APPLICATION NOTE | AN:039

Thermal Management for VIA™ and ChiP™ Modules

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Introduction

This application note provides guidelines for achieving effective thermal management of Vicor VIA- and ChiP-package converters. Proper thermal management provides improved module and system MTBFs, smaller size and lower product life-cycle costs.

Efficiency and Dissipated Power

Vicor converters process power from an input source and provide regulation and/or current multiplication of the output power for delivery to a load. Not all of the input power is converted to output power, however; some energy is dissipated from the module as heat. The ratio of delivered output power to input power is defined as the module's efficiency. Efficiency is a basic figure of merit that can be used to relate power dissipation directly to module output power:

$$\eta = \frac{P_{OUT}}{P_{IN}} \tag{1}$$

$$P_{DISS} = P_{OUT} \bullet \left(\frac{1}{\eta} - 1\right) \tag{2}$$

Where P_{DISS} is the converter internal power dissipation, P_{OUT} is output power, P_{IN} is input power and η is efficiency.

The first step in evaluating cooling requirements is to calculate the worst-case power dissipation based on the module efficiency and highest anticipated load power. Clearly, higher efficiency will translate into lower power dissipation and simplify the cooling problem.

Removing Heat from the Module

For VIA modules, heat can be removed from the pin-side surface, the non-pin-side surface, or both. For ChiP modules, heat can be removed from the top surface, the bottom surface, and the leads.

Heat flow is transferred from higher temperature regions to lower temperature regions through a thermal interface. This is achieved through three basic methods:

Radiation: Electromagnetic transfer of heat between materials at different temperatures.

Conduction: Transfer of heat through a solid medium.

Convection: Transfer of heat through the medium of a fluid; typically air.

All three of these heat transfer methods are active to some degree in every application. Non-dominant effects will provide an added contribution to cooling and in some cases they may result in undesirable and unanticipated thermal interactions between components and subassemblies.

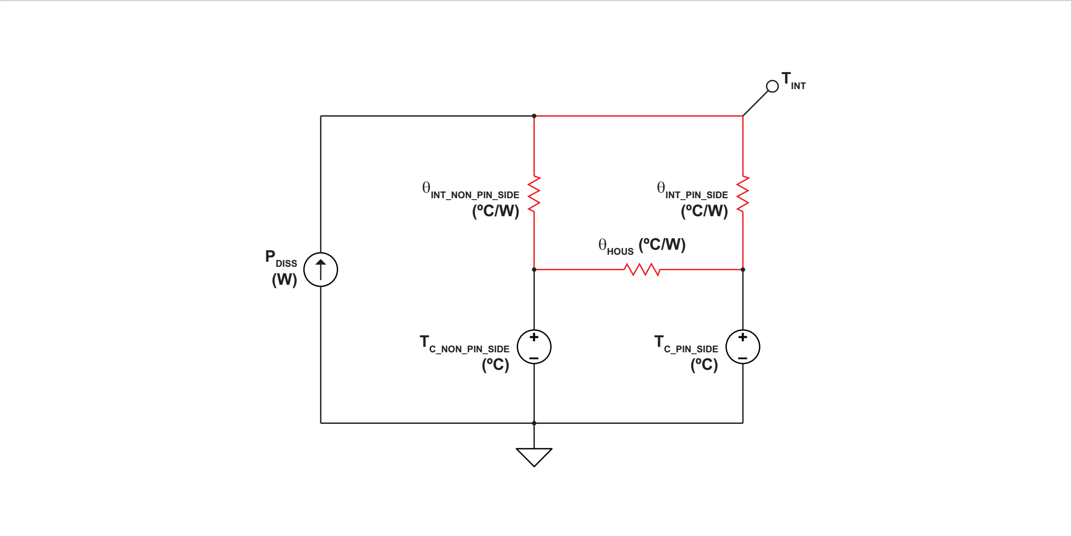
All three of these methods should be given consideration when developing a successful cooling strategy. This application note will focus on both conduction and convection cooling strategies for matching Vicor heat sinks to VIA and ChiP converters.

VIA™ and ChiP™ Thermal Models

In many applications, heat will be conducted from the module's top side into an attached heat sink or heat conducting member and through the module pins to the PCB. Cooling of the module through the board is a function of how much copper is surrounding the module, how much air is passing over that copper, and how much heat is coupled into the PCB from surrounding components. To design an effective thermal management system, a thermal model of the converter is needed.

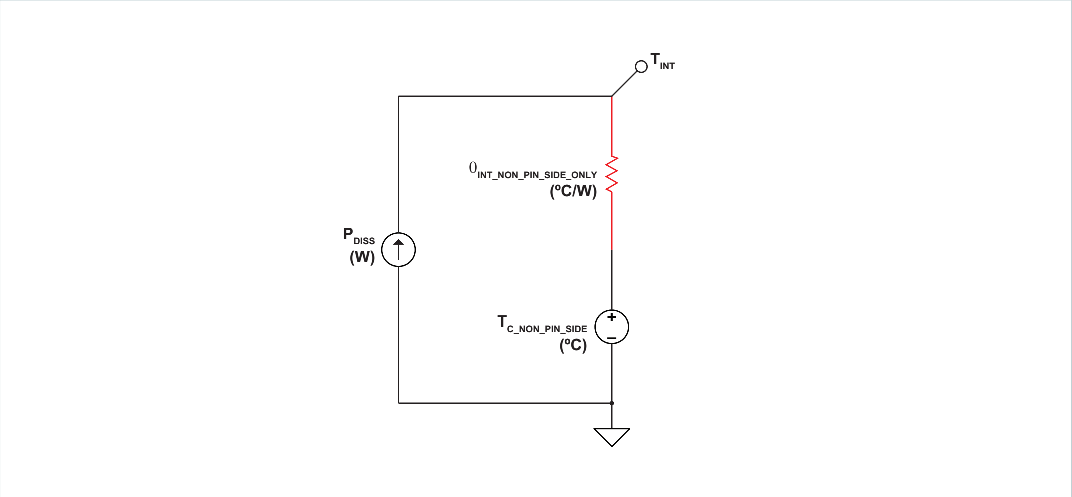
The "thermal circuit" is comprised of some basic elements: power dissipation is modeled as a current source, isothermal surface temperatures are represented as voltage sources, and the thermal resistances are represented as resistors. A "thermal circuit" for the VIA module is shown below with the VIA thermal model highlighted in red:

Figure 1
VIA Thermal Model
Double-Sided Cooling



$\theta_{INT\_NON\_PIN\_SIDE}$, $\theta_{INT\_PIN\_SIDE}$, and θ_{HOUS} are the estimated thermal resistances of the non-pin side, pin side, and the coupled top-to-bottom housing of the VIA modules. T_{INT} is a virtual representation of the maximum internal temperature. $T_{C\_NON\_PIN\_SIDE}$ and $T_{C\_PIN\_SIDE}$ are the non-pin-side and pin-side surface temperatures.

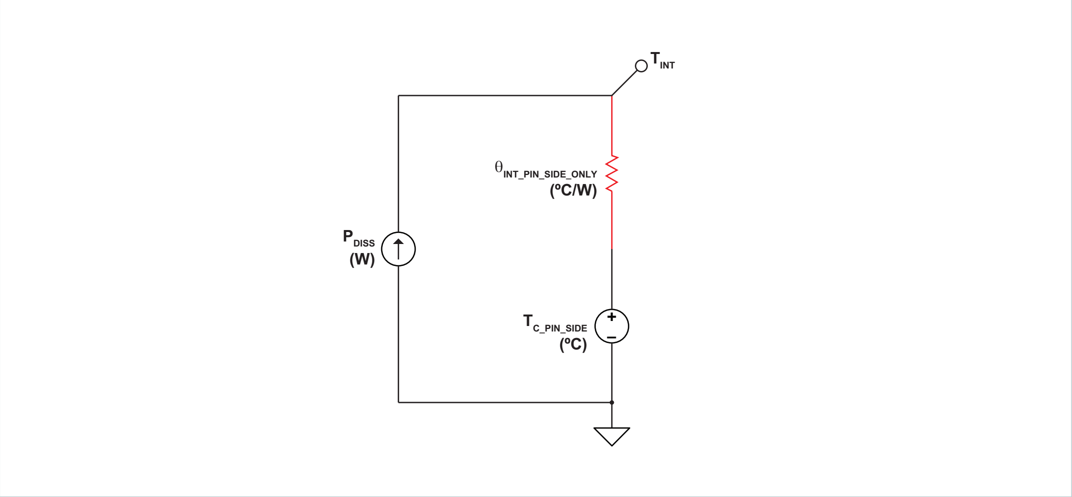
Figure 2
VIA Thermal Model
Non-Pin-Sided Cooling



$\theta_{INT\_NON\_PIN\_SIDE\_ONLY}$ is the simplified resistor network of the pin side, non-pin side, and housing resistances when only the non-pin side is cooled:

$$\theta_{INT\_NON\_PIN\_SIDE\_ONLY} = \frac{(\theta_{INT\_PIN\_SIDE} + \theta_{HOU}) \bullet \theta_{INT\_NON\_PIN\_SIDE}}{\theta_{INT\_PIN\_SIDE} + \theta_{HOU} + \theta_{INT\_NON\_PIN\_SIDE}} \qquad (3)$$

Figure 3
VIA™ Thermal Model Pin-Sided Cooling

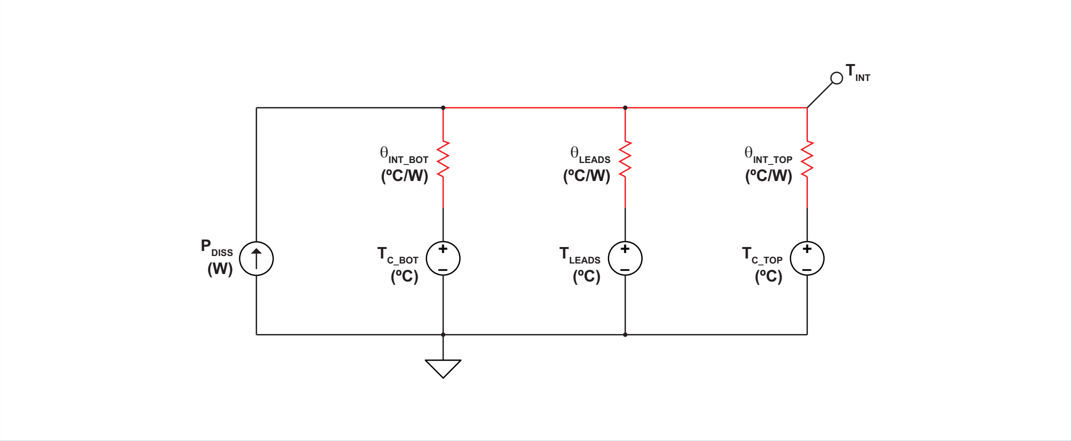


$\theta_{INT\_PIN\_SIDE\_ONLY}$ is the simplified resistor network of the pin side, non-pin side and housing resistances when only the pin side is cooled:

$$\theta_{INT\_PIN\_SIDE\_ONLY} = \frac{(\theta_{INT\_NON\_PIN\_SIDE} + \theta_{HOU}) \bullet \theta_{INT\_PIN\_SIDE}}{\theta_{INT\_PIN\_SIDE} + \theta_{HOU} + \theta_{INT\_NON\_PIN\_SIDE}} \qquad (4)$$

The ChiP thermal model is slightly different than the VIA thermal model as the ChiP converters do not have thermal coupling between top and bottom surfaces. A "thermal circuit" for the ChiP module is shown below with the ChiP thermal model highlighted in red:

Figure 4
ChiP™ Thermal Model Double-Sided and Leads Cooling



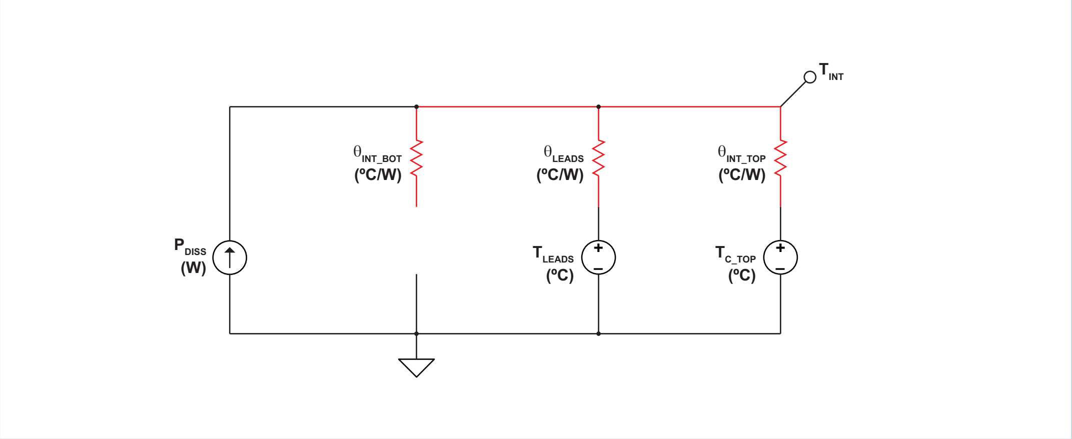


Figure 5
ChiP™ Thermal Model
Single-Sided
and Leads Cooling

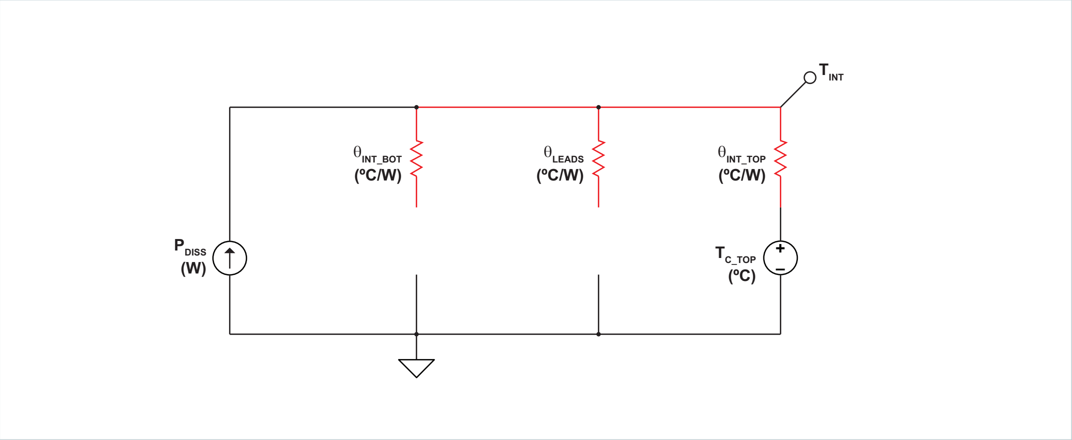


Figure 6
ChiP Thermal Model
Single-Sided Cooling

θ_{INT_TOP}, θ_{INT_BOTTOM} and θ_{LEADS} are the thermal resistance characteristics of the module; and the top and bottom surface temperatures are represented as T_{C_TOP} and T_{C_BOT}. T_{LEADS} is the temperature of the PCB at the leads.

Conduction

Cold plates are an effective and popular solution for thermal management. A cold plate is a temperature controlled heat sink designed to keep a surface at a desired temperature through liquid cooling.

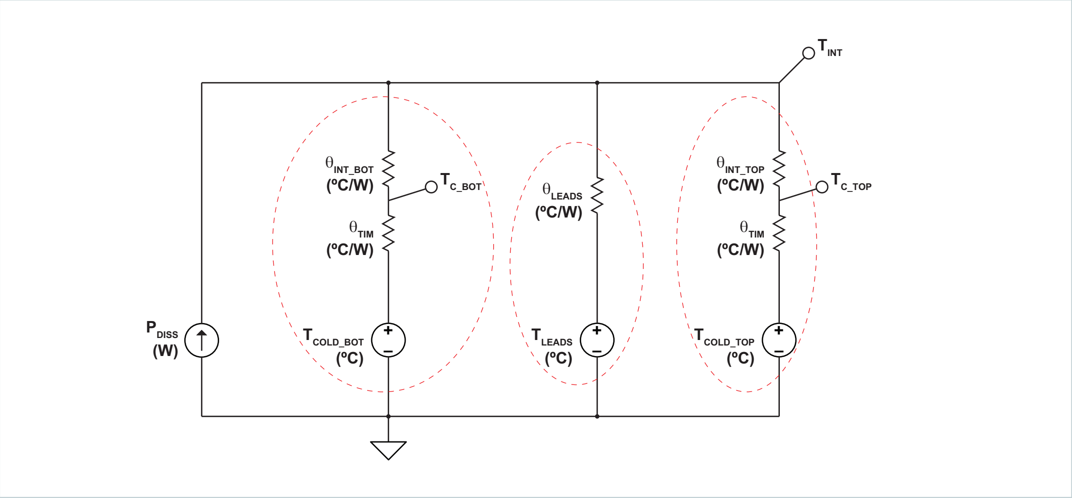
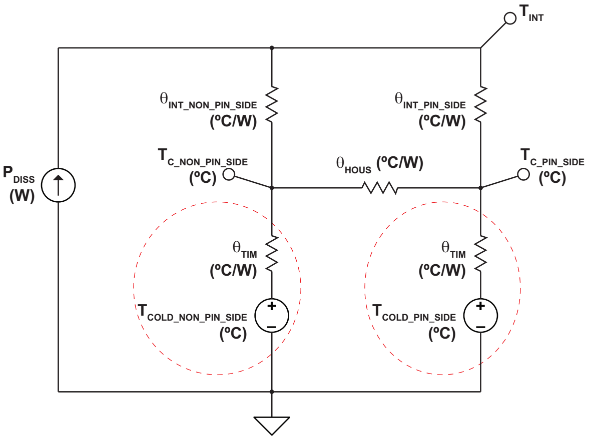


Figure 7
ChiP Module
with Cold Plate
Thermal Circuit

Figure 8
VIA™ Module with Cold Plate Thermal Circuit



Figures 7 and 8 show the thermal circuit for a ChiP and VIA that is cooled with cold plates. T_{COLD_BOT} and T_{COLD_TOP} are the cold plate temperatures of the bottom and top side of the ChiP. $T_{COLD\_NON\_PIN\_SIDE}$ and $T_{COLD\_PIN\_SIDE}$ are the cold plate temperatures of the non-pin side and pin side of the VIA. θ_{TIM} is the thermal resistance for a thermal interface material (TIM).

The TIM, usually thermal compound or a thermal pad, provides thermal coupling between the module and cooling member and also fills surface irregularities.

The thermal resistance for TIM:

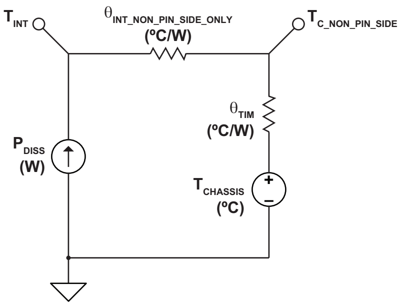
$$\theta_{TIM} = \frac{t}{k \bullet A} \tag{5}$$

Where t is the thickness of the material, k is thermal conductivity, and A is surface area. Maximizing the thermal conductivity and area while minimizing the thickness will minimize the TIM resistance.

Basic steps for designing a cold plate solution:

1. First the maximum power of the application should be defined. Use this to find the converter efficiency defined in the datasheet. The online Vicor PowerBench Whiteboard is also available to provide the converter efficiency at various operating conditions. The converter thermal model and thermal resistance values can be found in the datasheet. Review the datasheet de-rating curves for the module, which will provide a general range for the operating case temperature.
2. Calculate the maximum power dissipation using Equation 2.
3. Calculate the TIM thermal resistance using Equation 5.
4. Using Figure 7 or 8, analyze the thermal circuit to solve for the maximum cold plate temperature(s). The elements circled in red in Figures 7 and 8 can be removed based on the cooling strategy, i.e., remove the thermal resistances in the bottom side (or non-pin side for VIA) thermal branch if only cooling with the top side (or pin side for VIA) and leads. Please refer to Example 1 for a detailed analysis.

Figure 9
VIA™ Module with Single-Side Chassis Cooling Only



A chassis mount VIA thermal circuit is shown in Figure 9 where $T_{CHASSIS}$ is the chassis temperature on the non-pin side of the VIA module. The chassis acts like a cold plate and the design process is similar to the heat sink design process that is outlined in the next section.

Convection

Convective heat transfer into air is a common method for cooling Vicor modules. "Free or "natural" convection refers to heat transfer from a dissipative surface into a cooler surrounding mass of otherwise still air. Forced convection refers to heat transfer into a moving air system.

Forced convection cooling is show in Figures 10 and 11. Case temperature depends on the temperature of the air (T_A), total dissipated power, the thermal resistance of the TIM between the case and the heat sink, and the heat sink-to-air thermal resistance(s) (θ_{HS_BOT} and θ_{HS_TOP}). The heat sink-to-air resistance is dependent on a variety of factors including heat sink material and geometry, air temperature, air density, and air flow rate.

Figure 10
ChiP™ Module Heat Sink Thermal Circuit

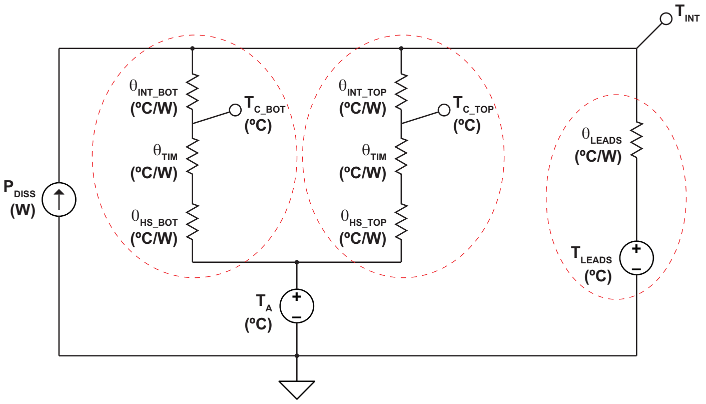
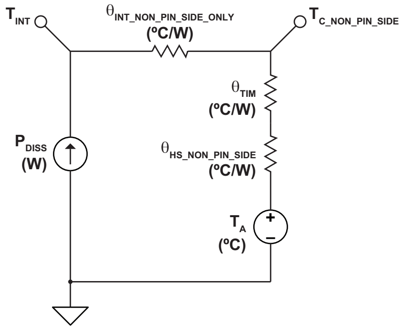


Figure 11
VIA™ Module
Heat Sink Thermal Circuit



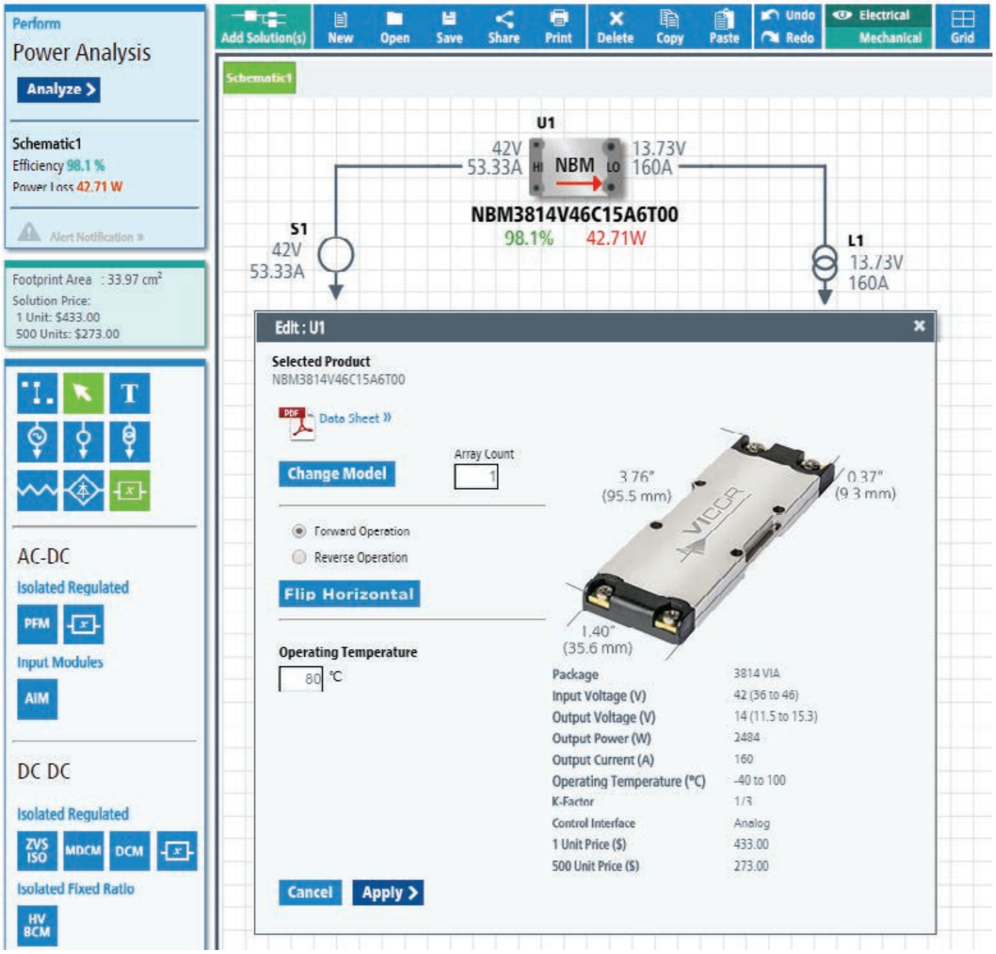
Designing forced convection cooling:

1. First the maximum power of the application should be defined. Use this to find the converter efficiency defined in the datasheet. The online Vicor PowerBench Whiteboard is also available to provide the converter efficiency at various operating conditions. The converter thermal model and thermal resistance values can be found in the datasheet. Review the datasheet de-rating curves for the module, which provide a general range for the operating case temperature. Find the hottest ambient temperature for the application.
2. Calculate the maximum power dissipation using Equation 2.
3. Calculate the TIM thermal resistance using Equation 5.
4. Using Figure 10 or 11, analyze the thermal circuit to solve for the maximum thermal resistance of the heat sink(s). The elements circled in red in Figure 10 can be removed based on the cooling strategy, i.e., remove the thermal resistances in the bottom-side thermal branch if only cooling with the top side and leads. Refer to Example 2 for a detailed analysis.

Vicor Online Tools

The Vicor Whiteboard simulates power systems with user defined operating conditions. Converter efficiency and power dissipation is simulated for use in thermal management design:
http://spicewebprd.vicorpower.com/PowerBench-Whiteboard

Figure 12
Vicor Whiteboard



Schematic1
Efficiency 98.1 %
Power Loss 42.71 W

Footprint Area : 33.97 cm^2
Solution Price:
1 Unit: $433.00
500 Units: $273.00

Selected Product
NBM3814V46C15A6T00

Array Count: 1

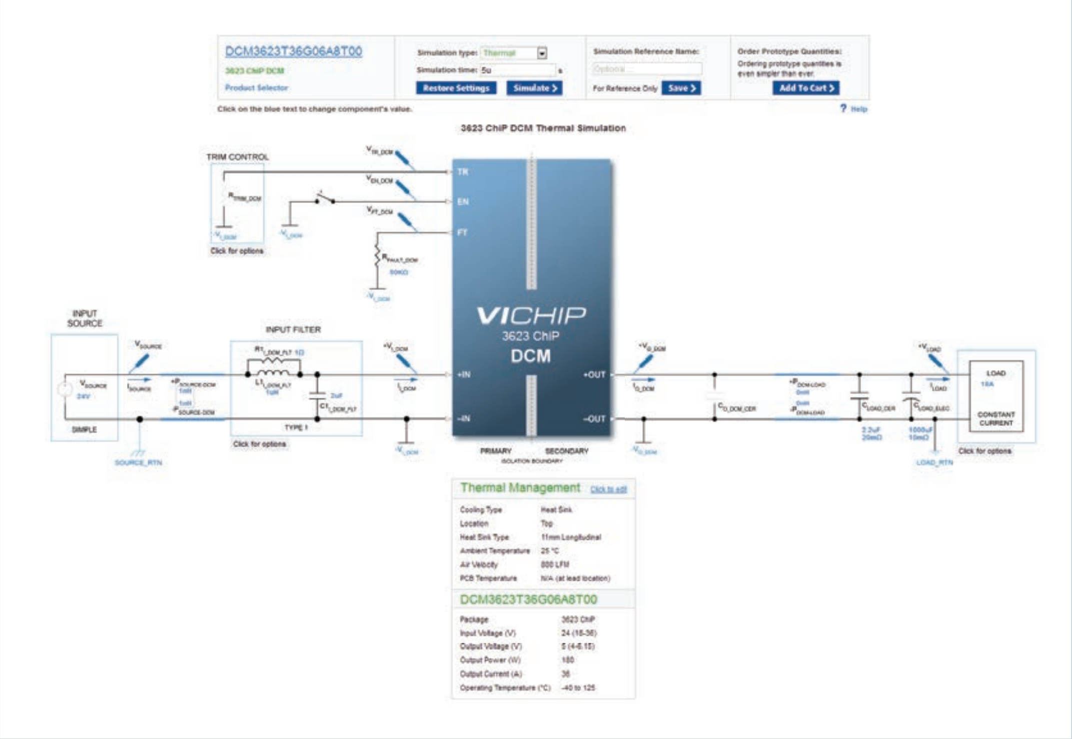
● Forward Operation
○ Reverse Operation

Operating Temperature: 80 °C

Package	3814 VIA
Input Voltage (V)	42 (36 to 46)
Output Voltage (V)	14 (11.5 to 15.3)
Output Power (W)	2484
Output Current (A)	160
Operating Temperature (°C)	-40 to 100
K-Factor	1/3
Control Interface	Analog
1 Unit Price ($)	433.00
500 Unit Price ($)	273.00

Vicor also offers an online simulator to evaluate various converters' electrical and thermal performance: http://www.vicorpower.com/simulation

Figure 13
Vicor PowerBench Example



DCM3623T36G06A8T00
3623 ChiP DCM
Product Selector

Simulation type: Thermal
Simulation time: 5u s

Simulation Reference Name: Optional
For Reference Only

Order Prototype Quantities:
Ordering prototype quantities is even simpler than ever.

Click on the blue text to change component's value.

3623 ChiP DCM Thermal Simulation

Thermal Management

Cooling Type	Heat Sink
Location	Top
Heat Sink Type	11mm Longitudinal
Ambient Temperature	25 °C
Air Velocity	800 LFM
PCB Temperature	N/A (at lead location)

DCM3623T36G06A8T00

Package	3623 ChiP
Input Voltage (V)	24 (18-36)
Output Voltage (V)	5 (4-6.15)
Output Power (W)	180
Output Current (A)	36
Operating Temperature (°C)	-40 to 125

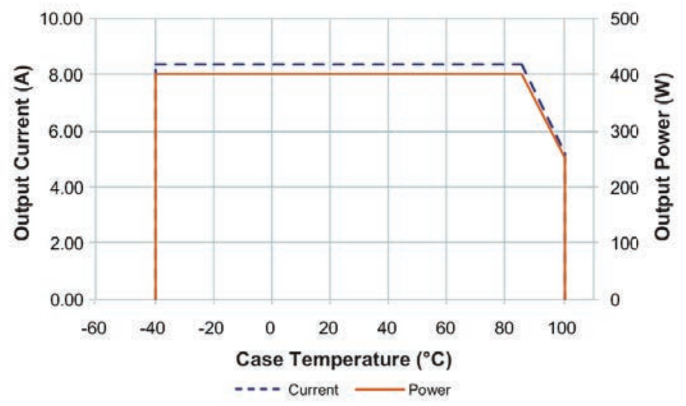
Figure 13 shows an example of a thermal simulation in the Vicor PowerBench tool using a DCM3623T36G06A8T00. The input source, input filter, output load and output filter, as well as various parasitics, can be modified by the user to reflect actual design conditions. A range of recommended thermal management options are available, including top and bottom-side heat sinks, or a cold plate. The thermal environment can also be modified by editing parameters for ambient temperature, air velocity, and TIM specifications.

Examples

Example 1. Determine the cold plate temperature for a PFM4414VB6M48D0C00 VIA™ module, input voltage of 230V_{AC}, thermal interface material with a 0.005in thickness and thermal conductivity of 0.7W/m-K, the cold plate is applied to the non-pin side of the module, and an output voltage of 48V.

Based on the safe operating area curve provided in the data sheet, let’s choose 80°C for a case temperature to get the full output power of 400W:

Figure 14
PFM4414VB6M48D0C00
Safe Operating Area



What we know so far:

$$T_{C\_NON\_PIN\_SIDE} = 80^{o}C$$

$$P_{OUT} = 400W$$

$$k = 0.7\,\frac{W}{m\text{-}K}$$

$$t = 0.005in = 127 \bullet 10^{-6}m$$

$$\eta = 92\%\ (full\ load,\ 230V_{AC},\ 80^{o}C\ case\ temp)$$

From the datasheet:

$$\theta_{INT\_PIN\_SIDE} = 1.34\,\frac{^{o}C}{W}$$

$$\theta_{INT\_NON\_PIN\_SIDE} = 1.72\,\frac{^{o}C}{W}$$

$$\theta_{HOUS} = 0.57\,\frac{^{o}C}{W}$$

The single-sided cooling thermal resistance for the VIA™ can be calculated:

$$\theta_{INT\_NON\_PIN\_SIDE\_ONLY} = \frac{\left(\theta_{INT\_PIN\_SIDE} + \theta_{HOU}\right) \bullet \theta_{INT\_NON\_PIN\_SIDE}}{\theta_{INT\_PIN\_SIDE} + \theta_{HOU} + \theta_{INT\_NON\_PIN\_SIDE}}$$

$$\theta_{INT\_NON\_PIN\_SIDE\_ONLY} = \frac{\left(1.34\,\frac{^{o}C}{W} + 0.57\,\frac{^{o}C}{W}\right) \bullet 1.72\,\frac{^{o}C}{W}}{1.34\,\frac{^{o}C}{W} + 0.57\,\frac{^{o}C}{W} + 1.72\,\frac{^{o}C}{W}} = 0.905\,\frac{^{o}C}{W}$$

The non-pin-side surface area of the 4414 VIA is 111 x 36mm. The TIM thermal resistance can be found:

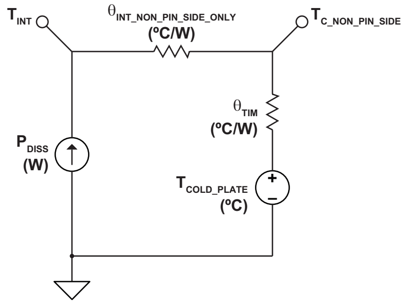
$$\theta_{TIM} = \frac{t}{k \bullet A} = \frac{127 \bullet 10^{-6}m}{0.7\frac{W}{m\text{-}K} \bullet 0.111m \bullet 0.036m} = 0.045\,\frac{^{o}C}{W}$$

The power dissipation can be calculated:

$$P_{DISS} = P_{OUT} \bullet \left(\frac{1}{\eta} - 1\right)$$

$$P_{DISS} = 400W \bullet \left(\frac{1}{0.92} - 1\right) = 34.78W$$

Figure 15
Thermal Circuit



Using the thermal circuit, we can now write the equation to calculate the maximum cold plate temperature:

$$P_{DISS} = \frac{T_{C\_NON\_PIN\_SIDE} - T_{COLD\_PLATE}}{\theta_{TIM}}$$

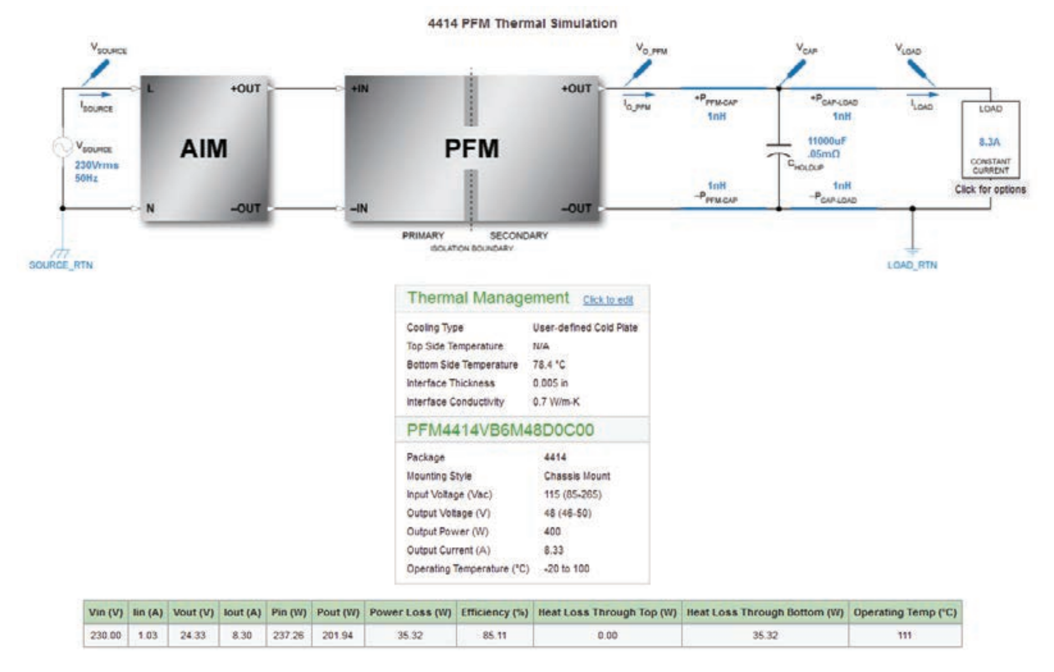
$$T_{COLD\_PLATE} = T_{C\_NON\_PIN\_SIDE} - \theta_{TIM} \bullet P_{DISS}$$

$$T_{COLD\_PLATE} = 80^{o}C - 0.045\frac{^{o}C}{W} \bullet 34.78W = 78.4^{o}C$$

In this case, the cold plate temperature nearly matches the case temperature as the thermal resistance of the TIM is very small. The thermal resistance of the VIA™ was not needed in this example as the case temperature chosen from the safe operating area curve provided the thermal boundary to ensure full power operation.

Using the online PowerBench tool, the system can be simulated:

Figure 16
PFM4414VB6M48D0C00
Online Thermal Simulation



Thermal Management

Cooling Type	User-defined Cold Plate
Top Side Temperature	N/A
Bottom Side Temperature	78.4 °C
Interface Thickness	0.005 in
Interface Conductivity	0.7 W/m-K

PFM4414VB6M48D0C00

Package	4414
Mounting Style	Chassis Mount
Input Voltage (Vac)	115 (85-265)
Output Voltage (V)	48 (46-50)
Output Power (W)	400
Output Current (A)	8.33
Operating Temperature (°C)	-20 to 100

Vin (V)	Iin (A)	Vout (V)	Iout (A)	Pin (W)	Pout (W)	Power Loss (W)	Efficiency (%)	Heat Loss Through Top (W)	Heat Loss Through Bottom (W)	Operating Temp (°C)
230.00	1.03	24.33	8.30	237.26	201.94	35.32	85.11	0.00	35.32	111

Although the part can process full power with a case temperature of 80°C, it is desirable to maintain an internal temperature as low as possible to increase reliability and operating life. Reducing power dissipation, external thermal resistance(s), cold plate temperature, or ambient air temperature will minimize the converter's internal operating temperature. A general rule-of-thumb for operating temperature states that a 10°C decrease in operating temperature doubles reliability and operating life of the internal components.

Another strategy to reduce the internal operating temperature is to use two or more parallel converters in place of a single converter. The thermal resistance for each converter remains the same, but the resultant heat flow for each is effectively divided. The total dissipated power is divided among the converters, therefore the internal operating temperature rise is also divided.

Example 2. Determine the maximum top-side heat sink thermal resistance for a 400W DCM4623TD2J13D0T00 ChiP™ module, with thermal pad, maximum case temperature of 75°C, 25°C ambient temperature, and 300V input delivering 12V at 200W.

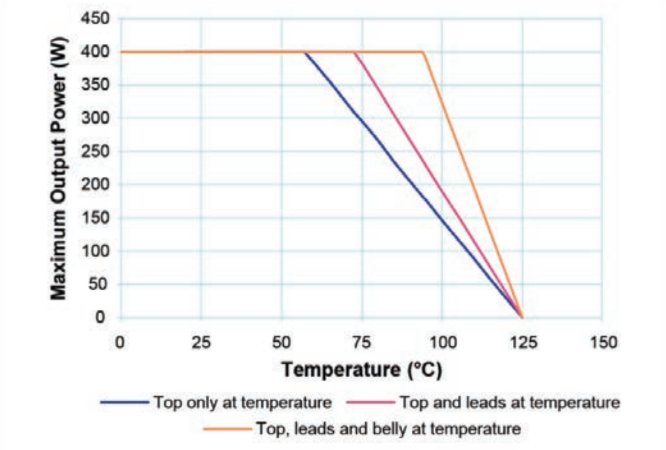
$$T_{C\_TOP} = 75^{o}C$$

$$T_{A} = 25^{o}C$$

$$P_{OUT} = 200W$$

Based on the safe operating curve for the DCM, 75°C top-side temperature will be cool enough for the converter to produce 200W:

Figure 17
DCM4623TD2J13D0T00
Safe Operating Area



Using the Whiteboard tool, the efficiency and power dissipation can be simulated using a top-side case temperature of 75°C:

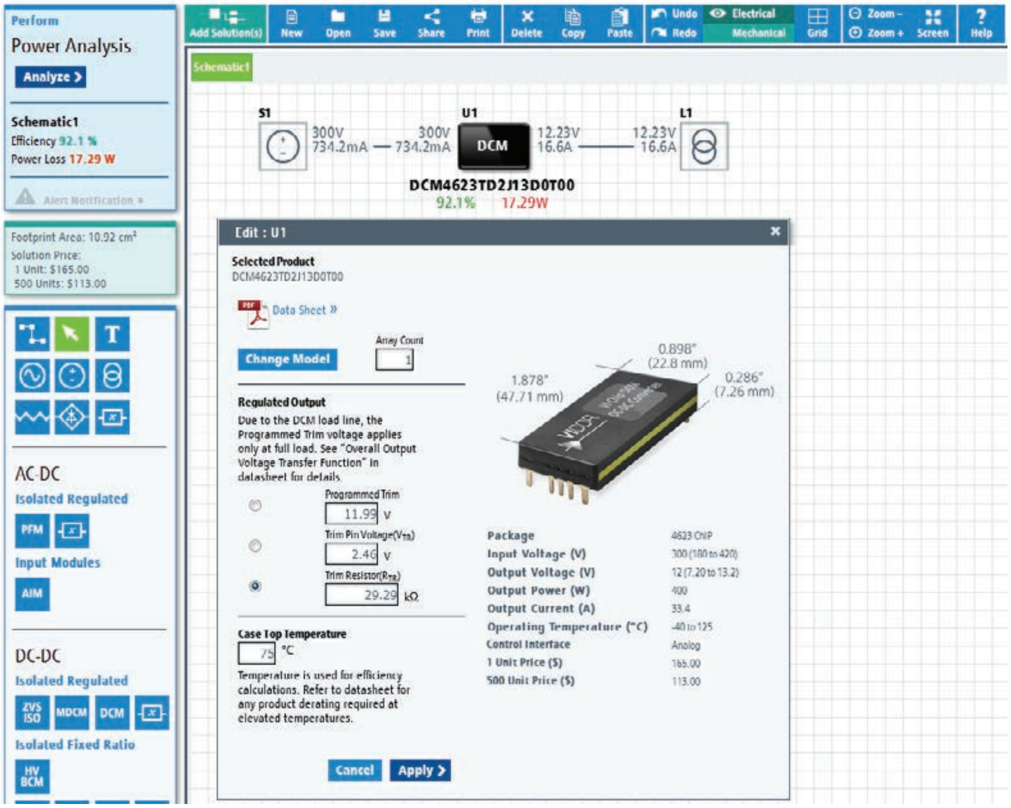


Figure 18
DCM4623TD2J13D0T00 Whiteboard

Schematic1
Efficiency 92.1 %
Power Loss 17.29 W

Footprint Area: 10.92 cm²
Solution Price:
1 Unit: $165.00
500 Units: $113.00

Selected Product
DCM4623TD2J13D0T00

Array Count: 1

Regulated Output
Due to the DCM load line, the Programmed Trim voltage applies only at full load. See "Overall Output Voltage Transfer Function" in datasheet for details.

○ Programmed Trim: 11.99 V
○ Trim Pin Voltage(V_{TR}): 2.46 V
● Trim Resistor(R_{TR}): 29.29 kΩ

Case Top Temperature
75 °C
Temperature is used for efficiency calculations. Refer to datasheet for any product derating required at elevated temperatures.

Package	4623 ChiP
Input Voltage (V)	300 (180 to 420)
Output Voltage (V)	12 (7.20 to 13.2)
Output Power (W)	400
Output Current (A)	33.4
Operating Temperature (°C)	-40 to 125
Control Interface	Analog
1 Unit Price ($)	165.00
500 Unit Price ($)	113.00

From the datasheet curves, the top-side thermal resistance is 1.92°C/W. The Whiteboard tool calculates a power dissipation of 17.29W under the specified operating conditions.

$$\theta_{INT\_TOP} = 1.92\,\frac{^{o}C}{W}$$

$$P_{DISS} = 17.29W$$

For this example, let's use a TIM with the following characteristics:

$$Thermal\ conductivity = k = 5\,\frac{W}{m\text{-}K}$$

$$Thickness = t = 0.508mm$$

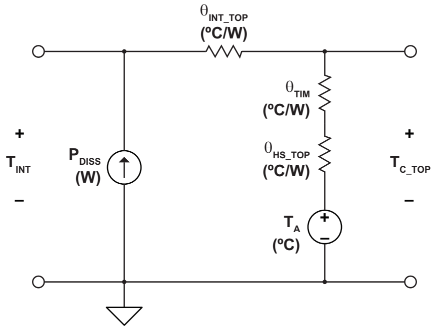
The top-side area of the 4623 ChiP is 47.91 x 22.8mm.

The thermal resistance of the TIM can be calculated:

$$\theta_{TIM} = \frac{t}{k \bullet A} = \frac{508 \bullet 10^{-6}m}{5\frac{W}{m\text{-}K} \bullet 0.04791m \bullet 0.0228m} = 0.093\,\frac{^{o}C}{W}$$

The thermal circuit can be drawn:

Figure 19
Thermal Circuit



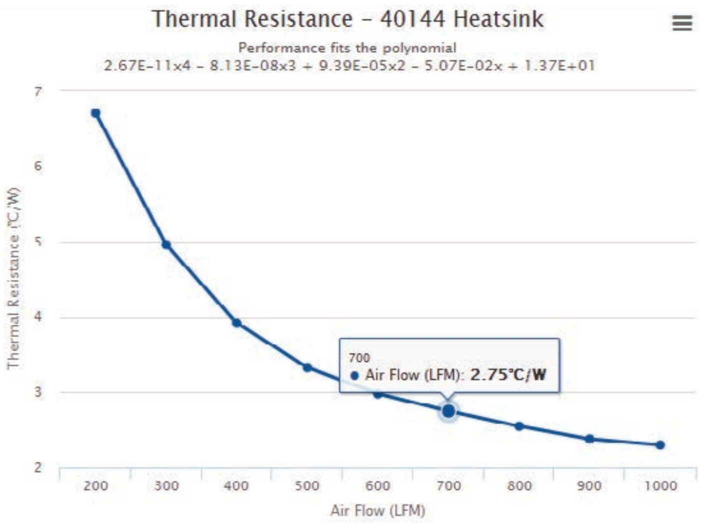
Now the maximum heat sink thermal resistance can be found by circuit analysis on the previous circuit diagram:

$$\theta_{HS\_TOP} = \frac{T_{C\_TOP} - T_A}{P_{DISS}} - \theta_{TIM} = \frac{75^oC - 25^oC}{17.29W} - 0.093 = \mathbf{2.78}\,\frac{\mathbf{^oC}}{\mathbf{W}}$$

Heat sinks are available on the Vicor Thermal Management Accessory product page:
http://www.vicorpower.com/accessories/thermal-management

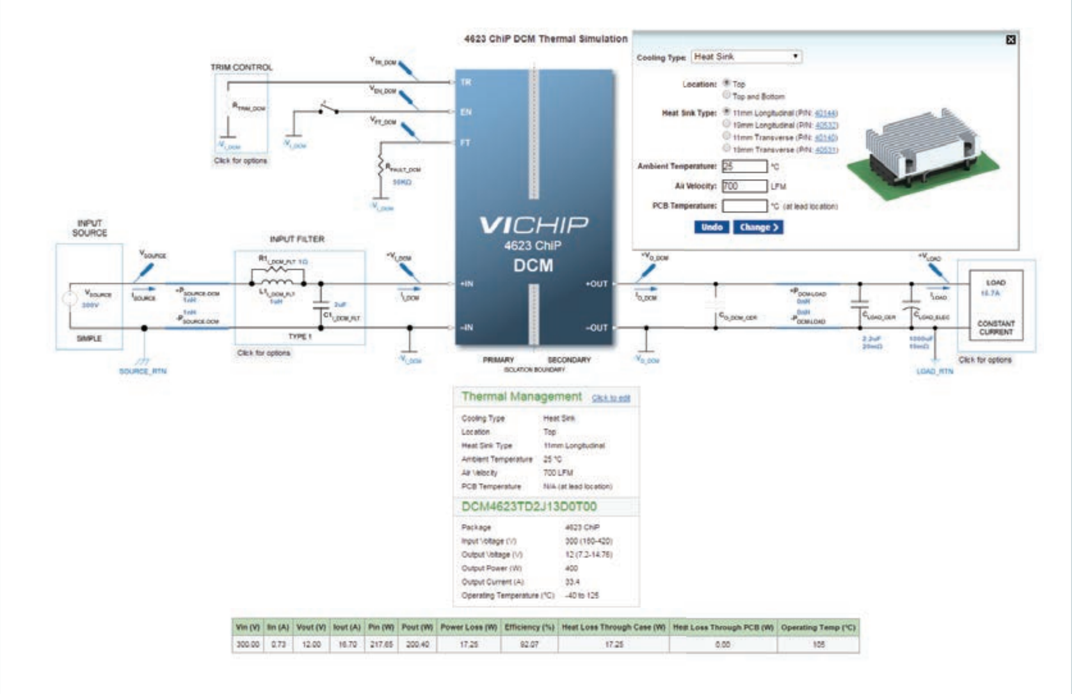
The 40144 top-side ChiP heat sink is able to provide a thermal resistance of 2.75°C/W at 700LFM, which will meet the needs of this thermal design:

Figure 20
Heat Sink Thermal Resistance



Using the online PowerBench tool, the system can be simulated. The result of the simulation is shown below:

Figure 21
DCM4623TD2J13D0T00
Online Thermal Simulation



4623 ChiP DCM Thermal Simulation

Cooling Type: Heat Sink

Location: ● Top ○ Top and Bottom

Heat Sink Type: ● 11mm Longitudinal (P/N: 40144) ○ 10mm Longitudinal (P/N: 40532) ○ 11mm Transverse (P/N: 40140) ○ 10mm Transverse (P/N: 40531)

Ambient Temperature: 25 °C

Air Velocity: 700 LFM

PCB Temperature: °C (at lead location)

Thermal Management Click to edit

Cooling Type	Heat Sink
Location	Top
Heat Sink Type	11mm Longitudinal
Ambient Temperature	25 °C
Air Velocity	700 LFM
PCB Temperature	N/A (at lead location)

DCM4623TD2J13D0T00

Package	4623 ChiP
Input Voltage (V)	300 (160-420)
Output Voltage (V)	12 (7.2-14.76)
Output Power (W)	400
Output Current (A)	33.4
Operating Temperature (°C)	-40 to 125

Vin (V)	Iin (A)	Vout (V)	Iout (A)	Pin (W)	Pout (W)	Power Loss (W)	Efficiency (%)	Heat Loss Through Case (W)	Heat Loss Through PCB (W)	Operating Temp (°C)
300.00	0.73	12.00	16.70	217.65	200.40	17.25	92.07	17.25	0.00	105

Using the 40144 top-side ChiP heat sink at 700LFM yields an internal operating temperature of 105°C. This is below the maximum specified internal temperature of 125°C. The thermal management parameters can easily be changed to simulate various conditions to characterize the effects of changing the air velocity, heat sink, ambient air and temperature.

Definitions

A	TIM surface area
k	TIM thermal conductivity
η	Efficiency P_{OUT}/P_{IN}
θ_{HOU}	Thermal coupling resistance between top and bottom case for VIA package
θ_{HS_BOT}	Bottom-side heat sink thermal resistance for ChiP module
$\theta_{HS\_NON\_PIN\_SIDE}$	Non-pin-side heat sink thermal resistance for VIA module
$\theta_{HS\_PIN\_SIDE}$	Pin-side heat sink thermal resistance for VIA module
θ_{HS_TOP}	Top-side heat sink thermal resistance for ChiP module
$\theta_{INT\_NON\_PIN\_SIDE\_ONLY}$	Equivalent thermal resistance for VIA non-pin side cooling thermal model
$\theta_{INT\_PIN\_SIDE\_ONLY}$	Equivalent thermal resistance for VIA pin side cooling thermal model
θ_{INT_TOP}	Top case thermal resistance for ChiP module
θ_{LEADS}	Thermal resistance of leads for ChiP module
θ_{TIM}	Thermal interface material thermal resistance
T_A	Ambient air temperature
T_{C_BOT}	Bottom case temperature for ChiP module
$T_{CHASSIS}$	Chassis temperature
$T_{C\_NON\_PIN\_SIDE}$	Non-pin-side case temperature for VIA module
$T_{C\_PIN\_SIDE}$	Pin-side case temperature for VIA module
T_{C_TOP}	Top case temperature for ChiP module
T_{INT}	Internal module temperature
T_{LEADS}	Leads temperature for ChiP module
T_{MAX}	Maximum case temperature (available in data sheet)

Thermal Equations

$$Efficiency = \eta = \frac{P_{OUT}}{P_{IN}}$$

$$Dissipated\ Power = P_{DISS} = P_{OUT} \bullet \left(\frac{1}{\eta} - 1\right)$$

$$Thermal\ interface\ material\ thermal\ resistance = \theta_{TIM} = \frac{t}{k \bullet A}$$

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