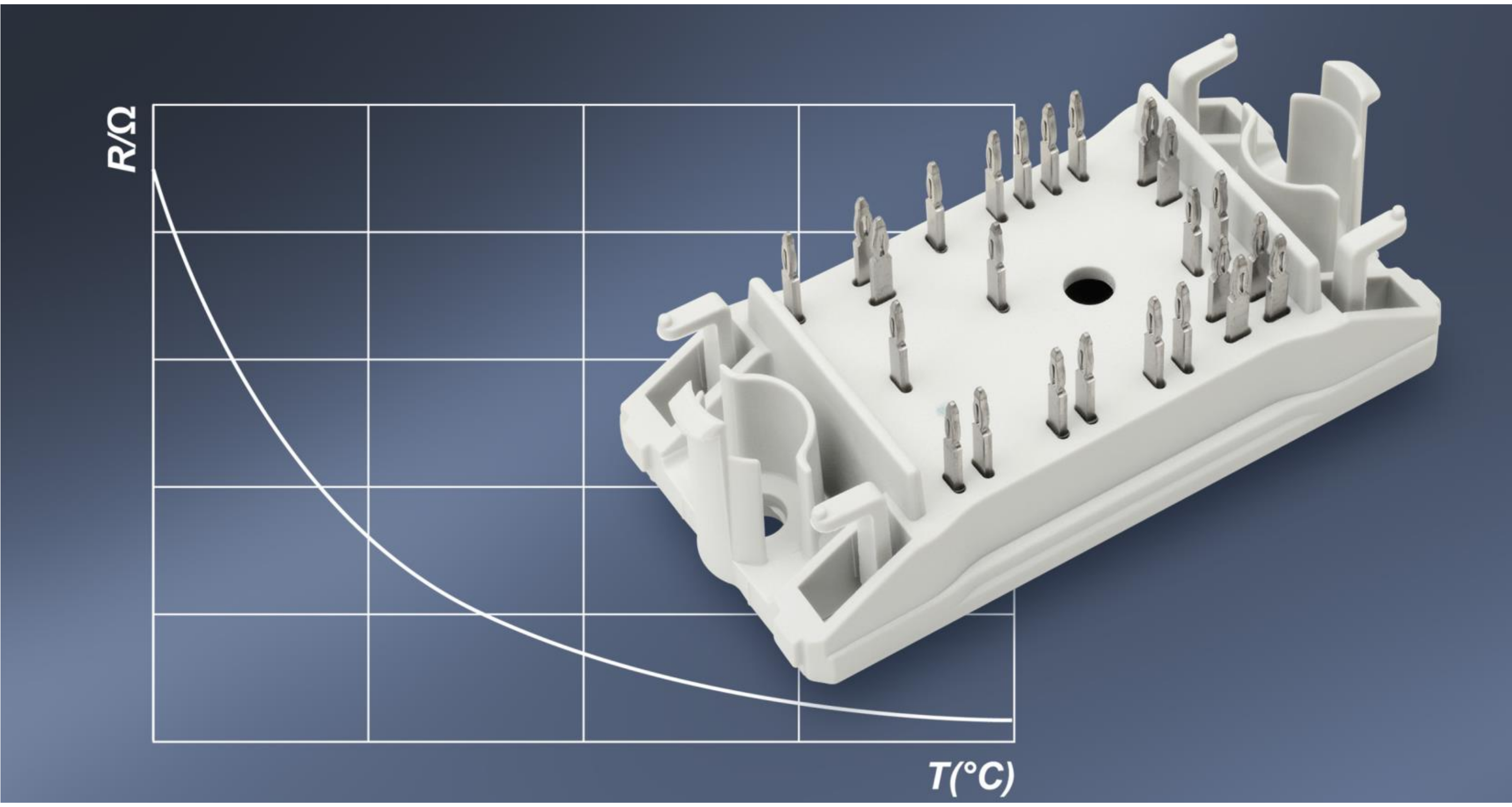
Thermal measurement with an integrated NTC Thermistor

Benefits and limitations



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Revision History

Date	Revision Level	Description	Page Number(s)
Oct. 2013	1	First release	10 pages
Nov. 2013	2	Revision of NTC resistance calculation, page 4	10 pages
Sept. 2015	3	Section “Thermal testing during development” added, revision of equation (page 13), new layout	13 pages

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1 Abstract

Most Vincotech power modules come with a thermistor designed to sense temperature. This paper explains how such components work and describes their benefits and limitations using an NTC thermistor as an example. It also presents this thermal element in the context of commonplace circuits so the reader can gain a better impression of its purpose and merits.

2 Introduction

An integrated thermal measurement circuit is an important part of a power module alongside its electrical power components. Vincotech power modules typically feature a convenient tool for measuring temperature, an NTC thermistor. Although these modules also come equipped with reliable heat sinks that have proven their merits in countless applications, it is still a good idea to monitor the device's temperature. Building an NTC thermistor into the device is a cost-effective means of enhancing power components' safety. The peripheral circuits needed to analyze the thermistor are easily implemented, which also helps contain secondary costs.

3 The integrated NTC thermistor

This component is a hot-carrier thermal resistor that is sensitive to temperature. The resistance decreases with increasing temperature, so it has a negative temperature coefficient—hence the designation NTC. This coefficient is not constant, so its behavior is described using two specific values—rated resistance, or R_{25}, and the curve-fit constant B in Kelvin. R_{25} specifies the resistance value at 25 °C ambient temperature (sometimes at 20 °C). B is a result of the material's characteristics. The actual NTC resistance R(T) can be related to its temperature using these values:

$$R(T) = R_{25} \cdot e^{\left(B_{25/100} \cdot \left(\frac{1}{T} - \frac{1}{T_{25}}\right)\right)}$$

R_{25} – rated resistance (datasheet value)

$B_{25/100}$ – curve-fit constant, also sensitivity index (datasheet value)

T_{25} – 25 °C in Kelvin (298.15 K)

T – NTC temperature in Kelvin

Vincotech datasheets contain a table with key points describing the curve's characteristic (see figure 7). The above formula is not precise over the full range of the NTC graph because of the negative nonlinear change of resistance with increasing temperature. The Steinhart-Hart equation, a third order approximation, can be used when a very precise value is needed.

$$\frac{1}{T} = A + Bln(R) + C\left(ln(R)\right)^3$$

T – NTC temperature in Kelvin

R – NTC resistance at temperature T

A,B,C – Steinhart-Hart coefficients

The NTC thermistor built into most Vincotech power modules has a rated resistance of 22 kΩ at 25 °C ambient temperature. The above equation results in the following typical NTC R/T curve:

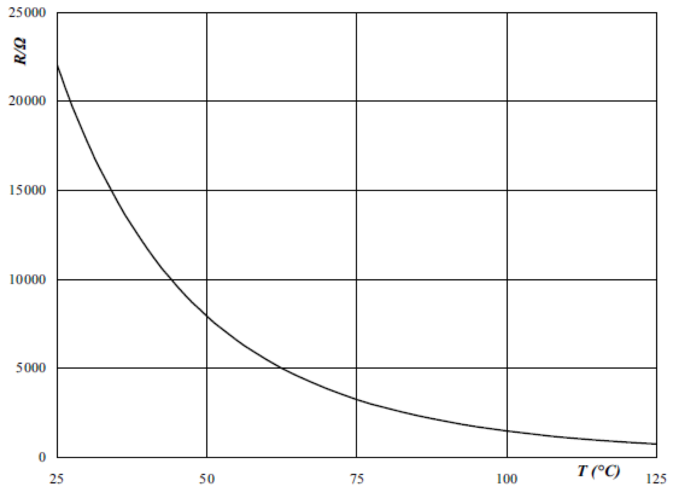

Figure 1: Typical NTC characteristic

4 Temperature monitoring during operation

There is more than one power component within a power module. What's more, the integrated NTC and the individual semiconductors are some distance apart. This is why the mapped temperature is generally closer to that of the heat sink than to the various junction temperatures.

Individual chips' thermal resistance R_{th} has to be taken into account to get an accurate reading of junction temperatures. This parameter is defined by the temperature difference between two points divided by power dissipation. In this context, it could be the measured temperature difference between junction and heat sink divided by the semiconductor’s power dissipation (as determined by a simple power analysis: $P = U_{\mathrm{CE}} \cdot I_{\mathrm{D}}$).

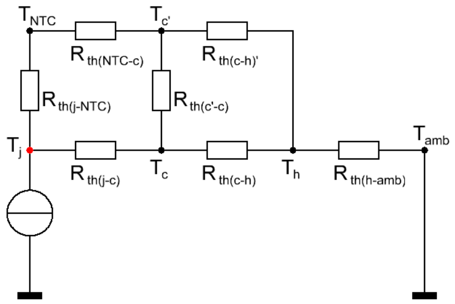

Figure 2: R_{th} model including the NTC

The thermal circuit diagram above shows the discrepancy between the NTC temperature mapped to the junction and to the heat sink temperature. There will always be thermal resistance from the junction (T_{j}) to the thermistor (T_{NTC}) because of the distance between the components. The situation is even more complex if more than one semiconductor is to be monitored by one thermistor. The case temperature below the semiconductor (T_{c}) and thermistor ($T_{\mathrm{c'}}$) is also different. The only value that can be related to all components is the heat sink’s temperature. Thermal spreading results in uniform temperature distribution, depending on how the power module overall is design and how the heat sink is set up.

Heat sources’ thermal coupling can also have a huge impact on thermal distribution within a module so that one area may be exposed to higher thermal stress than another. This can hardly be monitored by the NTC, depending on where components are placed.

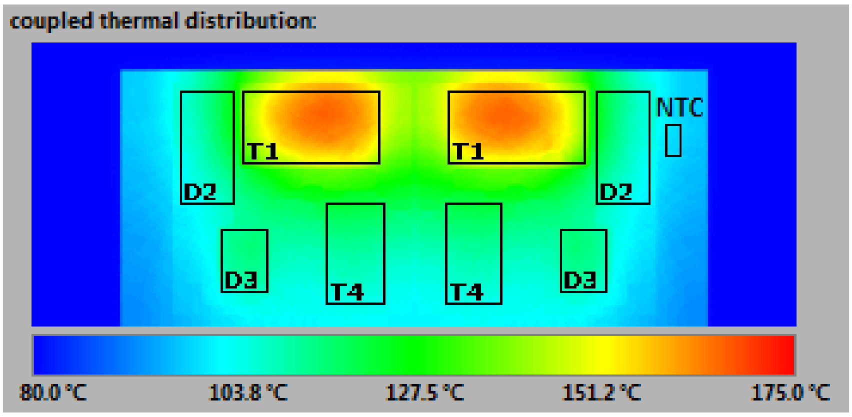

Figure 3: Example for thermal coupling within a power module

4.1 Calibrating the NTC signal

It is recommended that devices be tested under thermal stress when developing power electronic systems. The datasheets for the combined components merely offer an initial impression of their behavior, so testing under worst-case conditions is imperative.

Testing under worst-case conditions means the device should be operated under high ambient temperature with the maximum allowed electric power. If it is made to work under these conditions, tests will show exactly how the thermistor reacts and provide accurate information as to how this component helps mitigate the risk of thermal overstress for the power module.

The thermocouples' location is very important in obtaining reliable results because of the different ways heat spreads in the combined materials. Even a minor variation in the couples' positioning will bring about a huge discrepancy in ΔT and subsequently in R_{th}. Vincotech recommends measuring modules' temperatures in accordance with the IEC 60747-15 standard.

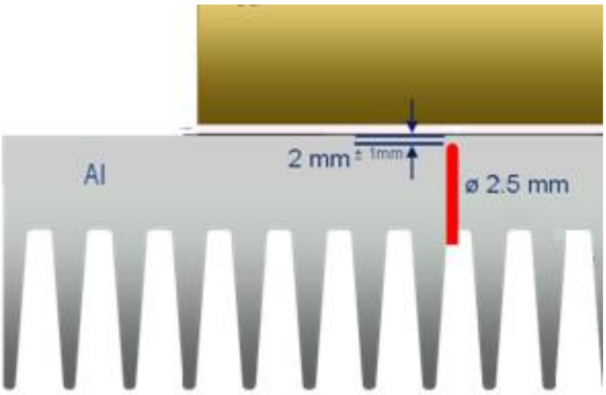

Figure 4: Recommended location for the thermocouple

A recommendation on how to determine the NTC thresholds follows:

1. Define the worst-case conditions for the application:
   ambient temperature, peak load conditions, etc.
2. Prepare the heat sink and the power module.
   Drill a hole from the bottom into the heat sink to place a thermocouple directly below the contact surface's midpoint and at other positions where hotspots are expected to be, given the inner circuit's layout. Use as few measuring points as possible and only as many as needed so as to rule out interference from the thermocouples.

The chip temperature can be calculated with the known power dissipation using the following equation:

$$T_{\mathrm{j}} = T_{\mathrm{s}} + P \cdot R_{\mathrm{th(j-s)}}$$

Chip temperatures may be measured even more precisely with the help of pre-fitted power modules. A module with thermocouples mounted on the chips or a milled housing with blackened chips may be ordered to study the temperature distribution using a thermal camera.

3. Operate the device under the predefined worst-case conditions. The reference point(s), chips and NTC's temperatures should be measured constantly throughout the test.
4. Conduct an analysis

   Now the NTC value is easily attributed to each semiconductor temperature in the power module, and an NTC threshold value can be defined for each calibrated load situation.

4.2 Operating with the NTC thermistor

There are several methods of assessing the values measured by the integrated NTC. It is possible to define a temperature threshold, for example, via an operational amplifier circuit. When this threshold is exceeded, a signal is generated to reduce the affected system’s load or stop it altogether. In this case, a switching hysteresis has to be defined to prevent a continuous start and stop loop. The hysteresis should be long enough to let the system cool down sufficiently.

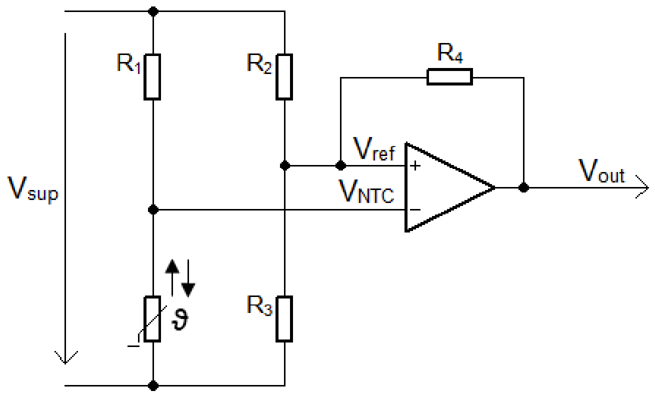

Figure 5: Basic temperature sensing circuit based on an inverting Schmitt trigger

A Schmitt trigger can be the solution. Figure 3 depicts a basic Schmitt trigger circuit. If the temperature rises, the NTC resistance decreases, and by extension, so does V_{NTC}. Once V_{NTC} arrives at a value of V_{ref}, the inverting Schmitt trigger sets its output high, which will be retained until V_{NTC} crosses the switch-off threshold. This is shown in the diagram below.

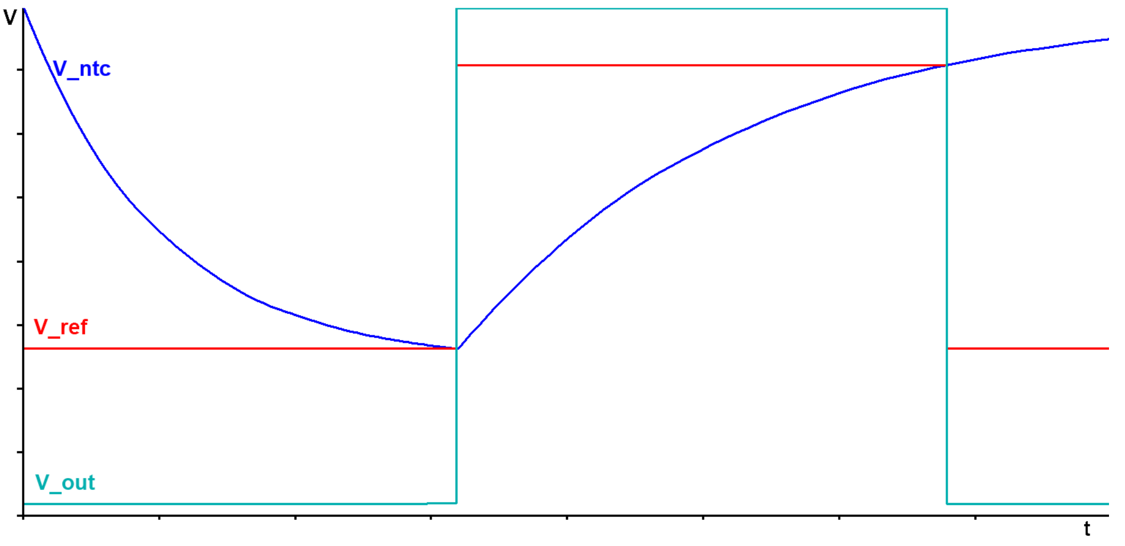

Figure 6: Principle voltage of the Schmitt trigger sensing circuit

This measurement can be calculated in three steps:

First define the desired temperature threshold and its corresponding voltage threshold $V_{\mathrm{NTC\_th}}$. The output voltage for the voltage divider containing R_1 and the NTC can be calculated using the related thermal resistance (here: R_{NTC}) out of the NTC's temperature graph and the equation given in section 3.

$$V_{NTC\_th} = \frac{V_{sup} \cdot R_{NTC}}{R_1 + R_{NTC}}$$

Then set the reference voltage to the same level as $V_{\mathrm{NTC\_th}}$.

$$V_{ref} = V_{NTC\_th} = \frac{V_{sup} \cdot R_3}{R_2 + R_3}$$

Finally, define the switching hysteresis.

The threshold voltage increases with an active output signal because of the feedback resistor R_4, resulting in two different switching levels. The desired hysteresis can be calculated using the following equations:

$$V_{out\_ON} = \left(V_{OP-} \cdot R_{2||3} + V_{ref} \cdot R_4\right) \cdot \frac{1}{R_{2||3} + R_4}$$

$$V_{out\_OFF} = \left(V_{OP+} \cdot R_{2||3} + V_{ref} \cdot R_4\right) \cdot \frac{1}{R_{2||3} + R_4}$$

V_{ON} – switching threshold for decreasing input voltage

V_{OFF} – switching threshold for increasing input voltage

$V_{\mathrm{OP}\pm}$ – supply voltage levels of operational amplifier

$R_{2||3}$ – paralleled reference voltage divider R_2 and R_3

R_4 – feedback resistor

In some cases it will be useful to obtain continuous information on the current heat sink temperature. The benefit of such a system is that it allows extensive statistical data to be collected. This data is helpful in designing durable products, especially for systems that operate under constantly changing loads and environmental conditions. To this end, the NTC resistance has to be monitored all the time, for example, by a (special temperature measurement) microcontroller. A simple voltage divider connected to the microcontroller’s analog-to-digital-converter channel can be a feasible option. The output voltage may be calculated as shown in step 1 of the Schmitt trigger calculation.

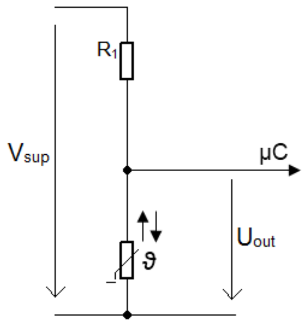

Figure 7: Simple voltage divider for temperature sensing

Please note that using the NTC to monitor heat sink temperature for the purpose of short-circuit protection is not an option because of the thermal time constant[1], which prevents the NTC from responding fast enough for this purpose.

4.3 Self-heating and measurement accuracy

The current flowing through a thermistor causes self-heating. This raises the temperature of the measurement component above ambient temperature and causes measurement error. The current flowing through the thermistor must be low enough to produce negligible self-heating error at maximum measuring temperature, but as high as possible to maximize system sensitivity. As a rule of thumb, the applied current should not exceed 100µA.

In this context, the thermal dissipation constant G_{th} is an important value. It specifies the power required to raise the thermistor’s body temperature by 1 K. It is commonly expressed in units of milliwatts per Kelvin ($\frac{\boldsymbol{mW}}{\boldsymbol{K}}$). With the help of this constant, it is possible to define the maximum allowed power dissipation for the desired measuring accuracy.

For example, if the power dissipation factor out of the datasheet is 3.5 $\frac{\boldsymbol{mW}}{\boldsymbol{K}}$, the temperature accuracy should be around 1 K and a safety margin of 50 % should be added. This can be calculated as follows:

$$P_{D\_NTC} = G_{th} \cdot T_{step} \cdot 0.5 = 3.5 \frac{mW}{K} \cdot 1K \cdot 0.5 = 1{,}75mW$$

$P_{\mathrm{D\_NTC}}$ – power dissipation of the NTC in mW

G_{th} – thermal dissipation constant in $\frac{\boldsymbol{mW}}{\boldsymbol{K}}$

T_{step} – desired measurement accuracy in K

In this example, the equation tells us that the NTC thermistor’s power dissipation should not exceed 1.75 mW to achieve the desired accuracy.

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[1] Definition: The time in seconds required for a thermistor to register a change of 63.2 % of the total difference between its initial and final body temperature when subjected to a step
function change in temperature under zero power conditions

The tolerance in the thermistor's resistance value is another reason for measurement imprecision. A thermistor is point-matched, meaning that it is calibrated and tested at a defined temperature to a tolerance of ±1 % or ±5 %, for example. This tolerance will increase regardless of the direction of temperature change, as the following table illustrates.

$T/°\mathrm{C}$	R_{nom}/Ω	R_{min}/Ω	R_{max}/Ω	$\Delta_{\mathrm{R/R}}/\pm\%$
−55	2089434.5	1506495.4	2672373.6	27.9
0	71804.2	59724.4	83884	16.8
10	43780.4	37094.4	50466.5	15.3
20	27484.6	23684.6	31284.7	13.8
25	22000	19109.3	24890.7	13.1
30	17723.3	15512.2	19934.4	12.5
60	5467.9	4980.6	5955.1	8.9
70	3848.6	3546	4151.1	7.9
80	2757.7	2568.2	2947.1	6.9
90	2008.9	1889.7	2128.2	5.9
100	**1486.1**	**1411.8**	**1560.4**	**5**
150	400.2	364.8	435.7	8.8

Table 1: Example of typical NTC resistance values

The NTC in this example is point-matched at 100 °C to a tolerance of 5 %. At room temperature, the tolerance is already above 13 %; at 150 ° it is almost 9 %. For power module applications, a temperature rating such as 100 °C is beneficial because then the NTC value is more precise at the critical temperature range for semiconductors.

4.4 Isolation coordination

The thermistor's potential is floating in most standard Vincotech modules. The isolation coordination has to be checked for peripheral monitoring components' electrical connections. Isolation is usually functional within the module. This means additional isolation can be realized, for example, by means of an interconnected optocoupler, in most cases where it is needed. The measurement circuit's output signal has to be converted into a PWM signal for this purpose.

5 Conclusion

The integrated NTC thermistor provides a convenient means of monitoring the power module and its heat sink’s thermal behavior. The peripheral circuits required to analyze the thermal element are easily realized with little design effort. Only basic and commonplace circuits are needed to obtain reliable results and achieve additional safety for the given application’s power stage.

If a concrete temperature value is to be used as a threshold, it has to be calculated carefully because a thermistor is a non-linear component. All data needed for this calculation are published in the datasheet for the chosen Vincotech power module. However, there are limits regarding accuracy because the thermistor is not able to map the given power components’ exact junction temperatures. The thermistor’s self-heating has to be factored into the equation if an exact temperature value is required.