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Performance of Power Converters at Cryogenic Temperatures

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PERFORMANCE OF POWER CONVERTERS AT CRYOGENIC TEMPERATURES

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ABSTRACT

Power converters capable of operation at cryogenic temperatures are anticipated to play an important role in the power system architecture of future NASA deep space missions. Design of such converters to survive cryogenic temperatures will improve the power system performance, and reduce development and launch costs.

Aerospace power systems are mainly a DC distribution network. Therefore, DC/DC and DC/AC converters provide the outputs needed to different loads at various power levels. Recently, research efforts have been performed at the NASA Glenn Research Center (GRC) to design and evaluate DC/DC converters that are capable of operating at cryogenic temperatures.

This paper presents a summary of the research performed to evaluate the low temperature performance of five DC/DC converters. Various parameters were investigated as a function of temperature in the range of 20 °C to –196 °C. Data pertaining to the output voltage regulation and efficiency of the converters is presented and discussed.

1. POWER ELECTRONICS IN AEROSPACE

The application of power electronics in aerospace technologies is becoming widespread. The potential and existing application areas include the International Space Station (ISS), aircraft and satellite power systems, motor drives in ‘more electric’ technology (MET) as applied to aircraft and Reusable Launch Vehicles (RLVs), starter/generators (S/G) and flywheel technology, servo systems embodying electro-mechanical actuation (EMA) and spacecraft including deep space probes, planetary orbiters and landers, and surface exploratory instrumentation.

The aerospace power systems are typically interconnection of power electronic converters, photovoltaic (PV) solar arrays and batteries in a DC-based distribution system. DC/DC and DC/AC converters are used to provide the required output voltage to different loads at various power levels.

2. LOW TEMPERATURE ELECTRONICS

Electrical components and systems for future NASA space missions, such as outer planetary exploration and deep space probes, must operate reliably and efficiently in very low temperature environments. For example, inter-planetary probe launched to explore the rings of Saturn would experience a temperature of about –183 °C. Table 1 shows the operational temperatures for an unheated spacecraft in the vicinity of each of the outer planets. Presently, spacecraft operating in some of these regions utilize Radioisotope Heating Units (RHUs) to maintain an operating temperature for the on-board electronics of approximately 20 °C [1]. RHUs require containment structures and thermal systems such as shutters to maintain the 20 °C over the course of an entire space mission. However, if the electronics were capable of operating at the temperature of the mission environment, the RHUs and their associated structures, and the thermal management systems could be eliminated, thus reducing the system size and weight and thereby reducing the development and launch costs, and improving reliability and lifetime [1].

In this paper, five low power DC/DC converter modules, with specifications that might fit the requirements of specific future space missions, have been selected for investigation. The specifications of these converters, ranged in electrical power from 10 W to 13 W and input voltage from 9 V to 72 V, as listed in Table 2. The converters were characterized in terms of their performance as a function of temperature in the range of 20 °C to –196 °C (liquid nitrogen). The experimental procedures along with the experimental data obtained on the investigated converters are presented and discussed [2–5].

3. EXPERIMENTAL SETUP

The converter modules listed in Table 2 were characterized as a function of temperature from 20 °C to –196 °C in terms of the output voltage regulation, efficiency, and input and output current distortions. At any given temperature, these properties were obtained at various input voltages and at different load levels; from no-load to full-load conditions. The tests were performed using an environmental chamber utilizing liquid nitrogen as the coolant. A temperature rate of change of 10 °C/min was used throughout the experiment. The converters were first tested at room temperature then at successive test temperatures with 20 °C decrement, down to –196 °C. At every test temperature, the device under test was allowed to soak at that temperature for a period of 30 minutes before any measurements were made. After the last measurement was taken at the lowest temperature, the converters were allowed to stabilize to room temperature and then the measurements were repeated at room temperature to determine the effect of one thermal cycle on the converters.

4. RESULTS AND DISCUSSIONS

During the investigations, data was generated for both steady and dynamic states. In this paper, only data pertaining to the steady state efficiency and voltage regulation of the tested converters are presented and discussed. More detailed results are reported in references [2–5].

Figures 1 through 5 show the output voltage and efficiency of the modules versus temperature for four conditions of input voltage and output load levels. These conditions include minimum input voltage under light and heavy loads, and maximum input voltage under light and heavy loads. For all modules, an offset in the output voltage occurs at both light and heavy loads due to the voltage drop in the wiring leads connecting the output terminals of the module to the electronic load where the output voltage was actually measured (a resistance of about 70 mΩ).

At a given load, the output voltage of module 1 maintains a steady value from room temperature to –120 °C. For temperatures beyond –120 °C, the converter begins to show loss in regulation. For example, the output voltage increases slightly when the input voltage is 36V but decreases drastically when the input voltage is 12V. As expected, the output voltage drops slightly when the load is increased. The effect of temperature on the efficiency of converter module 1 under different input voltage and load conditions is also shown in Figure 1. In general, the efficiency drops as the temperature is lowered with the heavy load condition having a higher efficiency than that of a light load. For the same loading, the efficiency is higher as the input voltage is decreased. For a given input voltage, the converter has lower efficiency when the load level is low.

Module 2 shows reasonable performance to –80 °C, but shows complete loss of voltage regulation for temperatures below –80 °C, as shown in Figure 2. It did, however, continue to operate with no regulation down to –196 °C. Similar trend was observed in the efficiency behavior with temperature.

The output voltage of module 3 does not exhibit any dependence on either the input voltage or the test temperature at low loads as shown in Figure 3. At heavy loads, it does however decrease slightly upon lowering the test temperature regardless of the level of the input voltage. In general, the efficiency of this converter exhibits a slight decrease with decreasing temperature. This reduction becomes apparent at temperatures below –60 °C, as shown in Figure 3.

Module 4 showed excellent output voltage regulation with temperatures down to –120 °C, as shown in Figure 4. The only exception is at –120 °C where at minimum input voltage and light load condition, the output voltage increased to over 4 volts. In addition, this module ceased to operate for temperatures below –120 °C, but regained operation once its temperature rose above –120 °C. The efficiency of this module held relatively steady values at heavy load to –60 °C and then dropped off as temperature decreased down to –120 °C.

Module 5 showed relatively good output regulation down to –120 °C, as depicted in Figure 5. Beyond that temperature, the output voltage seems to slightly increase as the temperature is decreased further. Its efficiency, however, exhibits a gradual decrease as temperature is decreased. Although this module ceased to operate for temperatures below –180 °C, it regained operation once its temperature rose above –180 °C.

5. CONCLUSIONS

Five low power, DC/DC converter modules were evaluated as a function of temperature in the range of 20 °C to -196 °C. Data pertaining to the output voltage regulation and efficiency of the tested converters were presented and discussed.

Test results obtained on the modules have shown that they operated as expected within their manufacturer's specified temperature range as well as with reasonably good performance down to temperatures between –80 °C and –100 °C. For temperatures below –100 °C, performance was either out of range, erratic, or non-existent.

In all cases, the temperature range for which these modules were designed and specified does not include the severe temperature range for which they were subjected to in this investigation. Additional testing taking into account long-term evaluation and thermal cycling may reveal the potential for extending the operational temperature range and/or improving their performance at these very low temperatures through component screening and/or modification to the module design.

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Table 1. Typical operational temperatures of an unheated spacecraft.

Mission	Temperature °C
Mars	–20 to –120
Jupiter	–151
Saturn	–183
Uranus	–209
Neptune	–222
Pluto	–229

Table 2. Converter module specifications and evaluations

Converter Specifications					**GRC Evaluations**	
Module	Input Voltage (V)	Output Voltage (V)	Power (W)	Operating Temp (°C)	Observations and Comments	Temp at which module ceased to operate (°C)
1	9–36	3.3	10	–40 to 60	V_o dropped to 2.4 V at –140 °C; chip functioned down to –160 °C.	–160
2	36–72	3.3	10	–40 to 85	V_o lost regulation at –100 °C; converter still functioned to –196 °C.	–196
3	18–36	3.3	10	–40 to 70	Chip worked very well down to –120 °C. Input current oscillations occurred at all temperatures under heavy loading.	–120
4	18-36	3.3	13	-40 to 85	Oscillations in input current started at –80 °C.	-120
5	9-36	3.3	10	-40 to 85	Oscillations in input current observed at –140 °C under heavy loading.	-180

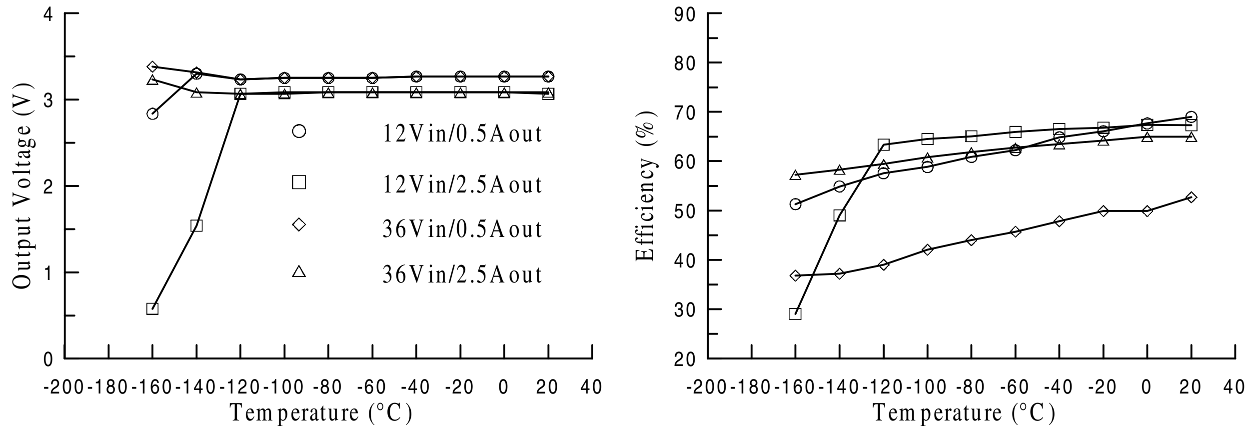

Figure 1. Voltage regulation and efficiency of module 1 versus temperature

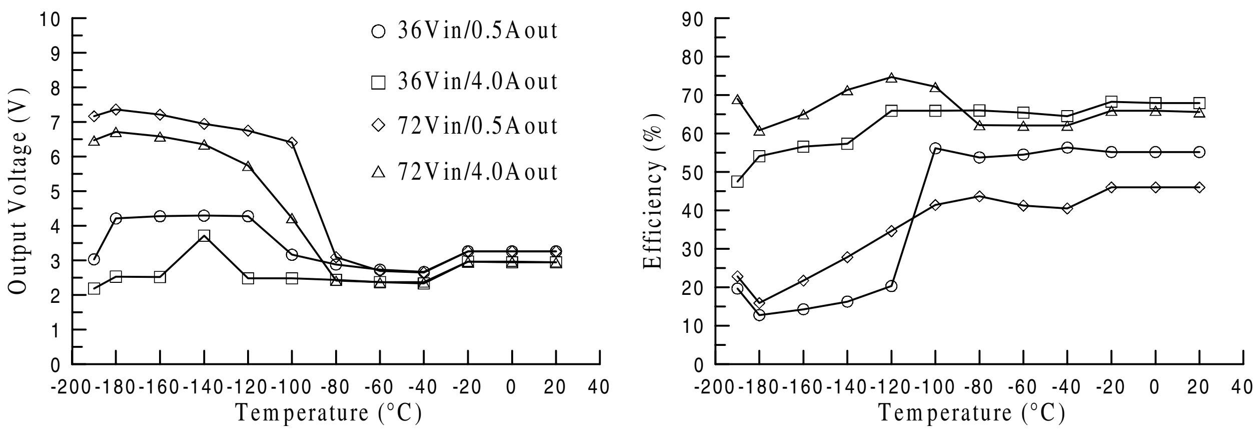

Figure 2. Voltage regulation and efficiency of module 2 versus temperature

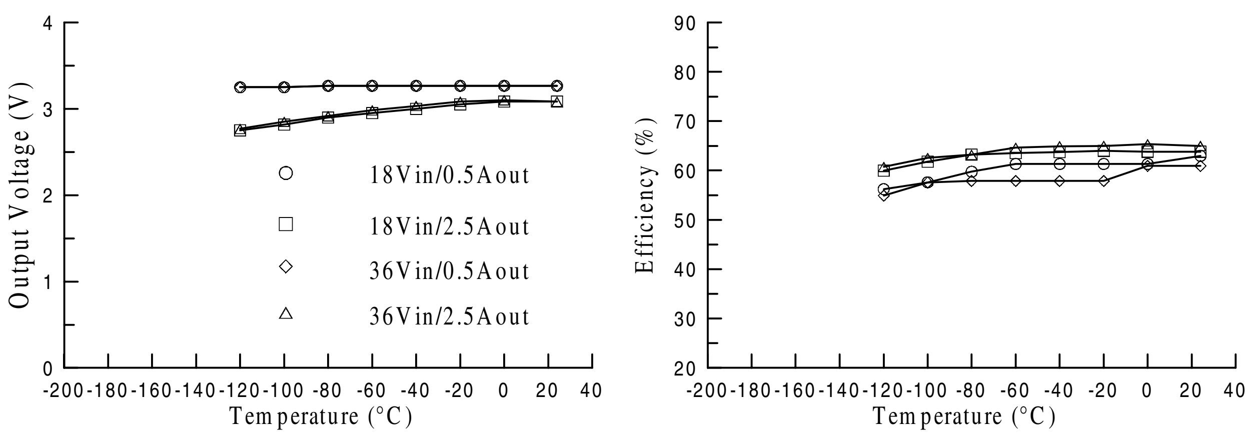

Figure 3. Voltage regulation and efficiency of module 3 versus temperature

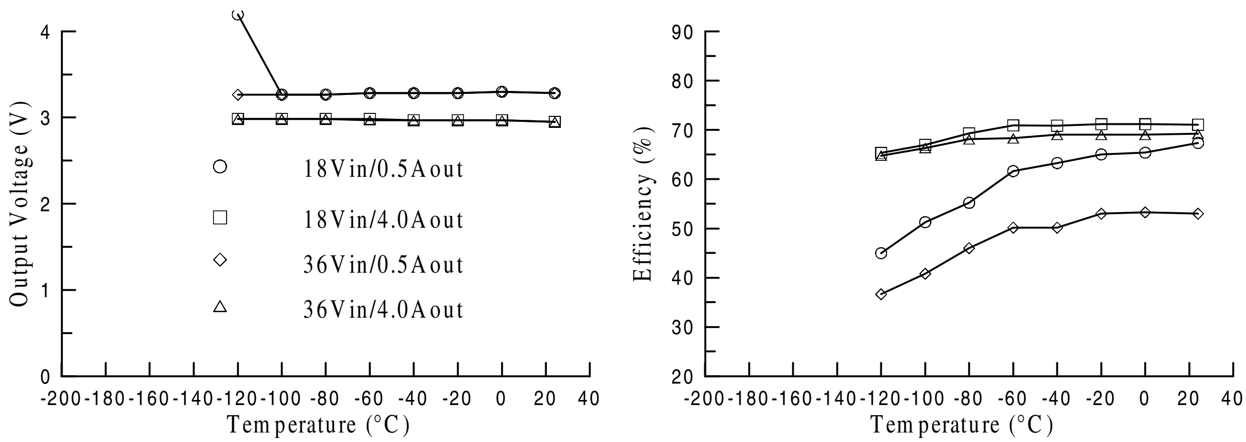

Figure 4. Voltage regulation and efficiency of module 4 versus temperature

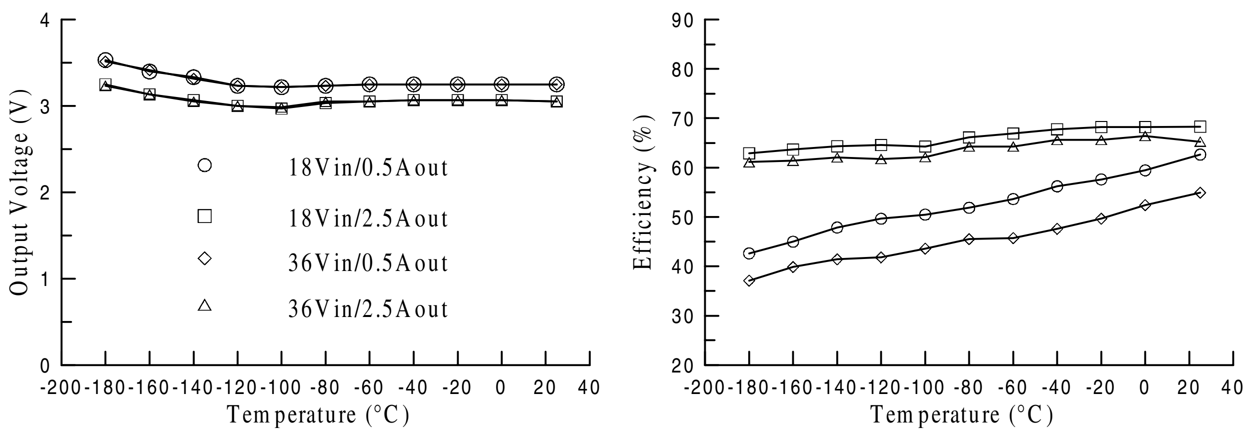

Figure 5. Voltage regulation and efficiency of module 5 versus temperature

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