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 ADC without an external voltage divider circuit. The verification results of the scheme are given.

Keywords: Low-power sampling, battery-powered
Introduction

The ADC module of MSP430FR2xx and MSP430FR4xx products is shown as in Figure 1. It can be seen that 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.

Equation 1 shows how to calculate the ADC conversion results.

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

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

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

\[
V_{CC} = \frac{2^{10}}{N_{ADC}} \times 1.5 \text{ V}
\]

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. The power consumption results are given with different configurations.

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)

<table>
<thead>
<tr>
<th>Clock Source</th>
<th>REFOCLK</th>
<th>XT1CLK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling frequency (Hz)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Power consumption (mA)</td>
<td>0.0929</td>
<td>0.0752</td>
</tr>
</tbody>
</table>

(1) Experimental conditions: 1. EnergyTrace™ technology as power measurement tool, 2. MSP430FR4133 LaunchPad™ development kit as hardware, 3. ADC sampling triggered by RTC, 4. ADC clock source is ACLK, 5. MCLK clock source is DCOCLK, 6. LPM3.

2.2 ADC Clock Source Selection

MSP430 FRAM series ADC clock source options are MODCLK, ACLK, and SMCLK. As we known, high-frequency means high power consumption, but it is not useful in this case. The following data is in LPM0 and LPM3 combined with hardware experimental results given the well choice of the clock:

• In LPM0, according to the data in Table 2, MODCLK will have lower power consumption to be ADC clock source.

Table 2. Power Consumption Data of Different Clock Sources With XT1CLK in LPM0

<table>
<thead>
<tr>
<th>ADC Clock Source</th>
<th>MODCLK (5 MHz)</th>
<th>ACLK (32 kHz)</th>
<th>SMCLK (5 MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling frequency (Hz)</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Power consumption (mA)</td>
<td>0.2533</td>
<td>0.2672</td>
<td>0.2536</td>
</tr>
</tbody>
</table>

• In LPM3, while MODCLK and SMCLK are disabled by default, they can also work if they are used as the ADC clock source. Because MODCLK or SMCLK can be started automatically when ADC is triggered as ADC clock source. And they will be closed when the ADC conversion is completed (see the MSP430FR4xx and MSP430FR2xx Family User's Guide for details). Table 3 lists MODCLK as ADC clock will have lower power consumption in this condition.

Table 3. Power Consumption Data of Different Clock Sources With XT1CLK in LPM3(1)

<table>
<thead>
<tr>
<th>ADC Clock Source</th>
<th>MODCLK (5 MHz)</th>
<th>ACLK (32 kHz)</th>
<th>SMCLK (5 MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling frequency (Hz)</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Power consumption (mA)</td>
<td>0.0754</td>
<td>0.0873</td>
<td>0.0757</td>
</tr>
</tbody>
</table>

(1) Experimental conditions: 1. EnergyTrace technology as power measurement tool, 2. MSP430FR4133 LaunchPad development kit as hardware, 3. ADC sampling triggered by RTC.
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 4 lists the power consumption comparison data for these two cases:

Table 4. GPIO Pin Initialization Configuration Power Consumption Comparison(1)

<table>
<thead>
<tr>
<th>Unused GPIO</th>
<th>Unconfigured</th>
<th>Pulldown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling frequency (Hz)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Power consumption (mA)</td>
<td>0.7033</td>
<td>0.0929</td>
</tr>
</tbody>
</table>

(1) Experimental conditions: 1. EnergyTrace technology as power measurement tool, 2. MSP430FR4133 LaunchPad development kit as hardware, 3. Unused GPIO number is 59, 4. ADC sampling triggered by RTC, 5. LPM3.

2.4 ADC Trigger Source Selection

The ADC of MSP430 family MCUs can operate in multiple operating modes and support the trigger sampling mode. The trigger sampling mode can make the ADC in lower power consumption state. The following experiment with ADC contrast different sources of power consumption data in Table 5.

Table 5. ADC Power Consumption With Different Trigger Sources(1)

<table>
<thead>
<tr>
<th>ADC Trigger</th>
<th>RTC</th>
<th>TimerA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-power mode</td>
<td>LPM0</td>
<td>LPM0</td>
</tr>
<tr>
<td>Trigger clock source</td>
<td>SMCLK (1 MHz)</td>
<td>SMCLK (1 MHz)</td>
</tr>
<tr>
<td></td>
<td>LPM3</td>
<td>VLOCLK</td>
</tr>
<tr>
<td></td>
<td>LPM3</td>
<td>ACLK</td>
</tr>
<tr>
<td>Power consumption (mA)</td>
<td>0.2554</td>
<td>0.2569</td>
</tr>
<tr>
<td></td>
<td>0.075</td>
<td>0.075</td>
</tr>
</tbody>
</table>

(1) Experimental conditions: 1. EnergyTrace technology as power measurement tool, 2. MSP430FR4133 LaunchPad development kit as hardware, 3. ADC sampling frequency is 1 Hz, 4. System clock source is XT1, 5. ADC clock source is ACLK.

The above data shows that the power consumption of the two trigger sources is comparable, but the RTC trigger has the following two advantages with clock source of VLOCLK (10 kHz):

- The VLOCLK can be combined with the RTC clock divider to extend the overflow interrupt period to 1.8 hours (TimerA has a maximum overflow interrupt time of 2 minutes with clock source of ACLK).
- The VLOCLK can operate in LPM3.5 mode. It is suitable for applications with longer sampling intervals due to the wake up the CPU once per sample triggered.

2.5 ADC Window Comparison Function

The MSP430 ADC also features window comparison. In this mode, you can set a threshold that wakes up the CPU for processing when the ADC sample value across the threshold.

In summary, according to the system application to flexibly set the MCU operating mode, system clock, ADC mode of operation and reference clock source, you can greatly optimize the ADC sampling power consumption.

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.

\[ \text{ADC}_{\text{calibrated}} = \text{ADC}_{\text{raw}} \times \text{Factor}_{\text{gain}} \times \frac{1}{2^{15}} - \text{ADC}_{\text{offset}} \]

where
- \( \text{ADC}_{\text{calibrated}} \) = calibrated value
- \( \text{Factor}_{\text{gain}} \) = ADC gain calibration factor
- \( \text{ADC}_{\text{offset}} \) = ADC offset calibration factor

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 \( \text{ADC}_{\text{offset}} \).

3.2 Accuracy Experiment Test

Table 6 lists the test data that uses on-chip ADC to detect supply voltage.

<table>
<thead>
<tr>
<th>Power Supply (V)</th>
<th>ADC Raw</th>
<th>Without Calibration</th>
<th>With Calibration (V)</th>
<th>Error (With Calibration)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.562</td>
<td>597</td>
<td>2.570</td>
<td>2.569</td>
<td>0.27%</td>
</tr>
<tr>
<td>2.812</td>
<td>544</td>
<td>2.820</td>
<td>2.819</td>
<td>0.24%</td>
</tr>
<tr>
<td>3.327</td>
<td>461</td>
<td>3.328</td>
<td>3.327</td>
<td>0%</td>
</tr>
</tbody>
</table>

(1) Experimental conditions: 1. Test hardware is MSP430FR2311 LaunchPad development kit, 2. \( \text{Factor}_{\text{gain}} = 0\times8011 \), \( \text{ADC}_{\text{offset}} = 0 \), 3. Room temperature.

4 Time-Division Multiplexing ADC to Achieve Other Channel Acquisition

The ADC can also be used as an acquisition for other analog signals when using the ADC as a battery voltage acquisition function. Because battery voltage changes slowly, the battery voltage acquisition interval can be long. During idle time, the ADC can be used by the user to acquire other analog signals. And the use of battery voltage as a reference voltage, it can increase the measurement range compared with 1.5-V reference. What’s more, it can cut off 1.5-V reference voltage to reduce power consumption. But the accuracy may be lower than 1.5-V reference.

5 Summary

This article proposes direct use of on-chip ADC sampling battery voltage solution based on the MSP430FR MCU. The solution can save user’s costs, PCB volume, and system power consumption. What’s more, it introduces the low-power sampling design in detail and gives the experimental results in different scenarios. Finally, the measurement accuracy is calibrated and tested.

6 References

2. MSP430FR413x Mixed-Signal Microcontrollers
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