

PRELIMINARY STUDY OF AC POWER FEEDERS FOR AGS BOOSTER

M. Meth

October 1985

Collider Accelerator Department
Brookhaven National Laboratory

U.S. Department of Energy

USDOE Office of Science (SC)

Notice: This technical note has been authored by employees of Brookhaven Science Associates, LLC under Contract No. DE-AC02-76CH00016 with the U.S. Department of Energy. The publisher by accepting the technical note for publication acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this technical note, or allow others to do so, for United States Government purposes.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or any third party's use or the results of such use of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof or its contractors or subcontractors. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Accelerator Division
Alternating Gradient Synchrotron Department
BROOKHAVEN NATIONAL LABORATORY
Associated Universities, Inc.
Upton, New York 11973

Accelerator Division Technical Note

No. 220

PRELIMINARY STUDY OF AC POWER FEEDERS FOR AGS BOOSTER

M. Meth

Introduction

It has been proposed that the AGS Heavy Ion/Proton Booster⁶ be excited directly from the electric power distribution system without intervening an energy storage buffer such as an MG set or a magnetic energy buffer.

The average power requirement of the AGS Booster is less than many single-loads presently housed on the lab site. However, the power swing will be the largest single pulsating load on the lab site. The large power swings will impact on the power grid producing utility-line disturbances such as voltage fluctuations and harmonic generation. Thus, it is necessary to carefully evaluate the quality of the electric power system resulting from the interconnection, such that the utility system is not degraded either on the lab site or at LILCO's substation.

Methodology

The investigation reported in this document has four major phases. In this section the scope of the study is reviewed by outlining each section. In the body of the report each phase is detailed.

Phase One consists of developing a network description of the power distribution system on site, including its tie into the LILCO power grid. For this phase LILCO supplied a site map of its distribution system feeding the lab, the impedance levels of the bus at LILCO's Brookhaven substation, and the

impedances of the 69 kV feeders. Figures 1 and 2 are reproductions of this information. LILCO routinely gives the positive and negative sequence impedances (Z_1) and the zero sequence impedance (Z_0) on its drawings. Plant Engineering supplied a one-line drawing of the on-site 69 kV and 13.8 kV distribution systems. This information was combined with the monthly power sheets to generate a description of the local distribution system and its loading. A quasi network representation of the system is given in Figure 3.

Phase Two is a conceptual design of the magnet power supplies. This design was required to calculate the power requirements at the AC bus bars. To minimize the amplitude flicker, the system was designed to minimize MVAR's at the beginning of the inversion cycle. This can be achieved by using a modular arrangement of power supplies, and utilizing a fewer number of supplies during the inversion phase than is used in the rectification phase. The proposed design compensates the MVAR's at the transition between rectify and invert by combining the dipole and quadrupole supplies, such that the composite power surge is predominantly real. Since the distribution system is predominantly reactive, a reactive power swing generates amplitude flicker while a real power swing generates phase flicker. The real power swing is intrinsic. Thus, the design concept is optimal, in the sense of minimizing flicker. Figures 7 and 9 give the total required power at the AC bus bars for the slow cycle (Heavy Ion Acceleration) and the fast cycle (Proton Acceleration).

Phase Three consists of calculating the voltage variations experienced by the distribution system on the lab site and at LILCO's Brookhaven Substation due to the periodic loading of the Booster power supplies, as given in Figures 7 and 9. The Booster was connected to the power grid at three points.

- 1) The 13.8 kV bus bar at the 5th Avenue substation.
- 2) To the existing 69 kV feeder (69-858) at the 5th Avenue substation through a dedicated 20/27 MVA, 69 kV/13.8 kV transformer.
- 3) Directly to the LILCO Brookhaven substation through the alternate feeder (69-861) and a dedicated 20/27 MVA, 69 kV/13.8 kV transformer.

For each configuration and for each of the two cycles, the voltages were calculated at each node within the distribution system as a function of time (or Booster loading). The calculations were performed using the MODIFY routine of the circuit analysis program ECAP. This program is ideally suited for this task as it accepts both positive valued and negative valued circuit elements, as is required for the modeling of the rectify and invert portions of each cycle. The results of these calculations are summarized by giving the amplitude and phase flicker at the LILCO substation or at the 5th Avenue substation, depending on the system configuration. These results are given in Figures 11 and 12.

Phase Four consists of evaluating the effect of these disturbances in the distribution system on different users. A library search revealed very few references to the subject of the quality of the electric power system¹. Quantitative limits on allowable flicker for different class of users does not appear to exist. A major exception is the topic of the perception of flicker in incandescent lamps.^{2,3} It appears that each system must be considered on an adhoc basis. Fortunately the lab houses the NSLS that is excited directly from the power grid. It is well known that this installation presented many electric power system problems, that have been successfully solved. The NSLS Booster can serve as a case study and measurements at the NSLS installation

can help establish flicker limits that are acceptable and unacceptable. A one-line diagram of the NSLS power system is given in Figure 14 and the measured values of flicker are given in the text. In addition flicker measurements were made at the 13.8 kV bus at Temple Place and selected locations on site.

Description of Power Grid

Brookhaven National Laboratory is fed by two independent 69 KV feeders from LILCO's Brookhaven substation,* see Figures 1 and 3. Feeder 69-863 is the prime feeder running to Temple Place (Bldg. 603) substation. Feeder 69-858 runs from Temple Place substation to the 5th Avenue (Bldg. 631) substation. In addition an alternate feeder, cable 69-861, runs from LILCO's Brookhaven substation directly into the 5th Avenue substation. Normally, the switch yard is configured such that the alternate feeder is disconnected. The primary and alternate feeds originate from the same 138/69 kV bank (transformer) at the LILCO substation. The alternate feed is used only when the primary feeder is not available, due to repairs or other contingencies.

Temple Place substation has three 69/13.8 kV transformers and two 13.8 kV bus bars. The tie between the two buses is normally open. The first bus is fed from two transformers designated as # 1 (20 MVA) and # 2 (10 MVA); the second bus is fed from transformer # 3 (30 MVA). The first bus powers the general laboratory site, excluding the AGS complex and the apartment area, but including the NSLS. The second bus powers the AGS complex including the Siemens MG set and in addition powers the apartment area. The only exception

*Brookhaven substation is LILCO's designation of the substation powering BNL. This substation is not on the lab site. LILCO's designation of the two substations on site are Temple Place and 5th Avenue.

to this division of load at Temple Place is that a single 13.8 kV feeder runs from the first bus to the AGS experimental area.

Fifth Avenue substation has three 20 MVA transformers designated as # 4, # 5, and # 6, forming a single 13.8 kV bus for feeding power to the AGS complex. The additional capacity of this bus is used to power the cryogenic facility compressors at Building 1005 that are planned for RHIC.

For power system studies involving evaluation of voltage regulation and flicker, the short circuit capacity (SCC) of components and buses are useful parameters, describing the power capabilities of electrical ports. The short circuit capacity at key points within the power grid has been calculated and is tabulated in Figure 4.

As presently constructed, the 5th Avenue substation can utilize only two of its three transformers. The interrupting capacity of the 13.8 kV circuit breakers is 500 MVA. It is normal practice to rotate the transformers with two on line and the third on standby. The third 20 MVA transformer can be dedicated to power the Booster. The peak power of the Booster is 9 MW and the average power is less than 1 MW. The additional transformer capacity can be used to power additional loads that are insensitive to the amplitude and phase flicker induced by the pulsating load, such as the RHIC compressors or air-conditioners.

This dedicated transformer can be connected to the 69 kV bus at 5th Avenue (69-858) or preferably connected directly to the LILCO substation through the alternate feeder (69-861). The latter is preferable from the view point of minimizing flicker and harmonic suppression.

Use of alternate feeder does not compromise the laboratory. In case one of the two feeders were out of service the system would revert to the other,

in which case the Booster is connected directly to the Laboratory's 69 kV bus together with all other loads.

The single most important parameter in evaluating the ability of a power grid to drive a pulsating load is the ratio of peak power and peak power swing to the SCC at the utility tie point. Table I summarizes these ratios for the proposed BNL AGS Booster, the CERN's SPS for a 400 GEV cycle, and Fermi's 200 GEV synchrotron. The two latter accelerators are powered directly from the local power grid.

The data for the power requirements and SCC of the utility at CERN and FERMI was extracted from the literature^{4,5}.

Booster Power Requirements

The relevant dipole and quadrupole parameters are given in Table II. The power supplies are designed to operate the Booster in either one of two modes:

- 1) As a heavy ion accelerator, with a period of 1 sec, or
- 2) as a proton accelerator, with a period of 0.1 sec.

The required current waveform for the two modes of operation are given in

Table I

Ratio of Peak Power to Utility SCC for BNL, CERN and FERMI

	AGS Booster	CERN SPS	FERMI Synchrotron
SCC of Utility	2310 MVA	15,120 MVA	18,000 MVA
Peak Power Swing	17 MW	230 MW	60 MW
Peak Power	10 MVA	162 MVA	72 MVA
Peak Power Swing/SCC	0.74 %	1.52 %	0.33 %
Peak Power/SCC	0.43 %	1.07 %	0.40 %

Table II

Magnet Parameters

	Dipole	Quadrupole
L	0.1 H	0.025 H
R	0.05 ohms	0.036 ohms
L/R	2 sec.	0.69 sec.

Figures 5 and 8. Based on the magnet parameters and the required waveforms⁶, the drive voltages and power requirements have been calculated at the magnet terminals. These results are also included in Figures 5 and 8. Table III summarizes the power requirements for the magnet.

The magnets are powered through multi-phase rectifiers/inverters operated from the AC line. The required voltage waveforms are generated through phase-control of the rectifiers. In controlling the DC output of the rectifiers, the AC current is delayed, requiring the flow of reactive current and power (Q) as well as real current and power (P).

Since the magnets are quite dissipative the voltage at the beginning of the invert period is less than at the end of the rectify period. This would normally require additional phase-back of the rectifiers at the beginning of

Table III

Magnet Power Requirements

	Slow Cycle 1.0 sec	Fast Cycle 0.1 sec
Storage Energy	1.67 MJ	0.34 MJ
Peak Power	9 MW	8.92 MW
Peak Power Swing	13.4 MW	16.9 MW
Average Power	0.77 MW	0.13 MW

the invert period, resulting in an increase of reactive power at the transition from rectify to invert. The increase in reactive power would normally be severe for the 1.0 sec cycle, since the quadrupole time constant is only 0.69 sec. By using a modular power supply structure and turning on a lesser number of supplies at the beginning of the invert period than is utilized at the end of the rectify period, the phase-back at the beginning of inversion is reduced. This can be made smaller than the phase-back at the end of the rectify period. Thus the reactive power is reduced at the transition.

This design procedure is illustrated for the 1.0 sec cycle with the aid of the phasor diagram given in Figure 6. The dipole is inverted with a smaller value of zero control voltage than is used in the rectify period; basically 2/3 of the supplies are used for invert. The quadrupole uses the same number of supplies for rectify and invert. At transition the decrease in reactive power for the dipole compensates for the increase in reactive power for the quadrupole. The power swing at transition involves predominantly real power.

The same design concept is used for the 0.1 sec cycle. Here the quadrupole is inverted with 2/3 of the number of supplies as is used for the rectify period. The dipole uses the same supply voltage for rectify and invert. At transition the reactive power is compensated and the power swing is mostly real.

A plot of the real power (P) and reactive power (Q), required to ramp the magnets is given in Figure 7 for the heavy ion (slow) cycle and in Figure 9 for the proton (fast) cycle. Figure 10 is a block diagram of the modular structured power supply.

Calculation of Flicker

The calculation of the voltage disturbances on the power grid was calculated for the three different connections to the power grid, and for the two Booster loading cycles, given in Figures 7 and 9. Calculations were performed with the aid of the circuit analysis program ECAP. Positive real power is modeled with a resistor; negative real power with a negative value for the resistor. Lagging reactive power is modeled with an inductor; leading reactive power, with a capacitor. The loading parameters were modified in eleven steps, including a set of parameters for the beginning and end of the rectify/invert transition period. The output impedance at the various ports of the power grid is predominantly reactive. Thus, real power induces a quadrature-voltage drop or phase shift; reactive power loading induces an in-phase voltage drop.

The calculations of the power line flicker with the Booster tied directly to the 13.8 kV bus at the 5th Avenue substation yielded an amplitude variation of 1.6% and a phase variation of 1.8° over a cycle. This level of flicker is excessive and is unacceptable for the other substation loads.

The calculations were repeated with a dedicated transformer rated at 20/27 MVA, 69 kV/13.8 kV, and short circuit impedance of 7.5%, powering the Booster. The transformer parameters are equivalent to the parameters of the substation transformers installed at 5th Avenue. If used for this application the automatic load tap changing must be modified to increase the dead-zone or perhaps removed. For these calculations the transformer was connected to the power grid at two points; either tied into LILCO via the alternate 69 kV feeder, or tied at the 69 kV level of the 5th Avenue substation. The results of the calculations are tabulated in Fig. 11. In addition the flicker at the Booster bus bars are included in this figure. The flicker waveforms at the LILCO substation are given in Figure 12.

Evaluation of Acceptable Power Line Disturbances

The effects of flicker on an incandescent lighting load was measured by Irving Langmuir.² The results of his investigation are reproduced in Figure 13. Based on this data amplitude flicker is limited on the fast cycle mode (10 Hz) to 0.5%. The slow cycle mode (1 Hz) can tolerate 1.3% of amplitude flicker. The effects of flicker on other loads were evaluated by operating experience and measurements made at the National Synchrotron Light Source and the lab site.

The NSLS complex is tied to the 13.8 kV bus at Temple Place and is fed from three 2500 KVA, 13.8 kV/480 volt transformers. A one-line diagram of the NSLS power system is given in Figure 14. Included in Figure 14 is the electrical path used in deriving the reference-voltage for measuring phase flicker at the NSLS.

Measurements of amplitude and phase flicker at the NSLS were obtained at the feeder to its Booster power supplies and the feeder to the UV ring. These results are given in Table IV. Included in Table IV are measured values of

Table IV

Measurement of Flicker at NSLS and Temple Place

Feeder	Maximum Amplitude Flicker	Maximum Phase Flicker
Booster	1.82%	2.66°
UV Ring	0.40%	0.50°
13.8 kV Bus at Temple Place	0.32%	0.43°
Building 815	0.27%	--
Building 911	0.68%	--

flicker of the 13.8 kV bus and hence on the lab site. The 13.8 kV bus flicker includes power surges from the NSLS as well as other load sources. Amplitude flicker was measured on site in Building 815, which is excited from the first 13.8 bus at Temple Place. In Building 911, which is excited from the second 13.8 kV bus at Temple Place, flicker as large as 0.68% was measured with the AGS pulsing. Operating experience at the NSLS restricts its Booster feeder to loads that are nonsensitive to flicker, such as air-conditioners. The feeder to the UV ring does not have this restriction and is used for power supplies and lighting loads.

The short circuit capacity of the NSLS Booster bus was calculated as 36.8 MVA. Based on a peak Booster load of 0.8 MVA, the voltage swing on the 480 volt bus was calculated to be 2.17%. The voltage swing at the entrance to Building 725 (NSLS) was calculated to be 0.35% and the swing at the 13.8 kV bus as 0.25%.

The effects of 0.5% amplitude flicker and 0.6° of phase flicker on the regulation of a typical multi-pulse phase-controlled magnet power supply has been calculated. For the purposes of this calculation, the following typical parameters were chosen:

inductance	-	200 mH
voltage	-	200 volts
peak current	-	1000 A
closed loop bandwidth of regulator	-	20 Hz

The ramp rate is 1000 A/sec. For an error of 0.5% in the amplitude of the supply voltage the maximum error in the magnet current is 0.04 A, corresponding to a maximum of the rectified-voltage. For a phase error of 0.6° the maximum error in the magnet current is 0.084 A, corresponding to a rectified

voltage of zero. The combined maximum error is 0.093 A.

It appears that based on operating experience at the lab site, empirical data on lighting loads, and calculation on magnet power supplies, reasonable limits can be established for flicker. These limits are an amplitude flicker of 0.5% and a phase flicker of 0.6° .

In addition, the effects of phase flicker on induction motor loads were evaluated. A test rig was assembled to introduce a step phase shift of 5° at a 10 Hz rate on a three phase 5 horsepower induction motor. The motor ran normally.

Conclusion and Additional Work

The proposed AGS Booster can be powered directly from the 69 kV electric distribution system without the use of local energy storage. This recommendation is based on a review of the Laboratory's distribution system, its tie into LILCO's grid, and a projection of the current power requirements of the Booster. The disturbances produced on the utility lines by the pulsating load are within acceptable limits.

The proposed system is economic, utilizing resources presently available to the laboratory; namely, the third or reserve transformer at the 5th Avenue substation and the alternate feeder. With this configuration, the maximum amplitude and phase disturbances of the electric distribution system are 0.31% and 0.4° . Based on experience at other accelerator installations, published data, and measurements performed on site, a limit has been established for allowable power line disturbances. These limits are 0.5% for amplitude flicker and 0.6° for phase flicker.

This investigation has not evaluated the effects of high-frequency harmonics generated by the power supplies. If required, harmonic filtering can be added to the 69 kV side of the transformer. The inductance of the alternate

feeder (2.52 mH), can be an element of this filter.

The proposed Booster design⁶ has the capability of accelerating to a proton energy of 2.5 GeV/C. Although not implemented in the present proposal, this feature increases the space charge limit further in the AGS and results in increased intensities. We propose to study the effects that the required power increase has on the power distribution system.

The reactive power requirements of the Booster can be further reduced by shunt capacitance at the 13.8 kV side of the transformer. The reduction of required reactive power and flicker must be evaluated against the cost of the capacitor bank.

The additional capability of the transformer used to power the Booster can be used to power flicker insensitive loads, such as air-conditioners and compressors since the average power of the Booster is low. The modular structured power supply can provide flexibility to the operational characteristics of the Booster.

Bibliography

- 1) M. Aro, and M. Halama, Quality Measurements in Electric Supply, Saehkoe (Finland), Vol. 53, No. 7-8, page 209-11, July-August 1980 (In Finnish).
- 2) Langmuir, Flicker of Incandescent Lamps on Alternating Current Circuits, Gen. Elec. Review 1914, Vol. 17, page 194.
- 3) Fink and Carroll, Standard Handbook for Electrical Engineers, 10th Edition, page 19-10.
- 4) O. Bayard, The Supply of the 148 MW Pulsed Power to the CERN SPS and the Associated Mains Voltage Stabilization and Filtering, NUC. SCI., NS-26, June 1979 page 4066-4068.
- 5) Cassel, Van Ness, Direct Powering of the 200 GEV Synchrotron Magnets from the Utility System, NUC. SCI., NS-16, June 1969, pages 672-676.
- 6) AGS Booster Conceptual Design Report - July, 1984, BNL 34989R or AGS ACCUM/Booster Proposal for the AGS - Feb., 1984.

Brookhaven 138KV - Bus $Z_1 = .0182 \angle 86.07^\circ$ p.u. on 100MVA
 $Z_0 = .0307 \angle 75.26^\circ$ p.u.

Brookhaven 69KV Bus. $Z_1 = .0437 \angle 82.67^\circ$ p.u.
 $Z_0 = .0515 \angle 85.89^\circ$ p.u.

Brookhaven 138/69KV Bank $Z_1 = .0012 + j.0636$ p.u.
 $Z_0 = .0012 + j.0636$ p.u.

Brookhaven - Fifth Ave $Z_1 = .008 + j.020$ p.u.
 $Z_0 = .050$ p.u.

Brookhaven - Temple Place $Z_1 = .011 + j.008$ p.u.
 $Z_0 = .02$ p.u.

Temple Place - Fifth Ave $Z_1 = .001 + j.004$ p.u.
 $Z_0 = .01$ p.u.

Fig. 2. Impedance Levels of Substation and Transmission Line

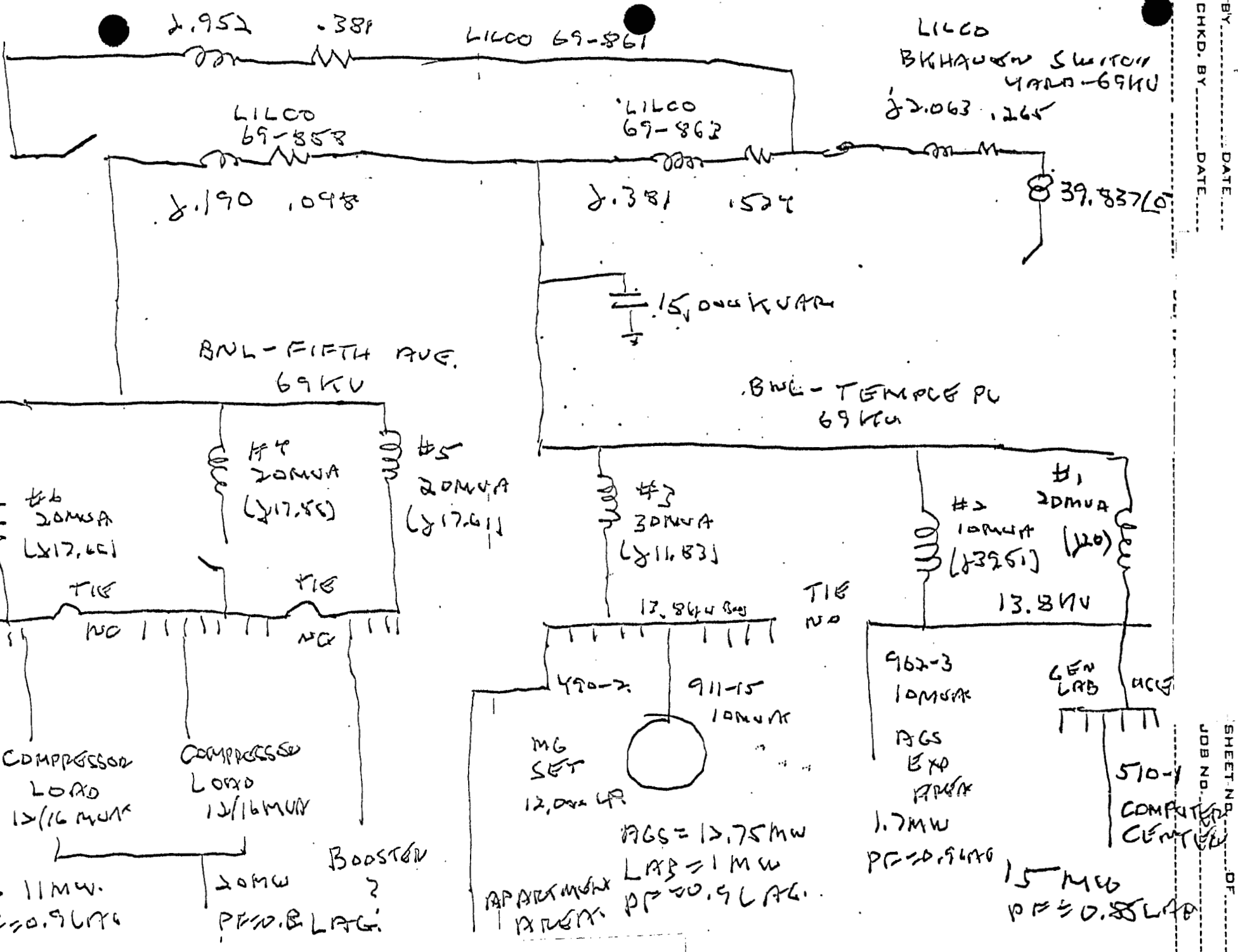


Fig. 3. Power Distribution System

BY _____ DATE _____
 CHKD. BY _____ DATE _____
 SHEET NO. _____ OF _____
 JOB NO. _____

LOCATIONSCC

LILCO SUBSTATION
(BROOKHAVEN)

2310 MVA

TEMPLE PL
69KV BUS

1950 MVA

13.8KV BUS
(TIE OF #1 & #2)

320 MVA

13.8KV BUS
#3

335 MVA

FIFTH AVE.

69KV BUS

1810 MVA

13.8KV BUS

(ONLY TWO
KFERS)

450 MVA

[270 MVA / KFER
from upland
bus]

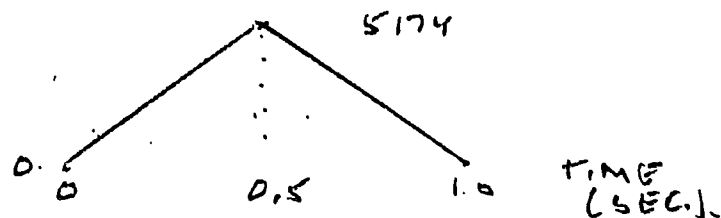
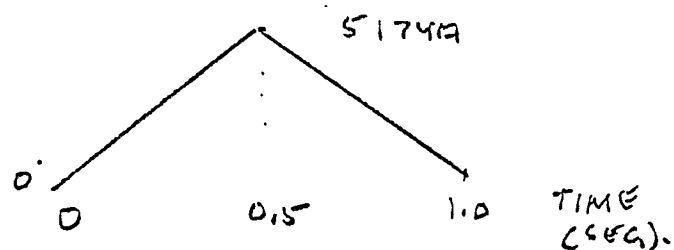
13.8KV BUS C.B. rated at 500 MVA
only two KFERS can be
paralleled at Fifth Ave.

Steady State Rating OF ENTRANCE
600A.

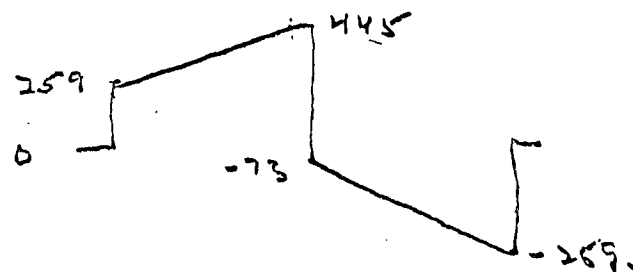
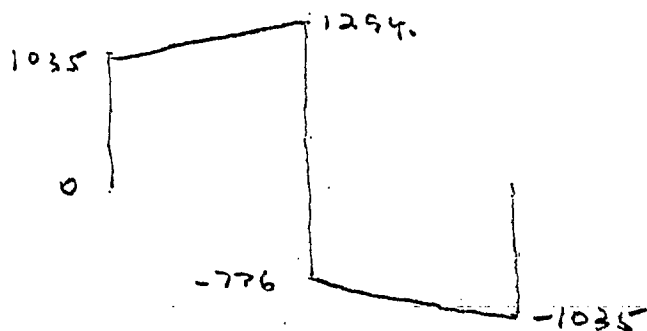
$$P = 71.7 \text{ MVA}$$

Fig. 4. Short Circuit Capacity

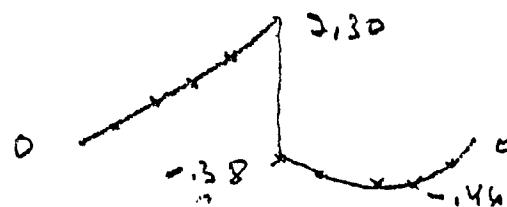
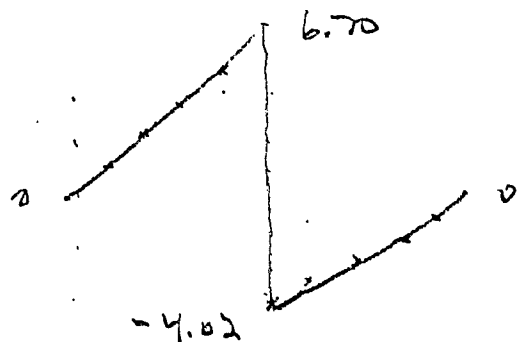
CURRENT



VOLTAGE



POWER (MW)



DIPOLE

$L = 0.1 \text{ H}$
 $R = 0.05 \text{ } \Omega$

Fig. 5. Magnet Waveforms and Power
 Slow Cycle

QUADRUPOLE

$L = 0.025 \text{ H}$
 $R = 0.036 \text{ } \Omega$

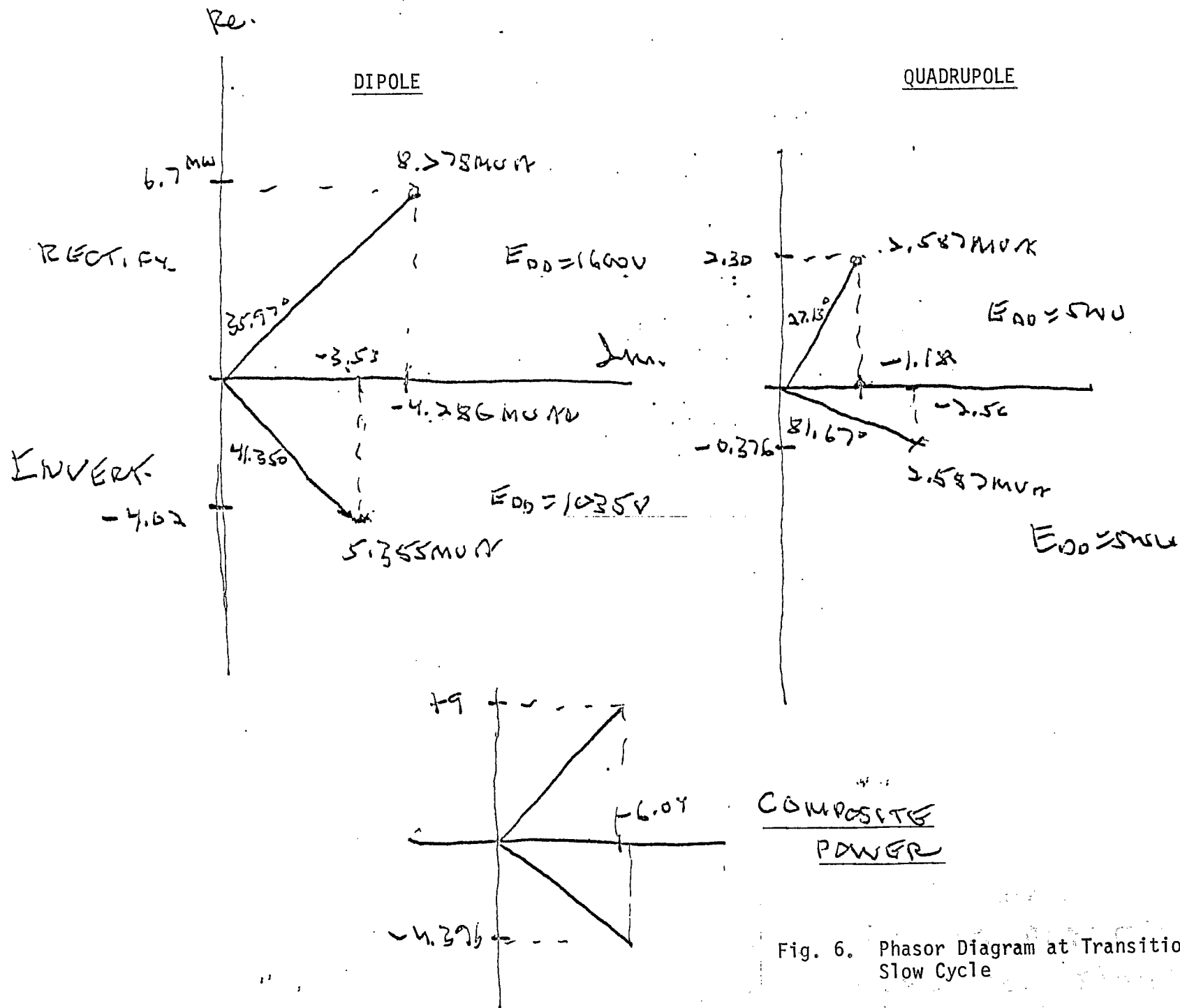


Fig. 6. Phasor Diagram at Transition Time Slow Cycle

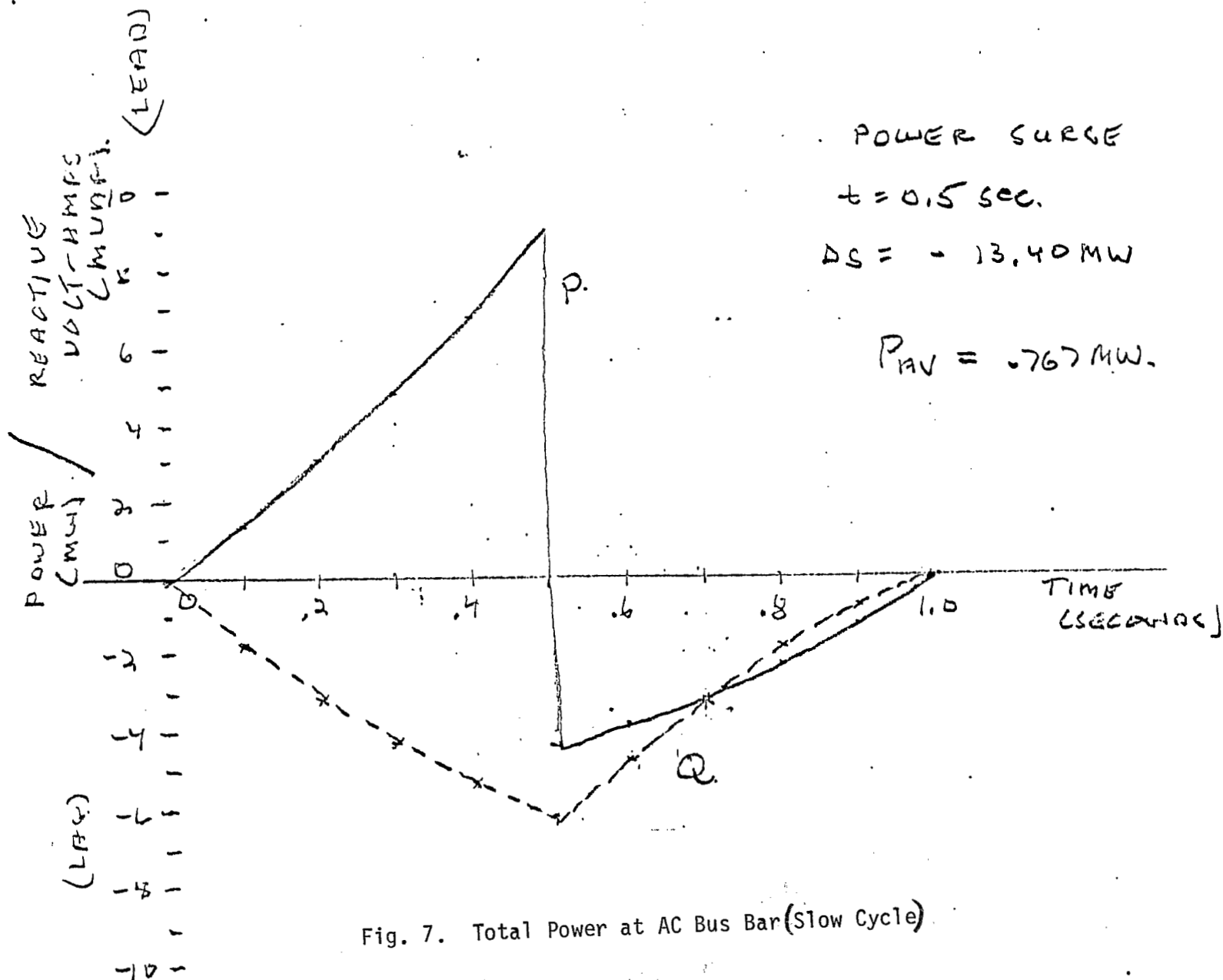
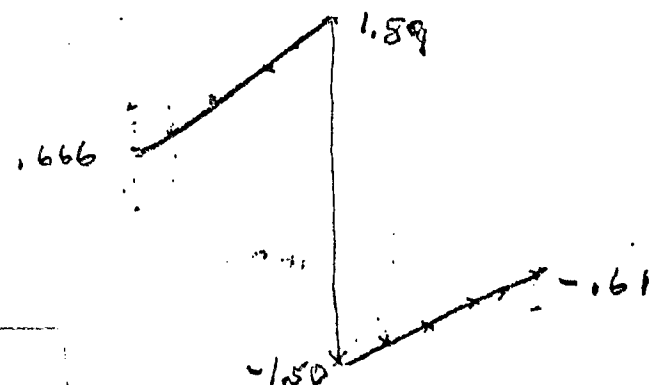
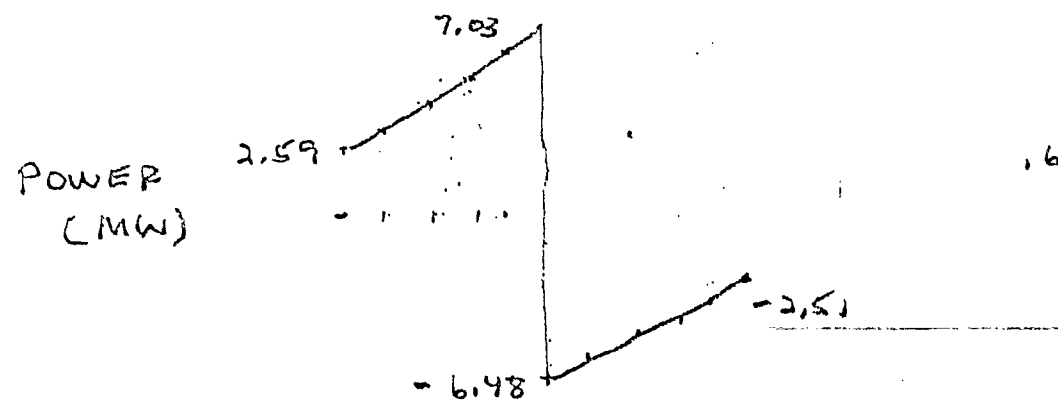
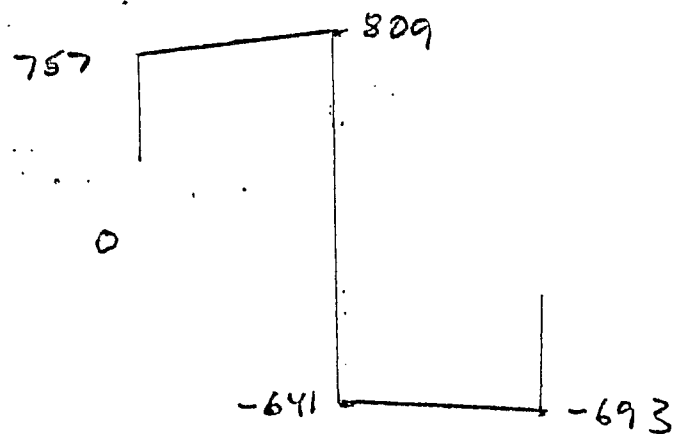
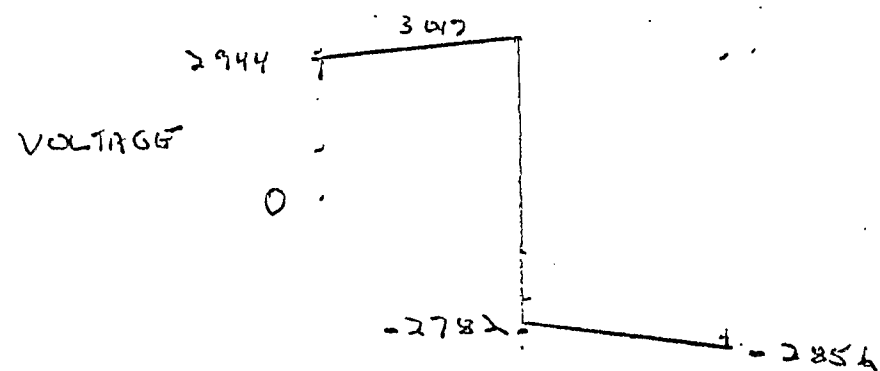
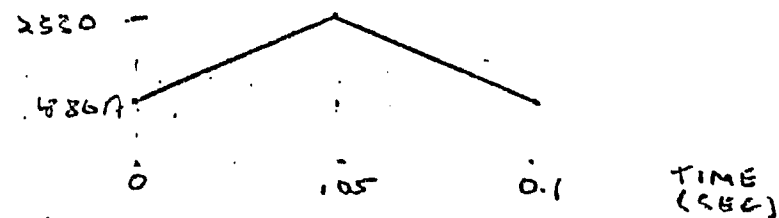
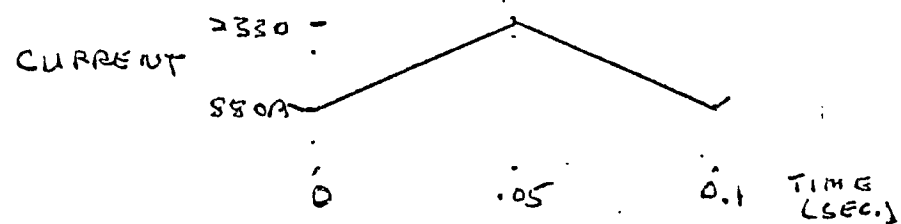


Fig. 7. Total Power at AC Bus Bar (Slow Cycle)



DIPOLAR
 $L = 0.1 \text{ H}$
 $R = 0.05 \text{ } \Omega$

Fig. 8. Magnet Waveforms and Power (Fast Cycle)

QUADRUPOLE
 $L = 0.025 \text{ H}$
 $R = 0.036 \text{ } \Omega$

POWER / REACTIVE
(MW) / VOLT - AMPERE
(MVAR)

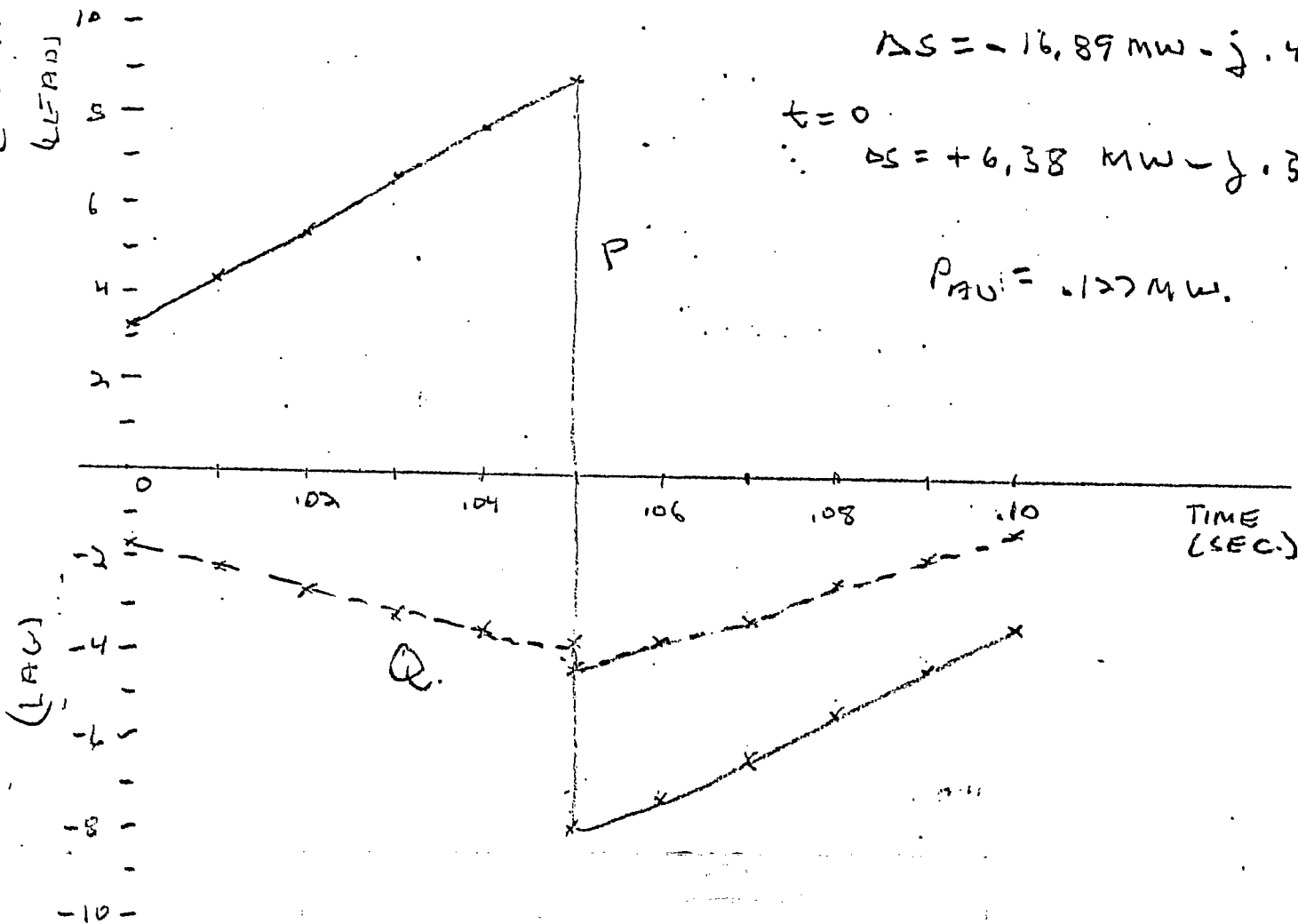
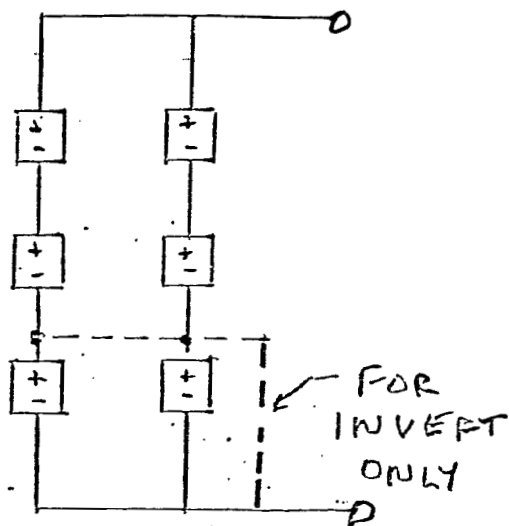


Fig. 9. Total Power at AC Bus Bar (Fast Cycle)

DIPOLE



BASIC MODULAR BLOCK

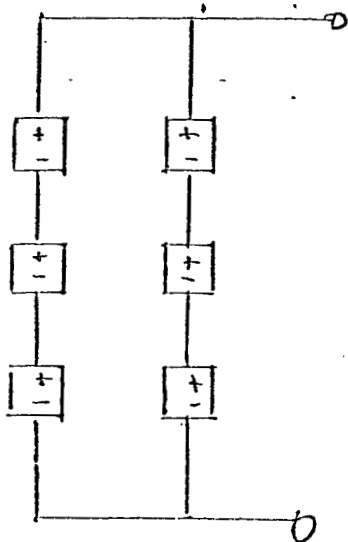
FOR DIPOLE

550V

2600A

1.43MW.

QUADRUPOLE



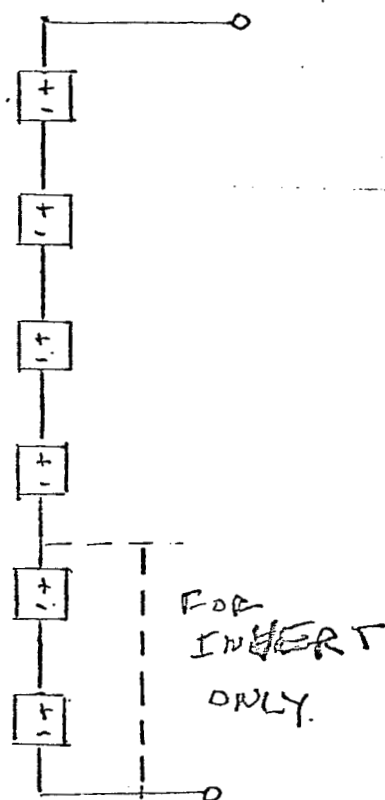
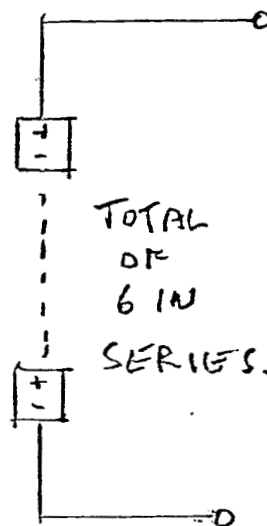
BASIC QUADRUPOLE
MODULAR
BLOCK.

175V

2600A

0.46MW

SHOW CYCLE



FAST CYCLE

Fig. 10. Modular Structured Power Supply

CONNECTION OF DEDICATED (XFMER).	CYCLE	MAXIMUM AMPLITUDE FLICKER.	MAXIMUM PHASE FLICKER
LILCO SUBSTATION	SLOW	0.31%	0.31°
	FAST.	0.18%	0.14°
FIFTY AVE SUBSTATION.	SLOW	0.48%	0.39°
	FAST.	0.35%	0.51°

POWER GRID FLICKER FOR DIFFERENT
CONFIGURATIONS.

CYCLE	AMPLITUDE FLICKER.	PHASE FLICKER
SLOW	2.88%	3.24°
FAST	1.52%	2.92°

Flicker at Booster Bus Bar

Fig. 11. Disturbances of Power Line Voltage
Due to Pulsating Booster Load

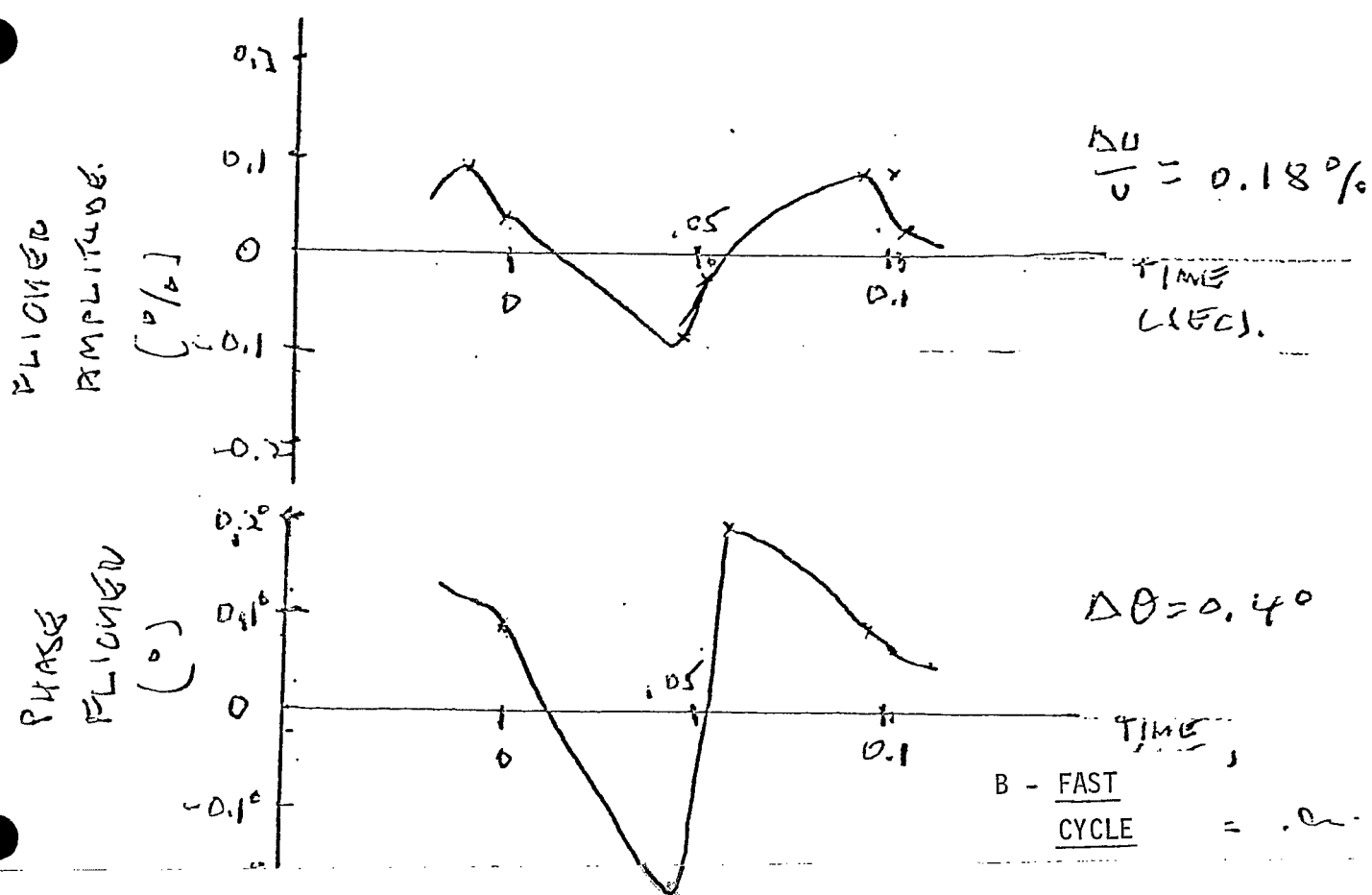
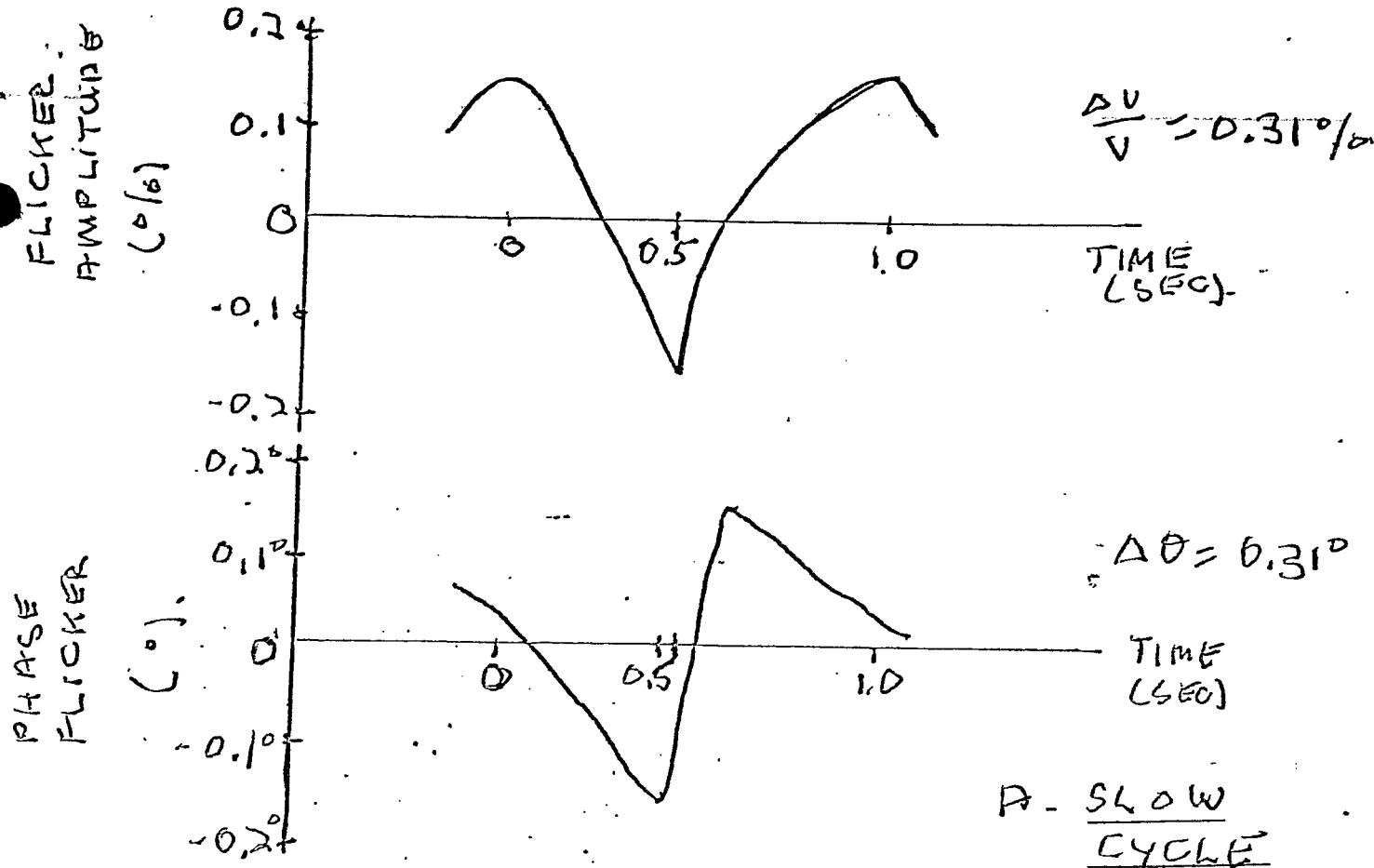


Fig. 12. Flicker at 69 kV AC Bus Bars

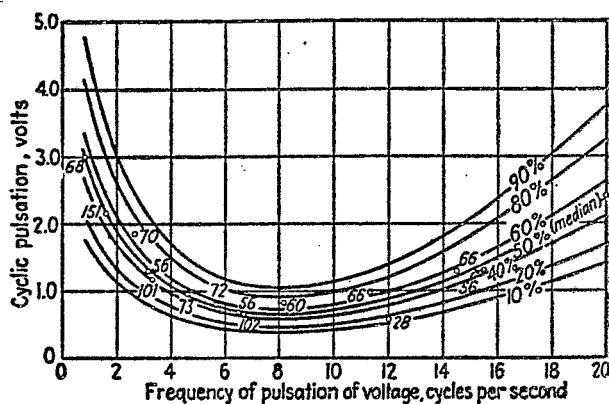


FIG. 19-9. Cyclic pulsation of voltage at which flicker of 115-volt tungsten-filament lamp is just perceptible. Derived from 1,104 observations by 95 persons in field tests of 25-, 40-, and 60-watt lamps conducted by Commonwealth Edison Co. Figures on curves denote percentages of observers expected to perceive flicker when cyclic voltage pulsations of indicated values and frequencies are impressed on lighting circuits. Plotted points denote medians of observations at various frequencies, the number of which in each case is indicated by the adjacent figure.

Fig. 13. Effect of Flicker on Incandescent from Standard Handbook for Electrical Engineers, 10th Edition.

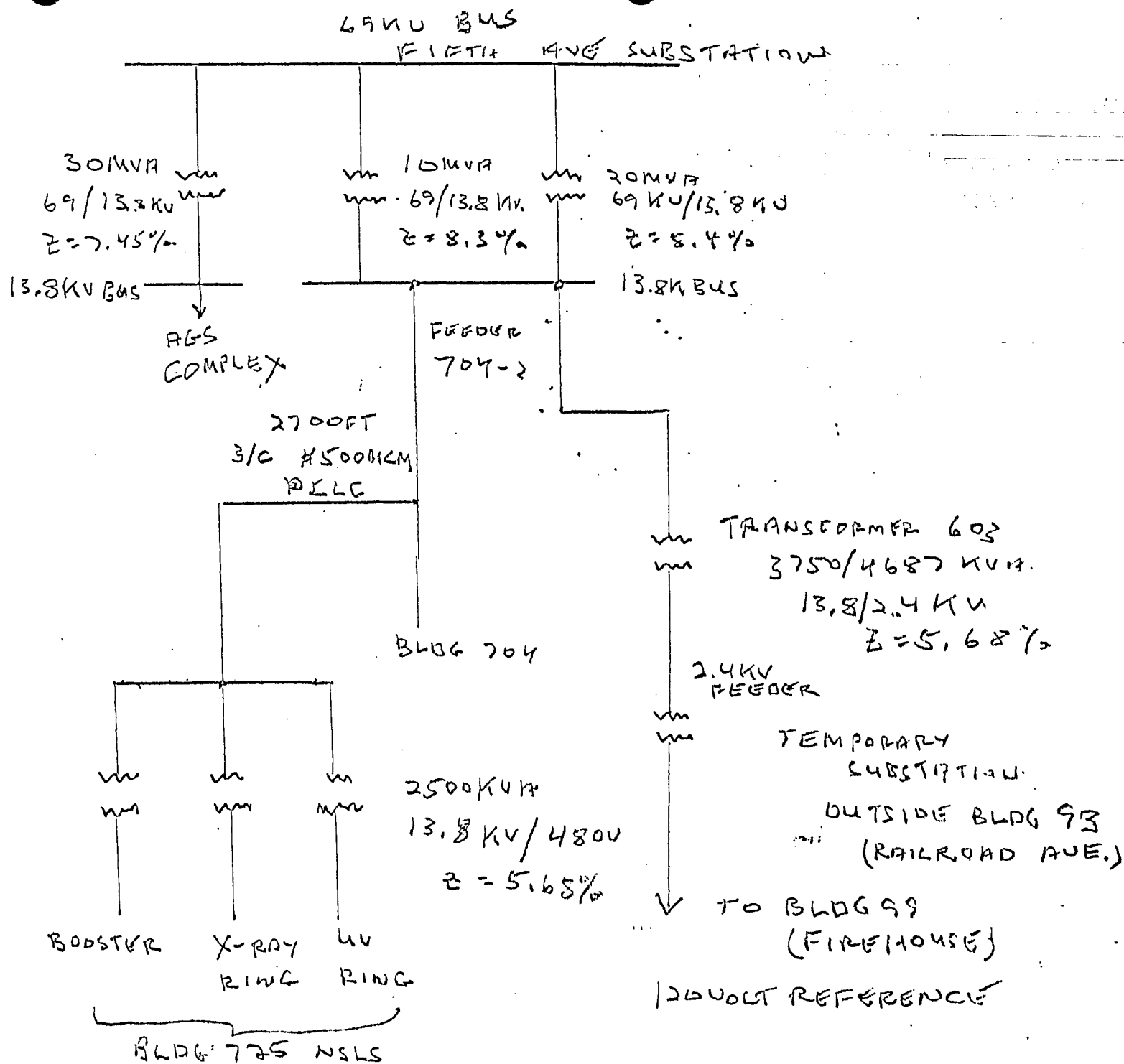


Fig. 14. Power Distribution System to NSLS Complex