COMPUTER AIDED ANALYSIS OF A SPACECRAFT POWER SYSTEM

by

GABRIEL PATRICK MUYSHONDT, B.S. in E.E.

A THESIS

IN

ELECTRICAL ENGINEERING

Submitted to the Graduate Faculty
of Texas Tech University in
Partial Fulfillment of
the Requirements for
the Degree of

MASTER OF SCIENCE

IN

ELECTRICAL ENGINEERING

Approved

Accepted

May, 1987

ALP
905
T-3
1997
No. 28
Cop. 2

ACKNOWLEDGMENTS

I would like to express my sincere appreciation to Jesse Chen and Dr. W. M. Portnoy for their guidance and helpful suggestions. Also, I would like to thank my wife, Donna, for her support.

CONTENTS

ACKNOWLEDGMENTS	ii
LIST OF FIGURES	v
LIST OF TABLES	viii

CHAPTER

I. INTRODUCTION	1
II. POWER SYSTEM WITH VOLTAGE CONTROLLED LOOP . . .	3
Description of the System	4
Numerical Instability Problem	5
Solution to the Numerical Instability	11
III. INTERACTION BETWEEN THE VOLTAGE LOOP AND THE CURRENT LOOP	29
Description of the System	29
Interaction Between the Loops	32
IV. POWER SYSTEM WITH MULTIPLE CONTROLLED LOOPS . .	38
Description of the System	38
Instability Problem	44
V. CONCLUSIONS	51
LIST OF REFERENCES	52

APPENDICES

A. INDUCTOR CURRENT	53
B. SPICE PROGRAM LISTING	61

C.	SMALL SIGNAL AC SPICE PROGRAM	63
D.	TRANSISTOR MODEL PARAMETERS	65
E.	SPICE PROGRAM LISTING OF THE POWER SYSTEM WITH VOLTAGE LOOP AND CURRENT LOOP	67
F.	VOLTAGE DROP ACROSS THE DIODES DVL AND DCL . .	71
G.	SPICE PROGRAM LISTING OF THE MULTI-LOOP POWER SYSTEM	77
H.	VOLTAGE DROP ACROSS THE DIODES DPPT, DVL, AND DCL	82

LIST OF FIGURES

1. Equivalent SPICE circuit model of the specified spacecraft electrical power system	4
2. Inductor current	6
3. Bus voltage waveform obtained using the trapezoidal method of integration, a 5 us step size, and an ideal transistor model	7
4. Bus voltage oscillations on expanded voltage and time scales	8
5. Bus voltage waveform obtained when the current source ILOAD was replaced by its equivalent resistive element using the trapezoidal method of integration, a 5 us step size, and an ideal transistor model	9
6. Small signal AC equivalent circuit model	10
7. Small signal gain	12
8. Small signal phase	13
9. Ebers-Moll model for a bipolar n-p-n transistor	14
10. Collector-emitter voltage waveform obtained using the trapezoidal method of integration, a 5 us step size, and an ideal transistor model (expanded scales)	15
11. Collector-emitter voltage waveform obtained using the trapezoidal algorithm, a 5 us step size, and a higher level transistor model (expanded scales)	17
12. Bus voltage waveform obtained using the trapezoidal algorithm, a 0.05 us step size, and an ideal transistor model	19

13.	Bus voltage waveform on expanded voltage and time scales	20
14.	Bus voltage waveform obtained using the trapezoidal algorithm, a 5 us step size, and a higher level transistor model	22
15.	Bus voltage waveform on expanded voltage and time scales	23
16.	Bus voltage waveform obtained using the Gear algorithm, a 5 us step size, and an ideal transistor model	24
17.	Bus voltage waveform on expanded voltage and time scales	25
18.	Bus voltage waveform using the Gear algorithm, a 5 us step size, and a higher level transistor model	26
19.	Bus voltage waveform on expanded voltage and time scales	27
20.	Block diagram of the power system with voltage loop and current loop	30
21.	Circuit diagram of the current loop	31
22.	Piecewise linear load current	33
23.	Bus current waveform	35
24.	Bus voltage waveform	36
25.	Block diagram of the multi-loop power system . .	39
26.	Peak power tracker circuit diagram	40
27.	Bandpass filter circuit diagram	41
28.	Load line of the input source	42
29.	Power versus voltage curve	43
30.	Circuit diagram of the entire system	46

31.	Input voltage to the peak power tracker	48
32.	Input current to the peak power tracker	49
33.	Voltage at node 260	50

LIST OF TABLES

1. Computing Times for Each Method of Solution . .	28
2. Duty Ratio Calculation for Each Loop	45

CHAPTER I

INTRODUCTION

As spacecraft power systems grow in complexity and tighter design constraints are imposed, the need for a reliable and accurate computer model plays a key role in power systems design. The development of computer-aided workbenches has facilitated and accelerated the laboratory testing process, which is usually difficult, time consuming, expensive, and, in some cases, destructive. Most workbenches use some form of SPICE (Simulation Program with Integrated Circuits Emphasis). This software package has proven to be very useful in the design of power electronic circuits [1,2]. In general, the brute force calculations have been used. These are called brute force because the large difference between the switching period and time constants of the circuit require hundreds of computations to observe the state variables for one time constant. This approach is direct: it requires the fewest number of approximations, and it has the advantage of predicting sub-harmonic oscillations.

Until the present time, it has not been certain if a brute SPICE model could simulate the behavior of a large, multiloop power system. This work was undertaken to

address this issue, and to determine if the large signal behavior of power systems could be simulated with a large signal SPICE model; and if not, to establish the reasons why such a model could not be used.

CHAPTER II

POWER SYSTEM WITH VOLTAGE CONTROLLED LOOP

Description of the System

The power system chosen as an example contains a DC/DC buck converter, a battery harness, three controlling loops, and a common output bus. The three controlling loops are a voltage controlled loop, an output current limiting control loop, and a peak power tracking control loop. Each loop was incorporated into the system by adding one at a time, followed by a transient analysis of the bus voltage.

The system in the first part of the simulation consists of an ideal voltage source, two low pass filters, a buck converter, a scaled load, a voltage control feedback loop, and a pulse width modulator. The equivalent SPICE circuit model is shown in Figure 1. In this model, unlimited current to the network is provided by the ideal voltage source. The filters are used to smooth the bus voltage (node 11 in the diagram). The buck converter transforms DC voltage levels, and the dynamic transfer of power is controlled by a bipolar junction transistor (BJT) which acts as a switch. The duty cycle of the switch controls the transformation ratio of the converter. The current through the inductor L1 determines the mode of

Figure 1. Equivalent SPICE circuit model of the specified spacecraft electrical power system.

operation of the converter, a non-zero inductor current corresponding to a continuous mode of operation. The inductor current for this mode is shown in Figure 2, and the respective data are tabulated in Appendix A. The data show that the current never goes to zero, so that the mode of operation of the converter is continuous.

Numerical Instability Problem

The SPICE program developed for this power system is listed in Appendix B. The simplest model incorporates an ideal transistor, and the default calculation uses the trapezoidal method of integration and a time step of 5 μ s. The transient bus voltage is the waveform of interest. The simulation failed to converge in the DC analysis, but convergence could be obtained by adding a small resistor at the base of the bipolar transistor. The results of the default calculation are illustrated in Figures 3 and 4. The initial voltage transient does not decay, but is followed by an oscillation. The same phenomenon occurs (Figure 5) when the load current, ILOAD, is replaced by its equivalent resistive load. These results were not observed in actual circuit operation nor were they predicted by the small signal AC analysis, which is based on the state-space averaging technique [3]. The small signal model for the power system is shown in Figure 6, and the corresponding SPICE program is listed in Appendix C. The Bode plots

Figure 2. Inductor current.

Figure 3. Bus voltage waveform obtained using the trapezoidal method of integration, a 5 us step size, and an ideal transistor model.

Figure 4. Bus voltage oscillations on expanded voltage and time scales.

Figure 5. Bus voltage waveform obtained when the current source ILOAD was replaced by its equivalent resistive element using the trapezoidal method of integration, a 5 us step size, and an ideal transistor model.

Figure 6. Small signal AC equivalent circuit model.

illustrated in Figures 7 and 8 indicate a gain margin of approximately 13 dB and a phase margin of 62 degrees, so that the system should be stable under the specified small signal conditions. The 180 degree crossover frequency of 25 KHz was perplexing, inasmuch as it corresponded to the frequency of oscillation predicted by the original large signal analysis. This prediction was found to be an artifact of the calculation (phantom oscillation), coincidentally being the same as the crossover frequency in the small signal Bode plot.

Solution to the Numerical Instability

SPICE contains a built-in DC model, based on the Ebers-Moll model (Figure 9), for a bipolar transistor; additional parameters can be incorporated to obtain a Gummel-Poon model; Appendix D contains a listing of these parameters. However, computing time imposes a practical limit on the number of parameters that can be introduced. The default model contains no capacitance, whereas the laboratory circuit used a MOS power transistor, which has significant input capacitance, as a switch. In order to conform more closely to laboratory conditions, a higher order model, incorporating two junction capacitances, was introduced for the bipolar switch. The collector-emitter voltage waveform during circuit operation is shown in Figure 10 for the ideal transistor model, and is

Figure 7. Small signal gain.

Figure 8. Small signal phase.

Figure 9. Ebers-Moll model for a bipolar n-p-n transistor.

Figure 10. Collector-emitter voltage waveform obtained using the trapezoidal method of integration, a 5 us step size, and an ideal transistor model (expanded scales).

illustrated in Figure 11 for the higher order model. It is clear that the introduction of the junction capacitances smooths the spikes in the collector-emitter voltage, inhibiting the excitation of the oscillation.

Furthermore, SPICE has available two integration algorithms; the default integration method being the trapezoidal algorithm. This method calculates the area under a curve on a bounded interval by linearizing the curve over a small interval (the step size) and summing the areas of the trapezoids thereby obtained. The trapezoidal algorithm incurs errors when the time step is larger than the inverse of the switching frequency or the shortest time constant of the network. The step size must therefore be chosen appropriately to avoid numerical integration errors.

The optional method (Gear algorithm) is effective in solving stiff equations (i.e., a system of equations whose solutions contain both very fast and very slow components). The Gear method fits a polynomial to the first derivative whereas the trapezoidal method uses a constant first derivative.

The program listing for the electrical power system is specified by using element cards. Additional cards are inserted for the model of the transistor, any optional features, the voltage to be plotted, and the type of analysis to be performed. In the model card, the transistor type and any parasitics are specified. If no

Figure 11. Collector-emitter voltage waveform obtained using the trapezoidal algorithm, a 5 us step size, and a higher level transistor model (expanded scales).

parameters are specified, the default values are selected by SPICE. Optional features of SPICE are selected by using an option card which resets the program control commands for specific simulations. The plot card plots the waveform of a specified voltage. The type of analysis is DC, AC, or transient. In this work, a transient card was used to specify the computing intervals and the step size. This procedure is quite flexible and permits a variety of calculations to be performed. Because of the uncertainty respecting the transistor model and the integration algorithm, four methods of solutions were used to test the validity of the calculations, trade-off between CPU time and accuracy being an important element of a solution. The first method used the trapezoidal algorithm and the ideal transistor model, but a reduced time step. At a small enough step size, the phantom oscillations disappeared (Figures 12 and 13). This technique, although successfully eliminating the oscillations, has the serious drawback that, at very small intervals (< 0.01 us), computing time increases considerably or computer memory overloads. However, computing time could be reduced and the oscillations eliminated with a time step of 0.05 us. The second method used the default algorithm and a 5 us step size, but included two 1000 pF capacitances in the transistor model, one between the collector and base, and the second between the base and emitter. The addition of these capacitances

Figure 12. Bus voltage waveform obtained using the trapezoidal algorithm, a 0.05 us step size, and an ideal transistor model.

Figure 13. Bus voltage waveform on expanded voltage and time scales.

reduced the spiking so that the phantom oscillation was not excited. The oscillations were reduced considerably, as shown in Figures 14 and 15, and computing time was approximately one-half the time required for the first solution.

The third method specified the Gear algorithm with a 5 us step and the ideal transistor model. Results similar to those of the second method were obtained. These results are illustrated in Figures 16 and 17. The last method used the Gear algorithm and the higher order transistor model. The oscillations disappeared (Figures 18 and 19), but the computing time increased substantially. The comparative computing times involved in each solution are contained in Table 1. The second method of solution, which uses the default integration algorithm and a higher order transistor model, appears to be quite practical for large signal analysis of more elaborate networks, unless a very high degree of precision is required, or considerable memory capacity is available.

Figure 14. Bus voltage waveform obtained using the trapezoidal algorithm, a 5 us step size, and a higher level transistor model.

Figure 15. Bus voltage waveform on expanded voltage and time scales.

Figure 16. Bus voltage waveform obtained using the Gear algorithm, a 5 us step size, and an ideal transistor model.

Figure 17. Bus voltage waveform on expanded voltage and time scales.

Figure 18. Bus voltage waveform using the Gear algorithm, a 5 us step size, and a higher level transistor model.

Figure 19, Bus voltage waveform on expanded voltage and time scales.

Table 1
Computing Times for Each Method
of Solution

Method	CPU Time	Comments
1. Trapezoidal algorithm, 0.05 us step size, ideal transistor model	64.5 min	Oscillations vanished
2. Trapezoidal algorithm, 5 us step size, higher order transistor model (two 1000 pF junction capacitances)	36.0 min	Smoothed out oscillations
3. Gear algorithm, 5 us step size, ideal transistor model	36.2 min	Smoothed out oscillations
4. Gear algorithm, 5 us step size, higher order transistor model	102.3 min	Oscillations vanished

CHAPTER III
INTERACTION BETWEEN THE VOLTAGE LOOP
AND THE CURRENT LOOP

Description of the System

After the phantom oscillation had been eliminated, the current loop, which takes over the control of the converter when output current reaches some maximum, was incorporated into the system. A block diagram of the system containing the current loop is illustrated in Figure 20, and the circuit diagram of the current loop is shown in Figure 21. The loop was designed to be activated when the load current exceeds 17 A. This value can be adjusted according to different load requirements of the system by raising or lowering the voltage of the voltage source VC1. A higher (lower) maximum current can be obtained by increasing (decreasing) VC1. The voltage loop and the current loop are connected together through two diodes (DVL and DCL) facing each other. The diodes prevent any current flow from the operating loop into the inactive loop. A current path is provided by inserting a one ohm resistor between the common point of connection point of the diodes to ground. The inclusion of the one ohm resistor in the circuit not only ensures a voltage drop of at least

• BUS VOLTAGE

Figure 20. Block diagram of the power system with voltage loop and current loop.

0.7 volts across the diodes, but provides a current path to ground and helps place the matrix pivots in the same range.

Interaction Between the Loops

The interaction between the two loops can be examined by obtaining the voltage drop across DVL and DCL. A voltage drop greater than 0.7 volts across DVL (DCL) indicates that the voltage loop (current loop) is controlling. A piecewise linear current source was used as a load to simulate different loads. When the current is below 17 A, only the voltage loop operates. However, when the load current increases above 17 A, the current loop begins to control.

The load current waveform shown in Figure 22 was selected to simulate this behavior in the system. The appropriate SPICE program is listed in Appendix E. The load current starts at 16 A and then steps back to 16 A. The voltage drop across DVL and DCL was obtained. These voltages are listed in Appendix F. As the data demonstrate, the switching between the two loops is not instantaneous. Several milliseconds elapse between the transition from one loop to the other. The transition time is not symmetrical: two milliseconds are required to change from the voltage loop to the current loop, and around four milliseconds are required to switch from the current loop to the voltage loop. The transition times differ because of the different

Figure 22. Piecewise linear load current.

magnitudes of the storage elements contained in each loop. For example, in the current loop, the transition time depends on the time constant of the capacitor C29 (100 μ F) and the resistor R36 (5100 ohms). Several time constants are required to discharge the capacitor, and to disable the current loop. In the same manner, it requires several milliseconds to discharge the storage components associated with the voltage loop.

In addition to the data obtained for the voltage drop across the two diodes, the bus voltage and current waveforms were also obtained. The bus current is depicted in Figure 23; the bus voltage, in Figure 24. The bus voltage waveform has been divided into six regions to illustrate the interaction between the two loops. The first region is defined from zero to 0.5 ms. In this interval, under the previous load conditions, the load current is 16 A and the voltage loop is in command. The bus voltage corresponds to its transient voltage. In the second region, which consists of the time interval between 0.5 ms and 2.5 ms, the load current has increased from 16 A to 40 A, and the voltage loop begins to lose control, causing the bus voltage to decrease. The third region, between 2.5 ms and 6 ms, corresponds to the time interval during which the current loop is in control. The load current remains at 40 A and the bus voltage decreases rapidly. In the fourth region, which is between 6 ms and 10.5 ms, the load current drops

Figure 23. Bus current waveform.

Figure 24. Bus voltage waveform.

back to 16 A; however, the bus current, which is the current flowing through the inductor L3, cannot change instantaneously, so that the current loop controls until the bus current drops below 17 A. As the bus current decreases, the bus voltage begins to ramp up. The fifth region is the interval between 10.5 ms and around 14 ms. In this region the voltage loop is again in control, but the bus voltage is much higher than its steady state value. The converter therefore needs to be turned off for several milliseconds to permit the bus voltage to decrease to a lower value. The converter is, in fact, operating in a discontinuous mode as can be seen from the zero value of the bus current during this time interval. In the last region, between 14 ms and 15 ms, the bus current has stepped up to a non-zero positive value, and the voltage loop begins to regulate the bus voltage again, with the bus voltage approaching its steady-state. The interaction between the two loops cannot be determined only by examining the voltage drop across the two diodes: the bus voltage waveform must also be considered. It must also be noted that the transition time between the loops depends on the storage elements associated with each loop.

CHAPTER IV
POWER SYSTEM WITH MULTIPLE
CONTROLLED LOOPS

Description of the System

The last loop incorporated into the system was the peak power tracker. A block diagram of the entire system is shown in Figure 25, and a circuit diagram of the peak power tracker is illustrated in Figure 26; Figure 27 contains the circuit diagram for the bandpass filter in the peak power tracker. The input is modeled as a voltage source in series with a 2.5 ohm resistor in order to limit the current in the system. The load line (current vs. voltage) is illustrated in Figure 28. The open circuit voltage (113 V) corresponds to the input voltage source, and the maximum current, 45.2 A, that can be drawn is the ratio of the input voltage to the series resistance. Power vs. voltage is plotted as shown in Figure 29. The peak power point is 56.5 V.

The peak power tracker takes control of the converter when the load power exceeds the capabilities of the input source. At small loads, the input source is operating close to its open circuit voltage. However, as the load increases, more current is drawn from the system, causing

Figure 25. Block diagram of the multi-loop power system.

Figure 27. Bandpass filter circuit diagram.

Figure 28. Load line of the input source.

Figure 29. Power versus voltage curve.

the output voltage control loop to move the operating point from its open circuit voltage toward the peak power point. When the operating point is at the peak power point, the peak power tracker is activated. In the case that the power system contains several loops, such as a voltage loop, a current loop and a peak power tracker the loop with the smallest duty ratio will dominate, and take control of the converter. The duty ratio for each loop is defined in Table 2.

Instability Problem

Using the same approach as previously, the SPICE file was modified to include the peak power tracker. The program is listed in Appendix G. The circuit diagram of the entire system is shown in Figure 30. This is merely a schematic representation. Elements and nodes have been identified in Figures 1, 21, 26, and 27. The peak power tracker contains two multipliers, making the peak power tracker a nonlinear network. The gain of the loop depends not on the magnitude of the input but also on the gain of the multipliers. An 8 A current source was used as the load. Under this load condition, the voltage loop should be in control; however, this did not occur. As the data in Appendix H indicate, the voltage drop across the diodes DPPT, DVL, and DCL is such that the diode DPPT is conducting at all times, so that the peak power tracker is in

Table 2
Duty Ratio Calculation for Each Loop

Duty Ratio	
Voltage loop	$B = \text{bus voltage} / \text{operating voltage}$
Current loop	$B = \text{bus current} / \text{operating loop current}$
Peak power tracker	$B = \text{bus voltage} / \text{peak power point}$

Figure 30. Circuit diagram of the entire system.

control. When the voltages and currents in the peak power tracker were more closely examined, it was found that the input voltage and current fed to the peak power tracker (Figures 31 and 32, respectively) contained a sharp spike; the magnitude of these spikes were large enough to trigger unstable behavior of the loop, and a large voltage was obtained at node 260 (Figure 33). This prediction was in agreement with a stability analysis performed elsewhere [4], using describing functions [5]. Although a peak power tracker is desirable, the predicted instability does not permit its use and it was eliminated from the circuit.

Figure 31. Input voltage to the peak power tracker.

Figure 32. Input current to the peak power tracker.

Figure 33. Voltage at node 260.

CHAPTER V

CONCLUSIONS

The results of this work indicate that SPICE can be used for large signal analysis of power systems. Although there were convergence problems, they can be eliminated by changing some element values and model parameters. Stability artifacts can be avoided by considering the time constants of the system to be modeled. These can be circumvented by using a better computation algorithm, shorter computation intervals, or higher order transistor models. The validity of the predictions of instability in the case of the peak power tracker was demonstrated by comparison with other results [4]. The value of the procedure was in its ability to predict system behavior, and permit design modifications, such as the elimination of the peak power tracker in the representative system used in this work.

LIST OF REFERENCES

1. V. G. Bello, "Computer Aided Analysis of Switching Regulators Using SPICE2," IEEE Power Electronics Specialists Conference, 1980 Record, pp. 3-11.
2. M. Liffing, "SPICE Compatible Sampled Data for Switching Regulators," IECEL Proceedings, 1985.
3. R. P. Severns and G. E. Bloom, "Modern DC-to-DC Switchmode Power Converter Circuits," Van Nostrand Reinhold Company, New York, 1985.
4. J. Chen and M. Glass, "Stability and Transient Modeling of a Large Spacecraft Power System," IECEC 1986 Proceedings.
5. K. Ogata, "Modern Control Engineering," Prentice-Hall, Inc., New Jersey, 1970.

APPENDIX A
INDUCTOR CURRENT

Time	Current
[sec]	[amps]
0.000E+00	1.600E+01
3.000E-06	3.910E+01
1.000E-05	4.688E+01
1.500E-05	4.809E+01
2.000E-05	5.120E+01
2.500E-05	5.860E+01
3.000E-05	6.671E+01
3.500E-05	7.225E+01
4.000E-05	7.764E+01
4.500E-05	7.252E+01
5.000E-05	7.275E+01
5.500E-05	7.670E+01
6.000E-05	8.033E+01
6.500E-05	8.260E+01
7.000E-05	8.369E+01
7.500E-05	7.458E+01
8.000E-05	7.200E+01
8.500E-05	7.156E+01
9.000E-05	6.942E+01
9.500E-05	6.523E+01
1.000E-04	6.076E+01
1.050E-04	5.640E+01
1.100E-04	5.226E+01
1.150E-04	4.820E+01
1.200E-04	4.873E+01
1.250E-04	4.643E+01
1.300E-04	4.632E+01
1.350E-04	4.681E+01
1.400E-04	4.579E+01
1.450E-04	4.459E+01
1.500E-04	4.772E+01
1.550E-04	4.984E+01
1.600E-04	5.115E+01
1.650E-04	4.728E+01
1.700E-04	4.191E+01
1.750E-04	4.022E+01
1.800E-04	3.867E+01
1.850E-04	3.552E+01
1.900E-04	3.120E+01
1.950E-04	3.310E+01
2.000E-04	3.310E+01
2.050E-04	3.058E+01
2.100E-04	2.810E+01
2.150E-04	2.688E+01
2.200E-04	2.664E+01
2.250E-04	2.675E+01
2.300E-04	2.704E+01
2.350E-04	2.758E+01
2.400E-04	2.844E+01
2.450E-04	2.955E+01
2.500E-04	2.207E+01
2.550E-04	1.879E+01
2.600E-04	1.785E+01
2.650E-04	1.637E+01
2.700E-04	1.352E+01
2.750E-04	1.757E+01
2.800E-04	1.723E+01
2.850E-04	1.502E+01
2.900E-04	1.350E+01
2.950E-04	1.308E+01

Time	Current
[sec]	[amps]
3.000E-04	1.307E+01
3.050E-04	1.297E+01
3.100E-04	1.280E+01
3.150E-04	1.281E+01
3.200E-04	1.317E+01
3.250E-04	6.993E+00
3.300E-04	5.010E+00
3.350E-04	4.624E+00
3.400E-04	9.759E+00
3.450E-04	1.119E+01
3.500E-04	1.093E+01
3.550E-04	1.137E+01
3.600E-04	1.278E+01
3.650E-04	3.923E+00
3.700E-04	7.784E+00
3.750E-04	1.002E+01
3.800E-04	1.076E+01
3.850E-04	9.709E+00
3.900E-04	8.330E+00
3.950E-04	7.228E+00
4.000E-04	8.600E+00
4.050E-04	9.984E+00
4.100E-04	9.634E+00
4.150E-04	1.076E+01
4.200E-04	1.187E+01
4.250E-04	9.724E+00
4.300E-04	6.903E+00
4.350E-04	1.034E+01
4.400E-04	7.177E+00
4.450E-04	1.013E+01
4.500E-04	9.064E+00
4.550E-04	4.853E+00
4.600E-04	3.889E+00
4.650E-04	8.603E+00
4.700E-04	4.307E+00
4.750E-04	7.917E+00
4.800E-04	4.476E+00
4.850E-04	6.307E+00
4.900E-04	4.245E+00
4.950E-04	7.402E+00
5.000E-04	6.850E+00
5.050E-04	3.550E+00
5.100E-04	5.149E+00
5.150E-04	7.453E+00
5.200E-04	7.457E+00
5.250E-04	6.960E+00
5.300E-04	6.794E+00
5.350E-04	6.983E+00
5.400E-04	7.209E+00
5.450E-04	1.651E+00
5.500E-04	1.893E-03
5.550E-04	1.666E+00
5.600E-04	1.877E-01
5.650E-04	1.658E+00
5.700E-04	5.285E-02
5.750E-04	1.065E+00
5.800E-04	7.782E-01
5.850E-04	3.178E+00
5.900E-04	2.942E+00
5.950E-04	4.938E+00
6.000E-04	4.250E+00
6.050E-04	6.901E+00
6.100E-04	8.008E+00

Time	Current
[sec]	[amps]
6.150E-04	8.845E+00
6.200E-04	9.710E+00
6.250E-04	9.381E+00
6.300E-04	6.098E+00
6.350E-04	9.218E+00
6.400E-04	1.007E+01
6.450E-04	9.440E+00
6.500E-04	8.912E+00
6.550E-04	1.024E+01
6.600E-04	1.080E+01
6.650E-04	1.045E+01
6.700E-04	9.430E+00
6.750E-04	9.598E+00
6.800E-04	1.021E+01
6.850E-04	6.089E+00
6.900E-04	9.364E+00
6.950E-04	1.021E+01
7.000E-04	7.205E+00
7.050E-04	6.904E+00
7.100E-04	3.475E+00
7.150E-04	8.977E+00
7.200E-04	8.267E+00
7.250E-04	9.131E+00
7.300E-04	6.682E+00
7.350E-04	6.908E+00
7.400E-04	6.857E+00
7.450E-04	3.896E+00
7.500E-04	6.817E+00
7.550E-04	7.266E+00
7.600E-04	5.221E+00
7.650E-04	7.163E+00
7.700E-04	7.236E+00
7.750E-04	7.169E+00
7.800E-04	7.362E+00
7.850E-04	7.756E+00
7.900E-04	8.172E+00
7.950E-04	8.528E+00
8.000E-04	8.849E+00
8.050E-04	3.309E+00
8.100E-04	3.707E+00
8.150E-04	5.361E+00
8.200E-04	6.740E+00
8.250E-04	6.780E+00
8.300E-04	6.853E+00
8.350E-04	8.117E+00
8.400E-04	9.825E+00
8.450E-04	6.063E+00
8.500E-04	8.581E+00
8.550E-04	6.412E+00
8.600E-04	6.046E+00
8.650E-04	7.453E+00
8.700E-04	9.229E+00
8.750E-04	9.311E+00
8.800E-04	7.531E+00
8.850E-04	8.701E+00
8.900E-04	9.942E+00
8.950E-04	1.059E+01
9.000E-04	1.092E+01
9.050E-04	1.195E+01
9.100E-04	1.241E+01
9.150E-04	1.314E+01
9.200E-04	1.405E+01
9.250E-04	1.500E+01

Time	Current
[sec]	[amps]
9.300E-04	1.592E+01
9.350E-04	1.649E+01
9.400E-04	1.702E+01
9.450E-04	1.759E+01
9.500E-04	1.095E+01
9.550E-04	7.505E+00
9.600E-04	1.074E+01
9.650E-04	1.415E+01
9.700E-04	1.424E+01
9.750E-04	1.308E+01
9.800E-04	1.266E+01
9.850E-04	1.327E+01
9.900E-04	1.422E+01
9.950E-04	8.188E+00
1.000E-03	5.282E+00
1.005E-03	7.486E+00
1.010E-03	1.033E+01
1.015E-03	1.014E+01
1.020E-03	9.010E+00
1.025E-03	8.718E+00
1.030E-03	9.402E+00
1.035E-03	1.037E+01
1.040E-03	1.112E+01
1.045E-03	5.425E+00
1.050E-03	3.015E+00
1.055E-03	4.604E+00
1.060E-03	7.082E+00
1.065E-03	7.023E+00
1.070E-03	6.465E+00
1.075E-03	6.823E+00
1.080E-03	8.540E+00
1.085E-03	1.043E+01
1.090E-03	1.207E+01
1.095E-03	1.347E+01
1.100E-03	9.424E+00
1.105E-03	8.576E+00
1.110E-03	1.209E+01
1.115E-03	1.412E+01
1.120E-03	1.418E+01
1.125E-03	1.448E+01
1.130E-03	1.570E+01
1.135E-03	1.710E+01
1.140E-03	1.475E+01
1.145E-03	1.058E+01
1.150E-03	1.342E+01
1.155E-03	1.665E+01
1.160E-03	1.730E+01
1.165E-03	1.673E+01
1.170E-03	1.679E+01
1.175E-03	1.782E+01
1.180E-03	1.193E+01
1.185E-03	8.526E+00
1.190E-03	1.404E+01
1.195E-03	1.678E+01
1.200E-03	1.629E+01
1.205E-03	1.518E+01
1.210E-03	1.515E+01
1.215E-03	1.608E+01
1.220E-03	1.010E+01
1.225E-03	7.130E+00
1.230E-03	1.169E+01
1.235E-03	1.416E+01
1.240E-03	1.364E+01

Time	Current
[sec]	[amps]
1.245E-03	1.264E+01
1.250E-03	1.266E+01
1.255E-03	1.355E+01
1.260E-03	7.933E+00
1.265E-03	5.446E+00
1.270E-03	1.044E+01
1.275E-03	1.195E+01
1.280E-03	1.102E+01
1.285E-03	1.021E+01
1.290E-03	1.056E+01
1.295E-03	1.162E+01
1.300E-03	6.423E+00
1.305E-03	4.302E+00
1.310E-03	3.526E+00
1.315E-03	6.449E+00
1.320E-03	7.544E+00
1.325E-03	1.042E+01
1.330E-03	1.039E+01
1.335E-03	1.054E+01
1.340E-03	1.227E+01
1.345E-03	1.456E+01
1.350E-03	1.642E+01
1.355E-03	1.183E+01
1.360E-03	1.039E+01
1.365E-03	1.168E+01
1.370E-03	1.559E+01
1.375E-03	1.603E+01
1.380E-03	1.533E+01
1.385E-03	1.569E+01
1.390E-03	1.705E+01
1.395E-03	1.859E+01
1.400E-03	1.982E+01
1.405E-03	1.564E+01
1.410E-03	1.135E+01
1.415E-03	9.959E+00
1.420E-03	1.582E+01
1.425E-03	1.805E+01
1.430E-03	1.701E+01
1.435E-03	1.583E+01
1.440E-03	1.601E+01
1.445E-03	1.715E+01
1.450E-03	1.887E+01
1.455E-03	1.987E+01
1.460E-03	1.280E+01
1.465E-03	9.326E+00
1.470E-03	8.277E+00
1.475E-03	1.379E+01
1.480E-03	1.515E+01
1.485E-03	1.390E+01
1.490E-03	1.299E+01
1.495E-03	1.345E+01
1.500E-03	1.466E+01
1.505E-03	1.616E+01
1.510E-03	1.696E+01
1.515E-03	1.044E+01
1.520E-03	7.727E+00
1.525E-03	6.768E+00
1.530E-03	1.146E+01
1.535E-03	1.201E+01
1.540E-03	1.069E+01
1.545E-03	1.014E+01
1.550E-03	1.069E+01
1.555E-03	1.295E+01

Time	Current
[sec]	[amps]
1.560E-03	1.454E+01
1.565E-03	9.317E+00
1.570E-03	8.120E+00
1.575E-03	8.100E+00
1.580E-03	1.281E+01
1.585E-03	1.366E+01
1.590E-03	1.330E+01
1.595E-03	1.393E+01
1.600E-03	1.573E+01
1.605E-03	1.825E+01
1.610E-03	1.832E+01
1.615E-03	1.393E+01
1.620E-03	1.268E+01
1.625E-03	1.500E+01
1.630E-03	1.827E+01
1.635E-03	1.815E+01
1.640E-03	1.744E+01
1.645E-03	1.788E+01
1.650E-03	1.929E+01
1.655E-03	2.121E+01
1.660E-03	1.616E+01
1.665E-03	1.205E+01
1.670E-03	1.072E+01
1.675E-03	1.671E+01
1.680E-03	1.884E+01
1.685E-03	1.780E+01
1.690E-03	1.670E+01
1.695E-03	1.698E+01
1.700E-03	1.870E+01
1.705E-03	2.004E+01
1.710E-03	1.323E+01
1.715E-03	9.828E+00
1.720E-03	8.720E+00
1.725E-03	1.418E+01
1.730E-03	1.550E+01
1.735E-03	1.427E+01
1.740E-03	1.342E+01
1.745E-03	1.395E+01
1.750E-03	1.567E+01
1.755E-03	1.688E+01
1.760E-03	1.054E+01
1.765E-03	7.789E+00
1.770E-03	6.787E+00
1.775E-03	1.146E+01
1.780E-03	1.203E+01
1.785E-03	1.076E+01
1.790E-03	1.022E+01
1.795E-03	1.099E+01
1.800E-03	1.306E+01
1.805E-03	1.467E+01
1.810E-03	1.578E+01
1.815E-03	1.108E+01
1.820E-03	1.007E+01
1.825E-03	1.014E+01
1.830E-03	1.491E+01
1.835E-03	1.610E+01
1.840E-03	1.596E+01
1.845E-03	1.634E+01
1.850E-03	1.801E+01
1.855E-03	1.557E+01
1.860E-03	1.367E+01
1.865E-03	1.574E+01
1.870E-03	1.736E+01

Time [sec]	Current [amps]
1.375E-03	1.980E+01
1.880E-03	1.926E+01
1.885E-03	1.978E+01
1.890E-03	2.130E+01
1.895E-03	1.757E+01
1.900E-03	1.373E+01
1.905E-03	1.247E+01
1.910E-03	1.833E+01
1.915E-03	2.084E+01
1.920E-03	2.068E+01
1.925E-03	1.993E+01
1.930E-03	2.027E+01
1.935E-03	2.144E+01
1.940E-03	1.495E+01
1.945E-03	1.169E+01
1.950E-03	1.055E+01
1.955E-03	1.618E+01
1.960E-03	1.813E+01
1.965E-03	1.725E+01
1.970E-03	1.602E+01
1.975E-03	1.686E+01
1.980E-03	1.830E+01
1.985E-03	1.219E+01
1.990E-03	9.431E+00
1.995E-03	8.372E+00
2.000E-03	1.340E+01

APPENDIX B
SPICE PROGRAM LISTING

```

* Equivalent Power Circuit *
* Ideal Voltage Source *
VIN 1 0 113V
* Input Filter *
L2F 1 2 12UF
R1F 2 3 1.35
C2F 3 0 5UF
C3F 2 0 10.8UF
R2F 2 4 0.025
* Buck Converter *
QT 4 5 6 TBUK
RT 5 7 0.0001
EQP 7 6 19 18 5
D1 0 6 DID
RV2 6 8 0.005
L1 8 9 12UH
C1 9 0 1.7UF
* Output Filter *
R3 9 10 1.98
C4 10 0 3.9UF
L3 9 11 12UH
CG 11 0 1.5UF
* Scaled Load *
RL 11 12 0.143
CL 12 0 3500UF
RL1 11 0 100K
ILOAD 11 0 16A
* Voltage Feedback Loop *
EC 13 0 11 0 0.1485
R30 13 14 75K
C30 14 17 0.0012UF
R31 14 16 9.09K
C31 16 17 0.018UF
EOUT 17 0 15 14 100K
RREF 15 0 10
VREF 15 0 5V
* Pulse Width Modulator *
EIN 18 0 17 0 -13.6
RIN 19 18 100MEG
VTRI 19 0 PULSE(1 5 1US 0.9US 3.9US 0.1US 4.9US)
.MODEL TBUK NPN
.MODLE DID D
.TRAN 5US 2MS
.PLOT TRAN V(11)
.OPTION LIMPTS=100K ITL1=500 ITL4=50 ITL5=100K
.OPTION LIMTIM=100 CPTIME=2K
.END

```

APPENDIX C
SMALL SIGNAL AC SPICE PROGRAM


```
* GAIN AND PHASE *
L2F 0 2 12UH
R1F 2 3 1.35
C2F 3 0 5UF
C3F 2 0 10.8UF
R2F 2 44 0.025
ED 4 44 18 0 378.9
GD 44 0 18 0 16
VSE 4 5 0V
ET 5 0 6 0 3.35
FT 0 6 VSE 3.35
RV2 6 8 0.005
L1 8 9 12UH
C1 9 0 1.7UF
R3 9 10 1.98
C4 10 0 3.9UF
L3 9 11 12UH
CG 11 0 1.5UF
RL 11 12 0.143
CL 12 0 3500UF
RL1 11 0 100K
RPS1 18 0 10
X1 50 18 COMP
VPERT 50 0 AC
RPS2 50 0 10
.SUBCKT COMP 5 18
R15 5 0 100MEG
EC 13 0 5 0 0.1485
R30 13 14 75K
C30 14 17 0.0012UF
R31 14 16 9.09K
C31 16 17 0.018UF
EOUT 17 0 0 14 100K
EIN 18 0 17 0 -3.4
.ENDS
.AC DEC 10 1 100KHZ
.PLOT AC VP(11) VDB(11)
.END
```

APPENDIX D
TRANSISTOR MODEL PARAMETERS

Name	Parameter	Units	Default	Example
IS	transport saturation current	A	1.0E-16	1.0E-15
BF	ideal maximum forward beta	-	100	100
NF	forward current emission coefficient	-	1.0	1
VAF	forward Early voltage	V	infinite	200
IKP	corner for forward beta			
	high current roll-off	A	infinite	0.01
ISE	B-B leakage saturation current	A	0	1.0E-13
NE	B-B leakage emission coefficient	-	1.5	2
BR	ideal maximum reverse beta	-	1	0.1
NR	reverse current emission coefficient	-	1	1
VAR	reverse Early voltage	V	infinite	200
IKR	corner for reverse beta			
	high current roll-off	A	infinite	0.01
ISC	B-C leakage saturation current	A	0	1.0E-13
NC	B-C leakage emission coefficient	-	2	1.5
RB	zero bias base resistance	Ohms	0	100
IRB	current where base resistance falls halfway to its min value	A	infinite	0.1
RBM	minimum base resistance at high currents	Ohms	RB	10
RE	emitter resistance	Ohms	0	1
RC	collector resistance	Ohms	0	10
CJE	B-E zero-bias depletion capacitance	F	0	2PF
VJE	B-E built-in potential	V	0.75	0.6
MJE	B-E junction exponential factor	-	0.33	0.33
TF	ideal forward transit time	sec	0	0.1Ns
XTF	coefficient for bias dependence of TF	-	0	
VTF	voltage describing VBC dependence of TF	V	infinite	
ITF	high-current parameter for effect on TF	A	0	
PTF	excess phase at freq=1.0/(TF*2PI) Hz	deg	0	
CJC	B-C zero-bias depletion capacitance	F	0	2PF
VJC	B-C built-in potential	V	0.75	0.5
MJC	B-C junction exponential factor	-	0.33	0.5
XCJC	fraction of B-C depletion capacitance connected to internal base node	-	1	
TR	Ideal reverse transit time	sec	0	10Ns
CJS	zero-bias collector-substrate capacitance	F	0	2PF
VJS	substrate junction built-in potential	V	0.75	
MJS	substrate junction exponential factor	-	0	0.5
XTB	forward and reverse beta temperature exponent	-	0	
EGH	energy gap for temperature effect on IS	eV	1.11	
XTI	temperature exponent for effect on IS	-	3	
KF	flicker-noise coefficient	-	3	
AF	flicker-noise exponent	-	1	
FC	coefficient for forward-bias depletion capacitance formula	-	0.5	

APPENDIX E

SPICE PROGRAM LISTING OF THE POWER SYSTEM
WITH VOLTAGE LOOP AND CURRENT LOOP

```

*****
** PTLOOPS.CKT
** VGS = 113V
** ILOAD (INCLUDING RL1=100K)
** NO UIC IS=1.0E-16
** CLIPPING DIODES IN V-LOOP, I-LOOP, AND PPT
** RINDI 22 0 1
** PRINT V(11)
*****
** SOURCE 2 **
*****
.WIDTH IN=72 OUT=72
VGS 1 0 113V
RGS 1 50 2.5
VSE 50 200 0V
VSIN 300 200 SIN(0 .1 2KHZ)
*****
** INPUT FILTER **
*****
L2F 300 2 12UH
R1F 2 3 1.35
C2F 3 0 5UF
C3F 2 0 10.8UF
R2F 2 4 0.025
*****
** SWITCH **
*****
QT 4 5 6 TBUK
RT 5 7 0.0001
EOP 7 6 40 41 10
D1 0 6 D10
*****
** OUTPUT FILTER **
*****
RV2 6 160 0.005
VR2 160 8 0V
L1 8 9 12UH
C1 9 0 1.7UF
R3 9 10 1.98
C4 10 0 3.9UF
L3 9 11 12UH
CG 11 0 1.5UF
VSEN 11 110 0V
*****
** SCALED LOAD 1 **
*****
RL 110 12 0.143
CL 12 0 3500UF
RL1 110 0 100K
VLOAD 110 109 0V
ILOAD 109 0 PWL(0 16 .5M 16 .55M 40 6M 40 6.05M 16 15M 16)
*****
**VOLTAGE LOOP**
*****
E1 15 0 11 0 0.1485
R17 15 17 74.1K
C17 17 19 1200PF
C18 17 18 0.018UF
R18 18 19 8980
E2 19 0 16 17 100K
*****
RDTOP 19 70 0.005
D70 70 71 D10

```

```

V70 71 0 12V
D71 72 70 DIO
V71 72 0 -12V
*****
RREF 16 0 10
VREF 16 0 5V
E3 21 0 70 0 -13.6
DVL 21 22 DIO
RINDI 22 0 1
*****
** CURRENT LOOP **
*****
*****
DCL 75 22 DIODE
RDCL 23 75 0.005
D75 75 76 DIO
V75 76 0 12V
D76 77 75 DIO
V76 77 0 -12V
*****
R24 24 23 1K
C28 37 24 15UF
R23 37 23 20K
VCC 27 0 12V
R26 26 0 20K
R28 26 27 10K
R27 28 27 10K
ECL 23 0 26 37 100K
RGPM 28 37 1K
R35 33 35 3K
VC1 34 0 5V
VC2 35 0 12V
R34 32 34 3K
R32 32 0 16.9K
R31 31 0 5.62K
R30 30 31 1.21K
Q2 33 32 31 MOD1
Q1 28 29 30 MOD1
C29 29 0 100UF
R36 36 29 5.1K
HCV 36 0 VLOAD 0.25
*****
** TRIANGULAR WAVE **
*****
EST1 41 0 22 0 1
REST1 41 40 1MEG
VST 40 0 PULSE(1 5 1US 0.9US 3.9US 0.1US 4.9US)
*****
** BATTERY HARNESS **
*****
D2 111 110 DIO
RH1 111 112 0.004
LH1 112 113 3UH
RAC 113 114 0.0064
RDC 114 115 0.00003
D3 116 115 DIO
VDC 116 0 28V
CH1 114 0 184F
*****
.MODEL TBUK NPN CJE=1000PF CJC=1000PF
.MODEL MOD1 NPN
.MODEL DIO D IS=1.0E-16
.MODEL DIODE D IS=1.0E-16

```

```
.TRAN 50US 15MS 0 10US  
.PRINT TRAN V(11) I(VR2)  
.OPTION METHOD=GEAR  
.OPTION LULTIM=1 ITL3=20  
.OPTION LIMPTS=100K ITL1=500 ITL4=50 ITL5=500K  
.OPTION LINTIM=100 CPTIME=20K  
.END
```

APPENDIX F
VOLTAGE DROP ACROSS THE
DIODES DVL AND DCL

Time	DVL	DCL
[sec]	Voltage	Voltage
	[volts]	[volts]
0.000E+00	9.501E-01	-1.662E-01
5.000E-05	9.672E-01	-1.011E+00
1.000E-04	9.706E-01	-1.256E+00
1.500E-04	9.707E-01	-1.260E+00
2.000E-04	9.731E-01	-1.454E+00
2.500E-04	9.767E-01	-1.777E+00
3.000E-04	9.796E-01	-2.079E+00
3.500E-04	9.802E-01	-2.143E+00
4.000E-04	9.808E-01	-2.216E+00
4.500E-04	9.827E-01	-2.431E+00
5.000E-04	9.845E-01	-2.661E+00
5.500E-04	9.775E-01	-1.859E+00
6.000E-04	9.798E-01	-2.096E+00
6.500E-04	9.795E-01	-2.069E+00
7.000E-04	9.790E-01	-2.014E+00
7.500E-04	9.782E-01	-1.929E+00
8.000E-04	9.787E-01	-1.988E+00
8.500E-04	9.797E-01	-2.090E+00
9.000E-04	9.779E-01	-1.902E+00
9.500E-04	9.792E-01	-2.037E+00
1.000E-03	9.789E-01	-2.000E+00
1.050E-03	9.787E-01	-1.978E+00
1.100E-03	9.781E-01	-1.923E+00
1.150E-03	9.777E-01	-1.884E+00
1.200E-03	9.774E-01	-1.849E+00
1.250E-03	9.770E-01	-1.808E+00
1.300E-03	9.765E-01	-1.760E+00
1.350E-03	9.759E-01	-1.708E+00
1.400E-03	9.753E-01	-1.653E+00
1.450E-03	9.747E-01	-1.595E+00
1.500E-03	9.740E-01	-1.534E+00
1.550E-03	9.733E-01	-1.470E+00
1.600E-03	9.725E-01	-1.403E+00
1.650E-03	9.718E-01	-1.349E+00
1.700E-03	9.711E-01	-1.290E+00
1.750E-03	9.699E-01	-1.201E+00
1.800E-03	9.688E-01	-1.116E+00
1.850E-03	9.676E-01	-1.034E+00
1.900E-03	9.663E-01	-9.485E-01
1.950E-03	9.649E-01	-8.591E-01
2.000E-03	9.633E-01	-7.675E-01
2.050E-03	9.617E-01	-6.739E-01
2.100E-03	9.598E-01	-5.778E-01
2.150E-03	9.587E-01	-5.195E-01
2.200E-03	9.561E-01	-4.021E-01
2.250E-03	9.532E-01	-2.824E-01
2.300E-03	9.504E-01	-1.758E-01
2.350E-03	9.511E-01	-2.009E-01
2.400E-03	9.421E-01	7.127E-02
2.450E-03	9.267E-01	3.676E-01
2.500E-03	9.161E-01	4.896E-01
2.550E-03	8.838E-01	6.621E-01
2.600E-03	7.524E-01	7.307E-01
2.650E-03	5.474E-01	7.311E-01
2.700E-03	3.318E-01	7.311E-01
2.750E-03	1.098E-01	7.311E-01
2.800E-03	-1.206E-01	7.311E-01
2.850E-03	-3.572E-01	7.311E-01
2.900E-03	-6.014E-01	7.311E-01
2.950E-03	-8.519E-01	7.311E-01
3.000E-03	-1.108E+00	7.311E-01

Time	DVL	DCL
[sec]	Voltage	Voltage
	[volts]	[volts]
3.050E-03	-1.371E+00	7.311E-01
3.100E-03	-1.641E+00	7.311E-01
3.150E-03	-1.918E+00	7.311E-01
3.200E-03	-2.202E+00	7.311E-01
3.250E-03	-2.494E+00	7.311E-01
3.300E-03	-2.792E+00	7.311E-01
3.350E-03	-3.098E+00	7.311E-01
3.400E-03	-3.410E+00	7.311E-01
3.450E-03	-3.728E+00	7.312E-01
3.500E-03	-4.052E+00	7.312E-01
3.550E-03	-4.382E+00	7.312E-01
3.600E-03	-4.718E+00	7.312E-01
3.650E-03	-5.061E+00	7.312E-01
3.700E-03	-5.411E+00	7.312E-01
3.750E-03	-5.767E+00	7.312E-01
3.800E-03	-6.132E+00	7.312E-01
3.850E-03	-6.502E+00	7.312E-01
3.900E-03	-6.877E+00	7.312E-01
3.950E-03	-7.260E+00	7.312E-01
4.000E-03	-7.647E+00	7.312E-01
4.050E-03	-8.041E+00	7.312E-01
4.100E-03	-8.440E+00	7.312E-01
4.150E-03	-8.845E+00	7.312E-01
4.200E-03	-9.257E+00	7.312E-01
4.250E-03	-9.676E+00	7.312E-01
4.300E-03	-1.010E+01	7.312E-01
4.350E-03	-1.053E+01	7.312E-01
4.400E-03	-1.097E+01	7.312E-01
4.450E-03	-1.141E+01	7.312E-01
4.500E-03	-1.186E+01	7.312E-01
4.550E-03	-1.231E+01	7.312E-01
4.600E-03	-1.277E+01	7.313E-01
4.650E-03	-1.324E+01	7.313E-01
4.700E-03	-1.371E+01	7.313E-01
4.750E-03	-1.419E+01	7.313E-01
4.800E-03	-1.467E+01	7.313E-01
4.850E-03	-1.516E+01	7.313E-01
4.900E-03	-1.566E+01	7.313E-01
4.950E-03	-1.616E+01	7.313E-01
5.000E-03	-1.666E+01	7.313E-01
5.050E-03	-1.717E+01	7.313E-01
5.100E-03	-1.769E+01	7.313E-01
5.150E-03	-1.821E+01	7.313E-01
5.200E-03	-1.874E+01	7.313E-01
5.250E-03	-1.927E+01	7.313E-01
5.300E-03	-1.981E+01	7.313E-01
5.350E-03	-2.035E+01	7.313E-01
5.400E-03	-2.090E+01	7.314E-01
5.450E-03	-2.144E+01	7.314E-01
5.500E-03	-2.198E+01	7.314E-01
5.550E-03	-2.253E+01	7.314E-01
5.600E-03	-2.307E+01	7.314E-01
5.650E-03	-2.362E+01	7.314E-01
5.700E-03	-2.416E+01	7.314E-01
5.750E-03	-2.471E+01	7.314E-01
5.800E-03	-2.525E+01	7.314E-01
5.850E-03	-2.580E+01	7.314E-01
5.900E-03	-2.635E+01	7.314E-01
5.950E-03	-2.689E+01	7.314E-01
6.000E-03	-2.744E+01	7.315E-01
6.050E-03	-2.744E+01	7.315E-01
6.100E-03	-2.759E+01	7.315E-01

Time	DVL	DCL
[sec]	Voltage	Voltage
	[volts]	[volts]
6.200E-03	-2.810E+01	7.315E-01
6.250E-03	-2.833E+01	7.315E-01
6.300E-03	-2.855E+01	7.315E-01
6.350E-03	-2.876E+01	7.315E-01
6.400E-03	-2.895E+01	7.315E-01
6.450E-03	-2.912E+01	7.315E-01
6.500E-03	-2.928E+01	7.315E-01
6.550E-03	-2.942E+01	7.316E-01
6.600E-03	-2.955E+01	7.316E-01
6.650E-03	-2.966E+01	7.316E-01
6.700E-03	-2.975E+01	7.316E-01
6.750E-03	-2.984E+01	7.316E-01
6.800E-03	-2.990E+01	7.316E-01
6.850E-03	-2.996E+01	7.316E-01
6.900E-03	-2.999E+01	7.316E-01
6.950E-03	-3.001E+01	7.316E-01
7.000E-03	-3.002E+01	7.316E-01
7.050E-03	-3.001E+01	7.317E-01
7.100E-03	-2.999E+01	7.317E-01
7.150E-03	-2.995E+01	7.317E-01
7.200E-03	-2.990E+01	7.317E-01
7.250E-03	-2.983E+01	7.317E-01
7.300E-03	-2.975E+01	7.317E-01
7.350E-03	-2.966E+01	7.317E-01
7.400E-03	-2.955E+01	7.317E-01
7.450E-03	-2.943E+01	7.317E-01
7.500E-03	-2.929E+01	7.318E-01
7.550E-03	-2.914E+01	7.318E-01
7.600E-03	-2.898E+01	7.318E-01
7.650E-03	-2.880E+01	7.318E-01
7.700E-03	-2.861E+01	7.318E-01
7.750E-03	-2.840E+01	7.318E-01
7.800E-03	-2.818E+01	7.318E-01
7.850E-03	-2.795E+01	7.318E-01
7.900E-03	-2.771E+01	7.319E-01
7.950E-03	-2.745E+01	7.319E-01
8.000E-03	-2.718E+01	7.319E-01
8.050E-03	-2.689E+01	7.319E-01
8.100E-03	-2.659E+01	7.319E-01
8.150E-03	-2.628E+01	7.319E-01
8.200E-03	-2.595E+01	7.319E-01
8.250E-03	-2.562E+01	7.319E-01
8.300E-03	-2.527E+01	7.320E-01
8.350E-03	-2.491E+01	7.320E-01
8.400E-03	-2.453E+01	7.320E-01
8.450E-03	-2.414E+01	7.320E-01
8.500E-03	-2.374E+01	7.320E-01
8.550E-03	-2.333E+01	7.320E-01
8.600E-03	-2.290E+01	7.320E-01
8.650E-03	-2.246E+01	7.321E-01
8.700E-03	-2.201E+01	7.321E-01
8.750E-03	-2.155E+01	7.321E-01
8.800E-03	-2.107E+01	7.321E-01
8.850E-03	-2.059E+01	7.321E-01
8.900E-03	-2.009E+01	7.321E-01
8.950E-03	-1.958E+01	7.321E-01
9.000E-03	-1.906E+01	7.322E-01
9.050E-03	-1.852E+01	7.322E-01
9.100E-03	-1.797E+01	7.322E-01
9.150E-03	-1.741E+01	7.322E-01
9.200E-03	-1.684E+01	7.322E-01
9.250E-03	-1.626E+01	7.322E-01
9.300E-03	-1.567E+01	7.322E-01

Time [sec]	DVL Voltage [volts]	DCL Voltage [volts]
9.350E-03	-1.507E+01	7.323E-01
9.400E-03	-1.445E+01	7.323E-01
9.450E-03	-1.382E+01	7.323E-01
9.500E-03	-1.319E+01	7.323E-01
9.550E-03	-1.253E+01	7.323E-01
9.600E-03	-1.187E+01	7.323E-01
9.650E-03	-1.120E+01	7.324E-01
9.700E-03	-1.052E+01	7.324E-01
9.750E-03	-9.822E+00	7.324E-01
9.800E-03	-9.118E+00	7.324E-01
9.850E-03	-8.403E+00	7.324E-01
9.900E-03	-7.676E+00	7.324E-01
9.950E-03	-6.938E+00	7.324E-01
1.000E-02	-6.190E+00	7.325E-01
1.005E-02	-5.431E+00	7.325E-01
1.010E-02	-4.660E+00	7.325E-01
1.015E-02	-3.880E+00	7.325E-01
1.020E-02	-3.088E+00	7.325E-01
1.025E-02	-2.287E+00	7.325E-01
1.030E-02	-1.476E+00	7.326E-01
1.035E-02	-6.556E-01	7.326E-01
1.040E-02	1.753E-01	7.326E-01
1.045E-02	8.980E-01	6.130E-01
1.050E-02	9.507E-01	-1.867E-01
1.055E-02	9.593E-01	-5.487E-01
1.060E-02	9.726E-01	-1.410E+00
1.065E-02	9.809E-01	-2.220E+00
1.070E-02	9.836E-01	-2.547E+00
1.075E-02	9.876E-01	-3.099E+00
1.080E-02	9.896E-01	-3.404E+00
1.085E-02	9.924E-01	-3.880E+00
1.090E-02	9.948E-01	-4.326E+00
1.095E-02	9.970E-01	-4.769E+00
1.100E-02	9.989E-01	-5.196E+00
1.105E-02	1.001E+00	-5.608E+00
1.110E-02	1.002E+00	-6.004E+00
1.115E-02	1.004E+00	-6.384E+00
1.120E-02	1.005E+00	-6.748E+00
1.125E-02	1.006E+00	-7.095E+00
1.130E-02	1.007E+00	-7.427E+00
1.135E-02	1.008E+00	-7.743E+00
1.140E-02	1.009E+00	-8.042E+00
1.145E-02	1.010E+00	-8.325E+00
1.150E-02	1.011E+00	-8.592E+00
1.155E-02	1.011E+00	-8.843E+00
1.160E-02	1.012E+00	-9.078E+00
1.165E-02	1.013E+00	-9.297E+00
1.170E-02	1.013E+00	-9.500E+00
1.175E-02	1.013E+00	-9.686E+00
1.180E-02	1.014E+00	-9.857E+00
1.185E-02	1.014E+00	-1.001E+01
1.190E-02	1.015E+00	-1.015E+01
1.195E-02	1.015E+00	-1.027E+01
1.200E-02	1.015E+00	-1.038E+01
1.205E-02	1.015E+00	-1.047E+01
1.210E-02	1.016E+00	-1.054E+01
1.215E-02	1.016E+00	-1.060E+01
1.220E-02	1.016E+00	-1.064E+01
1.225E-02	1.016E+00	-1.066E+01
1.230E-02	1.016E+00	-1.067E+01
1.235E-02	1.016E+00	-1.066E+01
1.240E-02	1.016E+00	-1.064E+01
1.245E-02	1.016E+00	-1.060E+01

Time [sec]	DVL Voltage [volts]	DCL Voltage [volts]
1.250E-02	1.016E+00	-1.055E+01
1.255E-02	1.015E+00	-1.047E+01
1.260E-02	1.015E+00	-1.039E+01
1.265E-02	1.015E+00	-1.028E+01
1.270E-02	1.015E+00	-1.016E+01
1.275E-02	1.014E+00	-1.002E+01
1.280E-02	1.014E+00	-9.872E+00
1.285E-02	1.014E+00	-9.703E+00
1.290E-02	1.013E+00	-9.518E+00
1.295E-02	1.013E+00	-9.317E+00
1.300E-02	1.012E+00	-9.100E+00
1.305E-02	1.011E+00	-8.866E+00
1.310E-02	1.011E+00	-8.617E+00
1.315E-02	1.010E+00	-8.351E+00
1.320E-02	1.009E+00	-8.070E+00
1.325E-02	1.008E+00	-7.772E+00
1.330E-02	1.007E+00	-7.458E+00
1.335E-02	1.006E+00	-7.128E+00
1.340E-02	1.005E+00	-6.781E+00
1.345E-02	1.004E+00	-6.419E+00
1.350E-02	1.002E+00	-6.041E+00
1.355E-02	1.001E+00	-5.647E+00
1.360E-02	9.991E-01	-5.236E+00
1.365E-02	9.972E-01	-4.810E+00
1.370E-02	9.950E-01	-4.367E+00
1.375E-02	9.927E-01	-3.925E+00
1.380E-02	9.901E-01	-3.494E+00
1.385E-02	9.875E-01	-3.086E+00
1.390E-02	9.874E-01	-3.067E+00
1.395E-02	9.876E-01	-3.105E+00
1.400E-02	9.869E-01	-2.992E+00
1.405E-02	9.865E-01	-2.940E+00
1.410E-02	9.864E-01	-2.920E+00
1.415E-02	9.863E-01	-2.910E+00
1.420E-02	9.864E-01	-2.924E+00
1.425E-02	9.862E-01	-2.901E+00
1.430E-02	9.861E-01	-2.877E+00
1.435E-02	9.860E-01	-2.866E+00
1.440E-02	9.860E-01	-2.870E+00
1.445E-02	9.861E-01	-2.885E+00
1.450E-02	9.863E-01	-2.911E+00
1.455E-02	9.866E-01	-2.947E+00
1.460E-02	9.863E-01	-2.910E+00
1.465E-02	9.864E-01	-2.924E+00
1.470E-02	9.864E-01	-2.929E+00
1.475E-02	9.868E-01	-2.979E+00
1.480E-02	9.870E-01	-3.003E+00
1.485E-02	9.868E-01	-2.981E+00
1.490E-02	9.866E-01	-2.957E+00
1.495E-02	9.870E-01	-3.014E+00
1.500E-02	9.870E-01	-3.013E+00

APPENDIX G
SPICE PROGRAM LISTING OF THE
MULTI-LOOP POWER SYSTEM

```

*****
** PTCKT.CKT
** VGS = 113V
** ILOAD (INCLUDING RL1=100K)
** NO UIC IS=1.0E-16
** CLIPPING DIODES IN V-LOOP, I-LOOP, AND PPT
** RINDI 22 0 1
*****
** SOURCE 2 **
*****
.WIDTH IN=72 OUT=72
VGS 1 0 113V
RGS 1 50 2.5
VSE 50 200 0V
VSIN 300 200 SIN(0 .1 2KHZ)
*****
** INPUT FILTER **
*****
L2F 300 2 12UH
R1F 2 3 1.35
C2F 3 0 5UF
C3F 2 0 10.8UF
R2F 2 4 0.025
*****
** SWITCH **
*****
QT 4 5 6 TBUK
RT 5 7 0.0001
EDP 7 6 40 41 10
D1 0 6 D10
*****
** OUTPUT FILTER **
*****
RV2 6 160 0.005
VR2 160 8 0V
L1 8 9 12UH
C1 9 0 1.7UF
R3 9 10 1.98
C4 10 0 3.9UF
L3 9 11 12UH
CG 11 0 1.5UF
VSEN 11 110 0V
*****
** SCALED LOAD 1 **
*****
RL 110 12 0.143
CL 12 0 3500UF
RL1 110 0 100K
ILOAD 110 0 8A
*****
** VARIABLE RESISTOR **
*****
*RSN 110 59 0.005
*VSE11 59 60 0V
*H11 60 0 POLY(2) VSE11 VSE12 0 0 0 0 1
*IST 0 61 PWL(0 16 .2M 16 .21M 34 1M 34 1.01M 7 1.8M 7 1.81M 16 2M 16)
*VSE12 61 62 0V
*RLN 62 0 0.005
*****
**VOLTAGE LOOP**
*****
E1 15 0 11 0 0.1485
R17 15 17 74.1K

```

```

C17 17 19 1200PF
C18 17 18 0.018UF
R18 18 19 8980
E2 19 0 16 17 100K
*****
RDTOP 19 70 0.005
D70 70 71 DIO
V70 71 0 12V
D71 72 70 DIO
V71 72 0 -12V
*****
RREF 16 0 10
VREF 16 0 5V
E3 21 0 70 0 -13.6
DVL 21 22 DIO
RINDI 22 0 1
*****
** CURRENT LOOP **
*****
**DCL 23 22 DIO
*****
DCL 75 22 DIO
RDCL 23 75 0.005
D75 75 76 DIO
V75 76 0 12V
D76 77 75 DIO
V76 77 0 -12V
*****
R24 24 23 1K
C28 37 24 15UF
R23 37 23 20K
VCC 27 0 12V
R26 26 0 20K
R28 26 27 10K
R27 28 27 10K
ECL 23 0 26 37 100K
RGPM 28 37 1K
R35 33 35 3K
VC1 34 0 5V
VC2 35 0 12V
R34 32 34 3K
R32 32 0 16.9K
R31 31 0 5.62K
R30 30 31 1.21K
Q2 33 32 31 MOD1
Q1 28 29 30 MOD1
C29 29 0 100UF
R36 36 29 5.1K
HCV 36 0 VSEN 0.25
*****
** TRIANGULAR WAVE **
*****
*IRST 40 0 10
EST1 41 0 22 0 1
REST1 41 40 1MEG
VST 40 0 PULSE(1 5 1US 0.9US 3.9US 0.1US 4.9US)
*****
** BATTERY HARNESS **
*****
D2 111 110 DIO
RH1 111 112 0.004
LH1 112 113 3UH
RAC 113 114 0.0064

```



```

RDC 114 115 0.00003
D3 116 115 DIO
VDC 116 0 28V
CH1 114 0 184F
*****
** PEAK POWER TRACKER **
*****
EVK1 201 0 200 0 0.5
C43 201 202 0.0018UF
C44 202 203 0.0018UF
R178 203 0 178K
R340 202 204 24.3K
R350 204 205 10.5K
C45 204 205 0.0068UF
R370 204 0 200
R380 205 206 59K
EBP1 205 0 203 204 100K
R390 206 207 59K
C47 207 0 330PF
C46 206 208 2400PF
C48 208 209 68PF
R410 208 209 3.9K
R400 208 0 1K
EBP2 209 0 207 208 100K
C7349 209 210 0.012UF
R420 210 0 3.09K
EM2 220 0 POLY(2) 210 0 250 0 0 0 0 0 .222
*****
R6061 220 221 13.3K
C64 221 260 0.027UF
EHINT 260 0 0 221 100K
HIN 230 0 VSE 0.3
RIN 230 0 100MEG
EM1 240 0 POLY(2) 201 0 230 0 0 0 0 0 0.04
*****
RPPTL 260 261 0.005
D261 261 262 DIO
V261 262 0 12V
D263 263 261 DIO
V263 263 0 -12V
*****
DPPT 261 22 DIO
*****
C43Z 240 242 0.0018UF
C44Z 242 243 0.0018UF
R178Z 243 0 178K
R340Z 242 244 24.3K
R350Z 244 245 10.5K
C45Z 244 245 0.0068UF
R370Z 244 0 200
R380Z 245 246 59K
EBP1Z 245 0 243 244 100K
R390Z 246 247 59K
C47Z 247 0 0.00033UF
C46Z 246 248 0.0024UF
C48Z 248 249 68PF
R410Z 248 249 3.9K
R400Z 248 0 1K
EBP2Z 249 0 247 248 100K
C7349Z 249 250 0.012UF
R420Z 250 0 3.09K
.MODEL TBUK NPN CJE=1000PF CJC=1000PF
.MODEL MOD1 NPN

```

```
.MODEL DIO D IS=1.0E-16  
.TRAN 20US 2MS 0 10US  
.PRINT TRAN V(11)  
.PLOT TRAN V(11)  
.OPTION METHOD=GEAR  
.OPTION LVLTIM=1 ITL3=20  
.OPTION LIMPTS=100K ITL1=500 ITL4=50 ITL5=500K  
.OPTION LINTIM=100 CPTIME=40K  
.END
```

APPENDIX H
VOLTAGE DROP ACROSS THE DIODES
DPPT, DVL, AND DCL

Time	DPPT	DVL	DCL
[sec]	Voltage	Voltage	Voltage
	[volts]	[volts]	[volts]
0.000E+00	-8.993E-01	9.501E-01	-1.721E-01
2.000E-05	-1.368E+00	9.610E-01	-6.415E-01
4.000E-05	-1.765E+00	9.710E-01	-1.285E+00
6.000E-05	1.010E+00	-5.862E+00	-8.469E+00
8.000E-05	1.018E+00	-9.467E+00	-1.146E+01
1.000E-04	1.018E+00	-1.020E+01	-1.150E+01
1.200E-04	1.018E+00	-1.019E+01	-1.152E+01
1.400E-04	1.018E+00	-1.023E+01	-1.153E+01
1.600E-04	1.018E+00	-1.028E+01	-1.153E+01
1.800E-04	1.018E+00	-1.031E+01	-1.153E+01
2.000E-04	1.018E+00	-1.036E+01	-1.154E+01
2.200E-04	1.018E+00	-1.041E+01	-1.156E+01
2.400E-04	1.018E+00	-1.046E+01	-1.157E+01
2.600E-04	1.018E+00	-1.051E+01	-1.158E+01
2.800E-04	1.018E+00	-1.056E+01	-1.159E+01
3.000E-04	1.018E+00	-1.060E+01	-1.159E+01
3.200E-04	1.018E+00	-1.065E+01	-1.160E+01
3.400E-04	1.018E+00	-1.069E+01	-1.160E+01
3.600E-04	1.018E+00	-1.074E+01	-1.160E+01
3.800E-04	1.018E+00	-1.079E+01	-1.160E+01
4.000E-04	1.018E+00	-1.084E+01	-1.160E+01
4.200E-04	1.018E+00	-1.089E+01	-1.160E+01
4.400E-04	1.018E+00	-1.094E+01	-1.161E+01
4.600E-04	1.018E+00	-1.100E+01	-1.161E+01
4.800E-04	1.018E+00	-1.105E+01	-1.161E+01
5.000E-04	1.018E+00	-1.111E+01	-1.161E+01
5.200E-04	1.018E+00	-1.117E+01	-1.161E+01
5.400E-04	1.018E+00	-1.122E+01	-1.162E+01
5.600E-04	1.018E+00	-1.128E+01	-1.162E+01
5.800E-04	1.018E+00	-1.134E+01	-1.162E+01
6.000E-04	1.018E+00	-1.140E+01	-1.162E+01
6.200E-04	1.018E+00	-1.147E+01	-1.162E+01
6.400E-04	1.018E+00	-1.153E+01	-1.162E+01
6.600E-04	1.018E+00	-1.159E+01	-1.162E+01
6.800E-04	1.018E+00	-1.166E+01	-1.162E+01
7.000E-04	1.018E+00	-1.173E+01	-1.162E+01
7.200E-04	1.018E+00	-1.180E+01	-1.162E+01
7.400E-04	1.018E+00	-1.187E+01	-1.162E+01
7.600E-04	1.018E+00	-1.194E+01	-1.162E+01
7.800E-04	1.018E+00	-1.201E+01	-1.162E+01
8.000E-04	1.018E+00	-1.209E+01	-1.162E+01
8.200E-04	1.018E+00	-1.216E+01	-1.162E+01
8.400E-04	1.018E+00	-1.224E+01	-1.162E+01
8.600E-04	1.018E+00	-1.232E+01	-1.162E+01
8.800E-04	1.018E+00	-1.239E+01	-1.162E+01
9.000E-04	1.018E+00	-1.248E+01	-1.162E+01
9.200E-04	1.018E+00	-1.256E+01	-1.162E+01
9.400E-04	1.018E+00	-1.264E+01	-1.162E+01
9.600E-04	1.018E+00	-1.272E+01	-1.162E+01
9.800E-04	1.018E+00	-1.281E+01	-1.162E+01
1.000E-03	1.018E+00	-1.290E+01	-1.162E+01
1.020E-03	1.018E+00	-1.298E+01	-1.162E+01
1.040E-03	1.018E+00	-1.307E+01	-1.162E+01
1.060E-03	1.018E+00	-1.317E+01	-1.162E+01
1.080E-03	1.018E+00	-1.326E+01	-1.162E+01
1.100E-03	1.018E+00	-1.335E+01	-1.162E+01
1.120E-03	1.018E+00	-1.345E+01	-1.162E+01
1.140E-03	1.018E+00	-1.354E+01	-1.162E+01
1.160E-03	1.018E+00	-1.364E+01	-1.162E+01
1.180E-03	1.018E+00	-1.374E+01	-1.162E+01
1.200E-03	1.018E+00	-1.384E+01	-1.162E+01

Time	DPPT	DVL	DCL
[sec]	Voltage	Voltage	Voltage
	[volts]	[volts]	[volts]
1.220E-03	1.018E+00	-1.394E+01	-1.162E+01
1.240E-03	1.018E+00	-1.404E+01	-1.162E+01
1.260E-03	1.018E+00	-1.414E+01	-1.162E+01
1.280E-03	1.018E+00	-1.425E+01	-1.162E+01
1.300E-03	1.018E+00	-1.436E+01	-1.162E+01
1.320E-03	1.018E+00	-1.446E+01	-1.162E+01
1.340E-03	1.018E+00	-1.457E+01	-1.162E+01
1.360E-03	1.018E+00	-1.468E+01	-1.162E+01
1.380E-03	1.018E+00	-1.479E+01	-1.162E+01
1.400E-03	1.018E+00	-1.491E+01	-1.162E+01
1.420E-03	1.018E+00	-1.502E+01	-1.162E+01
1.440E-03	1.018E+00	-1.514E+01	-1.162E+01
1.460E-03	1.018E+00	-1.525E+01	-1.162E+01
1.480E-03	1.018E+00	-1.537E+01	-1.162E+01
1.500E-03	1.018E+00	-1.549E+01	-1.162E+01
1.520E-03	1.018E+00	-1.561E+01	-1.162E+01
1.540E-03	1.018E+00	-1.573E+01	-1.162E+01
1.560E-03	1.018E+00	-1.586E+01	-1.162E+01
1.580E-03	1.018E+00	-1.598E+01	-1.162E+01
1.600E-03	1.018E+00	-1.611E+01	-1.162E+01
1.620E-03	1.018E+00	-1.623E+01	-1.162E+01
1.640E-03	1.018E+00	-1.636E+01	-1.162E+01
1.660E-03	1.018E+00	-1.649E+01	-1.162E+01
1.680E-03	1.018E+00	-1.662E+01	-1.162E+01
1.700E-03	1.018E+00	-1.675E+01	-1.162E+01
1.720E-03	1.018E+00	-1.689E+01	-1.162E+01
1.740E-03	1.018E+00	-1.702E+01	-1.162E+01
1.760E-03	1.018E+00	-1.716E+01	-1.162E+01
1.780E-03	1.018E+00	-1.730E+01	-1.162E+01
1.800E-03	1.018E+00	-1.743E+01	-1.162E+01
1.820E-03	1.018E+00	-1.757E+01	-1.162E+01
1.840E-03	1.018E+00	-1.772E+01	-1.162E+01
1.860E-03	1.018E+00	-1.786E+01	-1.162E+01
1.880E-03	1.018E+00	-1.800E+01	-1.162E+01
1.900E-03	1.018E+00	-1.815E+01	-1.162E+01
1.920E-03	1.018E+00	-1.829E+01	-1.162E+01
1.940E-03	1.018E+00	-1.844E+01	-1.162E+01
1.960E-03	1.018E+00	-1.859E+01	-1.162E+01
1.980E-03	1.018E+00	-1.874E+01	-1.162E+01
2.000E-03	1.018E+00	-1.889E+01	-1.162E+01

PERMISSION TO COPY

In presenting this thesis in partial fulfillment of the requirements for a master's degree at Texas Tech University, I agree that the Library and my major department shall make it freely available for research purposes. Permission to copy this thesis for scholarly purposes may be granted by the Director of the Library or my major professor. It is understood that any copying or publication of this thesis for financial gain shall not be allowed without my further written permission and that any user may be liable for copyright infringement.

Disagree (Permission not granted) Agree (Permission granted)

Student's signature

4. Patrick Hughes

Student's signature

Date

4/7/87

Date