

Low-Power Battery Voltage Measurement Using the On-Chip VREF and 10-Bit ADC of MSP430FR4xx and MSP430FR2xx MCUs

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ABSTRACT

MSP430™ MCUs have low power consumption characteristics, making them widely used in battery-powered products. To ensure the stability of the system power supply, this application report describes how to detect the power supply voltage. A low-voltage alarm is performed when the voltage is lower than the set safe power supply threshold. The traditional method of battery voltage detection is usually through a power supply voltage divider and sampling through the ADC to achieve detection. The voltage divider detection solution needs extra external circuits, which increases the system cost, volume and power consumption.

Based on the MSP430 FRAM series of MCUs, for the application of battery direct power supply, a scheme of low-power supply voltage detection is proposed, using the on-chip 10-bit ADC without an external voltage divider circuit. The verification results of the scheme are given.

Keywords: Low-power sampling, battery-powered

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1 Introduction

The 10-bit ADC module of MSP430FR2xx and MSP430FR4xx products is shown in [Figure 1](#). The ADC acquisition channel can directly sample the internal voltage reference (typically 1.5 V, see the data sheet for details), and the ADC reference voltage can be configured as the supply voltage. The ADC input channel detailed information can be found in the "ADC Channel Connections" table in the device data sheet. Configure the ADCINCHx bits in the ADCMCTL0 register as defined in the table to use a 1.5-V reference as the input voltage. The reference voltage for the ADC is configured as 000b for the ADCSREFx bits.

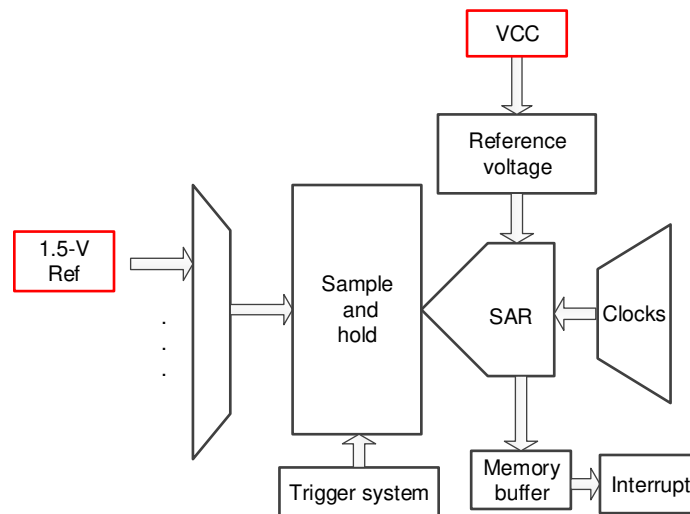


Figure 1. On-Chip Measurement of Battery Voltage Diagram

[Equation 1](#) shows how to calculate the 10-bit ADC conversion results.

$$N_{\text{ADC}} = 2^{10} \times \frac{V_{\text{in}} - V_{\text{R-}}}{V_{\text{R+}} - V_{\text{R-}}}$$

where

- N_{ADC} = ADC conversion results
 - V_{in} = Channel acquisition voltage
 - $V_{\text{R+}}$ = Reference voltage positive
 - $V_{\text{R-}}$ = Reference voltage negative
- (1)

Set V_{in} to the on-chip 1.5-V reference source, set $V_{\text{R+}}$ to V_{CC} , and set $V_{\text{R-}}$ to V_{SS} . [Equation 2](#) shows the formula to calculate the supply voltage.

$$V_{\text{CC}} = \frac{2^{10}}{N_{\text{ADC}}} \times 1.5 \text{ V}$$
(2)

Compared with the traditional solutions, on-chip ADC detection solution has the following advantages:

- **Power consumption:** the traditional method requires a peripheral voltage divider circuit, while the voltage divider circuit gives the system extra power consumption.
- **Cost:** the use of on-chip measurement method can save four resistors and a transistor; in addition, it can save 1 to 2 I/O resources.
- **Volume:** there is no peripheral voltage divider circuit that can reduce the size of the PCB for users.

2 ADC Low-Power Sampling Software Design

This document lists the main factors that affect power consumption with the on-chip ADC sample solution in MSP430FR4xx/FR2xx devices with 10-bit ADC. The power consumption results are given with different configurations. This example uses the 1.5-V internal reference voltage. Because the ADC trigger signal does not stop or start the 1.5-V internal reference voltage automatically, software can enable the 1.5-V REF and wait approximately 30 μ s before triggering the ADC in the RTC interrupt. Software can also stop the reference in the ADC conversion ready interrupt. The following test is based on this approach. Developers can optionally keep the internal reference enabled all the time at the expense of higher power consumption.

Some MSP430FR4xx and MSP430FR2xx devices have a 12-bit ADC with an internal reference voltage that can be turned on and off automatically during an ADC conversion. Besides this exception, the implementation of battery voltage measurement with these devices is similar to the devices with 10-bit ADC; however, implementation details are outside the scope of this document.

2.1 System Clock Source Selection

Two main MSP430 system clock sources are available: the internal 32-kHz low-frequency REFOCLK and the external crystal XT1CLK. [Table 1](#) compares the power consumption of the system clocks DCOCLK and ACLK using these clock sources. Using the external XT1CLK as the system clock source results in outstanding power consumption.

Table 1. Power Consumption With Different System Clock Source⁽¹⁾

Clock Source	REFOCLK	XT1CLK
Sampling frequency (Hz)	1	1
Power consumption (μ A)	19	1.2

⁽¹⁾ Experimental conditions:

1. Device uses a free running MCLK at 1 MHz
2. Test hardware is the MSP430FR4133 LaunchPad™ development kit
3. ADC clock source is SMCLK
4. LPM3 low-power mode
5. ADC sample hold time is 8 ADCCLK cycles
6. Unused pins are pulled down

2.2 ADC Clock Source Selection

The options for the 10-bit ADC clock source in MSP430 FRAM MCUs are MODCLK, ACLK, and SMCLK. In LPM3, MODCLK and SMCLK are disabled by default. An ADC conversion start signal can enable them and then automatically disable them again when the ADC conversion is complete. To highlight the differences between the power consumption with different clock sources, the sample rate is 100 Hz.

Table 2. Power Consumption Data of Different Clock Sources With XT1CLK in LPM3⁽¹⁾

ADC Clock Source	MODCLK (5 MHz)	ACLK (32 kHz)	SMCLK (5 MHz)
Sampling frequency (Hz)	100	100	100
Power consumption (mA)	0.131	0.184	0.026

⁽¹⁾ Experimental conditions:

1. Device uses a free running MCLK at 1 MHz
2. Test hardware is the MSP430FR4133 LaunchPad development kit
3. XT1CLK as the clock source
4. ADC sample hold time is 8 ADCCLK cycles
5. Unused pins are pulled down

2.3 Initialization of Unused GPIO Pins

Users can set corresponding bit in register PxREN to enable the on-chip pullup or pulldown resistor to avoid pin level be floating. [Table 3](#) lists the power consumption comparison data for these two cases:

Table 3. GPIO Pin Initialization Configuration Power Consumption Comparison⁽¹⁾

Unused GPIO	Unconfigured	Pulldown
Sampling frequency (Hz)	1	1
Power consumption (µA)	400	1.2

⁽¹⁾ Experimental conditions:

1. Device uses a free running MCLK at 1 MHz
2. Test hardware is the MSP430FR4133 LaunchPad development kit
3. XT1CLK as the clock source
4. LPM3 low-power mode
5. ADC sample hold time is 8 ADCCLK cycles
6. ADC clock source is SMCLK

3 ADC Error Correction and Experimental Testing

3.1 Error Correction

The use of on-chip ADC measurement of battery voltage, the error comes mainly from two aspects: ADC measurement error and 1.5-V reference voltage error. The data sheet shows calibration formulas for the measurement error of ADC and the error of 1.5-V reference voltage respectively.

However, the calibration factor used for the calibration of the 1.5-V reference is used only when 1.5 V used as the ADC reference. This calibration factor no longer applies when 1.5 V is used as an ADC input channel. Because 1.5 V is used as a reference voltage, it passes through a Reference Buffer, which is not available on the ADC input channel. In this case, calibrate only the ADC error.

[Equation 3](#) shows the formula to calibrate the ADC.

$$ADC_{\text{calibrated}} = ADC_{\text{raw}} \times \text{Factor}_{\text{gain}} \times \frac{1}{2^{15}} - ADC_{\text{offset}}$$

where

- $ADC_{\text{calibrated}}$ = calibrated value
- $\text{Factor}_{\text{gain}}$ = ADC gain calibration factor
- ADC_{offset} = ADC offset calibration factor

(3)

Because different series of calibration coefficients have different memory addresses, see the device-specific data sheet for the addresses of $\text{Factor}_{\text{gain}}$ and ADC_{offset} .

3.2 Accuracy Test

Table 4 lists the test data that uses the on-chip 10-bit ADC to detect supply voltage.

Table 4. Use the 10-Bit ADC to Measure the Supply Voltage Test Data⁽¹⁾

Power Supply (V)	ADC Raw	Without Calibration (V)	With Calibration (V)	Error (With Calibration)
2.562	597	2.570	2.569	0.27%
2.812	544	2.820	2.819	0.24%
3.327	461	3.328	3.327	0%

⁽¹⁾ Experimental conditions:

1. Test hardware is the MSP430FR4133 LaunchPad development kit
2. Factor_{gain} = 0x8011, ADC_{offset} = 0
3. Room temperature

4 Time-Division Multiplexing of the ADC to Achieve Additional Channel Acquisition

Because the battery voltage changes slowly, the battery voltage acquisition interval can be long. During idle time, the ADC can be used by software to acquire other analog signals. When measuring these other signals, the ADC can use the battery voltage as a reference voltage, which can increase the measurement range compared with 1.5-V reference. In addition, the 1.5-V reference voltage can be disabled to reduce power consumption. However, using the battery as a reference can result in lower accuracy that using the 1.5-V reference.

5 Summary

This document proposes a solution based on the MSP430FR4133 MCU that uses the on-chip 10-bit ADC to sample battery voltage. The solution can save costs, PCB volume, and system power consumption. This document also introduces low-power sampling software solutions and gives the consumption results in different scenarios. Finally, the measurement accuracy is calibrated and tested.

6 References

1. [MSP430FR4xx and MSP430FR2xx Family User's Guide](#)
2. [MSP430FR413x Mixed-Signal Microcontrollers](#)

Revision History

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

Changes from March 23, 2018 to November 4, 2019	Page
• Changed the document title.....	1
• Updated the text in Section 2 ADC Low-Power Sampling Software Design	3
• Changed the power consumption values and the experimental conditions in Table 1 Power Consumption With Different System Clock Source	3
• Changed all contents in Section 2.2 ADC Clock Source Selection	3
• Changed the power consumption values and experimental conditions in Table 3 GPIO Pin Initialization Configuration Power Consumption Comparison	4
• Deleted former section 2.4 <i>ADC Trigger Source Selection</i> and former section 2.5 <i>ADC Window Comparison Function</i> ...	4
• Updated Section 5 Summary	5

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