

THERMAL CONSIDERATIONS: ASSURING PERFORMANCE OF 2ND GENERATION HIGH-DENSITY DC-DC CONVERTER MODULES

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As the modular DC-DC converter industry realizes greater power densities, proper thermal management must be achieved in order to get the most usable power to the load. Efficiency, while an important element in thermal management, is not the only item to consider. Dealing with the heat generated by the conversion process should not be underestimated nor overlooked when designing or selecting a power supply.

All power product manufacturers specify the maximum operating temperature of their products. Product reliability and operating life are inversely proportional to operating temperature. Assuring a robust design requires that the temperature limit not be exceeded under any operating conditions and that sufficient margin be built in. This requires careful analysis, understanding of the application and verification through experimentation that the chosen thermal management approach can deal effectively with the environmental and load induced demands.

The first step in this process is to determine the worst-case power dissipation that the system is likely to develop. Use the following equations to determine the efficiency of the converter over the desired operating range and the maximum loading the device will deliver. Conversion efficiency is defined as:

$$\eta = \frac{P_o}{P_{in}} \quad (1)$$

Where P_o is the output power and P_{in} is the input power.

The manufacturer of the device will normally publish efficiency values. However, one should not assume that the published efficiency specification applies at all operating conditions; ask the manufacturer to provide a plot of the efficiency as a function of the parameters specific to your application. Figure 1 shows a plot for Vicor DC-DC converter Model V300A48C500A; a 300Vdc nominal input, 48Vdc at 500 Watt output taken at room temperature.

Figure 1 shows that the efficiency remains very flat over most of the operating range. Traditionally, DC-DC converter manufacturers provide efficiency information that applies

at a specific line and load combination. Unfortunately, the device is usually not operated at only this one point; that is why it is important to look at the full efficiency map. For a good thermal management design, use the worst-case efficiency expected over your operating range in the calculation to determine the worst-case power dissipation.

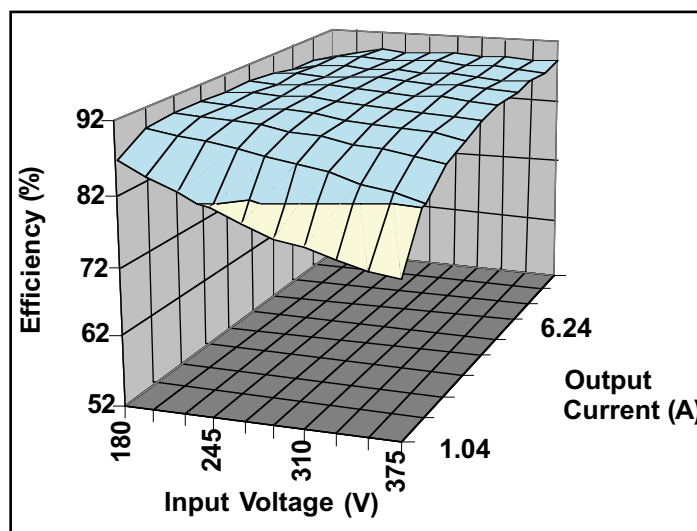


Figure 1. Efficiency vs. Input Voltage and Output Current for Vicor DC-DC Converter Model V300A48C500A

From Figure 1, the efficiency at nominal line is 89% for most of the output range. We'll use this as the worst-case efficiency in our examples. If this converter were operating at full load ($P_o = 500W$), the power dissipated (P_d) as heat is:

$$P_d = \frac{P_o}{\eta} - P_o \quad (2)$$

Therefore $P_d = 61.8W$.

Now we must determine the baseplate temperature rise over ambient caused by this power dissipation.

All manufacturers publish thermal data for their converters. For the product in question, the maximum specified operating temperature, as measured at its baseplate, is 100°C (Tb). The published thermal impedance (θ) value in free air is 4.9°C/W. Therefore, the temperature rise over ambient is simply:

$$Tr = Pd * \theta \quad (3)$$

or 302.8°C.

In this case, considering the large temperature rise, the module could not be operated at full load in free air. Even if the module's efficiency were 92%, the temperature rise over ambient would be 213°C, far in excess of the 100°C baseplate rating. High efficiency alone will not solve this operating system problem.

A heat sink or other means of reducing the thermal impedance of the baseplate is needed. To find a suitable heat sink, we need to find the allowable temperature rise in order to determine the thermal impedance required to keep the baseplate temperature within specification. The allowable temperature rise is the difference between the maximum baseplate temperature and the maximum expected ambient temperature.

If the maximum ambient temperature were 55°C, for example, the allowable temperature rise for this Vicor product would be 45°C (= 100°C - 55°C). The thermal impedance needed is the allowable temperature rise divided by the maximum power dissipated, Pd (Equation 4).

$$\theta_{\max} = \frac{T_{\text{allowed}}}{P_d} \quad (4)$$

In this example, the thermal impedance is calculated as 0.73°C/W. This is the maximum thermal impedance that can be tolerated, and will result in the module operating at its maximum specified temperature when delivering full rated load at the maximum expected ambient temperature. This thermal impedance is not just that of the heatsink but the sum total of all the individual interface impedances in the system. This has particular importance with respect to the selection of a thermal interface material. In all cases, the lower the thermal impedance of this interface, the better. Vicor offers a unique phase change material called "ThermMate" that offers a factor of 10 improvement over dry-style thermal pads.

It is never good practice to design to the limits. Picture yourself in a manual transmission car and, rather than upshifting, you run the engine to the red line to attain the speed you want and keep it like that for miles and miles. Even though the manufacturer says the rpm range is available, you instinctively know that this type of driving shouldn't be done. The same principle applies to power

devices. For robustness and longevity, the cooler the device operates the better. A derating factor of 0.75 should be applied to the maximum thermal impedance needed whenever possible.

Applying the derating factor results in a more desirable θ of 0.547°C/W. This low impedance is achieved by employing one of the following cooling methods:

Natural Convection Cooling - transfer of heat energy to a fluid, primarily air.

Forced Convection Cooling - transfer of heat energy to a moving fluid.

Conduction Cooling - transfer of heat through a solid medium.

Natural convection cooling to air is best realized by maximizing surface area, either in the form of a heat sink or mounting the module to a heat-conducting surface. Many manufacturers offer heat sinks as an integral part of their product. Depending upon the application, forced air may be necessary to keep the device within its limits. Some manufacturers also provide heat sinks as accessory products. Other heat sink manufacturers will design a custom solution based on the information you provide. When conduction cooling is employed, the thermal energy is usually dissipated to the surrounding air through convection.

Consider the following thermal circuit: Within a module, the heat generated by the switching elements is conducted to the module baseplate. It then conducts through a thermal interface material to a metal panel within a rack. The panel then dissipates the heat energy into the air via convection. A power supply mounted within a sealed NEMA enclosure is an ideal application for conduction cooling because the heat generated is transferred to the box itself and then to the surrounding air. When conduction cooling is employed, the user must ensure that the product remains within its limits. Because the surface to which the product is mounted may not dissipate the heat efficiently, the user will need to make a series of tradeoffs to successfully implement the thermal management scheme. Some of the variables will be the physical space available, airflow, and orientation of the product within the system.

A conservative design philosophy, with whichever cooling method is utilized, is recommended. Verification of the thermal management system by direct measurement is encouraged. Obstructions, eddies, and installation errors can all serve to hinder airflow resulting in a significant loss of cooling capacity of an otherwise acceptable "paper" design.

A couple of thermal examples are given below.

Example 1

Find the maximum ambient temperature at which a module can deliver 400W given the following information:

$$\begin{aligned}\eta &= 86\% (0.86) \\ \theta_{\max} &= 0.77^{\circ}\text{C/W} \\ T_b &= 100^{\circ}\text{C}\end{aligned}$$

SOLUTION: Rearrange equations 4 and 3;
 $T_{\text{ambient max}} = T_b - (\theta_{\max} * (P_d))$
 $T_{\text{ambient max}} = 49.86^{\circ}\text{C}$

Example 2

Determine the maximum tolerable thermal impedance from the module baseplate to air for a system delivering 300W to a load given the following:

$$\begin{aligned}T_{\text{ambient maximum}} &= 60^{\circ}\text{C} \\ \eta &= 91\% (0.91) \\ T_b &= 100^{\circ}\text{C}\end{aligned}$$

SOLUTION: Determine the power dissipated (P_d) from equation 3

$$P_d = 29.67\text{W}$$

Calculate the maximum allowable temperature rise from

Equation 4:

$$\begin{aligned}T_r \text{ allowable} &= T_b - T_{\text{ambient maximum}} \\ T_r \text{ allowable} &= 40^{\circ}\text{C} \\ \text{Calculate the maximum thermal impedance:} \\ \theta_{\max} &= T_r \text{ allowable} / P_d \\ \theta_{\max} &= 1.35^{\circ}\text{C/W}\end{aligned}$$

Web-based calculators on the Vicor Internet site easily perform all these calculations; the user simply enters the known values and selects the parameter to calculate.

If volume utilization is not critical to the application, the addition of a heat sink to lower the thermal impedance is relatively trivial. One simply chooses the largest heat sink and fin combination for the space available and attaches it to the module with the appropriate thermal interface material. What is more typical, however, is that there is barely enough room to squeeze in the power module. Many telecom applications have large rack-mounted units that contain multiple PCBs very close together. This inter-board spacing is referred to as "pitch". In order to maximize the utility of their products, the more PCB cards they can get into a given space the better. This makes component height above the PCB an important issue.

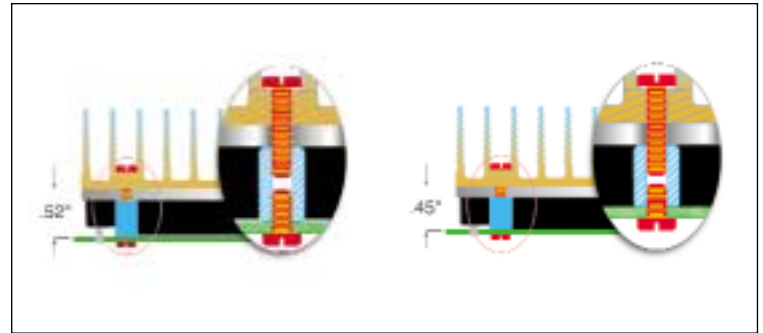


Figure 2. On-board mounting (left) vs. in-board mounting (right)

As illustrated above, the height above the board advantage gained by recessing the belly of this module within the PCB is lost with the addition of a traditional heat sink. What is needed is a low profile heat sink that offers reasonable thermal characteristics. Fortunately, Vicor does offer such a product (Figure 3).

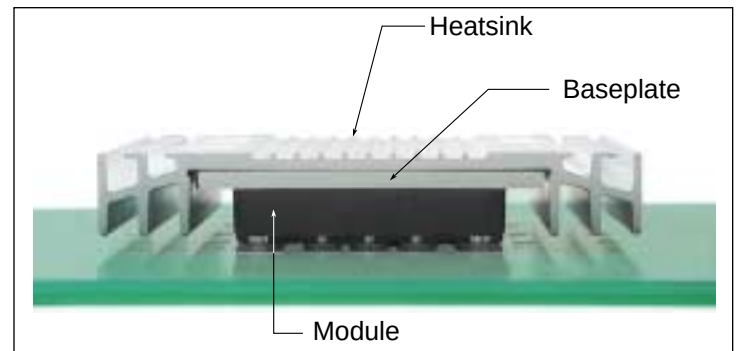


Figure 3. Low-profile side fin heat sinks

Side-fin heat sinks (Part #s 20394, 20393, and 20392 for the Maxi, Mini, and Micro family respectively) add only 0.125 inches to the module baseplate by shifting the cooling fins to the side of the module as opposed to the top. Having the fin tips in close proximity to the PCB forms a convenient duct through which directed forced air can flow.

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Aug 00 TPB_106 Rev 1 page 3 of 3