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Development and Testing of a Source Subsystem for the Supporting Development PMAD DC Test Bed

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NASA

DEVELOPMENT AND TESTING OF A SOURCE SUBSYSTEM FOR THE SUPPORTING DEVELOPMENT PMAD DC TEST BED

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ABSTRACT

The Supporting Development Power Management and Distribution (PMAD) DC Test Bed is described. Its benefits to the Space Station *Freedom* Electrical Power System design are discussed along with a short description of how the PMAD DC Test Bed has been systematically integrated. The Source Subsystem of the PMAD DC Test Bed consisting of a Sequential Shunt Unit (SSU) and a Battery Charge/Discharge Unit (BCDU) is introduced. The SSU is described in detail and component level test data is presented. Next, the BCDU's operation and design is given along with component level test data. The Source Subsystem is then presented and early test data is given to demonstrate an effective subsystem design.

INTRODUCTION

The Space Station *Freedom* (SSF) Electrical Power System (EPS) is a multi-kilowatt DC power system. The eventual goal is to provide 75kW (100kW peak) of power through eight (8) 9.3kW (12.5kW peak) channels. Each channel is comprised of a source subsystem, a 160Vdc primary distribution system, and a 120Vdc secondary distribution system. The source subsystem generates and regulates the 160Vdc primary power. The primary distribution power is converted to 120Vdc by DC to DC Converters (DDCUs). The secondary distribution system then distributes the 120Vdc power to the SSF users.

A Power Management and Distribution (PMAD) DC Test Bed has been developed to provide early component and systems level data to support the development of flight hardware and EPS designs. The PMAD DC Test Bed consists of breadboard hardware from power sources to user loads. [1]

Currently, the PMAD DC Test Bed has procured power hardware for one complete 12.5kW channel with plans to finish two complete channels. All of the hardware is controlled through an in-house developed control system. The hierarchical control system is comprised of Compaq 386-based local controllers running Ada driver software. Each controller is networked through an 802.4 data bus and communicates with each piece of power hardware through a MIL-STD-1553B data bus. With the recently completed Facility Data System, the PMAD DC Test Bed is entering a systems test program which will yield valuable data for the SSF Electrical Power System design.

Before the end-to-end PMAD DC Test Bed could be assembled and ready for testing, a structured approach to systems integration has taken place. As each piece of hardware arrived at NASA Lewis it was tested as a component to verify its design and manufacture and to characterize the hardware as a stand alone unit. The unit was then integrated and tested with other pieces of hardware which made up a defined subsystem.[2]

One such subsystem is the Source Subsystem. It is comprised of a Sequential Shunt Unit (SSU), a Battery Charge/Discharge Unit (BCDU), a DC Switching Unit (DCSU), and associated facility hardware which simulates the actual power sources (Solar Array and Batteries). The following sections describe in detail the SSU, BCDU, and the Source Subsystem test results.

SEQUENTIAL SHUNT UNIT

The Sequential Shunt Unit (SSU) being tested in the PMAD DC Test Bed was designed, developed, and built by Loral Corp. of Palo Alto, CA., a major subcontractor to Rocketdyne. The unit is a second generation breadboard and is functionally equivalent to the eventual flight unit.

The SSU is used to regulate the voltage output of an unregulated array of photovoltaic cells. Current designs for the SSF Solar Array indicate that the array will be comprised of over 30,000 solar cells arranged into 82 "strings". Each string will have an open circuit voltage, V_{oc}, of 250Vdc, and a short circuit current, I_{sc}, of 2.6Adc (Figure 1). Since the nominal primary distribution voltage is 140-180Vdc, the solar array will be operating on the "current leg" of its I-V curve. At this voltage each string acts as a 2.5Adc current source. The SSU regulates the primary bus voltage by actively shunting and unshunting solar array strings until the current from the SSU matches the load at the desired voltage.

Sequential Shunt Unit Description

The Loral SSU is contained in a standard 7ft. instrument rack. Due to the SSU's extremely high efficiency, only fan forced air cooling is necessary. The shunt units are contained on eleven (11) slide-in circuit cards each containing eight (8) shunt circuits. The power regulation control circuits are housed in the PhotoVoltaic Control Element (PVCE) which is shielded to prevent excessive electromagnetic interference (EMI). A Data Bus Interface (DBI) was developed and integrated by Rocketdyne for the two (2) Loral SSUs at NASA Lewis. The DBI provides control and command of the SSU through the 1553B standard data bus in the PMAD DC Test Bed.

A simplified block diagram of the SSU is shown in Figure 2. The SSU takes 82 strings as power input from either the NASA Lewis Solar Array field or a solar array simulator. The current delivered from each string is either passed on to the load through an ORing diode, or shorted back to the source by the power FET. The shunting of each string is controlled by a series of shunt driver circuitry. Each circuit in the SSU is hardware configured

to shunt its string when the Error Bus voltage, from the PVCE, is below a certain threshold. Each shunt circuit card also contains a ramp generator which fixes the shunt switching frequency at 20kHz.

The heart of the Loral SSU is the PhotoVoltaic Control Element or PVCE. This unit contains the essential voltage regulators which determine much of the SSU's characteristics. The PVCE is comprised of three identical voltage regulators connected in a majority voting scheme to prevent single event failures from disabling the SSU. The regulators use a standard operational amplifier which drive the Error Bus voltage from 0 to 30Vdc. The feedback circuit is a parallel RC network designed to provide adequate response time to any system transients. The regulators have a DC gain which provides for 4Vdc of droop over the entire power range of the SSU. The voltage droop regulation complements the BCDU controls discussed later, and is expected to ease the paralleling of SSUs should the requirements change.

Sequential Shunt Unit Testing

For the tests described below, one SSU was connected to the NASA Lewis Solar Array field and a simple resistive load bank was used as a load. The Solar Array field is configured to have similar characteristics to that of the proposed SSF flight array. The field is divided into 80 strings with each string supplying up to 2.6Adc and a V_{oc} of up to 260Vdc depending upon atmospheric conditions and temperature. When weather conditions prevent using the NASA Lewis Solar Array field, a Solar Array Simulator (SAS) is used as the source for the SSU. The SAS was designed and built at NASA Lewis for the PMAD DC Test Bed.[3] The simulator consists of 82 transistor circuits which closely approximate the solar array I-V curve. The Source Subsystem Tests described later use the Solar Array Simulator exclusively.

Turn On Transient Tests

The Loral SSU was checked for stable transitions from the OFF, or shunted state, to the ON, or regulation state. First, the SSU was turned on into a 155Adc load with a total of 190Adc available from the Solar Array. The
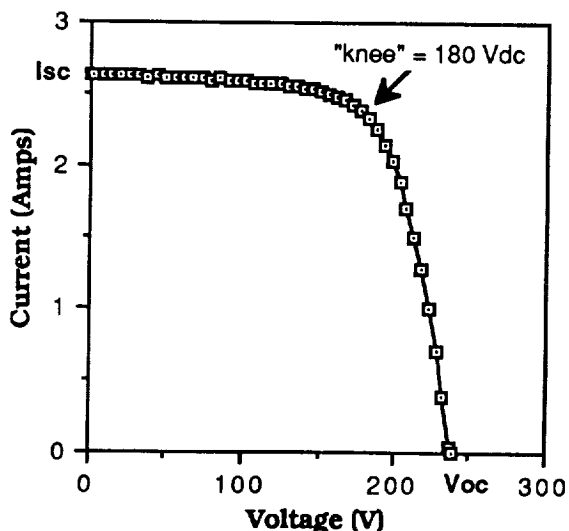

Figure 1 — Typical Solar Array String I-V Curve

output voltage made a smooth transition from 0Vdc to 149Vdc in 1.6ms with no voltage overshoot. The test was repeated for turn on into a low load of 10Adc at 150Vdc. For the low load case, the output voltage overshot to 167Vdc in 0.8ms and settled to the 150Vdc setpoint within another 0.8 ms. All turn-on transients were characterized by very smooth transitions with no apparent oscillations.

Load Transient Tests

Load transients of 50Adc were applied to the SSU while operating at a low load of 10Adc. Conditions were identical to those described above. The SSU responded to the 50Adc load addition within about 10µs and the output voltage never dropped below the eventual steady state level. This test also demonstrated the SSU's voltage droop characteristic. Before the transient, the output voltage was 152Vdc and after the load addition the voltage dropped to 150.6Vdc. When the 50Adc load was removed, the SSU responded much slower to the transient. The output voltage slowly rose from 150.6Vdc back to 152Vdc in 2.2ms. There was no voltage overshoot. These transients represent only a small percentage of the total SSU capability. Larger load transients will be tested later in the Source Subsystem Tests.

BATTERY CHARGE/DISCHARGE UNIT

The Battery Charge/Discharge Unit (BCDU) being tested in the PMAD DC Test Bed was designed, developed, and built by TRW Space Systems of Redondo Beach, CA. The BCDU is the power interface between the low voltage battery bus (100Vdc) and the high voltage power distribution bus (160Vdc). During solar insolation the BCDU is programmed to charge the batteries at a constant current rate. As the primary bus voltage drops off during eclipse, the BCDU automatically switches from charge to discharge mode and regulates the primary bus voltage (or DCSU Bus voltage) at its programmed setpoint. The transition is to be smooth and not detected by the EPS users. When the solar arrays re-enter insolation, the primary bus voltage rises above the BCDU voltage setpoint and the BCDU automatically returns to the charge mode.

Battery Charge/Discharge Unit Description

The TRW BCDU is constructed in a typical breadboard fashion with wire wrapped circuit cards and custom made magnetics. The BCDU is designed to be actively cooled by a PMAD DC Test Bed cold table. The cold table is an 8'x4' aluminum table with built-in water channels. All of the
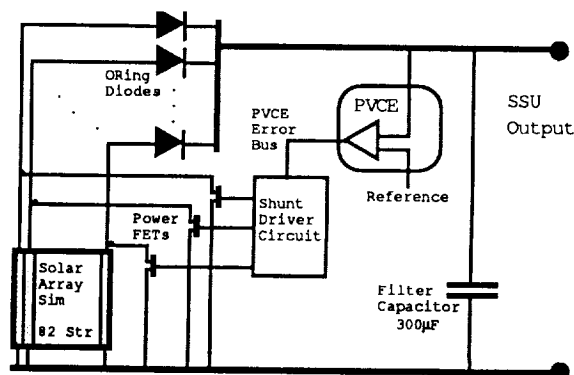

Figure 2 — Sequential Shunt Unit Block Diagram

major heat producing elements in the BCDU (power IGBTs, magnetics, diodes, etc..) are mounted to an aluminum base plate. The base plate is then securely attached to the cold table to promote good heat transfer. Facility cooling water (<70°F) is then pumped through the tables to remove the heat.

The BCDU utilizes a bi-directional "buck-boost" power circuit topology. A block diagram is shown in Figure 3. The design is very simple and utilizes only half-wave rectification. The BCDU is comprised of two paralleled 3kW power modules for a total power capability of 6kW. The two modules are controlled in a master/slave configuration. The transformer coupling of the power stages provides isolation in the event of a fault and allows the unit to be referenced for positive and negative ground configurations.

The control scheme implemented by TRW is based on a voltage droop regulation of the primary bus voltage. A diagram of the controls' transfer function is shown in Figure 4. Many of the controls' parameters can be adjusted by computer command. This flexibility enables investigation of various control schemes with little or no hardware modification.

The BCDU has four distinct modes of operation. The modes are defined by the relationship of the primary bus voltage to the BCDU Bus Voltage Setpoint. When the SSU is supplying power and regulating the primary bus, the BCDU is in the Charge Mode. In the charge mode, the BCDU regulates the charge current to the batteries and is designed to always operate at the charge current limit. The charge current limit is settable from 0 to 55 Adc and will be varied throughout the insolation portion of the orbit to accommodate optimal charge profiles. The batteries are also protected from overcharging by a charge voltage limit of 130Vdc.

As the solar arrays enter eclipse, or excess load is applied, the SSU goes out of regulation and the primary bus voltage

begins to drop. The BCDU automatically transitions to one of three other modes to attempt to regulate the bus voltage. The first is the charge reduction mode (depicted by the steeply sloped line in Figure 4). The charge reduction mode is simply the BCDU's attempt to regulate the primary bus voltage by reducing its charge rate. As the charge rate is reduced, the SSU is able to regulate the bus with the power available. This mode is mainly used to accommodate power demand peaking during insolation.
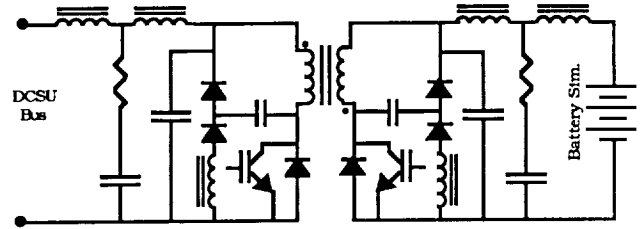

Figure 3 - TRW BCDU Power Stage

While transitioning from insolation to eclipse, the BCDUs stop charging altogether (the flat horizontal line labeled as "Adjustable Deadband"). This "deadband" area when the BCDU is neither charging nor discharging provides hysteresis to prevent the BCDU from oscillating between charge and discharge mode. The width of the deadband is programmable from 0 to 1 Vdc.

Lastly, as the bus voltage drops even further, the BCDU finally enters the discharge mode. In discharge mode, the BCDU regulates the bus voltage to its setpoint value (140-160Vdc) minus a voltage droop dependent on load. The maximum voltage droop allowed is set by varying the gain of the discharge mode controller. The different gains are depicted in Figure 4 by the three sloped lines in the discharge mode. The discharge gain of the BCDU is programmable to provide a full load voltage droop from 1 to 10Vdc. The purpose of the variable discharge gains is to ease the paralleling of three BCDUs. Also, it is expected that during the life of the SSF, batteries of different ages
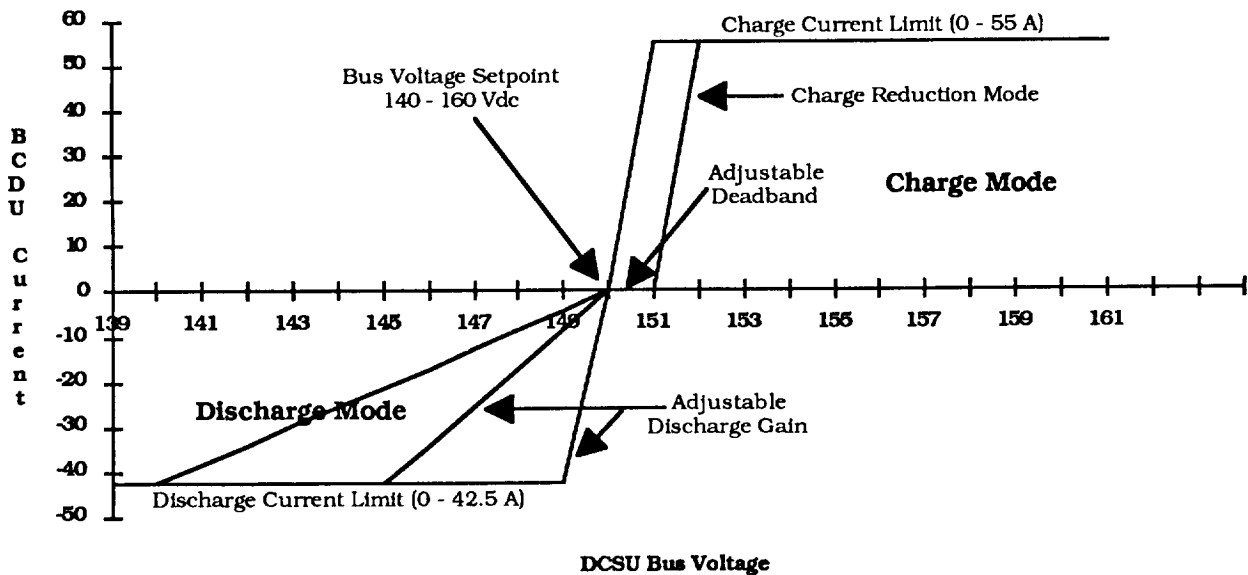

Figure 4 — TRW BCDU Charge and Discharge Mode Characteristics

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will be operating at the same time. In order to preserve the older cells it will be necessary to discharge them at lower rates than the new cells. By simply selecting different discharge gains, the BCDUs will automatically discharge at varying rates while maintaining a steady bus voltage.

The BCDU also protects the primary distribution bus from overloads and short circuits by employing a discharge current limit. The BCDU can be programmed to limit the discharge current from 0 to 42Adc.

Battery Charge/Discharge Unit Testing

The first of three TRW BCDUs arrived at NASA Lewis in November 1990. The BCDU was first checked out as a single component in the NASA Lewis Power Electronics Laboratory (PEL). Control power was applied to verify correct communication and command through the 1553B interface, and then the BCDU was tested under low and high power conditions in both charge and discharge modes.

After completing the PEL tests, the BCDU was integrated with the NASA Lewis Battery Simulator for more extensive component level testing. The Battery Simulator was developed at NASA Lewis as the power source for the BCDU. The Battery Simulator consists of eight 12Vdc lead-acid batteries, an impedance network, a power supply for charge conditioning, and a load bank to dissipate excess charge current. Short circuit testing of Ni/H$_2$ and lead-acid battery cells have shown that the lead-acid cells had a faster rise time and lower source impedance.[5] To accurately simulate a Ni/H$_2$ battery, an external impedance is added to the lead-acid cells. If during testing the batteries are either charged or discharged beyond normal limits, the power supply or load bank is paralleled with the batteries to prevent damage to the cells. Testing the BCDU with the Battery Simulator not only verified its transitions through the four modes, but also provided a means for checking out the Battery Simulator.

SOURCE SUBSYSTEM TESTING

Once the power components (SSU and BCDU) and facility support hardware (Solar Array Simulator and Battery Simulator) had been fully checked out as components, they were integrated into the Source Subsystem shown in Figure 5. The Source Subsystem is one of three subsystems which were integrated and tested prior to assembling the complete end-to-end PMAD DC Test Bed. Included with the sources is the DC Switching Unit (DCSU). The DCSU is the interface and distribution controller for the SSF sources. It contains five DC Remote Bus Isolators (RBIs) and a
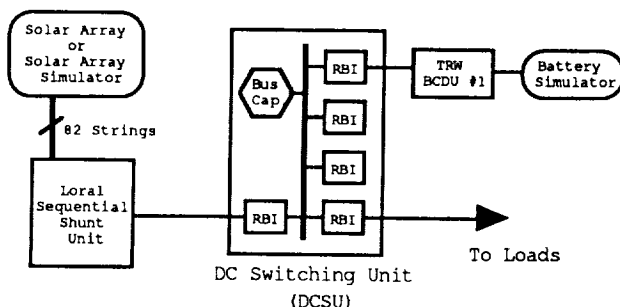
proposed stabilizing bus capacitance of 4000μF. [4]

Testing of the Source Subsystem included steady state power quality of the SSU and BCDU, and simulated mode changes from insolation to eclipse.

Steady State Power Quality

Power quality measurements were taken for the BCDU, the SSU, and for both units operating in parallel. Voltage and current ripple on the bus were measured and the frequency recorded when there was appreciable magnitude. The results are summarized below.

Sequential Shunt Unit Power Quality

The SSU was connected to the DCSU with the bus capacitor present and a resistive load bank attached to the DCSU. Three loading conditions were tested and the resulting output current and voltage were measured for peak-to-peak ripple magnitude. SSU output voltage setpoint was set to 160.0Vdc.

No Load (300W min load):
$$\text{Vout ripple} = <160\text{mV}_{p\text{-}p}$$
$$\text{Iout ripple} = 0.06\text{A}_{p\text{-}p} @ 20\text{kHz}$$
Middle Load (13kW)
$$\text{Vout ripple} = 150\text{mV}_{p\text{-}p}$$
$$\text{Iout ripple} = 0.2\text{A}_{p\text{-}p} @ 20\text{kHz}$$
High Load (28.6kW)
$$\text{Vout ripple} = 280\text{mV}_{p\text{-}p}$$
$$\text{Iout ripple} = 0.06\text{A}_{p\text{-}p} @ 20\text{kHz}$$

The SSU displayed good power quality, well within its design limits of $0.5\text{V}_{p\text{-}p}$.

Battery Charge/Discharge Unit Power Quality

During this test, the BCDU was connected to the DCSU through its RBI. A resistive load bank was connected to the DCSU. Again, the BCDU's output voltage and current during discharge were measured for peak-to-peak ripple.

BCDU setpoints were:
Bus Voltage = 155.0V
Discharge Limit = 42 A
Discharge Gain = 1.0V / 42A
                 10.0V /42A

Loading	Voltage Ripple p-p		Current Ripple p-p	
	Gain=1V	Gain=10V	Gain=1V	Gain=10V
No Load	14.0V	12.8V	18.0A	6.0A
1A load	0.7V	—	0.1A	—
2A load	—	0.5V	—	0.06A
17A load	—	0.6V	—	2.7A
24A load	0.8V	—	1.4A	—
39 A load	0.7V	0.6V	0.5A	1.3A

The BCDU exhibited good power quality during discharge as long as a minimum load of 1A (160W) was applied. Also, testing found maximum current ripple magnitudes at mid-load points. The current ripple did not result in excessive voltage ripple and is being investigated further.

Figure 5 - Source Subsystem Block Diagram

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Paralleled SSU and BCDU Power Quality

For this test both the SSU and BCDU were connected to the DCSU bus. Two resistive load banks were attached to the DCSU to provide >30kW of load. The subsystem was incrementally loaded until the BCDU had transitioned from full charge to discharge. Power quality was measured at the DCSU bus voltage and the SSU and BCDU currents.

Setpoints:

SSU voltage = 160.0Vdc
BCDU voltage = 155.0Vdc
Charge Limit = 54A
Discharge Limit = 42 A
Discharge Gain = 1.0V/42A

Loading		Ripple p-p		
BCDU I	R load	DCSU V	BCDU I	SSU I
38A	2A	0.6V	0.5A	0.56A
38A	81A	0.6V	0.7A	0.75A
25A	126A	0.5V	0.7A	0.88A
2A	185A	0.3V	0.4A	0.2A
-5A	215A	0.5V	0.8A	0.56A

The source subsystem demonstrated excellent power quality with resistive loads, even above designed power levels. However, the true test of the stability of the subsystem will come when it is integrated with the active loads in the end-to-end system tests.

Source Subsystem Transition Tests

The transition tests consist of an SSU and BCDU operating in parallel with the BCDU charging the battery. The system is forced into a state which requires the BCDU to switch from charge to discharge (simulated eclipse) and the resultant transient is recorded via a digital oscilloscope. The system is then forced back into an insolation mode and the BCDU transitions from discharge to charge .

Three methods of simulating eclipse were investigated. The first method used one of the DCSU RBIs to remove the SSU as a power source. This transient proved to be too fast (actual orbital eclipse times are expected to be around 1-2 seconds) and resulted in excessive bus voltage dropout.
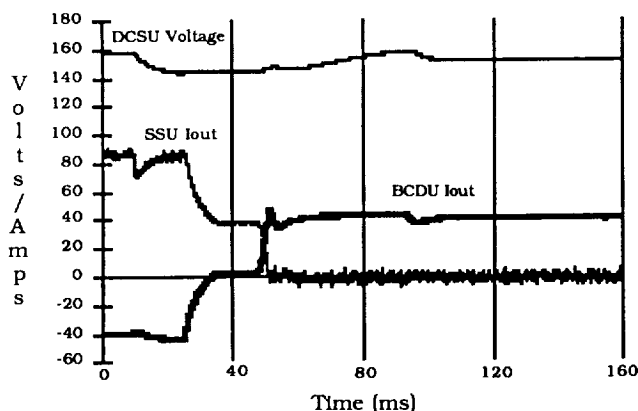
The next method involved turning down the DC power supply which powered the Solar Array Simulator. This method proved to be too slow due to the extremely large output capacitors in the power supply. The last method involved changing the SSU output voltage setpoint from 160Vdc to 145Vdc. The drop off in bus voltage is much less severe than the first method and results in a more realistic transition, although it is much faster than the 1-2 seconds expected.

Insolation to Eclipse Transition Test

The simulated insolation to eclipse transition test data is shown in Figure 6. The DCSU or primary bus voltage is shown along with the currents from the SSU and BCDU. Initially, the BCDU was charging the batteries at a current of 55A (-40A of bus current) and an additional 6kW of resistive load was connected to the DCSU bus. As the voltage setpoint of the SSU was switched from 160Vdc to 145Vdc the transition occured. Concentrating on the BCDU current it is easy to see the three mode transitions take place. First, the charge reduction mode is shown as the charge rate to the batteries is decreased to zero. Next, the deadband, or hysteresis, area is shown as the BCDU's current is zero for about 12ms. Lastly, the transition to discharge mode is accompanied by a recovery of the DCSU bus voltage to the 155Vdc setpoint of the BCDU. The entire transition from charge to discharge covered approximately 40ms. Although the response time is slow in this case, during a normal eclipse transition lasting 1 to 2 seconds, the response time will be adequate to ensure a smooth transition.

Eclipse to Insolation Transition Test

The simulated transition from eclipse to insolation test data is shown in Figure 7. The test set-up is identical to that described above. Again, the BCDU current plot clearly shows the transition of the subsystem through the four modes. First, the BCDU is in full power discharge and regulating the DCSU Bus voltage to 153Vdc. As the SSU is set back to 160Vdc the BCDU begins to transition out of discharge mode and back into full power charge mode. The DCSU bus voltage exhibits no overshoots or voltage spikes and power quality remain good throughout the transition.
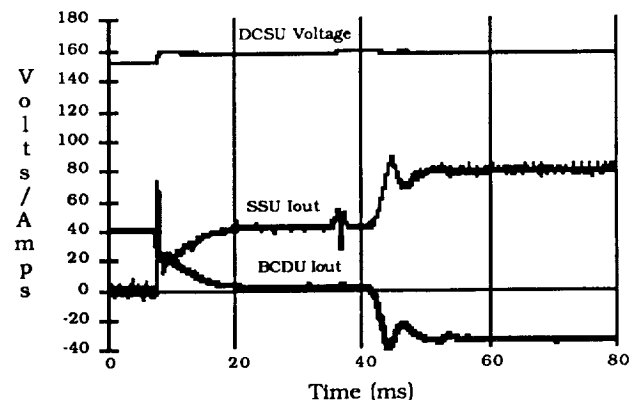

Figure 6 — Insolation to Eclipse Transition

Figure 7 — Eclipse to Insolation Transition

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CONCLUSIONS

A Sequential Shunt Unit (SSU) and Battery Charge/Discharge Unit (BCDU) were integrated into a Source Subsystem. Each piece of hardware was tested as a stand-alone component to characterize its design and performance. The SSU and BCDU were then integrated with a DC Switching Unit (DCSU) and a bus stabilizing capacitor to complete the Source Subsystem. Testing of the subsystem proved an effective droop regulation technique during subsystem transitions from solar insolation to eclipse. Measured power quality was good in all regimes.

FUTURE TEST PLANS

Future testing will begin with the integration of two more BCDUs into the source subsystem. In this configuration, the droop regulation technique will be exhaustively exercised as the BCDUs are paralleled in the discharge mode. Lastly, the completed Source Subsystem will be integrated into the complete end-to-end PMAD DC Test Bed to conduct system level tests.

ACKNOWLEDGEMENTS

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