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PROPOSED 5,800 kW POWER SUPPLY USING SILICON CONTROLLED RECTIFIERS FOR ELECTROMAGNETS

I. INTRODUCTION

The development of high powered silicon-controlled rectifiers has allowed the construction of large dc power supplies for lower prices than were possible with rotating machinery. The application of SCR's in regulated power supplies requiring a large range of voltage control has resulted in the need for the development of a system to give a high power factor throughout its range and one that maintains a low harmonic content in the ac power supplied to the unit.

Ling Electronics (Div. of L.T.V.) has proposed a series-parallel combination of SCR power supplies controlled in a cascaded method to meet the overall objectives of high power factor and low ac harmonics while at the same time providing a precision ($\pm$ 0.1%) current regulated power supply with a wide range of control.

This report will deal with some of the main features proposed for this power supply; we must wait for its final construction to see if these objectives can be satisfactorily met.

II. CRITERIA

The 5,800 kW power supply is to have a rating of 525 volts dc at 11,050 amps and is to meet the following minimum criteria (see SLAC Specifications PS-900-518-R1 for details) when supplying power to an electromagnet with solid iron yokes.

1. Not less than 80% power factor from full voltage to 30% output voltage and less than 1,300 KVAR at less than 30% output voltage.
2. Harmonic currents in the feeder lines to be less than 0.7% rms (for any harmonic) of the rms value of the fundamental line current at full load.
3. Load characteristics: 0.032 to 0.067 ohms, and 0.12 to 2 henries.
4. Current regulation: $\pm$ 0.1% of maximum value from 200 amps to 11,000 amps.
5. 24 phase ripple for 80% (minimum) of maximum power.
6. 80% (minimum) of power shall be derived from a type of voltage control that will not shift the ripple phase when the dc output voltage is changed.

III. DESIGN

The system proposed uses four nearly identical transformers with multiple windings which feed four different power supplies connected in series-parallel. The primary windings of each transformer are designed for the appropriate phase shift to produce 24 phase rectifier groups using a set of secondary windings from each transformer in each power supply group (see Fig. 1).

The main circuit breaker CB-1 is furnished by SLAC as part of a main substation. Relays K21, K22 and K23 are Jennings vacuum switches used to apply 12.47 kV ac to transformers T1, T2, T3 and T4 in a sequential manner to minimize the in-rush current to the power supply. The Jennings vacuum switches are able to carry the available short circuit current, but must have some provision made to be sure that they are never required to open under a short circuit condition; Ling is presently considering normally closed switches properly interlocked with the main 12 kV circuit breaker to provide this protection.

The choice of the type of rectifier used in each of the power supply groups was a compromise of economy, available component ratings and required component deratings. The main transformers will be of dry-type construction; the secondary windings will be constructed with water cooled windings thus decreasing the size of the transformers. The transformer will have three electrostatic shields between the primary and secondary windings to help minimize RFI on the primary 12 kV lines.

IV. SERIES RECTIFIER OPERATION

The total power supply voltage is made up of four SCR controlled rectifier power supplies (see Fig. 2). The units are turned on and phase controlled progressively starting with the highest voltage units M-N then progressing to N-O, O-P, and P-Q. Each section is phase controlled to 97% full-on and high power factor before the next successive unit is turned on. (The magnet current passes through the free wheeling diodes of those sections not turned on.) A small amount of overlap will be provided to give smooth control. It is assumed that the voltage vs phase shift of the firing circuits F1, F2, F3 and F4 are identical; therefore the voltage gain of the amplifier (or dividers A1, A2, A3 and A4) must be different to give the appropriate loop gain of the system throughout the total voltage range of the power supply.

A transductor will probably be used as the current detector for the regulation system. A voltage feedback circuit will probably be used to stabilize the regulation loop and give the required response time. A consideration may be made to make this voltage loop conductively isolated from the high power dc busses; all of the critical amplifiers can be near ground potential if this type of isolation is provided. Without this isolation the amplifiers and reference voltage must be able to operate at 525 volts above ground since we must be able to ground either of the dc output terminals of the power supply.

V. PERMITTED MAGNET RIPPLE CURRENT AND VOLTAGE

The specifications allow a peak-peak current ripple of 0.10% of maximum output current (this is 11 amps) including ripple current and all other possible variables such as drift and those changes due to line voltage and load changes. The configuration of the magnets (see Fig. 5) is such that we cannot depend upon any attenuation of percentage field ripple vs percentage current for those configurations without poles in the magnet.

The minimum inductance of the load is given as 0.12 henries (1100 ohms at 1440 cps). This is probably reduced to 120 ohms because of the effect of the solid iron yokes (i vs e phase $< \sim -80^{\circ}$ maximum). Ling is assuming a conservative value for the ac resistance of 0.5 ohms over the frequency range of 5 to 60 cps.

The maximum inductance (with poles in the magnet) is given as 2. henries (18,000 ohms at 1440 cps). This is probably reduced to 180 ohms because of the effect of the solid iron yokes and poles. (i vs e phase $< \sim 70^{\circ}$ maximum).

The maximum ripple voltage permitted on the magnet is approximately $2 \times 120 = 240$ volts pk to pk at 1440 cps or $240 \div 12 = 20$ volts at 120 cps.

The ripple voltage to be expected on terminals M-Q (see Fig. 2) will be a maximum at about 100 dc output of the power supply; it will have a magnitude of about 55 volts at 1440 cps. System unbalances may produce 10 volts at 120 cps at maximum voltage, but it should be satisfactory because we can probably allow 20 volts of magnet voltage ripple at this low frequency.

VI. FILTER VS REGULATION REQUIREMENT

The minimum time constant of the specified loads is given as 0.12 ÷ 0.48 2.5 seconds at 0.001 cps; this may be only 0.5 seconds at the higher frequencies involved with line voltage steps. It would seem reasonable to allow a deviation of 0.05% in the magnet current for a 1% step line voltage change. Ling claims that a 1% line voltage change will show up as only a 0.3% dc output change, because of automatic compensation in the type of firing circuits used (the amount of automatic compensation will be reduced somewhat when a particular rectifier bank is its limit). The recovery from the transient change is corrected by the regulator within 0.1 seconds. Ling's proposal indicates that their design of the networks will give zero loop gain at $\sim$ 60 cps. An L-C filter with a cutoff frequency of about 20 cps will be used to minimize the transient current changes to the magnet faster than the SCR regulator can follow.

VII. POWER FACTOR CONSIDERATIONS

The proposed power supply has 6 cells in series to develop the required power; this number of cells reduces the expected efficiency to about 94%. The maximum voltage available at low line voltage should be at least 537 volts to give some over-drive for linearity of loop gain at full-rated output. All factors concerned will probably result in a power factor of -93% at rated output; total input will be about 6,420. KVA maximum.

Figures 3 and 4 show the expected relationships between KW and KVAR for the proposed power supply as shown in Figs. 1 and 2.

VIII. HARMONIC VOLTAGE DISTURBANCE

The full ac load current is expected to be about 300 amperes without line filters. There will be approximately 12 amperes or 4% of 23rd or 25th ac harmonic primary current. The specification limits this value to 0.7%; therefore some harmonic filtering will be required at the 23rd, 25th and possibly other harmonics. There are many factors that will influence the amount of filter required. The exact value will be determined during the test period, although some provisions must be made for the filters during the design stages of the power supply.

IX. RADIATED RADIO FREQUENCY INTERFERENCE

1. The specifications call for meeting the requirements of F.C.C. regarding radio frequency interference. This requirement is brought about from two main concerns:

   a. There is a radio science antenna located just 1.2 miles from the SLAC project that surveys frequencies that are at cosmic noise levels. Some of the rf bands of interest are those that are likely to be transmitted by an SCR power supply.

   b. The SLAC project will be using many sensitive electron devices in the vicinity of this power supply. The beam from the 2-mile linear accelerator will be at a repetition rate of 360 cps and this might be in synchronism with any radiated RFI from power supplies.

2. The F.C.C. requirements are interpreted as being:

<u>RF Noise Generation</u> - The design and construction of the power supply shall include provisions to minimize electrical noise generated internally from being transmitted out of the cabinet by any means. The RFI shall be checked over the frequency range from 10 kilocycles to 25 megacycles using a Radio Interference Field Intensity Meter with a Quasi-Peak detector. The maximum permitted RFI either radiated or conducted shall conform to the following:

a. Radiated RFI - The electromagnetic fields as measured at 100 feet from the power supply shall not exceed 24,000/F microvolts per meter (where F is the frequency in the kilocycles) for frequencies from 10 kc to 1600 kc. The field strength shall not exceed 15 microvolts per meter at 100 feet for frequencies from 1600 kc to 25 megacycles. These maximum field strengths shall apply for any permitted operating condition. (See FCC Rules and Regulation, Vol. II, parts 15 and 18.) The permitted rf levels at other distances are to be calculated inversely proportional to distance.

b. Conducted RFI - The maximum conducted electrical noise (radio noise-influence voltage) from 10 kc to 25 megacycles on any ac or dc power cable connected to the terminals of the subject power supply shall be 50 microvolts as measured per NEMA Publication No. 107, "Method of Measuring Radio-Noise," Figs. 1 or 2. (Note that an external L-C filter may be used to isolate the effects of externally connected cables.)

X. CONTROL CIRCUITS

Some of the following features of the control circuits to be used should be pointed out for clarity (see the specifications for details):

1. Three terminal strips TS1, TS2 and TS3 are designated for external connects to the SLAC's controls. These TS designations should be maintained.

a. TS2. Magnet warning lights and magnet temperature interlocks. This exact circuit is to be provided including the contact of K6-A tied to TS1-5 that will be used to energize a warning light when the power supply is on.

b. Note the provisions for 4 extra external interlocks; these could be provided as additional terminals on TS-1 or by a new TS-4.

c. TS-1 is to be wired as shown with the jumpers as indicated. This TS will be used to provide remote controls to the power supply. Note the provisions for Programmed "off" as well as Emergency OFF.

d. TS-3 is to be wired as shown. Note the dc battery interlock K10; the contact of this relay is used in the interlock chain to guarantee that there is dc battery available for control before the control chain is completed. Note that the seal in circuit K11 actually indicates that the main breaker is closed; the operator must hold his finger on the "ON" button long enough for this contact to seal in. Ling intends to automatically sequence the vacuum relays after this seal-in function. There will be a time delay that turns off the power supply if the vacuum relays do not operate correctly. Note that the wires returning to the 12 kv CB from TS-3 and 9 are to insure that the 12 kv breaker is off in case that there is no dc battery available for control at the power supply.

2. The slow run down feature is required so that an operator can push a button and have the current run down slowly, then automatically turn off the power supply when the current reaches zero. It was agreed that the motor drive on the helipot for current control would be used for this rundown feature.

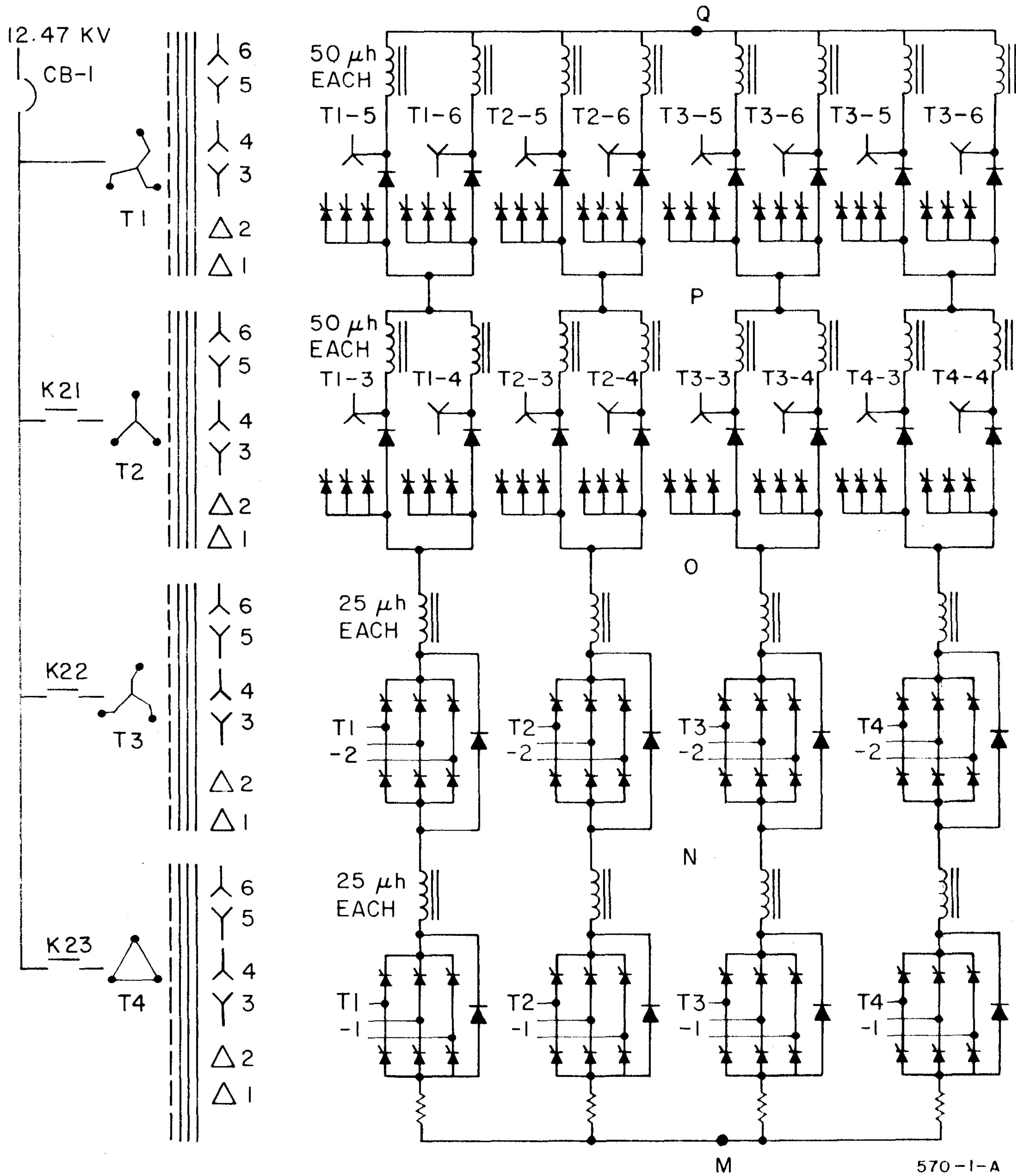
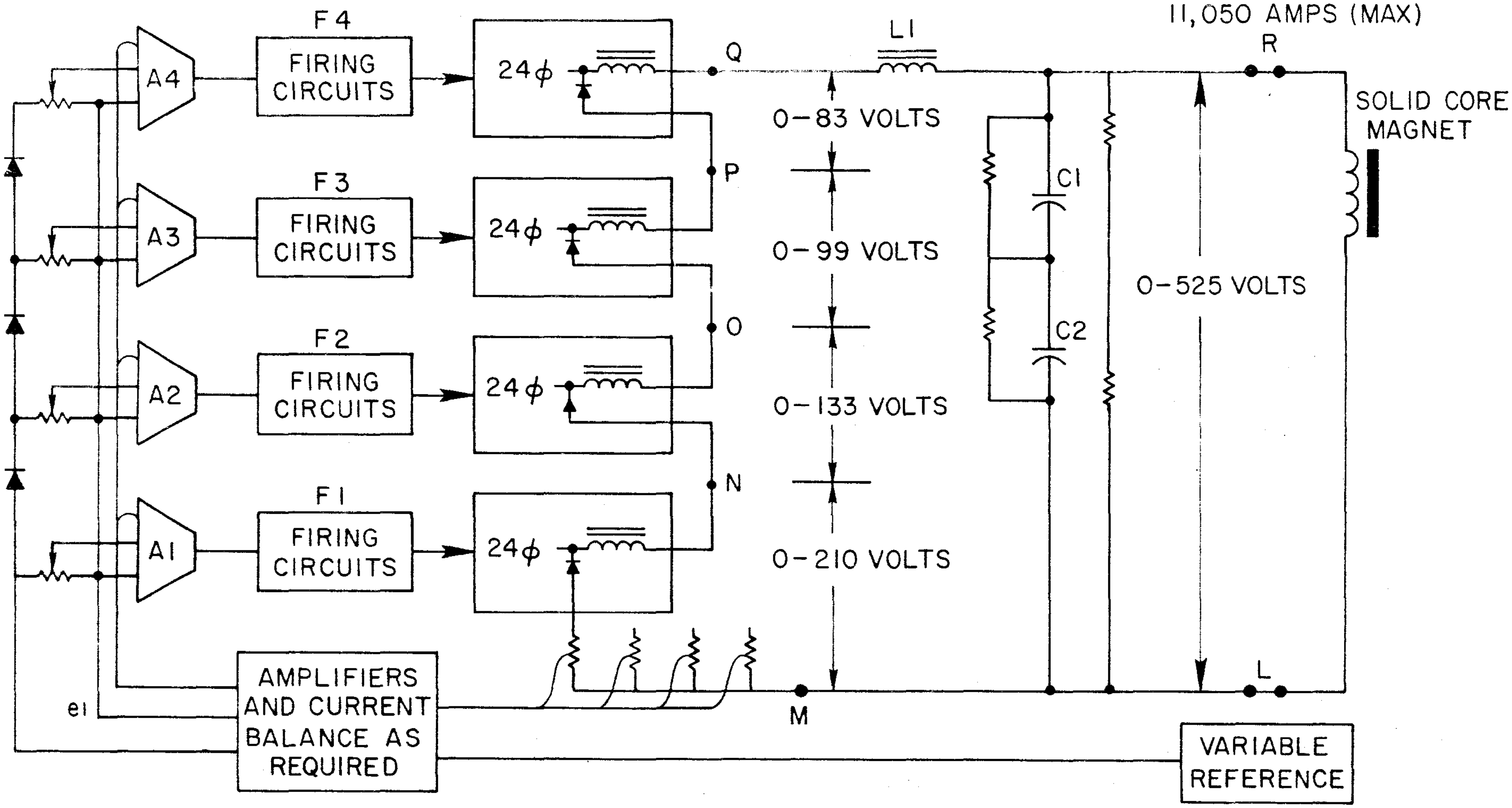


FIGURE 1 -- A 5,800 KW POWER SUPPLY WITH HIGH POWER FACTOR AND LOW HARMONICS USING SILICON CONTROLLED RECTIFIERS.



NOTE:

THE FIRING CIRCUITS ARE DESIGNED WITH A BUILT IN SYSTEM FOR LINE VOLTAGE COMPENSATION.

570-2-A

FIGURE 2

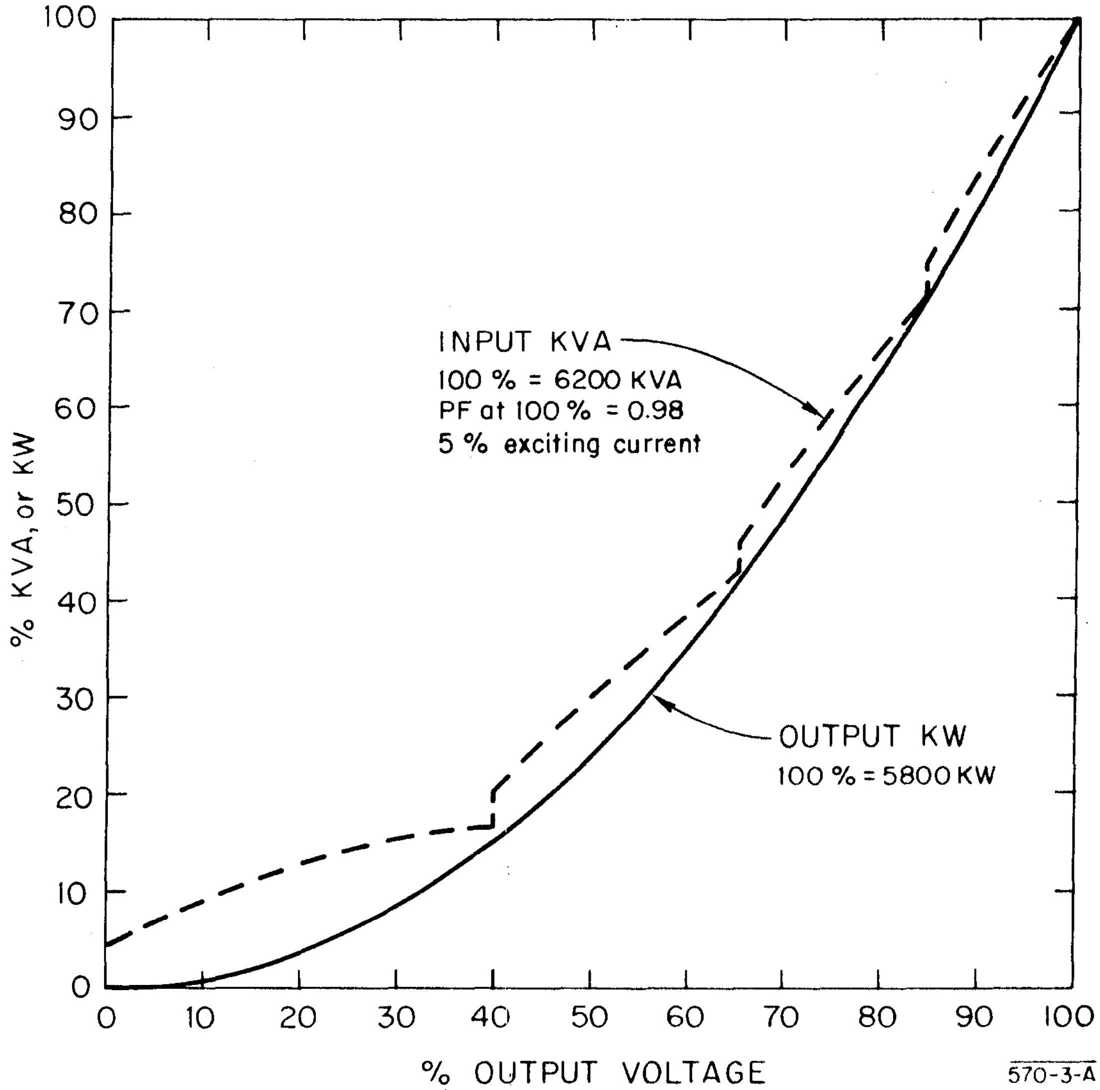

% KVA, or KW
% OUTPUT VOLTAGE
INPUT KVA
100 % = 6200 KVA
PF at 100 % = 0.98
5 % exciting current
OUTPUT KW
100 % = 5800 KW
0
10
20
30
40
50
60
70
80
90
100
570-3-A

FIGURE 3

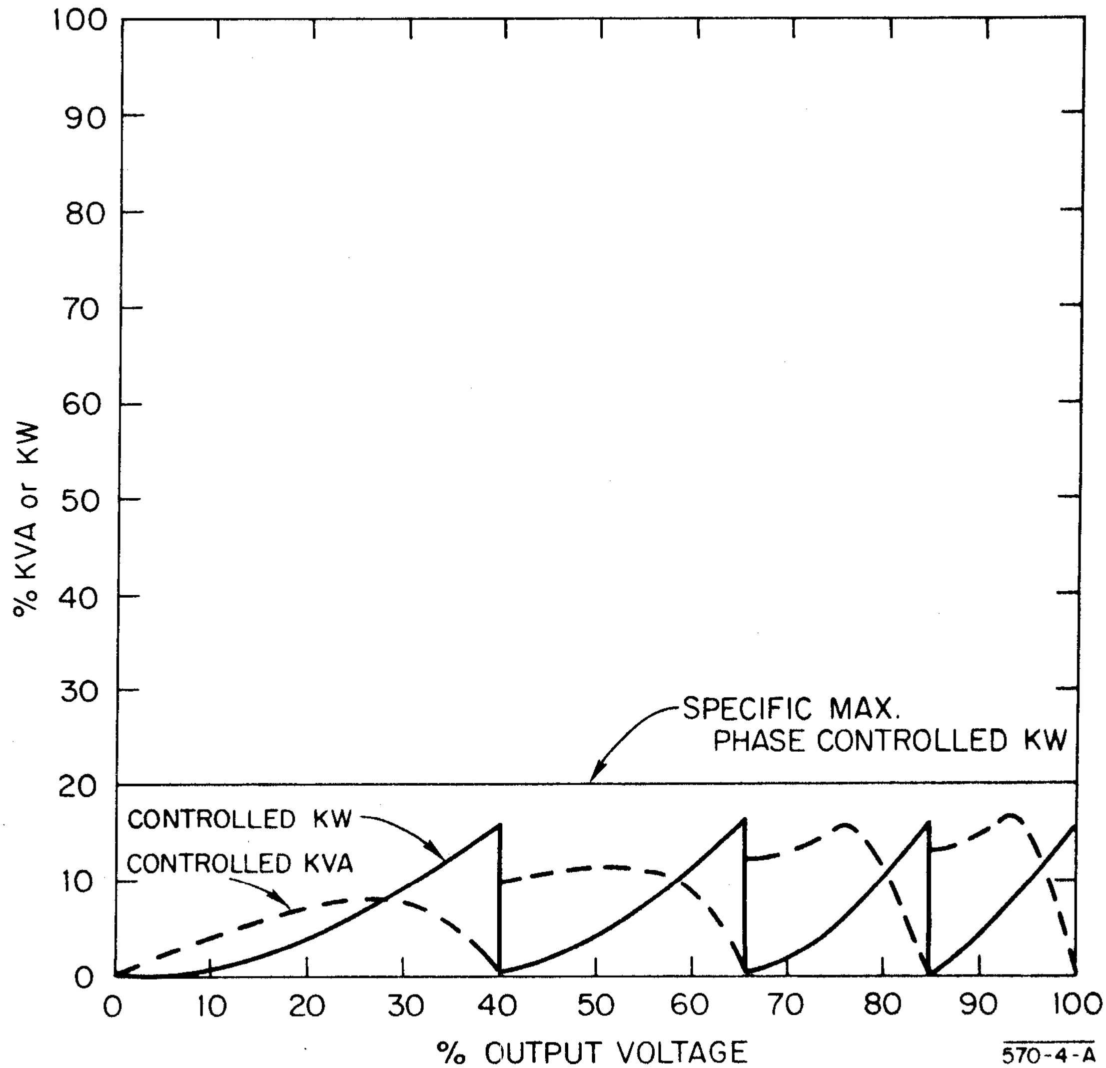

100
90
80
70
60
50
40
30
20
10
0
% KVA or KW
SPECIFIC MAX.
PHASE CONTROLLED KW
CONTROLLED KW
CONTROLLED KVA
0
10
20
30
40
50
60
70
80
90
100
% OUTPUT VOLTAGE
570-4-A

FIGURE 4

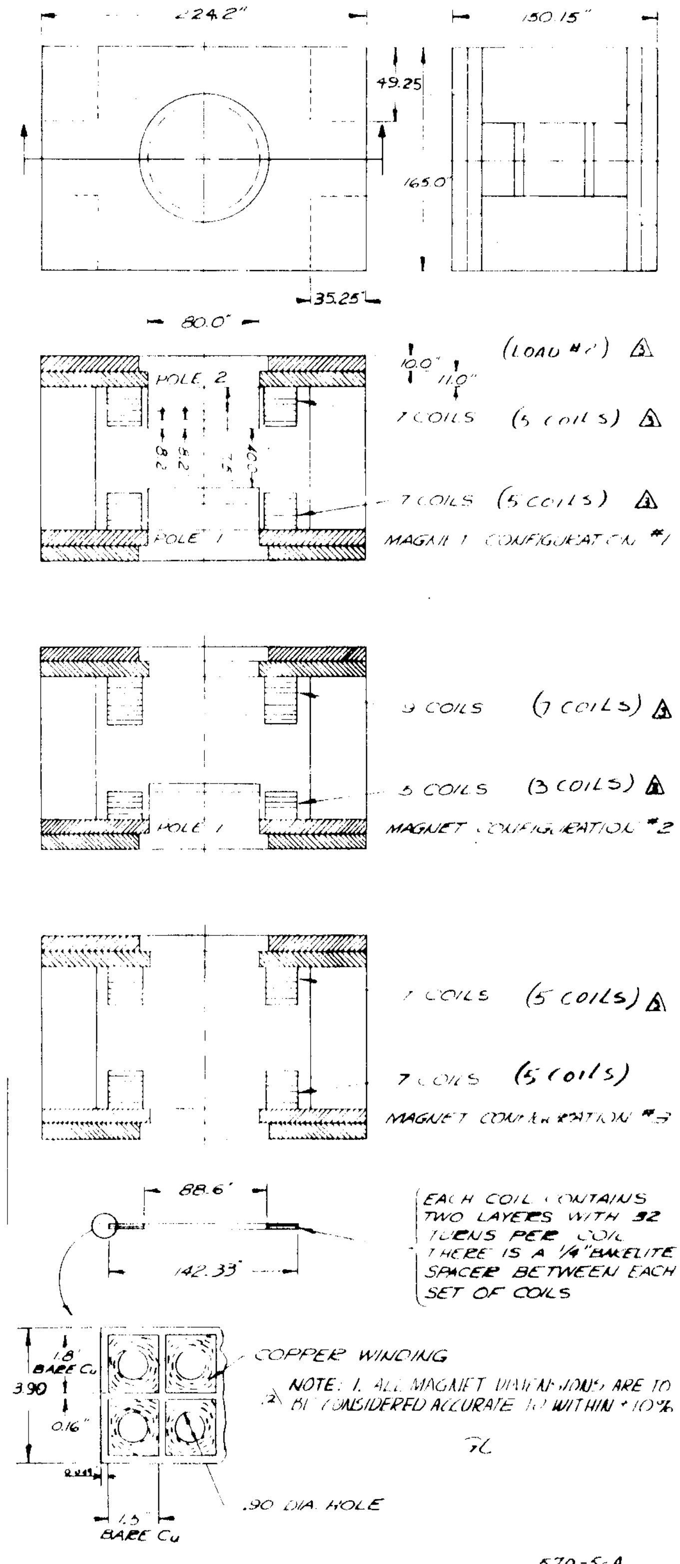

224.2"
150.15"
49.25
165.0"
35.25"
80.0"
POLE 2
POLE 1
10.0"
11.0"
(LOAD #2) 2
7 COILS (5 COILS) 3
7 COILS (5 COILS) 3
MAGNET CONFIGURATION #1
9 COILS (7 COILS) 3
5 COILS (3 COILS) 3
MAGNET CONFIGURATION #2
7 COILS (5 COILS) 3
7 COILS (5 COILS)
MAGNET CONFIGURATION #3
88.6"
142.33"
EACH COIL CONTAINS TWO LAYERS WITH 32 TURNS PER COIL
THERE IS A 1/4" BAKELITE SPACER BETWEEN EACH SET OF COILS
1.8" BARE Cu
3.90
0.16"
1.5" BARE Cu
COPPER WINDING
.90 DIA. HOLE
NOTE: 1. ALL MAGNET DIMENSIONS ARE TO BE CONSIDERED ACCURATE TO WITHIN ±10%
570-5-A

FIGURE 5