Case Study: Radiation Design and Testing of Hybrid DC-DC Converters

Testing data show that COTS DC-DC converters have good radiation characteristics, but can be made even better by replacing the main switching MOSFET with a rad-hard version.

Using standard product hybrid DC-DC converters in space applications offers a tremendous price and lead-time advantage. However, very few manufacturers publish radiation data on standard products and often do not take radiation considerations into the design of these products. The present alternatives are to buy expensive "space qualified", radiation-hardened, DC-DC converters that have very long lead times or use standard products and hope for the best.

However, testing results show that excellent total dose and single-event effects (SEE) radiation performance can be achieved in DC-DC converters at very reasonable costs by incorporating a few simple design techniques. Once these techniques are incorporated, radiation performance can be greatly extended by simply replacing the main switching MOSFET with a rad-hard MOSFET.

VPT conducted total dose and SEE testing on several hybrid DC-DC converters. To underscore the success of design modifications over baseline commercial converters, data is presented on both standard products and radiation-enhanced products where the only difference is use of a rad-hard power MOSFET.

Designing for Radiation Effects

Designing for radiation effects requires properly using converter topologies and selecting components with desirable characteristics. Additionally, designs using magnetic feedback instead of opto-coupler feedback will have enhanced radiation tolerance.

The first step in designing for radiation effects is choosing the appropriate power converter topology. Converters which have a direct short circuit path from a low impedance source to ground through MOSFETs will always be sensitive to single event upsets. These converters include the half-bridge, full-bridge, voltage-fed push-pull and active-clamp forward. All single-ended converters such as the forward or the flyback are acceptable. The current-fed push-pull converter is also acceptable. For feedback compensation, it is best to avoid using opto-couplers and instead employ magnetic isolated feedback.

As far as proper component selection is concerned, the critical parts in question are the power MOSFET, pulse-width-modulator IC, voltage sense op-amp, comparator for under-voltage lockout and zener reference for regulation (Figure 1). *It is critical to check available data bases maintained by NASA and DOD for the latest radiation data on various parts and manufacturers as this data changes frequently.* Table 1 shows a sample of recommended parts.

In hybrid DC-DC converter design, it is possible to design the substrate layout to accommodate both a conventional MOSFET and its radiation-hardened counterpart. The die of the radiation-hardened part is slightly larger; however, if the substrate is designed for the rad-hard version, then it will also work for the non-rad-hard version.

For the PWM, there are several ICs that have good radiation data available. In general, one must avoid using

Component	Recommended Part(s)
MOSFET	IRF510, IRF5301
PWM IC	UC1843
Op-Amp	LM158, LM124
Comparator	LM139
Zener	LT1009, RH1009

Table 1

These components have been found advantageous to creating inherently rad-hard DC-DC converters.

BiCMOS parts such as the UC1803. These parts are susceptible to both total dose and single-event radiation effects.

The critical op-amp parameter with regard to radiation is offset voltage or offset current. This will directly impact the output voltage regulation or the short circuit current regulation of the converter. When using a meter shunt resistor to sense output current, the circuitry can be particularly sensitive to changes in offset voltage due to total dose radiation effects. The critical voltage comparator parameter with regard to radiation is also offset voltage. This will directly impact the turn-on voltage of the converter. Changes in the zener diode reference voltage with radiation directly impacts the output voltage regulation of the converter. Therefore it is important to choose a stable zener reference.

Total Dose Radiation Test Method

Of the two primary types of radiation testing, single-event effects and total dose, total dose radiation testing on DC-DC converters can be performed relatively inexpensively at a number of different places such as Lockheed-Martin's Gamma Cell facility in Valley Forge, Pennsylvania. It's necessary to perform a complete data sheet test on the converter prior to radiation exposure and at regular intervals in order to see the gradual effect of radiation exposure.

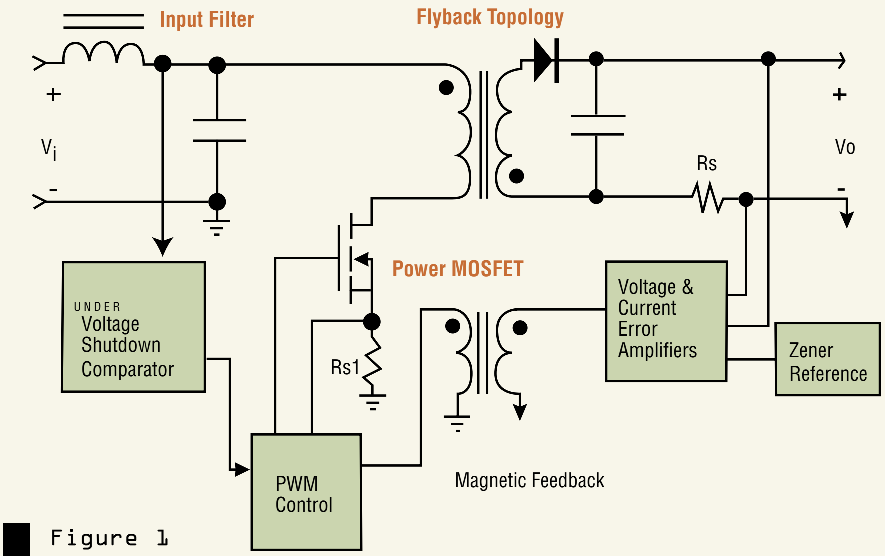

Figure 1

Typical power converter block diagram showing the major functional blocks. The functional blocks in the lower half are the ones most critical in rad-hard designs.

Total Dose Test Results for Standard Products

Several of the company's standard product hybrid DC-DC converters were tested, including the following:

- DVSA2805S (28Vin, 5W/5V – hybrid)
- DVHF2805S (28Vin, 15W/5V – hybrid)
- DVFL2812S (28Vin, 100W/5V – hybrid)
- DVTR10005S (100Vin, 30W/5V – hybrid)
- DVST3R30508R5T (28Vin, +3.3, +5.0V, +8.5V/ 30W – Plastic encapsulated)

The following parameters were tested on each of these parts at 10 Krad (Si) intervals:

- Output Voltage Line Regulation
- Output Voltage Load Regulation
- Short Circuit Current Regulation
- Switching Frequency Variation
- Input Current (Efficiency)
- Leakage Current (Input current when converter is inhibited)
- Undervoltage Lockout Point
- Vcc Internal Voltage Regulation

For each of these parts the total dose radiation failure mode was the same. After

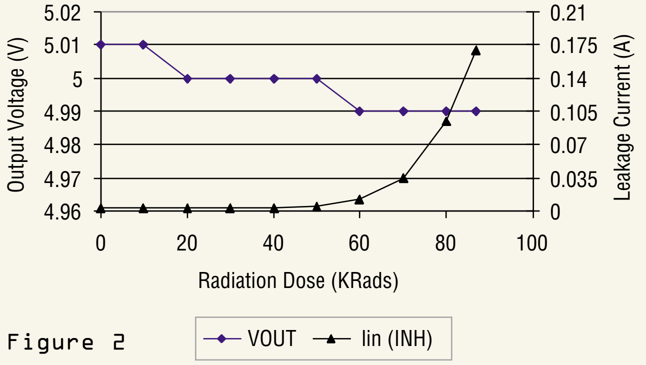

Figure 2

DVSA2805S Total Dose Radiation Performance. Although there is an increase in leakage current after about 60 Krads (Si), many space applications require only 30 Krads (Si). These parts may be acceptable for some radiation applications.

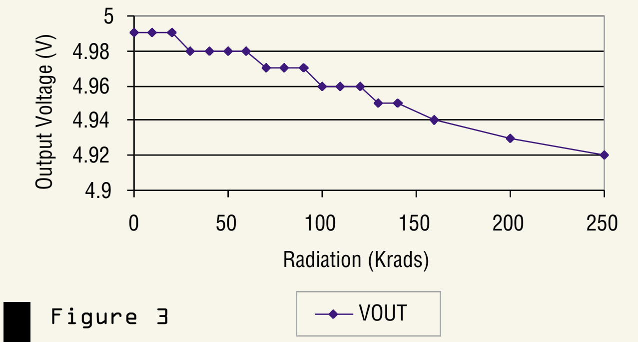

Figure 3

DVSA2805S-R Total Dose Radiation Performance. There is a gradual degradation in output voltage with increasing radiation, but the device can easily withstand total dose of 100 Krads (Si)—about 3x higher than with the pure commercial equivalent device.

about 50-80 Krads (Si), the leakage current would start to drastically increase. All other parameters stayed within part specifications. This can satisfy the total dose radiation requirements for a significant number of space missions. A large number of space missions only require 30 Krads (Si) of total dose capability.

The failure was understandable, as the common failure mode of power MOSFETs due to total dose radiation is a reduction in gate threshold voltage. Eventually, the gate threshold voltage actually becomes negative. If the OFF state gate voltage used in the design is zero volts, then the MOSFET will always be ON causing the converter to draw excess current. Designers can extend the total dose radiation capability of DC-DC converters by forcing a negative voltage during the OFF state of the power MOSFET. However, this will exacerbate single event radiation effects, notably single event gate rupture.

Figure 2 shows the radiation performance of the DVSA2805S – 5V/5W hybrid DC-DC converter. As seen in the figure, the output voltage experiences a very minor degradation at increased radiation levels, dropping from 5.01V to 4.99V after 60 Krads (Si). However, the leakage current starts to increase rapidly after 60-70 Krads (Si) from 3 ma to 40 ma at 70 Krads (Si). All other parameters (not shown) had minimal change. All of the other standard product converters tested had a very similar characteristic.

Total Dose Test Results for Radiation-Enhanced Products

As mentioned earlier, if radiation considerations are taken into account during the design stage, then radiation performance can be greatly enhanced by simply replacing the main power MOSFET with a radiation-hardened power MOSFET. The following radiation-enhanced hybrid DC-DC converter products were tested for total dose radiation:

- DVSA2805S-R (28Vin, 5W/5V – hybrid)
- DVHF2815S-R (28Vin, 15W/15V – hybrid)
- DVTR2805S-R (28Vin, 30W/5V – hybrid)
- DVTR10005S-R (100Vin, 30W/5V – hybrid)

When the radiation-hardened MOSFET is employed, the leakage current increase seen earlier in Figure 2 is no longer present. The total dose radiation limiting factor in a good design will be either the output voltage regulation or the short-circuit current regulation. Both of these are caused by drifts in the op-amp offset voltage.

Figure 3 shows the total dose radiation performance of the DVSA2805S-R,

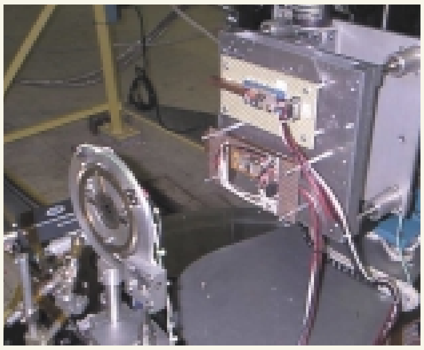

Figure 4

Photograph of two delidded hybrid DC-DC converters in preparation for SEE Testing.

the hardened version of the device shown in Figure 2. The converter experiences a very graceful degradation in the output voltage all the way up to 250 Krads (Si). All other parameters stay within specification. This result can satisfy more critical space missions that require total dose radiation capability up to 100 Krads (Si).

These results were very similar to the other radiation-enhanced products tested. The total dose capability ranged from at least 120 Krads to as high as 300 Krads. Short circuit current regulation, in particular, can be very sensitive to radiation if, as in this case, output current is sensed with a resistor instead of a current transformer. Amplifying the small voltage across a meter shunt resistor is very sensitive to changes in the op-amp offset voltage.

S.E.E. Radiation Test Method

Beyond total dose testing, testing DC-DC converters for single-event effects (SEE) is much more difficult, costly and subjective than total dose testing. SEE testing is performed at Brookhaven National Laboratory (BNL). The user can select from a variety of particle beams with different energies and focus the beam from a very narrow area (less than the width of a semiconductor die) to a maximum of 1.5" diameter. The tests are performed in a vacuum with the unit under test (UUT) delidded.

When testing hybrid DC-DC converters, the particle beam is focused on the ceramic substrate containing all the semiconductor dies. On parts where there are two ceramic substrates greater than one inch apart, the series of tests must be run twice—once for each board. The UUT is mounted on a board with a connector. It is critical that the parts be well heatsunk as they heat up very quickly in the vacuum. The connector wires are run through a vacuum feedthrough, to the test area. Figure 4 shows a photograph of two delidded hybrid DC-DC converters mounted prior to SEE testing.

Once vacuum is achieved and the beam focused, the user sets the particle flux, typically around 10^4 particles/sec, and the exposure time, typically around 100 seconds for a total fluence of 10^6 particles. Each UUT is exposed at various line (low to high input voltage) and output load conditions (1) low line, light load (LL/LL), (2) low line, maximum load (LL/ML), (3) high line, light load (HL/LL), and (4) high line, maximum load (HL/ML). While the UUT is being exposed the output voltage is viewed on an oscilloscope looking for the severity and frequency of transient upsets or if a catastrophic failure occurs.

S.E.E. Radiation Test Results for Standard Products

The following standard product hybrid DC-DC converters were tested for SEE:

- DVHF283R3S (28Vin, 3.3V/15W)
- DVSA2805D (28Vin, 5W/5V dual)
- DVTR2805S (28Vin, 30W/5V)
- DVFL2815D (28Vin, 100W/15V dual)

Table 2 shows the results for the DVHF283R3S when exposed to bromine ions (37 MeVcm^2/mg). This converter was tested by NASA-Goddard Space Flight Center (GSFC), and NASA's report served as a means of baselining all the remaining tests.

NASA then increased the energy level to Iodine ions (60 MeVcm^2/mg). The transients shown in Table 2 increased in frequency at light load. However, when the load was increased to maximum, a catastrophic failure occurred. This is to be expected, as standard (nonradiation-hardened) MOSFETs are

Operating Condition	Spike	Transient Frequency	Transient Duration
LL/LL	0.5V	~1 every 2 sec.	100µsec.
LL/ML	0.5V	~1 every 2 sec.	100µsec.
HL/LL	0.5V	~1 every 2 sec.	100µsec.
HL/ML	0.5V	~1 every 2 sec.	100µsec.

Table 2

SEE Bromine Test Results for the COTS DVHF283R3S. Bromine ions provide moderate energy density of 37 MeVcm^2/mg. The operating conditions provide "four corner" testing, from low line to high line input, and low load to maximum load output.

Operating Condition	Spike	Transient Frequency	Transient Duration
LL/LL	1.0V	~1 every 2 sec.	100µsec.
LL/ML	1.0V	~1 every 2 sec.	100µsec.
HL/ML	1.0V	~1 every 2 sec.	100µsec.

Table 3

DVTR2805S SEE Iodine test results for rad-hard DC-DC converters. Iodine ions impart more energy than Bromine to the DC-DC converter, and NASA rated this device to Category 2. The equivalent standard product would not have passed the test.

subject to single event gate rupture (SEGR) at high linear energy transfer (LET) levels.

Regardless, NASA classified the commercial DVHF283R3S as a Category 2 device—recommended for NASA-GSFC applications, but may require mitigation techniques. This is the second highest NASA rating. Mitigation can take the form of some additional output filtering if the load electronics are sensitive to the small transients. A very similar result was obtained for all the standard products tested.

S.E.E. Radiation Test Results for Radiation-Enhanced Products

The following radiation-enhanced standard product hybrid DC-DC converters were tested for SEE:

- DVTR2805S -R(28Vin, 30W/5V)
- DVFL2815D-R (28Vin, 100W/15V dual)

When exposed to the lighter Bromine ions, these units all experienced the same transients that their equivalent standard product versions experienced. However, by using the radiation-hardened MOSFET, these converters could be safely exposed to the higher energy Iodine ions.

Table 3 shows the test results for the DVTR2805S-R hybrid DC-DC converter when exposed to Iodine ions (60 MeVcm^2/mg). No catastrophic events occurred; however, the transients were larger than when exposed with Bromine ions. Based on NASA's classification, the DVTR2805S-R would be considered at least a Category 2 device. Note that the standard product exhibited catastrophic failure with Iodine ion bombardment.

Minor Modifications Yield Big Results

The results show that for the standard products tested, the total dose capability is approximately 50-60 Krads (Si). Above this level, the converter input current becomes excessive due to the MOSFET gate threshold voltage dropping close to zero. The single event capability is 37MeV (bromine level) with some minor transients. These have been characterized by NASA-GSFC as Category 2 devices and recommended for use in NASA applications with minor mitigation.

On the other hand, the test results show that for the radiation-enhanced standard products, the total dose capability is at least 100 Krads (Si) and as high as 300 Krads. The single event capability is at least 60MeV (Iodine level) with minor transients. All of the power converters characterized in this paper are available from VPT Inc. ▮▮

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