POWER SOLUTION BRIEF

Use of Circuit Models in Thermal Calculations

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Thermal modeling is a vital part of power system design, as exceeding the maximum internal temperature of a component can result in device failure. Additionally, operating power components at temperatures below the maximum offers further benefits.

While power components can be operated up to the maximum of the specified internal temperature range, it is always better to operate any electronic device at as low a temperature as possible. The power FETs utilized inside the product will typically have a lower drain-to-source resistance with lower temperature. Electrical resistance of copper also decreases with reduced temperature – copper resistance at 100°C is about 30% higher than the resistance at 25°C. The result of this is that the component will typically have a greater efficiency at a lower operating temperature.

Reliability and operating life also improve with lower operating temperature, as it is a generally accepted rule-of-thumb that a 10°C decrease in electronics operating temperature doubles reliability and operating life.

Thermal circuit models

Thermal circuit models are analogous to electrical circuits and contain resistors, current sources and voltage sources. Electrical resistors are replaced in this analogous circuit model with thermal resistances in units of degrees Celsius per watt (°C/W). A current source is analogous to a heat source in units of watts (W). The voltage source is used as an analogous temperature source in this circuit model with units of degrees Celsius (°C).

Use of circuit models

Physics dictates that the temperature of a power component is driven by its power dissipation, which can be calculated using output power and the efficiency given in the data sheet. Data sheets also typically show temperature-dependent efficiency and power dissipation in graphical format.

Since a primary goal in thermal management is to determine the maximum value for internal temperature, the data sheet values for efficiency / power dissipation used in the calculation need to be those given at an elevated temperature. The graph shown in Figure 1 below plots efficiency and power dissipation at an 80°C case temperature for a range of output power (current).

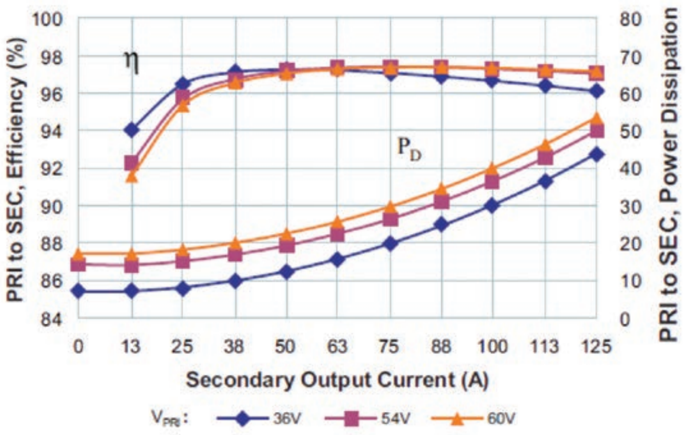


Figure 1

6123 BCM K 1/4 efficiency and power dissipation graph

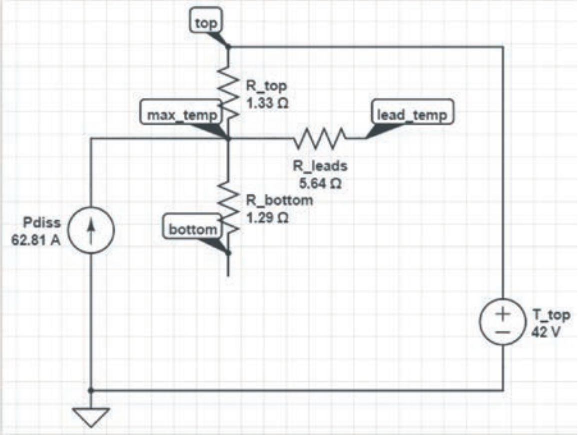
Once the power dissipation is added to the circuit model, what remains is for the designer to add their thermal environment, i.e., whether the component is conduction cooled with a coldplate or convection cooled with a heat sink.

The simple case is when the engineer uses a coldplate to cool the component. For this application, a temperature boundary condition is added to the circuit model as an analogous voltage source, since voltage in an electrical circuit is analogous to temperature in a thermal circuit.

The circuit model of a ChiP™ BCM® with coldplate cooling through the top of the package is shown in Figure 2. For a 1750W output at 96.5% device efficiency, the temperature of the coldplate must be maintained at or below 42°C to keep the internal temperature of the ChiP within the 125°C maximum of the operating temperature range for the component as defined by the data sheet. The thermal resistance of any thermal interface material between the ChiP top face and the coldplate is assumed here to be negligible; otherwise the thermal interface resistance should be added in series between the $R_{TOP\ RESISTANCE}$ and the T_{TOP} temperature boundary.

Figure 2

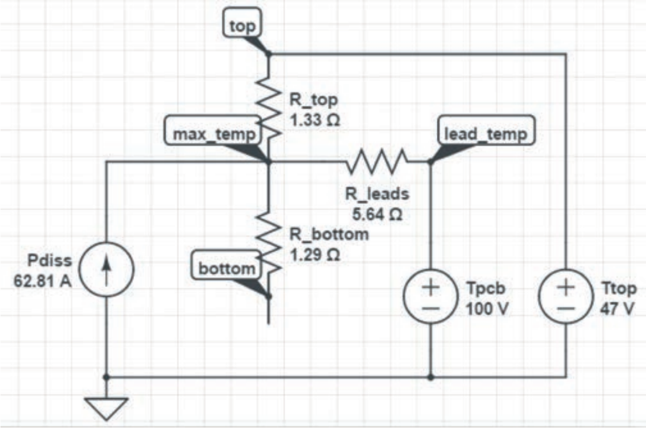
ChiP BCM with top coldplate cooling



The ChiP thermal resistance from the maximum internal temperature to the device leads is also included in the data sheet for through-hole devices. This can be incorporated into the thermal solution by the engineer if they have a prior knowledge of the PCB temperature; they may have historical or experimental knowledge of the expected PCB temperature. In some cases, a power system will have significant copper traces within the PCB for current carrying capability that may also contribute to cooling of the ChiP. For the example shown in Figure 3, the designer has characterized their expected PCB temperature to be 100°C.

Figure 3

ChiP BCM with top coldplate and PCB cooling added

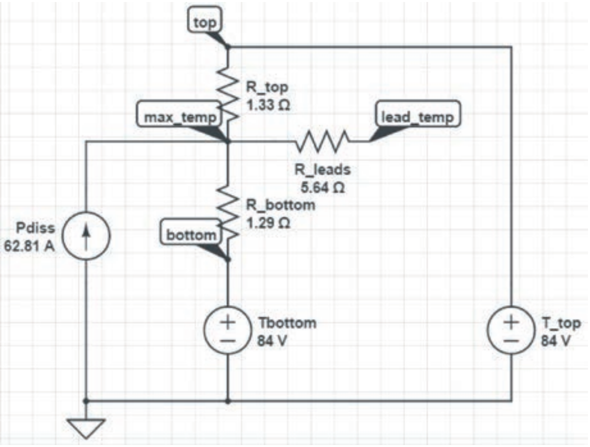


The maximum allowable temperature of the coldplate (T_{TOP}) can be 47°C and maintain the maximum internal temperature of the component to less than 125°C. The model can also be used to determine how much heat is conducted into each thermal boundary. In the example shown in Figure 3, about 4.4W of the total 62.81W dissipated by the ChiP™ is conducted into the PCB. This knowledge allows the designer to prepare for adequate cooling of the PCB.

Adding a second coldplate to the ChiP BCM® to cool both the top and bottom would allow the two coldplates to operate at significantly higher temperatures than a single coldplate cooling solution for the device (84°C versus the previous 42°C for our example), while still keeping the maximum internal temperature of the ChiP within the operating temperature range. The circuit model of this system is shown in Figure 4. In this case, the lead resistance is not connected. This implies an adiabatic condition at the end of the resistance, meaning there is no heat flow from the internal temperature node to the PCB through this dissipation path.

Figure 4

ChiP BCM with coldplate attached top and bottom

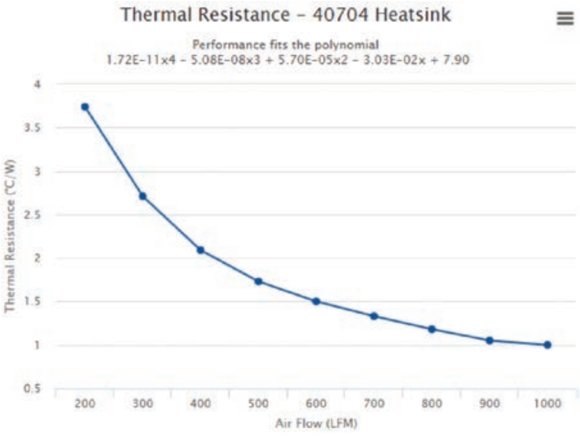


Impact of airflow

For most heat sinks, data is available that will allow the engineer to add the heat sink thermal behavior to their circuit model. This heat sink performance is characterized as a graph and corresponding polynomial equating thermal resistance as a function of air flow. Figure 5 shows a thermal resistance graph for an 11mm Vicor heat sink (P/N 40704).

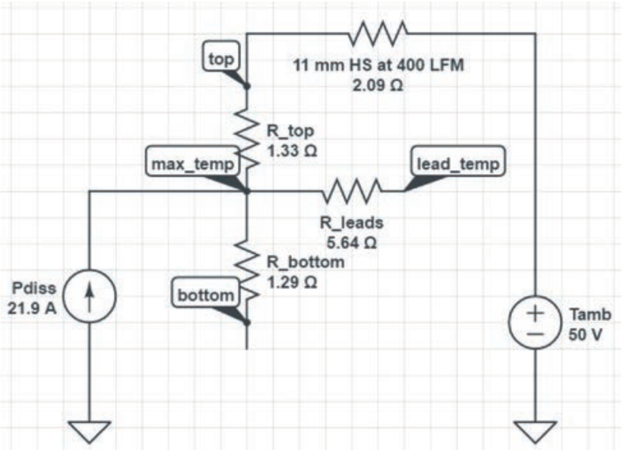
Figure 5

Thermal resistance graph and polynomial fit for 11mm P/N 40704 heat sink



If the engineer adds this heat sink to a ChiP with a thermal boundary condition of 50°C ambient air temperature, the resultant circuit model is as shown below in Figure 6. It can be seen from the circuit model that the power dissipation must be limited to less than 21.9W under these conditions to maintain an internal ChiP temperature less than the maximum 125°C of the operating temperature range.

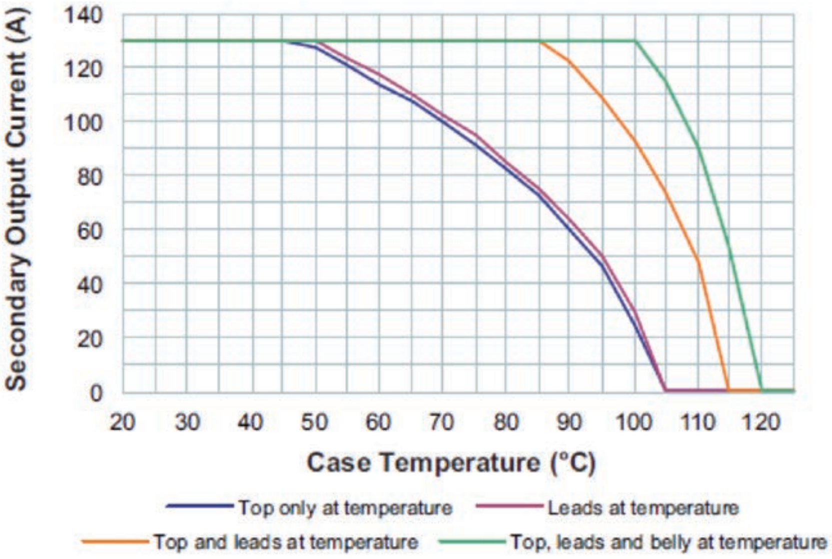
Figure 6
Circuit model of ChiP™ BCM®
with 11mm heat sink



Thermal Operating Area

Component data sheets also contain graph(s) that show the acceptable thermal operating area. An example of this graph is shown in Figure 7 below.

Figure 7
Specified thermal
operating area graph



Adherence to the conditions in the graph is intended to keep the maximum internal temperature of the component within the allowable operating temperature range. The assumption in the graph is that the case temperature denoted on the X axis is uniform along the face of the package. This is essentially the condition that would result from a ChiP being attached to a heat sink or coldplate with a thin layer of thermal grease as an interface material.

Heat sinks and coldplates are typically constructed out of aluminum or copper; both materials have a thermal conductivity several orders of magnitude greater than those materials present on the face of a power component package. The high thermal conductivity means the temperature gradient in these materials is minimal, such that temperature measurements made at the base of a heat sink or on a coldplate are relatively immune to specific location requirements, are accurate and are repeatable. A single location temperature measurement is usually sufficient to represent the temperature of the heat sink base or coldplate.

Conclusion

Thermal circuit modeling is a useful design aide for the development and characterization of an effective thermal management system for power components. Operating power components well below the maximum specified internal temperature ensures increased reliability and MTBF. Thermal models, efficiency and power dissipation curves and safe-operating-area plots are provided in the data sheet for every Vicor converter. This data, along with knowledge of the application environment, can be used to create a thermal circuit model to estimate the internal temperature of the power component and ensure operation within the allowable range.

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