Current Measurement Sampling Rate

Why Sampling Rate (and Bandwidth) Matters

After reading this whitepaper you should appreciate why sampling rate and bandwidth are important requirements to making accurate current measurement of battery powered devices.

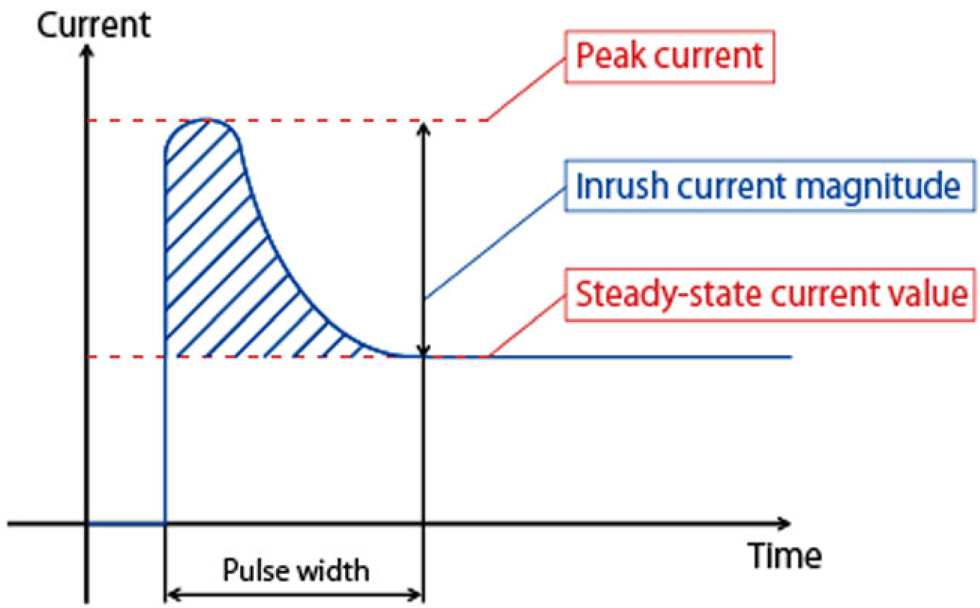
Measuring voltage with contemporary digital oscilloscopes (DSOs) has made us take for granted the very high sampling rates these (inexpensive) tools provide. >1GHz sampling rates and >100MHz analog bandwidths are common. Most battery powered embedded designs operate well under those frequencies, and we don't even think twice about measuring the I2C bus signals, which might be 400KHz.

Current measurement solutions are more difficult to design and therefore don't offer excessive sampling rates or bandwidth. One needs to understand the measurement limitations given these restrictions.

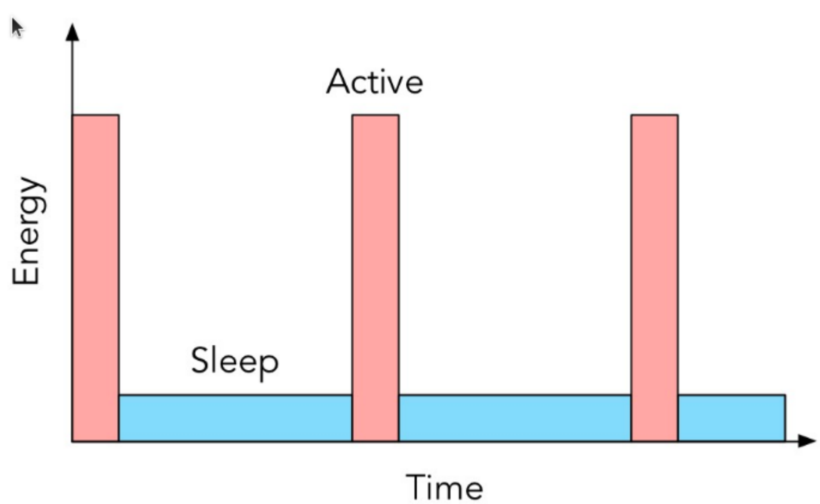
What to Expect with Embedded Current Profile

Contemporary Battery powered designs employ several circuit techniques to maximize battery life. Let's consider three common techniques and what the impact is on the current (time domain) profile.

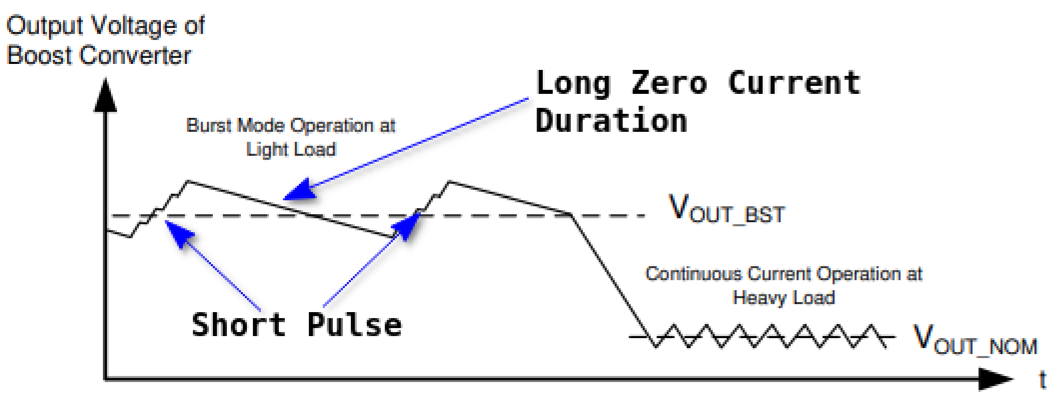
The first technique is "power gating". Power gating is when a portion of the circuit (a sub-circuit) is turned off when it is not in use. Consider a radio module that is only turned on once a day to send a payload. Or perhaps it's a sensor that is only powered when it takes a measurement. Power gating is typically done with a Linear Drop Out (LDO) regulator integrated circuit (IC) that has an enable input. The amount of time that the sub-circuit is powered will depend on its function. A simplified current profile of a power gated sub-circuit is a square wave with a duty cycle. This is a simplified profile because we are not considering what the dynamic current of that sub-circuit might be. It's also simplified because when a sub-circuit is initially powered on, there will be an "in-rush" current that charges up the sub-circuit decoupling capacitors. At time zero (when the sub-circuit) turns on, that current can be very high requiring a high dynamic measurement range, and it tapers off as the capacitors charge. The pulse width of the in-rush current is typically very short.



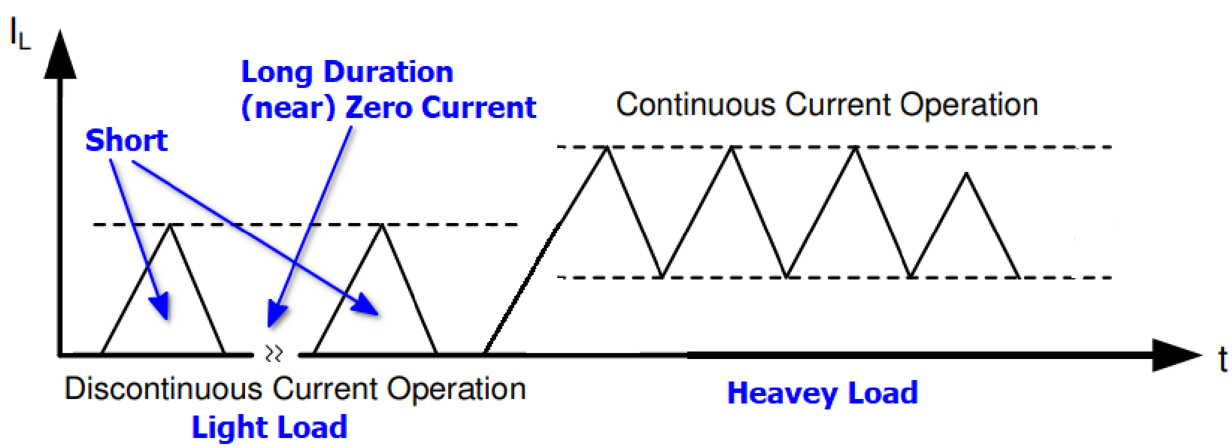
The second technique is “clock gating” that happens within the embedded microcontroller. Microcontrollers may have various levels/modes of “standby”, or “sleep” and “deep sleep”, which are generally various states of enabled clocks within its internal “clock tree”, controlled by software. For example, the ARM microcontroller architecture supports (when enabled with appropriate software) turning off the main MCU clock when there is no pending work to be done. The MCU clock can be re-enabled based on a timer, or an external interrupt. The result is that the current profile of the microcontroller will look like a square wave as the MCU transitions between these internal states. The microcontroller may also implement “power gating” to internal peripherals.



The last technique that will be mentioned is that of Switched Mode Power Supplies (SMPS) that implement Pulse Skipping/Burst Modes. In a previous whitepaper (a10-MAR-DDR_BatteryLife201_01) it was shown how these power ICs can improve the battery life of a design and they are very common in contemporary designs. In brief, historical SMPS, under light loads had poor efficiency due to their Pulse Width Modulation (PWM, continuous mode) design. Given that an embedded design would like to have a "light load" most of the time, it became prudent that SMPS ICs implement new tech to improve efficiency at light loads. The result is Pulse Skipping/Burst Mode which typically takes the SMPS out of (continuous) PWM mode to a mode that monitors voltage. When the output voltage drops below a certain value (V_{OUT_BST}), the SMPS kicks the output back up. If the output voltage drops below another value (V_{OUT_NOM}), it will revert back to PWM (continuous) mode. This picture describes these states,



As shown in the next diagram, when the SMPS kicks the voltage, there is a corresponding short duration current pulse, and the current in between short pulses is (near) ZERO.



When the SMPS is in Pulse Skipping/Burst mode, the time it takes the voltage to drop to V_{OUT_BST} is dependent on the circuit load, and can be quite large… ten to hundreds of milliseconds, during which time the current is (near) ZERO. Yet the current spike to pump the voltage may be very fast, on the order of 1-2 milliseconds, and >1mA.

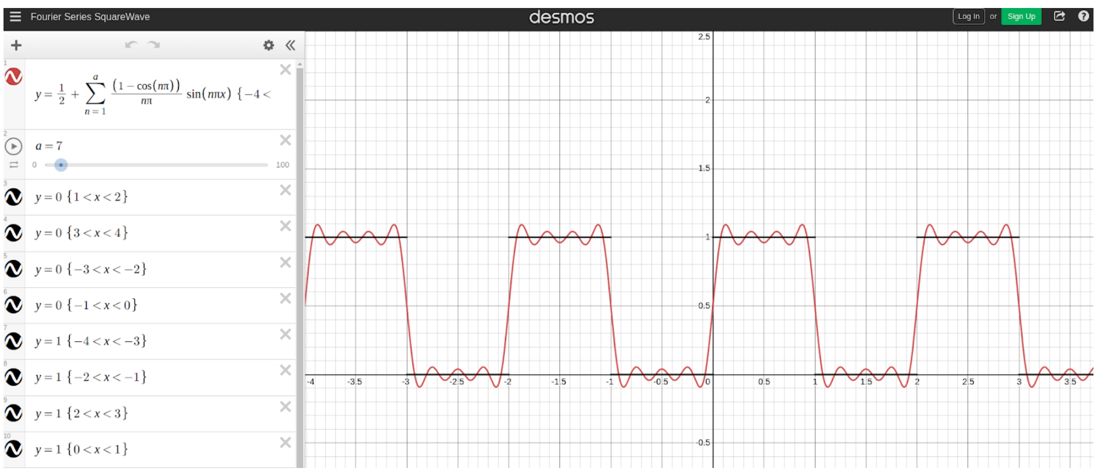
Thus the current profile will look like a short duration pulse followed by a long "no current" duration (see the picture above). The frequency content of such a waveform is very high, because the pulse current is very short. At low currents, all the current the DUT is consuming is in that short duration pulse. If the measurement system can't sample that pulse sufficiently, the measurement will be inaccurate.

All the techniques described above result in the requirement of the current measurement tool to be able to sample the active, or "on", state current with enough samples to accurately integrate that current in order to predict battery life. Undersampled time domain signals will give inconsistent results.

Nyquist Sampling Theorem

A bandlimited continuous-time signal can be sampled and perfectly reconstructed from its samples if the waveform is sampled over twice as fast as its highest frequency component.

Everything is a sine wave, even a square wave. Try this interactive demo.



A square wave is a sum of sine waves at every odd harmonic. If the above square wave was 1KHz, then it would be the sum of sine waves of 1KHz, 3KHz, 5KHz, 7KHz, etc… to infinity. The above plot shows 7 harmonics, thus 13KHz to represent that 1KHz square wave.

The point here is that if we think of the embedded current profile in simple terms of current being turned on/off like a square wave, then to properly sample that square wave, we need as much sampling rate as possible to accurately measure it.

If for example a microcontroller is turning on for 0.5 ms every 1 second, that pulse has an equivalent frequency of 1KHz, and thus to properly measure it, we will need a sampling rate >5KHz.

When you play with the online demo, notice the rise time of the leading (or falling) edge of the square wave. Notice that as harmonics (bandwidth) are added, the faster that edge is. This demonstrates the relationship between bandwidth and the ability to measure that edge.

Digital Multimeters

When it comes to measuring current, the most common test equipment we have at hand is the digital multimeter (DMM). Most DMMs, whether handheld or benchtop, allow one to measure current by having the power lead connect thru the DMM. The DMM has a (current) sense resistor and calculates the current via Ohm's Law (V = I * R). The approach of using a sense resistor to measure current has the downside of “burden voltage”, which is the voltage drop across that sense resistor, which may or may not affect the device under test (DUT). Do an internet search on “burden voltage” to learn more about it as it is also important but beyond the scope of this paper.

The other factor to be aware of with using a DMM to make a current measurement is the sampling rate of the DMM. Most DMMs display the current as a number to the user updated at ~1Hz. The DMM will have an internal sampling rate, which is common to be less than 1KHz, more common is 1-100 Hz sampling rates. Check the specs of your DMM, determine what the sampling rate is. And also make note of the analog bandwidth.

The profile of the current for your device under test (DUT) may or may not be measurable by the DMM. At one end of the spectrum the load might simply be a resistor, and there is no dynamic activity of the current. In this case the current is DC, and certainly a DMM can characterize it.

However, if the DUT is an embedded processor, that is in standby most of the time, but turns on every 1 second for 1ms to update a tic counter, then there is no way a DMM will be able to measure that. The DMM will undersample that current, and report a lower value compared to the true value.

What is the value of an undersampled signal?

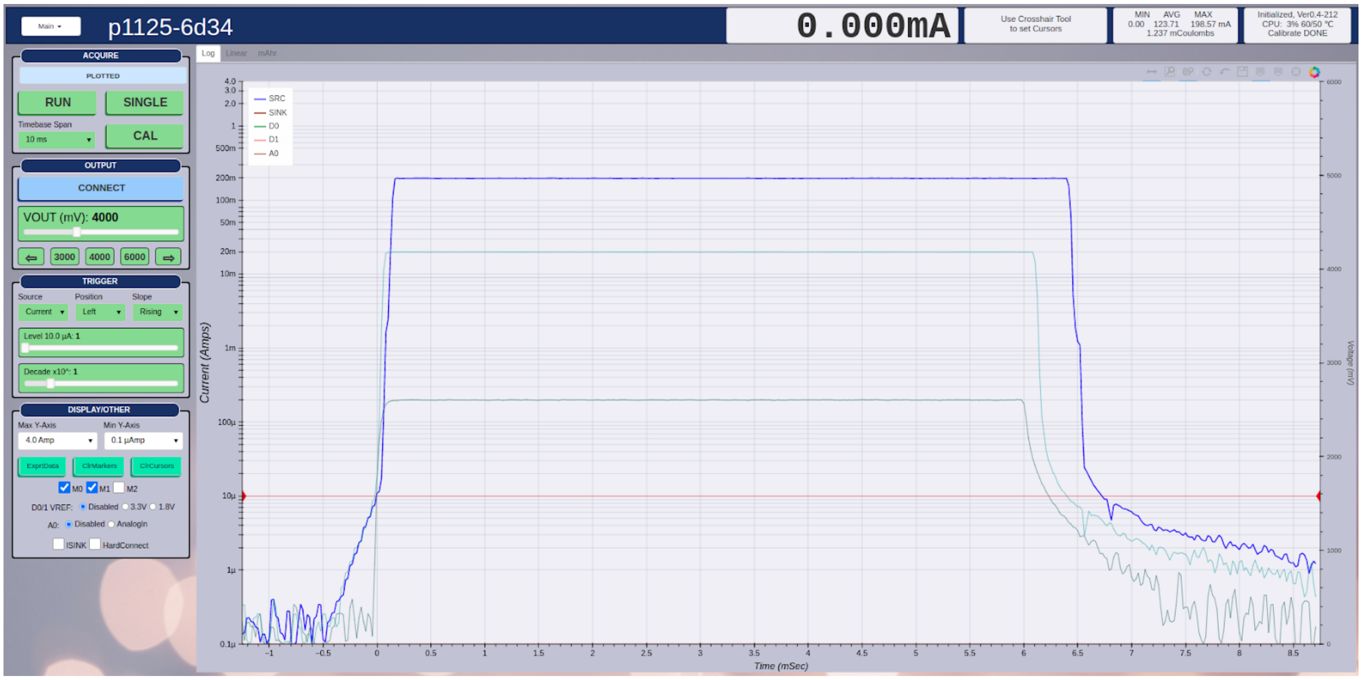
When measuring a signal that is undersampled, the result will “bounce around”. Sometimes the number will be higher than the true value, sometimes lower. It depends on many factors related to the profile of the signal, and the sampling rate of the DMM.

Consider this, would you use a DMM to measure an I2C bus signal? Of course not. But the DMM will still report a value. The value will be the rail voltage when I2C is not active, and it will be some other number when I2C is active. The average voltage of the I2C signal has little practical value. The same is true for the average current of a target device if the current is undersampled.

P1125 Performance

The P1125 excels at measuring fast dynamic current profiles in order to accurately present real time events and calculate the average current, and thus battery life.

Here the P1125 measures various magnitude step current loads, 200uA, 20mA and 200mA, in less than ~300usec. With the Log scale the current measurement's wide dynamic range is showcased.



The P1125 ***ALWAYS*** has a fast 48KHz sampling rate with an analog BW ~10KHz and wide dynamic current measurement range, 1uA to 3.2 Amps.

Even when using the long running “mAhr” plot which averages samples to 10ms, the underlying data acquisition is running at 48KHz and integrating the samples to produce the 10ms average current. Thus, fast transient events are being captured in the reported current. This translates into repeatable measurements because there is less likelihood of undersampled data.

When you search for a solution to measure your design, research its sampling rate, analog bandwidth and current measurement range to determine if it will meet your needs. There are many low cost current measurement solutions that have such low sampling rates or analog bandwidth as to make them useless for current profiling or battery life estimation.

And finally, consider the current measurement dynamic range, many competitive solutions make you decide between current range and accuracy. None show current on a Log scale for that reason, else you would see their quantization noise.