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SIMPLE LINEARIZING SCHEMES MAKE IT EASY TO USE THERMISTORS TO IMPLEMENT VOLTAGE-REGULATOR DESIGNS WITH TEMPERATURE-DEPENDENT OUTPUTS.

Using thermistors in temperature-tracking power supplies

Most power-supply regulators, by definition, provide an output voltage that is stable despite variations in line (input voltage), load, and temperature. However, a temperature-dependent output voltage is an advantage for some applications. This article provides a tutorial, a design procedure, and circuit examples that use NTC (negative-temperature-coefficient) thermistors in temperature-tracking power supplies.

By far the most common application for temperature-dependent regulation is in LCD-bias supplies, in which the contrast of the display varies with ambient temperature. Applying a temperature-dependent bias voltage can automatically cancel the LCD's temperature effects to maintain constant contrast over a wide temperature range. Although the following examples are targeted toward LCD-bias supplies, you can apply the design procedures and equations to a variety of circuits.

NTC thermistors provide a near-optimum device for temperature-dependent regulation. They are low-cost, readily available through a variety of suppliers, such as Murata (www.murata.com) and Panasonic (www.panasonic.com), and available in small surface-mount packaging from 0402 to 1206 size. Furthermore, you can easily apply these devices to your circuit with only a basic understanding of them.

LINEARIZING THE NTC THERMISTOR CHARACTERISTICS

As the name implies, a thermistor is just a temperature-dependent resistor. Unfortunately, its dependence is highly nonlinear (**Figure 1**), and, by itself, it is unhelpful for most applications. Fortunately, there are two easy techniques to linearize a thermistor's behavior.

The standard formula for NTC-thermistor resistance as a function of temperature is as follows, where R_{25C} is the thermistor's nominal resistance at room temperature, β is the thermistor's material constant in Kelvins, and T is the thermistor's actual temperature in degrees Celsius:

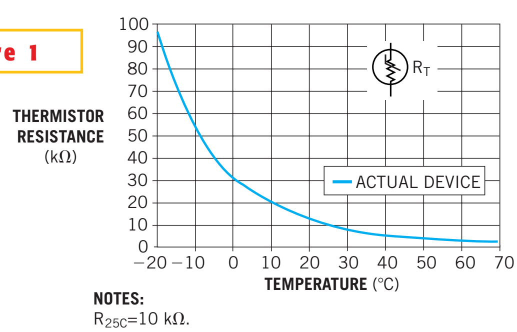
$$R_T = R_{25C}\, e^{\left\{\beta\left[\left(\frac{1}{T+273}\right)-\left(\frac{1}{298}\right)\right]\right\}}. \quad (1)$$

This equation is a close approximation of the actual temperature characteristic (**Figure 2**). (**Figure 1** refers to this equation as the beta formula). Note the use of log scale for the Y-axis. Manufacturers typically publish R_{25C} and β in the thermistor data sheet. Typical values of R_{25C} range from 22Ω to 500 kΩ. Typical values of β are from 2500 to 5000K.

Higher values of β provide increased temperature dependence and are useful when you need higher resolution over a narrower temperature range (**Figure 3**). Conversely, lower values of β provide a temperature-dependence curve with a lower slope, which may be more desirable when they operate over a wider temperature range.

A thermistor is a resistor, and, just like any other resistor, it produces heat energy when current passes through it. The heat energy causes the NTC thermistor's resistance to decrease, which then indicates

Figure 1



An NTC thermistor's resistance-versus-temperature characteristic is highly nonlinear, which makes it difficult to use a thermistor without a linearizing network.

a temperature slightly greater than ambient temperature. In the manufacturer's data sheets and application notes, you can usually find tables, formulas, and text detailing this phenomenon. However, you may largely ignore this information if you keep the current through the thermistor relatively low so that self-heating error is small compared with the required measurement accuracy, as in the following design examples.

LINEARIZE WITH RESISTANCE OR VOLTAGE

An NTC thermistor is easiest to use when you apply the thermistor in a linearizing circuit. Two simple techniques exist for linearization: resistance mode and voltage mode.

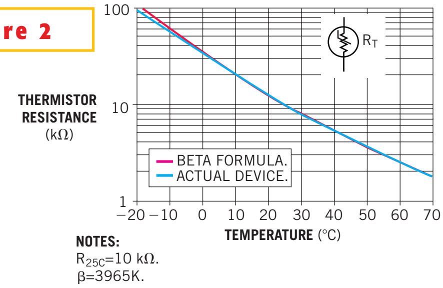
In resistance-mode linearization, a normal resistor sits in parallel with the NTC thermistor and linearizes the combined circuit's resistance. If you choose a resistor value that's equal to the thermistor's resistance at room temperature (R_{25C}), then the region of relatively linear resistance will be symmetrical around room temperature (**Figure 4**).

Note that lower values of β produce linear results over a wider temperature range, whereas higher values of β produce increased sensitivity over a narrower temperature range. The equivalent resistance varies from roughly 90% of R_{25C} at low temperature (−20°C) to 50% of R_{25C} at room temperature (25°C) to roughly 15% of R_{25C} at high temperature (70°C).

In voltage-mode linearization, the NTC thermistor connects in series with a normal resistor to form a voltage-divider circuit. A regulated supply or a voltage reference, V_{REF}, biases the divider circuit to produce an output voltage that is linear over temperature. If you choose a resistor value that equals the thermistor's resistance at room temperature (R_{25C}), then the region of linear voltage will be symmetrical around room temperature (**Figure 5**).

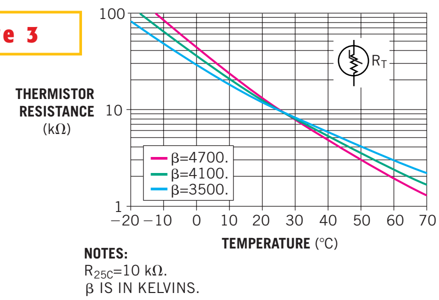
Again, note that lower values of β produce linear results over a wider temperature range, and higher values of β produce increased sensitivity over a narrower temperature range. The output voltage varies from near 0V at cold (−20°C) to $V_{REF}/2$ at room (25°C) to near V_{REF} at hot (70°C).

Figure 2



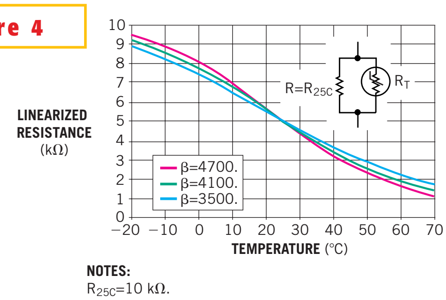
Thermistor resistance versus temperature is almost linear on a semilog graph. The actual measured thermistor resistance matches the β formula to a fairly high degree of precision.

Figure 3



You specify an NTC thermistor by its room-temperature resistance, R_{25C}, and its material constant, β, which is a measure of the slope of temperature dependence.

Figure 4



To implement resistance-mode linearization, you place a normal resistor, R, in parallel with the thermistor. If $R=R_{25C}$, the region of nearly linear resistance versus temperature is symmetrical around 25°C.

DESIGN-PROCEDURE REVIEW

To create a regulated output voltage that varies linearly with temperature, you apply the linearized-thermistor circuit to the regulator's feedback network.

The resistance-mode circuit is the simplest way to create a temperature-dependent regulated output voltage because regulator-feedback networks almost always contain a resistive-voltage divider. As **Figure 6** shows, the linearized-thermistor circuit is in series with one of the feedback resistors. In this case, the linearized circuit is in series with the top resistor of the feedback-divider network, R_1, to create a negative-temperature-coefficient output voltage at V_{OUT}, as LCD bias generally requires. To create a positive-temperature-coefficient output, you place the linearizing circuit in series with the bottom resistor, R_2, of the feedback divider.

The design procedure is relatively simple. First, find the appropriate feedback-network bias current, i_2, from the regulator's data sheet. It usually falls in the range of tens to hundreds of microamps, and some latitude in its exact value exists. Then, calculate the NTC thermistor value, where T_C is the negative temperature coefficient of V_{OUT} in percent per degrees Celsius:

$$R_{25C} = -T_C\left(\frac{Vout_{25C}}{i2}\right). \quad (2)$$

You should adjust the value of i_2 until R_{25C} becomes a readily available NTC-thermistor value.

For a simplified design calculation, select R_2 and R_1 as follows, where V_{FB} is the nominal feedback voltage as given in the regulator's data sheet:

$$R_2 = \frac{V_{fb}}{i_2}. \quad (3)$$

$$R_1 = R_2\left(\frac{Vout_{25C}}{V_{fb}} - 1\right) - \frac{R_{25C}}{2}. \quad (4)$$

For a more accurate design calculation, you need to modify the final value of i_2 to match the thermistor's β to the desired T_C. Therefore, calculate the thermistor's resistance at 0 and 50°C. The standard formula for NTC-thermistor resistance as a function of temperature is as follows, where R_{0C} is the resistance at 0°C and R_{50C} is the resistance at 50°C:

$$R_{0C} = R_{25C}\, e^{\left\{\beta\left[\left(\frac{1}{273}\right)-\left(\frac{1}{298}\right)\right]\right\}}. \quad (5)$$

$$R_{50C} = R_{25C} e^{\left\{\beta\left[\left(\frac{1}{323}\right)-\left(\frac{1}{298}\right)\right]\right\}}. \quad (6)$$

Then, calculate the linearized resistance at the two temperatures, RL_{0C} and RL_{50C}, respectively:

$$RL_{0C} = \frac{1}{(1/R_{0C} + 1/R_{25C})}. \quad (7)$$

$$RL_{50C} = \frac{1}{(1/R_{50C} + 1/R_{25C})}. \quad (8)$$

Calculate the value of R_2 and i_2:

$$R_2 = \frac{2 \times V_{fb}}{-T_C \times Vout_{25C}} \bullet (RL_{0C} - RL_{50C}), \text{ and} \quad (9)$$

$$i_2 = \frac{V_{fb}}{R_2}. \quad (10)$$

And, lastly, calculate the value of R_1 using **Equation 4**, as before.

RESISTANCE-MODE DESIGN EXAMPLE

A system running on a single-cell Li+ rechargeable battery needs an LCD bias voltage. The desired bias voltage is V_{OUT}=20V at room temperature, where T_C=−0.05%/°C, and the selected regulator is the MAX1605. You use the previous design formulas to calculate the required component values. Per the data sheet, i_2 should be greater than 10 μA for less than 1% output error. Therefore, choose i_2 to be about five times larger for less error, or i_2=50 μA. Then, according to **Equation 2**, R_{25C}=20 kΩ.

For this example, consider an NTC thermistor with R_{25C}=20 kΩ, β=3965K, and linearizing the thermistor with a parallel 20-kΩ resistor. The MAX1605 has a nominal feedback voltage of V_{FB}=1.25V. According to the simplified design formulae of **equations 3** and **4**, R_2=25 kΩ, and R_1=365 kΩ.

Per the more accurate design calculations of **equations 5** and **6**, the thermistor's resistances at 0 and 50°C are, respectively, R_{OC}=67.6 kΩ, and R_{50C}=7.14 kΩ. The linearized resistances at 0 and 50°C are then, respectively, RL_{0C}=15.4 kΩ, and RL_{50C}=5.26 kΩ. You can then calculate the values of R_2, i_2, and R_1: R_2=25.4 kΩ, i_2=49.3 μA, and R_1=371 kΩ.

In this case, these more accurate values are not substantially different from those you obtain using the simplified calculations. **Figure 7a** shows the final circuit, and the output voltage exhibits nearly ideal temperature dependence (**Figure 7b**).

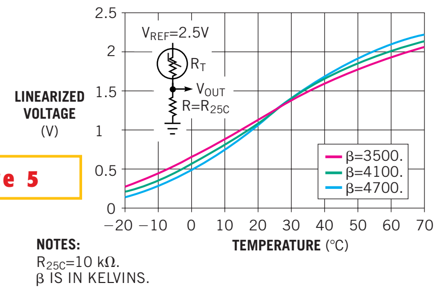


Figure 5

To achieve voltage-mode linearization, you place a resistor in series with the thermistor and bias the resulting resistive-voltage divider with a constant-voltage source. If $R=R_{25C}$, the region of nearly linear output voltage versus temperature is symmetrical around 25°C.

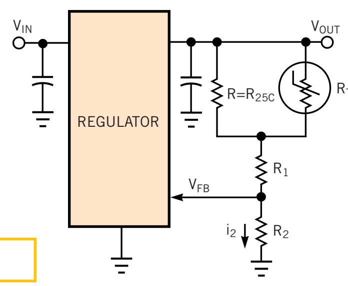


Figure 6

The resistance-mode linearized-thermistor circuit replaces a portion of the resistors—the part that depends on the required temperature coefficient of the regulator's output—in the feedback network of a voltage regulator.

VOLTAGE MODE HAS ADVANTAGES

Although more complicated than the resistance-mode circuit, the voltage-mode circuit has some unique advantages. First, the voltage-mode circuit provides a temperature-dependent analog voltage that is easy to digitize with an ADC to provide temperature information to the system's microprocessor. Additionally, the regulator's output-voltage temperature coefficient is easy to adjust by changing the value of only one resistor. This benefit allows for simple trial-and-error design in the laboratory and may also be valuable for accommodating multisourced thermistors or LCD panels in production.

As **Figure 8** shows, a voltage reference biases the linearized-thermistor circuit to generate a temperature-dependent voltage, V_{TEMP}. Then, the circuit sums V_{TEMP} into the feedback node through R_3, which sets the gain of the temperature dependence. So that V_{TEMP} does not need buffering, keep the nominal resistance of the thermistor much lower than R_3. As connected in **Figure 8**, the regulator exhibits an NTC output voltage at V_{OUT}, as generally required in LCD-bias solutions. To create a positive-temperature-coefficient output, reverse the position of R and R_T.

Although not mandatory, the simplest implementation of **Figure 8** is when $V_{REF}=2\times V_{FB}$. Conveniently, many regulators have V_{FB}=1.25V, many voltage references have V_{REF}=2.5V, and many ADCs have an input-voltage range of 0 to 2.5V. When $V_{REF}=2\times V_{FB}$, V_{TEMP} equals V_{FB} at 25°C, and i_3 equals zero. This situation allows R_1 and R_2 to set the nominal output voltage at 25°C independent of R_3 and the thermistor. Select R_2 according to the recommendations in the regulator's data sheet, and calculate R_1 and i_2 as follows:

$$R_1 = R_2\left(\frac{Vout_{25C}}{V_{fb}} - 1\right), \text{ and} \quad (11)$$

$$i_2 = \frac{V_{fb}}{R_2}. \quad (12)$$

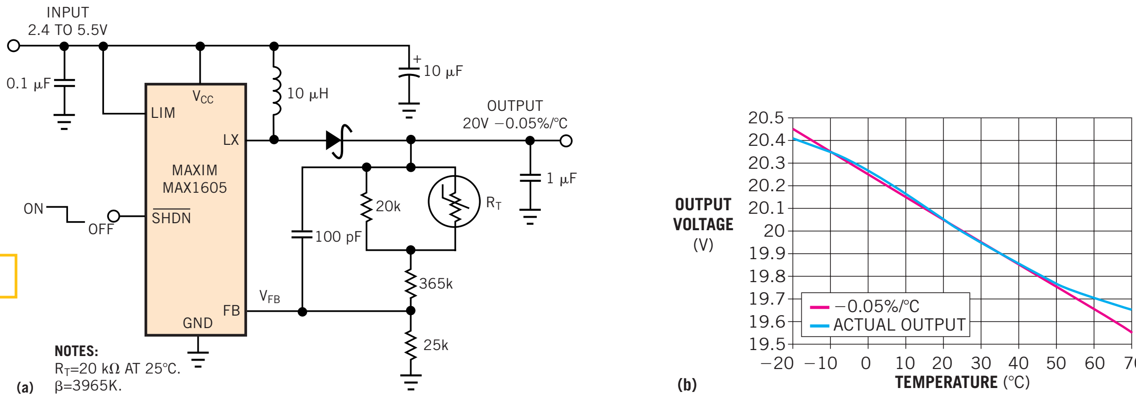
Then, calculate the approximate value of R_3, where T_C is the negative temperature coefficient of V_{OUT} in percent per degrees Celsius:

$$R_3 \cong \frac{2 \times V_{fb} \times R_1}{Vout_{25C} \times T_C}. \quad (13)$$

This value of R_3 suffices for a simplified design calculation, and you can adjust the value later through experimentation in the laboratory. Then, to avoid the need for a buffer amplifier between V_{TEMP} and R_3, choose a nominal thermistor value of $R_{25C}\le 0.05\times R_3$.

For a more accurate calculation, you can slightly modify the final value of R_3 so that the thermistor's β matches the desired T_C. To find this value, first calculate the thermistor's resistance at 0 and 50°C.

Figure 7



An NTC thermistor and boost converter implement a resistance-mode design (a). The actual temperature dependence of this circuit is close to the target temperature coefficient of −0.05%/°C over most of the extended consumer-temperature range (b).

Again, you use the standard formulas for NTC-thermistor resistance as a function of temperature in **equations 5** and **6**. Then, you calculate the linearized voltage, V_{TEMP}, at the two temperatures:

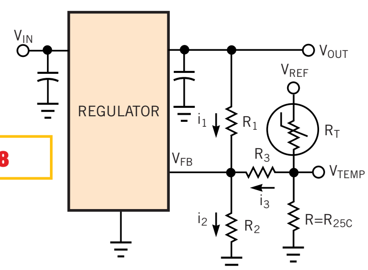
$$V_{TEMP0C} = \frac{R_{25C}}{(R_{25C}+R_{0C})} \times V_{ref}. \quad (14)$$

$$V_{TEMP50C} = \frac{R_{25C}}{(R_{25C}+R_{50C})} \times V_{ref}. \quad (15)$$

The following equation gives a more accurate value of R_3:

$$R_3 = \frac{2 \times R_1}{\dfrac{Vout_{25C} \times T_C}{(V_{TEMP0C} - V_{TEMP50C})}} \bullet \quad (16)$$

Figure 8

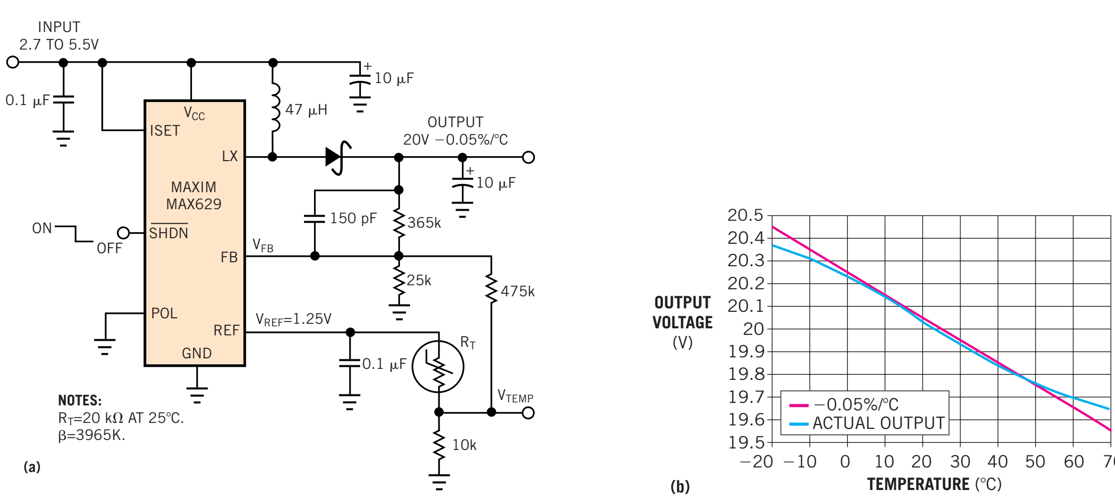


The voltage-mode linearized-thermistor circuit in the feedback network of a voltage regulator essentially adds current i_3 into the feedback node so that $i_1 = i_2 + i_3$.

For this example, as before, a system running on a voltage Li+ battery needs an LCD-bias voltage. The desired bias voltage is V_{OUT}=20V at room temperature with T_C=−0.05%/°C. In this case, the selected regulator is the MAX629 because it has a reference-voltage output that you can use to bias the thermistor-linearizing network. Using the voltage-mode design formulas in **equations 11**, **12**, and **13**, you calculate the required components as follows: Per the data sheet, R_2 should be 10 to 200 kΩ, and V_{FB}=1.25V. Therefore, R_2=25 kΩ, R_1=375 kΩ, i_2=50 µA, and $R_3 \simeq$938 kΩ. The thermistor's nominal resistance should be less than 46.9 kΩ. Therefore, choose an NTC thermistor with R_{25C}=20 kΩ and β=3965K, and linearize the thermistor with a series 20-kΩ resistor and V_{REF}=2.5V bias.

Per the more accurate design calculation of **equations 5** and **6**, the thermis-

Figure 9



An NTC thermistor and boost converter realize a voltage-mode design where $V_{REF} \neq 2 \times V_{FB}$ (a). The actual temperature dependence of this circuit is very close to the target temperature coefficient of −0.05%/°C over most of the extended consumer-temperature range (b).

tor's resistance at 0 and 50°C, respectively, is R_{0C}=67.6 kΩ, and R_{50C}=7.14 kΩ. The linearized voltage at 0 and 50°C, per **equations 14** and **15** respectively, are V_{TEMP0C}=0.571V, and $V_{TEMP50C}$=1.84V. You can then calculate the new value of R_3=952 kΩ. In this case, the more accurate R_3 value is not substantially different from the value you obtain using the simplified calculations. Thus, choose the nearest standard resistor value.

DESIGN EXAMPLE WHEN V_{REF} IS NOT 2×VFB

In the previous voltage-mode design example, if the system doesn't already include a V_{REF}=2.5V supply, it may be costly to add one. Fortunately, any regulated voltage is sufficient. For this example, you can use the REF pin of the MAX629 and V_{REF}'=1.25V. Compared with the previous example, V_{TEMP} then varies over half as wide a range. Therefore, you must halve R_3 to R_3'=475 kΩ to maintain the same output-voltage temperature coefficient of T_C=−0.05%/°C. Also, you should reduce the thermistor value and linearizing-resistor value to R=R_{25C}=10 kΩ. Furthermore, because V_{TEMP} is lower than V_{FB} at 25°C, i_3 is nonzero, and the regulator's output voltage is slightly higher than you desire by the following amount:

$$\Delta Vout_{25C}=\left(\frac{R_1}{2\times R_3'}\right)\times V_{ref}'=0.493V. \quad (17)$$

To eliminate this effect, you can reduce R_1 from 375 kΩ to R_1', where

$$R_1'=R_1-\left(\frac{\Delta Vout_{25C}}{V_{fb}}\times R_2\right)=365\ k\Omega. \quad (18)$$

Figure 9a shows the final circuit, and the output voltage exhibits nearly ideal temperature dependence (**Figure 9b**).□

Author's biography

Karl R Volk is a senior corporate applications engineer at Maxim Integrated Products (Sunnyvale, CA). He defines power-supply products for portable equipment and aids in the design and use of these products. He holds a BSEE from San Jose State University (San Jose, CA). His hobbies include astroimaging, surfing, wine-tasting, and spending time with his three-year-old daughter.