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Spectrum analysis of the power line flicker induced by the electrical test of the prototype Booster dipole

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INTRODUCTION:

Testing of the prototype Booster dipole magnet at full current produced measurable disturbances of the beam position at the National Synchrotron Light Source. Power for the magnet and the NSLS are distributed from three substation transformers at Temple Place. Normally the substation configuration is for two independent 13.8 KV buses, derived from the 69 KV LILCO distribution. The buses are connected through a circuit breaker that is normally open circuited; see Figure 1 for a one-line drawing of the power distribution. Power for the magnet test is derived from one of the 13.8 KV buses and power for the NSLS is derived from the second bus. Coupling of the pulsating magnet load and the NSLS is at the 69 KV level.

However, on the days that the interference was first observed at the NSLS only one-half of the substation transformers at Temple Place were in service. The 13.8 KV tie breaker was closed and the full substation load was supplied from this common bus. Thus the coupling between the pulsating magnet load and the NSLS was at the 13.8 KV level. The short circuit capacity of the 13.8 KV bus is $^1/_6$ of the SCC of the 69 KV line. Establishing the normal two bus configurations at Temple Place appeared to reduce the disturbance. In addition, a number of control boards within the power supplies at the NSLS were replaced, upgrading its performance. Presently the magnet testing does not adversely affect the NSLS.

These events suggested a controlled experiment to measure the magnet power swing and the induced powerline flicker; and from these measurements project the flicker on the lab site generated by the Booster operating at full energy. This experiment could corroborate the validity of the electrical models used in analyzing the power flow from the LILCO power grid and its distribution on the Lab site described in Accelerator Division Technical Note 220.[1]

OUTLINE OF EXPERIMENT:

The peak power swing used for the electrical test of the prototype dipole is approximately 5% of the required swing for the Booster operating at full energy. The values of the amplitude and phase flicker generated by the pulsating test load on the Lab site, approximately 0.02% and 0.04°, are difficult to measure using oscilloscopic techniques. As an alternative the spectrum of the 60 Hz power was recorded using the Hewlett Packard 3561A Dynamic Signal Analyzer. The analyzer employs a Fast Fourier Transform algorithm to generate the complex coefficient of the spectrum. The analyzer interprets the coefficients in terms of an amplitude and a phase spectrum. Typical spectrums are given in Figures 2 and 3. Figure 2 is the amplitude and phase spectrum for the 480 volt line exciting the magnet. Figure 3 is the amplitude spectrum at the light source. Both spectrums are for a power swing of 1.2 Megawatts.

Examination of the spectrum reveals that it has characteristics of a typical communication spectrum, carrier plus order-pairs of sidebands. The carrier is the power line frequency (60 Hz) and the sideband spacing is the machine cycle period, 7.5 Hz for the proton cycle. For a periodic waveform, such that it can be described by a discrete spectrum, the machine cycle must be commensurate with the power line frequency. An eight to one frequency divider was constructed. The divider is driven by the 60 Hz power line and its output cycles the magnet and triggers the waveform analyzer. Further examination of the spectrum reveals an asymmetrical distribution of sidebands about the 60 Hz carrier. The signal is neither pure amplitude nor pure angle (or frequency) modulation; but a combination of amplitude and angle modulation. Each pair of sidebands can be resolved into an inphase (I) and a quadruture phase (Q) component.[2] The inphase component produces amplitude flicker; the quadruture component, phase flicker.

If $\underline{B}_1$ and $\underline{B}_2$ are the complex values of the upper and lower sidebands respectively and the carrier line is a real number, then each pair of sidebands is resolved into two pairs of sidebands. One pair of sidebands ($\underline{A}_s$) is symmetrical with respect to the carrier and produces pure amplitude modulation; the second pair is anti-symmetrical ($\underline{A}_q$) and produces pure angle modulation. The symmetrical ($\underline{A}_s$) and anti-symmetrical ($\underline{A}_q$) components are calculated from $\underline{B}_1$ and $\underline{B}_2$ as

$$\underline{A}_s = \frac{\underline{B}_1 + \underline{B}_2^*}{2}$$

$$\underline{A}_q = \frac{\underline{B}_1 - \underline{B}_2^*}{2}$$

where $\underline{B}_2^*$ is the complex conjugate of $\underline{B}_2$. See Fig. 4A for the relationship between the spectrum sidebands $\underline{B}$ and the resolute components $\underline{A}_s$ and $\underline{A}_q$. Combining the various orders for $\underline{A}_s$ in a Fourier Series permits a calculation of the peak amplitude flicker. Similarly the various orders of $\underline{A}_q$ are combined in a Fourier Series, and the peak phase flicker is calculated from the series.

The power swing at the magnet was measured by recording the current and voltage at the magnet terminals on a Nicollete Digital Oscilloscope and multiplying these two quantities. Figures 5A and 5B show the raw voltage and current at the magnet terminal. Figure 5C shows the filtered voltage waveform and Figure 5D is the real power swing. In these figures negative voltage (and power) are for the rectify period, positive quantitative for invert.

The resulting measured flicker is scaled to project the flicker for full Booster energy. The scaling is directly proportional to the peak swing and inversely proportional to the power grid's SCC at the coupling node.

The test swing is 1.2 MW, the full energy swing is 22 MW. The test coupling node (Temple Place Substation) has a SCC of 1950 MVA. The Booster will be energized from the alternate feeder with the coupling node at the LILCO Brookhaven Substation with a SCC of 2310 MVA.

Thus, the flicker measured at the NSLS or measured at the Fifth Avenue Substation is scaled by

$$\frac{22}{1.2} \times \frac{1950}{2310} = 15.4$$

The SCC of the local 2.5 MVA transformer energizing the magnet test is 44.6 MVA thus the flicker measured at the test site is scaled by

$$\frac{22}{1.2} \times \frac{44.6}{2310} = .35$$

FLICKER CALCULATION:

The flicker data, spectrum given in Figure 2, is analyzed to yield the amplitude and phase flicker. The raw data is scaled such that the 60Hz line is at 0° phase and 10^4 units of amplitude. The scaled data is given in Table I.

FREQUENCY (Hz)	AMPLITUDE	PHASE
75	37	- 71°
67.5	79	-226°
60	10^4	0°
52.5	112	-321°
45	34	-101°

TABLE I
RAW DATA

The raw data was paired by sideband order and resolved into paired symmetrical ($\underline{A_s}$) and paired quadruture ($\underline{A_q}$) sidebands. The first order sidebands is at 52.5 Hz and 67.5 Hz; the second order, at 45 Hz and 75 Hz. This information is given in Table II.

Sideband Order	As	Aq
First	17.4 ∠ -22.9°	95.32 ∠ 138.1°
Second	2.85 ∠ -15.2°	35.4 ∠ -74.8°

Table II
Symmetrical and Quadruture Components of Sidebands

The phasor relationship between the sidebands and carrier is shown in Fig. 4A for the first order sidebands. For this diagram and ensuing analysis; ρ represents the modulating frequency, $2\pi \times 7.5$ rad per sec.

The first and second order value of $\underline{A_s}$ are combined to give I(t) and the first and second order value of $\underline{A_q}$ are combined to give Q(t).

$I(t) = 34.8 \cos(\rho t - 22.9°) + 5.7 \cos(2\rho t - 15.2°).$

$Q(t) = 190.6 \sin(\rho t + 138.1°) - 70.8 \sin(2\rho t - 74.8°)$

The composite phasor is given in Fig. 4B. The maximum and minimum values of I(t) are approximately 39.7 and -29.9. The amplitude flicker is

$$\frac{[39.7 - (-29.9)]}{10^4} \times 100\% = .70\%$$

The maximum and minimum values of Q(t) are approximately 180 and -180. The phase flicker is

$$\frac{180 - (-180)}{10^4} \text{ rad} = .036 \text{ rad} = 2.06°$$

Scaled to the Booster operating at full energy and powered from the alternate feed, the flicker projects as .25% and .72°.

CONCLUSION:

These values are compared to the flicker calculations based on the model given in Booster Technical Note 54[3], Table III.

	Amplitude Flicker	Phase Flicker
Projected From Measurements	.25%	.72°
Calculated From Model	.27%	.51°

TABLE III
FLICKER MEASUREMENTS AND CALCULATIONS

It is interesting to compare the sideband structure recorded at the magnet test site and at the NSLS Figures 2 and 3. The sidebands at the NSLS are 31 db below the sidebands at the test site. This ratio should correspond to the ratio of the two scaling factors

$$\frac{15.4}{.35} = 44 \text{ or } 32.9 \text{ db.}$$

It is instructive to project the expected increase in power line flicker at the NSLS, as compared to the flicker present at the NSLS during the magnet test period and Temple Place configurated with a single 13.8 KV bus. The expected flicker is increased by a factor of

$$\frac{22}{1.2} \times \frac{320}{2310} = 2.54$$

References:

1. Meth, Marvin; Preliminary Study of AC Power Feeders for AGS Booster, Accelerator Division Technical Note 220, October 1, 1985.

2. Goldman, Sanford; Frequency Analysis Modulations and Noise, McGraw Hill 1948 pgs. 167-175.

3. Meth, Marvin; Calculation of Booster Power Requirements and Power Line Flicker For 1.5 GEV Proton Operation, Booster Technical Note 54, July 17, 1986.

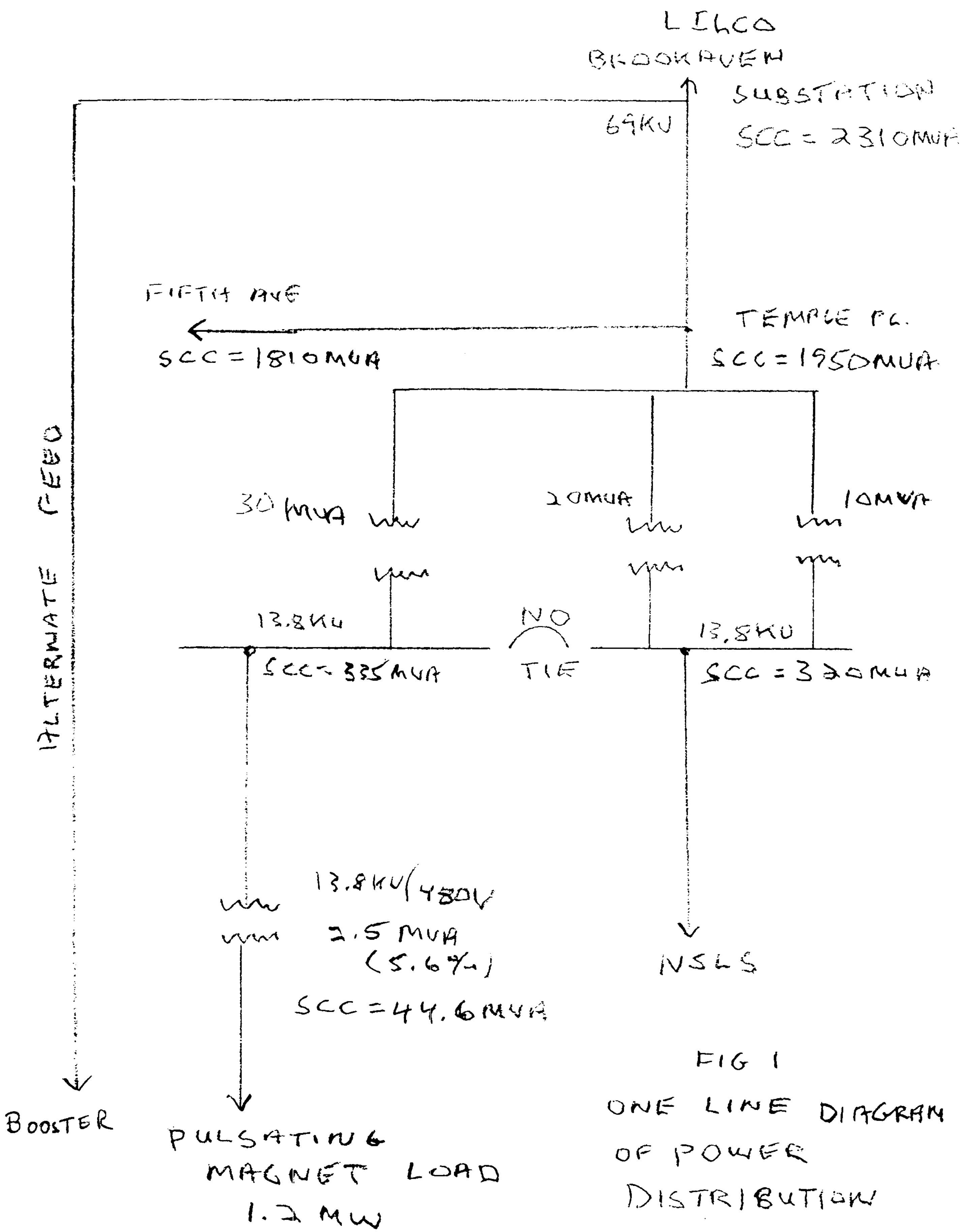

FIG 1
ONE LINE DIAGRAM
OF POWER
DISTRIBUTION

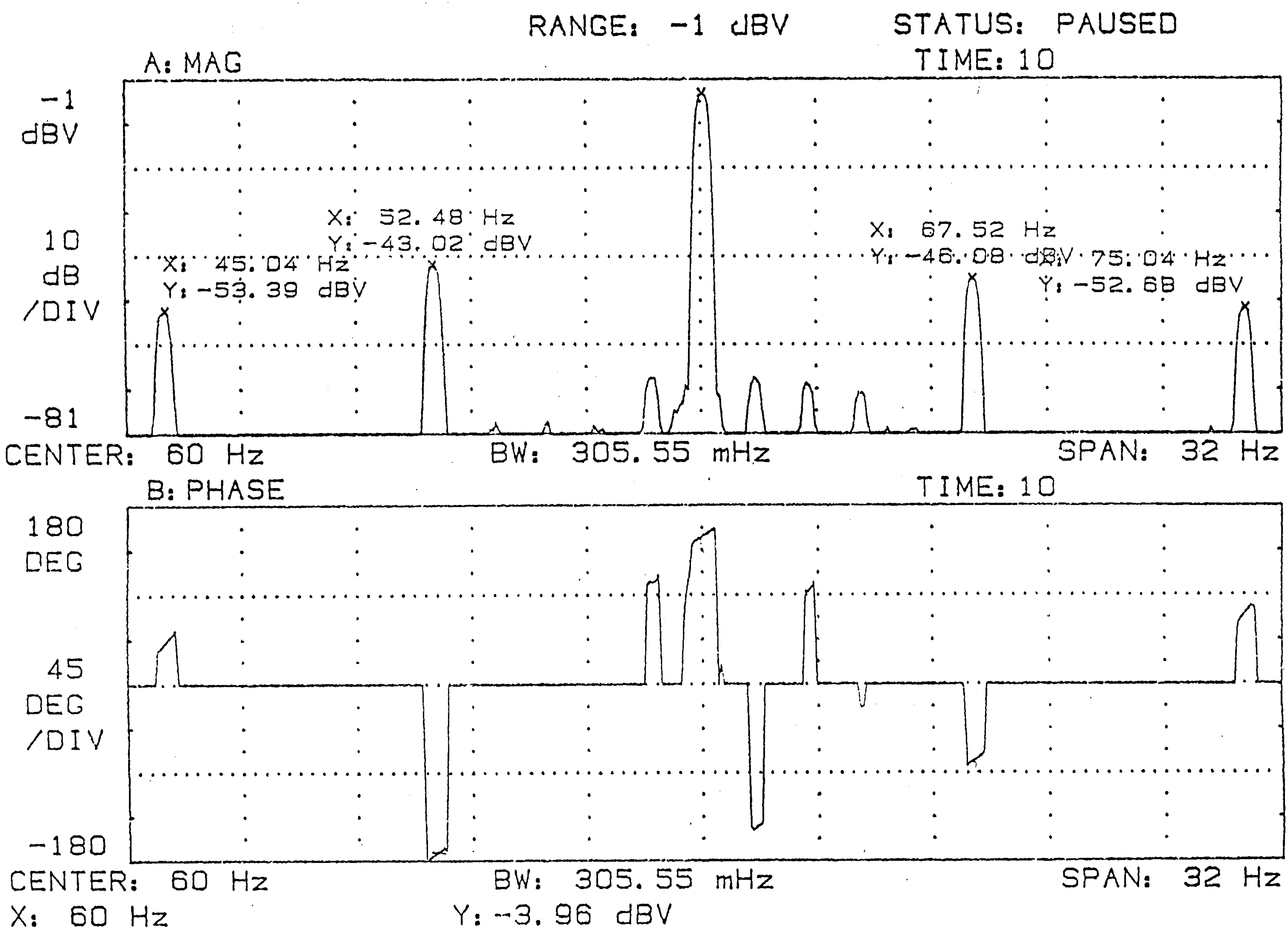

FIGURE 2
SPECTRUM OF 60 Hz VOLTAGE AT MAGNET. POWER SWING = 1.2MW

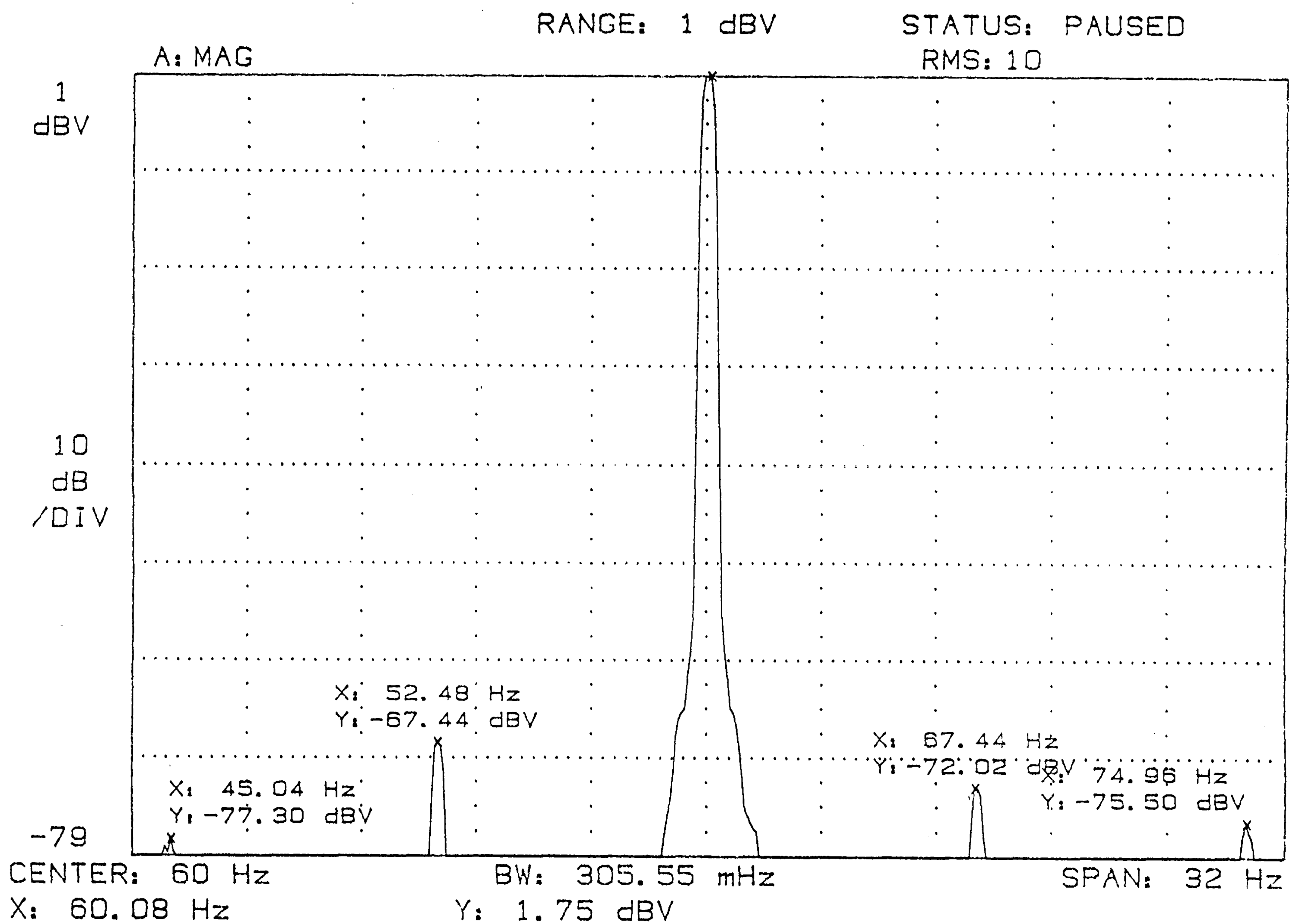

FIGURE 3
SPECTRUM OF 60 Hz VOLTAGE AT NSLS DUE TO PULSATING LOAD. POWER SWING - 1.2MW.

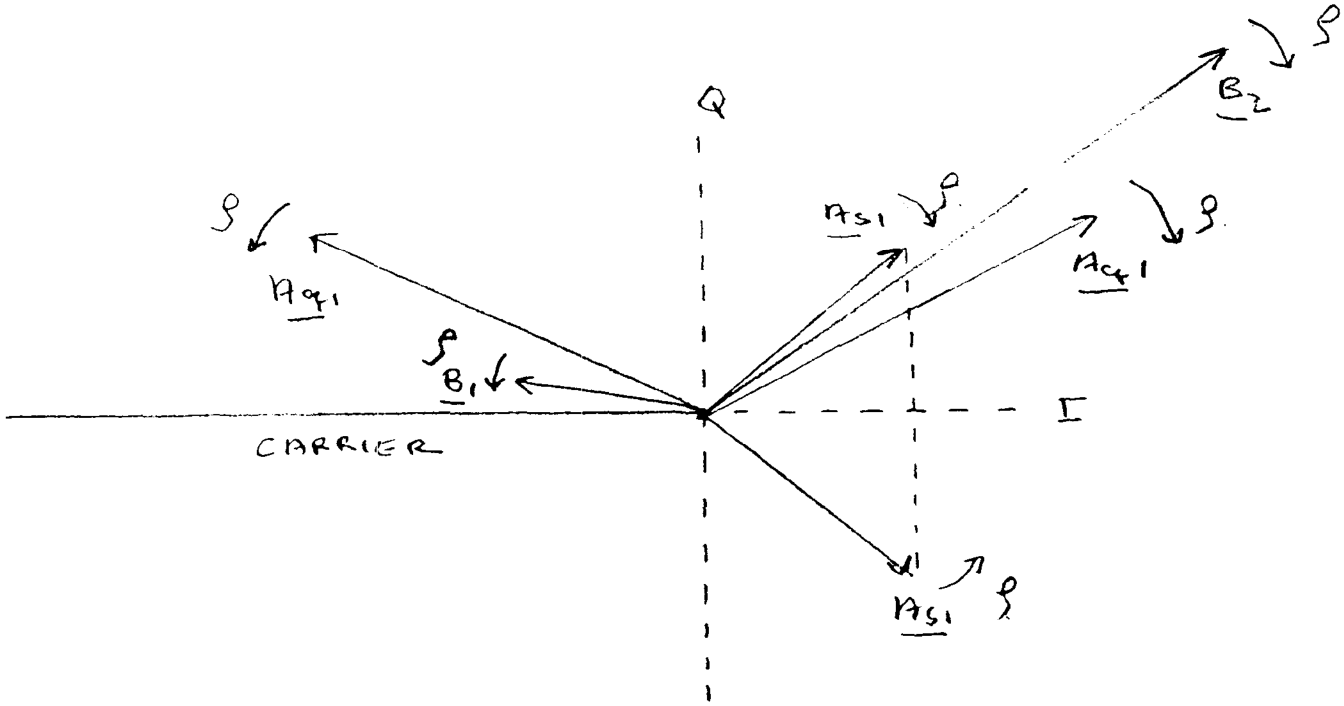

FIG 4A
CARRIER WITH FIRST ORDER SIDEBANDS B1 AND B2 RESOLVED INTO SYMMETRICAL (As) AND ANTISYMMETRICAL (Aq) SIDEBANDS

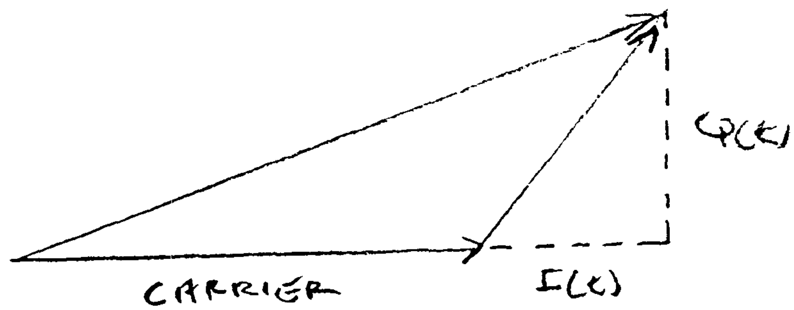

FIG 4 B
COMPOSITE PHASOR

FULL POWER

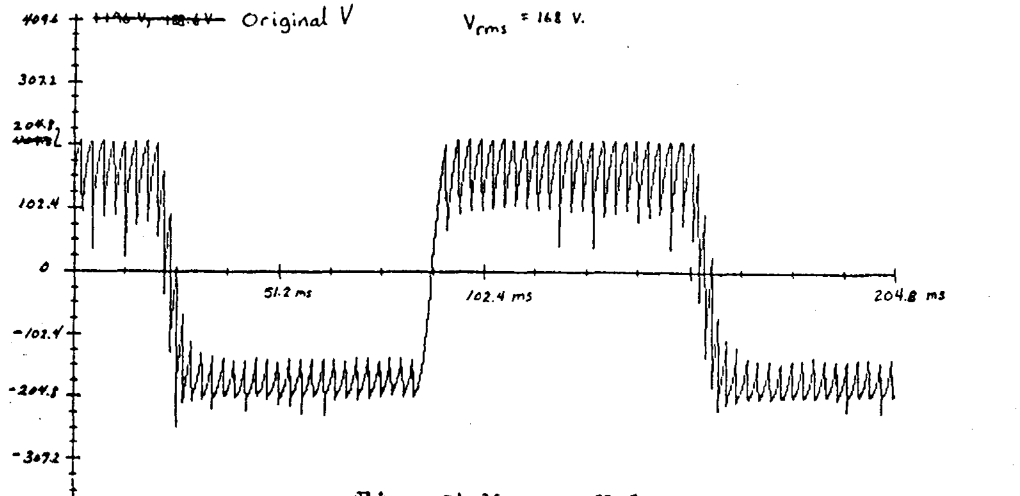

Fig. 5A Magnet Voltage

FULL POWER

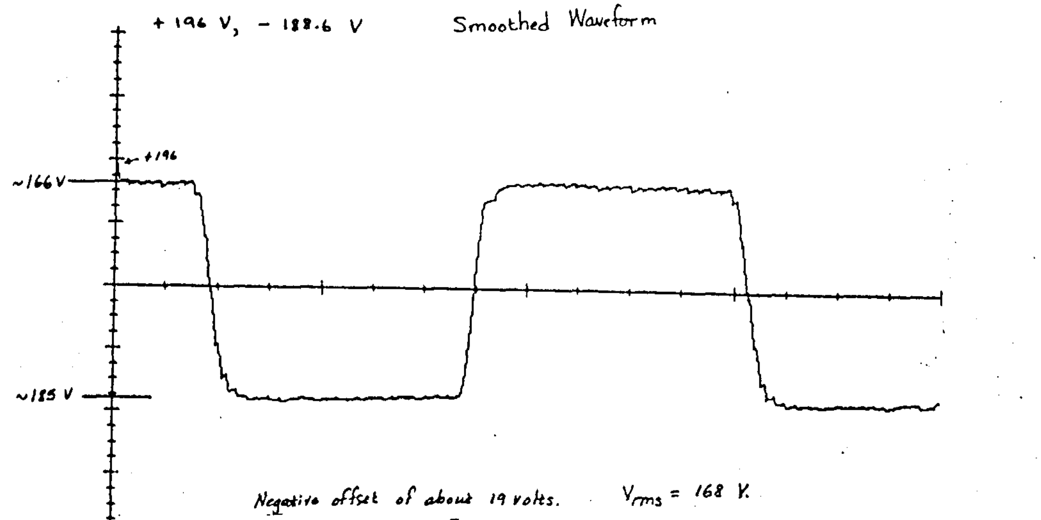

Fig. 5C Filtered Magnet Voltage

Original I

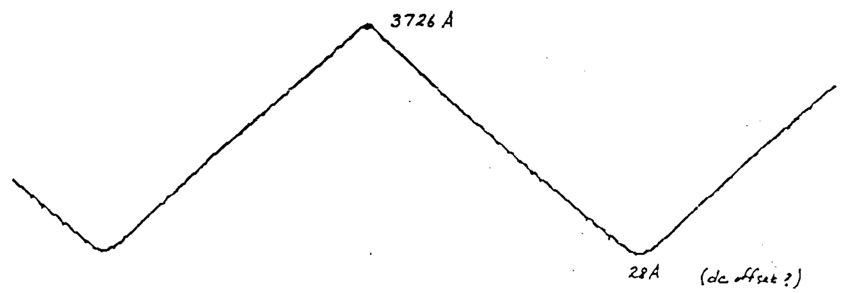

Fig. 5B Magnet Current

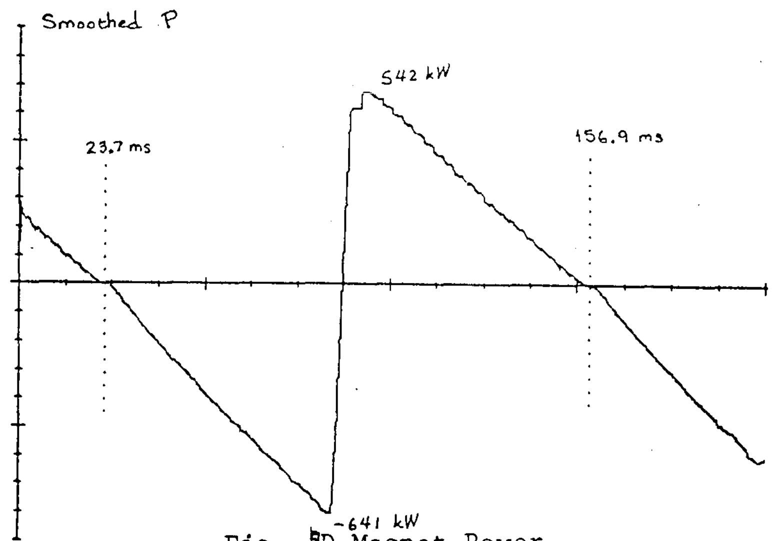

Fig. 5D Magnet Power

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18 Nov 1986      11:36:35      Power loss measurement.
  MagPower
Emax   980.0, Emin   -943.0
Imax  1863.0, Imin     14.0
Zeros:       237      892      1569
E           -9.0    -10.0    +11.0
I          +24.0  +1855.0    +24.0
Voltage pk/rt2  138.6 Volts   Current pk/rt2   2635 Amperes
Voltage (rms)  168.4 Volts   Current (rms)   2151.1 Amperes
The sum of the products of E and I is:  -22 kW
The integral using Simpson's 1/3 Rule is:  -22 kW.

  Peak powers over entire waveform and over 1 cycle.
  542 kW   542 kW  -641 kW  -641 kW
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Cycle is 156.9 − 23.7 = 133.2 ms long.