AVR353: Voltage Reference Calibration and Voltage ADC Usage

Features

- **Voltage reference calibration.**
  - **1.100V +/-1mV (typical) and < 90ppm/°C drift from –10°C to +70°C.**
- **Interrupt controlled voltage ADC sampling.**
- **Calculation of voltage and temperature from voltage ADC measurements.**

1 Introduction

Some of the new Atmel AVR® Smart Battery devices contain a very accurate low power bandgap voltage reference which when calibrated correctly has less than 90ppm/°C drift from –10°C to +70°C and absolute accuracy of typically +/-1mV. This is the reference used for the internal Voltage ADC and Coulomb Counting ADC. ATmega16HVA and ATmega406 are examples of devices featuring this.

To achieve the high accuracy, the reference has to be calibrated according to the algorithm described in this application note. For some devices this calibration is done at the Atmel factory and the results are stored in the signature row. Calibration is then just a matter of reading out the data and storing it in relevant registers. Both methods are demonstrated in this application note.

The devices that have an internal 12-bit sigma delta Voltage ADC feature inputs with pre-scaling to enable sampling Li-Ion cell voltages directly, but also other inputs without pre-scaling to enable sampling of the internal temperature sensor, external thermistors or other inputs. When the bandgap reference is calibrated and by using gain and offset data stored in the device's signature row Atmel guarantee accuracy better than 0.5%. A demonstration of resulting V-ADC measurement after calibration, and calculated results, is included in this application note. For details on use of the Coulomb Counter ADC please see application note AVR352.

2 Theory of operation

To achieve the specified accuracy the bandgap voltage reference must be calibrated using the algorithm described in this application note. The algorithm specifies measuring the voltage reference externally and then adjusting the voltage reference registers, but calibration can also be performed using the internal Voltage ADC to measure an external voltage reference as demonstrated in this application note. In the case of Atmel factory calibrated part, calibration is simply reading out the signature data and storing them in the right registers. This application note checks if such data exists and if they exist, uses them instead of running the calibration algorithm.

2.1 Signature byte reading

The signature row in the smart battery devices contains comprehensive data that can be used for calibration of various modules and calculations for ADC results. See the datasheet of the relevant device for a complete summary. The data can be read out runtime with the LPM instruction by setting the SIGRD and SPMEN bits in SPMCSR, as demonstrated in this application note.

2.2 Voltage ADC measurements

Both the proposed calibration algorithm, as well as normal operation, is dependant on accurate Voltage ADC measurements. To obtain the best possible results of Voltage ADC measurements, data for gain and offset is measured at Atmel Factory and stored in the device signature row. These are used in calibration if performed, and subsequent Voltage ADC measurements.

2.2.1 Cell measurements

The cell inputs feature a scaling of approximately 0.2x, enabling measurement of Li-Ion cells directly. The gain factor together with the offset ensures that measurements can be converted to actual input voltages in mV with very high accuracy. The formula is given in Equation 2-1.

Equation 2-1. VADC Cell voltage calculation

$$Cell_n[mV] = \frac{(VADC - VADC\,Cell_n\,Offset)*VADC\,Cell_n\,Gain\,Cal\,Word}{16384}$$

2.2.2 ADC inputs

The standard VADC inputs does not feature pre-scaling, but a formula similar to the cell voltages is used as seen from Equation 2-2. These inputs are proposed used for measurements of thermistors but can also be used for other tasks including calibration if desired.

Equation 2-2. VADC input voltage calculation

$$VADC_n[mV] = \frac{10*(VADC - VADC_n\,Offset)*VADC_n\,Gain\,Cal\,Word}{16384}$$

2.2.3 Temperature measurements

The bandgap reference circuit features a voltage that is proportional to absolute temperature, which can be used to measure chip temperature. Calculation of actual temperature is shown in Equation 2-3. The temperature can be used to calculate the Slow RC Oscillator period for calibration of system clocks, as shown in application note AVR351. It could also be used for measuring system temperature.

Equation 2-3. Temperature calculation

$$Temperature[K] = \frac{(VADC) * VADC\ Temperature\ Calibration\ Word}{16384}$$

The stated accuracy for the temperature sensor is +/-5 K accuracy, but this is to be determined definitively.

2.3 Voltage reference

The voltage reference is an internal low power bandgap reference that is used as reference for the On-chip Voltage Regulator, the V-ADC and the CC-ADC, so all ADC measurements are dependant on the reference being correctly calibrated. It should be calibrated to 1.100V +/-1mV by adjusting the Bandgap Calibration R Register (BGCRR) and Bandgap Calibration C Register (BGCCR) according to the algorithm given in section 2.3.1.

BGCRR is used for temperature gradient adjustment. Figure 2-1 illustrates VREF as a function of temperature. It has a positive temperature coefficient at low temperatures and negative temperature coefficient at high temperatures. Depending on the process variations, the top of the VREF curve may be located at higher or lower temperatures. BGCRR is used to adjust the curve to minimize the temperature drift in the temperature range of interest. The bits are thermometer coded, resulting in 9 possible settings: 00000000, 00000001, 00000011, 00000111, … , 11111111.

Figure 2-1. Voltage reference as function of temperature.
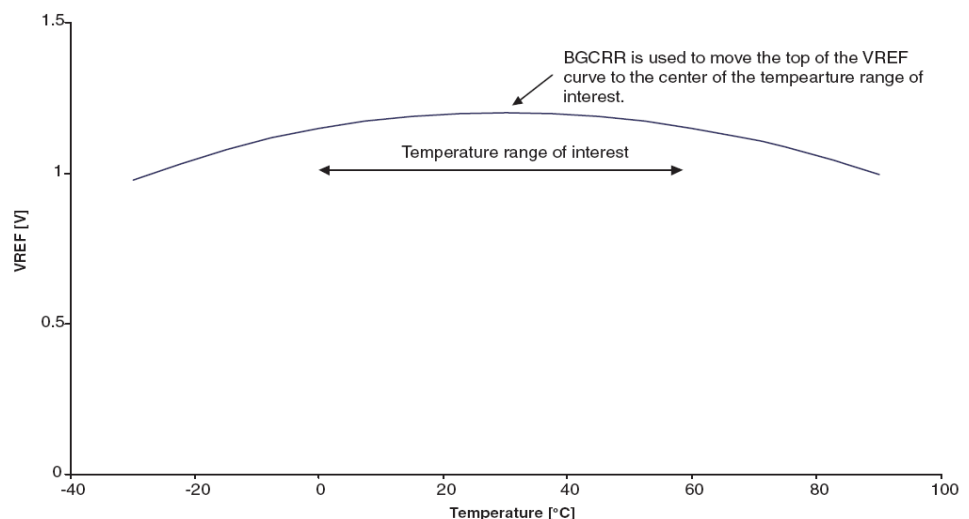
BGCCR is used for fine-tuning the reference voltage. The six lowest bits are used (bit 5 to 0) and step size is approximately 2mV. Care must be exercised when changing BGCCR as it adjusts both the BOD and VREG level. The BOD value changes quickly, while the VREG changes more slowly due to the external capacitor, and a false BOD condition might occur. To allow the voltage regulator to reach the new level between each step, a delay of 20 µs should be added between each update of the BGCCR values with the recommended CREG of 2.2uF.

2.3.1 Calibration algorithm

The calibration of the voltage reference is done in two steps. The first step is always conducted at Atmel factory at T_{HOT} temperature (70°C/85°C):

1. BGCRR = 0x0F and BGCCR is adjusted until Vref is 1.100 V.

The next steps are conducted at room temperature, either when the device board is tested, or in a second insertion at Atmel factory. The steps are:

2. BGCRR = 0x0F and BGCCR = value found in previous test (stored in signature row).

3. Measure Vref and adjust BGCRR according to Table 2-1:

Table 2-1. Selected BGCRR versus VREF deviation at room temperature.

VREF@room - VREF@HOT°C low limit [mV]	VREF@room- VREF@HOT°C high limit [mV]	Selected BGCRR
-infinite	-3.0	0xFF
-3.0	-2.0	0x7F
-2.0	-1.0	0x3F
-1.0	0.0	0x1F
0.0	2.5	0x0F
2.5	5.5	0x07
5.5	8.0	0x03
8.0	10.0	0x01
10.0	+infinite	0x00

4. Adjust BGCCR until Vref is 1.100V.

Depending on the calibration being correctly carried out, the reference is now guaranteed to have less than 90ppm/°C drift from −10°C to +70°C.

2.3.2 Calibration in Atmel factory

If the device has been calibrated at a second insertion in Atmel Factory, it is done according to the above algorithm. The results of the calibration are stored in the signature row, where they can be read out runtime for easy calibration of the voltage reference.

2.3.3 Calibration against external reference

By using an external reference and the internal Voltage ADC the VREF can be calibrated according to the algorithm without external measurement equipment. If the internal reference is correct the measurements will also be correct, but if the internal reference is different from 1.100V the result will differ. The relationship is given in Equation 2-4.

Equation 2-4. Calculated external reference voltage given wrong internal VREF.

$$Measured\ value = Expected\ value * \frac{Ideal\ VREF\ (1.100V)}{Actual\ VREF}$$

A reference of 4096mV is proposed used as input on Cell1 (PV1), as it is in the middle of the most relevant voltage range of Li-Ion cells thus ensuring maximum accuracy, and also because of availability. Alternatively 4096 / 5 mV is used as input on ADC0, but other voltages and inputs may also be used for calibration. Equation 2-1 or Equation 2-2 is used for calculating the "Measured value".

By using Equation 2-4 with 4096mV and inserting values from Table 2-1 we will get the results shown in Table 2-2.

Table 2-2. Selected BGCRR with measurements of 4096mV external reference.

VREF difference low limit [mV]	VREF difference high limit [mV]	Measured Voltage @ 4096mV input [1]	Difference from ideal	Selected BGCRR
-infinite	-3.0	4107	11	0xFF
-3.0	-2.0	4103	7	0x7F
-2.0	-1.0	4100	4	0x3F
-1.0	0.0	4096	0	0x1F
0.0	2.5	4087	-9	0x0F
2.5	5.5	4076	-20	0x07
5.5	8.0	4066	-30	0x03
8.0	10.0	4059	-37	0x01
10.0	+infinite	Infinite	Infinite	0x00

Notes: 1. VREF difference high limit is used.

Alternatively some devices provide a Cell1 raw measurement that was the actual Cell1 measurement in production with 4096mV applied. By using this value one can avoid a 16-bit multiplication and a subtraction, but needs to use a 4096mV reference and a typical Cell1 raw values thus reducing accuracy slightly. The calibration values are still calculated using Equation 2-4, but with inserting the typical ADC raw values (can be found in the source code).

3 Code examples

This application note contains source code that can be downloaded with the application note from Atmel AVR web, http://www.atmel.com/products/avr/. The complete source documentation, including compiler information can be accessed by opening readme.html. The source doesn't provide any visual feedback and must be debugged with e.g. a JTAGICEmkII and watching variables.

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