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MATHEMATICAL MODEL FOR THE DC-AC INVERTER
FOR THE SPACE SHUTTLE

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Final Report

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ABSTRACT

The purpose of this report is to inform the reader of what has been done for the mathematical modeling of the DC-AC inverter for the Space Shuttle. The mathematical modeling of the DC-AC inverter is an essential element in the modeling of the electrical power distribution system of the Space Shuttle. The electrical power distribution system which is present on the Space Shuttle is made up of three strings each having a fuel cell which provides DC to those systems which require DC, and the inverters which convert the DC to AC for those elements which require AC. The inverters are units which are two-wire structures for the main DC inputs and two-wire structures for the AC output. When three are connected together a four wire wye connection will result on the AC side. The method of modeling will be performed by using a Least Squares curve fitting method. A computer program will also be presented for implementation of the model along with graphs and tables to demonstrate the accuracy of the model.

INTRODUCTION

The purpose of this report is to inform the reader of what has been done for the mathematical modeling of the DC-AC inverter for the Space Shuttle. The mathematical modeling of the DC-AC inverter is an essential element in the completion of the modeling of the electrical power distribution system of the Space Shuttle which the in-house support contractor had started by producing a model for the DC portion of the electrical power distribution system. The electrical power distribution system which is present on the Space Shuttle is made up of three strings each having a fuel cell which provides DC to those systems which require DC, and the inverters which convert the DC to AC for those elements which require AC. The inverters are units which are two-wire structures for the main DC inputs and two-wire structures for the AC output. When three are connected together a four wire wye connection will result on the AC side. Therefore, with three strings on the Shuttle there are nine inverters. For this report only three inverters will be modeled. There was enough input data taken on the performance of the inverters that it was not necessary to write any equations describing the

internal operations of the inverter. Therefore the method of modeling will be performed by using a Least Squares curve fitting method. A computer program will also be presented for implementation of the model along with graphs and tables to demonstrate the accuracy of the model. The following table is given as a tool to help the reader identify any symbols that are used in this report.

V.....	voltage
Hz.....	frequency cycles per second
VA.....	volt ampere
Pu.....	per unit
E _{dc}	voltage DC
I _{dc}	current DC
E _{ac}	voltage AC
I _{ac}	current AC
PF.....	power factor
P _{in}	DC power in
P _{out}	AC power out
EF & Eff.....	efficiency
TF.....	temperature

The first step taken in developing the math model for the inverter was to find out what function the inverter performs and what data was available on the inverter. The inverters are units which can convert 28VDC nominal input to a single phase AC output of 117V, 400Hz, rated at 750VA continuous, and 1125VA for 30 minutes with power factor ranging from 0.7 lagging to 0.9 leading including unity. The full rated load at 1.0Pu is:

$$I=750VA/117V$$

This defines the steady state operation of the inverter for constant inputs as a single phase unit.

Data on the inverter was available in the form of written reports and experimental data. The reports that were found and used are referenced at the end of this report. An example of the experimental data is given in Table 1. The experimental data shows the input and output conditions of the inverter keeping the power factor, input and output voltage, and frequency constant while changing the load.

%-VA	Edc	Idc	Eac	Iac	PF	Pout	TEMP	Pin	%-EF
0	30	3.14	117	0.00	.0	0.0	112.7	94.1	0.0
20	30	5.69	117	1.36	.6	96.8	111.6	170.5	56.8
40	30	8.63	117	2.59	.6	180.6	107.7	258.2	69.9
50	30	10.59	117	3.30	.6	232.9	108.1	316.6	73.3
60	30	12.16	117	3.88	.6	272.9	108.4	362.3	75.3
80	30	15.88	117	5.12	.6	361.6	110.8	473.7	76.3
100	30	20.39	117	6.47	.6	449.4	115.1	607.1	74.0
125	30	26.86	117	8.17	.6	579.5	122.6	797.4	72.6
150	30	33.53	117	10.05	.6	700.8	133.1	997.9	70.2
200	30	48.43	117	13.29	.6	926.8	123.8	1424.3	65.0

TABLE-1: EXAMPLE OF EXPERIMENTAL DATA FOR INVERTER A

This procedure was repeated for each of the three inverters for the following conditions: 24, 26, 28, and 30 volts DC input and -0.6, -0.7, -0.85, 1.0, and 0.9 power factor at each of the DC voltage inputs.

MODEL

The math model of the inverter was designed to produce as many input and output conditions as possible based on a limited number of inputs to the math model. The inputs to the model are as follows:

1. Percent Load
2. Input Voltage DC
3. Power Factor

the outputs from the math model are as follows:

1. Input Current DC
2. Output Current AC
3. Input Power DC
4. Output Power AC
5. Percent Efficiency
6. Temperature In Degrees F

In order to do this, two different modeling methods were investigated. These modeling methods are as follows:

1. Least Squares (LS) fitting of the data.
2. Data fitting by use of a set of orthogonal polynomials (OP).

Each of these methods are found in software that is already available. The least squares fitting was found in the Statistical Analysis System (SAS) routines and the method of using orthogonal polynomials for curve fitting was found in the International Mathematical and

Statistical Libraries (IMSL) routines.

Based on analysis of the percent efficiency data it was decided that a fourth order model would best approximate the data. The reason for using the efficiency data to determine the order of the model was because this data went through the largest number of cycles over the range of 0 to 200 percent load. Using a fourth order model for each of the two cases listed above produced results which tracked the data very well. After being assured that each method produced satisfactory results, it was decided to use just the least squares fitting of the data to model the remaining sets of data. The reason for this decision was based on the observation that the least squares method of data fitting produced a tighter fit.

PROGRAM

Using the data that was supplied for each inverter a fourth order regression equation using the percent load as the independent variable was produced to model each of the six variables that were used from each sheet of the data for the inverters. Each inverter was tested at 24, 26, 28, and 30 volts DC input. At each voltage setting, it was tested at -0.6, -0.7, -0.85,

1.0, and 0.9 power factor. Using the results of these tests a set of regression equations was produced to represent the input current DC, input power DC, output current AC, output power AC, percent efficiency, and temperature in degrees fahrenheit for each setting of voltage and power factor. This produced a set of 120 regression equations for each inverter. Twenty regression equations are used to describe each of the above referenced output parameters.

Each set of 20 regression equations is used to produce a matrix for all voltage and power factor settings, for each inverter. An example of the matrices that represent all of the input parameters for a load of 100 percent for inverter C is shown below:

	-0.6	-0.7	-0.85	1.0	0.9
24	24.02708	26.80123	33.31841	26.70104	40.88011
26	23.49872	27.47219	31.48396	37.36097	37.46921
28	20.90991	25.11707	28.68474	21.02460	35.56254
30	20.47581	23.31632	27.19581	33.18778	44.52682

DC INPUT CURRENT FOR 100 PERCENT LOAD FOR INVERTER C

	-0.6	-0.7	-0.85	1.0	0.9
24	64.79873	63.91091	64.56882	63.93892	63.57912
26	65.91304	64.58717	66.15194	63.23208	63.20073
28	64.79345	64.45176	65.94344	63.48076	63.68013
30	64.49525	65.50586	64.74864	58.59911	62.55650

AC OUTPUT CURRENT FOR 100 PERCENT LOAD FOR INVERTER C

	-0.6	-0.7	-0.85	1.0	0.9
24	562.0085	635.5890	784.0984	970.1697	960.8156
26	583.8451	673.9015	788.1099	962.5731	954.8917
28	587.7390	692.4550	790.6331	978.7694	970.1374
30	611.5838	690.3112	815.6928	1022.1897	1008.9542

DC INPUT POWER FOR 100 PERCENT LOAD FOR INVERTER C

	-0.6	-0.7	-0.85	1.0	0.9
24	457.3632	522.5542	639.8809	746.2821	669.2880
26	461.2574	533.8483	636.5393	738.5239	666.9812
28	450.8919	528.9160	643.1387	741.7915	672.3812
30	454.0515	539.8164	643.8911	746.7502	670.5568

AC OUTPUT POWER FOR 100 PERCENT LOAD FOR INVERTER C

	-0.6	-0.7	-0.85	1.0	0.9
24	76.98697	80.62087	79.11906	74.81590	67.30208
26	76.46641	77.63451	83.97259	74.75730	68.18011
28	76.08212	76.09306	79.57481	74.34234	67.70587
30	74.93172	71.25590	77.79884	71.92826	64.74466

PERCENT EFFICIENCY FOR 100 PERCENT LOAD FOR INVERTER C

	-0.6	-0.7	-0.85	1.0	0.9
24	10.61268	11.22281	11.32683	11.76665	13.42805
26	11.28422	12.14870	11.54441	12.57221	12.17178
28	10.99731	11.23885	12.34068	10.67528	12.72728
30	11.89918	12.72210	12.58744	13.61134	13.33829

TEMPERATURE FOR 100 PERCENT LOAD FOR INVERTER C

This method of reproducing the data was chosen over having the data stored in a data file and reading the desired portion of the data file into the program.

At this point the program will perform a least squares on each matrix for each voltage setting using the power factor as the independent variable. This will produce four regression equations which will then be used to calculate four points, one for each voltage setting. With these four points another least squares will be performed using the voltage as the independent variable. This will produce one equation which will then give the desired value of current for the input of the percent load, input voltage DC, and power factor.

This procedure was repeated for each of the three inverters. Once this point is reached the following output is produced:

	INVERTER-A	INVERTER-B	INVERTER-C
Input Current DC..	27.19581	27.05088	27.21824
Output Current AC.	6.47486	6.27590	6.35214
Input Power DC....	815.69282	803.43621	808.26576
Output Power AC...	643.89115	624.95208	631.83659
Inverter % Eff....	77.79884	76.52319	75.55965
Inverter Temp. F..	125.87446	117.18629	107.85057

OUTPUT FOR EACH INVERTER AS A SINGLE PHASE UNIT

This represents the output for three single phase inverters. The next step is to combine these three inverters into a 4 wire wye connection with the

following phase sequence: inverter A, 0 degrees; inverter B, 120 degrees; and inverter C, 240 degrees. Using this phase sequence the next set of output that is supplied is the voltage line to neutral, phase current, neutral current, and power. This output is now represented as follows:

	REAL	IMAG.
Inverter-A Output Voltage	117.00000	0.00000
Inverter-B Output Voltage	- 58.49374	101.32858
Inverter-C Output Voltage	- 58.51251	-101.31774
Total Three Phase Voltage	- 0.00625	0.01084
Inverter-A Output Current	4.58541	4.67805
Inverter-B Output Current	- 6.06423	1.01328
Inverter-C Output Current	1.71725	- 6.16466
Total Return Current	0.23842	0.07286
Inverter-A Output Power	377.87152	385.50606
Inverter-B Output Power	361.95492	369.26788
Inverter-C Output Power	367.28991	374.71066
Total Three Phase Power	1107.11637	1129.48461

THREE PHASE OUTPUT FOR THE INVERTERS

A complete set of graphs is provided in appendix A for inverter A which shows the results of the math model calculated values against the experimental values for the following set of parameters:

	EXPERIMENTAL	CALCULATED
Input Current DC	IDC	IDCC
Output Current AC	IAC	IACC
Power In	PIN	PINC
Power Out	POUT	POUTC
Percent Efficiency	EF	EFC
Temperature	TF	TFC

CONCLUSION

Thus far three inverters have been modeled by using the input/output data that was supplied. This data was modeled by use of a Least Squares fitting technique to produce a set of equations which approximates the output conditions and also some of the input conditions, given certain inputs to the model like percent load, input voltage DC, and power factor.

At this point only a steady state model for a balanced three phase system exists for one set of inverters. It is proposed to complete the steady state modeling by performing the following tasks:

1. To increase the accuracy of the model by increasing the order of the system or by use of other modeling methods.
2. To give the model the ability to handle unbalanced loads.
3. To include into the model an option that would allow for dropping of an inverter and then calculating the output of the remaining inverters.

With these additions to the present model a very good representation of the DC-AC Inverter for the steady state can be produced.

REFERENCES

IMPLEMENTATION AND OPERATION PROCEDURES

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Contract NAS9-15800

SPECIFICATION-INVERTER, POWER STATIC, 117 VOLT, SINGLE PHASE, 400 Hz

Prepared by Rockwell International, Downey, California

QUALIFICATION TEST PROCEDURE SPACE SHUTTLE POWER STATIC INVERTER, 117 VOLTS, SINGLE PHASE, 400Hz

Prepared by Westinghouse, Lima, Ohio
Document N5-118

FINAL TEST REPORT FOR OV-101 EPDC BREADBOARD EVALUATION TEST SERIES

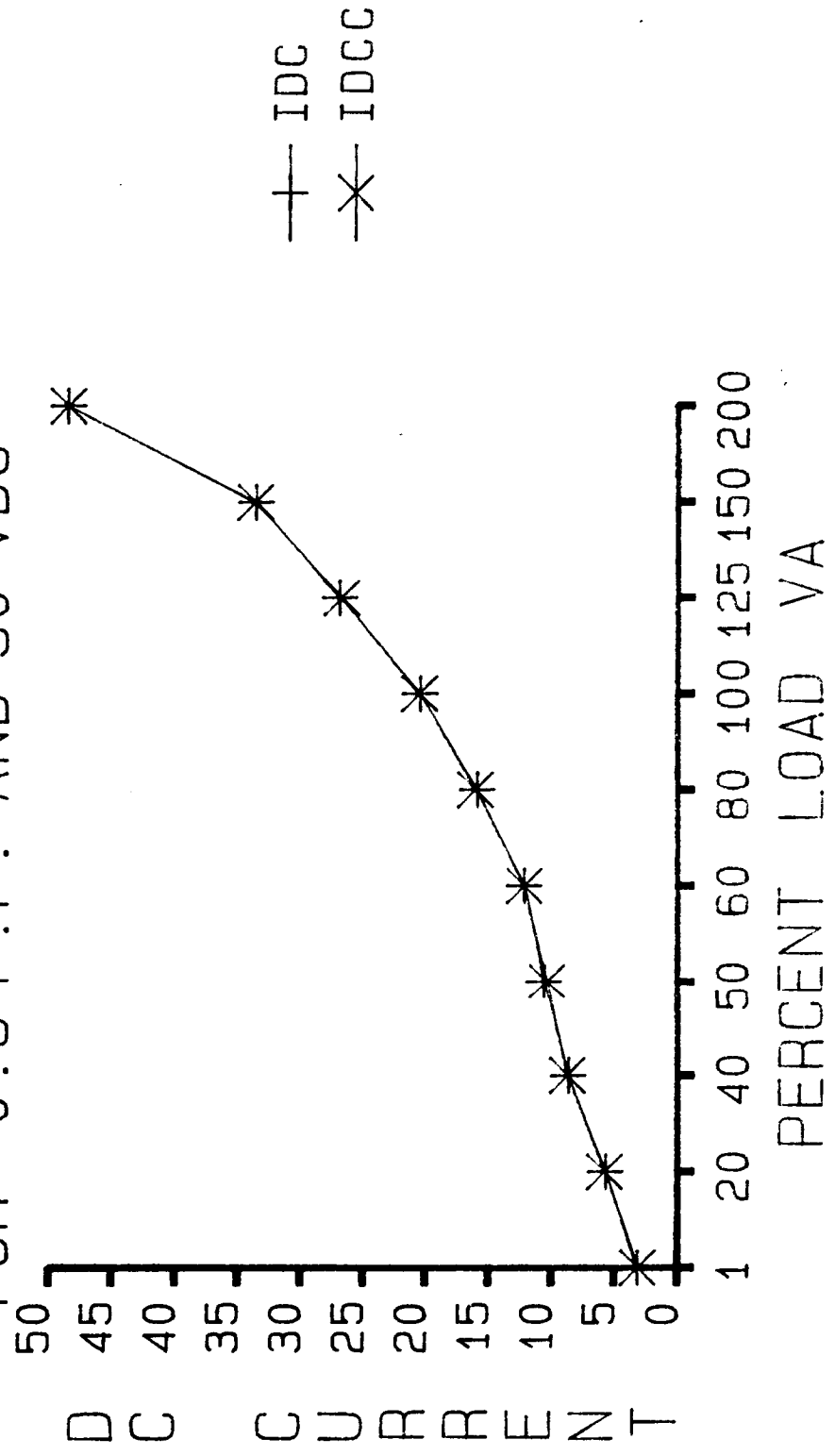
Internal Note JSC 77-EG-12

INTERIM TEST REPORT FOR OV-102 BREADBOARD EVALUATION TEST SERIES

Internal Note ASD 78-EH-16

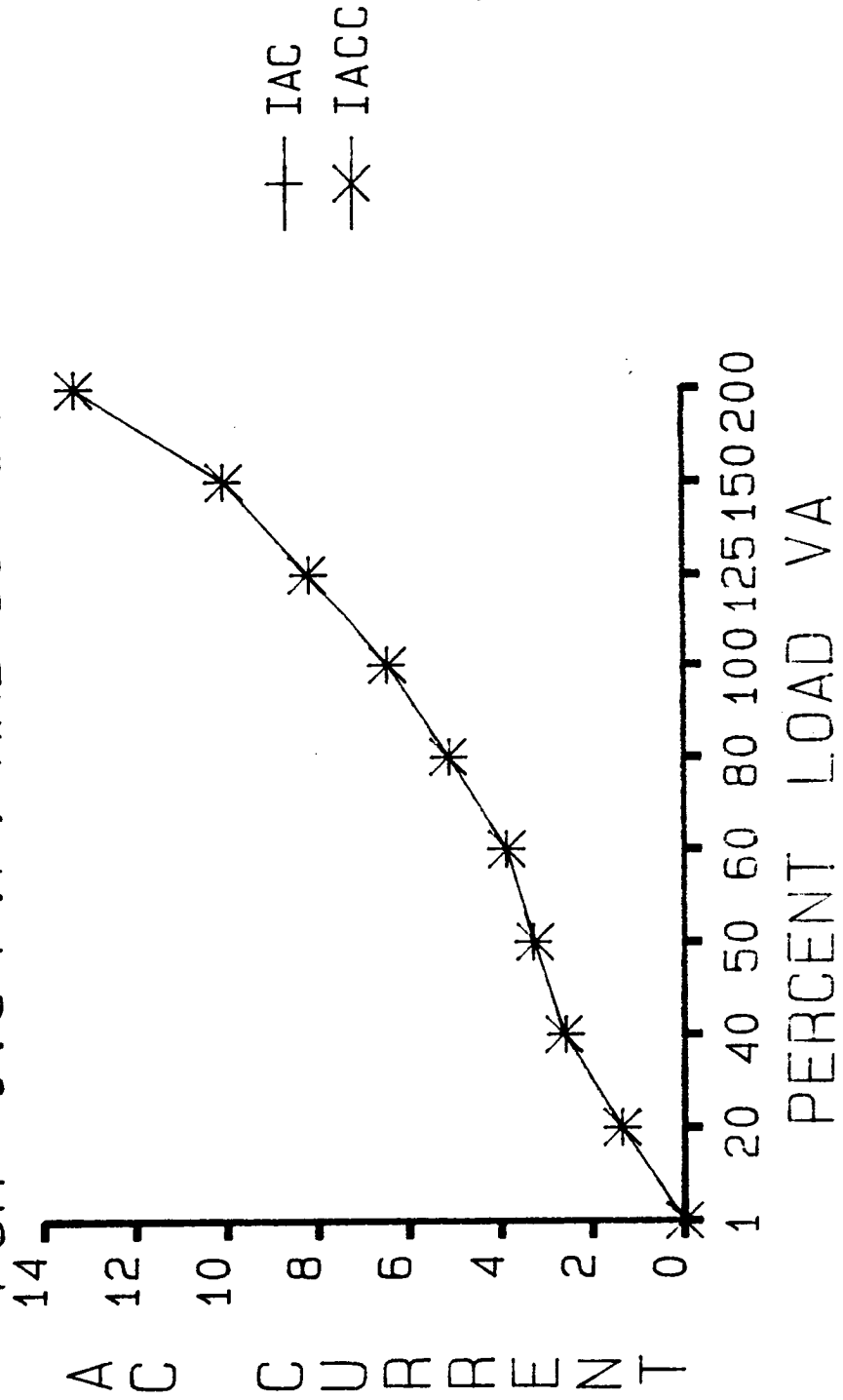
INVERTER A TEST RESULTS

FOR -0.6 P.F. AND 30 VDC



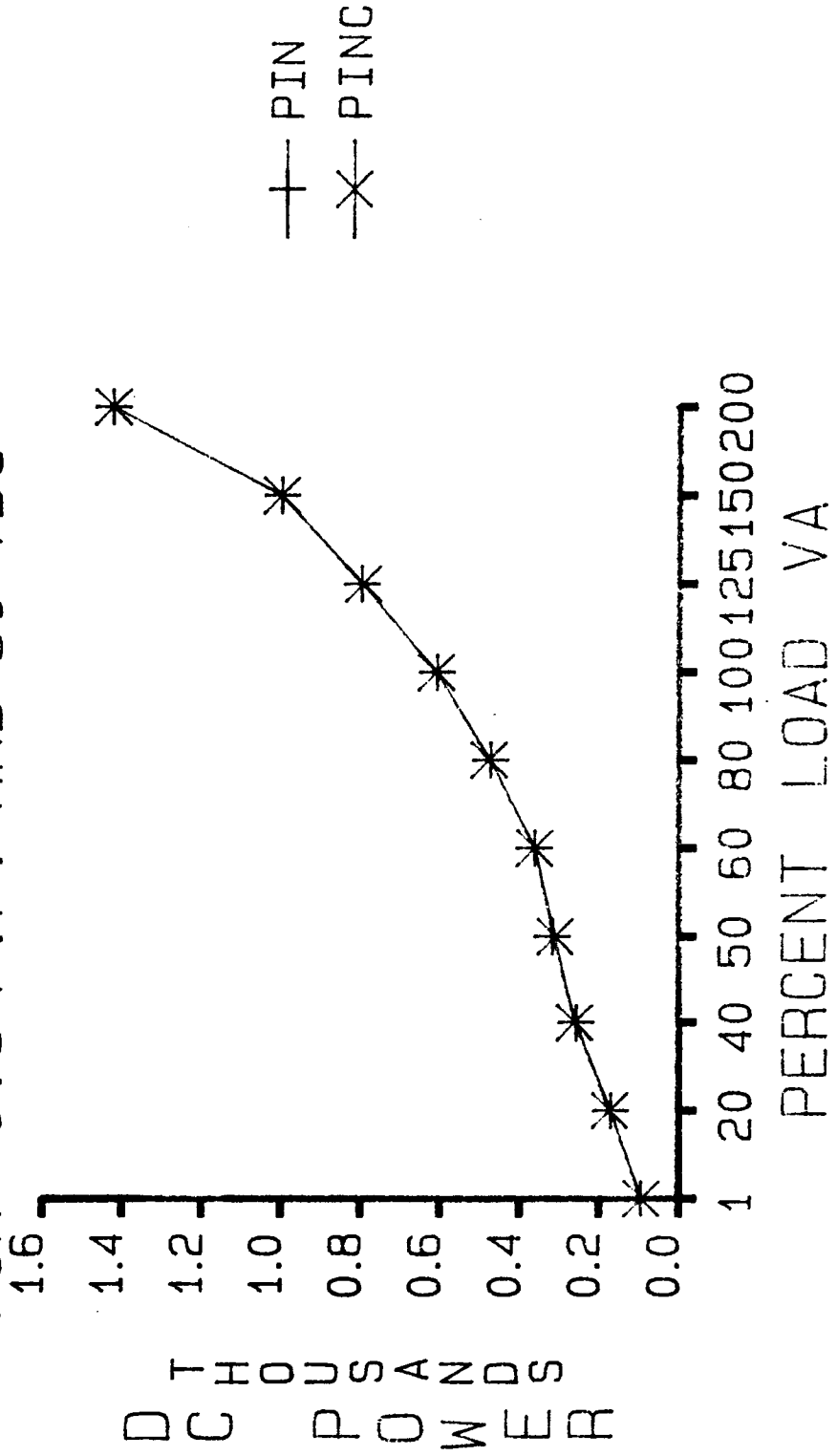
INVERTER A TEST RESULTS

FOR -0.6 P.F. AND 30 VDC



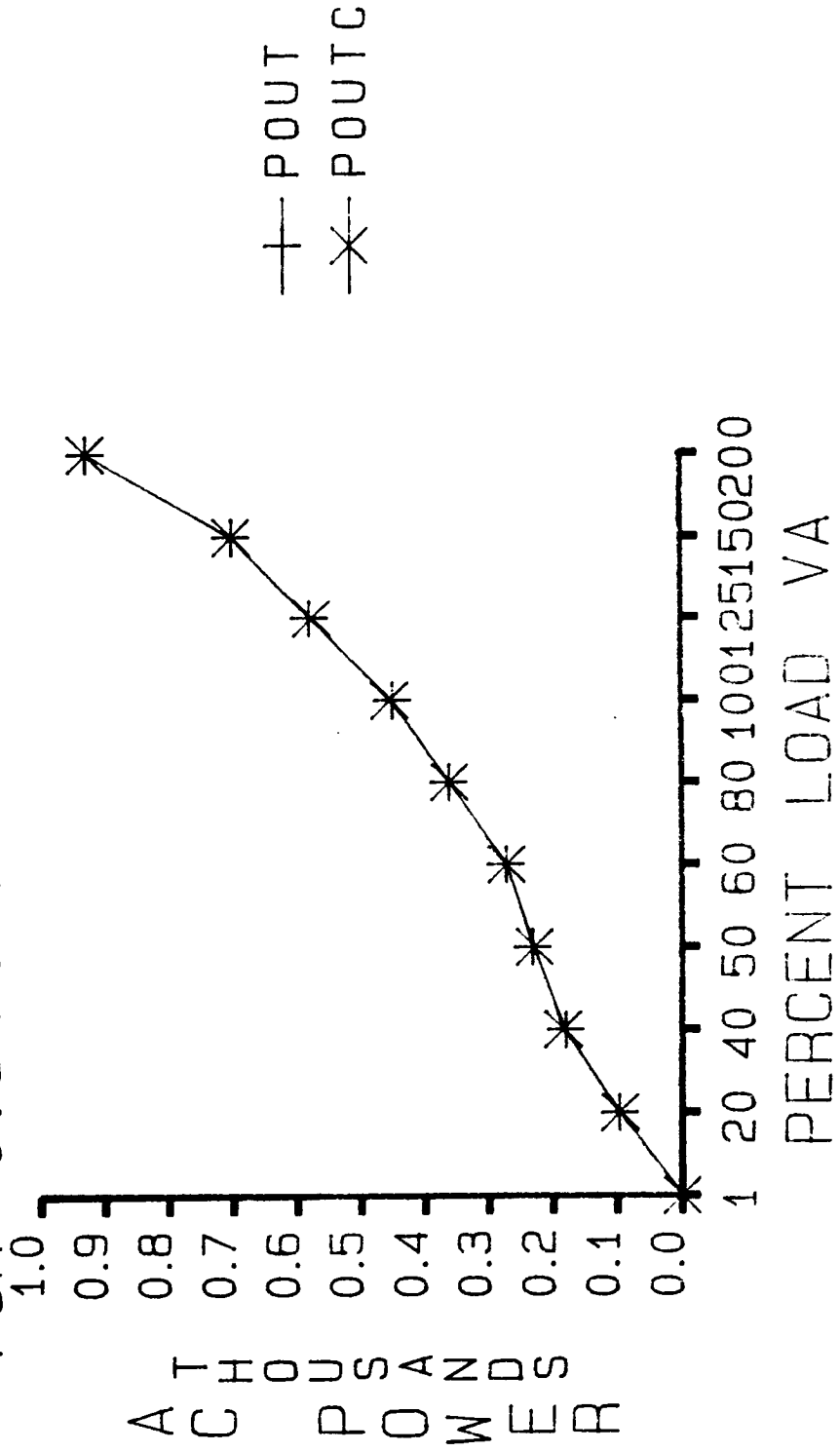
INVERTER A TEST RESULTS

FOR -0.6 P.F. AND 30 VDC



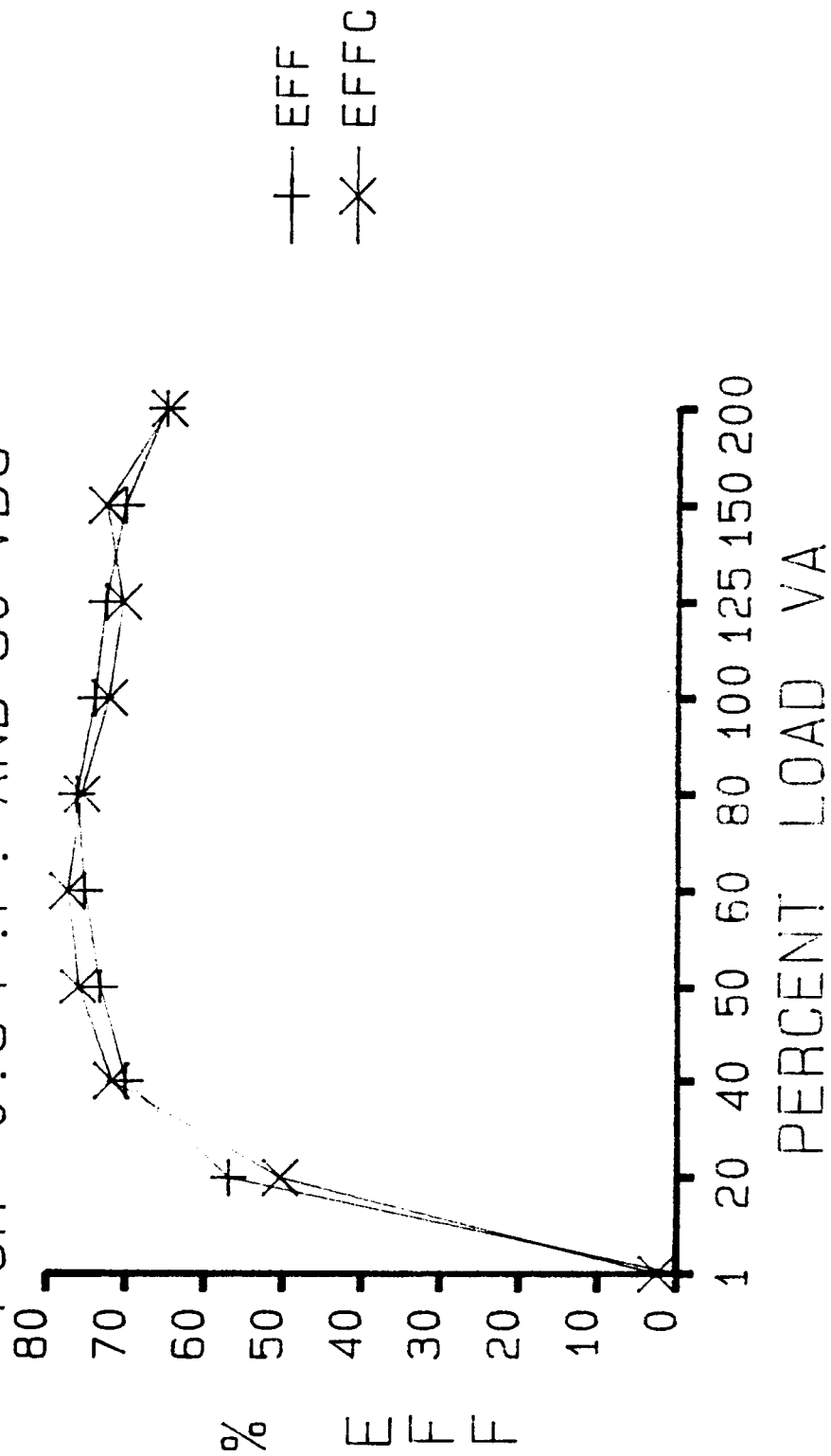
INVERTER A TEST RESULTS

FOR -0.6 P.F. AND 30 VDC



INVERTER A TEST RESULTS

FOR -0.6 P.F. AND 30 VDC



INVERTER A TEST RESULTS

FOR -0.6 P.F. AND 30 VDC

