Measuring energy consumption in embedded systems

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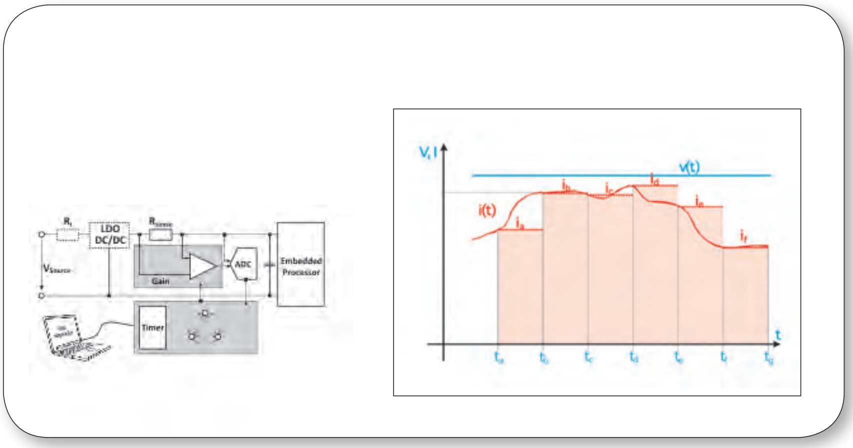
Ultra-low power embedded processing systems challenge engineers working on system integration, as well as hardware and software designers optimising their portion of the overall system for energy efficiency. An energy measurement system allowing them to see the effects of various improvements helpfully supports development and debugging.



■ The energy measurement systems in ultra-low-power applications are usually powered from a DC supply and are subject to current profiles via numerous power modes and situations, a huge dynamic range of the supply current, and highly fragmented non-periodical task responses. The energy efficiency achieved via these methods can help extend the operating time of portable equipment using primary or secondary batteries. Another energy-sensitive area is energy harvesting applications that need very careful energy-optimised designs. The ability to accurately measure energy consumption and optimise it for various conditions widens the application of energy harvesting products.

The primary advantage of having an energy measuring method is to see the energy consumption during the development of the system hardware and software. Any enhancements or additions to the activity profile of the product as well as the impact of such additions, both negative and positive, can be measured based on the energy demand. The integrated development environment can offer energy-related debug support. For the majority of cases the relative energy consumption is the key value. In ultra-low energy applications many short interrupts or other events are a major contributor to the energy consumption. The measurement system needs to catch such energy contributors enabling the development of ultra-low energy efficient designs. Electrical energy is defined by three factors: voltage, current and time of observation or consumption. The formula for the electrical energy is usually simplified to $E = V * I * t$ which may or may not cover the real conditions in the application system. Most energy measurement systems measure voltage and current with discrete components like analog-to-digital converters. Any precise measurement of the energy requires a power (integral over v(t) and i(t)) integrating sensor with high resolution and dynamic range. The precision of time is less of a challenge and it can be considered that the time delta $(t1 - t0)$ is in the range of microseconds or smaller.

The voltage in embedded processing systems is constant. It is typically stable enough to introduce no significant error to the energy measurement result. The voltage ripples on power supplies in such systems are minimal and in the millivolt range. Capacitors are placed within close distances to the terminal of the embedded processor for sourcing high current peaks and keeping the voltage stable. A shunt resistor and operational amplifier convert the current flowing through the shunt resistor into a voltage to be digitised with the ADC. The energy can also be measured in such a way that the product of current i(t) and the time is used. A variant of this method is to replace the energy ΔE that is used while keeping the voltage v(t) stable.

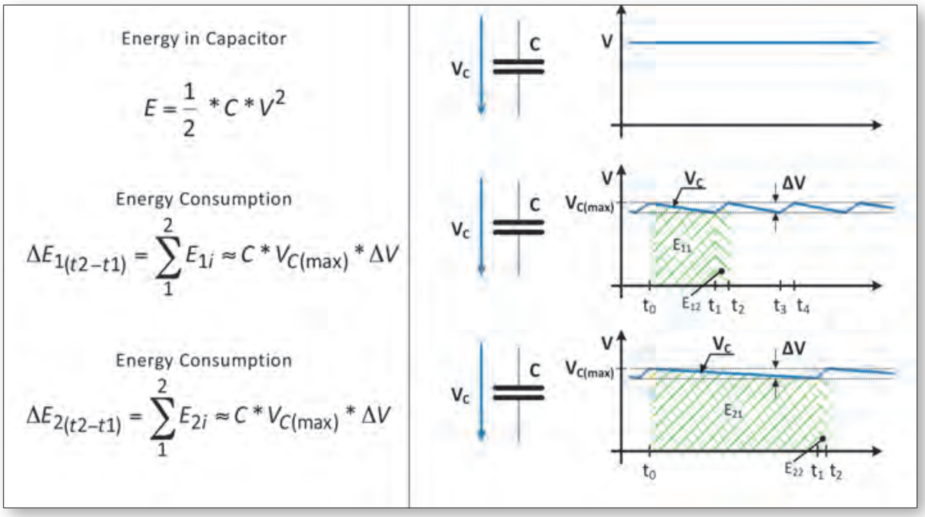
First, the focus is on the three parameters that are needed to measure energy i.e. voltage V, current I and time t. Two main sources of energy used with embedded processor systems are power supplies and batteries. Many systems use power supplies with an output capacitor and deliver a good dynamic load regulation. Such power supplies can be based on LDOs or DC/DC converters. Other systems use primary or secondary types of batteries. Even if these have a higher dynamic resistance they are capable of delivering a stable supply voltage. As mentioned previously, the V-I-t method uses A/D converters to get data about the voltage and current parameters.

The analog-to-digital conversion used to measure the supply voltage level for the energy calculation is precise enough to match accuracy requirements. A 12-bit ADC usually has more than 11-bit ENOB and delivers accurate results, which are in the 0.5 per cent range. Current measurement in ultra-low power systems faces the challenge of highly dynamic current profiles. The dynamic range of power modes is shown for some MCUs in table 1. The resolution can be considered to be better than 1ppm and 10nA.

Device Power Mode	Device A (16-bit)	Device B (16-bit)	Device C (32-bit)	Device D (32-bit)
	uA	uA	uA	uA
Active Mode [1]	10100	1600	8400	8100
RTCC Mode LPM3.5[2]	2.5	0.36	0.9	0.7
Off Mode LMP4.5[3]	0.18	0.05	0.02	0.18
Resolution of $I_{Measure}$	**.01**	**.01**	**.01**	**.01**
Dynamic Range	**>1,010,000 : 1**	**>160,000 : 1**	**>752,000 : 1**	**>810,000 : 1**

[1] @ maximum frequency, peripheral will add additional current consumption
[2] Real-Time Clock & Calendar Mode, EFM LFRC instead of 32kHz XTAL
[3] Deepest Power Mode

The most general power modes are listed showing the huge dynamic range confronting the measurement system.



The principle of measuring discrete electrical energy

There are two common approaches for calculating energy usage. In the case of the V-I-T method for calculating energy, the basic measurement circuit uses a current sensing resistor, and precision amplifier with two sensitivity ranges, an analogue-to-digital converter and a timer. As shown in figure 1, the timer controls the finite state machine FSM (or a programmable controller). This in turn triggers the A/D conversion that measures the supply current and the supply voltage. The FSM or controller selects the gain of the amplifier system. The amplifier system can be built upon different implementation ideas getting the required gain needs resolved. The ability to allow for different gain settings is needed due to the huge dynamic range of ultra-low energy applications. Two possible designs are discussed. First, one amplifier is used and the controller decides to select the low-gain or high-gain. This method is faced with the gain-select delay and hysteresis control needed for proper gain decision. A second option is to use two amplifiers and convert both outputs. For the final energy consumption the highest valid value can be used in the energy calculation. An important factor is the timing resolution and the precision of the current signal path. The discrete sampling of A/D results has an upper limit of conversions per second. The accuracy of the energy measure depends on the activity profile of the application system to report valid energy figures to the user.

On the other hand, the ΔE method for energy calculation uses an element to store energy to power the application. The simplest electrical component is a capacitor; and it is easily available and cost-effective. The electrical energy in a capacitor is defined by the capacitance and the voltage across the terminals. The energy consumption is the voltage drop at the capacitor per time of the voltage drop. The basic principle to get the energy consumption for an observation period is to accumulate all individual delta charge (ΔE) events during that period. The capacitor element in this measurement principle is the integrator delivering the current to the high dynamic system load and is highly independent of the current waveform.

Ultimately, both methods have their strengths and weaknesses. If the main objective is to design the software and hardware for the best utilisation of the available energy the ΔE method has the advantage of integrating the current over time. The V-I-T method has advantage that the peak current can be observed as long as the events are long enough to be sampled effectively by the ADC. The bandwidth of the current-voltage operational amplifier system and the conversion rate define the accuracy of the system.

The energy measurement using the V-I-T method requires very fast, high resolution amplifiers and A/D converters with sufficient bandwidth in ultra-low power applications. The programmable amplifier requires fast load change detection and response down to the nA-range. The ultra-low power burst mode principle - which is the key to such ULP applications - is the driver for these requirements and poses challenges to develop the energy measurement system with acceptable resolution and accuracy level.

The ΔE method uses the integration capability for common passive components, a capacitor in the discussion here, to avoid the challenge and cost of highly precise electronic components and circuit. The consumed charge is reported individually or accumulated. The number of re-charge events results finally in the used energy. Slowly changing supply voltage, as it is typically for such applications, can be measured with simple A/D converters. Energy measurement is the most effective method to optimise applications for effective consumption by streamlining both software algorithms and hardware requests. Effective energy measurement techniques allow us to significantly improve battery life and open doors for a wider range of energy-sensitive applications. ■