Using NTC Temperature sensor integrated into power module

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Introduction:

Most power modules include a temperature sensor. Usually it is a Negative Temperature Coefficient (NTC) thermistor with resistance that decreases while temperature increases.

With its low cost, the NTC thermistor is the device of choice for module temperature measurements and over-temperature protection, but other devices like PTC (Positive Temperature Coefficient) resistors are preferable for specific temperature control applications.

Using the information from the temperature sensor is easy, but some care must be taken regarding safety considerations within the equipment.

1. Module internal structure.

The NTC thermistor is located close to the power dice, on the same ceramic substrate (see figure 1).

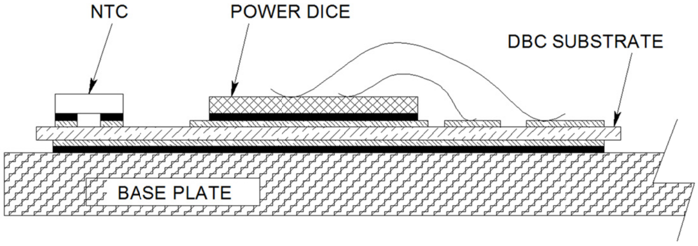

Fig 1: NTC thermistor location on a substrate

Because of negligible self-heating, the NTC thermistor remains at almost same temperature as the power module case. Also, since the case to heat-sink thermal resistance $R_{\theta CS}$ of a power module is in general very small, the measured temperature is assumed to be close to the heat sink temperature.

An NTC thermistor can never be used to monitor the junction temperature of the power devices directly; it would need to be integrated in the power die, which is not the case here. The junction temperature can be estimated based on the NTC thermistor temperature and case-to-sink thermal resistance, as will be shown.

2. NTC thermistor features.

The NTC thermistor is useful for protecting a power system from overheating or cooling system failures because of the following features:

- Low cost
- More sensitive response than thermocouples
- Easy to use
- Immune to noise
- Temperature range is well matched to power module operating temperature range

An NTC thermistor has a time constant in the range of a few seconds, meaning that it takes at least a few seconds to detect a change in temperature in a module.

Due to its slow response, the NTC thermistor is not suited to detect rapid changes in temperature and therefore can only be used to protect the system from slow changes in temperature. The NTC thermistor cannot be used for short circuit or over current protection.

The response of the NTC thermistor is exponential. In spite of its nonlinearity, the NTC thermistor is useful for module temperature measurements because:

- A simple threshold circuit can be used to indicate an over-temperature condition, which will be discussed.
- The exponential response can be processed by analog circuitry or by software in a digitally controlled system.

The NTC thermistors used in power modules have the following characteristics.

Symbol	Characteristic	Value
R_{25}	Resistance @ 25°C	22kΩ ± 5%
$B_{25/85}$	Curve fit constant	3980K

Symbol	Characteristic	Value
R_{25}	Resistance @ 25°C	50kΩ ± 5%
$B_{25/85}$	Curve fit constant	3952K

The equation for the NTC thermistor response is:

$$R_T = \frac{R_{25}}{\exp\left[B_{25/85} \cdot \left(\frac{1}{T_{25}} - \frac{1}{T}\right)\right]} \qquad (1)$$

R_T is the thermistor resistance, T is its temperature in Kelvin, and T_{25} is the Kelvin temperature at 25°C (298.15K).

3. Circuit Implementation

The NTC thermistor can easily be used for module protection without computing the actual thermistor temperature. Comparing the voltage across the NTC thermistor to a reference voltage (see figure 2), and stopping the operation of the module if it becomes too hot reduces the risk of module failure.

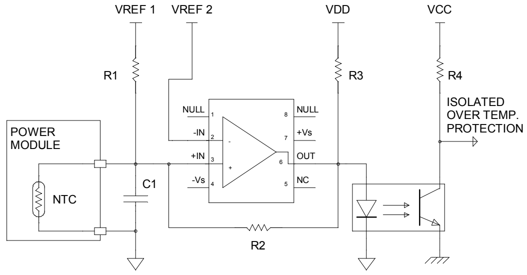

Fig 2: Example of NTC thermistor comparator circuit

If the NTC thermistor is placed in the bottom leg of a voltage divider as in figure 2, the resulting voltage at the input of the comparator decreases from almost $VREF_1$ to the voltage trigger level $VREF_2$ as the NTC thermistor temperature increases.

Assuming the temperature trigger level needs to be set at 100°C and the resulting comparator voltage trigger level is set at half the voltage reference level ($VREF_1$ / 2), the top resistor R_1 has to be set to the same value as the NTC thermistor resistance at 100°C. The thermistor resistance at a given temperature can be calculated using equation (1) or looked up in a table provided in a later section. In the case of this example, $R_T = R_1 = 3.43k\Omega$ at 100°C. If the thermistor temperature is lower than 100°C, the output state of the comparator is high. If the thermistor temperature is higher than 100°C, the output state of the comparator is low.

The position of the thermistor and R_1 can be swapped. In this case, the resulting voltage at the input of the comparator increases from almost zero volts to the trigger level voltage $VREF_2$ as the temperature increases. Whatever the position of R_1 and the NTC thermistor time constants and noise immunity level remain the same.

In practice, a comparator with hysteresis is used, and resistors R_1 and R_2 must be adjusted to set the amount of hysteresis. The hysteresis equals the output swing of the comparator attenuated by the resistive divider of $R_1//R_T$ and R_2. Assuming rail-to-rail output swing of the comparator in figure 2,

$$V_{hyst} = \frac{V_{DD} \cdot R_1 \cdot R_T}{R_2 \left(R_1 + R_T\right) + R_1 \cdot R_T}$$

Solving for R_2:

$$R_2 = \frac{R_1 \cdot R_T}{R_1 + R_T} \cdot \frac{V_{DD} - V_{hyst}}{V_{hyst}}$$

To increase the noise immunity of the NTC thermistor, which exhibits a resistance of a few thousand Ohms at rated temperature, it is recommended to parallel a capacitor. This capacitor (C_1 in figure 2) must be between 10 to 100nF. Even using a 100nF decoupling capacitor, which guarantees a very high noise immunity level, the time constant at 25°C is only 320 microseconds, e.g., $\tau = (R_1 // R_T).C_1$, more than 1000 times lower than the time constant of the NTC thermistor itself. In most cases, a 10nF decoupling capacitor is more than enough to ensure good noise immunity.

The maximum power in the thermistor must not exceed 20mW whatever the temperature to not affect temperature measurement by self-heating.

4. Temperature Measurement

Solving equation (1) for temperature (in Kelvin) we get:

$$T = \frac{B_{25/85} \cdot T_{25}}{B_{25/85} - T_{25} \cdot \ln\left(\frac{R_{25}}{R_T}\right)} \qquad (2)$$

We know the values of $B_{25/85}$, T_{25}, and R_{25}: for example 3952K, 298.15K, and 50kΩ respectively. Once we determine the value of R_T we can compute the temperature. Referring to figure 2, the voltage V_T across the NTC thermistor is

$$V_T = V_{REF1} \cdot \frac{R_T}{R_T + R_1} \qquad (3)$$

Now we can solve for the thermistor resistance.

$$R_T = \frac{R_1 \cdot V_T}{V_{REF1} - V_T} \qquad (4)$$

Note that accuracy is improved if R_1 has a neutral temperature coefficient.

Finally, equation (4) can be substituted into equation (2) to compute the thermistor temperature in Kelvin.

$$T = \frac{B_{25/85} \cdot T_{25}}{B_{25/85} - T_{25} \cdot \ln\left(\frac{R_{25} \cdot (V_{REF1} - V_T)}{R_1 \cdot V_T}\right)} \qquad (5)$$

The result from equation (5) can be converted from Kelvin to Celsius by subtracting 273.15. Equation (5) looks fairly complex but can easily be solved by a microprocessor or a DSP in digitally controlled systems. Alternatively, equation (5) can be used in a spreadsheet program to create a lookup table stored in a header file, eliminating temperature computation run-time in a digital controller.

The NTC thermistor remains at almost the same temperature as the power module case, so the thermistor temperature can simply be used for the power module base plate (case) temperature T_C.

Knowing the module case temperature T_C, the junction-to-case thermal resistance, and the power dissipation for each die, the power die junction temperature can be determined with the formula $T_J = (P \cdot R_{\theta JC}) + T_C$.

The heat sink temperature can be calculated as $T_{HS} = T_C - R_{\theta CS} \cdot P$, where T_{HS} is the heat sink temperature, P is the power dissipation, and RθCS is the case-to-sink thermal resistance.

Since the case-to-heat sink thermal resistance RθCS of a power module is generally very small, the thermistor temperature can be assumed to be close to the heat sink temperature. If appropriate, a correction of -5 to -10°C can be subtracted from the temperature measurement to estimate the heat sink temperature. For example, 10°C corresponds to 100W dissipated in a module with 0.1°C/W case-to-heat sink thermal resistance.

5. Safety Issues

Severe damage inside the module can lead to the destruction of the power dice, creating under extreme conditions the generation of plasma. The propagation of this plasma is unpredictable and it might be in contact with the NTC thermistor circuit, exposing it to dangerously high voltages.

Temperature monitoring using a NTC thermistor presents a potential risk of high voltage exposure of this part of the circuit. It is the responsibility of the system designer to ensure that appropriate measures are taken to provide reliable insulation.

Following are some examples to achieve good isolation:

- The NTC thermistor is used in a comparator circuit, which is isolated from the control logic by an opto-coupler (see figure 2). Usually other protections like short-circuit, over-current, over-temperature, etc. are also performed at the switch level. The resulting fault signals can all be summed together and transmitted via the same opto-coupler.

- The complete equipment is covered with an appropriate isolation material or enclosure.

Each application is unique and the designer must take the most efficient actions to ensure system operator's safety.

6. NTC Thermistor resistance table

6.1 50kΩ NTC Thermistor Resistance Table

The following table is data taken from the NTC thermistor manufacturer. Similar results are obtained by solving equation (1), which is valid for NTC thermistors used in power modules. Using the table 1 or equation (1), it is very easy to determine the NTC thermistor resistance at a specific temperature. Note that the data sheet lists R_{25} = 50 kΩ.

T (°C)	Rt/R_{25} nominal	Temp coef (%/°C)	B deviation (*)(± %)
-50	61.32	6.91	8.96
-45	43.66	6.68	8.18
-40	31.45	6.46	7.41
-35	22.89	6.25	6.67
-30	16.835	6.05	5.95
-25	12.498	5.87	5.25
-20	9.363	5.69	4.57
-15	7.074	5.52	3.90
-10	5.389	5.37	3.26
-5	4.137	5.21	2.63
0	3.199	5.01	2.02
5	2.5	4.86	1.57
10	1.968	4.71	1.15
15	1.56	4.58	0.75
20	1.245	4.45	0.37
25	1	4.32	0
30	0.808	4.21	0.35
35	0.6567	4.09	0.69
40	0.5367	3.98	1.01
45	0.4409	3.88	1.32
50	0.3641	3.78	1.62
55	0.3022	3.68	1.93
60	0.2520	3.59	2.23
65	0.2111	3.49	2.51
70	0.1777	3.41	2.76
75	0.1502	3.32	3.02
80	0.1274	3.24	3.25
85	0.1086	3.17	3.47
90	0.0928	3.09	3.68
95	0.0797	3.02	3.87

T (°C)	Rt/R_{25} nominal	Temp coef (%/°C)	B deviation (*)(± %)
100	0.0686	2.95	4.05
105	0.0593	2.88	4.15
110	0.0514	2.82	4.25
115	0.04475	2.75	4.34
120	0.03907	2.69	4.44
125	0.03421	2.63	4.54
130	0.03004	2.57	4.64
135	0.02646	2.51	4.74
140	0.02337	2.46	4.84
145	0.02069	2.41	4.94
150	0.01837	2.38	5.05
155	0.01633	2.32	5.15
160	0.01456	2.27	5.25
165	0.01301	2.22	5.36
170	0.01166	2.17	5.47
175	0.01047	2.12	5.57
180	0.00943	2.08	5.68
185	0.00851	2.03	5.78
190	0.00769	1.99	5.89
195	0.00697	1.95	5.99
200	0.00633	1.93	6.11
205	0.00575	1.90	6.21

Table 1: Data from NTC thermistor manufacturer (50kΩ).

(*) The deviation resulting from the tolerance on the material constant Beta. The deviation must be added to the resistance tolerance of the part as specified at 25°C.

- To calculate Rt/R_{25} at temperatures other than those listed in the table 1, use the following equation:

$$\frac{R_t}{R_{25}} = \exp\left(A + \frac{B}{T} + \frac{C}{T^2} + \frac{D}{T^3}\right)$$

$R_{25} = 50k\Omega$

R_t = thermistor resistance

T = temperature in Kelvin

$K = °C + 273.15$

Temp range (°C)	A	B	C	D
-50 to 0	-1.7718174E+01	6.9923532E+03	-6.2682835E+05	3.4307893E+07
0 to 50	-1.6391831E+01	6.3460312E+03	-5.5838575E+05	3.6804552E+07
50 to 100	-1.6267345E+01	6.3651593E+03	-6.0889839E+05	4.6929412E+07
100 to 150	-1.5586597E+01	5.8374988E+03	-4.9895349E+05	4.4005223E+07
150 to 200	-1.4360600E+01	4.5701737E+03	-1.0221320E+05	1.0155939E+07
200 to 250	-1.4956600E+01	5.1897766E+03	-3.1375858E+05	3.4668554E+07

- To calculate the actual thermistor temperature as a function of the thermistor resistance, use the following equation:

$$\frac{1}{T} = a + b\left(\ln\frac{R_t}{R_{25}}\right) + c\left(\ln\frac{R_t}{R_{25}}\right)^2 + d\left(\ln\frac{R_t}{R_{25}}\right)^3$$

Rt/R_{25} range	a	b	c	d
61.32 to 3.199	3.3600620E-03	2.5313332E-04	4.9240651E-06	-5.9119386E-08
3.199 to 0.3641	3.3540176E-03	2.6025088E-04	3.3044941E-06	-8.6084408E-08
0.3641 to 0.06862	3.3534734E-03	2.5896369E-04	2.5490046E-06	-1.0052993E-07
0.06862 to 0.01837	3.3446840E-03	2.5229699E-04	1.2806632E-06	-1.0221063E-07
0.01837 to 0.00633	3.3065226E-03	2.3663693E-04	4.3893009E-08	-2.9026088E-08
0.006331 to 0.00263	3.3021333E-03	2.3643631E-04	-9.6846436E-08	-8.2833871E-08

6.2 22kΩ NTC Thermistor Resistance Table

NTC R/T Calculation 5,0
Type 805
R/T characte 8502
R at 25°C = 22000,0 [Ohm]

Ordering code = 'B57421V2223J062'
B(25/100) = 4000,0 [K] ± 3,0%
R nom at 25°C = 22000 [Ohm] ± 5,0%

T[°C]	R nom[Ohm]	R min[Ohm]	R max[Ohm]	deltaR/R [+-%]	deltaT [+-°C]	alpha [%K]
-55	2115500	1696400	2534500	19,8	2,7	7,4
-50	1471600	1198200	1745000	18,6	2,6	7,1
-45	1036800	856400	1217200	17,4	2,5	6,9
-40	739330	619040	859630	16,3	2,4	6,6
-35	533340	452320	614350	15,2	2,4	6,4
-30	388990	333930	444050	14,2	2,3	6,2
-25	286710	248980	324440	13,2	2,2	6,0
-20	213440	187390	239490	12,2	2,1	5,8
-15	160430	142320	178540	11,3	2,0	5,6
-10	121690	109030	134350	10,4	1,9	5,4
-5	93115	84220	102010	9,6	1,8	5,3
0	71846	65571	78121	8,7	1,7	5,1
5	55880	51441	60319	7,9	1,6	4,9
10	43795	40649	46940	7,2	1,5	4,8
15	34575	32346	36804	6,4	1,4	4,7
20	27487	25911	29064	5,7	1,3	4,5
25	22000	20900	23100	5,0	1,1	4,4
30	17721	16709	18734	5,7	1,3	4,3
35	14363	13450	15276	6,4	1,5	4,1
40	11710	10893	12528	7,0	1,7	4,0
45	9601,8	8874,0	10330	7,6	1,9	3,9
50	7915,9	7269,7	8562,2	8,2	2,1	3,8
55	6560,2	5987,6	7132,9	8,7	2,4	3,7
60	5464,1	4957,2	5971,1	9,3	2,6	3,6
65	4573,2	4124,6	5021,9	9,8	2,8	3,5
70	3845,4	3448,3	4242,6	10,3	3,0	3,4
75	3247,9	2896,2	3599,7	10,8	3,2	3,3
80	2755,1	2443,3	3067,0	11,3	3,5	3,2
85	2346,8	2070,1	2623,6	11,8	3,7	3,2
90	2007,0	1761,1	2252,9	12,3	4,0	3,1
95	1723,0	1504,2	1941,9	12,7	4,2	3,0
100	1484,7	1289,6	1679,8	13,1	4,5	2,9
105	1284,0	1109,8	1458,2	13,6	4,7	2,9
110	1114,2	958,48	1270,0	14,0	5,0	2,8
115	970,15	830,62	1109,7	14,4	5,3	2,7
120	847,43	722,22	972,64	14,8	5,5	2,7
125	742,54	629,98	855,10	15,2	5,8	2,6

7. PTC Resistor (Positive Temperature Coefficient)

As opposed to a NTC thermistor, a PTC resistor increases resistance with temperature, and the variation is linear. The PTC resistance value can easily be determined by the formula below.

$$R_T = R_0 \cdot (1 + \alpha T)$$

R_T = PTC resistance at temperature T
T = delta of temperature
α = temperature coefficient
R_0 = resistance at 0°C

NTC thermistor is the most common device used for temperature protection in power systems. If fine temperature control is required a PTC device with better accuracy and most of all a linear variation versus temperature may be preferred.

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