Lower Operating Voltages Force Higher Efficiency Conversion in Battery Operated Appliances

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Contact Information:

Jim Schuessler
Strategic Marketing Manager
National Semiconductor Corp.
james.schuessler@nsc.com
530-274-4972

Unlike Chicken Little, who seemed to fear the sky falling, Engineers today have good reason to welcome lower operating voltages. As the fundamental power equation shows, dropping the operating voltage on CMOS gates is the only exponential factor in an otherwise linear relationship between power, capacitance and switching frequency. ($P = f_{SW} \bullet C \bullet V^2$) In short, lower operating voltages give the biggest bang for the buck when longer operating life in battery powered devices is your goal.

However, since battery voltages are not changing, lower operating voltages bring new challenges to the power supply designer to wring every last watt-hour from the battery. Two major factors contribute to the power conversion circuit's ability to accomplish this task. The obvious metric to check is the basic conversion efficiency when the power supply is operating. Not so obvious may be the voltage at which the power supply stops operating.

Operating Efficiency

Although a good understanding of the effect efficient energy transfer has on operating life and heat buildup seems intrinsic to every engineer, the ease with which this information is extracted from some semiconductor data sheets sometimes requires far too much guesswork. Most often efficiency data is presented at fixed input voltages. Designers of battery operated equipment *never* have the luxury of assuming a relatively fixed input voltage. As the battery discharges, input voltage clearly declines dramatically, thus altering the efficiency of the conversion circuit. An <u>average</u> operating efficiency is needed over the discharge profile of the battery.

When using a Low-dropout Regulator (LDO), the linear conversion efficiency is proportional to $V_{IN} - V_{OUT}$, making an estimate of average efficiency over the life of the battery relatively simple. Inductor-based switching regulators have highly variable efficiency as input voltage changes, thus making the task of producing an average operating efficiency number difficult.

Dropout Voltage

All too often devices today force users to discard (or at least change) batteries "before their time". Regardless of the amount of energy remaining in the battery, when the power supply stops working, so do you. The critical factor here is dropout voltage. (By the way, keep those batteries for your flashlights!) For instance a Lithium-ion (LiIon) battery can be safely operated between about 4.2V and 2.5V. If an LDO needed to produce a 3.3V output, it may stop working at 3.45V -- assuming a 150mV dropout voltage. In the case of a coke anode type LiIon battery, over 40% of the energy is unused! A 3-cell Alkaline pack still contains 33% of its power under the same conditions.

Another factor driving the engineer's focus on dropout voltage is the effect highly variable or pulsed loads have on the output voltage of the battery. Depending on the equivalent series resistance (ESR) of the battery, output voltage can drop substantially as the applied load changes.

Lithium-ion Powers the World of Cellular Telephones

Nowhere is a pulsed load more prevalent than in Cellular Telephone devices. The increasingly popular time-division multiple access (TDMA) protocols used in GSM (Europe), PCS (USA) and PDC (Japan) all require rapid pulsing of the Cell Phone power amplifier (PA). As the PA draws 1000 to 1500mA, input voltage to the power supplies for the digital signal processor (DSP), frequency synthesizers, mixers, low-noise amplifiers, audio and display circuitry may dip 0.5V or more for LiIon batteries. Although the LiIon chemistry provides the highest available energy density measured by both weight and size; unfortunately the ESR can be much higher when compared with NiCad or NiMH type batteries. In addition, it increases as the cell discharges.

A power supply's ability to operate with a very low minimum input voltage becomes critical to extending the talk-time of the phone.

Today's Requirements Drive Focus on Dropout Voltage

When the input voltage (3.6V nominal from LiIon) is close to the desired output voltage (see Table 1.), using LDO to generate these voltages is a fairly high efficiency proposition. For a 3.3V rail, an LDO achieves about 88% average efficiency over the portion of the battery discharge cycle it uses. As output voltage requirements drop, efficiency will linearly decline. But do we care? In fact, empirical evidence would suggest we don t. Users today enjoy over 200 hours of standby time on cellular telephones -- the vast majority of which the PA is inactive. Market data suggests that users will not pay more for more standby time; what they want, and will pay for, is more talk time. Talk time is dominated at an 8:1 to 10:1 ratio by the PA power consumption. If all the other circuitry in the phone is consuming only 10% of the power, increasing conversion efficiency on that portion does not noticeably effect talk time.

So what is the limiting factor to talk time? Many transmit power amplifiers shut down around 3.0V today (they are typically connected directly to the battery). However, since LDO cannot boost, any supply rail above about 2.9V shuts down earlier. That may be acceptable, except that these steady-state assumptions do not account for the load profile of TDMA phones. As the PA pulses on, drawing an amp or more, the ESR of the battery causes a transient voltage drop that may knock an LDO out of regulation long before it normally would with a lower steady load.

This effect is shown in Figure 1. The top line is the typical 1C (1C refers to the load applied to the battery where C is equal to the Amp-hour rating. The battery shown is rated at 275mAh, thus a 1C discharge rate would be 275mA) discharge curve of voltage verses time for a graphite anode type LiIon battery. The bottom curve shows the effect of the battery's ESR as the load is doubled. Note that ESR increases

Non-PA Power Usage Within Phone

Rail	Today		Tomorrow	
V	mA	mW	mA	mW
1.8	0	0	50	90
2.5	0	0	125	313
2.9	40	116	10	29
3.0	150	450	0	0
5.0	5	25	3	15
		591		**447**

Table 1. Hypothetical power used for everything except the PA.

slightly as the battery becomes depleted, amplifying the effect of lower than normal input voltage to the power supply.

This increasing ESR burdens the power supply with very low input voltages, even though the battery has a large amount of energy remaining. For example, one commercially available 600mAh graphite anode battery has an 830 milli-Ohm ESR at 3.5V, dropping the output voltage to 3.0V with a 1200mA load. Now at 3.5V, 12% of the battery capacity remains unused. (Other LiIon chemistries, such as coke anode materials can result in much higher remaining capacities.)

Tomorrow's Voltages Present a Dual Challenge

We have found that from a power supply perspective, a low minimum input voltage (dropout voltage) has the biggest effect on increasing talk time, since it utilizes the battery more completely. However as *output* voltages decline (See Table 1) the conversion efficiency of an LDO-based power supply architecture becomes a much bigger factor. A 1.8V rail results in an awful 49% average efficiency using an LDO alone. Not only is the low dropout important, but increasing efficiency now has a 5 to 10% effect on increased talk time.

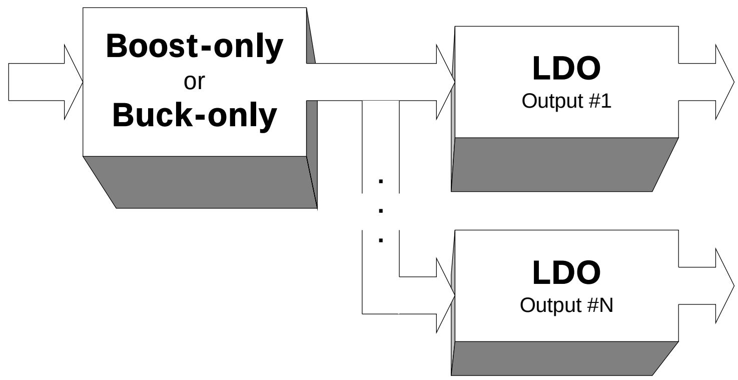

Figure 2. Boost-only can result in poor efficiency while Buck-only has a very high minimum input voltage.

Buck-Boost Switched Capacitor Solution

One method cellular telephone power supply designers have used to combat this problem is by fronting the LDOs with either inductive boost or inductive buck regulators. See Figure 2. Boosting a LiIon battery above its fully charged voltage (about 4.2V) and then using LDOs has the advantage of utilizing the full battery capacity, but with the penalty of poor conversion efficiency especially at lower output voltages. Buck-only solutions suffer from a higher dropout voltage, especially when used to generate voltages between 3.3 and 3.0V. So although good efficiency can be obtained during operation, some significant portion of battery energy will remain untapped, shortening potential operating life.

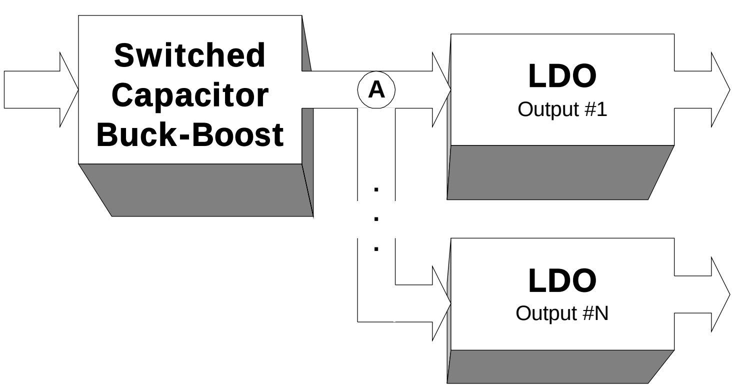

Figure 3. Lacking the need for any inductors, Switched Capacitor architectures are becoming available with Buck-Boost functionality.

Using step-up/step-down or buck-boost converters solves both problems since an output voltage can be picked that allows efficient conversion with trailing LDOs, and yet utilizes the full battery capacity due to very low minimum input voltages. For instance choosing a 3.0V output at "A" in Figure 3 will satisfy the "Tomorrow" voltage requirements in Table 1. at relatively high efficiency, and enable users to get maximum talk time by fully utilizing the battery.

Only now are Switched Capacitor architectures becoming available that dynamically move between buck and boost modes depending on the input voltage and output load. Average operating efficiency compares quite favorably with single-ended primary inductance (SEPIC) converters. Utilizing multiple gain modes to optimize efficiency, one buck-boost switched capacitor converter achieves between 82 and 84% average efficiency over the discharge profile of both coke and graphite anode LiIon batteries when producing a 3.0V output voltage. Since the input voltage range encompasses the entire operating range of the battery, the full battery capacity can be converted for the loads.

No Inductors Means Lower System Costs

Most inductive SEPIC converters require two inductors while buck-only or boost-only require one. Removing the need for inductors in portable systems not only saves space and allows thinner designs, it also can lower manufacturing costs and ease difficult procurement issues in high volume production. In addition to being more expensive than capacitors, inductors can increase manufacturing costs due to more stringent soldering requirements. And although newer thin inductors are available, they are frequently single-sourced items, which introduces another potential for line-down conditions in manufacturing.

Switched capacitor buck-boost regulators are not a panacea however. In particular care must be taken to mitigate switching noise caused by the relatively fast current flow into and out of the switching capacitors. Fortunately the trailing LDOs in this distributed power architecture can act as effective filters providing up to 60dB of noise isolation depending on the frequency of the noise.

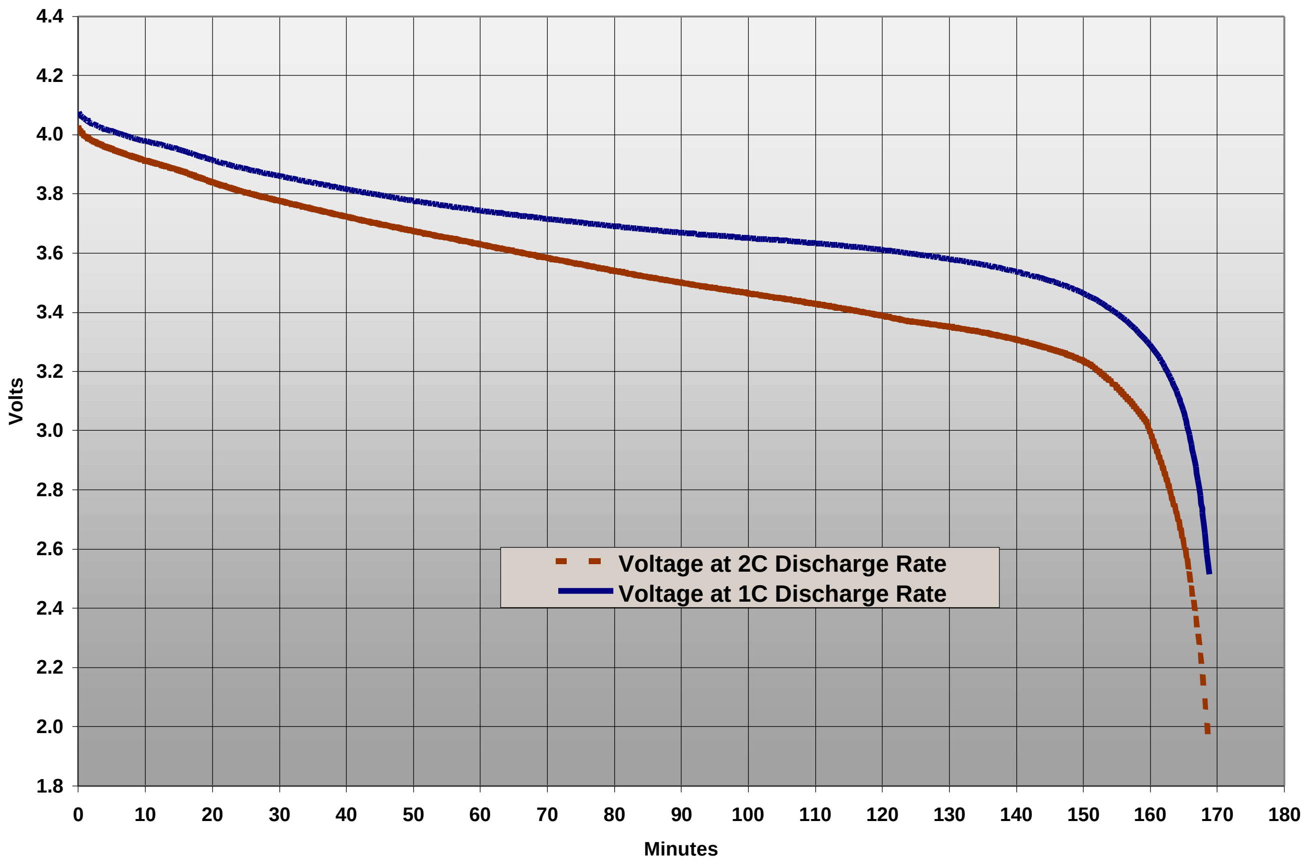

Figure 1. Although the graphite anode LiIon battery has a very flat discharge characteristic, the ESR can cause a substantial voltage drop as heavy loads are applied. 1C=275mA for this battery.