Application Note

Enhance Temperature Measurement Performance With BQ769x2 and TMP6x for Battery Management System

Kian Lin

ABSTRACT

Achieving fast and accurate temperature measurement is critical to a battery management system (BMS) to protect battery cells against unusual situations. The BMS needs support for sufficient temperature measurement channels for multi-string battery packs. Some standards, such as GB/T 34131-2023, require measuring the temperature of every single cell with an error of less than ±1°C from -20°C to 65°C.

This document shows the user how to expand the thermistor measurement channels and improve the temperature measurement accuracy with using BQ769x2 series battery monitor and TMP6x linear thermistor.

Table of Contents

Trademarks

All trademarks are the property of their respective owners.

1 Introduction

The temperature that the battery operates in plays a major role in battery performance, charging, discharging and longevity. Prolonged exposure to high temperatures can accelerate aging and can result in thermal runaway and explosion. Conversely, low temperatures increase the battery resistance causing the charge capacity to drop significantly. The Li-ion battery is generally recommended to operate in the 0-45°C charge temperature range and -20-6°C discharge temperature range.

To address this, the BMS is used to monitor the temperature data from battery and then transfer the data to host microcontroller for regulating battery temperature. The silicon-based linear thermistor, TMP61, which has a tolerance of ±1% between 0°C to 70°C and a wide operating range of -65°C to 150°C, is recommended for temperature measurement. The high-accuracy battery monitors and protectors for battery packs, BQ76972, which is designed especially for applications using lithium-ion, lithium-polymer or lithium-phosphate cells, are used for measuring TMP61 voltage.

The BQ76972 device can support up to nine external thermistors measurements. But, in high cell count applications, the system requires more channels to measure every single cell temperature. A multiplexer circuit can be used together with BQ76972 to support more thermistor measurements.

This document shows the design considerations of expanding temperature measurement channels and improving measurement accuracy.

2 BQ769x2 Temperature Measurement System

The BQ769x2 device can support up to nine external thermistors on multifunction pins (TS1, TS2, TS3, CFETOFF, DFETOFF, ALERT, HDQ, DCHG, and DDSG). All nine pins are connected to the one internal pullup resistor through an internal multiplexer, meaning that only one thermistor draws current from the bias supply at a time, which allows for the lowest current consumption when multiple thermistors are used.

The internal pull-up resistor has two options which can set the pull-up resistor to either 18kΩ or 180kΩ (or none at all). The resistor values are measured during factory production and stored within the device for use during temperature calculation. Figure 2-1 shows the block diagram of BQ769x2 temperature measurement system.

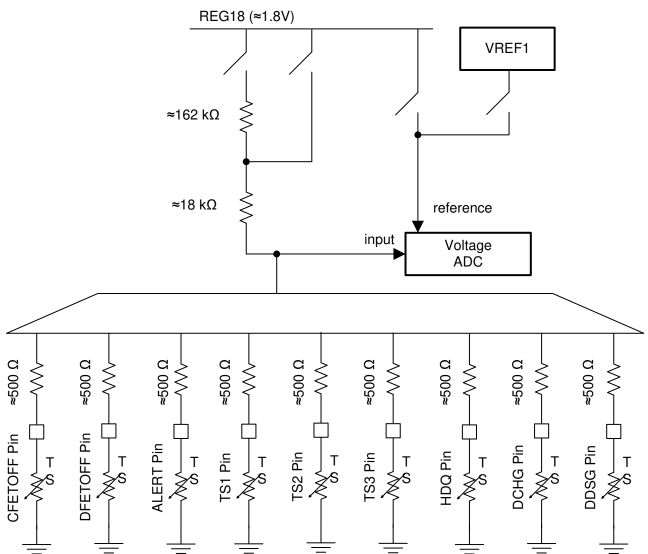

Figure 2-1. BQ769x2 Temperature Measurement System

The temperature of the pin configured as thermistor input can be calculated using the BQ769x2 internal polynomial by writing the specific coefficients into the temperature model registers or using the host microcontroller by reading the measured voltage raw count.

The voltage raw counts are measured in a continuous repeating measurements loop that consists of multiple measurement slots, as shown in Figure 2-2.

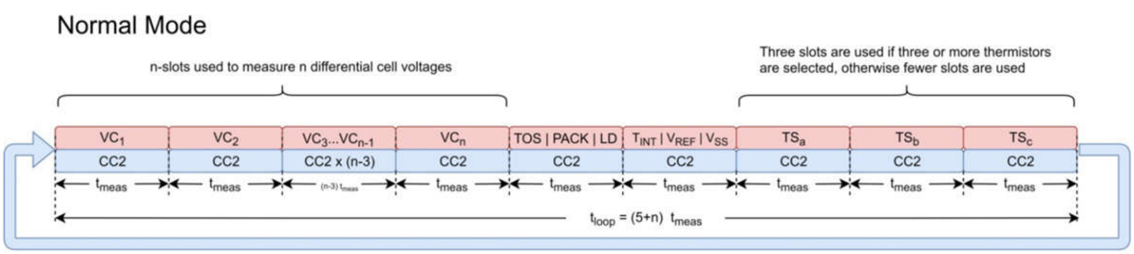

Figure 2-2. BQ76972 NORMAL Mode Measurement Loop

Each measurement loop (ADCSCAN) contains up to 21 measurement slots. The last three slots are used for multifunction pins measurement only when the pins are configured as thermistor inputs or ADCIN. The nine pins (if configured to thermistors inputs or ADCIN) are measured in the sequence of CFETOFF, DFETOFF, ALERT, TS1, TS2, TS3, HDQ, DCHG, and DDSG, which take three measurement loops to collect the full data as one FULLSCAN cycle. The tmeas slot time default is 3ms, but that time can be reduced to 1.5ms by setting the [FASTADC] bit, with a reduction in conversion resolution. One ADCSCAN takes 31.5ms (FASTADC = 1) or 63ms (FASTADC = 0), so one FULLSCAN take 94.5ms (FASTADC = 1) or 189ms (FASTADC = 0). The internal temperature polynomial is calculated every 250ms.

3 Multiplexer to Expand Thermistor Measurement Channel

However, most of these pins also can support other features which can be required in the system, such as the alarm interrupt to the host processor, or a hardware pin-control for FET turnoff. If an application requires support for more thermistors than the BQ76972 can natively support, additional multiplexer circuitry can be included to enable this, as Figure 3-1 shows.

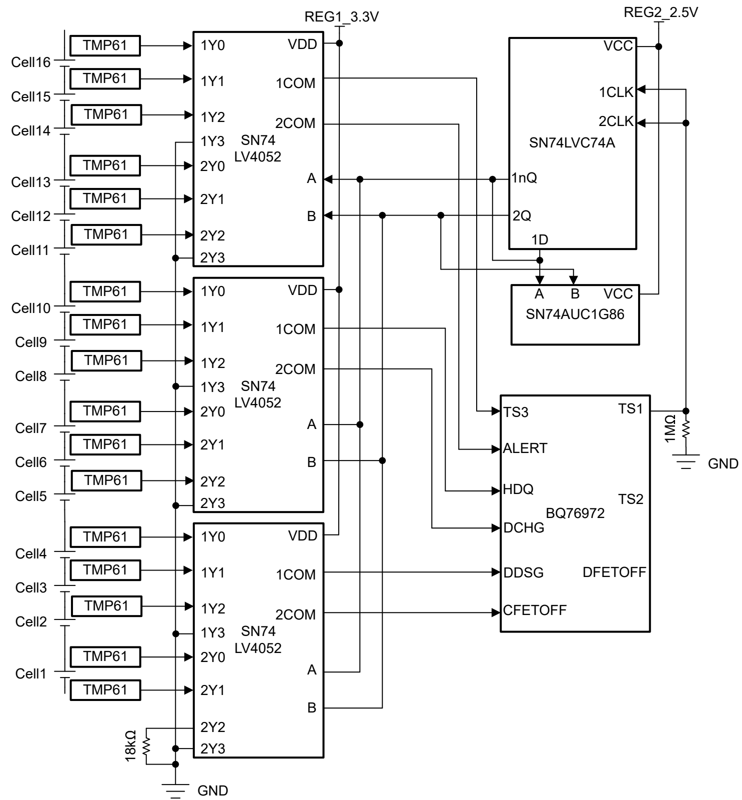

Figure 3-1. Thermistor Multiplexer Block Diagram

Six multifunction pins are muxed by 4:1 multiplexers so a total of 17 thermistors, 1 fix resistor and six ground voltages are measured by one BQ76972 in this configuration. TS2 pin is reserved for wake-up function and DEFTOFF pin is used for charging and discharging MOSFETs fast turnoff. There are also many variants if the designer wants to reserve some pins for other purposes. These circuits can be modified based on the basic principles demonstrated in the rest of this section.

Because this design configures nine pins as thermistor inputs, the design takes three ADCSCAN to measure nine pins, called as FULLSCAN. One FULLSCAN cycle duration is appromixately 94.5ms (FASTADC = 1) or 189ms (FASTADC = 0). This design uses a 4:1 multiplexer to measure 17 thermistors so one full temperature sensing cycle (FULLTEMP) takes around 378ms (FASTADC = 1) or 756ms (FASTADC = 0). See *Improving Voltage Measurement Accuracy in Battery Monitoring Systems* for more information.

The timing of when the MUX is changed requires some coordination with the regular measurement loop of the BQ76972, to avoid a corrupted measurement if the MUX was changed in the middle of a measurement. This design uses an approach to automatically control the timing of the MUX changes, shown in Figure 3-1. The TS1 pin is used with a 1MΩ resistor to generate the *clock* signal for an external binary counter that counts zero to three. The binary counter can be built simply by a dual-channel D-type flip-flop and a OR-gate, shown in Figure 3-2.

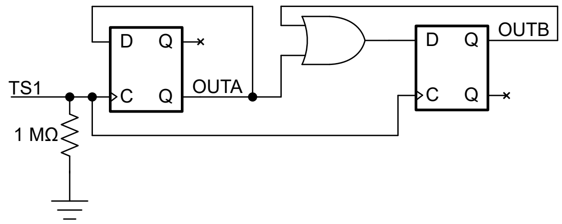

Figure 3-2. Binary Counter

Figure 3-3 shows the output signals of binary counter when FASTADC=1.

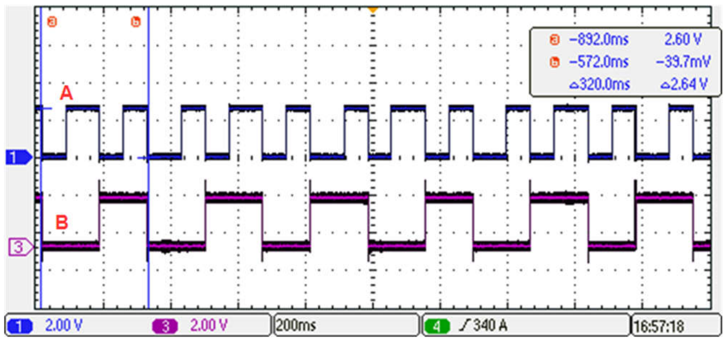

Figure 3-3. Binary Counter Output Signals

The count controls a multiplexer that switches three thermistors and one ground on each MUX into one of 6 pins, thus supporting a maximum of 18 total thermistors. The ground channel is used for multiplexer circuit diagnostic, meaning the multiplexer works correctly if you can see a ground detection every four measurements on one pin. One of the 18 channels is connected to a high-accuracy fix resistor for temperature measurement calibration.

The nine pins are measured in the sequence of CFETOFF, DFETOFF, ALERT, TS1, TS2, TS3, HDQ, DCHG, and DDSG, but BQ76972 only measures the pins that are configured as thermistor inputs. As TS1 is used as clock input, TS2 is not used as a real thermistor to avoid any MUX settling transients that can affect the measurement because TS2 is measured immediately after the TS1 pin. The user needs to implement the thermistor-related temperature protections through the host microcontroller because the pin temperature of the BQ76972 moves between three thermistors and one ground.

As the multiplexer switches every FULLSCAN cycle and is not synchronized with the internal polynomial calculation cycle, the user needs to use the ADC raw data to calculate the temperature instead of the internal temperature polynomial. To calculate the temperature with ADC raw data the user can do the following:

1. Read out the stored pullup and pad resistance, R_{pu} and R_{pad} from BQ769x2.
2. Configure the selected multifunction pins to thermistor measurement in ***Settings:Configuration:ALERT Pin Config, CFETOFF Pin Config, DFETOFF Pin Config, TS1 Config, TS2 Config, TS3 Config, HDQ Pin Config, DCHG Pin Config, and DDSG Pin Config*** configuration registers.
3. Set the FULLSCAN mask bit in ***Settings:Alarm:Default Alarm Mask*** register.
4. Wait for a measurement cycle to complete by monitoring the *0x62 Alarm Status()[FULLSCAN]* bit.
5. Send *0x0076 DASTATUS6()* and *0x0077 DASTATUS7()* subcommands to read the raw ADC counts of multifunction pins.
6. Multiply raw ADC counts by the 0.358µV LSB to obtain the measured thermistor voltage V_{sense}. Each FULLTEMP cycle, V_{sense} becomes approximately 0V once.
7. Back-calculate thermistor resistance R_T from V_{sense}, R_{pu}, R_{pad} and the multiplexer switch resistance R_{on}, and then convert R_T to a temperature value in the microcontroller.

4 Calculate Temperature With TMP6x

A silicon-based linear thermistor has a linear positive temperature coefficient (PTC), TMP61, is used for better temperature measurement accuracy. The TMP61 has good linear behavior across the whole temperature range. Unlike an NTC, which is a purely resistive device, the TMP61 resistance is affected by the current across the device and the resistance changes when the temperature changes. The *TMP6-THERMISTOR-DESIGN* only offers the R-T table for TMP61 with a fix 10kohm bias resistor so the user needs to use specific R-T table provided by TI if BQ769x2 is used to measure the TMP6x.

To convert V_{sense} to temperature, one of the common software methods is using a look-up table. This method results in a simple setup for the R-T table but puts high demand on the flash memory requirements for the MCU and a lengthy array-parsing program. This can also be inaccurate due to system errors such as tolerance variations and temperature coefficients which can lead to divergence from the R-T table.

With the use of the TMP6 linear thermistor, however, a much better algorithm is available for converting is the 5th order polynomial regression model as Equation 1 shows:

$$T = A5 \times {R_T}^5 + A4 \times {R_T}^4 + A3 \times {R_T}^3 + A2 \times {R_T}^2 + A1 \times R_T + A0 \quad (1)$$

where T = temperature (in Celsius); R = measured resistance value; A0-A5 are the calculated polynomial coefficients. R_T is back-calculated from V_{sense}, R_{pu}, R_{pad} and R_{on} as Equation 2 shows:

$$R_T = \frac{V_{sense}}{1.8 - V_{sense}} \times R_{pu} - R_{pad} - R_{on} \quad (2)$$

To obtain the coefficients value, a 5th-order polynomial fit is performed to obtain the best fit to a series of data points in the R-T table. Based on the R-T table of TMP61DEC package, these are:

- A0 = - 3.513960E+02
- A1 = 9.021910E-02
- A2 = - 1.011904E-05
- A3 = 7.112242E-10
- A4 = - 2.612301E-14
- A5 = 3.863465E-19

The coefficients are only for a 1.8V bias voltage, a 18kΩ pullup resistor and TMP61DEC package.

5 Improve Temperature Accuracy

The TMP61 shows the methods needed to achieve high accuracy in *How to Achieve ±1°C Accuracy or Better Across Temperature With Low-Cost TMP6x Linear Thermistors*, which includes:

- How to perform the single-point offset correction to remove the tolerance errors from TMP6x and other components in the thermistor biasing circuit.
- How to implement oversampling and software filtering to reduce noise and increase measurement precision.

Besides these methods, additional system level considerations can also be implemented to improve temperature measurement accuracy.

5.1 Multiplexer Selection

The multiplexer selection also effects the accuracy of temperature measurement. The key specifications and features are on resistance(R_{ON}), on capacitance(C_{ON}) and on and offleakage current(I_{ON},I_{OFF}). The on resistance contributes to signal loss and degradation, low R_{ON} tradeoffs must be considered. Total on capacitance also must be considered because this can affect response time, settling time and fanout limits. Leakage current contribute to DC errors both when the switch is ON and when the switch is OFF, but only the on leakage current introduces error in the Figure 3-1 configuration.

The user can select precision multiplexers to minimize the errors and signal distortion from multiplexers. For example, TMUX1109, a 2-channel precision multiplexer with a typical 2.5Ω R_{ON}, 35pF C_{ON} and 3nA I_{ON} can be used as an alternative to the SN74LV4052A.

5.2 Capacitor on Thermistor Pins

Due to thermistors often being attached to cells and possibly needing long wires to connect back to the BQ769x2, it may be helpful to add a capacitor from the thermistor pin to the device VSS to filter the unexpected noise. However, it is important to not use too large of a value of capacitor, since this affects the settling time when the thermistor is biased and measured periodically. A general rule recommended in BQ769x2 datasheet is to keep the time constant of the circuit < 5% of the measurement time. When Settings:Configuration:Power Config[FASTADC] = 0, the measurement time is approximately 3ms, and with [FASTADC] = 1 the measurement time is halved to approximately 1.5ms.

To obtain temperature accuracy, the value of capacitor is recommended to be smaller based on the test results. When measuring a fix 18kΩ resistance with a 1nF filter capacitances, slow signal edges of thermistor pin voltage are observed in Figure 5-1. This results in 2mV voltage measurement error which effects the temperature measurement accuracy. Figure 5-2 shows the result of reducing capacitance to 220pF. The measured voltage is close to the value without capacitor on the pin.

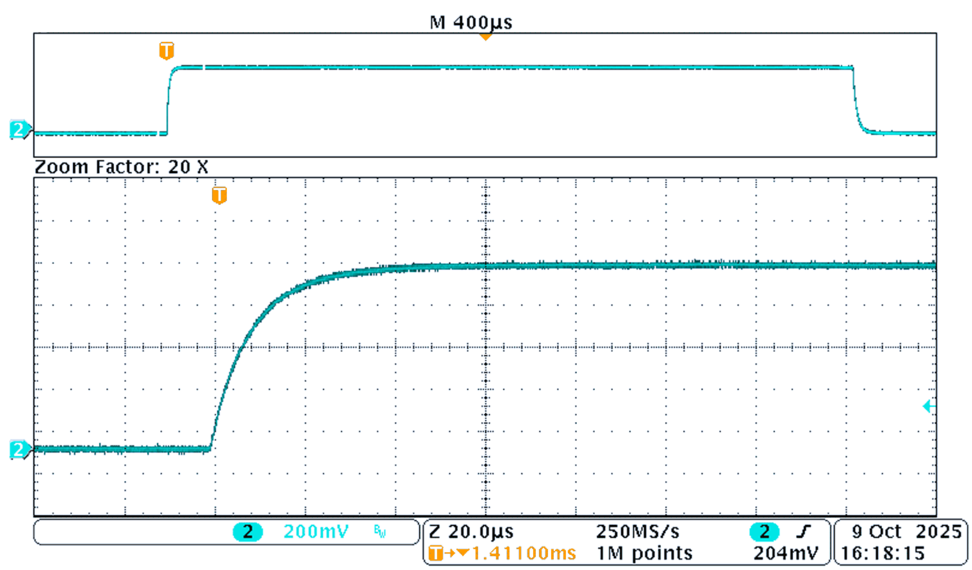

Figure 5-1. Thermistor Pin Voltage with 1nF Capacitance, 18kΩ Fix Resistance

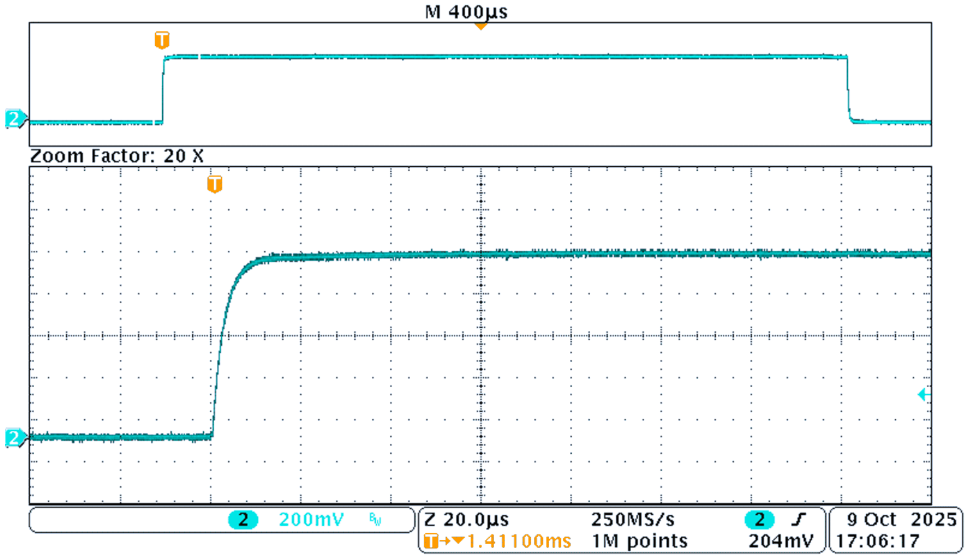

Figure 5-2. Thermistor Pin Voltage with 220pF Capacitance, 18kΩ Fix Resistance

5.3 Fix Resistor Calibration

The resistance of TMP61 varies from 6kΩ to 18kΩ over a temperature range of -40 to 125°C, corresponding to a voltage of 0.45 to 0.9V. The measured voltage range is narrow compared to the ADC input range of -0.2 to 5.5V, so the errors caused by ADC are not very different.

The fix resistor on one of the thermistor pins can be used to calibrate the ADC errors. The resistor with low resistance tolerance and temperature coefficient is recommended to achieve better accuracy.

This document tests the error between the actual and theoretical voltages with different fix value resistances; the results are listed in Table 5-1.

Table 5-1. ADC Errors with Fix Resistances

Measured Voltage	Resistance	Theoretical Voltage	Voltage Error
508.18mV	6796 ohm	510.38mV	2.20mV
687.82mV	11006 ohm	690.28mV	2.46mV
896.25mV	17960 ohm	898.45mV	2.20mV

The ADC errors of each measurements do not differ significantly. So the measured voltage can be calibrated by adding the same ADC error of each measurements.

5.4 Test Results

The TMP6x thermistors are unique in that these thermistors have a fairly consistent error across temperature as compared to traditional negative temperature coefficient (NTC) thermistors. Therefore, in this document, the TMP61 tolerance error is calibrated across temperature by simply subtracting the error at one single temperature point.

After calibrating the ADC error with fix resistor, and the TMP61 tolerance error by performing the single-point offset correction at 0°C, the measured temperature errors are showed in Figure 5-3. The error is less than ±1°C in the range of -20°C to 125°C.

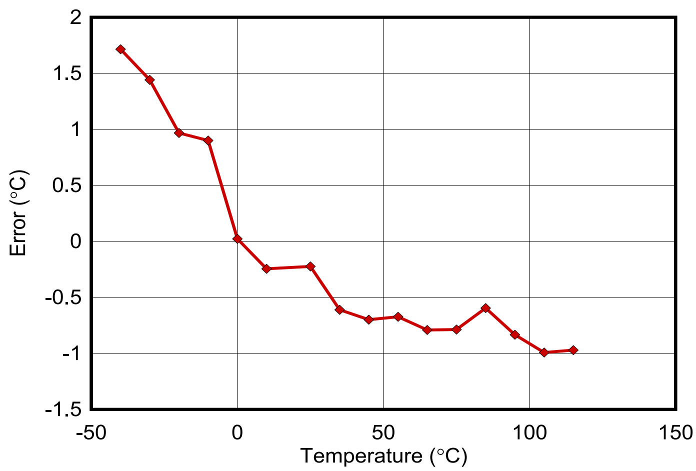

Figure 5-3. Temperature Measurement Accuracy Test Results

6 Summary

This document introduces the design considerations when using BQ769x2 to measure temperature with TMP6x. After the recommended calibration methods, the test results show an error of less than ±1°C in the range of -20°C to 125°C.

7 References

- Texas Instruments, *BQ769x2 Technical Reference Manual*, technical reference manual.
- Texas Instruments, *NTC Thermistor to TMP6 Linear Thermistor Replacement Guide*, user's guide.
- Texas Instruments, *How to Achieve ±1°C Accuracy or Better Across Temperature With Low-Cost TMP6x Linear Thermistors*, application note.
- Texas Instruments, *Improving Voltage Measurement Accuracy in Battery Monitoring Systems*, application note.