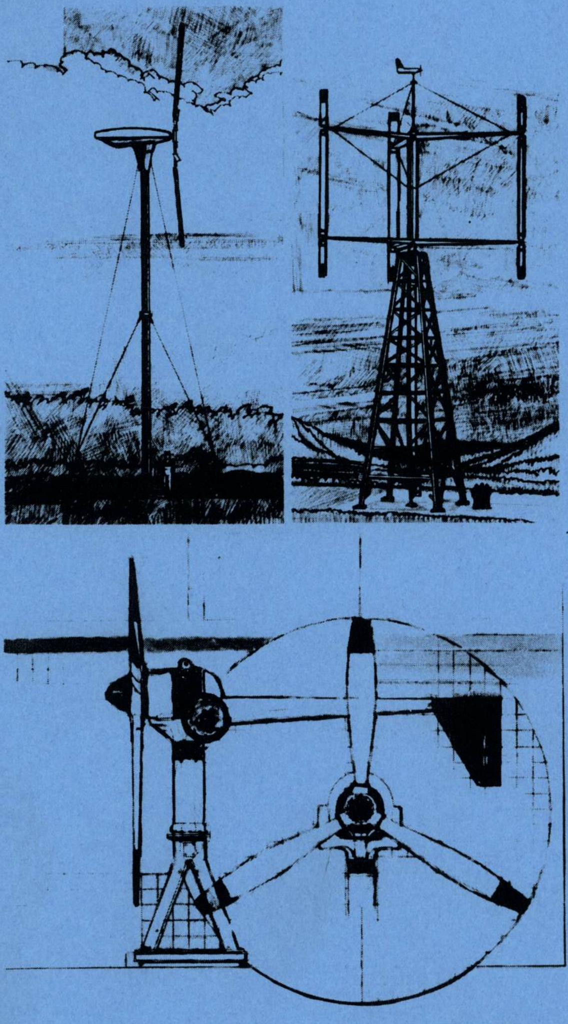
RFP-3449
UC-60

INTERFACING A GEMINI SYNCHRONOUS (LINE-COMMUTATED) INVERTER WITH A LOCAL UTILITY AND A MINI-GRID

Test Results

OCTOBER 1981



Prepared by the
DOE Rocky Flats
Wind Energy Research Center

For
Rockwell International Corporation
Energy Systems Group
Post Office Box 464
Golden, Colorado 80402-0464

For the:
UNITED STATES DEPARTMENT OF ENERGY
WIND TECHNOLOGY DIVISION
FEDERAL WIND ENERGY PROGRAM

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ABSTRACT

This report presents data generated by interfacing a single-phase synchronous (line-commutated) inverter to a local utility and to a minigrid which simulated a 25 percent utility penetration. Line-commutated synchronous inverters are used by some wind systems manufacturers for interfacing the direct current or rectified alternating current output of wind-turbine generators directly to utility ac power lines.

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LIST OF ABBREVIATIONS

A or amp - ampere
ac - alternating current
dB - decibel
Δ - change or variance
dc - direct current
eff. - efficiency
FFT - fast fourier transform
ft - foot
FWR - full-wave rectified
HWR - half-wave rectified
I - current
in. - inch
K - thousand
kVA - kilovolt-ampere
kW - kilowatt (1000 watts)
kWh - kilowatt hour
lb - pound
LGMAG DB - log magnitude decibels
MAG - magnitude
m - meter
pf - power factor
PSCO - Public Service Company of Colorado
RI - Rockwell International
RF - Rocky Flats
rms - root mean square
rpm - revolutions per minute
SWECS - Small Wind Energy Conversion Systems
V - volt
VAR - volt-amperes-reactive
W - watt
WERC - Wind Energy Research Center

1.0 INTRODUCTION

The testing of electrical interface equipment is a vital part of the overall testing program for small wind energy conversion systems (SWECS) at the Rocky Flats Wind Energy Research Center (WERC). One of the goals of such electrical testing is to define the operational characteristics of electrical inverters used with SWECS. There are many types of inverters on the market today. However, this report will deal only with the one specific type of inverter generally supplied with a dc or rectified ac output wind turbine. This device is known as a line-commutated inverter and must directly interface dc or rectified ac SWECS output to an existing ac power grid.

Data from line-commutated inverters are required to satisfy several specific needs. One important need is the definition of procedures for safe and proper use of such inverters. Another need is for test data from interface equipment that is used as part of a wind system configuration when connected to a small isolated ac system rather than to a local utility company grid. In this situation, the interface can be represented by a unit such as a diesel engine-generator to represent the mini-grid. This mini-grid also permits the testing of simulated high penetration dc (solar or wind) to ac conversion equipment that may be used extensively for on-site power generation in remote applications. Finally, interface equipment data is needed to satisfy the increasing need for such data by industry and utilities.

A wind-driven generator can be directly connected to the utility ac system through the inverter with or without a battery bank in parallel with the generator. When a battery bank is used, the generator and inverter operate over a rather narrow range of dc voltages due to the voltage characteristics of the battery bank. When a battery bank is not used, the generator and inverter operate over a very wide range of dc voltages. Testing discussed herein is applicable only to the latter case.

This report describes the interface of a line-commutated inverter to the local utility (Public Service Company of Colorado) and to a Rocky Flats designed mini-grid. The inverter used in these interfaces was a single-phase Gemini Synchronous Inverter, manufactured by Windworks, Inc., Mukwonago, Wisconsin, prior to 1978. A special adjustable voltage dc source was used to simulate the wind range of dc voltage outputs from a wind-driven generator.

Since 1978, Gemini inverters have been modified by the manufacturer. When known, these modifications have been referenced in this report. However, since the modifications were not retrofitted in the test specimen, test results in this report do not reflect performance of circa 1982 Gemini inverters.

2.0 OPERATION OF A SINGLE-PHASE GEMINI SYNCHRONOUS INVERTER

The Gemini unit can be used to interface a wind system to a utility either from direct output of the wind system or output of a charged battery. Input to the Gemini in the tests described herein was an adjustable voltage dc source. Information on the installation and operation of the Gemini is contained in instruction manuals available from the manufacturer. Consequently, such information will not be discussed in this report. However, several operating notes deserve attention.

In order to make maximum use of energy sources such as a wind system, two different modes of inverter operation are utilized. In one case, the energy source is used to charge a battery and the battery and source are then connected through the inverter to the ac grid. Since the battery can only operate over a fairly restricted voltage range, the inverter controls must recognize these restrictions. This program did not include testing of a restricted voltage dc source (battery). If the energy source output is to be maximized when not connected in parallel with a battery (the second mode), it must be capable of being loaded into the ac grid over a wide voltage range without exceeding the maximum rating of the inverter. A Gemini can be used advantageously by providing an extended range of energy transfer from low voltage to high voltage, using current limit to protect itself from exceeding rated output.

In operation, the Gemini essentially connects the dc source via semi-conductors to the ac line, at the proper timing intervals, to transfer power to the ac line on its positive cycle and (through reverse polarity) switch to the dc source on the negative cycle. When using sources of low impedance, it is necessary to insert impedance in the source to "soften" the blow of momentary connection of the dc source to the ac line. This is accomplished most effectively by inserting in the dc line a low loss inductance - a standard component available from Windworks. The Gemini used at RF was supplied with a 20-millihenry, air core reactor for use with low impedance dc sources. Electrolytic capacitors for filtering were also supplied.

Due to transformer saturation, the Gemini should not be operated above 215 to 220 volts dc to prevent unnecessary fuse blowing.

3.0 INVERTER CHARACTERISTICS TERMINOLOGY

The Gemini, like other line-commutated inverters, is a volt-amperes-reactive (VAR) consumer with respect to the utility grid. Some terms used in this report relating to inverter control may be unfamiliar to the reader. This section defines those terms and offers graphical presentations for further clarification.

Current Limit - The current limit control sets the maximum amount of current permitted to be inverted. This provides current protection for the inverter and current source - small wind energy conversion system (SWECS) or photovoltaic device (PV). Figure 1 displays a typical range of the current limit control.

Voltage Cut-in - The voltage cut-in control sets a voltage level at which dc to ac inversion begins. This permits a SWECS to come up to speed without being loaded unnecessarily. Figure 1 also displays a typical range of the voltage cut-in control.

Current Slope - The current slope control determines the voltage differential that allows the current to rise from zero to the pre-determined current limit. This voltage change, which is proportional to speed, is expressed as a voltage rise (VR) above the cut-in point. Figure 2 displays a typical range of the current slope control.

Figure 2 shows a voltage cut-in of 100 V and a current limit of 20 A. Three different values of current slope settings are displayed: 125, 100, and 75 volt rises.

Using the 100 volt cut-in point, the 125 volt rise would not allow 20 A to be conducted below 225 V which is 25 V above the voltage rating of the inverter. Consequently maximum current and power cannot be delivered at the rated voltage of 200 volts.

The 100 volt rise will allow 20 A to be conducted at 200 V, thus permitting maximum current and power to be output as desired.

The 75 volt rise will allow 20 A to be conducted at 175 V, 25 V below the voltage rating of the inverter. Maximum current is consequently programmed to be met earlier and sustained longer. This smaller voltage rise will produce a larger power output at a lower speed. The reader must keep in mind that the current source (SWECS, etc.) may become overheated if the current exceeds design specifications of 20 amperes.

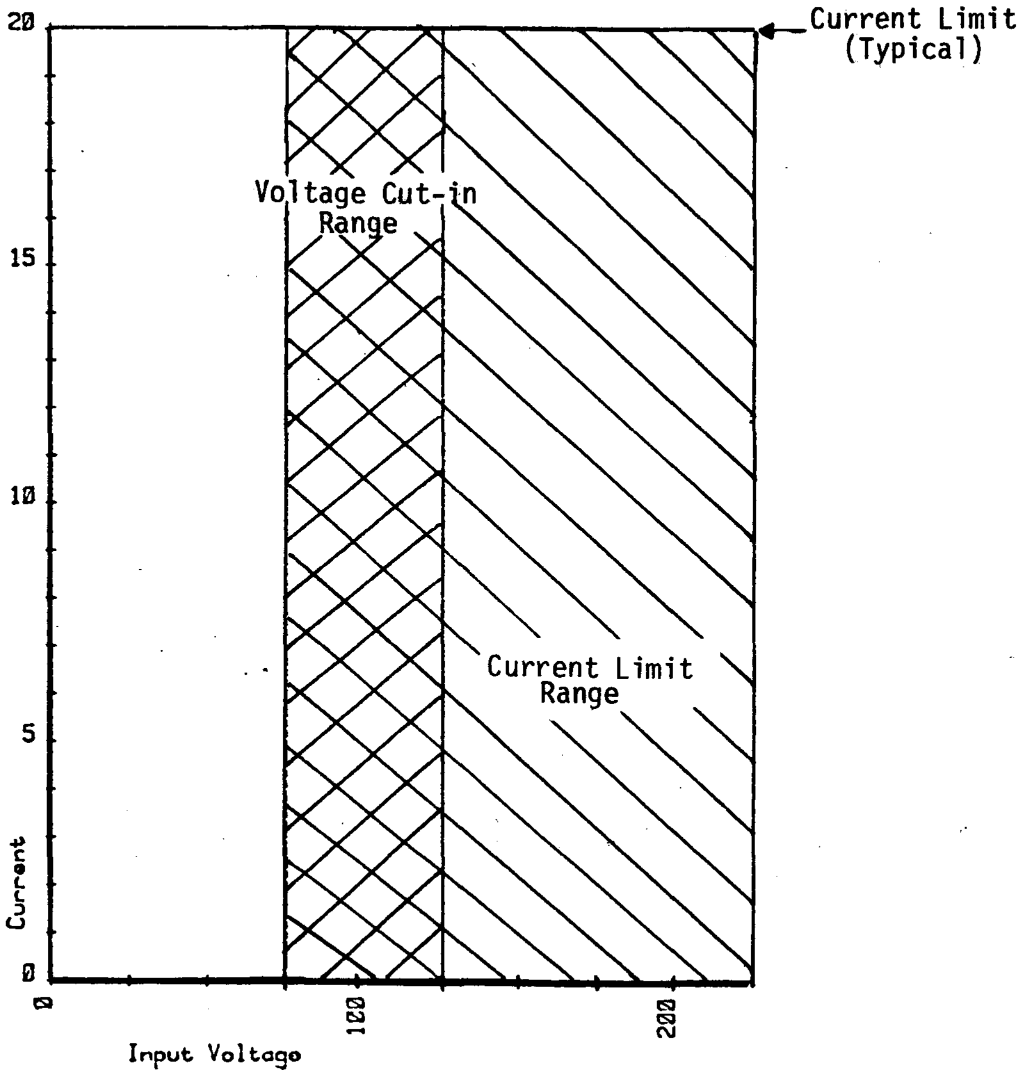


Figure 1

Current Limit and Voltage Cut-In

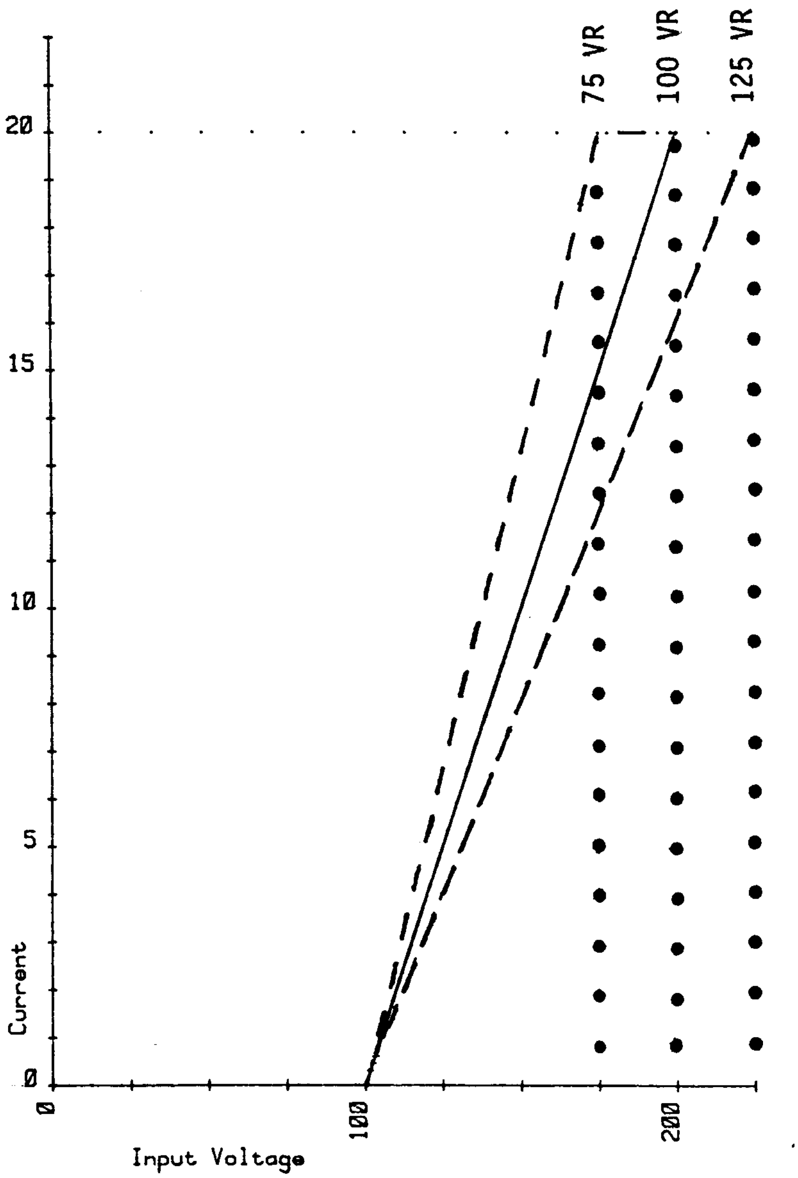


Figure 2

Typical Current Slope Control Characteristics

4.0 INTERFACE OF A GEMINI SYNCHRONOUS INVERTER WITH A LOCAL UTILITY

For purposes of this report, the Gemini is characterized alone, without being connected to a wind system. Thus the variable voltage dc source was again used for testing. A schematic showing the first utility test circuit is shown in Figure 3.

Due to the nonsinusoidal currents and harmonics expected, special attention was given to accurate measurement of voltage, current and power. True rms values of voltage, current, and instantaneous power were measured using a Magtrol Model 4610 Power Analyzer which has accuracy within 1/2 percent over the frequency range of 0-2000 Hz and is National Bureau of Standards (NBS) traceable.

Voltage waveforms were recorded on magnetic tape and displayed on an oscilloscope. Current waveforms were taken directly from a standard 15-ampere current shunt with a 50 millivolt output. Both voltage and current waveforms were checked for harmonic content (Appendix B) with a spectrum analyzer (Hewlett-Packard Model 5420). The analyzer performs a fast fourier transform (FFT) of the waveform and calculates the power in each harmonic present. The horizontal axis of the analyzer output is frequency measured in Hz. The vertical axis is a normalized representation of power and is expressed in both magnitude (MAG) and log magnitude decibels (LGMAG DB). When comparing MAG and LGMAG DB, it should be remembered that DB power equals ten times the log of the linear power ratio.

Figure 4 and Table I represent the operating characteristics of the Gemini with a constant 200 Vdc input and the current limit control adjusted to various current levels. Figures 5 through 7 and Tables II through IV present the operating characteristics of the inverter at three different current slopes (125 V, 100 V, 75 V, respectively) and 20 A current limit. Methods used to calculate inverter efficiency, system efficiency, power factor (PF) and volt ampere reactive (VAR) are given below:

Inverter Efficiency = Wac output ÷ (Wdc input - choke loss)
System Efficiency = Wac ouput ÷ Wdc input
Power Factor (PF) = Wac output ÷ (Vac x Iac)
VAR = Wac output x tan (inv cos PF)

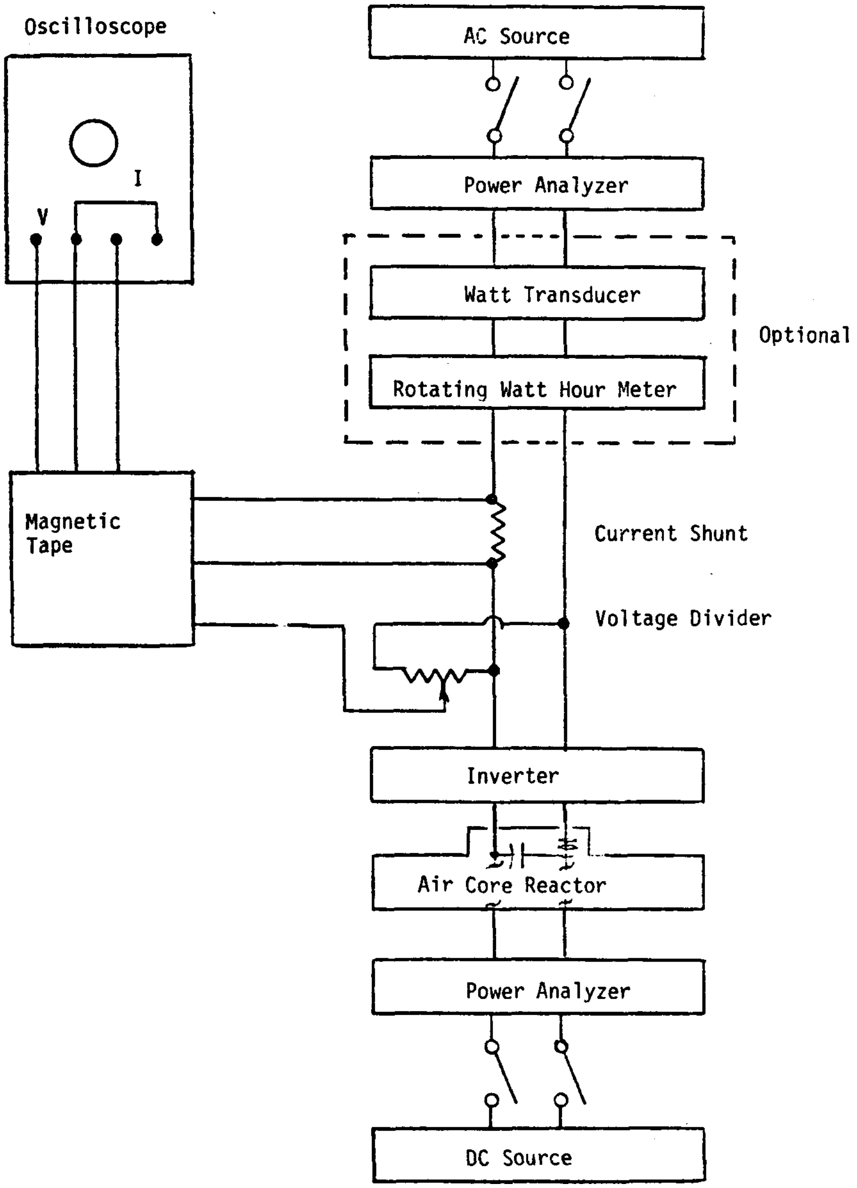
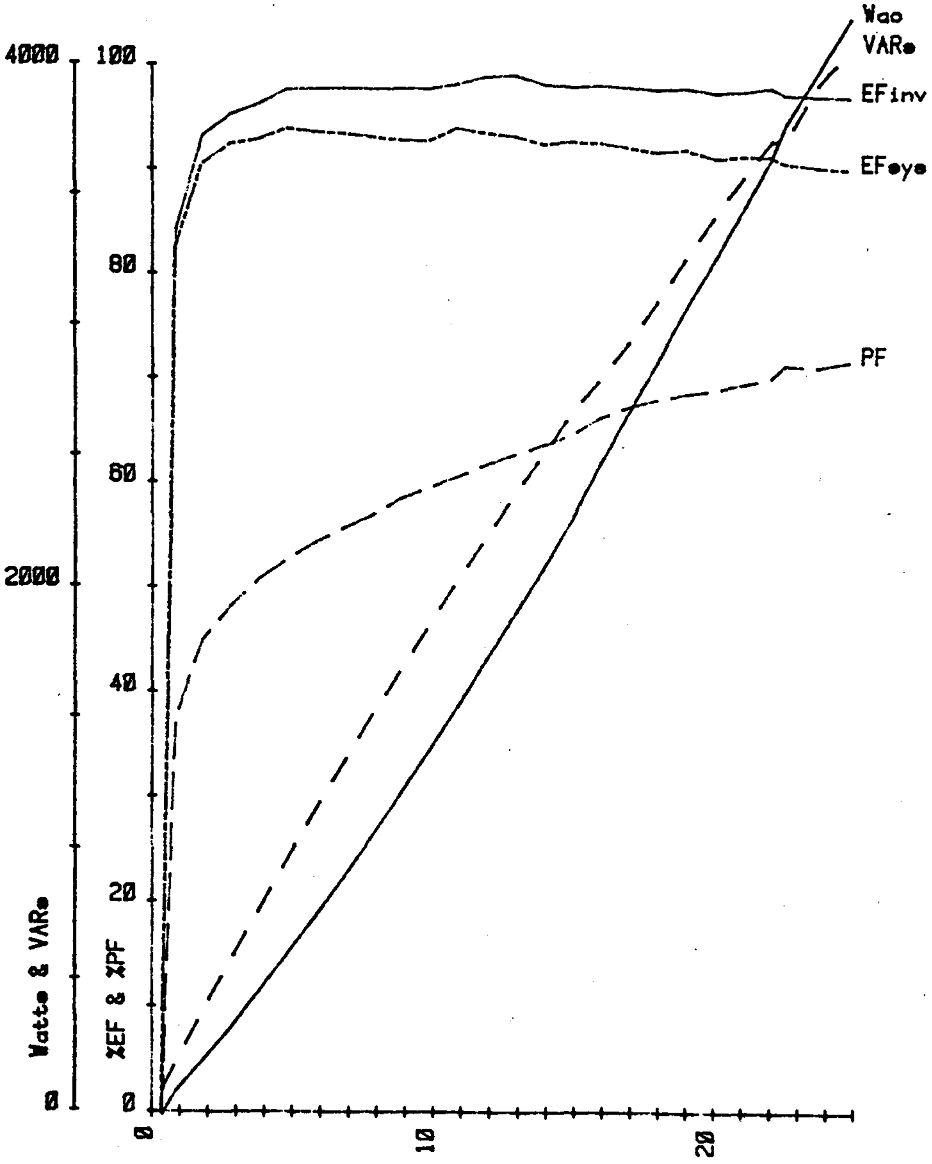


Figure 3

Utility Test Circuit



Output Current at Constant 200 Vdc Input Voltage

Figure 4

Gemini Operating Characteristics
0-25 Amp at Constant 200 Vdc Input
(Varying Current Limit Control)

TABLE I

0-25 Amp at Constant 200 Vdc Input
(Varying Current Limit Control)

DC INPUT			CHOKE LOSS	AC OUTPUT				CALCULATIONS		
AMPS	VOLTS	WATTS	WATTS	AMPS	VOLTS	WATTS	VAR	%P.F.	SYS. %EFF.	INV. %EFF.
0.00	0.0	0.0	0.0	0.36	235	-15.0	82.5	17.7*	0.0	0.0
1.00	200	91.0	2.0	0.85	236	75.0	185	37.5	82.4	84.3
2.01	200	211	6.0	1.80	236	191	379	45.0	90.5	93.2
3.01	200	342	10	2.78	236	316	575	48.2	92.4	95.2
4.03	200	488	17	3.78	236	453	769	50.8	92.8	96.2
5.03	200	633	24	4.78	236	594	959	52.7	93.8	97.5
6.01	200	787	33	5.75	236	736	1140	54.2	93.5	97.6
7.04	200	954	42	6.78	236	891	1329	55.7	93.4	97.7
8.00	200	1115	52	7.74	236	1038	1503	56.8	93.1	97.6
9.05	200	1299	65	8.78	235	1205	1675	58.4	92.8	97.6
10.1	200	1480	76	9.80	235	1371	1850	59.5	92.6	97.6
11.0	200	1640	70	10.8	235	1540	2023	60.6	93.9	98.1
12.1	200	1840	100	11.9	235	1720	2190	61.8	93.5	98.9
13.1	200	2040	120	12.9	235	1900	2356	62.8	93.1	99.0
14.0	200	2240	130	13.8	235	2070	2509	63.6	92.4	98.1
15.0	200	2440	130	14.9	235	2260	2668	64.6	92.6	97.8
16.0	200	2670	150	15.9	235	2470	2794	66.2	92.5	98.0
17.1	200	2910	170	16.9	235	2680	2944	67.3	92.1	97.8
18.0	200	3120	190	17.9	235	2860	3088	68.0	91.7	97.6
19.1	200	3340	200	19.0	236	3070	3262	68.5	91.9	97.8
20.1	200	3580	230	20.0	236	3260	3426	68.9	91.1	97.3
21.2	200	3790	240	21.1	236	3460	3578	69.5	91.3	97.5
22.1	200	3990	270	22.0	236	3640	3706	70.1	91.2	97.8
23.0	200	4160	280	22.5	235	3770	3707	71.3	90.6	97.2
24.1	200	4410	310	23.7	236	3980	3930	71.2	90.2	97.1
25.2	200	4640	330	24.8	235	4180	4061	71.7	90.1	97.0

* Lagging Power Factor

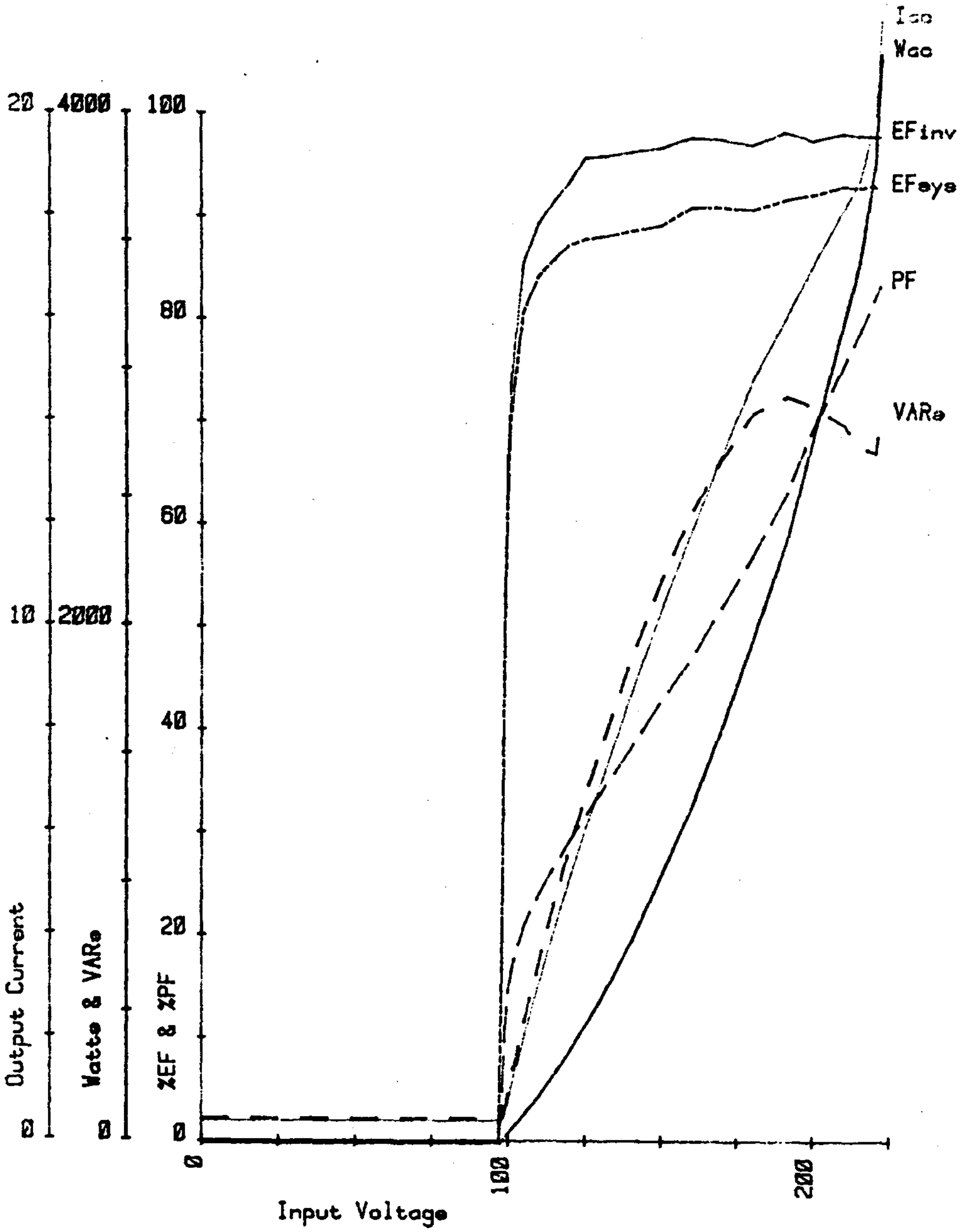


Figure 5
Gemini Operating Characteristics
220 Vdc (20 Amp Current Limit) - 125 V Rise

TABLE II

220 Vdc (20 Amp Current Limit)

125 V Rise

DC INPUT			CHOKE LOSS	AC OUTPUT				CALCULATIONS	SYS.	INV.
AMPS	VOLTS	WATTS	WATTS	AMPS	VOLTS	WATTS	VARs	%P.F.	%EFF.	%EFF.
0.00	0.0	0.0	0.0	0.35	234	-15.0	81.5	18.3*	0.0	0.0
0.00	97.0	0.0	0.0	0.35	234	-15.0	81.5	18.3*	0.0	0.0
0.49	98.0	17.4	0.7	0.41	232	3.0	95.3	3.1	17.2	18.0
0.78	99.0	31.6	1.4	0.63	233	16.0	146	10.9	50.6	53.0
1.05	100	45.7	2.0	0.87	233	29.0	200	14.4	63.5	66.4
1.32	101	61.0	2.7	1.12	233	43.0	257	16.5	70.5	73.8
2.30	105	124	7.0	2.06	233	100	469	20.8	80.6	85.5
3.40	110	209	12	3.14	233	176	710	24.1	84.2	89.3
4.43	115	302	19	4.17	233	259	936	26.7	85.8	91.5
5.42	120	401	26	5.15	233	350	1148	29.2	87.3	93.3
6.35	125	508	42	6.08	233	446	1345	31.5	87.8	95.7
7.26	130	624	51	6.98	233	549	1531	33.8	88.0	95.8
9.00	140	877	70	8.73	233	777	1880	38.2	88.6	96.3
10.6	150	1159	91	10.4	233	1033	2184	42.8	89.1	96.7
12.1	160	1430	100	11.9	233	1300	2446	46.9	90.9	97.7
13.6	170	1770	120	13.4	232	1610	2654	51.9	91.0	97.6
15.0	180	2150	140	14.8	232	1950	2829	56.8	90.7	97.0
16.1	191	2540	170	16.0	232	2330	2896	62.7	91.7	98.3
17.2	200	2970	160	17.1	232	2740	2856	69.2	92.3	97.5
18.2	210	3430	180	18.2	233	3190	2780	75.4	93.0	98.2
18.7	215	3680	190	18.7	233	3420	2700	78.5	92.9	98.0
20.0	220	4090	200	20.0	233	3810	2675	81.8	93.2	97.9
21.8	222	4560	240	21.8	233	4230	2812	83.3	92.8	97.9

* Lagging Power Factor

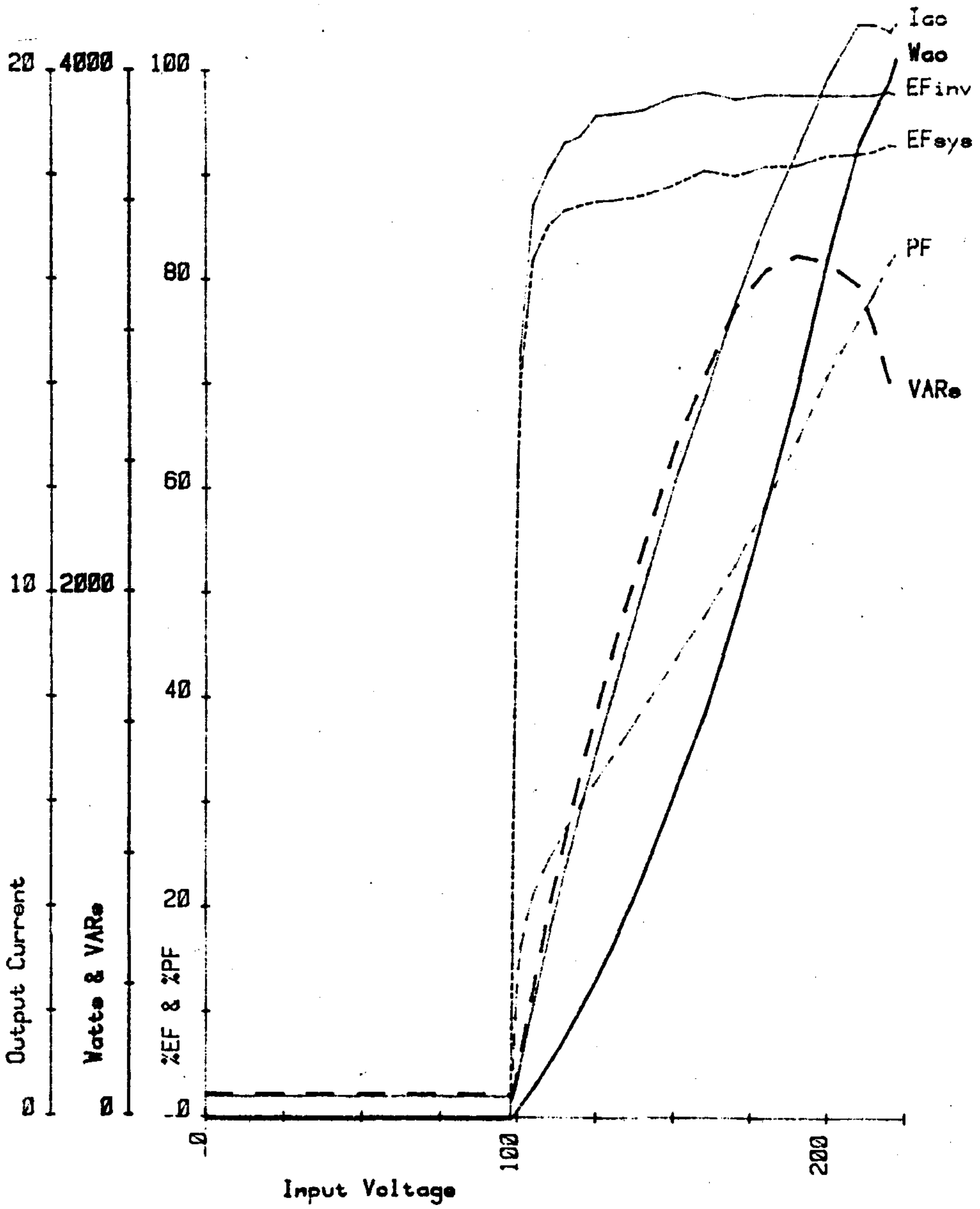


Figure 6
Gemini Operating Characteristics
220 Vdc (20 Amp Current Limit) - 100 V Rise

TABLE III

220 Vdc (20 Amp Current Limit)

100 V Rise

DC INPUT			CHOKE	AC OUTPUT				CALCULATIONS		
AMPS	VOLTS	WATTS	LOSS WATTS	AMPS	VOLTS	WATTS	VARs	%P.F.	SYS. %EFF.	INV. %EFF.
0.00	0.0	0.0	0.0	0.36	235	-15.0	82.5	17.7 *	0.0	0.0
0.00	97.0	0.0	0.0	0.36	234	-15.0	81.9	17.8 *	0.0	0.0
0.20	98.0	5.9	0.4	0.32	235	-10.0	73.6	13.3 *	0.0	0.0
0.61	99.0	23.2	0.8	0.50	234	8.0	116	6.9	34.5	35.7
0.96	100	40.4	1.3	0.78	234	24.0	182	13.1	59.4	61.4
1.28	101	58.5	2.5	1.08	234	41.0	249	16.3	70.1	73.2
2.45	105	133	8.0	2.20	234	109	503	21.2	82.0	87.2
3.78	110	237	14	3.52	234	202	799	24.5	85.2	90.6
5.00	115	347	24	4.72	234	301	1063	27.3	86.7	93.2
6.16	120	470	33	5.89	234	410	1316	29.7	87.2	93.8
7.26	125	598	51	6.99	234	524	1549	32.0	87.6	95.8
8.30	130	734	63	8.03	234	644	1765	34.3	87.7	96.0
10.4	140	1042	88	10.1	234	919	2175	38.9	88.2	96.3
12.3	150	1379	119	12.1	234	1230	2553	43.4	89.2	97.6
13.9	160	1700	130	13.8	234	1540	2830	47.8	90.6	98.1
15.7	170	2130	160	15.6	234	1920	3096	52.7	90.1	97.5
17.3	180	2570	180	17.2	233	2340	3239	58.6	91.1	97.9
18.6	190	3050	210	18.5	233	2780	3294	64.5	91.1	97.9
19.9	200	3560	210	19.9	233	3280	3271	70.8	92.1	97.9
20.9	210	4030	230	20.9	234	3720	3182	76.0	92.3	97.9
20.9	215	4160	230	20.9	234	3850	3023	78.6	92.5	98.0
20.8	220	4260	220	20.8	234	3970	2808	81.6	93.2	98.3
21.0	222	4350	220	20.9	234	4050	2758	82.7	93.1	98.1

* Lagging Power Factor

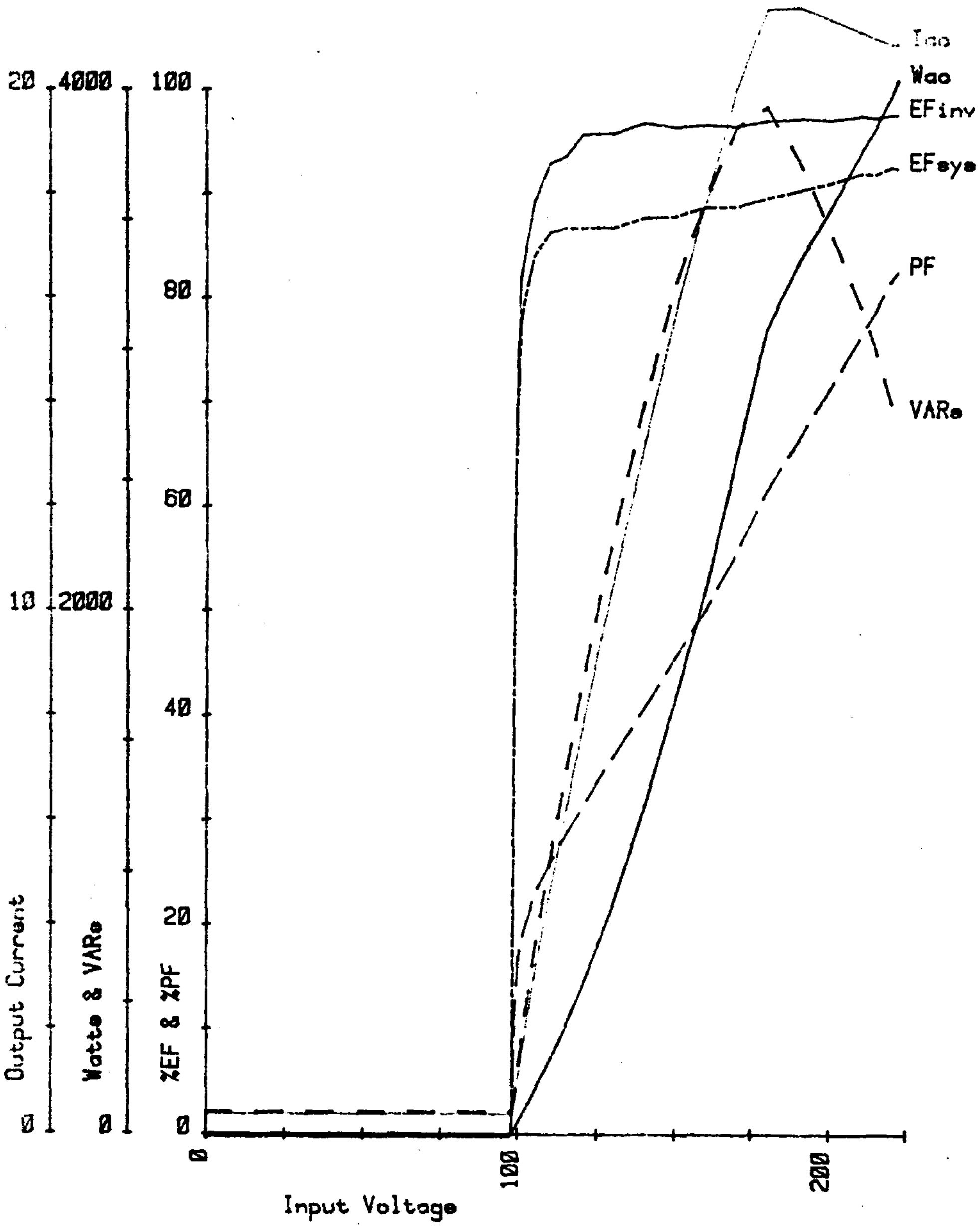


Figure 7

Gemini Operating Characteristics

220 Vdc (20 Amp Current Limit) - 75 V Rise

TABLE IV

220 Vdc (20 Amp Current Limit)

75 V Rise

DC INPUT			CHOKE LOSS	AC OUTPUT				CALCULATIONS		
AMPS	VOLTS	WATTS	WATTS	AMPS	VOLTS	WATTS	VARs	%P.F.	SYS. %EFF.	INV. %EFF.
0.00	0.0	0.0	0.0	0.36	234	-15.0	81.7	17.8 *	0.0	0.0
0.00	97.0	0.0	0.0	0.36	234	-15.0	81.7	17.8 *	0.0	0.0
0.35	98.0	11.6	0.5	0.34	233	-4.0	79.8	5.0 *	0.0	0.0
0.85	99.0	34.7	1.4	0.69	233	19.0	158	11.9	54.8	57.1
1.29	100	58.3	2.5	1.08	233	41.0	249	16.2	70.3	73.5
1.71	101	82.0	4.0	1.49	233	64.0	341	18.4	78.0	82.1
3.24	105	187	11	2.98	233	157	676	22.6	84.0	89.2
4.90	110	324	23	4.63	233	280	1042	26.0	86.4	93.0
6.48	115	477	35	6.20	233	414	1384	28.7	86.8	93.7
7.97	120	643	60	7.70	233	558	1705	31.1	86.8	95.7
9.42	125	823	77	9.15	232	715	1999	33.7	86.9	95.8
10.8	130	1012	95	10.5	232	879	2274	36.0	86.9	95.9
13.4	140	1423	133	13.2	232	1250	2798	40.8	87.8	96.9
15.9	150	1887	167	15.7	232	1660	3242	45.6	88.0	96.5
18.0	160	2340	190	17.9	232	2080	3584	50.2	88.9	96.7
20.2	170	2910	230	20.0	232	2590	3858	55.7	89.0	96.6
21.6	180	3430	260	21.5	232	3080	3935	61.6	89.8	97.2
21.7	190	3680	260	21.6	232	3330	3742	66.5	90.5	97.4
21.4	200	3880	240	21.4	232	3540	3468	71.4	91.2	97.3
21.2	210	4080	230	21.1	233	3760	3175	76.4	92.2	97.7
21.0	215	4190	230	21.0	233	3860	3003	78.9	92.1	97.5
20.9	220	4290	220	20.9	233	3980	2798	81.8	92.8	97.8
20.9	222	4360	230	20.9	234	4040	2752	82.6	92.7	97.8

* Lagging Power Factor

5.0 INTERFACE OF A GEMINI SYNCHRONOUS INVERTER WITH A MINI-GRID

Data on previous pages of this report were generated from the interface of a single Gemini Synchronous Inverter and a utility system. However, there exists a distinct need for data on the effects of large amounts of synchronous inverter output on a utility grid. To address this need through simulation, a mini-grid was created at the WERC using the same 4 kW Gemini inverter as was previously interfaced, a 15 kW diesel generating set and an 8.8 kW resistive heating load (see Figure 8). Thus the Gemini had an approximate 25% (4 kW/15 kW) system penetration level and an approximate 50% (4 kW/8.8 kW) energy penetration level.

To eliminate any possible feedback interaction from the diesel set, system waveforms were closely observed with the diesel voltage regulation in both automatic and manual modes of excitation. No differences were observed. Consequently, all data collected were obtained with automatic regulation. The variable voltage dc source was the input for a steady-state controlled test.

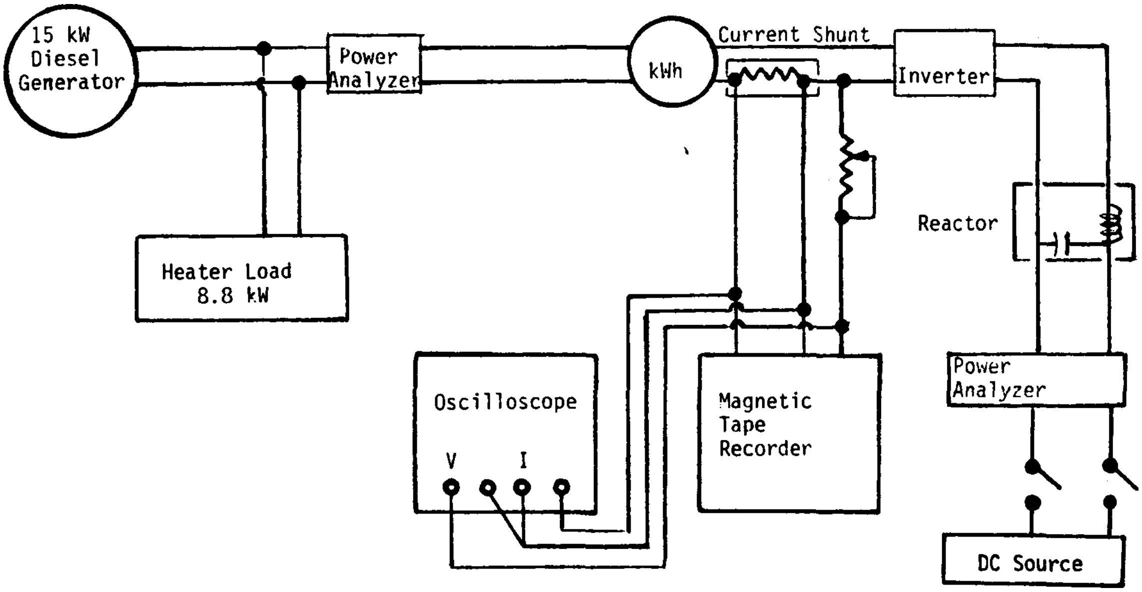


Figure 8
Mini-Grid Test Circuit

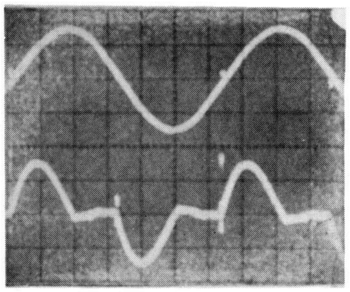
6.0 ANALYSIS OF TEST RESULTS

Voltage and current waveforms at several current ratings are shown in Figure 9. In each photograph, the voltage trace (V) is on top and the current trace (I) is below. Harmonic analyses of these voltage and current waveforms (LGMAG DB and MAG) are presented in Appendix B. Looking again at Figure 9, the reader will notice that the current pulse width increases as output increases. At rated output, the pulse width is maximized and the waveform has more semblance of a sinusoidal shape. Consequently total harmonic distortion (THD) of the current spectra varies inversely with output current.

Rated Current	THD
25%	30%
50%	15%
75%	5%
100%	3%

In order to further compare results of the utility and mini-grid interface tests, voltage waveforms of both sources without the Gemini must be adequately interpreted. Table V compares the attenuation of the first 26 harmonics of both tests and the closeness of the data values can be readily seen. It can, therefore, be concluded that the two sources were nearly identical in harmonic content. The voltage amplitudes were kept nearly equal also. Only impedance matching prevented absolute simulation.

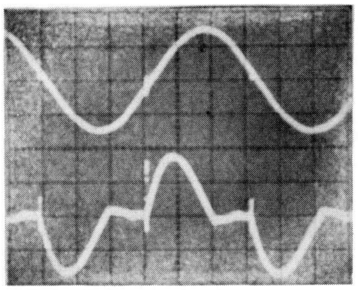
Having these data as a basis to work from allows us to infer the effect of a large penetration of Gemini inverters on a utility line. From the component and high penetration simulation test results, it would appear that large amounts of Gemini 4 kW inverter output on a utility line will not produce harmonic distortion noticeable to the utility or to customers on the line. A possible exception would be a resonant condition at a specific harmonic frequency.



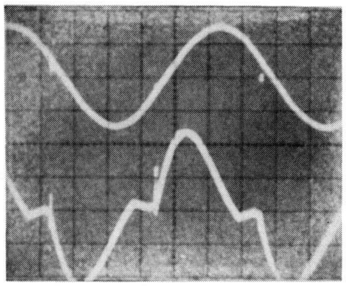
25% Rated Current

V (225/div) V

I (10A/div) I



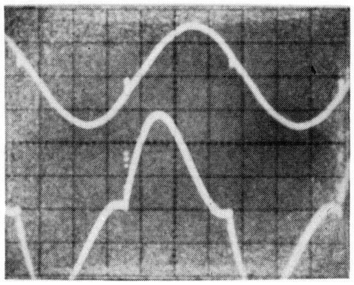
50% Rated Current



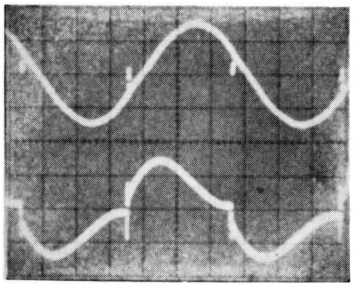
75% Rated Current

V (225V/div) V

I (10A/div) I



100% Rated Current



125% Rated Current

V (225V/div)

I (25A/div)

Figure 9
Voltage and Current Waveforms
Gemini 4kW Synchronous Invertor

TABLE V

Attenuation of X^{th} Harmonic in the Voltage Waveform

(without a Gemini Synchronous Inverter)

X^{th} Harmonic	Public Service Company	Mini-Grid
2	50	46
3	39	43
4	62	65
5	43	32
6	68	69
7	43	46
8	66	69
9	56	55
10	72	71
11	58	45
12	73	72
13	66	71
14	71	74
15	67	65
16	73	75
17	62	62
18	73	76
19	65	67
20	72	75
21	69	70
22	74	77
23	70	65
24	75	75
25	73	69
26	79	65

Table VI

Attenuation of X^{th} Harmonic

		Voltage at Given % Rated Load				Current at Given % Load			
AC SOURCE	X_{th}	25%	50%	75%	100%	25%	50%	75%	100%
PSCO	2	48	47	46	46	30	31	33	34
Mini-Grid		46	47	46	46	30	31	33	34
PSCO	3	41	41	41	40	5	7	11	14
Mini-Grid		44	44	44	39	6	11	17	19
PSCO	4	66	64	69	67	34	37	44	45
Mini-Grid		65	68	70	65	37	48	47	47
PSCO	5	45	46	47	44	25	22	20	23
Mini-Grid		33	31	31	31	26	21	27	28
PSCO	6	68	68	68	66	38	37	44	47
Mini-Grid		70	70	68	65	44	45	45	45
PSCO	7	43	42	41	39	22	27	28	29
Mini-Grid		43	52	46	40	23	29	30	33
PSCO	8	65	69	71	69	43	43	45	51
Mini-Grid		72	71	74	72	45	47	55	51
PSCO	9	54	52	55	57	30	28	38	33
Mini-Grid		50	58	51	46	31	39	34	36
PSCO	10	68	71	68	71	41	46	47	52
Mini-Grid		73	71	73	74	47	51	53	52
PSCO	11	57	55	55	69	32	40	42	33
Mini-Grid		46	45	57	44	33	37	36	38
PSCO	12	70	71	71	69	46	45	50	53
Mini-Grid		73	71	76	70	55	52	58	56
PSCO	13	54	57	70	55	32	36	41	39
Mini-Grid		59	52	53	52	34	38	42	41
PSCO	14	69	72	71	70	45	50	52	54
Mini-Grid		73	74	71	74	54	61	59	56
PSCO	15	68	61	60	60	44	36	43	41
Mini-Grid		68	58	55	51	46	42	45	43
PSCO	16	69	70	71	69	43	48	53	56
Mini-Grid		71	74	72	75	60	56	60	54
PSCO	17	60	65	58	58	39	44	45	43
Mini-Grid		56	58	56	54	39	51	49	44
PSCO	18	67	67	69	70	45	46	52	55
Mini-Grid		75	74	74	73	56	58	59	56
PSCO	19	63	64	66	60	44	42	56	43
Mini-Grid		66	62	65	52	48	50	52	45
PSCO	20	65	68	71	69	43	48	52	57
Mini-Grid		76	74	72	72	55	59	59	56
PSCO	21	64	63	67	64	40	44	54	46
Mini-Grid		63	63	66	53	46	49	56	46
PSCO	22	67	70	72	71	42	49	56	58
Mini-Grid		75	71	74	69	57	61	57	58
PSCO	23	63	69	72	62	41	53	55	50
Mini-Grid		64	65	66	54	46	50	60	47
PSCO	24	70	72	74	74	45	52	61	62
Mini-Grid		71	72	75	70	51	55	56	56
PSCO	25	70	71	71	70	46	54	58	55
Mini-Grid		65	64	64	55	64	56	62	48
PSCO	26	75	76	75	74	49	57	65	64
Mini-Grid		69	69	75	66	55	54	56	57

Efficiency of the Gemini is quite high (96.7% average) and nearly constant above the 5% power level. The power factor is rather low and leading at 58.6% average. The VAR requirement from the utility or minigrid could be improved with capacitors.

Safety Analysis

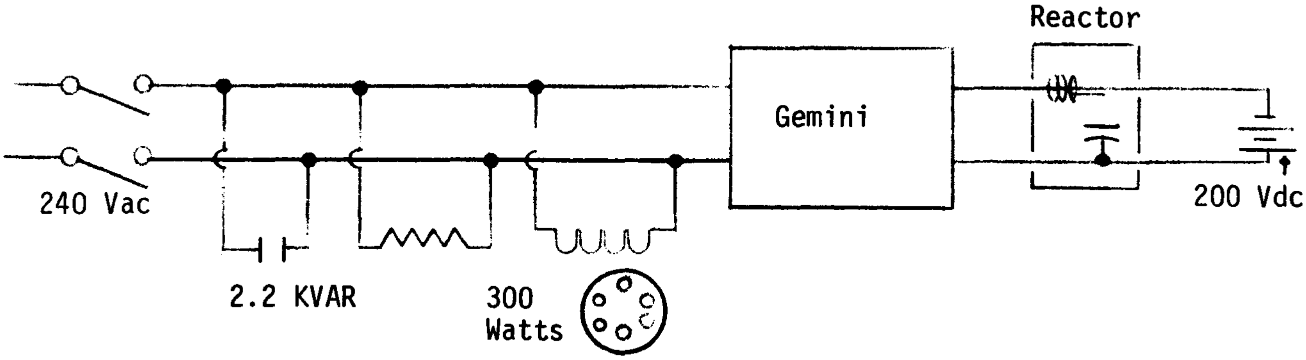
A safety consideration when using inverters is the inverter's ability to break or isolate the dc source on loss of local utility power. This would prevent energizing an assumed dead line.

The stand-alone test configuration is shown in Figure 10. The Gemini was operated at a moderate 10 Adc and 125 Vdc steady-state conversion rate while feeding a single-phase 240 Vac line with 2.2 kVAR capacitance (approximately unity power factor correction) and 300 watts of light bulbs and induction motor loads. The utility line was opened, allowing the Gemini to "see" only the capacitance and the 300 W load. The Gemini self-excited for approximately three seconds with an oscillating voltage and then was cleared by a 15 A fuse in the dc line. Lack of equipment limited this test to only one value of capacitance and load.

The controlled safety tests of dc isolation (Figure 10) excluded the power factor capacitance and 300 W load (and motor). During these tests, the Gemini was again brought to a moderate 10 Adc and 125 Vdc steady-state conversion rate feeding directly to a 240 Vac line. The utility was interrupted by opening a manual disconnect switch on the 240 Vac line. The Gemini dc isolation relay contacts opened but failed to clear the circuit due to arcing across the open contacts. This resulted in dc being fed to the isolation transformer, thereby causing the Gemini dc line fuse to clear the short circuit condition. Although the dc isolation relay was damaged beyond repair, no other damage to the Gemini was found. To substantiate this test, another 4 kW Gemini was tested in a similar configuration with the results being identical. To prevent possible dc on a disconnected ac

Figure 10

4 kW Gemini Self-Excitation Test Circuit



line, all Gemini inverters used anywhere should be installed with a transformer close to the Gemini ac output terminals and the dc voltage limited to 215-220 V to prevent saturation.

Analysis of Operation

In order to operate a Gemini correctly, cognizance of panel meter characteristics is important. The 200 Vdc voltmeter of the unit under test read relatively close to rms values throughout its scale. The 0-20 Adc ammeter read very low at the lower scale reading but improved as the meter reached full scale deflection (Table VII). Additional information on metering is presented in Appendix A.

One very important characteristic of the Gemini should be mentioned. Testing disclosed that as input voltage was raised above 222 dc, current limiting control was lost. Further increase in voltage will lead to very sharp increases in current due to saturation that will clear the dc fuse. Therefore, input voltage should be limited to approximately 92% of the rated line voltage of the interface (.92 x 240 Vac) or less.

TABLE VII

Magtrol/Gemini Meter Reading Comparisons

	Magtrol	Gemini	%diff		Magtrol	Gemini	%diff
	8.76	7.0	-20		122	119	-2.5
	10.35	8.5	-17.8		131	126	-3.8
	11.80	10.0	-15.3		140	135	-3.6
	13.40	11.5	-14.2		150	145	-3.3
	14.90	13.0	-12.8		160	155	-3.1
CURRENT	16.30	14.6	-10.4	VOLTAGE	170	165	-2.9
	17.52	16.0	- 8.7		180	174	-3.3
	18.70	17.6	- 5.9		191	184	-3.7
	19.95	19.5	- 2.3		201	195	-3.0
	21.12	*21.0	- .6		211	*205	-2.8

* Off-scale extrapolated readings.

7.0 ELECTROMAGNETIC INTERFERENCE

An AM/FM radio and a black and white (UHF/VHF) television set were operated on the mini-grid system with the Gemini at 0% and 50% energy penetrations. The test receivers were within three feet of the inverter and on the same electrical circuit as the inverter. No audio or video distortion was detected, with the exception of noise on the lower AM band tuned to weak stations. (This noise will vary with each receiver's sensitivity and selectivity characteristics and distance from the inverter/choke.) Since the diesel generating set used as the mini-grid was an older style which utilized a brush-type dc pilot exciter and a slip ring alternator, it is quite likely that the source of some of the interference was the mini-grid itself. Telephones in the direct vicinity of the inverter tests demonstrated no interference or modulation losses.

8.0 SUMMARY AND CONCLUSIONS

Testing at the WERC has shown that the Gemini has an overall system efficiency of 90% which agrees with the manufacturer's prediction; however, the power factor at leading (.586 average) is far from ideal. Harmonic analyses show that Gemini output current would have negligible influence on a utility voltage waveform even at a simulated high (25%) penetration level, and the disturbance to a utility by a Gemini is no more severe than that caused by common energy consuming devices with similar current waveforms (i.e., modern solid state motor speed controls and incandescent lamp dimmers or "soft" starters). A resonant condition at a specific harmonic frequency would be a possible exception. Although some safety concerns were discovered during testing, it is felt that use of a contactor with a higher dc voltage and/or current rating would help eliminate these problems. In fact, the manufacturer has recently switched to a heavy duty contactor.

Proper set-up of Gemini controls was found to be essential to match the dc source's output capabilities. Also, the dc source voltage must be limited to approximately 92% of the ac line voltage.

Overall, the Gemini line-synchronous, line-commutated inverter proved to be an effective device for interfacing a dc power source with a utility grid.

APPENDIX A

Metering

Measurement precision and NBS traceability are very important at RF to ensure accurate data. True rms values of voltage and current and true power are prime concerns. This appendix offers a brief overview of metering principles to help the reader who may be unfamiliar with these concerns.

Meters are either analog or digital in design and may read either true rms values or average values. It is important to understand that for a general periodic function, f(t), with period T, the average value:

$$Fav = 1/T\int_0^T f(t)\,dt.$$

The same function f(t) has an effective value:

$$Frms = (1/T\int_0^T f(t)^2 dt)^{1/2}.$$

Frms/Fav is defined as form factor.

Analog instruments normally used to measure electrical quantities are of two types: D'Arsonval and electrodynamometer. The D'Arsonval instrument has a coil, carrying current I, that is placed in a magnetic field, Ø, established by a permanent magnet and restrained by a spring. If one thinks of torque being produced by two magnetic fields that are attempting to align themselves to a common axis, then the meter is designed so that the torque T is proportional to the product IØmagnet, where Ømagnet is a constant and I produces a flux in the coil. The scale will then be linear. This type of instrument or meter will measure amps or volts in a direct current circuit and would follow slow changes in a varying circuit. If used directly in an ac circuit the pointer might vibrate, but average torque would equal zero since it reads average values.

The D'Arsonval element is typically found in dc voltmeters, ammeters and in most multimeters. In order to use it on ac, the meter is equipped with either a half-wave or full-wave rectifier. A special scale calibration is made to convert the average value to an rms reading. This is done on the assumption that the wave to be measured is a single frequency sinusoid. The meter is correct only for this case. Figures 11 and 12 illustrate the scaling calibration factor.

The second type of analog measuring instrument is the electrodynamometer element which has two coils and a restraining spring. Torque is a function of the product of the current in each coil and the sine of the angle between them. When this element is used as a voltmeter or ammeter, the coils are placed in series and torque T is proportional to the rms current (or rms voltage) squared. The scale distribution is, therefore, a squared function and thus very nonlinear. This meter will read correctly on dc and ac and will also include the harmonics up to the frequency limit of the meter (usually around the seventh harmonic).

When the electrodynamometer element is used as a wattmeter, current is applied to one coil, voltage to the other, and the meter torque equation becomes $Tm \propto V_{dc}I_{dc} + V_1I_1 \cos \phi_1 + V_2I_2 \cos\phi_2 + \text{---}V_nI_n \cos\phi_n$, where V_n and I_n are rms values of a single frequency harmonic and ϕ_n is the angle between this voltage and current. It will correctly meter average power from dc to the frequency limit of the instrument. The scale distribution is now linear as the torque equation indicates.

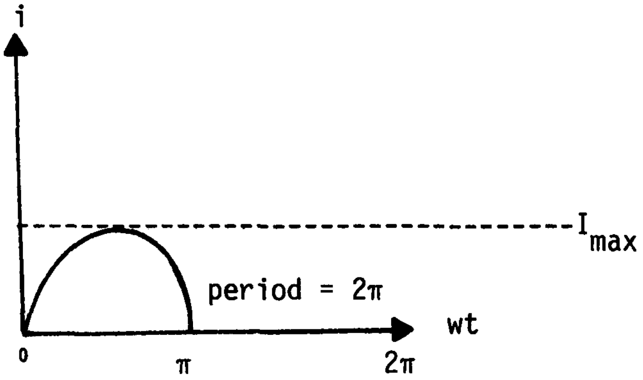
The ac rotating watthour meter is an extremely efficient ac induction disc motor that drives only the register to indicate the watthours passing through the meter. It integrates torque produced by the fundamental and the harmonics over a period of time to give watthours.

Digital ammeters and voltmeters can also be either true rms or average reading with a multiplier to give rms values. The vast majority are average reading, due to cost, and are frequently very sensitive to harmonics since they make use of the zero crossing to start the sampling routine. Average readings can be greatly in error, depending on the harmonics present, and can be especially misleading when instruments are used in rectifier circuits.

Digital wattmeters sample the instantaneous product of the voltage and current waveforms and calculate an average value over several cycles. Digital watthour meters integrate the instantaneous voltage-current product over a period of time.

Power factor meters must not be used except where both the voltage and current are single frequency sinusoids and contain no harmonics. If used when harmonics are present, they give completely erroneous readings.

The instrument used in tests discussed in this report was a Magtrol Model 4610 Power Analyzer. It is a digital true rms meter that simultaneously displays volts (0-600 V), amps (0-50 A) and watts (0-30,000 W). Typical accuracy of the Magtrol is 1/2 percent and NBS traceable.

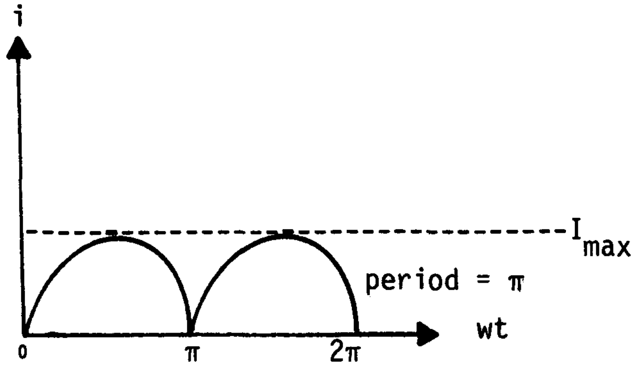


$$I_{av} = \frac{1}{2\pi}\{\int_0^{\pi} I_{max}\sin wt\,dwt + \int_{\pi}^{2\pi} 0 \sin wt\,dwt\} = .318\ I_{max}$$

$$I_{rms} = \sqrt{\frac{1}{2\pi}\{\int_0^{\pi} (I_{max}\sin wt)^2 dwt + \int_{\pi}^{2\pi} (0 \sin wt)^2 dwt\}} = .500\ I_{max}$$

Scaling Factor = .500/.318 = 1.57

Figure 11
Half-Wave Rectified Waveform



$$I_{av} = \frac{1}{\pi}\int_0^{\pi} I_{max}\sin wt\,dwt = .637\ I_{max}$$

$$I_{rms} = \sqrt{\frac{1}{\pi}\int_0^{\pi} (I_{max}\sin wt)^2 dwt} = .707\ I_{max}$$

Scaling Factor = .707/.637 = 1.11

Figure 12
Full-Wave Rectified Waveform

If HWR meter reads:

1. HWR Signal: $I_x = .318(1.57) = .500\ I_{max} = I_{rms}$
2. FWR Signal: $I_x = .637(1.57) = 1.000\ I_{max} = 2I_{rms}$

If FWR meter reads:

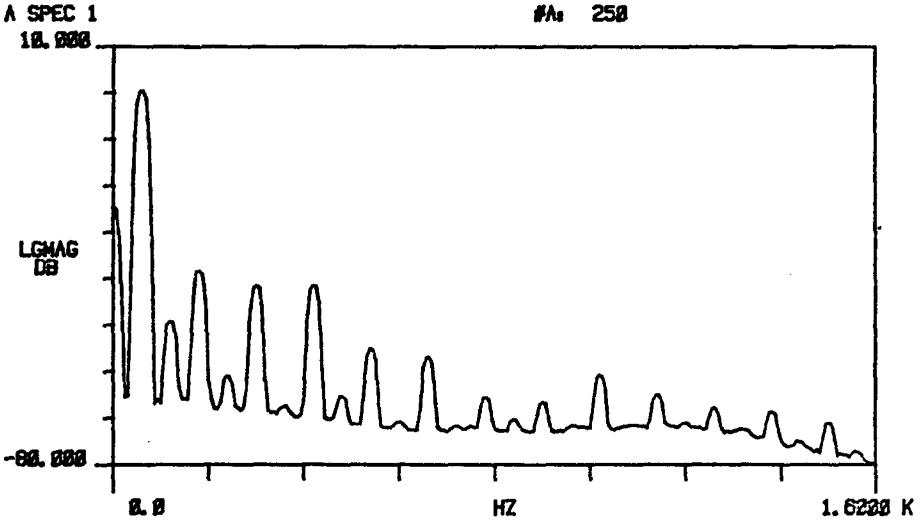
1. HWR Signal: $I_x = .318(1.11) = .353\ I_{max} = .706\ I_{rms}$
2. FWR Signal: $I_x = .637(1.11) = .707\ I_{max} = I_{rms}$

Please be aware that erroneous readings can be obtained from average reading meters with the scaling factor on nonsinusoidal waveshapes. Figure 9 clearly indicates that some nonsinusoidal current waveshapes are produced.

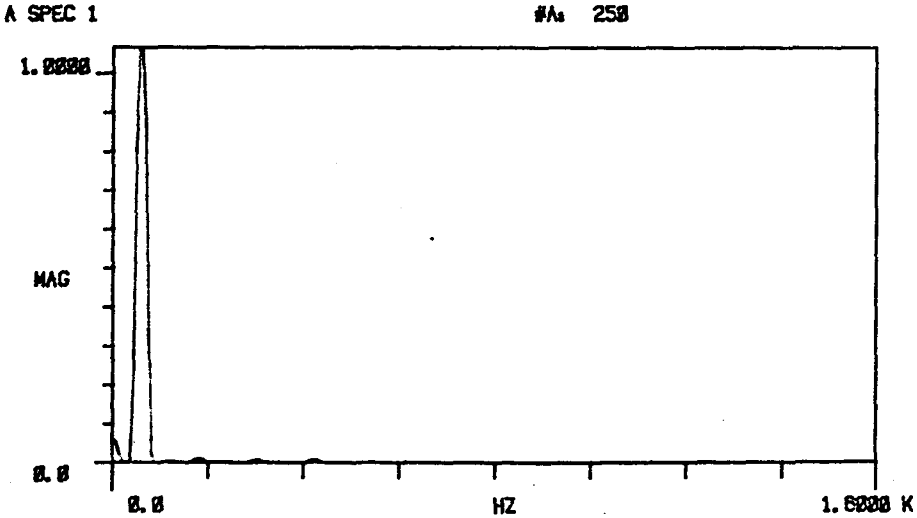
APPENDIX B

Voltage and Current Autospectrums

a. Decibel Scale Display



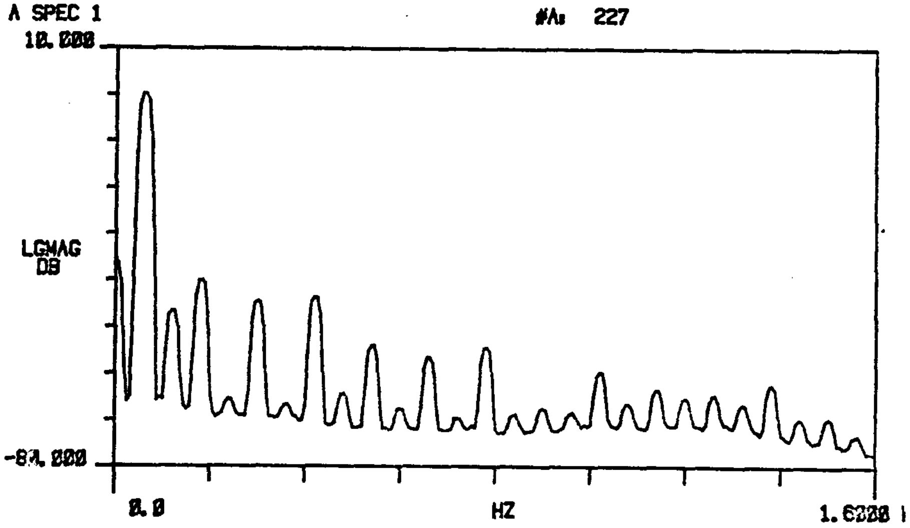
b. Magnitude Scale Display



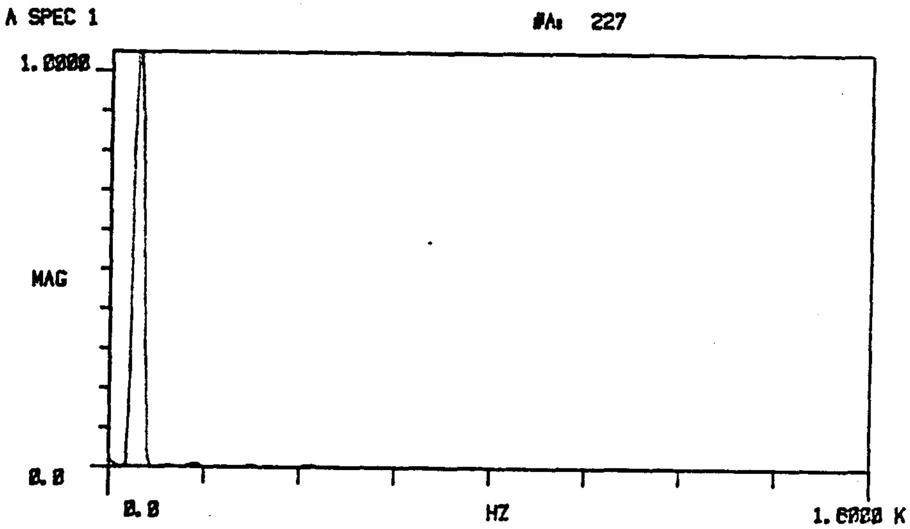
Figures 13a and 13b

Voltage Autospectrums at 0% Rated Current

a. Decibel Scale Display



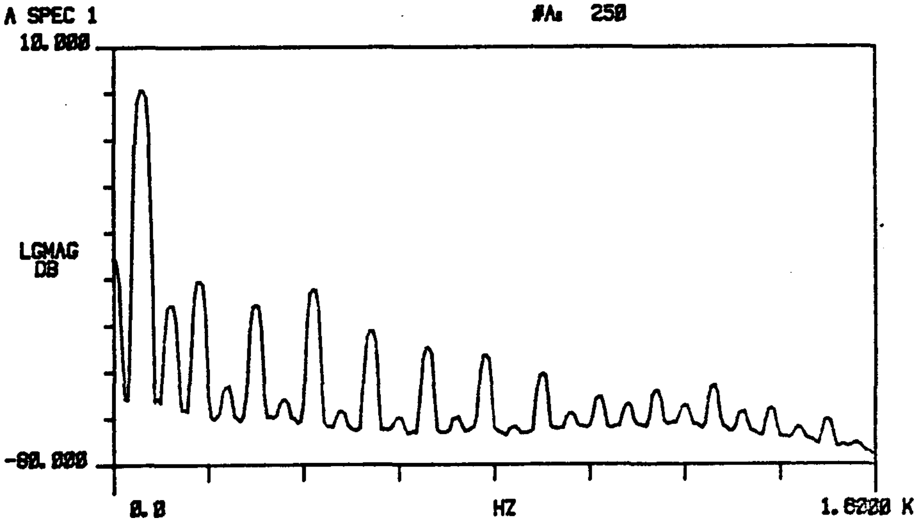
b. Magnitude Scale Display



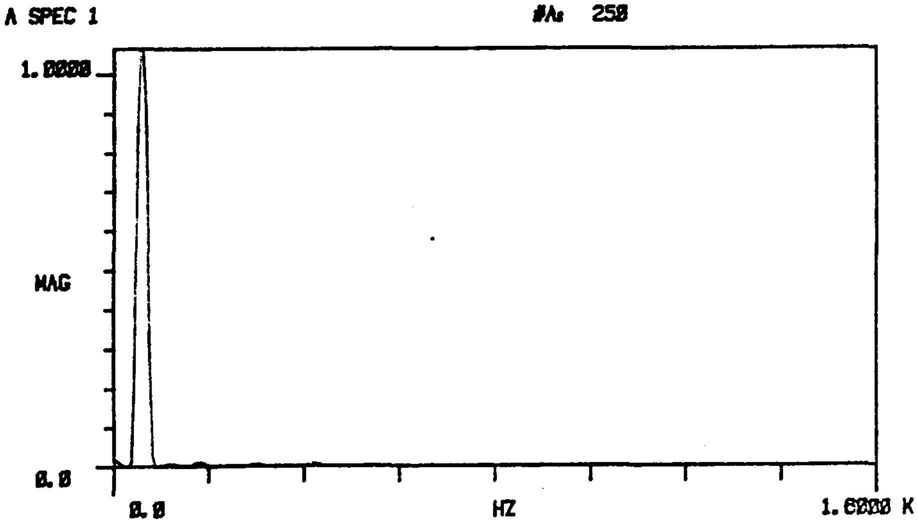
Figures 14a and 14b

Voltage Autospectrums at 25% Rated Current

a. Decibel Scale Display



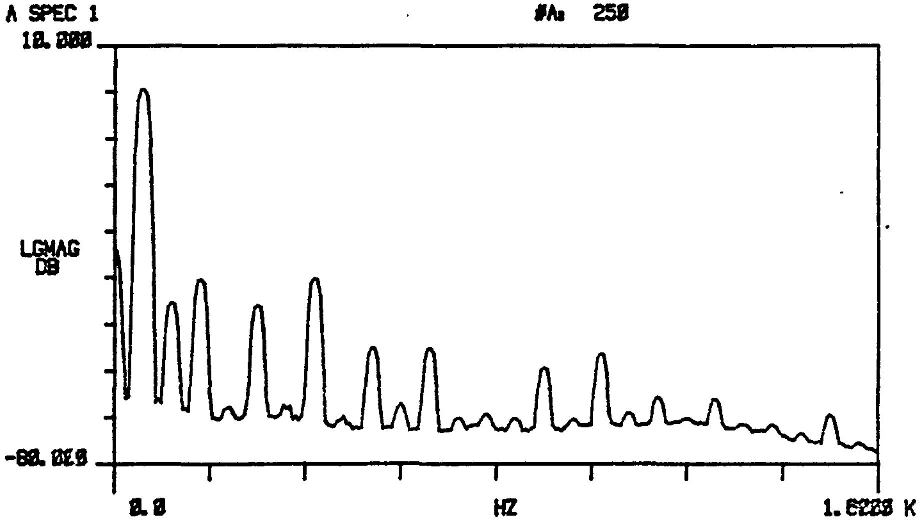
b. Magnitude Scale Display



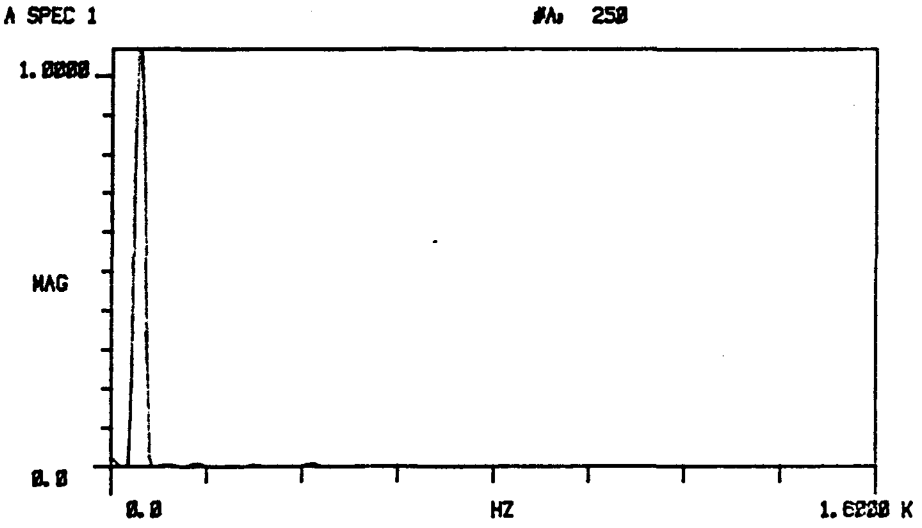
Figures 15a and 15b

Voltage Autospectrums at 50% Rated Current

a. Decibel Scale Display



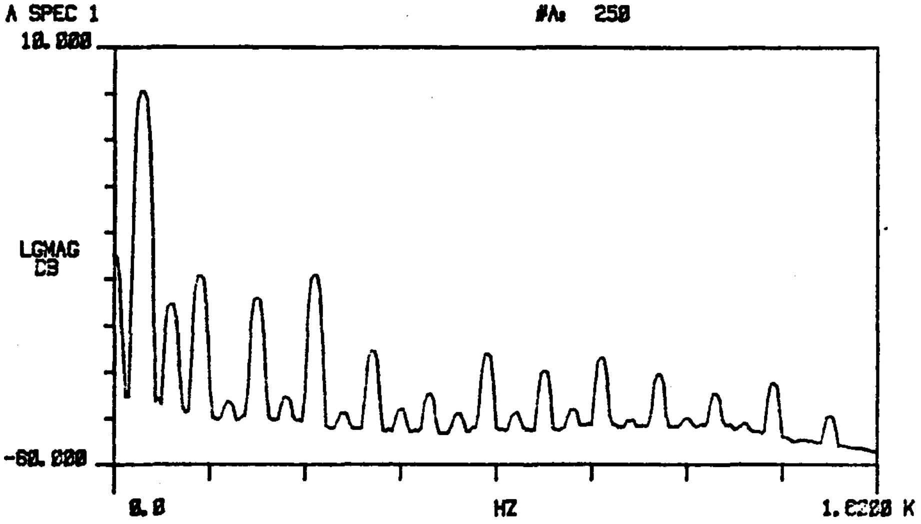
b. Magnitude Scale Display



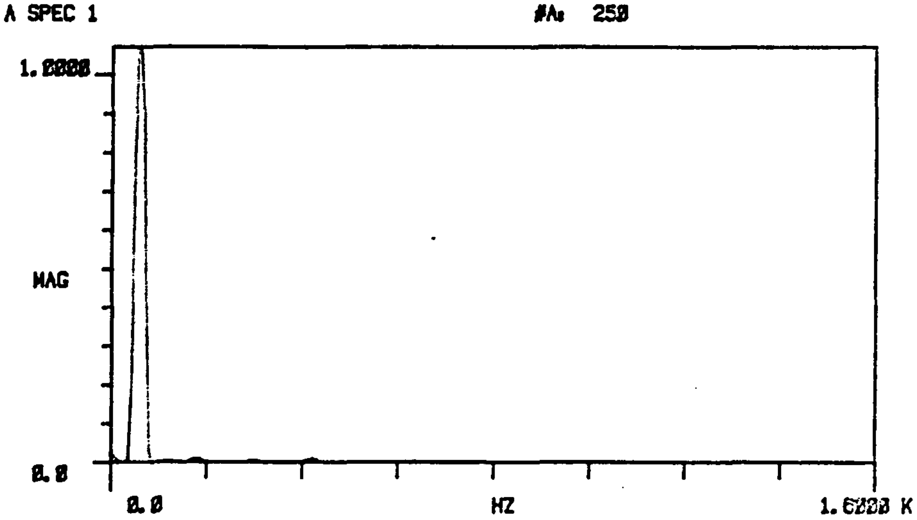
Figures 16a and 16b

Voltage Autospectrums at 75% Rated Current

a. Decibel Scale Display



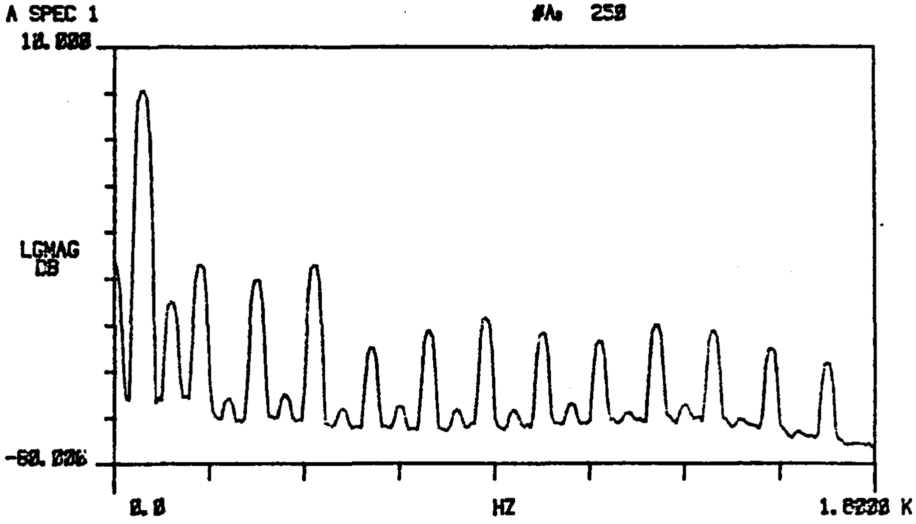
b. Magnitude Scale Display



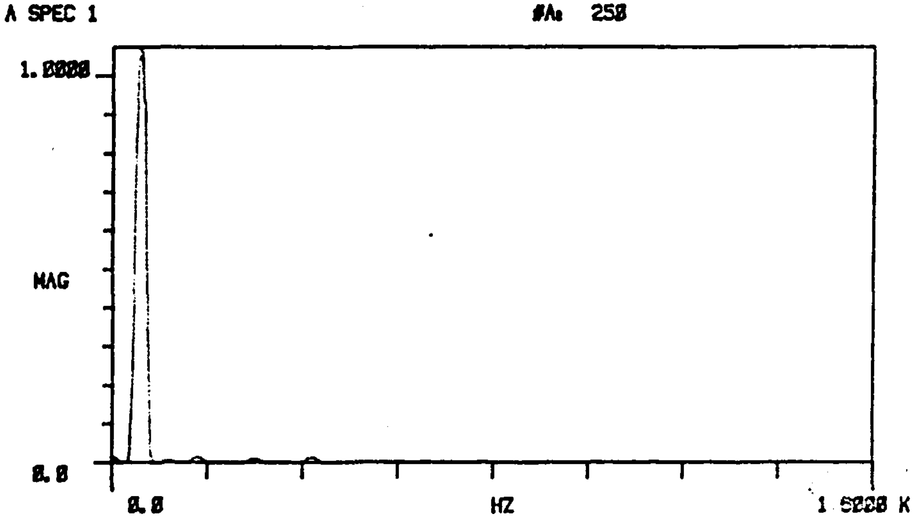
Figures 17a and 17b

Voltage Autospectrums at 100% Rated Current

a. Decibel Scale Display



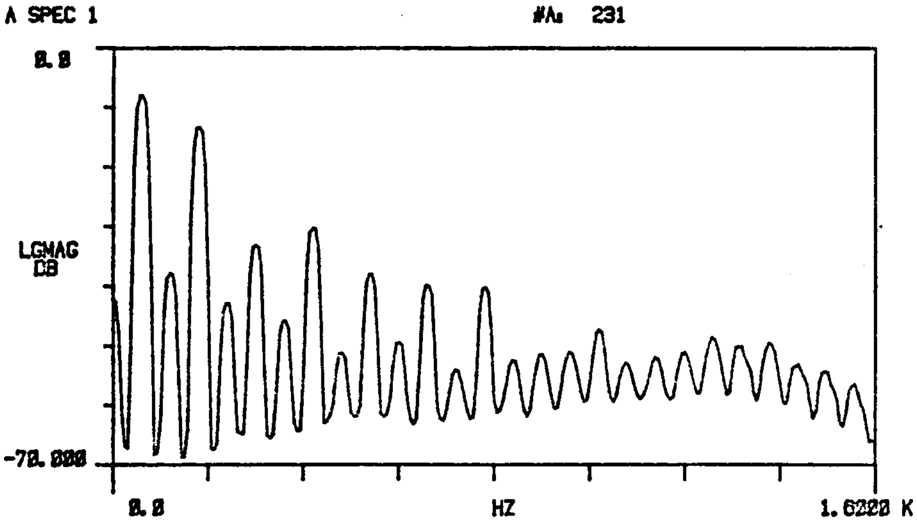
b. Magnitude Scale Display



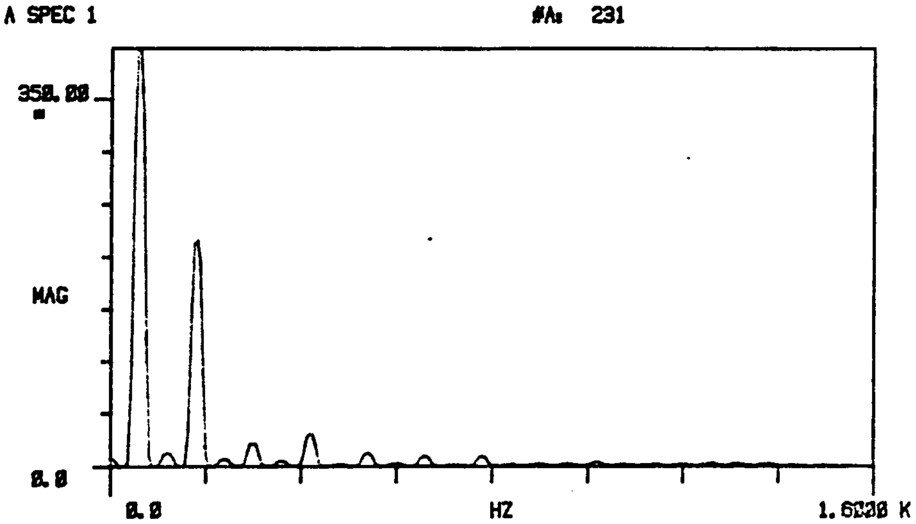
Figures 18a and 18b

Voltage Autospectrums at 125% Rated Current

a. Decibel Scale Display



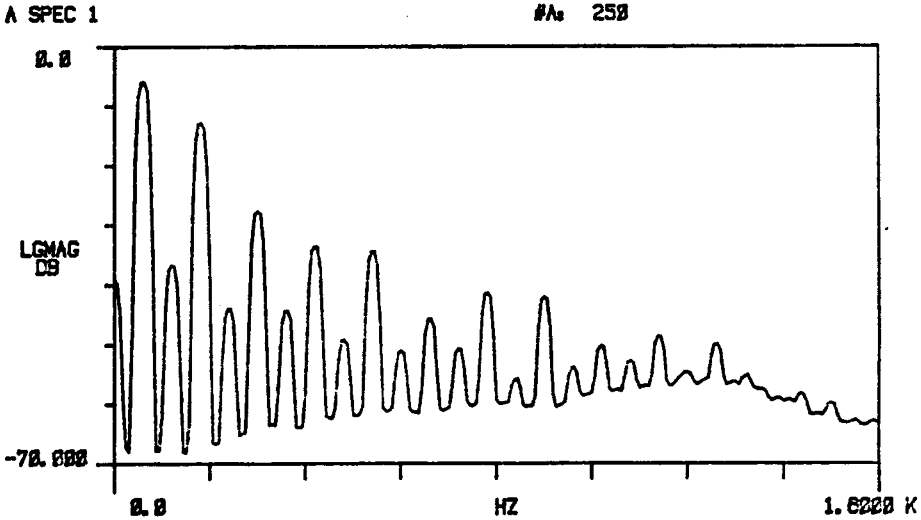
b. Magnitude Scale Display



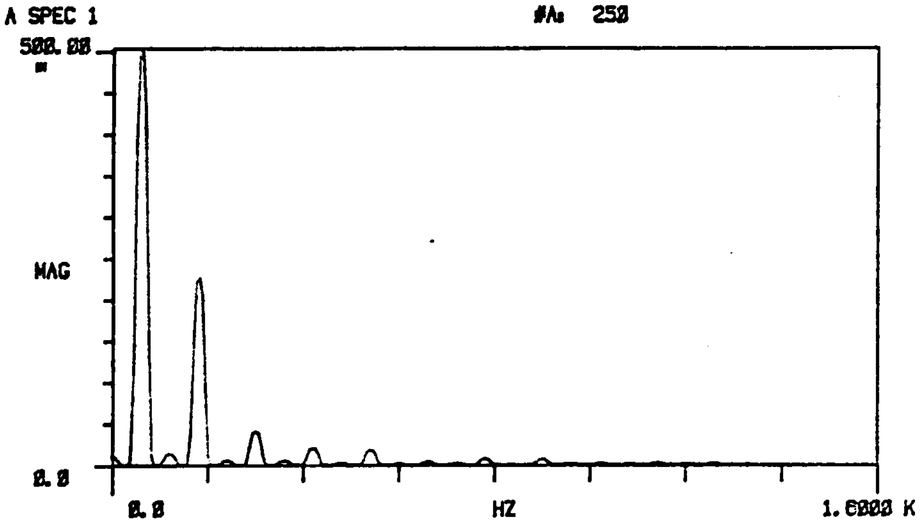
Figures 19a and 19b

Current Autospectrums at 25% Rated Current

a. Decibel Scale Display



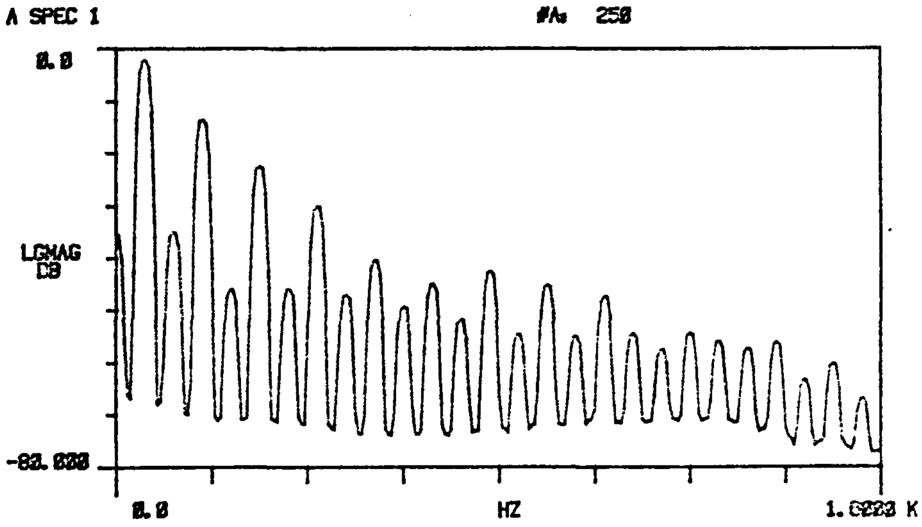
b. Magnitude Scale Display



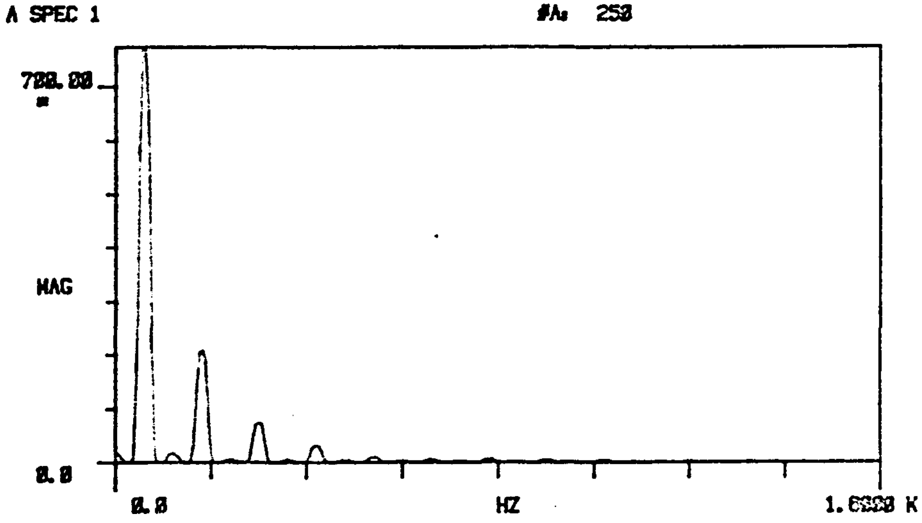
Figures 20a and 20b

Current Autospectrums at 50% Rated Current

a. Decibel Scale Display



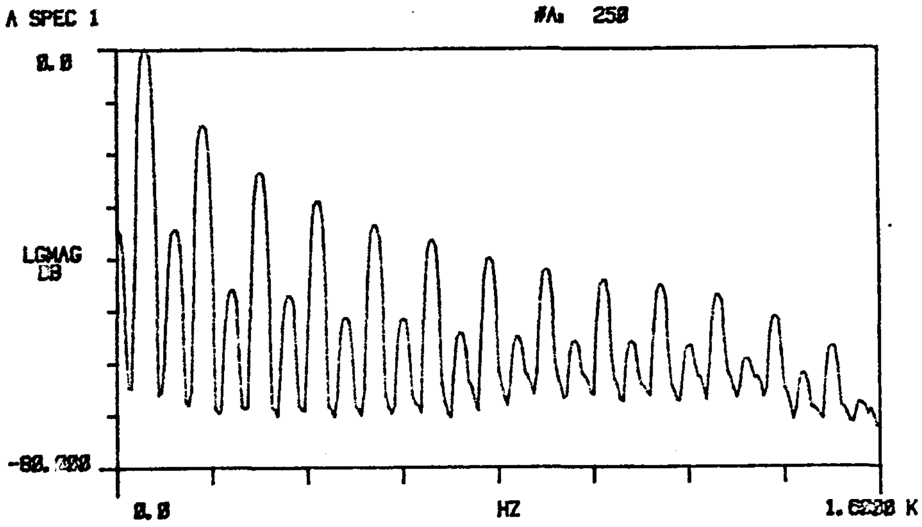
b. Magnitude Scale Display



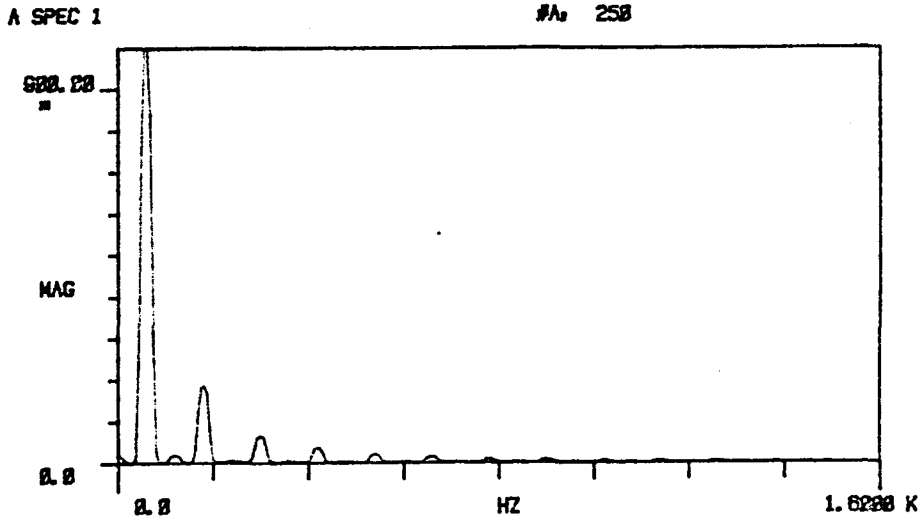
Figures 21a and 21b

Current Autospectrums at 75% Rated Current

a. Decibel Scale Display

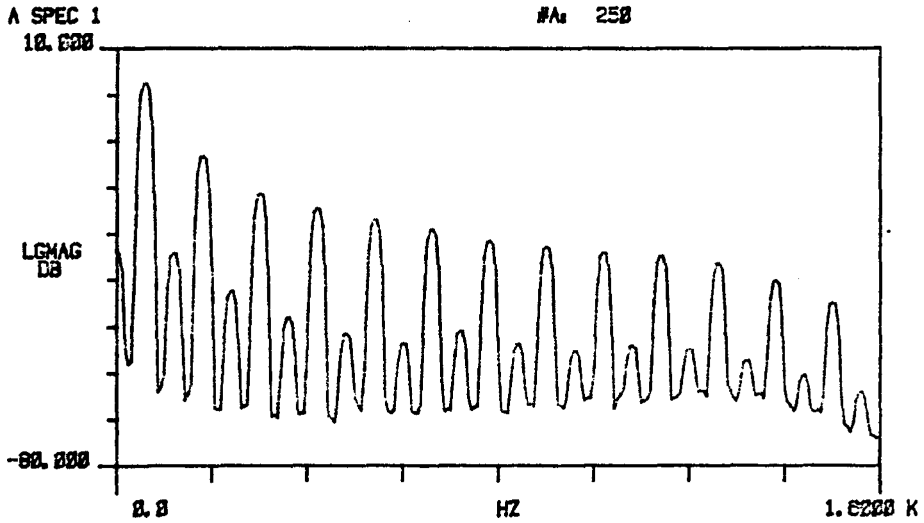


b. Magnitude Scale Display

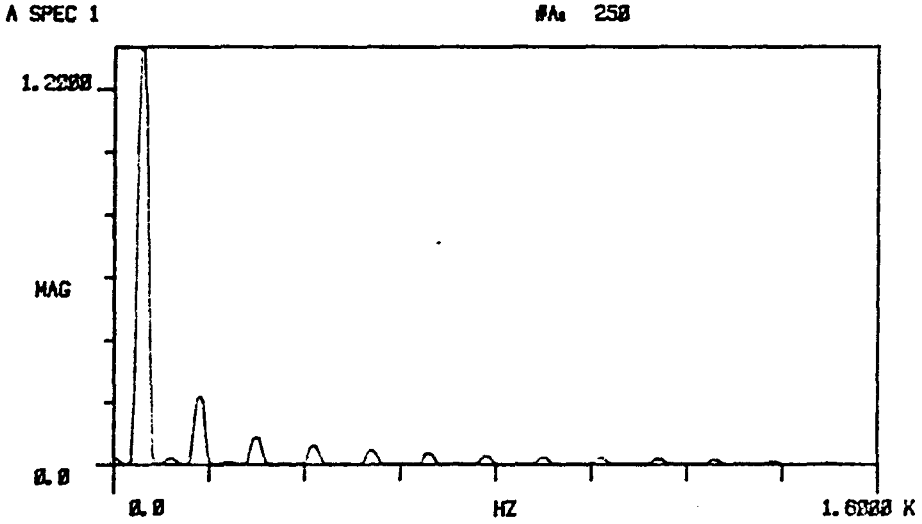


Figures 22a and 22b

Current Autospectrums at 100% Rated Current



a. Decibel Scale Display

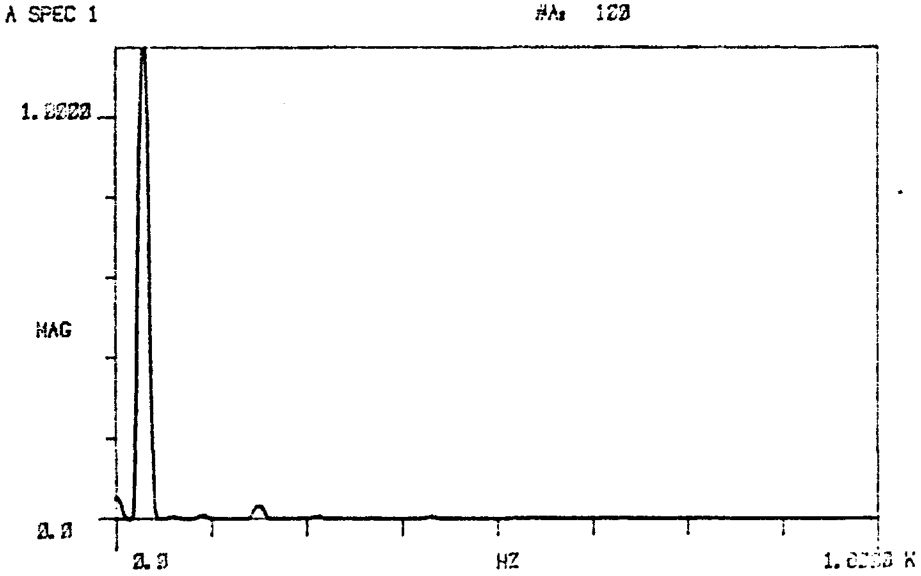


b. Magnitude Scale Display

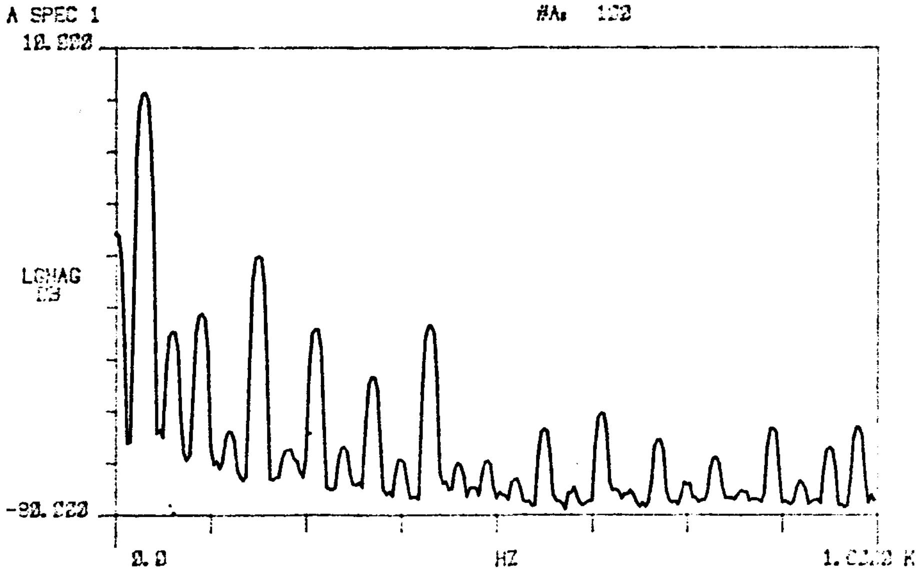
Figures 23a and 23b

Current Autospectrums at 125% Rated Current

a. Magnitude Scale Display



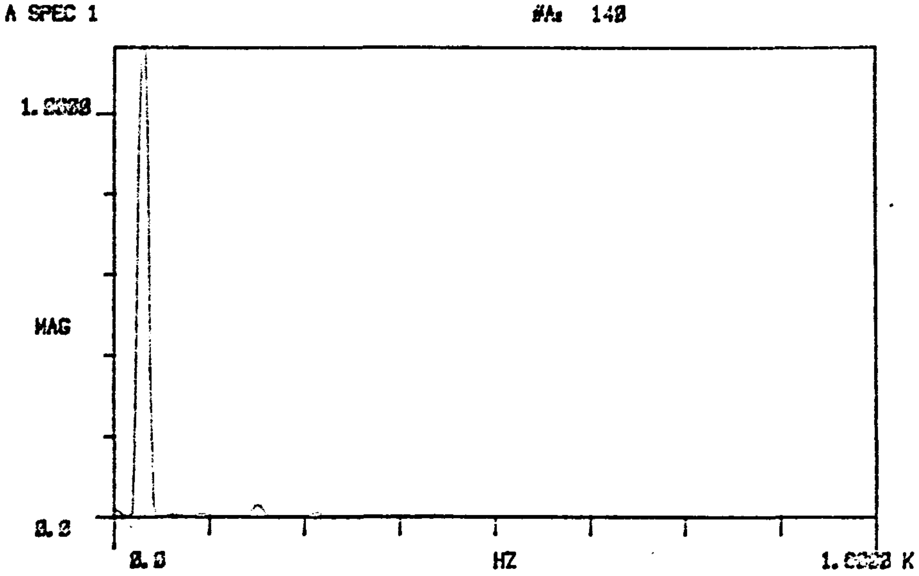
b. Decibel Scale Display



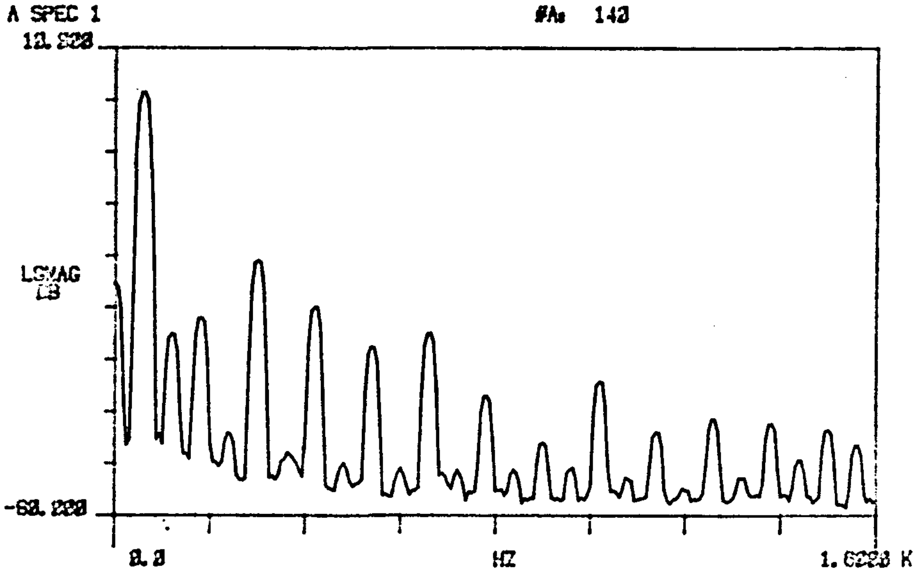
Figures 24a and 24b

Mini-Grid Voltage Autospectrums at 0% Rated Current

a. Magnitude Scale Display



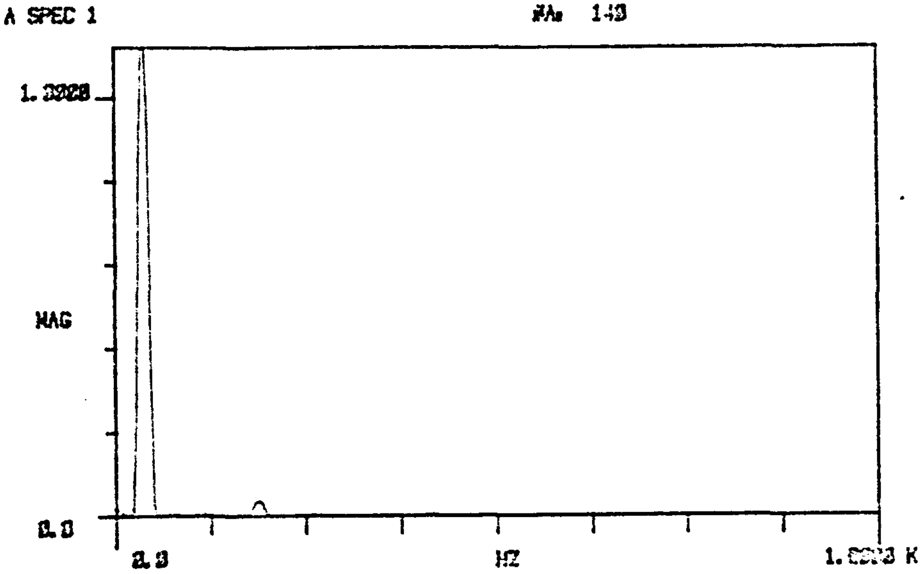
b. Decibel Scale Display



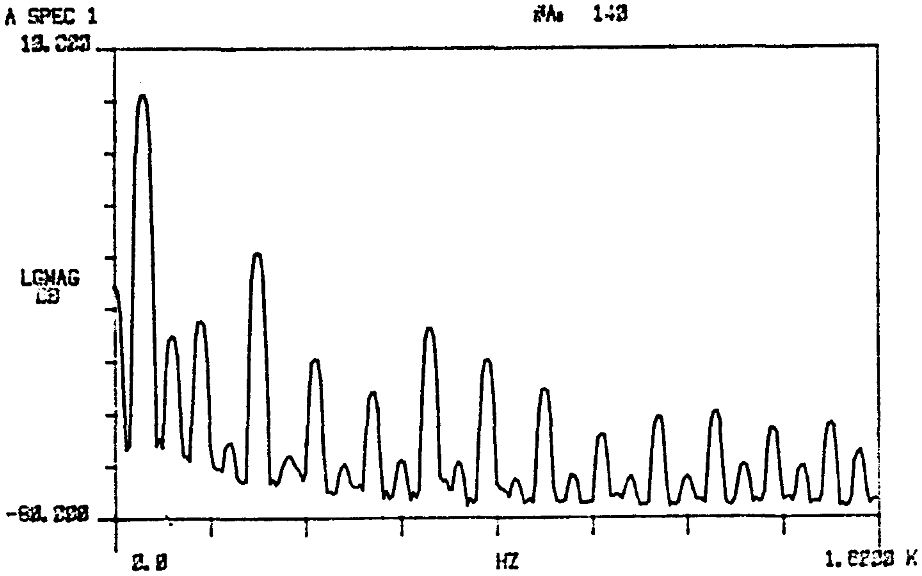
Figures 25a and 25b

Mini-Grid Voltage Autospectrums at 25% Rated Current

a. Magnitude Scale Display



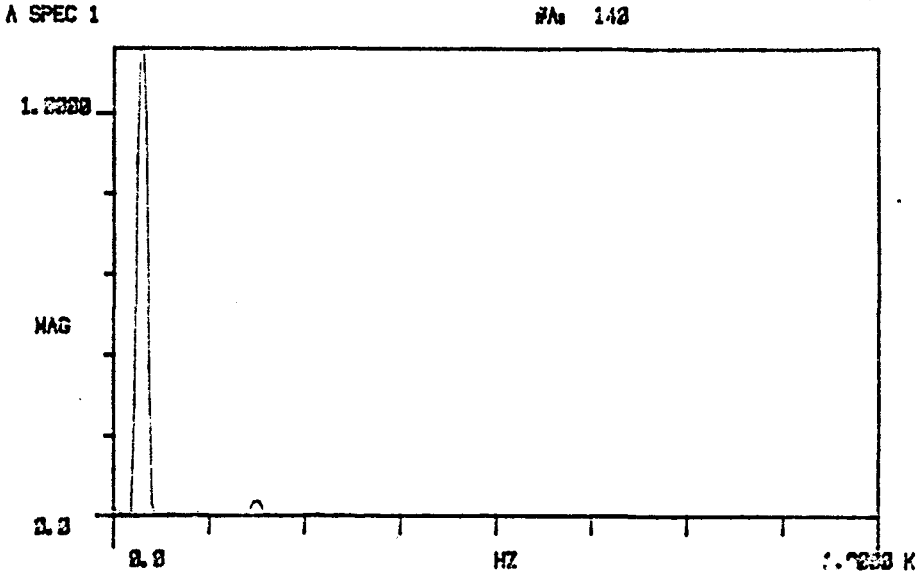
b. Decibel Scale Display



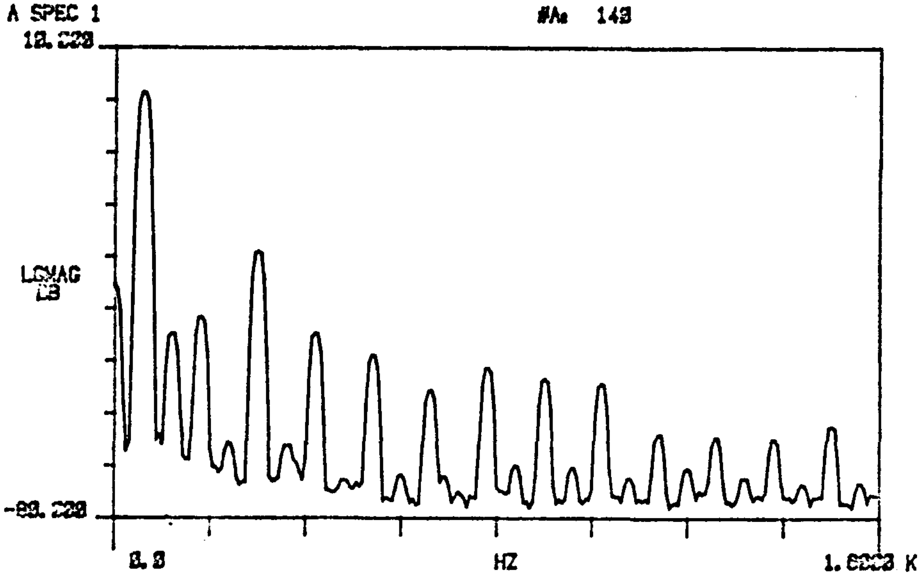
Figures 26a and 26b

Mini-Grid Voltage Autospectrums at 50% Rated Current

a. Magnitude Scale Display



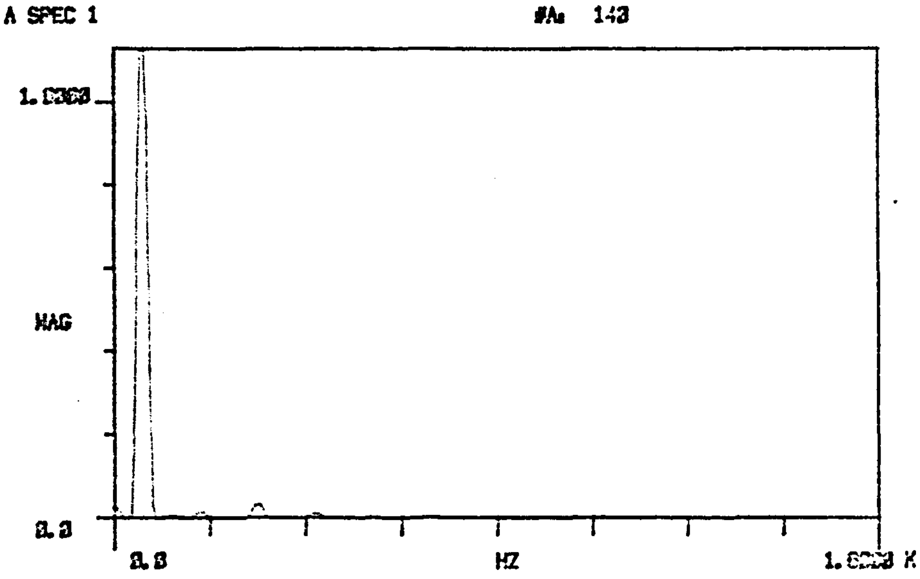
b. Decibel Scale Display



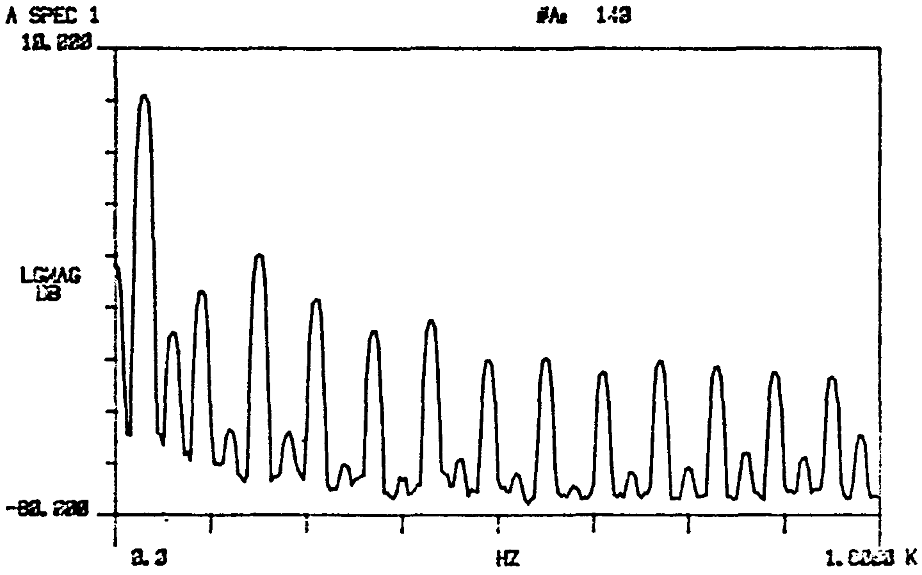
Figures 27a and 27b

Mini-Grid Voltage Autospectrums at 75% Rated Current.

a. Magnitude Scale Display



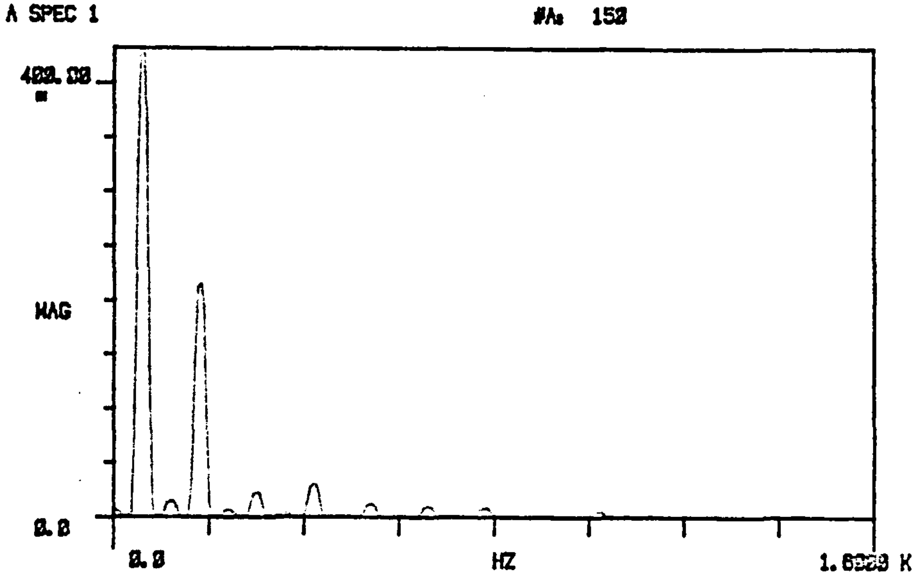
b. Decibel Scale Display



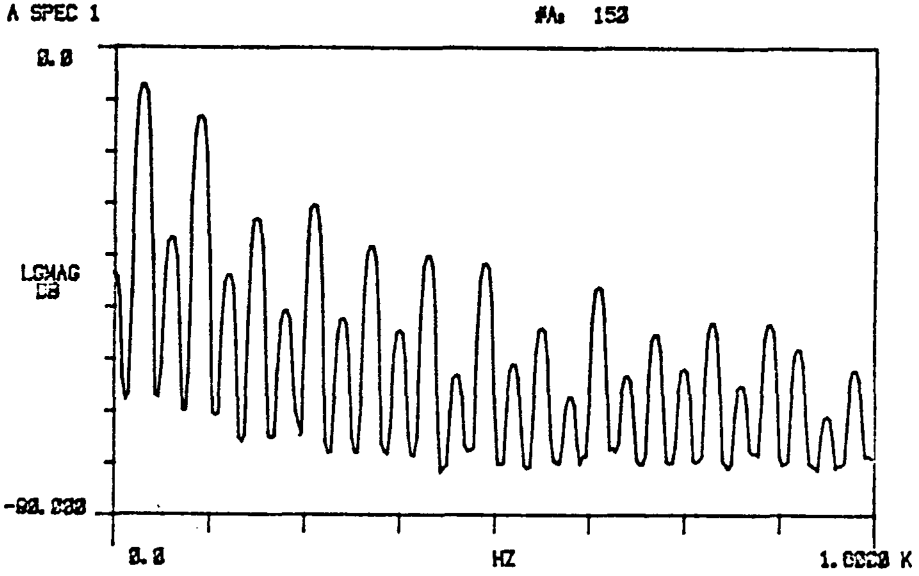
Figures 28a and 28b

Mini-Grid Voltage Autospectrums at 100% Rated Current

a. Magnitude Scale Display



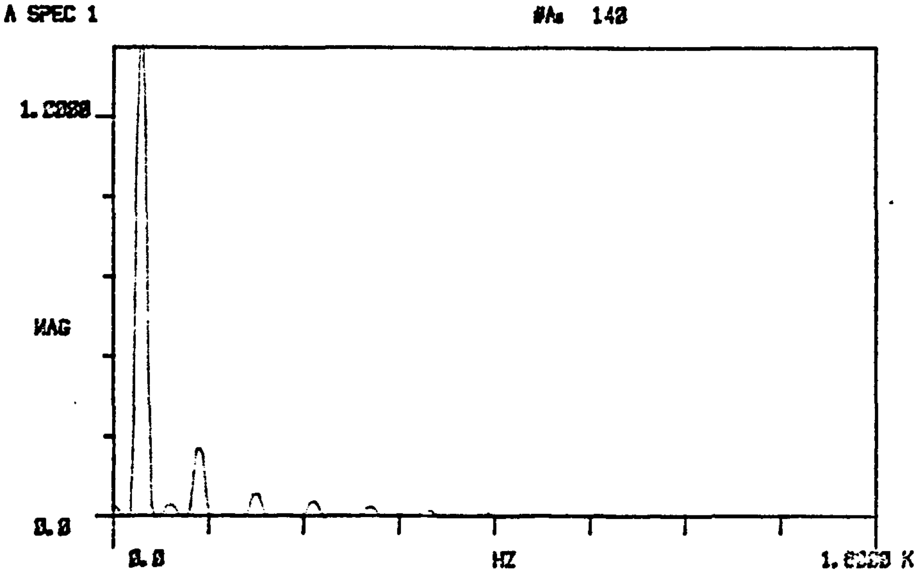
b. Decibel Scale Display



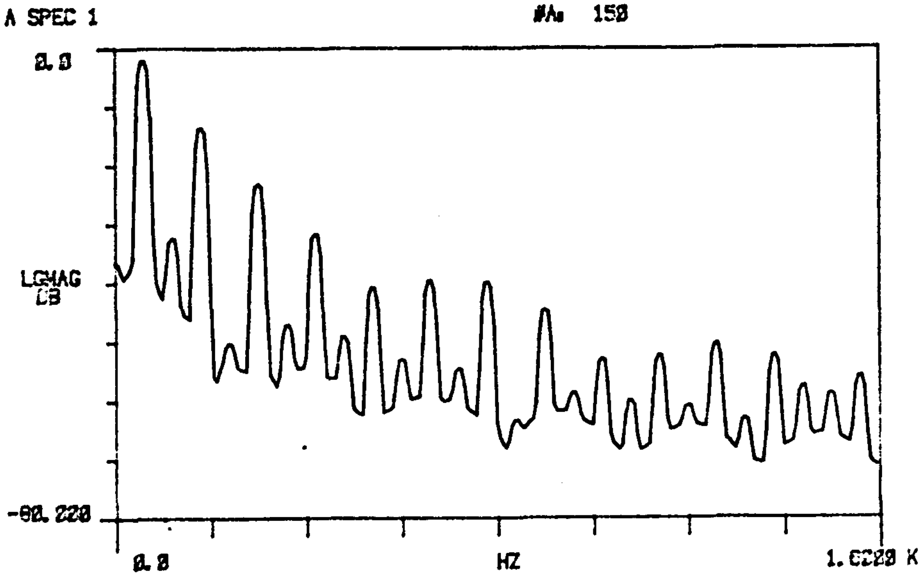
Figures 29a and 29b

Mini-Grid Current Autospectrums at 25% Rated Current

a. Magnitude Scale Display



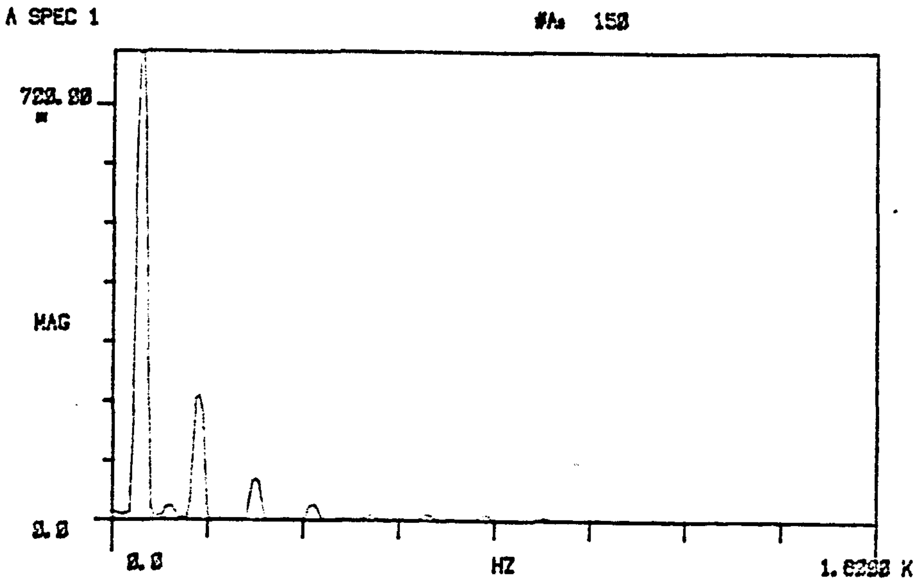
b. Decibel Scale Display



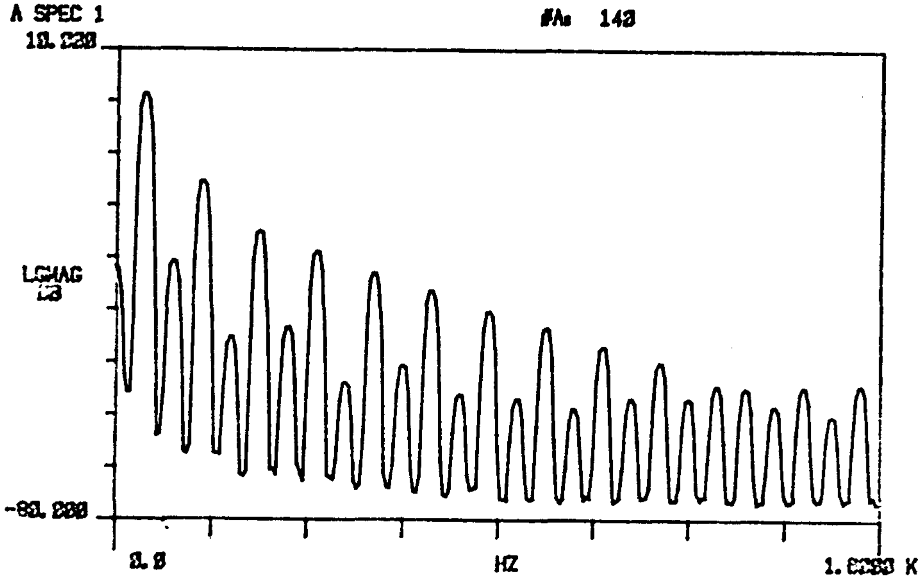
Figures 30a and 30b

Mini-Grid Current Autospectrums at 50% Rated Current

a. Magnitude Scale Display



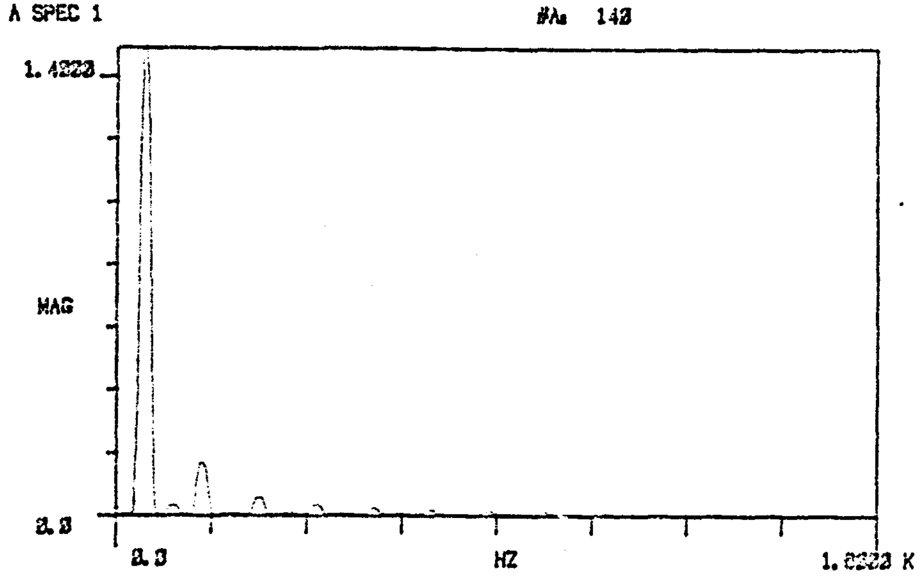
b. Decibel Scale Display



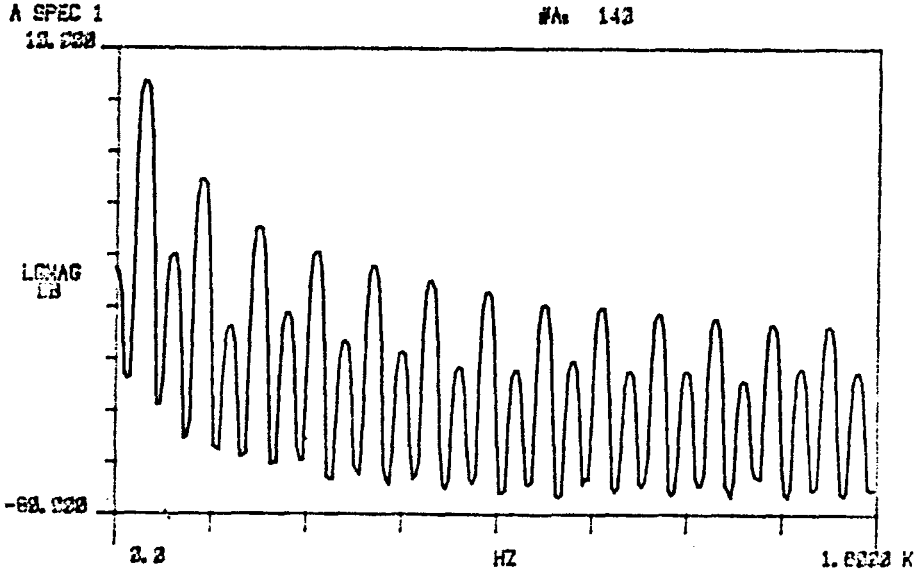
Figures 31a and 31b

Mini-Grid Current Autospectrums at 75% Rated Current

a. Magnitude Scale Display



b. Decibel Scale Display



Figures 32a and 32b

Mini-Grid Current Autospectrums at 100% Rated Current