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The Development of Test Beds to Support the Definition and Evolution of the Space Station Freedom Power System

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Prepared for the
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16. Abstract

Since the beginning of the Space Station Freedom Program (SSFP), the Lewis Research Center (LeRC) and the Rocketdyne Division of Rockwell International have had extensive efforts underway to develop test beds to support the definition of the detailed electrical power system design. Because of the extensive redirections that have taken place in the Space Station Freedom Program in the past several years, the test bed effort has been forced to accommodate a large number of changes. A short history of these program changes and their impact on the LeRC Test Beds is presented to understand how the current test bed configuration has evolved. The current test objectives and the development approach for the current DC Test Bed are discussed. A description of the Test Bed configuration, along with its power and controller hardware and its software components, is presented. Next, the uses of the Test Bed during the mature design and verification phase of SSFP are examined. Finally the uses of the Test Bed in operation and evolution of the SSF are addressed.

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ABSTRACT

Since the beginning of the Space Station Freedom Program (SSFP), the Lewis Research Center (LeRC) and the Rocketdyne Division of Rockwell International have had extensive efforts underway to develop test beds to support the definition of the detailed electrical power system design. Because of the extensive redirections that have taken place in the Space Station Freedom Program in the past several years, the test bed effort has been forced to accommodate a large number of changes. A short history of these program changes and their impact on the LeRC Test Beds is presented to understand how the current test bed configuration has evolved.

The current test objectives and the development approach for the current DC Test Bed are discussed. A description of the Test Bed configuration, along with its power and controller hardware and its software components, is presented. Next, the uses of the Test Bed during the mature design and verification phase of SSFP are examined. Finally the uses of the Test Bed in operation and evolution of the SSF are addressed.

INTRODUCTION

Although the SSFP program has gone through numerous changes since its beginning, it still will be the largest power system ever flown in space. In addition, it will be built and evolved incrementally and be "utility like" in its ability to accommodate changing loads much like a terrestrial power system. Furthermore, the system is characterized by its large number of power processing elements both in the source and distribution areas. The power processing elements in the source system present a higher than normal source impedance to the distribution system elements and thereby poses unique challenges in assuring that the system is stable under all operating conditions. Likewise the power processing elements in the secondary are current limited and present problems in providing a robust protection system. The characterizations of higher than normal source impedance and current limited distribution elements results because most space craft power systems have historically had very stiff sources such as batteries or fuel cells to act as the source element. Because of the historical precedent in dealing with systems of this type their development is considered to be generally straightforward. However, because of the unique characteristics of the SSFP, it is imperative that early experience be gained in the development and operation of power systems of that type. The data developed from the LeRC Test Bed can then be provided to the prime contractor (Rocketdyne) to support and facilitate their development effort.

HISTORY OF THE TEST BED EFFORT AT LeRC

The development of test beds in support of the Space Station Freedom Program began in 1985. The development chronology is shown in Figure #1. At that time, the program had baselined 20kHz AC as the Power Management and Distribution System (PMAD) of choice.

The initial test bed developed was the PMAD PV Test Bed. It was a proof of concept test bed consisting of a 20khz Mapham Inverter which drove several 440 Volt, 20kHz load converters to provide power at the final user power type (400Hz AC, 28 Volts DC, etc). This test bed was completed in 1987 and was used to support component design studies. Further information on this activity is available in Reference [1].

The PMAD System Test Bed was the next activity and was begun in June 1987. The primary purpose of the this test bed was to address system level design issues. The test bed consisted of a 25 KW, 20 kHz resonant inverter with a 440 Volt primary and 120 Volt secondary distribution system. Attached to the secondary, were solid state remote power controllers (RPCs) clustered into load centers called Power Distribution and Control Units (PDCAs). In addition, the test bed contained several load converters as well as a distributed control system programmed in Ada. Further information on this test bed is available in Reference [2].

The last activity of the 20 khz era was the development of the Integrated Test Bed which consisted of higher fidelity source and distribution hardware as well as an enhanced control system. This activity progressed up through the Preliminary Design Review (PDR) in December 1988 when the SSFP baselined a hybrid 20 kHz/DC power distribution system. In this system the primary power was distributed at 440 Volts 20kHz and the secondary power (power inside the modules) was distributed at 120 Volts DC.

When the distribution system was rebaselined as a hybrid, it was decided to combine the current PMAD System Test Bed with the activity to develop the Integrated Test Bed. The combined activity utilized the power hardware from the PMAD System Test Bed and merged it with the control system under development for the Integrated Test Bed and evolved it into the PMAD 20khz/DC Test Bed.

At the time the PDR for the PMAD 20khz/DC Test Bed, the SSFP determined that changing to the end-to-end DC system would be more cost effective. The new distribution system features a nominal 160 Volts DC primary system and 120 Volt DC the secondary system. Further information on this system can be found in Reference [3]. This caused the test bed program to be reset one more time. The plan was then to utilize the control system hardware and software from the PMAD 20khz/DC test bed and to modify and procure new power hardware.

Since the change in August 1989 the test bed power hardware components have remained relatively stable. However, other Space Station Freedom Activities have taken place which have resulted in a restructured Man Tended Configuration (MTC). During the restructure the SSFP reduced the power channel size from a nominal 18.75 KW to 9.375 KW. This has caused some modifications in plans for the final test bed build-up. In addition, the restructure has caused changes to be made in the interprocessor communications data bus being used for control and to severely limit the functionality of the control system through the "scrubbing of software." The Test Bed Program is in the process of adapting to this latest "scrub." However, because of the maturity of the work done in the control area, along with its usefulness in a ground based application, it was decide to complete the implementation. Reallocating on-orbit and ground control functions to adapt to these new ground rules will be on-going activity during the next year.

KEY TEST BED OBJECTIVES

Throughout these periods of change the overall purpose of the LeRC Test Bed program has remained consistent; that being to evaluate the unique requirements of the power system for the SSFP application. To address these unique needs results in the following key test objectives:

Evaluate source / distribution system interaction with the solar array -- This testing addressees the high power level of the SSFP power system and the higher than normal impedance characteristics of the source system, to provide early evaluation of true end-to-end system performance and behavior. Further information can be found in Reference [4].

Evaluate primary / secondary system protection concepts -- This testing addressees the protection of the high power primary system as well as examining the unique challenges associated with the "current limited nature" of the secondary distribution power processing elements. Further information on this can be found in Reference [5].

Evaluate primary / secondary power quality and user load interactions -- This testing addresses the problems of conducted EMI along with the start-up, shutdown and interaction of user loads with the high power distribution system.

Evaluate control concepts and Ada Software Performance -- This development and testing provides early programming and implementation experience with a real time distributed control system using the Ada programming language. Further information on this can be found in References [6] - [8].

Generate early data to calibrate / validate system models and simulators -- This testing provides early data to anchor and refine system models and simulations. Further information on this can be found in Reference [9].

TEST BED DEVELOPMENT APPROACH

The development philosophy of the PMAD DC Test Bed is to replicate a significant enough portion of the Space Station Freedom PMAD System to investigate the above test objectives. The current PMAD system for the Manned Tended Configuration consists of two 9.375 kW nominal / 12 kW peak power channels which distribute solar array or battery power to via a primary distribution system to a set of DC to DC Converter units (DDCUs) and finally through a set of switching assemblies (SPDAs and TPDAs) to the user.

To develop a meaningful subset of the SSF electrical power system which can provide early test results and which can evolve as the SSF program matures, a three phase development effort has been undertaken. In Phase A, a single end-to-end power channel of 9.375 kW is being assembled using "hardware of convenience." Hardware of convenience is considered to be functionally equivalent to the hardware which will be eventually used on the Space Station but more readily available. In some cases, the hardware contains additional functionality which may not necessarily be in the final flight system but allows the evaluation of alternate design options. Currently the test bed program has completed the Phase A. In Phase B, the intent is to build a second power channel using copies of the breadboard hardware being built for the Space Station Freedom application. Finally, in Phase C the goal is to parallel and integrate the two power channels built-up during phase A and B. This requires replacing the four RBIs (Remote Bus Isolators) used in the Phase A and B with the newly developed High Power RBIs (HRBIs) that are rated for the higher available fault current. The completion of Phase C is currently being reevaluated in light of the program restructure. Further Information on the HRBI can be found in Reference [10].

TEST BED DESCRIPTION

Figure #2 shows a diagram of the PMAD DC Test Bed. Shown in the Diagram is the completed Phase A portion of the Test Bed. The Phase B activity will add another channel similar to the one shown and is expected to be completed within the next calendar year. The test bed consists of two major elements, the power element and the control element.

TEST BED POWER ELEMENT

The source power for the test bed consists of an 82 string solar array switching unit which regulates the primarily bus to a nominal 160 Volts during solar insolation. The SSU regulates raw power either from the 35 KW LeRC Solar Array Field, or from the LeRC designed Solar Array Simulator. Further information on this simulator can be found in Reference [11].

The power from the SSU flows into the Direct Current Switching Unit (DCSU). This unit consists of switches called Remote Bus Isolators or RBIs for power switching and source protection as well as a large capacitor (4000uf) to provide primary bus stabilization. The DCSU directs the power into energy storage through two Battery Charge / Discharge Units BCDUs. The BCDUs provide regulated current and voltage to charge the batteries during insolation and regulate the primary bus voltage during eclipse.

Power from the DCSU flows though a rotary power transfer device (roll ring) into a Main Bus Switching Unit (MBSU). The MBSU also contains Remote Bus Isolators (RBIs) which are used to enable and disable power to the DC to DC Converter Units (DDCUs), as well as provide primary source protection. The DDCUs provide the interface between the primary distribution system and the secondary. At the interface the DDCUs convert the voltage from 160 Volts on the primary to 120 Volts for use on the secondary. In addition, they provide EMI and grounding isolation between the primary and secondary distribution systems.

The power out of the DDCUs energies the secondary distribution system which contains the Secondary and Tertiary Distribution Units (SPDAs and TPDAs). The SPDA and TPDAs are made up of Remote Power Controllers (RPCs) that emulate the secondary and tertiary switching functions found inside a manned module. Finally, load converters (LC) which are DC to DC converters and provide constant power loads are used to exercise the test bed. It is expected that a majority of the loads on the Space Station will be of the constant power type. Currently the test bed contains five one kW 120 Volts to 28 Volt load converters to provide loads of this type. Information on the characteristics and testing of these converters can be found in Reference [12].

Test Bed Power Components

The test bed power components in the phase A configuration are devices that are functionally equivalent to the hardware that will eventually fly, however, they are more readily available. The principal characteristics of the key components are outlined below.

Solar Array Switching Unit (SSU) -- The SSU is a shunt regulator. It regulates the output voltage by shunting solar array strings to ground and passing the output of the other strings to the load

- o 32KW Total Power Capability
  - 80 Solar Array Strings
  - Each String 2.5 Amps at 160 VDC
- o Programmable Voltage, Current and Undervoltage Setpoints via Mil-STD-1553B Interface

Battery Charge / Discharge Regulator (BCDU) -- The BCDU controls the charge and discharge current and voltage to the batteries from the main power bus and visa-versa.

- o Topology -- Two Parallelled Bi-Directional 3.0 KW Buck / Boost Modules
- o Charge Mode
  - 120 to 157 Input Voltage
  - 90 to 130 Output Voltage
- o Discharge Mode
  - 75 to 150 Input Voltage
  - 120 to 157 Output Voltage
- o Mil-STD-1553B Interface for Data Monitoring and Commands

DC to DC Converter Unit (DDCU) -- The DDCU is a DC to DC Converter which converts the 160 VDC primary power to 120 VDC for the secondary distribution. In addition, it provides EMI isolation and grounding between the primary and secondary distribution systems.

- o Output power -- 12.5 kW (Nominal)
- o Topology -- Two 6.25 kW Parallel Resonant Modules
- o Input Voltage -- 125 - 170 VDC
- o Output Voltage -- 120 - 128 VDC +/- 1% Programmable
- o Efficiency full load -- 91 % (excluding control power)
- o Current Limit -- Programmable
- o Mil-STD-1553B Interface for Data Monitoring and Commands

Further Information on the SSU, BCDU and DDCU can be found in Reference [13].

Remote Bus Isolator (RBI) -- The RBI are hybrid switching devices which contain a relay in parallel with a solid state switch to control DC current. The RBIs are the primary components used to construct the MBSU and DCSU.

- o 160 VDC 220 Amp Normal Operation
- o 400 Amp Interrupt Capability
- o 200 Volt / 200 Amp Dead Face Relay
- o Supports Overcurrent and Differential Protection
- o Settable Overcurrent Trip Points
- o Different Devices can Support both Unidirectional and Bi-Directional Capability
- o Mil-STD-1553B Interface for Data Monitoring and Commands.

Remote Power Controller (RPCs) -- The RPC are solid state devices which control DC Current and limit current during a fault. The RPCs are the primary components used to construct the SPDAs and TPDAs.

- o Ratings
  - 10 Amps @ 120 Volts
  - 42 Amps @ 120 Volts
  - 150 Amps @ 150 Volts
- o Overcurrent and Differential Protection
- o Settable Current Limiting During Faults
- o Timed Undervoltage Fault Detection Circuit
- o 1553b Interface for Data Monitoring and Commands

Further Information on the RBI and RPC devices can be found in Reference [14].

TEST BED CONTROL ELEMENT

The test bed control systems consists of hierarchically networked computers which simulate the Electric Power System Controllers which will exist on the actual station. The control software includes a set of control algorithms along with utility communication software, all of which is programmed in Ada. The hardware, controller algorithms and software development are outlined below.

Test Bed Control Hardware

The controller hardware consists of an Operator Interface System or OIS which provides the operator with command and display capability. This computer communicates with the Power Management and Control Computer (PMC), which regulates the operation of the overall Test Bed. The PMC then communicates with Photovoltaic Controller, or PVC, and the Main Bus Controller, or MBC, over an IEEE 802.4 communications network. The PVC and MBC are the next layer in the control hierarchy. The PVC controls, monitors and passes setpoints to the SSU, DCSU and the BCDU over a Mil-Std-1553b data bus. Likewise the MBC performs similar functions to the MBSU and the DDCUs.

Finally, the PMC communicates over a separate data link (802.4) to the Load Management Controller. The LMC provides the capability to communicate with the switches in the SPDAs and TPDAs as well as the load converters. The LMC functions, although not a LeRC Space Station Work Package (WP-04) responsibility, is required to address system level issues.

The control hardware for the test bed is characterized by the need to be cost effective but also be as compatible as possible with the control hardware proposed for the SSF. This led to the utilization of Compaq 386/20e PCs. These computers are based on the 80386 processor and have a 20mHz clock rate.

Test Bed Control Software

The test bed control software is divided into two major categories, the utility software and the algorithm software.

The design of the utility software provides the major communications for the test bed. The software is characterized by five major modules: 1) a Router which directs both inter and intra processor communication; 2) a Text Interface which handles communication between the system and user; 3) a Network Interface which handles communication between the distributed computer controllers over the 802.4 bus; 4) a Power Component Interface which handles communication between the controller and power components over the 1553B bus; and 5) an Algorithm Interface which provides the test bed designer and developers with a uniform link to exercise various control algorithms. Using just the utility software the test bed can be run in what is know as manual mode via the operator inputing commands directly to the power components.

The test bed algorithm software consists of a series of functions that utilize the algorithm interface to facilitate the control of the test bed. When these algorithms are used the test bed is considered to be in the Automatic Mode. In the automatic mode the operator has functions that provide for orderly start-up and shutdown of the test bed. In addition, the automatic mode has functions such digital filtering to smooth the sensed data, a state estimator to detect bad data, and fault detection algorithms to back-up the hardware fault protection system in the areas of overcurrent detection, undervoltage detection, and power interrupt detection. With the exception of the start-up and shutdown functions, which are test bed specific, the use of the automatic mode functions for the on-board system is currently being assessed in light of the restructured program.

Test Bed Control Software Development

The test bed control system software has been written using the Alsys 386 Version 4.3.3 Ada compiler. The software was developed using object oriented design techniques to provide portability and flexibility. The initial software design was started in June 1988 and became operational in September 1979. Since that time, the utility software has been used to control both the PMAD System Test Bed (20Khz) and the current PMAD DC Test Bed. The control algorithms for the PMAD System Test Bed were rewritten to accommodate the new all DC Configuration. In porting the utility software from one test bed to the other, the target computer was changed from an 8086 based single board controller to its current host, the Compaq 386 PC.

ROLE OF THE TEST BED IN SPACE STATION DESIGN VERIFICATION AND OPERATIONS

As the Space Station Program evolves from the developmental stage, through the verification stage to the operational stage the test bed can provide valuable information. The test bed can provide early system data in the many areas discussed previously to drive the final design. Because the LeRC Solar Array Field is the only one currently in the program that can be used to test electrical function performance, one critical test is to demonstrate end-to-end operation of the test bed using the array field. This, along with other tests, will provide greater confidence in the final product and hopefully reduce downstream design changes.

In the verification phase, the test bed can be used to perform "edge of the envelope" tests which may damage higher fidelity hardware and thereby impact the development schedule. In addition, because of the breadboard or brassboard nature of all of its components it is much easier to debug and troubleshoot anomalies. The reason for this is that the breadboards provide easy access to most of the components, as opposed to the engineering model or flight hardware which is "buttoned up."

During the operational phase of Space Station Freedom, the Test Bed can be used to evaluate alternate design approaches and new components before they are evaluated in a higher fidelity test facility. Furthermore, the test bed can be used to evaluate advanced control and automation approaches which can be used to reduce electrical power system operational costs. This may include items such as power utilization scheduling, system diagnostics and component diagnostics. Current work being done in this area is outlined in Reference [15].

CONCLUSION

The LeRC PMAD DC Test Bed evolved from a concept to working hardware in a little over 15 months. It is already generating useful test data to support the on-going SSFP development effort. It is expected to continue to provide high quality test, verification and operational information for many years.

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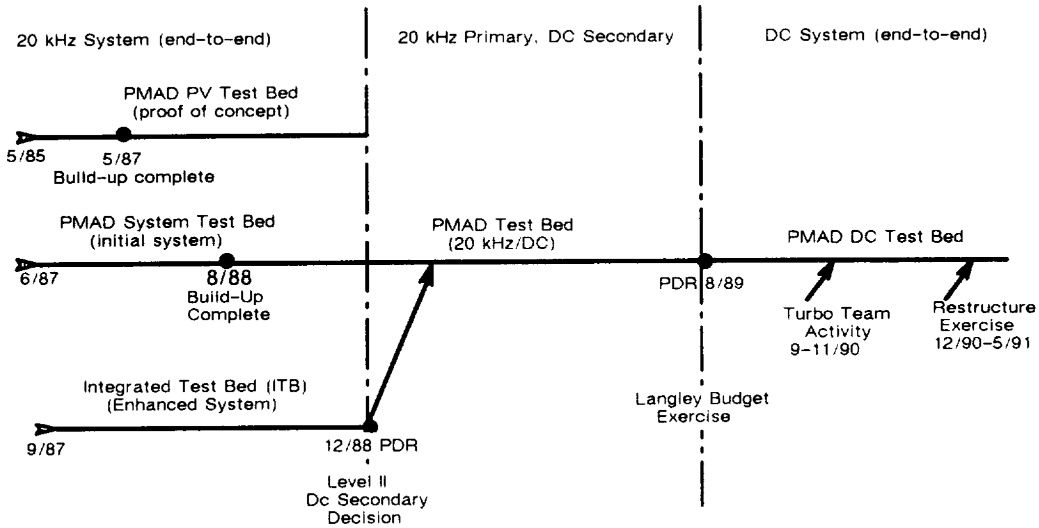

Figure 1 – PMAD Test Bed Development History

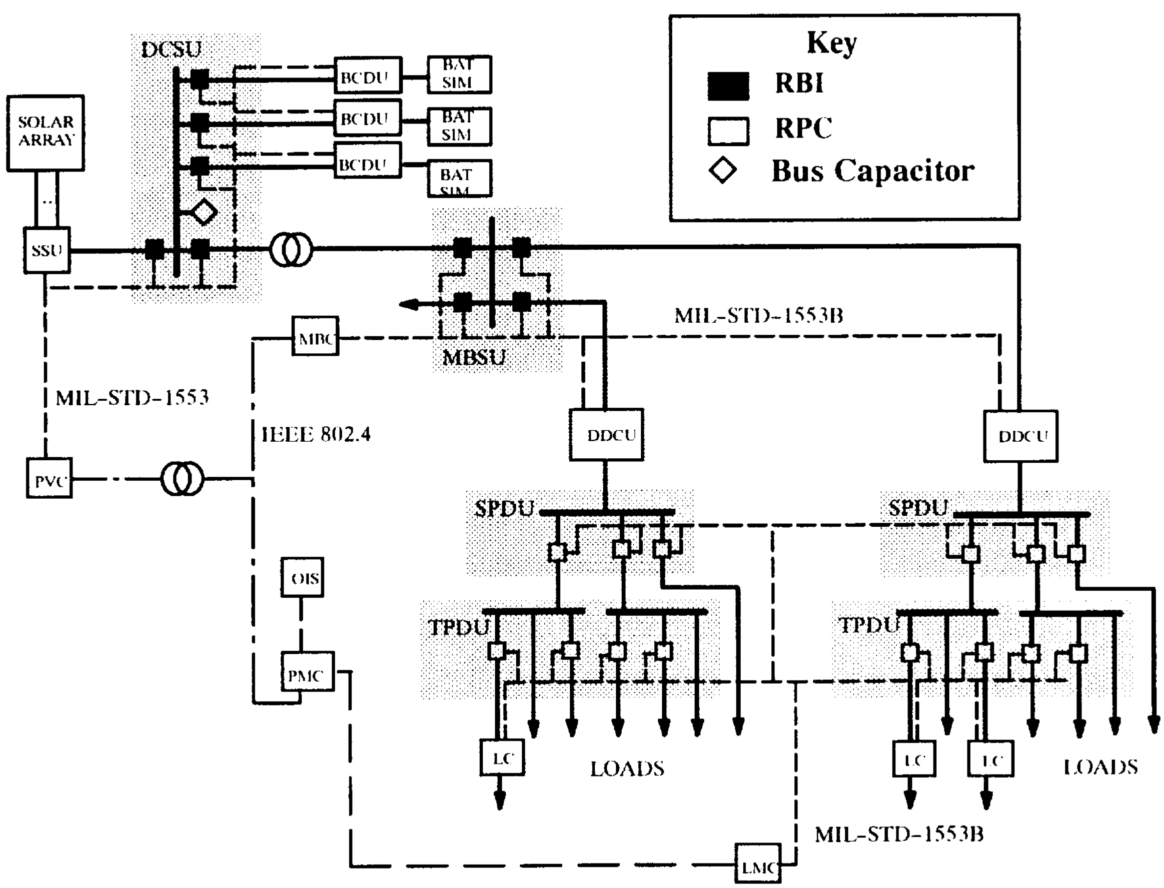

Figure 2 – Power Management and Distribution DC Test Bed

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