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Test Results of Selected Commercial DC/DC Converters under Cryogenic Temperatures – A Digest

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Background

Semiconductor parts and electronic systems for use in certain NASA space missions must operate reliably and efficiently in extreme temperature environments. For example, an inter-planetary probe launched to explore the rings of Saturn would experience a temperature of about -183 °C near the planet. Other missions where electronics are expected to be exposed to cryogenic temperatures are listed in Table I. Presently, spacecraft operating in these environments utilize some kind of heating mechanism in order to maintain an operating temperature for the on-board electronics of approximately 20 °C. For example, some of the present spacecraft operating in the cold environment of deep space carry on-board a large number of radioisotope heating units (RHUs) to maintain an adequate operating temperature [1]. This is not an ideal solution because the radioisotope heating units are always producing heat, even when the spacecraft may already be too hot, thus requiring an active thermal control system for the spacecraft. In addition, RHUs add cost and mass and also require containment structures to spread the heat. Besides support and containment structures for the other types of temperature controls, some form of heat may be needed to power up electronics. These measures would result in design complexity, heavier systems, and reduced payload capability.

Electronics capable of operation at cryogenic temperatures will not only tolerate the hostile environment of deep space but also reduce system size and mass by eliminating radioisotope heating units and associated structures; thereby reducing system development and launch costs, improving reliability and lifetime, and increasing energy densities.

In addition to space, electronics that can operate under extreme temperatures have potential uses in terrestrial applications that include magnetic levitation transportation systems, medical diagnostics, cryogenic instrumentation, and super-conducting magnetic energy storage systems.

Table 1: Typical operational temperatures for unheated spacecraft.

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

DC/DC Converters

DC/DC converters are critical items in spacecraft power systems. They accept power from the solar arrays or batteries at a range of voltages depending on the power bus design and mission conditions (typically 24V to 36V for many NASA satellites, around 70V for some commercial satellites, and as high as 125V for the International Space Station) and deliver voltage regulated outputs at the levels needed by various digital and analog systems [2]. DC/DC converters that are capable of operating at cryogenic temperatures are anticipated to play an important role in the development of microelectronics for future NASA deep space missions. In addition to the discrete types, a large number of the currently available DC/DC converters are complex hybrid devices that use a variety of active and passive elements such as power MOSFETs, diodes, pulse width modulators, capacitors, optocouplers, inductors/transformers, etc., and are specified for various input/output voltages, efficiencies, and power ratings ranging from a few watts to over 100 watts. Their reliability, however, has long been a major concern for NASA parts and application engineers [3]. Recent failures of DC/DC Converters in NASA Projects have not all been attributable solely to design and manufacturing flaws in the hybrid versions. Several problems can be traced to varying electrical conditions which occur during integration and test, that are outside of the safe or rated operating area of the part [4]. In addition, both hybrid and discrete builds have experienced fatigue-induced problems related to solder joints and stress relief. These problems are closely related to packaging design and proper methods for wire bonding, and attaching packaged components to mechanically and thermally active elements in the assembly such as the hybrid lid, the hybrid substrate, the printed circuit board, and the part chassis [2]. Miniaturization of DC/DC converters to meet more stringent requirements in terms of volume and weight may also contribute to inefficient cooling and, thus, premature failure.

Design of DC/DC converters to survive cryogenic temperatures will improve the power system performance, simplify design, and reduce development and launch costs. Recently, there has been a tremendous progress in the design of high power density converters. When compared to standard conventional converter designs, the new converters can operate at power densities of more than 50% higher. This increase in power density was achieved by new designs, advanced devices and components, and packaging techniques. For example, the newly developed synchronous-rectifier-based DC/DC converter modules provide more usable output power without the use of a heat sink than do the conventional, schottky diode-based converters with a heat sink and thick-film components. However, all of the existing DC/DC converter systems are specified to operate within a limited temperature range. Most of the commercially available devices are rated between -40 °C and + 100 °C. As a result, efforts were taken at the NASA Glenn Research Center (GRC) to investigate the performance of commercial-off-the-shelf (COTS) converters. These efforts, which are supported by the NASA Electronic Parts and Packaging (NEPP) Program, were to establish performance and suitability of these COTS units for use under extreme temperatures in space exploration missions. The results of this work will expand the knowledge base on the reliability of electronic parts, and the information will be disseminated to mission planners and users groups for the design of efficient and reliable systems for space and aerospace applications.

Research Work

The performance of nine COTS modular, low-to-medium power DC/DC converters, with specifications that might fit the requirements of specific future space missions, was investigated under cryogenic temperatures. The converters were evaluated in terms of their output regulation, efficiency, and input and output current characteristics. At a 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 as a function of temperature using an environmental chamber cooled by liquid nitrogen using a temperature rate of change of 10 °C/min. Each of the test articles were allowed to soak for a period of 30 minutes at the selected test temperature so that thermal stability was achieved prior to recording measurements. Table II lists some of the specifications of these DC/DC converters.

Table II. DC/DC converter module specifications and performance.

Converter Specifications					
Manufacturer	**Part Number**	**Input Voltage (V)**	**Output Voltage (V)**	**Rated Power (W)**	**Operating Temperature (°C)**
Astrodyne	ASD10-12S3	9 - 36	3.3	10	-40 to 60
Power Trend	PT4110A	36 - 72	3.3	10	-40 to 85
Lambda	PM10-24S03	18 - 36	3.3	10	-40 to 70
Power One	DFA20E24S3.3	18 - 36	3.3	13	-40 to 85
CDI	1003S12HN	9 - 36	3.3	10	-40 to 85
Interpoint	SMHF283R3S/KR	16 - 40	3.3	15	-55 to 125
Calex	24S3.15HE	18 - 36	3.3	75	-40 to 100
SynQor	PQ48050HNA30	36 - 75	3.3	100	-40 to 115
Vicor	V48C12C150A	36 - 75	12	150	-20 to 100

Results

The results obtained on the evaluations of the nine DC/DC converters varied widely in terms of extending capability of operation at temperatures lower than their specified limit. A brief summary on the performance of each of the converters is described in Table III. It is important to note that any observed variation in the operational characteristics or the malfunctioning exhibited by any or all of the tested converters due to exposure to the cryogenic test temperatures was transitory in nature as all devices recovered upon elimination of the cold temperature stress.

Table III. Performance summary of tested converters.

Converter	Operating Temperature (°C)	Experimental Observations	Decisive* Temperature (°C)
Astrodyne	-40 to 60	V_{out} dropped to 2.4 V at –140 °C. Chip functioned down to –160 °C.	-160
Power Trend	-40 to 85	V_{out} lost regulation at –100 °C. Converter still functioned to –195 °C.	----
Lambda	-40 to 70	Chip worked very well down to -120 °C. Input current oscillations occurred at all temperatures under heavy loading.	-120
Power One	-40 to 85	Oscillations in input current started at –80 °C.	-120
CDI	-40 to 85	Oscillations in input current observed at –140 °C under heavy loading.	-180
Interpoint	-55 to 125	Low frequency oscillations with high peaks observed in input current at –120 °C and below.	-160
Calex	-40 to 100	Although the module ceased to work at -40 °C during steady state, it worked down to -100 when tested under a step change in load from full to no-load and vice-versa.	-40
SynQor	-40 to 115	Output voltage increased as temperature was lowered below 20 °C.	-80
Vicor	-20 to 100	Oscillation in input current started at –40 °C; more noticeable under heavy load conditions.	-120

* Temperature at which module ceased to operate.

The results depicted in Table III indicate that while some of the DC/DC converters continued to function at low temperatures well below their specified limit, others did not fare as well. The difference in the performance of these devices could be attributed to many factors which include:

- Design topology and architecture of the converter module such as buck, boost, etc.
- Selection of material used in the manufacturing of the modules as electrical, chemical, and physical properties were temperature-dependent. For instance diode's voltage drop, transistor's threshold voltage, capacitor's dielectric loss, and inductor's quality factor are very much influenced with temperature variation.
- Temperature-induced offset or drift in the biasing conditions for proper operation of some of the module's on-board components.
- Sensitivity of the individual parts to combined effects of electrical (loading) and thermal stressing.

In order to postulate the reasons for the change in the behavior of these devices, the data have to be examined on a case-by-case basis. Device packaging, interconnects, and wire-bonding issues should also be addressed via testing under long term conditions and, in particular, under thermal cycling. Finally, destructive testing followed by physical analysis would identify the damage and the associated failure mechanisms and, thereby, recommendations might be established to improve the design of newer devices and mitigate risks associated with exposure to extreme temperatures.

Conclusion

DC/DC converters are widely used in space power systems in the areas of power management and distribution, signal conditioning, and motor control. Design of DC/DC converters to survive cryogenic temperatures will improve the power system performance, simplify design, and reduce development and launch costs. In this work, the performance of nine COTS modular, low-to-medium power DC/DC converters was investigated under cryogenic temperatures. The converters were evaluated in terms of their output regulation, efficiency, and input and output currents. At a given temperature, these properties were obtained at various input voltages and at different load levels. A summary on the performance of the tested converters was given. More comprehensive testing and in-depth analysis of performance under long-term exposure to extreme temperatures are deemed necessary to establish the suitability of these and other devices for use in the harsh environment of space exploration missions.

References

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