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Description of the PMAD DC Test Bed Architecture and Integration Sequence

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DESCRIPTION OF THE PMAD DC TEST BED ARCHITECTURE AND INTEGRATION SEQUENCE

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ABSTRACT

The National Aeronautics and Space Administration (NASA), Lewis Research Center is responsible for the development, fabrication and assembly of the electric power system (EPS) for the Space Station Freedom (SSF). The SSF power system is radically different from previous spacecraft power systems in both the size and complexity of the system. Unlike past spacecraft power systems the SSF EPS will grow and be maintained on orbit and must be flexible to meet changing user power needs. The SSF power system is also unique in comparison with terrestrial power systems because it is dominated by power electronic converters which regulate and control the power. Although spacecraft historically have used power converters for regulation they typically involved only a single series regulating element. The SSF EPS involves multiple regulating elements, two or more in series, prior to the load. These unique system features required the construction of a test bed which would allow the development of spacecraft power system technology. This paper provides a description of the Power Management and Distribution (PMAD) DC Test Bed which was assembled to support the design and early evaluation of the SSF EPS. A description of the integration process used in the assembly sequence will also be given along with a description of the support facility.

INTRODUCTION

The primary purpose of the PMAD DC Test Bed is to address system issues associated with the distribution and control of multi-kilowatt dc power for the SSF Freedom. The SSF power system is totally different from any past aircraft or spacecraft power system because it is being designed to have the same attributes as a terrestrial utility power system. This implies that the SSF power system shall be secure under all conditions, provide power to a multitude of users who are guaranteed a certain power availability, power quality, and independent load control, and can evolve and grow

as SSF needs require. Because NASA and the Aerospace industry did not have experience with the design and operation of this type of electric power system it was necessary to assemble a systems test bed to gain experience prior to final design and fabrication of the flight power system [1].

Some of the salient features incorporated in the SSF power system design, in order to achieve the above attributes, include the following:

- 1.) Multiple power sources
- 2.) Multiple paths from sources to loads
- 3.) Power peaking capability for unscheduled load demands
- 4.) Large ratio of maximum to connected load (Diversity factor)
- 5.) System protection to maximize user power availability

Although the SSF power system architecture was developed to function in a utility like fashion, there are major differences between earth based utility power systems and the station power system. The SSF power system is a self-sufficient island with limited power sources and storage, and a predominance of power processors (i.e. source and secondary converters, load converters) that condition the power. Also, there is no interconnection to a power pool that can be used under severe operating conditions to minimize the effects of a disturbance. This type of "soft" source must limit the current, during an overload or fault condition, to a value that will not result in failure of the power converter.

The SSF PMAD system is composed of a number of orbital replacement units (ORU) and associated wire, cables and connectors necessary to interconnect the ORU's. All PMAD hardware such as converters and switchgear are located within these ORU's, allowing growth and maintenance of the flight power system. The test bed power system includes functional equivalent breadboards of all types of ORU's in the flight power system. Functional equivalence implies that the test bed ORU's have the same internal busses, the same

interfaces for data and power, and the same electrical and control response as the hardware to be used in the flight ORU's. This type of functionality in the ORU's along with the correct parameters for the power cables results in a test bed system response similar to the flight system.

Figure 1 shows a one line diagram of the test bed system and part of the support facility. The Sequential Shunt Units (SSU) receive input string power from either the solar array or solar array string simulators and regulate the output voltage at a nominal value of 160vdc. The DC Switching Unit (DCSU) contains the source bus and Remote Bus Isolator (RBI) switchgear which connects the source power through the SSU to the battery storage simulator through the Battery Charge Discharge Units (BCDU). The DCSU bus is connected to the Main Bus Switching Unit (MBSU) through the alpha joint roll ring simulator. The MBSU contains the necessary RBI switchgear to interconnect each Dc to Dc Converter Unit (DDCU) with the primary distribution system.

The secondary distribution system consists of a DDCU which steps down and regulates the secondary distribution voltage to 120vdc. Each secondary distribution subsystem contains two bus assemblies, a Secondary Power Distribution Unit (SPDU) and a Tertiary Power Distribution Unit (TPDU). The SPDU's and TPDU's connect the Load Converter Units (LCU) and loads to the power distribution system through Remote Power Controllers.

The test bed as configured can be used to address many system issues. The following is a partial list of issues that will be addressed using the test bed power system.

- 1.) Fault detection, isolation and system reconfiguration
- 2.) Power sharing among primary (BCDU) and secondary (DDCU) converters
- 3.) End to end system voltage regulation
- 4.) Power channel paralleling
- 5.) DDCU paralleling
- 6.) Energy management
- 7.) Contingency analysis for defensive control action
- 8.) Conducted EMI (Primary and secondary)
- 9.) Power Quality
- 10.) System start-up and shutdown procedures
- 11.) System peaking procedures
- 12.) System power availability

TEST BED INTEGRATION SEQUENCE

The test bed power system is being assembled in phases. Phase A involves the integration of all power channel A hardware and software, and phase B corresponds to channel B. Currently the test bed is involved in phase B, with all power channel A hardware integrated into the

test bed power system. The integration process for the hardware and software was broken down into four types of testing.

The test bed power system shown in Figure 1 contains hardware from multiple sources [1]. In order to facilitate the integration of the hardware into the test bed it was decided to break the integration process into phases. Each phase of the test bed corresponded to the assembly of a power channel. The phase A integration activity began in August 1990 with the build up of the primary distribution system for channel A and was completed in May 1991. The phase B activity involving the integration of power channel B will start following delivery of Rocketdyne breadboard hardware in August 1991 and will finish in March 1992. Each channel during the integration process was treated as an independent power system with its own software, control power, sources, and loads. The final configuration of the test bed linking both channels together to form a single power system will occur following completion of channel B integration.

As indicated in the introduction one of the reasons for assembling the test bed at the Lewis Research Center was to understand the problems associated with system integration. An Integration Plan was developed for the test bed which specified test procedures for each type of testing (i.e. components, assembly units/ORU's, subsystems, and system). This allowed for early verification of hardware and software performance as well as identification of problems and potential solutions. Tests performed at each level in the integration sequence involved only the necessary tests to demonstrate successful hardware and software operation.

All power channel A hardware and software have been integrated into the test bed and a description of the components and Assembly Units (ORU's) will be given in the following section.

TEST BED COMPONENT AND ASSEMBLY UNIT DESCRIPTIONS

The PMAD DC Test Bed is located in room 100 in the Power Systems Facility (PSF), building 333 at the NASA Lewis Research Center in Cleveland, Ohio. As indicated earlier, power channel A of the test bed is currently in operation. The hardware used in this channel is functionally similar to the hardware being developed for the SSF program. The following descriptions provide general information on the topology and operation of the test bed hardware.

Sequential Shunt Unit - The SSU is the primary source regulator during the insolation period of the SSF orbit.

The solar array is segmented into 82 strings each capable of supplying about 2.5 Amps of current at an array voltage of 160 Volts. Each string is input to the SSU which regulates the output voltage by shunting individual strings to neutral to maintain a nominal output voltage of 160 Vdc. The rated output capability of the SSU is dependent on the solar array or solar array simulator input with a maximum of 40 kW. Two types of shunt units are currently under test at the Lewis Research Center [2]. These units were developed by Loral and TRW and have similar power topology but different control loops. Both units have a Mil. Std. 1553 data bus interface that allows monitoring of the output voltage and current. Commands issued to the units through the data bus allows adjustment of the output voltage setpoint, and on/off status.

Battery Charge Discharge Unit – The BCDU is the primary source bus regulator during the eclipse portion of the SSF orbit [2]. The BCDU during eclipse converts the battery output voltage (80 Vdc to 104 Vdc) to the distribution bus voltage of 160 Vdc. During the insolation phase the BCDU allows control of the battery charge current so that the state of charge for each battery set can be equalized prior to eclipse. The BCDU uses a buck boost circuit topology for the charge and discharge converter. The BCDU's used in the test bed are rated for 6.2 kW at a distribution bus voltage of 160vdc. Power channel A of the test bed utilizes BCDU's developed by TRW, Space Systems Division [3]. The TRW BCDU's are bi-directional units that utilize transformer primary and secondary windings for the buck and boost inductors and a common control for charge and discharge operation. The test bed BCDU's all contain a 1553 data bus interface that allows monitoring of the input and output voltage, current, and power. Set point commands for charge and discharge operation are also issued through the data bus interface.

Remote Bus Isolator – The RBI is a controlled switch used to monitor and protect the primary distribution system. The RBI's used in the test bed were developed by Westinghouse, Electrical Systems Division [4]. All RBI's are rated at 160 V, 210 Amps, and can interrupt currents up to a maximum of 400 Amps. Switching operation is accomplished in the RBI using a hybrid circuit with an electro-mechanical relay in parallel with a transistor. Make and break operation is accomplished with the transistor and the relay is used to carry steady state current. Over-current and differential current trip capability is also included in the RBI's. Communication with all RBI's is done through a 1553 data bus interface unit which allows monitoring of the input and output voltage and current, power and switch status.

Over-current and differential trip thresholds and switch on/off commands are also issued through the data bus.

DC to DC Converter Unit – The DDCU is used to regulate the secondary bus and provide isolation between primary and secondary. The DDCU developed by TRW [3] contains two parallel 6.25 kW modules for a rated output power of 12.5 kW. The DDCU has a common input filter element that feeds the two, phase displaced, 20kHz, series resonant dc to ac inverters having rectifier elements and first-stage output filters, followed by a common second-stage filter. The DDCU has been designed to allow parallel operation of two 12.5 kW units, and can adjust the power sharing between the units to maximize system power transfer to the loads. A 1553 data bus interface allows monitoring of the input voltage and current, the output voltage, current, power, and power sharing, and on/off status.

Remote Power Controller – The RPC's are controlled switches that are used to monitor and protect the secondary distribution system. RPC's are solid state switches incorporating current limiting for turn-on and faulted operation. A family of RPC's (10Amp, 42Amp, 130Amp) have been developed by Westinghouse for use in the test bed [4]. All RPC's have over-current, differential, and under-voltage trip capability. Telemetry data from the RPC consists of input voltage, current, output voltage, current, power, and switch status. Setable current limit, differential, and under-voltage trip thresholds and switch on/off commands are also issued through the data bus.

Load Converter Units – LCU's are used in the power system to convert the secondary distribution bus voltage to a final value dependent on the user load needs. The LCU can be considered as a power supply typically located within the load unit. A family of bulk load converters have been developed for the PMAD DC Test Bed [3,4]. All LCU's are rated 120v input, 1 kW output at 28vdc. Four topologies (full bridge converter, series resonant, zero voltage switched, and series inductor) have been utilized in order to provide a spectrum of load converter types. This will allow testing [5] of the test bed secondary with bulk load conditions similar to what is expected on the SSF.

DC Switching Unit – The DCSU used in channel A of the test bed is an assembly of Westinghouse RBI's and a power bus that functionally represents the SSF ORU. The DCSU is used to monitor and control the source distribution at the point where the BCDU's and SSU are paralleled. DCSU bus protection is implemented using differential and over-current protection.

Main Bus Switching Unit – The MBSU like the DCSU is assembled using Westinghouse RBI switchgear. The

MBSU is used to monitor and control the primary distribution system at the point where two source distribution systems are tied together. MBSU bus protection is implemented using differential and over-current protection.

Secondary / Tertiary Power Distribution Assembly - The SPDA/TPDA are used to monitor and control the secondary and tertiary distribution system. SPDA's and TPDA's are assembled using Westinghouse RPC switchgear. The secondary and tertiary distribution assemblies for the SSF are equivalent in function to a substation in a utility power system. Bus protection can be implemented using differential and over-current methods.

Distribution System - As can be observed from Figure 1 the distribution system for the test bed utilizes radial networks for both the primary and secondary distribution systems. The cross tie linking the channel A and channel B MBSU's is operated in the normally open state and is closed following loss of either source bus. The current SSF design does not parallel source channels.

As mentioned in the introduction, the cables used in the test bed were selected in order to achieve the same system response as the flight system. This required that the cable impedance parameters match those being evaluated for the SSF. The cables for the SSF have inductance and resistance values per length of cable which closely match that of welding cable of the same gauge. The test bed cables in the primary therefore were chosen to be of the same length and gauge as the flight cables since the primary of the test bed contains the same number of switchgear in series with the DDCU as the station. For the secondary the cable gauges are the same as the SSF but lengths were increased since the test bed secondary does not have as many RPC's as the station. Therefore total distribution impedance on the output of the DDCU more closely approximates that expected for the station.

Several concepts for the protection system for the SSF are being evaluated using the test bed channel A system [6]. These concepts all involve over-current, differential, and under-voltage methods. The distribution system was divided into zones with the boundaries determined by the location of the primary and secondary switchgear. All zones overlap at the switchgear defining the end of the adjacent zones. This provides protection to the entire test bed including any fault that could occur within a power component. Both back-up and primary protection was implemented for all zones.

Controller Network - The controller network for channel A of the test bed consists of five processors that are linked together using an IEEE 802.4 data bus. At the highest level in the control system [7] hierarchy is the Power Management Controller (PMC) and the Load Management Controller (LMC). The PMC and LMC coordinate all lower level controllers for the primary and secondary distribution systems. All second tier controllers (PVC, MBC, SPC, TPC) communicate with lower level components and assemblies through 1553 data busses.

All controllers in the test bed use Compaq 386 based computers with math co-processors. Several generations of Ada software have been developed which allow communication with all hardware, capture and display of test bed data, and algorithms for system control. The test bed software resembles a SCADA system used by utility power systems.

SUPPORTING FACILITY DESCRIPTION

The basic configuration of the PMAD DC Test Bed support facility allows for the connection of a variety of sources and loads to the test hardware. The facility provides water cooled tables for the mounting of test hardware, Figure 2. Cooling tower water is provided at 50 psig at 70-80 deg. F. A control and data system is provided to control facility related equipment and provide storage and display of both external instrumentation and test hardware generated data. The final configuration will provide fourteen 4 X 6 foot cold plate tables to mount test hardware on. To date, eight cold plate tables are installed.

The PMAD DC Test Bed Facility includes as sources, a solar array field, two solar array string simulators, four battery simulators, four 90 kWatt(kW) dc power supplies, and a steady state solar array simulator. Four types of electronic loads and six fixed resistance heater element loads are available representing 208 kW of available user loads. A personal computer (PC) based, networked system, running GENESIS control series software by Iconic's Inc. provides facility control, data collection and data archival. The following sections detail the PMAD DC Test Bed support facility.

Sources

Various sources of DC power are available to the PMAD DC Test Bed, Table 1. The majority of these sources are located in a termination room in PSF. The termination room has a power patch panel that allows power to be distributed throughout PSF. Four cables are routed through a wiring trench to the PMAD DC Test Bed where dc contactors tie the test bed to the power sources.

Solar Array Field – The solar array field consists of 960, 2.5 A, 17 V silicon solar cell modules configured in 80 strings at selectable open circuit voltages of 120/135/150/165/180 V. All 80 strings are brought into the termination room power patch panel. The maximum useable array power is 30 kW at 160 V.

Solar Array String Simulator – The solar array simulators consists of 90 (82 strings with 8 spare strings) water cooled MOSFET stages that simulate the I-V characteristics of a solar array [8]. It operates at a maximum short circuit current of 2.6 A and a maximum open circuit voltage of 210 V. The simulator provides 44.7 kW maximum power. The solar array string simulators are located on the floor with the PMAD DC Test Bed.

Battery Simulators – Each of the four battery simulators consists of a string of eight 80 ampere-hours (AH), 12Vdc, sealed lead-acid batteries in parallel with a 10 kW Sorensen DCR 160-62T dc power supply and a 2 ohm load. The power supply and load are independently switched in through contactors depending upon the battery voltage. Using the batteries alone during the discharge mode, each simulator can provide nominally up to 80 A at 96Vdc for a half an hour. When the battery voltage drops below 90Vdc the power supply is switched in to provide up to 62 A at 86Vdc. During the charge mode the batteries can accept the nominal AH that were previously discharged at a maximum of 117Vdc. When the battery voltage exceeds 117 Vdc, the parallel load switches in to absorb up to 6 kW at 118 Vdc. The simulators can be remotely controlled automatically through the data system or manually from the operators console.

Dc Power Supplies – Four 90 kW, 400 Adc, 225 Vdc Dynapower Corporation power supplies located in the termination room and are available to the PMAD DC Test Bed via the power patch panel. Remote control of two of the power supplies is provided in the test bed. The physical layout of the test bed facility is shown in Figure 2.

Loads

The PMAD DC Test Bed has a number of different types of loads, Table 2. There are four electronic load banks which provide active, fast response loading using semiconductors as the load elements. Two of the loads were manufactured by Energy Systems Inc., one load was manufactured by PPM Corp, and one by Hewlett-Packard. Another type of load currently available in the test bed but not detailed in this paper consists of discrete water cooled resistive loads. These loads are referred to as bulk loads.

All of the loads in the PMAD DC Test Bed except three portable ones, are controllable from the Load Controller. The Load Controller is a standalone PC running a QBASIC program developed at NASA that communicates to the Energy Systems Load Banks, the Hewlett-Packard loads, and the PPM loads via an IEEE-488 bus. The bulk loads are controlled by a METRABYTE Corp. digital input/output (I/O) board that is connected to the load controller via an RS-232 serial port. The loads may be controlled individually or they can all follow a predetermined load profile that is downloaded to the main program. All of the loads are discussed in detail in the following paragraphs. A summary of all the loads is shown in Table #1.

Programmable Load Banks – The PMAD DC Test Bed utilizes four types of programmable electronic load banks. Two of the programmable load banks are Energy Systems 32 kW load banks that consist of two program control modules (PCMs) and sixteen water-cooled power absorbing modules (PAMs). Eight of the PAMs operate at dc to 20 kHz and can dissipate 4 kW at 200 V. The other eight operate at dc or 400 Hz and can dissipate 4 kW at 150 V with a power factor of +/-0.7 to 1. Each PCM is a single board IBM-PC compatible computer that programs up to eight PAMs for constant voltage, power, current, or resistance with various trip levels and load profiles. The PAMs can be programmed locally through a front keypad or remotely through an IEEE-488 interface.

Another programmable load is a 7.2 kW Hewlett Packard load bank that consists of four multiple load, air-cooled, mainframes (HP 6050A), four 240 V, 250 W load modules (HP 60504A) and thirteen 60 V, 600 W load modules (HP 60503A). Each mainframe can dissipate up to 1800 W so a combination of load modules can be installed into any one mainframe. The modules can be programmed for constant current, resistance or voltage with various slew rates and duty cycles. Programming can be done via the front keypad or via an IEEE-488 interface.

The final programmable load is a 32 kW PPM load bank that consists of a control unit and sixteen water-cooled 200 V, 2 kW load modules. The load modules can be programmed for constant current, power or resistance with various load profiles. Programming can be done through the front key panel or through an IEEE-488 interface.

Data System

At the center of the PMAD DC Test Bed support facility is the GENESIS Control Series software by Iconics, Inc. GENESIS is a powerful PC based, process control software package that provides icon based process

control and data acquisition. The data system consists of four networked AT&T 386 PC's running GENESIS. Data is obtained from two main sources. External data is collected by remote processors called uMAC-6000's by Analog Devices. External data is essentially all test bed data except the Mil-Std 1553 data. External data includes test bed voltages, currents, temperatures, and cooling water pressures and flowrates. Remote PC's monitor the Mil-Std 1553 data bus and transmit the 1553 data to the GENESIS nodes via an ARCNET network interface. Transient data is obtained with Hewlett-Packard digital oscilloscopes.

CONCLUSIONS

The PMAD DC Test Bed assembled at the Lewis Research Center is a unique facility encompassing all the necessary hardware and software to allow early evaluation of system issues in support of the SSF Freedom Program. The test bed system because of its power level, control capability, and flexibility is also an asset for development of system technology to support future NASA spacecraft programs involving large power or more automated levels of control.

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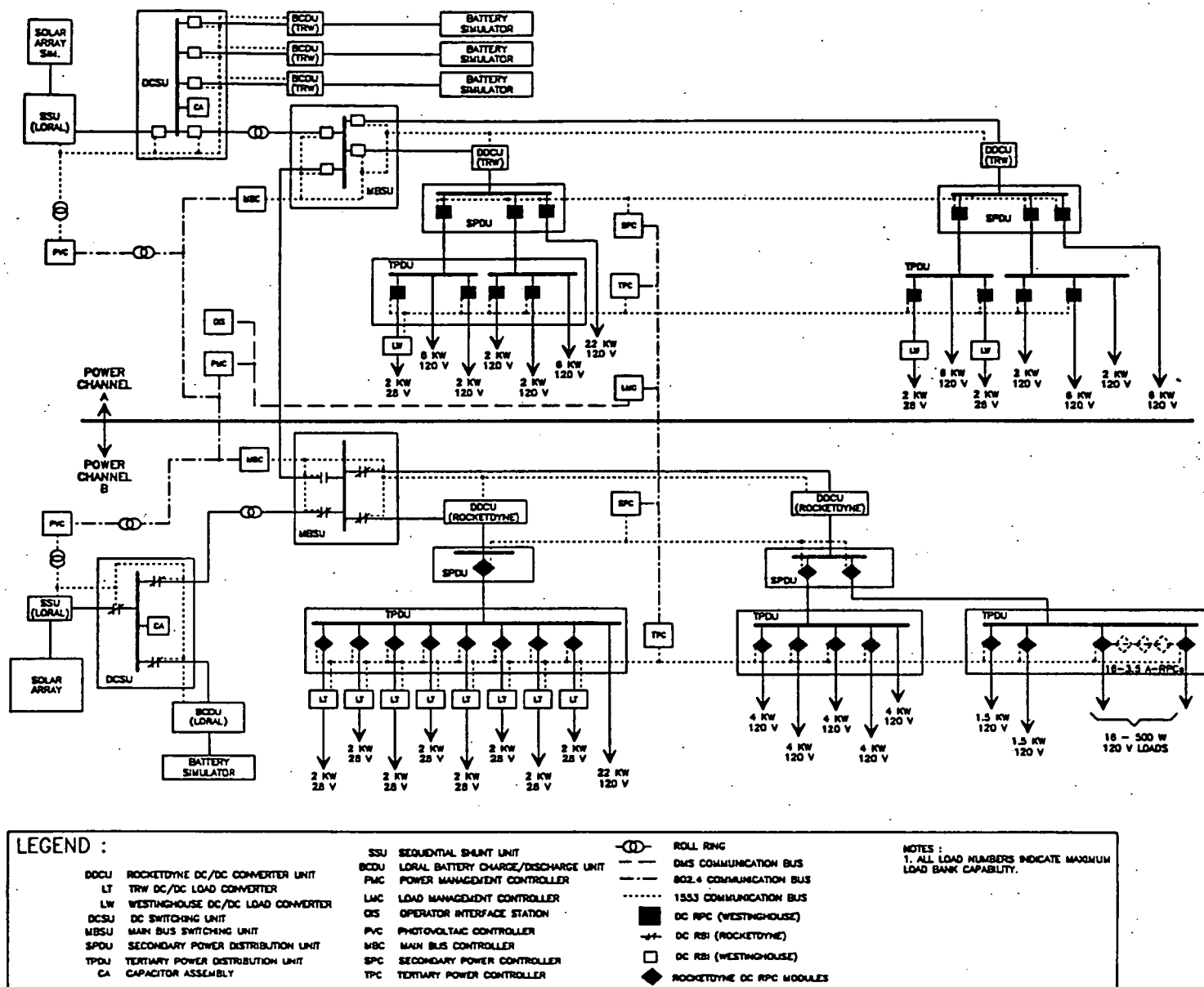


Figure 1 PMAD DC Test Bed One-line Configuration Diagram

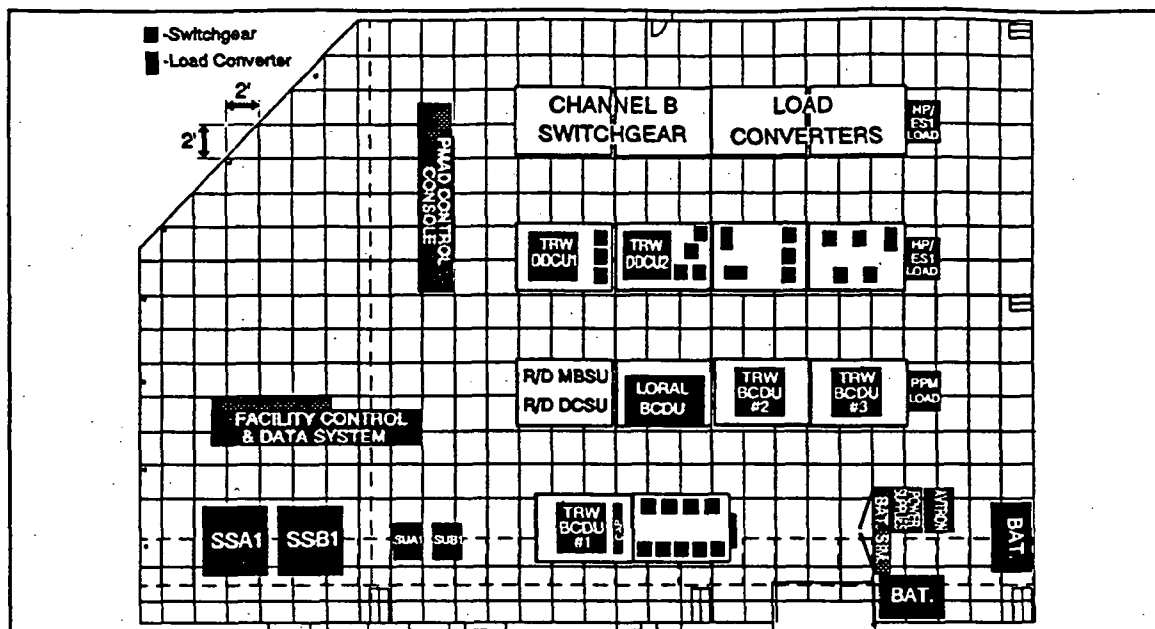


Figure 2: PMAD DC Test Bed

PMAD DC TESTBED SOURCE SUMMARY

	Power	Max. Voltage	Notes
Solar Array Field	30kW	180	80 - 2.5A Strings
Solar String Simulator	44.7kW	210	90 - 2.6A Strings
Battery Simulators	6.0kW	120	4
DC Power Supplies	90kW	225	4 (Dynapower Corp.)
Solar Array Simulators	45kW	200	2 (Abacus Corp.)

Table 1: Source Table

PMAD DC TESTBED LOAD SUMMARY

	Capacity	Resolution	Modularity	Max.Volt.	Modes	Programmable	Interface	Cooling
ES-1,	32kW	I-0.1A P-1W R-0.1Ω	8-4kW	200V	I,R,P	YES	IEEE-488	Water 16gpm
ES-2,	32kW/ 32kVAR Capacitive	I-0.1mA R-0.1mΩ V-0.1mV P-0.1mW	8-4kW	120V	V,I, R,P	YES	IEEE-488	Water 16gpm
H-P,	(1) 8.55kW	I-0.28mA R-8mΩ V-64mV	3- 250W	240V	V,I,R	YES	IEEE-488	Air
	(2)	I-3.2mA R-0.14mΩ V-16mV	13- 600W	60V	V,I,R	YES	IEEE-488	Air
PPM,	32kW	I-0.5mA P-0.5W R-0.2mΩ	16-2kW	200V	I,R,P	YES	IEEE-488	Water 15gpm
BULK LOADS	73.3kW (1)	750W	19.5kW	120V	R	YES	RS-232	Water 10gpm Total 2gpm
	(2)	750W	19.5kW	120V	R	YES	RS-232	
	(3)	750W	21kW	120V	R	YES	RS-232	
	(4)	1.3kW @ 180V	13.3kW	240V	R	NO	MANUAL	
AVTRON,	30kW (1)	1A	15kW	150V	I	NO	MANUAL	Air
	(2)	1A	15kW	150V	I	NO	MANUAL	Air

Table 2: Load Table

1-Energy Systems

2-Hewlett-Packard

3-PPM Corp.

4-Avtron Corp.

5- I:Constant Current, V:Constant Voltage, R:Constant Resistance

P:Constant Power

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