source.

Maximum Fault Current - The maximum available fault current I_{max} that can be produced by the total SSFC's operating in a common bus configuration at any 3-phase fault location in the distribution system. I_{max} is used to determine the interrupting rating of a protective device.

Minimum Fault Current - The minimum available fault current I_{min} that can be produced at any 3-phase fault location in the distribution system by a SSFC on line with all bus ties open. I_{min} is used to select the tripping rate of a protective device.

Short Circuit - Zero-impedance fault.

Solid State Frequency Changer - Equipment which converts the 60 Hz power to 400 Hz power, also known as static frequency converter.

SSFC Current Limit - The maximum current I_{cl} that drives SSFC into the current limit mode in a very short time (SSFC characteristics) before the shutdown. It is also known as the SSFC short-circuit current.

SSFC Fault Current - SSFC output current I_f that is greater than its full load or rated current but less than the current which force the SSFC into the current limit mode.

SSFC Full Load Current - The maximum continuous current supplied by a SSFC, and also known as the SSFC rate current.

SSFC Overload Current - Current greater than the full-load rating of a SSFC, but less than its fault current rating. The SSFC maintains rated voltage while supplying overload current.

SSFC Voltage Regulation Mode - Normal operating mode of a SSFC. In this mode, the SSFC regulates its output voltage to a constant 450V, and its output current is in the normal range or temporary overload range.

314-1-d. Symbols and Abbreviations

Symbol	Term/Parameter	Unit
CLD	Current limiting device	-
CTS	Current-time sensing and signaling device	-
E	SSFC output line-to-neutral voltage	Volt
SSFC	Solid state frequency changer	-
I_{cl}	SSFC current limit	Ampere
I_f	SSFC fault current	Ampere

I_{fl}	SSFC full load current	Ampere
I_{ol}	SSFC overload current	Ampere
I_{max}	Maximum fault current	Ampere
I_{min}	Minimum fault current	Ampere
V_{LL}	System line-to-line voltage	Volt
Z_F	Fault impedance (Z_{F1}....Z_{F4}) for I_{max} calculation	Ohm
Z_F'	Fault impedance (Z_{F1}'...Z_{F4}') for I_{min} calculation	Ohm

314-1-e. **General**

The power supply in a distribution system should be designed to be able to respond to a fault and dynamic load changes while maintaining reliability and survivability of the entire system. Although typically caused by a short circuit within the load, fault can occur as a result of a variety of circumstances including inadvertent maintenance mistakes or unforeseen operation conditions. The design and operation problem is to protect the complete system load from the time the fault occurs until it is cleared. If the source (SSFC) has shut down for self-protection, all loads experience complete power loss. If it has gone into current-limiting mode, all loads experience a lower input voltage. Since most equipment is most sensitive to voltage fluctuations for a very short time, the user equipment will shut down by itself under voltage protection or malfunctions. The fault current analysis and protective device coordination are the subjects of this design data sheet to assist designing of 400 Hz power system protection.

The coordination techniques of a protective device for both 60 Hz and 400 Hz systems are similar. However, the method for fault current calculations involving a SSFC power source is modified from the method used for the electromechanical power source (MG sets).

314-1-f. **Calculation of Fault Currents and Coordination of Protective Devices**

The fault current analysis is performed based on the assumptions specified in appendix B and characteristics of system parameters or components selected from applicable references (a) through (i). The following steps should be applied for the fault current calculations and protective device coordinations:

Step 1 - Calculation of Component Impedances and Development of Impedance Diagram

Each element (cable, transformer, circuit breaker, etc.) of a typical 400 Hz power distribution system as shown in Figure 1 of example I, is assumed modeling with its per-phase impedance value. The system impedance diagram should be drawn as shown in Figure 2 of example I.

Step 2 - Calculation of Fault Impedances

The equivalent impedance from a zero-impedance fault to the source is determined by combining all component impedances in the fault circuit.

Step 3 - Calculation of Fault Currents

The maximum fault current is calculated as follows:

$$I_{max} = \left(\frac{E}{Z_F} \right)$$

The minimum fault current is calculated as follows:

$$I_{min} = \left(\frac{E}{Z_F'} \right)$$

Where Z_F' is the equivalent impedance from the source to the line side of the next circuit breaker beyond the fault location in question.

If the calculated I_{max} and I_{min} are greater than the maximum overcurrent capacity of the SSFC, NI_{cl} and I_{cl} respectively, I_{max} and I_{min} will be set equal to:

$$I_{max} = NI_{cl} \qquad I_{min} = I_{cl}$$

Where N is the number of SSFC's on the line.

If CLD's are used, the initial values for I_{max} and I_{min} must be compared with the CLD threshold (predetermined) current. If either I_{max} or I_{min} exceeds the CLD threshold current, then the fault currents must be recalculated by including the CLD impedance in step 1 and then repeat steps 2 and 3.

Step 4 - Selection of Protective Devices

The type, rating, and size of a protective device are selected to satisfy maximum continuous load, system overload and fault protection requirements.

I_{max} is used to determine the required interrupting rating of a protective device. Normally, I_{max} does not exceed the maximum output of the SSFC's capacity which is limited to a value well within the rating of the selectively protective device.

I_{min} is used to determine the tripping rating of a protective device.

1. Circuit Breakers

Circuit breakers and fuses shall be selected from the applicable references (e) and (f), and (g) respectively in accordance with the following conditions:

- The circuit breaker (or fuse) interrupting rating shall be equal to or greater than the maximum fault current at a fault location in the system to be protected.

- The circuit breaker continuous rating or frame size shall be equal to or next above the maximum load current of the distribution circuit being protected.

- The circuit breaker thermal or long time delay trip element shall be selected to be equal to or next size above the normal load current. The trip element rating shall be less than I_{min}.

- The circuit breaker magnetic or instantaneous trip element shall be selected such that the trip element shall activate when the current through the circuit breaker exceeds the circuit load current plus the associated load transients. The instantaneous trip element rating shall be less than I_{min}.

2. Current-Time Sensing and Signaling Device

CTS units are not initially selected for use in the 400 Hz system protection. They should be selected after a coordination study has been performed. If a miscoordination exists, the CTS may be inserted to the system to improve coordination. The CTS rating must be equal or greater than the circuit load current. The CTS may be selected in accordance with reference (h).

3. Current Limiting Devices

The CLD can be applied at the outputs of various feeders to improve the system survivability. The fault current is detected by the CLD which will insert a current limiting impedance into the circuit. By limiting the current to a value which is supportable by the SSFC, the voltage throughout a balanced distribution system is maintained within acceptable limits allowing normal operation. Since the CLD allows sufficient amount of current to pass to the load, the appropriate circuit breaker clears the fault without impacting the rest of the distribution system and the SSFC may stay in the regulation mode or overcurrent mode during the fault.

To select a CLD, the following parameters and conditions must be considered:

- The continuous current of a CLD must be equal or greater than the maximum load current through the CLD.
- The sum of the maximum let-through current rating (or required current in feeder with CLD) of the CLD and the resultant load currents in other feeders should be less than the overload current rating of a SSFC.
- The CLD must not activate for normal load currents.
- The CLD must allow the start-up of loads without tripping the upstream circuit breaker.
- The CLD must let through enough current to allow downstream circuit breakers to selectively trip.

In this DDS, the CLD rating is referred to the maximum current that the CLD will pass at its high-impedance state. For example, a 500A CLD should let through a maximum of 500 ± 5% of the steady state amperes when its load terminals are shorted together.

Step 5 - Coordination of Protective Devices

Once I_{max} and I_{min} are determined and the ratings of protective devices are selected, a circuit coordination drawing will be developed by drawing the time-current curves of the SSFC's and the protective devices on the same graph paper. The time-current curves of the devices are usually provided by manufacturers. Appendix A shows how a SSFC's time-current curve is drawn.

Normally, not all time-current curves of protective devices need to be drawn. Only worst case must be checked, such as:

- The bus-tie protective device with the SSFC internal protection and output protective device.
- The SSFC output protective device with the SSFC internal protection.
- The largest switchboard feeder protective device with the SSFC internal protection and the SSFC output protective device.
- The largest circuit breaker on a power or distribution panel should be checked for coordination with all protective devices servicing that power or distribution panel.

If a system were checked for proper coordination, there should be no instances in which one protective device services another protective device of the same size and rating. For example, a power panel containing an AQB-A101 circuit breaker of with 100A frame size and INST set at HI, and feeding a distribution panel should not be fed from the switchboard by an AQB circuit breaker of the same size and rating. A condition such as previously described will show a miscoordination on the coordination drawing for the distribution panel being serviced from the power panel.

In many cases, the SSFC output protective device will not need to be coordinated with the SSFC internal protection because the output protective device can only be tripped by a shunt-trip signal from the SSFC. If this is the case, the SSFC output protective device coordination can be ignored.

314-1-g. Examples of Calculation of Fault Currents and Coordination of Protective Devices

Example I - The distribution system shown in Figure 1 will be used for this example. It is a radially fed distribution system supplied by two SSFC's. Each SSFC has the following current characteristics:

Full load Current (I_{fl}):	157A	for	$0 < t < \infty$
Overload Current (I_{ol}):	196A	for	$0 < t < 1800s$
Fault Current (I_f):	235A	for	$0 < t < 900s$
Short-Circuit Current (I_{cl}):	431A	for	$0 < t < 1.5s$

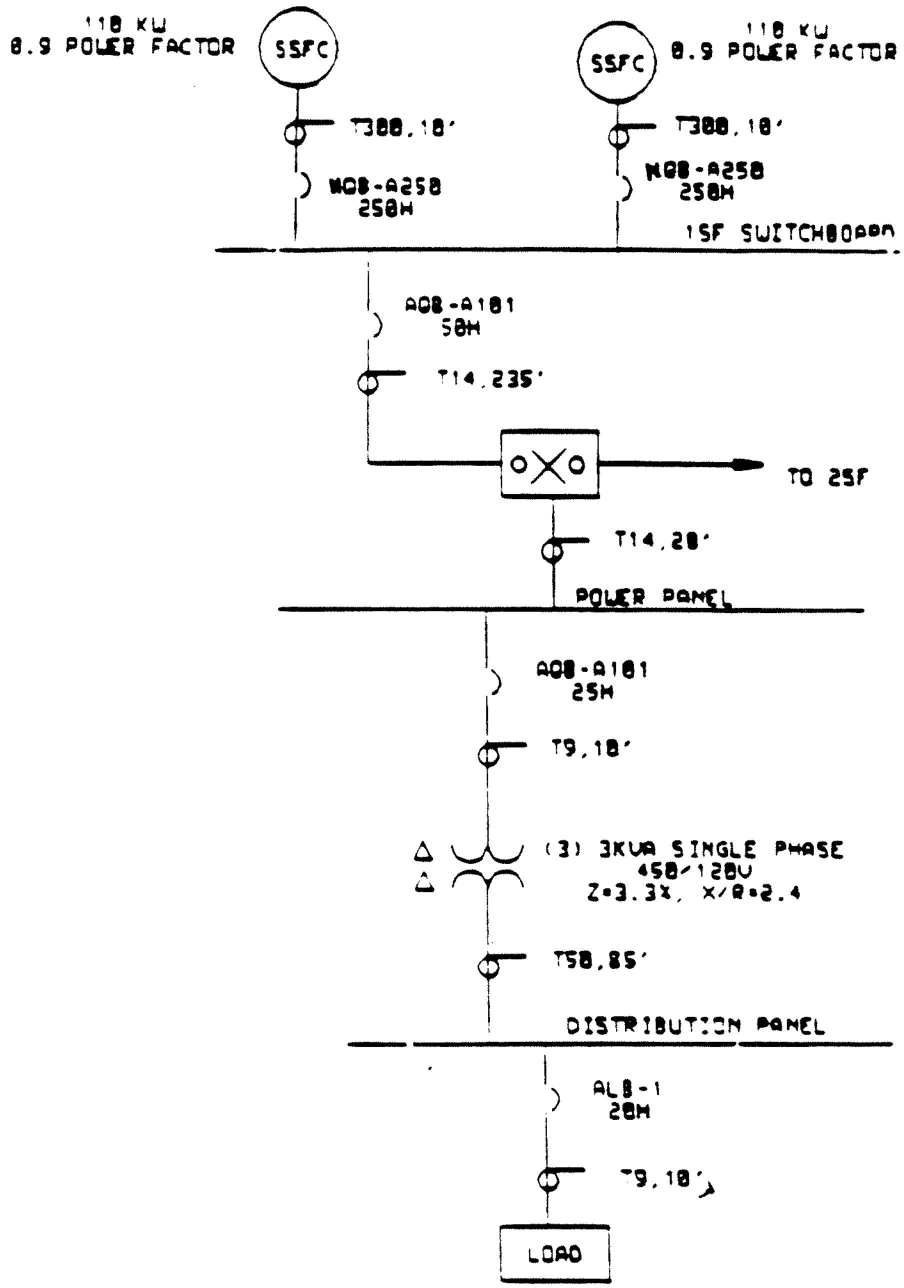


Figure 1. Distribution System One-line Diagram

The calculations can be done in the per-unit system or actual quantities. Appendix C discusses the per-unit system.

Step 1 - Calculation of Component Impedances and Development of Impedance Diagram

The impedances of the system components in Figure 1 are calculated and drawn as shown in Figure 2. In this example, the circuit breaker and SSFC internal impedances are neglected. Therefore, the result is a slightly conservative solution to the fault current calculations. Cable impedances may be obtained from tables in reference (c). The use of actual transformer impedance is recommended if it is available. If not, a conservative calculation will be obtained by using an impedance of 2 percent and a ratio (X/R) of 3.

In Figure 2, Z_1 represents the impedance of a 10-foot T300 cable. From Table XIV of reference (c) the values of R and X are:

$$R = 0.000610\ \Omega/\text{ft}$$
$$X = 0.001730\ \Omega/\text{ft}$$

The phase angle (θ) is calculated as follows:

$$\begin{aligned}\Theta &= \tan^{-1}(X/R)\\ &= \tan^{-1}(0.173/0.061)\\ &= 70.58°\end{aligned}$$

Then,

$$\begin{aligned}Z_1 &= 0.000610 + j0.001730\\ &= 0.0018344\underline{/70.58°}\end{aligned}$$

Other cable impedances in the system are calculated in the same manner.

Consider 3 one-phase transformers of 3kVA each, (equivalent to one 3-phase 9kVA transformer) which have an impedance of 3.3% and ratio (X/R) of 2.4. The phase angle is calculated as follows:

$$\begin{aligned}\Theta &= \tan^{-1}(X/R)\\ &= \tan^{-1}(2.4)\\ &= 67.38°\end{aligned}$$

To convert 3.3% to per unit on the transformer base (9kVA):

$$\begin{aligned}Z_{pu} &= 3.3/100\\ &= 0.033\end{aligned}$$

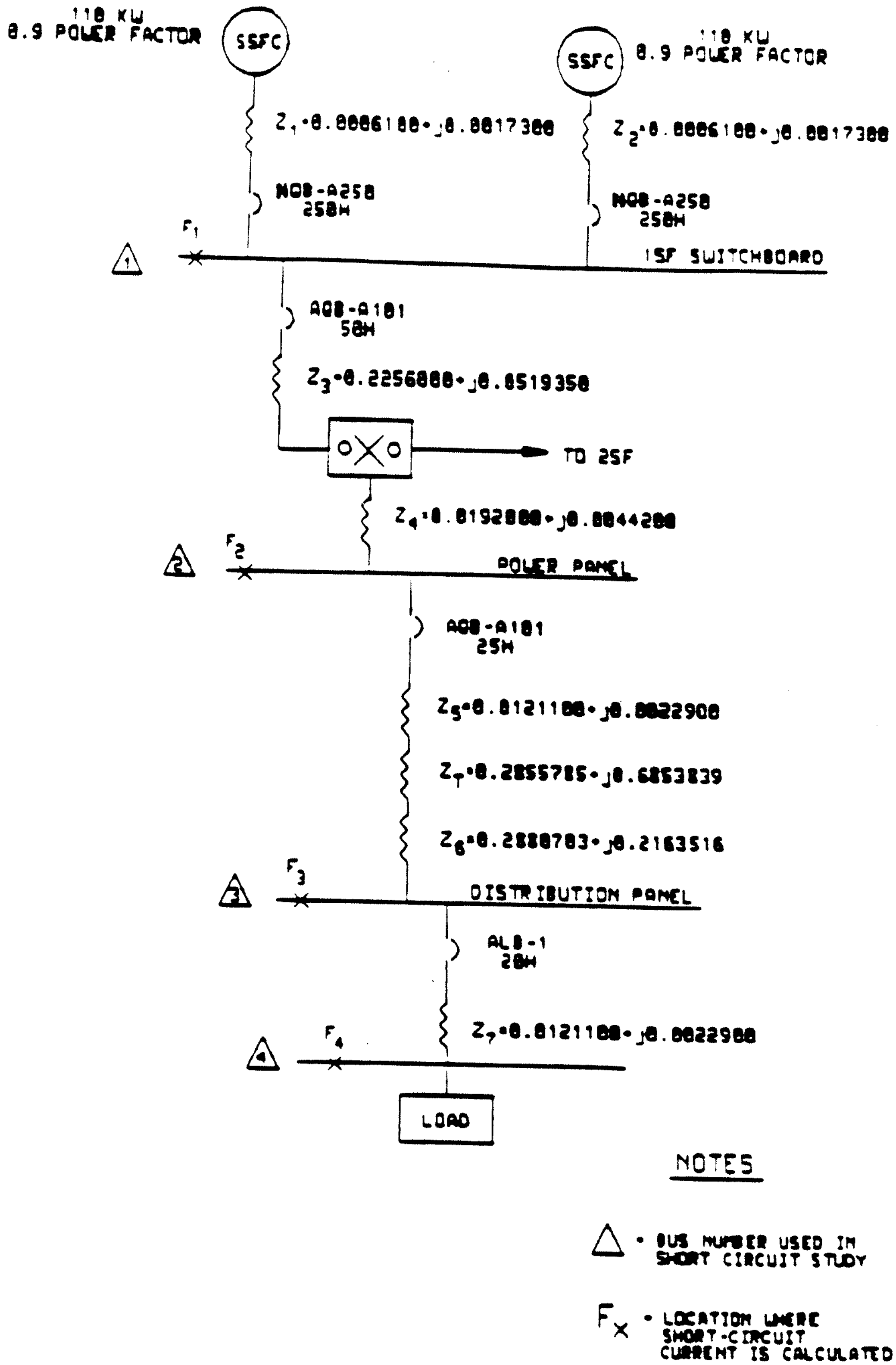


Figure 2. Distribution System Impedance Diagram

To change from per unit to ohm at 450 volts:

$$Z = (0.033)[(V)^2_{base}/(kVA)_{base}]$$
$$= (0.033)[(450)^2/(9)(1000)]$$
$$= 0.285578 + j0.685383$$
$$= 0.7425 \underline{/67.38°}$$

Notice that the component impedances in the transformer secondary side (120V base) to the fault location must be converted from a 120 volt base to a 450 volt base. This transformation is performed as follows:

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

Notice also that the values for Z_6 and Z_7 in Figure 2 are assumed in the 450V base.

Step 2 - Calculation of Fault Impedances

In Figure 2, the corresponding fault impedances from various fault locations toward the sources are:

Location F1:

The equivalent of fault impedance for I_{max} calculation is:

$$Z_{F1} = (Z_1Z_2)/(Z_1 + Z_2)$$
$$= 0.000865 + j0.000305$$
$$= 0.000917\underline{/70.58°}$$

The equivalent of fault impedance for I_{min} calculation is:

$$Z_{F1}' = Z_1 + Z_3 + Z_4$$
$$= 0.000610 + j0.001730 + 0.225600 + j0.051935 + 0.019200 + j0.004420$$
$$= 0.245410 + j0.058085$$
$$= 0.252190\underline{/13.31°}$$

Location F2:

$$Z_{F2} = Z_{F1} + Z_3 + Z_4$$

$$
\begin{aligned}
Z_{F2} &= 0.000305 + j0.000865 + 0.225600 + j0.051935 \\
&\quad + 0.019200 + j0.004420 \\
&= 0.245105 + j0.057220 \\
&= 0.251695\underline{/13.14^\circ}
\end{aligned}
$$

$$
\begin{aligned}
Z_{F2}' &= Z_{F1}' + Z_5 + Z_T + Z_6 \\
&= 0.244800 + j0.056355 + 0.012110 + j0.002290 \\
&\quad + 0.285579 + j0.685384 + 0.288070 + j0.216352 \\
&= 0.831169 + j0.962111 \\
&= 1.271416\underline{/49.18^\circ}
\end{aligned}
$$

<u>Location</u> <u>F3:</u>

$$
\begin{aligned}
Z_{F3} &= Z_{F2} + Z_5 + Z_T + Z_6 \\
&= 0.245105 + j0.057220 + 0.012110 + j0.002290 \\
&\quad + 0.288070 + j0.216351 + 0.285578 + j0.685383 \\
&= 0.830864 + j0.961246 \\
&= 1.270560\underline{/49.16^\circ}
\end{aligned}
$$

$$
\begin{aligned}
Z_{F3}' &= Z_{F2}' + Z_7 \\
&= 0.831169 + j0.962111 + 0.012110 + j0.002290 \\
&= 0.843279 + j0.964401 \\
&= 1.281089\underline{/48.83^\circ}
\end{aligned}
$$

<u>Location</u> <u>F4:</u>

$$
\begin{aligned}
Z_{F4} &= Z_{F3} + Z_7 \\
&= 0.830864 + j0.961244 + 0.012110 + j0.002290 \\
&= 0.842974 + j0.963536 \\
&= 1.280237\underline{/48.82^\circ}
\end{aligned}
$$

$$
\begin{aligned}
Z_{F4}' &= Z_{F3}' \\
&= 0.843279 + j0.964401 \\
&= 1.281089\underline{/48.83^\circ}
\end{aligned}
$$

<u>Step</u> <u>3</u> - <u>Calculation</u> <u>of</u> <u>Fault</u> <u>Currents</u>

Location F1:

Since the feedback signal of voltage regulator is taken from the location F1 (main switchboard) to the SSFC, the effective impedance is considered zero. Therefore, the maximum fault current at F1 is mathematically infinite.

$$I_{max} = E/|Z_{F1}|$$
$$= (450/\sqrt{3})/(0)$$
$$= \infty$$

$$I_{min} = E/|Z_{F1}'|$$
$$= 450/\sqrt{3}(0.252190)$$
$$= 1030.20A$$

The maximum overcurrent capacity (for the worst case, I_{cl} is used) of the 2 SSFC's is:

$$NI_{cl} = (2)(431A)$$
$$= 862A$$

Since I_{max} and I_{min} are respectively greater than NI_{cl} and I_{cl}, the SSFC's are in current limit mode. I_{max} and I_{min} are then set equal to the SSFC's overcurrent capacities:

$$I_{max} = NI_{cl} \qquad I_{min} = I_{cl}$$
$$= 862A \qquad = 431A$$

Location F2:

$$I_{max} = E/|Z_{F2}|$$
$$= 450/\sqrt{3}(0.251695)$$
$$= 1032.23A$$

$$I_{min} = E/|Z_{F2}'|$$
$$= 450/\sqrt{3}(1.271416)$$
$$= 204.34A$$

Again I_{max} is greater than NI_{cl} and the SSFC's are still in current limit mode. I_{max} is set equal to NI_{cl}.

Location F3:

$I_{max} = E/|Z_{F3}|$

$= 450/\sqrt{3}(1.270560)$
$= 204.48A$

$I_{min} = E/|Z_{F3}'|$

$= 450/\sqrt{3}(1.281089)$
$= 202.80A$

Since I_{max} is less than NI_{cl}, the SSFC's will not go into the current limit mode.

Location F4:

$I_{max} = E/|Z_{F4}|$

$= 450/\sqrt{3}(1.280237)$
$= 202.94A$

$I_{min} = E/|Z_{F4}'|$

$= 450/\sqrt{3}(1.281089)$
$= 202.80A$

The SSFC's are still operating in the voltage regulation mode because I_{max} is below the SSFC short-circuit current.

Steps 4 & 5 - Selection and Coordination of Protective Devices

The protective devices shown in Figure 2 are selected to satisfy the values of I_{max} and I_{min}. Figure 3 shows the SSFC's time-current curves. The time-current curves for circuit breakers are shown in Figures 4, 5, and 6. The filled-in black portions of the curves represent fault currents between I_{max} and I_{min}. Figure 4 shows the curves with the AQB-A101 circuit breakers' instantaneous trip settings are on HI. The instantaneous trip settings are on MEDIUM in Figure 5, and on LOW in Figure 6. The following conclusions can be made by inspection of Figures 4, 5, and 6:

- With both AQB instantaneous trip settings on HI, the 50A circuit breaker does not coordinate with the SSFC. For a fault at location F2 (see Figure 2) the SSFC will go into current limit mode and eventually shut down without the fault

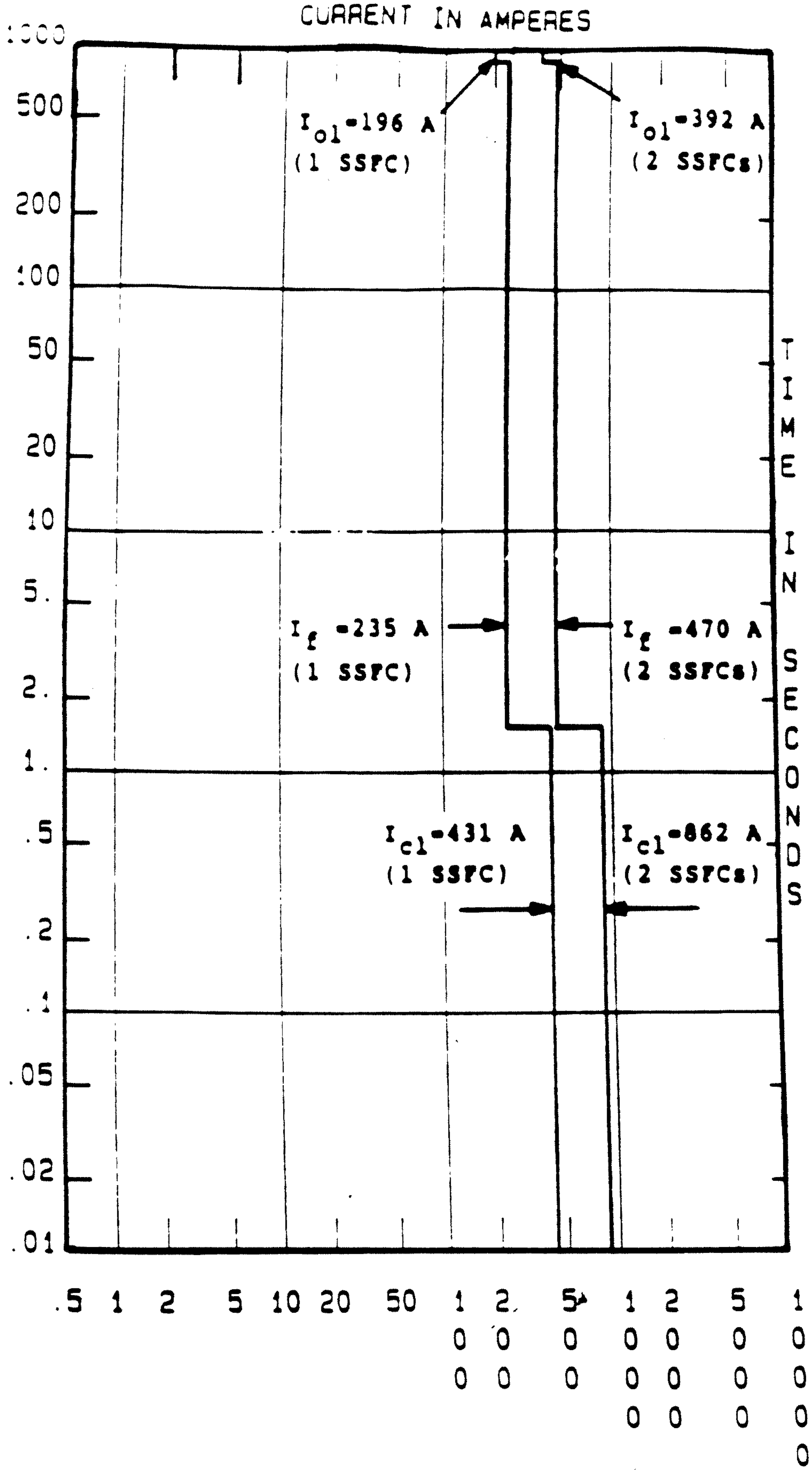


Figure 3. SSFC Time-current Curve.

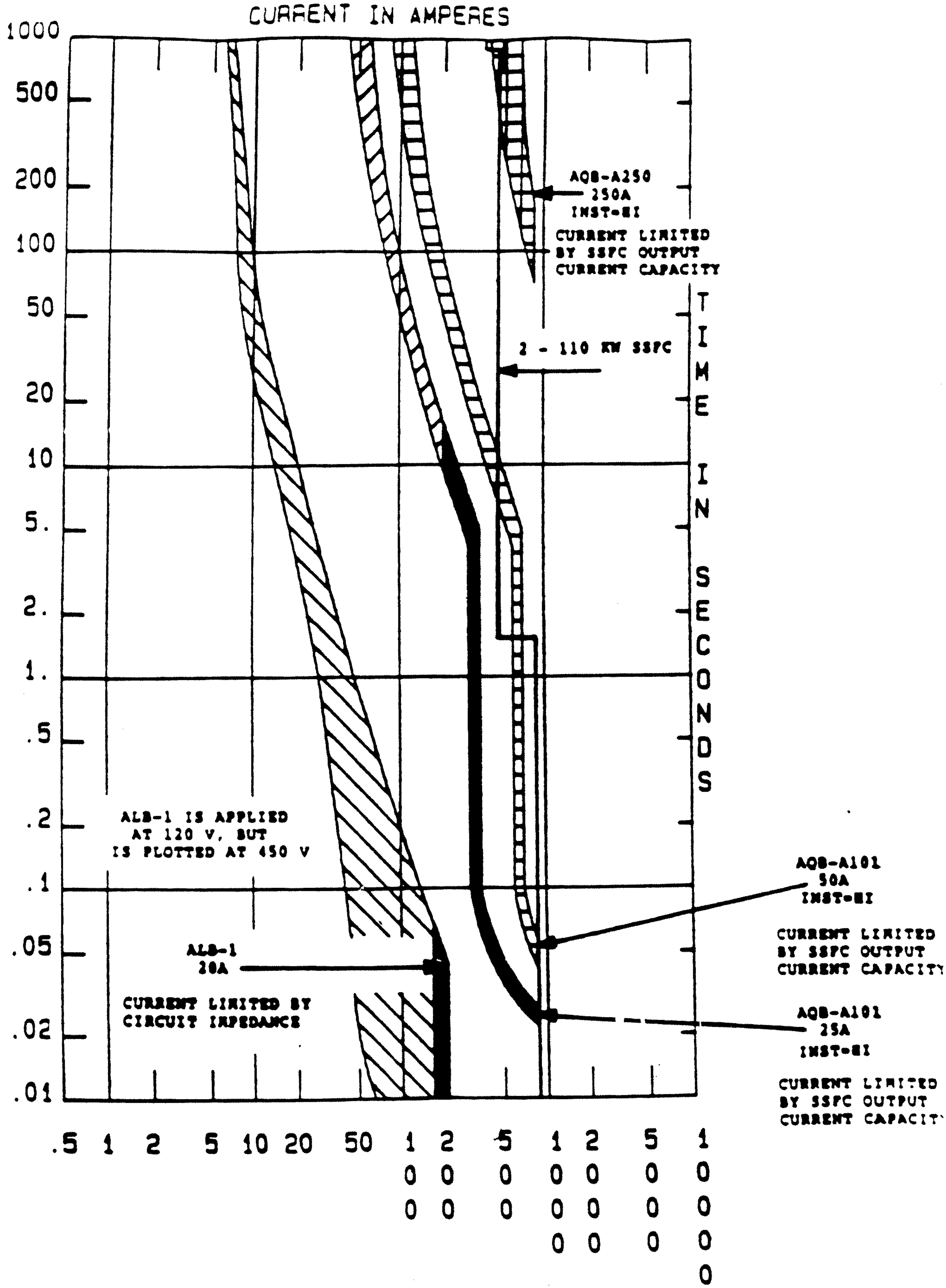
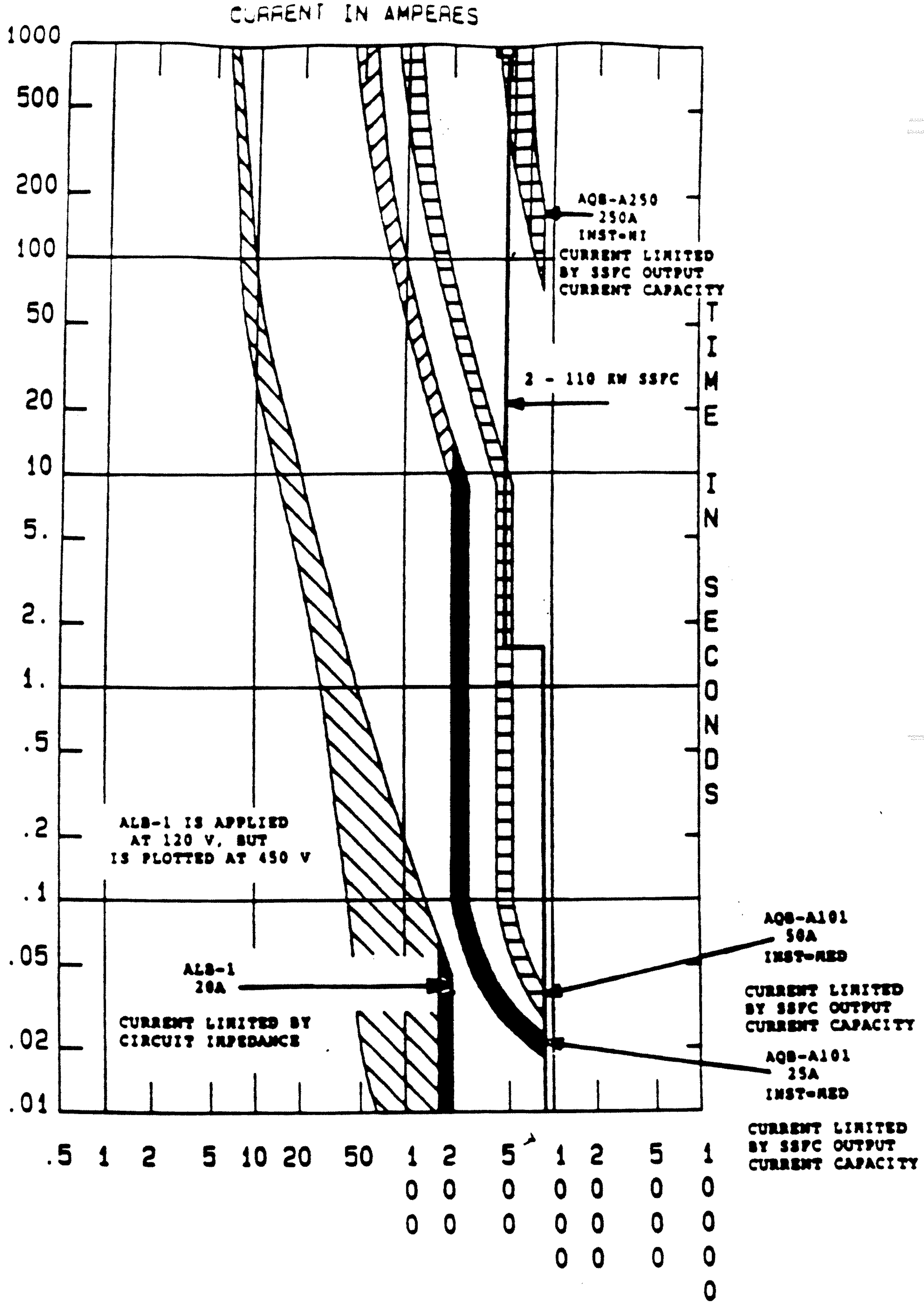


Figure 4. Coordination Curve with Instantaneous Trip Setting of AQB-A101 on HI.



Fifure 5. Coordination Curve with Instantaneous Trip Setting of AQB-A101 on MED.

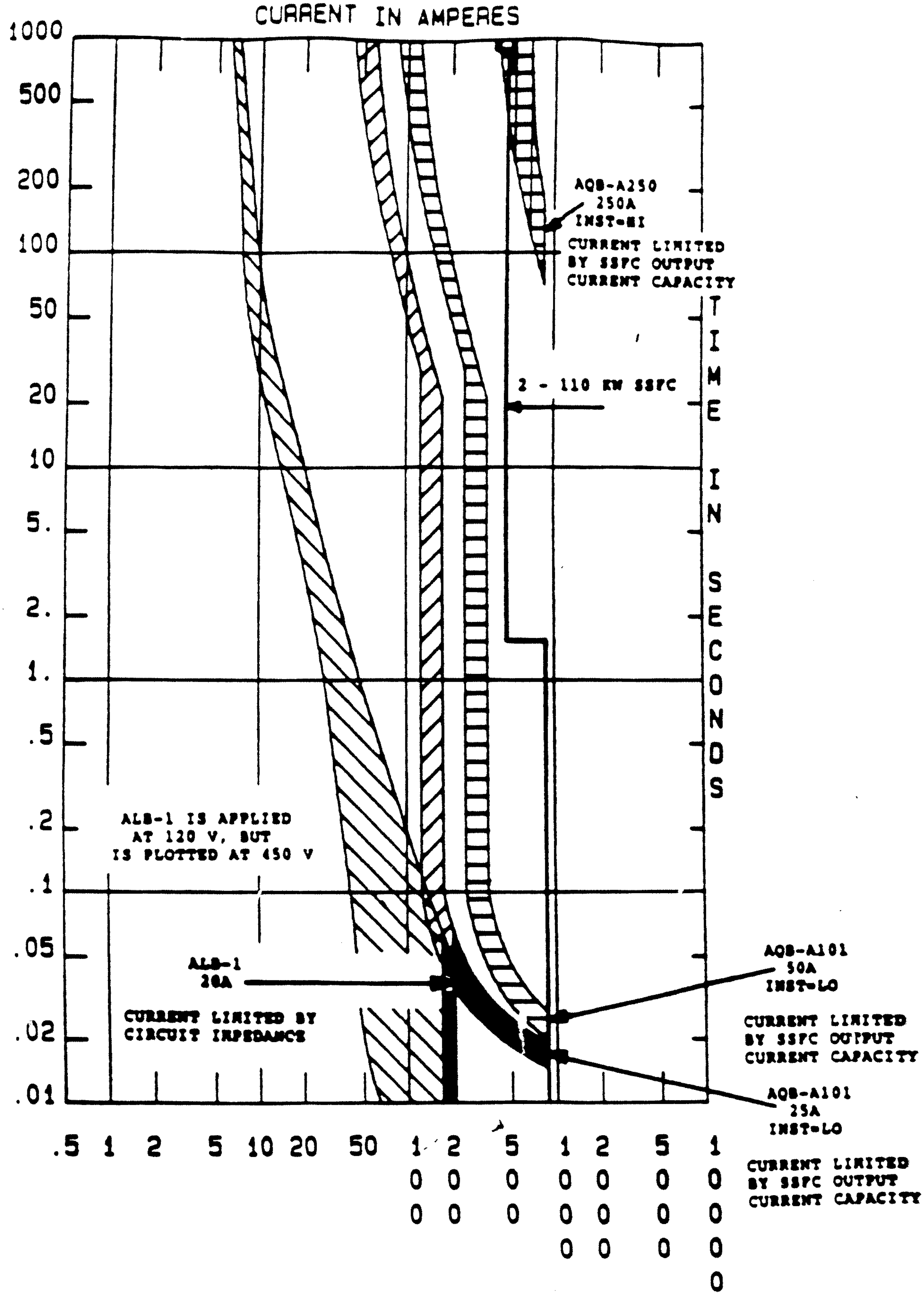


Figure 6. Coordination Curve with Instantaneous Trip Setting of AQB-A101 on LO.

being cleared. This is shown by the SSFC curve crossing the AQB curve in the 10-second range. The SSFC will shut down before this circuit breaker would trip. Note that for these settings, the circuit breakers coordinate with each other. However, the good coordination between circuit breakers is not sufficient to insure that the distribution system is coordinated for proper fault clearing.

- With both AQB instantaneous trip settings on MEDIUM, the 50A circuit breaker again does not coordinate with the SSFC. The distribution system circuit breakers do coordinate with each other.

- With both AQB instantaneous trip settings on LO, the 50A circuit breaker still does not coordinate with the SSFC. There is also miscoordination between the 25A AQB circuit breaker and the 20A ALB circuit breaker for fault currents between 115A and 200A. The ALB circuit breaker is not adjustable.

- It is not possible to obtain selective circuit breaker tripping with the existing system protective devices. Therefore, CTS units must be selected to have a system coordinated.

Figure 7 shows the protection system with CTS units added to the AQB-A101 circuit breakers. Initially, the ratings of the CTS units were selected to be the same as their associated circuit breakers. However, as shown in Figure 7, the proper coordination cannot be obtained by using those CTS units.

The ratings of the CTS units were increased as shown in Figure 8. In this case, good coordination is obtained, and the protection system can be expected to successfully clear the faults in the 400 Hz system.

Figure 9 shows the same coordination curve, except the 20A ALB circuit breaker has been replaced by a 30A FRN fuse per reference (g). As the curve illustrates, good coordination can also be obtained when fuses are used in the distribution panels.

Ideally, the system protection is designed to achieve proper coordination for both I_{max} and I_{min}. However, if this is not possible, the system should be designed for the normal operating condition.

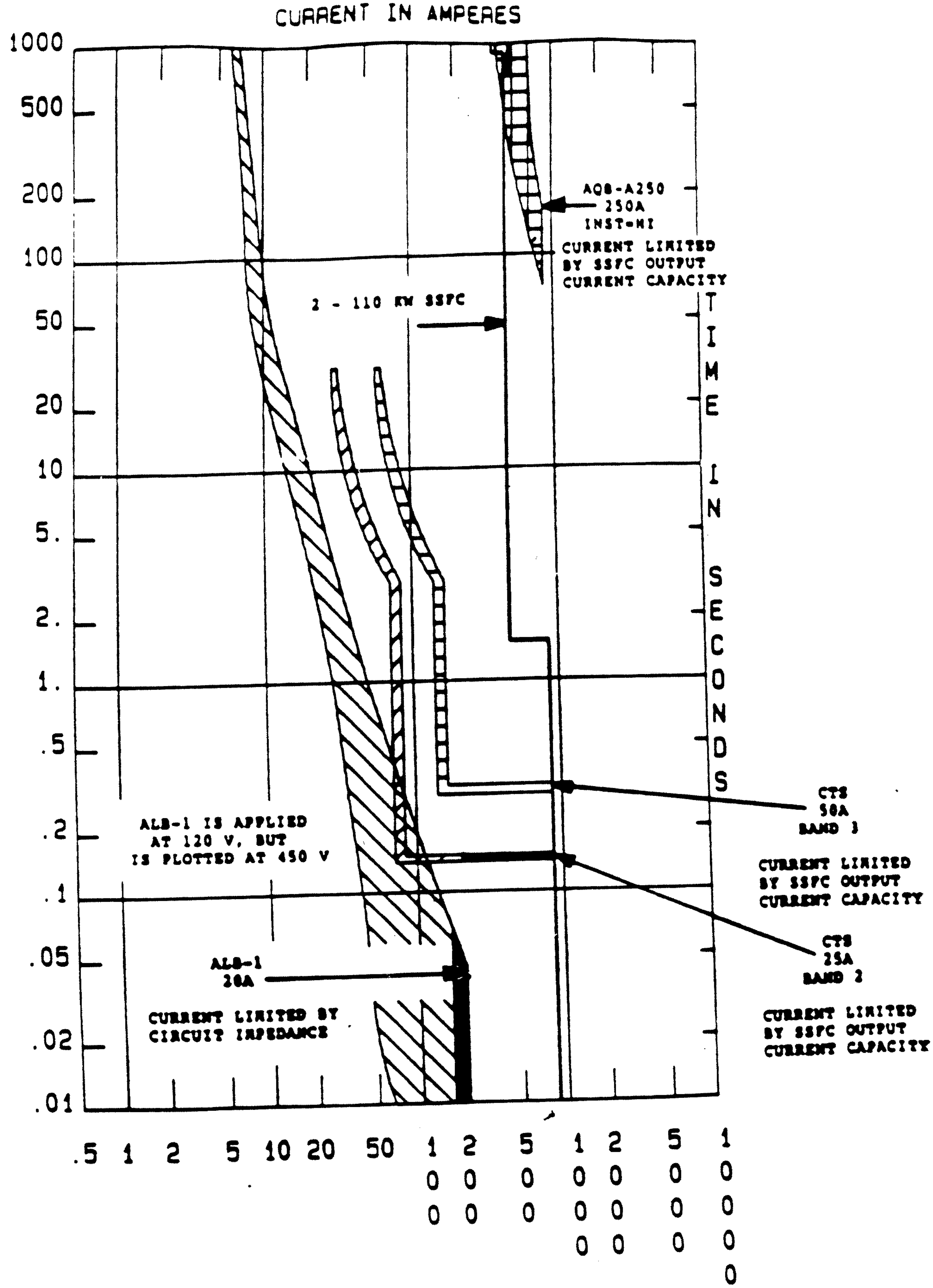


Figure 7. Coordination Curve with CTS in the System.

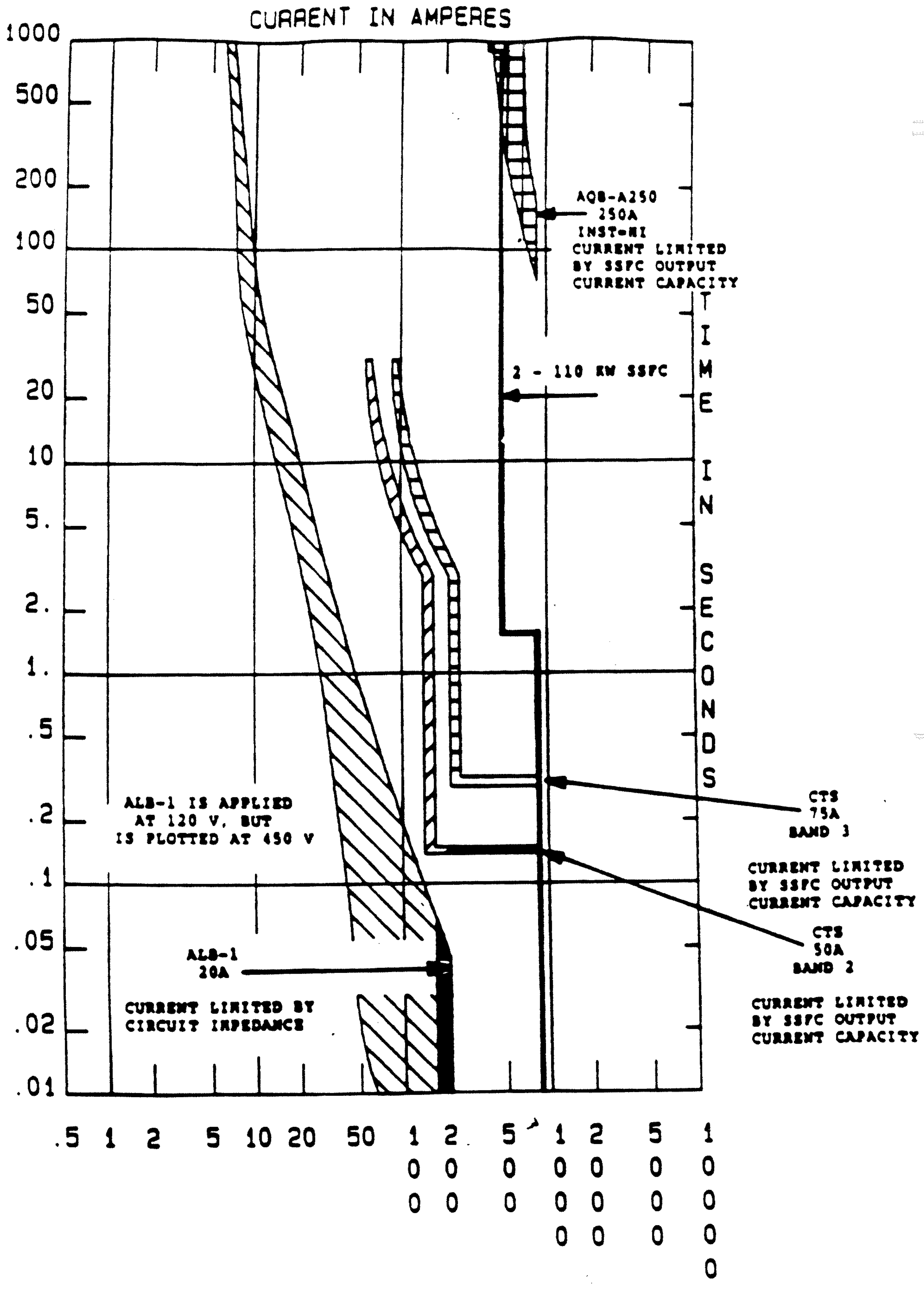


Figure 8. Coordination Curve with Higher Setting of CTS.

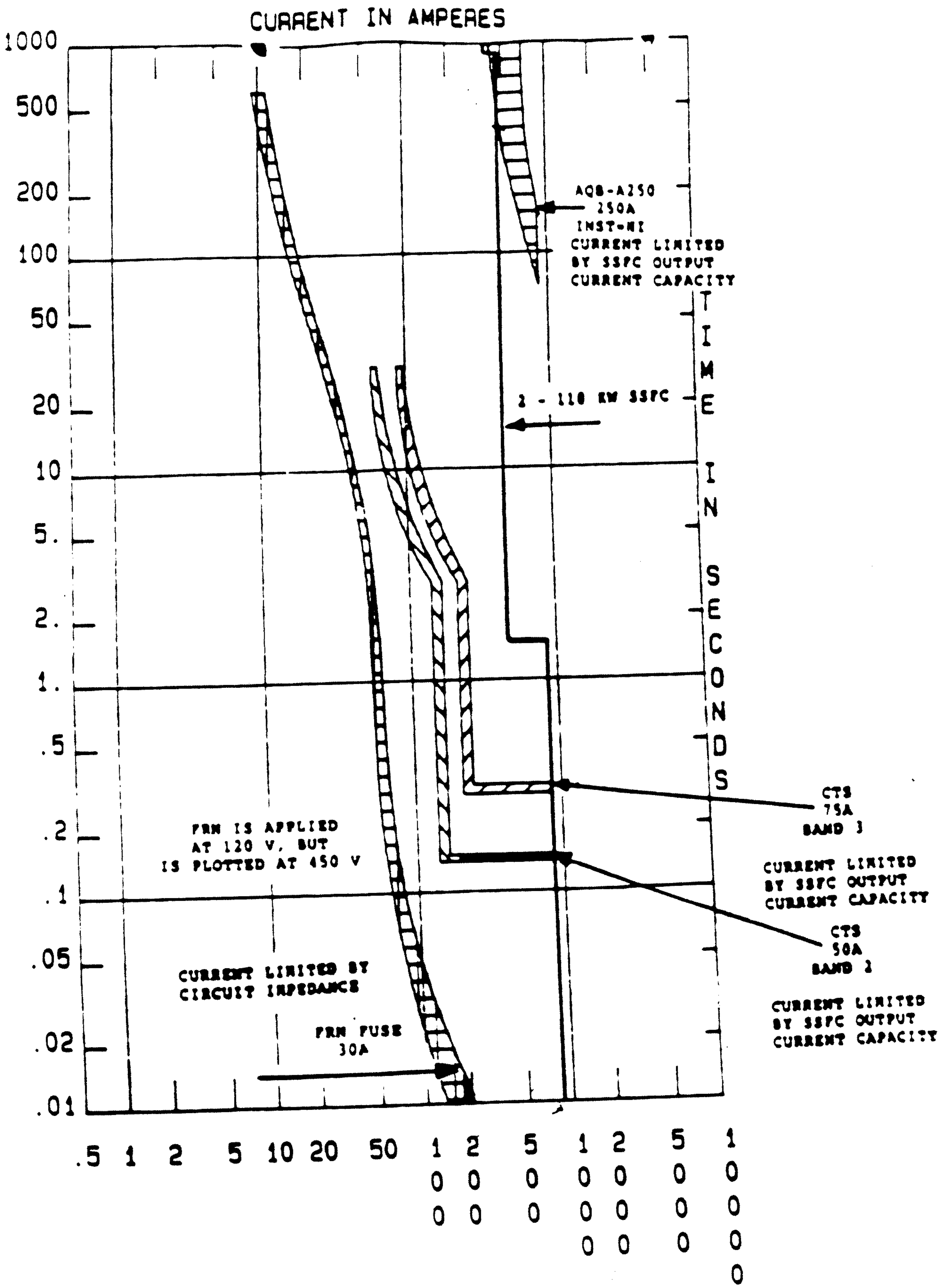


Figure 9. Coordination Curve with Fuse in the System.

Example II - The distribution system is shown in Figure 10. It is the same system used in Example I, but supplied only by a SSFC. Load currents required by other feeders in the system are included so the short-circuit current plus the load currents may be large enough to cause the SSFC to change to a current limit mode. The impedance diagram is shown in Figure 11.

The CLD is introduced to prevent the SSFC from going into its current limit operating mode during a fault clearance. The result will be an improved voltage regulation at the switchboard during fault clearance. It may be necessary to install CLD's on all switchboard feeders supplied from the same SSFC or from a number of SSFC's operating in parallel because a fault on any feeder not protected by a CLD will cause voltage regulation on the entire switchboard to be degraded, even though all other feeders have CLD's on them.

The CLD parameters should be selected to meet the conditions discussed in step 4 of section 314-1-f. The lowest rating of a CLD, which meets those conditions is the preferred rating since the current demand on a SSFC will be the lowest. Only one CLD rating for a system is preferred.

In this example, the SSFC is assumed operating close to the overload condition of 196 amperes output current (I_{ol}). The total resultant load currents (I_L) in all feeders except the faulted feeder is assumed to be 80 amperes at unity power factor. The CLD is assumed to have purely reactive impedance. The actual magnitude of current through the faulted feeder containing the CLD is calculated as follows:

$$I_{CLD} = I_{ol} - I_L$$

$$= I_{ol}\cos\{\sin^{-1}[(I_L/I_{ol})\sin(\alpha - \theta)]\} - I_L\cos(\alpha - \theta)$$

Where,

α = Complex conjugate of the power factor angle of the total loads (I_L) in other feeders.

$= -\cos^{-1}(1)$

θ = Complex conjugate of the CLD power factor angle.

$= -90°$ (CLD impedance is assumed purely reactive).

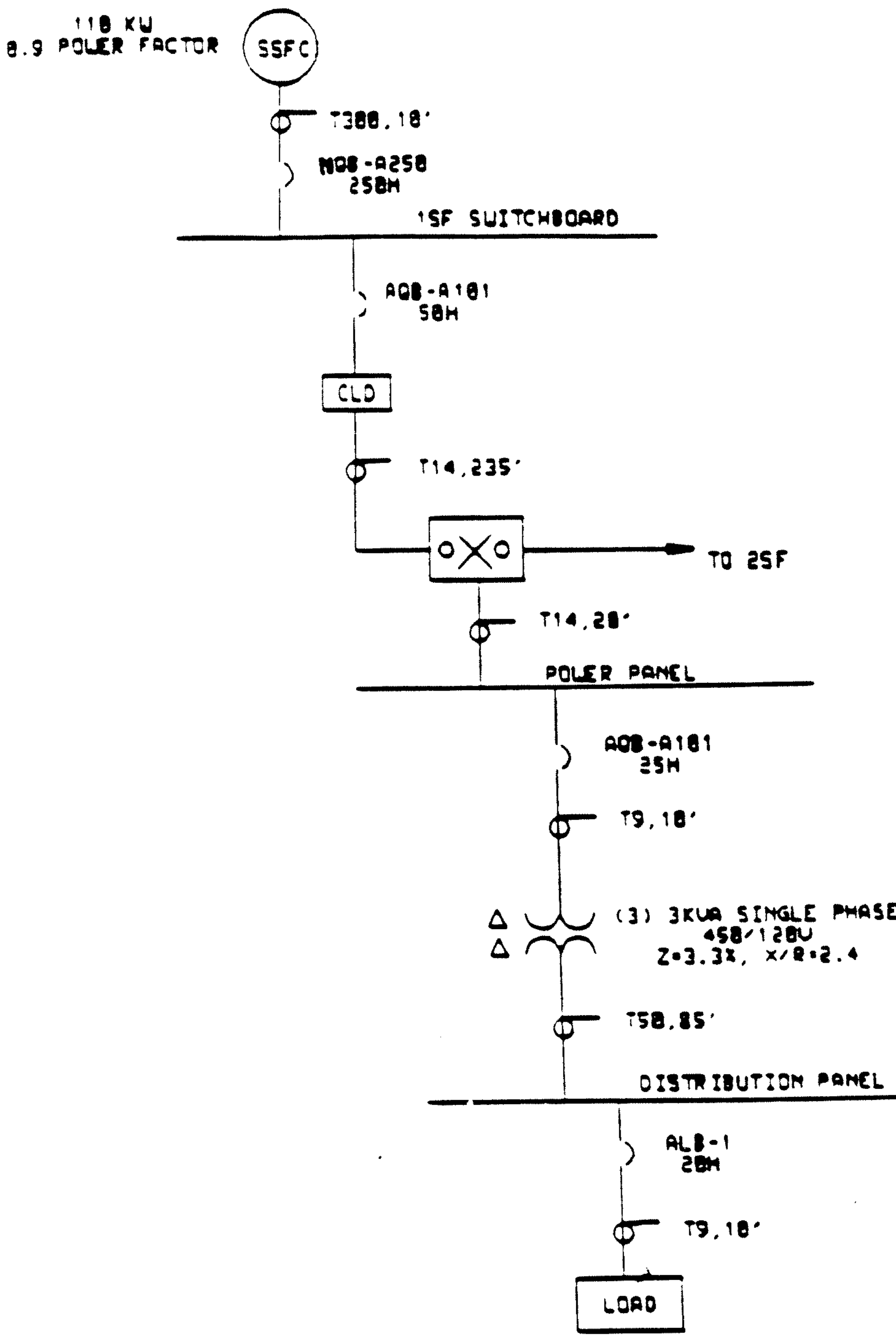


Figure 10. Distribution System One-line Diagram.

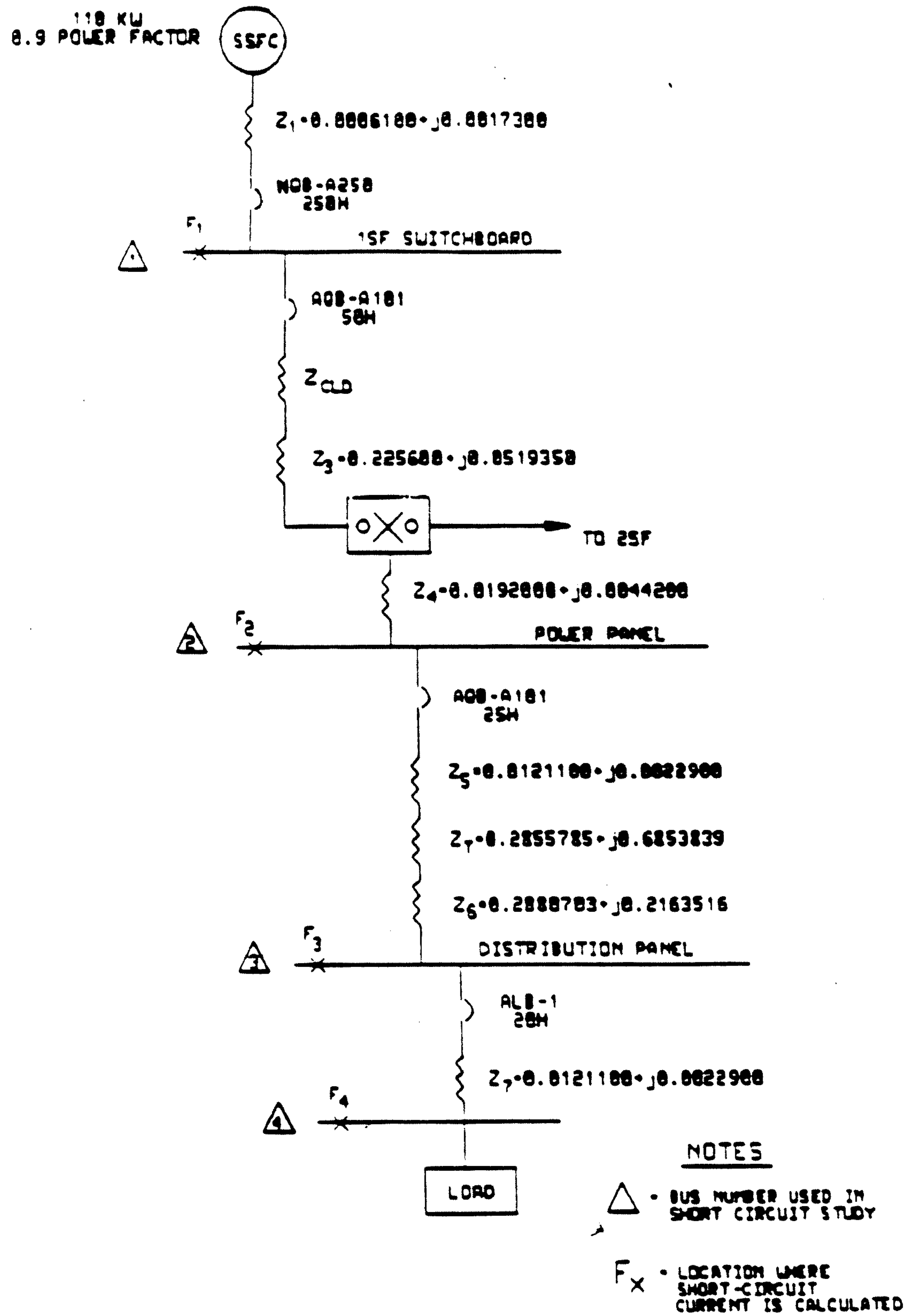


Figure 11. Distribution System Impedance Diagram.

Numerically,

$$I_{CLD} = 196\cos\{\sin^{-1}[(80/196)\sin(0° - (-90°))]\} - 80\cos[0° - (-90°)]$$

$$= 179A$$

So, the maximum let-through current rating of the CLD cannot be greater than 179 amperes.

For this example, the CLD rating is initially selected at 100 amperes which is well below the maximum allowable current rating. The CLD impedance at 100 amperes is calculated as follows:

$$Z_{CLD} = V_{LL}/\sqrt{3}I_{CLD}$$
$$= 450/\sqrt{3}(100)$$
$$= 0 + j2.598076\Omega$$

With the addition of Z_{CLD}, the fault impedances are obtained as follows:

$Z_{F1} = 0.001834\underline{/70.58°}$ $\quad Z_{F2} = 2.667474\underline{/84.72°}$

$Z_{F3} = 3.655923\underline{/76.86°}$ $\quad Z_{F4} = 3.660924\underline{/76.68°}$

Since the system is supplied only by one SSFC, the fault impedances for I_{min} calculations are equal to:

$Z_{F1}' = Z_{F2}$ $\quad Z_{F2}' = Z_{F3}$,

$Z_{F3}' = Z_{F4}$ $\quad Z_{F4}' = Z_{F4}$

The new fault currents values are calculated as follows:

<u>Location F1:</u>

$$I_{max} = E/|Z_{F1}|$$
$$= 450/\sqrt{3}(0)$$
$$= \infty$$

$$I_{min} = E/|Z_{F1}'$$
$$= 450/\sqrt{3}(2.667474)$$
$$= 97.40A$$

Since N is equal to one (1 SSFC) and I_{max} is greater than NI_{cl}, I_{max} is set equal to:

$$I_{max} = (1)I_{cl}$$
$$= 431A$$

<u>**Location F2:**</u>

$$I_{max} = E/|Z_{F2}|$$
$$= (450/\sqrt{3})/2.667474$$
$$= 97.40A$$

$$I_{min} = E/|Z_{F2}'|$$
$$= (450/\sqrt{3})/3.655923$$
$$= 71.10A$$

I_{max} is less than NI_{cl}, then the SSFC is in the voltage regulation mode.

<u>**Location F3:**</u>

$$I_{max} = E/|Z_{F3}|$$
$$= (450/\sqrt{3})/3.655923$$
$$= 71.10A$$

$$I_{min} = E/|Z_{F3}'|$$
$$= (450/\sqrt{3})/3.660924$$
$$= 71A$$

<u>**Location F4:**</u>

$$I_{max} = E/|Z_{F4}|$$
$$= (450/\sqrt{3})/3.660924$$
$$= 71A$$

$$I_{min} = E/|Z_{F4}'|$$

$$= (450/\sqrt{3})/3.660924$$

$$= 71A$$

The continuous current of the CLD must be greater than the normal rating of the feeder. The load in this particular feeder is less than 50 amperes; therefore, the continuous rating of the CLD must be 50 amperes or higher.

The CLD must also allow the start-up of motors without shunt-tripping the upstream circuit breaker. In this example, assume the total connected load consists of four 1hp motors (92% efficiency) operating at a power factor of 0.8. If these four motors are started simultaneously, the current seen by the CLD can be calculated as follows:

$$I_{fl} = \left(\frac{1}{0.8}\right)\left(\frac{1\ hp}{0.92}\right)\left(\frac{0.746kW}{1\ hp}\right)\left(\frac{1}{0.12kV}\right)$$

$$= 8.45A \qquad \text{(for one motor)}$$

The locked-rotor current (I_{lr}) is found by multiplying the full-load current by an assumed factor. For 400 Hz systems, a multiplying factor of six is generally used. The results are as follows:

For one motor:

$$I_{lr} = (6)(8.45A)$$
$$= 50.70A$$

For four motors:

$$I_{lr} = (4)(50.70A)$$
$$= 202.8A$$

The locked-rotor current is multiplied by the transformer voltage ratio to determine the equivalent current at 450 volts. The result would be:

$$I_{lr} = (202.8A)(120/450)$$
$$= 54A$$

This value must be less than the current which causes the CLD to change from a low-impedance state to a high-impedance state. Therefore, the selected CLD must allow 54 amperes to pass while remaining in a low-impedance state.

The CLD let-through current should be good enough to ensure selective tripping of the downstream circuit breakers. For this condition, the coordination curves for the system must be redrawn using the fault currents calculated with the CLD's in the circuit. The CLD time-current curve should also be shown on the system coordination curves.

Figure 12 shows the coordination curve for the feeder a CLD. Notice that the CTS unit on the AQB-A101, 50A circuit breaker has been eliminated. The CLD is equipped with its own shunt trip circuit; therefore, the use of a CTS is unnecessary. The CLD's shunt trip signal will cause the 50A circuit breaker to trip after a predetermined time delay. The delay is assumed to be 0.750 seconds for the example. Figure 12 also shows that the 100A CLD does not allow enough short-circuit current to pass to have selective tripping of the circuit breakers. For a fault at location F2, the CLD will shunt trip the 50A circuit breaker before the 50A CTS can operate to clear the fault.

To solve this miscoordination, a 150A CLD will be put in the circuit. The CLD impedance at 150 amperes is:

$$
\begin{aligned}
Z_{CLD} &= 450/\sqrt{3}(150) \\
&= 0 + j1.73205\Omega
\end{aligned}
$$

The fault currents must be recalculated with the inclusion of the CLD impedance. The new Z_F and Z_F' at each fault location are:

$$Z_{F1} = 0.001834\underline{/70.58^\circ}, \qquad Z_{F1}' = 1.806878\underline{/82.19^\circ}$$

$$Z_{F2} = 1.806878\underline{/82.19^\circ}, \qquad Z_{F2}' = 2.819478\underline{/72.85^\circ}$$

$$Z_{F3} = 2.819478\underline{/72.85^\circ}, \qquad Z_{F3}' = 2.825257\underline{/72.63^\circ}$$

$$Z_{F4} = 2.825257\underline{/72.63^\circ}, \qquad Z_{F4}' = 2.825257\underline{/72.63^\circ}$$

The new fault current values are as follows:

Location F1:

$$I_{max} = \infty, \qquad I_{min} = 144A$$

I_{max} is greater than NI_{cl}, then it is set equal to NI_{cl}:

$$I_{max} = 431A$$

Location F2:

I_{max} = 144A, I_{min} = 92A

Location F3:

I_{max} = 92A, I_{min} = 92A

Location F4:

I_{max} = 92A, I_{min} = 92A

Figure 13 shows the coordination curve for the feeder with the 150A CLD. In this case, the CLD still does not allow enough short-circuit current to pass to obtain selective circuit breaker operation.

The CTS rating can be reduced to 25A as shown in Figure 14. A slight miscoordination between the ALB-1 circuit breaker and the CTS exists; however, it is acceptable given a good coordination achieved upstream. The miscoordination is placed at the lowest level of usage, i.e., where it minimizes the amount of equipment removed from service.

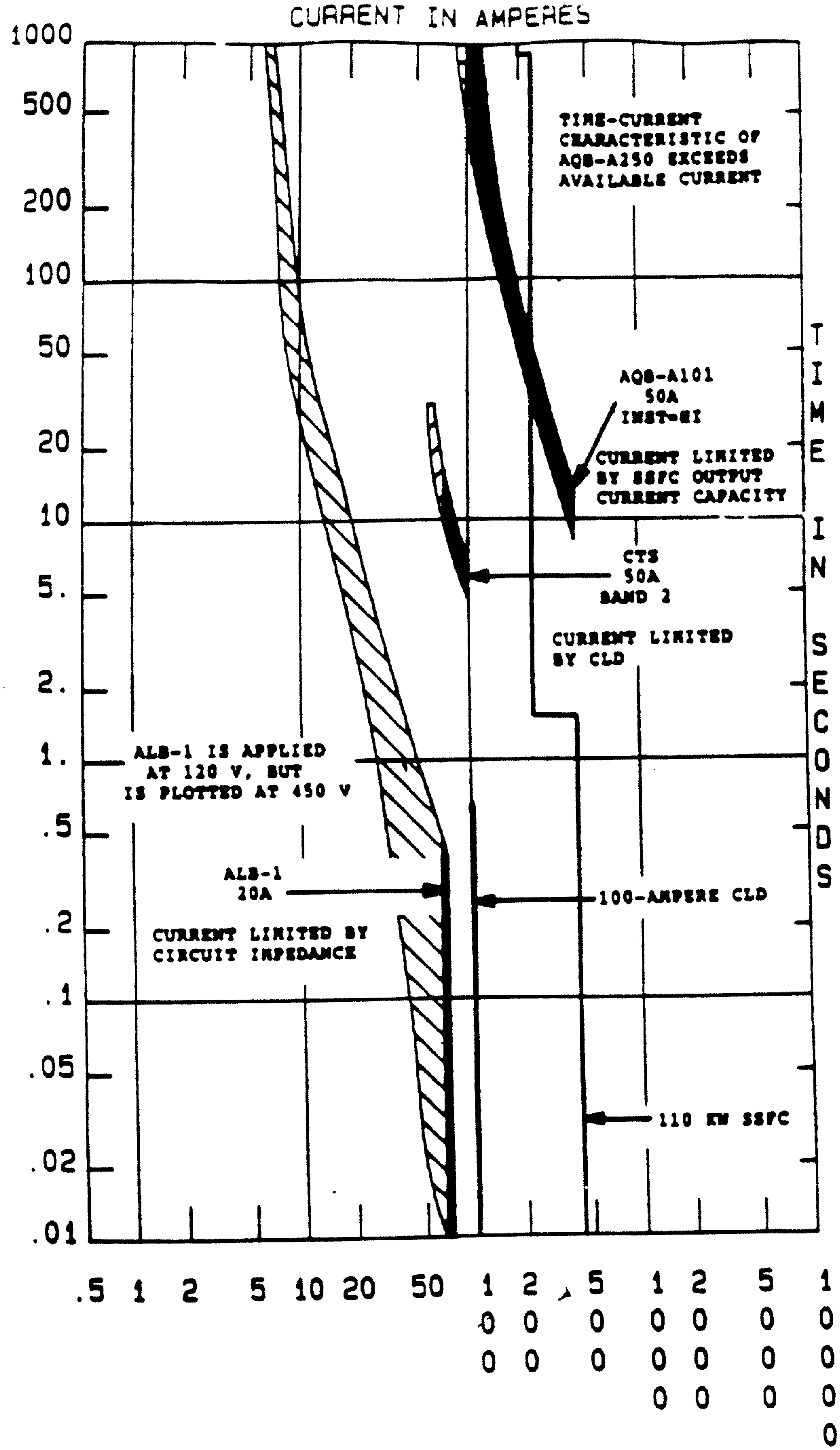


Figure 12. Coordination Curve with CLD-100A in the System.

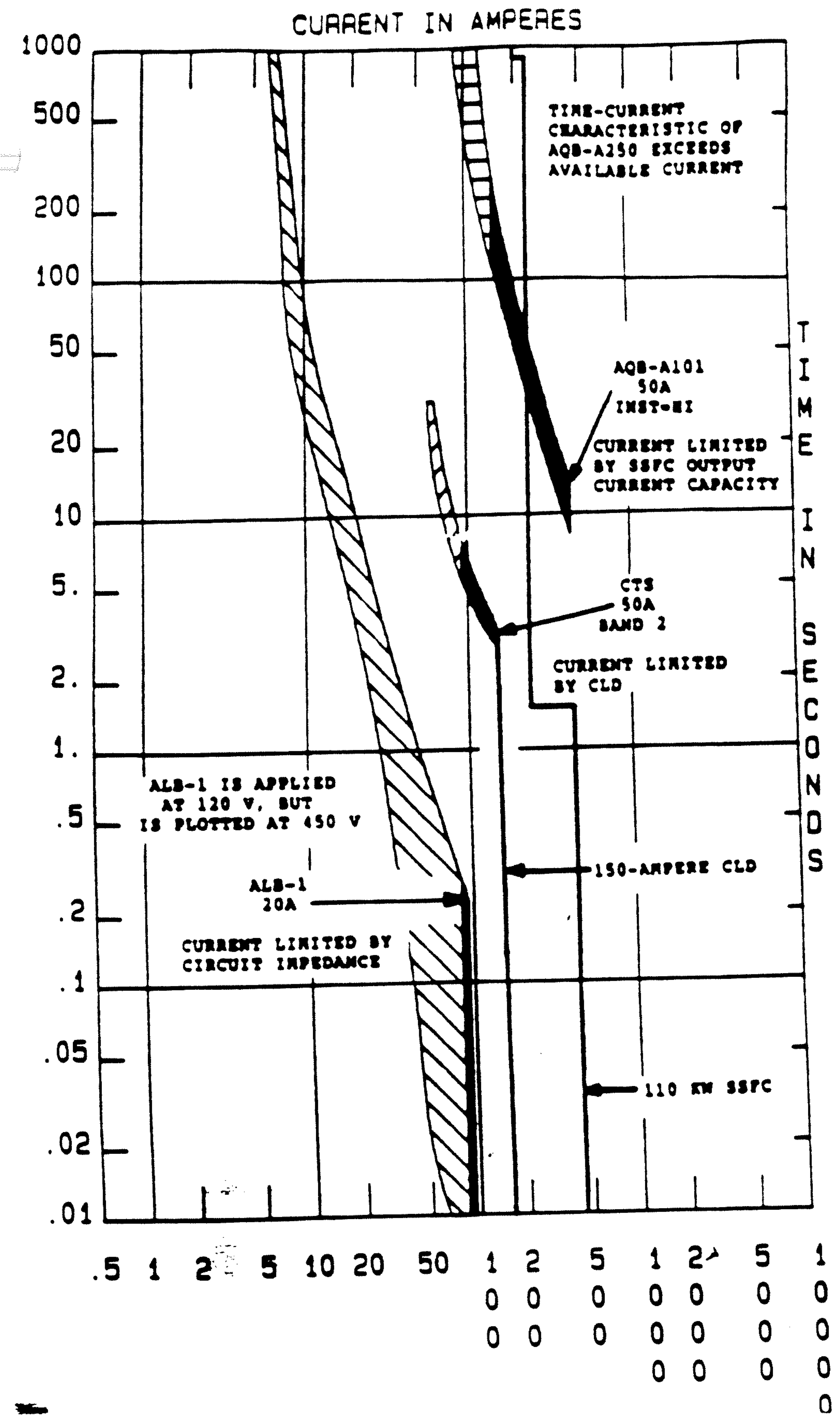


Figure 13. Coordination Curve with CLD-150A in the System.

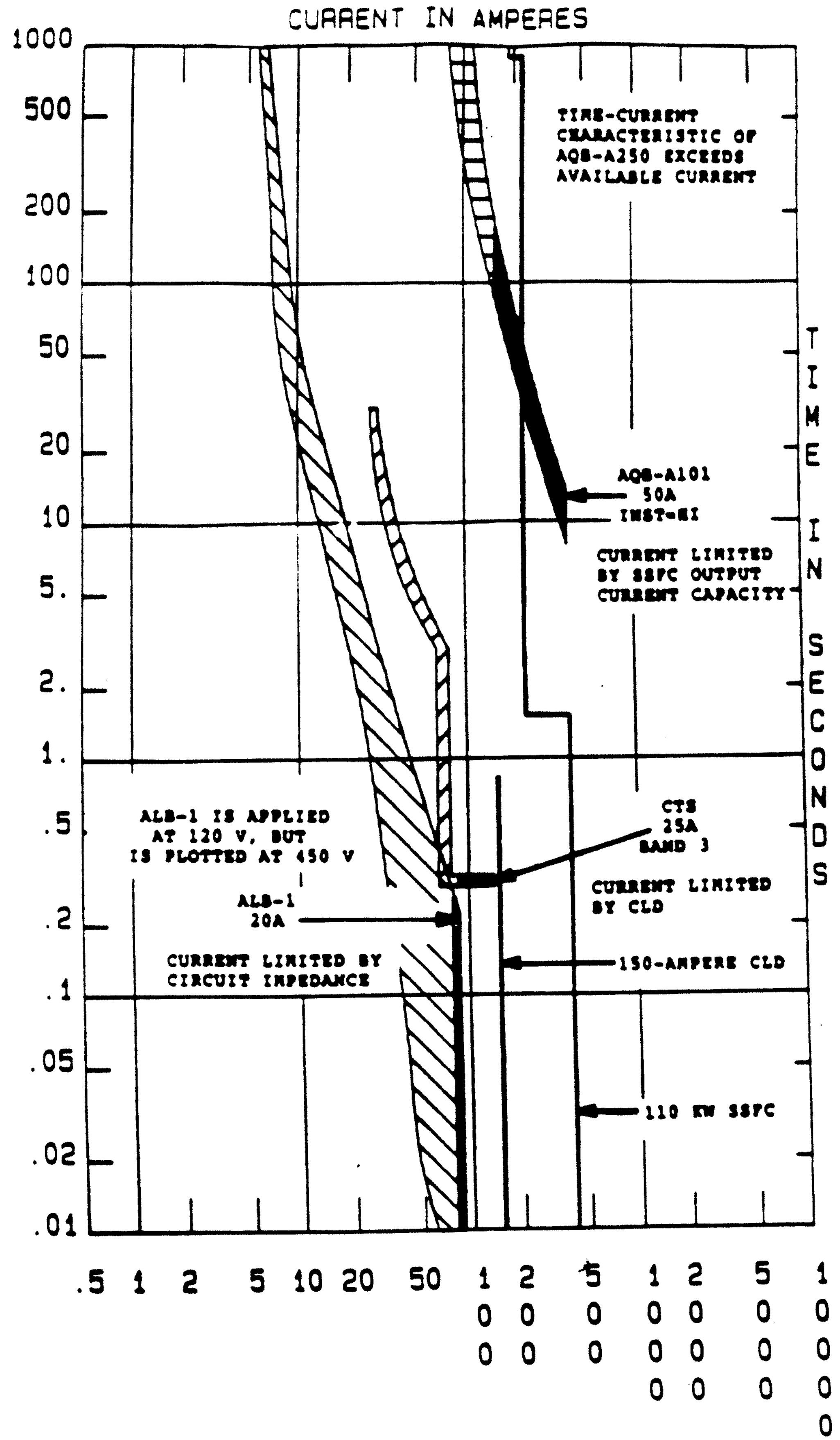


Figure 14. Coordination Curve with Lower Setting of CTS.

Example III - The example will illustrates how CLD's can be selected for systems with two SSFC's operating in parallel. The distribution one-line diagram and system impedance diagram are shown respectively in Figures 15 and 16.

The total resultant of connected load current I_L in all feeders except the faulted feeder is 80 amperes at unity power factor. The CLD is assumed to have a purely reactive impedance. The maximum current passing through the CLD is:

$$I_{CLD} = \sqrt{I_{ol}^2 - I_L^2}$$

$$= \sqrt{392^2 - 80^2}$$

$$= 384A$$

So, the maximum let-through rating of the CLD cannot be greater than 383A.

For the example, the CLD rating is initially selected to be 300A which is well below the maximum allowable current rating. The CLD impedance at this current is:

$$Z_{CLD} = 450/\sqrt{3}(300)$$

$$= 0 + j0.866025\Omega$$

The new magnitudes of Z_F and Z_F' for the fault locations are found as follows:

$$Z_{F1} = 0.00183\underline{/70.58^\circ} \qquad Z_{F1}' = 0.956141\underline{/75.13^\circ}$$

$$Z_{F2} = 0.955227\underline{/75.13^\circ} \qquad Z_{F2}' = 2.008211\underline{/65.55^\circ}$$

$$Z_{F3} = 2.007301\underline{/65.55^\circ} \qquad Z_{F3}' = 2.015336\underline{/65.26^\circ}$$

$$Z_{F4} = 2.014423\underline{/65.26^\circ} \qquad Z_{F4}' = 2.015336\underline{/65.26^\circ}$$

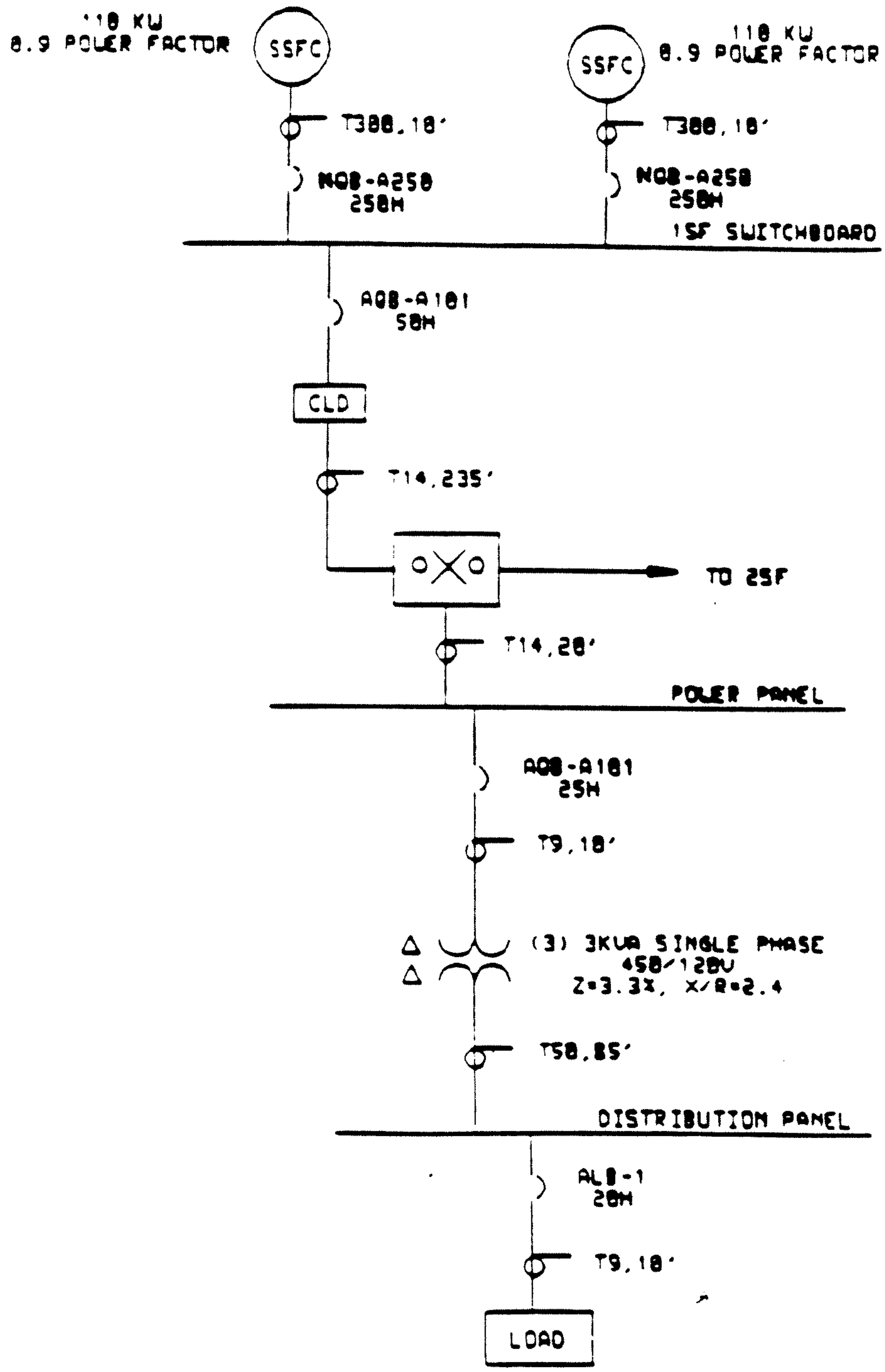


Figure 15. Distribution System One-line Diagram.

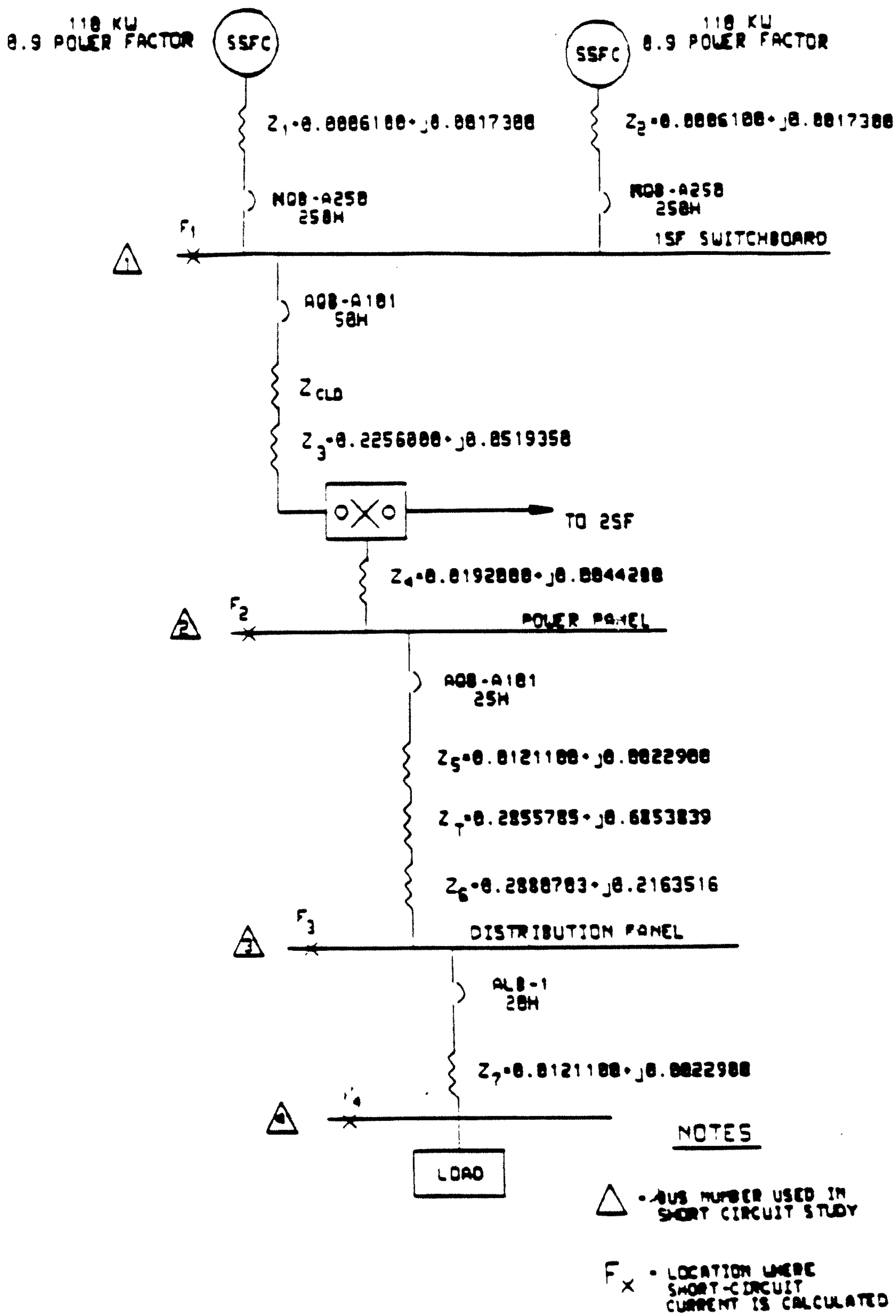


Figure 16. Distribution System Impedance Diagram.

The fault currents at each location are recalculated using the same approaches as in the previous examples:

Location F1:

$I_{max} = \infty$ $I_{min} = 272.73A$

$NI_{cl} = 862A$

I_{max} is greater than NI_{cl}, then it is set equal to NI_{cl}:

$I_{max} = 862A$

Location F2:

$I_{max} = 271.99A$ $I_{min} = 129.37A$

Location F3:

$I_{max} = 129.43A$ $I_{min} = 128.92A$

Location F4:

$I_{max} = 128.97A$ $I_{min} = 128.92A$

The continuous rating of the CLD must be greater than the load current of the feeder. The load in the fault feeder is less than 50A. Therefore, the continuous rating of the CLD must be at least 50A.

The CLD must also allow the start-up of motors without shunt tripping the upstream circuit breaker. Refer to Example II for proper method to assure that the motor start-up will not be affected by the CLD.

The CLD let-through current should be good enough to ensure selective tripping of the downstream circuit breakers. To address this condition, the coordination curve for the system must be redrawn using the fault currents calculated with the CLD's in the circuit. The CLD time-current curve should be shown on the system coordination curves.

Figure 17 shows the coordination curve for feeder which includes the CLD. Notice that the CTS unit on the 50A AQB-A101 circuit breaker has been eliminated as it was in Example II.

Again, because the CLD is equipped with its own shunt trip circuit, the use of a CTS is unnecessary. The CLD's shunt trip signal will cause the 50A circuit breaker to trip after a predetermined time delay. For the example, the delay is assumed to be 750 milliseconds.

Figure 17 shows that the system is properly coordinated with a 300A CLD.

Notice that a protection system should be designed for the worst case. Therefore, if only one SSFC is used to supply power to a 400 Hz system under any operating conditions, the system should be designed for this case. If the CLD's are sized based on one SSFC, the addition of SSFC's will not be detrimental in any way. However, if the CLD's are sized based on two SSFC's, the operation with only one may be detrimental. The result may be the loss of voltage at the switchboard or poor protective device coordination. Either result is undesirable and may reduce the availability and reliability of the 400 Hz power system.

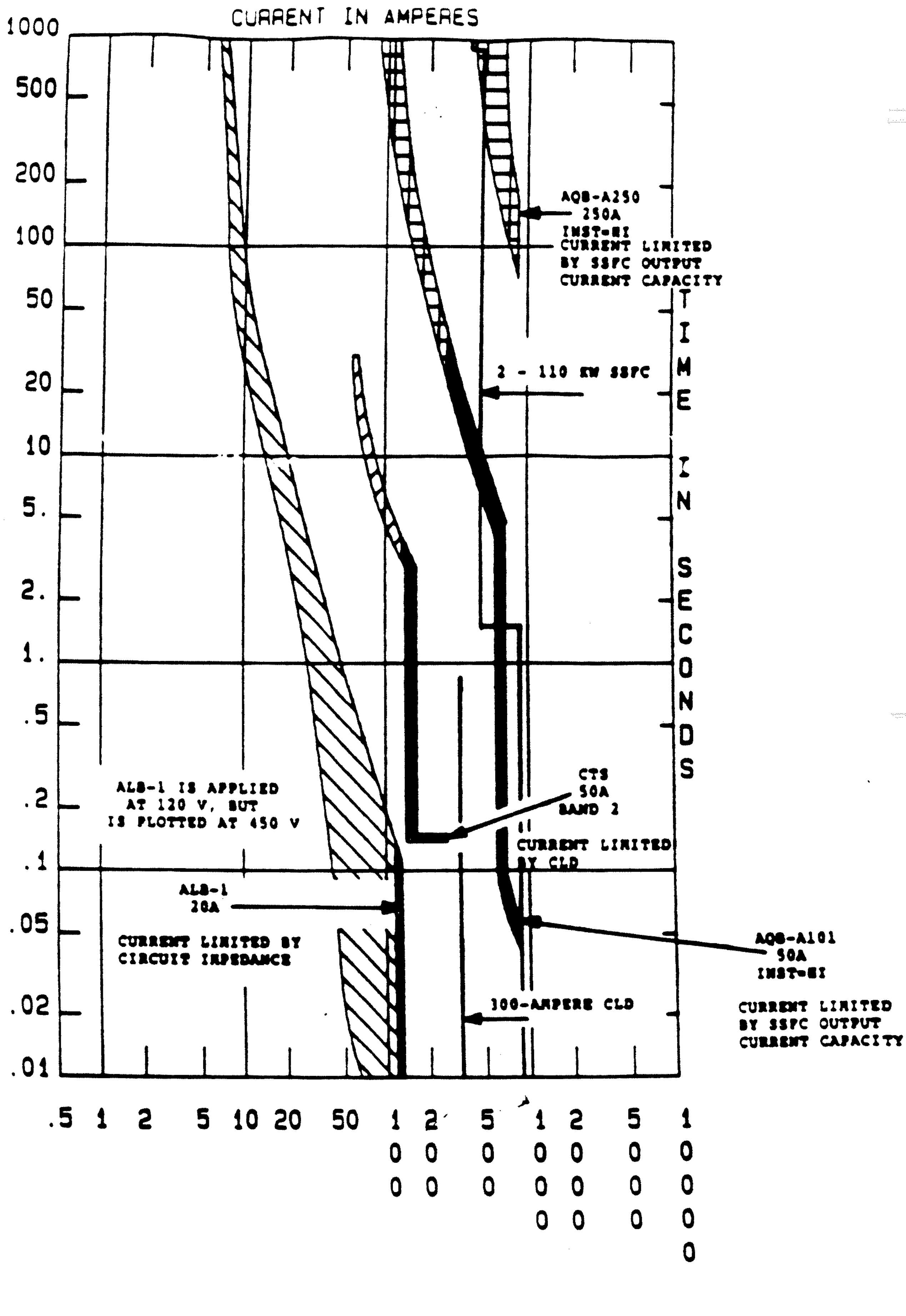


Figure 17. Coordination Curve with CLD in the System.

Example IV - This example illustrates how the bus-tie circuit breaker must be coordinated with the SSFC internal protection. The system one-line diagram and system impedance diagram are shown in Figures 18 and 19 respectively.

The purpose of coordinating the bus-tie circuit breakers with the SSFC internal protection is to ensure that a fault on one switchboard, which causes the SSFC to shut down, will be isolated from the other switchboard before the SSFC supplying that switchboard will also shut down.

The fault current at either F1 or F2 must be calculated. Because the fault in each case is placed at the switchboard, the SSFC supplying the faulted switchboard will go into current limit mode and eventually shut down. The bus-tie circuit breaker should trip and isolate the faulted switchboard.

At F1 or F2, the available fault current, I_{min}, supplied by the SSFC is 431 amperes. Table I of reference (f) shows that the minimum instantaneous trip setting of an AQB-A250 is 910 amperes; this circuit breaker can not be used alone. As shown in Figure 20, the SSFC will shut down before the bus-tie circuit breaker can open. Therefore, a control device such as a CTS or voltage monitor (VM3) is needed to provide signal to trip the circuit breaker.

To eliminate this miscoordination, a voltage monitor which may be selected in accordance with reference (i), is applied to the system . The VM3, equipped with a shunt-trip mechanism, will open the bus-tie circuit breaker when an under-voltage condition is detected. Figure 21 shows the placement of the voltage monitor.

If a CTS is used, its rate setting must be carefully analyzed. For example, if the CTS is set at 250 amperes which is equal to the maximum rating element of the circuit breaker, the per unit current ratio of the available fault current, I_{min}, to the CTS rate setting is 1.72 (ratio = 431/250). As indicated by Figure 1 of reference (h), the CTS will not operate for approximately 6.5 seconds while the SSFC will shut down in 1.5 seconds. As shown in Figure 22, the CTS setting is not effective.

Now, if the CTS is set at 150 amperes, the unit current ratio is approximately 2.9. Figure 1 of reference (h) shows that the CTS will operate in the 0.7 ± 5% second band. The coordination will be achieved.

Generally, the use of a voltage monitor is preferred to ensure a good coordination between the SSFC and the bus-tie circuit breakers.

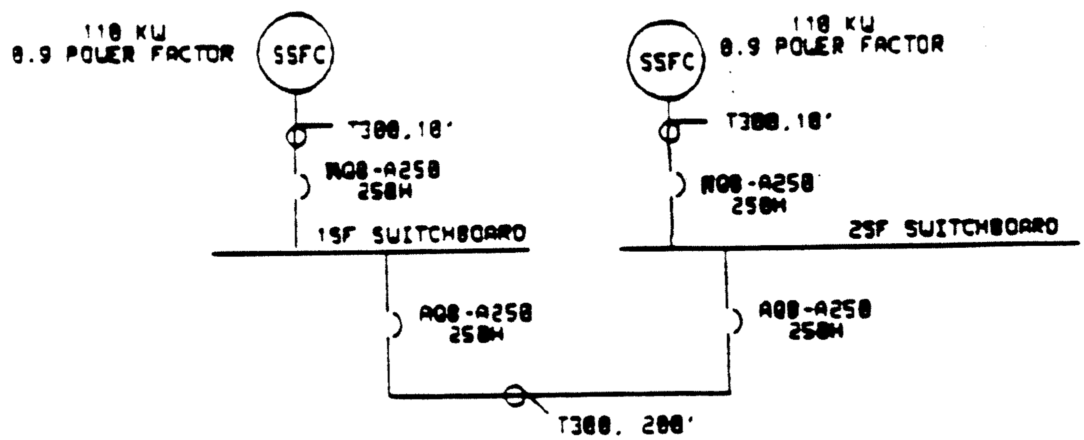


Figure 18. Bus-tie Circuit Diagram.

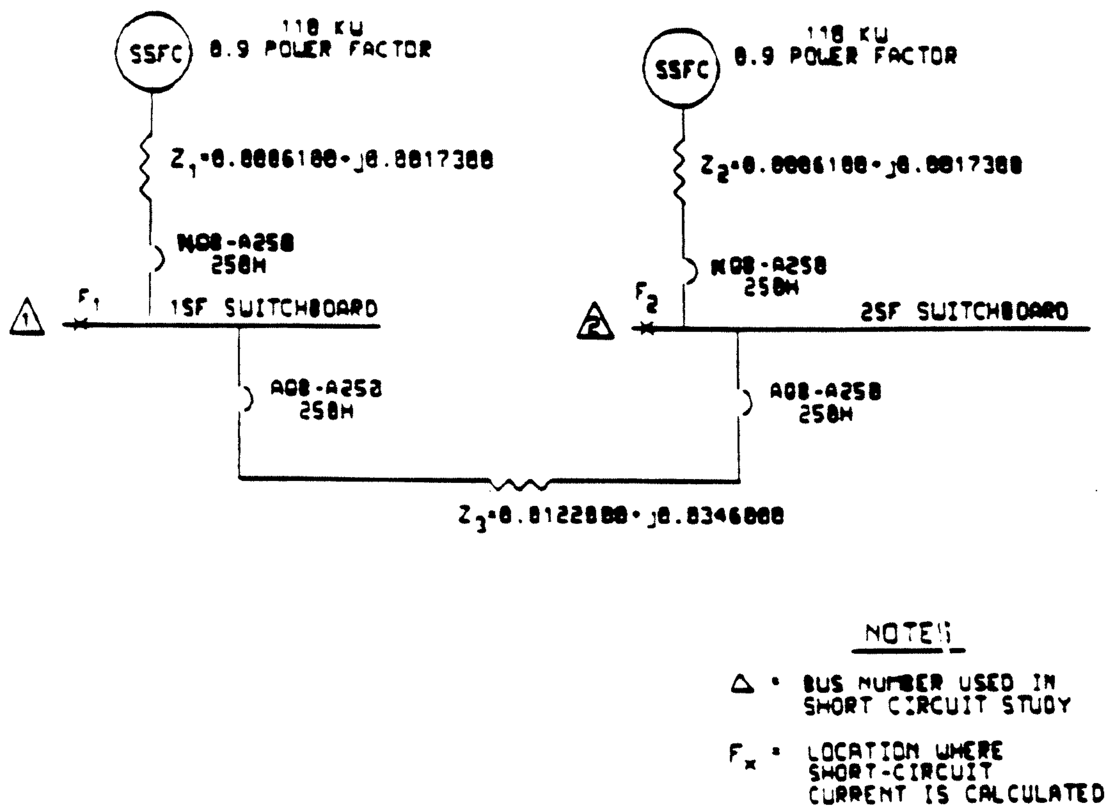


Figure 19. Bus-tie Circuit Impedance Diagram.

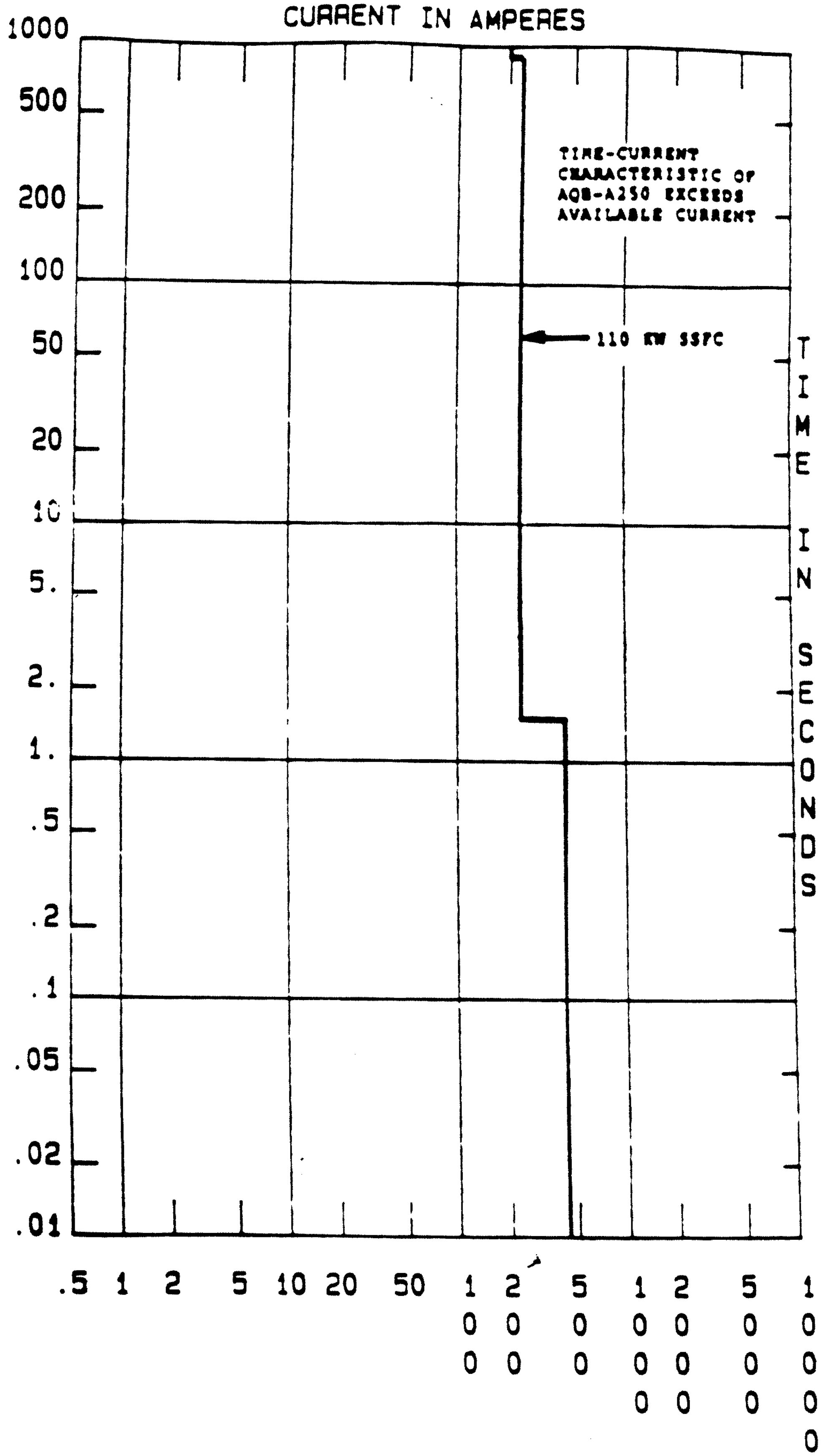
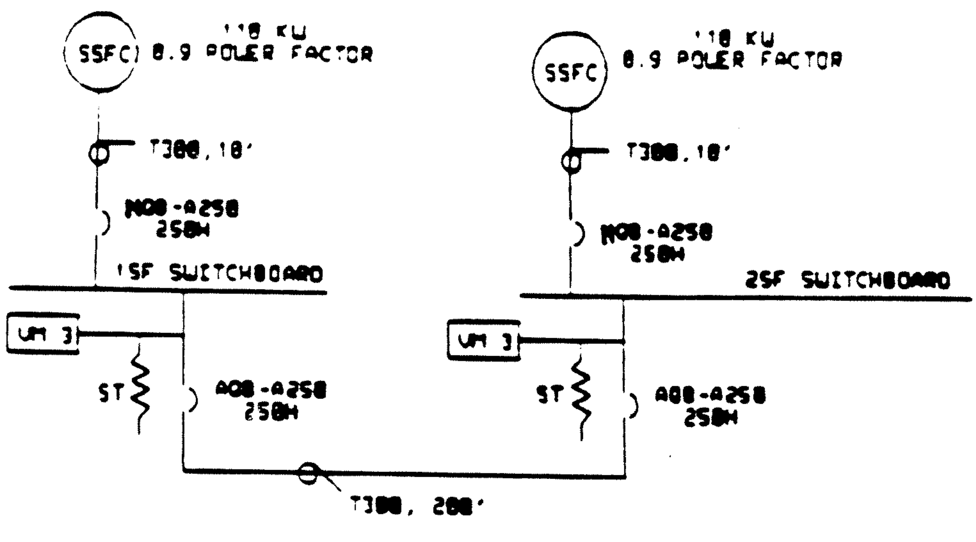


Figure 20. Coordination Curve For Bus-tie Circuit.



NOTE: ST IS THE SHUNT TRIP MECHANISM

Figure 21. Voltage-Monitore For Bus-tie Circuit.

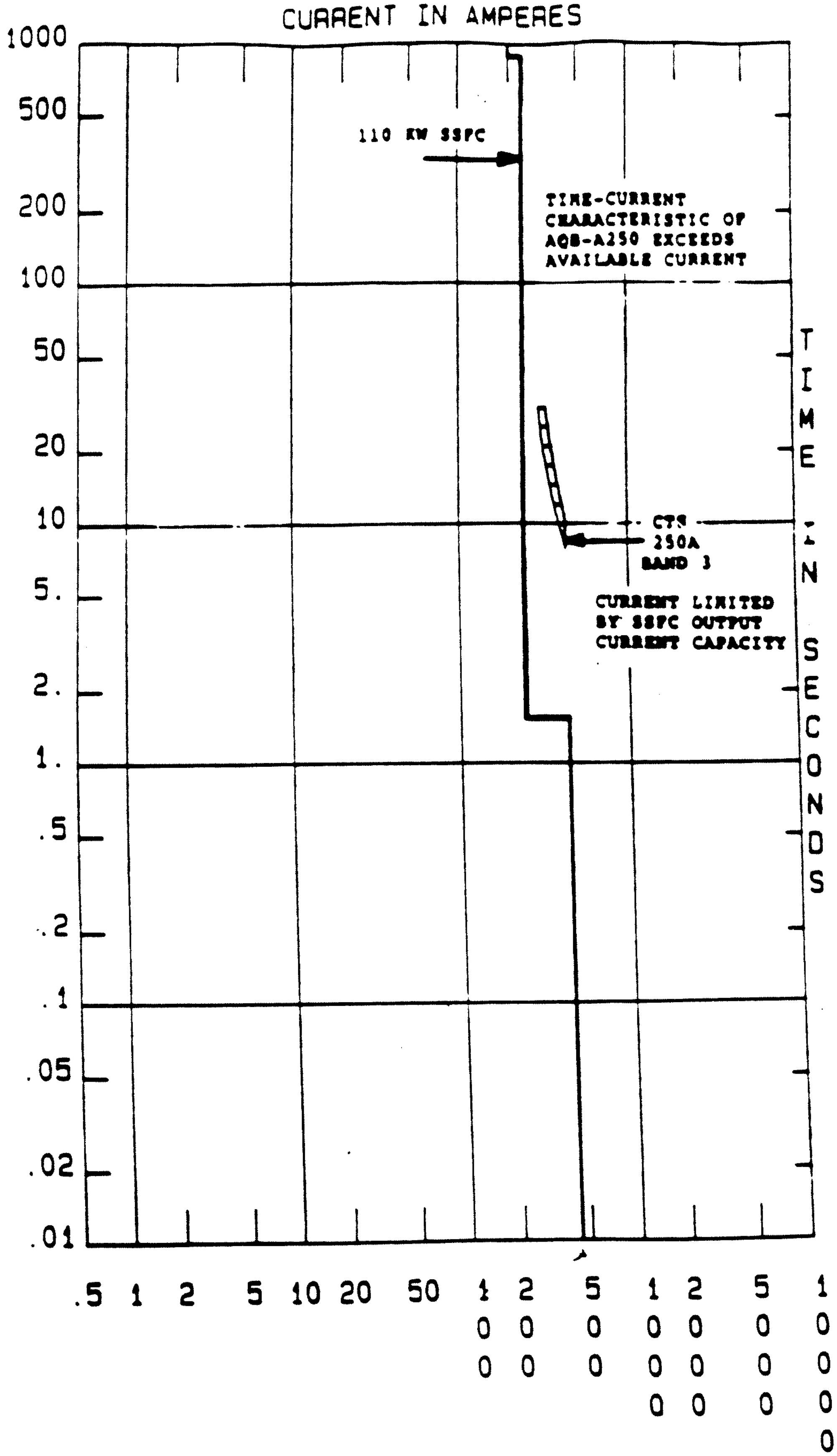


Figure 22. Coordination Curve with CTS in the Bus-tie Circuit.

Appendix A. SSFC Characteristics

Two types of SSFC's have been used in ship 400 Hz power distribution system: the Silicon Controlled Rectifier (SCR) and Transistor SSFC's. The following are output characteristics of SSFC's built in accordance with MIL-F-24638(SH):

a. Rated Current

The maximum continuous current that can be derived from the SSFC kW rating is:

$$I_{fl} = \left(\frac{\text{kW Rating}}{\sqrt{3}(V_{LL})(Pf)} \right)$$

Where V_{LL} is in kV and usually 0.450 kV.

b. Overload Current

The SSFC can provide and sustain a maximum overload current of 125 percent of its rated current for a period of 30 minutes at its rate output voltage. The SSFC will automatically shut down if critical component or air temperature are exceeded.

c. Fault Current

The output current between 125 and 150 percent of the rated current is considered fault current. The SSFC must be able to provide and sustain a current up to 150 percent of rate current for a period of 15 minutes when a fault develops at its load circuit.

d. Short-circuit Current

The maximum output current above 150 percent of rated current is considered a short circuit current or current limit capacity. The SSFC is operating in the current limit mode. The SSFC must be able to provide at least 275 percent of its rated current for a period of 1.5 seconds before automatically shut down.

e. Response Events

Assuming the events of the above characteristics are taking place one after another without any interruption until the SSFC is in the current limiting mode. The SSFC overcurrent shutdown can occur in milliseconds. The output voltage may remain at nominal rate for a very short time before decaying toward zero. These responses are summarized in Table I and plotted as shown in Figure 23. The starting times for the events of overload, fault, and short circuit are represented by t_o, t_1, and t_2 respectively.

Table I: SSFC Output Current Characteristics in Accordance with MIL-F-24638(SH)

Output Current Characteristics	**I amperes**	**t seconds**
Rate Current (I_{fl})	I_{fl}	$0 < t < \infty$
Overload Current (I_{ol})	$1.25I_{fl}$	$0 < t < 1800$
Fault Current (I_f)	$1.50I_{fl}$	$0 < t < 900$
Short-Circuit Current (I_{cl})	$2.75I_{fl}$	$0 < t < 1.5$

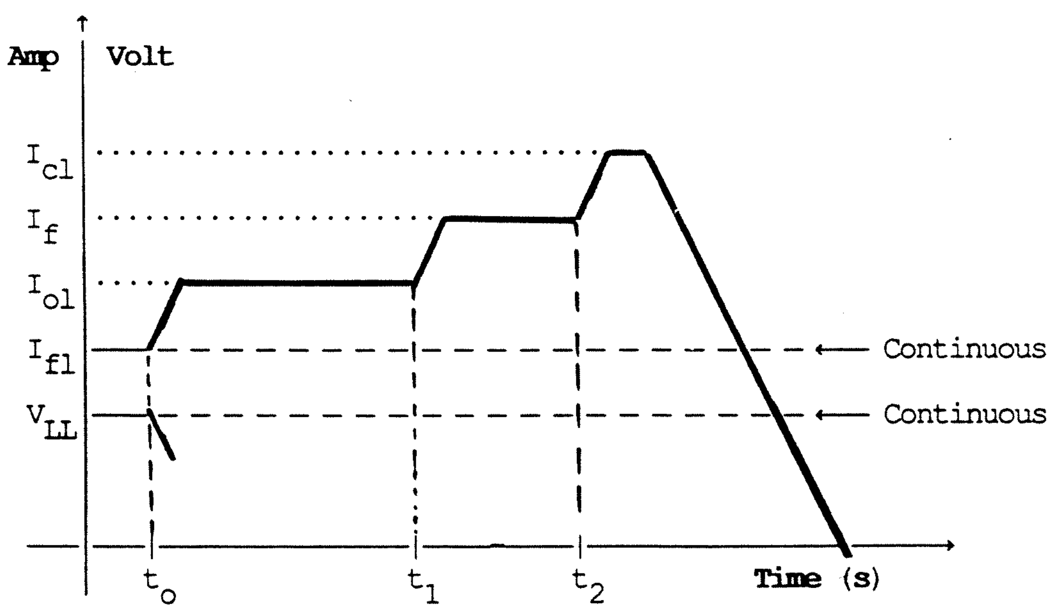


Figure 23. SSFC Responses.

f. SSFC Time-Current Curves

For circuit coordination, the SSFC's output characteristics in Table I are plotted as shown in Figures 24. The current values on the X-axis are in the per-unit basis. The plotted curves should be used only with the circuit breaker time-current curves when making a coordination study using SSFC's built in accordance with MIL-F-24638(SH).

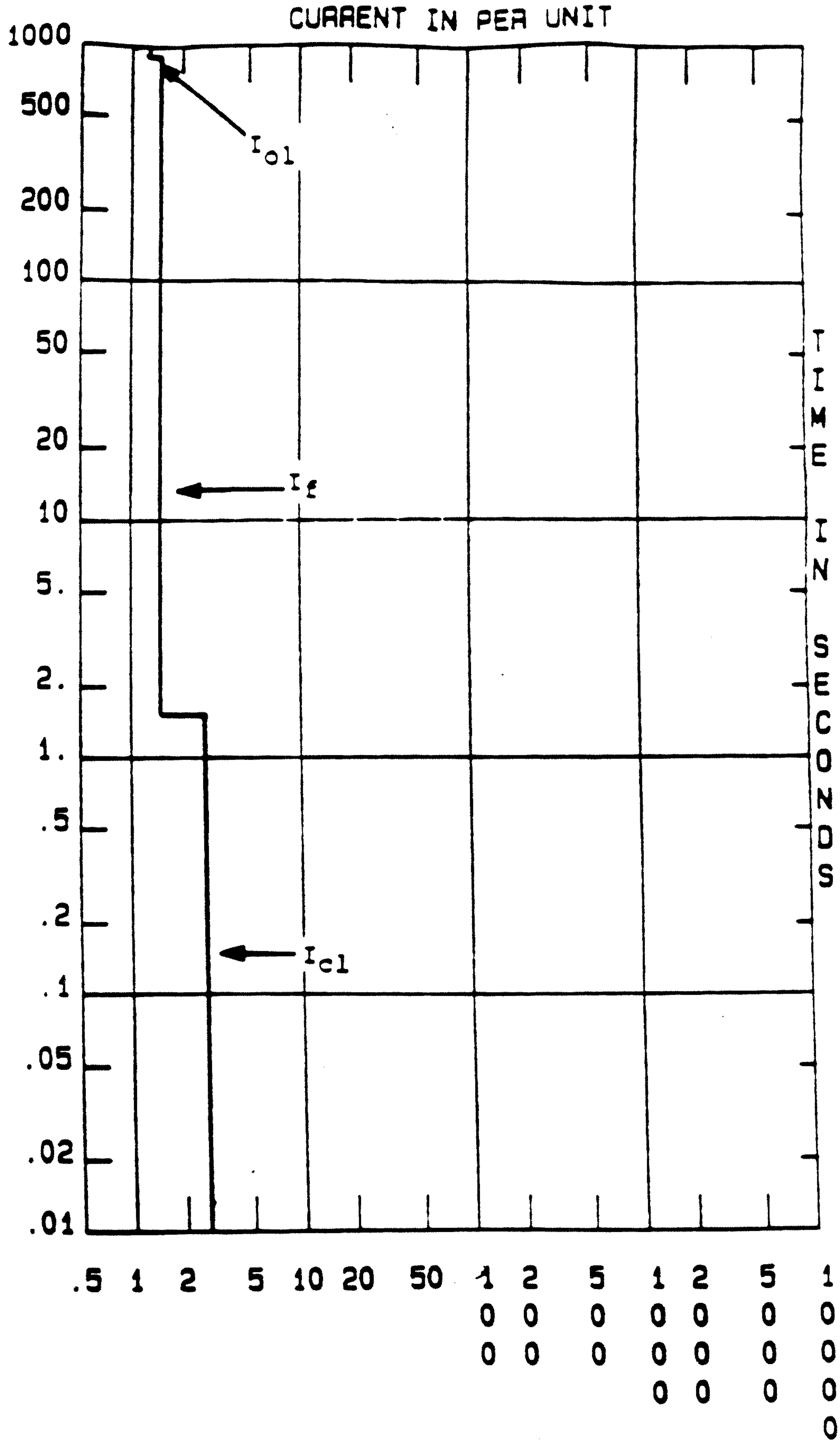


Figure 24. SSFC Time-current Curve (MIL-F-24638).

Appendix B. Assumptions and Necessary Data for Fault Current Calculations and Protective Device Coordinations

The following assumptions should be made for the fault current calculations:

Assumption	Rationale
The load currents in a fault line are neglected.	Since no motors over 10hp are connected which would contribute to the total fault current.
The phase voltages of all SSFC's are equal in magnitude; all adjacent-phase angles are 120°.	The SSFC is designed for Type III 400 Hz operating voltage and phase angle tolerances.
The power system network impedances are balanced except at the fault location.	Any deviation of lengths of cable between phases is small when compared to the overall cable lengths. Also, the use of 3 individual single-phase transformers with equal impedance supports the assumption of a balanced network.
All shunt admittances (cable charging, power factor correction and EMI filter capacitors, etc.) are neglected.	The inclusion of shunt admittances would momentarily increase the available fault current slightly due to the stored energy in these devices. However, this contribution of fault current is separate from the SSFC contribution which is the limiting factor in the analysis. Also, the increase in fault current is too brief to be sensed by CTS and circuit breakers.
The SSFC is connected to an infinite 60 Hz bus.	The SSFC has a high tolerance of input voltage drop and overall power and fault current requirements that are small when compared to the capacity of the 450V, 60 Hz system.

The effect of voltage and current harmonics is neglected.	The effects of user equipment current harmonics and SSFC voltage harmonics are specified to be small in comparison with the fault current available.
The CLD impedance is neglected in the off state and assumed constant in the on state.	In the off state, the CLD has very small impedance with respect to its impedance in the on state. The CLD activates only during the fault conditions; therefore, its impedance in the on state should be considered only in the fault calculations.

The following data may be necessary for fault current calculations and protective device coordinations:

Cable:

- Type and size.
- Length.
- Impedance.
- Number of cables per phase.

Circuit Breaker:

- Type.
- Size/rating.
- Settings.
- Time-current curve.

Current-Time Sensing and Signaling Device:

- Size/rating
- Settings
- Time-current curve.

Current Limiting Device:

- Type.
- Size/rating.
- Continuous current rating.
- Shunt trip time.

Fuse:

- Type.
- Size/rating.
- Time-current curve.

Solid State Frequency Changer:

- kW rating.
- Power factor.
- Input/Output characteristics.
- Time-current curve.

Load:

- Total rated loads on each bus.
- The largest rated load on each bus.

Transformer:

- kVA rating.
- Impedance (usually in percent).
- Configuration (delta/delta, wye/wye, etc.).
- Voltage ratios.

Appendix C. Per-unit notation

The per-unit value of any quantity is defined as the ratio of the quantity to a base value expressed as a decimal. The voltage, current, kilovoltamperes, and impedance are related so that the selection for any two of them determines the base values of the others. Unless otherwise specified, the given value of a base voltage in a three-phase system is a line-to-line voltage, and the given value of a base kilovoltampere or megavoltampere (MVA) is the total three-phase base. The per-unit value is defined as follows:

$$\textbf{Per-unit value} = \left(\frac{\text{Actual value}}{\text{Base value}}\right)$$

The base impedance and base current can be computed directly from the three-phase values of base kV and base kVA as follows:

Base Current

$$I_{base} = \left(\frac{(kVA)_{base}}{\sqrt{3}\,(kV)_{base}}\right)$$

Base Impedance

$$Z_{base} = 10^3\left(\frac{(kV)_{base}}{\sqrt{3}I_{base}}\right)$$

$$= 10^3\left(\frac{(kV)^2_{base}}{(kVA)_{base}}\right)$$

$$= \left(\frac{(kV)^2_{base}}{(MVA)_{base}}\right)$$

Changing Bases

$$(Z_{pu})_{new} = (Z_{pu})_{old}\left(\frac{(kVA)_{new}}{(kVA)_{old}}\right)$$

Changing Percent Impedance to Per-unit Impedance

$$Z_{pu} = \frac{Z_{(\%)}}{100}$$