Application Report
SLAA398A–September 2008–Revised August 2018

Using an MSP430™ MCU and TPS60313 to Implement a Single-Battery-Cell Powered Thermostat

MSP430 Applications

ABSTRACT

Powering an MSP430™ microcontroller (MCU) from a single 1.5-V battery cell is desirable in a number of applications. These applications require the use of a charge-pump-based dc/dc converter. This application report describes dc/dc converter basics and selection, and presents the implementation of a single-cell thermostat using an MSP430 MCU and a TPS60313 dc/dc converter. Analysis of the single-cell plus dc/dc converter solution includes the current consumption and the expected battery life.

Source code related to this solution is available for download from www.ti.com/lit/zip/slaa398.

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Trademarks

1 Introduction

With a properly selected charge pump, the designer can implement a single-cell powered application and still maintain low-power performance and battery life. The thermostat that is described in this application report is based on the MSP430F4794 MCU and the TPS60313 dc/dc charge pump converter, which is optimized for low-power single-cell applications. The MSP430F47x4 is a high-pin-count microcontroller with many peripherals. This application requires only one of the four SD16 modules (used to sample temperature) and the Basic Timer (used for periodic wakeup). It is left to the reader to decide how functionality can be added to take full advantage of the device’s feature set.

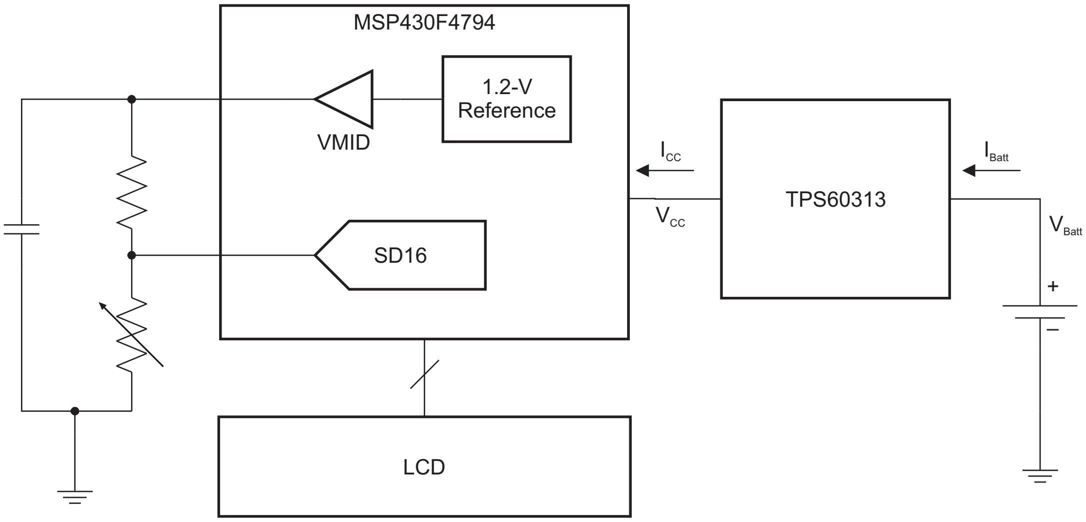

Figure 1. System Overview

2 DC/DC Converter Basics – P_{IN} vs P_{OUT}

It is important to understand the relationship between power in, power out, and efficiency when selecting a converter. For an ideal physical system, the power in is equal to the power out. For the system overview depicted in Figure 1, this can be expressed as:

$$V_{Batt} \times I_{Batt} = V_{CC} \times I_{CC}$$

For example, if the battery voltage V_{Batt} = 1.3 V, the MSP430 current I_{CC} = 10 µA, and the MSP430 voltage V_{CC} = 3.3 V, then, ideally, from the equation above, solving for I_{Batt} yields:

$$I_{Batt} = (V_{CC} \times I_{CC}) / V_{Batt} = 25\ \mu A$$

This means that in order for an ideal dc\dc converter to supply 10 µA at 3.3 V to the MSP430, the battery would need to supply 25 µA at 1.3 V to the dc/dc converter. Ideal implies 100% efficiency but, of course, no real system is 100% efficient. Sources of inefficiency include power dissipation in the form of heat generation, switching losses, and quiescent current of the dc/dc converter itself. The graph in Figure 2 (taken from the TPS60313 datasheet) shows that when V_{IN} = 1.3 V and V_{OUT} = 3.3 V, the device is approximately 75% efficient when supplying an output current of 10 µA.

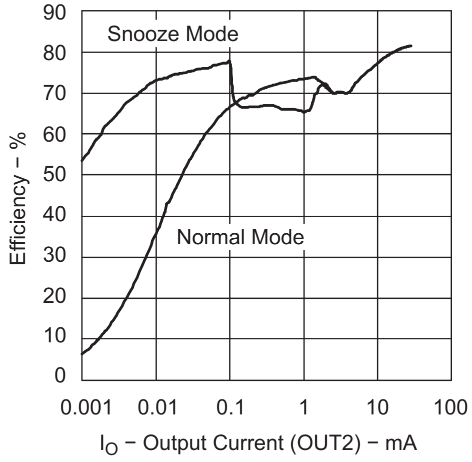

Figure 2. TPS60313 Efficiency vs Output Current (V_{IN} = 1.3 V, V_{OUT} = 3.3 V)

If we reconsider the equation $P_{IN} = P_{OUT}$ taking into account the efficiency of the dc/dc converter:

$$V_{Batt} \times I_{Batt} = (1 / eff) \times V_{CC} \times I_{CC}$$

Then solving for I_{Batt}:

$$I_{Batt} = (1 / eff) \times ((V_{CC} \times I_{CC}) / V_{Batt}) = 34\ \mu A$$

Using the same values for V_{Batt}, I_{CC}, and V_{CC}, I_{Batt} is found to be 34 µA. This means that to provide 10 µA at 3.3 V to the MSP430, the battery must supply a total of 34 µA at 1.3 V to the dc\dc converter.

3 TPS60313 Description and Features

For the application described in this document, the TPS60313 inductorless dc/dc charge-pump converter was selected for its low quiescent current and high-efficiency performance at low operating currents. These attributes make it an ideal fit for use with MSP430 microcontrollers in single-cell applications.

The TPS60313 step-up, regulated charge pump generates a 3-V output voltage from a 0.9-V to 1.8-V input voltage. Only five small 1-µF ceramic capacitors are required to build a complete high-efficiency dc/dc charge-pump converter.

In SNOOZE mode, the TPS60313 operates with a typical operating current of 2 µA, while the output voltage is maintained at 3 V ± 10%. Load current in SNOOZE mode is limited to 2 mA. If the load current increases above 2 mA, the device automatically exits the SNOOZE mode and operates in normal mode to regulate to the nominal output voltage with higher output currents.

While the SNOOZE mode enables greater efficiency at low currents, users must recognize that the output voltage ripple is greater than when SNOOZE mode is disabled (see Figure 3).

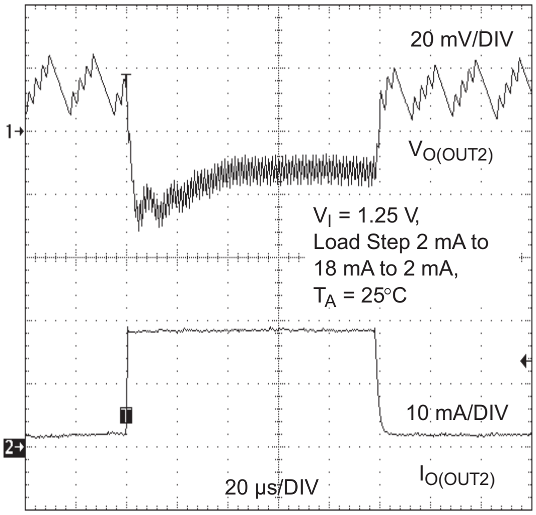

Figure 3. TPS60313 Load Transient Response

Channel 1 shows the effect of the SNOOZE feature on the regulated output voltage. Channel 2 shows the output current transitions that cause the device to enter and exit SNOOZE mode. This behavior can possibly affect ADC conversion results or other processes that are sensitive to supply ripple, so it is recommended to take the device out of SNOOZE mode before doing any A/D conversions. Once SNOOZE mode is disabled, the output voltage is regulated with greater accuracy, but the quiescent current is higher.

4 MSP430 + Charge Pump Implementation for Single-Cell Thermostat

The MSP430 + charge pump implementation is shown on the next page. The only external components required for the charge pump circuit are five 1-µF ceramic capacitors. The $\overline{\text{SNOOZE}}$ pin is connected to one of the MSP430's GPIO pins. In the event that higher current (more than 2 mA) is required, the charge pump automatically exits snooze mode but, in the case of an A/D conversion, it is best practice to disable $\overline{\text{SNOOZE}}$ in software by setting the appropriate MSP430 pin high before the conversion is initiated.

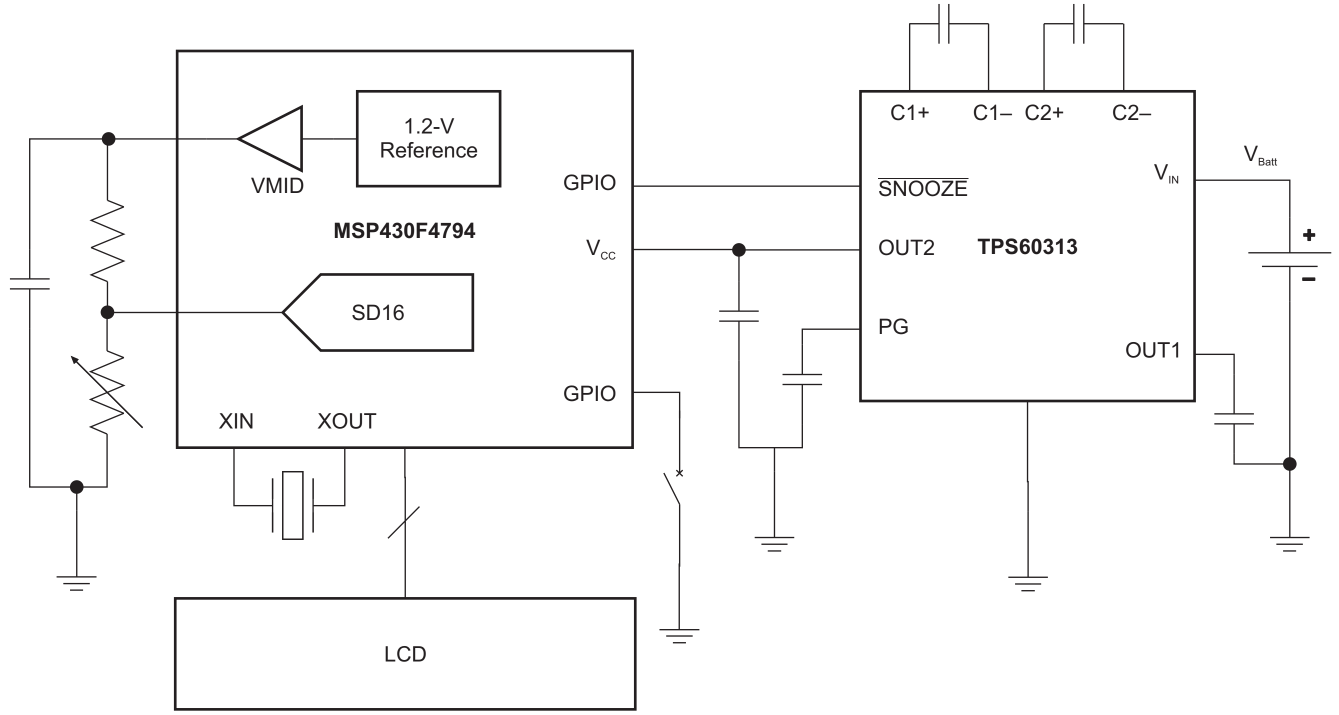

Figure 4. MSP430F4794 and TPS60313 Block Diagram

5 Thermostat Application Description

The thermostat software is based on periodic one-second interrupts and a counter whose value increments from 0 through 6 to determine which of the processes (A, B, or C) should be executed. Because the LCD segments that are used to display the time and temperature are shared, the time is displayed for thee seconds and then the temperature is displayed for three seconds. The Basic Timer interrupt occurs to execute process A, the RTC function, and increment the count. If the count is 3, then process B is also executed to update the time on the LCD. If the count is 6, process C is also executed, during which the thermistor is sampled, temperature is calculated and displayed on the LCD replacing the time, and the count is reset to zero, completing the six-second cycle.

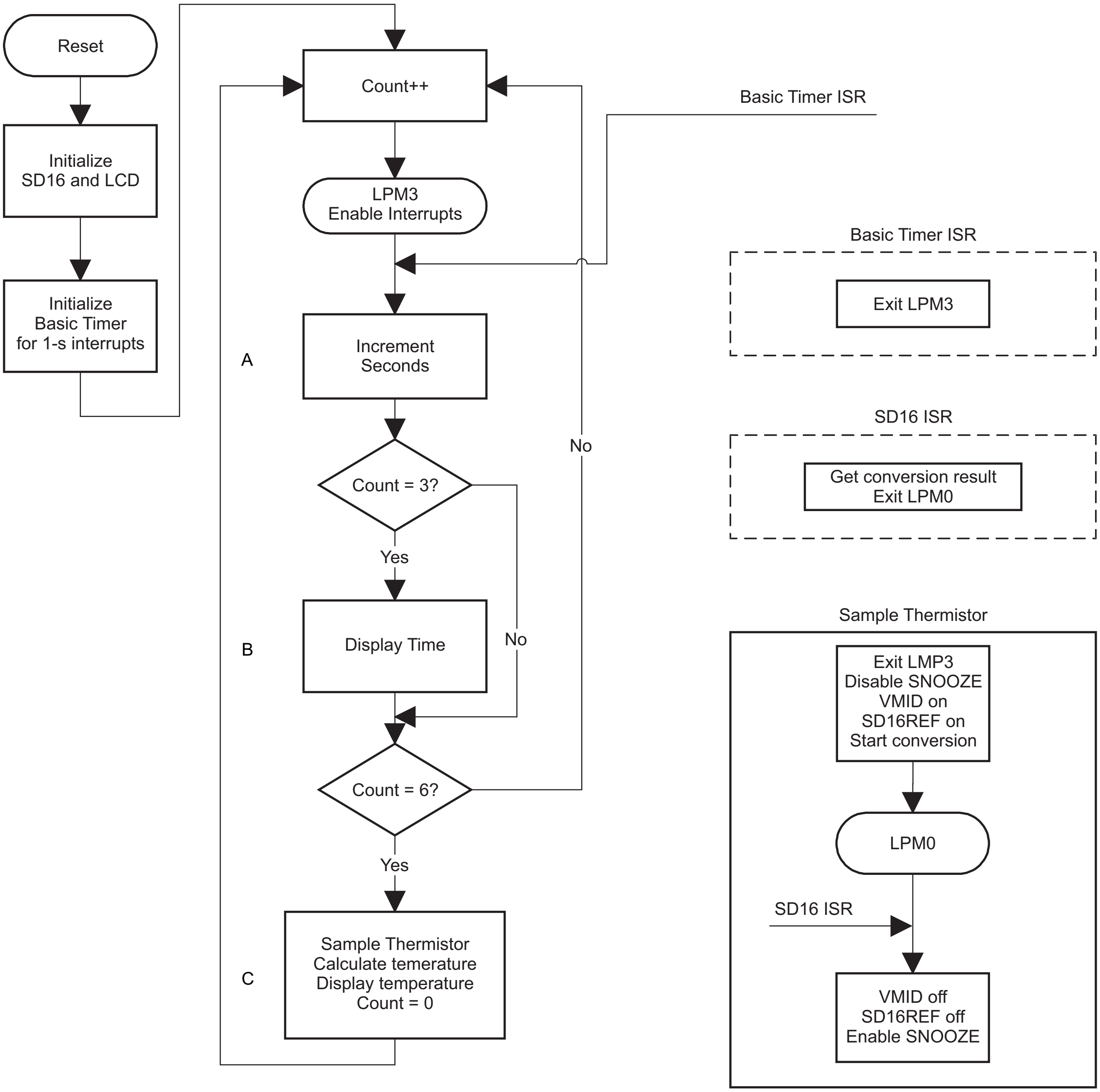

Figure 5. Code Flow Diagram

To obtain the temperature, the SD16 1.2-V reference is applied to the thermistor plus 47-kΩ series resistor combination, and the thermistor voltage is sampled via the SD16 to obtain a raw value. This raw value is then converted to a voltage by first subtracting 8000h from the result, because 8000h corresponds to a voltage level of 0 V. Next, this value is multiplied by the voltage step per bit, which is 1.2 V / (2^{16} – 18 µV/bit.

$$V_{thermistor} = (\text{RawValue} - 8000\text{h}) \times 18\ \mu\text{V/bit}$$

Once the voltage is known, the resistance is determined by solving for the thermistor value that produces the measured thermistor voltage based on the voltage divider equation.

$$V_{thermistor} = V_{ref} \times (R_{thermistor} / (R_{thermistor} + 47\ \text{k}\Omega))$$

Rearranging the equation to solve for $R_{thermistor}$ yields

$$R_{thermistor} = V_{thermistor} \times (47\ \text{k}\Omega / (V_{ref} - V_{thermistor}))$$

Once the thermistor resistance is known, a look-up table from the thermistor manufacturer's data sheet is referenced to determine the corresponding temperature.

6 Current Measurements – Two Cell and Single Cell

Current measurements were carried out to determine the I_{CC} and I_{Batt} of the MSP430 + TPS60313 one-cell thermostat system. They are summarized in Table 1 for the condition V_{CC} = 3.0 V and V_{Batt} = 1.5 V.

Table 1. I_{Batt} and I_{CC} Typical and Max

MSP430 State	I_{CC} (µA)		I_{Batt} (µA)	
	Typ	Max	Typ	Max
LPM3	1.3	3	6	8
LCD_A (2 mux)	2.7	3.5	11	15
VMID+REF	385	600	1570	2446
SD16	730	1050	2700	3883
AM	420	560	1660	1876

Figure 6 shows when each of the one second processes is executed with respect to time. The total time required to run through count = 1 to count = 6 is six seconds.

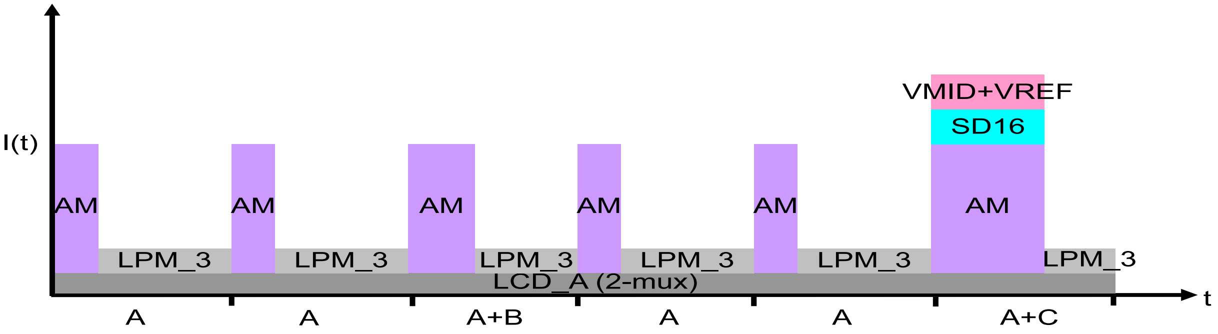

Figure 6. Current Profile For Complete 6 Second Cycle

The average current consumption for each second is calculated by finding the area under I(t) vs t plot. Current required by each of the one-second processes is calculated based on the amount of the time spent by the MSP430 device in each of the states for which current consumption was measured (see Table 2).

Table 2. Current Consumption

	Current Sink		**I_{Batt} (µA)**	
			Typ	**Max**
Process A	AM	7.50E-05 s	0.12	0.14
	LPM3	1 – (7.50E-05) s	6	8
	LCD_A (2 mux)	1 s	11	15
		Total	17.1245	23.14
Process B	**Current Sink**		**I_{Batt} (µA)**	
			Typ	**Max**
	AM	7.17E-04 s	1.19	1.35
		Total	1.19	1.35
Process C	**Current Sink**		**I_{Batt} (µA)**	
			Typ	**Max**
	AM	4.67E-03 s	7.75	8.76
	VMID+REF	9.00E-04 s	1.41	2.2
	SD16	9.00E-04 s	2.43	2.43
		Total	11.6	13.39
Average Current			**I_{Batt} (µA)**	
			Typ	**Max**
6 seconds (6A + B + C)			115.53	153.58
1 second (6A + B + C)/6			19.26	25.6

Finally, the expected battery life of the single-cell thermostat is calculated based on the mA•hr ratings given for Duracell AA and AAA batteries. The method for calculating the battery life is as follows.

First convert the battery rating of mA•hr to µA•sec.

µA•sec = (mA•hr) (1000 µA / 1 mA) (60 min / 1 hr) (60 sec / 1 min)

Then divide the battery rating in µA•sec by the average current consumption in µA for one second to get the estimated number of seconds the battery will last.

sec = µA•sec / µA

Now that the seconds are known, calculate the equivalent years:

years = (sec) (1 min / 60 sec) (1 hr / 60 min) (1 day / 24 hr) (1 year / 365 days)

Table 3. Typical and Minimum Expected Battery Life

Battery Type	**Battery Rating (mA•h)**	**Battery Life (yrs)**	
		Typical	**Min**
AA	2850	16.90	12.71
AAA	1000	5.93	4.46

The results in Table 3 are based on the assumption that V_{Batt} remains a constant 1.5 V throughout the battery's lifetime. In reality, the voltage falls over time as the battery discharges, so the TPS60313 has been designed to be most efficient at 1.2 V, as this represents the battery's average voltage over its lifetime. Optimizing for operation at 1.2 V helps to maximize the overall system lifetime.

7 Schematic

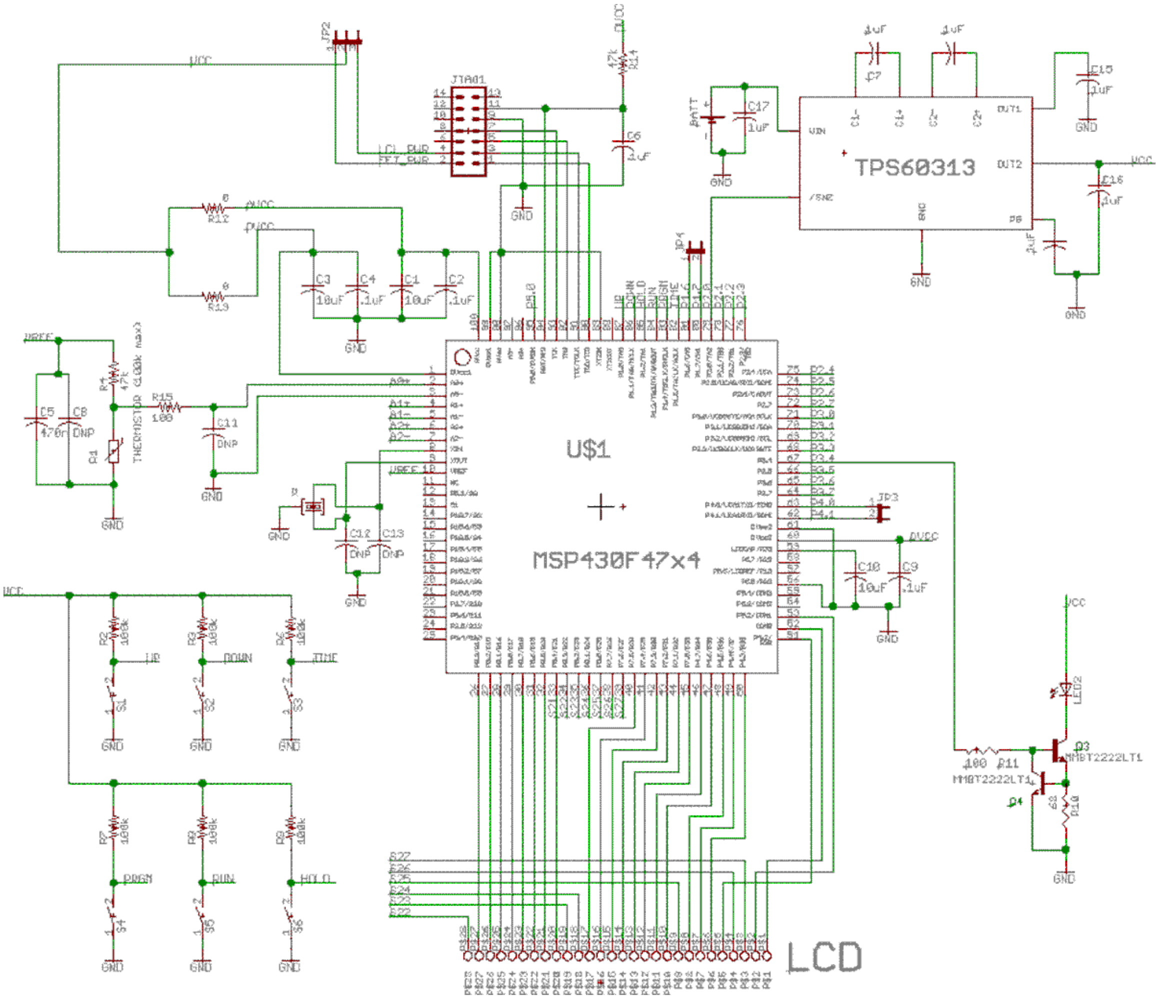

Figure 7. Single-Cell Thermostat Schematic

8 Conclusion

The expected battery lifetime for the MSP430 + TPS60313 single-cell thermostat is quite good with the worst case being about 4.5 years for a AAA battery and almost 13 years for a AA battery. In practice, the self-discharge rate of the battery limits the lifetime of the application more than the current consumption of the microcontroller + dc/dc converter. In conclusion, the TPS603xx family of dc/dc charge-pump converters is an excellent dc/dc converter solution, enabling single-cell MSP430 applications that can maintain very good low-power performance with excellent battery lifetimes.

9 References

1. MSP430F47x3, MSP430F47x4 Mixed-Signal Microcontrollers data sheet
2. Vishay 2322 640 3/4/6 thermistor data sheet
3. TPS60310, TPS60311, TPS60312, TPS60313 Single-Cell to 3-V/3.3-V, 20-mA Dual Output, High-Efficiency Charge Pump With Snooze Mode data sheet
4. Power Management Guide

Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from September 16, 2008 to August 6, 2018	Page
• Editorial and formatting changes throughout document	1
• Changed title of this document	1
• Removed former Section 3, *TI DC/DC Solutions*	3

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