BNL-105232-2014-TECH

Booster Technical Note No. 188;BNL-105232-2014-IR

AGS BOOSTER PULSED POWER LINE MONITORING AND INTERLOCKING

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January 1990

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Brookhaven National Laboratory

U.S. Department of Energy

USDOE Office of Science (SC)

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AGS BOOSTER PULSED POWER LINE MONITORING AND INTERLOCKING

BOOSTER TECHNICAL NOTE
NO. 188

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JANUARY 25, 1990

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I. INTRODUCTION

The AGS Booster synchrotron is a machine capable of rapid cycling at frequencies up to 7.5 Hz, of accumulating beams for several seconds, and for accelerating heavy ion species, at low frequencies, up to atomic masses of ~200 up to 3.5 GeV / amu. It was decided to power the ring via multiphase thyristor controlled rectifier type power supplies operating directly off the local power grid.[1,2]

Large pulsed accelerator synchrotron magnet loads are highly inductive and usually require large amounts of energy to charge up and then must be discharged quickly thus releasing the large amount of stored energy. This flow of energy into the load and back into the line can cause amplitude and phase "flicker" type disturbances to the power lines. This can effect users local to the synchrotron area and other users outside of the site. Thus, studies were conducted to determine these effects.[3,4,5] These studies characterized the level of the problem at the BNL site boundary to be not troublesome.

In discussions with the local Long Island power company (LILCO), it was decided to study the effects on the company transmission and generating equipment. Therefore a study was commissioned to the GE Company to analyze the LILCO system for resonances, instabilities and voltage fluctuations.[6] Many different cases were studied which included different sets of generating equipment on line as well as variations in the transmission system. The major problems identified were certain system resonances in the 1- 4.8 Hz frequency regime and certain shaft torsional resonances on generating equipment at frequencies greater than 10 Hz, especially on the Shoreham nuclear generating facility.

In order to interlock their system against inadvertent operation of the Booster in modes dangerous to LILCO, GE was contracted to build a protection relay to monitor Booster operation. The Power Pulsation Monitor Relay (PPMR) measures the average power being consumed and generated by the Booster main ring magnet power supply and then performs a Fast Fourier Transform (FFT) to determine the frequency components of the power waveform. The PPMR computer will trip the protection relay when pre-programmed limits are exceeded. If the PPMR trips, the LILCO 69 KV feeder which powers the main dipole power supply will be disconnected until reset by LILCO operations. If the relay is inoperative, the Booster will also be off.

The PPMR was tested at BNL during the month of September, 1990. This note is a description of how the PPMR works and a summary of test results.

II. THE PPMR

The PPMR inputs are derived from the 69 KV current transformers (CT's) and Potential Transformers (PT's). Input circuits are based on the Burr Brown ISO-100 isolation amplifier. PT inputs are scaled by resistors before the isolation amplifiers and the CT amplifiers are connected directly across 70.7 mohm shunts. See figure 1.

Analog multipliers combine each pair of scaled CT and PT inputs yielding three outputs of instantaneous power for each phase :

$$Pinst = (Vln * Sin (wt)) * (I * Sin (wt+phi))$$

The three instantaneous power waveforms are summed by an analog adder circuit and averaged by filtering. The resulting waveform is an analog signal representing the average power for the system.

The average power waveform is digitized by a commercial 12 bit Analog to Digital Converter (ADC) card mounted in the PPMR computer. The ADC digitizes at 1 KHz. Data is taken for 4 seconds and then loaded into a Data translation DT-7010 Array Processor Board (APB) which is also plugged into the PPMR computer. The APB pads the 4000 data points with 96 trailing zeros and does an FFT on the 4096 data points.

The data resulting from the FFT has a resolution in frequency domain given by:

$$\text{Frequency Resolution} = \frac{1}{(\text{period of sample rate} * \text{\# of samples})}$$

= .2441 Hz for 4096 samples taken at 1 KHz

Data points, or bins, in the frequency domain are spaced by the resolution frequency. See figures 2,3. The PPMR computer displays the frequency of the bin with the highest magnitude.

A potential problem exists in determining the magnitude the power at this frequency. If the actual frequency of the power waveform is exactly on a bin, the magnitude information for that bin may be read directly. If the frequency is between bins, energy is spread among several bins, resulting in the FFT error "leakage". Some correction scheme is used by the Data Translations software to correct the power display so that it is accurate to about +/- 10 % no matter how the power is distributed in the frequency bins.

III. BOOSTER AVERAGE POWER WAVEFORMS

In the fast mode, or proton operation, the Booster main ring power supply generates a triangle waveform of current in the main dipoles and quads. During commissioning this may be a continuous waveform and later during physics runs it will be a burst of four current triangles followed by a 1.5 to 3 second rest period.

The power waveforms and the spectrum expected from the two modes of operation are shown is figures 4 and 5. Note that in continuous operation, the second harmonic power is significant, at about 0.4 times peak power, and is the limiting factor in allowable power. In burst operation, with a rest period, the average power is down by the duty cycle factor and operation is not restricted by present relay settings.

In the slow cycle, or Heavy Ion mode, the power waveform has most of it's power at the fundamental frequency. This is because the waveform is rounded as the period of the current "triangle" approaches L/R, the time constant of the main ring magnets, quads, and connecting cables, and the power supply dc voltage is limited. See figure 6 for an example of the slow power waveform that we used.

IV. RESULTS OF PPMR TESTING

PPMR testing was done in the 911 Westinghouse MG set area. Acme power supply, No. 607, a 600 KW power supply with a 1.3 second time constant load, was used to simulate Booster main magnet power supply operation; see figure 7. An arbitrary function generator, Wavetek model 75, was connected to 607's SCR phase control board to simulate various Booster main magnet current waveforms.

AC input power was simulated at a ratio of 627 to 1. 60 to 1 ratio CT's were used to measure ps 607 input AC current and 3.75 to 1 ratio PT's were connected "wye-delta" to supply input 480/120 volt line to neutral voltage for each phase.

The PPMR digitizes the analog power waveform and computes the FFT based on the digitized data. The PPMR displays the main component of the power waveform spectrum on an EGA display. The analog power waveform was also tapped at Test Point #18 and fed by coaxial cable to a Keithley 194A high speed voltmeter. The 194 was used to digitize the power waveform and perform an off line, independent FFT on a second computer.

The test results are shown in figures 8 to 13. PPMR measured average power at the fundamental frequency is plotted with peak power of analog power waveform. The alarm condition is a warning resulting in no action, a trip condition opens a 69 KV LILCO breaker. The most serious discrepancy found during testing is the location of the limits for alarm and trip conditions. Figure 14 shows the resulting windows of allowed operation. Figure 15 shows how the "walls" are actually half way between FFT frequency bins.

V. THE OCTOBER 10, 1990 LILCO/GE/BNL MEETING

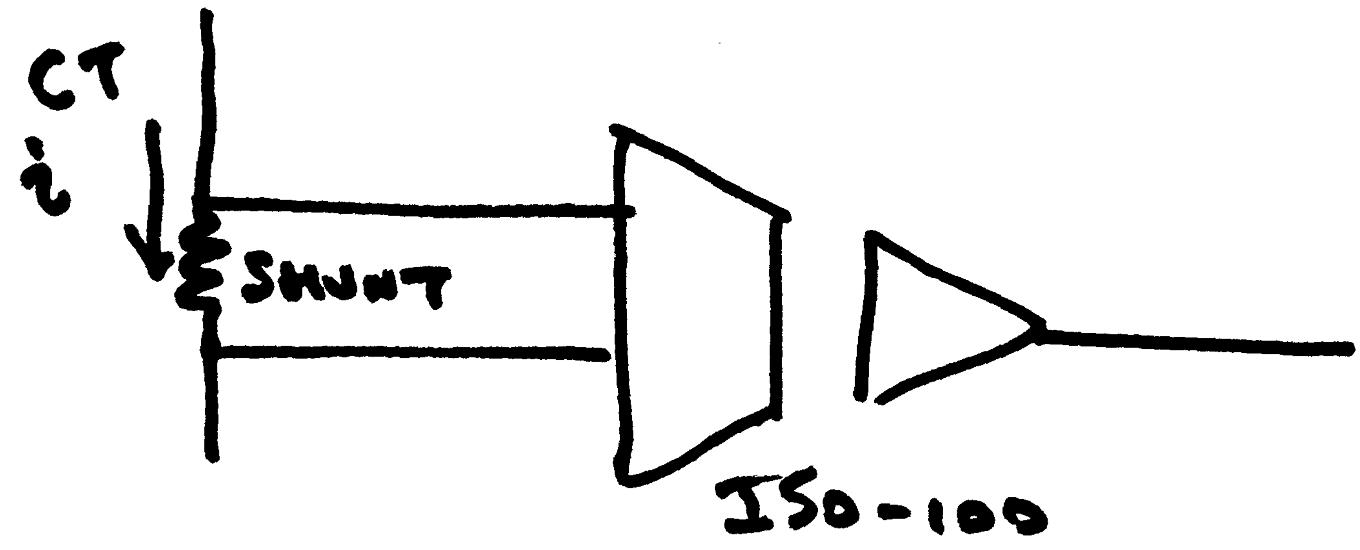
A meeting was held at BNL to discuss the PPMR test results and future changes to the unit. New windows of allowed operation were agreed upon; see figures 16,17.

LILCO proposed a possible hardware re-design where the PPMR sampling windows would be triggered by a BNL start trigger to synchronize with our waveforms. Variable length windows intended to minimize leakage were also discussed. All parties agreed to postpone such changes to a future model of the PPMR if needed.

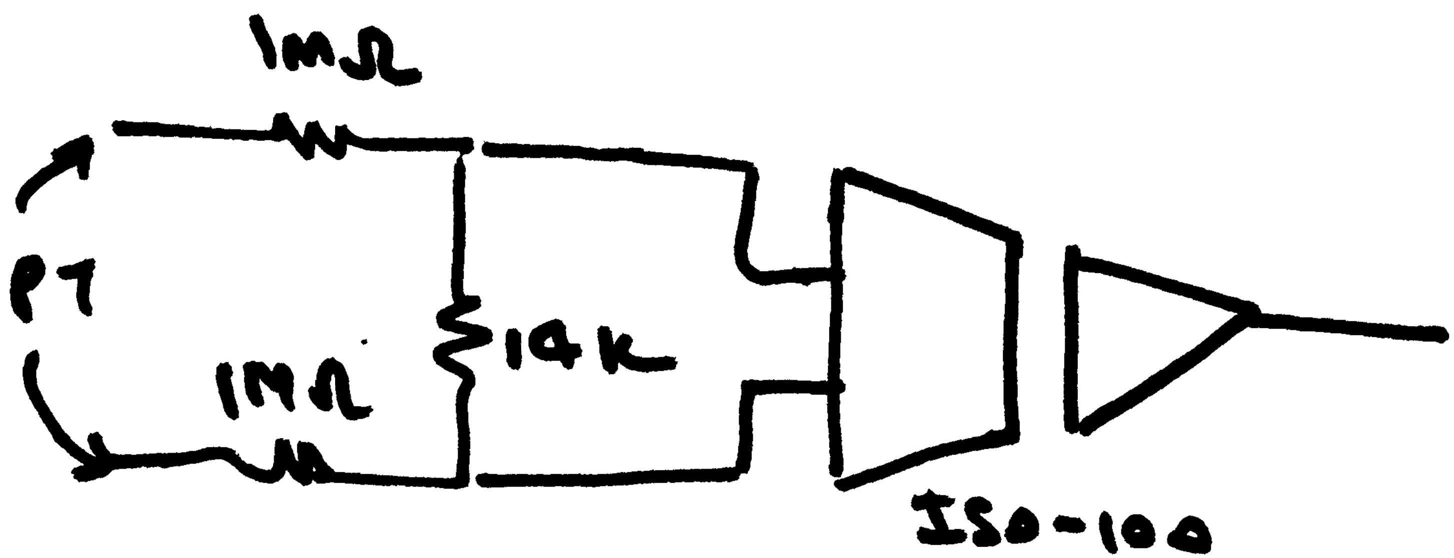
BNL proposed an isolated analog output of the power waveform for on site testing and transmission of the signal to the AGS control room. This proposal is being studied.

LILCO agreed to supply the "alarm" contacts or bit to the BNL control room to give a pre-trip warning. This will enable Booster cycle changes or alterations to prevent a trip out of input power.

LILCO and BNL discussed post trip procedures and PPMR maintenance. LILCO assumes responsibility for PPMR maintenance. In the event of trip, the



CT CONNECTIONS



PT CONNETIONS

fig 1

FAST FOURIER TRANSFORM (FFT)

SAMPLE RATE (ts)

DETERMINES FREQUENCY DOMAIN FULL SCALE FREQUENCY

0 Hz 1/(2*ts) Hz

WINDOW LENGTH (T = sample time * no. of samples)

DETERMINES THE RESOLUTION AND THE LOWEST OBSERVABLE FREQUENCY

0 Hz 1/(ts * #SAMPLES) Hz

(FIRST FREQUENCY BIN)

THERE IS NO KNOWLEDGE OF AN EVENT OUTSIDE OF THE WINDOW, THE WAVEFORM IS ASSUMED TO BE CONTINUOUS

ERRORS OCCUR IF THE WINDOW DOES NOT CONTAIN AN INTEGRAL # OF PERIODS OF THE SIGNAL

FFT IS A SIMPLIFIED ALGORITHM FOR SOLUTION OF THE DFT AND REQUIRES THE NUMBER OF TIME DOMAIN SAMPLES TO BE 2^n

fig. 2

PPMR DETERMINATION OF FREQUENCY

ts = 1 mS, NUMBER OF SAMPLES = 4096, WINDOW = 4.096 S

FULL SCALE FREQUENCY = 500 HZ

RESOLUTION = .2441 Hz

PPMR FREQUENCY BINS

BIN LOCATION	PPMR LABEL	BIN LOCATION	PPMR LABEL
.24	.25	4.15	4.25
.49	.50	4.39	4.50
.73	.75	4.64	4.75
.98	1.00	4.88	5.00
1.22	1.25	5.13	5.25
1.46	1.50	5.37	5.50
1.71	1.75	5.62	5.75
1.95	2.00	5.86	6.00
2.20	2.25	6.10	6.25
2.44	2.50	6.35	6.50
2.69	2.75	6.59	6.75
2.93	3.00	6.84	7.00
3.17	3.25	7.08	7.25
3.42	3.50	7.32	7.50
3.66	3.75	7.57	7.75
3.91	4.00	7.81	8.00
		8.06	8.25
		8.30	8.50
		8.54	8.75
		8.79	9.00

fig. 3

PPMR LABEL IS FREQUENCY DISPLAYED ON PPMR MONITOR FOR INPUT @ BIN FREQ.

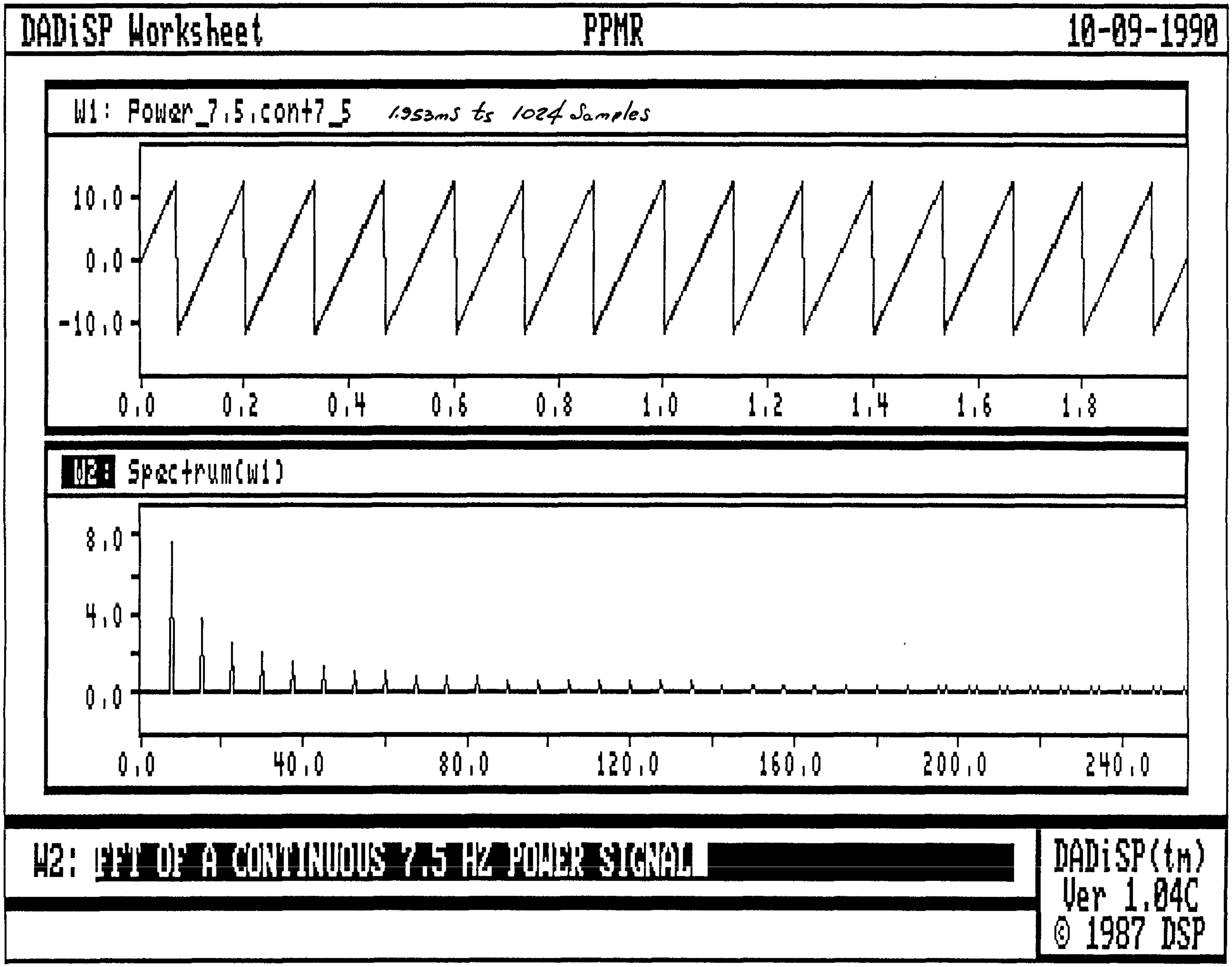

DADiSP Worksheet
PPMR
10-09-1990
W1: Power_7.5.cont7_5
1.953mS ts 1024 Samples
10.0
0.0
-10.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
W2: Spectrum(w1)
8.0
4.0
0.0
0.0
40.0
80.0
120.0
160.0
200.0
240.0
W2: FFT OF A CONTINUOUS 7.5 HZ POWER SIGNAL
DADiSP(tm)
Ver 1.04C
© 1987 DSP

Fig 4

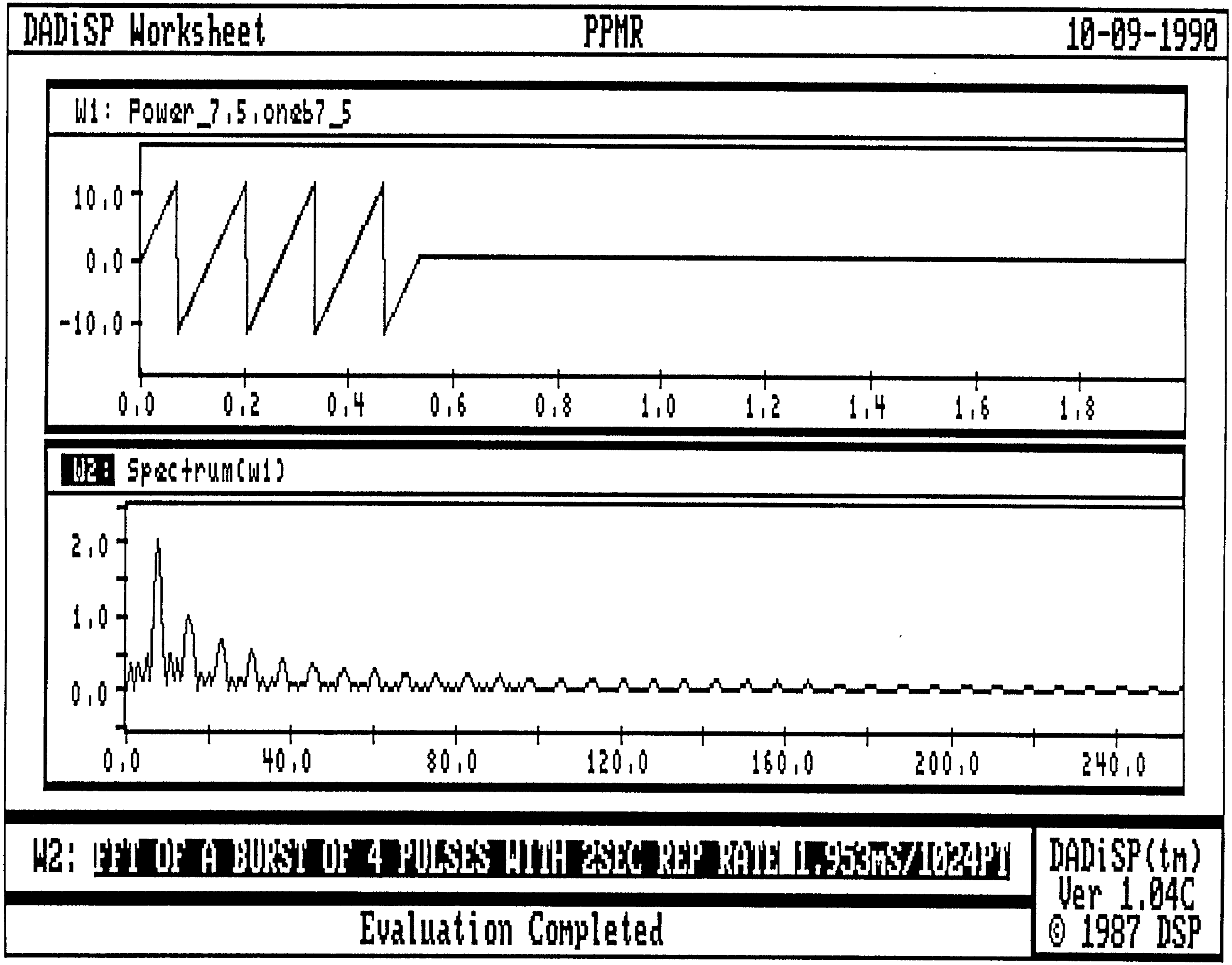
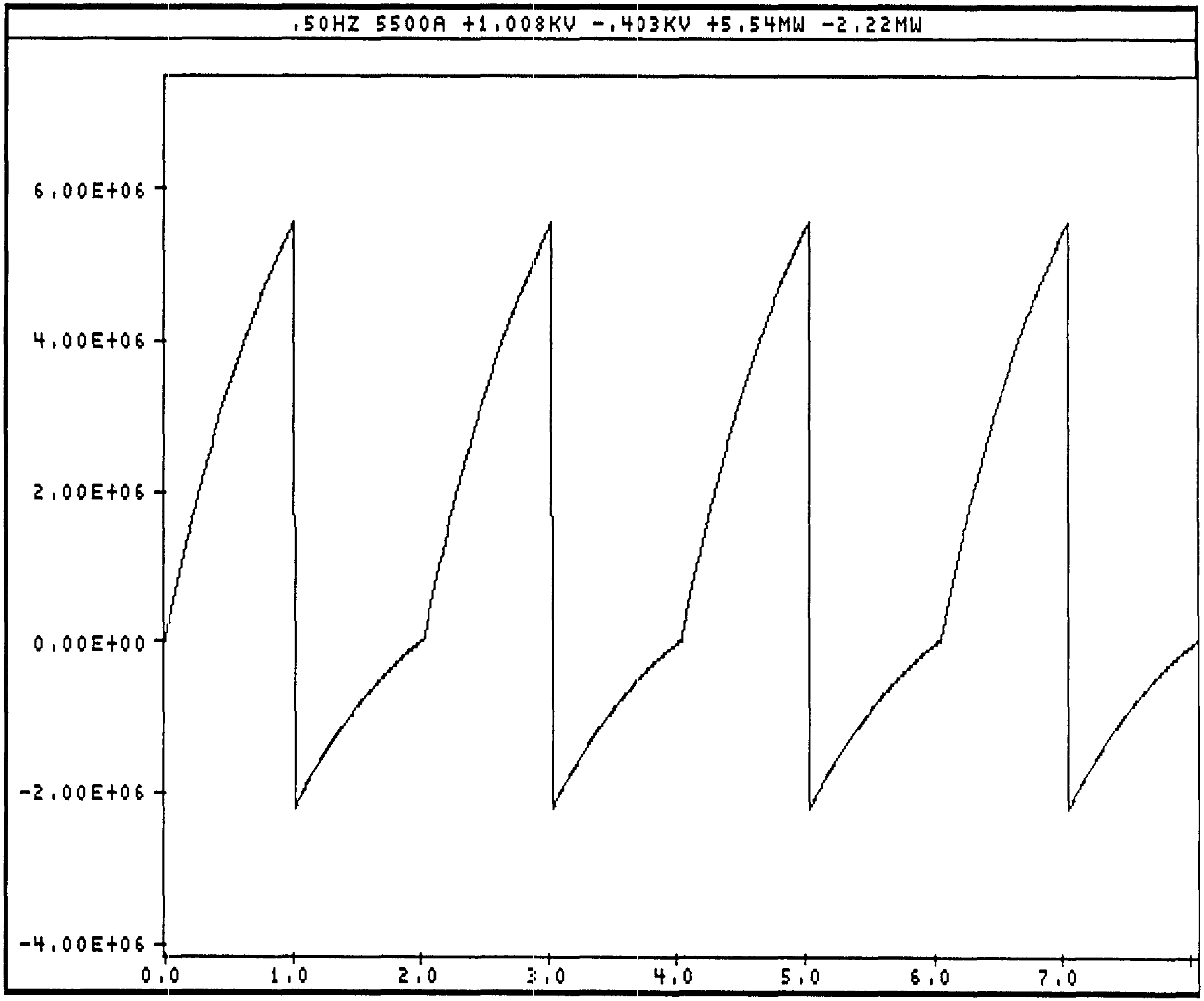

DADiSP Worksheet
PPMR
10-09-1990
W1: Power_7.5,oneb7_5
10.0
0.0
-10.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
W2: Spectrum(w1)
2.0
1.0
0.0
0.0
40.0
80.0
120.0
160.0
200.0
240.0
W2: FFT OF A BURST OF 4 PULSES WITH 2SEC REP RATE 1.953mS/1024PT
Evaluation Completed
DADiSP(tm)
Ver 1.04C
© 1987 DSP

fig. 5



Simulated DC conditions
120 mh, 110 mohms, tau 1.091 S

fig. 6

TEST SET UP FOR BNL EVALUATION OF LILCO / GE PPMR

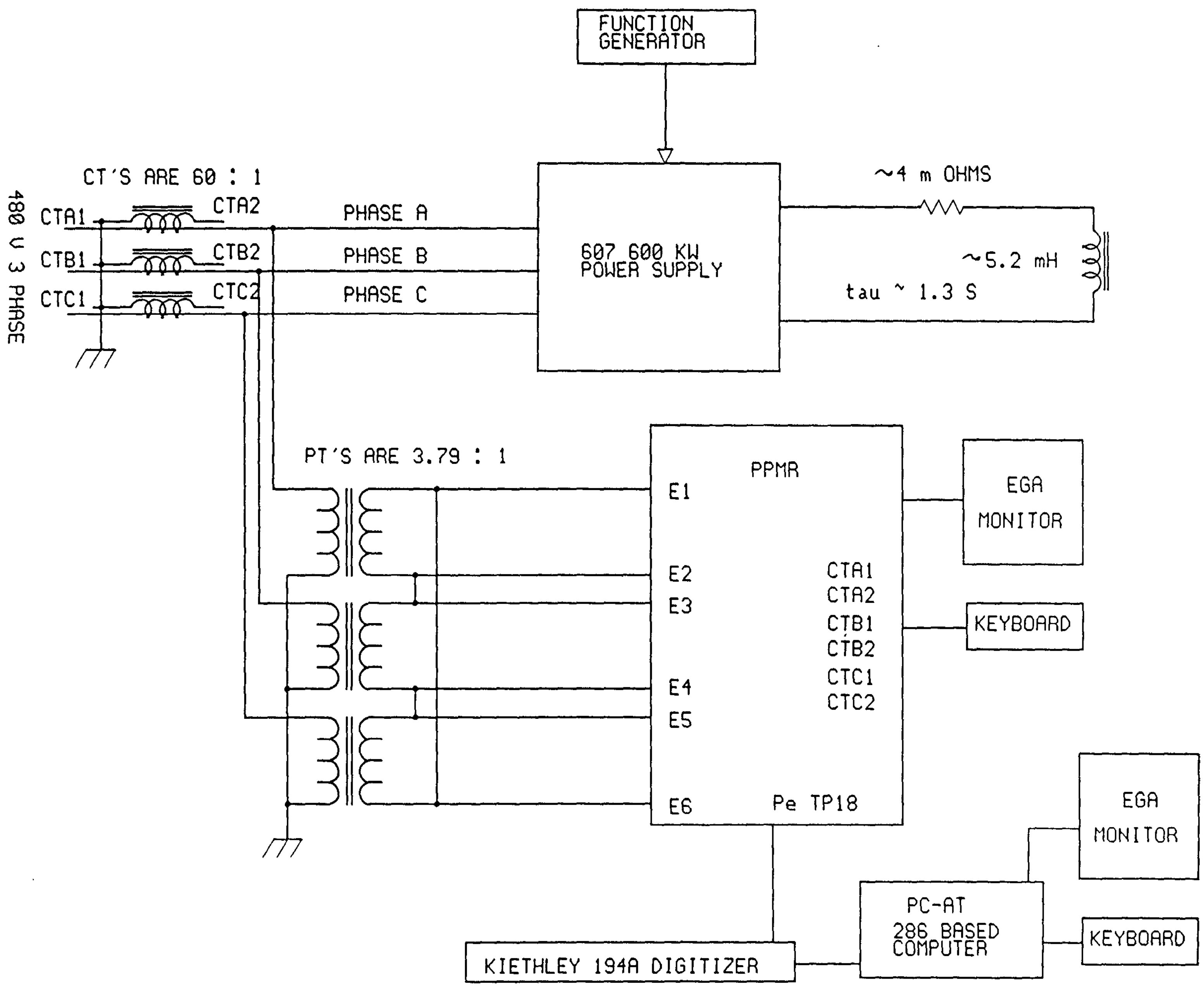


fig. 7

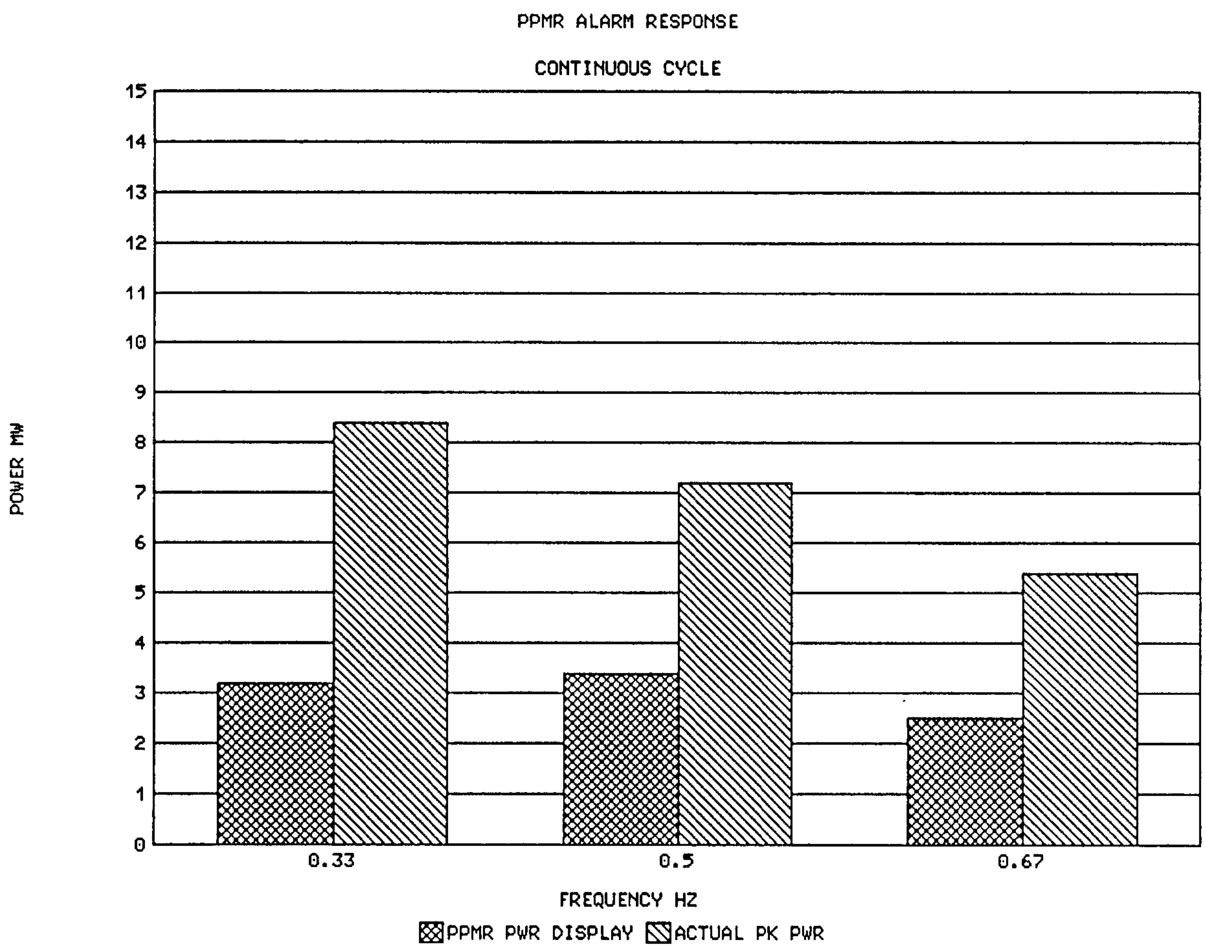

PPMR ALARM RESPONSE
CONTINUOUS CYCLE
POWER MW
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
0.33
0.5
0.67
FREQUENCY HZ
PPMR PWR DISPLAY
ACTUAL PK PWR

fig. 8

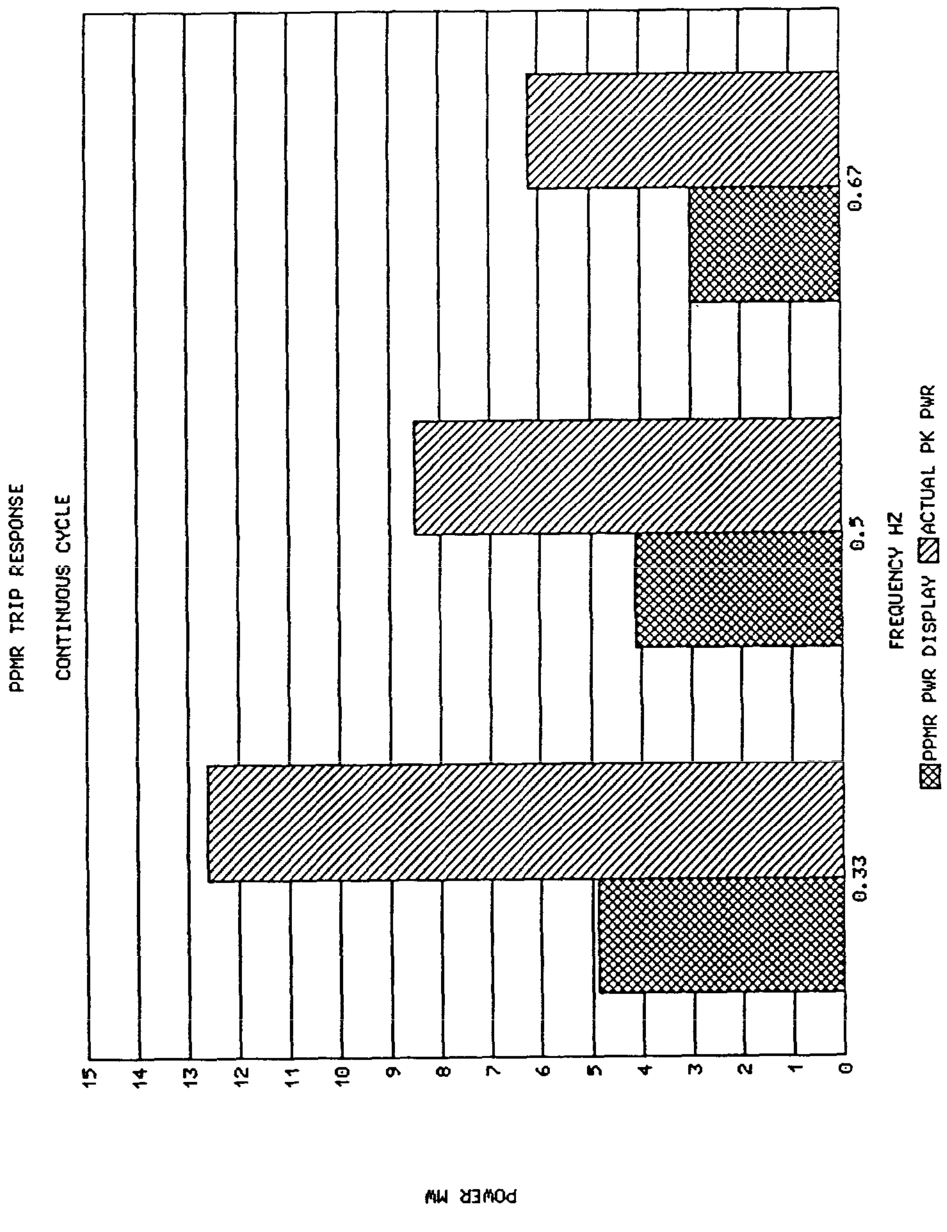

PPMR TRIP RESPONSE
CONTINUOUS CYCLE
POWER MW
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
0.33
0.5
0.67
FREQUENCY HZ
PPMR PWR DISPLAY
ACTUAL PK PWR

fig. 9

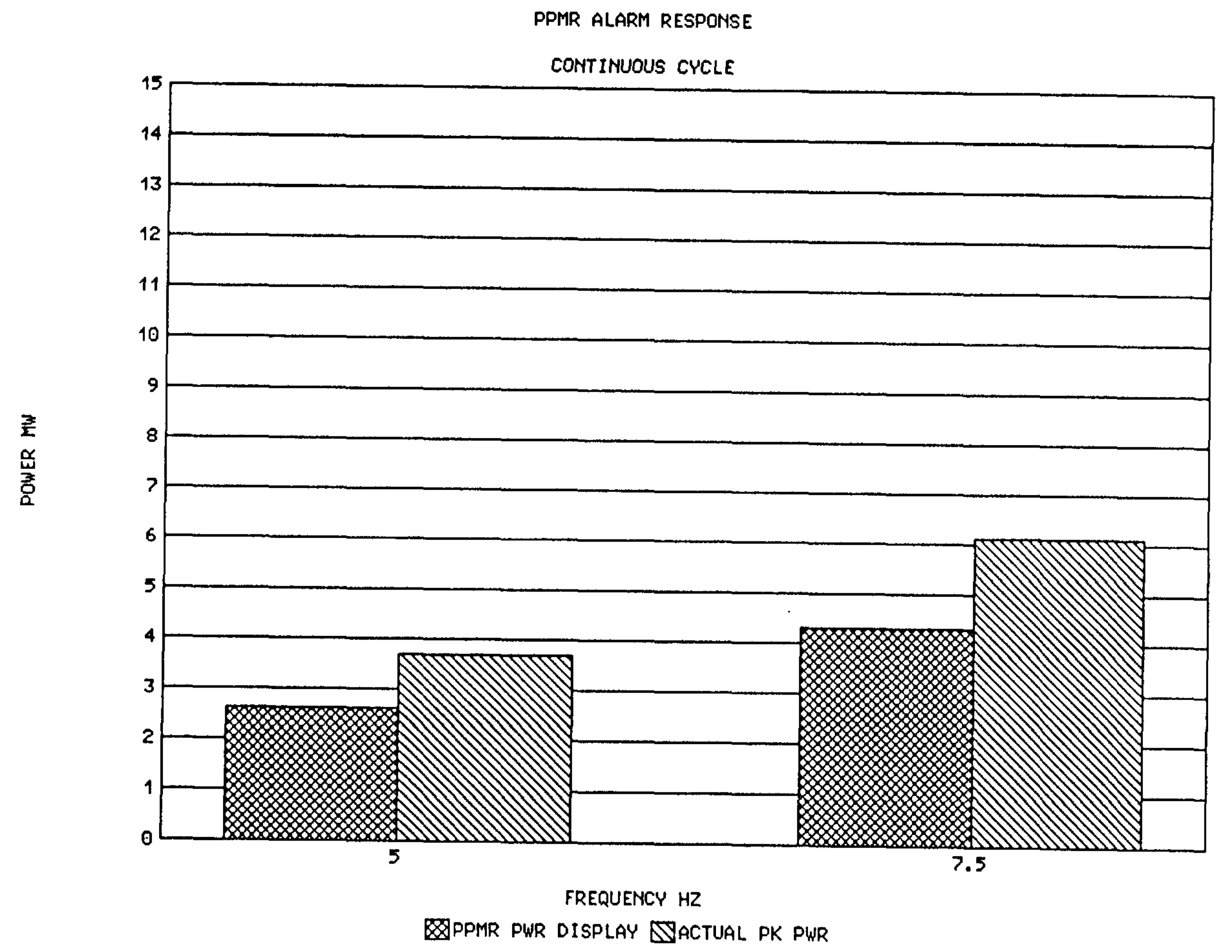

PPMR ALARM RESPONSE
CONTINUOUS CYCLE
POWER MW
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
5
7.5
FREQUENCY HZ
PPMR PWR DISPLAY
ACTUAL PK PWR

fig. 10

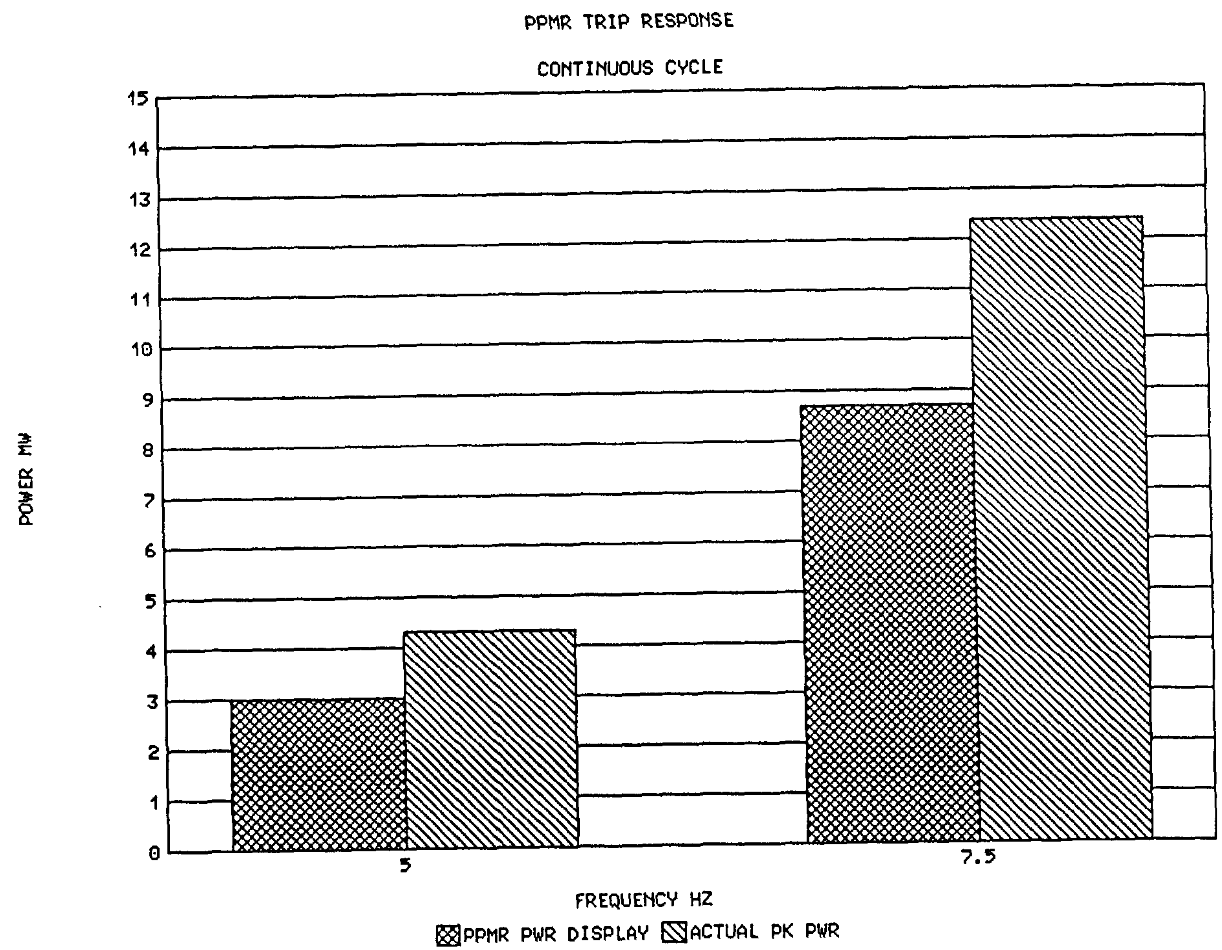

PPMR TRIP RESPONSE
CONTINUOUS CYCLE
POWER MW
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
5
7.5
FREQUENCY HZ
PPMR PWR DISPLAY
ACTUAL PK PWR

fig. 11

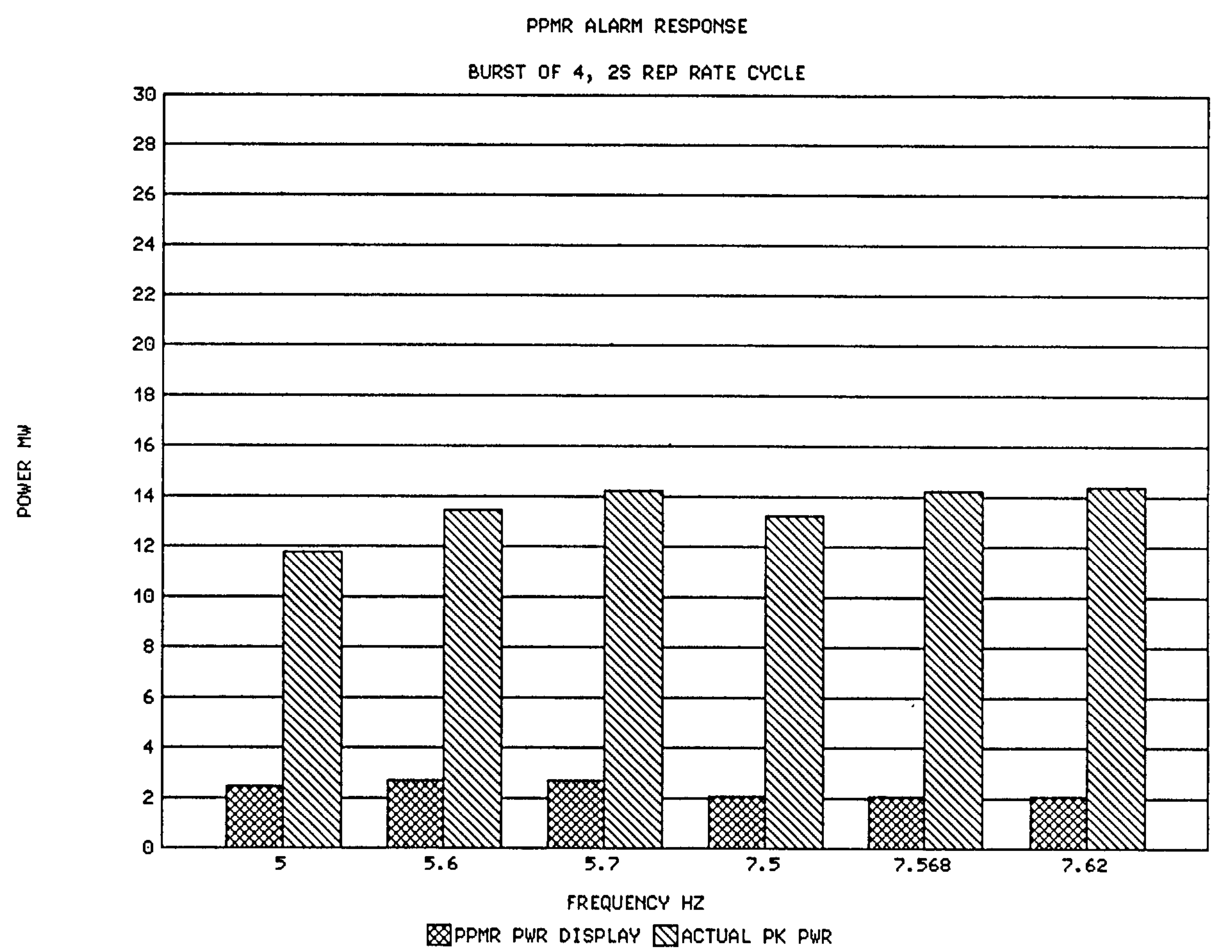

PPMR ALARM RESPONSE
BURST OF 4, 2S REP RATE CYCLE
POWER MW
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
5
5.6
5.7
7.5
7.568
7.62
FREQUENCY HZ
PPMR PWR DISPLAY
ACTUAL PK PWR

fig. 12

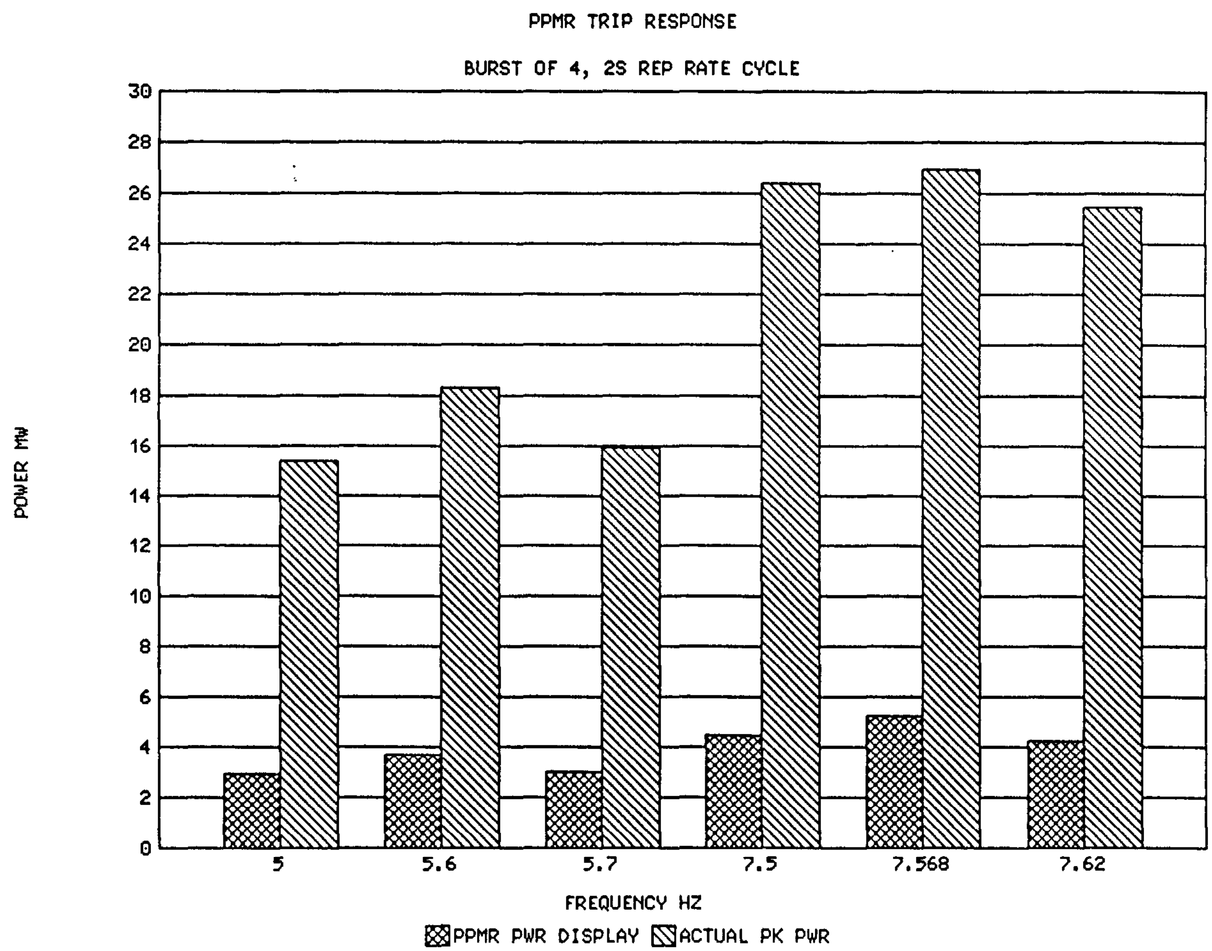

PPMR TRIP RESPONSE
BURST OF 4, 2S REP RATE CYCLE
POWER MW
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
5
5.6
5.7
7.5
7.568
7.62
FREQUENCY HZ
PPMR PWR DISPLAY
ACTUAL PK PWR

fig. 13

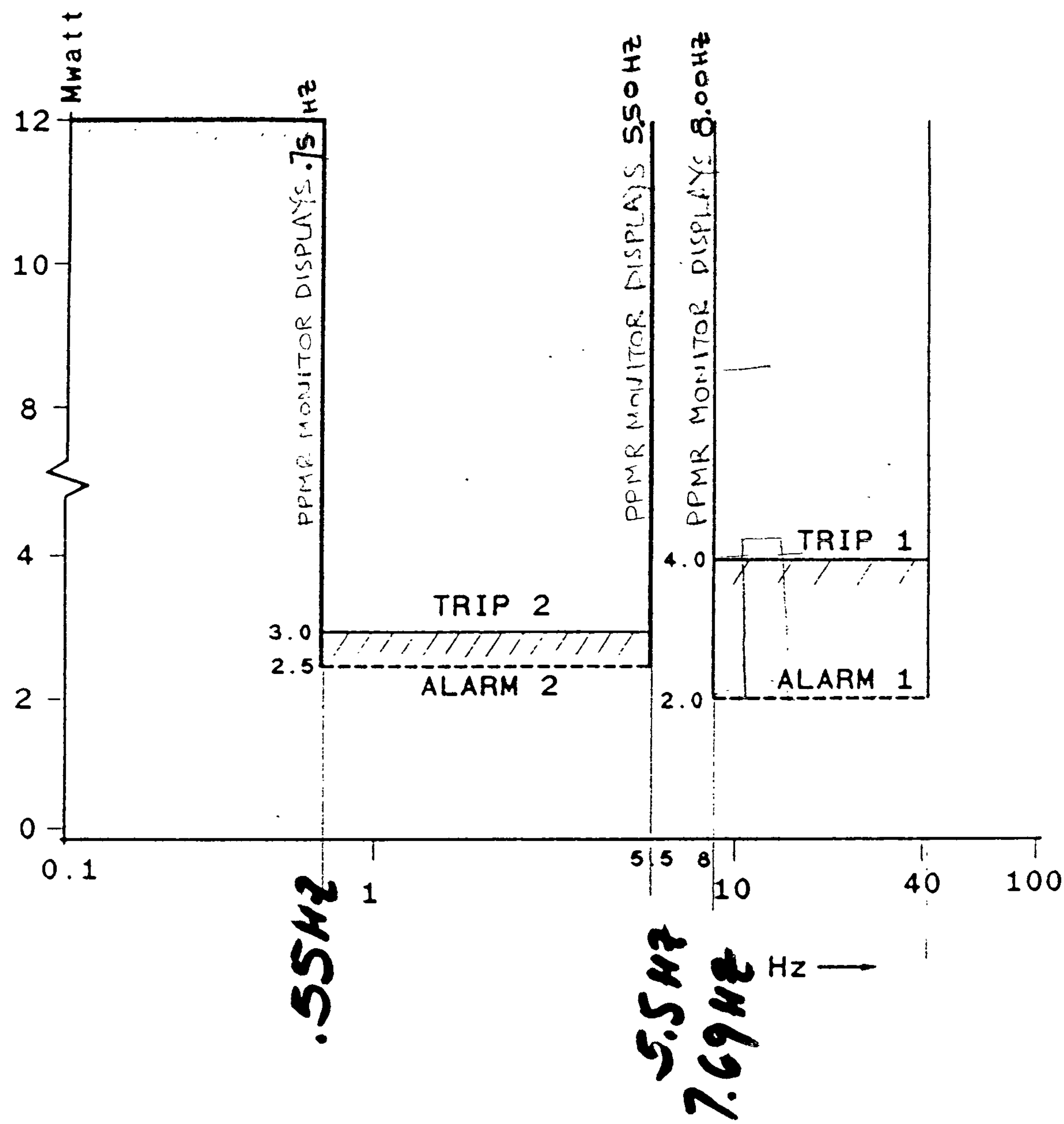


Figure 14 Trip & Alarm Settings

PPMR ACTUAL FREQUENCY LIMITS

```
                 Bin Location
7.69 HZ              7.81 HZ              7.93 HZ
  |<--------8.00 HZ LABEL DISPLAYED------->|
 WALL

 5.25 HZ             5.37 HZ              5.50 HZ
  |<-------5.50 HZ LABEL DISPLAYED------->|
                                       WALL

 ~.55 HZ             .73 HZ               .86 HZ
   |<------.75 HZ LABEL DISPLAYED-------->|
  WALL
```

fig. 15

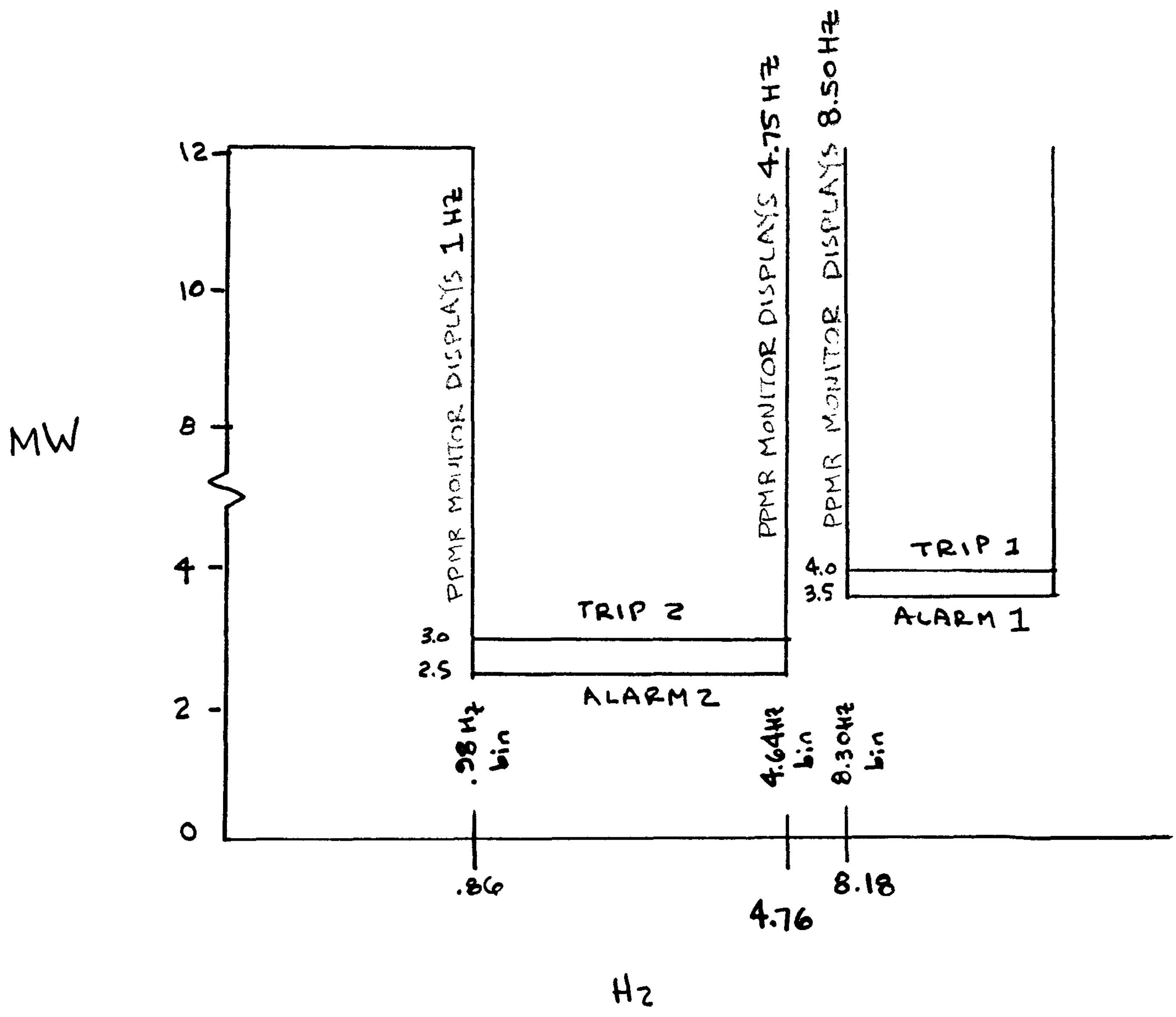


Fig. 16 Modified Trip & Alarm Settings

PPMR FREQUENCY LIMITS AFTER MODIFICATION

```
                  Bin Location
8.18 HZ             8.30 HZ             8.42 HZ
 |<--------8.50 HZ LABEL DISPLAYED------->|
WALL


 4.52 HZ             4.64 HZ             4.76 HZ
  |<-------4.75 HZ LABEL DISPLAYED------->|
                                        WALL


 .86 HZ              .98 HZ             1.10 HZ
   |<------1.00 HZ LABEL DISPLAYED-------->|
  WALL
```

fig. 17