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TUTORIAL 671

Energy Management for Small Portable Systems

Apr 07, 2011

Abstract: This application note describes power-management schemes for portable applications with four- and three-cell battery systems. Optimal designs and uses for step-up/down converters, linear regulators, voltage converters, charge pumps, and inductorless regulators are shown. Several Maxim power-management devices are featured.

Numerous diverse and conflicting constraints burden the designer of small handheld products. Aside from the customary restrictions on size and weight, these constraints include cost limitations, strict time schedules, battery-life goals measured in weeks instead of hours, and host computers that are (sometimes) overtaxed with the demands of power management.

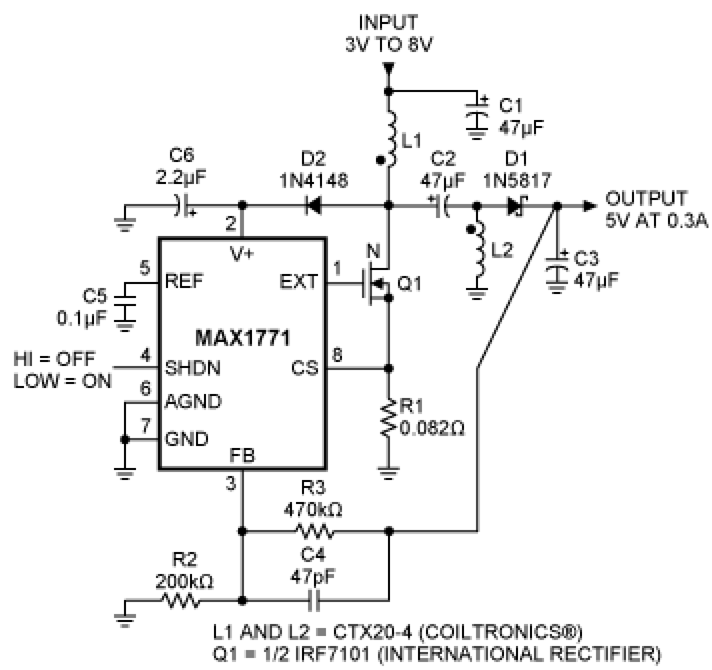
Because power requirements for handheld applications vary widely with product use, no single "best" power source exists for these applications. A device used intermittently is more concerned with no-load quiescent current than with full-load efficiency, and can operate satisfactorily with alkaline batteries. Cell phones, however, must contend with high peak loads and frequent use. This mode of operation emphasizes conversion efficiency over quiescent current, so cell phones are better served with a rechargeable battery.

In handheld product design, size limitations often dictate the number of battery cells early in the process. This is frustrating to the electrical engineer, and a substantial constraint, since the number (and type) of cells allowed determines the operating-voltage range. This, in turn, strongly affects the cost and complexity of the power supply. High cell counts enable the use of linear regulators and simple circuitry at the cost of extra weight and limited efficiency. Low cell counts compel the use of a more costly switching regulator, but the low cost of the battery may justify this expense.

Designs with Four Cells

A design with four single-cell batteries often provides an attractive compromise between weight and operating life. That number is particularly popular for alkaline batteries because they are commonly sold in multiples of four. Four-cell power for 5V circuitry presents a design challenge, however. As a battery discharges, the regulator must first step down and then step up. This requirement precludes use of the simpler, one-function regulator topologies that can only step down, step up, or invert.

One effective solution to this problem is the single-ended primary inductance converter (SEPIC), in which V_{OUT} is capacitively coupled to the switching circuitry (**Figure 1**). The absence of a transformer is one of several advantages that this configuration has over flyback-transformer regulators and combination step-up/linear regulators.



EFFICIENCY AT I_{LOAD}

INPUT VOLTAGE	10mA	100mA	200mA	300mA
3.5V	81%	83%	84%	84%
4.0V	82%	84%	84%	85%
5.0V	82%	84%	85%	86%
6.0V	82%	84%	86%	86%

Figure 1. This regulator topology features the MAX1771 step-up controller. It supplies 5V for inputs ranging from 3V to 8V. The operation shifts smoothly between step-up and step-down conversion without steps or mode changes. During shutdown, the output turns off completely and sources no current.

As another improvement over boost designs (in which current drains from the battery during shutdown unless you add a cutoff switch—see **Figure 2**), the SEPIC output fully turns off in response to a shutdown command. As V_{IN} falls during normal operation, the SEPIC circuit smoothly regulates V_{OUT} without shifting its mode of operation as V_{OUT} approaches V_{IN}. Its power-conversion efficiency peaks at 86%, near 200mA (Figure 1).

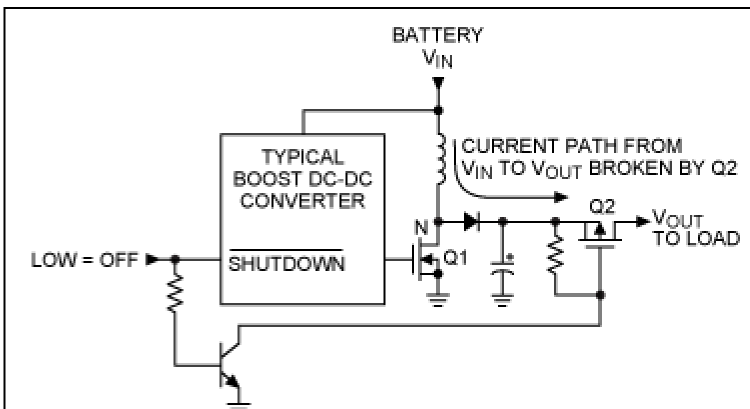


Figure 2. Typical DC-DC boost converters provide a current path from input to output, even when powered down. To interrupt this path, you must add a disconnect switch (Q2).

Coils L1 and L2 (Figure 1) should be the same type and have the same value, but coupling between them is not required. They can be wound on the same core for convenience, but the circuit works equally well if they are completely separate. Each coil passes only one-half of the peak switching current (I_{PEAK} = 100mV/R1 = 1.22A), so each can be rated accordingly.

Capacitor C2 couples energy to the output and requires low effective series resistance (ESR) to handle high ripple currents. A low-ESR SANYO® OS-CON capacitor, for instance, offers 3% more efficiency than a less expensive 1µF ceramic capacitor. Tantalum capacitors are not recommended because high ESR causes them to self-heat at high ripple currents.

Diode D2 provides a supply voltage for the IC (pin 2) by capturing switching pulses at the drain of Q1. Although this voltage (approximately the sum of V_{IN} and V_{OUT}) limits the maximum V_{IN} to 8V, it improves the startup capability under full load and improves the low-V_{IN} efficiency by boosting gate drive to the external MOSFET. If V_{IN} does not fall below 4V, you can substitute a 3V-threshold FET for Q1 and omit D2. In that case, pin 2 connects directly to V_{IN}, which assumes an upper limit of 16.5V.

Three Cells to 3.3V

For 3-cell designs, the MAX8625A high-efficiency step-up/down regulator with integrated power MOSFETs provides 3.3V and up to 0.8A output capability. The device includes a True Shutdown™ feature, which disconnects the output from the input when the IC is disabled. Together with four internal MOSFETs (two switches and two synchronous rectifiers) and with internal compensation, the circuit of **Figure 3** minimizes external components.

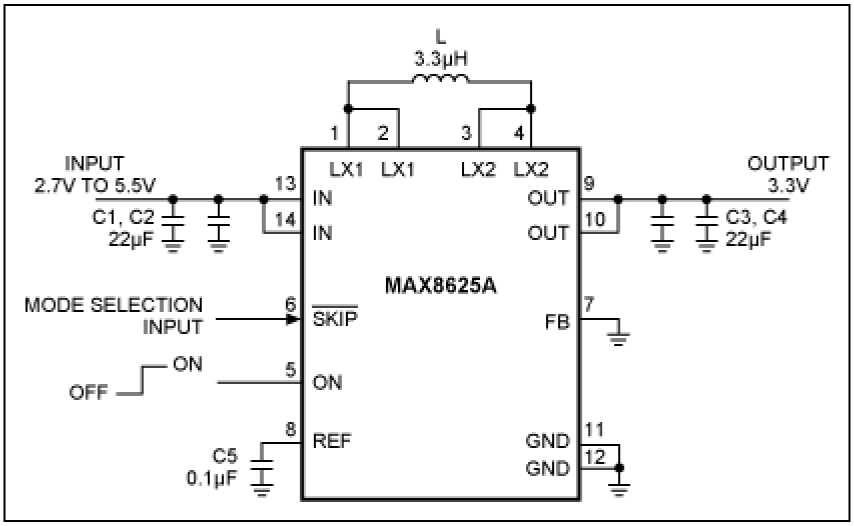


Figure 3. Typical application circuit (fixed 3.3V output).

Low-Dropout, Step-Down Converter

Low-voltage logic, such as that powered from 3.3V, now enables the use of 4-cell inputs for simple step-down configurations that optimize efficiency and cost. For 3.3V outputs, the key specification is dropout voltage—the minimum allowable difference between V_{IN} and V_{OUT}. "End-of-life" voltage for the battery varies according to cell type and the product's pattern of use, but for all but lithium batteries it falls in the range of 0.8V to 1V per cell. As a result, it is not uncommon for 3.3V regulators to operate with input voltages as low as 3.6V.

The design of **Figure 4** offers an uncomplicated means for delivering intermediate current loads at 3.3V from four cells. The IC drives a low-threshold p-channel MOSFET and minimizes current-sense losses with a low current-sense voltage of 110mV. For best performance, the MOSFET on-resistance should be specified in conjunction with the circuit's lowest operating voltage, about 3.6V in this case.

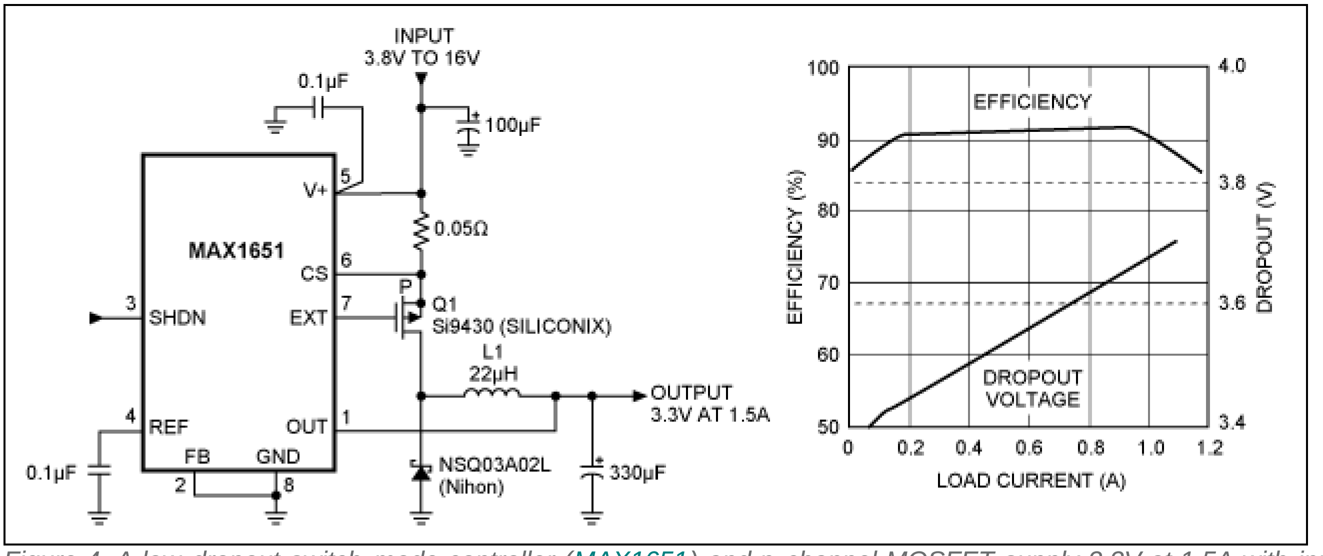


Figure 4. A low-dropout switch-mode controller (MAX1651) and p-channel MOSFET supply 3.3V at 1.5A with inputs as low as 3.8V. Efficiency exceeds 90% for most of the operating range.

Linear Regulators

Still the lowest-cost approach for many step-down applications (short of no regulator at all) is linear regulation, provided that its efficiency and battery-life limitations are acceptable and that its power dissipation at higher V_{IN} is manageable.

For portable designs, even a simple linear regulator can provide some challenges. As an example, dropout voltage (the low-V_{IN} level at which output regulation is lost) should often be regarded as a part of normal operation rather than a fault. That is, to extend operating time, it may be advisable to allow the regulator to fall out of regulation without shutting down. The regulator's behavior during dropout (especially its quiescent current) is important in these designs.

The simple linear regulator of **Figure 5** offers exceptional dropout behavior with little effect on operating current. Essentially an 8-pin surface-mount package, it delivers more than 400mA. Because the internal pass element is a MOSFET instead of a bipolar transistor, the circuit's dropout voltage is nearly zero at light loads. Moreover, its quiescent current does not rise as V_{IN} approaches V_{OUT}.

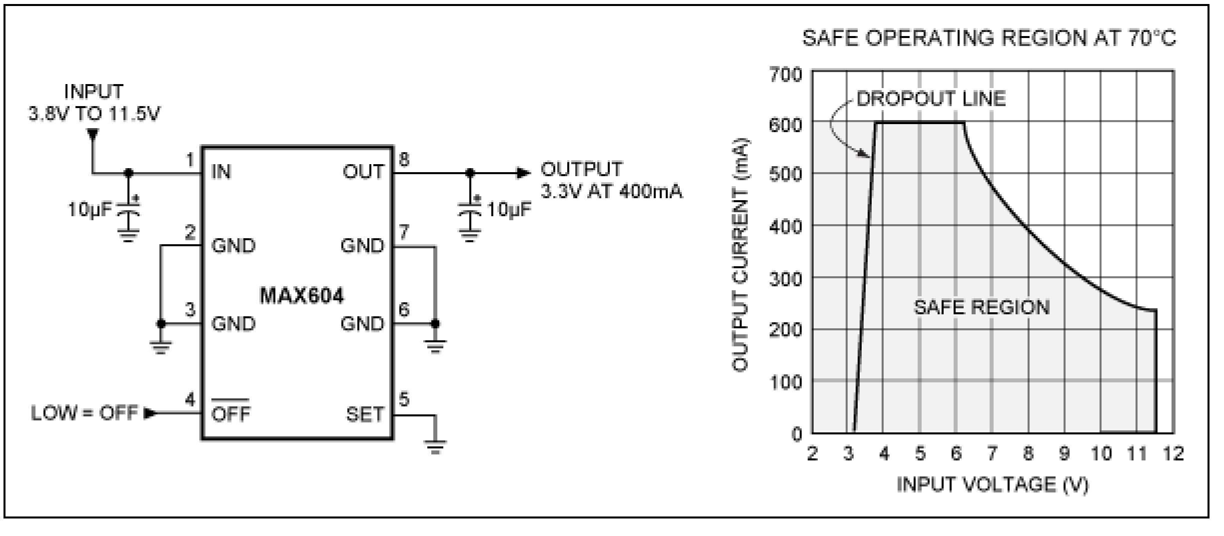


Figure 5. This combination of internal MOSFET pass transistor and high-power SO-8 package provides a linear regulator (MAX604) with low dropout, an operating current of 15µA, and an output capability of over 400mA.

This last characteristic is especially important for small portables whose steady-state load is no greater than 100µA. In such designs, the milliamp or more of quiescent-current rise (typical of a low-dropout regulator with bipolar-pass transistor) accelerates the battery discharge at a time when the battery can least afford it: near the end. Typically, the IC in Figure 5 draws 15µA of operating current whether in or out of dropout.

Boosting from Low-Cell-Count Batteries

The cell count for batteries in earlier-generation designs was high—not to provide more energy, but rather to allow generation of the system voltages with low-cost linear regulators (or even with no regulator at all). The latest generation of voltage-conversion ICs, however, lets you reduce the cell count while adding a minimum number of external parts. Usually, this extra cost is more than offset by the benefits of lower cell count: smaller size, less weight, and (sometimes) longer battery life. To illustrate, the 4.5Whr of available energy in two AA cells exceeds the 3Whr in a 6-cell, 9V alkaline battery by 50%, even though the two battery topologies are comparable in size and weight.

The step-up regulator of **Figure 6a** provides high, 88% efficiency for 2-cell and 1-cell inputs; its high, 500kHz switching frequency enables the use of very small inductors. The IC's quiescent current is only 60µA at light or zero loads—an attractive feature for portable products whose supply voltage must remain active when the product is turned off. As the product enters such an idle or suspend mode, load current falls to microamps and must not be dominated by current into the regulator IC. For equipment that truly shuts down, the IC provides a very low-current shutdown mode in which it draws less than 1µA.

One-Cell Regulators

It makes sense to operate from a 1-cell battery when size is of paramount importance. Reasonable efficiency and cost are now possible when operating with inputs below 1V, so many handheld applications have become new candidates for 1-cell operation. The switching frequency for low-cost ICs now approaches 1MHz, which permits the use of small magnetic components available from multiple sources. It is not unusual, therefore, for the DC-DC circuitry to occupy less space than the battery it replaced.

In Figure 6a, the addition of Q1 and Q2 within the dashed lines allows the regulator to start with lower input voltages and higher load currents. Q1 also disconnects the load and battery from each other during shutdown. The on-chip comparator does not allow Q1 to turn on again until V_{OUT} has risen to at least 3V. **Figure 6b** illustrates this circuit's loaded-start capability and its remarkably low typical startup voltage (0.8V).

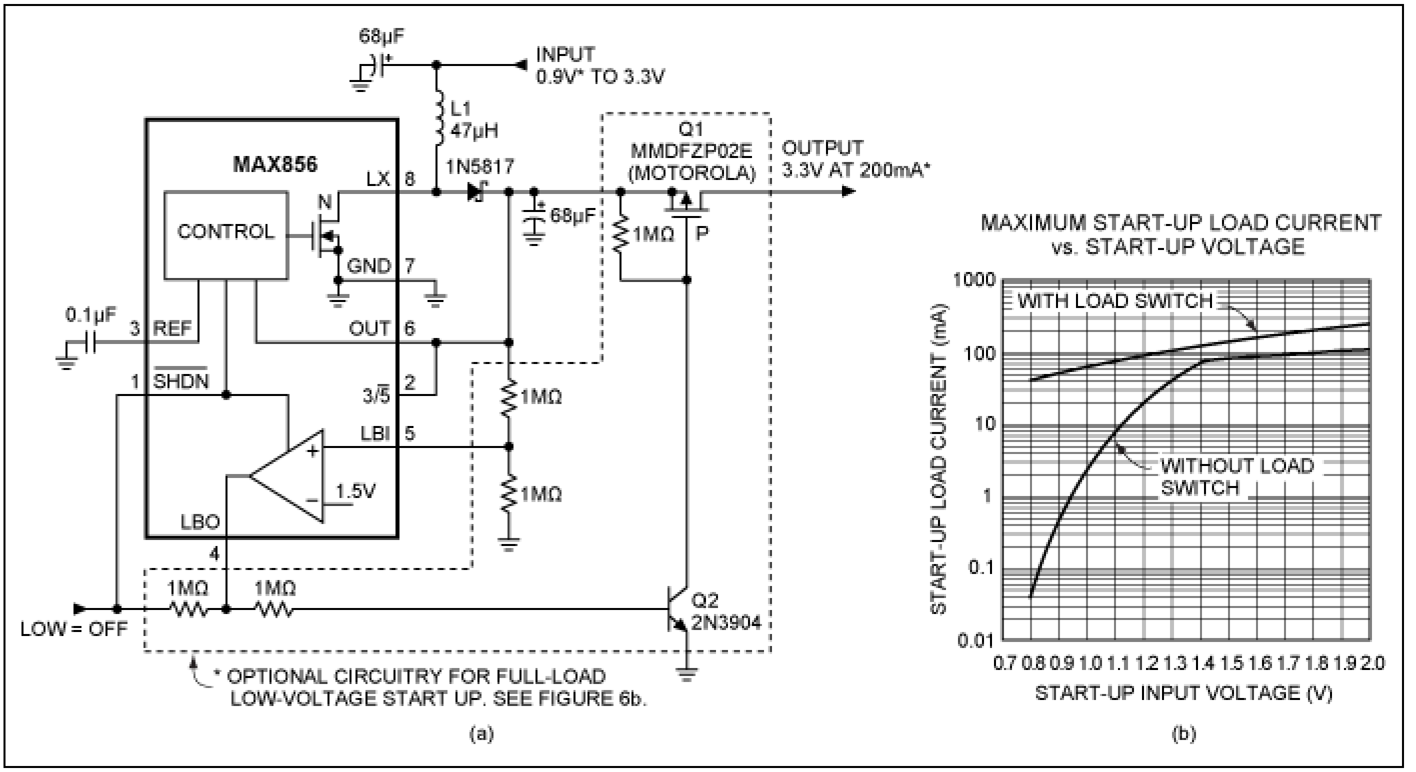


Figure 6. This low-power, CMOS step-up converter (MAX856) (a) generates 3.3V from 1-cell and 2-cell inputs. The optional load-disconnect circuitry (dashed lines) enables the circuit to start with inputs as low as 0.8V (b).

Figure 7 also shows a high-power, high-efficiency step-up regulator that operates down to 0.7V (once started) and has a startup voltage of 0.9V. The output can be fixed at 5V or adjustable step-up (2.5V to 5.5V) and is capable of sourcing up to 1.5A current.

The MAX1703 comes in a 16-pin narrow SO package and includes an uncommitted comparator that generates a power-good or low-battery-warning output.

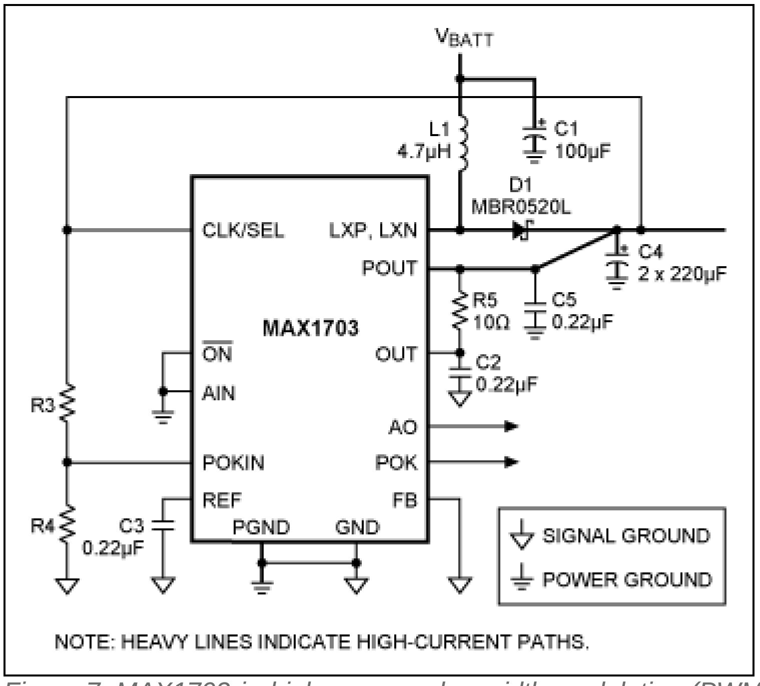


Figure 7. MAX1703 in high-power pulse-width modulation (PWM) mode.

Inductorless Conversion Suits Tight Spaces

Despite the advances made in inductor-based switching regulators, most designers would regard the ideal converter circuit as one that has no inductor. The capacitor-based alternatives (charge-pump converters) were hampered in the past by their lack of regulation and limited output current. Though still low compared to that of switching regulators, their output current is now adequate for many designs. And in some cases, the charge-pump advantages are compelling: low cost, small size, and reduced electromagnetic interference (EMI). Charge pumps are particularly useful in Personal Computer Memory Card International Association (PCMCIA) systems and other "credit-card" products in which the component height is limited.

Figures 8, **9**, and **10** illustrate three inductorless voltage converters. In Figure 8, the output of a 2-cell battery or other low-voltage source is converted to a regulated 5V ±4%. The IC changes its operational mode with input voltage, producing a tripler at low V_{IN}, a doubler at high V_{IN}, and a tripler-doubler at midrange that changes modes every switching cycle. Efficiency ranges from 85% to 65%. Low supply current (typically 75µA for no-load operating conditions and 1µA in shutdown) makes the circuit useful as a coin-cell-powered backup supply for DRAM or pseudostatic RAM (PSRAM).

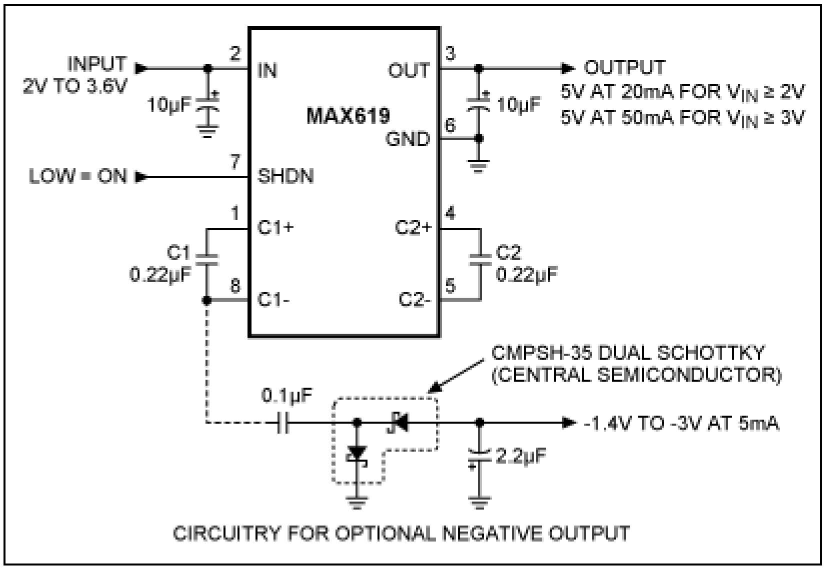


Figure 8. With a few external capacitors, the MAX619 boosts a 2-cell or 3-cell input to 5V, and delivers 50mA (for 3V inputs) with only 75µA of quiescent current. With an additional dual diode in a SOT23 package and two capacitors, it also produces a small negative output.

The optional diode-capacitor network in Figure 8 generates an unregulated negative voltage between -1.4V and -3V. Acting as a negative supply, this output simplifies analog designs by allowing the use of inexpensive op amps. The negative rail assures that such op amps can swing completely to ground.

Another charge-pump circuit, built in less than 0.1in² of board area, converts 5V to the 12V level required for programming flash memory chips (Figure 9). Common in PCMCIA cards, flash memory is popular for compact portable applications because it provides large amounts of nonvolatile storage in a small space, and because it needs power only for read and write operations. Some flash ICs operate on 5V, but those with the highest memory densities require 12V for programming.

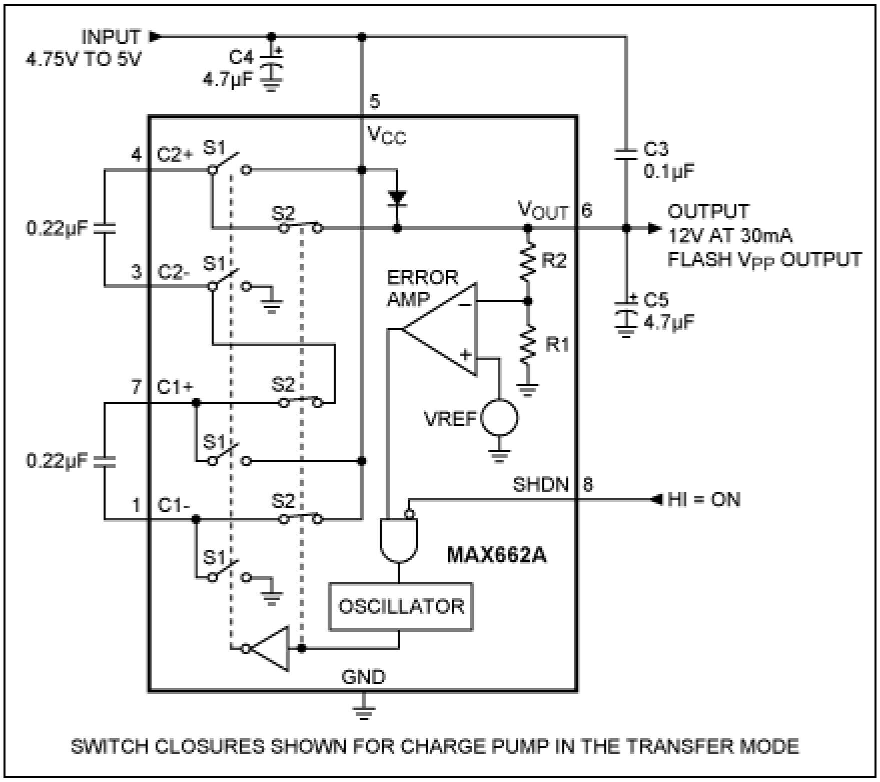


Figure 9. For programming flash memory, this circuit (MAX662A) generates a regulated 12V/30mA programming voltage without inductors. It is small enough to fit into smart cards that are the size of a credit card.

A third application that benefits from the use of charge pumps is the optimization of RF-transmitter efficiency in cellular and other voice/data wireless transceivers. "Talk time" in these transceivers is extended by the use of power amplifiers based on gallium-arsenide FETs (GaAsFETs), which are more efficient than those based on bipolar transistors.

Though more efficient, a GaAsFET costs more and requires a small negative-bias voltage. Typical charge pumps generate too much noise for this application, but an output voltage regulator in the chip of **Figure 10** keeps the output noise and ripple at $1mV_{P-P}$. Tying the FB terminal to ground sets the regulated output to -4.1V. (You can set other output levels with two external resistors.) Regulation and low noise are achieved with an output linear regulator, unlike the circuits of Figures 8 and 9 which regulate by gating the charge pump's switching action.

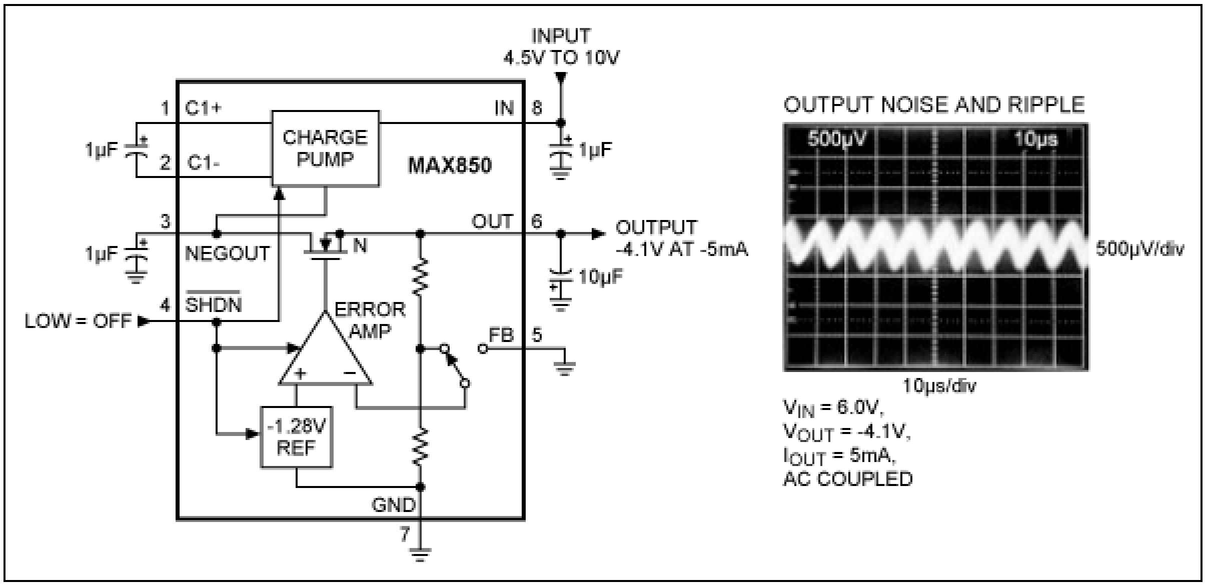


Figure 10. Intended for biasing efficient GaAsFET RF power amplifiers, this charge-pump voltage inverter (MAX850) includes a super-quiet linear regulator that limits output ripple and noise below 1mV$_{P-P}$.

Intermittent High-Current Loads

A second requirement in many handheld wireless designs is a quick response to abrupt load changes. The power supply may idle at milliamp levels for most of the time, but to handle short RF transmissions or bursts of CPU activity, it must also deliver high-amplitude currents for short intervals. Especially demanding is the RF transmitter in a GSM cellular telephone or other digital wireless system employing time-division multiple access (TDMA) techniques.

For cellular handsets, a desirable battery combination for minimal size and weight is three NiCd cells. The lowest-cost RF transmitters for this application operate at or near 6V. You might expect the expense of a switching regulator capable of delivering 2W at 6V to force the use of a 5-cell battery. But, the high current is drawn only for 600µs or so at a 10% duty cycle, so a small step-up IC can supply the load.

In **Figure 11**, a reservoir capacitor powers both the TDMA logic and the RF circuitry. The capacitor supplies an average 200mA, but at 1.5A its output drop is less than 500mV after 577µs. A 1Ω resistor (R1) isolates the RF load from the DC-DC converter. While 4 x 470µF is certainly a lot of buffer capacitance in a handheld device, the four surface-mount capacitors are far smaller and cheaper than two additional battery cells. The circuit's average power-conversion efficiency is 80% and its quiescent supply current is only 60µA.

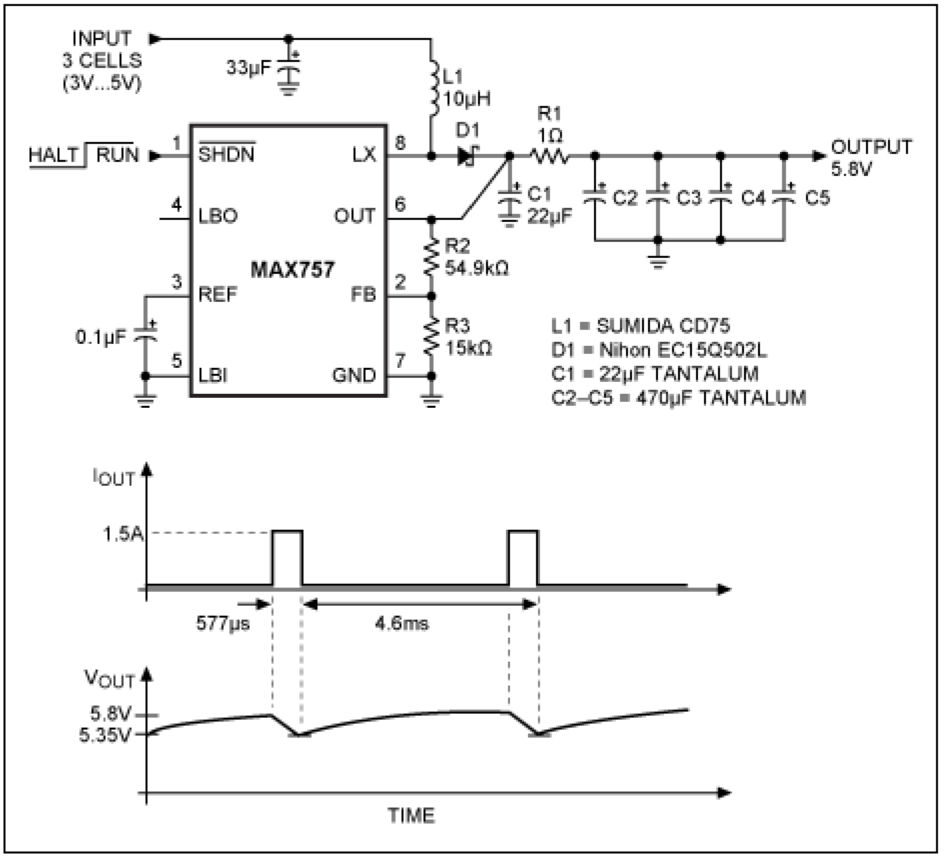


Figure 11. This circuit features the MAX757 step-up converter and includes a large capacitive reservoir that supplies 1.5A transient loads in a GSM cellular telephone. The average load is only 200mA, so the 8-pin, surface-mount, boost-regulator IC requires no external MOSFET.

LCD Bias Supplies

The bias requirements for LCD panels in portable gear cover broad ranges of voltage and current, depending on the display's technology, screen size, and cost. Bias voltages can be positive or negative and as high as ±30V. The boost converter in **Figure 12**, for example, produces an output range of 20V to 30V, adjusted either by digital control or by an external potentiometer (pot). This circuit's high switching frequency and adjustable inductor-current limit enable the use of small surface-mount inductors and output-filter capacitors. For loads below 10mA, for instance, the Murata-Erie LQH4 coil shown is only 2.6mm high.

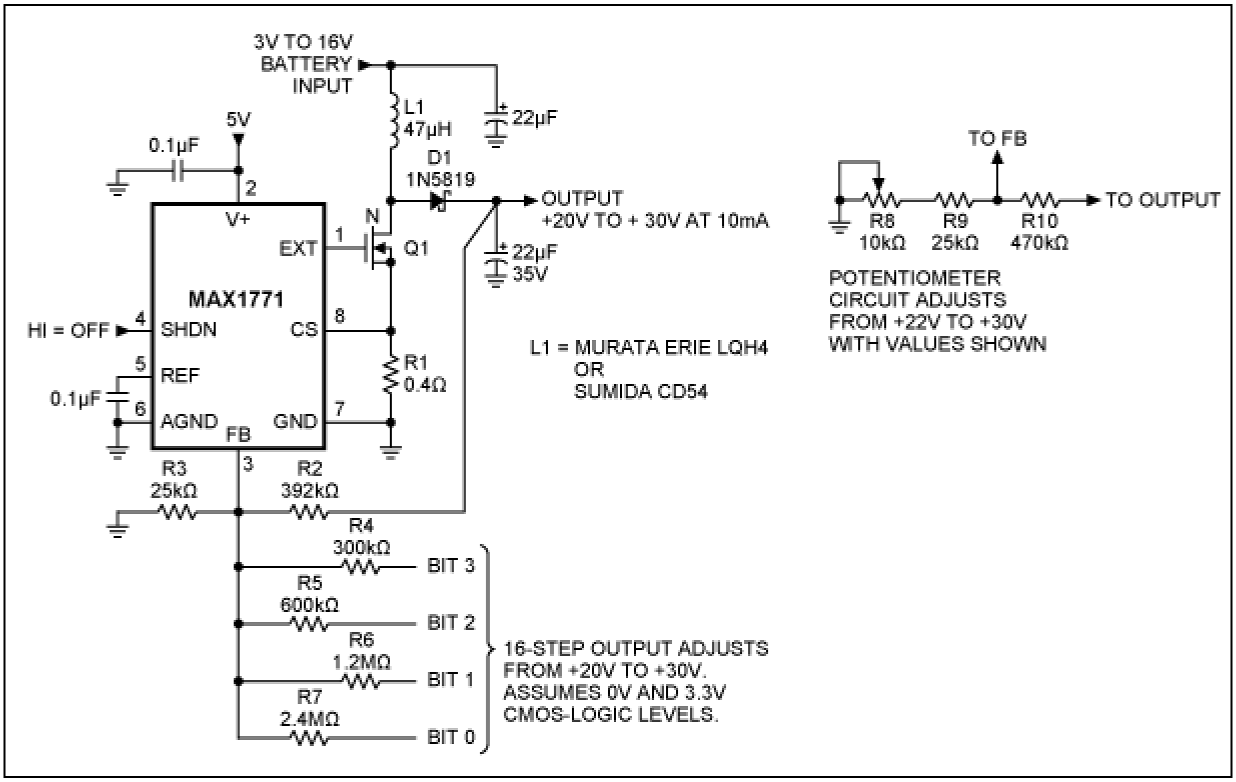


Figure 12. This circuit produces a bias (contrast) voltage for LCD panels that can be adjusted either with a potentiometer or digitally with a 4-bit DAC.

Note that the pot's configuration is not arbitrary (see the optional circuit in Figure 12). Connecting the pot between FB and ground (rather than FB and V_{OUT}) ensures that an open or noisy pot wiper will produce a low-output voltage rather than a maximum (and possibly destructive) output. Moreover, connecting the pot and its wiper to ground minimizes the trace area at FB; if you swap R8 and R9, the V_{OUT} noise will likely increase.

In 2- or 3-cell applications, you can optimize efficiency by biasing the IC from 5V (if available) instead of the battery voltage. The inductor still draws current from the battery, but higher voltage at the chip's V+ pin improves efficiency by providing more gate drive to Q1. This, in turn, lowers its on-resistance. However, if battery voltage exceeds 5V then V+ should connect directly to the battery. V_{OUT} can be adjusted by a 4-bit, 3.3V CMOS digital code or by the optional pot, as shown.

Multiple Supply Voltages

Many portable designs require more than one supply voltage. Even as IC manufacturers add to the list of functions that can be powered from standard 3.3V and 5V levels, the need to optimize performance, weight, battery life, and cost continues to justify additional voltages. Fortunately, the use of multi-output ICs minimizes the number of components needed to create these voltages. These ICs minimize the board area and the number of "glue" components required, while improving the system's low-load efficiency and other performance parameters.

The MAX1748/MAX8726 triple-output DC-DC converters in a low-profile TSSOP package provide the regulated voltages required by active-matrix, thin-film transistor (TFT) liquid-crystal displays (LCDs). These devices convert the 2.7V to 5V input-supply voltage into three independent output voltages: one high-power DC-DC converter (up to 13V output), and two low-power charge pumps independently regulate one positive output (up to +40V) and one negative output (down to -40V).

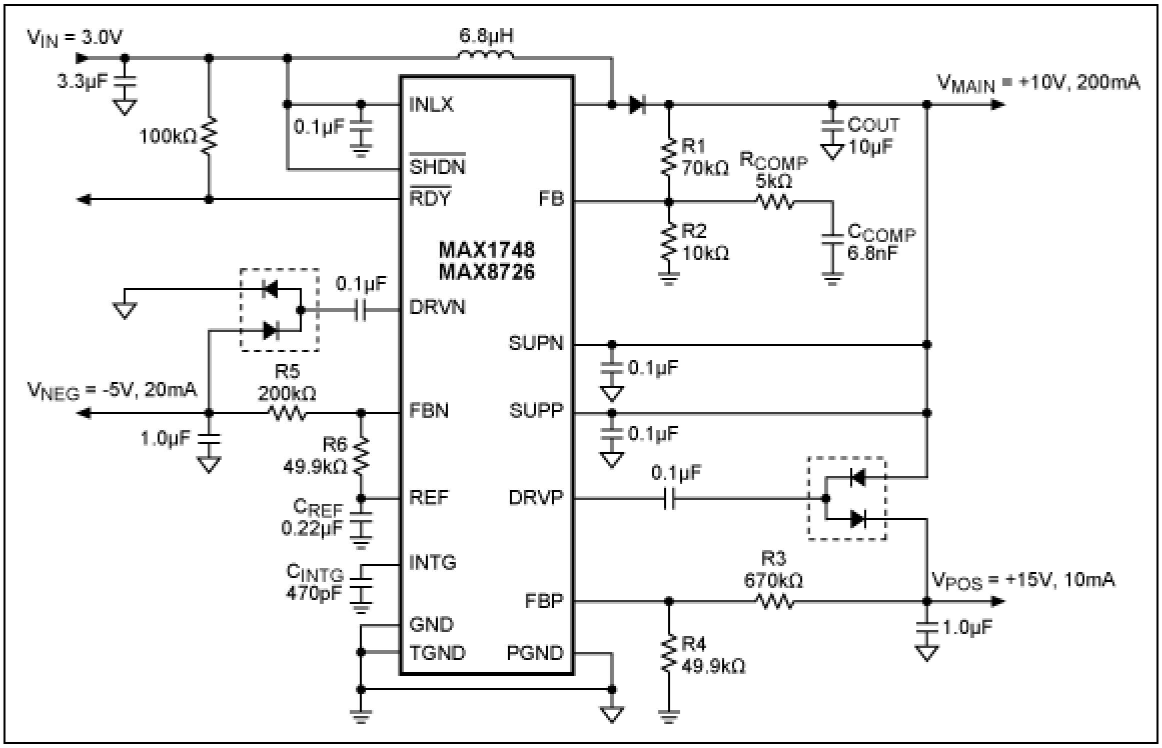


Figure 13. The MAX1748/MAX8726 generate three independent outputs from 3 alkaline cells or 1 single lithium-ion (Li+) cell.

Simple Battery Charging

For small handheld products, a lack of space and a limited budget often preclude sophisticated schemes for battery monitoring and charging. The goal in these cases is to squeeze the maximum performance from utilizing integrated stand-alone chargers.

The MAX846A is a cost-saving, multichemistry battery-charger system that comes in a space-saving 16-pin QSOP. This integrated system allows different battery chemistries (Li+, NiMH, or NiCd cells) to be charged using a single circuit.

In its simplest application, the MAX846A is a stand-alone (**Figure 14**), current-limited float-voltage source that charges Li+ cells. It can also be paired up with a low-cost microcontroller (µC) to build a universal charger capable of charging Li+, NiMH, and NiCd cells.

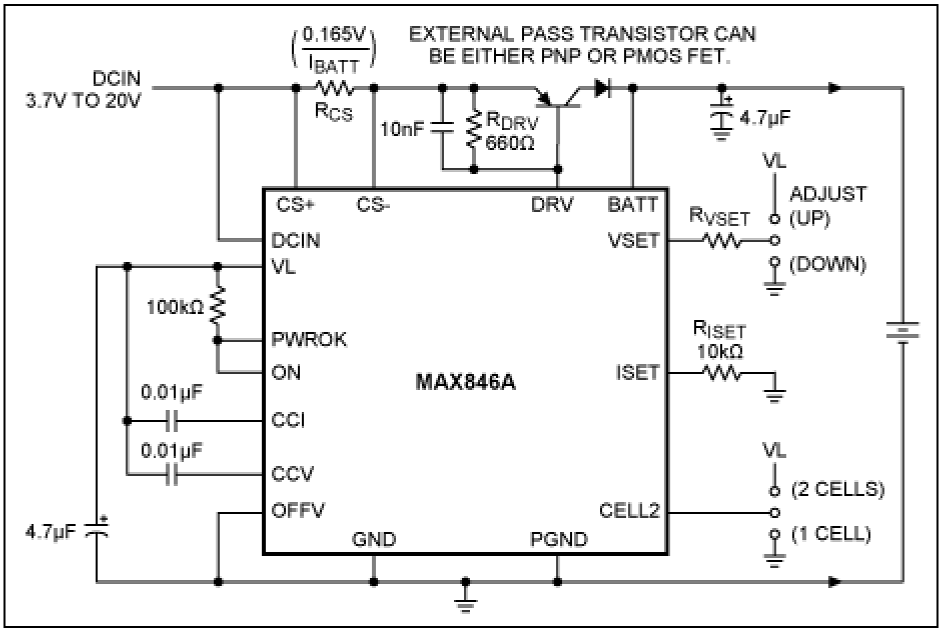


Figure 14. MAX846A stand-alone Li+ charger.

USB offers great opportunities as a power source for all types of low-power electronics, many of which are battery operated. The widespread availability of USB presents unique opportunities, as well as challenges for battery-charging designs. Fortunately, many chargers are handily available to ease USB designs. For example, the MAX8856 (**Figure 15**) is a complete 1-cell Li+ battery charge-management IC that operates from either a USB port or AC adapter. The device integrates a battery-disconnect switch, current-sense circuit, PMOS pass element, and thermal-regulation circuitry, while eliminating the external reverse-blocking Schottky diode. This creates a simple and small charging solution.

For dual AC-adapter and USB power inputs, the MAX8903 series can be used instead (**Figure 16**).

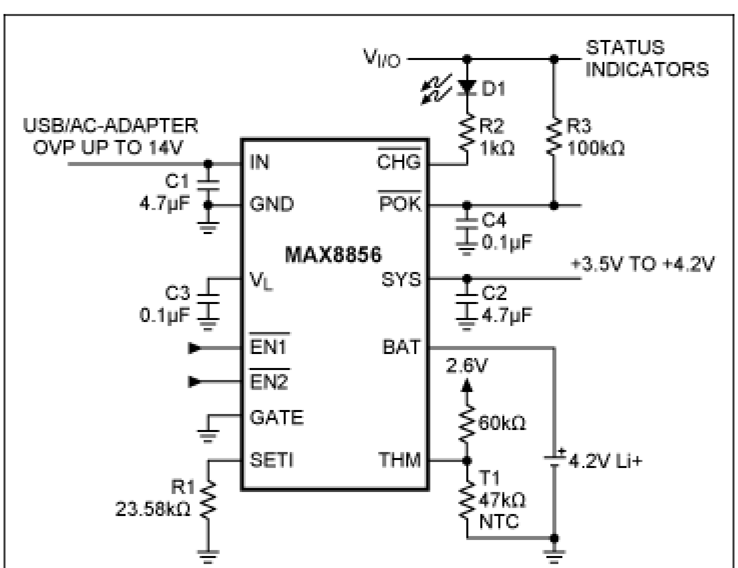


Figure 15. Single Li+ cell stand-alone application.

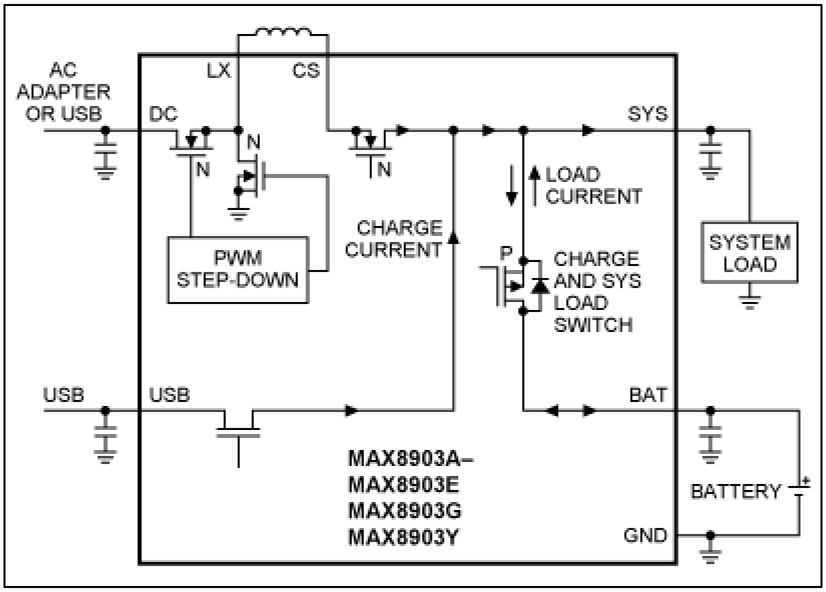


Figure 16. Single Li+ cell charger with dual AC-adapter and USB power inputs.

Reference

[1]Severns, Rudy, and Wittlinger, Hal, *High Frequency Power Converters*, Intersil Semiconductor application note 9208, April 1994.

Related Parts		
MAX1651	5V/3.3V or Adjustable, High-Efficiency, Low-Dropout, Step-Down DC-DC Controller	Free Samples
MAX1703	1-Cell to 3-Cell, High Power (1.5A), Low-Noise, Step-Up DC-DC Converter	Free Samples
MAX1748	Triple-Output TFT-LCD DC-DC Converters	Free Samples
MAX1771	12V or Adjustable, High-Efficiency, Low I_Q, Step-Up DC-DC Controller	Free Samples
MAX604	5V/3.3V or Adjustable, Low-Dropout, Low-I_Q, 500mA Linear Regulators	Free Samples
MAX649	5V/3.3V/3V or Adjustable, High-Efficiency, Low-I_Q, Step-Down DC-DC Controllers	
MAX662A	12V, 30mA Flash Memory Programming Supply	Free Samples
MAX757	3.3V/5V/Adjustable-Output, Step-Up DC-DC Converters	Free Samples

MAX846A	Cost-Saving, Multichemistry, Battery Charger System	Free Samples
MAX850	Low-Noise, Regulated, Negative Charge Pump Power Supplies for GaAsFET Bias	Free Samples
MAX856	3.3V/5V or Adjustable Output, Step-Up DC-DC Converters	Free Samples
MAX8625A	High-Efficiency, Seamless Transition, Step-Up/Down DC-DC Converter	Free Samples
MAX8903A	2A 1-Cell Li+ DC-DC Charger for USB and Adapter Power	Free Samples

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