APPLICATION NOTE

Thermal Considerations for Hybrid DC-DC Power Converters

DC-DC CONVERTERS AND ACCESSORIES

Sales Information: (phone) 425-353-3010 • (fax) 425-353-4030 • vptsales@vptpower.com • www.vptpower.com

Contents:

Sales Information: (phone) 425-353-3010 • (fax) 425-353-4030 • vptsales@vptpower.com • www.vptpower.com

Introduction

VPT's DV series Hybrid DC-DC converters are rated for the full military temperature range of -55°C to +125°C and can be operated at full rated power within that range as long as the power dissipation and temperature rise is properly addressed. This document discusses the thermal management considerations for various assembly configurations of hybrid DC-DC converters.

Solid state DC-DC power converters always have efficiency less than 100%, and therefore always waste a percentage of their input power. This wasted power is dissipated as heat and will cause the temperature of the DC-DC converter to rise above the ambient system temperature. The temperature rise of the DC-DC converter must be considered during the system mechanical and thermal design to ensure the converter does not exceed its maximum rated operating temperature.

Characteristics of Hybrid Packaging

Thick film hybrid packaging technology uses bare semiconductor die and high thermal conductivity materials to achieve high temperature operation. A diagram of the typical hybrid package is shown in Figure 1. In its basic form, the bare silicon die is mounted to a ceramic substrate, usually Al2O3 (alumina), which is mounted to the metal package, usually steel or Kovar. Power is dissipated in the semiconductor die, which may be an IC, power transistor, or power rectifier. The die has a maximum semiconductor junction operating temperature, typically 150°C or 175°C, as specified by the manufacturer.

Sales Information: (phone) 425-353-3010 • (fax) 425-353-4030 • vptsales@vptpower.com • www.vptpower.com

The semiconductor junction temperature inside the hybrid, Tj, is determined by the following formula:

$$Tj = Tcase + \Delta T \quad (1)$$

$$\Delta T = Pd \cdot \theta jc \quad (2)$$

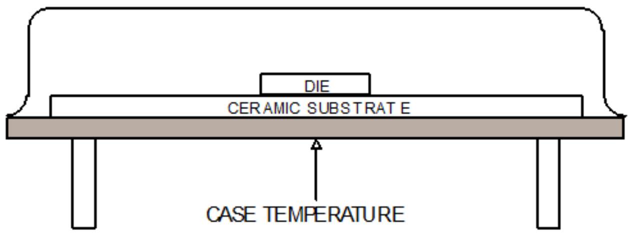

Figure 1. Internal Hybrid Construction.

Tcase is the case temperature of the hybrid; ΔT is the temperature rise from junction to case; Pd is the power dissipated in the die; and θjc is the thermal resistance from the junction to the case. θjc is the sum of any intermediary thermal resistances, in this case the ceramic substrate, the attachment materials, and the case itself.

Thermal Resistance Calculation

The thermal resistance θ for any material can be calculated according to the formula:

$$\theta = \frac{x}{K \cdot A} \quad (3)$$

Where A is the cross sectional area normal to the direction of the heat flow, x is the distance that the heat travels, and K is the thermal conductivity of the material. For example a 0.75" tall aluminum spacer block with dimensions 1" x 0.4" which could be mounted under the flange of the DVTR package has a thermal resistance of:

$$\theta = \frac{0.75in}{3.957\frac{W}{in - C} \cdot 1.0in \cdot 0.4in} = 0.47\frac{°C}{W} \quad (4)$$

The thermal conductivity of aluminum is 3.957W/in-C. From (2), each Watt of power dissipated through this aluminum block causes a temperature rise across the block of 0.47°C.

DC-DC Converter Application

The maximum operating temperature range of VPT's hybrid DC-DC converters is -55°C to +125°C. From Figure 1, it is apparent that the thermal path is entirely through the bottom of the package. The operating temperature is specified and must be measured on the bottom surface of the case. The lid offers very little path for heat transfer. Any temperatures measured on the lid will give inaccurate results, and any heatsinking added to the lid will have only minimal effect. The system thermal design must allow for the primary thermal path through the bottom of the package.

The case temperature will always be slightly higher than the heatsink or ambient temperature due to the power dissipated in the hybrid and the thermal resistance of the assembly. Case temperature cannot be assumed to be equal to the heatsink or ambient temperature. This wrong assumption is the cause of many system thermal problems. Proper system design will allow high system temperatures, in excess of 100°C, yet maintain hybrid component temperatures well below 125°C.

If the case of the hybrid is maintained below +125°C, the internal semiconductor junction temperatures will remain at safe levels, typically between 130° and 140°C, well below their maximum ratings. If the output power of the hybrid is reduced, the maximum allowable case temperature can be increased further without increasing the internal junction temperatures. The derating criteria for the DV series hybrid DC-DC converters is from full rated power at +125°C, linearly to half power at +130°C, and to zero power at +135°C, as shown in Figure 2.

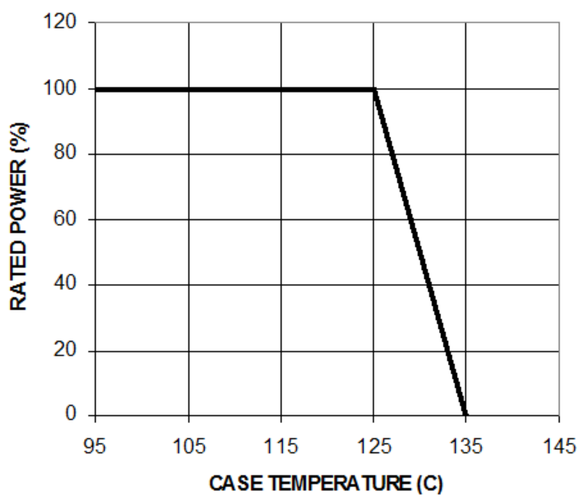

Figure 2. Temperature Derating Curve

Although hybrid DC-DC converters can be operated up to +125°C, reliability can be increased by operating them at a lower case temperature. Every electronic component has a failure rate which is in theory related to its operating temperature. Lowering the operating temperature of the hybrid by 5°C can result in a 10-20% increase in MTBF according to MIL-HDBK-217 type calculations. In general, the system design should attempt to reduce thermal resistances and minimize the temperature rise between the DC-DC converter and the system ambient. For maximum reliability, the DC-DC converter should be operated as close as possible to the ambient temperature rather than near its maximum operating temperature.

Determining Internal Junction Operating Temperatures

The maximum internal temperature rise for any individual semiconductor junction is given in the absolute maximum ratings section of the DC-DC converter datasheet and is typically between 5° and 15°C. For example, the DVTR2800S datasheet gives and internal "Junction Temperature Rise to Case" of 15°C. The internal junction temperatures are all within 15°C of the case temperature. Since a typical hybrid package contains many semiconductor junctions, the datasheet parameter refers to the internal junction with the largest temperature rise and is given at rated load.

An internal thermal resistance from junction to case is often required for reliability calculations. It is not practical to consider every distinct semiconductor junction, but an overall effective thermal resistance can be calculated as follows:

$$\theta jc = \Delta T / Pd, \qquad (5)$$

Where ΔT is the junction temperature rise to case and Pd is the power dissipation at full load, both from the absolute maximum ratings section of the datasheet. For example, the DVTR2800S datasheet gives ΔT = 15°C and Pd = 13W. The effective internal thermal resistance from junction to case would be:

$$\theta jc = 15°C / 13W = 1.15\ °C/W. \qquad (6)$$

Sales Information: (phone) 425-353-3010 • (fax) 425-353-4030 • vptsales@vptpower.com • www.vptpower.com

The maximum internal junction temperature can then be calculated at reduced output power. For an application requiring 12V at 30W, the efficiency of the DVTR2812S is 83% read from the graph in the datasheet. The power dissipated under this condition is:

$$P_D = P_{OUT}\left(\frac{1}{Eff} - 1\right) = 30W\left(\frac{1}{83\%} - 1\right) = 6.1W \qquad (7)$$

The effective temperature rise from junction to case under this condition would be:

$$\Delta T = 6.1W * 1.15\ °C/W = 7°C \qquad (8)$$

If the case of the hybrid were held at 90°C by the system, the effective internal maximum junction temperature would be 97°C.

Considerations for Proper Mounting

DV series DC-DC converters are typically used in applications where the dominant mode of heat transfer is conduction. Any radiation or convection cooling is usually neglected in the thermal analysis. Low power models such as DVCH and DVSA, and high efficiency models such as the DVHE and DVPL, can often be mounted without a heatsink or rely on the PCB for heatsinking, depending on the ambient temperature. On the other hand, the higher power DVFL will usually require a low thermal resistance connection to a substantial heatsink, such as a system chassis.

Aluminum is typically used for a heatsink or heatspreader material, since it has high thermal conductivity, low weight, and is easily machined. A thermally conductive gap filler material should be used between the mounting surface of the hybrid and the heatsink. This gap filler is typically a thermal pad, thermal grease, or adhesive. It will fill any surface irregularities and decrease the thermal resistance of the interface. Materials are available from various manufacturers with various properties: thickness, hardness, dielectric breakdown, adhesive, outgassing, etc.

VPT offers pre-cut thermal pads sized to fit various hybrid packages. The thermal resistances of these thermal pads are given in Table 1.

Sales Information: (phone) 425-353-3010 • (fax) 425-353-4030 • vptsales@vptpower.com • www.vptpower.com

VPT P/N	Use With	Thermal Resistance θtp [°C/W]
TP-001	DVFL2800S, DVFL2800D, DVME28	0.06
TP-002	DVHF2800S, DVHF2800D, DVHF+2800T, DVSB2800D, DVGF+2800T	0.14
TP-003	DVTR2800S, DVTR2800D, DVHV2800S, DVHV2800D, DVEHF2800T, DVHE2800S	0.10
TP-004	DVTR2800T, DVETR2800S, DVETR2800D	0.09
TP-005	DVSA2800S, DVSA2800D	0.24

Table 1. Thermal resistance of TP-xxx thermal pads.

The DC-DC converter should be mounted securely to the heatsink for good thermal conductivity. The flange package, adhesive, or a mounting strap is recommended for best performance. Some gap filler materials require adequate mounting pressure to maintain good thermal performance. Solder connections to the pins are usually not sufficient if a good thermal interface is required.

Determining the Case Temperature

The operating temperature of the hybrid should be verified by both analysis and measurement. For design purposes the operating temperature can be calculated using computerized finite element analysis methods or a simple thermal resistance model. A thermocouple mounted on the baseplate of the hybrid in the actual system is a good method of verification, but usually must wait until late in the development cycle. Basic thermal resistance calculations will be presented in this paper for several mounting configurations. These calculations, usually approximate, are a good design tool early in the development cycle before full system thermal models are developed.

Sales Information: (phone) 425-353-3010 • (fax) 425-353-4030 • vptsales@vptpower.com • www.vptpower.com

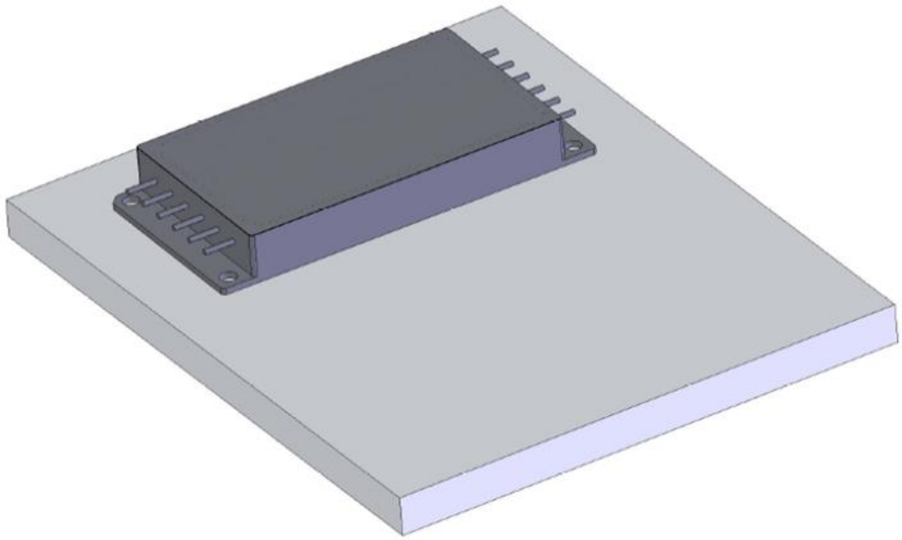

Figure 3. DVFL mounted directly to metal heat spreader.

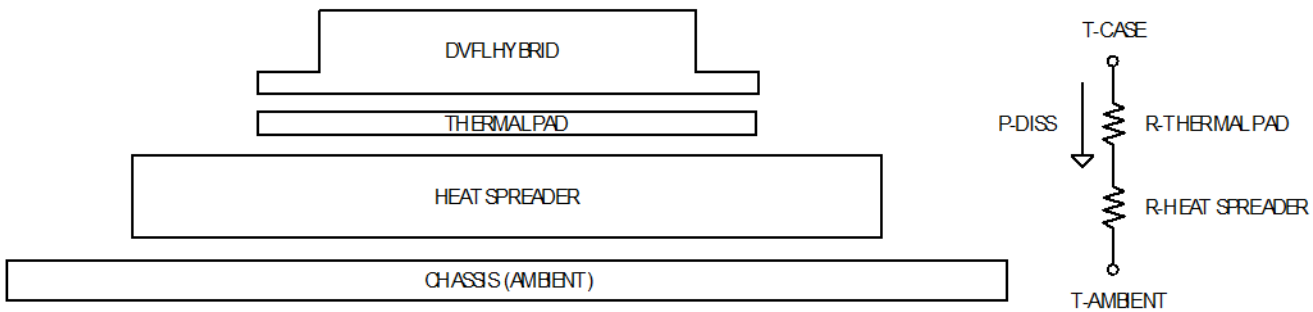

Figure 4. Mechanical stackup and thermal resistance model for DVFL.

Figure 3 shows a side-leaded DVFL hybrid mounted directly to a heatspreader. Figure 4 shows the mechanical stackup and equivalent thermal resistance model, assuming the heatspreader is mounted to a chassis with a known ambient temperature.

Sales Information: (phone) 425-353-3010 • (fax) 425-353-4030 • vptsales@vptpower.com • www.vptpower.com

The case temperature of the DVFL is calculated similarly to (1) and (2):

$$\text{Tcase} = \text{Tamb} + \text{Pd} \cdot \sum\theta \qquad (9)$$

Tamb is the known ambient temperature of the system chassis. Pd is the total power dissipation of the hybrid and can be calculated from (7) where the efficiency has been measured or read from the datasheet graph at the correct operating condition. The total thermal resistance ∑θ is the sum of all intermediate thermal resistances from the hybrid to the ambient, in this case the thermal pad and the heat spreader.

$$\sum\theta = \theta\text{thermalpad} + \theta\text{heatsink} \qquad (10)$$

The thermal resistance of the thermal pad can be read from Table 1. The thermal resistance of the heatsink can be obtained from its manufacturer or calculated according to equation (3). The power dissipated internal to the hybrid can be assumed to be spread evenly across its baseplate, so the area in (3) would be the area of the DVFL baseplate, not the entire area of the heat spreader. If the heatsink is unusual or nonrectangular in shape, its thermal resistance can be approximated by breaking it up into rectangular blocks which are in series with respect to the heat flow. The thermal resistance of each block can be calculated individually and summed to obtain the total thermal resistance.

For this example: the ambient temperature is 70°C; the power dissipated for the DVFL2815S at 28V input; full load is 30W; the thermal resistance of the thermal pad TP-001 is 0.06°C/W from table 1. The aluminum heat spreader is 0.5” thick. From (3) the thermal resistance of the heat spreader is:

$$\theta = \frac{0.5in}{3.957\dfrac{W}{in-C}\cdot 3.0in \cdot 1.5in} = 0.028\frac{°C}{W} \qquad (11)$$

And the case temperature of the DVFL is:

$$\text{Tcase} = 70°\text{C} + 30\text{W} \cdot (0.06°\text{C/W} + 0.028°\text{C/W}) = 72.64°\text{C} \qquad (12)$$

This configuration with the hybrid mounted directly to a heatsink will usually result in the lowest possible operating case temperature. It can be applied to down-leaded type packages such as the DVHF and DVTR by adding clearance holes in the heatsink for electrical connections to the pins.

Sales Information: (phone) 425-353-3010 • (fax) 425-353-4030 • vptsales@vptpower.com • www.vptpower.com

"Deadbug" Style Mounting

Figure 5 shows an example of "deadbug" style mounting for the DVTR hybrid in the flanged package. This is a common mounting configuration for severe vibration environments. Electrical connections to the pins can be made with discrete wires or a flexible or rigid printed circuit board.

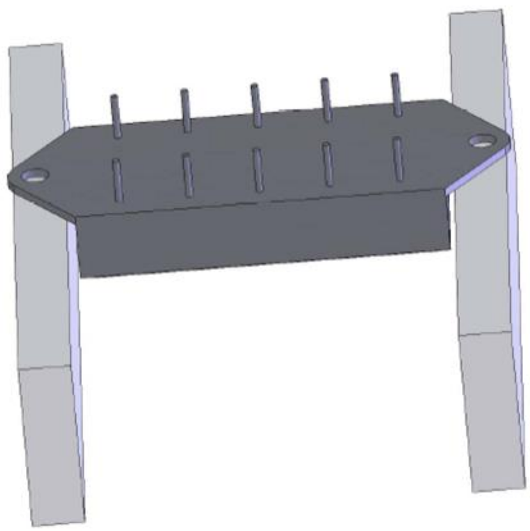

Figure 5. "Deadbug" Style Mounting for Downleaded Flanged Units.

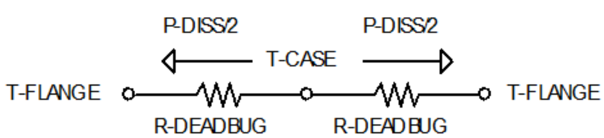

Figure 6. "Deadbug" thermal model.

Sales Information: (phone) 425-353-3010 • (fax) 425-353-4030 • vptsales@vptpower.com • www.vptpower.com

In this case, heat is transferred only through the mounting flanges. The maximum temperature is assumed to be in the center of the hybrid, and there is an additional thermal resistance and temperature rise from the center to the mounting flange. For this configuration since power is dissipated across the surface of the baseplate, finite element methods were used to obtain an effective thermal resistance, R-deadbug, from the center of the package to the flange, as shown in Figure 6. This effective thermal resistance will give a valid hot spot case temperature when used in conjunction with the total power dissipation of the hybrid. This effective thermal resistance is given in Table 2 for various flanged packages.

Converter Model	Thermal Resistance [°C/W]
DVHF, flanged package	4.06
DVTR, flanged package	6.22
DVTR, triple output, flanged package	4.80

Table 2. Thermal resistance of the hybrid case for “dead-bug” mounting (from center of package to mounting locations).

The hot spot temperature in the center of the hybrid is given by (13) where each flange is held at the same temperature, Tflange. The power dissipated, Pd is divided by 2 since there are two parallel thermal paths, one to each flange.

$$T_{case} = T_{flange} + \frac{P_d}{2} \cdot \theta_{deadbug} \qquad (13)$$

The “deadbug” mounting method will usually result in higher case temperatures than the direct heatsink configuration of Figure 3.

Sales Information: (phone) 425-353-3010 • (fax) 425-353-4030 • vptsales@vptpower.com • www.vptpower.com

“Deadbug” Style Mounting with Heat Spreader

For applications with high power dissipation or high ambient temperature, the case temperature of the hybrid can be lowered by adding a heat spreader to the basic “deadbug” mounting configuration, as shown in Figure 7. The heat spreader should have a thermal conductivity greater than that of the hybrid package (cold rolled steel, K = 1.318W/in-C). For example, for the DVTR package an aluminum bar 0.6” x 2.9” x 0.1” thick could be used. To be effective, the spreader must clear the electrical pins and maintain thermal contact along its entire length; a thermally conductive adhesive is recommended.

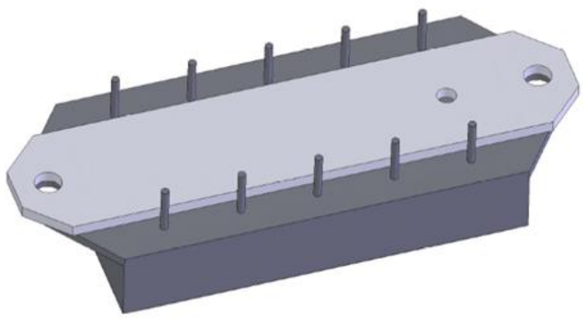

Figure 7. Heat Spreader Attached to DVTR to Reduce Thermal Resistance.

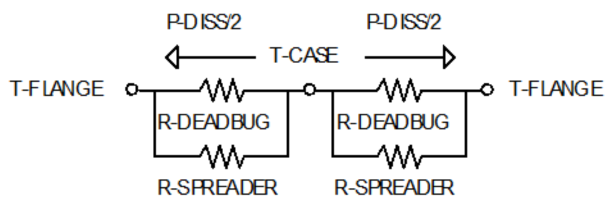

Figure 8. Thermal model for “deadbug” mounting with heat spreader.

Sales Information: (phone) 425-353-3010 • (fax) 425-353-4030 • vptsales@vptpower.com • www.vptpower.com

Again using finite element methods, an approximate thermal resistance model can be derived for this configuration. The thermal resistance of the heat spreader can be assumed to be in parallel with the effective thermal resistance of the package with an additional factor of 2. This additional factor was derived through finite element modeling to account for the fact that heat is actually transferred to the heat spreader along its entire length, instead of simply at the center of the hybrid. The thermal resistance of the spreader is calculated for heat flow along its length, and for this case, would be:

$$\theta_{spreader} = \frac{1.275in}{3.957\frac{W}{in-C}\cdot 0.6in\cdot 0.1in} = 5.37\frac{°C}{W} \qquad (14)$$

Where x is the distance from the center of the package to the center of the flange. Using the formula for parallel resistors, the case temperature of the hybrid would be:

$$T_{case} = T_{flange} + \frac{P_d}{2}\cdot\frac{1}{\frac{1}{\theta_{deadbug}}+\frac{1}{\theta_{spreader}/2}} \qquad (15)$$

Note that θ-spreader is divided by 2 as mentioned above. It is apparent that this configuration with the heat spreader (15) will always result in a lower case temperature than the previous configuration without the heat spreader (13). The thermal resistance of the heat spreader must be low enough to have a significant impact; it must be made of a high thermal conductivity material and have adequate size.

Sales Information: (phone) 425-353-3010 • (fax) 425-353-4030 • vptsales@vptpower.com • www.vptpower.com

PCB Mounting

Lower power hybrids can often be mounted directly to the circuit board or PCB as shown in Figure 9. Good thermal contact should be maintained between the hybrid and the board. An adhesive is often used. Mounting flanges or a mounting strap across the top of the hybrid can also help maintain good thermal contact. The thermal resistance of the PCB should be calculated lengthwise through the PCB material from the center of the hybrid to the mounting locations of the PCB using (3). The case temperature can be calculated from (9). Typical PCB materials are not good thermal conductors. Copper planes are often employed to improve thermal conductivity along the length of the PCB. Likewise, thermal vias are used to improve thermal conductivity through the PCB, usually under the hybrid or at the board mounting locations.

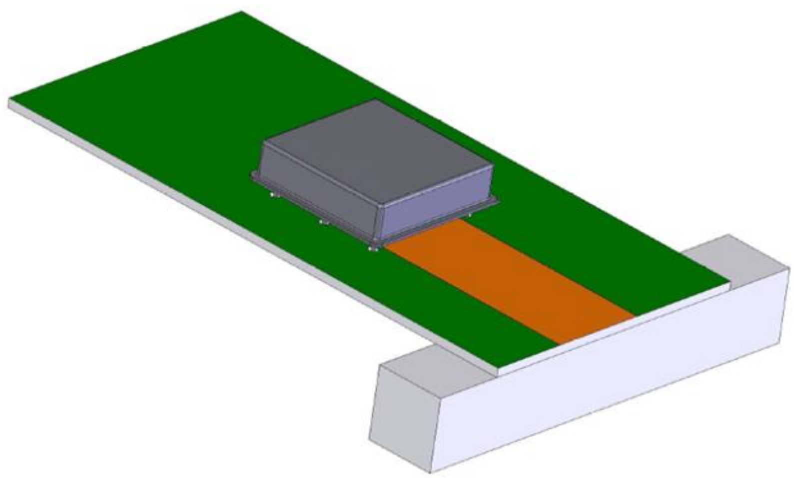

Figure 9. DVSA Mounted to a Circuit Board.

Sales Information: (phone) 425-353-3010 • (fax) 425-353-4030 • vptsales@vptpower.com • www.vptpower.com

PCB Mounting with Heat Spreader

When the PCB alone is not sufficient to carry heat away from the hybrid, a heat spreader can be added to the assembly as shown in Figure 10. In this case, the thermal path through the PCB can usually be ignored and the case temperature of the hybrid can be calculated directly from (9). Additionally, intentionally isolating the thermal spreader and hybrid from the PCB can serve to lower the temperature of the PCB and surrounding components.

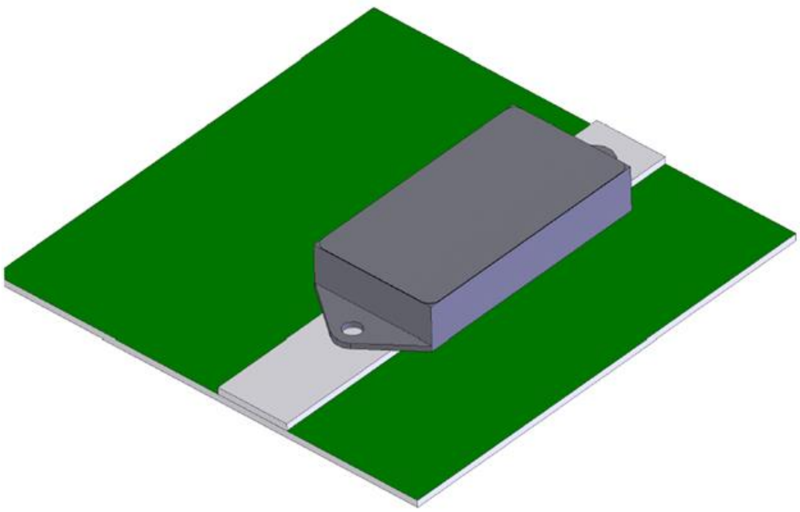

Figure 10. Converter/Heat Spreader/PCB Assembly.

Another option is to cut a hole in the PCB, and allow a heat spreader to protrude up and make contact with the heat spreader. The mechanical mounting should again be sufficient to ensure good thermal contact between the baseplate and the heat spreader.

Sales Information: (phone) 425-353-3010 • (fax) 425-353-4030 • vptsales@vptpower.com • www.vptpower.com

Conclusion

Proper system thermal design is necessary to allow hybrid DC-DC converters to operate reliably over the full military temperature range. To ensure maximum ratings are not exceeded, it must be recognized that the hybrid operating temperature will be greater than the ambient or heatsink temperature. The hybrid operating temperature is specified at the bottom center of the baseplate. It can be determined either by analysis or measurement. Knowing the actual temperature will allow accurate reliability calculations and proper tradeoffs between design complexity and reliability.

Contact Information

For further information about any of VPT's products, policies, or programs contained herein, or to request a quotation or place orders please contact your sales representative or the VPT Inc. Sales Department at:

Phone: (425) 353-3010
Fax: (425) 353-4030
E-mail: vptsales@vptpower.com
Website: www.vptpower.com

Sales & Marketing Headquarters:
19909 120th Avenue NE
Suite 102
Bothell, WA 98011

Company Headquarters:
1971 Kraft Drive
Blacksburg, VA 24060