NASA Technical Memorandum 102335

Development and Refinement of Test Bed Simulations

N.V. Dravid and D.R. Miller
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio

A.G. Patterson
Analex Corporation
NASA Lewis Research Center
Cleveland, Ohio

F.J. Gombos
Rockwell International
Rocketdyne Division
Canoga Park, California

Prepared for the
24th Intersociety Energy Conversion Engineering Conference
cosponsored by the IEEE, AIAA, ANS, ASME, SAE, ACS, and AIChE
Washington, D.C., August 6-11, 1989

NASA

(NASA-TM-102335) DEVELOPMENT AND REFINEMENT OF TEST BED SIMULATIONS (NASA. Lewis Research Center) 8 p CSCL 14B

N89-27702

Unclas
G3/20 0225954

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N.V. Dravid and D.R. Miller
NASA Lewis Research Center
Cleveland, OH

A.G. Patterson
Analex Corporation
NASA Lewis Research Center
Cleveland, OH

F.J. Gombos
Rockwell Corporation
Rocketdyne Division
Canoga Park, CA

1. Abstract

Lewis Research Center of NASA (Lewis), with support from Rocketdyne, has been engaged in non real time computer simulation effort for the Space Station Freedom Electric Power System (EPS) [1]. EASY5, a simulation package developed by Boeing Computer Services, Inc. (BCS), is used as the primary tool for this activity. Early in the design of the EPS, two test beds have been set up at Lewis. The Integrated Test Bed (ITB), that combines and upgrades these test beds, is in the planning stage. The test beds are designed to functionally represent many of the components of the EPS and their interconnections. The simulation effort is primarily directed towards these test beds. Model verification is performed using test bed data.

This paper will present many of the component models, results of simulations, and results of model verification activity.

2. Introduction

Lewis was assigned the responsibility to direct the efforts to design, develop, and fabricate the electrical power system for the proposed Space Station Freedom. Rocketdyne Division of Rockwell International Corporation was selected by Lewis as the prime contractor for this effort. It was decided to set up test beds to investigate new concepts in power management and distribution (PMAD), e.g., 20 kHz distribution, to support the design process. Development of computer simulations of the test beds was undertaken as an important adjunct activity.

While it is desirable for the simulation to precede the test bed hardware design and installation, the two activities took place almost concurrently for the first two test beds. However, for the ITB the modeling task was completed ahead of the test bed fabrication. This will help in the evaluation of test bed performance before critical design review.

The availability of test beds during the early modeling phase was critical to determine acceptable levels of model fidelity to yield useful results. Since many of the components from the earlier test beds would be conceptually repeated in the ITB, the task of ITB simulation is greatly simplified.

This paper describes simulations of the test beds and verification of the models using experimental data from the test beds whenever possible. References are provided for information about test bed details and test bed simulation development.

3. Test Bed Development

The evolution of test beds at Lewis began with a components test bed, followed by a systems test bed, and shall culminate with an advanced test bed, the ITB. Following is a brief description of these test beds. [2,3,4]

The PMAD/PV test bed, supplied by General Dynamics Corporation(GDC) in 1987, was primarily built to test 20 kHz technology components. The test bed consists of 20 kHz inverters , ac switches, high frequency (Litz wire) 440V, primary distribution cable, 440V/208V transformers, and three types of load converters to convert 208V, single phase, 20 kHz ac to a type to meet load requirements. The test bed is set up to evaluate replacements for any of the above mentioned components. The dc source to the inverters can either be a power supply or the output of the Solar Array field nearby.

The PMAD Systems test bed was assembled at LeRC from components supplied by Rocketdyne, Westinghouse, TRW, and Allied Signal. The test bed has the following major components: Solar Array Simulator, Solar Dynamic Simulator, 20 kHz main inverter units (MIU), 1200 Hz to 20 kHz frequency converter, Main Bus Switching Assembly, MBSA, and Power Distribution and Control Assembly, PDCA. The PDCA and the MBSA contain power switching devices capable of implementing overcurrent and differential protection schemes. System related issues such as protection against faults, end-to-end voltage regulation, load sharing among inverters, etc., are being investigated in this test bed.

The ITB represents a two channel power distribution system containing many of the EPS functional components. Initially, dc power supplies will be used as sources to the inverters. Solar Array input will follow when array regulators are added. The ITB will have a complete primary and a representative secondary distribution system. The test bed will be used to address distribution system design issues such as conducted EMI, efficiency, power availability, etc.. Another important feature of this test bed is the hierarchical control architecture which will allow investigation of a variety of methods of power system control.

4. Simulation Development

Simulation activities for the EPS began in 1985, with a grant to Virginia Polytechnic Institute & State University(VPI), to generate a computer model of the PMAD/PV test bed, and continued through Rocketdyne as part of the Advanced Development program. Rocketdyne developed computer models for many of the EPS components while integrating those developed by VPI. Initially, Lewis concentrated on monitoring the task order contracts and exercising the models thus generated. Later, independent modeling activity began at Lewis to support test bed operational issues. Presently, modeling work continues at all the three places. The following briefly describes some of the major components and subsystem models that have been developed.

Mapham Resonant Inverter Model: Developed to simulate the PMAD/PV test bed MIU, the model consists of two inverters, paralleled on the dc input side and series connected on the ac output side. This permits voltage control by controlling the phase angle between the individual ac output voltages. The simulation of this inverter is based primarily on modeling the operation of SCR switches as ideal switches (for simplicity). The switch operation is based on clock pulses at 20 kHz. This model has provided satisfactory information for issues such as output voltage harmonic distortion, and general inverter operation control.[5]

TRW Resonant Inverter Model: This model was developed to simulate the PMAD Systems test bed MIU (two inverters in parallel). Each inverter consists of switching elements arranged in a bridge configuration around a resonant circuit. The switches are power transistors, but modeled as ideal switches. A 20 kHz clock is used to control the switch operation. Output voltage control of individual inverters is obtained by controlling the energy being supplied to the resonant circuit. This model also has performed satisfactorily in giving results quite similar to the hardware operation.[6]

Transmission Line Model: A transmission line model generally consists of lumped parameter elements. The simulation allows for a variety of models depending upon the fidelity requirements and simulation time constraints. On one extreme, the line model consists of 5 sections, connected in cascade, each section being a lumped element L network to represent one-fifth of the line length. The number 5 is a compromise between fidelity and reasonable computing time. Depending upon the length of the line, even a single section Π network may suffice. On the other hand, when a large system with many states is simulated, it may be sufficient to represent the line without any propagation time, i.e., as an equivalent resistance to simulate the line loss. This is true when one is not interested in the very high frequencies associated with a transmission line.[7]

Ac Remote Bus Isolator (RBI) Model: Developed by Rocketdyne, it simulates all the functions of an intelligent switch with built-in sensing and operating logic. There is a provision to also simulate the device as a closed switch thereby reducing considerably the number of states. This model also includes representation of the Remote Power Controller (RPC), a device capable of inturrupting a circuit faster than the RBI. However, the RPC is a lossy device because it does not have a mechanical relay parallel to the solid state switch.[8]

Load Converter Model: Three types of load converter models have been developed to represent power conversion from 20 kHz, 208V, single-phase ac. They are: 1) load converter model to obtain 120V dc; 2) load converter model to obtain variable frequency, variable voltage ac for loads such as motors; and 3) bi-directional 20 kHz, 208V ac / 120V dc load converter model for special applications. Load converter models are still evolving because of the changing requirements of the base line design. Some of the models have closed loop controls to regulate output voltage/frequency for variable loads.[8,9]

Power Distribution and Control Unit Model: Also known as PDCU, this represents a subsystem which acts as a mini substation. It consists of RBIs, RPCs, and Transformers, A simple controller model for the PDCU is also available. Another similar model is that of the Main Bus Switching Unit (MBSU) which is functionally similar to a switching station. Presently, the models of both PDCU and MBSU utilize the passive, ac RBI/RPC models. In future, they will be replaced by the active, ac RBI/RPC models which have many built-in sensing and logic functions for fault protection.

Photovoltaic Source System Model: A simple model has been developed for the PV Source System which includes the solar array, battery charge/discharge converter, array regulator, and controller. The time response of this system is substantially slower than that of the 20 kHz EPS network. Therefore, the model will mainly be used to study the PV Source System and its interactions with the MIU. It should be noted that this model is undergoing continued refinement to reflect latest available data.

Solar Dynamic Simulator: A model has been developed for the BRU-F Alternator, which has been proposed as an alternative to the PV source. This model is not presently in use but can be revived if the EPS program necessitates.[1]

Switch-State Models: Initially, the forward Euler rule for numerical integration was utilized. At times, this resulted in unstable solutions, especially for models which include considerable amount of switching, e.g., inverters, RBI, etc.. Later, Switch-State representation was proposed as a better alternative allowing the use of the BCS Gear, variable time step, numerical integration method (see page 164 of [8] and also [12]). Many of the models have since been converted to this approach.

Other Models: Many other models such as R-L-C loads, transformers, instrumentation, dc RBI, etc. have been developed to meet the requirements of simulation

5. Simulation Results

After development, the models were exercised to verify their operation. Generally, the simulations were performed as functions of time. These included either cold starts or a steady state operation subjected to a disturbance Although many cases were run, only one representative case for each test bed is shown here as an example. More simulation results can be found in the references given.

5.1 PMAD / PV Test Bed Simulation

Figure 5.1 shows a configuration of this test bed for which some simulation results are given. Test bed parameters were used whenever available. Three, paralleled MIUs are connected to a 100 m cable, feeding into a 4.84 kW resistive load and a dc load converter supplying a resistive load. The simulation begins with zero initial conditions and the system is brought to a steady state. The load converter load is doubled to 2 kW, as a step, to create a disturbance. Resulting changes in the MIU output voltage, the line current, and the load converter response are shown. The load converter and system responses appear satisfactory.[10]

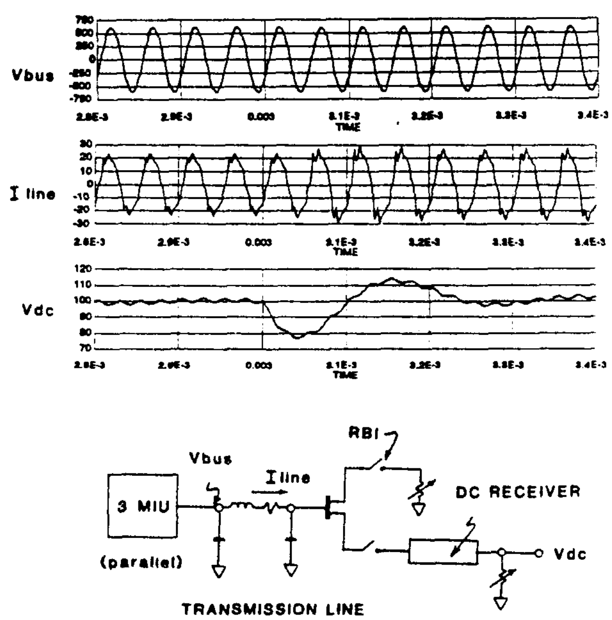

Figure 5.1: Simulation Example for PMAD / PV Test Bed

5.2 PMAD Systems Test Bed Simulation

The PMAD Systems Test Bed model was developed to investigate the response of a distributed system to a variety of disturbances, e.g., varying load profiles, network topology changes, faults,etc.. The test bed simulation was also intended to focus on the TRW MIU and to provide subsystem level information such as inverter load sharing, load change response, fault response, etc..

For MIU subsystem analyses, only a small part of the test bed model was utilized as shown in figure 5.2. The distribution network is represented as a transmission line supplying a resistive load. Step load changes are applied one millisecond apart; the first step is from 4 kW to 8 kW while the second being its reverse. Plots of inverter output voltage and current are shown.

This type of simulation provides information about the TRW inverter response to load changes which, in turn, can be used to design voltage control loop for optimum performance.[6]

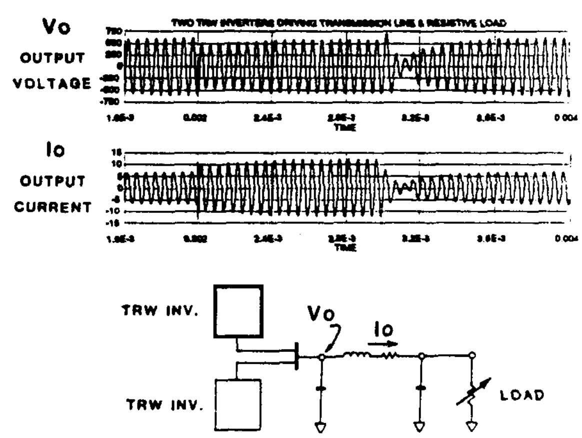

Figure 5.2: Simulation Example for PMAD Systems Test Bed

5.3 ITB Simulation

Simulation of the complete ITB system presented a challenge due to the limitations of the computer resources. The large number of states associated with the ITB simulation require excessive amounts of execution time. Some economies were realized by using the simplest form of transmission line model (see section 4). Therefore, the ITB simulations are limited to a demonstration of steady state operation to rule out hidden programming errors. However, subsystem simulations for the ITB were performed with applied disturbances. Figure 5.3 shows a schematic of the ITB system including the hierarchical control system and data network. It must be noted that the PDCU and MBSU blocks contain many RBI/RPC models and, thus, have large number of states. The figure also shows representative bus voltage plots, labeled as V1 and V2, from the two separate, nonconnected rings. These plots show the almost identical waveforms for corresponding quantities. The phase angle differences are due to those between the respective sources. For other simulation results of the ITB, please refer to [8].

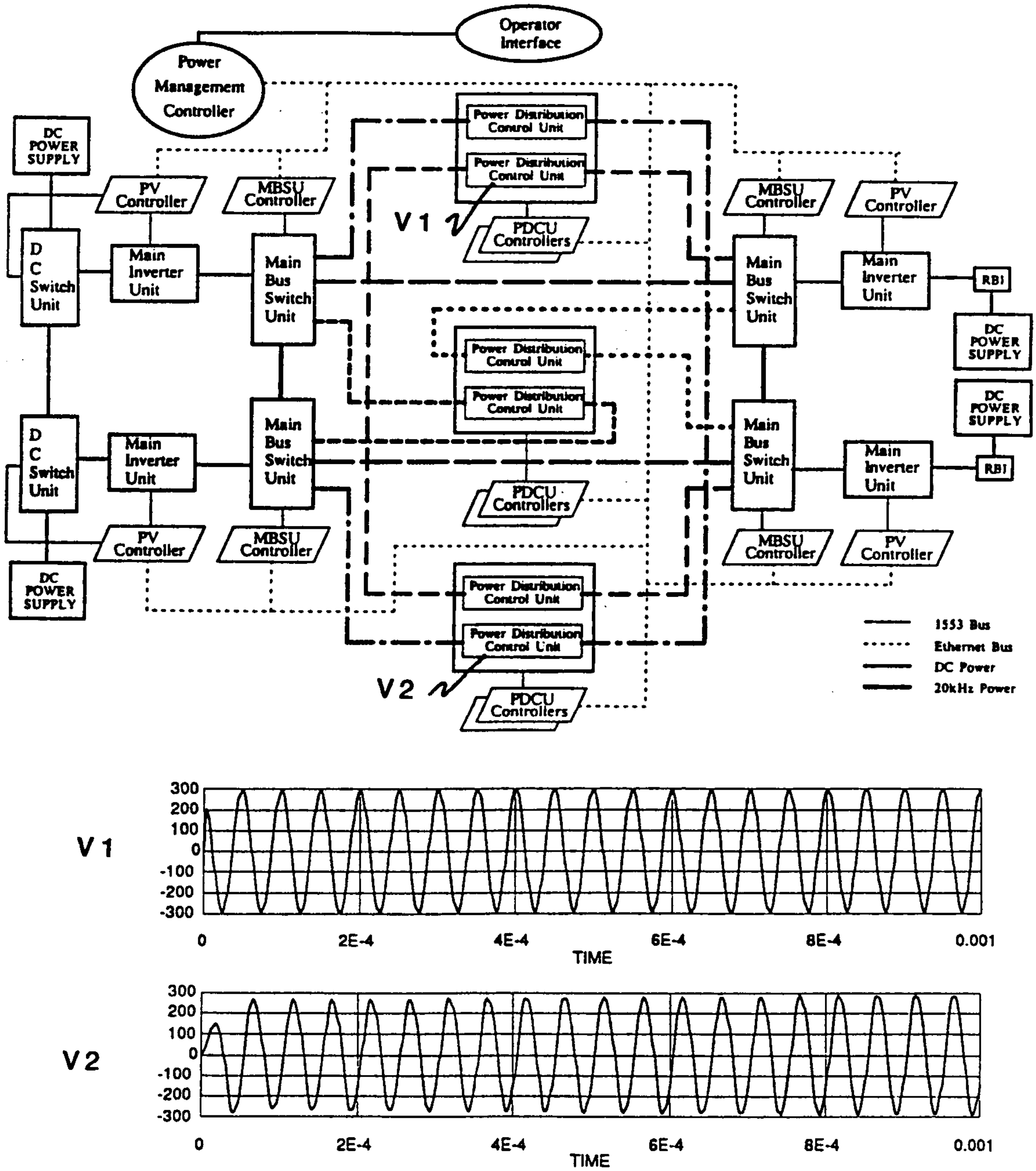

Figure 5.3: PMAD ITB Configuration and sample Simulation results

6. Simulation Verification from Test Bed Data

As noted before, the need for verification of the models from test bed data is paramount. These data could come in different forms. Comparing time function plots from the test bed to corresponding plots from the simulation is the time honored approach. However, due to limitations of model fidelity, such comparisons are likely to show some mismatch. Nevertheless, such a comparison will be shown. Another method of verification is comparison of derived data from steady state operation of the model and the test bed. This is likely to yield closer comparison even with the limitation mentioned earlier. Some of these are also shown. For more information, please refer to [5,10].

6.1 Total Harmonic Distortion (THD)

Due to the existence of many power processing devices, control of generated harmonics will be a significant issue for the EPS. Therefore, the amount of total harmonic distortion is an important specification for the design and performance of the EPS. Harmonic distortion from the MIU is, among other things, a function of the ratio of clock to resonant frequencies (fsn). Experiments were performed on the PMAD/PV test bed to determine this function. The same was repeated using the test bed model. Figure 6.1 shows the comparison of the results.[5,10,11]

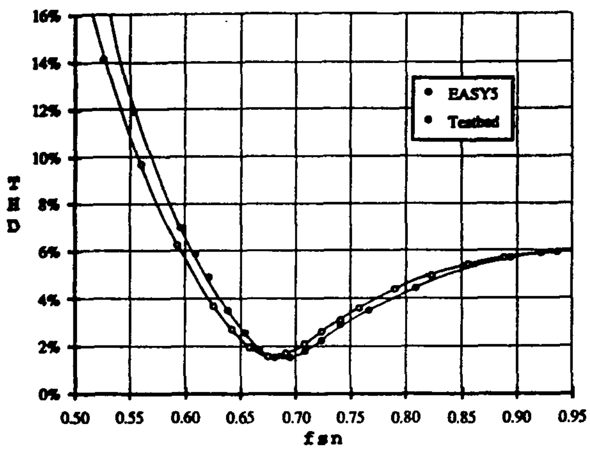

Figure 6.1: Comparison of THD

6.2 MIU Input Characteristics

A Mapham inverter, when connected to a PV source, may have an unstable operating point due to the nonlinear voltage-current characteristics of each device. In order to investigate this phenomenon, input characteristics of the inverter were experimentally found from the test bed and and also determined by simulation. Figure 6.2 shows the comparison.[10]

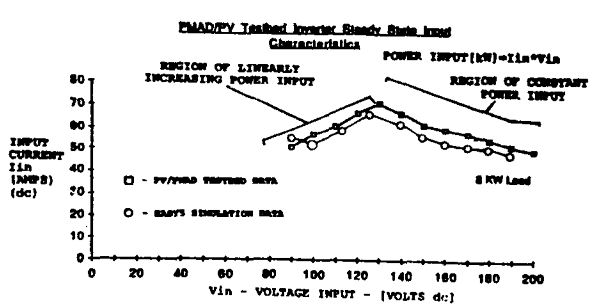

Figure 6.2: MIU Input Characteristics

6.3 Inherent Voltage Regulation of Inverter

Looking back from the 20 kHz side, the inverter should appear as any other ac source with some amount of output impedance. Such a source must inherently exhibit voltage regulation, i.e., the output voltage must decrease with increasing power output. Figure 6.3 shows comparison of the voltage regulation characteristics of a Mapham inverter as obtained experimentally and from simulation.[10]

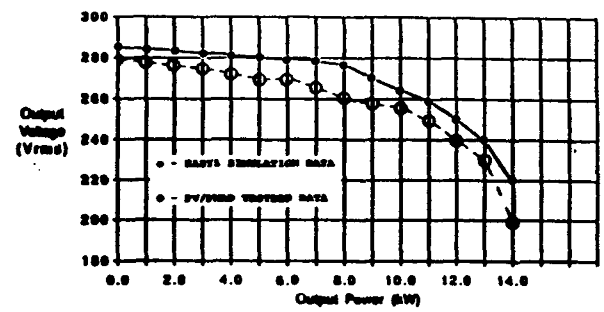

Figure 6.3: Inverter Voltage Regulation

6.4 TRW MIU Start-up verification

The start-up of a TRW MIU is somewhat peculiar because of the nature of the control system presently employed. Since the simulation is supposed to mirror the test bed the control system was also modeled in its present form. Comparison of the MIU start-up characteristics is shown in figure 6.4 which verifies the fidelity of the models.[6]

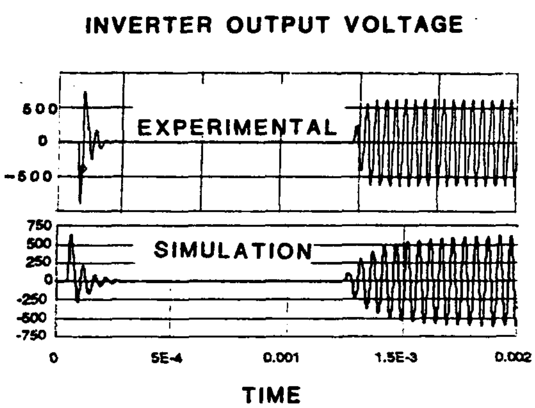

Figure 6.4: TRW MIU Start-Up

7. Conclusions

Development and refinement of 20 kHz Test Bed simulation for the EPS has been described and the model verification process demonstrated. The high degree of correlation between the test bed data and the simulation results has been shown. Test bed simulations will be performed prior to hardware tests to uncover any hidden problems. Simulations will be substituted where hardware tests are not practical or convenient.[5]

EASY5, as a software modeling tool, has generally performed satisfactorily. However, it has required excessive amounts of computer time for certain simulations having a large number of states. By improving upon the EASY5 software and by selective reduced order modeling, it may be possible to reduce computation time to a reasonable level([12]). Additionally, other software modeling tools will be evaluated and utilized to conduct specific investigations concerning the EPS.[7]

8. Acknowledgments

The authors wish to acknowledge the assistance provided by the following in supplying information for this paper.

R. Sundberg for PMAD / PV test bed data, R. Beach for PMAD Systems test bed data, Dr. Ponlee Li for the initial model of the TRW inverter power stage, A. Peuron for the ac RBI model, and E. Pongracz-Bartha / J. Kidder for ITB simulation results.

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Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-102335		

4. Title and Subtitle	5. Report Date
Development and Refinement of Test Bed Simulations	
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
N.V. Dravid, D.R. Miller, A.G. Patterson, and F.J. Gombos	E-5043
	10. Work Unit No. 474-42-10
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191	11. Contract or Grant No.
	13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546-0001	14. Sponsoring Agency Code

15. Supplementary Notes

24th Intersociety Energy Conversion Engineering Conference cosponsored by the IEEE, AIAA, ANS, ASME, SAE, ACS, and AIChE, Washington, D.C., August 6-11, 1989. N.V. Dravid and D.R. Miller, NASA Lewis Research Center; A.G. Patterson, Analex Corporation, NASA Lewis Research Center; Cleveland, Ohio 44135. F.J. Gombos, Rockwell International, Rocketdyne Division, Canoga Park, California.

16. Abstract

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17. Key Words (Suggested by Author(s))	18. Distribution Statement
Simulation Power system Computer modeling	Unclassified – Unlimited Subject Category 20

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No of pages	22. Price*
Unclassified	Unclassified		

NASA FORM 1626 OCT 86

*For sale by the National Technical Information Service, Springfield, Virginia 22161