Electrical current measurement system for energy harvesting applications

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Abstract. The measurement of the dynamic power consumption is an important task in the field of energy harvesting regarding the characterization and optimization of low power systems. This paper reports on the development and characterization of a computer-controlled measurement system for the measurement of the dynamic current consumption of low power systems in a range from 100 nA to 100 µA, with a time resolution down to 1 µs.

1. Introduction

From a deterministic point of view there is a general rule: “The better a system is understood, the more it can be improved”. In energy harvesting, a system first of all is “better” if it is thoroughly optimized for minimum power consumption, which secondly leads to maximum functionality, reliability and availability. To achieve this, the power consumption, i.e. the current draw of an electronic circuit has to be well known, which typically is an easy task by measuring current with a multimeter. However, the current consumption of low power circuits and of embedded systems is not constant over time from several reasons: First, to increase power efficiency, only the circuit parts used for the current task are powered, while unneeded parts are turned off or set into a sleep mode. Second, the system itself shows a high dynamics in power consumption, with e.g. a low current draw for sensing and a significantly higher current draw for wireless communication. Such a change in power consumption will happen rapidly, i.e. within microseconds, and potentially over a large range of supply current.

Astonishingly, currently there is no commercial measurement system available that can perform a real-time current measurement analogous to an oscilloscope for small currents in the microampere range. Most suitable for this task is the picoammeter B2980A from Keysight with a maximum sample rate up to 20 kHz which is by far too low to detect, for example, the readout of a sensor or a short-time - but high power - wireless data transmission [1]. Another approach is the EnergyTrace™ Technology developed by TI for their microcontroller platforms. By deriving the clock rate and the number of cycles of the switching signal of a buck-converter integrated in the debug-interface they calculate the power consumption for a logging period up to 5 min [2]. However, this system has to be powered by the debug interface, therefore self-sufficient systems cannot be analysed, as well as the power consumption of individual parts of the circuit cannot be measured. In this research, we present a system, which bridges all these gaps, and allows for measurement of all single components in a typical wireless energy-autonomous embedded system with a time resolution of up to 10 µs for currents from 0.1 µA to 100 µA.
2. Concept and preliminary considerations

2.1. Hardware concept

The goal of the project was the development of a low-cost measurement system, which is able to measure the dynamic power consumption of an embedded system in a range from 100 nA to 100 µA with a resolution of 1 µs. To achieve a simple system operation, the device should be controlled by a computer to enable an efficient post-processing of the data and the possibility of automated long-term measurements. The measurement principle of the system is identical to that of a multimeter, i.e., the measured current is derived from the voltage drop over a current sense resistor put in series to the investigated electronic circuit, by applying Ohm’s law. To minimize the effect of a decreasing current consumption with decreasing supply voltage, respectively to maintain the proper functioning of the device under test, the measurement system is designed such, that the voltage drop over the sense resistor does not exceed a voltage of 10 mV. To evaluate such small voltage drops at the sense resistor the signal has to be amplified. The sense resistor is located at the high-side of the power supply chain, in order to prevent errors in the device under test from different ground levels. Therefore, the current sense amplifier needs a high common mode rejection ratio (CMRR) which is guaranteed by using an instrumentation amplifier.

A high resolution over the whole measurement range from 100 nA to 100 µA is achieved by splitting the measurement range into three ranges (see figure 1). To switch between the ranges, the total value of the current sense resistor is changed dynamically via two relays. The highest resistor value is always connected to the amplifier as a load, to protect the inputs from high voltage peaks, and further resistors are connected in parallel to decrease this value as required. As a safety feature a reverse voltage protection is implemented by a symmetric supply of the amplifier, which also allows the measurement of negative currents, but with half of the resolution.

2.2. Interpretation of dynamic measurement results

One problem of dynamic current measurements is, that any amplifier typically shows a low-pass behavior, in combination with a limited slew rate. Both factors lead to a specific rise and fall time of the output signal, during which the measure of the output current is incorrect. On the other hand, an embedded system controlled by an internal microcontroller tends to show a stepped current consumption with a staircase-like behavior. Therefore, to minimize errors induced by the current sense amplifier, an averaged current approach can be used. For this, the energy present in a staircase step of the current curve can be calculated by integration of the current sense amplifier’s output signal over time. A requirement to apply this method is an identical positive respectively negative slew rate of this amplifier.
3. Circuit design

The core of the measurement circuit is a low-noise instrumentation amplifier with a low offset voltage and a sufficiently high slew rate to guarantee high signal fidelity. Moreover, the amplifier should have a high input impedance to minimize measurement errors introduced by the input offset currents of the amplifier. The best accordance to these requirements shows the monolithically integrated instrumentation amplifier INA217 from TI. At a gain of 100, the amplifier shows an appropriate bandwidth of 800 kHz, a slew rate of 15 V/µs, a CMRR of 116 dB, a moderate input offset current of 100 nA and a maximum input offset voltage of 300 µV [3]. Since an input offset voltage of 300 µV already introduces a measurement error of 3%, the offset voltage needs to be compensated. This can be achieved by adjusting the voltage at the REF-pin of the amplifier. In order to maintain the good ease of use, the circuit should perform the offset compensation automatically, which is realized with a microcontroller MSP430F5529 from TI. The controller measures the offset voltage with its internal ADC and sets an appropriate compensation resistance using a MAX5481 (Maxim Integrated) digital potentiometer (see figure 2). Thereby, a theoretical resolution of 39 µV can be achieved. As the offset voltage is by an order of 100 smaller than the output voltage of the instrumentation amplifier, it is again amplified by a factor of 40 with a chopper-stabilized operational amplifier (TLC2652, TI), showing a maximum offset voltage of 0.5 µV, to take benefit of the whole input range of the ADC. To prevent the amplifier from saturation during a measurement, a relay is used to disconnect the offset measurement circuit.

For digitizing the instrumentation amplifier’s output signal, a 12-bit ADC (MAX11108, Maxim Integrated), is used. This ADC is controlled via an SPI interface and capable of sampling up to 3 million times per second. Due to the unipolar input of the ADC, the output signal of the instrumentation amplifier must be shifted by half of the reference voltage using a precise voltage divider together with low offset operational amplifier (OPA2333, TI) as a buffer. The digital resolution (LSB) is therefore decreased to 610 µV at a reference voltage of 2.5 V.

4. Measurements results

4.1. DC Measurements

In a first measurement series, the transfer function of the circuit was characterized. Therefore, DC currents in a range from 100 nA to 100 µA generated by a sourcemeter (Keithley 2450) were applied and the output voltage was measured with a multimeter (Agilent U1252B). As expected, a linear transfer characteristic with different slopes depending on the measurement ranges (see figure 3) could be determined with an $R^2 > 0.999$.

![Figure 3](image-url). Output voltage of the measurement system as a function of positive input currents for the three measurement ranges.

![Figure 4](image-url). Current course (black) recorded with the ADC at a sample rate of 500 kHz for a dummy load (red) toggling between 0 µA, 4 µA and 8 µA.
To test the compensation of the offset voltage, the output voltage of the amplifier was measured five times with the multimeter before and after the automated offset compensation. Over the five measurements the initial offset voltage could be reduced from 8.48 mV to a maximum offset voltage of 84.0 µV. As this voltage represents only 13.8% of the LSB, the error caused by the offset voltage can be neglected.

A further error source is related to the input common mode voltage which cannot be perfectly suppressed by the amplifier. To determine this error, a voltage signal with a differential voltage of 5 mV and a variable common mode voltage varying between 0 V and 3 V was generated with the two outputs of a function generator (Agilent 33500B). With increasing common mode voltage a decrease of the amplified differential voltage could be detected. Considering the measurement at 0 V common mode as a reference, a maximum error of 1.37 % (mean 0.76 %) in the output signal is measured at a common mode voltage of 3 V.

4.2. AC Measurements

To determine the error related to the rise and fall time of the amplifier, rectangular pulses generated by the function generator, with an amplitude of 5 mV at a common mode voltage of 0 V were applied to its input. The output signal was recorded with an oscilloscope (Tektronix TDS2024B) and post processed in MATLAB. As expected, the error increases with the increasing influence of the rise and fall time. Up to a pulse length of 10 µs the error stays below 4 %, and for pulses up to 1 µs it is still below 7 %.

The function of the ADC was tested by applying a dummy load drawing a current between 0 µA and 4 µA respectively approx. 8 µA for different time intervals. The ADC is sampled with a frequency of 500 kHz. As the recorded current course in figure 4 shows, the signal is of low noise and depicts the course of the real current consumption.

5. Conclusion and outlook

This paper reports the development of a measurement system for the measurement of the dynamic current consumption of low power circuits in a range from 100 nA -100 µA (see figure 5). The implementation of an automated offset compensation with a maximum error of 13.8% of the LSB and a LabVIEW user interface leads to a system with a high ease of use. With a price of only 50 € for the electronic components and the housing, the system is affordable to everyone. For dynamic current measurements, an error of less then 4% is achieved for pulses of up to 10 µs, and an error less than 7% for pulses up to 1 µs.

For the future a real time measurement function is planned, which makes use of the internal USB interface of the microcontroller. However, the interface only supports USB 2.0 Full speed. The expected sample rate is therefore limited to 500 kHz for a 12-bit resolution and can probably be increased to 1 MHz by decreasing the resolution to 8-bit [3]. Furthermore, a digital compensation of the limited system bandwidth is envisaged via means of digital signal processing.

References

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