Comprehensive Evaluation of Power Supplies at Cryogenic Temperatures For Deep Space Applications

Richard L. Patterson
NASA Glenn Research Center
MS 301-5
Cleveland, OH 44135

Ahmad Hammoud
QSS Group, Inc.
NASA Glenn Research Center
Cleveland, Ohio 44135

Scott Gerber
ZIN Technologies
3000 Aerospace Parkway
Brook Park, Ohio 44142

Malik E. Elbuluk
Electrical Engineering Department
University of Akron
Akron, Ohio 44325-3904

ABSTRACT

The operation of power electronic systems at cryogenic temperatures is anticipated in many future space missions such as planetary exploration and deep space probes. In addition to surviving the space hostile environments, electronics capable of low temperature operation would contribute to improving circuit performance, increasing system efficiency, and reducing development and launch costs. DC/DC converters are widely used in space power systems in the areas of power management, conditioning, and control. As part of the on-going Low Temperature Electronics Program at NASA, several commercial-off-the-shelf (COTS) DC/DC converters, with specifications that might fit the requirements of specific future space missions have been selected for investigation at cryogenic temperatures. The converters have been characterized in terms of their performance as a function of temperature in the range of 20 °C to - 180 °C. These converters ranged in electrical power from 8 W to 13 W, input voltage from 9 V to 72 V and an output voltage of 3.3 V. The experimental set-up and procedures along with the results obtained on the converters' steady state and dynamic characteristics are presented and discussed.

I. INTRODUCTION

Electrical power components and systems in many future space missions, such as outer planetary exploration and deep space probes, must operate reliably and efficiently in very low temperature environments. Table 1 shows operational temperatures for unheated spacecraft in the environments of the outer planets. These spacecraft include deep space probes, planetary orbiters and landers, and surface exploratory instrumentation. For example, inter-planetary probe launched to explore the rings of Saturn would experience an average temperature of about –183 °C.

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

Presently, spacecraft operating in the cold environment of deep space carry on-board a large number of radioisotope heating units to maintain an operating temperature for the electronics of approximately 20 °C [1]. This is not an ideal solution because the radioisotope-heating units are always producing heat, even when the spacecraft is already too hot, thus requiring an active thermal control system for the spacecraft. In addition, these units are very expensive and require elaborate containment structures. Electronics capable of operation at cryogenic temperatures will not only tolerate the hostile environment of deep space but will also reduce system size and weight 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 deep space applications, low temperature electronics have potential uses in terrestrial applications that include magnetic levitation transportation systems, medical diagnostic, cryogenic instrumentation, and super-conducting magnetic energy storage systems. The utilization of power electronics designed for and operated at low temperature is expected to result in more efficient systems than room temperature systems. This improvement results from better electronic, electrical, and thermal properties of materials at low temperatures [2,3]. In particular, the performance of certain semiconductor devices improves with decreasing temperature down to liquid nitrogen temperature (-

196 °C) [3,4]. At low temperatures, majority carrier devices demonstrate reduced leakage current and reduced latch-up susceptibility. In addition, these devices show higher speed resulting from increased carrier mobility and saturation velocity [3-5]. An example is the power MOSFET that has lower conduction losses at low temperature due to the reduction in the drain-to-source resistance $R_{DS(on)}$ resulting from increased carrier mobility [4,6,7].

II. LOW TEMPERATURE ELECTRONICS AT NASA

The Low Temperature Electronics Program at the NASA focuses on research and development of electrical components and systems suitable for applications in deep space missions [8]. Research is being conducted on devices and systems for use down to cryogenic temperature (-196 °C). Some of the components that are being characterized include semiconductor switching devices, resistors, magnetics, and capacitors [9-11]. A number of DC/DC converters have also been built and characterized in-house at low temperatures. The converters were designed or modified to operate from room temperature to -196 °C using commercially available components such as CMOS-type devices and MOSFET switches. These systems had output power range from 5 W to 1 kW with switching frequencies of 50 kHz to 200 kHz. Pulse-width modulation technique was implemented in most of these systems with open- as well as closed-loop control. The topologies included buck, boost, multi-resonant, push-pull and full-bridge configuration [1,3,7,9,12,13].

In this work, a number of commercial-off-the-shelf modular, low power DC/DC converter modules, with specifications that might fit the requirements of specific future space missions, have been selected for investigation at cryogenic temperatures. These converters, which ranged in electrical power from 8 W to 13 W, input voltage from 9 V to 75 V and an output voltage of 3.3 V, were characterized in terms of their performance as a function of temperature in the range of 20 °C to – 180 °C. The experimental set-up and procedures along with the data obtained on the investigated converters are presented and discussed. The results include the effect of temperature on the steady- state and dynamic characteristics under different input voltage and loading conditions.

III. HIGH-DENSITY DC/DC CONVERTER MODULES

Most of aerospace power management systems are DC-based and they require DC/DC power converters that operate with different input and various outputs from 1.5 V to 15 V at various power levels. Recently, there has been a tremendous progress in the design of high power density DC/DC converters. Converters that operate at power densities of 50% or more greater than the available standard conventional converter designs have been developed. This increase in power density is achieved using new designs, advanced devices and components, and packaging techniques. For example, the newly developed synchronous rectifier-based DC/DC converter modules with multi-layer thick film hybrid packaging provide more usable output power without the use of a heatsink than do the conventional, schottky diode based converters with a heatsink and thick-film single layer packaging. However, all of the existing DC/DC converter systems are specified to operate at low temperatures between –40 °C and –55 °C.

Our preliminary, low temperature tests on selected converter modules with nominal input voltage of 24V or 48 V, output voltage of 3.3 V and a power of 10 W have shown that the performance degrades rapidly, and in some cases a complete failure takes place at temperatures about –100 °C to –120 °C.

IV. EXPERIMENTAL SET-UP AND PROCEDURES

Several DC/DC converters with different ratings, acquired from various manufacturers, were investigated in this work. Some of the manufacturers' converter specifications are listed in Table II. The converters were characterized as a function of temperature from 20 °C to -180 °C in terms of their steady state and dynamic characteristics.

TABLE II. RATINGS OF DC/DC CONVERTER MODULES

Module Number	V_{in} (V)	V_{out} (V)	Power (W)	Temperature Range (°C)
	9 -36	3.3	10	-40 → +60
2	36-72	3.3	10	-40 → +85
3	9-36	3.3	10	-40 → +80
4	18-36	3.3	10	-40 → +70
5	18-36	3.3	13	-40 → +85
6	9-36	3.3	10	-40 → +85

A. *Steady-State Performance*

To evaluate the steady-state performance for each converter, the output voltage regulation, efficiency, and input and output current distortions were investigated. 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 a Sun Systems environmental chamber utilizing liquid nitrogen as the coolant. A temperature rate of change of 10 °C/min was used throughout this work. The modular converters were tested separately at the following temperatures: 20; 0; -20; -40; -60; -80; -100; -120; -140; -160; and –180 °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 thermal cycling on the converters.

B. *Dynamic Performance*

The dynamic characteristics of each converter were obtained by monitoring the transient response of the output voltage due to a step change in the load. Two responses were recorded, one from no load to full load and the other from full load to no load. These two tests were performed at two input voltage levels.

V. RESULTS AND DISCUSSIONS

A total of seven converter modules were evaluated under various test parameters and, thus, an enormous amount of data was generated during this investigation. Selected data pertaining to some of the tested converters will only be presented and discussed in this paper. In particular, the steady state and dynamic performance of modules 1 and 4 listed in Table II are presented.

A. *Steady-State Performance*

Figure 1a shows the output voltage of converter module # 1 as a function of temperature at different loads and input voltages. At a given load, the output voltage, corresponding to a specific input voltage, maintains a steady value from room temperature to -120 °C. For temperatures beyond –

120 °C, the converter begins to show loss in regulation. The direction of regulation, however, is dependent on the input voltage level. For example, while the output voltage increases slightly when the input voltage is 36V, it decreases drastically when the input voltage is 12 V. As expected, the output voltage drops slightly when the load is increased. The output voltage of module # 4 does not exhibit any dependence on either the input voltage or the test temperature at low loads as shown in Figure 2a. At heavy loads, it does however decrease upon lowering the test temperature regardless of the level of the input voltage.

The effect of temperature on the efficiency of converter module # 1 under different input voltage and load conditions is shown in Figure 1b. 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. Similar behavior was observed in regard to the effect of loading and input voltage variation on the efficiency of converter module # 4 as shown in Figure 2b at various test temperatures. The changes, however, are not as significant as those displayed by module #1.

The output voltage and input and output current ripple waveforms of the converter under light load at 20 °C and -120 °C are shown in Figure 3 for module # 1. Waveforms of these properties obtained at the same two temperatures under heavy load conditions are depicted in Figure 4. At room temperature, it can be seen that operating the converter under heavy load causes an increase in amplitude of both input and output current ripples. While this increase is very slight in the output current ripple, it is quite significant (about a factor of three) for the input current ripple (notice change of scale). Similar trend is observed due to loading of the converter at -120 °C but the intensity of the increase in the input current ripple is not as severe as that occurring at 20 °C. At a given load, a decrease in test temperature results in increase in both the amplitude as well as the frequency of the input and output ripple currents. For example, under heavy load at -120 °C, the input ripple exhibited about 25% increase in intensity and about 30 % increase in frequency compared to the room temperature values.

Similar behavior was observed for these properties of converter module # 4, as shown in Figure 5 at test temperatures 20 °C and -120 °C, respectively. For heavy load, the results are shown in Figure 6. The effect of decreasing temperature or increasing load, however, has more profound increase in the amplitude rather than the frequencies of both the input and output ripple currents. It is important to note that while this module ceased to operate at temperatures below -120 °C, it did recover when temperature was brought back to 20 °C. This indicates that the low temperature exposure, down to -120 °C, tends to only affect the performance of this module without causing a catastrophic failure. Similarly, converter module # 1 regained normal operation behavior when it was allowed to recover to 20 °C.

B. Dynamic Performance

The dynamic response for module #1, represented by output voltage response to a step change in the load current, is shown in Figure 7. It is very clear that the step change from no load to full load exhibits a slow dynamic response compared to a step change from full load to no load. The different responses are a clear indication of the nonlinear behavior of the module and may also reflect the effect of low temperature on the components and devices in the converter. The corresponding results for module # 4 are shown in Fig. 8. It is interesting to note that the dynamic response of this module resembles that of module # 1 only during a step change in the load current from no load (0 A) to full load (2.5 A). When the load current is switched from full load to no load, however, the output voltage of module # 4 exhibits a lightly-damped sinusoidal variation for duration of about one cycle. This behavior, which is more prominent at test temperature of 23 °C, is not ideal and cannot be explained. More testing and complete evaluation is needed to fully understand the operational dynamic characteristics and their dependence on temperature.

VI. CONCLUSIONS

Several commercially available DC/DC converters were characterized in terms of their performance as a function of temperature in the range of 20 °C to - 180 °C. The converters' evaluation included the output voltage regulation, efficiency, input and output current ripples and dynamic behavior in response to environmental temperature. Although data pertaining to only two converters were displayed and discussed in this paper, all converters generally displayed somehow similar behavior with change in temperature. The intensity of any occurring changes, however, varied with the converter type and the test temperature.

ACKNOWLEDGEMENT

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LIST OF FIGURES

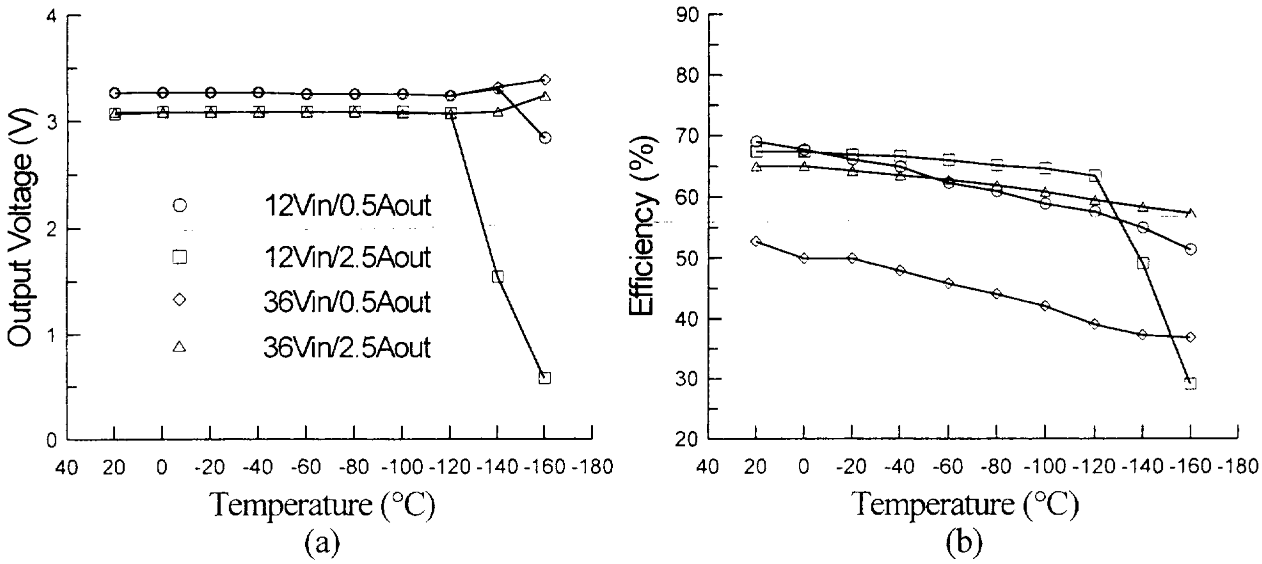


Figure 1. Output voltage and efficiency versus temperature for Module #1.

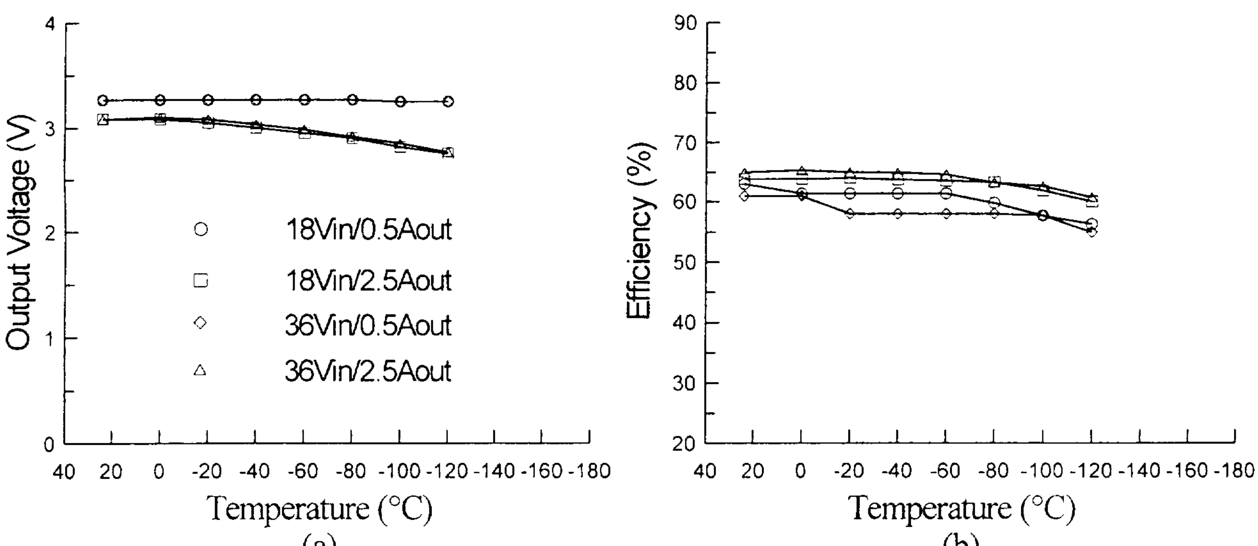
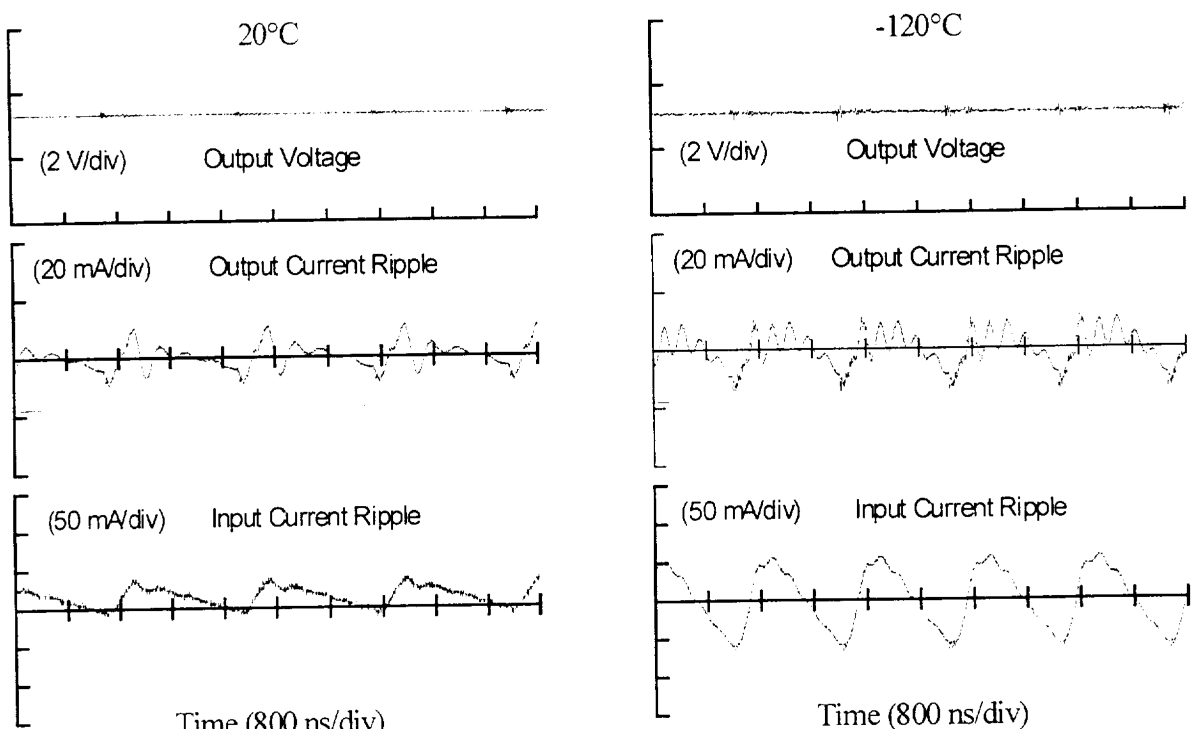


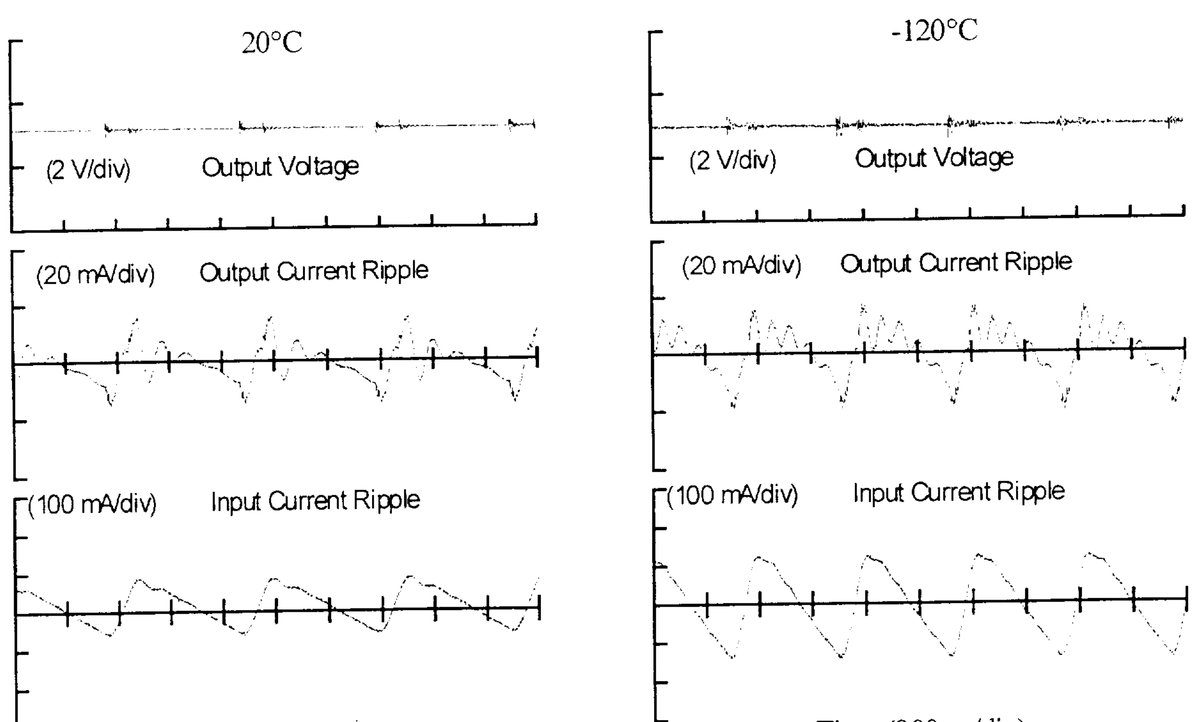
Figure 2. Output voltage and efficiency and versus temperature for Module #4.



Time (800 ns/div)
(a) 20°C

Time (800 ns/div)
(b) -120°C

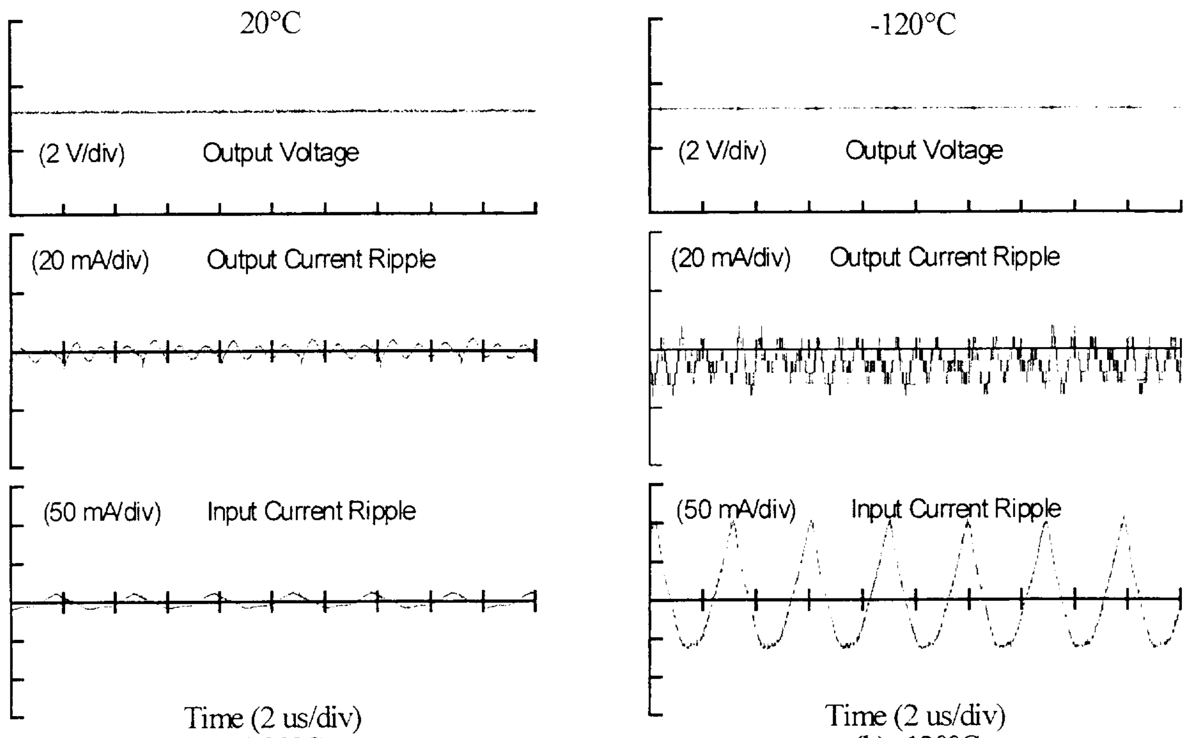
Figure 3. Module #1 operation with 36V input and under light load condition.



Time (800 ns/div)
(a) 20°C

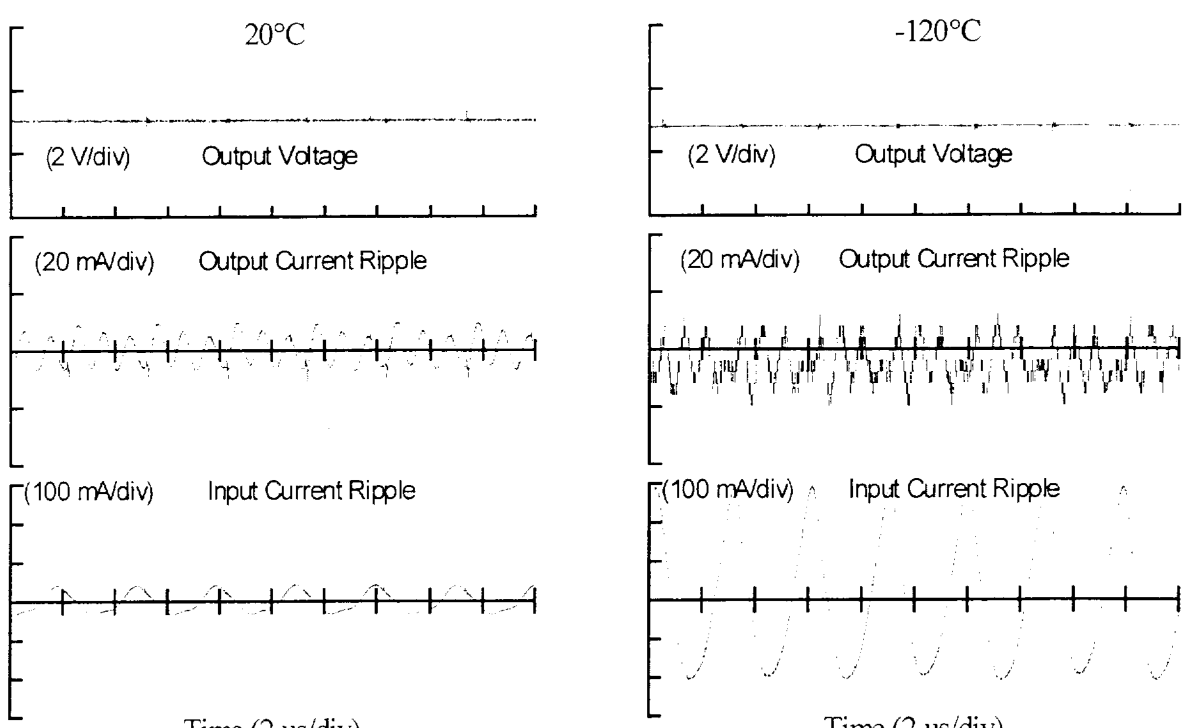
Time (800 ns/div)
(b) -120°C

Figure 4. Module #1 operation with 36V input and under heavy load condition.



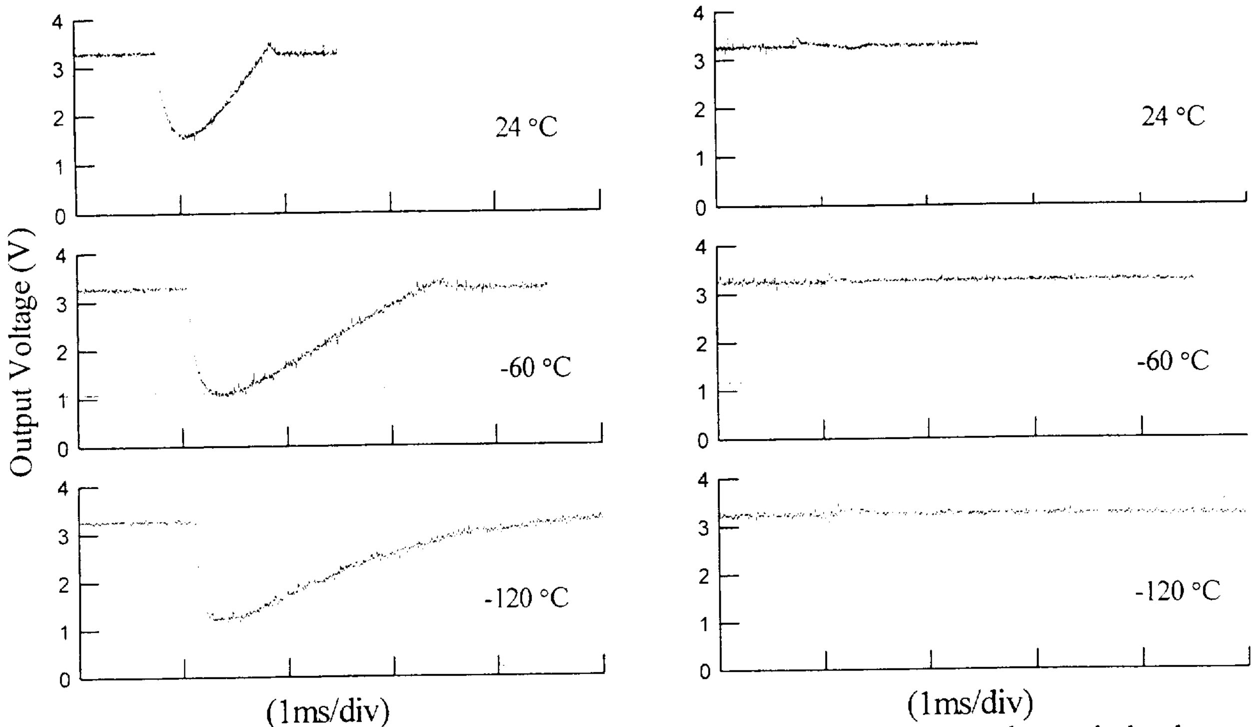
(a) 20°C (b) -120°C

Figure 5. Module #4 operation with 36V input and under light load condition.



(a) 20°C (b) -120°C

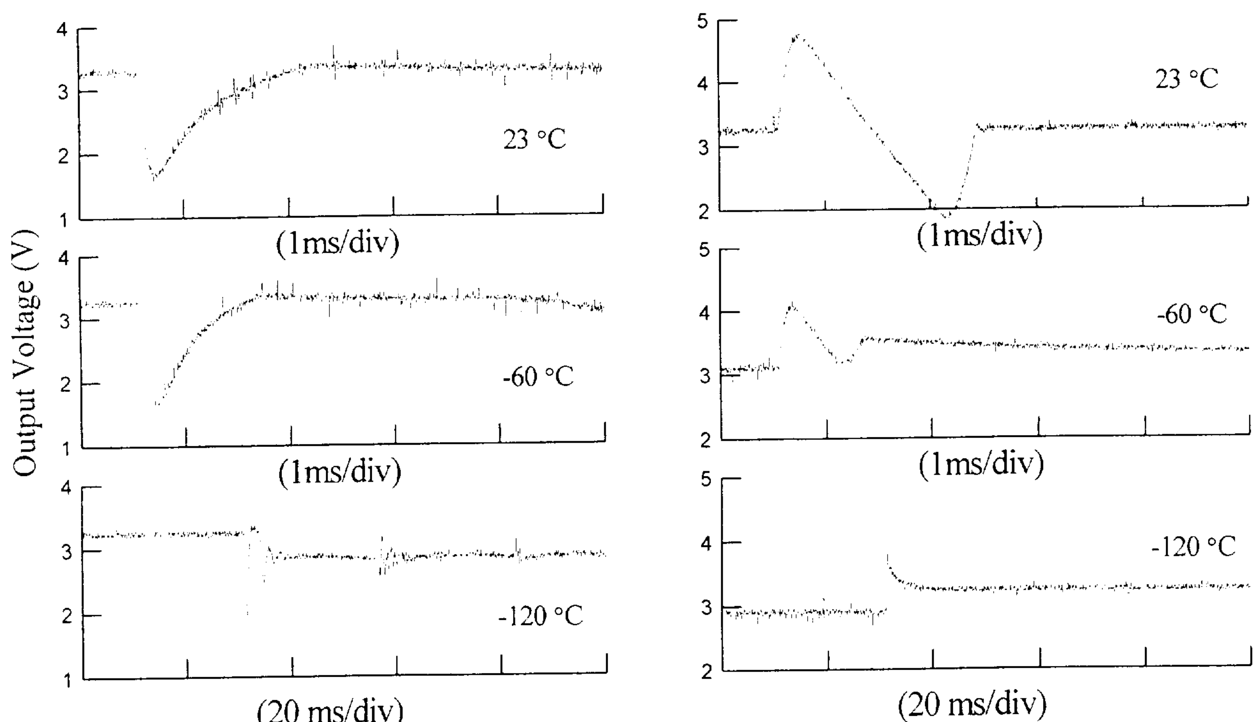
Figure 6. Module #4 operation with 36V input and under heavy load condition.



(a) 0 to 2.5A step change in load

(b) 2.5 to 0A step change in load

Figure 7. Module #1 transient response with 18V input.



(a) 0 to 2.5A step change in load

(b) 2.5 to 0A step change in load

Figure 8. Module #4 transient response with 18V input.