

# Wide temperature range linear negative temperature coefficient (NTC) output using PTC temperature sensor circuit



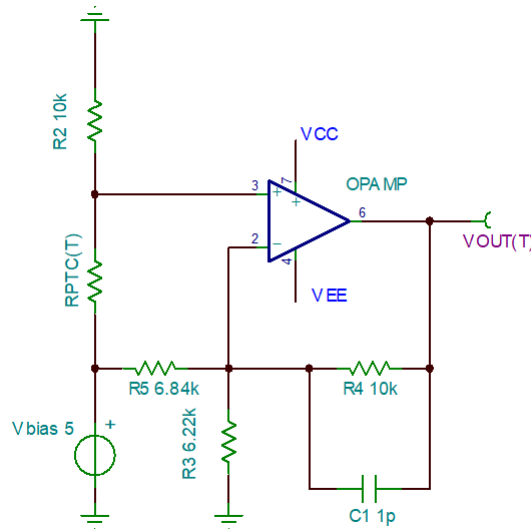
## Design Goals

Temperature		Output Voltage		Supply		
$T_{Min}$	$T_{Max}$	$V_{outMin}$	$V_{outMax}$	$V_{bias}$	$V_{cc}$	$V_{ee}$
-40°C	125°C	5V	0V	5V	12V	0V

## Design Description

This temperature-sensing circuit uses minimal passive components and a single voltage source resulting in an ultra-small form factor. The circuit design allows for easy customization to accommodate various configurations and output voltage ranges. An operational amplifier (op amp) is used to offset and amplify the input signal as needed to utilize the full ADC range and improve measurement accuracy. The output of the PTC temperature sensor is fed to the non-inverting input of the amplifier, while a resistor network connected to high- and low-voltage sources offset the output as required.

The following figure shows the circuit schematic for the wide temperature NTC sensor.



## Design Notes

1. Use the op amp in a linear operating region. Linear output swing is usually specified under the AOL test conditions.
2. Choose R1 based on the temperature range and the value of the PTC.
3. Using high-value resistors can degrade the phase margin of the amplifier and introduce additional noise in the circuit. It is recommended to use resistor values around 10kΩ or less.
4. A capacitor placed in parallel with the feedback resistor will limit bandwidth, improve stability and help reduce noise.
5. Typical resistance values are selected from the PTC resistor resistance characteristics across temperature. Take consideration for the minimum and maximum resistance limits of the PTC resistor, per temperature.
6. For single op-amp supply conditions, the output cannot swing exactly to 0V but can swing to 5V utilizing the 12-V supply. Increase  $V_{outMin}$  to the linear output swing usually specified under the AOL test conditions to improve accuracy.

## Design Information

- **T**: Temperature
- **$V_{out}(T)$** : Output voltage as a function of temperature
- **$V_{NTC}(T)$** : Voltage divider output voltage as a function of temperature. The voltage range of  $V_{NTC}(T)$  should not violate the input common mode range of the amplifier
- **$R_{PTC}(T)$** : Resistance of the PTC as a function of temperature
- **$V_{bias}$** : Voltage source connected to PTC
- **$V_{out}(T)$**  is defined as:

$$V_{out}(T) = V_{NTC}(T) \times \left( 1 + R_4 \times \left( \frac{R_3 + R_5}{R_3 \times R_5} \right) \right) - V_{bias} \times \left( \frac{R_4}{R_5} \right)$$

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### Note

For this example the TMP61 10-kΩ *Linear Thermistor* is utilized.

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- **$V_{NTC}(T)$**  is defined as:

$$V_{NTC}(T) = V_{bias} \times \left( \frac{R_2}{R_{PTC}(T) + R_2} \right)$$

- Where  **$R_{PTC}(T)$**  is defined as:

$$R_{PTC}(T) = A_4(T^4) + A_3(T^3) + A_2(T^2) + A_1(T) + A_0$$

- The constants  $A_4$ – $A_0$  can be derived from the TMP61 design tools for voltage dividers using a given  $V_{bias}$  and  $R_{bias}$ . More information is found in the [Thermistor Design Tool \(SBOC595\)](#).
- **$R_{PTC}(T)$**  constants are specific to the  $V_{bias}$  selected
- **$R_{bias}$**  is defined as R1 in this example

## Design Steps

Determine the given output voltage range and supply conditions for the application circuit. For this example the following conditions are used:

- $V_{outMin} = 5V$
- $V_{outMax} = 0V$
- $V_{CC} = 12V$
- $V_{bias} = 5V$
- $V_{EE} = 0V$
- $T_{MIN} = -40\text{ }^{\circ}C$
- $T_{MAX} = 125\text{ }^{\circ}C$

1. Using the TMP61 look up table in the [Thermistor Design Tool \(SBOC595\)](#), find the approximate  $R_{PTC\_Min}$ ,  $R_{PTC\_Max}$ , and  $R_{PTC\_Nom}$  for the given application supply conditions.  $R_{PTC\_Min}$  and  $R_{PTC\_Max}$  are selected near the local minimum or vertex of the PTC curve.

- a.  $R_{PTC\_Min}(-40) = 6.537k\Omega$

- b.  $R_{PTC\_Max}(125) = 17.852k\Omega$

- c.  $R_{PTC\_Nom}(25) = 9.962k\Omega$

2. Per the [Thermistor Design Tool \(SBOC595\)](#), a resistor value of  $10k\Omega$  is selected for R1

$$R1 = 10k\Omega$$

3. A feedback resistor of  $10k\Omega$  will be selected for this example

$$R4 = 10k\Omega$$

4.  $V_{NTC}(T)$  will be treated as a linear function to solve for the output across a given output range. The  $V_{out}(T)$  equation can be treated as a line as  $V_{NTC}(T)$  is considered linear.

$$V_{out}(T) = V_{NTC}(T) \times \left(1 + R4 \times \left(\frac{R3 + R5}{R3 \times R5}\right)\right) - V_{bias} \times \left(\frac{R4}{R5}\right)$$

$$Y(X) = X \times M + B$$

5. The minimum and maximum  $V_{NTC}$  values must be calculated using the given conditions. The curve will be optimized using the PTC resistor end points.

$$V_{NTC\_Min}(-40) = V_{bias} \times \left(\frac{R2}{R_{PTC}(-40) + R2}\right) = 5V \times \left(\frac{10k\Omega}{6.537k\Omega + 10k\Omega}\right)$$

$$V_{NTC\_Min}(-40) = 3.02V$$

$$V_{PTC\_Min}(125) = V_{bias} \times \left(\frac{R2}{R_{PTC}(125) + R2}\right) = 5V \times \left(\frac{10k\Omega}{17.853k\Omega + 10k\Omega}\right)$$

$$V_{PTC\_Min}(125) = 1.80V$$

6. The 'slope' of the line, M, can be calculated using the desired output voltage range:

- a.  $V_{outMin} = 5V$

- b.  $V_{outMax} = 0V$

$$M = \left(\frac{V_{outMax} - V_{outMin}}{V_{NTC\_Max} - V_{NTC\_Min}}\right) = \left(\frac{0V - 5V}{1.80 - 3.02V}\right) = 4.07$$

7. The non-inverting gain term of the equation can be substituted as M to solve for R5. R5 will be solved using  $V_{outMin}$  and  $V_{NTC\_Min}$ :

$$V_{outMin} = V_{NTC\_Min} \times \left(1 + R_4 \times \left(\frac{R_3 + R_5}{R_3 \times R_5}\right)\right) - V_{bias} \times \left(\frac{R_4}{R_5}\right)$$

$$V_{outMin} = V_{NTC\_Min} \times (M) - V_{bias} \times \left(\frac{R_4}{R_5}\right)$$

$$5V = 3.02V \times (4.07) - 5V \times \left(\frac{10k\Omega}{R_5}\right)$$

$$R_5 = -\left(\frac{V_{bias} \times R_4}{V_{outMin} - V_{NTC\_Min} \times M}\right) = -\left(\frac{5V \times 10k\Omega}{5V - 3.02V \times 4.07}\right) = 6.842k\Omega$$

8. Solve for R3 using the slope of the linear approximation, M:

$$M = \left(1 + R_4 \times \left(\frac{R_3 + R_5}{R_3 \times R_5}\right)\right)$$

$$4.07 = \left(1 + 10k\Omega \times \left(\frac{R_3 + 6.842k\Omega}{R_3 \times 6.842k\Omega}\right)\right)$$

$$R_3 = 6.217k\Omega$$

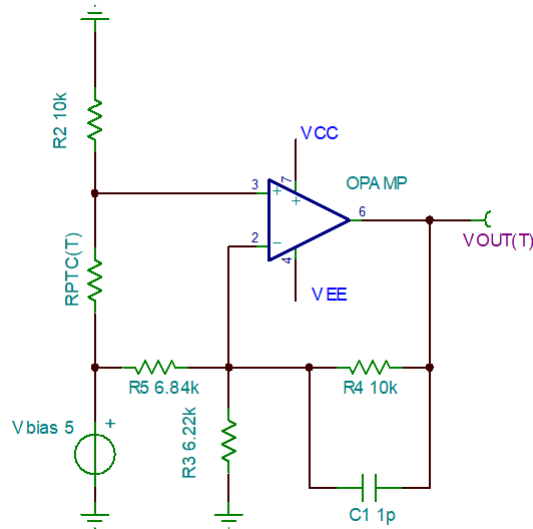
9. Using the linear approximation the resistor network has been solved achieved the desired output voltage range.
- R1 = TMP61
  - R2 = 10kΩ
  - R3 = 6.217kΩ
  - R4 = 10kΩ
  - R5 = 6.842kΩ

10. The following table highlights the resistor values for different design cases:

Temperature		Output Voltage		Supply		
T <sub>Min</sub>	T <sub>Max</sub>	V <sub>outMin</sub>	V <sub>outMax</sub>	V <sub>bias</sub>	V <sub>cc</sub>	V <sub>ee</sub>
-40°C	125°C	3V	0.33V	3.3V	3.3V	0V
Resistor Values:		R1 = TMP61	R2 = 10kΩ	R3 = 8.1kΩ	R4 = 10kΩ	R5 = 9.1kΩ
-40°C	125°C	1.7V	0.1V	1.8V	1.8V	0V
Resistor Values:		R1 = TMP61	R2 = 10kΩ	R3 = 5.5kΩ	R4 = 10kΩ	R5 = 6.6kΩ

## Design Simulations

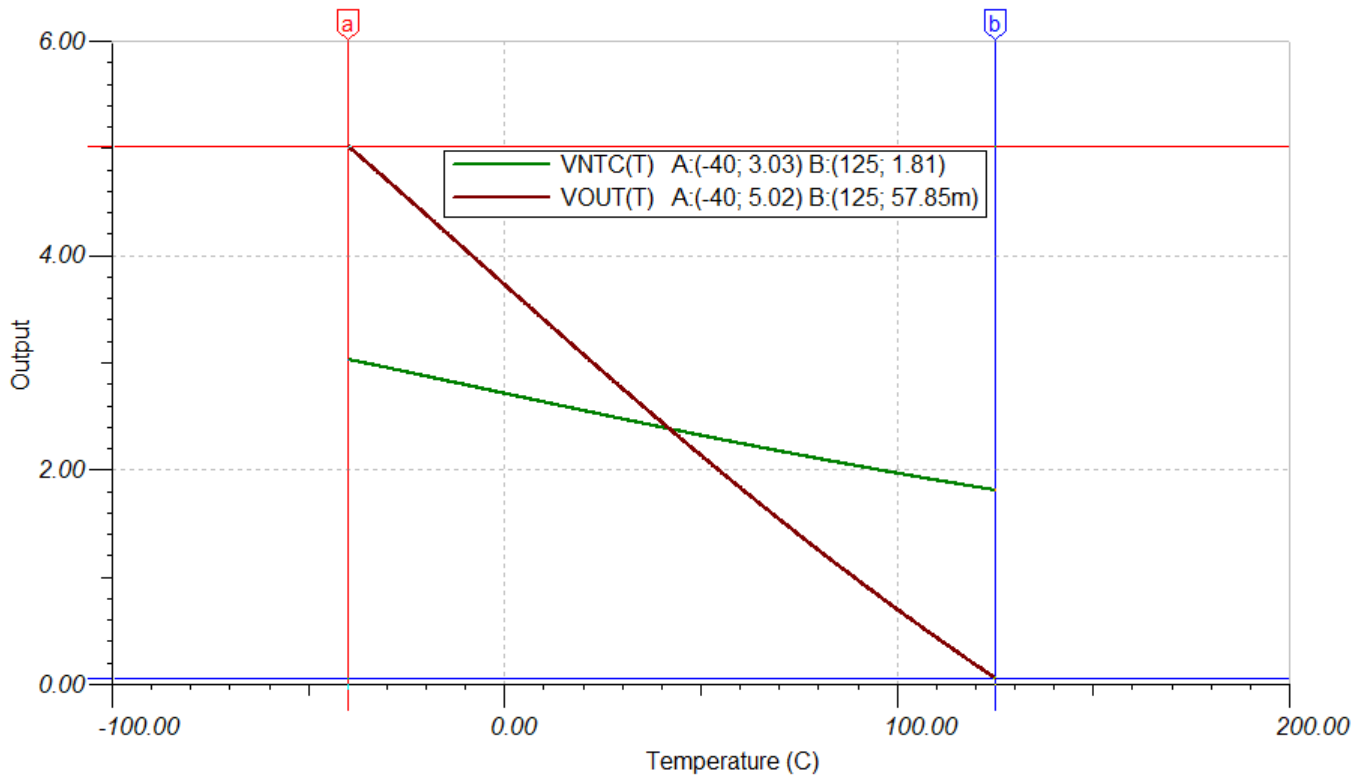
The following image shows the circuit schematic for the wide temperature NTC sensor circuit.



1. The TMP61 model was obtained via the reference design “ptc term foldback op amp mock” which is available for download from the design and development tab of the [TMP61 Product Folder \(SLOM480\)](#).
2. The TMP61 resistance across temperature response varies based on Vbias. The simulated PTC resistor must be edited in TINA-TI when changing Vbias to ensure the behavior matches the actual TMP61 values across temperature.
  - a. The temperature coefficients can be edited in the properties of the resistor.
  - b. The TMP61 lookup table is found in the [Thermistor Design Tool \(SBOC595\)](#).

## DC Simulation Results

The desired circuit output voltage response can be simulated in TINA-TI utilizing resistor values calculated in the design section. The following image shows the wide temperature NTC temperature sensor output voltage response simulated using TINA-TI.



The output voltage curve is not linear and appears almost quadratic. This is due to the TMP61 thermistor response across temperature and the inherent non-linearity of a voltage divider.

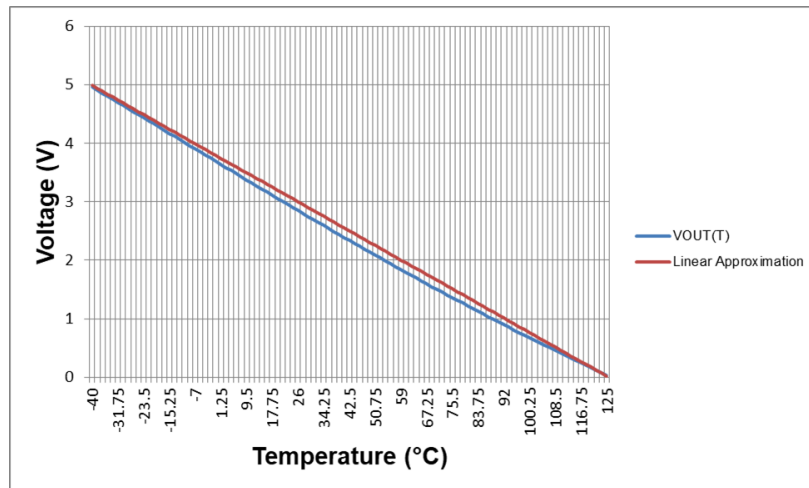
## Sensor Circuit Accuracy Using a Linear Approximation

The TMP61 linear thermistor was selected due to its resistance response over temperature. To solve for the resistor network the TMP61 resistance response over temperature was assumed to be completely linear. The error pertains to the slight non-linear behavior of the voltage divider output as a function of temperature,  $V_{NTC}(T)$ .

$$V_{out}(T) = V_{bias} \left( \frac{R_2}{R_{PTC}(T) + R_2} \right) \times \left( 1 + R_4 \times \left( \frac{R_3 + R_5}{R_3 \times R_5} \right) \right) - V_{bias} \times \left( \frac{R_4}{R_5} \right)$$

The error is exhibited as a difference between the actual temperature and the calculated temperature from the ADC. The output temperature of the sensor circuit is most accurate at the temperature extremes (end points). This is because the endpoint values of  $V_{NTC}(T)$  were utilized in the linear approximation. The highest loss of accuracy is at the local minimum or vertex of  $V_{NTC}(T)$ . A comparison of the linear approximation and the simulated response is shown in the following figure.

In the following image, the comparison of  $V_{out}(T)$  to the linear approximation is used to calculate the resistor values.  $V_{out}(T)$  represents the actual where the linear approximation represents the calculated temperature.



The calculated worst-case output error is approximately 6.6°C. This error occurs at the vertex of  $V_{OUT}(T)$  where the voltage delta between  $V_{OUT}(T)$  and the linear approximation is at its largest. The temperature reading from the ADC is approximately 54.05°C while the actual temperature is 47.45°C. The accuracy greatly improves near the endpoints and where the  $V_{NTC}(T)$  is most linear. To reduce the temperature error, an offset can be applied to the equation shifting the output voltage response lower. Applying an offset to the curve will reduce the error at the vertex of the curve but sacrifice accuracy towards the endpoints.

## Improving Accuracy of the Sensor Circuit

- The temperature accuracy of the circuit can be improved while continuing to use a linear approximation to solve for the resistor network. In this example the temperature range will be optimized from 0°C to 90°C. This is accomplished by decreasing the offset term of the  $V_{OUT}(T)$  equation.

$$V_{out}(T) = V_{NTC}(T) \times \left( 1 + R_4 \times \left( \frac{R_3 + R_5}{R_3 \times R_5} \right) \right) - V_{bias} \times \left( \frac{R_4}{R_5} \right)$$

- Recall,  $V_{OUT}(T)$  is treated as a linear equation to solve for the resistor network:

$$Y(X) = X \times M + B$$

- Therefore, the y-intercept, B, of the equation can be used to offset the curve along the Y-Axis. In this case the y-intercept of the equation is:

$$B = V_{bias} \times \left( \frac{R_4}{R_5} \right)$$

- To shift the center of the  $V_{OUT}(T)$  curve the negative inverting gain will be shifted 1.86%. The 1.86% shift was selected by calculating the change needed to shift the midpoint of the simulated  $V_{OUT}(T)$  curve towards the midpoint of the theoretical  $V_{OUT}(T)$  curve. The calculations needed to improve the accuracy of the NTC circuit are as follows:

$$V_{out\_sim}(midpoint) = 2.34$$

$$V_{out\_new}(midpoint) = 2.385$$

$$\left( 1 - \frac{2.63}{2.68} \right) = 0.018$$

- The new  $V_{OUT}(T)$  can be obtained by multiplying the ratio of R4 to R5 by 1.018 as follows:

$$V_{bias} \times \left( \frac{R_4}{R_5} \right) = V_{bias} \times 1.018 \times \left( \frac{R_4}{R_5} \right)$$

$$5V \times \left( \frac{10k\Omega}{6.842k\Omega} \right) = 5V \times 1.018 \times \left( \frac{10k\Omega}{R_5} \right)$$

$$R_5 = 6.965k\Omega$$

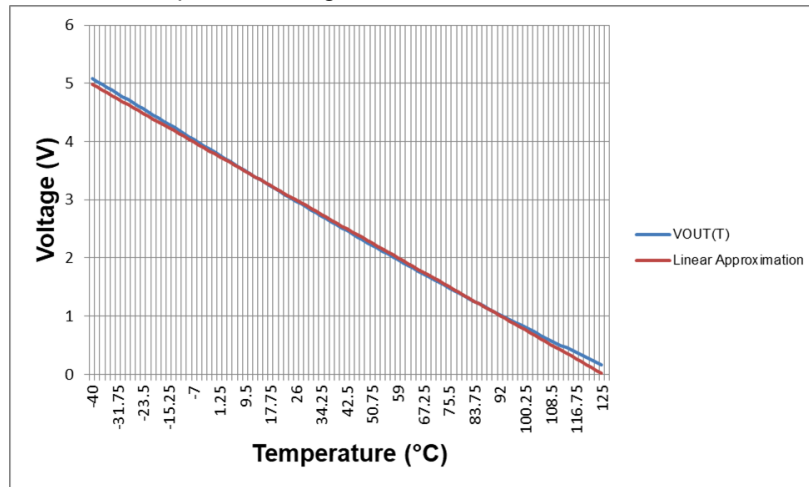
- The final resistor, R3, can be solved for using the new R5 value. Note, this approach will slightly affect the inverting gain of the circuit however, the non-inverting gain of the circuit will remain unchanged which will not impact the gain of the voltage divider output voltage as a function of temperature ( $V_{NTC}(T)$ ).

$$4.07 = \left( 1 + 10k\Omega \times \left( \frac{R_3 + 6.965k\Omega}{R_3 \times 6.965k\Omega} \right) \right) ; R_3 = 6.119k\Omega$$



7. Using the linear approximation the resistor network for the desired temperature range is as follows:
  - a.  $R_1 = 10k\Omega$
  - b.  $R_2 = \text{TMP61}$
  - c.  $R_3 = 6.119k\Omega$
  - d.  $R_4 = 10k\Omega$
  - e.  $R_5 = 6.965k\Omega$

In the following image, the comparison of  $V_{OUT}(T)$  to the linear approximation is used to calculate the resistor values.  $V_{OUT}(T)$  represents the output voltage including the non-linear portion of the TMP61 temperature range. Linear approximation represents the calculated temperature assuming the TMP61 resistance response is linear across full temperature range.



8. Solving the resistor network for the optimized temperature range improved the accuracy across the overall temperature range of the sensor. The temperature error across the optimized temperature range is approximately 1.65°C which occurs at 49.1°C. The temperature reading from the ADC is approximately 50.75°C while the actual temperature is 49.1°C. However, the error at the end points increases.

## Design References

See the [Analog Engineer's Circuit Cookbooks](#) for TI's comprehensive circuit library.

TMP61 lookup table found in the [Thermistor Design Tool](#).

## Design Featured Op Amp

TLV197-Q1	
$V_{CC}$	4.5V–36V
$V_{inCM}$	Rail-to-rail
$V_{out}$	Rail-to-rail
$V_{os}$	5 $\mu$ V
$I_q$	1mA
$I_b$	5pA
UGBW	10MHz
SR	20V/ $\mu$ s
#Channels	1
<a href="http://www.ti.com/product/tlv197-q1">www.ti.com/product/tlv197-q1</a>	

## Design Alternate Op Amp

OPA2991-Q1	
$V_{CC}$	2.7V–40V
$V_{inCM}$	Rail-to-rail
$V_{out}$	Rail-to-rail
$V_{os}$	0.125mV
$I_q$	0.56 $\mu$ A
$I_b$	10pA
UGBW	4.5MHz
SR	21V/ $\mu$ s
#Channels	2
<a href="http://www.ti.com/product/opa2991-q1">www.ti.com/product/opa2991-q1</a>	

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