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Test and Evaluation of Load Converter Topologies Used in the Space Station Freedom Power Management and Distribution DC Test Bed

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TEST AND EVALUATION OF LOAD CONVERTER TOPOLOGIES USED IN THE SPACE STATION FREEDOM POWER MANAGEMENT AND DISTRIBUTION DC TEST BED

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ABSTRACT

The Power Management and Distribution (PMAD) DC Test Bed at the National Aeronautics and Space Administration Lewis Research Center in Cleveland, Ohio, is a unique facility for testing power components hardware in support of the Space Station Freedom dc Electrical Power System (EPS). One type of breadboard hardware tested at this facility is the dc Load Converter Unit, which constitutes the power interface between the electric power system and the actual load. These units are dc to dc converters that provide the final system regulation before power is delivered to the load.

Three load converter topologies have been tested in the test bed and in the Power Electronics Laboratory These are a series resonant converter and a series inductor switchmode converter, developed by TRW, and a switching full–bridge forward converter developed by Westignhouse. This paper describes, in general, the topology, operation principles, and tests results. A comparative analysis of the three units is given with respect to efficiency, regulation, short circuit behavior (protection), and transient characteristics. A fourth topology, the TRW zero voltage switching converter, will be tested in the near future and test results compared with information presented in this paper.

INTRODUCTION

The NASA Lewis Research Center is responsible for the development of the Space Station Freedom (SSF) Electrical Power System. In order to identify system level issues during the SSF Program design and development phases, a systems test bed was assembled. Some of the objectives of this test bed facility are the evaluation of system efficiency, power quality, system protection and reconfiguration, and system stability.

The test bed power system consists of a 160V dc primary distribution system which is converted to a 120V dc for secondary distribution to the user loads [1]. In this system, regulation is provided at three different locations within the distribution system. Primary distribution regulation is provided at the sources [2] (Sequential Shunt Unit and Battery Charge/Discharge Unit) to convert and regulate solar array or battery voltage to 160Vdc. The test bed secondary subsystem utilizes two dc to dc converters which provide power to secondary and tertiary power distribution units, and three load converter units. The dc to dc converter unit provides regulation by converting the primary voltage to 120V dc for secondary distribution. Finally, dc load converter units provide the last stage of regulation by converting the secondary voltage to 28 Vdc. The final regulating unit is required on the space station because a majority of user loads require voltage levels different from the 120 Vdc secondary bus voltage.

General specifications were given for the development of load converters, however, some specifications were listed as goals so that the developer had the flexibility to include features deemed appropriate for this type of application. The following is a partial list of the specifications for the load converters: Input Voltage 120 Vdc nominal (+/– 18 Vdc); Output Voltage 28 Vdc(+/– 1%); Output Power 1 kW; Input Current Ripple +/– 1% peak to peak; Output Voltage Ripple +/– 1% peak to peak; 90% Efficiency at full load (design goal);Output Short Circuit current limiting; and Input Under/Over voltage turn off.

TOPOLOGIES DESCRIPTION AND TEST PERFORMANCE

Series Resonant Topology

Each converter topology is made up of three stages: input filter, power stage, and output filter. The series resonant design [3] is shown in Figure 1. It consists of four power MOSFET switches. Q1 and Q2 are driven at 100kHz, 50% duty cycle and are 180 degrees out of phase. Transistors Q3 and Q4 are pulse width modulated, with Q4 pulsed while Q1 is on, and Q3 pulsed while Q2 is on. Output voltage control is achieved by varying the pulse width on Q3 and Q4 to control the current through the transformer. The LC tank circuit results in a resonant sinusoidal current through the transformer, which reduces switching losses. The unit control power is obtained from the 120 Vdc input power source.

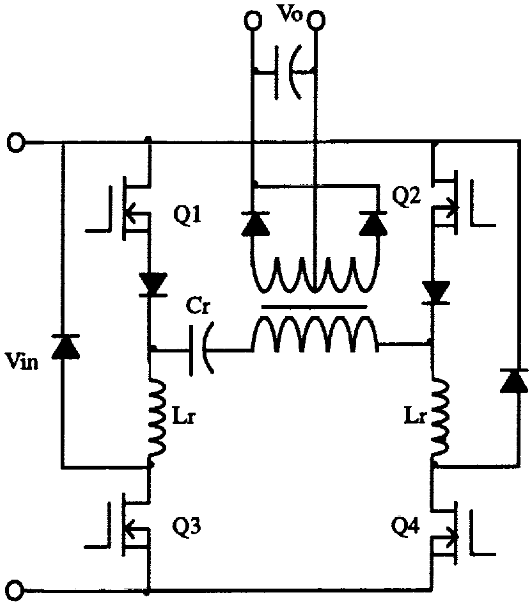

Figure 1. Series Resonant Topology Power Stage

This unit's operating features include output current limit protection, and input under–voltage and over–voltage trip capability. Its control commands are ON/OFF, output voltage setpoint, and output current limit setpoint. These commands can be applied either manually or through a Data Interface Unit (DIU) for operation with a controller and a Mil. Std. 1553B data bus. The unit, when operated with the DIU, allows monitoring of the input voltage and current, output voltage and current, input/output power, current limit setpoint, status, and temperature.

Efficiency, Ripple, and Voltage Regulation Tests

The performance test setup consisted of a 120 Vdc power supply input to the load converter , and a programmable load bank in resistive mode connected to its output. Steady state efficiency tests were performed on the series resonant converter, increasing the load level from 10% (100W) to full load (1 kW). The unit's efficiency at full load was 86.4% and varied between 85% and 87% throughout the load range. The measured output voltage regulation was 0.3% which met the 1% regulation specified for the unit. Input current ripple at full load was 1% peak to peak, and the full load output voltage ripple was 1.6% peak to peak.

Transient Tests

Turn on, turn off, short circuit, and load step transient tests were also performed on the series resonant converter. For turn on tests, the 120 Vdc supply was connected to the input of the load converter to allow the input filter to chage up while the unit was still off. The unit was then commanded on into a resistive load (36 A). At the instant of turn on a current spike of approximately 10 A was observed decreasing to 0 A and increasing again to a constant value of approximately 9 A in 16 msec. Output voltage built up to a value of 28 volts in approximately 1msec. Output current, in a similar way, increased smoothly to its full load value of 36 A in 16 msec. The unit had a similar behavior for turn on into a 50% or 100% load. When the 120 Vdc supply contactor was closed into the discharged input filter with the unit in the on state (100% load connected), approximately 488 msec elapsed before the output voltage and current started to build up.

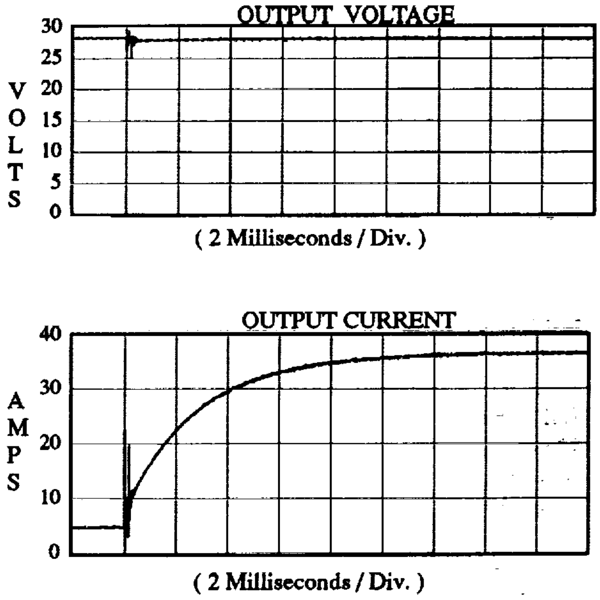

Figure 2. Series Resonant Converter Load Step Response

For load dropout tests the output load of the converter was reduced from 100% to 10% (36 A to 3.6A) using a switch to disconnect part of the load. The result of these tests demonstrates that this load converter is able to withstand a large drop in load without significant effect on the output voltage. When load was restored to its full load value (see Figure 2), input and output currents increased to their nominal values, settling in 16 msec.

Short Circuit Tests

Short circuit tests were conducted at a 50% output load condition (18 A) to evaluate the protective features of the unit. After the output current had reached steady state, a short circuit was applied at the load converter output using a knife switch. As soon as the short circuit was applied (see Figure 3), output current increased to 120 A, but dropped to its current limit setpoint of 41.6 A in less than 1.6 msec.

The unit continued to operate indefinitely at an output voltage sufficient to sustain an output current of 41.6 A. Input current increased from its initial value of approximately 4 A to a value of 7.5 A and oscillated down to a constant value of 1.25 A with a settling time of 1.6 msec. When the fault was removed, output voltage increased to 28 volts in approximately 0.1 msec. Output current decreased from 41.6A to 0 A in 81 microsec and started to ramp back up reaching a value of 10 A in 2.86 msec.

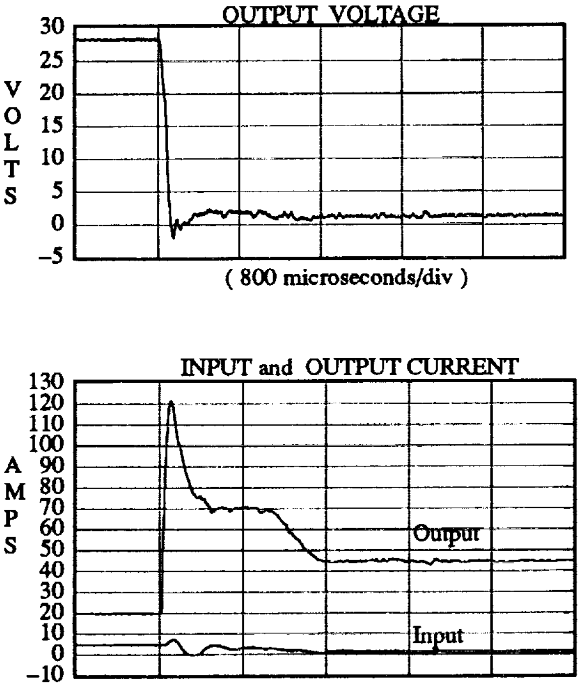

Figure 3. Series Resonant Converter Short Circuit Test

Series Inductor Switchmode Topology

The Series Inductor switchmode device [3] consists of the same three stages common to all of these load converter topologies. The input and output filters are similar in design to the Series Resonant Converter. The power stage, shown in Figure 4, uses a similar switching scheme. In this case, Q1 and Q2 are driven at 100 kHz with a 50% duty cycle. Moreover Q3 and Q4 are pulse width modulated, but Q3 is pulsed during the Q1 on state while Q4 is pulsed during the Q2 on state. Because this topology has a discrete inductor instead of a resonant circuit, the current through the isolation transformer will approach a square wave. The current through this inductor will always flow in the same direction because it will act as a current source when both Q3 and Q4 are off.

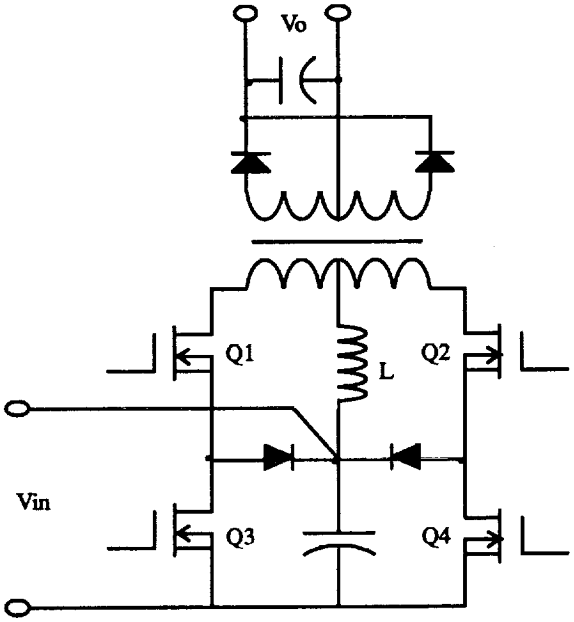

Figure 4. Series Inductor Topology Power Stage

The operating features are equivalent to the Series Resonant Converter, allowing the user to set the output voltage, output current limit, and turn the unit on or off both manually and via a DIU. The protection and monitoring capabilities are identical to the series resonant converter.

Efficiency, Ripple, and Voltage Regulation Tests

The same tests and test set ups were run as on the series resonant unit, with similar results. The efficiency of this unit at full load (1kW) was 90%, dropping to a low of 75% at one–tenth of rated load (100W).

The output voltage regulation, 0.17%, fell within design goals. The output current ripple was within 1% for all loads tested, except the 10% of full load case for which the ripple was just under 1.1%. Input ripple stayed around one–half of one percent, well within the required range.

Transient Tests

To test the start up characteristics of this device, the input filter was charged by applying 120Vdc to the input while the unit is off. The device was then switched on and the response observed. In this case, the input current spike was reduced (about 5 Amps) and the output voltage smoothly rose to 28V in less than 70us. Under 75% load, the output current rose exponentially to the required value (27A) in approximately 12ms. Similar results were observed using other load values. This test was also run with the input filter discharged, The unit in the on state, and the input breaker switched on applying 120Vdc to the device. This resulted in an input current spike of about 100Amps. The output voltage suddenly switched on to 28Vdc after about one–half second.

Load drop–out tests were performed with an identical test set–up as for the series resonant unit. These tests showed some oscillation in the output current and the input current when the load was switched from full load to 10% load. The output voltage, however, stayed steady. Likewise, the restoration of the load showed effective voltage regulation and much smoother current transitions (see Figure 5). In both cases, the output currents reached steady state in 8ms.

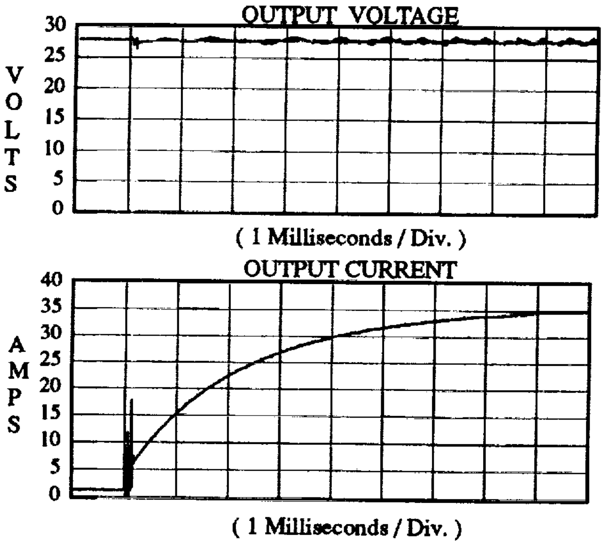

Figure 5. Series Inductor Converter Load Step Response

Short Circuit Tests

Applying a short circuit across the output of the unit (see Figure 6) produced some oscillation in the input and output currents and the output voltage of about 3 or 4 KHZ. The output current spiked to about 105Amps before reaching the current limiting value in 200us. The unit continued to supply the current limit setpoint current indefinitely (this setpoint was manually varied from 40 to 52 Amps in multiple runs). The input current spiked to less than 10Amps.

Recovery by removing the fault showed the same oscillating frequency, taking 610us to settle to the normal output voltage. The output current oscillated before reaching steady state in 610us.

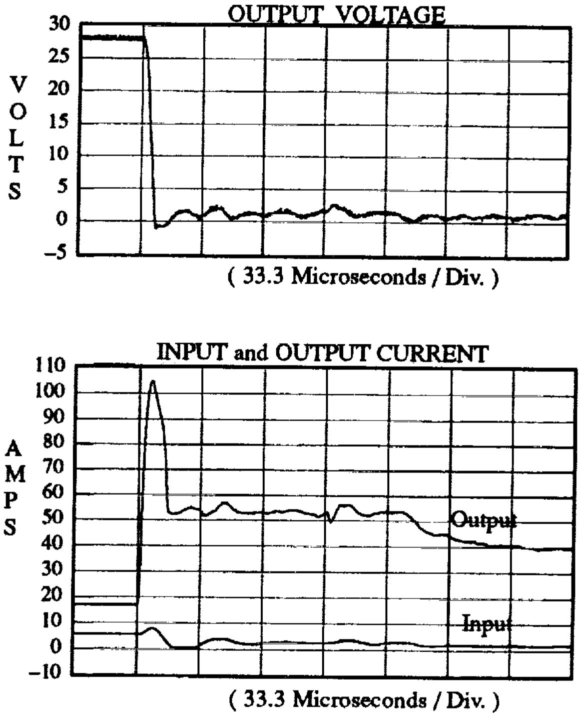

Figure 6. Series Inductor Converter Short Circuit Test

Switching Full Bridge Topology

The design of this unit is similar to the Series Inductor Switchmode converter. The magnetizing inductance of the transformer takes the place of the discrete inductor and the current is switched directly through the transformer with no other components in series with the FETs. This device has the simplest power stage design of the three topologies [4] (see Figure 7). The switching frequency of the unit is 10kHz, one tenth the value of the other units. This unit also contains a FET operated in the linear mode in series with the input filter to provide input current limiting.

The switching scheme is as follows: Q1 and Q2 are switched with square waves 180 degrees out of phase, and Q3 and Q4 are pulse width modulated. Q4 is pulsed during Q1 ON state, while Q3 is pulsed during Q2 ON state. The current through the transformer approaches a square wave as the PWM approaches 50%. The output voltage is controlled by varying the pulse widths.

The unit has the capability to "soft start" by ramping the output voltage to the desired setting in an adjustable 30–800us turn–on period. The unit's output voltage is adjustable via a Mil. Std.1553B data bus as is the output current limit setpoint. The undervoltage input trip can also be disabled, if desired.

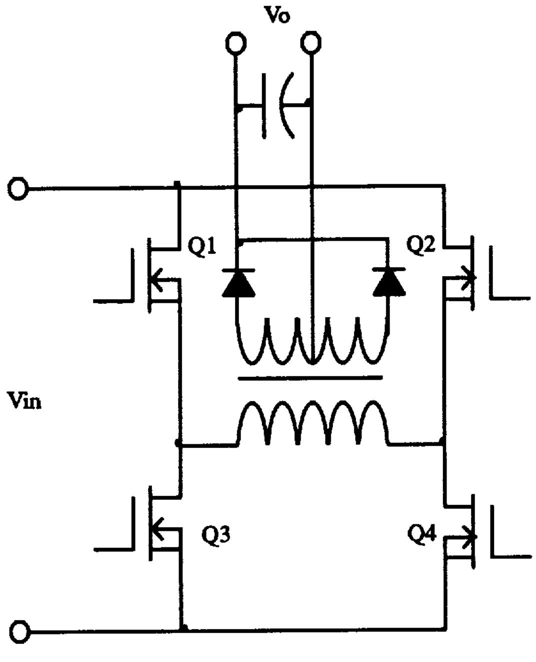

Figure 7. Switching Full Bridge Power Stage

Efficiency, Ripple, and Voltage Regulation Tests

With a testing set–up similar to those used for the other units, this load converter unit was found to have an efficiency in the mid 90% range (93%–97%). The output voltage regulation was accurate to 0.7% over a full range of loads. The output current ripple was well within the 1% design goal, and the input current ripple was just at the 1% threshold.

Transient Tests

Turning the unit on with a fully chaged input filter into a variety of resistive loads showed smooth input and output current and output voltage response, with no oscillation. This is due to the ramping capability that this unit provides. The output voltage rose to rated value in approximately 700ms.

The same test without the input filter pre–energized also showed a lack of any major oscillation in the output (to a resolution of about 50us), and in this case the output voltage rose to the rated value in less than 10 ms, with a maximum input current spike of 150 Amps.

By varying the slew rate of the slow start–up function, the unit was set to reach a steady–state output voltage with a variety of settling times.

The load drop–out tests, performed by dropping the load from full rated to about 10% of rated, showed only a slight dip in the output voltage for both the drop out and recovery. For drop–out the output current dropped in two steps with a slight rise between them, settling out in about 350us. The input current smoothly dropped down in about 550us. For load restoration step (see Figure 8), output current increased to its nominal value (36 A) in 16 msec, after a brief oscillation with peak value of 20 Amps.

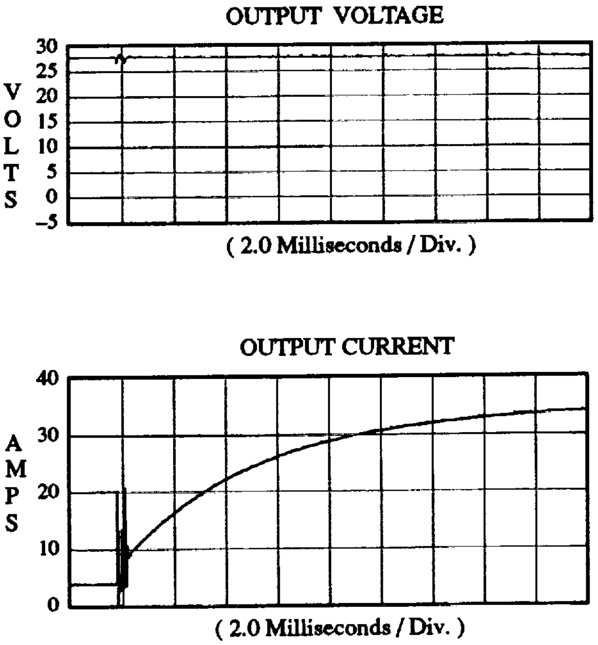

Figure 8. Switching Full Bridge Conv. Load Step Response

Short Circuit Tests

The short circuit test data for the switching full bridge unit is shown in Figure 9. At the time the short was applied, an output current spike of magnitude over 170Amps was observed, quickly dropping down to 50Amps within 4ms. During current limiting state, output current oscillated between 52 and 58 amps. At shut–down, the output current and voltage quickly dropped to zero.

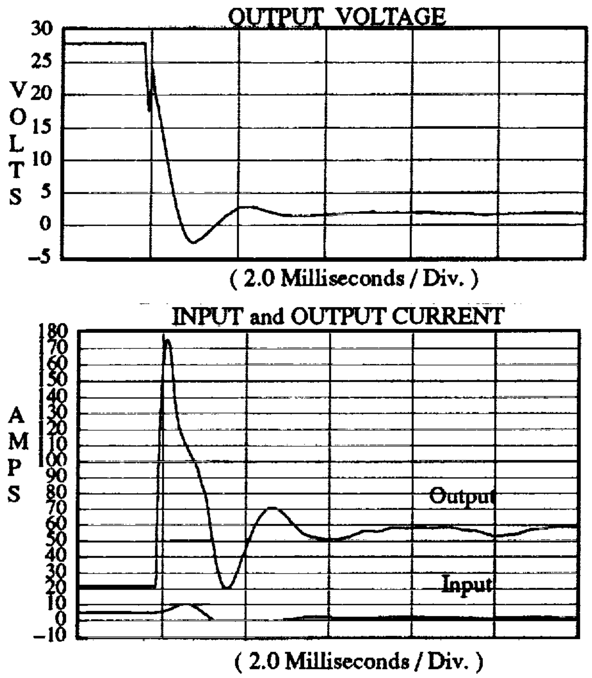

Figure 9. Switching Full Bridge Cnvrtr. Short Circuit Test

COMPARATIVE ANALYSIS

It is difficult to directly compare the units because of differences in design capabilities and features. The switching full bridge unit contains a number of monitoring and protection features not available on the other units. For example, the unit can current limit the input and ramp the output voltage. This ramping capability allows much smoother start-up characteristics and is a definite advantage in applications where load control is required.

Despite the differences in features and capability of the units a comparison is made in this section using test data. This comparison is made for those parameters considered critical to the user (i.e. regulation, short circuit protection) and power system (i.e. efficiency, transient behavior, power quality).

Figure 10 shows the measured efficiencies for the three load converters at different load levels. The efficiency data along with weight information can be used to select an ideal application for these load converters in a space station like environment. The switching full bridge unit has the highest efficiency and maintains this efficiency back to less than 10% of full load. This converter also has the highest relative weight and therefore would make an ideal bulk load converter, where part power efficiency is critical and the unit remains on orbit. The other two units also have high efficiency at full load and approach the efficiency of the switching full bridge unit. This type of efficiency characteristic along with there lower relative weight, males these units useful for a power supply load converter application. For this application the power supply and load are carried to orbit and changed as needed The maximum efficiency point can be chosen to correspond to the applied load.

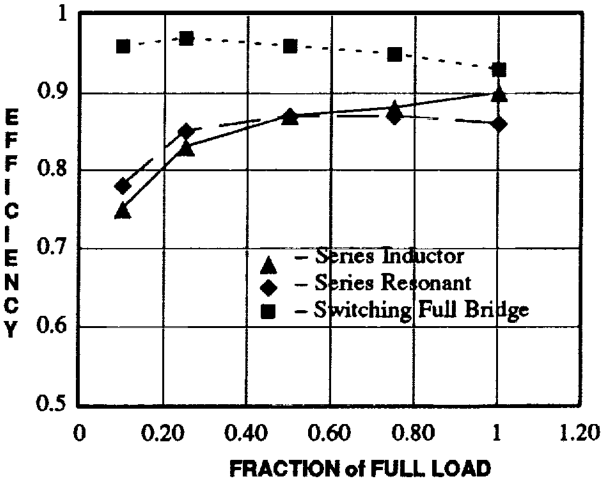

Figure 10. Load Converter Topologies Efficiencies

Figure 11 shows steady state ripple and regulation results at full load condition. Input current ripple for the three units met the design goal of 1%. The unit with lowest input current ripple was the series inductor converter. Output voltage ripple specifications (1%) were met only by the switching full bridge unit. The output filters on the series resonant and series inductor units are appreciably smaller than the switching full bridge unit. Further additions to the output filters of the series resonant and series inductor units can be made with minor impact on the weight and efficiency of the units and is expected to be done to meet the design specification. All three units fell within the required limits of output voltage regulation, the series inductor proved to have the best output voltage regulation characteristics.

For load step transients (load dropout and restoration) the three units behaved well and all units had an overdamped response. The switching full bridge unit responded the slowest taking approximately 16millisecs to reach steady state, while the other two units took about half that time.

	Input Current Ripple (p–p)	Output Voltage Ripple (p–p)	Output Voltage Regulation
Series Resonant	1 %	1.6 %	0.3 %
Series Inductor	0.42 %	3.57 %	0.17 %
Switching Full Bridge	1 %	0.03 %	0.7 %

Figure 11. Full Load Ripple and Regulation Parameters

All of the units provide short circuit capability to allow for the incorporation of user protective devices in downstream loads. The units also incorporated fold back characteristics to convert from constant power to constant resistance, providing the necessary protection to the unit from the power system.

SUMMARY

All of the converters described in this paper are first generation units developed for use on the PMAD DC Test Bed at the Lewis Research Center. The component level tests demonstrated that these units met most of the design goals and requirements specified. The requirements and specifications for these units were established in early 1989, just after the SSF Program change to a dc secondary. Further work in the program has established more complete specifications for load converter units. Modifications of these units will be made to comply with the latest specifications as they become available.

In addition, there may be other load converter designs being developed in the Space Station Freedom Program which will be evaluated as they become available. A variety of bulk and individual load converters from the multi–kilowatt range down to the tens of watts are expected to be available in the near future.

All of these units need to be tested in a secondary system environment, where their interactions and compatibility with other system components will be addressed. It will be the system tests that will provide the data necessary for a detailed comparison of load converter types. The PMAD DC Test Bed is expected to be used to provide early evaluation of load converters in support of the SSF Program.

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