AFWAL-TR-81-2016

HIGH CURRENT POWER CONTROLLER

P. E. McCOLLUM
Author

ROCKWELL INTERNATIONAL
AUTONETICS STRATEGIC SYSTEMS DIVISION
3370 MIRALOMA AVENUE
P.O. BOX 4192
ANAHEIM, CA 92803

APRIL 1981

FINAL REPORT for period SEPTEMBER 1978 THROUGH DECEMBER 1980

AERO PROPULSION LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio 45433

NOTICE

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture use, or sell any patented invention that may in any way be related thereto.

This report has been reviewed by the Office of Public Affairs (ASD/PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

DUANE G. FOX
Project Engineer
Power Systems Branch
Aerospace Power Division

PAUL R. BERTHEAUD
Technical Area Manager
Power Systems Branch
Aerospace Power Division

FOR THE COMMANDER

JAMES D. REAMS
Chief, Aerospace Power Division
Aero Propulsion Laboratory

"If your address has changed, if you wish to be removed from our mailing list, or if the addressee is no longer employed by your organization please notify AFWAL/POOS-2, W-PAFB, OH 45433 to help us maintain a current mailing list".

Copies of this report should not be returned unless return is required by security considerations, contractual obligations, or notice on a specific document.

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: AFWAL-TR-81-2016	2. GOVT ACCESSION NO: AD-A101 643
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): HIGH CURRENT POWER CONTROLLER	5. TYPE OF REPORT & PERIOD COVERED: Final September 1978-December 1980
	6. PERFORMING ORG. REPORT NUMBER: C80-904/201
7. AUTHOR(s): P. E. McCollum	8. CONTRACT OR GRANT NUMBER(s): F33615-78-C-2272
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Rockwell International, Autonetics Strategic Systems Division, 3370 Miraloma Avenue, P. O. Box 4192, Anaheim, CA 92803	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 62203F, 3145 29 53
11. CONTROLLING OFFICE NAME AND ADDRESS	12. REPORT DATE: April 1981
	13. NUMBER OF PAGES: 135
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): Aero Propulsion Laboratory (AFWAL/POOS), Air Force Wright Aeronautical Laboratories, Air Force System Command, Wright Patterson Air Force Base, Ohio 45433	15. SECURITY CLASS. (of this report)
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release, distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

High Current Power Controller
Solid State Power Controller
Microcomputer
Single Phase Controller
Three Phase Controller
I^2t Algorithm
Load Sensor
Aircraft Electrical System
Electrical Distribution

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report documents the design, development, and test of High Current Power Controllers (HCPCs) by Rockwell International. HCPCs are a combination of solid state and electromechanical technologies, combined for reduction of high power dissipation/voltage drop experienced in present Solid State Power Controllers (SSPCs) in the high current (10 ampere to 400 ampere) area. In addition, solid state advantages over the conventional electromechanical configuration, such as EMI reduction, longer life, etc., are retained. This report includes results of tests conducted during the study.

PREFACE

This document is the final technical report for the High Current Power Controller Program. The work was performed by Autonetics Strategic Systems Division of Rockwell International, Anaheim, California under Air Force Contract No F33615-78-C-2202.

The work was administered under the direction of the Power Systems Branch, Aerospace Power Division, Aero Propulsion Laboratory, Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio, by Mr. Duane Fox (POOS-2), Project Engineer.

C. E. Young of Rockwell International was technically responsible. Major contributions were made by C. O. Linder, P. E. McCollum, J. McGray, and W. A. McFall.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

LIST OF TERMS AND ABBREVIATIONS

HCPC	High Current Power Controller
SSPC	Solid State Power Controller
A	Ampere
I	Current
SCR	Silicon Controlled Rectifier
msec	Millisecond
mA	Milliampere
W	Watt
V	Volt
lb	Pound
Hz	Hertz
μA	Microampere
ZVC	Zero Voltage Crossing
ZIC	Zero Current Crossing
ADC	Analog to Digital Converter
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
LSB	Least Significant Bit
in.	Inch
PCB	Printed Circuit Board
MCMT	Mean Corrective Maintanence Time
MTBF	Mean Time Between Failures
DWV	Dielectric Withstanding Voltage
JFET	Junction Field Effect Transistor
EMI	Electromagnetic Interference
I^2t	Current (Squared) Times Time
CMRR	Common Mode Rejection Ratio
AMPS	Amperes
COO	Cost Of Ownership

SECTION I

SUMMARY

This report documents the High Current Power Controller (HCPC) development program performed by Autonetics Strategic Systems Division of Rockwell International. Aspects of the development covered by this report are basic HCPC concepts, design philosophies, fabrication techniques, and test results. Also included are reliability, maintainability, safety, and packaging considerations.

The HCPC program consisted of three phases, which were: Phase I, the preliminary design and breadboard study, Phase II, the development of the final designs, and Phase III, the fabrication, test and evaluation of the controllers designed in Phase II. The goal was to develop and deliver three of each type of HCPC: 10 ampere one phase, 10 ampere three phase, 50 ampere 3 phase, and 400 ampere 3 phase, all utilizing 115 volts, 400 Hz power.

Phase I activities included numerous trade studies and breadboard efforts to evaluate microcomputer performance, current sensing techniques, relay/contactor selection, volume, weight, and power dissipation.

Phase II consisted of refining the basic designs of Phase I with breadboard testing and design iterations with the goal of arriving at a common design core of electronics for use in any of the four configurations of power controllers.

Phase III, fabrication, evaluation, and test results, with problems encountered and appropriate solutions, provided confirmation of an acceptable design.

The major design activities of the HCPC program included: (1) the development of the microcomputer software for the timing, control, and trip functions, (2) selection of latching contactors with suitable current carrying capability and minimal size, (3) development of electrically isolated squaring current sensors, (4) development of a small efficient power supply and (5) packaging

the controllers in a flightworthy configuration.

The primary design goal of the development of a controller incorporating the advantages of both solid state and electromechanical switches has been met, with the result being significantly less switching EMI than the electromechanical configuration and less power dissipation than the conventional solid state configuration.

SECTION II

INTRODUCTION

2.1 Background

Aero Propulsion Laboratory sponsored development of Solid State Power Controllers (SSPCs) had previously emphasized current ratings of less than five amperes. Although higher current SSPCs have been developed, high power dissipation has been a major drawback. A hybrid configuration of solid state switches and electromechanical relays, the High Current Power Controller (HCPC) technique, combines the advantages of both technologies without the disadvantages of each, i.e. high power and limited life. The solid state element operates during the transition states of the switch - it applies power to the load at zero voltage crossing and removes power at zero current crossing, thus minimizing electromagnetic interference. It also limits the voltage across the opening or closing relay contacts to less than two volts, which prevents arcing across the contact and extends contact life. The relay is used to apply the steady state current to the load at a voltage drop and power dissipation approximately one tenth that of a solid state switch.

Rockwell, in late 1976 and early 1977, investigated the feasibility of using a Solid State Power Controller (SSPC) and electromechanical relay combination similar to the HCPC technique. That application extended power controller technology for requirements greater than 2 amperes while preserving the advantages of relays. The investigation indicated significant advantages in performance and potential cost reductions and served as a base for the HCPC program.

2.2 Objective

The objective of the HCPC program was to develop 115 volt, 400 Hz power controllers at current levels of 10, 50, and 400 amperes, using a combination of solid state and electromechanical switches.

2.3 Approach

Rockwell's approach utilized the following primary electrical building blocks:

(1) A solid state switch with a low steady state voltage drop and high current carrying transient characteristics

(2) Relays with high current capability and low contact resistance

(3) Low power dissipation control and drive electronics

(4) Low power dissipation load current sensors

The solid state switch was mechanized with silicon controlled rectifiers (SCRs). A digital microcomputer with a multiplexed analog-to-digital converter (ADC) provided the control and trip functions. A current shunt, coupled with a modulator/demodulator type sensor circuit, was used for load current sensing.

This approach paralleled the original proposed mechanization with the exception of the load current sensing technique. A Hall Effect current sensor was tentatively proposed but was discarded based primarily on its large size and its output variations with temperature.

General packaging considerations included volume, thermal dissipation, and cost. The proposed technique for the control electronics assembly or electronics module envisioned joining NMOS and hybrid thin/thick film technologies. Although this approach utilized minimum volume, its disadvantage was its greater cost. An approach using a discrete component mechanization that retained the module technique was found to meet all volume requirements and was more cost effective.

SECTION III

TECHNICAL DISCUSSION

3.1 Mechanization/Design

3.1.1 HCPC Configuration

The configurations selected by Rockwell for mechanization of the High Current Power Controllers are shown in Figure 1 and 2. The addition of current limiting resistors in series with the mechanical contacts and the substitution of a modulator/demodulator type of current sensor is a modification of the configuration originally proposed.

Current limiting resistors aid in diverting load current to the SCRs in the event of an overcurrent condition.

Analysis of the various methods of load current sensing available indicates that a modulator/demodulator type of sensing circuit offered overall advantages in size and was determined to be less of a design risk.

3.1.2 Primary HCPC Circuit Elements

The primary elements developed or selected were as follows: (see Figures 1 and 2):

(1) Microcomputer with appropriate software for the trip and control functions
(2) A small, electrically isolated, high current sensor
(3) Solid state switch with suitable high current transient characteristics
(4) Latching mechanical contactors with high current capability
(5) Low power switch drive electronics
(6) Low resistance fuse for the 10 ampere configurations
(7) Small, efficient, electrically isolated power supply

The four basic modes of operation are: (1) Normal turn-on, (2) Steady state on,

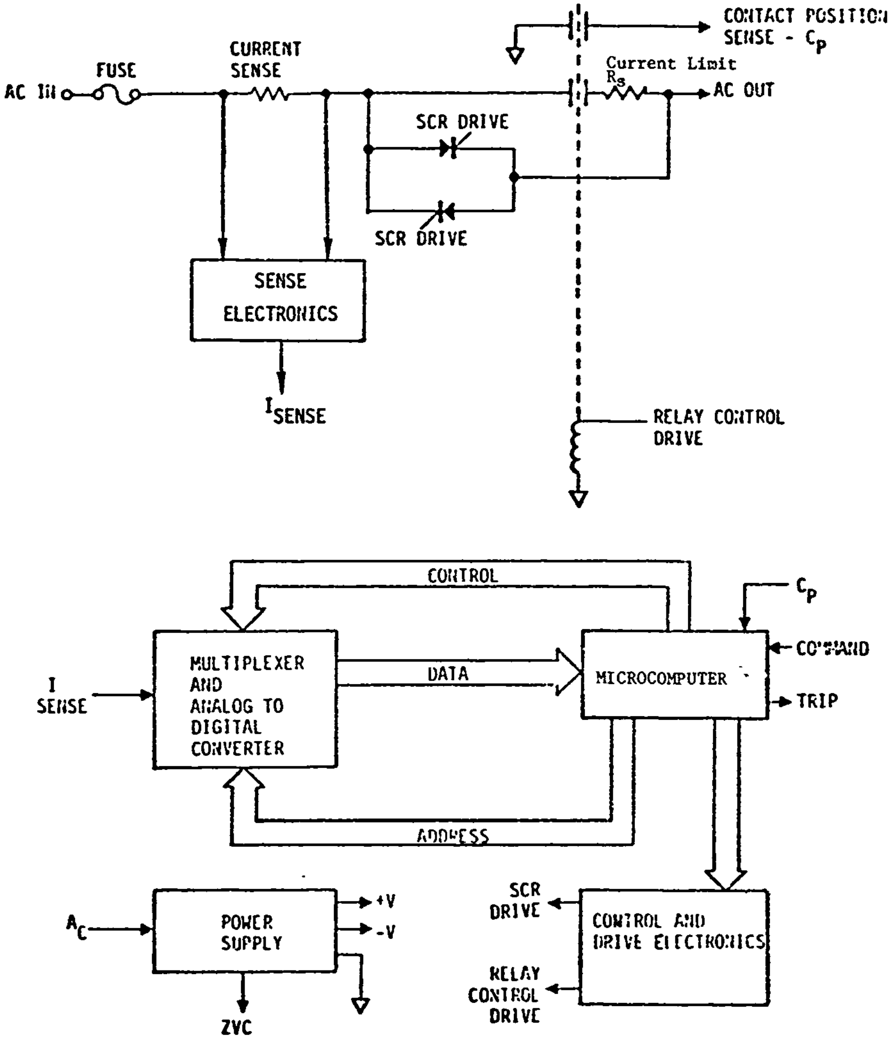


FIGURE 1. SINGLE PHASE POWER CONTROLLER BLOCK DIAGRAM

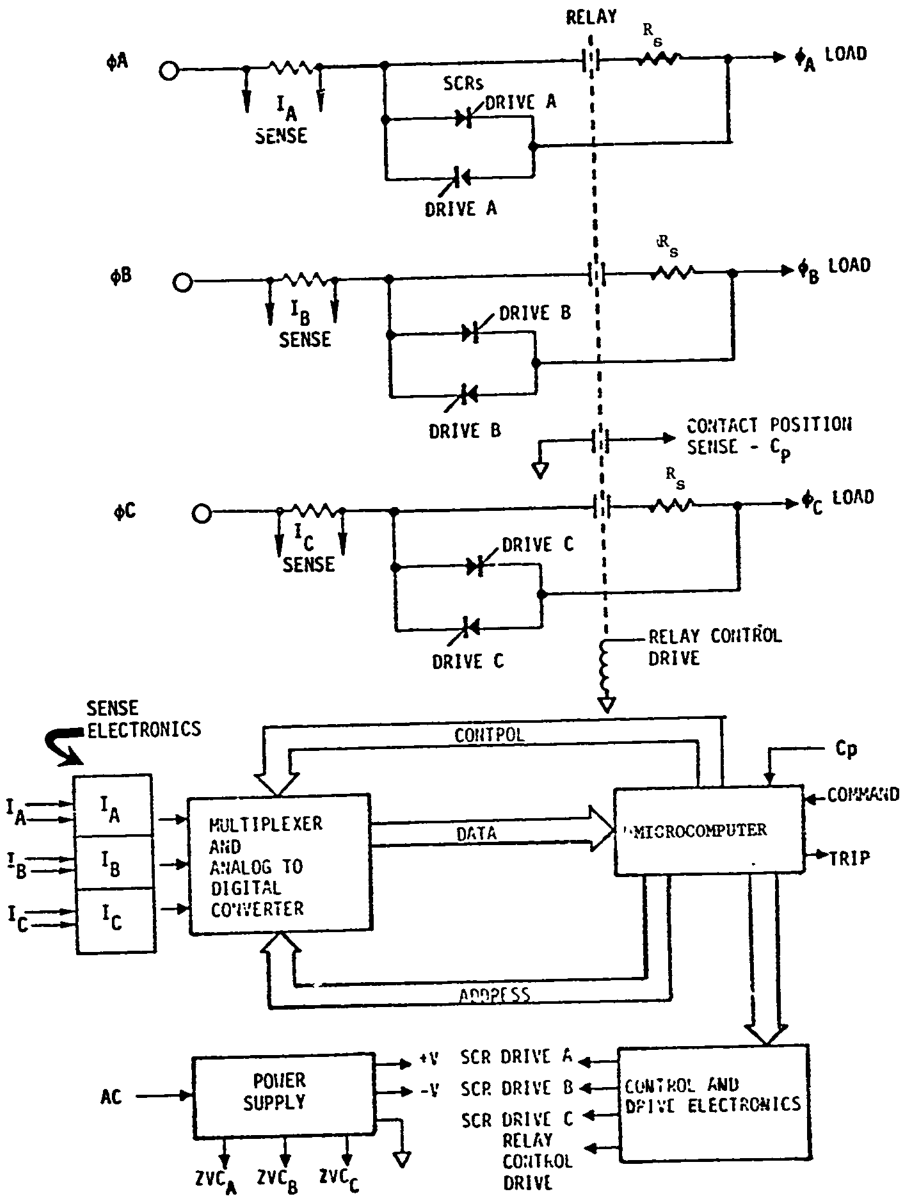


FIGURE 2. THREE PHASE POWER CONTROLLER BLOCK DIAGRAM

(3) Normal turn-off, and (4) Overcurrent based trip. In each mode the microcomputer performs a monitor and control function to insure that the relay is provided with a maximum of protection.

A "normal" operation of a three phase controller, assuming a normal turn-on with a period of steady state on time, followed by a normal turn-off, includes the following sequence of events: upon receipt of a +5 volt signal on the control input, the microcomputer begins counting ZVC pulses, while monitoring the control input. If the control input remains high for 2.5 to 5.0 milliseconds, (1-2 ZVC pulses) the microcomputer initiates the turn on sequence shown in Figure 3. First, each pair of solid state switches controlling a phase is turned on at that phase's next zero crossing, establishing power to the load. In conjunction with the SCR drives, the relay is commanded on. After the relay latches on, the solid state switches are turned off, and steady state monitoring for an overcurrent or a turn off command begins. The microcomputer samples the current in each phase, via the analog-to-digital converter, every 200 microseconds. The current data is then processed using an I^2t trip algorithm, which results in a trip if an overcurrent is present. However, the steady-state-on period is normally terminated by a turn off command. When a turn off command is received, the solid state switches are turned on, the relay unlatched, and then the switches cycled off such that the load voltage is removed on the same slope as turn on occurred.

Overcurrent based trip can occur by either of two means. If the overcurrent is greater than 100 percent but less than 1000 percent (100 to 250 percent for the 400 ampere controllers) of rated load, a timed, or I^2t trip results. If an overcurrent of great magnitude (greater than 1000 percent) is sensed, an instanteous trip is initiated. In either case, once a trip state is initiated, the solid state switches are turned on, the relay latched off, and subsequently the switches turned off immediately. However, if the controller is commanded on into the large fault, having been in the off state, the relay is not allowed to turn on. In that case, the load would only experience a single half cycle of that load voltage.

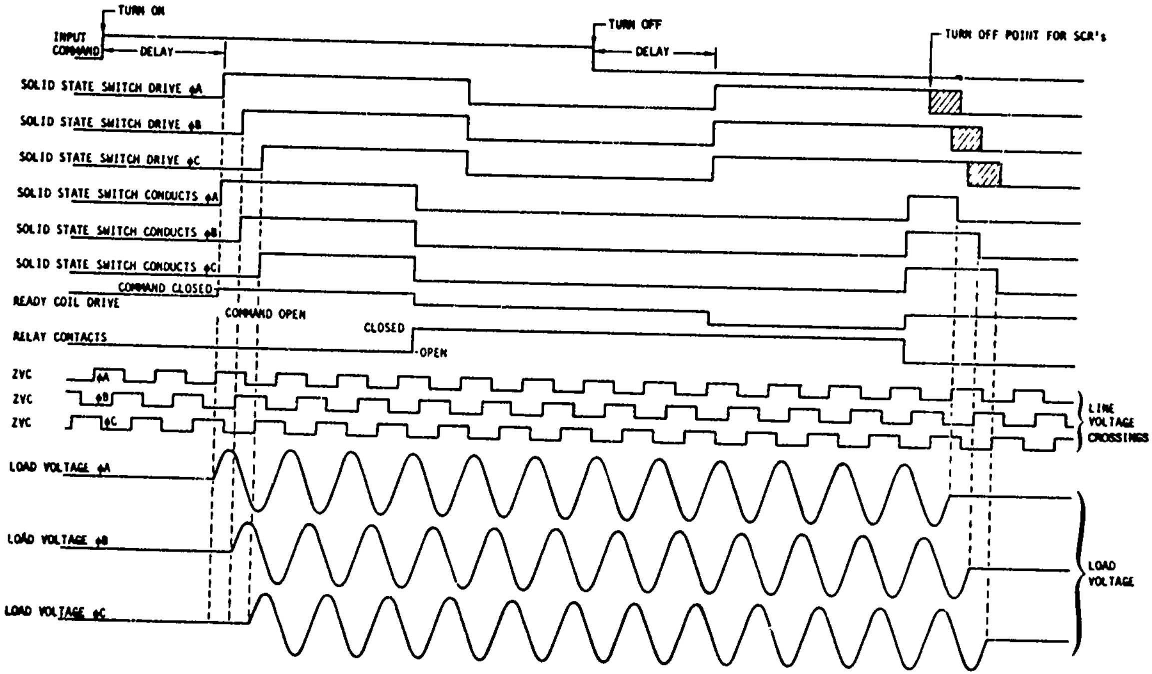


Figure 3 - Timing Diagram - Turn On and Turn Off

3.1.2.1 Microcomputer and Analog to Digital Converter (ADC)

A Rockwell International Model 6500/1 microcomputer and a National Semiconductor ADC (ADC 0808) were selected to perform the digital processing. The Rockwell International microcomputer replaced the Intel Model 8748 originally proposed due to superior processing speed and extensive in-house development aids.

3.1.2.1.1 Trip Mechanization and Control Functions

Considerable time and effort was expended in devising the trip algorithm and developing the software for the HCPC control and trip functions. The algorithms evaluated were:

(1) $\text{Accumulator}_n = \text{Accumulator}_{n-1} + I^2$ for $I >$ minimum trip

$= \text{Accumulator}_{n-1} - I^2$ for $I <$ minimum trip and $\text{Accumulator}_{n-1} > (\text{minimum trip})^2$

(2) $\text{Accumulator}_n = \text{Accumulator}_{n-1} + I^2 - (\text{minimum trip})^2$

In algorithms 1 and 2, the power controller will trip if the Accumulator is greater than a fixed value.

(3) Trip time is based on $I^2_{n-1} - I_n \times I_{n-2}$ being greater than a time specified by a lookup table. This algorithm requires a sample rate above 10 samples per cycle on each phase, but it permits the use of a trip time-current characteristic curve of any shape.

Algorithm No. 2 was selected as the preferred method to mechanize the trip function. This algorithm provides for the same computations to be made on each sample of the load current rather than the multi-decision mechanization of algorithm No. 1. Algorithm No. 3 requires a higher sample rate of the load current and the variable trip characteristic feature provides no advantage when the only trip response required is an I^2t curve.

Early work included the evaluation of the advantages and disadvantages of squaring I in the microcomputer compared to providing an I^2 output from the sensor to the microcomputer. The study concluded that the microcomputer could accommodate either method. However, the subcontractor developing the current sensor indicated that higher accuracy could be attained with a squared output rather than a linear output. The decision was made to perform the squaring in the sensor.

Figure 4 is a flow chart of the software developed and is identical for all four HCPC configurations. The software includes the capability of being scaled for any of the steady-state currents of 10, 50 or 400 amperes and can accommodate either a one phase or a three phase configuration.

The use of a microcomputer provided flexibility and programability to the HCPC design. Programmable selection of HCPC full scale current, which is achieveable by digital code selection, will change (1) the fast trip point, (the high current that causes an immediate trip), (2) the first trip point (the minimum current that will effect a trip), and (3) the constant value to which the accumulator is compared (this provides the shape and slope of the trip response curve). The zero voltage crossing (ZVC) is derived by the ZVC circuits for Phase A and used by the microcomputer to turn on the Phase A SCRs and to derive the turn-on times for Phase B and C.

A similar technique is used to develop the timing for Zero Current Crossing (ZIC). Phase A SCR gate drive is turned off at Phase A negative voltage maximum and the microcomputer then times the Phase B and C gate turn-off points based on the Phase A maximum.

A turn-on and turn-off delay of 2.5 to 5 msec, (1-2 zero voltage crossings) in response to a change in the Control Input signal, has been incorporated into the timing sequence to reduce the sensitivity of the Control Input to noise transients.

The auxiliary contact of the mechanical switch is used to provide relay status (open or closed) to the microcomputer.

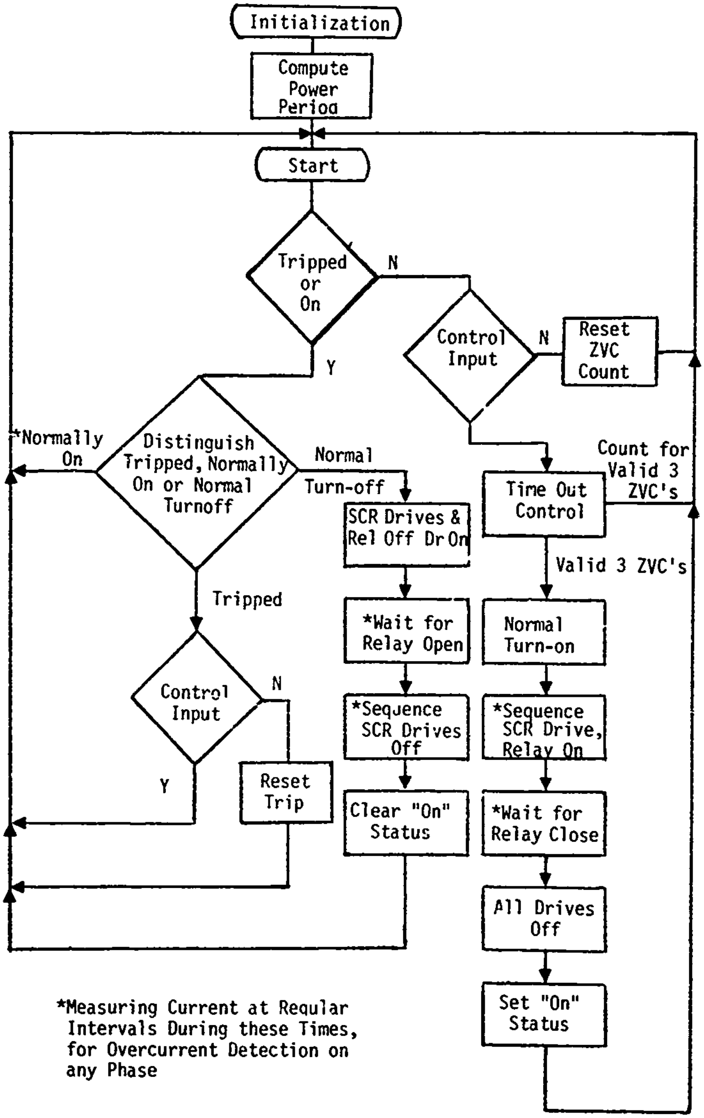


Figure 4. SIMPLIFIED HCPC FLOW DIAGRAM

3.1.2.2 Load Current Sensor

A shunt current sensor approach was selected as the technique to sense the magnitude of the load current. This represents a change from the Hall Effect current sensor originally selected. The Hall Effect sensor technique was discarded as an approach because of its larger size and the drift with temperature. Two current sensor suppliers were contacted and asked to quote to a general set of requirements. One of the suppliers responded verbally, stating that the size limitations could not be met and that they did not wish to expend further effort. The other supplier submitted a quotation to include preliminary drawings and cost. The 50 and 400 ampere designs were within size constraints; the 10 ampere design size was not.

Quote on 50 Amp Sensor (Magnetics Only):

Current Range	0 to 1760 Amps
Size	1.5 x 1.5 x 0.5 inches
Linearity	3 percent
Offset	$\leq$ 16 mV
Offset Drift	40 μ V/°C
Frequency Response	< 5 percent accuracy, DC to 400 Hz

The sensor design selected makes use of an HCPC internal conductor as a resistance element for current sensing. The material selected for the conductor is manganin, a copper alloy that was chosen for its very low temperature coefficient of resistivity. The voltage across the element is thus directly proportional to line current for all values of temperature within the required operating range.

The characteristics of the manganin with respect to temperature or current will directly affect the operation of the total sensor circuit. The relevant characteristics have been analyzed and are listed in Table 1.

TABLE 1.

MANGANIN CHARACTERISTICS

Rated Current	Resistance (Ohms)	Peak Current	Power Dissipation at Rated Current	Fusing Time at Peak Current
10A	0.005	423A	0.5 W	0.89 sec
50A	0.001	2121A	2.5 W	0.89 sec
400A	0.000125	4383A	20 W	13.3 sec

The temperature characteristics of sample pieces of manganin were confirmed by laboratory tests. The results are shown in Table 2.

TABLE 2.

MANGANIN RESISTANCE VS

TEMPERATURE TEST DATA

Temperature (deg C)	Resistance Ohms (1)	Percent Error	Resistance Ohms (2)	Percent Error
-55	0.00450	-0.9	0.00749	-0.8
-34	0.00452	-0.4	0.00750	-0.7
-17	0.00452	-0.4	0.00755	0
0	0.00454	0	0.00755	0
+17	0.00454	0	0.00755	0
+35	0.00456	+0.4	0.00755	0
+75	0.00454	0	0.00755	0
+100	0.00454	0	0.00755	0
+125	0.00454	0	0.00755	0

(1) ≈0.05 x 0.4 x 6 inch sheet sample

(2) ≈0.09 x 0.12 x 5 inch rod STO 0170A30045 Type II

The voltage across the manganin is modulated at a 35 kHz rate, passed through a transformer for isolation, then through a squaring amplifier for gain and demodulation. The signal is then filtered and supplied to the ADC for digitizing. The squaring isolation amplifier general characteristics are in Table 3.

TABLE 3

SQUARING ISOLATION AMPLIFIER DATA

Function:	$V_o = 8.26\ (V_{in})^2$
Accuracy:	2% of point or 2 mV (whichever is greater) dc to 400 Hz
Isolation:	1000 Vrms
CMRR:	>100 dB
V_o Range:	0 to +5 volts
Power:	≈0.150 Watt at ± 15 Vdc
Size:	1.4 x 1.1 x 0.475 in. (may be further reduced)
Packaging:	Hermetic high permeability nickel alloy case with glass pin seals

This sensor was selected on the basis of its high accuracy over the operating temperature range. Tests of the sensor confirmed the quoted accuracies at room temperature. Table 4 shows the complete test data.

TABLE 4

TEST DATA ON

SQUARING ISOLATION AMPLIFIER

V_{in} (rms) at 400 Hz	Average Vout	Expected Vo	Percent Error	Frequency Response at 0.5 Vrms Input	Average Vo	Percent Error
				DC	2.065	0.0
0.00	0.000	0.0000	0.0	100	2.065	0.0
0.05	0.021	0.0207	1.5	200	2.065	0.0
0.10	0.084	0.0826	1.7	300	2.063	0.0
0.20	0.331	0.3304	0.3	400	2.062	0.1
0.30	0.747	0.7434	0.5	500	2.060	0.2
0.40	1.319	1.322	0.2	1000	2.058	0.34
0.50	2.062	2.065	0.1	2000	2.033	1.5
0.60	2.973	2.974	0.0	4000	1.961	7.5
0.70	4.050	4.047	0.1	6000	1.847	10.5
				10000	1.554	25

<u>Output Noise</u> <1 mV

<u>Common Mode Rejection</u> <2 mV with 115 Vrms applied to both input terminals.

<u>Linearity</u> <1.7% error, 0 to + 8.1 Vpk Out

3.1.2.3 Solid State Switch

A Silicon Controlled Rectifier (SCR) was the selected solid state switch for the HCPC application. For the 10 ampere configurations, the Motorola 2N6507 was selected to replace the originally proposed Unitrode L1SR05554F, due to the cancellation of the entire Unitrode line of "Chipstrate" devices. The SCRs for the 50 and 400 ampere applications have been changed to the Semikron SKKT 90 from the General Electric C380x500. The Semikron devices are prepackaged in thyristor-modules as opposed to the "hockey-puck" configuration of the General Electric SCRs that require bulky pressure clamps and isolation techniques. The Semikron devices were found to be superior in utilizing volume while still meeting the electrical requirements. For the 400 ampere application, two SKKT 90 were paralleled for each half side of conduction required, giving a total of four SCRs per phase. Series resistors are included in each SCR leg to force current sharing in event that any mismatch in the forward voltage drop of any SCR could cause current "hogging". Table 5 lists the critical SCR parameters.

TABLE 5

SCR PARAMETERS

PARAMETER	CONTROLLER USE					
	10A, 1 & 3 Ø		50A, 3 Ø		400A, 3 Ø	
	Req.	2N6507	Req.	SKKT 90	Req.	SKKT 90(2)
Blocking Voltage	>254V	400V	>254V	400V	>254V	400V
RMS on Current	10A RMS	25A RMS	50A RMS	145A RMS	400A RMS	290A RMS
Fault Current (from Table 6)	225 A	400 A	1400 A	2000 A	2000 A	4000 A
Leakage Current	1 mA	4 mA	1 mA	4 mA	5 mA	8 mA
di/dt (non-repetitive)	1A/µs	≥10A/µsec	5A/µsec	100A/µsec	12.5A/µsec	200A/µsec
dv/dt (Circuit)	690V/usec	≥50V/µsec	690V/µsec	500V/µsec	690V/µsec	500V/µsec

The dynamic resistance of an SCR (RSCR) was one of the key characteristics in the selection of the HCPC SCRs. Consider Figure 5:

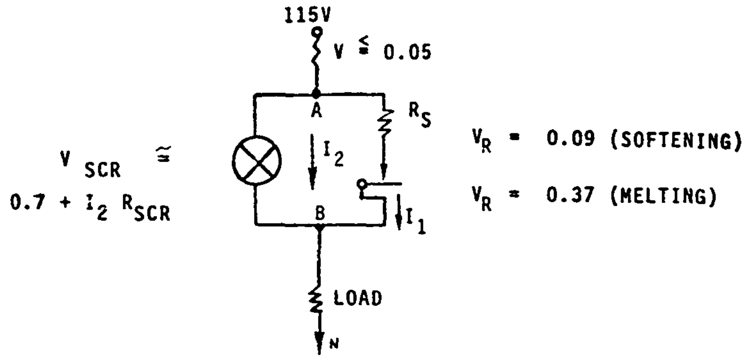


Figure 5. Relay - SCR Current Sharing

To prevent arcing across the relay contact, the voltage across the latter must be less than 12 volts. This is no problem at steady state turn-on, since the voltage from A to B will be less than 2 volts. At turn-off, with the relay contact closed, and $V_R \leq 0.1$ volt, the SCR will assume the steady-state current as the relay contact opens and clamps the voltage from A to B at less than 2 volts. In the contact closed condition and with a large sudden over-current, opening the relay contact (trip condition) with the SCR closed could possibly overheat the contacts if the current was not limited through the contact. The resistance R_S has been added to increase the voltage drop across the contact section and let the SCR assume a share of the overcurrent.

The SCRs selected are shown in Table 6.

Table 6

SCR SELECTION

Configuration	Specified Rupture Current	I_1 (Relay)	I_2 (SCR)	Condition
10A	400A	175A	225A	$V_R \leq 0.3V$ $R_{SCR} \leq 0.008\Omega$ 2N6507
50A	2000A	600A	1400A	$V_R \leq 0.3V$ $R_{SCR} \leq 0.001\Omega$ SKKT 90
400A	5000A	3000A	2000A	$V_R \leq 0.3V$ $R_{SCR} \leq 0.0005\Omega$ (2) SKKT 90

The leakage current of the SCRs sized for HCPC current levels exceed the HCPC specified maximum. A study by Dalziel and Lagen in the March 1941 issue of Electronics titled "Muscular Paralysis Caused by Electric Currents" found that 97.5 percent of their test population could release a 12 mA rms, 400 Hz sinusoidal current and a 10 mA rms, 60 Hz sinusoidal current. Selection of the 10 ampere SCRs for minimum leakage current would probably reduce the total leakage current to 4 mA, still in excess of the 1 mA HCPC requirement, but appreciably below the 12 mA muscular paralysis level.

The possibility of reducing the 50 and 400 ampere SCR leakage current levels to below 5 mA by selecting SCRs is very low. Consequently, other methods were considered. These included (1) grounding the HCPC output when not connected to the aircraft load, (2) providing a resistive path to ground, (3) using a "make-make" contact relay. This would have to be a specially designed relay that would have one set of contacts in series with the solid-state switch in addition to the load current contacts. The SCR would close at a time between the "make" of the two contacts (the contact in series with the SCR would close first); the sequence would be reversed on opening. The possibility of having such a relay designed has not been explored, but it is expected to be more expensive than the presently selected relays and contactors.

Providing a resistive path to ground for the leakage current was selected as the most economical and easily mechanized approach. To minimize power dissipation, a positive temperature coefficient resistor is connected from the HCPC output to ground. The resistor provides a path of approximately 100 ohms to ground when the HCPC is "off" ($V_{out} = 0$), but when the HCPC is "on" (V_{out} = 115V 400 Hz), the effective resistance of the resistor exceeds one megohm. This approach effectively shunts away current for the no load off or high impedence load condition, minimizing the potential shock hazard.

3.1.2.4 Relays and Contactors

Selection of suitable mechanical switches for the HCPCs was preceded by a detailed analysis of switch contact characteristics. As probably could have been anticipated, the primary characteristics of concern is contact temperature. Overheating (and consequent contact deterioration) is due to excessive current, arcing, or high contact resistance. Accordingly, the contact size must be matched to the maximum steady-state current. The contact resistance is kept low by selecting contact material with high conductivity and by providing sufficient contact pressure. The effects of arcing are minimized by opening the contacts rapidly and by using metal alloys developed for such applications.

The great majority of all relays and contactors in the 10 to 400 ampere class use silver cadmium oxide as the contact material. The softening voltage of this material is 0.09 volt and the melting voltage is 0.39 volt. The current limiting resistance values in the HCPCs, in conjunction with the SCRs, are designed to limit the contact voltage at approximately 0.3 volts, or below the melting voltage. No other material offered significant additional advantages. Consequently, silver cadmium oxide was the contact material selected.

In the area of overcurrents, relay and contactors generally are able to withstand rupture currents (and still open) of approximately 10 times rated current. However, the same devices can withstand higher overcurrents for the circuit breaker compatibility condition (withstand current, contact is not required to open). In HCPC usage, the SCR assumes varying amounts of the over currents, thus, larger overcurrents can be tolerated in the HCPC configurations compared to pure relay applications.

Leach relays, types JDL and KDL, were selected for the 10 ampere configurations, respectively, based on their size, maximum steady-state current rating, and circuit breaker compatibility. Two KDLs connected in parallel was the choice for the 50 ampere HCPC for the same reasons. The Hartman B-382 was selected for the 400 ampere configuration.

An analysis of the mechanisms involved with the operation of electrical contacts demonstrated some of the advantages of augmenting the electromechanical contacts with a solid state switch. Typical militarized power contactors are designed to limit the steady state temperature rise of the power input and output terminals to 65°C above the maximum rated ambient temperature. The primary source of heat is the I^2R power dissipated by the contacts where R is the resistance of the closed contacts and I is the load current. The magnitude of

R is maintained at sufficiently low values by providing sufficient contact pressure, large enough contacts, and low resistance terminal-to-contact wiring.

Designing for a satisfactory contact life requires additional design considerations. Long contact life requires that the contacts are not consistently overheated when closing or opening, to prevent temporary melting and subsequent erosion of the contacts. In addition to the heating of a closed set of contacts due to I^2R, the contacts are also heated due to arcing when opening. It is convenient to express this heating as caused by VIt, where I is the current through the contact, V is the voltage across the contacts and t is equal to the time the contacts are arcing. For this discussion, assume a resistive load. The magnitude of V for an opening set of silver cadmium contacts varies from a value of approximately 0.4 volts (the melting voltage) for the closed, but now opening contacts, to a value equal to the supply voltage while the contacts are arcing. The arc is extinguished when the contact separation is sufficiently large or the voltage or current drop below the minimum values that will sustain an arc (approximately 12 volts for silver cadmium). The majority of military power contactors are used with DC, or with 60 Hz or 400 Hz as the supply frequency. The following conclusions can be drawn:

(1) Since the voltage impressed across an opening set of contacts is instantaneously the rated supply voltage, a DC application of a contactor would be more severe on contact life compared to the cyclic 60 and 400 Hz amplitudes

(2) The 60 Hz application is more severe than the 400 Hz, since $t \propto \frac{1}{2f}$

Typical electromechanical power contactors achieve the necessary contact life (for given contact materials) and normal steady state maximums by:

(1) Providing "double break" contacts; this doubles the distance the switched voltage must arc, thus allowing larger voltage ratings for given contact travel

(2) Rating the contacts as a function of the frequency of the switched voltage and switched voltage V maximum. The 65°C temperature rise limitation of the terminals determines the maximum current rating.

Since the solid state switch in an augmented power contactor limits the voltage across the making or breaking contacts of the electromechanical contactor to less than two volts, arcing will not occur. Thus the above design considerations required to extend contact life for electromechanical contactors are not required for the augmented configurations. The result is that physically smaller contactors could be used in the latter configurations compared to electromechanical units. For example, the Hartman B-241 DM contactor is rated for 350A (resistive load) at 115/200V, and 125A at 264/458V 400 Hz. Used in an augmented circuit, the contactor could operate with 350A at 264/458V, 400 Hz. The Hartman B-382 is rated at 120A, 120/208V at 60 Hz and at 200A for both 60 and 400 Hz. It is estimated that contactors used in an augmented type of AC circuit could be at least 30% less in weight and volume than their electromechanical counterparts, assuming the same voltage, frequency and current.

It would appear that high voltage DC controllers would benefit most from eliminating the heating caused by EIt or arcing. However this apparent advantage may be negated in whole or in part by the additional circuitry that would be needed to provide the extra transistor base or gate drive when the solid state switch is required to divert high rupture currents.

A contactor could also conceivably be redesigned to be a single break contact type and theoretically double its current carrying capacity, without changing its physical size. The Hartman B-382 is rated for 200A at 400 Hz and uses double break contacts for each phase. The HCPC technique allows the two series contacts to be connected in parallel and thus conduct 2 x 200A of current. The modification is shown in Figure 6. This modification or equivalent is necessary to meet the weight and volume requirements of the 400A production configuration.

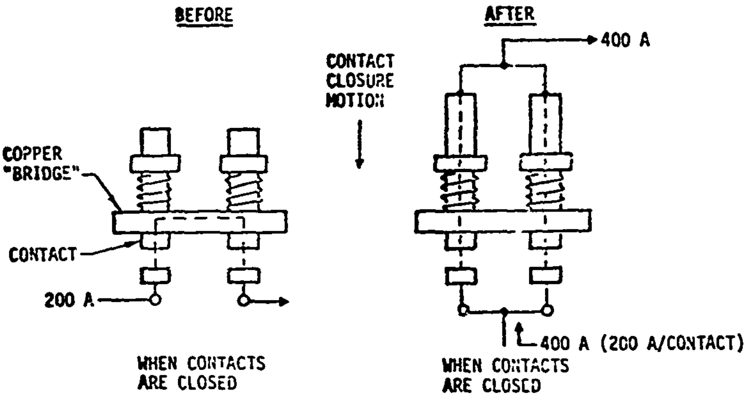


Figure 6 B-382 Contact Modification

This change assumes that the wiring to both sides of the two pairs of contacts (two parallel input lines and two parallel output lines) is sized to conduct 200A through each contact pair, or 400A total. This change also assumes that the weight of the additional wiring on the moving half of the contacts (flexible, suspended, welding cable could be used) will not seriously impair the opening or closing action or operating time of the contacts. Since the solid state switch applies power to the load in the first positive cycle (1.25 MS for 400 Hz), and waits for the relay to close, slowing down the parallel connected contacts slightly does not appear to be a serious drawback.

3.1.2.5 Switch Drive Electronics

The SCR Drive Circuit selected uses 50 kHz, transformer coupled power from the HCPC Power Supply and is controlled through optically coupled devices. The use of line for drive power as originally considered, consumed too much power. A drive circuit similar to the one used for B-1 solid state power controllers was developed and used on the 10 ampere breadboard configuations; however, the large number of parts required ruled out this approach.

The drive circuit was designed to accommodate a wide range of SCR requirements. By the selection of a resistor, drive current can be varied from 0 to 150 milliamperes. In addition, a JFET provides a low impedance resistance path from gate to cathode during the off state, to prevent dv/dt degradation due to SCR leakage.

3.1.2.6 Fail Safe Fuse

The fuse concept developed by Autonetics for its 2 ampere solid-state power controllers was used to generate the 10 ampere design required. In addition to the requirement to clear at above 10 amperes, the maximum fuse resistance was set at 10 milliohms to correspond to a fuse voltage drop of 0.1 volt, maximum. Since the 2 ampere fuse was two series elements with a total resistance of approximately 70 milliohms, the 10 ampere fuse was initially conceived as consisting of a number of parallel 2 ampere sections to reduce the resistance. Tests of seven 2 ampere, two-section fuses connected in parallel indicate that such a combinati lears in 10 seconds at 40 amperes. This clearing time is within the planned fu learing area. The next step was to combine the electrical properties of the seven elements into one composite element. This was accomplished and verified by test. Figure 7 illustrates the design concept.

3.1.2.7 Power Supply

The power supply is a multiple output flyback AC-to-DC converter operating at 50 kHz. Regulation is accomplished by pulse-width-modulated drive to a MOSFET switch that controls the rectified and filtered 400 Hz voltage. Pulse width modulation is based on voltage/current information received via a separate feedback winding that also supplies power to the switching regulator control IC. The multiple outputs provide isolated SCR drive and four levels of voltage (+ 28 Vdc, + 15 Vdc, -15 Vdc, and + 5 Vdc) for use by the control electronics.

The control IC and the drive electronics for the MOSFET power switches are initially bootstrapped into operation with the incoming line power until the feed back-winding-derived power approaches the regulation point. The bootstrap supply is then turned off and normal steady state operation begins. The power supply provides approximately 2.0 watts with 85 percent efficiency during steady state operation.

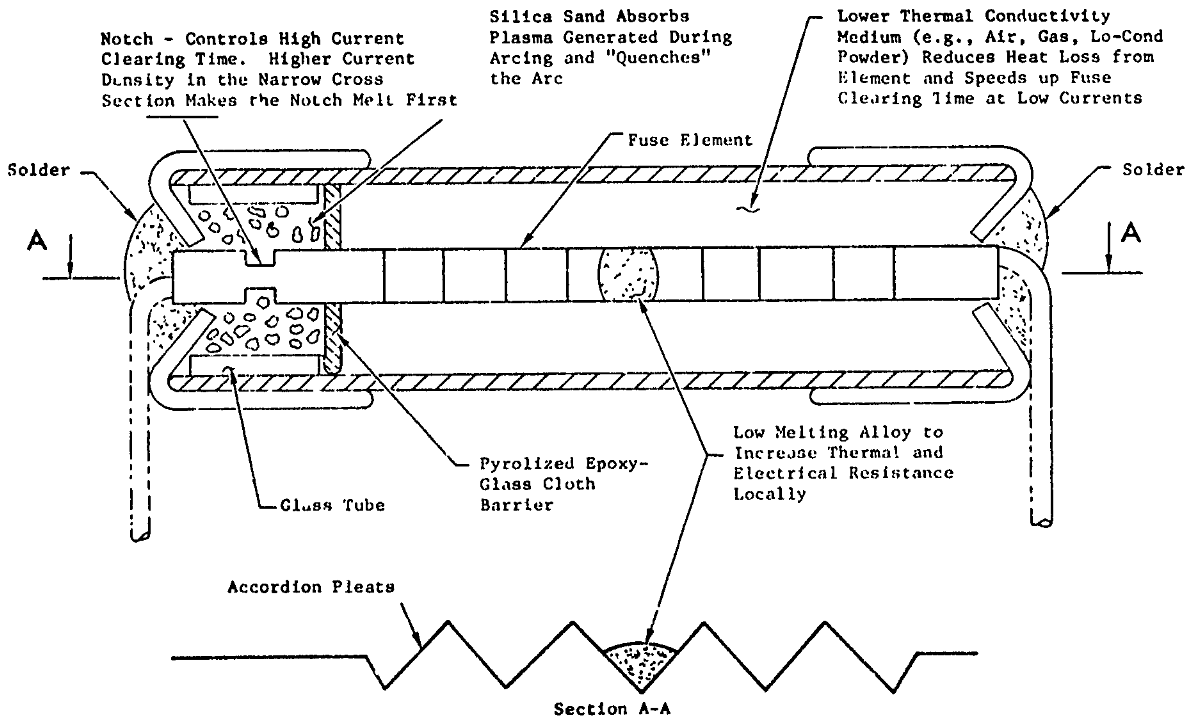


Figure 7 Fuse Design Concept

3.2 Packaging

The final package designs for the four types of HCPC configurations were the result of a lengthy progression of design interactions centering primarily on minimum volume and cost. Several of the primary design considerations included the following:

(1) Standard modules for the common electronics
(2) Standardized off-the-shelf drawn metal enclosures
(3) Standard module size for ease of repairability/maintainability
(4) Potting material for sealing and to provide rigidity

The final package configurations are expected to meet all the design criteria for minimum volume, lowest cost, vibrational and shock characteristics, electrical isolation, and efficient thermal dissipation. The steps taken to arrive at the final designs will be described in the following sections.

3.2.1 Packaging Detail

End item designs evolved through modification of Phase I packaging concepts, which proposed using three methods to assemble the HCPC components:

(1) Two-sided printed circuit board (PCB) modules mounted to the insides of the enclosure housings
(2) Subassemblies mounted to the base of the housings
(3) The sense resistors, fuses, and power input terminals mounted on the inside of the lids of the controller enclosures

However, these concepts were found to be volumetrically inefficient after electrical design and parts evaluations were finalized. Further packaging studies conducted subsequent to a first cut layout of the module projected to the most dense indicated a more efficient approach would be to: (1) standardize the size and contents of the PCB modules to the furthest degree, and (2) mount the components projected for the lid on the PCBs.

The need was established for the PCBs of three major types:

(1) An AC to DC power supply module including a power transformer and the zero voltage crossing detection circuits (See Figure 8)

(2) A microcomputer/ADC module containing the control and timing circuitry (See Figure 9)

(3) The SCR drive module that provided drive to one pair of solid state switches. One of these modules is required per phase (See Figure 10)

Careful consideration was given to PCB design aspects such as circuit current carrying requirements, line spacing for voltage isolation, the system grounding scheme, and minimum volume utilization. Once an optimization of the PCBs was completed, packaging them in a metal enclosure was addressed.

Original plans for the metal enclosure included a cast or brazed housing with machined metal lid and an RF gasket seal. However, this concept presented the following disadvantages:

(1) Large size; due to the need for additional internal board support, mounting flanges or module guides were required.

(2) Large wiring service loops required for final module integration

(3) Insulation requirements around terminals projecting through the metal cover

(4) Large costs associated with machining requirements

After evaluating possible alternatives, the decision was made to use a standard deep-drawn can, a metal screen for an RF shield, and thermally conductive potting material to hold the modules and screen in place and dissipate heat. The decision to use potting material eliminated the need for heavy metal heat sinks and/or module guides, increased electrical isolation within the enclosures, and enhanced vibrational and shock characteristics. Coupled with a standard drawn can approach, virtually all the costly machining for the metal lid and housing was eliminated.

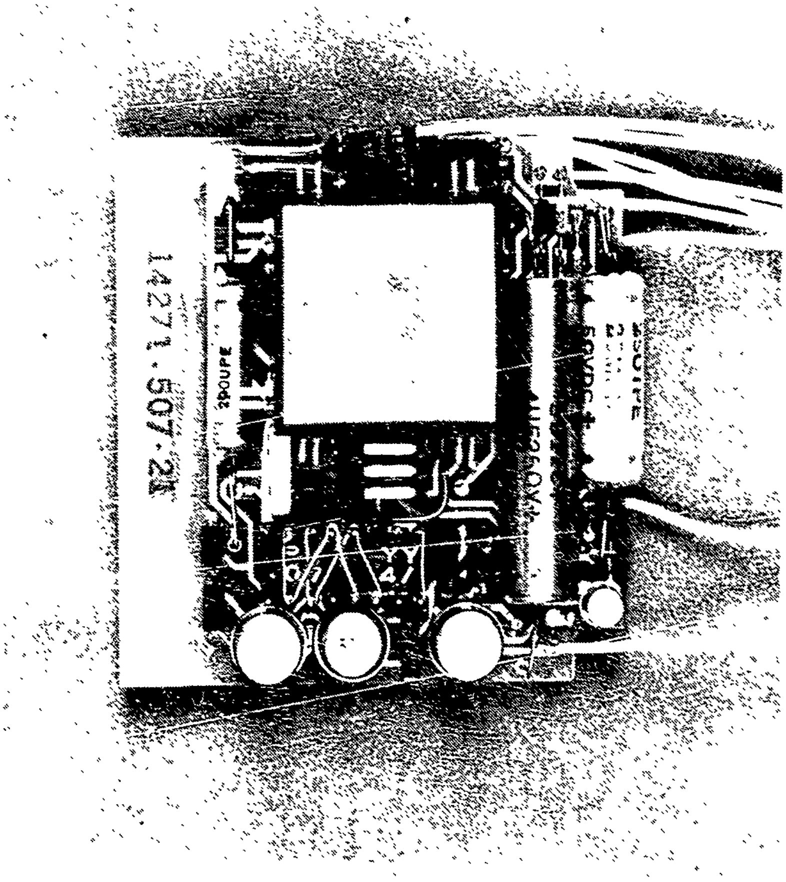


Figure 8. Power Supply Assembly

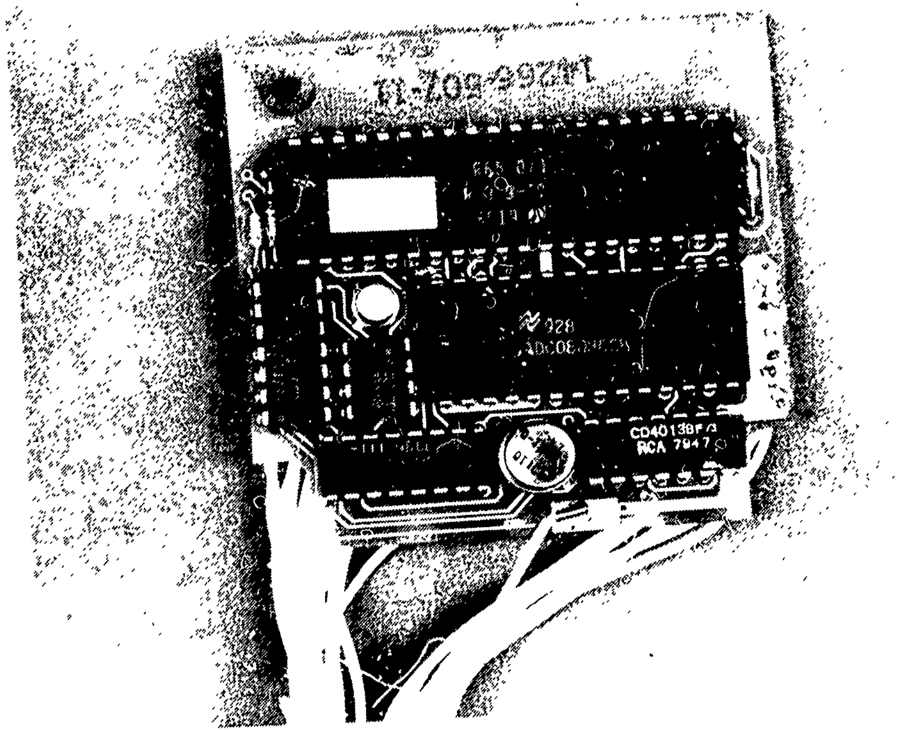


Figure 9. ADC/μC Assembly

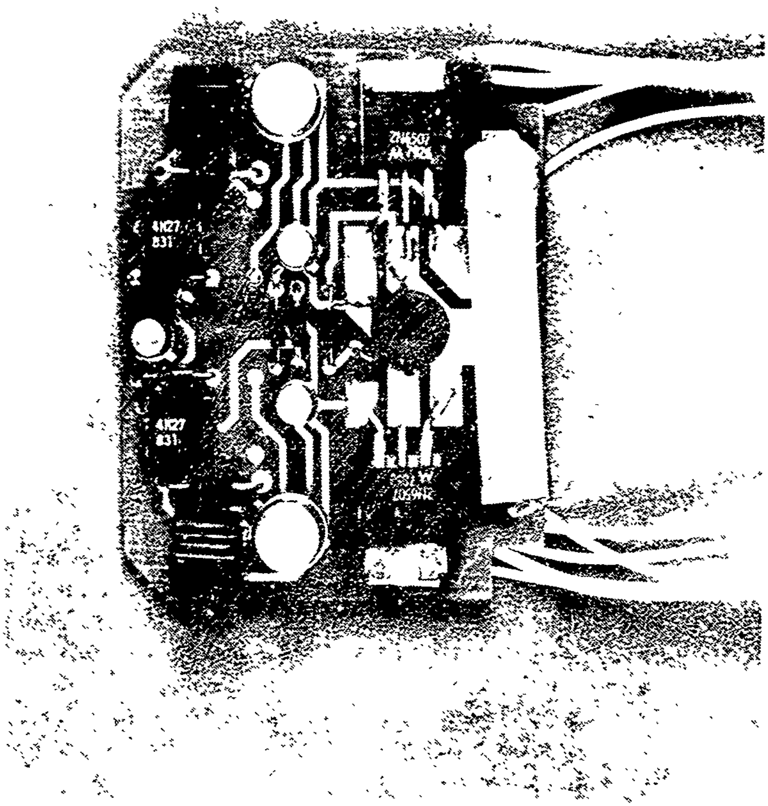


Figure 10. SCR Drive Assembly

Two different types of potting were planned for prototype and production use: a "soft" (RTV 511 Silicone) filler for the prototypes and a "hard" cap (Scotchcraft 281 epoxy) for production usage. Production controllers would not be filled with the soft material due to the large weight penalty, but just "capped" to provide the required environmental seal. The cap would consist of approximately one quarter to one half an inch of potting material at the top of the enclosure. Filling the prototypes with just the soft potting provided an ease of repairability. Figures 11 - 15 illustrate the packaging methods for the four configurations. Table 7 summarizes the final enclosure dimensions, volumes, and weights. Table 8 contains the breakdown of the various component weights.

Table 7

Summary of Enclosure Dimensions

CONFIG.	DIMENSIONS (INCHES)		VOLUME (CU INCHES)		WEIGHT (POUNDS)	
	SPEC	UNIT	SPEC	UNIT	SPEC	UNIT
10A 1Ø	2.3x2.5x2.6	2.31x2.5x2.63	14.95	15.17	1.2	1.06
10A 3Ø	2.3x2.6x4	2.31x2.75x4.5	23.92	28.61	1.9	1.927
50A 3Ø	2.3x4.4x6.4	2.3x4.4x6.4	64.77	64.77	4.3	4.59
400A 3Ø	4.5x4.6x10.5	4.5x4.6x10.5	217.35	217.35	15.7	15.69

The 50 ampere, three phase and 400 ampere, three phase controllers were packaged and delivered in brassboard configurations that were designed to be as close to production configurations as possible. All the PCBs are mounted to a metal base using L-shaped brackets, with the current sensing subassemblies and the relays directly mounted to the base. Layout of the various subassemblies, modules, and components was done with the same considerations given to production design, such as minimum wire service loops, terminal spacing requirements, etc. A cooling fan was added to each of the 400 ampere controller brassboards to compensate for the thermal dissipation capabilities lost from the production design by the absence of thermal potting material and metal enclosures.

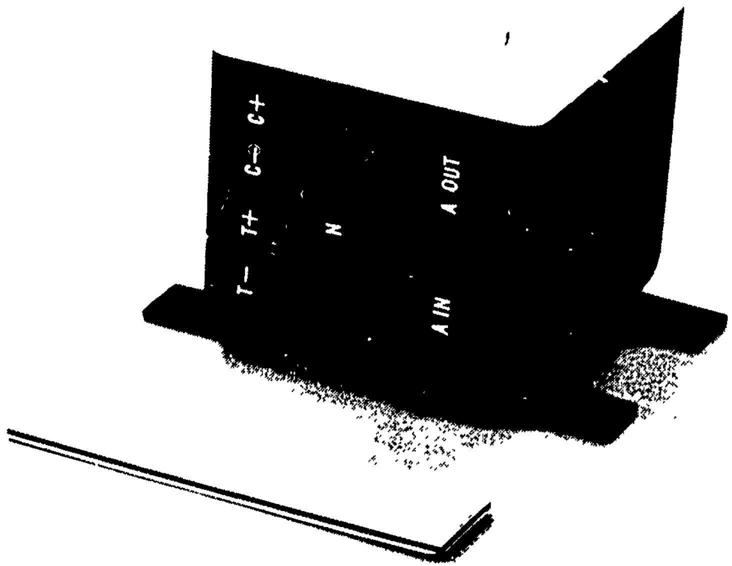


Figure 11. 10 AMP Single Phase Flightworthy Assembly

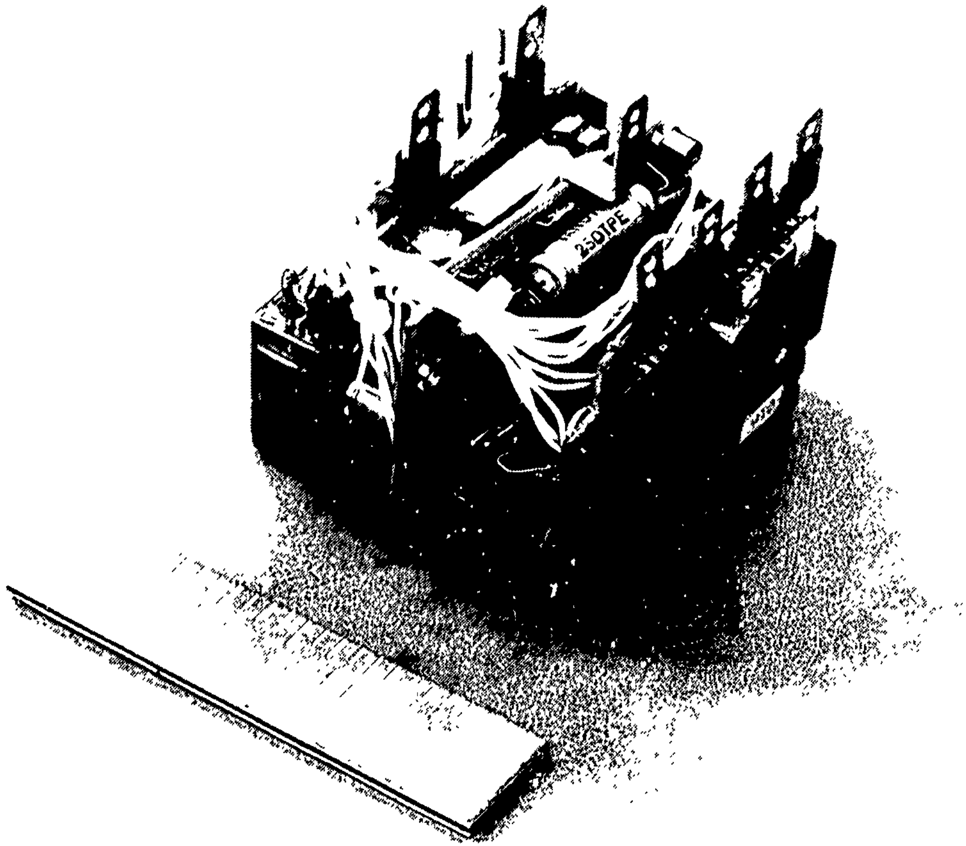


Figure 12. 10 Amp Single Phase Uncased Flightworthy Assembly

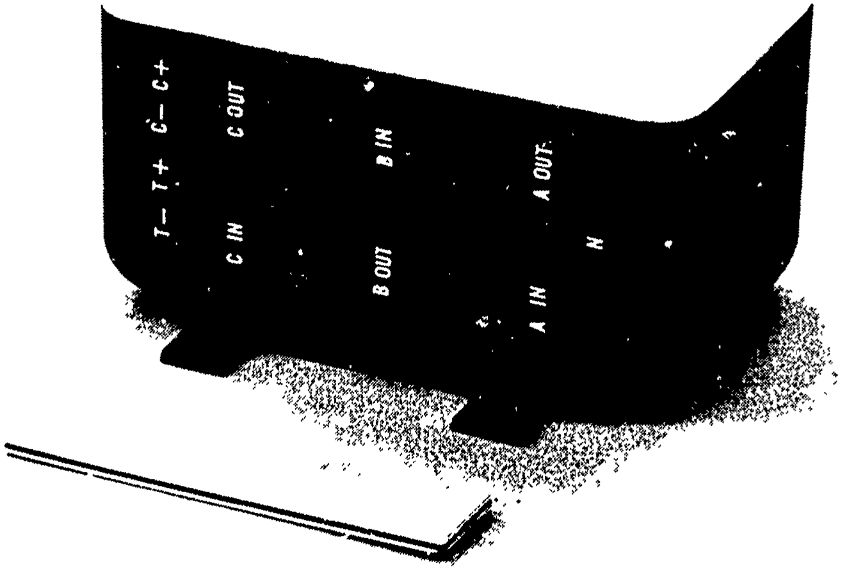


Figure 13. 10 AMP 3 Phase Flightworthy Assembly

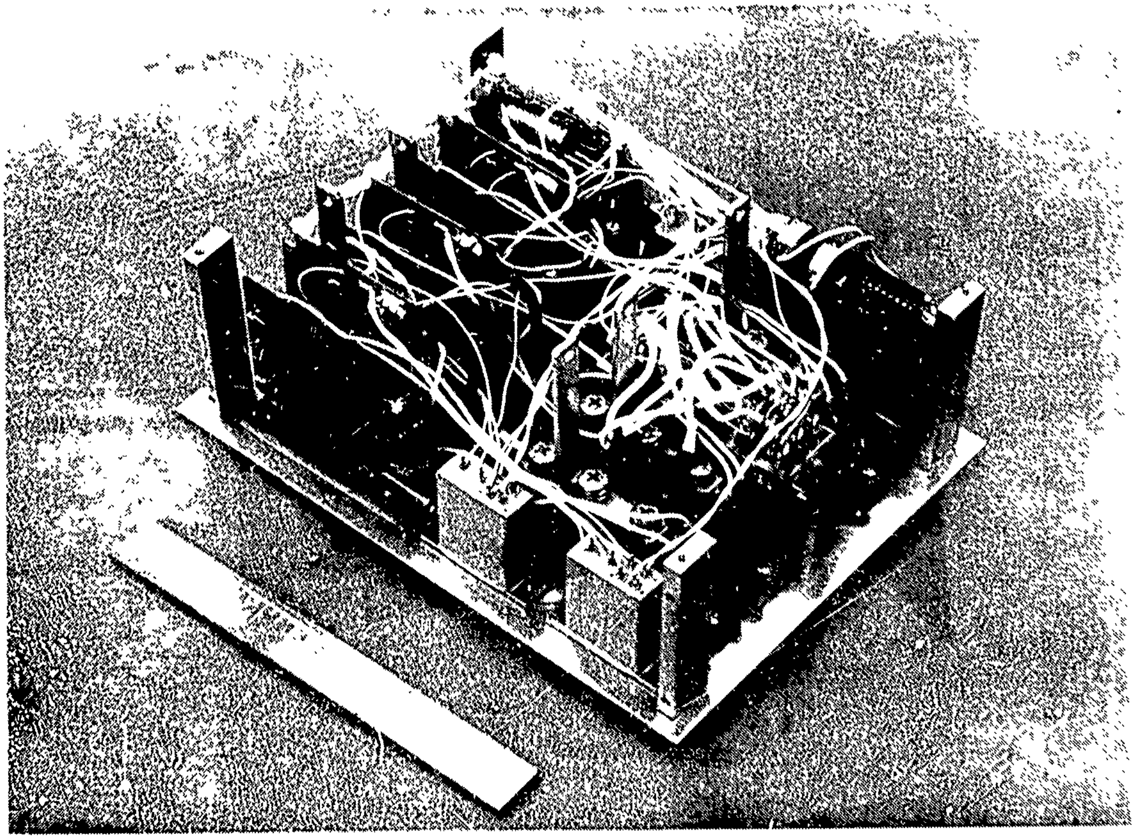


Figure 14. 50 AMP 3 Phase Brassboard Assembly

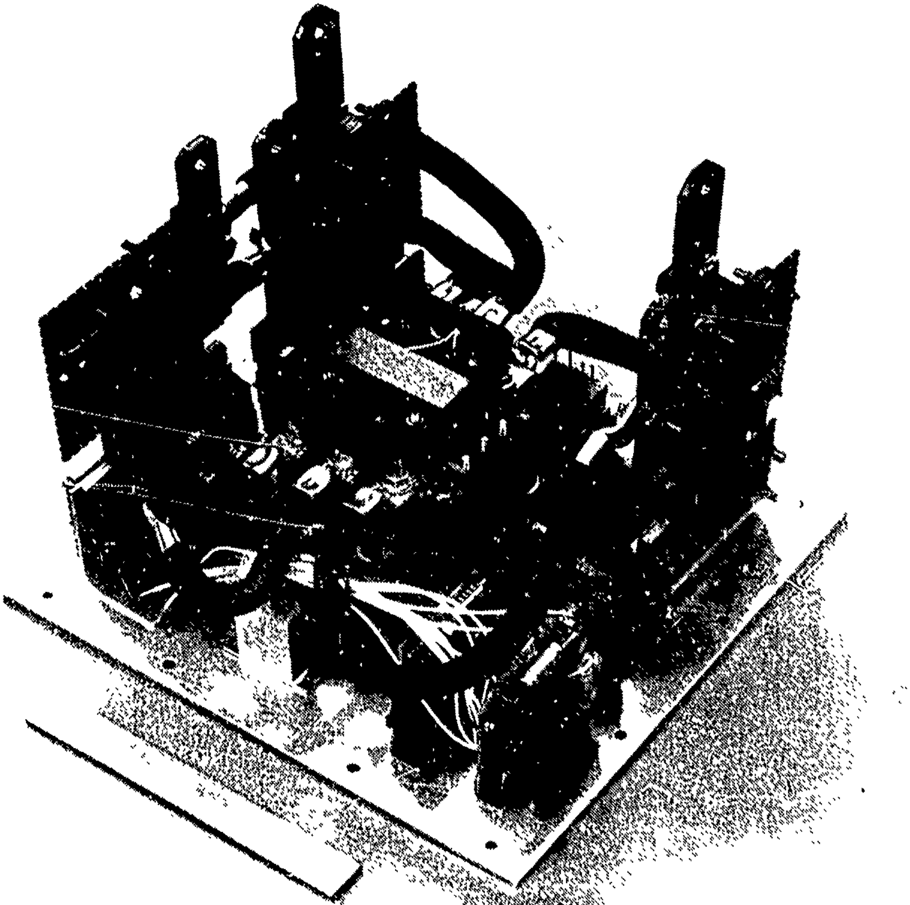


Figure 15. 400 AMP 3 Phase Brassborad Assembly

TABLE 8

WEIGHT BREAKDOWN

	1Ø - 10A	3Ø - 10A	3Ø - 50A	3Ø - 400A
Relay	*0.073	*0.146	0.292	3.0
Sensor	*0.06	*0.18	0.18	0.18
Terminals	on boards	on boards	0.226	0.913
SCR BD(s)	*0.065	*0.195	0.144	0.108
SCR	-	-	1.056	3.3
Wire	0.002(Est)	0.002(Est)	0.046	1.006
Sense Resistor	on board	on board	-	0.618
Power Supply	*0.180	*0.180	0.184	0.184
ADC/μp	*0.065	*0.065	0.07	0.07
Chassis	*0.145	*0.185	0.432	1.004
Mrg Screws	on chassis	on chassis	0.034	0.068
Potting	0.47	.973	1.928(Est)	5.24(Est)
TOTAL (Pounds)	1.06	1.927	4.59	15.69

*These weights were updated to reflect current actual weight of completed components. The 50/400 ampere weights were not updated, since completed components reflect the brassboard configurations, which are heavier than the above flightworthy configurations.

3.2.2 Assembly Problems

Difficulties in the actual assembly of the controllers, that are common to all configurations, were manifested most fully in the 10 ampere, three phase controllers, resulting in a change from the originally chosen can size.

The original can size for the three phase 10 ampere unit was selected based on component heights and volumes in the basic design. The can size selected was 2.32" x 2.65" x 4.00" and was calculated to be sufficient to accommodate the components, boards and wiring. However, following the fabrication and assembly of the modules and the assembly of the units, the total length of the unit exceeded the 4.00 inch dimension by approximately 0.2 inches. Closer examination revealed several contributing areas of dimensional build-up.

(1) The fuse end caps caused the height of the fuses above the boards to be .050 inches higher than planned

(2) The height of the transformer was .100 inches over the planned dimension

(3) The height of the capacitors was the maximum dimension rather than the planned nominal dimension

(4) The crystal configuration required two insulators for spacing as opposed to one, thereby increasing the overall height

(5) Due to wire routing over components, additional packaging space was taken

The larger can was also thicker gauge metal, resulting in more outside volume and more weight. The larger can required more potting, hence additional weight. Further refinement of individual component placement and design would result in optimization of can size.

As a final note regarding assembly, the capability for repairing a unit potted with the soft material was verified toward the final part of the program. Two units were returned from the potting area in a non-operating mode. The external metal housing was cut away and the soft potting material carefully picked apart in the suspected trouble area. A broken wire was repaired and a short removed.

The units were then repotted in new metal enclosures. Retest verified correct operation.

3.3 Test Results

Tests were conducted in accordance with the approved Test Plan (Appendix A) to verify the basic functional operation of each unit delivered. Two units of each type were tested for delivery.

3.3.1 Basic Functions

The following tests were chosen from the Test Plan as basic functions for a high current power controller:

(1) Turn On/Turn Off Times
(2) Trip Out Time
(3) Overload Trip Indication
(4) Output Voltage Drop
(5) Zero Voltage Turn On/Same Slope Turn Off
(6) Power Dissipation

A brief description of each test is included in the following sections, together with the test results. Generalized results are listed in Tab!c 9.

3.3.1.1 Turn On/Turn Off Times

3.3.1.1.1 Test Requirement

The turn-on response requirement was identical for each configuration and was 1ʳ milliseconds maximum. The turn-off response was required to be 20 milliseconds maximum for the 10 ampere and 50 ampere controllers, while the 400 ampere controller was allowed a maximum of 30 milliseconds. Turn-on time was measured from the application of the minimum turn-on control signal to the receipt of AC power to the load. Turn-off time was measured from the application of the maximum turn-off control signal to the removal of AC power to the load.

TABLE 9

SUMMARY OF TEST RESULTS*

TEST NAME	10A 1Ø		10A 3Ø **		50A 3Ø		400A 3Ø	
	S/N 001	S/N 002	S/N 001	S/N 002	S/N 001	S/N 002	S/N 001	S/N 002
TURN ON/OFF TIMES	PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS
TRIP OUT TIME	PASS	PASS	PASS	PASS	FAIL	PASS	PASS	PASS
TRIP INDICATION	PASS(1)	PASS	FAIL(2)	PASS	PASS	PASS	PASS	PASS
VOLTAGE DROP	PASS	PASS	PASS	PASS	PASS	PASS	FAIL	FAIL
ZERO VOLTAGE TURN ON	PASS	PASS	PASS	FAIL(3)	PASS	PASS	PASS	PASS
SAME SLOPE TURN OFF	PASS	PASS	PASS		PASS	PASS	PASS	PASS

* These are tests that were conducted on every unit. In addition Control/Reset Input Voltage and Current, Output Leakage Current and Removal Time to Reset were run on one 10A three phase unit. The unit passed each test.

** INTERMITTENT RELAY

(1) LEAKAGE IN OFF STATE = 140 μA

(2) SINKS 10 MA BUT WILL NOT WITHSTAND 30 VOLTS

(3) EXCEEDED REQUIREMENT BY 2 VOLTS

3.3.1.1.2 Test Results

The maximum turn-on time for any controller was recorded as 7.5 milliseconds. The following maximum turn-off times were observed:

10A 1Ø : 7 milliseconds

10A 3Ø and 50A 3Ø : 15 milliseconds

400A 3Ø : 25 milliseconds

3.3.1.2 Trip Out Time

3.3.1.2.1 Test Requirements and Results

Trip times for each configuration are required to stay within the boundaries of "trip curves" graphed on a log-log scale, based on families of I^2t lines. The trip time data for each controller was overlayed on the graphs (see Figures 16-22) to verify compliance with requirements. All the controllers met the requirements with the exception of S/N 001 of the 50 ampere configuration. The one controller would require a small modification to the ADC reference to correct the deficiency.

3.3.1.3 Overload Trip Indication

3.3.1.3.1 Test Requirements and Results

For all configurations, the state indication, when tripped, was required to sink 10 milliamperes (maximum) with a voltage drop of 1.5 volts dc (maximum). When in the "not tripped" state, the indication was required to have a maximum leakage of 50 microamperes while applying 30 volts dc.

No difficulty was encountered for the tripped state requirements, but one of the units would not withstand the 30 Vdc requirement, due to the wrong transient protector being placed in parallel with the indication. A 12 volt part was inserted instead of a 36 volt part. In addition, one of the units exceeded the allowed leakage by 90 microamperes. Both failures could be corrected without difficulty.

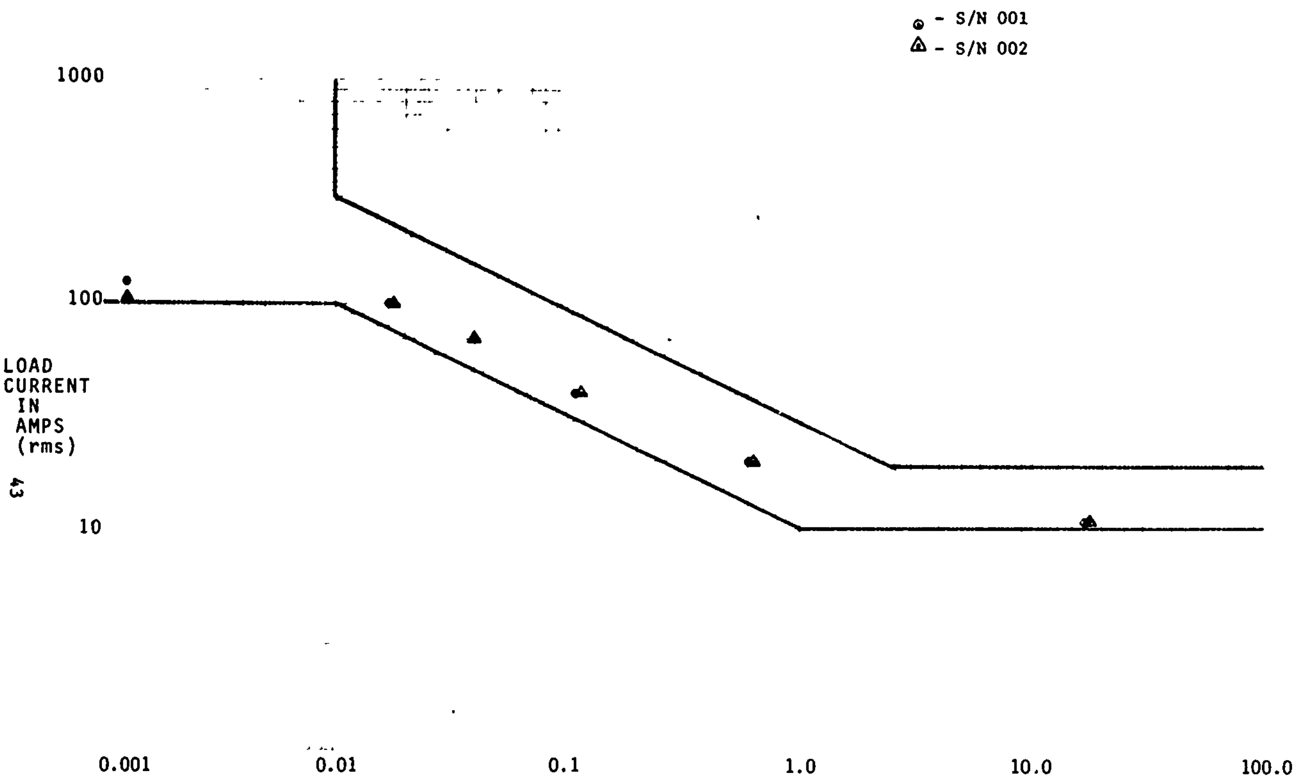


Figure 16. 1Ø TRIP CURVES

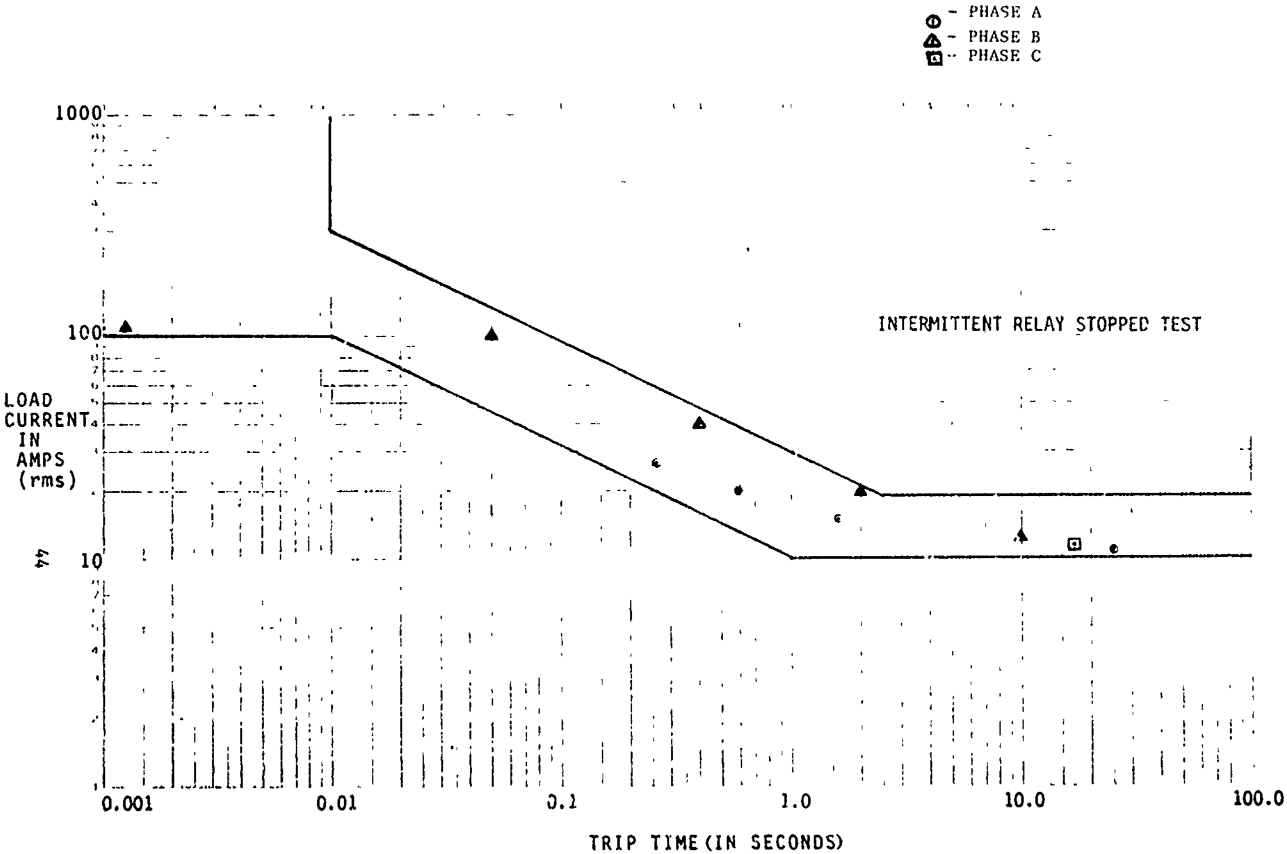


Figure 17. 10A 3Ø S/N 001 TRIP CURVES

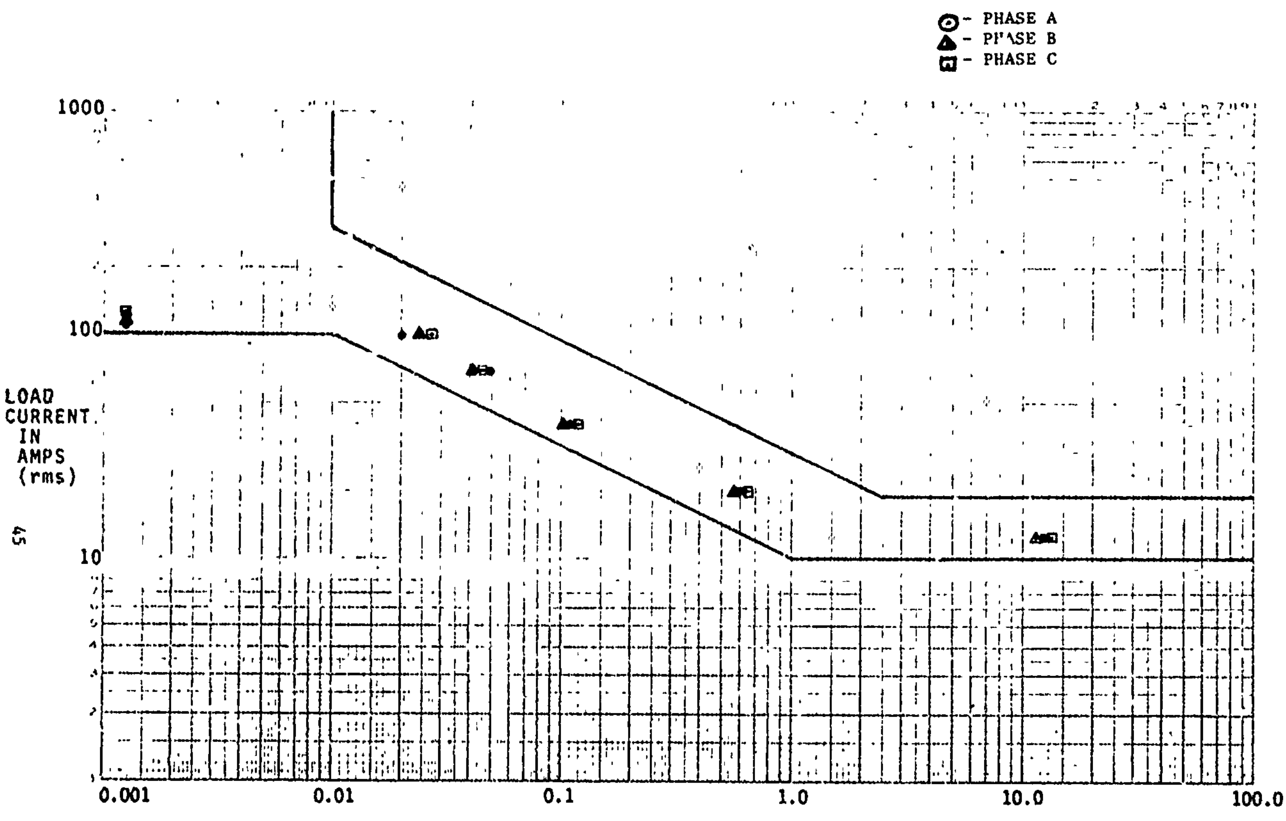


Figure 18. 10A 3Ø S/N 002 TRIP CURVES

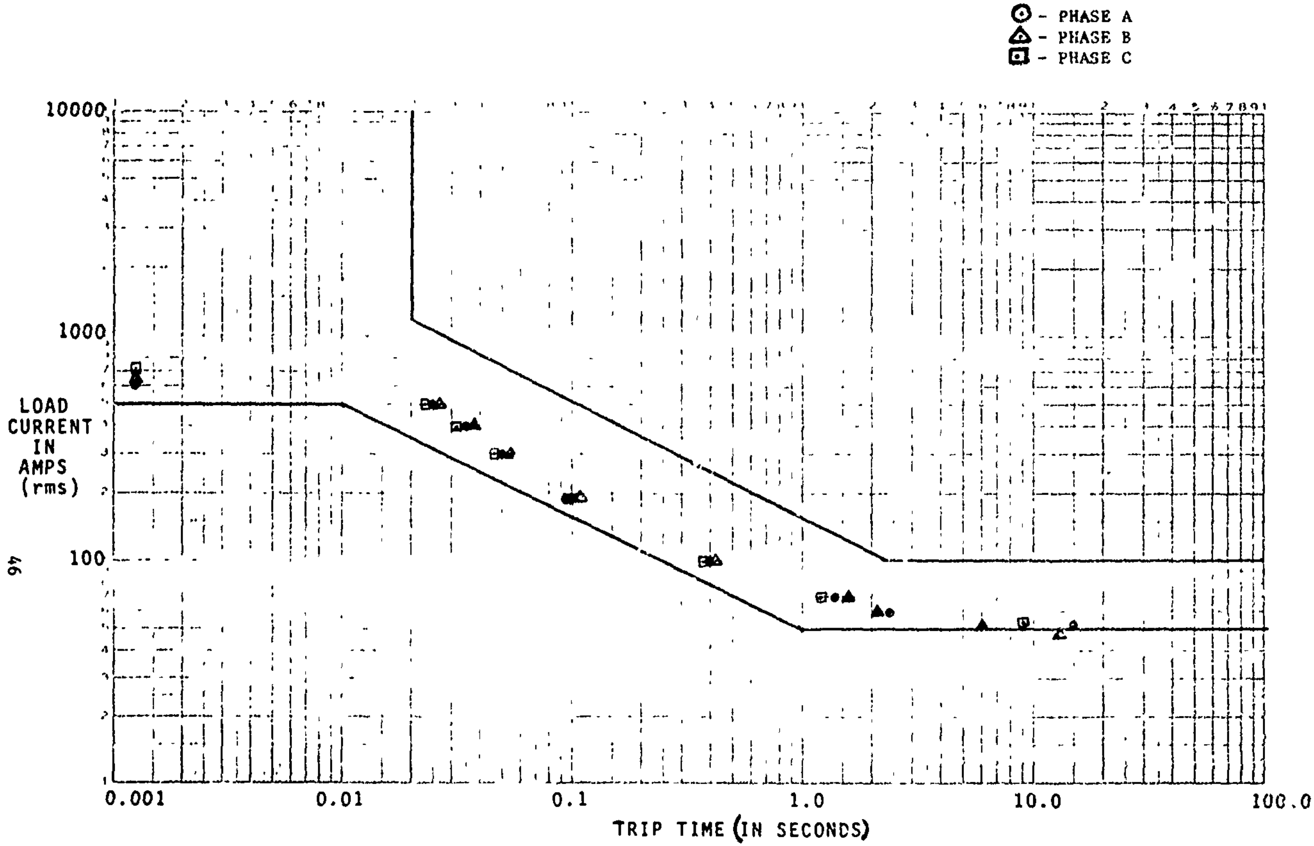


Figure 19. 50A 3Ø S/N 001 TRIP CURVES

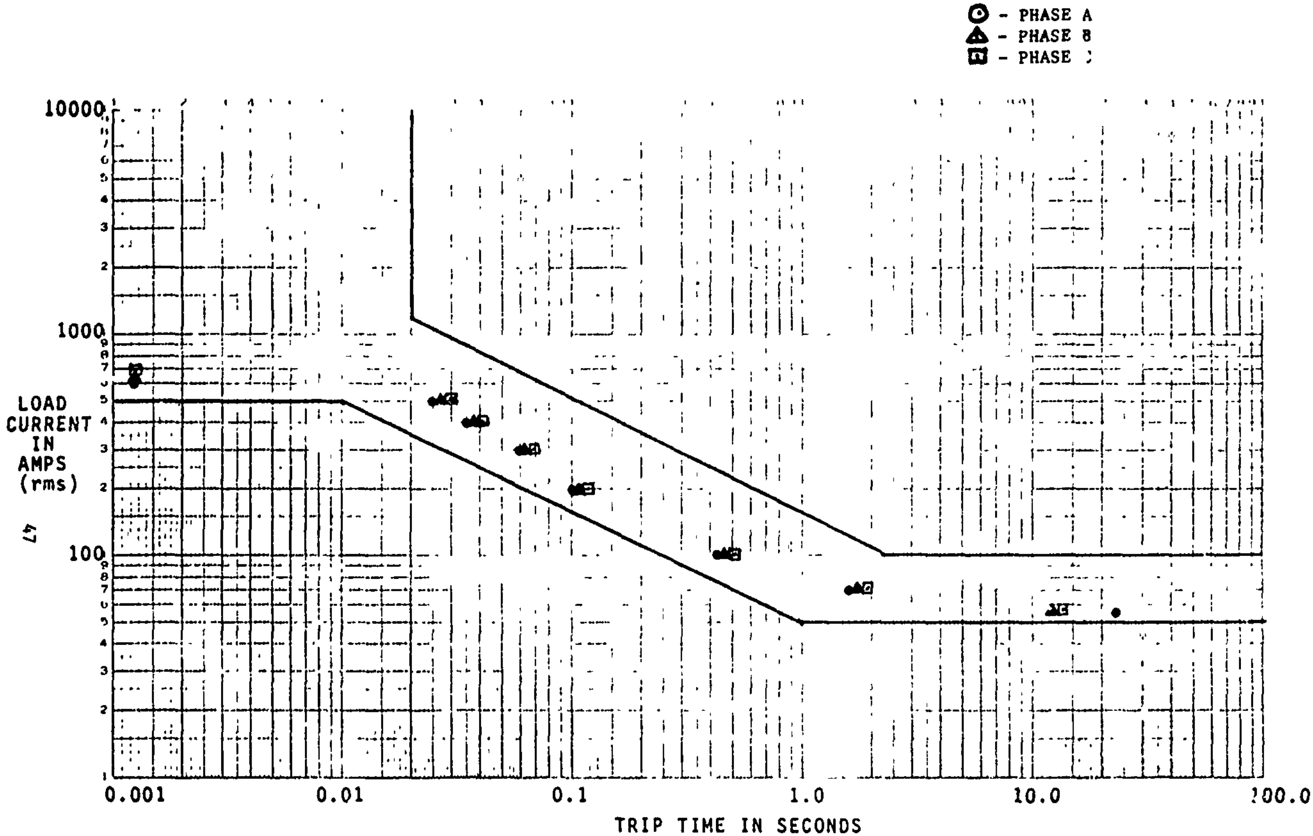


Figure 20. 50A 3Ø S/N 002 TRIP CURVES

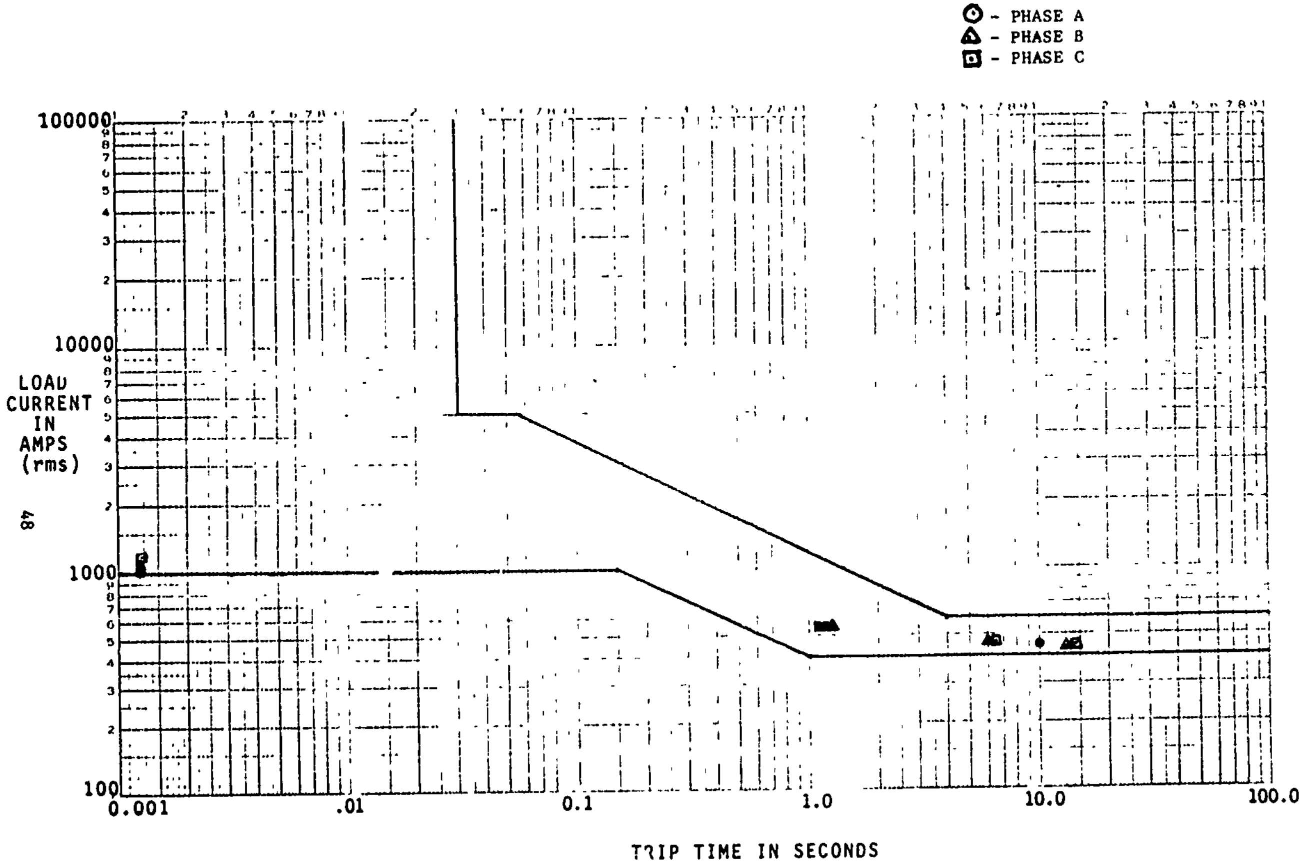


Figure 21. 400A 3Ø S/N 002 TRIP CURVES

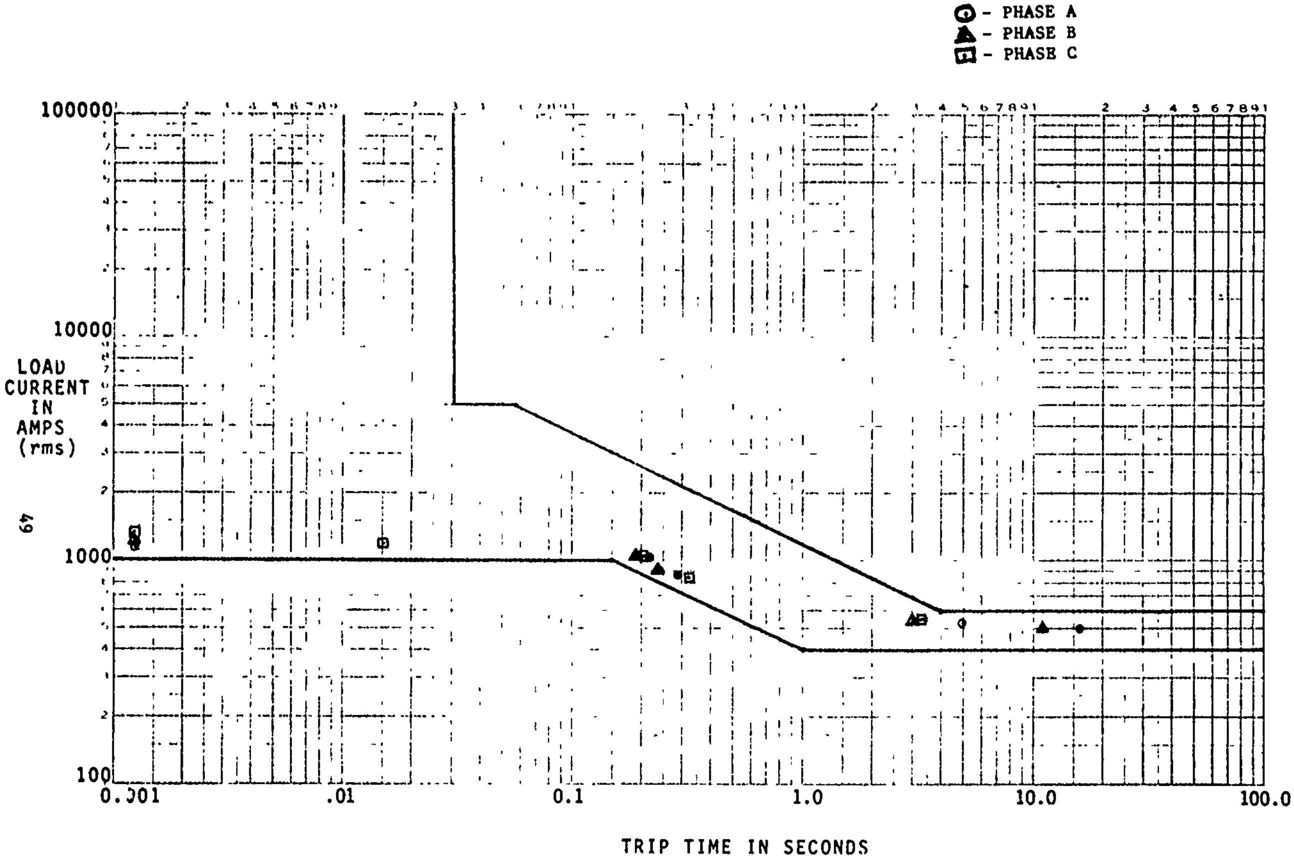


Figure 22. 400A 3Ø S/N 003 TRIP CURVES

3.3.1.4 Output Voltage Drop

3.3.1.4.1 Test Requirements

For all configurations, the HCPCs were required not to exceed 0.300 VRMS drop across the power-in to power-out terminals when carrying rated load. No difficulty was encountered, with the exception of the 400 ampere units. Test analysis showed the problem to be with terminal-to-cable interfaces and not with the relay or sense resistors.

Table 10

Voltage Drop (in volts) at 100 Percent Rated Load

		Ø A	Ø B	Ø C
10A 1Ø	S/N 001	0.259		
	S/N 002	0.252		
10A 3Ø	S/N 001	0.245	0.250	0.253
	S/N 002	0.222	0.217	0.220
50A 3Ø	S/N 001	0.280	0.230	0.228
	S/N 002	0.257	0.250	0.239
400A 3Ø	S/N 002	0.360	0.390	0.388
	S/N 003	0.360	0.372	0.390

The 400 ampere voltage drop could be reduced an average of 100 millivolts by soldering the terminal-to-cable connections in the main current conduction path.

3.3.1.5 Zero Voltage Turn On/Same Slope Turn Off

3.3.1.5.1 Test Requirements/Results

All configurations were required to complete turn-on (apply load voltage) at zero voltage crossover ± 10 volts. In addition, each controller was required to turn-on and turn-off at the same voltage slope. All units except S/N 002 of 10A, three phase configuration, passed without difficulty. S/N 002 turn-on occurred at ± 12 volts but met the same slope requirements.

3.3.1.6 Power Dissipation

3.3.1.6.1 Requirements and Results

Controllers were required to meet no load maximums as well as rated load maximums. Results are plotted with requirements in Figures 23-30, and are based on the analysis of power supply dissipation plus the voltage-drop-times-current dissipation experienced in each controller. With the exception of the 400 ampere three phase controller, all configurations met their requirements. The 400 ampere difficulty is caused by excess voltage drop, whose cause has been defined and isolated. See the voltage drop section, paragraph 3.3.1.

3.3.2 Test Conclusions

Test results verified that operation of the High Current Power Controllers was in accordance with the greater part of design goals. Each type controller performed satisfactorily in each area of testing with the exception of voltage drop in the 400 ampere units. All problems were identified as correctable with a minimum of further effort.

3.4 Reliability/Maintainability

The design inherent reliability of each of the High Current Power Controllers (HCPCs) has been predicted in accordance with the provisions of the reliability prediction handbook. The results of these predictions have been used to project the maintainability characteristics of the HCPC units. The maintainability and reliability potentials of the HCPSs were then compared to the operational reliability and maintainability characteristics of a conventional electromechanical power controller. As shown in the following paragraphs and tables the new design will provide improvements in both the reliability and the maintainability of the power controllers. Appendix B contains the predicated reliability calculations.

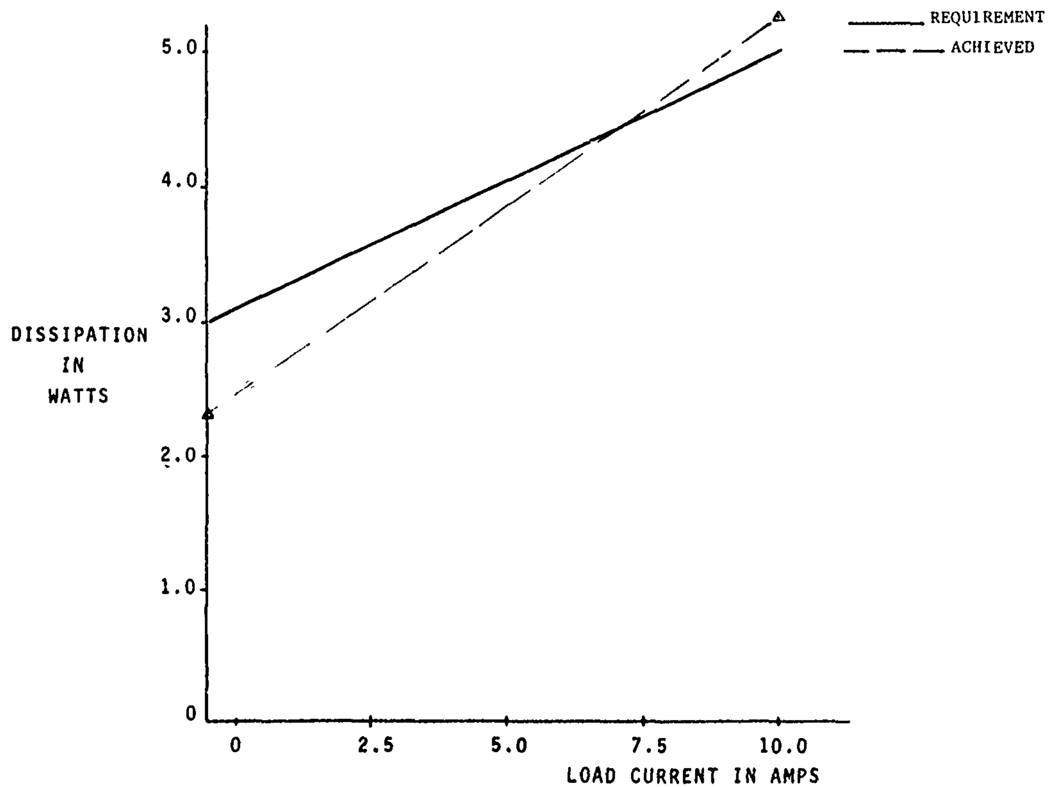


FIGURE 23 POWER DISSIPATION OF 10A 1Ø S/N 001

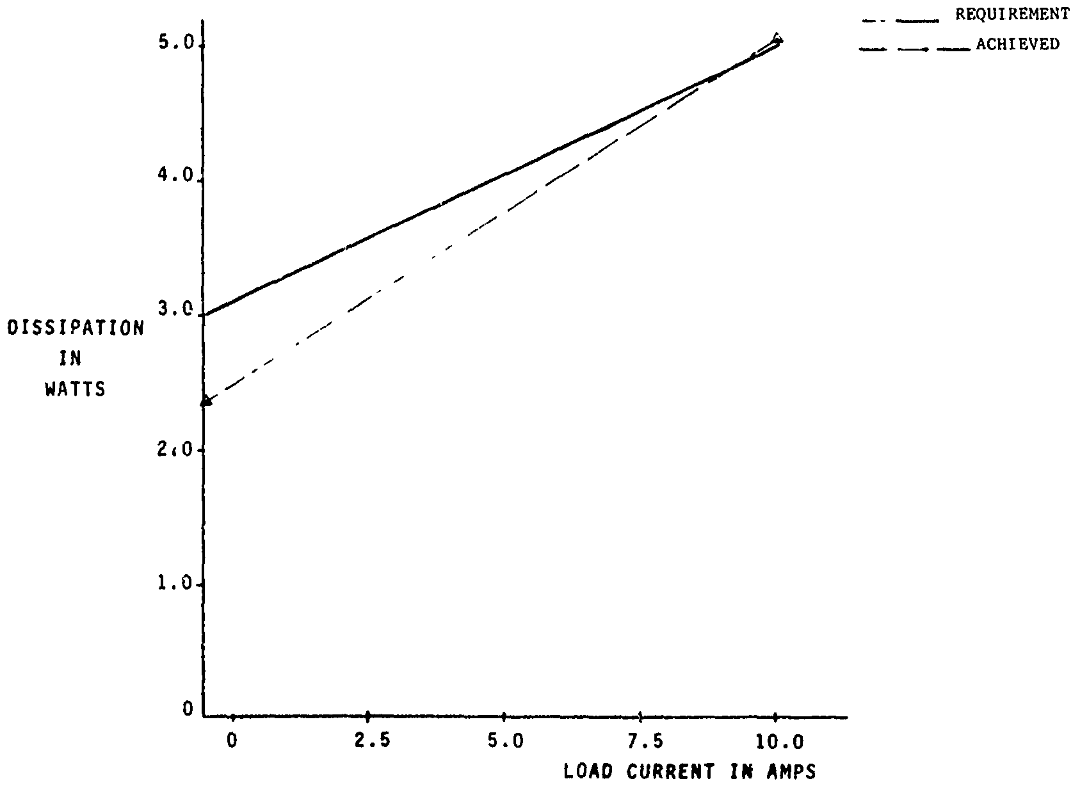


FIGURE 24 POWER DISSIPATION OF 10A 1Ø S/N 002

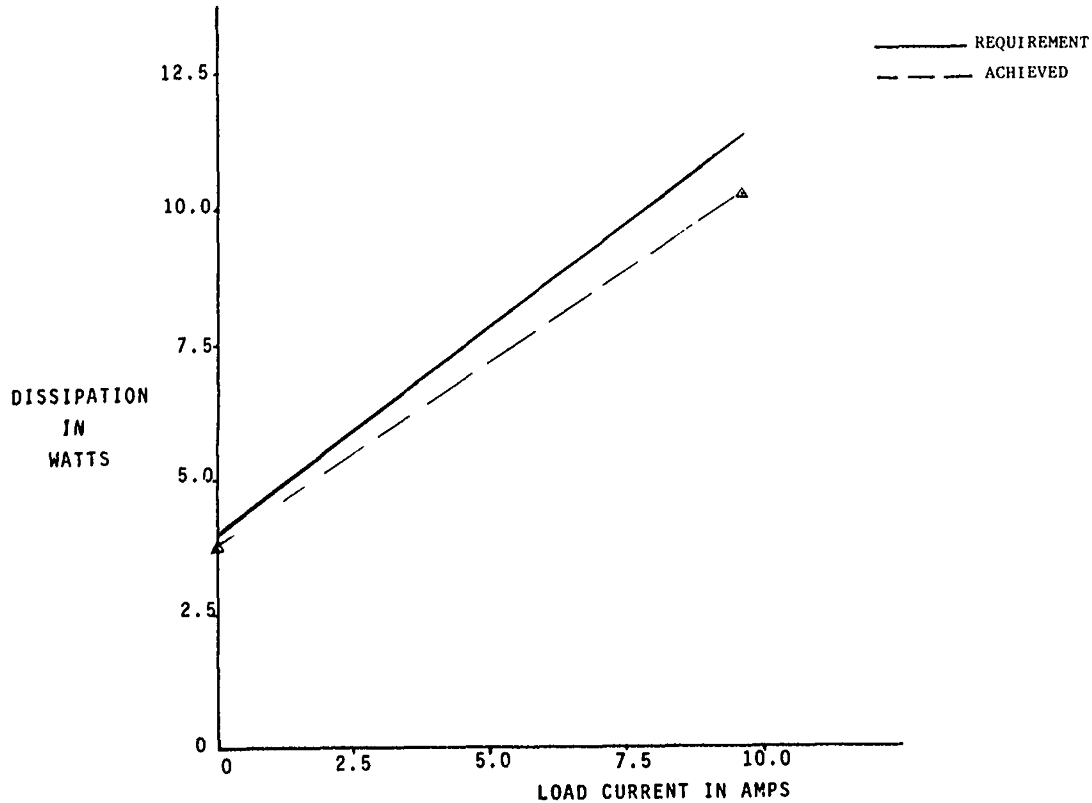


FIGURE 25 POWER DISSIPATION OF 10A 3Ø S/N 001

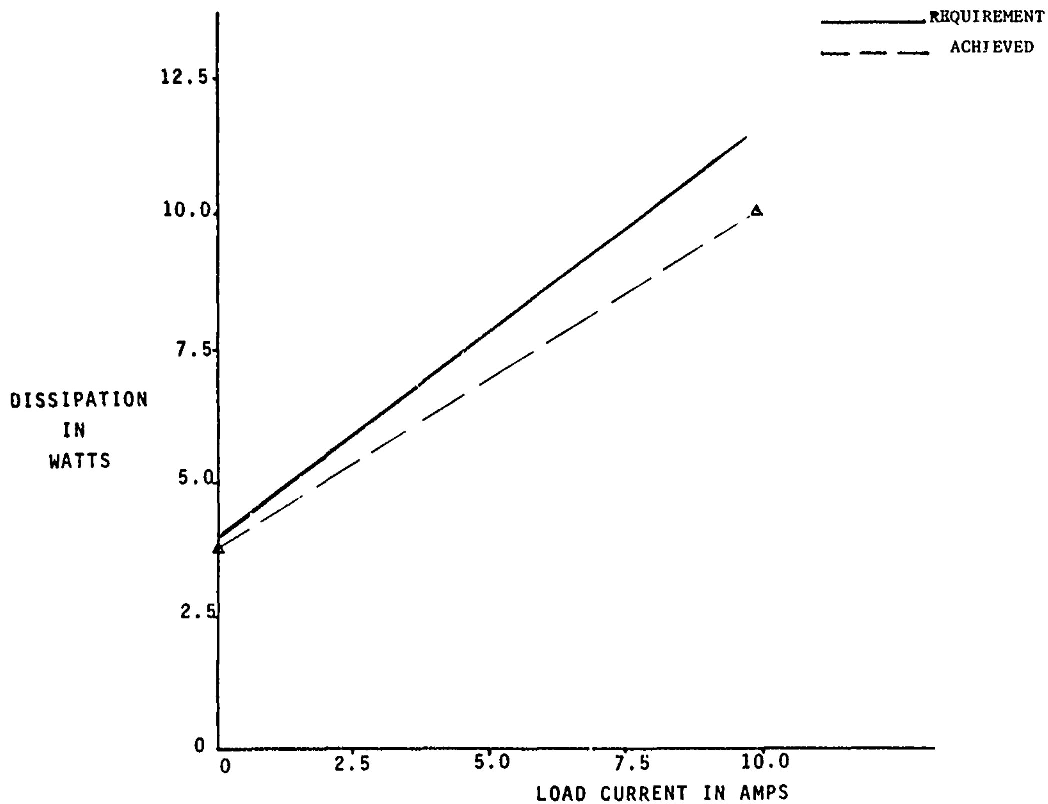


FIGURE 26 POWER DISSIPATION OF 10A 3Ø S/N 002

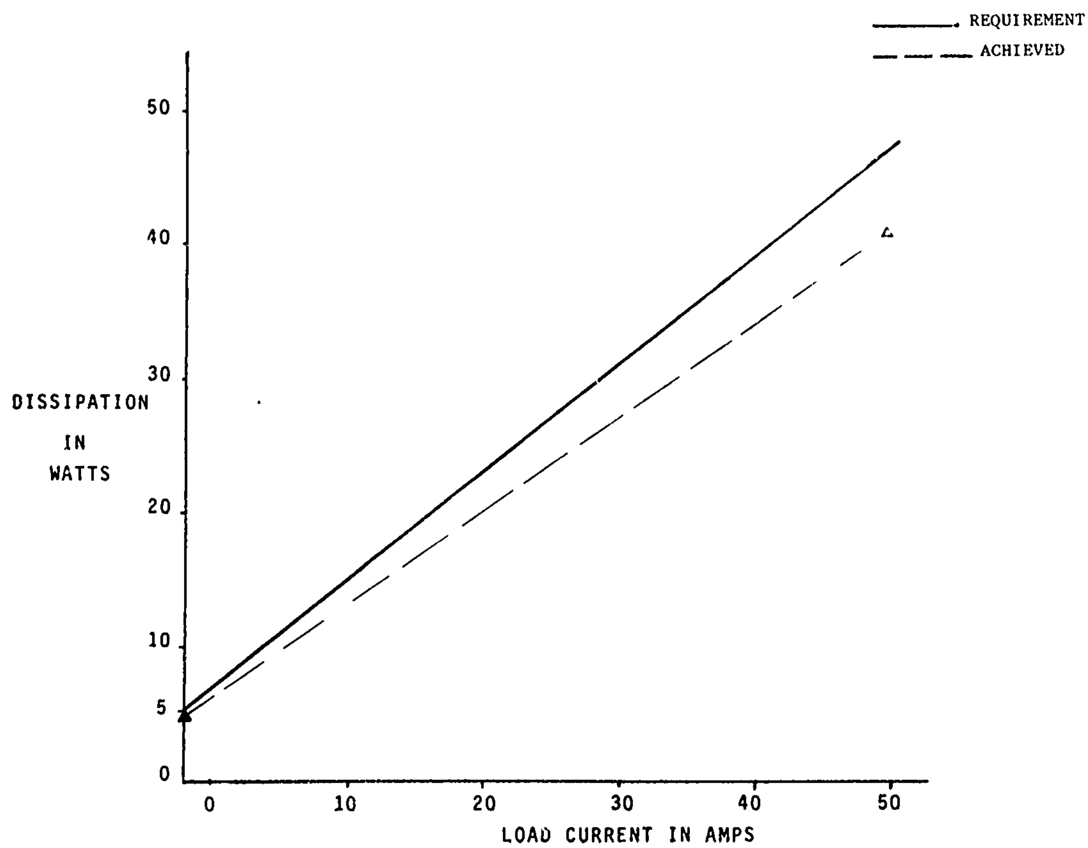


FIGURE 27 POWER DISSIPATION OF 50A 3Ø S/N 001

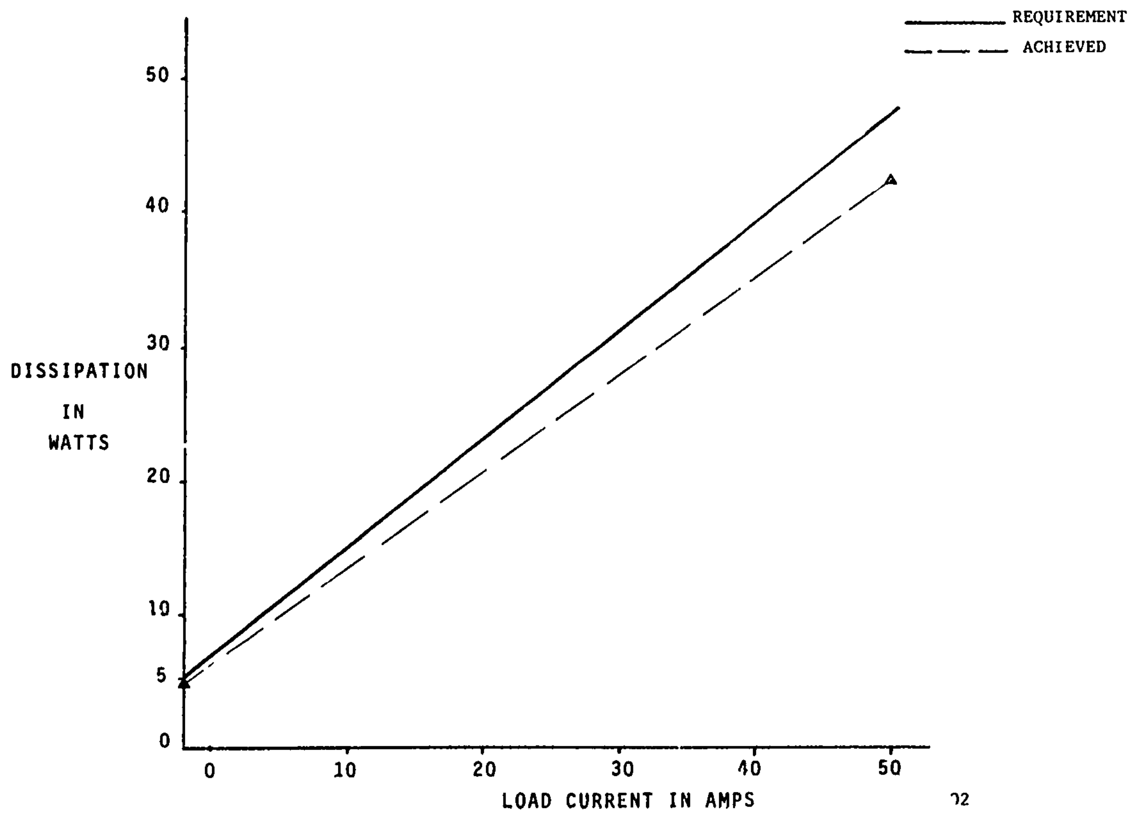


FIGURE 28 POWER DISSIPATION OF 50A 3Ø S/N 002

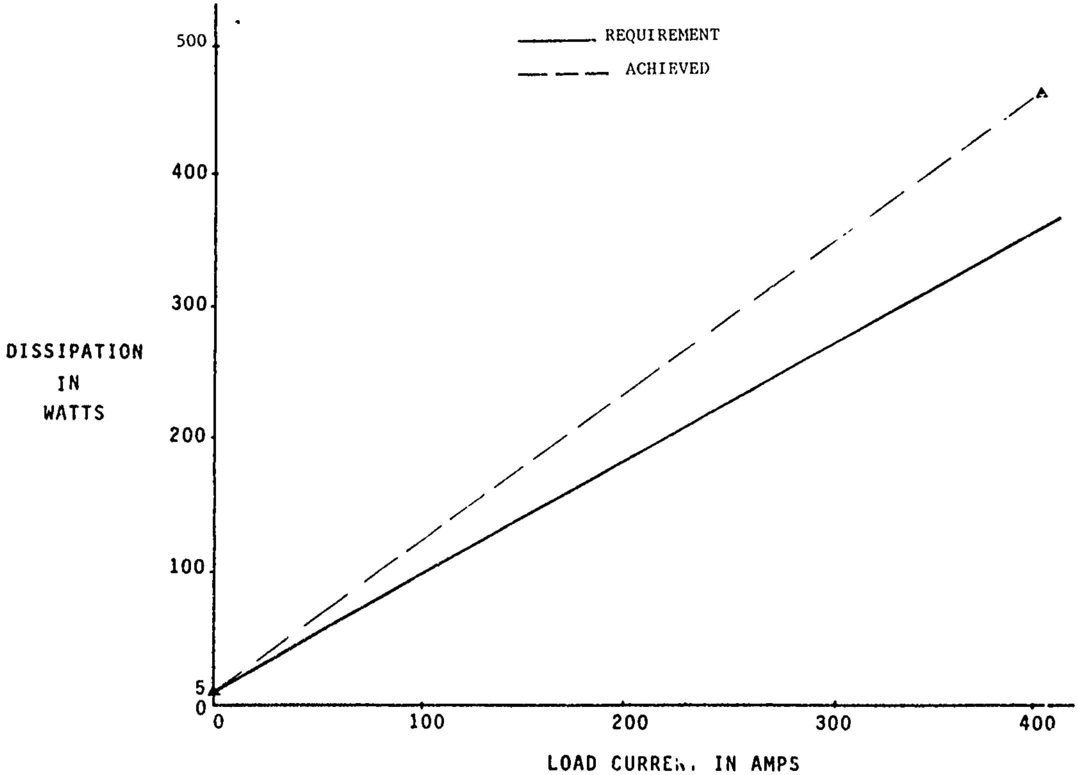


FIGURE 29 POWER DISSIPATION OF 400A 3Ø S/N 002

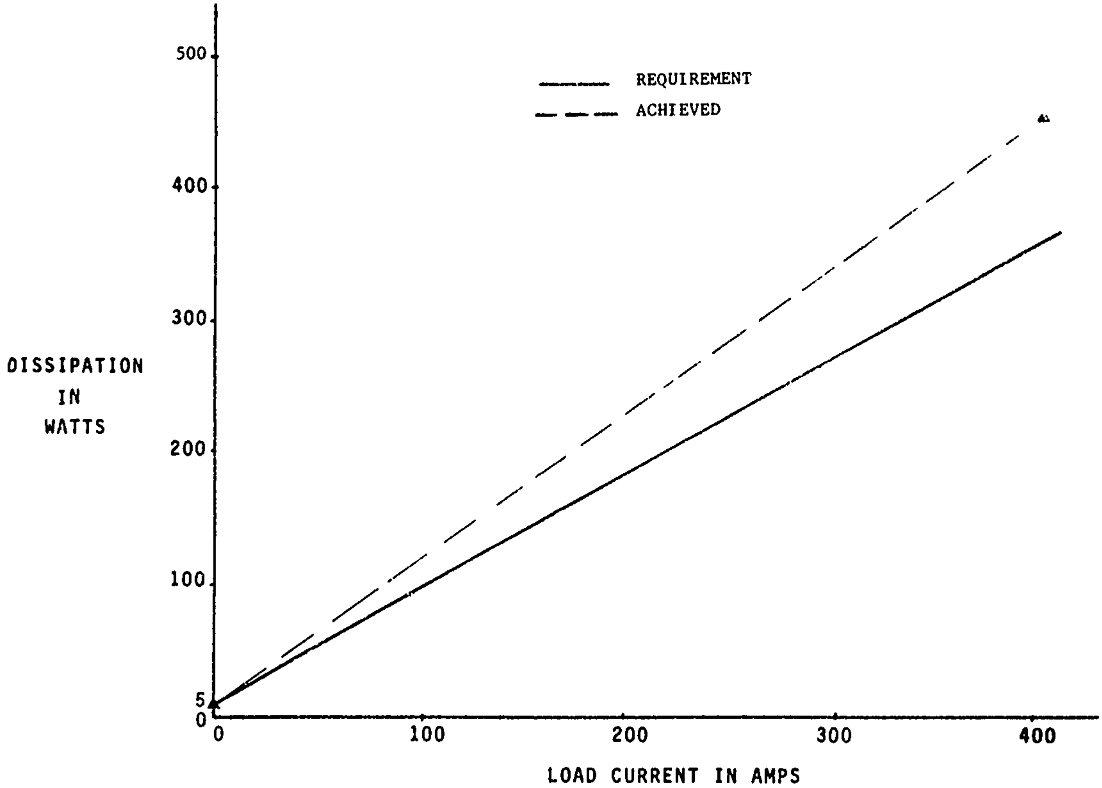


FIGURE 30 POWER DISSIPATION OF 400A 3Ø S/N 003

3.4.2 Reliability

The predicted Mean-Time-Between Failures (MTBF) for each of the four HCPC configurations are summarized in Table 11. Those values are the results of the predictions which were prepared per the provisions of MIL-HDBK-217C Notice 1, "Reliability Prediction of Electronic Equipment". The part failure rate models used for these predictions were taken from this reliability handbook. These part failure rate models include the effects of part electrical stress, thermal stress, operating environment, quality level and complexity through the appropriate factors. Since none of the HCPC contain redundancy in their design, the part failure rates were combined using the model for a series system (summation of individual part failure rates).

These predictions reflect the design inherent reliability of mature units which are comprised of high quality parts. For the predictions the following part quality levels were assumed: (1) all transistors and diodes are JANTX, (2) all capacitors and resistors are level R, (3) all integrated circuits are class B, and (4) all other parts are of an equivalent high quality level.

In lieu of more precise data, average part stress values have been used for both the electrical and thermal stress conditions. The average ambient operating temperature was estimated to be 50°C. The electrical stress ratios were estimated to be 0.6 for all parts used in normally active circuits and 0.1 for parts used in circuits which are normally off or in a standby mode.

3.4.3 Maintainability

A maintainability study of the HCPC controller was completed to afford a basic for determining realistic and meaningful maintainability requirements.

The preliminary corrective maintenance time prediction which reflects the new HCPC design, was derived using the procedures described in MIL-HDBK-472. The mean corrective maintenance time ($\bar{M}_c$) was calculated using the following formula:

TABLE 11

PREDICTED RELIABILITY

Component Type	10 Amp 1 Phase		10 Amp 3 Phase		50 Amp 3 Phase		400 Amp 3 Phase	
	QTY	λ Failures/10^6 HR	QTY	λ Failures/10^6 HR	QTY	λ Failures/10^6 HR	QTY	λ Failures/10^6 HR
Capacitor	38	0.61640	58	0.93098	58	0.93098	58	0.93098
Resistor	38	0.10331	52	0.12338	56	0.19133	71	0.28985
Diode	22	1.80288	25	1.90368	26	1.96416	26	1.98432
Transistor	12	2.23402	22	3.28926	22	3.28926	24	3.42966
SCR	2	0.80000	6	2.40000	9	4.20000	14	6.24000
IC	12	0.75878	12	0.75878	12	0.75878	12	0.75878
Relay	1	0.00703	1	0.02814	2	0.05628	1	0.05979
Sensor	1	1.08476	3	3.25428	3	3.25428	3	3.25428
Miscellaneous	11	1.09358	21	1.46322	22	1.56322	24	1.85858
TOTAL	137	8.50076	200	14.15167	210	16.20829	234	18.80624
MTBF	117,637 HR		70,663 HR		61,697 HR		53,174	

$$\overline{M}_c = \frac{\Sigma(\lambda M_c)}{\lambda} \qquad (1)$$

Where:

λ = average part failure rates in failures per 10^{-6} hours

M_c = corrective maintenance time in hours

The predicted corrective maintenance times for each of the HCPC's, LRU's and SRUs, have been summarized in the following table.

TABLE 12

Predicted Mean Corrective Maintenance Time Summary

LRU	$\overline{M}_c$
10 AMP 1 PHASE	52 Min
10 AMP 3 PHASE	52 Min
50 AMP 3 PHASE	53 Min
400 AMP 3 PHASE	54 Min
SRU	**$\overline{M}_c$**
POWER SUPPLY	56 Min
MICRO PROCESSOR	58 Min
SCR ELECTRONICS	56 Min

3.4.4 Qualitative Comparison

A qualitative comparison was made between the HCPC and a conventional electro-mechanical power controller. The conventional design uses a circuit breaker, a relay and a relay driver. This conventional design, though less complex (fewer parts) will be less reliable and will require more maintenance then the new HCPC. The improvement in reliability has been achieved primarily by eliminating the circuit breaker and reducing the electrical stress on the relay. Both of these actions eliminate or minimize possible mechanical wearout modes.

The prototype design incorporates several unique maintainability design features. They include the use of "standard modules", used throughout the different LRU configurations. All configurations use the same Power Supply, Microprocessor and SCR module. Also all equipment required is packaged in one LRU configurations. They require no adjustment at the LRU level. The Power Controllers require no schedule maintenance or on aircraft adjustments.

Table 13 summarizes pertinent characteristics of the HCPC and electro-mechanical units for comparison.

TABLE 13
Qualitative Characteristics Comparison

Function/Item	Current Design	New Design	Comparison Comments
Circuit Breaker Function			
1) Configuration	Mechanical	Electronic	
2) Design Environment	Inhabited only	Inhabited or uninhabited	New design allows for remotely located Power Controller
3) Failure Modes (Electro-Mechanical)	a) Contact Bounce b) Arcing when switched under load. c) Particle Contamination due to contact action d) Limited life due to wearout	DNA	a) Improved reliability b) Improved maintainability c) Improved availability d) Lower cost due to repair
Relay/Relay Driver			
1) Design Environment	Same	Same	
2) Part Quality Level	Same	Same	
3) Package/Mounting	Same	Same	
4) Material Cost	Same	Same	
5) Failure Modes	Switched under load-arc damage to contacts.	No load switching No arcing	Improves: a) Reliability b) Maintainability c) Cost of repair d) Availability

TABLE 13

Qualitative Characteristics Comparison (contd)

Function/Item	Current Design	New Design	Comparison Comments
General Design			
Module Design	DNA	3 Modules	1) Plug-In Modules 2) Interchangeable between plug-in slots 3) Standard modules for multiple configuration application.
Standard Modules	DNA	Modules	1) Fewer part types to control 2) Reduces overall mfg. cost ● Material ● Fab ● Test 3) Reduces overall repair cost ● Customer COO 4) Some advantages to packaging design
Packaging	3-LRUs	1-LRU	1) Fewer interface connections with user hardware 2) Decreases weight, cost, value 3) Requires less overall setup and test time 4) Improves maintenance and repair time ● Plug-in module design reduces failure evaluation and test time ● Lends itself to higher reliability applications 5) Fewer items tc spare-trade-off between cost of sparing for 3 vs 1 item even though the unit cost of 1 item may exceed that of the 3 items.
Adjustments	Unknown	None	
Scheduled Maintenance	None	None	
Non Scheduled Maintenance	Baseline	Much Improved	

3.4.5 Quantitative Comparison

For further comparison purposes the operational reliability of the conventional electromechanical controller has been established by assuming that the units will meet the reliability requirements of the B-1 specifications. Table 14 lists the predicted reliabilities and corrective maintenance times of the various units.

TABLE 14

Predicted Reliability & Maintainability

		NEW HCPC DESIGN			
		10 Amp 1 Phase	10 Amp 3 Phase	50 Amp 3 Phase	400 Amp 3 Phase
MTBF	NEW DESIGN	117,637 Hr.	70, 663 Hr.	61,697 Hr.	63,174 Hr.
	EXISTING DESIGN	38,110 Hr.	38,110 Hr.	38,110 Hr.	38,110 Hr.

3.5 Safety

A hazard analysis was conducted on the High Current Power Controllers, as high voltages/currents are handled as a matter of course. Terminal layout, relative to voltage isolation between phases and leakage current were of primary concern. All precautions in the design were taken to minimize hazard to personnel.

During normal operation, HCPCs pose no hazard, but under certain operating conditions potential hazards do exist. They are:

(1) During any activity where power is applied to the HCPC and touching, probing or otherwise making contact with the controller is planned

(2) With power applied to the controller and no load attached to the power-out terminal, or with system wiring attached but no load connected, a potential shock hazard exists should an out-of-specification HCPC be employed. Care should be exercised not to make contact with either the power out terminal or the unloaded end of the system wiring.

The hazard analysis results are shown in Table 15.

TABLE 15

HAZARD ANALYSIS

	AREA CONSIDERED		COMMENTS
(a)	Isolation of Energy Sources	(1)	Interface terminal separation 0.5 inch minumum. Metal can electrically isolated from all non-insulated elements within can by a minimum of 30 mils of potting. The potting has a volume resistivity larger than 10^{14} ohm-cm.
(b)	Fuels and Propellants		None
(c)	System Environmental Constraints		None except those specified in the procurement specification, i.e., the case (can) temperature (operating) shall be -40° to 75°, acceleration is 20g, mechanical shock is 50g for 11 milliseconds.
(d)	Explosive Device		None
(e)	Compatibility of Materials	(1)	Compatible materials used.
		(2)	Potting of assemblies protects against corrosion.
(f)	Effects of Radiation	(1)	Electromagnetic radiation from unit prevented by metal case and metal screen.
		(2)	Effect of nuclear radiation on unit not a requirement.
(g)	Pressure Devices		None
(h)	Crash Safety		Unit will not cause a problem.
(i)	Safe Operation and Maintenance of System	(1)	Possible excess leakage current diverted to power neutral.
		(2)	Interface terminals can be insulated after connections are made.
		(3)	Metal case can be connected to system ground.
		(4)	Unit can be disassembled to a moderate degree for maintenance.

TABLE 15

HAZARD ANALYSIS (continued)

AREA CONSIDERED	COMMENTS
(j) Training	Deferred to production phase.
(k) Egress, rescue, etc.	Not applicable.
(l) Life Support Requirements	Not applicable.
(m) Fire Ignition and Propagation	Unit will not ignite or propagate a fire; potting eliminates source of oxygen.
(n) Resistance to Shock Damage	Excellent - unit potted.
(o) Environmental Factors	Not applicable.
(p) Fail Safe Design Considerations	10 ampere units contain a fail safe fuse, fuse not required on 50 and 400 ampere units.
(q) Safety from a Vulnerability and Survivability Standpoint	Excellent; unit is compact, potted in a metal case-contains no exposed elements that will readily break.
(r) Protective Clothing, Equipment or Devices	None required.
(s) Lightning and Electrostatic Protection	Metal case can be grounded to vehicle structure.
(t) Human Error Analysis	Not applicable.

3.6 Design to Cost

Consideration was given to a specific design-to-cost effort in each phase of the HCPC program. All decisions relative to HCPC design, especially in the packaging area, contained basic design-to-cost criteria.

The key elements providing the lowest possible costs consistent with reliable power controllers are:

(1) Standardized electronics, including the microcomputer concept that allowed sufficient flexibility for use in four configurations
(2) Standard module size for maintainability/repairability
(3) Maximum use of two sided PCB's to mount and interconnect the electronic parts
(4) Minimum number of sub-assembly types, including PCBs
(5) The decision to pot all the hardware in the enclosures was partly based on anticipated lower costs; this eliminated the need for most of the loose hardware and the assembly steps that would have been required to fasten the sub-assemblies in various areas of the enclosures.
(6) The costs associated with fabricating the interconnections and assembling the SCRs into back-to-back switches for the 50A and 400A configurations (the method originally proposed) were eliminated by replacing this design approach with purchased pre-assembled SCR pairs
(7) The enclosures are "drawn" off-the-shelf cans or modifications of the same, replacing the more expensive cast or brazed housings selected for the preliminary designs

Decisions relative to short versus long term production and production volumes are critical in a development program. Tooling costs, mask charges, assembly techniques, etc. can be absorbed with a minimum impact on a larger production program. Should a production follow-on be initiated, further studies would need to be conducted concerning elements such as hybrid versus discrete mechanization and wire harness versus mother board/connector approaches.

SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

The HCPC development program has added a new, desirable candidate configuration to the area of high voltage, high current power controllers. HCPCs provide all the electronic benefits of solid state power control without the disadvantages of high power dissipation/voltage drop and DC offset voltage associated with solid state switch elements. HCPC advantages over the electromechanical configurations include reduced EMI, full cycle control, i.e. load voltage slope control during turn-on and turn-off, and increased reliability. The program also:

(1) Provided operating prototypes of flightworthy versions of the 10 ampere, one phase and 10 ampere, three phase controllers and brassboard models of the 50 ampere, three phase and 400 ampere three phase controllers
(2) Provided a method for the virtual elimination of potential shock hazard, during a no load condition, to maintanence personnel
(3) Verified the concept of microcomputer flexibility for power controllers

The HCPC development effort also indicated the desirability, from a cost and functional operation viewpoint of further modifying the augmented circuit configurations. The system design changes recommended are:

(1) Replace the relatively expensive magnetic current sensor (1 per phase) with CMOS microcomputers (1 per phase); the costs of 3 CMOS μCs and 3 ADCs is expected to be significantly lower than the cost of the 3 magnetic current sensors replaced.
(2) Recent breadboard test indicated that SCR gate drive current could be obtained through field effort transistor switches from the power bus. Such a change would significantly reduce the current required from the HCPC power supply.
(3) The use of the inherently low power CMOS μCs (they were not available during Phase I and II of the HCPC program) plus deriving SCR gate power directly from the power bus, would allow a significant reduction in the size and complexity of the HCPC power supply module.

Recommendations concerning detailed design changes include:

(1) Problems were encountered with reducing the noise coupled to the input of the ZVC circuit. It is recommended that future HCPC configurations move this circuit from the Power Supply module to the Microcomputer module.

(2) The power transformer should be redesigned to include an electrostatic shield between the primary and secondary windings. This change would not be necessary if the HCPCs convert to the simplified power supplies previously mentioned.

(3) Several moderate problems are foreseen with repairing the hard potted units (the production packaging) indicating that the approach should be modified to replace the epoxy potting used as the housing lid with an inherently hard material such as epoxy glass board. This would allow a reusable lid, a reduction in weight, and enhance the ease of repairability of the controllers.

APPENDIX A

HIGH CURRENT POWER CONTROLLER (HCPC) RESEARCH & DEVELOPMENT TEST PLAN CONTRACT F33615-78-C2202

1. SCOPE

1.1 Introduction

This document defines the Compliance Test requirements for High Current Power Controllers (HCPC's).

This document is prepared to satisfy the requirements of Contract Data Requirement List (CDRL) Sequence 008, "Research and Development Test Plan".

1.2 HCPC Description

The HCPC is primarily planned for use to control 115 volt, 400 Hz AC power within an aircraft. Four types of HCPC's are herein to be tested; (1) a 10 ampere, 1 phase, (2) a 10 ampere, 3 phase, (3) a 50 ampere, 3 phase, and (4) a 400 ampere, 3 phase controller.

1.3 Administrative Data

1.3.1 Purpose of Test

The tests listed in this document shall be performed to satisfy the requirements for a functional test of the deliverable HCPC's specified by the AFAPL F33615-78-C-2202 Procurement Specification.

1.3.2 Manufacturer Test Item Description

10A	1 φ	Flightworthy HCPC	: 14255-507-1
10A	3 φ	Flightworthy HCPC	: 14256-507-1
50A	3 φ	Flightworthy HCPC	: 14257-507-1
400A	3 φ	Flightworthy HCPC	: 14258-507-1
50A	3 φ	Breadboard HCPC	: 14259-507-1
400A	3 φ	Breadboard HCPC	: 14260-507-1

1.3.3 Items To Be Tested

All items delivered shall be tested as indicated in this specification.

1.3.4 Security Classification

Unclassified

1.3.5 Test Location

Rockwell International, ASSD, Anaheim, California, Buildings 231, 251, and 252.

1.3.6 Disposition of Test Specimen

To be delivered to AFAPL as specified in Section J, Paragraph Xi of contract.

2.0 APPLICABLE DOCUMENTS, MATERIAL AND EQUIPMENT

2.1 Documents Required By This Specification

The following documents, to the extent indicated, form a part of this specification. In the event of any conflict between the requirements of this specification and the listed documents, the requirements of this specification shall govern.

2.1.1 Specifications

Drawings, Specification or Exhibits

Autonetics:	C79-463.1/201 HCPC Research and Development Test Plan
AFAPL	F33615-78-C-2202 HCPC Development Specification

2.2 Documents Calling Out This Specification

In the event of any conflict between the requirements of this specification and documents calling out this specification, the requirements of the document calling out this specification shall take precedence.

2.3 Equipment and Material

2.3.1 Equipment and material used shall be selected to achieve the purpose of this process specification.

2.3.2 External components specified in this document may be replaced by components with equivalent electrical characteristics.

2.3.3 Test equipment such as switches, meters, loads and power supplies shown in Figure 1 are used to indicate the stimuli and responses required to conduct a particular functional test. Other test equipment and/or test sequences that provides the same stimuli and responses and that performs an equivalent functional test may be used.

3 REQUIREMENTS

3.1 General Requirements

3.1.1 Safety Precautions

3.1.1.1 Electric potentials in excess of 200 volts and currents exceeding 400 amperes may exist in the HCPC or on the test equipment connected to the HCPC. Extreme caution should be observed in touching, probing or otherwise making contact within the HCPC or the test equipment.

3.1.1.2 The HCPC shall not be connected to or removed from energized equipment.

3.1.2 Environmental Conditions

3.1.2.1 Operations required by this process shall be performed at ambient temperature of 25 (+15, -5)°C, a barometric pressure of 30 ± 2 inches of mercury, and a relative humidity up to 90 percent.

3.1.2.2 Cooling air, at a temperature of 25, +15, -5 C and a relative humidity of less than 90% shall be supplied to the HCPC at a flow rate equal to or greater than 50 CFM.

3.1.3 Record of Data

3.1.3.1 Test data required by this specification may be recorded on any suitable form.

3.1.3.2 Paragraphs preceded by (R) require recording data.

3.1.4 Preliminary Examination

3.1.4.1 Before testing, the unit shall be checked to see that it has passed assembly inspection.

3.1.5 Measurements

3.1.5.1 When determining the acceptability of a test value, the specification limits shall be considered absolute, regardless of the number of decimal places, and are to be used as if they were continued with zeros.

3.1.5.2 Absolute values are specified herein. The calibrated tolerances of the measuring equipment must be subtracted from the absolute limits.

3.1.5.3 Unless otherwise specified, meter tolerances shall, at no time, be greater than 5 percent of the voltage and current specified. This does not apply to waveform measurements.

3.1.6 Test Personnel

3.1.6.1 Personnel performing the requirements of this specification shall have a working knowledge of the type of equipment used to test the HCPC.

3.1.7 Equipment Calibration

3.1.7.1 Personnel performing the requirements of this specification must confirm that the test equipment used to test the HCPC is calibrated and sealed.

3.1.8 HCPC Power, Signal, and Load Requirements

To demonstrate the electrical performance of the HCPC, the following power levels and loads shall be used.

3.1.8.1 Power Requirements

Symbol	(Volts)	(Hz)	Maximum Current Requirement
ο* AC IN	(80 - 150) VRMS +	3φ 400 ± 22	4000 A
CONTROL	0.0 - 8.0**	DC	10 mA
TRIP	30.0, + 0 - 0.3	DC	10 mA (current limited)

+ Voltage is nominally 115 RMS, but is variable throughout range specified.

* Terms are A through C.

**Voltage is variable throughout range specified.

3.1.8.2 Signal Requirements

3.1.8.2.1 Trip Indication

3.1.8.2.1.1 The HCPC Trip Output signal shall be at non-tripped condition during normal operation and at the tripped condition following on electrical overload as follows:

Term	State	Vt	It
TRIP	Non-Tripped	30, +0 - 0.3 Vdc	<0.05 mA
TRIP	Tripped	≤ 1.5 Vdc	10 ± 0.1 mA

3.1.8.2.2 Control Input Signal

3.1.8.2.2.1 The HCPC AC output is commanded by the Control Input signal. The Control Input Signal is True to command the AC Switch "ON" and False to command the AC Switch "OFF".

Term	State	V_1	I_2
CONTROL	True (ON)	5 + 3.0, -1.5 Vdc	$\leq$ 10 mA
CONTROL	False (OFF)	0.0 + 2.0, -0.0 Vdc	< 1.0 mA

3.1.8.2.3 All alternating voltages and currents are R.M.S. unless otherwise specified.

3.1.9 Test Sequence

Unless otherwise specified, the test requirements of this specification may be performed in any sequence.

3.2 Detail Requirements

Testing of the HCPC will include but not be limited to the test outlined in Table I.

3.2.1 HCPC Tests

3.2.1.1 Control Input Voltage & Current

TABLE I.

Compliance Test For High Current Power Controller

	Examination or Test	MIL-P-81653B Paragraph Req.	Method	Items To Be Tested 10A 1φ	10A 3φ	50A 3φ	400A 3φ
1.	Control/Reset Input Voltage and Current	3.11.1	4.8.7.1	All	All	All	All
2.	Control Input Transients	3.11.22	4.8.7.22	-	1	-	-
3.	Overload Trip Indication	3.11.14	4.8.7.14	All	All	All	All
4.	Turn-On & Turn-Off Times	3.11.2	4.8.7.2	All	All	All	All
5.	Isolation	3.11.4	4.8.7.4	1	1	-	-
6.	Output Voltage Drop	3.11.6	4.8.7.6	All	All	All	All
7.	Output Leakage Current	3.11.7	4.8.7.7	All	All	All	All
8.	Operating Voltage Transients	3.11.19	4.8.7.19	-	1	-	-
9.	Zero Voltage Turn-On, Zero Current Turn-Off	3.11.23	4.8.7.23	All	All	All	All
10.	Trip Out Time	3.11.9.2	4.8.7.9.2	All	All	All	All
11.	Power Dissipation	3.11.8	4.8.7.8	1	1	1	1
12.	Radio Interference (Conducted)	3.15	4.8.18	-	1	-	-
13.	Removal Time To Reset	3.11.13.2	4.8.7.13	-	1	-	-
14.	Trip Free Characteristics	3.11.17	4.8.7.17	-	1	-	-
15.	Fail-Safe	3.12		-	1	-	-
16.	Rupture Capacity	3.11.11	4.8.7.11	1	1	1	1
17.	Temperature/Altitude	3.13	4.8.14	-	1	-	-
18.	Shock	3.13	4.8.19	1	1	-	-
19.	Vibration	3.13	4.8.11	1	1	-	

3.2.1.1.1 Requirement. When tested as specified, the turn-on and turn-off voltage shall be as follows:

Control Circuit (All Configurations)

Supply Voltage	+8.0 Vdc maximum +5.0 Vdc rated
Turn-on Voltage Rate of Change	+3.5 Vdc minimum 0.5 volts/microsecond/minimum
Turn-off Voltage Rate of Change	+2.0 Vdc maximum 0.5 volts/microsecond/minimum
Input Current	10 milliamperes maximum +5.0 volts rate input voltage

3.2.1.1.2 Test Method. The turn-on and turn-off voltages shall be verified as follows:

Turn-on Voltage. With the controller connected as shown in Figure 1, apply rated supply voltage and adjust the load resistance for rated load ± 10 percent. Apply the minimum turn-on voltage with the control function generator and note that the controller turns ON. Record results as Pass/Fail.

Turn-off Voltage. With the controller ON at rated control, apply the maximum turn-off voltage with the function generator and note that the controller turns OFF. Record results as Pass/Fail.

3.2.1.2 Control Input Transients

3.2.1.2.1 Requirements. When tested as specified, the controller shall not be damaged.

3.2.1.2.2(R) Test Method The following transients shall be applied between the signal ground terminal and the control terminal (source impedance is 500 ohms):

A train of ten pulses of plus and minus 100 volt peak amplitude and 100 microsecond duration each, repeated 10 times at 3 second intervals.

Repeat test (1) between terminals, trip indication and ground.

Record results as Pass/Fail.

3.2.1.3 Overload State (Trip Indication)

3.2.1.3.1 Requirement. When controllers are tested as specified, the state indication shall be as follows:

State Indication Signal	(All Configurations)
Tripped	1.5 volts dc maximum, sink 10 mA maximum
Not Tripped	50 microamperes maximum dc leakage at 30 volts

3.2.1.3.2(R) Test Method. Connect the controller as shown in Figure 1. Apply rated supply voltage and adjust the load resistance for 200 ± 10 percent rated load. Apply control signal and observe that the controller turns ON and trips out. With the indication sinking 10 mA, measure and record the voltage drop from "Trip" to ground. It must not exceed 1.5 Vdc. Remove the control signal and observe the controller reset. Measure and record leakage of indication when applying 30 Vdc ± 1%. It must not exceed 50 microamperes.

3.2.1.4 Turn-On & Turn-Off Times

3.2.1.4.1 Requirement. When tested as specified, the turn-on and turn-off times shall be as follows:

Response (All Configurations)	
Turn-On Time	15 milliseconds maximum
Response (10 A, 50 A)	
Turn-Off Time	20 milliseconds maximum
Response (400 A)	
Turn-Off Time	30 milliseconds maximum

3.2.1.4.2(R) Test Method. Measure and record turn-on and turn-off times with the controller operated as follows.

Turn-On Time With the controller connected as shown in Figure 1, apply rated supply voltage and adjust the load resistance for rated load ± 10 percent. Apply the minimum turn-on voltage with the control function generator and note that the controller turns ON. Record the time between application of control and receipt of ac power to the load.

Turn-Off Time With the controller ON at rated control voltage, apply the maximum turn-off voltage with the function generator and note that the controller turns OFF. Record the time between removal of control and removal of AC power from the load.

3.2.1.5 Isolation

3.2.1.5.1 Requirements. When tested as specified, the following requirements apply:

Dielectric Withstanding Voltage. There shall be no leakage current in excess of 1.0 milliampere (ma) nor evidence of damage to arcing (air discharge), flashover (surface discharge), or insulation breakdown (puncture discharge).

Insulation Resistance. The insulation resistance shall be greater than 100 megohms.

3.2.1.5.2(R) Test Method. The power-in terminal, power-out terminal and power-ground terminal shall be shorted together. Where applicable, the control terminal, state indication terminal, and signal ground terminal shall be shorted together. Measurement shall be made in accordance with the following MIL-STD-202 paragraphs, except the points of application shall be between the signal ground and power ground terminals.

Insulation Resistance. Controllers shall be tested in accordance with Method 302 of MIL-STD-202. The following details shall apply:

a. Test Condition - A

b. Preparations - None

c. Points of Measurement - The terminals shall be shorted together and measurements taken between enclosure and terminals.

d. Electrification Time - 2 minutes

e. Measurement Error - As specified in MIL-STD-202.

3.2.1.5.2(R) Continued

Dielectric Withstanding Voltage. Controllers shall be tested as follows:

At Atmospheric Pressure. Controllers shall be tested in accordance with Method 301 of MIL-STD-202. The following details shall apply:

a. Preparations - Not applicable

b. Test Voltage - 1000 vRMS

c. Nature of Potential - AC

d. Duration - As specified in MIL-STD-202

e. Points of Application - All terminals shall be shorted together and the test voltage applied from terminals to case.

f. Leakage Current - 1.0 mA maximum

g. Following these tests, controllers shall be examined for evidence of arcing, flashover, insulation breakdown and damage.

3.2.1.6 Output Voltage Drop

3.2.1.6.1 Requirements. When tested as specified, the voltage drop shall not exceed 0.3 vRMS maximum (per phase) for load current values from no load to 100% rated.

3.2.1.6.2(R) Test Method. With the controller connected as shown in Figure 1, measure and record the voltage between the power-in and power-out terminals while operating at 10, 50, and 100 percent rated load. A true RMS voltmeter shall be used.

3.2.2.7 Output Leakage Current

3.2.1.7.1 Requirement. When tested as specified, the leakage current shall not exceed the following values:

10 A and 50 A Configurations	1 mA (Per Phase) at rated voltage
400 A configurations	10 mA (Per Phase) at rated voltage

3.2.1.7.2(R) Test Method. Connect the controller as shown in Figure 1. With the load resistance adjusted for a maximum of 10K ohms rated supply voltage applied and the control circuit open, measure and record the leakage current.

3.2.1.8 Operating Voltage Transients

3.2.1.8.1 Requirements. When tested as specified with the control signal OFF, the controller shall not be damaged, be tripped or deviate from the OFF state. With the control signal ON, the controller shall not be damaged or tripped, but may go to the OFF state.

3.2.1.8.2(R) Test Method. Connect the controller as shown in Figure 1. Adjust load resistor for rated load and control function generator for maximum turn-off voltage. Apply control signal and perform the following tests, verifying the requirements in 3.2.2.8.1 with Pass/Fail.

a. Apply rated supply voltage and frequency for 5 seconds and then apply 180 volts rms for a period of 0.120 seconds.

b. Apply rated supply voltage and frequency for 5 seconds and then apply 140 volts rms for a period of 1.3 seconds.

c. Apply rated supply voltage and frequency for 5 seconds and then apply 65 volts rms for 0.020 seconds.

3.2.1.9 Zero Voltage Turn-On/Zero Current Turn-Off

3.2.1.9.1 Requirement. When tested as specified, controller turn-on shall occur at zero voltage crossover ± 10V, and the controller turn-off shall occur at zero current crossover ± 0.5A, ± 2A and ±20A for the 10A, 50A and 400A configurations, respectively. The controller shall turn-on and turn-off at the same voltage slope (turn-off at the opposite half-cycle from turn-on).

3.2.1.9.2(R) Test Method. Connect the controller as shown in Figure 1. Apply rated supply voltage and adjust load resistor for rated load. With the control function generator adjusted for rated turn-on voltage, first apply and then remove the control signal and monitor the load voltage and current. Measure and record the turn-on and turn-off points.

3.2.1.10 Trip-Out Time

3.2.1.10.1 Requirements

a. Non-repetitive Reset. When tested as specified, the trip time shall be within the limits specified in Figure 2 A, B, C and D (minimum 2.0 seconds between resets).

b. Repetitive Reset. When tested as specified, the controller trip times shall be within the limits specified in Figure 2. The controller shall not be damaged.

3.2.1.10.2 Test Method. Connect the power controller as shown in Figure 1.

a. Non-repetitive Reset. With rated supply voltage, verify that the controller meets the specified trip characteristics at overcurrent levels of 200%, 700% and 1250% of maximum rated current.

b. Repetitive Reset. With rated supply voltage and load resistor adjusted for 200 ± 10% rated load, apply control signal 10 times at 5 second intervals, observing the controller trip each time the control is applied. Record the results on a Pass/Fail basis.

3.2.1.11 Power Dissipation

3.2.1.11.1 Requirements. When tested as specified, the power dissipation shall not exceed the values specified in Figure 3 A, B, C and D for 'ON' and the following for OFF.

OFF	10 A, 1 ϕ	=	3.0 watts
OFF	10 A, 3 ϕ	=	4.0 watts
OFF	50 A, 3 ϕ	=	5.0 watts
OFF	400 A, 3 ϕ	=	5.0 watts

3.2.1.11.2(R) Test Method. Connect the controller as shown in Figure 1 with the load resistance adjusted for short circuit. With rated supply voltage applied, and the controller OFF, measure and record the power dissipation for the OFF state. Measure and record the power dissipation for the ON state for loads of 10, 50, and 100 percent rated load with the rated control voltage applied.

3.2.1.12 Radio Interference (Conducted)

3.2.1.12.1 Requirement. When tested as specified, controllers shall meet the requirements of MIL-STD-461.

3.2.1.12.2(R) Test Method. Controllers shall be tested as specified in MIL-STD-461.

3.2.1.13 Removal Time To Reset

3.2.1.13.1 Requirement. When tested as specified, the controller shall not reset when the control signal is removed for a time duration less than the minimum time specified (5.0 milliseconds) and reapplied. The controller shall reset when the control signal is removed for the maximum time specified (20 milliseconds) or longer and reapplied.

3.2.1.13.2(R) Test Method. Connect the controller as shown in Figure 1. Apply rated supply voltage and adjust the load resistance for 200 ± 10 percent rated load. Adjust control function generator for rated control voltage. Apply control signal and observe that the controller turns ON and trips out. Apply reset signal, and observe that the controller resets.

Follow this same procedure, except the reset signal shall be applied for a time duration less than the minimum specified time. Observe that the controller does not reset. Apply a reset signal for longer than the maximum time specified. Observe that the controller does reset. Record all results on a Pass/Fail basis.

3.2.1.14 Trip Free Characteristics

3.2 1.14.1 Requirement. When tested as specified, the controller shall reset, trip out, and stay tripped out for the duration of the test.

3.2.1.14.2(R) Test Method. With the controller connected as shown in Figure 1, apply rated voltage, adjust load resistor for short circuit, and apply rated control voltage. Observe the controller trips out. Reset the controller by removing rated control voltage. Maintain no control voltage for one minute and verify that the controller resets only once.

3.2.1.15 Fail-Safe (10 Amp HCPC)

3.2.1.15.1 Requirement. The controllers shall incorporate a "fail-safe" feature in the event the "trip circuit" fails to perform its function during an overload condition. When tested as specified, the Fail-Safe element (fuse) shall open the circuit between 2 seconds and 20 seconds for an overcurrent of 40 amperes and between 0.1 seconds and 1 second for an overcurrent of 250 amperes.

3.2.1.15.2(R) Test Method. An HCPC must be constructed with the "pass sections" intentionally shorted with no more than 0.05 ohms across any solid state device. Connect the shorted power controller as shown in Figure 1. Adjust load resistors for 40 amperes and 250 amperes. Apply rated supply voltage and record time Fail-Safe element takes to clear. Repeat for each value specified.

3.2.1.16 Rupture Capacity

3.2.1.16.1 Requirement. When tested as specified, the controller shall trip and there shall be no damage to the controller. The controller shall be resettable within 10 minutes after each test.

3.2.1.16.2(R) Test Method. The controller shall be connected per Figure 1, except that the power source shall be calibrated for the specified rupture current with the power terminals of the controller shorted. The open circuit voltage before application of the rupture current shall be rated voltage. Records of voltage, current and time shall be obtained. The controller shall be subject to the following test sequence.

a. Four (4) tests with the controller on before application of the rupture current.

b. Four (4) tests with the controller off, rupture circuit completed, and rupture current initiated by the controller being turned on.

c. After preceding tests, test dielectric withstanding voltage and 150% trip time.

There shall be sufficient time between rupture tests to allow temperature stabilization.

3.2.1.17 Temperature - Altitude

3.2.1.17.1 Requirement. Controllers shall turn-on, turn-off and trip when overloaded when subjected to the temperature - altitude conditions specified below.

3.2.1.17.2(R) Test Method. With the controller connected as shown in Figure 1, test the controller in accordance with Procedure 7, Method 504, of MIL-STD-810. The following details and exceptions shall apply:

a. Equipment Category - 6

b. Test Conditions - The minimum and maximum operating temperatures shall be -40°C and +75°C, respectively.

c. Test Item Operation - Full load

d. Heat Removal - During controller operation, the heat removal apparatus shall be adjusted to allow the case temperature to rise to a maximum of 75°C.

e. Inspection after tests shall consist of a visual inspection of the design and construction, a dielectric withstanding voltage test and verification that the controllers turn on with maximum rated current, turns off and trips with an overcurrent.

3.2.1.18 Shock

3.2.1.18.1 Requirements. Controllers shall operate satisfactorily during and after exposure to the shock stresses specified below.

3.2.1.18.2 Test Method. Controllers shall be connected as shown in Figure 1 and tested in accordance with Procedure IV, Method 516 of MIL-STD-810. The following details and exceptions shall apply:

a. Pulse Configuration - 50 G for 11 milliseconds

b. Electrical Load Conditions - In each of the six directions, the controller shall be "ON" full load for the first shock pulse and "OFF" for the second.

c. (Repeat 3.2.1.17.2 e.)

3.2.1.19 Vibration

3.2.1.19.1 Requirement. Controllers shall operate satisfactorily during and after exposure to the vibration levels specified below.

3.2.1.19.2 Test Method. Controllers shall be connected as shown in Figure 1 and tested in accordance with Procedure II, Method 514 of MIL-STD-810. The following details and exceptions shall apply:

a. In Part 1, the sinusoidal vibration test curve shown in Figure 4 of this specification shall be used.

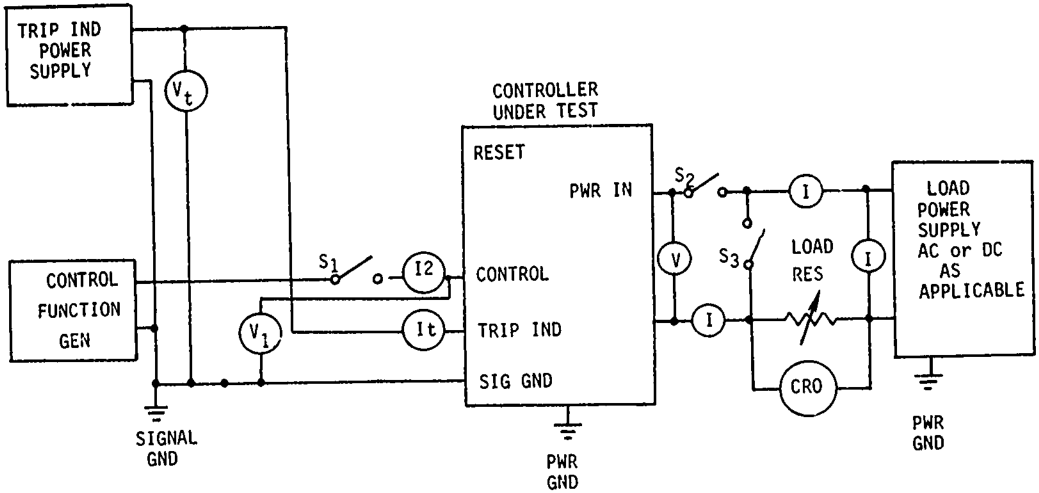
b. Delete Part 2.

c. In Part 3, curve AH shall be used.

d. The time schedule of Table 514.2-IV shall be used.

e. Inspections during test - During the entire vibration schedule, the controller shall be cycled 15 minutes "OFF" and 15 minutes "ON", full load. All parameters shall be monitored continuously.

f. Repeat 3.2.1.17.2 e.



NOTE: S_1 is a bounceless switch

Figure 1. Test Circuit

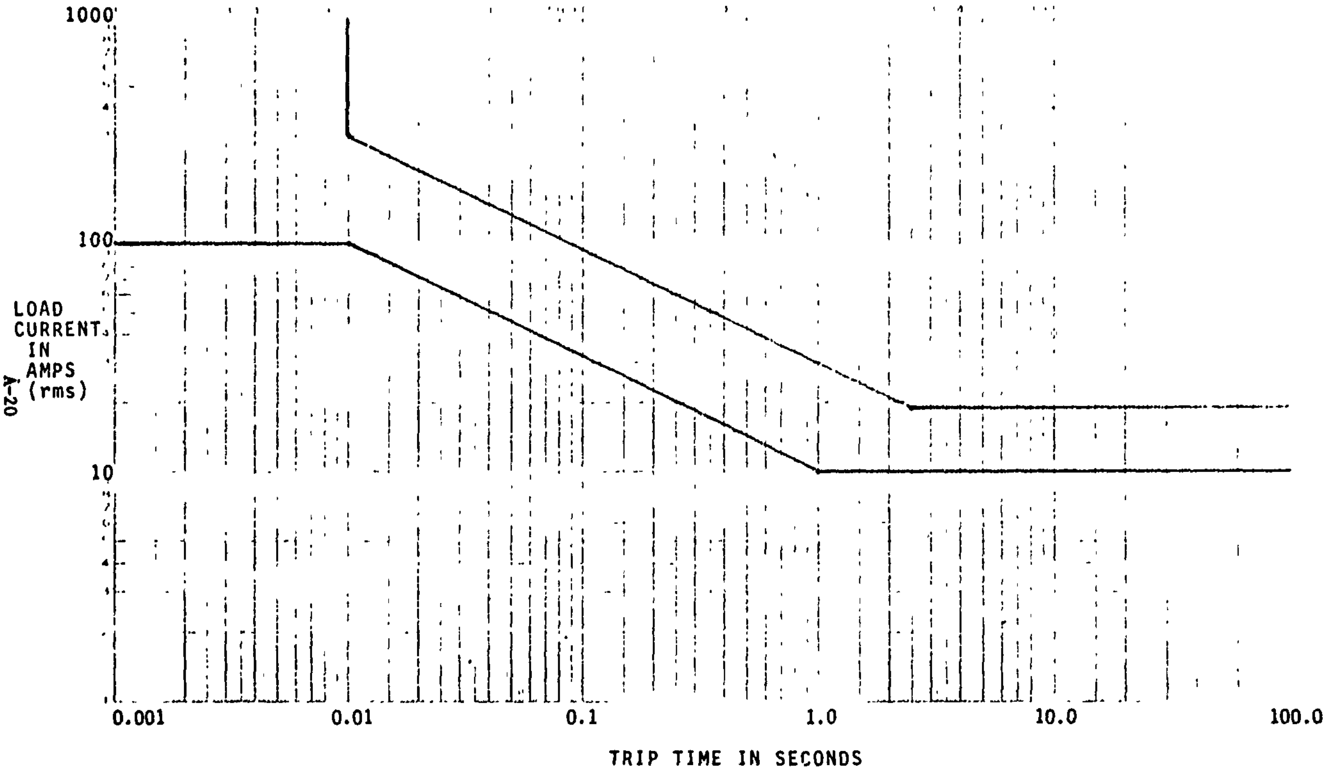


Figure 2A 10A Trip Curve

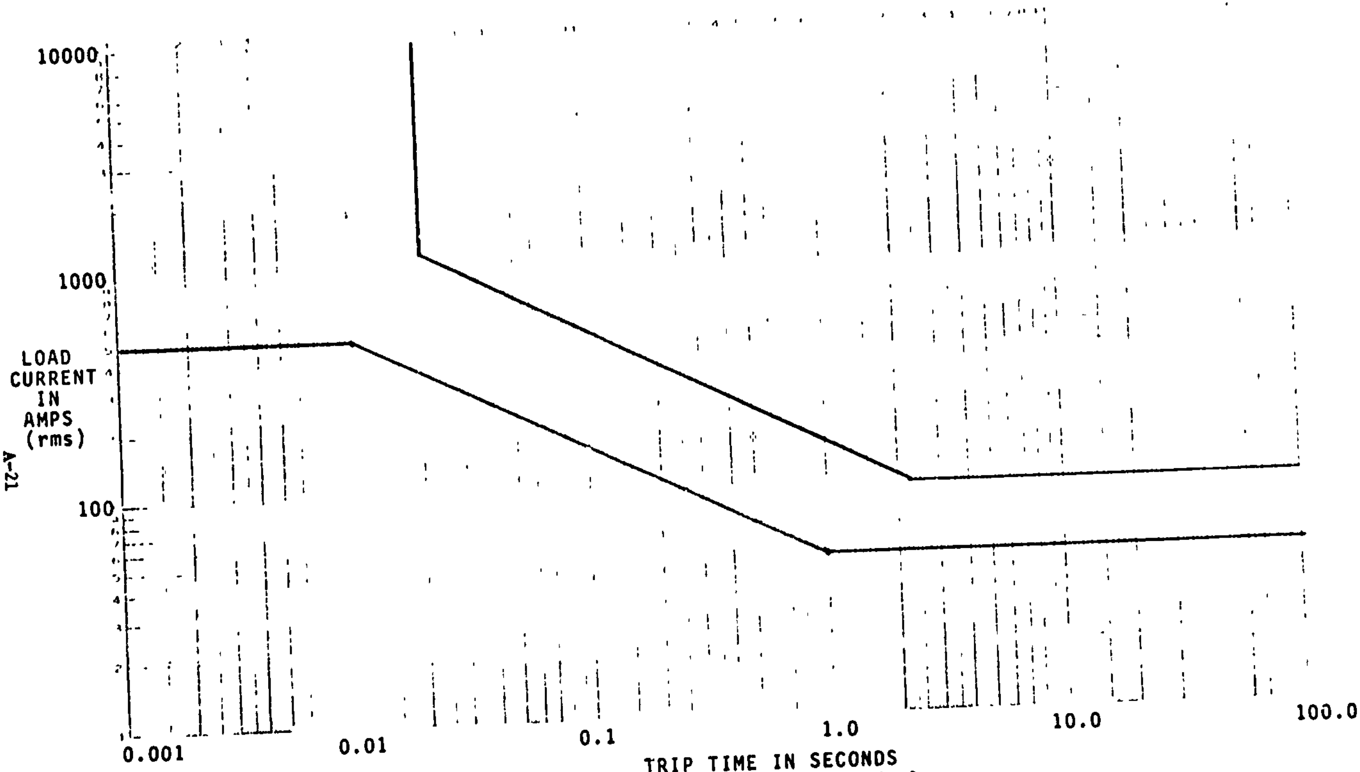


Figure 2B 50A Trip Curve

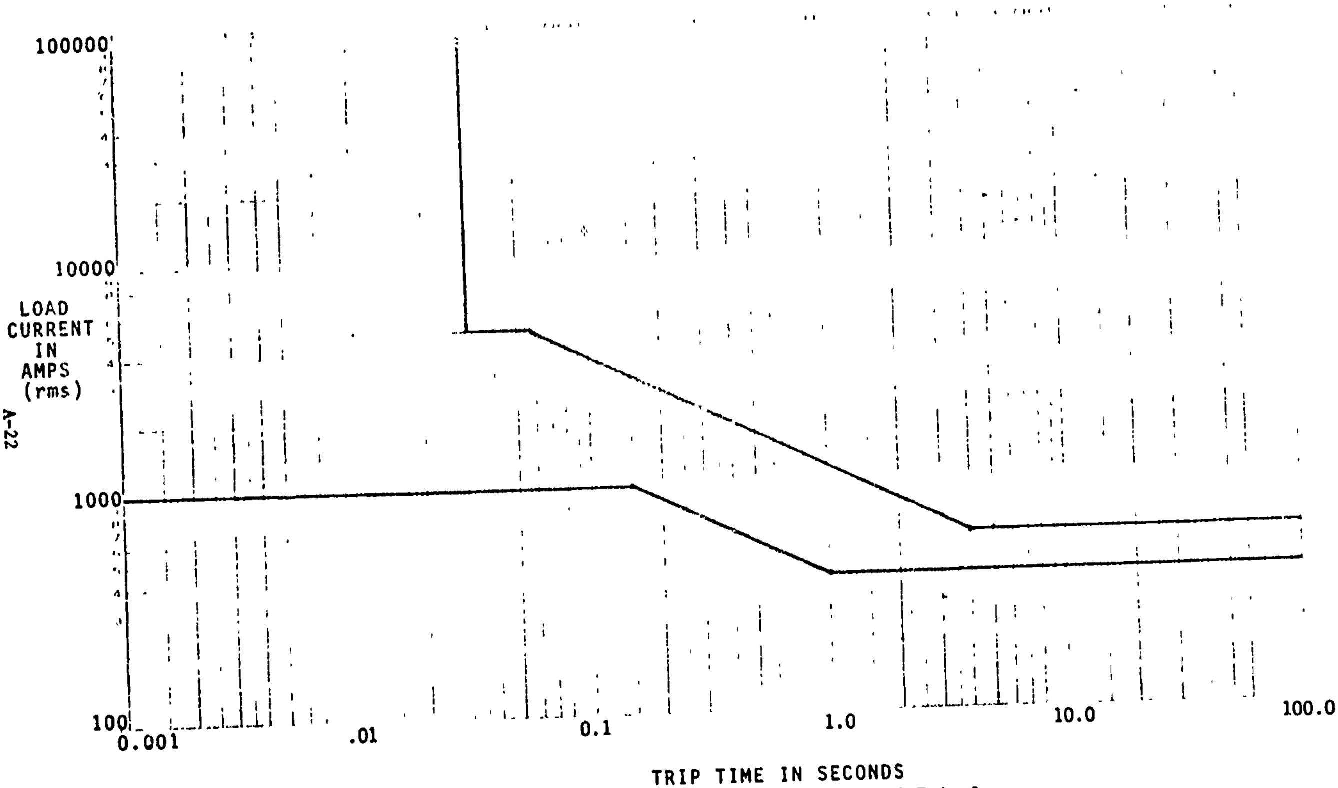


Figure 2C 400A Trip Curve

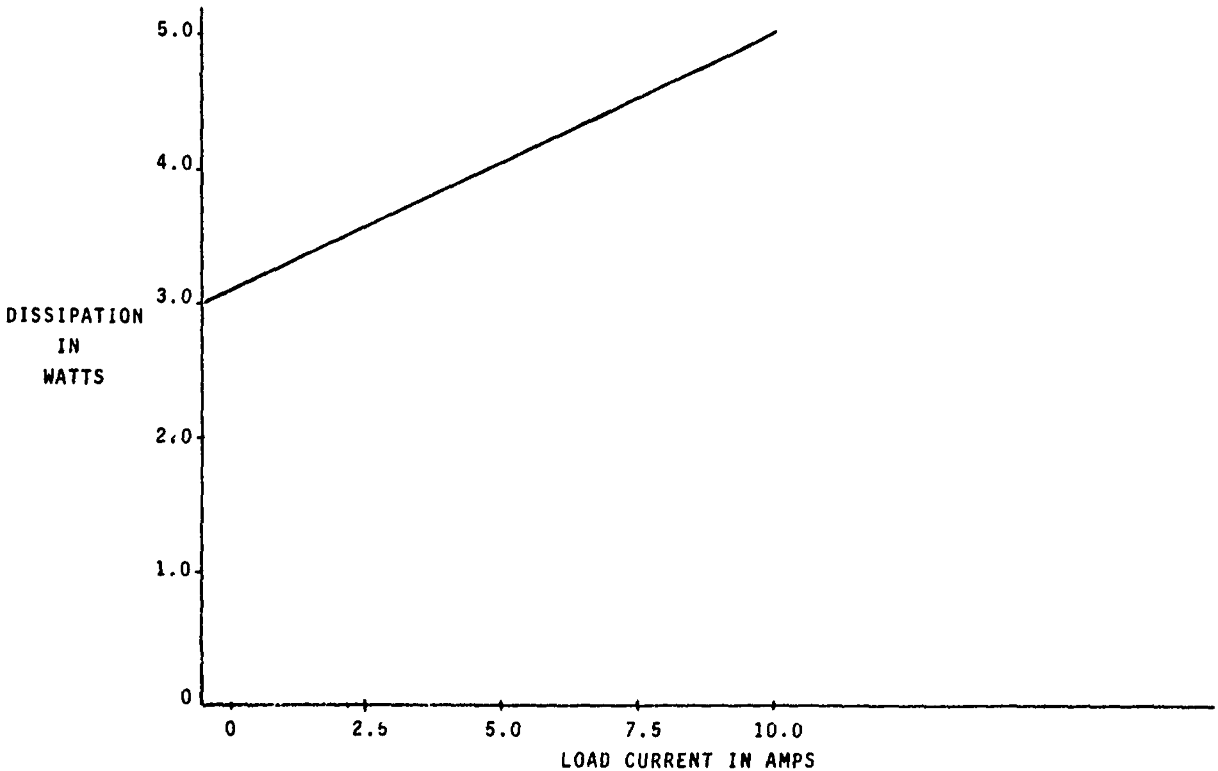


Figure 3A - Power Dissipation of 10A 1Ø

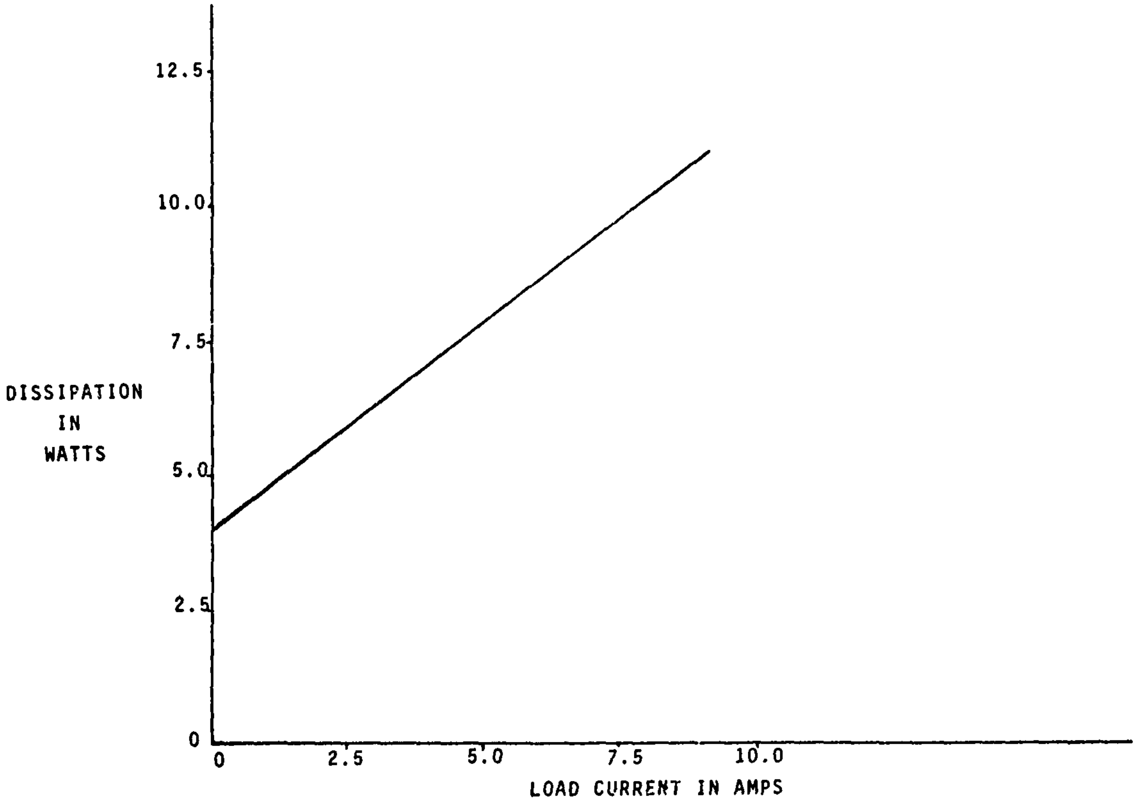


Figure 3B - Power Dissipation of 10A 3Ø

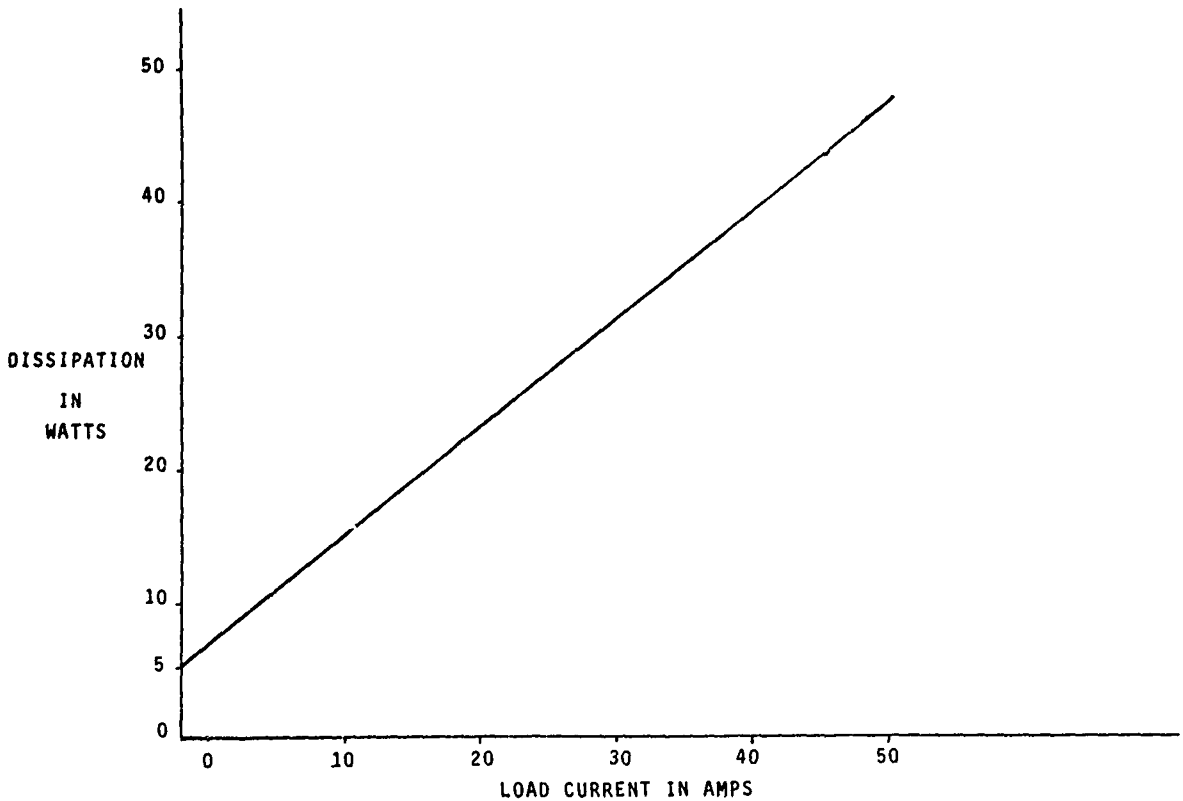


Figure 3C - Power Dissipation of 50A 3Ø

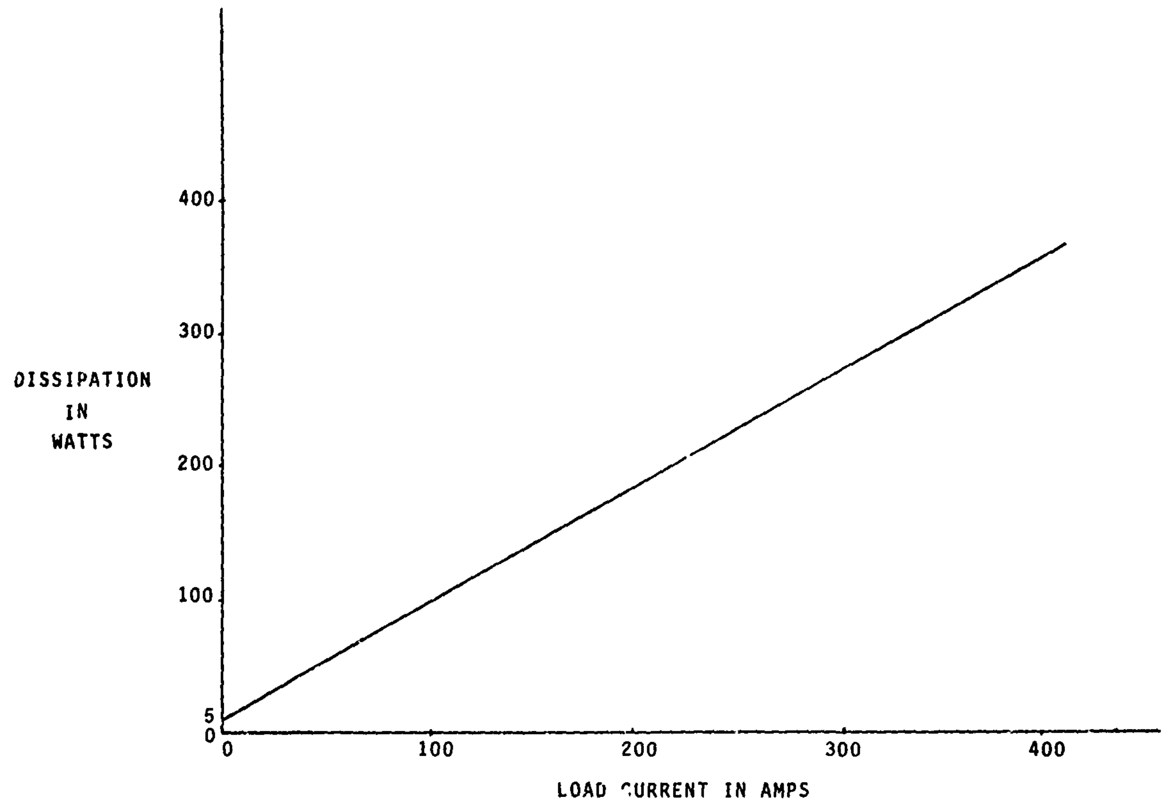


FIGURE 3D - POWER DISSIPATION OF 400A 3Ø

APPENDIX B

RELIABILITY CALCULATIONS

TABLE 1

PREDICTED RELIABILITY

SUMMARY

Component Type	10 Amp 1 Phase		10 Amp 3 Phase		50 Amp 3 Phase		400 Amp 3 Phase	
	QTY	λ Failures/10^6 Hr	QTY	λ Failures/10^6 Hr	QTY	λ Failures/10^6 Hr	QTY	λ Failures/10^6 Hr
Capacitor	38	0.61640	58	0.93098	58	0.93098	58	0.93098
Resistor	38	0.10331	52	0.12338	56	0.19133	71	0.28985
Diode	22	1.80288	25	1.90368	26	1.96416	26	1.98432
Transistor	12	2.23407	22	3.28926	22	3.28926	24	3.47966
SCR	2	0.80000	6	2.40000	9	4.20000	14	6.24000
IC	12	0.75878	12	0.75878	12	0.75878	12	0.75878
Relay	1	0.00703	1	0.02814	2	0.05628	1	0.05979
Sensor	1	1.08476	3	3.25428	3	3.25428	3	3.25428
Miscellaneous	11	1.09358	21	1.46322	22	1.56322	24	1.85858
TOTAL	137	8.50076	200	14.15167	210	16.20829	234	18.80624
MTBF	117,637 Hr		72,663 Hr		61,697 Hr		53,174	

TABLE 2

PREDICTED RELIABILITY

10A 1Ø

Component Type	Power Supply		ADC/ µP		SCR Elect		Package		TOTAL	
	QTY	λ Failures/10^6 Hr	QTY	λ Failures/10^6 Hr	QTY	λ Failures/10^6 Hr	QTY	λ Failures/10^6 Hr	QTY	λ Failures/10^6 Hr
Capacitor	23	0.38921	5	0.06990	10	0.15729			38	0.61640
Resistor	23	0.07256	8	0.02074	7	0.01001			38	0.10331
Diode	18	1.43784	2	0.28440	2	0.08064			22	1.80288
Transistor	6	1.64304	1	0.06336	5	0.52762			12	2.23402
IC	5	0.31805	7	0.44073					12	0.75878
Relay							1	0.00703	1	0.00703
Sensors							1	1.08476	1	1.08476
Miscellaneous	4	0.65750	2	0.25126	5	0.18482			11	1.09358
SCR					2	0.80000			2	0.80000
TOTAL	79	4.51820	25	1.13039	31	1.76038	2	1.09179	137	8.50076

TABLE 3

PREDICTED RELIABILITY

10A 3Ø

Component Type	Power Supply QTY	Power Supply λ Failure/10^6 Hr	ADC/μP QTY	ADC/μP λ Failure/10^6 Hr	SCR Elec (3 mod) QTY	SCR Elec (3 mod) λ Failure/10^6 Hr	Package QTY	Package λ Failure/10^6 Hr	TOTAL QTY	TOTAL λ Failure/10^6 Hr
Capacitors	23	0.38921	5	0.06990	30	0.47187			58	0.93098
Resistors	23	0.07256	8	0.02074	21	0.08003			52	0.17333
Diodes	17	1.37736	2	0.28990	6	0.24192			2[illegible]	1.90918
Transistors	6	1.64304	1	0.06336	15	1.58286			22	3.28926
IC	5	0.31805	7	0.44073					12	0.75878
Relay							1	0.08814	1	0.08814
Sensor							3	3.25428	3	3.25428
Miscellaneous	4	0.65750	2	0.25126	15	0.55446			27	1.40322
SCR					6	2.4000				
TOTAL	78	4.45772	25	1.13039	93	5.28114	4	3.28242	200	14.15167

TABLE 4

PREDICTED RELIABILITY

50A 3Ø

Component Type	Power Supply		ADC/μ		SCR Elect (3 mod)		Package		Total	
	QTY	λ Failures/10^6 Hr	QTY	λ Failures/10^6 Hr	QTY	λ Failure/10^6 Hr	QTY	λ Failure/10^6 Hr	QTY	λ Failure/10^6 Hr
Capacitor	23	0.38921	5	0.06990	30	0.47187			58	0.03098
Resistor	23	0.07256	8	0.02074	21	0.03003	4	0.06800	56	0.19133
Diode	18	1.43784	2	0.28490	6	0.24192			26	1.96416
Transistor	6	1.64304	1	0.06336	15	1.58286			22	3.28926
IC	5	0.31805	7	0.44073					12	0.75878
Relay							2	0.05628	2	0.05628
Sensor							3	3.25428	3	3.25428
Miscellaneous	4	0.65750	2	0.25126	15	0.55446	1	0.10000	22	1.56322
SCR					6	2.40000	3	1.80000	9	4.20000
TOTAL	79	4.51820	25	1.13039	93	5.28114	13	5.27856	210	16.20829

TABLE 5

PREDICTED RELIABILITY

400A 3Ø

Component Type	Power Supply		ADC/μP		SCR Elect (3 mod)		Relay Driver		Package		TOTAL	
	QTY	λ Failure/10^6	QTY	λ Failure/10^6	QTY	λ Failure/10^6	QTY	λ Failure/10^6	QTY	λ Fail/10^6	QTY	λ Failure/10^6
Capacitor	23	0.38921	5	0.06990	30	0.47187					58	0.93098
Resistor	23	0.07256	8	0.02074	21	0.03003	11	0.03052	8	0.13600	71	0.28985
Diode	17	1.37736	2	0.28440	6	0.24192	1	0.08064			26	1.98432
Transistor	6	1.64304	1	0.06336	15	1.58286	2	0.14040			24	3.42966
IC	5	0.31805	7	0.44073							12	0.75878
Relay									1	0.05979	1	0.05979
Sensor									3	3.25428	3	3.25428
SCR					6	2.40000	2	0.24000	6	3.6000	14	6.24000
Miscellaneous	4	0.65750	2	0.25126	15	0.55446	2	0.29536	1	0.10000	24	1.85858
TOTAL	79	4.45772	25	1.13039	93	5.28114	18	0.78692	19	7.15007	234	18.80624

APPENDIX C

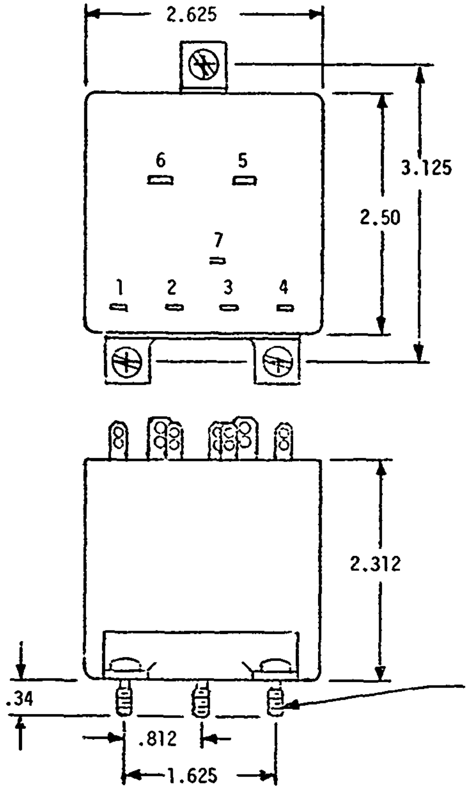
UPDATED HCPC SPECIFICATION SHEETS

Specification Sheet

High Current Power Controller

SPST 10A Normally Open

The complete requirements for procuring the controllers described herein shall consist of this document and the latest issue of MIL-P-81653.



TERMINAL IDENTIFICATION	
TERMINAL	FUNCTION
1	CONTROL +
2	CONTROL -
3	TRIP SIGNAL +
4	TRIP SIGNAL -
5	POWER IN
6	POWER OUT
7	NEUTRAL

Figure 1. Power Controller Package

Mechanical Characteristics

Configuration	See Figure 1
Dimensions	Inches
Enclosure	Type 3 (Sealed, other than hermetic)
Weight	20.0 ounces
Mounting Torque	15 in-lb
Terminal Strength	
Pull Test	Condition A, 5 pounds
Bend Test	5 pounds
Thermal Resistance	
Case-to-sink	0.25^{o}C/watt with specified mounting torque

Electrical Characteristics (-40^{o}C to 75^{o}C Case Temperature unless otherwise noted)

General

Circuit Arrangement	SPST
Insulation Resistance	100 megohms minimum
Dielectric Withstanding Voltage	Applicable
Isolation	Applicable
Life (Operating Cycle)	10^6 minimum
Radio Interference	Applicable
Leakage Current	1 mA maximum at rated voltage
Common Mode Rejection	Application
Power Dissipation On	See Figure 2
Power Dissipation Off	3.0 watt maximum

Power Circuit

Supply Voltage	115v nominal per MIL-STD-704

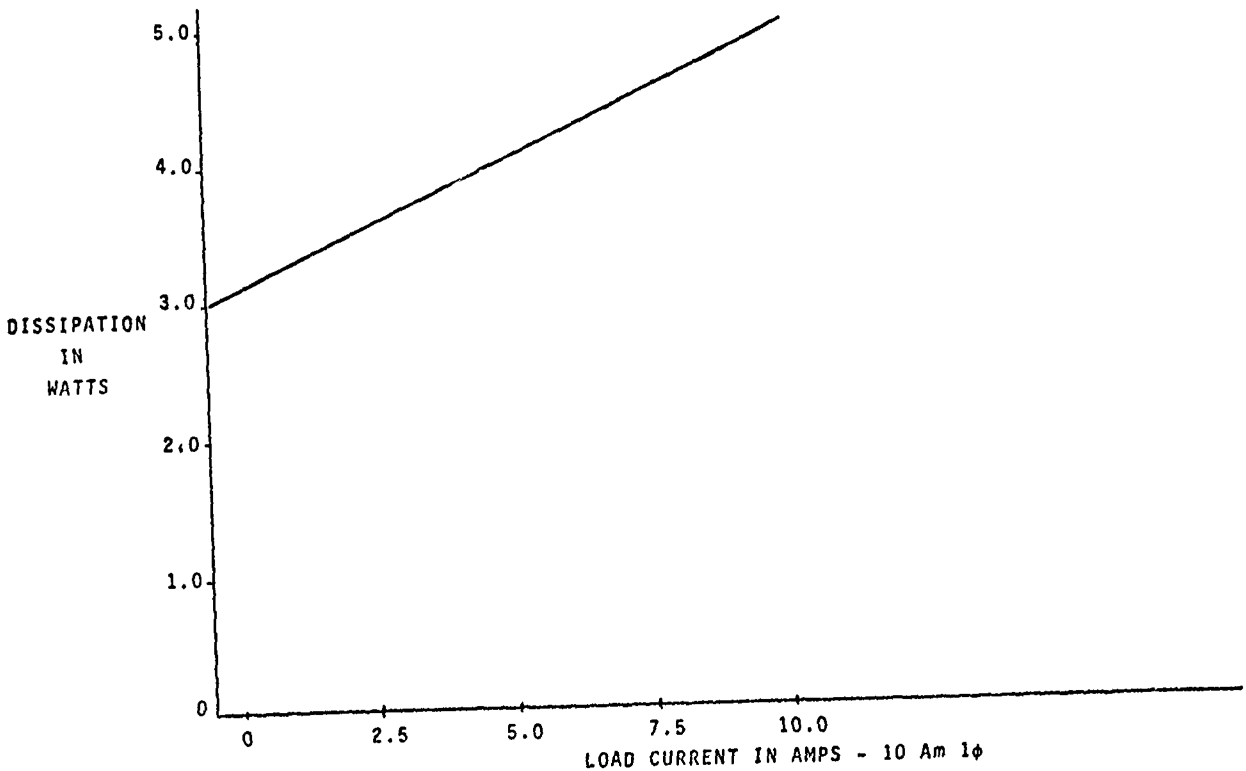


Figure 2. Power Dissipation vs. Load

Current	10 amperes
Frequency, rated	400 Hz ± 5%
Current Limiting	Not applicable
Vdrop	0.3V maximum
Ripple Current	Not applicable
Rupture Capacity	400 ampere minimum
Overshoot Current	Not applicable
Fail-safe Current	Upper limit of trip curve
Reset Immunity	Applicable
Transients	
Operating Voltage	Applicable
Spike Overvoltage	Applicable
Standby Power	Applicable
Response	
Turn-on Time	15 milliseconds maximum
Turn-off Time	20 milliseconds maximum
Trip Free	Applicable
Trip Time	See Figure 3
Nonrepetitive Reset	Applicable (2.0 seconds minimum between resets)
Repetition Reset	Applicable
Trip Indication Signal	
Tripped	1.5 volts dc maximum, sink 10 mA maximum
Not Tripped	50 microamperes maximum, dc leakage at 30 volts
3-Phase Power Controller	N/A
Zero Voltage Turn-on	Applicable
Zero Current Turn-off	Applicable

10 AMP TRIP CURVE

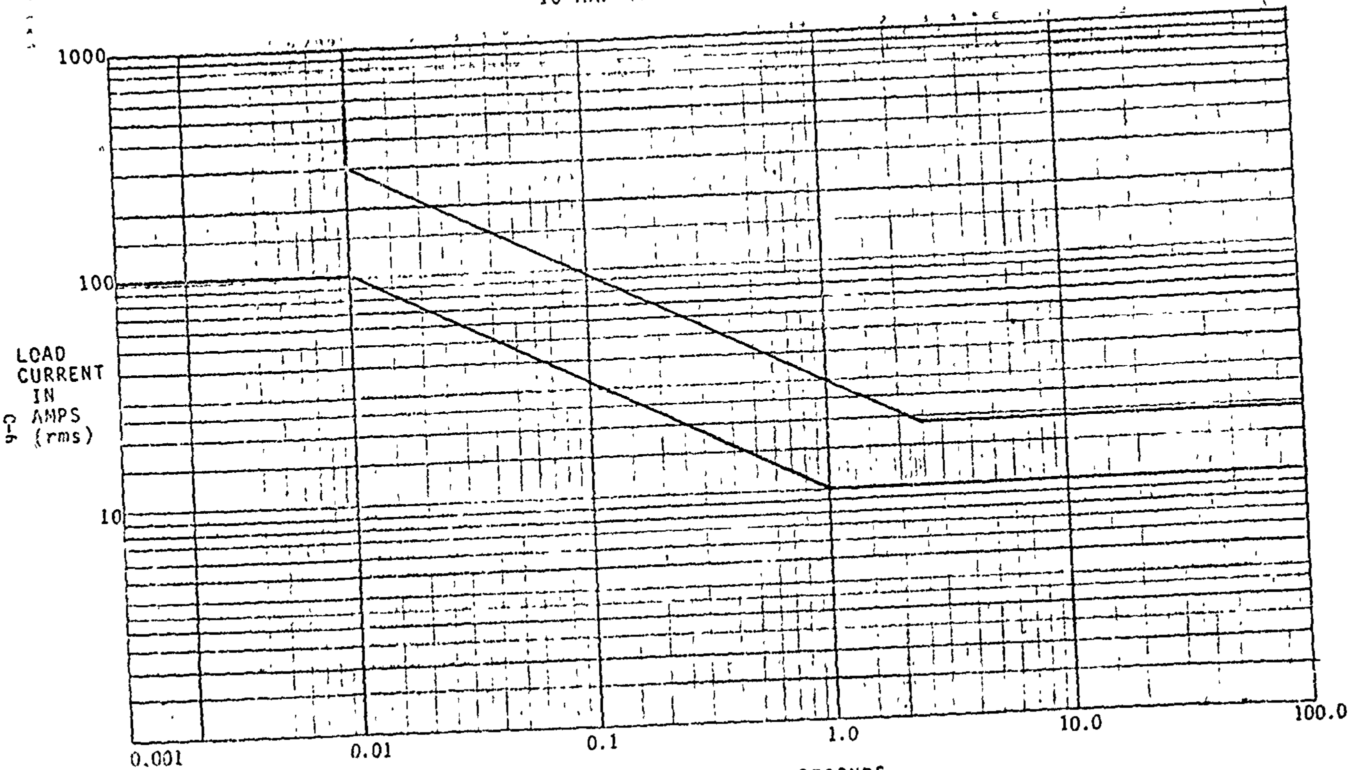


Figure 3. TRIP CURVE

Control Circuit

Supply Voltage	+8.0 Vdc maximum +5.0 Vdc rated
Turn-on Voltage Rate of Change	+3.5 Vdc minimum 0.5 volts/microsecond minimum
Turn-off Voltage Rate of Change	+2.0 Vdc maximum 0.5 volts/microsecond minimum
Input Current	10 milliamperes maximum at +5.0 volts rate input voltage
Input Transient	Applicable
Time to Reset Removal	5.0 millisecond minimum 20.0 millisecond maximum

Environmental Characteristics

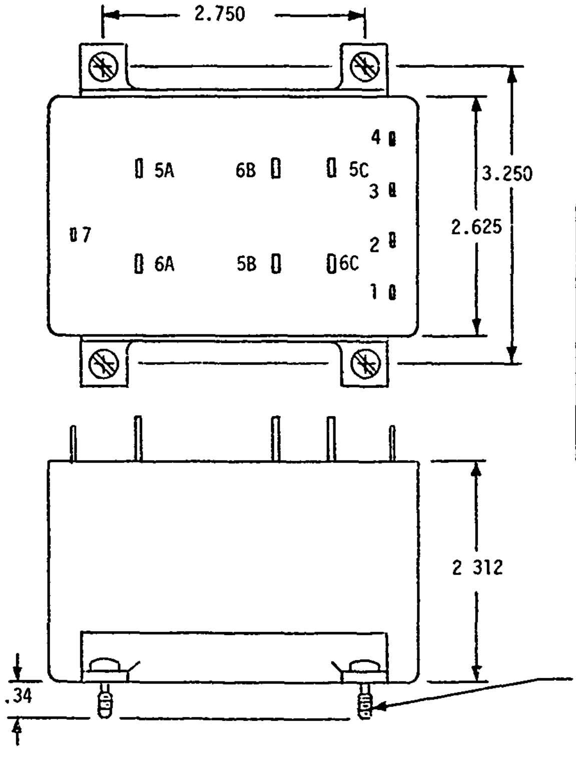
Case Temperature Operating Storage	 -40°C to $+75^{\circ}$C -65°C to $+100^{\circ}$C
Shock Mechanical Temperature	 50G for 11 millisecond -54°C and 75°C
Vibration	Applicable
Acceleration	20G
Salt Fog	Applicable
Humidity	Applicable
Operation at Temperatures Extreme	Applicable
Temperature Altitude	Applicable
Operating Ambient Temperature	-40°C to 75°C Sea Level to 70,000 feet

Specification Sheet

High Current Power Controller

3PST 10A Normally Open

The complete requirements for procuring the controllers described herein shall consist of this document and the latest issue of MIL-P-81653.



TERMINAL IDENTIFICATION	
TERMINAL	FUNCTION
1	CONTROL +
2	CONTROL -
3	TRIP SIGNAL -
4	TRIP SIGNAL -
5A, B, C	POWER IN
6A, B, C	POWER OUT
7	NEUTRAL

Figure 1. Power Controller Package

Mechanical Characteristics

Configuration	See Figure 1
Dimensions	Inches
Enclosure	Type 3 (Sealed, other than hermetic)
Weight	31.0 ounces
Mounting Toroue	15 in-lb
Terminal Strength Pull Test Bend Test	Condition A, 5 pounds 5 pounds
Thermal Resistance Case-to-sink	0.25°C/watt with specified mounting torque

Electrical Characteristics (-40°C to 75°C Case Temperature unless otherwise noted)

General

Circuit Arrangement	3PST
Insulation Resistance	100 megohms minimum
Dielectric Withstanding Voltage	Applicable
Isolation	Applicable
Life (Operating Cycle)	10^6 minimum
Radio Inte, ference	Applicable
Leakage Current per phase	1 mA maximum at rated voltage
Common Mode Rejection	Application
Power Dissipation On Off	See Figure 2 4.0 watt maximum

Power Circuit

Supply Voltage	115v nominal per MIL-STD-704

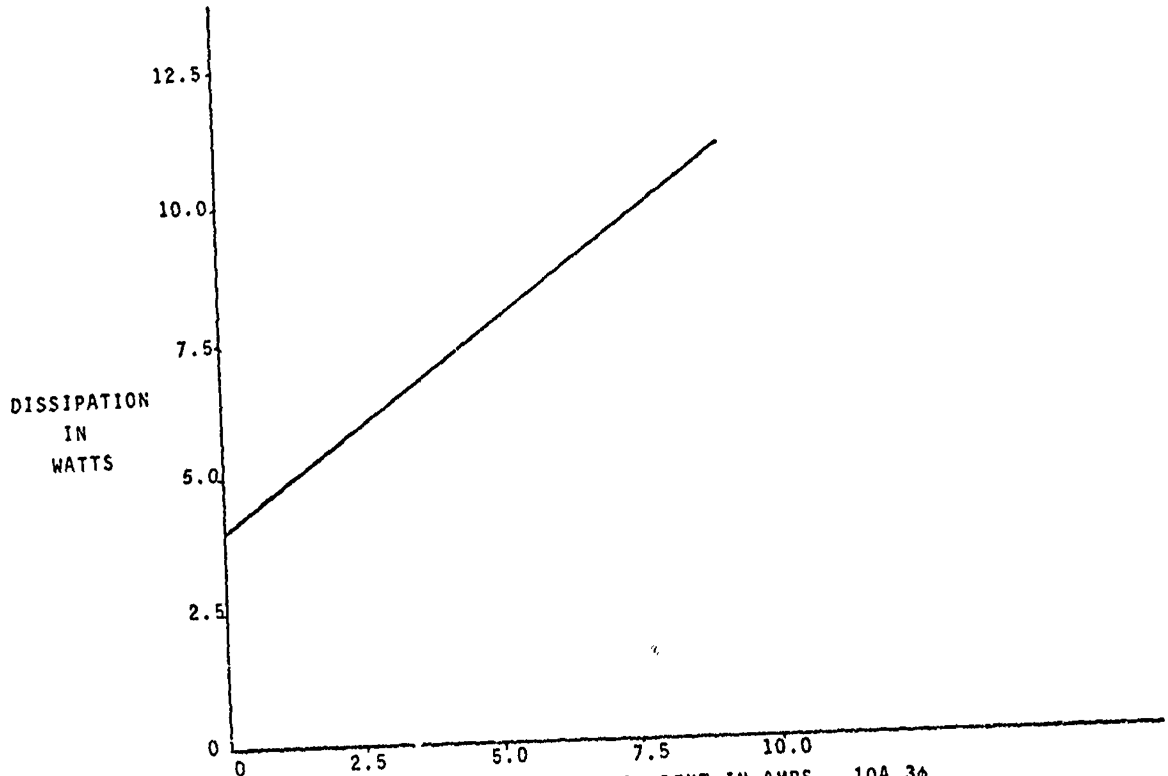


Figure 2. Power Dissipation vs. Load

Current	10 amperes per pnase
Frequency, rated	400 Hz ± 5%
Current Limiting	Not applicable
Vdrop	0.3V maximum per phase
Ripple Current	Not applicable
Rupture Capacity	400 ampere minimum per phase
Overshoot Current	Not applicable
Fail-safe Current	Upper limit of trip curve
Reset Immunity	Applicable
Transients	
Operating Voltage	Applicable
Spike Overvoltage	Applicable
Standby Power	Applicable
Response	
Turn-on Time	15 milliseconds maximum
Turn-off Time	20 milliseconds maximum
Trip Free	Applicable
Trip Time	See Figure 3
Nonrepetitive Reset	Applicable (2.0 seconds minimum between resets)
Repetition Reset	Applicable
Trip Indication Signal	
Tripped	1.5 volts dc maximum, sink 10 mA maximum
Not Tripped	50 microamperes maximum, dc leakage at 30 volts
3-Phase Power Controller	Overcurrent shall trip all 3 phases
Zero Voltage Turn-on	Applicable
Zero Current Turn-off	Applicable

10 AMP TRIP CURVE

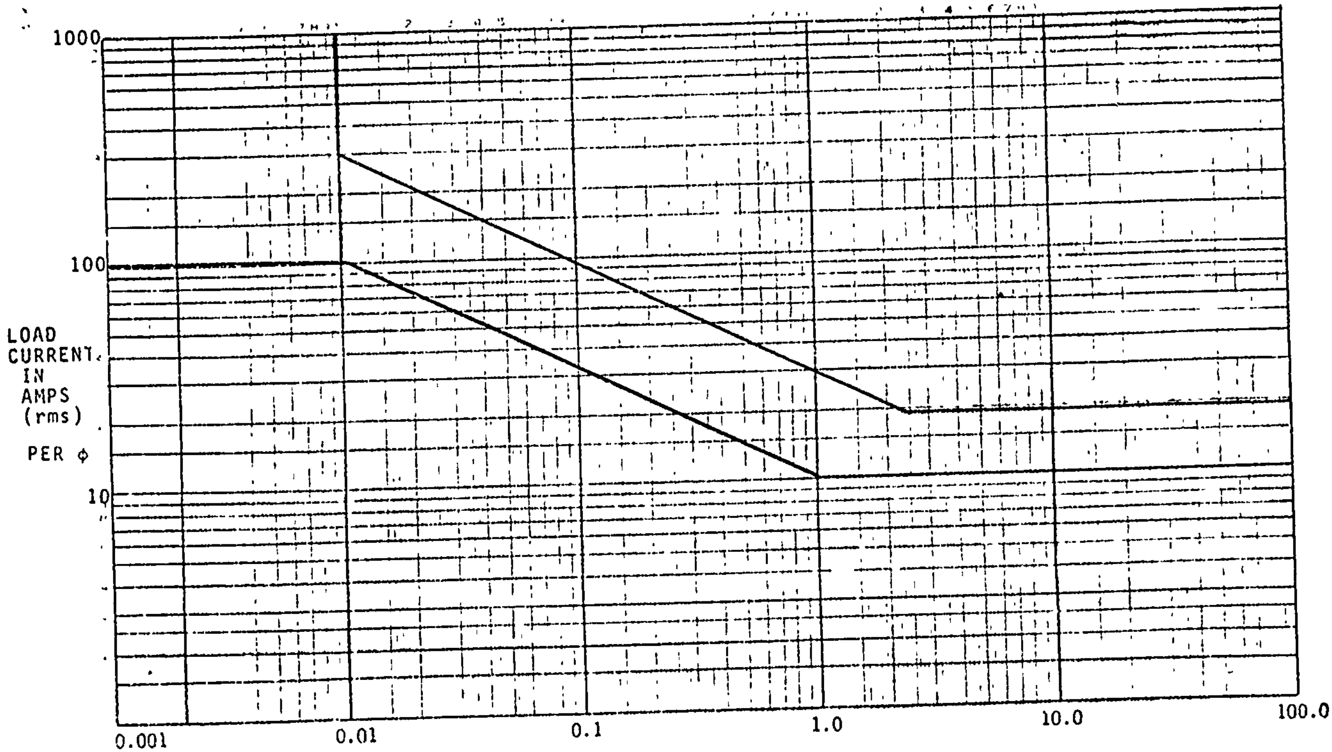


Figure 3. TRIP CURVE

Control Circuit

Supply Voltage	+8.0 Vdc maximum +5.0 Vdc rated
Turn-on Voltage Rate of Change	+3.5 Vdc minimum 0.5 volts/microsecond minimum
Turn-off Voltage Rate of Change	+2.0 Vdc maximum 0.5 volts/microsecond minimum
Input Current	10 milliamperes maximum at +5.0 volts rate input voltage
Input Transient	Applicable
Time to Reset Removal	5.0 millisecond minimum 20.0 millisecond maximum

Environmental Characteristics

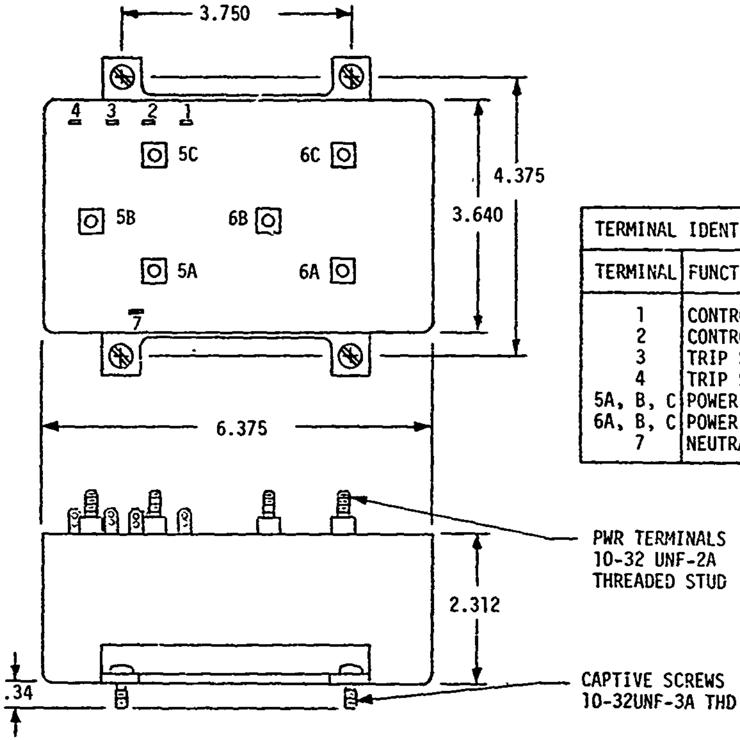
Case Temperature	
Operating	$-40^{o}C$ to $+75^{o}C$
Storage	$-65^{o}C$ to $+100^{o}C$
Shock	
Mechanical	50G for 11 millisecond
Temperature	$-54^{o}C$ and $75^{o}C$
Vibration	Applicable
Acceleration	20G
Salt Fog	Applicable
Humidity	Applicable
Operation at Temperatures Extreme	Applicable
Temperature Altitude	Applicable
Operating Ambient Temperature	$-40^{o}C$ to $75^{o}C$ Sea Level to 70,000 feet

Specification Sheet

High Current Power Controller

3PST 50A Normally Open

The complete requirements for procuring the controllers described herein shall consist of this document and the latest issue of MIL-P-81653.



TERMINAL IDENTIFICATION	
TERMINAL	FUNCTION
1	CONTROL +
2	CONTROL -
3	TRIP SIGNAL +
4	TRIP SIGNAL -
5A, B, C	POWER IN
6A, B, C	POWER OUT
7	NEUTRAL

Figure 1. Power Controller Package

Mechanical Characteristics

Configuration	See Figure 1
Dimensions	Inches
Enclosure	Type 3 (Sealed, other than hermetic)
Weight	69 ounces
Mounting Torque	15 in-lb
Terminal Strength	
Pull Test	Condition A, 5 pounds
Bend Test	5 pounds
Thermal Resistance	
Case-to-sink	0.15 °C/watt with specified mounting torque

Electrical Characteristics (-40°C to 75°C Case Temperature unless otherwise noted)

General

Circuit Arrangement	3PST
Insulation Resistance	100 megohms minimum
Dielectric Withstanding Voltage	Applicable
Isolation	Applicable
Life (Operating Cycle)	10^6 minimum
Radio Interference	Applicable
Leakage Current per phase	1 mA maximum at rated voltage
Common Mode Rejection	Application
Power Dissipation On	See Figure 2
Off	5.0 watt maximum

Power Circuit

Supply Voltage	115v nominal per MIL-STD-704

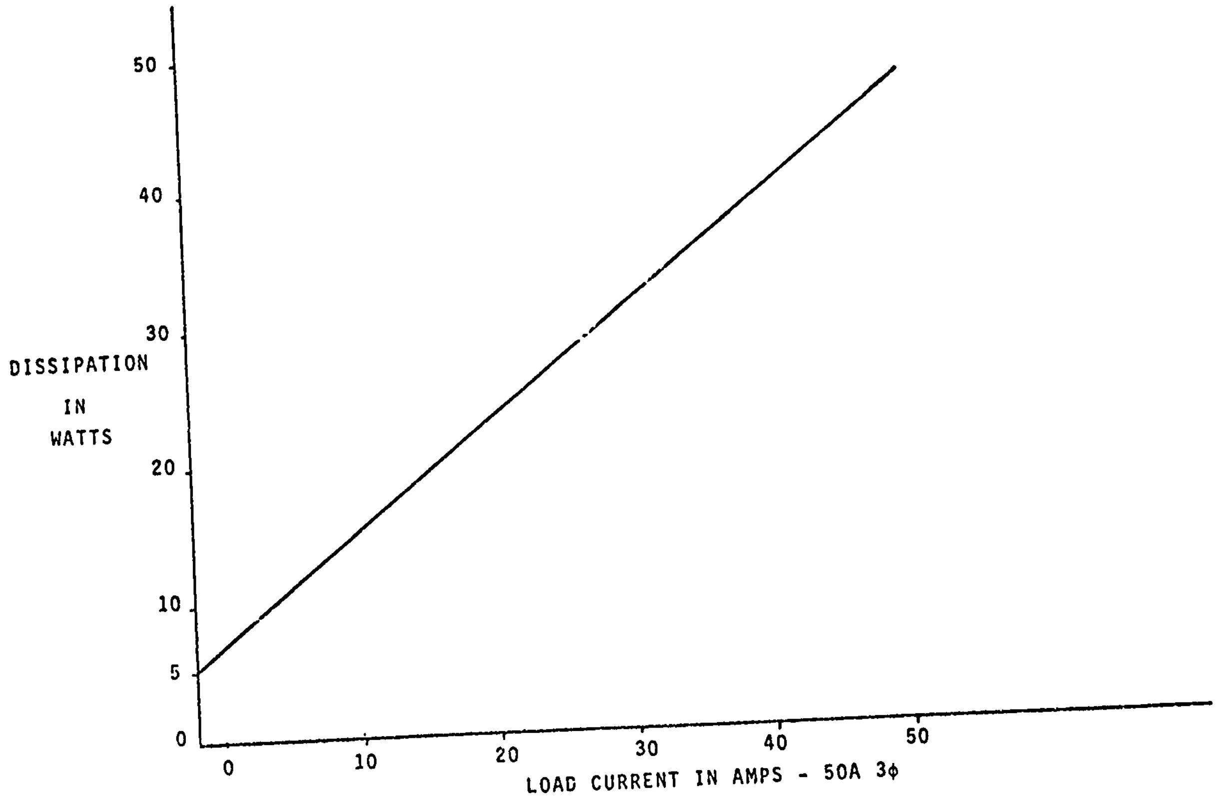


Figure 2. Power Dissipation vs. Load

Current	50 amperes per phase
Frequency, rated	400 Hz $\pm$ 5%
Current Limiting	Not applicable
Vdrop	0.3V maximum per phase
Ripple Current	Not applicable
Rupture Capacity	2000 ampere minimum per phase
Overshoot Current	Not applicable
Fail-safe Current	Upper limit of trip curve
Reset Immunity	Applicable
Transients	
Operating Voltage	Applicable
Spike Overvoltage	Applicable
Standby Power	Applicable
Response	
Turn-on Time	[illegible] milliseconds maximum
Turn-off Time	20 milliseconds maximum
Trip Free	Applicable
Trip Time	See Figure 3
Non[illegible]itive Reset	Applicable (2.0 seconds minimum between resets)
Repetition Reset	Applicable
Trip Indication Signal	
Tripped	1.5 volts dc maximum, [illegible]ink 10 mA maximum
Not Tripped	50 microamperes maximum, dc leakage at 30 volts
3-Phase Power Controller	Overcurrent shall trip all 3 phases
Zero Voltage Turn-on	Applicable
Zero Current Turn-off	Applicable

50 AMP TRIP CURVE

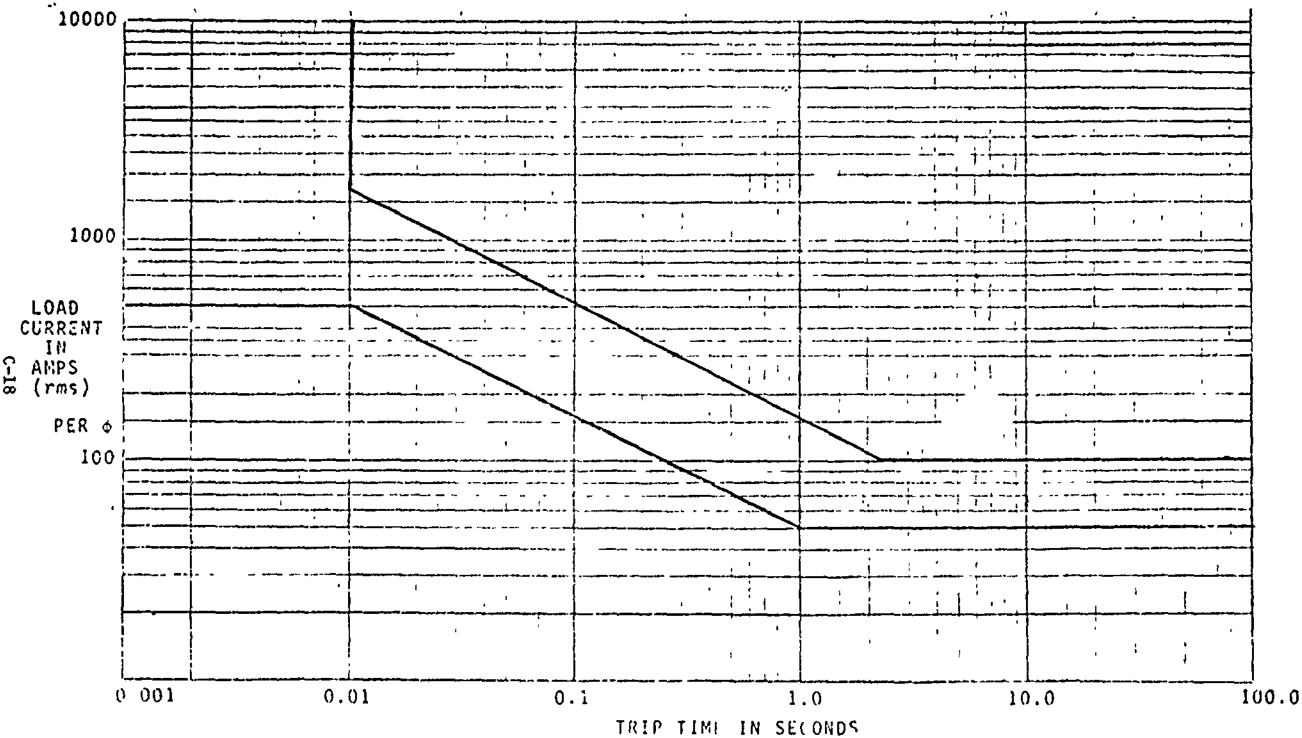


Figure 3. TRIP CURVE

Control Circuit

Supply Voltage	+8.0 Vdc maximum +5.0 Vdc rated
Turn-on Voltage Rate of Change	+3.5 Vdc minimum 0.5 volts/microsecond minimum
Turn-off Voltage Rate of Change	+2.0 Vdc maximum 0.5 volts/microsecond minimum
Input Current	10 milliamperes maximum at +5.0 volts rate input voltage
Input Transient	Applicable
Time to Reset Removal	5.0 millisecond minimum 20.0 millisecond maximum

Environmental Characteristics

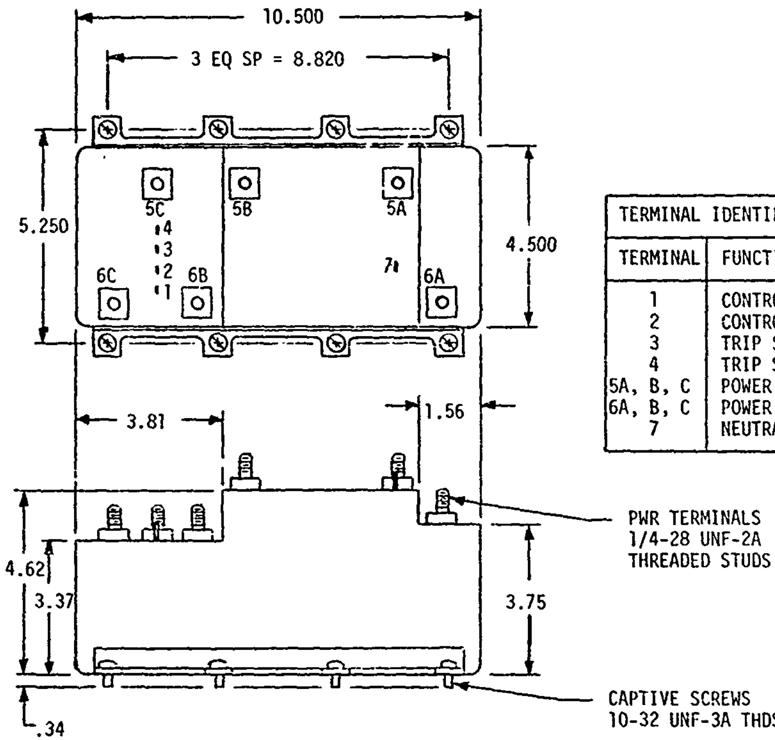
Case Temperature Operating Storage	 -40°C to +75°C -65°C to +100°C
Shock Mechanical Temperature	 50G for 11 millisecond -54°C and 75°C
Vibration	Applicable
Acceleration	20G
Salt Fog	Applicable
Humidity	Applicable
Operation at Temperatures Extreme	Applicable
Temperature Altitude	Applicable
Operating Ambient Temperature	-40°C to 75°C Sea Level to 70,000 feet

Specification Sheet

High Current Power Controller

3PST 400A Normally Open

The complete requirements for procuring the controllers described herein shall consist of this document and the latest issue of MIL-P-81653.



TERMINAL IDENTIFICATION	
TERMINAL	FUNCTION
1	CONTROL +
2	CONTROL -
3	TRIP SIGNAL +
4	TRIP SIGNAL -
5A, B, C	POWER IN
6A, B, C	POWER OUT
7	NEUTRAL

Figure 1. Power Controller Package

Mechanical Characteristics

Configuration	See Figure 1
Dimensions	Inches
Enclosure	Type 3 (Sealed, other than hermetic)
Weight	16 pounds
Mounting Torque	15 in-lb
Terminal Strength	
Pull Test	Condition A, 5 pounds
Bend Test	5 pounds
Thermal Resistance Case-to-sink	0.15 $^{\circ}$C/watt with specified mounting torque

Electrical Characteristics (-40°C to 75°C Case Temperature unless otherwise noted)

General

Circuit Arrangement	3PST
Insulation Resistance	100 megohms minimum
Dielectric Withstanding Voltage	Applicable
Isolation	Applicable
Life (Operating Cycle)	10^6 minimum
Radio Interference	Applicable
Leakage Current per phase	1 mA maximum at rated voltage
Common Mode Rejection	Application
Power Dissipation On	See Figure 2
Power Dissipation Off	5.0 watt maximum

Power Circuit

Supply Voltage	115v nominal per MIL-STD-704

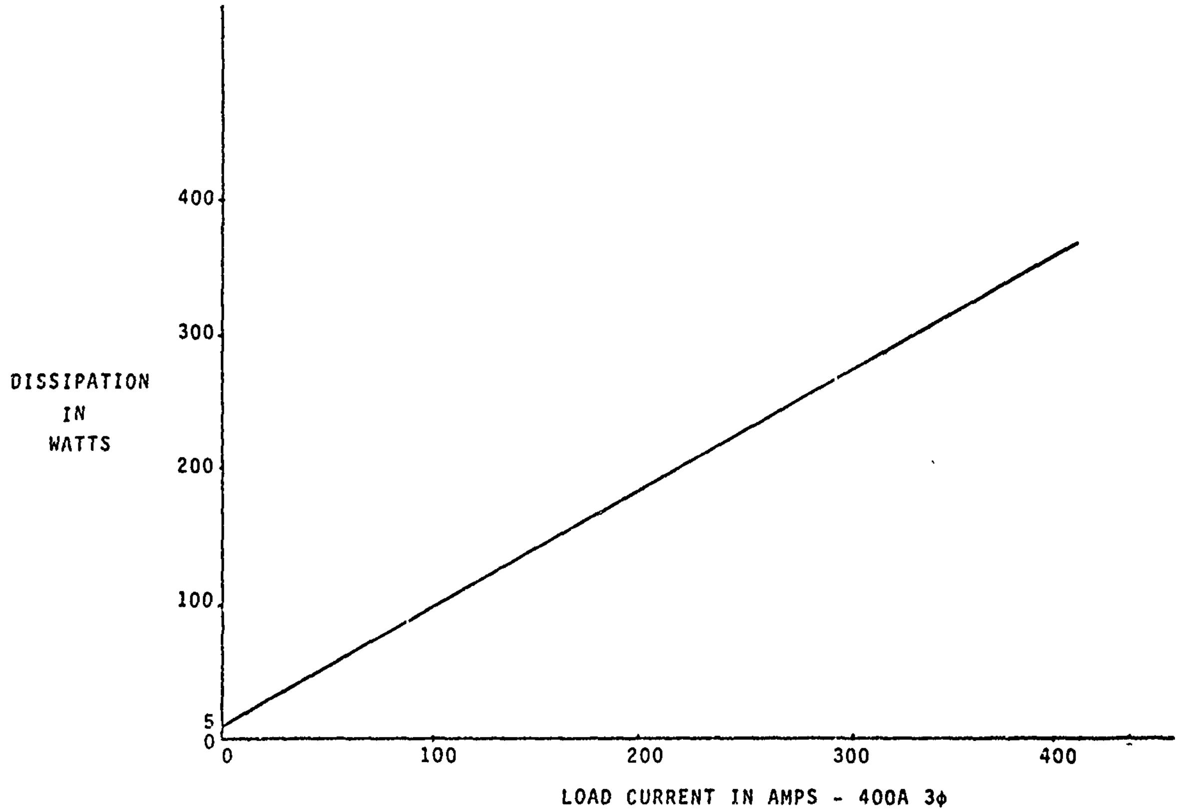


Figure 2. Power Dissipation vs. Load

Current	400 ampere per phase
Frequency, rated	400 Hz ± 5%
Current Limiting	Not applicable
Vdrop	0.3V maximum per phase
Ripple Current	Not applicable
Rupture Capacity	5000 ampere minimum per phase
Overshoot Current	Not applicable
Fail-safe Current	Upper limit of trip curve
Reset Immunity	Applicable
Transients	
Operating Voltage	Applicable
Spike Overvoltage	Applicable
Standby Power	Applicable
Response	
Turn-on Time	15 milliseconds maximum
Turn-off Time	30 milliseconds maximum
Trip Free	Applicable
Trip Time	See Figure 3
Nonrepetitive Reset	Applicable (2.0 seconds minimum between resets)
Repetition Reset	Applicable
Trip Indication Signal	
Tripped	1.5 volts dc maximum, sink 10 mA maximum
Not Tripped	50 microamperes maximum, dc leakage at 30 volts
3-Phase Power Controller	Overcurrent shall trip all 3 phases
Zero Voltage Turn-on	Applicable
Zero Current Turn-off	Applicable

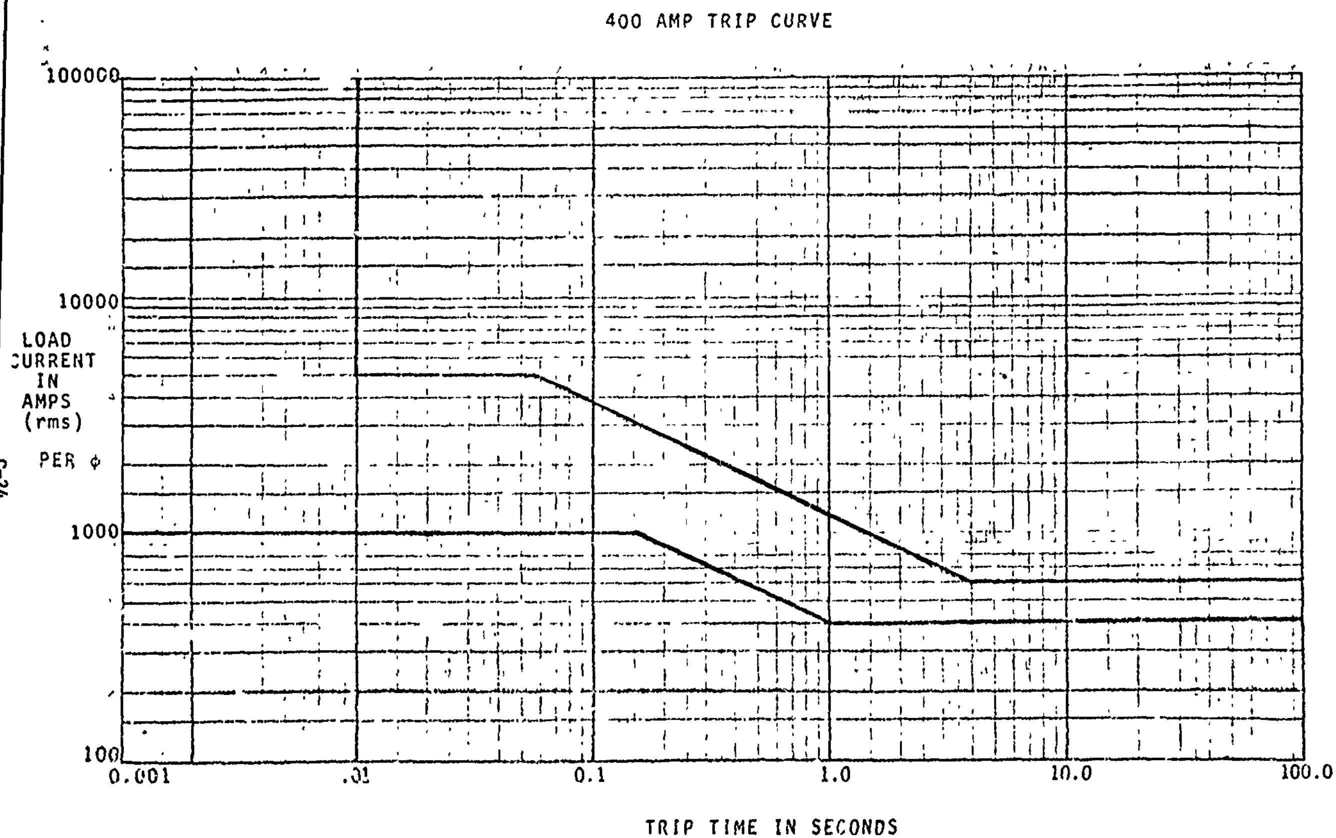


Figure 3. Trip Curve

Control Circuit

Supply Voltage	+8.0 Vdc maximum +5.0 Vdc rated
Turn-on Voltage Rate of Change	+3.5 Vdc minimum 0.5 volts/microsecond minimu.
Turn-off Voltage Rate of Change	+2.0 Vdc maximum 0.5 volts/microsecond minimum
Input Current	10 milliamperes maximum at +5.0 volts rate input voltage
Input Transient	Applicable
Time to Reset Removal	5.0 millisecond minimum 20.0 millisecond maximum

Environmental Characteristics

Case Temperature Operating Storage	-40°C to +75°C -65°C to +100°C
Shock Mechanical Temperature	50G for 11 millisecond -54°C and 75°C
Vibration	Applicable
Acceleration	20G
Salt Fog	Applicable
Humidity	Applicable
Operation at Temperatures Extreme	Applicable
Tempera... Altitude	Applicable
Operating Ambient Temperature	-40°C to 75°C Sea Level to 70,000 feet