TN-66-35
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MINIMIZING LINE VOLTAGE DISTURBANCES GENERATED BY 360 kW SCR POWER SUPPLIES

1. INTRODUCTION

The 360 kW silicon controlled rectifier power supplies (120 volt × 3,000 amp) purchased for the use in the end stations produce sufficient line voltage perturbations that they mutually interfere with each other. See Fig. 1 for the resultant line voltage perturbations during the commutation period of one of these 6 bridge rectifiers when operating at 2500 amps.

Figure 2 shows an expanded view of these two notches one from each of two power supplies operating at the same time on the same transformer bank. Note that the duration of the interference is a function of operating current. The damped oscillation at the beginning and end of the commutation period is approximately 50 kc with a Q of 4.

Two or more of these power supplies disturb each other if the firing times overlap; sometimes they disturb each other with a firing separation of anything less than that shown in Fig. 2.

The following report describes one possible method of cleaning up the 480 V power line to eliminate the cross interference between power supplies; power factor correction is added at the same time to aid in maintaining a lab power factor higher than 90% as required by the utilities power contract.

The addition of the recommended power factor correction will increase the number of power supplies that can be operated at high power levels on a single transformer.

2. AC POWER SYSTEM

More than seven power supplies may be fed from a single 3300 kVA transformer bank as shown in Fig. 3; therefore, it is very probable that two power supplies will be operating with coincident commutation periods.

The rectifier transformers are divided between Wye-delta and delta-delta connected units, but this will have little effect upon the transients put on the line during the commutation periods.

There will be several of these transformer banks and other larger silicon controlled rectifier power supplies connected to the 12.47 kV bus at the research area substation. See Fig. 4 for details of the complete system. This bus has a source impedence ranging from (0.04 + j 0.4) to (0.2 + j 1.5) ohms and can be expected to have harmonic ripple voltages in excess of those shown on Table 1; therefore, care must be taken to avoid a series resonance condition between the leakage reactance of T1, Fig. 3, and any added power factor correction on the 480 volt lines at the power supplies.

An inset is shown on Fig. 3 giving the pertinent details of the 360 kW power supplies involved.

3. DC POWER SUPPLY 120 V - 3,000 AMPS

Each of the power supplies were purchased to meet the SLAC specifications PS-900-523-00-R1. These units are 3 phase bridge rectifiers with an L-R-C filter (see Fig. 3). They are designed for $\pm$ 0.1% current regulation using SLAC supplied firing circuits (see Fig. 5), amplifiers and a transductor modeled from similar units at Lawrence Radiation Laboratory, Berkeley, California.

The open circuit no load voltage is about 147 volts on tap No. 1. The maximum voltage on a 0.037 ohm load is 122 volts. Additional taps on the transformer primary have been provided for 80%, 60%, and 40% output voltage to give higher power factors when operating at decreased outputs (see Fig. 6).

One half of these power supplies have a Wye-delta rectifier transformer the other half are delta-delta; this transformation helps reduce the 5 and 7 harmonic currents but is not complete because the units operate over a wide phase controlled range.

4. MEASURED EFFECT OF ADDED POWER FACTOR CORRECTION

Figures 7, 8, and 9 show the ac line voltage disturbances for no power factor correction, 15 kVAR, and 90 kVAR respectively when added inside of the power supply 1Q5. A "Twin T" filter has been used to suppress the 60 cps fundamental sine wave for these pictures. The fundamental would normally be as shown in Fig. 1 without the Twin T. Figs. 10 and 11 show the ac current to the capacitors in the 15 kVAR and 90 kVAR banks. A weston clip-on ammeter reads 105 amps and 200 amps respectively. The power supply was operating at 83 volts and 2500 amps dc output during these tests.

The damped waves shown in Figs. 8 to 11 correspond to a resonance between the leakage inductance of T1 and the added power factor capacitors.

TABLE I

12.47 kV Line Voltage Harmonics

The ac voltage fed to electrical and electronic equipment at the Stanford Linear Accelerator Center will have different degrees of ac harmonic voltages superimposed on the fundamental depending upon the type of accelerator operation and loading.

The following sets of data are given as a typical distribution of the RMS harmonic voltage that may be present on the 12 kV supply line. Care should be given in the application of electronic circuits that depend upon a constant ratio of peak to RMS voltage or in circuits that may have resonances in the regions involved.

Harmonic Number	Frequency CPS	Percent RMS of Fundamental Voltage (3) Condition (1)	Condition (2)	Harmonic % RMS Limit on P.F. Cap. (4)	
2	120	0.47		42.	kVA Limited
3	180	0.17		34.	
4	240	0.11		30.	
5	300	0.34	0.55	26.	
7	420	0.23	0.46	22.	
11	660	0.16	0.40	18.	
13	780	0.12	0.20	16.	
17	1020	0.20	0.90	13.	Current Limited
19	1140	0.14	0.55	12.	
23	1380	0.18	0.55	10.	
25	1500	0.16	0.50	9.	

These harmonics may result in a 7% peak to peak voltage disturbance on the 12 kV system or a total of 14% peak to peak disturbance on some selected 470 volt distribution systems.

1. The accelerator operating at a pulse rate of 60 pulses per second.
2. The accelerator operating at a pulse rate of 360 pulses per second.
3. Other harmonics may be present because of the operation of other large magnet power supplies.
4. This table shows the RMS voltage limit on harmonics on a power factor capacitor for a single harmonic applied simultaneously with 100% fundamental as limited by a maximum of 135% kVA (total) or 250% total of rated fundamental RMS current. The peak ac voltage must also be less than 1.51 times the rated RMS fundamental voltage; this puts a limit of 7% harmonic with 100% fundamental (see Nema Standard Publication No CP1 - 1965).

5. NECESSARY PRECAUTIONS

It is essential that certain precautions be taken when adding power factor capacitors to systems such as shown in Fig. 3; some of these precautions are as follows:

1. Capacitors for transient suppression must be added at each power supply. (See Fig. 3). Capacitors at 1Q5 power supply are only 50% effective in decreasing transients from 1Q6 and not effective for transients from 1D6. Capacitors may also be added very close to the power distribution panel.

2. Any capacitors added must be critically damped for the inductances involved, otherwise a build up of oscillation may occur when several similar power supplies are operating on one bank at random phasing.

3. The leakage inductance of T1 and power factor capacitors C1 forms a series resonance as looked at from the 12 kV bus, and could lead to destructive currents if not damped out. This must be avoided for all possible numbers of power supplies and loading on one transformer bank.

4. The ac harmonic currents in the capacitors must be within their capabilities for all possible conditions.

5. Care must be taken so as not to increase the di/dt currents in the silicon controlled rectifiers beyond their ratings by lowering the line impedance with the addition of these capacitors, or to allow the rate of recovery voltage after conduction to be excessive.

6. POWER SUPPLY CROSS INTERFERENCE

The interference noted when two power supplies without power factor correction have their commutation period coincident can amount to a jitter of the width of at least the commutation period 0.19 ms at 3,000 amps or about 0.4%. The addition of 90 kVAR power factor correction on one power supply causes a resonance at about the 12.5th harmonic (see Fig. 9) and 15% voltage. I can demonstrate a phase shift in firing corresponding to 6% output voltage when the phase of this harmonic is varied.

I believe then that the jitter in firing is a result of low frequencies on the power feeding the firing signals and is not directly the result of RFI or fast line transients,except that these power transients may excite resonances in the system. The step in the 470 volt supply to the main transformer (see Fig. 1) represents a discontinuity in the total average current out versus phase angle of firing and

and causes an effective change in loop gain for small deviations. The notch may be reduced with the addition of small amounts of capacitors, but provisions must be made to prevent excessive ringing.

A filter must be added on the ac power lines supplying the firing signals without introducing variable phase shifts and locally resonant systems (it will have to cut off sharply above 100 cps), but I believe that we should also clean up the 480 volt ac power lines with the application of power factor correction capacitors. We need them any way to obtain a better power factor and besides I do not believe that the 470 volt lines feeding other equipment should have the magnitude of transients shown in Fig. 1.

7. RECOMMENDED SOLUTION

I recommend that at least 100 kVAR of P.F. Correction be added to each power supply; this value will help eliminate the cross interference. 100 kVAR will correct a 200 kW 70% power factor load (a possibility) to a power factor of about 90% with a series resonance at the 10.8 harmonic with T1 Fig. 3. Other resonances with T1 for different numbers of power supplies on the line are shown in Table II with the required series resistances for critical damping.

TABLE II

No. of Power Supplies (100 kVAR in each)	Resonance Harmonic N	Critical Damping Resistance (ohms) $R_c = WL_1$
1	10.8	0.21; (9.0 kW total)
2	7.7	0.15
3	6.3	0.12
4	5.4	0.11
5	4.9	0.10
6	4.5	0.09
7	4.1	0.08
8	3.7	0.07
9	3.6	0.07
10	3.4	0.068

A comparison of the data in this table and the data in Table I shows that it will be almost impossible to avoid some critically resonant condition with the tolerances of standard components. I believe that we should start with these values but expect to add about 300 kVAR on each transformer bank as a base correction when more empirical data is available on the complete system.

It should not be necessary to design a system that will present the exact critical damping resistance for the resonance frequencies represented by all possible combinations of power supplies. A practical solution would be a resistance of about 0.2 ohms for the 100 kVAR in each power supply; this may be under damped with only one power supply turned on, but it will be more exact for a larger number of units in parallel. It is realized that there is a considerable difference whether or not the various power supplies are delivering current to a load, but the system must be designed to be reasonably safe from a series resonance coupling with most harmonics on the 12 kV line when all connected power supplies are adjusted to zero current.

8. WARNING

A word of caution should be mentioned at this time regarding the application of Power Factor Capacitors to power lines at SLAC. Please refer to Table I. Note that columns 3 and 4 are the expected amounts of harmonic voltages on the SLAC power lines per Paul Edwards. Note that Column 5 shows the maximum permissable single harmonic that can exist simultaneously with 100% rated fundamental voltage without damage to standard capacitors. It is readily apparent that if Paul's numbers are correct, then standard rated capacitors can be used in large banks to help reduce the line harmonics. Resonant traps must have Q's of less than 100 to prevent excessive single-harmonic currents.

9. LOCATION OF POWER FACTOR CORRECTION

It is possible to connect the P. F. Capacitors on either the line or load side of the main contactor.

I prefer these capacitors to be on the load side of the contactor. In this position they will help to minimize voltage transients on the silicon controlled rectifiers when the contractors are turned off at zero dc current and caused to break the transformer magnetizing current. The capacitors will also ring down when truned off, thus aiding in setting the transformer flux to zero for lower turn-on voltage transients. The step start relays should aid in energizing the capacitor banks with minimum inrush currents.

The overall ac power system may require more power factor correction than is represented by 100 kVAR in each power supply. Further studies and system checks must be made to determine where such capacitor banks should be connected to the system when all of the major loads are connected and operating.

10. POWER SUPPLY AC LINE CURRENTS

Figure 12 shows the 470 V ac line currents required by a 360 kW power supply versus the dc current to a typical load for various primary taps on the rectifier transformer without power factor capacitors.

Points B and C show the ac current that should be required when 100 kVAR or 200 kVAR of power factor correction is connected in parallel with the primary of the rectifier transformer. Actually the amount of current reduction to a power supply when 100 kVAR is added may be less than expected because of the harmonic currents involved unless steps are taken to affect a critically damped circuit. In one test with two different power supplies feeding the same type load, there was no difference in the primary ac current at a load of 2500 amps dc when one unit was without PF correction and the other had 90 kVAR connected without damping resistors. The resultant power factor for these curves can be approximated by the relationship between kW and kVA. This is shown in Fig. 6.

Note that it should be possible to run only 7 fully loaded power supplies on a single 3,300 kVA bank with no power factor capacitors added, but 9 power supplies with 100 kVAR of capacitors per power supply providing that harmonic currents do not increase the effective RMS current in the lines. Adding 220 kVAR of capacity would allow 10 power supplies per main transformer with a fully loaded power factor of 95%, but does not seem worth the added expense.

A study should be made to see if it is possible to shorten the commutation time by changing the values of the R-C surge protection across the main SCR's or by adding an R-C network across the secondary windings of the rectifier transformer. Indiscriminate changes or addition of this type of circuit can easily destroy the SCR's because of excessive di/dt at turn off, therefore care must be taken in this study. A shorter commutation time will help minimize energy in the transients on the power lines.

11. AC HARMONIC LINE CURRENTS

The ac current to a 6 pulse rectifier circuit is comprised of the fundamental 60 cps current and the various harmonic current determined by the type of rectifier circuit, load parameters, and the transformer commutation reactance.[1]

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1. Rectifier Circuits Theory and Design, Johannes Schaefer (1965).

The relative values of the harmonic currents for an ideal 6 pulse rectifier, i.e.; regular bridge connection, inductive load, no free wheeling action, and zero commutation reactance is given by,

$$I_N = \frac{I_o}{N} = \frac{100\%}{N}$$

I_N = Harmonic current at the N^{th} harmonic.

I_O = Fundamental Line current

N = Harmonic Number

The ac line harmonics (N) to be expected for this ideal case are: 5, 7, 11, 13, 17, 19, 23, 25, etc, $N = n6 \pm 1$. These harmonic currents will flow through the reactance of the main power system transformer or through any added shunt capacitors if their reactance is less than that of the transformer.

The practical rectifier will normally have less higher order harmonics present than the ideal case; (if we ignore system resonances) and will normally have other harmonics present because of system irregularities, unbalanced firing, free wheeling diode action, etc.

A 100 kVAR bank of power factor capacitors added without tuned inductances or damping resistors might be expected to absorb most of these currents above the 12^{th} harmonic; the 5^{th} and 7^{th} harmonic would still pass through the power transformer and could cause a voltage perturbation of:

$$E \text{ ripple} = \frac{540}{N} (0.02N)$$

$$= 10.8 \text{ volts or } 4\% \text{ for each harmonic}$$

This may be some of the reasons for the voltage perturbations in Fig. 9, but is not the cause of the damped wave of Fig. 8, because the permitted harmonics can not add up to a damped wave train.

Any capacitor banks added must be able to handle these harmonic currents or be appropriately trapped to keep these currents under control.

12. CONCLUSION

This report has pointed up some of the problems and possible solutions to the cross interference experience when these units were first turned on. The order in which those involved should find final solutions should be:

1. Add traps to the 470 volts feeding the firing circuits to eliminate the harmonics and high frequency transients.
2. Check desirability of decreasing the commutation time with circuits on the secondary of the rectifier transformers.
3. Add power factor correction to the power supply to decrease ac primary currents and minimize transients on the 470 volts.
4. Check interrelationship of added power factor correction and the rest of the power system.
5. Take a new set of power data similar to Figs. 6 and 12 with accurate instruments. The data in this report was a survey type investigation using a weston clip on ammeter and no watt meters.

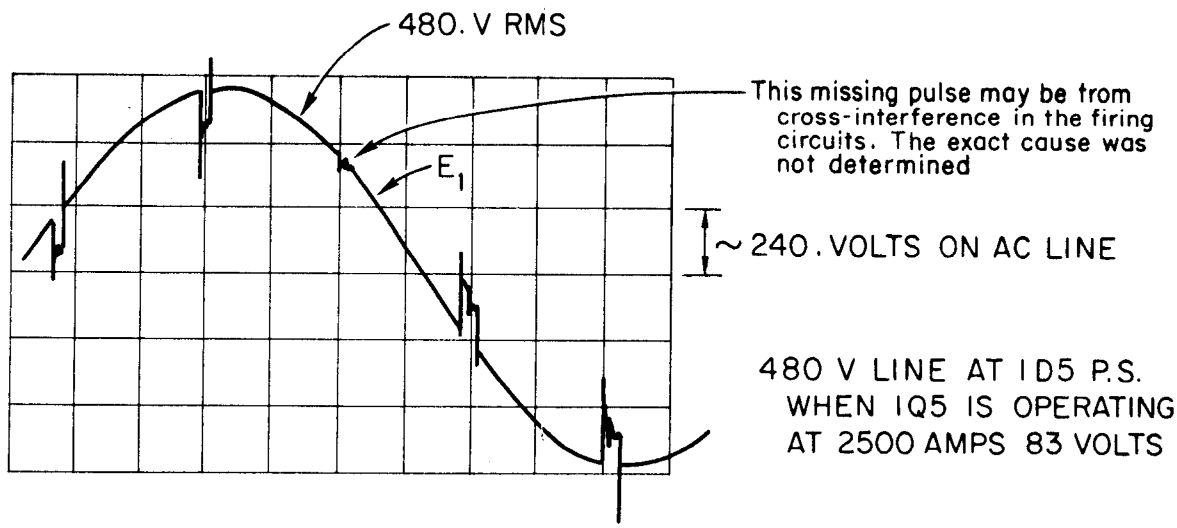

FIGURE 1

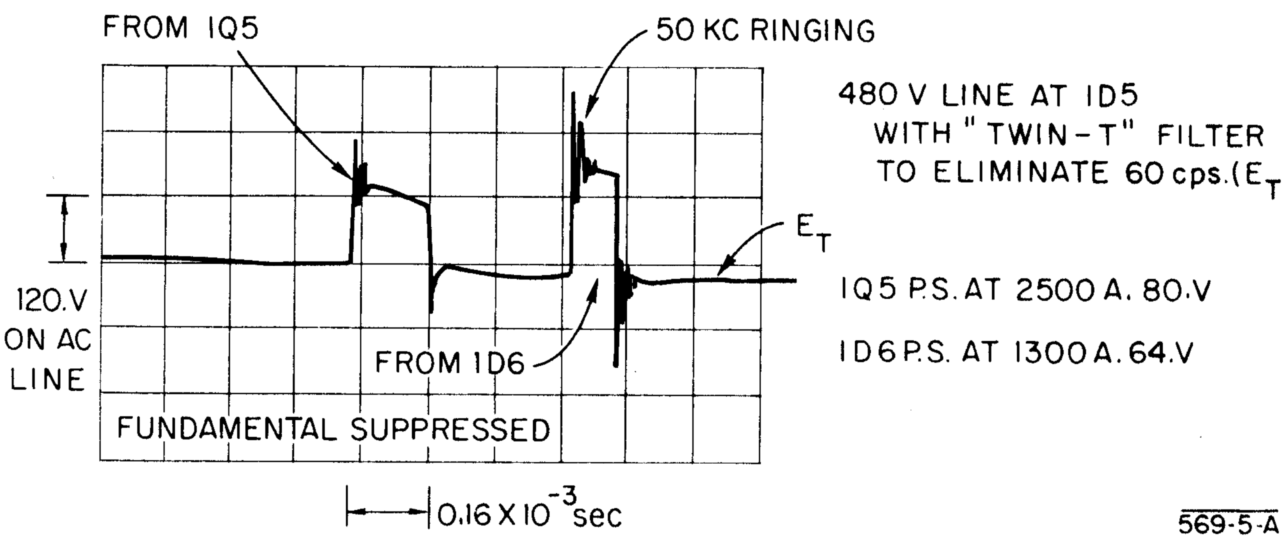

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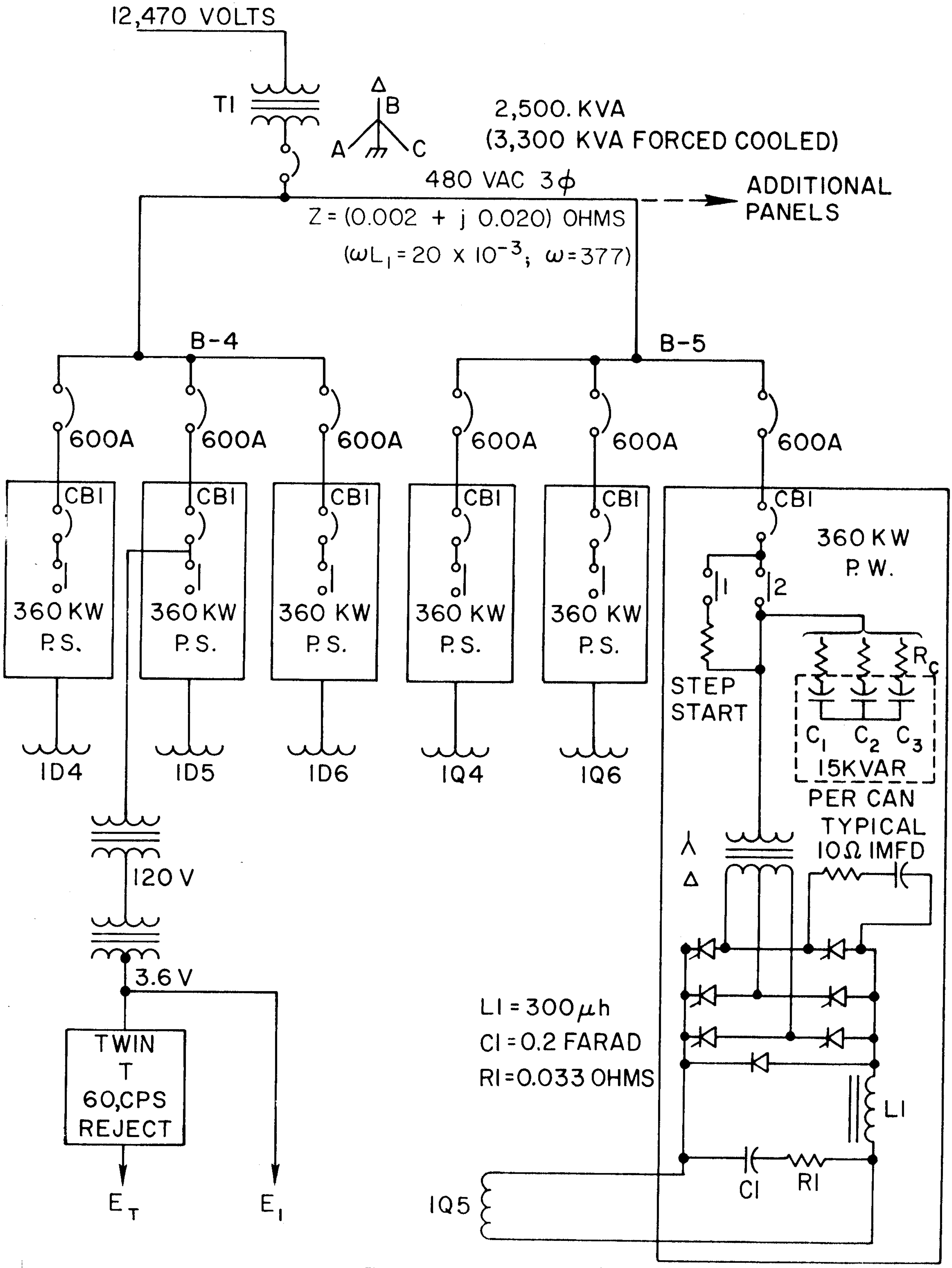
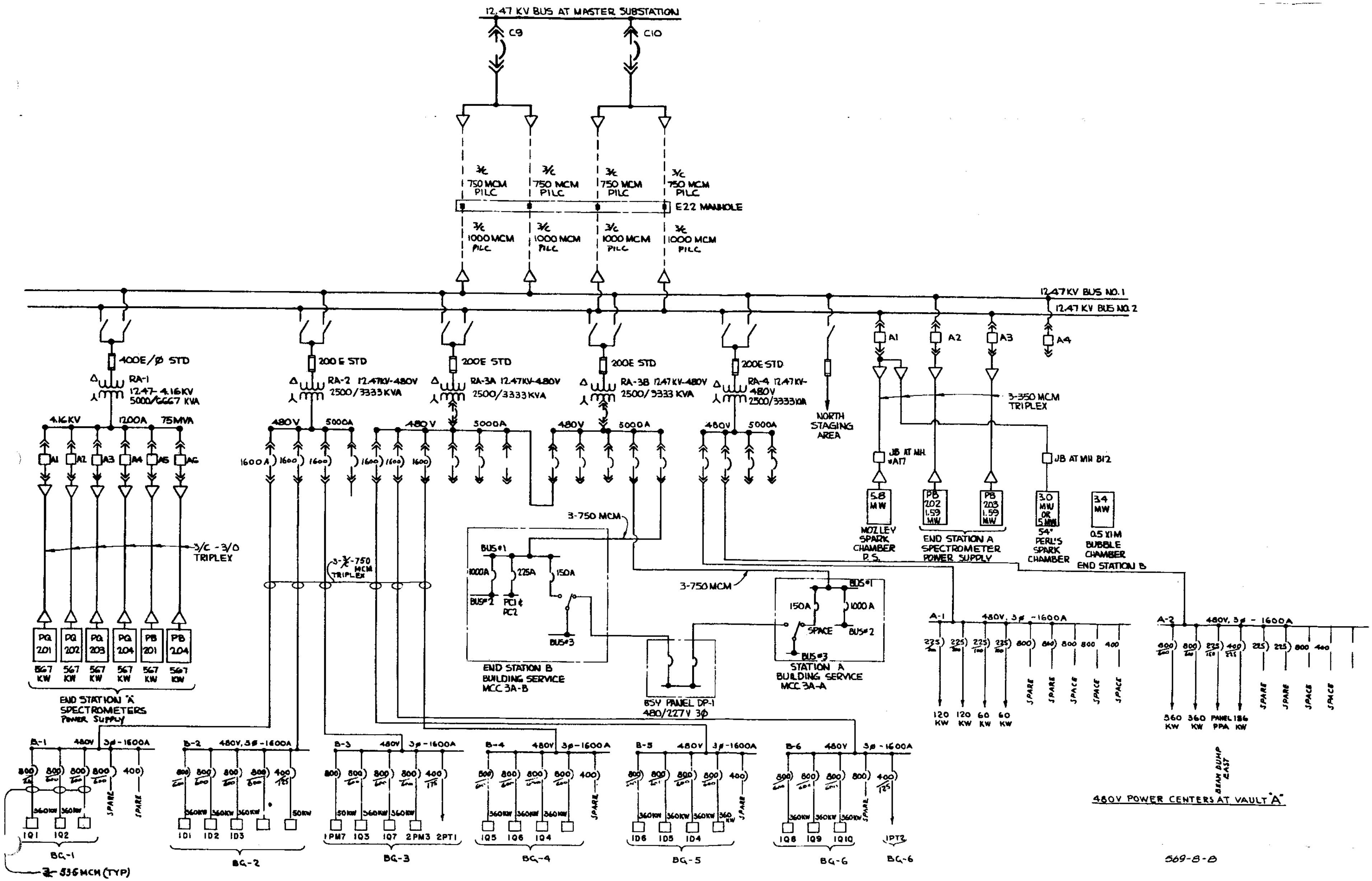
FIGURE 2



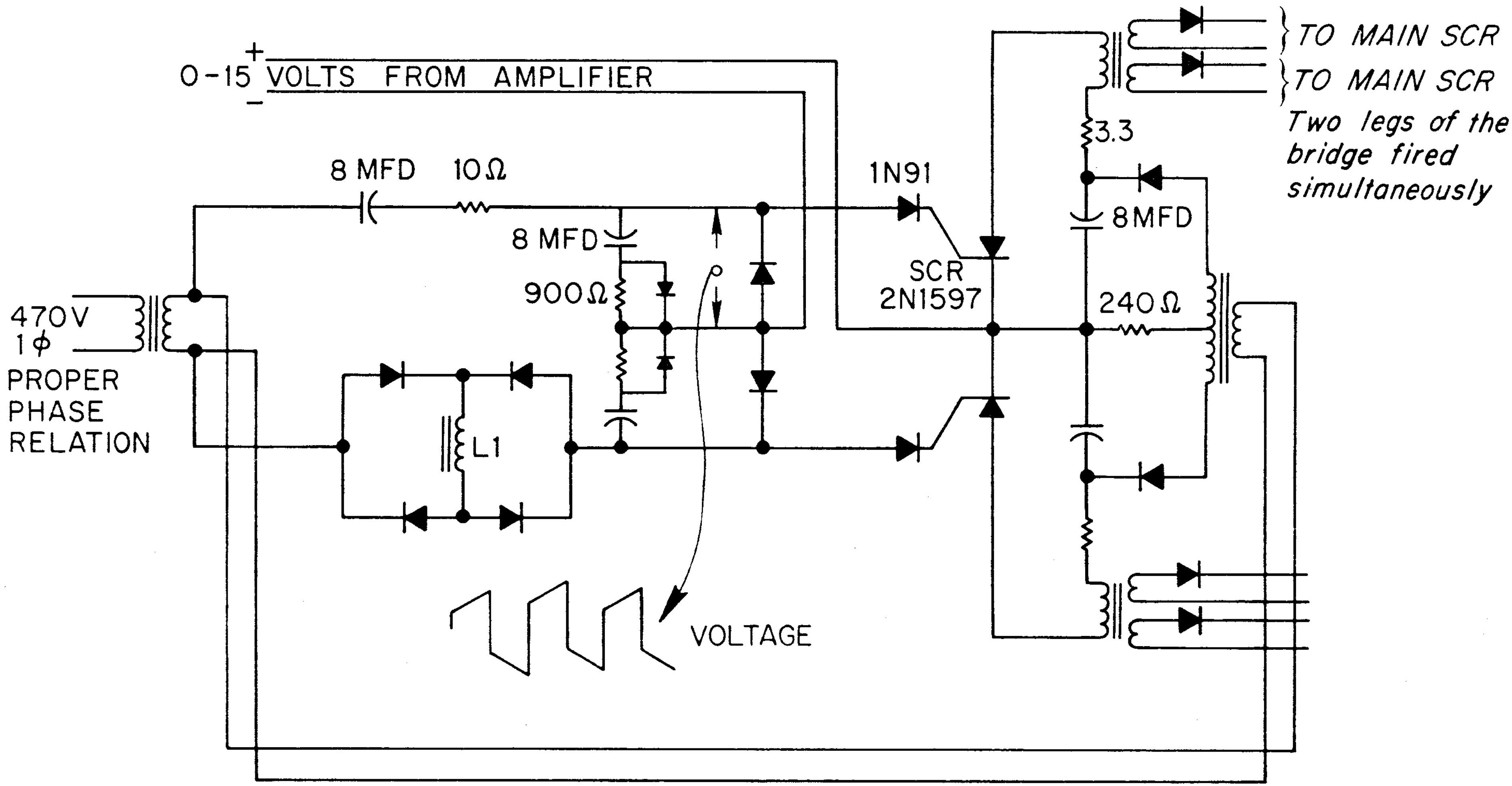
12,470 VOLTS
T1
Δ
B
A
C
2,500. KVA
(3,300 KVA FORCED COOLED)
480 VAC 3φ
ADDITIONAL PANELS
Z = (0.002 + j 0.020) OHMS
(ωL1 = 20 x 10-3; ω=377)
B-4
B-5
600A
600A
600A
600A
600A
600A
CB1
CB1
CB1
CB1
CB1
CB1
360 KW P.S.
360 KW P.S.
360 KW P.S.
360 KW P.S.
360 KW P.S.
360 KW P.W.
1D4
1D5
1D6
1Q4
1Q6
1
2
STEP START
Rc
C1 C2 C3
15KVAR PER CAN
TYPICAL 10Ω 1MFD
120 V
3.6 V
TWIN T 60,CPS REJECT
ET
E1
L1 = 300μh
C1 = 0.2 FARAD
R1 = 0.033 OHMS
L1
C1
R1
1Q5
569-3-A

FIGURE 3



12.47 KV BUS AT MASTER SUBSTATION
C9
C10
3/c 750 MCM PILC
E22 MANHOLE
3/c 1000 MCM PILC
12.47 KV BUS NO. 1
12.47 KV BUS NO. 2
400E/Ø STD
RA-1 12.47-4.16KV 5000/6667 KVA
200E STD
RA-2 12.47KV-480V 2500/3333 KVA
RA-3A 12.47KV-480V 2500/3333 KVA
RA-3B 12.47KV-480V 2500/3333 KVA
RA-4 12.47KV-480V 2500/3333 KVA
4.16 KV
1200A
75MVA
480V
5000A
NORTH STAGING AREA
3-350 MCM TRIPLEX
JB AT MH #A17
JB AT MH B12
5.8 MW
MOZLEY SPARK CHAMBER P.S.
PB 202 1.59 MW
PB 203 1.59 MW
END STATION A SPECTROMETER POWER SUPPLY
3.0 MW OR 5 MW
54" PERL'S SPARK CHAMBER
3.4 MW
0.5 XIM BUBBLE CHAMBER END STATION B
3/c - 3/0 TRIPLEX
3-3/c-750 MCM TRIPLEX
3-750 MCM
PQ 201
PQ 202
PQ 203
PQ 204
PB 201
PB 204
567 KW
END STATION "A" SPECTROMETERS POWER SUPPLY
END STATION B BUILDING SERVICE MCC 3A-B
BUS #1
BUS #2
BUS #3
1000A
225A
150A
PC1 & PC2
SPACE
BSY PANEL DP-1 480/227V 3Ø
STATION A BUILDING SERVICE MCC 3A-A
A-1 480V, 3Ø -1600A
120 KW
60 KW
SPARE
SPACE
A-2 480V, 3Ø - 1600A
360 KW
PANEL PPA
186 KW
BEAM DUMP EAST
480V POWER CENTERS AT VAULT "A"
B-1 480V 3Ø-1600A
B-2 480V, 3Ø-1600A
B-3 480V 3Ø-1600A
B-4 480V 3Ø-1600A
B-5 480V 3Ø-1600A
B-6 480V 3Ø-1600A
360KW
50KW
1Q1
1Q2
BQ-1
1D1
1D2
1D3
BQ-2
1PM7
1Q3
1Q7
2PM3
2PT1
BQ-3
1Q5
1Q6
1Q4
BQ-4
1D6
1D5
1D4
BQ-5
1Q8
1Q9
1Q10
1PT2
BQ-6
3-536 MCM (TYP)
569-8-8

FIGURE 4



The 470 volts fed to this circuit must have zero variable harmonic voltage content.

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FIG. 5--TYPICAL SCR FIRING PHASE CONTROL

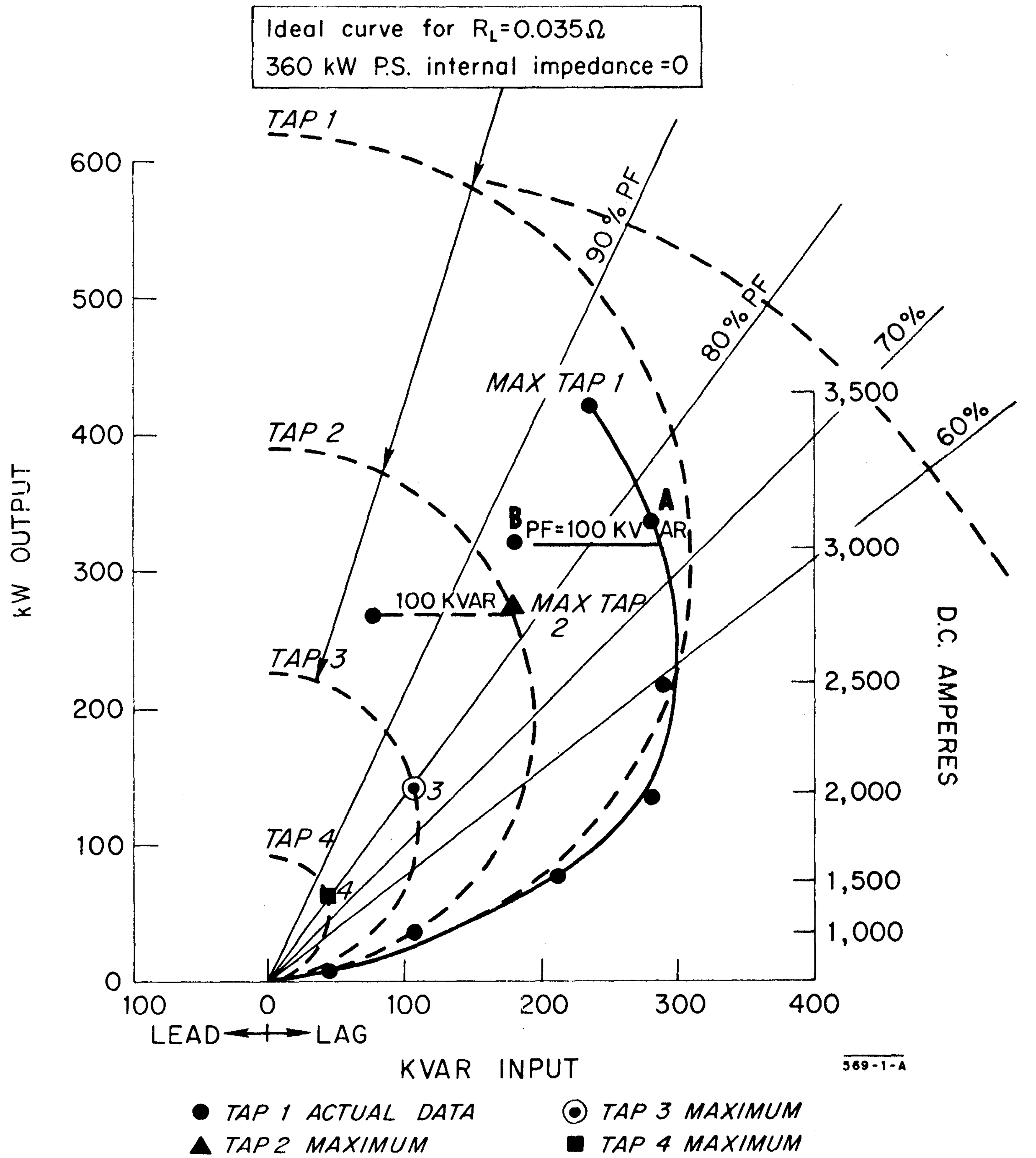
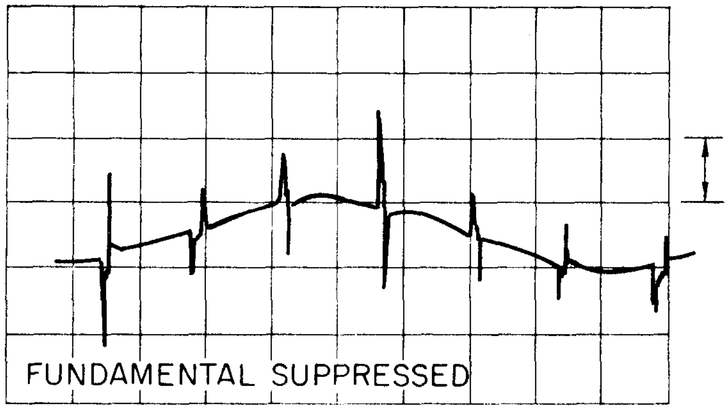


FIG. 6--360 kW POWER SUPPLY
Power Diagram



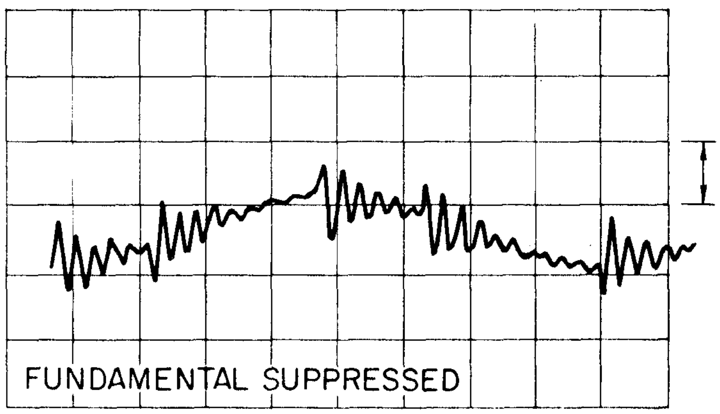
E_T VOLTAGE AT 1D5

1Q6 ON AT 2500. A dc

240.V ON AC LINE

NO CAPACITORS ON THE LINE

FIGURE 7



E_T VOLTAGE AT 1D5

1Q5 ON AT 2500. A

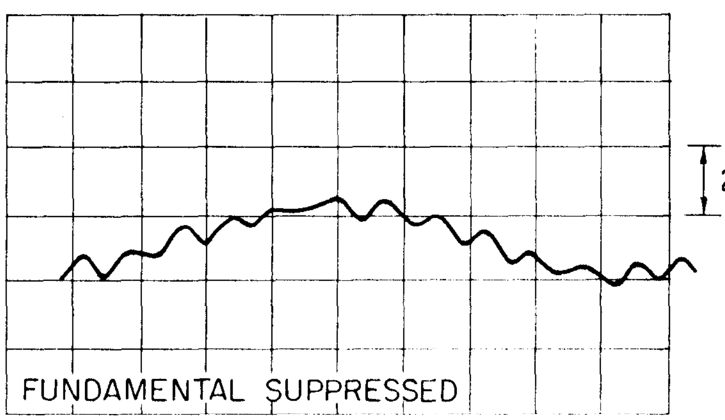
240.V ON AC LINE

POWER FACTOR CORRECTION

C_{1+2+3} = 15 KVAR

R_C = 0

FIGURE 8



E_T VOLTAGE AT 1D5

1Q5 ON AT 2500 A

240.V ON AC LINE

POWER FACTOR CORRECTION

C_{1+2+3} = 90 KVAR

R_C = 0

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FIGURE 9

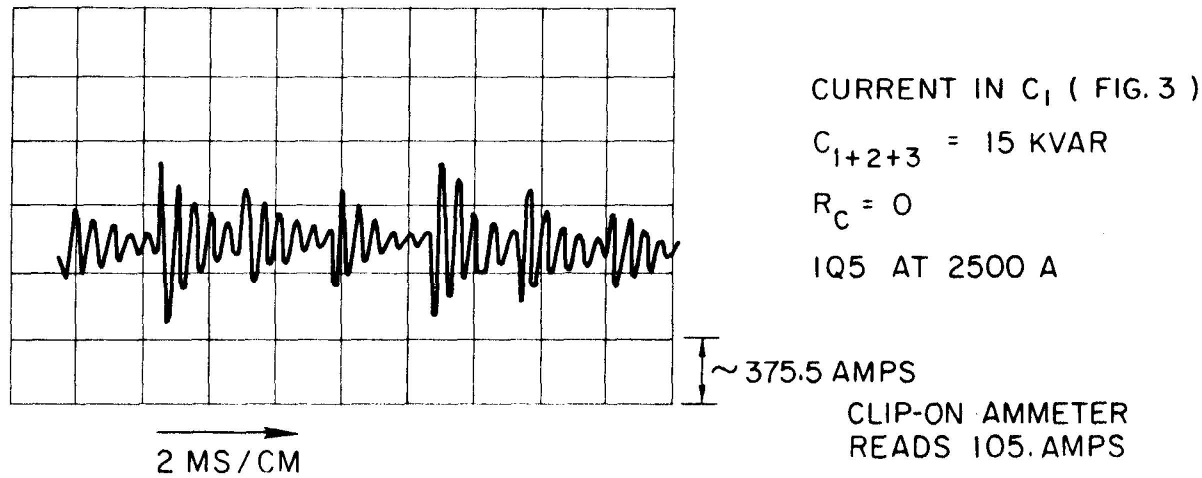

FIGURE 10

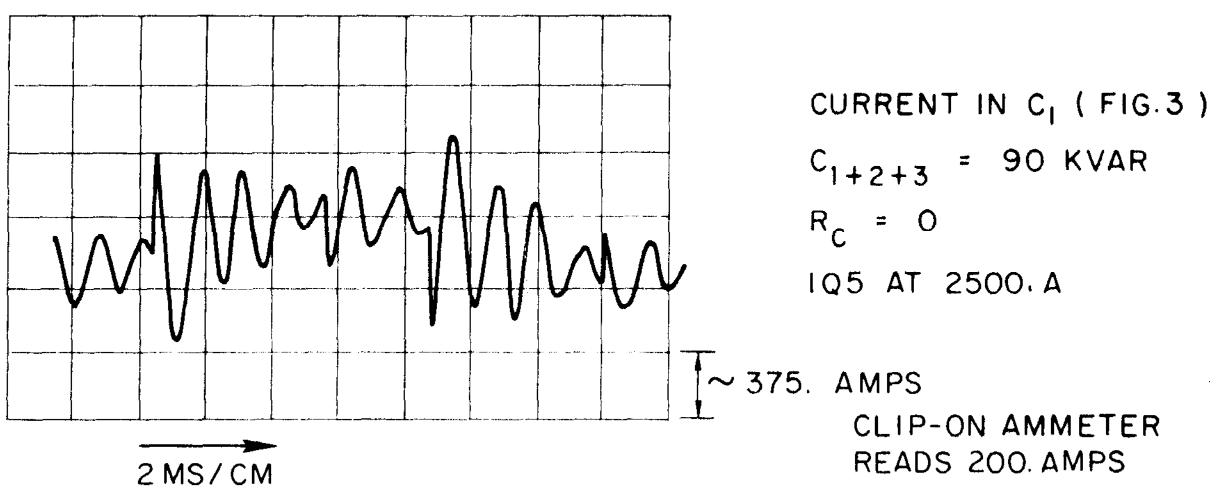

FIGURE 11

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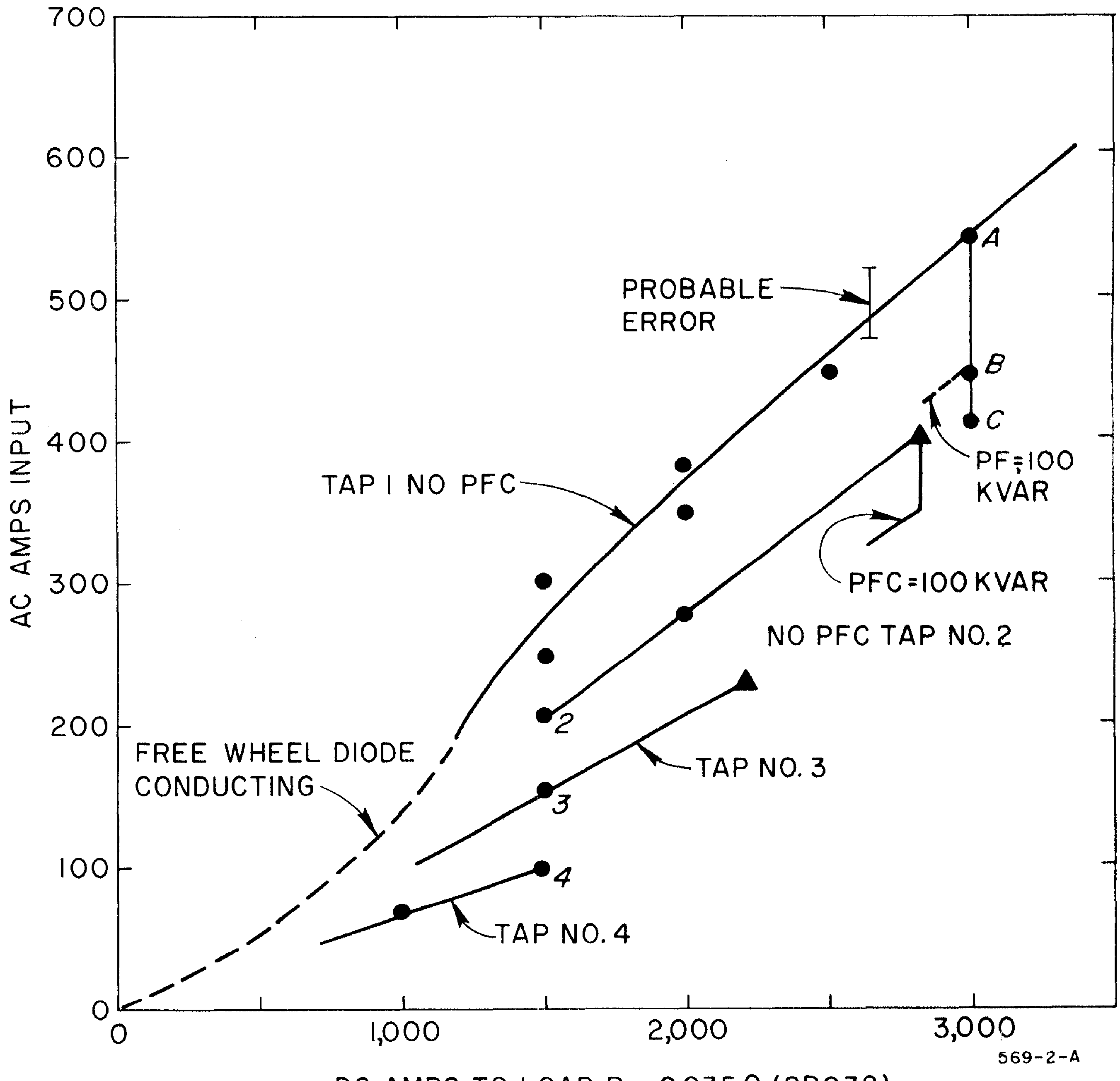

FIG. 12--360 KW POWER SUPPLY AC INPUT CURRENT VS DC LOAD CURRENT R_L=0.035Ω