Application Note

Designing the TS Pin Network for Battery Chargers with Current-Based Battery NTC Temperature Sensing

TEXAS INSTRUMENTS

Alec Lehman

ABSTRACT

This application note explains how to design the external TS pin network for battery chargers with current-based battery NTC temperature sensing. It is intended for system designers implementing battery temperature monitoring and applies when a specific charging profile is required for the battery that cannot be achieved through device configuration alone, or when the battery pack NTC thermistor does not match the type of NTC the charger was designed for, a 10kΩ at 25°C with β(25/85°C)=3435K. This application note presents a method to calculate the required series and parallel compensation resistors, verify the resulting temperature thresholds, and evaluate worst-case trip temperatures across component and device tolerances.

Table of Contents

Trademarks

All trademarks are the property of their respective owners.

1 Introduction

This application note explains how to design the external temperature sensing (TS) pin network for chargers with a current-based TS implementation. This applies when a specific charging profile is required for the cell that cannot be achieved through device configuration alone, or the battery pack NTC thermistor does not match the type the charger was designed for, a 10kΩ at 25°C with β(25/85°C)=3435K. In these cases, resistors in series and parallel with the NTC can be added to adjust the TS network resistance across temperature. This application note shows how to select these compensation resistors and verify the resulting temperature thresholds. Voltage-based TS implementations are not covered in this guide.

The current-based TS implementation uses an internal constant current source on the TS pin to bias the NTC, and the resulting voltage is compared against internal reference voltage thresholds that correspond to discrete temperature zones, typically COLD, COOL, WARM, and HOT. The TS pin voltage is therefore set by the resistance of the NTC, or by the equivalent resistance of the full TS network if external compensation resistors are added.

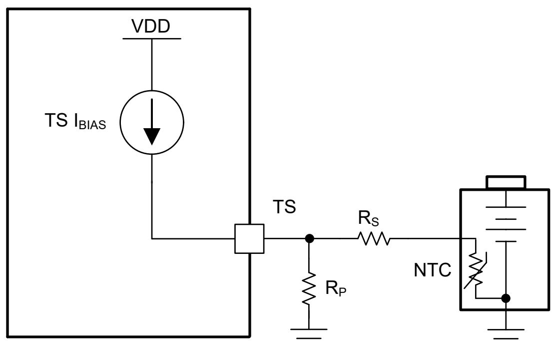

Figure 1-1. Current-Based TS Block Diagram

The internal TS voltage thresholds are designed for use with an NTC with a nominal resistance of 10kΩ at 25°C and a beta value of β(25/85°C)=3435K. When using this type of NTC, the NTC can be connected directly to the TS pin, and the temperature thresholds align with the values specified in the charger datasheet.

2 Design Procedure

2.1 Step-by-Step Calculation Method

Use the following procedure to calculate the required series and parallel compensation resistors.

1. Identify the required battery temperature thresholds from the cell datasheet.
2. Find the corresponding TS voltage thresholds in the charger datasheet. For some chargers, the TS voltage thresholds are configurable. Select the TS voltage thresholds that most closely match the desired temperature limits. For an NTC thermistor, a hotter threshold corresponds to a lower TS voltage threshold, and a colder threshold corresponds to a higher TS voltage threshold.
3. Determine the resistance of the NTC at T_{HOT} and T_{COLD}. If the NTC datasheet provides an R-T table, use the R_{NTC} values from that table. Otherwise, use the exponential form of the beta equation to approximate the resistance of the NTC across temperature:

$$R_T = R_{25} e^{\beta\left(\frac{1}{T} - \frac{1}{T_{25}}\right)} \quad (1)$$

   Where:

   - R_{25} is the NTC resistance at 25°C
   - T is the temperature (in kelvins)
   - T_{25} = 298.15K (25°C converted to kelvins)
   - β is the beta value (in kelvins)

4. Use the following equations to calculate the required series and parallel resistor values.

$$R_S = \frac{-(R_{HOT} + R_{COLD}) \pm \sqrt{(R_{HOT} + R_{COLD})^2 - 4\left(R_{HOT}R_{COLD} + \frac{V_{HOT}V_{COLD}}{(V_{HOT} - V_{COLD})I_{BIAS}}(R_{COLD} - R_{HOT})\right)}}{2} \quad (2)$$

$$R_P = \frac{V_{HOT}(R_S + R_{HOT})}{I_{BIAS}(R_{HOT} + R_S) - V_{HOT}} \quad (3)$$

   Where:

   - V_{COLD} is the cold temperature TS threshold
   - V_{HOT} is the hot temperature TS threshold
   - R_{COLD} is the NTC resistance at T_{COLD}
   - R_{HOT} is the NTC resistance at T_{HOT}
   - I_{BIAS} is the bias current from the internal constant current source on the TS pin

   Mathematically, only two temperature thresholds can be met exactly when using series and parallel compensation resistors. The compensated TS network has two unknowns, R_S and R_P. Specifying the TS voltage at two temperatures, T_{COLD} and T_{HOT}, provides two equations: $V_{TS}(T_{COLD})=V_{COLD}$ and $V_{TS}(T_{HOT})=V_{HOT}$, which can be solved simultaneously for R_S and R_P, resulting in Equations 2 and 3. In most cases, it is best to meet the COLD and HOT thresholds exactly and then check the resulting WARM and COOL thresholds.

5. Verify the HOT and COLD entry TS thresholds that are configured by the calculated R_S and R_P by plugging in R_{NTC} at the desired trip temperatures into Equation 4. Compare the resulting V_{TS} to the TS thresholds in the charger datasheet.

$$V_{TS} = I_{BIAS}(R_P \parallel (R_S + R_{NTC})) \quad (4)$$

   The remaining COOL, WARM, and exit thresholds can be checked by back-calculating the NTC resistance at each TS voltage threshold and then converting that resistance to temperature using the NTC R-T table or the beta equation given in Equation 14.

3 Design Examples

3.1 Example 1: BQ25190 with Standard NTC Beta Value, 10°C to 45°C

Design the current-based TS network for the BQ25190 to support the following charging requirements for a medical application:

Suspend charging when the battery NTC temperature is above 45°C or below 10°C.

1. Identify the required battery temperature thresholds.
   - T_{HOT} = 45°C
   - T_{COLD} = 10°C
2. Find the TS voltage thresholds from the BQ25190 datasheet.
   - V_{HOT} = 0.276V
   - V_{COLD} = 0.580V
3. Determine the resistance of the NTC at T_{HOT} and T_{COLD}.

   Assuming a 10kΩ at 25°C NTC with β(25/85°C)=3435K, the exponential form of the beta equation given in Equation 1 is used to calculate R_{HOT} and R_{COLD}:
   - R_{HOT} = 4,847Ω
   - R_{COLD} = 18,410Ω
4. Calculate the required series and parallel resistors.

   From the BQ25190 datasheet:
   - I_{BIAS} = 80μA
   - V_{HOT} = 0.276V
   - V_{COLD} = 0.580V

   Calculating the series resistor using Equation 2:
   - $R_{S,1}$ = 1.79Ω
   - $R_{S,2}$ = -23,259Ω

   Calculating the parallel resistor, R_P, using the valid solution, $R_{S,1}$, and Equation 3:
   - R_P = 11,959Ω

   Selecting standard E96 series (1% tolerance) resistor values from the calculated values:
   - R_S = 0Ω (short)
   - R_P = 12kΩ
5. Verifying the TS thresholds that result from these resistor values using Equation 4:
   - $V_{TS, HOT}$ = 80μA (12kΩ || (0Ω + 4,847Ω)) = 0.276V
   - $V_{TS, COLD}$ = 80μA (12kΩ || (0Ω + 18,410Ω)) = 0.581V

   These entry thresholds align with the COLD and HOT thresholds of the BQ25190 listed in step 2.

3.2 Example 2: BQ25188 with Different NTC Beta Value, 0°C to 45°C

Design the current-based TS network for the BQ25188 to support the following charging requirements for a wearables application:

Suspend charging when the battery NTC is above 45°C or below 0°C. Use a 10kΩ, β(25/85°C)=3610K NTC.

1. Identify the required battery temperature thresholds.
   - T_{HOT} = 45°C
   - T_{COLD} = 0°C
2. Find the TS voltage thresholds from the BQ25188 datasheet.

   The BQ25188 has configurable HOT and COLD voltage thresholds, so select the thresholds that most closely match the required temperature thresholds. HOT=45°C and COLD=0°C thresholds are available, but these correspond to a 10kΩ, β(25/85°C)=3435K NTC. Since a different NTC is being used, series and parallel resistors are needed.
   - V_{HOT} = 0.1850V
   - V_{COLD} = 1.0075V
3. Determine the resistance of the NTC at T_{HOT} and T_{COLD}.

   Using the given 10kΩ at 25°C NTC with β(25/85°C)=3610K, the exponential form of the beta equation in Equation 1 is used to calculate R_{HOT} and R_{COLD}:
   - R_{HOT} = 4,671Ω
   - R_{COLD} = 30,288Ω
4. Calculate the required series and parallel resistors.

   From the BQ25188 datasheet:
   - I_{BIAS} = 38μA
   - V_{HOT} = 0.1850V
   - V_{COLD} = 1.0075V

   Calculating the series resistor using Equation 2:
   - $R_{S,1}$ = 320Ω
   - $R_{S,2}$ = -35,279Ω

   Calculating the parallel resistor, R_P, using the valid solution, $R_{S,1}$, and Equation 3:
   - R_P = 198,178Ω

   Selecting standard E96 series (1% tolerance) resistor values from the calculated values:
   - R_S = 316Ω
   - R_P = 196kΩ
5. Verifying the TS thresholds that result from these resistor values using Equation 4:
   - $V_{TS, HOT}$ = 38μA (196kΩ || (316Ω + 4,671Ω)) = 0.1848V
   - $V_{TS, COLD}$ = 38μA (196kΩ || (316Ω + 30,288Ω)) = 1.0059V

   These thresholds align with the COLD and HOT thresholds of the BQ25188 listed in step 2.

3.3 Example 3: BQ25170 with Standard NTC Beta Value, -10°C to 60°C

Design the current-based TS network for the BQ25170 to support the following charging requirements for a personal electronics application:

Suspend charging when the battery NTC is above 60°C or below -10°C. Use vendor R-T curve data for a 10kΩ, β(25/85°C)=3435K NTC.

1. Identify the required battery temperature thresholds.
   - T_{HOT} = 60°C
   - T_{COLD} = -10°C
2. Find the TS voltage thresholds from the BQ25170 datasheet.
   - V_{HOT} = 0.188V
   - V_{COLD} = 1.04V
3. Determine the resistance of the NTC at T_{HOT} and T_{COLD}.

   From a vendor R-T table:
   - R_{HOT} = 3.02kΩ
   - R_{COLD} = 42.47kΩ
4. Calculate the required series and parallel resistors.

   From the BQ25170 datasheet:
   - I_{BIAS} = 38µA
   - V_{HOT} = 0.188V
   - V_{COLD} = 1.04V

   Calculating the series resistor using Equation 2:
   - $R_{S,1}$ = 2,301Ω
   - $R_{S,2}$ = -47,791Ω

   Calculating the parallel resistor, R_P, using the valid solution, $R_{S,1}$, and Equation 3:
   - R_P = 70,409Ω

   Selecting standard E96 series (1% tolerance) resistor values from the calculated values:
   - R_S = 2.32kΩ
   - R_P = 69.8kΩ
5. Verifying the TS thresholds that result from these resistor values using Equation 4:
   - $V_{TS,\ HOT}$ = 38µA (69.8kΩ || (2.32kΩ + 3.02kΩ)) = 0.188V
   - $V_{TS,\ COLD}$ = 38µA (69.8kΩ || (2.32kΩ + 42.47kΩ)) = 1.04V

   These thresholds align with the COLD and HOT thresholds of the BQ25170 listed in step 2.

4 Error Analysis

4.1 Worst-Case Analysis Method

The actual HOT and COLD trip temperatures vary with component and device tolerances. Therefore, to verify that the required charging limits are still met across all conditions, the TS network should be analyzed using worst-case analysis. This is the error analysis method implemented in the current-based TS calculator in the TI Charger GUI. In this note, worst-case analysis means calculating the most extreme HOT and COLD trip temperatures using the minimum and maximum values of the TS network parameters.

Use the following procedure to perform worst-case analysis on the TS network.

1. Identify the worst-case values of the TS network parameters.
   - NTC R_{25} tolerance
   - NTC beta tolerance
   - R_S and R_P resistor tolerances
   - TS bias current variation (min/typ/max)
   - TS threshold variation (min/typ/max)
2. Calculate the NTC resistance at the trip points for the worst-case parameter values using Equation 9. To derive Equation 9, convert the selected TS threshold voltage into an equivalent TS network resistance.

$$V_{TH} = I_{BIAS} R_{eq} \tag{5}$$

$$R_{eq} = \frac{V_{TH}}{I_{BIAS}} \tag{6}$$

Using the compensated TS network equation:

$$R_{eq} = R_P \parallel (R_S + R_{NTC}) \tag{7}$$

Solving for R_{NTC}:

$$R_{NTC} = \frac{R_{eq}(R_P + R_S) - R_P R_S}{R_P - R_{eq}} \tag{8}$$

$$R_{NTC} = \frac{\frac{V_{TH}}{I_{BIAS}}(R_P + R_S) - R_P R_S}{R_P - \frac{V_{TH}}{I_{BIAS}}} \tag{9}$$

The worst-case R_{NTC} equations are:

$$R_{NTC,max} = \frac{\frac{V_{TH,max}}{I_{BIAS,min}}(R_{P,min} + R_{S,min}) - R_{P,min} R_{S,min}}{R_{P,min} - \frac{V_{TH,max}}{I_{BIAS,min}}} \tag{10}$$

$$R_{NTC,min} = \frac{\frac{V_{TH,min}}{I_{BIAS,max}}(R_{P,max} + R_{S,max}) - R_{P,max} R_{S,max}}{R_{P,max} - \frac{V_{TH,min}}{I_{BIAS,max}}} \tag{11}$$

3. Convert the calculated R_{NTC} trip point resistance to temperature using the R-T table in the NTC datasheet. If the calculated R_{NTC} falls between two rows, linear interpolation can be used to calculate the corresponding temperature. If the calculated R_{NTC} falls within the error range for two rows, choose the worst-case temperature.
   - (T_1, R_1)
   - (T_2, R_2)

$$\frac{T - T_1}{T_2 - T_1} = \frac{R_{NTC} - R_1}{R_2 - R_1} \tag{12}$$

$$T = T_1 + \frac{R_{NTC} - R_1}{R_2 - R_1}(T_2 - T_1) \tag{13}$$

Repeat for the remaining cases to determine the worst-case trip temperature range.

If an R-T table is not available, the beta equation given in Equation 14 can be used to calculate the trip temperature using the worst-case values for beta and R_{25}.

$$T = \left(\frac{1}{T_0} + \frac{1}{\beta}\ln\left(\frac{R_{NTC}}{R_{25}}\right)\right)^{-1} \tag{14}$$

Where T is in kelvins

Worst-case minimum trip temperature:

$$T = \left(\frac{1}{T_{25}} + \frac{1}{\beta_{min}}\ln\left(\frac{R_{NTC,max}}{R_{25,min}}\right)\right)^{-1} \tag{15}$$

Worst-case maximum trip temperature:

$$T = \left(\frac{1}{T_{25}} + \frac{1}{\beta_{max}}\ln\left(\frac{R_{NTC,min}}{R_{25,max}}\right)\right)^{-1} \tag{16}$$

4.2 Example: Worst-Case Error Analysis for BQ25190, 10°C to 45°C

In Example 1 for a 10°C to 45°C temperature range, series and parallel resistors were selected:

- R_S = 0Ω (short)
- R_P = 12.0kΩ

1. Identify the worst-case values for the BQ25190.
   - R_S and R_P resistor tolerances: 1%
   - I_{BIAS}: 76.8µA (min), 80µA (typ), 83.2µA (max)
   - V_{COLD}: 0.576V (min), 0.580V (typ), 0.584V (max)
   - V_{HOT}: 0.272V (min), 0.276V (typ), 0.280V (max)
2. Calculate the equivalent TS network resistance for the worst-case parameter values using Equations 10 and 11.

   HOT

   - $R_{NTC,\ max}$ = 5,260Ω
   - $R_{NTC,\ min}$ = 4,477Ω

   COLD

   - $R_{NTC,max}$ = 21,127Ω
   - $R_{NTC,min}$ = 16,146Ω
3. Using the R-T table for the NTC, find the worst-case temperature that corresponds to the calculated worst-case R_{NTC}. Alternatively, use the beta equation to calculate the worst-case temperature. In this example, the beta equation is used.
   - Highest HOT entry temperature = 48°C
   - Lowest HOT entry temperature = 42°C
   - Highest COLD entry temperature = 14°C
   - Lowest COLD entry temperature = 6°C

   These results align with the output of the current-based TS calculator available on the TI Charger GUI.

Table 4-1. Current-Based TS Calculator Output

	Min	Typ	Max
Enter Cold	6	10	14
Exit Cold	8	12	16
Enter Hot	42	45	48
Exit Hot	39	42	45

5 NTC Thermistor Modeling

The resistance of an NTC thermistor across temperature can be approximated using the beta equation:

$$\frac{1}{T} = \frac{1}{T_{25}} + \frac{1}{\beta}\ln\frac{R_T}{R_{25}} \tag{17}$$

In ln(R) vs 1/T space, the beta equation has the familiar linear form y=mx+b. For most battery temperature ranges, the beta equation is usually accurate enough. However, it's important to consider the sources of error in the TS system to ensure the desired temperature sensing accuracy (±C°) is achieved.

The beta value of an NTC thermistor is a material constant (in kelvins) that describes the exponential relationship between its resistance and temperature. It describes how strongly resistance changes with temperature. NTC thermistor datasheets often specify the beta value for a certain temperature range. For example, β(25/85°C)=3435K. This is because the beta equation is only an approximation of the R-T curve of the NTC thermistor. In ln(R) vs 1/T space, the beta equation produces a perfectly straight line, but measured NTC data is not perfectly linear; the curve is slightly steeper at lower temperatures and flatter at higher temperatures. In other words, for a real NTC, resistance is more temperature-sensitive at lower temperatures and less temperature-sensitive at higher temperatures.

For this reason, β is typically specified for mid-range temperatures, where the slope of the real NTC in ln(R_T) vs 1/T space is very linear and matches the beta equation slope more closely. A beta of β(25/85°C) is calculated by experimentally measuring the resistance of the NTC at 25°C and 85°C, and using the beta equation at these two points:

$$\beta\left(\frac{25°C}{85°C}\right) = \frac{\ln\left(\frac{R_{25}}{R_{85}}\right)}{\frac{1}{T_{25}} - \frac{1}{T_{85}}} \tag{18}$$

Where T is in kelvins

NTC thermistor datasheets often specify β for a few different temperature ranges, such as β(25/85°C), β(25/100°C), β(25/50°C) for sensing around room temperature, or even β(0/50) for sensing around colder temperatures.

Typical lithium-ion or lithium iron phosphate battery charging ranges include:

- 0°C to 60°C
- 10°C to 45°C
- 0°C to 45°C

Therefore, for TS threshold monitoring, the beta value range which most closely matches the charging temperature range of the battery should be considered. For example, if the charging temperature range is 0°C to 60°C, use the β(25/85°C) value for the closest approximation of β. This is a very common beta value.

For a current-based TS implementation, the exponential form of the beta equation given in Equation 1 can be rewritten in terms of the voltage on the TS pin, V_{TS}:

$$V_{TS} = I_{BIAS}\left(R_{25}e^{\beta\left(\frac{1}{T} - \frac{1}{T_{25}}\right)}\right) \tag{19}$$

Where T is in kelvins

Equation 19 can be rewritten to include the series and parallel resistors:

$$V_{TS} = I_{BIAS}\left({R_P}^{-1} + \left(R_S + R_{25}e^{\beta\left(\frac{1}{T} - \frac{1}{T_{25}}\right)}\right)^{-1}\right)^{-1} \tag{20}$$

Equations 19 and 20 can be graphed to visualize the TS voltage across temperature.

6 Summary

This application note described how to design the external TS pin network for battery chargers with current-based battery NTC temperature sensing. External series and parallel compensation resistors can be used when a specific charging profile is required that cannot be achieved through device configuration alone, or when the battery pack NTC does not match the default type the charger was designed for. This application note presented a method to calculate the resistor values, verify the resulting thresholds, and evaluate worst-case trip temperatures across component and device tolerances. If available, use the NTC R-T table for the most accurate temperature calculations. Otherwise, use the beta equation as an approximation.

7 References

1. Texas Instruments, *BQ25190 I2C Controlled 1-Cell, 1A, Linear Battery Charger with Integrated Buck-Boost, DVS Buck, LDOs, ADC, and Power Path*, datasheet.
2. Texas Instruments, *BQ25188 I2C Controlled, 1-Cell, 1A Linear Battery Charger with Power Path, Ship Mode, Shutdown Mode, Battery Tracking VINDPM, and Wide VIN Support*, datasheet.
3. Texas Instruments, *BQ25170: 800-mA Linear Battery Charger for 1-Cell Li-Ion, and LiFePO4*, datasheet.
4. Texas Instruments, TI-Charger-GUI tool, webpage.