

## Application Requirements Drive Choice of Voltage Regulator in Portable Systems

by

David Brown

Senior Manager of Applications Engineering  
Advanced Analogic Technologies, Inc.

The rapid proliferation of feature sets in wireless handsets and other portable products has put engineers responsible for power system design in a tough spot. On the one hand, users are demanding a growing array of features from multiple color displays to embedded cameras, each demanding more power. On the other hand, the market increasingly associates the quality of a portable product with the length of its battery life. The longer a product's battery life, the higher its likelihood of market success. Never have skillful battery management and power efficiency been in higher demand.

The growing use of multi-voltage designs has further complicated the designer's task. Many of the new function blocks designers are introducing into portable devices do not operate at the same voltage as the system power source. For example, the typical single cell lithium-ion battery powering a cell phone operates in a range from 4.2V when it is fully charged down to about 3.0V or below when fully discharged. Yet many of the key circuits in the phone have different voltage requirements. The microprocessor core in the handset typically runs at or below 1.8V. The RF subsection, on the other hand, usually demands between 3.0V to 3.3V. Alternately, the white LEDs used to backlight the handset display or provide fashion lighting typically operate at 3.6V.

Every time a functional circuit requires a different voltage level than that provided by the battery, the system has to add a mechanism to step-up or step-down the power. Moreover, since the battery voltage is constantly changing as it discharges, the system must continually monitor and adjust the voltage conversion process. As an example, when the battery is fully charged, it supplies a voltage too high for the 3.6V required by white LEDs. Accordingly, the system must step-down the voltage to run the display backlight. But as the battery discharges and reaches the lower end of its range around 3.0V, the operating voltage must be stepped-up to meet the requirements of the white LED backlight circuits. If designers are not careful in how they convert the voltage to support those various features, they risk reducing the efficiency of the power system and, in the process, unnecessarily wasting power. Wasted power translates into shortened operating battery life and, in today's marketplace, reduced market share or possibly an unsuccessful product.

Managing power conversion efficiency is the key to meeting the contradictory demands found in a given system design. Designers must be knowledgeable of the variety of power conversion technologies and devices available on the market and must know which devices to use to address the unique power

conversion requirements of each functional block in the system. This article will review the power conversion options available to portable system designers and where they best fit in a design.

### **Three Options**

Designers can take advantage of any of three primary families of voltage conversion devices to address this power conversion problem: linear low dropout voltage regulators, switched capacitor charge pump converters, and inductive DC-DC converters.

#### ***Linear Voltage Regulators***

Linear voltage regulators are the simplest and most common device used for step-down voltage conversion functions. The typical internal architecture of a linear regulator consists of a series bipolar or CMOS pass transistor which is controlled by an integrated output feedback system that compares the regulator output to a precise reference. Linear regulators come in any of three types: standard regulators, low dropout or LDO regulators, and quasi LDO regulators. The system design and technology used for LDO regulators allows them to offer a low operating voltage headroom requirement. Most LDOs operate and maintain regulation within hundreds of millivolts or less from the input source supply. Portable applications use LDOs for linear voltage regulation because they make better use of the available input voltage than other types of linear regulators and therefore can operate longer into the discharge cycle of a battery.

An LDO's small package size and minimal external components make it an attractive solution for portable products. Typically, an LDO only needs a small input and output capacitor for circuit stability and to provide improved transient response. A third optional reference bypass capacitor can be used in some cases for very low noise applications. Unlike their older, bipolar counterparts, the newer CMOS LDOs that are available today offer excellent stability when used with ceramic capacitors. Ceramic capacitors are typically lower in cost, smaller in size, and more readily available than other types of capacitors.

Linear voltage regulators or LDOs don't just combine a small footprint with low cost. They also offer excellent input-to-output isolation making them highly attractive in designs using extremely noise-sensitive RF or audio circuits. For example, products such as wireless headsets, which combine a Bluetooth interface with an audio microphone, must deliver a highly isolated and clean power source to ensure high performance. By combining high ripple rejection and low noise, LDOs offer designers an excellent way to provide immunity and filtering from high noise sources within a system design. Moreover, LDOs are also relatively simple to implement.

These widely used devices only provide a voltage step-down function, however. If an application requires a higher voltage level than that supplied from the battery, such as a higher voltage for a display, designers must use some other type of voltage regulation method. Moreover, since LDOs are primarily designed to take a high voltage and convert it to a lower voltage in a linear fashion, they do not provide the most efficient voltage conversion solution. A linear regulator dissipates the power caused by the voltage difference from input to output in the form of heat. This inefficiency rises with the amplitude of the voltage drop across or the current through the regulator. Efficiency in some LDO applications can be as

low as 35 to 40 percent. This equates to system losses, in the form of heat, as high as 60 percent. Dissipating heat, particularly in compact portable applications, can pose a major obstacle to low-cost design.

On the other hand, if an LDO is responsible for minor voltage step down conversions, say from 3.3V to 3.0V, the device's inefficiency is less important an issue. But as the voltage input-to-output differential rises, that inefficiency and the heat the device dissipates becomes more problematic, particularly in highly integrated portable applications where thermal management plays a major role in the performance and reliability of the end product. Ultimately, LDOs provide an attractive compromise between very low cost, small size, and low noise attributes for applications that require less than ideal power conversion efficiency.

### ***Switched Capacitor Charge Pumps***

A second type of device used to convert power in portable systems is the switched capacitor charge pump. These devices utilize a system of low on-resistance MOSFET switches to configure an array of capacitors to charge, switch, and discharge in order to generate an output voltage higher than the input voltage. Conversely, the charge pump circuit architecture can be reversed to provide a voltage step-down function. Thus, in essence, switched capacitor charge pump devices can be used for both step-up functions and step-down functions. In its simplest form, the charge pump architecture uses three capacitors and four switches to provide a straight voltage doubling (2X) or dividing (1/2X) function. Additional charge pump stages can be added to provide addition voltage multiplication. Extra capacitor and switch combinations can also be configured to provide non-integer voltage multiplication such as a 1.5X boost.

Modern charge pump devices also employ some form of feedback and regulation control in order to provide a useful regulated constant voltage or current output. More advanced charge pump architectures feature multi-mode controls which provide combinations of 1X, 1.5X, 2X functions to utilize the best voltage step conversion for a given input-versus-output voltage scenario. By utilizing all the various combinations of the charge pump modes, designers can realize the best power conversion efficiency.

These increasingly popular voltage conversion devices offer a number of other attractive advantages. Since switched capacitor charge pumps do not utilize an inductor in the switching process, they do not radiate noise which can be picked up by other sensitive circuits in the system. Well-designed charge pumps also feature relatively low switching noise and ripple at the regulated output, as well as low back-injected noise to the system via the supply input. This inherent low noise characteristic makes charge-pump-based voltage converters ideal for low-power RF applications.

Switched capacitor charge pumps typically sell at a lower cost than inductive DC-DC converters and require fewer external components. Depending upon the architecture of the charge pump, a designer only needs three to four low-cost, external ceramic capacitors to implement the circuit. Accordingly, these regulators require less board space than competitive inductive DC-DC converter solutions. Switch capacitor converters are also simpler to integrate into a design than inductive DC-DC converters because they require less exacting signal traces and provide more margin for error.

Switched capacitor charge pumps are not ideal for every application. From an efficiency standpoint, they represent a good compromise between LDOs and inductive DC-DC converters. They offer more efficiency than comparable LDOs, but less than a competitive DC-DC converter. While charge pump devices serve as an excellent solution for lower power applications, they have difficulty supporting the power requirements for voltage conversion applications running in excess of 300mA.

### ***DC-DC Converters***

For high-current applications requiring high power efficiency, inductive DC-DC converters offer the best option. Instead of the linear conversion technique used in LDOs, these devices employ a switching technique which utilizes an inductor to transfer energy from input to output. Feedback circuitry regulates the power transfer to maintain a constant output voltage within the load limits of the circuit. Inductive DC-DC converters also offer the distinct advantage of being capable of both voltage step-up (or “boost”) and voltage step-down (or “buck”) functions. Circuit architectures can also be configured with additional internal MOSFET switches to affect a “buck/boost” or voltage step-up and step-down function in the same device. This capability is particularly convenient when the application input varies greatly above and below the required output voltage.

The primary benefit of a DC-DC converter is high efficiency regardless of the input to output voltage ratio. With the right selection of external components, an inductive DC-DC converter’s efficiency can range as high as 95 percent. Given this relatively high efficiency, these devices offer system designers lower power conversion losses and reduce thermal management issues.

DC-DC converters also offer high power density, a crucial consideration in footprint-constrained portable applications requiring higher levels of power. This advantage can prove crucial in applications supporting a core microprocessor which may consume 300mA to 400mA or more at low voltage levels. Using a buck converter, designers of a portable system can step down a battery-powered supply running from 4.2V to 3.0V to the core microprocessor’s 1.8V or 1.5V level while consuming 300mA to 400mA with minimal loss in the power conversion. A minimized power conversion loss can dramatically improve battery operating life and reduce thermal management issues associated with high density printed circuit layouts.

Designers using these devices must pay a price for increased efficiency, of course. Inductors are not cheap, nor small in size when compared to ceramic capacitors used by other voltage regulator solutions. In addition, an inductive DC-DC converter requires a relatively large number of external components so the system’s bill of materials will run higher than comparable voltage conversion alternatives. Moreover, a DC-DC converter’s relatively large number of external components requires more board space, a major consideration in space-constrained portable applications. Printed circuit board trace routing is critical for optimum circuit performance and adds time to the implementation process. A higher quality inductor can compensate for some of these deficiencies, but cost rises with quality.

### **Applications**

Today’s rapidly evolving smartphones offer a growing array of function blocks from wired and wireless RF connectivity, core processing, and memory to audio and DSP functions, display backlighting, and embedded camera features. Each block comes with its own unique set of power conversion requirements.

### ***RF Section***

The one functional block common to any mobile phone design is the wireless RF section. Containing transceiver circuits along with all supporting functions, the RF module typically runs at higher voltages than the processor core or baseband functions. Accordingly, the voltage difference between the battery-supplied power source and the RF circuit is not large. With the exception of the transmit power amplifier, most of the RF circuitry consumes little current. Given the RF section's small step-down voltage requirements and lower load current demands, power efficiency is less important here than it is in other functional blocks.

Power source noise is a high priority concern for sensitive RF circuits. Receiver circuits such as low noise amplifiers, VCOs, and mixers are highly susceptible to power supply noise. Such circuits affect receiver sensitivity performance and, subsequently, range. Transmitter circuits are equally susceptible to power supply noise issues and designers face additional constraints. Up-converted and amplified noise can degrade the quality of transmitted information, but can also create transmit spectral purity issues which are subject to strict government compliance standards. Therefore, designers must use an extremely low noise power source in RF designs to not only maximize performance, but also to ensure product compliance with existing communications regulations.

LDO linear regulators can be tailored to suit the needs of specialized wireless circuit applications. These devices can be designed not only to provide very low noise and excellent power supply rejection, but they can also be specialized for fast start-up timing, fast transient response, or add accessory features such as power ok flags to inform the system controller that the regulator output is operating correctly.

Given these characteristics, linear voltage regulators or LDOs provide the best match for this application. Offering excellent isolation in terms of input-to-output power than either switched capacitor charge pumps or inductive DC-DC converters, LDOs deliver a clean, ultra-low-noise power source at low cost. Moreover, their primary liability, low efficiency, is a minor disadvantage in this particular application because the RF section of a smartphone typically runs at a voltage close to the voltage supplied by the battery.

### ***Core Processing Block***

The core processing block in a smartphone brings an entirely different set of power conversion requirements. The core microprocessor typically consumes more power than any other function block in the system. When the block is fully active, core load current levels can run from 300mA to 400mA. To save power, most of the core processor and memory circuits also run at low operating voltages of 2.2V or less. Many of the processors used for baseband functions today run at 1.8V or 1.5V.

Efficiency is the driving requirement in this application. Given the core processor's high current demands and low operating voltage, it plays a key role in the system power budget and has a major impact on battery life. Moreover, any voltage conversion solution for the core processor must support a relatively large step-down from the average 3.6V supplied by the system battery. An LDO would prove far too inefficient in this application and would shorten battery life and create significant thermal management

issues. A switched capacitor charge pump offers a more efficient alternative, but cannot support applications that require much more than 200mA.

The optimal solution for this application is a step-down inductive DC-DC or “buck” converter. Offering a voltage step-down function with 85 to 95 percent efficiency, these devices can easily support the high current requirements of the core processor with the extremely high efficiency required to extend system battery life. In addition, high switching noise, which prohibits the use of an inductive DC-DC converter in most RF applications, is a less imposing liability in these applications because the digital circuits in the microprocessor block are less sensitive to switching noise.

A second design requirement to consider in this application is light load efficiency. In most systems, the core processor spends a significant percentage of time in standby or sleep mode. Yet, switching converters are typically less efficient in light load environments because losses attributed to MOSFET gate charge and operating quiescent current become more important than MOSFET conduction losses. If designers aren't careful, they may use a converter which consumes as much power as the core processor in standby state. It is crucial, therefore, that designers select converters with excellent light load as well as full load efficiency.

### ***Display Backlighting***

Display backlighting applications in portable products typically use arrays of three to six white LEDs. These devices also require a different and very specialized set of power requirements. White LEDs used for color TFT display backlighting behave the same as other light emitting diode devices; for a given forward current through the LED, a characteristic forward voltage will be established across the LED. Normally, white LEDs used for backlighting applications are driven with about 20mA of forward current to achieve maximum brightness. The typical forward voltage at this forward current level is approximately 3.6V.

The primary challenge that designers face in this application is how to constantly maintain this forward voltage as the battery discharges and the supply voltage varies above and below the required forward voltage of the backlight LED. To vary the brightness of the display backlight at the same time, the system must also be able to exert a high degree of control over the supplied current to the LED. One final critical detail for LED backlighting is brightness matching between LEDs. The forward voltage characteristic for white LEDs can vary significantly from LED to LED. The only way to equalize or match the brightness between an array of LEDs is to drive them all with the same current level.

When considering power management solutions for backlighting applications, noise is less of an issue when supplying power to the display section of the design. White LEDs used to backlight a display are typically not sensitive to small amounts of switching ripple. The most attractive and commonly used voltage conversion solution for this application is a switched capacitor, multi-mode charge pump device. When the supply voltage is higher than the output needed, the charge pump can be disabled and the device used as a simple linear regulator. This operation typically provides decent efficiency which can range from 85 to 95 percent. Once the supply voltage begins to drop below the forward voltage requirement of the LED, the charge pump can be activated in a fractional mode. Using a 1.5X charge

pump operation, the device can step-up the input supply voltage to power the LEDs and still maintain reasonable efficiency. As the input supply further decreases, the charge pump can switch again to a 2X mode to further boost power, if needed.

Charge pump devices for LED backlighting come with many options. Some simply provide a regulated constant voltage output. More complex and specialized solutions have multiple matched constant current sources or sinks to drive each LED in the array with a matched constant current to maintain matched brightness between LEDs.

Alternately, designers can drive white LEDs with an inductive DC-DC converter. This approach offers excellent brightness matching capabilities because the LEDs are connected in series and receive the same current regardless of their individual forward voltages. Moreover, boost converters offer good power conversion efficiency. However, inductive DC-DC converters typically have much greater switching noise issues when compared to capacitive charge pump solutions, and their switching frequency can vary with output voltage. Designers must often add shielding or special printed circuit board layout considerations to ensure spurious noise does not couple with the phone's audio baseband or RF sections. In addition, the required inductor is typically larger and more expensive than ceramic capacitors, so designers using this approach can pay a higher price in board area and cost than they would using a charge-pump-based solution.

Switched capacitor charge pumps can also be used to power photo-flash LEDs used in conjunction with the camera blocks embedded into most smartphones today. The flash function requires a higher voltage and current than most switched capacitor charge pumps are typically able to deliver. However, photo-flash LEDs only require boosted power for very short periods of time. A typical flash function usually lasts for just 250ms. Switched capacitor charge pump converters can supply pulsed currents of 400mA to 500mA for short durations of 250ms to 500ms. As with display backlighting applications, switched capacitor charge pumps can be used to supply high current for a flash function in a very efficient manner, in a smaller footprint, and at much less cost than an inductive DC-DC converter.

### ***Communications Block***

Many smartphones now offer some sort of connectivity to a notebook or desktop PC. Typically this is performed via a data port supporting the USB or the newer "USB-On-The-Go" standard. One of the unique demands of the USB standard is the requirement for a 5.0V power supply bus. Since most mobile phone batteries can only supply a maximum of 4.2V when fully charged, this application requires a step-up voltage conversion function. While the USB standard used in PC applications must be capable of sourcing up to 500mA of current, a battery-powered smartphone can hardly meet this requirement to support communications with a PC or notebook. For most applications, the USB VBUS for a smartphone can function with as little as 100mA. The newer USB-On-The-Go standard current requirement drops as low as 20mA.

Switched capacitor multi-mode charge pumps offer a highly efficient and cost-effective way to boost voltage for this application. The average battery discharge level is 3.6V; a 1.5X or 2.0X charge pump can easily meet the 5.0V output requirement. As the battery discharges and the supply voltage tracks

downward, a multi-mode charge pump device can manage the voltage conversion process to ensure that it is not over-boosting the supply. If the charge pump over-boosts the voltage, it must be regulated back down and power is wasted in the process.

The latest generation of intelligent multi-mode charge pumps available today is ideal for this application. These devices feature embedded control circuits that monitor the battery voltage and calculate the best fractional charge pump mode to avoid over-boosting the power. These new intelligent devices offer designers a low cost, low noise, voltage conversion solution for this particular application in a highly compact footprint.

### ***Audio Functions***

A smartphone must also be able to process a variety of audio signals ranging from voice to MP3 files. Analog audio signals are typically processed in a DSP and reverted to analog for output to the user. Most of these functions are managed by the system core supply.

This application presents its own unique design constraints, however. The microphone pickup circuit is usually a low noise function that is sensitive to power source noise, but only requires a very low operating current. Since current requirements are low, efficiency is less of a concern than minimizing power supply noise. For most audio applications, an LDO will provide the best low noise, low cost solution for this application.

### **Conclusion**

Today's smartphones and other portable devices offer an ever expanding plethora of functions. Coupled with the rising demands of multi-voltage designs, the next generation of new products poses a significant challenge as portable system designers struggle to manage power consumption and extend battery life. Fortunately, a variety of voltage conversion technologies are available to help designers tackle this task. By better understanding the tradeoffs that each voltage conversion approach offers and matching them with the unique requirements of each function block in a handset design, portable system designers can maximize power efficiency and, in the process, enhance the probability of their product's success in the marketplace.