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An Integrated and Modular Digital Modeling Approach for the Space Station Electrical Power System Development

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AN INTEGRATED AND MODULAR DIGITAL MODELING APPROACH FOR THE SPACE STATION ELECTRICAL POWER SYSTEM DEVELOPMENT

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Abstract

Rocketdyne is under a contract from NASA Lewis Research Center (LeRC) to design, develop, and build the electrical power system for the Space Station. This system provides for electric power generation, conditioning, storage, and distribution. The initial configuration uses photovoltaic power generation. Solar dynamic power generation will be added later. The power system control is based on a hierarchical architecture to support the requirements of automation.

In the preliminary design and technology development phase of the program, various modeling techniques and software tools were evaluated for the purpose of meeting the Space Station power system modeling requirements. Rocketdyne and LeRC jointly selected the EASY5 simulation software, developed by Boeing Computer Services, as a system-level modeling tool.

This paper describes the application of the selected analytical modeling approach to represent the entire power system. Typical results of model predictions are also summarized. The equipment modeled includes solar arrays, dc to dc converters, resonant inverters, battery storage system, alternator, transmission line, switch gear, and system level microprocessor controls.

During the advanced development phase of this program, several models have been developed using this approach.

Introduction

Preliminary design of the Space Station Electrical Power System (EPS) consists of a hybrid power generation system, Solar Dynamic (SD) and Photovoltaic (PV), together with an autonomous high frequency (20 kHz) Power Management and Distribution (PMAD) system. Figure 1 shows the EPS in a simplified schematic diagram. To develop and verify such a system, two different test beds are operating at LeRC. Also, an Integrated test bed (ITB), which incorporates both the power system and the hierarchical control system, is in the planning stage.

The modeling approach and simulation software were selected to support the preliminary design phases of the EPS, including test bed development. Design tradeoffs in equipment, controls, or even the entire system are supported by analytical models and computer simulations to minimize development risks.

This paper describes analytical modeling requirements, summarizes the status of model development,

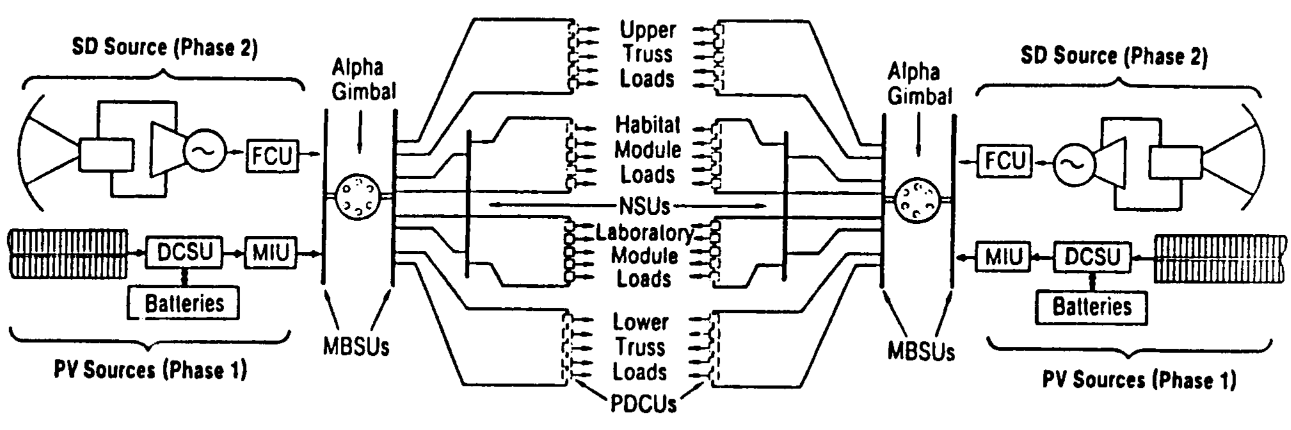

Figure 1. Space Station Electrical Power System Simplified Schematic Diagram

and reviews representative simulation results. Preliminary design of the EPS is supported by the development of power system test beds. The test beds will also support the assessment of various analytical modeling techniques, State-of-the-art simulation software, and test validation of selected modeling approaches. This paper presents results of this assessment. Also presented are representative results of the modeling effort with special emphasis on control system development requirements and system integration analytical support.

Power System Analytical Modeling Requirements

Analytical models are needed to support the design and development of components and systems. They are also essential for the development of controls and related software. The type of model, the model complexity, and the simulation tools utilized depend considerably on the purposes of the simulation.

System analysis, modeling of power components, and modeling of modules within the system model are based on the hybrid multiport representation. Parameters for such representation can be a function including nonlinearities. The EASY5 software is ideally suited for this type of representation.

The terminal characteristics of each function can be described by the following equation:

$$\begin{bmatrix} i_1 \\ i_2 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \cdot \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} \qquad (1)$$

The elements within equation (1) can be determined by utilizing state variable approach or frequency domain (transfer function) representation. EASY5 will perform the necessary time or frequency domain simulations.

The state variable approach is ideally suited for time domain simulations. In it, a linear, time invariant network is characterized by two equations of the following forms.

State equation:

$$d/dt\,[X] = [A][X] + [B][U] \qquad (2)$$

Output equation:

$$[Y] = [C][X] + [D][U] \qquad (3)$$

Where,

U = $m \times 1$ vector representing m inputs
Y = $p \times 1$ vector representing p outputs
X = $n \times 1$ vector of n independent variables
A, B, C, D are constant real matrices, called state equation matrices, of appropriate dimensions; **A** is always $n \times n$.

Equation (2) is a set of **n** first order differential equations usually referred to as the state equation in normal canonical form. The set of independent variables $X = (x_1, x_2, \ldots, x_n)$ is called the state vector. The main advantage of the state variable method is the ease with which it can be manipulated by many numerical methods of analysis. Furthermore, the state variable method can be extended, without much difficulty, to deal with nonlinear networks.

The state equations are solved using numerical integration techniques. The choice of a suitable technique is influenced by a number of factors, some of which can be problem dependent. For example, modeling of power electronic devices, when coupled with short transmission lines, results in a **stiff** system of circuit equations, i.e., a system with widely separated values of time constants. Also, full order modeling of power equipment requires handling of highly discontinuous functions. A numerical integration technique to solve such a system will require a relatively small value of an upper limit on the integration step size in order to ensure numerical stability.

Two numerical methods of integration were successfully utilized in the power system modeling without compromising numerical stability. They are the **forward Euler** and the **Boeing Modified Stiff Gear**.

Modeling Results

The EPS component models were developed using the hybrid multiport approach described earlier. These component models were integrated into subsystem level models from the modular elements stored in EASY5 Macro Library. The modular approach reduces the time needed for the development of large scale system models and permits model test validation at subsystem level. Following is a description of representative models and results of simulation.

Photovoltaic (PV) Source Model

The baseline PV subsystem topology uses sequential shunt regulation during sunlight to maintain array voltage below safe level, provide regulated dc power to inverters, and clamp the array at low voltage for safe maintenance. Eclipse power is provided from battery storage units at regulated level. The combined battery charge/discharge unit (BCDU) provides bus regulation during eclipse and individual charge management to maximize battery life.

The Solar cell model[1] is based on the classical equation for a solar cell that includes the effect of an equivalent shunt resistance.

$$I = I_g - I_o \{ \exp[q(V + I \cdot R_s)/(A \cdot k \cdot T)] - 1\} - [(V + I \cdot R_s) / R_{sh}] \qquad (4)$$

where: I = current output of the cell
I_g = light generated current
I_o = reverse saturation current
q = electronic charge
A = empirical fitting constant (one for ideal junction)
k = Boltzmann constant
T = absolute temperature, deg.K
V = voltage appearing at the cell terminals
R_s = series resistance
R_{sh} = shunt resistance
S = solar insolation

The equivalent circuit of this model is shown in Figure 2.

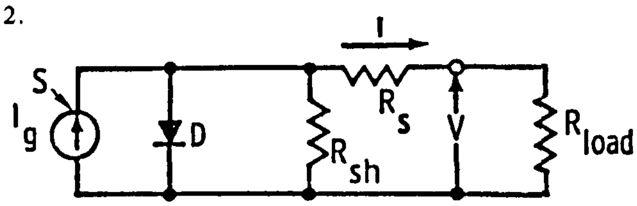

Figure 2. Solar Cell Equivalent Circuit

Newton iteration method is used to solve for I and V for a given load. Effects of illumination and temperature on the current and voltage of individual cells can be accounted for by correction coefficients. The performance of the solar array panel can be determined from individual cell data using known techniques[1].

The solar array power management approach uses a pulse width modulated (PWM) DC Switching Unit (DCSU) which provides a low dissipation method of matching array power delivery to load demand while maintaining voltage regulation (see Figure 3). The system consists of the Sequential Shunt Unit (SSU) and redundant photovoltaic control elements (PVCE). The PVCE provides a bus voltage error signal to the SSU's which shunt excess array power by shorting individual solar cell strings to ground.

In the SSU, each FET switch circuit is driven by a separate voltage comparator which compares the common bus voltage from a ramp generator. Each ramp signal is dc biased (level shifted) to a unique voltage level for each comparator. The average current through the associated regulating shunt element is proportional to the PWM duty cycle. The PWM implementation simplifies the electromagnetic compatibility (EMC) management by synchronization with the distribution bus frequency.

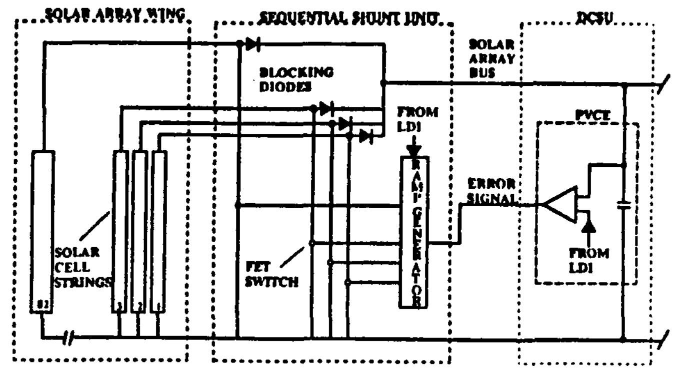

Figure 3. Solar Array Control Block Diagram

The nonlinear model developed for the SSU is based on the state differential equation representation of the error amplifier, a functional generation of the 20 kHz sawtooth reference signal, and the dc bias to determine the appropriate number of shunted solar array strings.

The computer model implementation of the PV Source subsystem is shown in Figure 4.

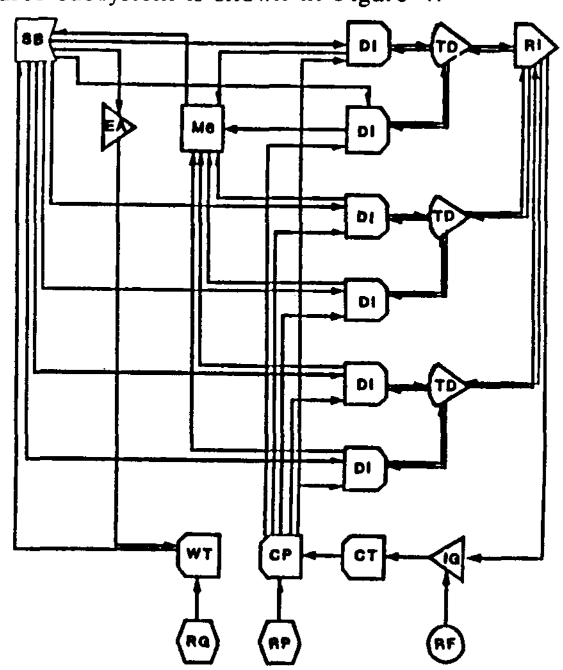

Figure 4. EASY5 block diagram of PV Source Subsystem Model

Transient responses of the PV source during startup and load switching have been predicted by the model including an idealized constant power load representing the negative impedance characteristic of a regulated inverter load, and by the actual inverter load. Details of the inverter model in this simulation are described elsewhere[2]

Simulation results shown in Figure 5 represent an optimum SSU control performance with the inverter input current completely filtered.

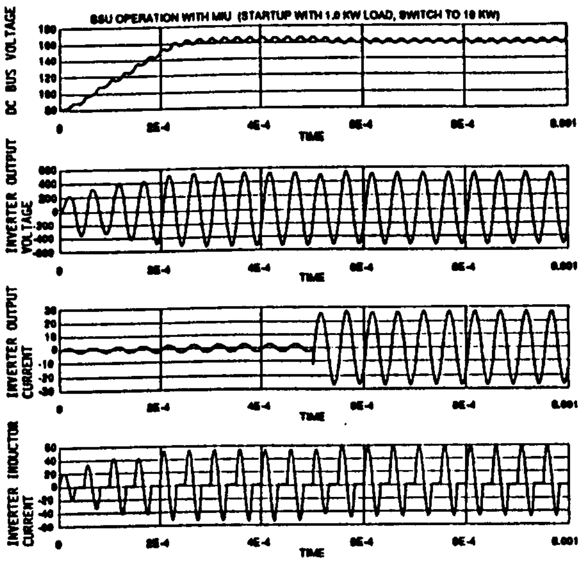

Figure 5. PV Source Subsystem Predicted Performance

Modeling of power equipment such as dc to dc converters, frequency changers, and resonant inverters, transmission lines, and remote power controllers (RPC) is based upon hybrid multiport representation . The parameters for the such representation are developed by utilizing the state-space approach. The elements in the hybrid multiport can be nonlinear or time varying.

Generally, two topological methods can be used for the formulation of system equations. One such method is the constant topology method while the other is the variable topology method[3]. In the modeling of dc-to-dc regulators, frequency changers (FCU), and the main inverter unit (MIU), the variable topology method was used. This method requires computation of the state matrices, which have both time varying elements as well as dimensions.

The power stage model of the battery charge converter (buck regulator) presents three possible topologies that exist in course of a complete switching cycle as shown in Figure 6. Similar set of equations were developed to represent the battery discharge converter (boost regulator) power stage. The control circuits can be modeled either by transfer functions or by state equations. The state equations were also used to model power equipment because of their ability to describe the circuit in more detail and also because nonlinearities such as op-amp saturation and protection functions can be easily added.

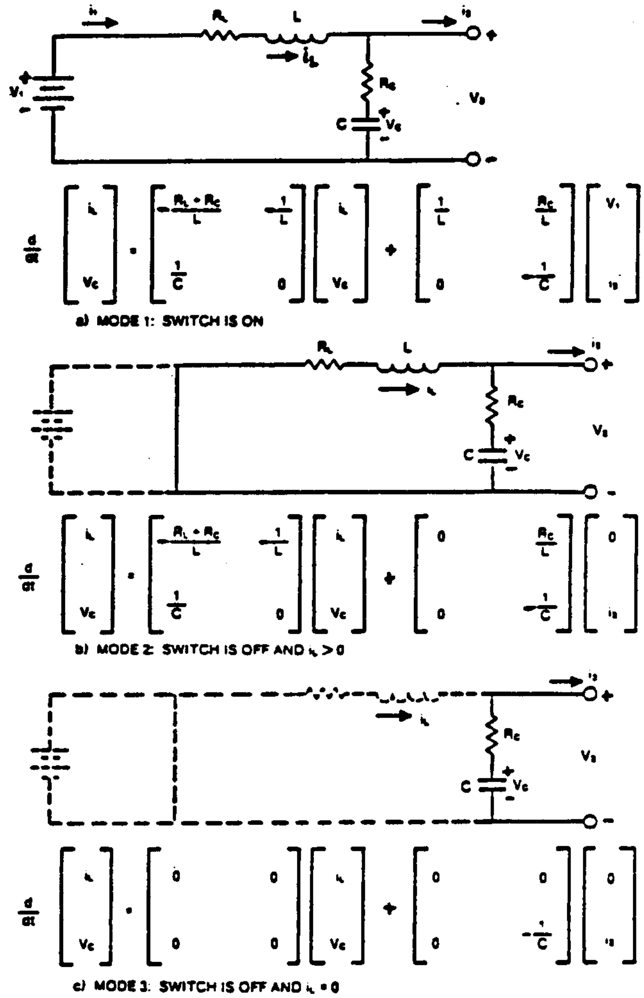

Figure 6. Buck Converter Power State Circuit Topology Modes and Model Equations

Power Management and Distribution (PMAD) Model

The PMAD subsystem will distribute power from the sources to the users. The distribution network will consist of three major dual power paths. The Power Distribution and Control Assembly (PDCA) will serve as the primary/secondary distribution tie point. Each PDCA will have the ability to isolate load faults, switch/balance loads from the dual busses, and can shed loads when under an overload condition. The widely separated source and load nodes in the system will be controlled by a distributed computer system with a hierarchical structure.

PMAD Subsystem Model

The PMAD subsystem model incorporates models for busses, remote bus isolators (RBI), transmission lines, transformers, load converters, switchable user loads, and analytical representation of higher level controls.

The capacitive bus model represents the summation of currents, the rate of rise of voltage being determined as: $dV_B / dt = \sum i / C$. In general, instrumentation loads, snubber circuits, and ac filters were added to the bus circuit as shown in Figure 7.

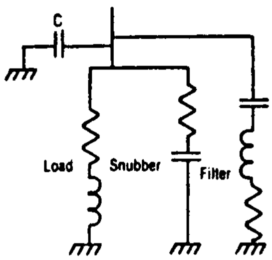

Figure 7. Bus Model Representation

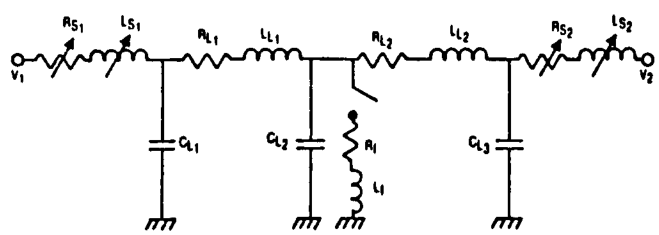

Figure 8. Generalized Transmission & RBI

The switching elements(SCR's) within the RBI are an integral part of the transmission line model as shown in Figure 8. The ac transmission line model (Nominal Π) incorporates the necessary elements for the representation of short transmission line transients with series R,L and shunt C elements. The switchable impedance, R_f & L_f, is provided to simulate faults.

AC Switch Model

The ac switch consists of solid state devices and other supporting electronics. The ac switch model, however, consists of a binary (two valued) series inductance and resistance circuit [3]. The two values represent **on** state and **off** state. The former are chosen to represent actual values for the switch itself as well as those due to connecting hardware. The latter are chosen to represent switch turn off characteristics in a simplified manner. Snubber circuits are not included in this model. Following a **turn off** command the current is allowed to cross zero. At the end of that time step, **off** state values of the inductance and resistance are invoked such that the non zero switch current asymptotically goes to zero with a specified time constant. The impedance of the **off** state switch should be large enough to permit the allowable level of leakage current. Figure 9 shows the logic of switch operation as incorporated in the model.

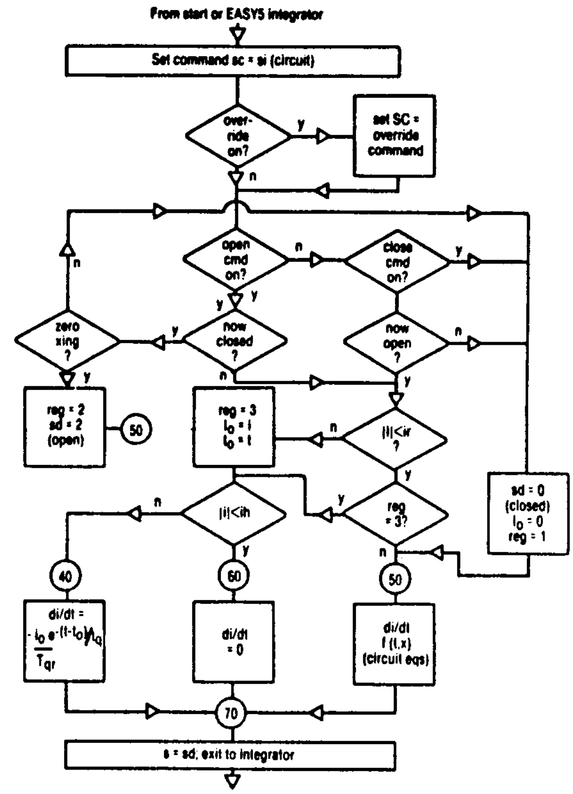

Figure 9. AC Switch Logic

The transformer model consists of an ideal transformer in series with an R-L circuit on the secondary side to represent leakage inductance and losses. Representation of magnetizing characteristics and inter-winding capacitance leads to an extremely stiff system and therefore difficulty with integration.

A digital model representation of the higher level controls has been developed and tested in order to support control system development. This model incorporates data transmission from sensors (including delay time), control algorithms, processor cycle time delay, and communication among the processors (see Figure 10).

Models of load converters, from 20 kHz to dc as well as ac, have been developed under a separate modeling effort [2].

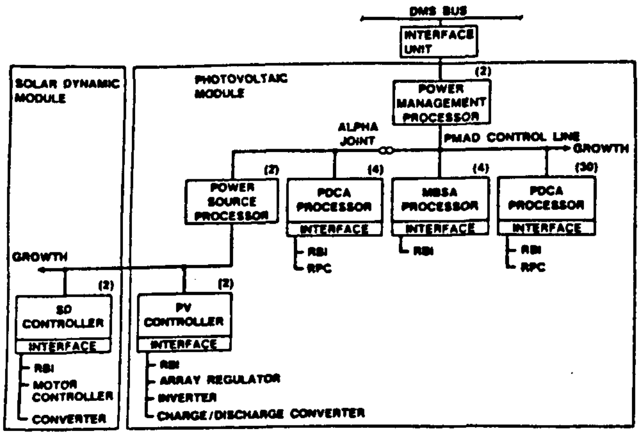

Figure 10. Electrical Power Control and Management System

Figure 11 shows the model of a Power Distribution Control Unit (PDCU) including the EASY5 blocks representing the overlaid circuit model. The purpose

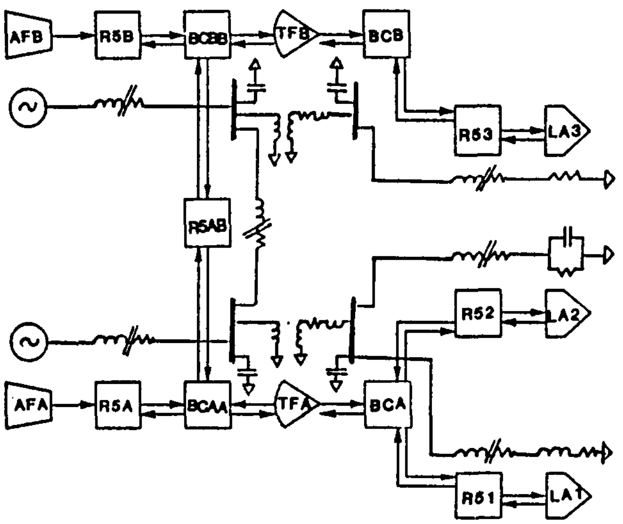

Figure 11. PDCU model with two test sources and three test loads

of the PDCU is to control the state of switches (RBI's and RPC's), either by command or automatically, e.g., to clear a fault. Additionally, the PDCU monitors currents, voltages, and powers associated with these switches. Results of a simulation on the PDCU model are shown in Figure 12. The three load currents are shown as a function of manual operations of the three RPC's. For reference, one of the source voltages is also shown. Two of the RBI's are also manually switched which affects two of the load currents as can been seen in the figure.

Solar Dynamic (SD) Source Model

LeRC had developed a Brayton cycle Rotating unit with foil bearings (BRU-F), turbine driven, 1200 Hz, modified Lundell Alternator for space power pur-

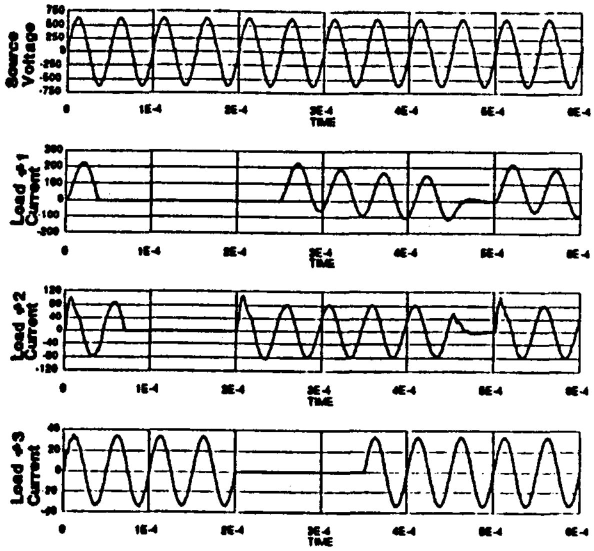

Figure 12. PDCU Simulation Results

poses[4]. This alternator was initially selected as the SD source for the EPS. In the PMAD System test bed, the SD source was replaced by an SD Simulator which consists of BRU-F Alternator powered by an air turbine. Since the air turbine lacks any speed governing mechanism, speed regulation is achieved by means of a balanced, 3 phase, parasitic load control scheme. Similar scheme will be used in the actual space station. The alternator is equipped with self excited shunt and series field windings which are controlled by a voltage regulator. The shunt field generates nominal terminal voltage while the series field compensates for voltage drop due to loading. Figure 13 is a schematic representation of the SD Simulator. The alternator is a 4 pole, 36000 RPM machine, rated at 14.3 kVA , 0.75 lagging pf, 120/208 volts. Mechanically, the machine is of the round rotor type but magnetically it is of the salient pole type.

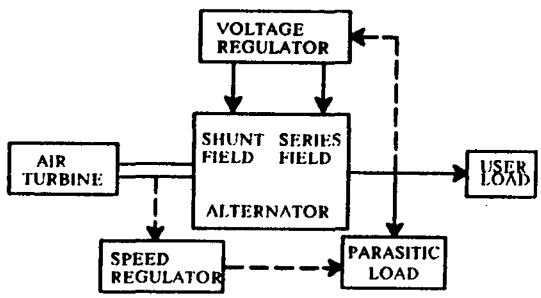

Figure 13. Solar Dynamic Simulator schematic

Alternator Modeling Equations

Modeling equations for the alternator as initially developed ([5]) are based on the well known **d-q axis** transformation principle which is routinely applied to the analysis of synchronous machines by the utility industry. With known information about the circuit constants of the stator, rotor, and the damper windings of the alternator, equations are developed which relate the winding currents, their respective flux linkages, and the voltages at their terminals.

The EASY5 implementation of the SD source includes dynamics of the rotating equipment, voltage regulator, parasitic load speed control, and user load [6].

The entire model was considerably improved upon ([7]) to reduce the run time. It should be noted that the simulation models continue to be improved upon with better definition of the control system and better knowledge of the circuit constants. Figure 14 shows some representative results of simulating a step load change at the alternator terminals.

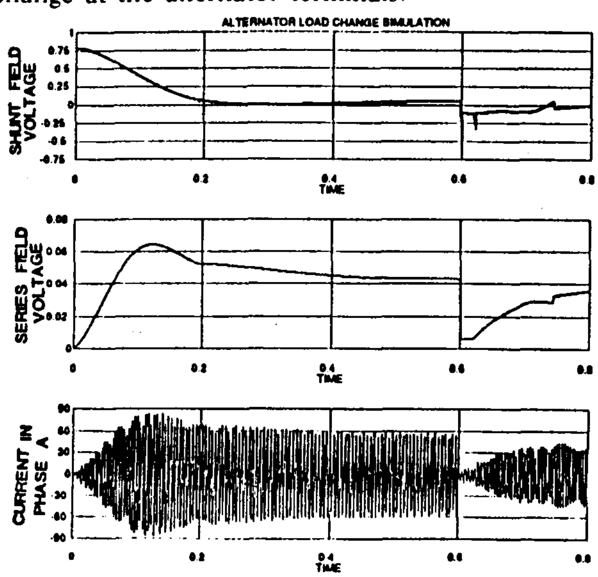

Figure 14. Load Change Disturbance

Conclusions

The paper presents an overview of the modeling approach for support of the Space Station EPS development. Representative simulation results are also presented. Test validation efforts, in progress, show that the models generally give correct results. The models will be an essential tool for the support of full scale development of the EPS.

The computing power required for this type of representation is substantial. Therefore, a proper mix of detailed models and reduced order models will be required for effective and efficient simulation support of the program.

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