Efficiency and Power Utilization Data Guide DC/DC Conversion Choices in Battery Operated Devices

James E. Schuessler
National Semiconductor Corp.
Grass Valley Design Center
Grass Valley, CA., USA
james.schuessler@nsc.com

As overall power consumption requirements decline in handheld equipment, the traditional portfolio of power supply tools; linear voltage regulators and inductor based switching power supplies, are being displaced by switched capacitor power supplies that can provide smaller, thinner, and more efficient solutions. Cell Phones, Satellite Phones, Pagers, Handheld PCs, PDAs and their integrated hybrids are all benefiting from enormous advances in CPU MIPS/Watt, more efficient reflective displays and low power memory. This trend lightens the corresponding load on the battery allowing smaller batteries, increased lifetime, and driving alternatives to the existing power conversion techniques. Switched Capacitor power conversion starts to offer physical volume, radiated EMI, efficiency and cost advantages as peak power requirements fall under 1 watt.

This paper will contrast efficiency and size data between Switched Capacitor, Switched Inductor and Linear power conversion techniques. Trends show the "sweet spot" expanding for Switched Capacitor supplies as regulation and higher power chips become available.

I. Old Constraints, New Answers

Cost, size and efficiency: The constraints for portable battery operated devices never seem to change, but developments in conversion technology are offering new answers to the same problems. In the same breath, its important to mention a host of other constraints that sometimes come to the fore depending on the type of device being designed. Radiated EMI, conducted noise, manufacturability, multiple sourcing, and delivery terms are all factors that can also become NUMBER 1 at some time in the development process. At the risk of over-generalizing, cost, size and efficiency tend to rise to the top of the list when designing compact, portable, battery operated devices for consumer markets.

How do these constraints trade-off one another? Almost always cost and efficiency are directly related – paying more generally results in higher efficiency conversion. However, the same cannot be said for cost and size. Some of the very lowest cost power conversion can be done with tiny discrete components or LDOs, albeit at terrible conversion efficiency. Looking at size verses efficiency, one finds the most variation and difficulty in generalizing.

A. Briefly: Inductive Switchers

Traditionally inductive switchers demanded a physically tall inductor for buck or boost conversion. Thinner inductors are becoming available, but they still carry the baggage of radiated EMI, manufacturability, single-sourcing and quality issues characteristic of most inductors. More complex and expensive buck-boost switchers typically require two inductors. Still, buck-only inductive switchers offer some of the highest conversion efficiencies available.

B. Briefly: Low-Dropout Linear Regulators

Linear regulators excel in almost all areas of interest for portable devices except one: efficiency. They are available in small sizes, offer low quiescient current and dropout voltage and deliver the added benefit of noise filtering. However, neglecting the quiescent current, their efficiency linearly decreases as the input to output voltage diverges. As operating voltages decrease from 3.3V to 2.5V and 1.8V, the efficiency of LDO conversion becomes unacceptable given a constant input voltage.

C. Briefly: Switched Capacitor Regulators

Switched capacitor voltage converters have been available for many years without regulation, offering double (2X), invert (-1X) and halving (1/2X) functions. In the past couple years, switched capacitor converters offering fractional conversion (3/2X, 2/3X) and regulation using both LDO and PWM/PFM methods have become available from several manufacturers. In many ways, switched capacitor regulators fit in between the many advantages and disadvantages of LDOs and inductive switchers. By their nature, no inductors are used in the external circuit, thus eliminating their size, sourcing and other difficulties. On the other hand, since they do switch a capacitor between the input and output, switching noise is a factor of similar proportions to inductive switchers.

For high volume devices (>100Kunits/yr. for instance), cost is of paramount importance, but in many cases a device will miss it's target market entirely if a certain minimum operating life is not achieved. (Early WinCE devices fell into this category.) Fortunately, as operating voltages decline, the power equation itself helps reduce the need for power and thus improves battery and operating life. (P=CV^2R/f) In systems where efficiency is a slightly higher priority than absolute lowest cost, switched capacitor regulators are offering new options.

II. The Portable Power Conversion Challenge

A strong case can be made that the most challenging power system design being done today is found in portable and handheld devices. These range from Cyrix M2, AMD K6 and Pentium II-based Notebook PCs to the tiniest security fob, with Digital Cameras, Cell Phones, and Organizer-class Computers making up the high volume middle ground. Although primary cells (non-rechargeable) will remain a strong option for these devices, rechargeable lithium ion (LiIon) batteries are taking market share from NiCad and NiMH at a rapid rate.

A. Primary Operating Voltage

Portable devices can require five or more voltages and supplies for various functions throughout the system. LCD display bias can require a larger positive or negative voltage, audio functions need a clean supply and still often require 5VDC. Typically a standby supply is separated from the main digital logic supply. Our investigation will focus on the supply that typically consumes the majority of the power, and thus has the largest impact on operating life. This primary operating voltage is the main digital power rail. Voltages here are declining precipitously from 3.3V to 2.5V and 1.8V today. Future portable systems are beginning to be designed with 1.0V and lower.

As these voltages decline, coupled with several power source (battery chemistry) options and power supply architectures, it becomes very difficult to easily compare one with another.

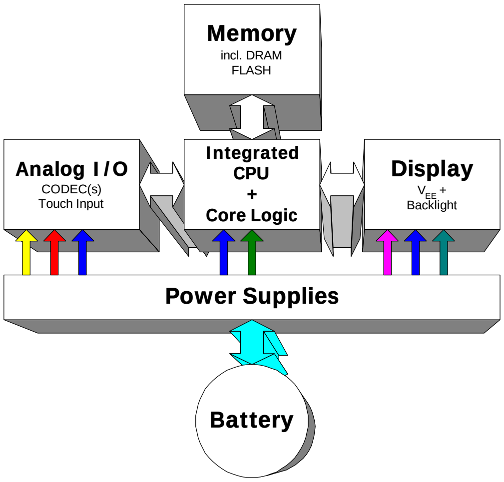

Fig.1. Five or more supplies can be required for portable devices.

III. Efficiency: More Than Meets The Eye

A single efficiency number is certainly a convenient metric to work with and compare power conversion methods. When that number is applied to systems with fixed, or relatively constant input voltages, the generalization is pretty accurate. However, with battery operated systems the input voltage can vary more widely and can easily fall outside the operating range of the power supply. Moreover, conversion efficiency can vary 2:1 or more over the extent of battery input voltages.

A. Data Sheet Efficiency

Most semiconductor data sheets are written to convey an understanding of power conversion efficiency at fixed input voltages. In particular, inductive switching power supplies most often show a graph of efficiency with output current as the independent variable (on the X-axis). These graphs typically show three to five curves at different fixed input voltages. Notice how efficiency can vary as input voltage changes. Although load certainly varies, especially between standby and operating states, it would also be very useful to see curves of efficiency verses input voltage at several fixed loads.

B. Average Operating Efficiency

Well if a fixed input voltage efficiency curve is not representative of the true efficiency observed in the system, how do we improve it? A much better measure is to compute an average operating efficiency number, based on the varying efficiency as input voltage declines over the life of the battery.

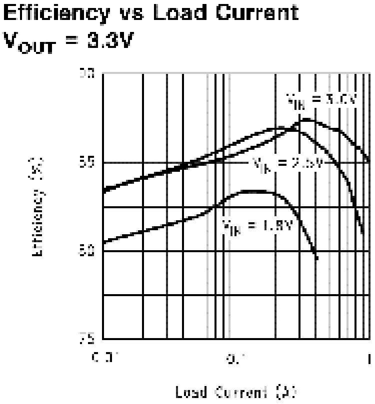

Fig. 2. Typical inductor-based efficiency curves.

To accomplish this, the discharge curve of the battery is needed, as well as good data on the efficiency of the power supply as input voltage varies. Loading this data into a spreadsheet, one can compute a piecewise integral of the efficiency as the battery discharges. Dividing by the discharge time gives an average efficiency.

The word “operating” is added because often the battery can be discharged to a voltage lower than the power supply can accept. This number is only the efficiency over the operating range of the power supply; it does not account for any remaining unused energy in the battery.

C. Effective Efficiency: Closer to the End User Perception

What if we could use ALL the energy in the battery? In many cases it is cost prohibitive or difficult to find a power supply to accept the full range of input voltage, but if the entire extent of input voltage from the battery could be used, device life would certainly be maximized. Effective Efficiency produces a single efficiency number taking into account any unused energy left in the battery. If the power supply is capable of accepting the full voltage range from the battery, then Effective Efficiency is equal to Average Operating Efficiency. If the supply stops operating at some voltage above full discharge, then Effective Efficiency will be lower proportional to the amount of Watt-Hours remaining.

Effective Efficiency allows comparison of efficiency numbers based upon the actual amount of power converted (from the battery) to operate the device. After all, even a 99% efficient conversion is of no use if only 20% of the battery energy can be converted.

IV. Assumptions

We’ll now turn to some real data to illustrate the different metrics described above. Developing such data is fraught with peril since it almost never matches the design goals of the system required.

Disclaimer: Although accurate for comparison purposes, generalizations over a class of power supply architectures or extrapolation to other supplies is not implied. The data was developed to educate one on the merits of looking more closely at efficiency, especially when different battery chemistries are combined with alternative power supply architectures.

In addition, battery discharge current for the Coke Anode Lithium Ion (LiIon) battery does not match the typical load assumed for the power supplies (700mA discharge verses 100mA to 300mA load). Since all supplies were compared with the same data, relative comparisons can still be made.

	Architecture	Vout	1-Cell LiIon (4.2V to 2.5V), Coke Anode	1-Cell LiIon (4.2V to 2.5V), Graphite Anode	3-Cell Alkaline (4.8V to 2.7V)
A	Low-dropout Regulator	3.3V			
		2.5V			
		1.8V			
B	Buck Switcher	3.3V			
		2.5V			
		1.8V			
C	Boost Switcher + LDO	3.3V			
		2.5V			
		1.8V			
D	Buck-Boost Switched Capacitor	3.3V			
		2.5V			
		1.8V			

Table 1.
A Representative Range of Battery Sources and Output Voltages are Compared with Several Conversion Architectures

A. The Power Supply Architectures

Based on these three primary power consuming voltages, we take a look at efficiency across four power conversion architectures and three battery chemistries. See Table 1. A load of between 100mA and 300mA was assumed.

Other options are of course theoretically possible, but in practice are difficult to find in monolithic form or have extremely prohibitive costs. Architectures in this category are an ideal inductive buck-boost converter with a 2.5V minimum input voltage, and a combined inductive boost converter followed by an inductive buck regulator.

1. Low-dropout Linear Regulator

The venerable Low-dropout Regulator (LDO) not only serves as a well-understood baseline, but is also used extensively in portable devices due to its low noise, small size and cost. A dropout voltage of 150mV was assumed.

2. Buck Inductive Switcher

A buck or step-down inductive switcher is a good choice when output voltages are lower than the minimum battery voltage. Several buck or step-down device specifications were used based on the output voltage. It would not be useful to use the same device for all outputs (3.3V, 2.5V and 1.8V) since this would not be done in practice. The disadvantage is that at higher output voltages, the architecture cannot use the full battery capacity.

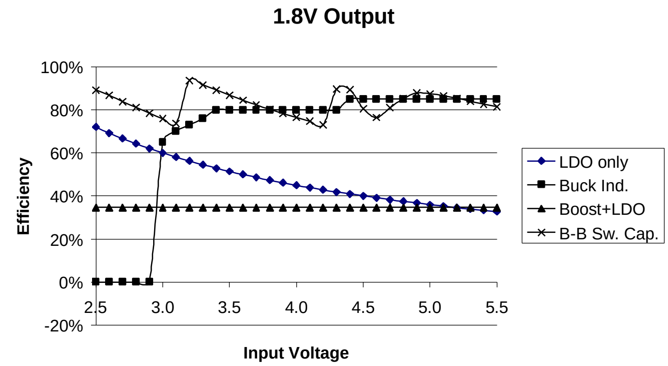

Fig. 3. Example Efficiency Over Input Voltage Range for 1.8V Output

3. Boost Inductive Switcher with LDO

This configuration was included because it can always be relied upon to utilize the full battery capacity. An inductive switcher boosts the input to a voltage slightly above (200mV) the maximum battery voltage and then uses an LDO to get the desired output.

4. Buck-Boost Switched Capacitor

Only now becoming available, a buck-boost switched capacitor regulator used multiple fractional gains in a switching matrix controlled by a DSP-like digital control loop. As input voltage or output load changes, the controller dynamically changes the capacitor conversion ratios to maintain optimal efficiency. This results in a saw-tooth type efficiency curve (eff. verses input voltage) as gains are changed over the input voltage range.

B. The Battery Power Source

Due to the increasing popularity of LiIon, we look at two anode materials that give similar V(min) and V(max) voltages, but quite a different shape to the discharge curve. In addition, a 3-cell Alkaline primary cell option is included since it can easily replace the LiIon cell due to a similar output voltage range.

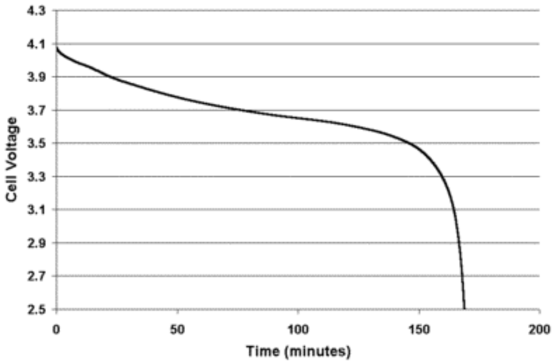

Fig. 4. LiIon Discharge using Graphite Core

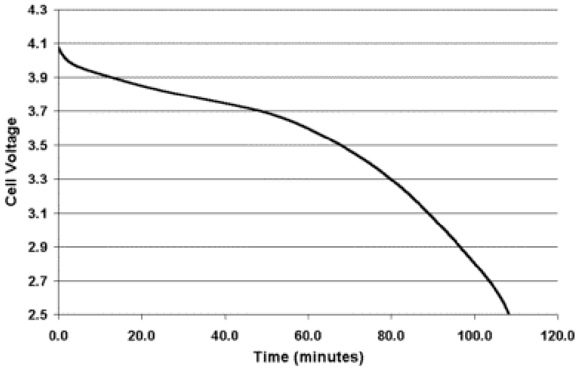

Fig. 5. LiIon Discharge using Coke Core

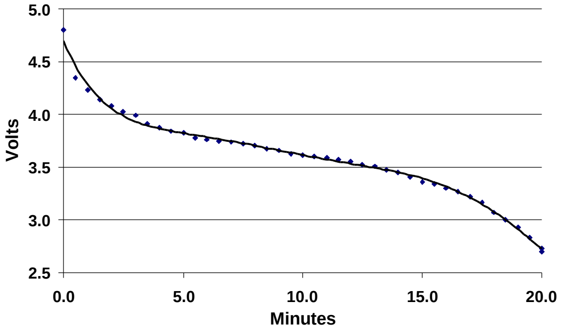

Fig. 6. Alkaline AA Cell. 100mA Constant Current Discharge

Discharge curves with low slope to the end of the discharge curve place a larger burden on the power supply to convert at lower input voltages. Since more energy is contained in the battery at a lower voltage, it becomes more important to be able to utilize that energy and extend the operating life of the device.

Note that the LiIon graphite anode material has a sharp roll-off characteristic of the NiCad. In the "sweet-spot" between 3.8V and 3.5V the graphite core battery delivers 60% of its energy whereas the coke core battery delivers only 37%.

V. Results

Another way to visualize the power delivered to the load is by looking at a graph that plots Watts verses Time for both output to the power supply and input to the load. The difference is obviously either energy dissipated as heat (inefficiency) or still remaining in the battery. The later is often overlooked as mentioned before. See Figure 7.

Average Efficiency and Effective Efficiency were computed for each of the four power supply architectures over the three battery chemistries and output voltages. See Tables 2, 3 and 4.

These efficiencies were drawn from tables such as Table 5, where Watt-Hours and minutes of discharge were collected. The cutoff voltages (minimum voltage where the power supply would stop working) were taken from the data sheets of readily available integrated circuits.

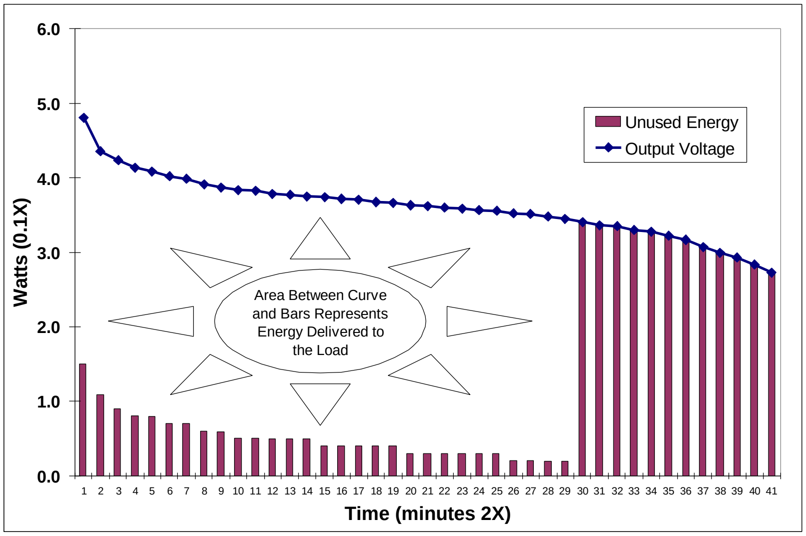

Fig. 7. A 3-Cell Alkaline input delivering a 3.3V output through and LDO. The bars meet the curve at 3.45V due to the 150mV droput of the LDO

A. Meeting Expectations

	Architecture		1-Cell LiIon (4.2V to 2.5V) Coke Anode ($)		
		Vout=	**3.3**	**2.5**	**1.8**
A	**Low-dropout Regulator**	Ave. Eff.	88%	71%	52%
		Effect. Eff.	**51%**	**70%**	**52%**
B	**Buck Switcher**	Ave. Eff.	90%	78%	78%
		Effect. Eff.	**52%**	**70%**	**70%**
C	**Boost Switcher + LDO**	Ave. Eff.	64%	48%	35%
		Effect. Eff.	**64%**	**48%**	**35%**
D	**Buck-Boost Switched Capacitor**	Ave. Eff.	82%	82%	82%
		Effect. Eff.	**82%**	**82%**	**82%**

Table 2. Efficiency Results for LiIon using Coke Anode

The results for the Low-dropout Regulator are illustrative of the process and serve well as a baseline for comparing the other architectures. In Table 2., the Ave. Eff. equals the Effective Eff. in both the 2.5V and 1.8V cases. Here the LDO utilizes the full capacity of the battery. The 150mV dropout has only a 1% effect for the 2.5V output. The discharge was stopped at 2.65V in this case, but because a negligible amount of energy is still in the battery, the efficiencies are essentially the same, albeit bad. Average Eff. is low due to the large differential voltage between input and output.

LiIon Battery: Coke Anode
Output Voltage: 3.3V

Voltage Fully Charged	**4.1V**
Voltage at Empty	**2.5V**
Total Watt-Hours	**4.50**
Ave. Discharge Current	**700mA**
Minutes to Empty	**108.22**

Architecture

A Low Dropout Linear Regulator

Cutoff Voltage (V)	**3.45**		
Discharge Time (min.)	**71.15**	Used Watt-Hours	**3.17**
		Percent Used	**58%**
Unused Time (min.)	**37.07**	Unused Watt-Hours	**1.34**
		Percent Unused	**42%**
		Average Efficiency	**87.9%**
		Effective Efficiency	**50.8%**

Table 5. "Raw" Results for 3.3V LDO

The 3.3V case shows the importance of looking at Effective Eff. Here the LDO achieves a very respectable 88% Ave. Eff. over the operating life of the device. However due to the 3.45V dropout voltage, some 42% of the battery capacity remains in the battery. Moreover, over 37 minutes of the 108 minute total discharge time was wasted.

The Effective Efficiency reflects this "gas in the tank" into the poor 51% result. It's also interesting to see the much better number for the LiIon Graphite Anode battery. Due to the flatter discharge curve, more energy can be converted before the dropout is reached. (Table 3., 80%)

	Architecture		1-Cell LiIon (4.2V to 2.5V) Graphite Anode ($$)		
		Vout=	**3.3**	**2.5**	**1.8**
A	**Low-dropout Regulator**	Ave. Eff.	89%	68%	49%
		Effect. Eff.	**80%**	**68%**	**49%**
B	**Buck Switcher**	Ave. Eff.	90%	80%	80%
		Effect. Eff.	**81%**	**79%**	**79%**
C	**Boost Switcher + LDO**	Ave. Eff.	64%	48%	35%
		Effect. Eff.	**64%**	**48%**	**35%**
D	**Buck-Boost Switched Capacitor**	Ave. Eff.	82%	82%	82%
		Effect. Eff.	**82%**	**82%**	**82%**

Table 3. Efficiency Results for LiIon using Graphite Anode

B. Exceeding Expectations

The real horse race here is between the Buck Switcher and the newer Buck-Boost Switched Capacitor circuit. Efficiencies are very similar, especially for the 2.5V and 1.8V cases. With the relatively high input voltage of the LiIon cell, a buck-only solution is a good choice for these outputs. However, a buck-only solution for a 3.3V output leaves considerable untapped capacity in the battery.

	Architecture	Vout=	3-Cell Alkaline (4.8V to 2.7V) **3.3**	**2.5**	**1.8**
A	**Low-dropout Regulator**	Ave. Eff.	90%	71%	51%
		Effect. Eff.	**61%**	**71%**	**51%**
B	**Buck Switcher**	Ave. Eff.	93%	79%	79%
		Effect. Eff.	**63%**	**77%**	**77%**
C	**Boost Switcher + LDO**	Ave. Eff.	65%	49%	35%
		Effect. Eff.	**65%**	**49%**	**35%**
D	**Buck-Boost Switched Capacitor**	Ave. Eff.	84%	84%	84%
		Effect. Eff.	**84%**	**84%**	**84%**

Table 4. Efficiency Results for 3-Cell Alkaline

At 3.3V, only the Buck-Boost Switched Capacitor solution converts all the energy from the battery. The Buck Switcher drops out about 200mV above the output voltage (calculations were done at 150mV), leaving a substantial amount of unutilized energy in the battery.