Introduction

Proper supply sequencing and supervision are key aspects of a stable multi-power-supply system, but supply specifications are often finalized near the end of the project. This puts pressure on the supervisor and sequencing components to remain versatile, even as they are built into the design.

The LTC2928 offers a solution to the problem of moving target designs by using a simple approach to sequencing and supervision—no complicated firmware or software needed. You can configure sequence and supervisor thresholds, supply sequence order and timing with just a few components. The number of sequenced and supervised supplies is unlimited—just cascade multiple LTC2928s through a single pin. System faults can be shutdown all controlled supplies immediately, and application faults are detected and reported by the LTC2928, making quick work of fault diagnosis.

A Simple But Powerful Design Idea

One of the best ways to avoid expensive design rework at the back end of a project is to use the LTC2928 in generic reusable circuit blocks that are added early in the system design with little regard to the final specific power requirements. Leave blocks unfinished—simply waiting for passive component values to be determined.

Loaded with Features

Designing with the LTC2928 requires little more than specifying a few resistors, capacitors and the biasing of some three-state pins. Design flexibility however, is virtually unlimited. Table 1 outlines a few design features and configuration options available in the LTC2928.
EDITOR’S PAGE

Issue Highlights

Power supply specifications are notoriously fickle in many electronics designs, often pushing final sequencing and supervisor requirements dangerously close to the back end of the project.

The LTC2928 supervisor/sequencer solves this problem by making it easy to change power supply sequence and supervisor programs at the back end. While firmware and other software solutions remain expensive, cumbersome and/or overly complex, the LTC2928 combines remarkable versatility with ease of use. You can configure sequence and supervisor thresholds, supply sequence order and timing with just a few external components. The number of sequenced and supervised supplies is unlimited—just cascade multiple LTC2928s through a single pin. System faults can shutdown all controlled supplies immediately, and application faults are detected and reported by the LTC2928, making quick work of fault diagnosis.

See our cover article for more about this breakthrough device.

This issue features five other new Linear devices including a Hot Swap controller for CompactPCI and PCI Express systems, space-saving PowerPath solutions and a dual, 2-phase tracking regulator. Seven new Design Ideas and four New Device Cameos start on page 23.

Linear Technology in the News...

25 Years of Results
This year Linear Technology celebrates its 25-year anniversary. During that time, Linear has set the standard for high-performance analog. The company’s strategy from the beginning was to design and develop cutting edge integrated circuits, to continuously develop new products, and to provide our customers with superior technical support.

Bob Swanson, Cofounder and Chairman of Linear Technology stated in the company’s 2006 Annual Report, “When Linear was founded in 1981, to succeed it had to overcome a lot of what was then conventional wisdom. Investors didn’t think there was still much of an opportunity to back a new chip venture, much less an analog chip company during the dawn of the ‘Digital Revolution.’ The vision of the founding team turned out to be correct. 25 years later we can say with pride, we did it our way and the results speak for themselves.”

Bob Dobkin, Cofounder, Vice President, Engineering and Chief Technical Officer, added, “Linear’s direction of high-performance standard analog products had many hurdles to overcome 25 years ago. From turning down requests for custom ICs to convincing customers that this new small company was a reliable supplier of new functions were problems taken in stride. Linear aimed to be the best with outstanding designs, first rate processing, test and packaging, data sheets and customer support. The entire team was dedicated and remains so today.”

EE Times Ultimate Products Winner
EE Times recently announced Linear Technology’s LTC3035 300mA VLDO™ Linear Regulator as the number one analog product in the publication’s Ultimate Products category. The device features input voltage capability down to 1.7V. To allow operation at low input voltages, the LTC3035 includes an integrated charge pump converter that provides the necessary headroom for the internal LDO circuitry. The LTC3035’s tight output voltage ±2% accuracy; low quiescent and shutdown currents of 100µA and 1µA, combined with fast transient response and a compact solution, make it ideal for battery-powered handheld devices such as Bluetooth-enabled devices, cellular phones, media players, handheld medical and industrial instruments.

EE Times’ Ultimate Products are selected based on user rankings for technical significance and usability of the best new products. Following are a few comments on the LTC3035 from EE Times’ readers:

❑ “Reliable and strong ... easy to integrate”
❑ “Clever technology, as usual from Linear Tech.”
❑ “The low input to low output capability of LTC3035 regulator is just the match the market needed. The performance will get broad applications.”
❑ “Fantastic characteristics in such a small DFN package! Definitely will keep in mind for future apps.”

Electronica Show
At Electronica 2006, held in Munich, Germany, November 14–17, Linear Technology will showcase new products in Hall A4, Booth 538. At the Linear booth, customers will get an overview of Linear’s major new products in the following key areas:

❑ Power Management—LED drivers, power µModule™ products, DC/DC converters and battery chargers
❑ Mixed Signal—high speed ADCs, DACs, Power over Ethernet and Hot Swap
❑ Signal Conditioning—ADC drivers, op amps, silicon oscillators, filters and references
❑ High Frequency—active mixers, quadrature modulators and demodulators, power amplifier controllers and RF power detectors

Come see us in Munich.
How to Set Up the LTC2928

This section describes how to calculate the component values required to set particular supervisor and sequence parameters. The calculations are not difficult, but we recommend using the LTC2928 Configurator, a free calculation tool that does much of the work for you (see “The LTC2928 Configurator Tool Designs It for You” above). Either way, be sure to call about the available demo board, which you can use to quickly evaluate any configuration.

Figures 1 and 2 show a generic LTC2928 application and waveforms for the discussion and calculations here.

To set the supervisor undervoltage threshold at the V1 input (UVTH1), calculate the ratio for the resistive divider (R1B, R1A) between supply voltage S1 and ground:

\[
\frac{R_{1B}}{R_{1A}} = \frac{0.5V}{V_{UVTH1}(V) - 1}
\]

The resistive dividers for the other positive supervisor inputs are calculated in the same way.

If a negative supply is monitored on the V1 input, tie the VSEL pin to VCC. Connect the ground side of R1A to the REF pin. The reference voltage provides level shifting of the negative supply to the ground sensing comparator on the V1 input. Calculate the resistive divider ratio using

\[
\frac{R_{1B}}{R_{1A}} = \frac{V_{UVTH1}(V)}{V_{REF}}
\]

where \(V_{REF}\) is nominally 1.189 volts.

In the power supply world, undervoltage thresholds are commonly discussed as a percentage below the nominal supply voltage. The same is true for the LTC2928, but all other thresholds in the LTC2928 (sequence-up, sequence-down and overvoltage) are keyed to the configured undervoltage thresholds on each respective input, and are expressed as a percentage of the undervoltage threshold. A bias on the OVA pin globally configures the overvoltage threshold for all positive supplies. Use a resistor to ground to configure overvoltage thresholds in the range of 12% to 32% above the undervoltage threshold. Use a resistor to VCC for overvoltage thresholds greater than 32% above the undervoltage threshold. Use Figures 3 and 4 to select the OVA biasing resistor.

Typically, a single resistor (RTn) sets the power supply’s sequencing time position. The normal sequence-down order is the reverse of the sequence-up order, and order is preserved regardless of the number of cascaded LTC2928 devices. The sequence up/down time positions can also be actively changed—see “Active Sequence

### Table 1. LTC2928 feature summary

<table>
<thead>
<tr>
<th>Feature</th>
<th>Available</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Voltage Operation: 7.2V to 16.5V</td>
<td>✔</td>
</tr>
<tr>
<td>Low Voltage Operation: 2.9V to 6V</td>
<td>✔</td>
</tr>
<tr>
<td>Power-Up and Power-Down Sequencing</td>
<td>✔</td>
</tr>
<tr>
<td>Positive and Negative Supplies</td>
<td>✔</td>
</tr>
<tr>
<td>Sequenced Shutdown upon Loss of VCC*</td>
<td>✔</td>
</tr>
<tr>
<td>±1.5% Accurate Under Voltage Comparators</td>
<td>✔</td>
</tr>
<tr>
<td>Over Voltage Comparators</td>
<td>✔</td>
</tr>
<tr>
<td>Sequence Threshold Comparators</td>
<td>✔</td>
</tr>
<tr>
<td>Negative Supply Comparator</td>
<td>✔</td>
</tr>
<tr>
<td>Fault Channel and Fault Type Reporting</td>
<td>✔</td>
</tr>
<tr>
<td>Controller Fault</td>
<td>✔</td>
</tr>
<tr>
<td>Under Voltage Fault</td>
<td>✔</td>
</tr>
<tr>
<td>Over Voltage Fault</td>
<td>✔</td>
</tr>
<tr>
<td>Sequencing Fault</td>
<td>✔</td>
</tr>
<tr>
<td>External Fault</td>
<td>✔</td>
</tr>
<tr>
<td>Auto Restart*</td>
<td>✔</td>
</tr>
<tr>
<td>N-Channel MOSFET Gate Drive</td>
<td>✔</td>
</tr>
<tr>
<td>Power Supply Capacitance Discharge*</td>
<td>✔</td>
</tr>
<tr>
<td>RESET Disable for Margining</td>
<td>✔</td>
</tr>
<tr>
<td>Single Pin Cascading for More Supplies and Time Positions</td>
<td>✔</td>
</tr>
<tr>
<td>Fast Shutdown at Power-Down*</td>
<td>✔</td>
</tr>
<tr>
<td>Individual Comparator Outputs</td>
<td>✔</td>
</tr>
<tr>
<td>Adjustable Sequence, Power-Good and Reset Timers</td>
<td>✔</td>
</tr>
</tbody>
</table>

*see data sheet
Linear Technology Magazine • September 2006

Positioning** below. In this generic application, supply S1 is shown to start in time position 5 (TP5). Time position resistor RT1 is connected between VCC and the RT1 input pin. Time position resistors and the corresponding ideal time position voltages are given in Table 2. To configure time position 5 for supply S1, a 9.53kΩ resistor is selected. Time positions 6, 7 and 8 are similarly selected with RT resistors for supplies S2, S3 and S4.

Any sequencer/supervisor channel that must be shut off or is otherwise unused may be disabled by pulling the corresponding RT pin low (ground). Prior to sequencing-up, with the ON pin low, any or all enable pins may be forced high by pulling the respective RT pin to VCC. In this manner, supplies may be tested individually or together in any combination.

Transition the ON pin to begin sequencing-up or down. The shortest time delay between two time positions (TP2–TP1 for this example) or the time delay between an ON pin transition and the next time position is defined to be equal to tSTMR (sequence timer delay). The time between two adjacent time positions is potentially stretched by a power supply’s rise time to its configured sequence-up threshold. In Figure 2, supply S1 has a finite rise time tRISE(S1) to the sequence-up threshold SQTH1. Using three-state pins SQT1 and SQT2 (not shown), sequence-up thresholds can be set to equal to 100%, 67% or 33% of the configured undervoltage threshold. The time between TP5 and TP6 is seen to be equal to tRISE(S1) plus one tSTMR. The sequence timer delay is set with capacitor CSTMR and is calculated from

\[ C_{STMR}(F) = \frac{t_{STMR}(S)}{8.67M\Omega} \]

The PTMR pin configures the power-good timer which is used as a watchdog for stalled power supplies. When sequencing-up, a sequence fault is generated if any sequenced supply fails to reach its undervoltage threshold during the power-good time-out period. When sequencing-down, a sequence fault is generated if any sequenced supply fails to reach its sequence-down threshold during the power-good time-out period. The power-good timer starts with the first enabled (disabled) supply and is terminated when the last supply reaches its undervoltage threshold (sequence-down threshold). The power-good timeout period is set with capacitor CPTMR and is calculated from

\[ C_{PTMR}(F) = \frac{t_{PTMR}(S)}{4.0M\Omega} \]

To disable the power-good timer, simply tie the PTMR pin to ground. To avoid generating sequence faults due to insufficient power-good timer period, be careful to add some time
margin to the minimum recommended power-good timeout period. The minimum recommended time consists of the time difference between the first and last enabled (disabled) supplies added to the sum of supply rise (fall) times. The minimum recommended power-good timeout is given by

$$t_{TPMR} \text{ (min)} = [TP(max) - TP(min)] \times t_{STMR} + \sum_{n=1}^{4} \text{Max} \left( t_{RISE}(Sn), t_{FALL}(Sn) \right)$$

In this example, with the simplifying assumption of equal rise and fall times for all four supplies, the minimum recommended power-good timeout period reduces to

$$t_{TPMR} \text{ (min)} = [8 - 4] \times t_{STMR} + 4 \times t_{RISE} = 4 \times t_{STMR} + 4 \times t_{RISE}$$

Again, adding some additional time margin to this minimum time is helpful to avoid bogus sequence faults. Details regarding the biasing (high, low or open) of the three-state configuration pins (MS1, MS2, SQT1, SQT2, RDIS) are discussed in the LTC2928 data sheet.

**Active Sequence Positioning**

In most sequencing applications, the sequence-down order is the reverse of the sequence-up order. While the LTC2928 easily handles such applications, it is not limited to same up, same down sequencing. Two methods are available to obtain flexible sequencing order. The first technique uses a simple analog multiplexer to switch the resistance seen at the RT pin(s). The second technique uses a rail-to-rail voltage output DAC, preferably with I²C interface, such as the LTC2629, to directly drive a programmed voltage to the RT pin(s). Both methods require changing the voltage ($V_{RT}$) seen at the RT pin(s), subject to the error bound specified in Table 2. The RT pin input resistance is nominally 12k.

Figure 5 shows how a simple analog multiplexer is connected to allow a different sequence position on the basis of the DONE signal. During sequencing-up, the DONE pin is high, so RT1_UP is selected. When sequencing-up is complete, DONE pulls low and RT1_DN is selected. Sequencing-down commences once the ON pin is pulled low.

Figure 6 demonstrates how the low-power LTC2629 ratiometric voltage output DAC can be used in place of resistors to actively program sequence positions. The LTC2629 uses a 2-wire I²C compatible serial interface and is available in a tiny 16-lead SSOP package. Supply range and output drive capability are compatible with the LTC2928. Most importantly, the LTC2629 incorporates a power-on reset circuit that forces the outputs to zero scale until a valid write and update take place. This feature prevents

continued on page 12

![Figure 3. External resistor from OVA to ground](image)

![Figure 4. External resistor from OVA to $V_{CC}$](image)

![Figure 5. Active sequence positioning using an analog multiplexer](image)

![Figure 6. Active sequence positioning using an I²C DAC](image)

<table>
<thead>
<tr>
<th>Position Number</th>
<th>$R_T$ (kΩ)</th>
<th>Ideal $R_T$ Pin Set Point ($V_{RT} / V_{CC}$) ±0.005</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>95.3</td>
<td>1/9 = 0.111</td>
</tr>
<tr>
<td>2</td>
<td>42.2</td>
<td>2/9 = 0.222</td>
</tr>
<tr>
<td>3</td>
<td>24.3</td>
<td>3/9 = 0.333</td>
</tr>
<tr>
<td>4</td>
<td>15.0</td>
<td>4/9 = 0.444</td>
</tr>
<tr>
<td>5</td>
<td>9.53</td>
<td>5/9 = 0.556</td>
</tr>
<tr>
<td>6</td>
<td>6.04</td>
<td>6/9 = 0.667</td>
</tr>
<tr>
<td>7</td>
<td>3.40</td>
<td>7/9 = 0.778</td>
</tr>
<tr>
<td>8</td>
<td>1.50</td>
<td>8/9 = 0.889</td>
</tr>
</tbody>
</table>
Reduce the Size and Cost of High Current, High-Power-Density Systems with Tracking Dual, 2-Phase Constant Frequency Step-Down Regulator

by Wilson Zhou and Henry Zhang

Introduction

PolyPhase® power converters offer several advantages over single phase converters, including higher efficiency, smaller size and lower capacitor ripple currents. The LTC3828 is a 2-phase, constant frequency, dual synchronous buck controller that minimizes both the size and total cost of the power system.

The LTC3828 offers voltage tracking with flexibility of start-up control, a fixed internal start-up time and an adjustable external soft-start. Multiple LTC3828s can be daisy-chained in applications that require more than two tracked and synchronized voltages.

The LTC3828 is well suited to high current and high density power solutions. Its adjustable operating frequency (260kHz–550kHz) allows the use of small surface mount inductors and capacitors, and powerful gate drivers and short dead time make it possible to achieve high efficiency over a wide range of load currents. Figure 1 shows a typical application and Figure 2 shows its efficiency.

Figure 1. The two outputs of this dual 2.5V/3.3V step-down converter operate out of phase to increase efficiency and reduce size. In this configuration, the channels track each other.

Figure 2. Efficiency of circuit in Figure 1

(a) Coincident tracking

(b) Ratiometric tracking

Figure 3. Two different methods of output voltage tracking
Tracking and Soft-Start

The two supply channels are ramped according to the voltages on the TRCKSS pins. The channel outputs track either coincidentally or ratiometrically, as shown in Figure 3.

To implement coincident tracking (Figure 3a), connect a resistive divider to the output of the master channel (for coincident tracking, the master must be the higher output voltage) and connect its midpoint to the slave channel’s TRCKSS pin. The ratio of this divider should be the same as the slave channel’s feedback divider (Figure 4a). To implement ratiometric tracking (Figure 3b), no extra divider is needed; simply connect one of the TRCKSS pins to the other channel’s VFB pin (Figure 4b).

Figure 5 shows the tracking function. At the input stage of the error amplifier, three diodes are used to clamp the equivalent reference voltage. The top two current sources are of the same value. When TRCKSS voltage is low, switch S1 is on and VOSENSE follows the TRCKSS voltage. When the TRCKSS voltage is close to the reference voltage, 0.8V, switch S1 is off and VOSENSE follows the reference voltage. Regulation of the channels’ outputs is not affected by the tracking mode. In the ratiometric tracking mode, the two channels do not exhibit cross talk.

When LTC3828 is configured to soft-start by itself, an external soft-start capacitor should be connected to the TRCKSS pin. A soft-start current of 1.2µA charges the soft-start capacitor. If during start-up, the voltage at TRCKSS pin is already higher than 0.8V, the soft-start for this particular channel is provided by an internal soft-start timer (about 450µs). If the voltage at TRCKSS pin is already high, but lower than 0.8V, this channel’s VOSENSE follows the internal soft-start voltage until the internal soft-start voltage higher than the voltage on TRCKSS pin.

During start-up, if the voltage on TRCKSS pin is lower than 60mV, there is no switching action to force the output to follow the tacking pin voltage. This is helpful to prevent the power supply from mis-tracking noise and potentially damaging the system. When the TRCKSS pin voltage ramps up and is lower than 0.6V, no negative inductor current is allowed and the converter stays in pulse skip mode. Figure 6 shows the output voltage and inductor current waveforms during start-up.

Power Good Monitor and Fault Protection

Two window comparators monitor the feedback voltages and the open-drain PGOOD output is pulled low when the feedback is not within the 7.5% of the 0.8V reference voltage. The PGOOD only monitors the channel when the channel is enabled (This channel’s RUN pin voltage is high). For example, if channel 1 is shutdown and channel 2 is enabled, PGOOD is high only

continued on page 28
Introduction
Servers that operate in critical industrial applications, such as communications and data-storage, must do so with near-zero down-time. Such high availability systems cannot be shut down to replace or upgrade circuit boards, so Hot Swap capabilities are paramount. Once a board is in the system, it is also important to continually monitor its power consumption to anticipate board failure. The LTC4245 makes it easy to satisfy both the Hot Swap and monitoring needs of high availability systems. It incorporates a quad-supply Hot Swap controller and an 8-bit ADC for board supply voltage and current monitoring. Access to supply monitoring data is via an I2C-compatible interface.

The LTC4245 is designed to be used in a CompactPCI (CPCI) Hot Swap board, where the four supplies are 12V, 5V, 3.3V, with an optional –12V. The LTC4245 can also work with one 12V and two 3.3V supplies as in a PCI Express system. Other features of the device include:

- External N-channel MOSFET switches on all four supplies allow flexible power distribution among the supplies.
- dl/dt limited inrush current control prevents supply glitches on backplane due to L • dl/dt drops.
- Each supply has a circuit breaker with a 20µs filter and a fast current limit at 3x the circuit breaker threshold, thus preventing minor load current surges from causing spurious resets.
- The four board supplies can be turned on together, in a built-in sequence or in any other sequence through the I2C interface.
- A power good input with timeout allows external supply monitors to turn off the board supplies in case of downstream faults.

- Integrated CPCI bus precharge voltage output and PCI reset signal logic saves board space in CPCI designs.
- All of the above is available in a 36-pin SSOP package and a space-saving 5mm × 7mm 38-pin QFN package. The QFN package includes two GPIO pins in addition to the one on the SSOP package.

Measure Board Power Consumption with Integrated ADC
As soon as the 12V supply is available to the LTC4245, the onboard ADC starts measuring its thirteen input channels one after another. Twelve of these are the input voltage, current sense voltage, and output voltage of each supply. The thirteenth channel can be multiplexed to any of the three GPIO pins. Each channel’s conversion result is written to a separate 8-bit register. The I2C interface is used to access the registers. The voltage and current data, when collected over a period of time, can provide insight into the health of a board. It also facilitates real-time power budgeting and management of the entire system.

The ADC can be halted by writing to a register bit. This can be used to convert only one channel repeatedly instead of allowing the ADC to cycle through all its inputs. It even allows reading and writing to the ADC data registers for software testing purposes.

Typical CompactPCI Hot Swap Application
In a CPCI application the LTC4245 resides on the plug-in board side of the connector, as shown in Figure 1. The four N-channel pass transistors, Q1–Q4, isolate the backend supplies from the inputs. Supply current sensing is provided by the voltage drop across resistors R1–R4. Resistors R5–R8 prevent high-frequency oscillations in Q1–Q4 respectively. C8 compensates the 12V current limit loop, while the other supply loops are compensated by their respective MOSFET gate capacitances and require no additional compensation components.

The CPCI male connector on the backplane has staggered pin lengths to ensure that all power supplies are physically connected before backend power is allowed to ramp. The following is a typical hot-plug sequence:
1. ESD clips make contact.
2. Long power (5V, 3.3V, V(I/O)) and ground pins make contact and the 1V PRECHARGE voltage becomes valid. Power is applied to the pull-up resistors connected to the HEALTHY# and BD_SEL# signals. LOCAL_PCI_RST# is held in reset. All power switches are held off.
3. Medium length pins make contact. The internal low voltage...
Figure 1. CompactPCI Hot Swap board application using the LTC4245 to control and monitor power on ±12V, 5V and 3.3V supplies. The bus I/O lines are precharged to 1V during insertion and extraction. The CPCI geographical slot address is used to set the PC slave address of the part.
DESIGN FEATURES

supply (INTVCC) powers up from the 12V supply. Other connector pins that mate are HEALTHY#, PCI_RST# and the bus I/O pins (which are precharged to 1V).

4. Short pin BD_SEL# makes contact. If it remains low for 100ms, the plug-in board power-up cycle may begin immediately. If the ON pin is tied high, turn-on is automatic, otherwise the LTC4245 waits for a serial bus turn-on command.

Power-Up Sequence

Figure 2 shows the backend supplies powering up after BD_SEL# goes low. Internal current sources charge up the gates to turn on the external switches. The TIMER pin is pulled up to 2.56V with 100µA and is then reset to ground by an internal switch. Current limit faults are ignored until TIMER falls to 0.23V. HEALTHY# pulls low at the end of this start-up timing cycle if all supply outputs are above their power bad thresholds. LOCAL_PCI_RST#, which was low, now follows PCI_RST#.

A 10µA current pulls up on TIMER to start the power good input timeout cycle. The PGI pin must remain high at the end of the cycle, or all the switches are turned off.

dI/dt Controlled Soft Start

The LTC4245 uses the capacitor at the SS pin to set the ramp rate of the inrush current (dI/dt) for each supply. Initially SS is at ground. At start-up it is pulled up with a 20µA internal current source. Each supply has a current limit amplifier that servo the gate of its external MOSFET so that the inrush current never exceeds an internal current limit set by the SS pin voltage. The voltage ramp on the SS pin sets the rate of rise of this internal limit. When the gate voltage reaches the MOSFET threshold voltage, the switch begins to turn on. The amplifier modulates the gate pull-up current so that the sense resistor voltage drop follows the internally set current limit. Figure 3 shows this for the 3.3V supply.

Isolating Faults Prevents System Resets

The other job of a Hot Swap controller, apart from controlling inrush current, is to prevent faults on the output from propagating to the input and affecting other boards in the system. The LTC4245 features an electronic circuit breaker with a 20µs filter and a fast current limit at 3× the circuit breaker threshold for each supply. In the event of a short circuit at the output, the fast current limit pulls the gate of the MOSFET to the source in less than 1µs. Figure 4 illustrates this for the 12V supply. This limits the fault current and prevents damage to board traces and connector pins. The 20µs filter prevents temporary load current surges from activating the gate pull-down, eliminating unnecessary board resets.

During start-up, if any of the supply outputs has a short to ground, the ramping internal current limit is folded back to a lower value to mini-

Figure 2. Typical power-up sequence activated 100ms after BD_SEL# goes low.

Figure 3. dI/dt controlled soft-start on 3.3V supply during sequenced turn-on. Inrush current rise rate of 750mA/ms is set by the SS pin capacitor.

Figure 4. Fast current limit responds to a short-circuit on 12V output in less than 1µs, by pulling down 12VGATE to 12VOUT 20µs later, the internal circuit breaker timer expires and all switches are turned off.

Figure 5. By setting the Sequencing Enable bit in the CONTROL register before taking BD_SEL# low, the supplies turn on in a 12V, 5V, 3.3V, –12V sequence. Compare this to Figure 2.
mize MOSFET power dissipation. If a supply is still in current limit at the end of the start-up timing cycle, all switches are turned off and the TIMER pin goes through a cool-down timing cycle using a 2µA pull-up current. If overcurrent auto-retry is enabled, the 2% duty-cycle protects the MOSFET from excessive heating.

**Switch On Supplies in Any Order**

The ON and BD_SEL# pins can be used to turn the external MOSFET switches on or off. The BD_SEL# pin must be low for 100ms and ON pin set high to turn all switches on. The 100ms delay takes care of pin debounce when the BD_SEL# signal goes across a connector to implement detection of card insertion and extraction. The default LTC4245 behavior is to turn-on all switches together under the control of a single TIMER and SS cycle, as shown in Figure 2.

The turn-on behavior can be modified by writing to the ON and CONTROL registers through the I²C interface. Setting the sequence bit in the CONTROL register before taking BD_SEL# low turns the switches on in a 12V, 5V, 3.3V, –12V sequence. This

**Figure 6.** PCI Express backplane application to hot-plug and monitor 12V, 3.3V main and 3.3V auxiliary power. Tying the CFG pin to INTVCC lowers the 5V undervoltage and power bad thresholds to 3.3V levels, while also disabling those functions on the VEE pins.

**Figure 7.** A 12V and 3.3V application, similar to Figure 6, but one less 3.3V supply.
is shown in Figure 5. The most flexible turn-on behavior is afforded by the ON register. For this the ON pin should be set low. Now when BD_SEL# goes low the switches remain off. The ON register has four bits to control the state of each supply switch. Writing a one to any of these bits turns on that particular switch. In this way a host controller can turn on the supplies in any desired sequence or combination.

**Extensive Fault Information Aids Diagnosis**

If a board fault occurs, diagnosing the problem is simplified by checking the LTC4245’s onboard fault information. One status and two fault registers contain a record of faults that are present or have occurred.

The STATUS register reports if any supply is in an undervoltage or power bad state and if any switch is potentially shorted. It also indicates the state of the SS, PCI_RST#, LOCAL_PCI_RST#, BD_SEL# pins and the ADC. The fault registers log any faults that have occurred but may no longer be present. Individual bits record input undervoltage, output power bad and overcurrent faults on each supply. Each of these faults has an auto-retry bit in the CONTROL register. If a fault occurs and its auto-retry bit is set, then once the fault is removed the LTC4245 turns off the external switches automatically. Otherwise the switches are latched off until the fault bit is cleared.

Another 8-bit register called the ALERT register controls whether the occurrence of a particular kind of fault triggers the LTC4245 to pull the ALERT# pin low. This can be used to interrupt a host controller in real-time so it can query the LTC4245 register information and take appropriate remedial action. When multiple LTC4245s are present in a system, the SMBus Alert Response Protocol can be used to find the faulting LTC4245. The default behavior is to not pull ALERT# low for any fault.

**Flexible Supply Configuration**

The CFG pin on the LTC4245 can be used to deal with applications that do not utilize a –12V supply, or use another 3.3V supply instead of 5V. In a normal CPCI application the CFG pin is tied low. When the –12V supply is absent, the CFG pin is left unconnected. In this case, the LTC4245 disables the undervoltage lockout and power bad comparators on –12V, thus allowing 12V, 5V and 3.3V to power-up. By tying the CFG pin to INTVCC, not only is the –12V undervoltage and power bad ignored but 5V thresholds change to 3.3V levels.

Figure 6 shows the LTC4245 on a PCI Express backplane controlling one 12V and two 3.3V supplies. The VEE pins are all tied to ground. PRST#1 and PRST#2 signals sense when the plug-in card is seated. These signals are used by the PCI Express Hot-Plug Controller to command the LTC4245 to turn the switches on and off. Figures 7 and 8 show the LTC4245 controlling just two supplies, one of them 12V, the other being either 3.3V or 5V.

**Conclusion**

The LTC4245 packs a 4-supply Hot Swap controller, ADC, I2C interface and numerous other features into a 5mm x 7mm QFN package, simplifying the task of inrush control, fault isolation and power monitoring on a plug-in board. The simple default behavior can be customized through onboard registers. It provides a space-saving Hot Swap solution for any high-availability system utilizing multiple supplies such as CompactPCI or PCI Express.

---

*LTC2928, continued from page 5*

unintended sequencing in the event that the ON pin is not in the correct state at power-up since the RT pins would be near ground (all sequencing channels disabled).

**Conclusion**

The LTC2928 greatly reduces the time and cost of power management design by eliminating the need to develop, verify and load firmware at back end test. System control issues such as sequence order, timing, reset generation, supply monitoring and fault management are all handled with the LTC2928.
CCD Bias Supply Integrates “Output Disconnect,” Schottkys and Feedback Resistors

Introduction

CCD imagers continue to advance in increased resolution, faster readout rates and continuous video capability. All of these advances require increased power, but power supply designs must add power without reducing efficiency or increasing size. The LT3487 monolithic switching regulator offers a tiny, highly integrated, efficient bias supply solution for CCD applications. It integrates both boost and inverting regulators, Schottky diodes, a boost side output disconnect and ground-side feedback resistors—all in a 3mm x 3mm DFN package. The LT3487’s boost side DC current limit of 750mA and inverting switch limit of 900mA is more than sufficient to power the latest and next generation CCD imagers. The output disconnect ensures that power is not wasted due to DC leakage to the load in shutdown.

CCD Draws High Power from Discharged Li-Ion

Figure 1 shows the LT3487 in a high power CCD application that provides 45mA at 15V and 90mA at –8V from a nearly discharged Li-Ion battery at 3.0V. This power handling allows the LT3487 to be used in digital cameras with video capability.

This particular converter operates over a wide input voltage range between 2.3V and 16V. Both channels run at a 2MHz switching frequency, enabling the use of tiny inductors and capacitors. The fixed frequency PWM control provides outputs with low, predictable ripple.

External components are minimized as both channels incorporate on-chip Schottky diodes. Each channel also requires only one external resistor to set the output voltage. The second resistor in each divider is provided on-chip and trimmed to provide an accurate 25µA input current.

Soft-Start and Sequencing

When a DC/DC converter begins delivering power into an uncharged output capacitor, it normally runs in current limit until the output comes up into regulation. This large spike of current pulled from the input may not be acceptable in many applications where VIN has limited current sourcing capability. The LT3487 has soft-start functionality that clamps the internal V+ node to a slowly rising soft-start voltage, limiting the peak switch current. This allows the current in the inductor to rise much more slowly. The output comes into regulation more slowly, and the spike of current from VIN is eliminated.

In multiple channel regulators, the sequencing of the outputs can also be important. A typical CCD requires the positive output to come into regulation before the negative, and to collapse after it when the regulator shuts down. The intelligent soft-start of the LT3487 provides sequenced soft-start of both channels with a single external capacitor. The LT3487 sources 1.4µA from the RUN/SS pin that charges the soft-start capacitor; to shut down the device, use an open drain transistor to sink this current. With an adequately sized soft-start capacitor, the positive channel slowly comes up into regulation, and then the negative channel begins its own slow rise into regulation. Figures 3 and 4 show the output voltages and input currents with and without a soft-start capacitor. Note that even without a soft-start capacitor, the negative channel does not start up continued on page 35
Single Device Combines Pushbutton On/Off Control, Ideal Diode PowerPath and Accurate System Monitoring

by Eko T. Lisuwandi

Introduction
The proliferation of handheld and battery powered devices has made controlling the power paths of two or more power sources a common power supply design task. Some designers turn to discrete components and onboard microprocessors to manage the power path between power sources and the systems they run. However, discrete component and microprocessor solutions tend to be incomplete, inconsistent and large. A better alternative is to use the LTC2952 PowerPath controller in solutions that are more robust, easier to design and more efficient than discrete and microprocessor solutions.

The LTC2952 integrates three important power management functions into a single device: pushbutton ON/OFF control, ideal diode PowerPath control and accurate system monitoring. The LTC2952's pushbutton input, which provides ON/OFF control of system power, has independently adjustable ON and OFF de-bounce times. A simple microprocessor interface involving an interrupt signal allows for proper system housekeeping prior to power down.

The ideal diode power paths provide low loss switchover between two DC sources by regulating two external P-channel MOSFETs to have a small 20mV forward drop. High reliability systems can utilize the LTC2952's system monitoring features to ensure system integrity. These monitoring features include: power-fail, voltage monitoring and µP watchdog.

Features
The overall power path management solution offered by LTC2952 is compact and low power. LTC2952 is available in a 20-pin QFN 4mm × 4mm or 20-pin TSSOP. In standby mode it only consumes 25µA of quiescent current. For systems that require efficient management of more than two power paths, multiple LTC2952s can be used together in a single system. Other features include:

- Low loss switchover between DC sources
- User control or automatic management of low loss PowerPath
- PowerPath priority
- Pushbutton ON/OFF control
- Accurate comparator for digital ON/OFF control
- Wide operating voltage range: 2.7V to 28V
- Guaranteed threshold accuracy: ±1.5% of monitored voltage over temperature
- Adjustable pushbutton ON/OFF timers
- Simple interface allows graceful µP controlled shutdown
- Extendable house keeping wait time prior to shutdown
- 200ms reset delay and 1.6s watch dog time out
- ±8kV HBM ESD on PB input
- PowerPath selection status

Operation
The LTC2952 is designed to simplify applications requiring management of multiple power sources. The three main features of the part are: pushbutton control, ideal diode PowerPaths and system monitoring. Figure 1 shows a typical application of the LTC2952 where it drives the output voltage (VS) to the higher of the V1 (wall adapter) or V2 (battery) inputs.

The ideal diode drivers regulate two external P-channel MOSFETs to achieve the ideal diode PowerPath behavior that allows for a low loss switchover between two DC sources. Each driver regulates the gate of the PFET such that the voltage drop across its source and drain is 20mV. When

![Figure 1. Typical application of LTC2952 with automatic power-ORing between wall adapter and battery and pushbutton control of a DC/DC converter](image-url)
the load current is larger than the PFET’s ability to deliver the current with a 20mV drop across its source and drain, the gate drive voltage clamps at 7V and the PFET behaves like a fixed value resistor.

The pushbutton function debounces any pushbutton event on the PB pin. Note that the ON and OFF debounce times can be programmed independently by using two separate capacitors on the ONT and OFFT pins respectively. A valid pushbutton ON sets the EN pin to high impedance and a valid pushbutton OFF drives the EN pin low. In a typical application the EN pin is tied to the shutdown pin of a DC/DC converter. Therefore by toggling the EN pin, the pushbutton pin has direct control over the enabling/disabling of an external DC/DC converter. This control of system turn ON/OFF is accompanied by a graceful interface to a µP to ensure proper system power up and power down.

The LTC2952 also provides system monitoring functions via the VM, WDE, RST and PFI, PFO pins. The VM and WDE pins are respectively the voltage monitoring and the watchdog input pins that determine the state of the RST output with 200ms reset time and 1.6s watchdog time. The PFI and PFO pins are the input and output of an accurate comparator that can be used as an early warning power fail monitor.

The KILL, M1 and M2 pins are inputs to accurate comparators with 0.5V thresholds. The outputs of these comparators interact with the internal logic to alter the ideal-diode power paths and the pushbutton control behavior. Specifically, the KILL input provides any application with a capability to turn off system power at any point during operation. M1 and M2 pins are mode pins that configure the part to have slightly different behavior in the power path switchover of the two DC sources.

**Power Path Configurations**

**Configuration A:** Pushbutton Controller with Automatic Power-ORing between Wall Adapter and Battery

Figure 2 shows both the M1 and M2 pins connected to ground, which enables both of the ideal diodes. In this setup, power from the VS node to the system is controlled via the EN pin, which is connected to the shutdown pin of a DC/DC converter. Pushbutton control at the PB input toggles the EN pin.

**Configuration B:** Pushbutton Controller with Preferential Wall Adapter Operation and Automatic Switchover to Battery

In Figure 3 the M1 pin is connected to ground and the M2 pin monitors the wall adapter input. When the wall adapter voltage is below the trip threshold, both ideal diodes are enabled. When the wall adapter voltage is above the trip threshold, the primary ideal diode driver is disabled (shutting off Q1 and Q3) and the secondary ideal diode driver is enabled (turning on Q2). This means the load current is supplied from the wall adapter (V2) regardless of the voltage level at the battery (V1).

Because of the possible current path through the PFET body diode, a back-to-back PFET configuration must be used for Q1, Q3 to make sure that no current flows from the battery (V1) to VS even if the wall adapter (V2) voltage is less than the battery (V1) voltage.

**Configuration C:** Pushbutton Control of Ideal Diode Drivers

In Figure 4, the M2 pin is tied to the M1 pin. Since the M1 pin has a 3µA internal pull-up current, this current causes both M1 and M2 to pull...
up above 0.515V (the typical M1 and M2 pins rising threshold). This setup causes the device to operate such that the PB pin has complete control on both the ideal diode drivers and the EN pin. The first valid pushbutton input turns on both of the ideal diode drivers, causing the VS pin to be driven to the higher of either the wall adapter or the battery input. Conversely, the second valid pushbutton input turns off the ideal diodes after a shutdown sequence involving an interrupt to the system.

**Configuration D:**
**Battery Backup with Pushbutton Power Path Controller**
In this configuration the M1 pin is left floating, causing its 3µA (typ) internal pull-up to pull it above its rising threshold. With M1 high, the device operates such that the rising edge and the falling edge on the M2 pin are interpreted as digital ON and OFF commands respectively.

In this particular battery back up application (Figure 5), the M2 pin monitors the wall adapter voltage. When power is first applied to the wall adapter so that the voltage at the M2 pin rises above its rising trip threshold (a digital ON command), both of the ideal diode drivers and the DC/DC converter are enabled. Thus, power is delivered to the system. As soon as the wall adapter voltage falls below its trip threshold (a digital OFF command), a shutdown sequence is immediately started. At the end of the shutdown sequence, the ideal diode drivers and the DC/DC converter are disabled. As a result power is cut off from the load and the system is in shutdown.

Once power is delivered to the system, the PB pin can be used to turn off the power. If PB is used to turn off the power in this configuration, there are two methods to turn the power back on: a valid pushbutton ON at the PB pin, or cycling of the wall adapter voltage (bringing the voltage level at the M2 pin down below its threshold and then back up above its threshold—a digital ON command).

The voltage threshold of the wall adapter input (as monitored at the M2 pin) is usually set higher than the battery input voltage. Therefore, the only time power is drawn from the battery (V1 pin) is during the shutdown sequence when the voltage at the wall adapter input (V2 pin) has collapsed below the battery input voltage level.

**Reverse Battery Protection**
To protect the LTC2952 from a reverse battery connection, place a 1k resistor in series with the respective supply pin intended for battery connection (V1 and/or V2) and remove any capacitance on the protected pin. In Figure 6, R12 protects the V1 pin from a reverse battery connection.
**Pushbutton Bounce**

When a pushbutton is pressed, the voltage on the pin does not seamlessly switch from the pull-up voltage to ground. The voltage fluctuates as the pushbutton makes and breaks contacts for quite a number of cycles before finally settling.

Figure 7 shows a scope photo with significant bounce on the pushbutton pin. The LTC2952 ignores all the noise and sets a clean internal ON/OFF signal only after the pushbutton stops bouncing for 26ms plus the additional programmed time determined by the external capacitors CONT and COFFT.

The value of the reverse battery protection resistor should not be too large because the V1 and the V2 pins are also used as the anode sense pins of the ideal diode drivers. When the ideal diode driver is on, the VS pin supplies most of the quiescent current of the part (60µA) and each of the supply pins supplies the remaining quiescent current (20µA each). Therefore, the recommended 1kΩ reverse battery protection resistor amounts to an additional 20mV (1kΩ×20µA) drop across the P-channel MOSFET.

**Pushbutton Input**

The PB pin is a high impedance input to an accurate comparator with a 10µA pull up to an internal low voltage supply (4.5V). The PB input comparator has a 0.775V falling trip threshold with 25mV of hysteresis. Due to novel protection circuitry, the PB pin can operate over a wide operating voltage range (–6V to 28V) as well as having an ESD HBM rating of ±8kV.

The pushbutton circuitry’s main function is to debounce the input to the PB pin into a clean signal that initiates a turn-on or a turn-off power sequence. A complete pushbutton consists of a push event and a release event.

The push event debounce duration on the PB pin can be increased beyond the fixed internal 26ms by using an external capacitor. Specifically, placing a capacitor on the ONT and OFFT pins increases the debounce duration for the push event to turn on and the push event to turn off, respectively. The following equations describe the additional debounce time that a push event at the PB pin must satisfy before it is recognized as a valid pushbutton ON or OFF command.

\[ t_{ONT} = C_{ONT} \times 9.3\text{[µF]} \]
\[ t_{OFFT} = C_{OFFT} \times 9.3\text{[µF]} \]

Where \( C_{ONT} \) and \( C_{OFFT} \) are the ONT and OFFT external programming capacitors respectively.

During a turn-off push event (Figure 8), the INT pin is asserted low after the initial 26ms debounce duration. The INT pin continues to assert low while the PB pin is held low during the OFFT debounce duration. If the PB pin pulls high before the OFFT time ends, the INT immediately turns high impedance. On the other hand, if the PB pin is still low at the end of the OFFT time, the INT continues to assert low throughout the ensuing shutdown sequence.

On a release event (rising edge) on the PB pin following a valid push event, the PB pin must be continuously held above its rising threshold (0.8V) for a fixed 26ms internal debounce time before the next push event is recognized. Figure 8 shows a particular sequence of PB signals being debounced into a clean internal ON/OFF signal, and its effect on the state of the INT pin.

**Accurate Comparator**

**Input Pins VM, PFI, KILL, M1 and M2**

VM, PFI, KILL, M1 and M2 are all high impedance input pins to accurate comparators with a falling threshold.
of 0.5V (typ). Note the following differences between some of these pins: the VM pin comparator has no hysteresis while the other comparators have 15mV of hysteresis and the M1 pin has a 3µA pull up current while the other inputs pins do not.

Figure 9 shows a typical application where the VM, PFI, KILL or M2 pin connects to a tap point on an external resistive divider between a positive voltage and ground. The following formula shows the falling trip voltage from the resistor’s value:

$$V_{FALLING-TRIP} = 0.5V \left(1 + \frac{R1}{R2}\right)$$

M1 is different from the other high impedance input pins in that it has a 3µA internal pull up current. Typically the M1 pin is usually either connected to ground or left floating. When left floating, the internal 3µA pull up drives the M1 pin above its rising threshold (0.515V). Note that this 3µA pull up current can be used to pull up any of the other high impedance input pins. For example, many applications call for shorting the M1 and M2 pins so both are pulled above their rising thresholds.

**Voltage Monitoring and Watchdog Function**

The first voltage monitor input is PFI. This pin is a high impedance input to an accurate comparator with 15mV hysteresis. When the voltage at PFI is higher than its rising threshold (0.515V), the PFO pin is high impedance. Conversely, when the voltage level at PFI is lower than its falling threshold (0.5V), the PFO pin strongly pulls down to GND.

The second voltage monitor input is VM. This VM pin together with the WDE pin (as a watchdog monitor pin) affects the state of the RST output pin. The VM pin is also a high impedance input to an accurate comparator. However, the VM comparator has no hysteresis and hence the same rising and falling threshold (0.5V). When the voltage level at VM is less than 0.5V, the RST pin strongly pulls down to GND. When the voltage level at VM rises above 0.5V, the RST output pin is held low for a reset time out period (200ms) before turning high impedance.

After the RST pin becomes high impedance, if the WDE input pin is not left floating or not in a high-Z state, the watchdog timer is started. The watchdog timer is reset every time there is an edge (high to low or low to high transition) on the WDE pin. The watchdog timer can expire if no valid edge occurs on the WDE pin in a watchdog timeout period (1.6s) after the RST pin transitions from pulling low to being high impedance. It can also expire if no valid edge occurs on the WDE pin in a watchdog timeout period since the last valid edge on the WDE pin while the RST pin is high impedance.

When the watchdog timer is allowed to expire while the voltage at the VM pin is higher than 0.5V, the RST pin strongly pulls down to ground for a reset time out period (200ms) before again being high impedance for a watchdog timeout period (1.6s). This continues until there is again an edge at the WDE pin, the voltage at VM goes below 0.5V, or the watchdog function is disabled (by leaving the WDE pin floating or in a high-Z state).

**Power Turn-On/ Turn-Off Sequence**

Figure 10 shows a typical system power-on and power-off timing diagram. Note that in this timing diagram only the clean internal ON/OFF signal is shown. A transition at this internal ON/OFF signal can be caused by a valid debounced pushbutton at the PB pin or a digital ON/OFF command through the mode input pins (M1/M2).

In this timing sequence, the KILL pin has been set low since power is first applied to the LTC2952. As soon as the Internal ON/OFF signal transitions high (t1), the EN pin goes high impedance and an internal 500ms timer starts. During this 500ms, KILL On Blanking period, the input to the KILL pin is ignored and the EN pin remains in its high impedance state. This KILL On Blanking period is designed to give the system sufficient time to power up properly.

Once the µP/system powers on, it should set the KILL pin high (t2) indicating that proper power up sequence is completed. Failure to set KILL pin high at the end of the 500ms KILL On Blanking period (t3) results in an immediate system shut down (EN pin pulling down). However, in this typical sequence, with the KILL pin high at the end of the KILL On Blanking period, the system transitions to normal operation with power turned on.

When the Internal ON/OFF signal transitions low (t4), a shutdown sequence is immediately started. Note that during the shutdown sequence the INT pulls low. However, the transition from high to low at the INT pin can either occur at the beginning of the shutdown sequence if the transition low at the internal ON/OFF signal is as a result of a digital OFF command or earlier if the transition at the internal

---

*continued on page 26*
**Introduction**

GPS navigators, PDAs, MP3 players and other handheld devices draw on an increasing array of power sources for recharging their batteries. These sources include USB (4.5V), low voltage AC adaptors (4.5V–5V), high voltage AC adaptors (12V–24V), Firewire and automotive batteries. USB has the advantage of convenience while the high voltage sources offer faster charging at home and in the car. One issue with high voltage sources is that the voltage difference between the high voltage source and the battery is large enough that a linear charger cannot handle the power dissipation, thus dictating the need for a switching regulator.

The LTC4089 and LTC4089-5 integrate a high voltage, wide input range (6V–36V) monolithic 1.2A buck switching regulator, a USB input, a PowerPath controller and a linear charger into a compact thermally enhanced 3mm × 6mm DFN package. The LTC4089’s buck regulator output voltage follows the battery voltage, thus minimizing the overall power dissipation, while the LTC4089-5 has a fixed 5V output.

The USB is current limited power, so the LTC4089’s PowerPath controller distributes the available power, with the load taking precedence and any remaining current used to charge the Li-ion battery.

If the load current exceeds available current from USB, the additional current needed is drawn from the battery. If a high voltage source is connected to the input of the buck regulator (HVIN), the current is drawn from this source instead of the USB.

Figure 1 shows a complete solution that fits into less than 2cm² with all components on one side of the PCB (Figure 2).

**Operation**

As shown in the simplified block diagram (Figure 3), both the LTC4089 and LTC4089-5 consist of an integrated high voltage monolithic buck regulator, a PowerPath controller and a Li-ion battery charger. They are designed to manage power from a high voltage source (e.g., FireWire/IEEE1394, 12V–24V automotive batteries, 12V–20V wall adaptors, etc.), a low voltage source (e.g., USB or 5V wall adaptor) and a single-cell Li-ion battery. When an external power source is connected to the supply pins, it delivers power to the OUT pin and charges a battery connected to the BAT pin.

When high voltage is present at the HVIN pin, the monolithic high voltage switching regulator regulates the HVOUT voltage. An external PFET between HVOUT (connected to the drain) and OUT (connected to the source) is controlled by the HVPR pin, allowing OUT to supply the power to the load and charge the battery. The LTC4089 maintains about 300mV between the OUT pin and the BAT pin, while the LTC4089-5 provides a fixed 5V OUT voltage. The HVIN input takes priority over the IN input (i.e., if both HVIN and IN are connected to power sources, load current and charge current are provided by the HVIN input).

Power supplies with limited current capability (such as USB) are connected...
DESIGN FEATURES

High Voltage Switching Converter Saves an Adaptor
The LTC4089 and LTC4089-5’s input voltage range is 6V to 36V, well within the range of automotive batteries, Firewire, and other high voltage sources—no extra conversion to a lower voltage is needed.

Adaptive Buck Output Voltage Minimizes Total Power Loss
The LTC4089’s buck converter output voltage, \( V_{\text{OUT}} \), regulates to 0.3V above the battery voltage so that the battery can be charged efficiently with the linear charger. Figure 4 shows the overall efficiency at various input voltages. The minimum \( V_{\text{OUT}} \) is 3.6V to ensure the system can operate even if the battery is excessively discharged.

USB PowerPath Controller/Charger Maximizes Power Available to the System and Solves Other Problems
In a traditional battery powered device, the input charges the battery and the system’s power is directly taken from the battery. This simple topology presents some significant problems:

- **Case 1.** The load current is restricted to the trickle charge current. If the battery is excessively drained, the charger enters trickle charge mode, thus reducing the available system current to the 50mA to 100mA trickle charge. This may not be enough to start up the system, forcing the user to wait until the charger is in constant-current mode.

- **Case 2.** The system will not work without a battery. If a battery is not present, some systems will not turn on because this is considered a fault, or the charger output oscillates.

![Figure 3. A block diagram of the LTC4089 and LTC4089-5 shows the PowerPath controller, wide-input-range buck regulator and battery charging features.](image)

to the IN pin, which has a programmable current limit via a resistor connected at CLPROG pin. Battery charge current is adjusted to ensure the sum of the load current (which takes priority) and the charge current does not exceed the programmed input current.

The high voltage buck regulator operates at 750kHz in constant frequency current mode, allowing the use of a small 10µH–33µH inductor while providing 1.2A nominal output current and minimizing the number of the external compensation components.

**Features**

High Voltage Switching Converter

### Table 1. Comparison of traditional dual input charger and LT power manager/charger

<table>
<thead>
<tr>
<th>Case</th>
<th>Scenario</th>
<th>Traditional Dual Input Charger</th>
<th>LT Power Manager/Charger</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Battery voltage below trickle charging voltage</td>
<td>Available current to system is only trickle charge current (50mA–100mA), which may not enough to start the system</td>
<td>Full adaptor/USB power available to system</td>
</tr>
<tr>
<td>2</td>
<td>Battery is not present</td>
<td>Most chargers consider this as a fault. System can’t start</td>
<td>Full adaptor/USB power available to system</td>
</tr>
<tr>
<td>3</td>
<td>( V_{\text{BATT}} = 3.2V ) or USB input</td>
<td>Available power to system is limited to 1.6W.</td>
<td>Worst case 2.2W available to system.</td>
</tr>
<tr>
<td>4</td>
<td>System consuming close to input power</td>
<td>Can’t distinguish the available charging current. Charger timer runs out before battery is fully charged</td>
<td>Charger timer increases charging time with decreasing available charging current. Battery always fully charged.</td>
</tr>
</tbody>
</table>

Linear Technology Magazine • September 2006
Case 3. Available power reduces with battery voltage. Because the available system load power depends on the battery voltage, when USB input is used, the available system power is restricted to 1.6W (3.2V battery voltage).

Case 4. The battery cannot be fully charged. In this scenario, the battery slowly charges because the system draws the bulk of the available power, leaving little current for the charger. The problem arises because the safety timer runs out before the battery can be fully charged.

The LT4089/LTC4089-5’s PowerPath controller/charger solves the above problems (see Table 1) and provides other benefits (see “Additional Features” below).

For instance, in Case 1, the system gets the current it needs—anything left over is available to trickle-charge the battery. The removal of the battery (Case 2) doesn’t affect the system’s available power, which is over 99% from a wall adaptor and 98% from the USB (0.1V drop on the 0.2Ω FET). This means that the available power to the system is at least 2.2W (assuming a 4.5V USB) versus 1.6W when battery is at low 3.2V (Case 3). The LTC4085 has a smart, adaptive safety timer, whose time extends inversely to the charging current in constant-current charging mode. This solves the problem in Case 4.

Additional Features

The LT4089/LTC4089-5 offers other advantages over a basic charger in line with a battery:

- Seamless transition between the three power sources: AC adaptor, USB input, and Li-ion battery.
- 200mΩ monolithic ideal diode from battery to system load.
An external FET gate signal is provided if user wants to use an external switch between the battery and the load to reduce $R_{DS(ON)}$ losses.

- Charging current is system load dependent, guaranteeing the compliance to USB current limits
- Constant-current/constant-voltage battery charge operation
- Thermal foldback to maximize charging rate without risk of overheating
- Accurate monitoring of USB current: 5% for 500mA and 10% for 100mA
- Preset 4.2V charge voltage with 0.8% accuracy
- NTC thermistor input for temperature qualified charging
- C/10 charge current detection output (CHRG)
- High voltage present indication (HVPR)

### Applications

Figure 5 shows a typical LTC4089/LTC4089-5 circuit schematic. Designing a complete USB, high voltage, battery charger circuit is relatively easy—only a few external components are needed to set the operating parameters:

- **IN pin (USB) current limit** is set by resistor connected to CLPROG pin (2.1kΩ for 475mA USB current limit with maximum of 500mA considering component tolerances)
- **Charge current** is set by a resistor connected to PROG pin (71.5kΩ for 700mA charge current)
- **Charge safety timer** is a function of $R_{PROG}$ (R4) and capacitor C4 connected to TIMER pin. A typical value is 0.15µF for a 3-hour charging time for the constant charging current of 700mA. The time for the constant current charge portion increases with decreasing available charging current to ensure the battery is always fully charged. The increase in charge time is reflected on the frequency of the triangular waveform on C4.

### Application Caveats

#### High Voltage Buck Input Surge Protection

The small size and low impedance of ceramic capacitors make them an attractive option for the input bypass capacitor at LTC4089/LTC4089-5’s buck HVIN pin. However, these capacitors cause problems if the circuit is plugged into a live supply (see Linear Technology Application Note AN88 for a complete discussion). The low loss ceramic capacitor combined with parasitic inductance in series with the source forms an under-damped LC tank circuit and the voltage at the HVIN pin can ring as much as twice the nominal input voltage, possibly exceeding the maximum voltage rating and damaging the part. If the input supply is poorly regulated or the user can hot plug the LTC4089/LTC4089-5 into an energized supply, an input network should be designed to prevent the overshoot.

Figure 6a shows the waveforms that result when an LTC4089 circuit is connected to a 24V supply through six feet of 24-gauge twisted wire. The first plot is the response with a 2.2µF ceramic capacitor at the input. The input voltage HVIN rings as high as 35V and the input current peaks at 20A. One method of damping the tank circuit is to add another capacitor with a series resistor to the circuit. In Figure 6b an aluminum electrolytic capacitor has been added. This capacitor’s high equivalent series resistance dampens the circuit and eliminates the voltage overshoot. The extra capacitor improves low frequency ripple filtering and can slightly improve the efficiency of the circuit, though it is likely to be the largest component in the circuit. An alternative solution is shown in Figure 6c. A 1Ω resistor is added in series with the input to eliminate the voltage overshoot (it also reduces the peak input current). A 0.1µF capacitor improves high frequency filtering. This solution is smaller and less expensive than the electrolytic capacitor. For high input voltages its impact on efficiency is minor, reducing efficiency less than one half percent for a 5V output at full load operating from 24V.

Continued on page 32
Introduction
Transformers are a key component in many switching regulator designs, providing an isolation barrier in dangerous high power systems, allowing very high step-down or step-up ratios in high voltage designs and (with an extra winding) easily accommodating multiple or inverting outputs. Flyback, forward and SEPIC converters all make use of transformers. This article tells you what you need to know to add transformers to LTspice/SwitcherCAD III simulations.

Draw Each Winding as an Inductor
Figure 1 shows the basic technique. One simply draws each winding of the transformer as an inductor and couples the inductors with a SPICE directive called a K-statement (e.g., "K1 L1 L2 1").

To add the directive, choose SPICE Directive from the Edit menu. This allows you to place text on the schematic that is included in the SPICE netlist. Once the inductor is mentioned in a K-statement, LTspice uses an inductor symbol with a visible phasing dot to indicate each winding's phasing.

Setting the turns ratio of the transformer is simply a matter of choosing the right inductor values. Remember, the inductance is proportional to the square of the turns ratio. In the example above, a turns ratio of 1:3 gives a 1:9 inductance ratio.

The last entry of the K-statement is the mutual coupling coefficient. This is on a scale of 0 to 1 where 1 means perfect coupling between the inductors (i.e., no leakage inductance.) Leakage inductance is usually not desired in a practical circuit. For example, in transformers that are intended to store energy, such as in a flyback converter, leakage inductance prevents the secondary from removing all of the energy stored by the primary. In a non-energy storage transformer, the leakage inductance's impedance can limit how well the secondary can shield the core from the primary current setting a hard limit on how much energy can be transformed through the transformer. Either way, leakage inductance can cause undesired voltage spikes or ringing which can lead...
to a requirement for snubbing circuits and their associated energy losses. We’ll get back to leakage inductance later, but for an initial simulation, it’s easier and often sufficient to ignore leakage inductance by setting the mutual coupling coefficient to 1.

**Multiple Secondaries**

When you have a transformer with more than one primary and one secondary you have to make sure that all mutual inductances are included. Consider a transformer with four windings: L1, L2, L3 and L4. A common error is adding only three mutual couplings with three separate K-statements for such a transformer with four windings:

\[
\begin{align*}
K1 & : L1 \leftrightarrow L2 \quad 1 \\
K2 & : L1 \leftrightarrow L3 \quad 1 \\
K3 & : L1 \leftrightarrow L4 \quad 1 \\
K4 & : L2 \leftrightarrow L3 \quad 1 \\
K5 & : L2 \leftrightarrow L4 \quad 1 \\
K6 & : L3 \leftrightarrow L4 \quad 1
\end{align*}
\]

LTspice will tell you that this transformer is impossible since it’s not possible for L1 to be perfectly coupled to L2 and L2 perfectly coupled to L3 without some coupling between L1 and L3. Yes, it is possible for two inductors to have no mutual inductance yet have some coupling to a third, but there are limits on how well they can be coupled to that third. LTspice analyzes the mutual coupling coefficient matrix and determines if your coupling coefficients are physically realizable.

A transformer with four windings usually has six non-zero mutual inductances:

\[
\begin{align*}
K1 & : L1 \leftrightarrow L2 \leftrightarrow L3 \leftrightarrow L4 \quad 1 \\
K2 & : L1 \leftrightarrow L2 \leftrightarrow L3 \leftrightarrow L4 \quad 1 \\
K3 & : L1 \leftrightarrow L2 \leftrightarrow L3 \leftrightarrow L4 \quad 1 \\
K4 & : L2 \leftrightarrow L3 \leftrightarrow L4 \quad 1 \\
K5 & : L2 \leftrightarrow L3 \leftrightarrow L4 \quad 1 \\
K6 & : L3 \leftrightarrow L4 \quad 1
\end{align*}
\]

In general, the number of mutual inductances in a transformer with N windings is \(N \times (N - 1)/2\). Note that the number grows as N squared, just like the inductance of each individual winding is proportional to the square of the number of turns.

Permuting all the inductor names by hand to generate individual mutual coupling statements for each mutual inductance is tedious at best and tends to be error prone. A better approach is to use a single K-statement that mentions all the inductors that are wound on the same core and let LTspice do the work:

\[
K1 : L1 \leftrightarrow L2 \leftrightarrow L3 \leftrightarrow L4 \quad 1
\]

LTspice understands this to mean that all these inductors are coupled to each other by the same mutual coupling coefficient. Figure 2 shows this technique used in a transformer with four windings configured as an autotransformer by connecting the windings in series.

**Leakage Inductance**

You may want to simulate the effects of leakage inductance in order to consider snubber designs or work out the commutation timing of a resonantly switched converter. There are two ways to add leakage inductance to your model. You can either put extra inductors in series with the leads of the winding inductors—a very direct approach—or use a mutual coupling coefficient of less than one. The leakage inductance, \(L_{LEAK}\), can be related to the winding inductance, \(L\), and coupling coefficient, \(K\), by the equation:

\[
L_{LEAK} = L \times (1 - K \times K)
\]

If \(K\) is close to 1, the two methods are electrically equivalent.

One note of caution: The modeling effort increases significantly when leakage is added, because once you add leakage inductance to a simulation, you also need to model the capacitances that can ring with it and the losses that limit the Q of the ringing, in order to get any agreement between simulated and measured effects. For this reason, I usually recommend starting simulating without any leakage inductance and then add it later if you feel you need to investigate the non-ideal behavior due to leakage inductance in the transformer.

**Conclusion**

To simulate a transformer in your LTspice/SwitcherCAD III simulations, just draw each winding of the transformer as an individual inductor. Then add a SPICE directive of the form \(K1 L1 L2 L3 ... 1\) to the schematic. That’s basically it!

For an example simulation file using coupled inductors in a SEPIC converter, visit the product page for the LTC1871 controller at www.linear.com and click on the Simulate tab for a ready-to-run a demonstration circuit.
Miniscule Step-Up Controller Yields Wide Input and Output Ranges

by Theo Phillips and Hong Ren

**Introduction**

Small in stature, but big in power, the LTC3872 boost controller can produce an expansive range of output voltages with the bare minimum in components. Its design forgoes a few features and pins (TRACK, SYNC, and MODE, for instance) to squeeze into a slender 8-pin 3mm × 2mm DFN or leaded TSOT-23 package. Nevertheless, it gives up little in versatility, providing up to 60V in regulated output from a 2.75V–9.8V input. This input range accommodates one or two lithium-ion batteries, in addition to the common 3.3V and 5V input rails.

**Space-Saving Design**

Matching the LTC3872’s small size, its 550kHz constant frequency operation allows the use of a small-footprint surface mount inductor and ceramic capacitors. This saves space over boost controllers that use a constant on-time switching scheme, which can result in a lower operating frequency and physically larger filter components. No RSENSE™ technology eliminates the need for a separate current-sensing resistor. Just a few additional resistors and capacitors are needed to program the output voltage and close the feedback loop; the user can adjust OPTI-LOOP® compensation to accommodate whatever output voltage and filter components are chosen.

**Light Load Efficiency**

At light loads, pulse skip mode maintains constant frequency operation. This has the dual benefit of minimizing ripple and keeping switching noise within a predictable, easily filtered band. Output voltage remains stable in the presence of transients, due to the LTC3872’s current mode architecture.
A 3.3V Input, 5V/2A Output Boost Converter

Figure 1 shows a typical LTC3872 application—a 3.3V input to 5V output boost regulator which can deliver up to 2A load current. Figure 2 shows the efficiency/power loss curve. In spite of the converter’s small size, efficiency peaks at 90% and stays above 80% down to 20mA. In shutdown mode it draws only 8µA.

The LTC3872 uses the drain to source voltage of the external N-channel MOSFET to sense the inductor current. Eliminating a separate sense resistor can increase efficiency by 1%-2% at heavy loads. Absent a short circuit at the output, the maximum current that the converter can draw from $V_{IN}$ is determined by the $R_{DS(ON)}$ of the MOSFET (a function of the gate drive voltage $V_{IN}$). This maximum current can be adjusted by using the three-state current limit programming pin IPRG.

A 5V Input, 48V/0.5A Output Boost Converter

Figure 3 shows the LTC3872’s ability to deliver high output voltage. In this topology, the limitation on $V_{OUT}$ is the 60V maximum rating of the SW pin. Where even higher output voltages are required, a sense resistor can be inserted between the source of the MOSFET and ground, with the SW pin tied to the high side of the sense resistor. The output is well-controlled against overshoot and undershoot during startup and load transients (Figure 4). At high duty cycle under heavy loads, the commutation cycle (here, 1/550kHz) is too brief to allow the average inductor current to equal the converter’s required input current. In this case, the on-time of MOSFET M1 is extended, and inductor current ramps up to the level required to maintain output regulation (Figure 5).

Conclusion

The LTC3872 is a tiny current-mode, non-synchronous boost controller that requires no sense resistor—a typical design occupies 2.25cm$^2$ (Figure 6). The small solution size and wide input voltage range make it an easy fit for a variety of applications.
High Voltage Step-Down Controller Delivers High Power with Minimum Number of Components

by Stephanie Dai and Theo Phillips

Introduction
The LTC3824 is a non-synchronous buck controller that accepts inputs from 4V to 60V and is robust in the presence of large input transient voltages (Figure 1). It draws just 40µA of quiescent current in Burst Mode operation, prolonging run time in battery-powered applications. To handle the wide range of temperatures found in automotive and industrial applications, the LTC3824 comes in a thermally enhanced 10-pin MSE package.

12V/2A from a Wide Input Voltage Range
A typical LTC3824 application (Figure 2) can deliver up to 2A of continuous load current, and provides up to 90% efficiency at 1A (Figure 3). Sturdy 2A, 8V gate drivers accommodate industrial high voltage P-channel MOSFETs. By using a P-FET as a main switch, the controller is able to operate up to 100% duty cycle, and does not require the boost capacitor and diode found in N-channel buck regulators. This means that whenever the input voltage dips below the programmed output voltage, the output voltage gracefully follows the input voltage (reduced by I²R losses through the sense resistor, P-FET and the inductor) (Figure 4). LTC3824’s current mode architecture provides excellent line and load transient response with few compensation components. Input current is continuously sensed through a resistor in series with the P-FET, providing accurate current limiting and rapid overvoltage and short circuit protection.

Two Modes of Operation
The LTC3824’s SYNC/MODE pin allows the user to select between operating modes that improve efficiency at light loads. If the pin is left open or held above 2V, the part commences Burst Mode operation at about 1/3 of the programmed current limit. During Burst Mode operation, switching cycles are skipped to reduce switching losses, especially important to extend battery life in mobile applications. Grounding or applying an external clock to the SYNC/MODE pin forces the controller into pulse skip mode at light load. In pulse skip mode, the burst clamp is set to zero current, which limits the minimum peak inductor current to a level set by the minimum on-time of the control loop. Although pulse skip mode is not quite as efficient as Burst Mode operation at very light loads, it reduces VOUT ripple while operating at a constant frequency, thus reducing possible noise in the radio and audio ranges and simplifying noise filtering. The operating frequency can be programmed with a single resistor RSET, or it can synchronize to an ex-
ternal clock from 200kHz to 600kHz. Synchronization facilitates integration into applications using other switching regulators.

**Essential Soft-Start, Short Circuit and Overvoltage Protection**

The LTC3827 includes a programmable soft-start time, which requires only a single external capacitor between the SS pin and ground. At high input voltages, a relatively large capacitor prevents inrush currents during start-up. This in turn prevents output overvoltage and sudden drops in \( V_{\text{IN}} \), which in the extreme case could force the LTC3824 below its 4V undervoltage lockout. During soft-start, the voltage on the SS pin, \( V_{\text{SS}} \), acts as the reference voltage that controls the output voltage ramp-up. The effective range of \( V_{\text{SS}} \) during ramp-up is 0V to 0.8V. The typical time for the output to reach the programmed level is determined by the selected soft-start capacitor and the SS pin’s 7µA pull-up current: \( T_{\text{SS}} = (C \cdot 0.8V)/7\mu A \).

Short circuit and overvoltage protection are designed to keep the LTC3824 operating normally even under extreme conditions. In normal operation, the feedback voltage \( V_{\text{FB}} \) is regulated to 0.8V. If \( V_{\text{FB}} \) drops below 0.5V, the LTC3824’s switching frequency folds back to 50kHz on the assumption that inductor current is ramping up too quickly during the MOSFET’s on-time. Runaway is avoided by providing extra time for the inductor current to discharge. An overvoltage comparator monitors the voltage at \( V_{\text{FB}} \), and in the event of an overshoot adjusts the \( V_C \) voltage downward, keeping the MOSFET off. The overvoltage protection (OVP) threshold is lowered during light load Burst Mode operation, which causes cycles to be skipped. The OVP threshold goes up when load current increases. This scheme maintains protection yet ensures the tightest possible output voltage regulation.

**Conclusion**

LTC 3824 is a high voltage step-down controller with essential features for many sophisticated industrial and automotive systems. It comes in a tiny thermally enhanced 10-pin MSE package (Figure 5) to save space, and is highly configurable, including the ability to synchronize with external frequency sources, two modes of light load operation, and programmable soft-start and current limit.

---

**Table 1. The phase relationships of the two output channels and the clock out (CLKOUT) pin depend on the voltage at the PHSMD pin.**

<table>
<thead>
<tr>
<th>( V_{\text{PHSMD}} )</th>
<th>GND</th>
<th>OPEN</th>
<th>INTVCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Controller 1</td>
<td>0°</td>
<td>0°</td>
<td>0°</td>
</tr>
<tr>
<td>Controller 2</td>
<td>180°</td>
<td>180°</td>
<td>240°</td>
</tr>
<tr>
<td>CLKOUT</td>
<td>60°</td>
<td>90°</td>
<td>120°</td>
</tr>
</tbody>
</table>

A comparator monitors the output for overvoltage condition. When the comparator detects the feedback voltage higher than 7.5% of reference voltage, the top MOSFET is turned off and the bottom MOSFET is turned on.

**Phase-Locked Loop and Phase Mode Selection**

The LTC3828 includes a phase-locked loop comprising an internal voltage controlled oscillator and phase detector. This allows the top MOSFET turn-on to be locked to the rising edge of an external source, where the frequency range of the voltage controlled oscillator is ±50% around the center frequency. A voltage applied to the PLLFLTR pin of 1.2V corresponds to a frequency of approximately 400kHz. The nominal operating frequency range is 260kHz to 550kHz.

In the LTC3828, there is an internal master oscillator running at a frequency twelve times that of each controller’s frequency. The PHSMD pin (UH package only) determines the relative phases between the internal controllers as well as the CLKOUT signal as shown in Table 1. The phases tabulated are relative to zero phase being defined as the rising edge of the top gate (TG1) driver output of controller 1. The CLKOUT signal can be used to synchronize additional power stages in a multiphase (3-, 4-, or 6-phase) power supply solution feeding a single, high current output or separate outputs. In the G28 package, CLKOUT is 90° out of phase with channel 1 and channel 2.

**Conclusion**

The LTC3828 is a constant-frequency dual high performance step-down switching regulator controller. Its high efficiency, high power density, current mode architecture make this product ideal for automotive, telecom and battery systems.
**94% Efficient, Low Noise, Step-Up DC/DC Converter in 2mm × 2mm DFN Package Offers Unrivaled Performance and Solution Size**

by Bert Hepfinger

**Introduction**

As handheld electronic devices shrink, the need for compact, high efficiency power converter solutions grows. The new LTC3427 is a full featured, low noise, step-up converter that is ideal for space constrained applications. It integrates a fixed frequency, internally compensated, synchronous boost converter with output disconnect, inrush current limiting and soft start into a low profile 0.75mm × 2mm × 2mm DFN package. A switching frequency of 1.25MHz minimizes the solution footprint by allowing the use of tiny, low profile inductors and ceramic capacitors. The LTC3427's fixed frequency operation makes it ideal for noise sensitive applications where the wide frequency spectrum associated with multiple mode converters may be undesirable. It is possible to fit a complete LTC3427-based, 2-Alkaline cell to 3.3V/200mA, low noise, power converter with efficiencies as high as 94% into only 45mm² of board real estate.

**Features**

The LTC3427 operates from input voltages as low as 1.8V and provides output voltages ranging from 1.8V to 5.25V, making it suitable for generating 3.3V or 5V from either dual Alkaline/NiMH cells or a single Li-Ion battery. The fixed frequency operation allows tighter regulation at light loads and provides very low output voltage ripple, which eliminates the load variable noise harmonics found in some multi-mode converters. High efficiency is achieved by the integration of low gate charge internal switches rated at 0.525Ω for the N-channel and 0.575Ω for the P-channel (typical).

The LTC3427 also provides inrush current limiting soft-start. During start-up, the LTC3427 slowly ramps the peak inductor current from zero to a maximum value greater than 500mA over a period of 2.5ms. Current mode control with slope compensation insures excellent response to input line and output load transients. Internal compensation for the feedback loop further eliminates external components, helping to lower cost and simplify the design process. Anti-ripping circuitry reduces EMI when the part is operating in discontinuous mode. In shutdown, the part draws less than 1µA of quiescent current and disconnects the output from the supply, allowing the output to discharge to 0V.

**Two Alkaline Cell to 3.3V, 650mW Converter**

The LTC3427 requires only a few external components to create a wide selection of low voltage, low power converter solutions. Figure 2 illustrates a 2-Alkaline cell to 3.3V converter with a maximum output current of 200mA. With careful board layout and the use of tiny input and output capacitors, it is possible to squeeze the entire LTC3427-based, 2-Alkaline cell to 3.3V/200mA, low noise, power converter with efficiencies as high as 94% into only 45mm² of board real estate. Continued on page 38.
Introduction

Simplicity, tight regulation, and high efficiency are no longer optional features in isolated power supplies, but achieving all three is traditionally difficult. High efficiency often requires the use of advanced topologies and home-brewed secondary synchronous rectification schemes. Tight regulation for a multi-output supply is often accomplished with inefficient, linear post regulators or efficient (but relatively expensive) switch-mode buck regulator ICs. All of these solutions fail the simplicity test in parts count and design complexity.

Fortunately, a breakthrough IC makes it possible to achieve high efficiency and tight regulation while maintaining the simplicity typically associated with a flyback supply. The LT3825 simplifies and improves the performance of low voltage, multi-output flyback supplies by providing precise synchronous rectifier timing and eliminating the need for optocoupler feedback while maintaining excellent regulation and superior loop response.

Figure 1. Simple, high efficiency, 36V_in–72V_in to 2.5V_out at 3A, 3.3V_out at 3A, and 5.0V_out at 2A synchronous flyback
48V Input to Triple Output: 5V at 2A, 3.3V at 3A and 2.5V at 3A

The circuit in Figure 1 shows an isolated, no-optoisolator, synchronous flyback, 48V to 5.0V at 2A, 3.3V at 3A, and 2.5V at 3A power supply. Figure 2 shows its efficiency. The converter’s efficiency of over 87% at the nominal input voltage of 48V and full rated output current on each output approaches that of a higher parts count forward converter. This is primarily the result of a simple, well-controlled implementation of synchronous rectification. As a result of this high efficiency, the greatest temperature rise of any component is only 35°C above the ambient temperature with a paltry 100LFM of airflow.

The feedback winding is used to regulate the output voltage instead of an optocoupler and secondary-side reference, with good results. The regulation curve shown in Figure 3 shows that ±1.6% is easily attainable when loading outputs proportionately. Even when the outputs are loaded in every possible 10% to 100% load current combination, the cross-regulation between all outputs is within ±3.6%. Figure 4 shows the supply’s transient response for a 1.5A-to-3A load step on the 2.5V output at 5A/μs slew rate and 36V input. With this 50% load step, all output voltages remain within ±2% of their set points.

This circuit also has the advantage of having extremely low ripple on the output voltages; exhibiting less than 10mV_p-p on all outputs at a switching frequency of 200kHz. This performance is attributable to the small, second stage, inductor/capacitor filter on each output.

**LT3825 Operation**

The synchronous rectifier output (SG pin) of the LT3825 makes driving the synchronous rectifier MOSFETs (Q2–Q4) simple while maintaining a low parts count. Setting the dead-time of these synchronous rectifiers relative to Q1 only requires one resistor to program. Avoiding traditional, more complicated, discrete timing circuits allows the designer to set optimum dead-times since this timing is well controlled within the LT3825. The LT3825 also precludes the need for a secondary-side synchronous control IC and its associated circuitry.

The easy-to-implement synchronous rectification also has another advantage: it tightens the output cross-regulation. An alternative to synchronous rectification is using Schottky diodes, which can vary by more than 0.25V over temperature and load. Under the same conditions, the voltage drop across the MOSFETs in Figure 1 vary only by 60mV, a factor of four better. The MOSFET-based topology tightly couples each output, thereby reducing voltage differences during extreme temperature and cross-loading conditions.

Instead of using a parts-intensive, secondary-side voltage reference and error amplifier to drive an optocoupler, the LT3825 uses the primary bias winding on the flyback transformer, T1 (see Figure 1). The voltage on this winding during the flyback pulse is the average of all output voltages as reflected to the primary. The LT3825 also precludes the need for a secondary-side synchronous controller IC and its associated circuitry.

The easy-to-implement synchronous rectification is reflected to the primary. The LT3825 feedback (FB) pin reads this voltage, which is then used to modulate the on-time of Q1 to regulate the output voltages. Cross-regulation performance is enhanced since the average of all outputs is presented to the controller as opposed to just one output voltage’s information as with an optocoupler. Another important benefit of this technique is that the output voltage information arrives at the controller immediately after the switching cycle is terminated. In a conventional optocoupler-based design, delays of tens to hundreds of microseconds occur in the optocoupler alone, severely limiting the converter’s transient response.

**Other Features**

An optional, resistor programmable, input undervoltage lockout is available. An optional soft-start capacitor
controls the slew rate of the output voltage during start-up, which limits the inrush current of the input power supply. Since the LT3825 incorporates current-mode control, both short-circuit behavior and ease of loop compensation are improved over voltage-mode controllers. The switching frequency can be set anywhere from 50kHz to 250kHz, making it possible to find the right balance of solution size and efficiency for a specific application. The switching frequency can be synchronized to an external system clock for further flexibility.

**It Is Possible to Reduce the Parts Count Even More**
For lower input voltages (5V to 20V) and simpler designs, the LT3837 complements the LT3825. The LT3837 starts up and runs from the lower input voltage connected directly to the \( V_{CC} \) pin, so several components are not needed to generate a bias supply, including D1, C6, R1, and R2.

**Conclusion**
The LT3825 allows a designer to improve the performance of multi-output isolated flyback circuits while lowering parts count and simplifying implementation.

---

**LTC4089, continued from page 22**

**High Voltage Buck Output Capacitor Selection**
All the ceramic capacitors used in the circuit are recommended to be X5R or better (X7R). However, be cautious about the claimed initial capacitance value (e.g., some 0805 size 22\( \mu \)F/6.3V X5R caps measure only 11\( \mu \)F at no bias) and derating with bias and temperature (some X5R caps derate to less than 20% of their initial values with full 6.3V voltage bias). It is critical to use a 22\( \mu \)F/6.3V ceramic cap at the output of the LTC4089 buck regulator (connected to HVOUT), as low capacitance causes duty-jitter in certain conditions. The LTC4089-5 can operate with a 22\( \mu \)F/6.3V ceramic cap at the output.

**High Voltage Buck Current Limit**
As shown in Figure 7, the buck output current capability is a function of inductance and the input voltage. For most of the input range, the output current limit is 1A for a 10\( \mu \)H inductor and 1.1A for a 33\( \mu \)H inductor. When powered from the high voltage source, if the sum of the system load current at the OUT terminal and charge current (set by \( R_{PROG} \)) exceeds the buck output current limit, the buck output voltage collapses to the battery voltage.

**Accept USB and 5V Adaptor with Different Current Limits**
Like all other LTC PowerPath controllers, the LTC4089/LTC4089-5 can be configured to accept 5V adaptor/USB input in the same USB connector or different connectors with different current limits by changing the resistance connected to CLPROG pin. Figure 8 shows the schematic diagrams.

**Conclusion**
The LTC4089 and LTC4089-5 combine a monolithic high voltage switching buck regulator, a full featured Li-ion battery charger, and a PowerPath controller in a tiny 3mm × 6mm DFN package. They solve many battery charging and power path problems and easily fits into handheld applications, such as portable GPS navigators and MP3 players, where a high voltage source and small PCB space are required.
Introduction
The LTC3549 is a monolithic synchronous step-down regulator designed specifically to save space, improve battery life and simplify the design of 2-cell alkaline, NiCd and NiMh powered applications. It is similar to the LTC3409, but it is smaller, without synchronization capability and has a 250mA maximum output current. It operates from a wide input voltage range, 1.6V to 5.5V, without the complexity and accompanying loss of efficiency of competing devices that require boost circuitry for generating internal voltages greater than $V_{IN}$. Space-saving features include a $2\text{mm} \times 3\text{mm}$ DFN package and a fixed 2.25MHz operating frequency, which allows the use of small surface mount capacitors and inductors. To extend battery life, two operating modes exist to improve light load efficiency, including Burst Mode operation, which consumes only 50µA of supply current at no load, and pulse skipping mode, which offers low ripple currents for noise-sensitive applications. The device consumes less than 1µA quiescent current in shutdown. The LTC3549 also provides soft start which limits inrush current at start-up.

Features
Soft-Start
The LTC3549’s soft-start function reduces inrush currents at start-up by linearly ramping up the output voltage in about 1ms. For instance, the average output current required during soft-start to charge a 10µF output capacitor to 1.8V in 1ms is 18mA. The total output current is the sum of the output capacitor charging current and the current delivered to the load as $V_{OUT}$ ramps up. Without soft-start, the average current during startup could be as high as $I_{limit}$, which is around 500mA.

Efficiency-Improving Operating Modes
The Mode pin has two states corresponding to two operating modes that improve efficiency at light loads: tied high for pulse skip mode, and tied low for Burst Mode operation. The choice between the two is a matter of weighing low output voltage ripple against light load efficiency. In pulse skipping mode, constant frequency operation is maintained at lower load currents to decrease the output voltage ripple, and therefore reduce the chance of interference with audio circuitry. If the load current is low enough, cycle skipping eventually occurs to maintain regulation. Pulse skipping mode is not quite as efficient as Burst Mode operation at light loads, but comparable when the output load exceeds 50mA (see Figures 1 and 2).

In Burst Mode operation, the internal power MOSFETs operate intermittently based on load demand. Short burst cycles of normal switching are followed by longer idle periods where the load current is supplied by the output capacitor. During the idle period, the power MOSFETs and any unneeded circuitry are turned off, reducing the quiescent current to 50µA. With no load, the output capacitor discharges slowly through the feedback resistors resulting in very low frequency burst cycles that add only a few microamps to the supply current. Burst Mode operation offers higher efficiency at low output currents than pulse skip mode, but when activated Burst Mode operation produces

continued on page 37
A J-FET’s self-biasing characteristic can be utilized to construct a DC/DC converter powered from as little as 300mV. Solar cells, thermopiles and single stage fuel cells, all with outputs below 600mV, are typical power sources for such a converter.

Figure 1, an N-channel J-FET I-V plot, shows drain-source conduction under zero bias (gate and source tied together) conditions. This property can be exploited to produce a self-starting DC/DC converter that runs from 0.3V to 1.6V inputs.

Figure 2 shows the circuit. Q1 and T1 form an oscillator with T1’s secondary providing regenerative feedback to Q1’s gate. When power is applied, Q1’s gate is at zero volts and its drain conducts current via T1’s primary. T1’s phase inverting secondary responds by going negative at Q1’s gate, turning it off. T1’s primary current ceases, its secondary collapses and oscillation commences. T1’s primary action causes positive going “flyback” events at Q1’s drain, which are rectified and filtered. Q2’s approximately 2V turn-on potential isolates the load, aiding start-up. When Q2 turns on, circuit output heads towards 5V. C1, powered from Q2’s source, enforces output regulation by comparing a portion of the output with its internal voltage reference. C1’s switched output controls Q1’s on-time via Q3, forming a control loop.

Waveforms for the circuit include the AC coupled output (Figure 3, trace A), C1’s output (trace B) and Q1’s drain flyback events (trace C). When the output drops below 5V, C1 goes low, turning on Q1. Q1’s resultant flyback events continue until the 5V output is restored. This pattern repeats, maintaining the output.

The 5V output can supply up to 2mA, sufficient to power circuitry or supply bias to a higher power switching regulator when more current is required. The circuit will start into loads of 300µA at 300mV input; 2mA loading requires a 475mV supply. Figure 4 plots minimum input voltage vs output current over a range of loads.

**Figure 2.** J-FET based DC/DC converter runs from 300mV input. Q1-T1 oscillator output is rectified and filtered. Load is isolated until Q2 source arrives at approximately 2V, aiding start-up. Comparator and Q3 close loop around oscillator, controlling Q1’s on-time to stabilize 5V output.

**Figure 3.** J-FET based DC/DC converter waveforms. When supply output (trace A) decays, C1 (trace B) switches, allowing Q1 to oscillate. Resultant flyback events at Q1 drain (trace C) restore supply output.

**Figure 4.** J-FET based DC/DC converter of Figure 2 starts and runs into 100µA load at $V_{IN} = 275$mV. Regulation to 2mA is possible, although required $V_{IN}$ rises to 500mV. Quiescent current control circuitry of Figure 5 slightly increases input voltage required to support load at $V_{IN} < 500$mV.
LT3487, continued from page 13

until the positive side reaches 87% of its final voltage. The output disconnect is also designed so that both channels can collapse together gently when the chip is shut down.

**Output Disconnect**

In a standard boost regulator, the inductor and Schottky diode provide a DC current path from the input to the output, even when the regulator is shut down. Any load at the output when the chip is shut down can continue to drain the V\text{IN} source. The LT3487 addresses this issue with an on-chip output disconnect. The output disconnect is a PNP pass transistor that eliminates the DC loss path. The pass transistor is controlled by a circuit that varies its base current to keep it at the edge of saturation, yielding the best compromise between voltage drop across the PNP and quiescent current. The disconnect in the LT3487 can support loads of 50mA with a V\text{CE} of less than 210mV.

**V\text{BAT} Pin**

The V\text{BAT} pin is an innovation that allows output disconnect operation in a wide range of applications. V\text{BAT} monitors the voltage at the input of the boost inductor and allows the positive output to stay active until the CAP node falls to 1.2V above V\text{BAT}. This ensures that output disconnect continues operating even after the part goes into shutdown. Since output disconnect continues to work, the positive output doesn’t fall sharply to ground before the negative bias discharges. The V\text{BAT} pin allows the inductors to be powered from a different source than V\text{IN} while still maintaining the disconnect operation. This can be useful in a system using a 2-cell supply where a low voltage boost provides 3.3V for the V\text{IN} supply. By connecting V\text{BAT} as well as the inductors to the 2-cell supply, the positive output is able to stay on as long as possible when the part goes into shutdown.

**Applications**

The LT3487 can be used in a CCD bias as well as other applications that require a positive and negative bias such as ±12V data acquisition systems. The boost channel can produce voltages up to 30V as long as the part can meet the required duty cycle. Similarly, the inverting channel can produce voltages down to –30V. This high voltage capability allows the LT3487 to be used in many LCD applications.

**Conclusion**

The LT3487 simplifies and shrinks CCD bias supplies without compromising on performance or features. The soft-start and output disconnect features ensure that the input battery doesn’t encounter current spikes or shutdown leakage. The high current capability satiates even the most power-hungry video applications.

**Figure 5.** Adding Q3, Q4 and bootstrapped negative bias generator reduces quiescent current. Comparator directed Q3 switches Q4, more efficiently controlling Q1’s gate drive. Q2 and zener diode isolate all loading during Q1 start-up.
New Device Cameos

New Timing and High Voltage Output Enhance Pushbutton On/Off Controller

The LTC2954 is an upgrade to the LTC2950 family of pushbutton controllers. Two features have been added: new pushbutton controlled interrupt timing, and a high voltage open drain enable output capable of 33V operation.

The LTC2954 now provides interrupt and power down modes to allow more flexible and reliable system shut down. Once in the powered on state, momentary presses on the pushbutton provide interrupts to system logic. This can be useful for system housekeeping and power down under firmware control. Should the system require a forced power down, a long duration press and hold of the pushbutton automatically releases the enable pin, thus turning system power off. The timing of this latter power down mode is adjustable with external capacitance on the power down timing pin.

The new high voltage enable output of the LTC2954-2 is ideally suited to drive the gate of a high voltage power PFET. This allows a user to connect/disk on the pushbutton input. This is available in 8-Pin 3mm × 2mm DFN and ThinSOT™ Packages. Two versions of the part are available to accommodate either positive or negative enable polarities.

20Mbps and Slew Rate Limited 15kV RS485/RS422 Transceivers

The LTC2856-1, LTC2856-2, LTC2857-1, LTC2857-2, LTC2858-1, and LTC2858-2 are the latest additions to Linear Technology’s family of rugged 5V RS485 transceivers offering a variety of advanced features for industrial, medical, and automotive applications. Discriminating features of these parts are summarized in Table 1.

The high speed LTC2856-1, LTC2857-1, and LTC2858-1 operate at data rates up to 20Mbps. The LTC2856-2, LTC2857-2, and LTC2858-2 are designed for applications where low-EMI operation is required. They feature driver output transitions with reduced slew rates for operation up to 250kbps.

High receiver input impedance supports up to 256 nodes on a single bus, while meeting RS485 load requirements. Failsafe operation guarantees a logic-high receiver output state when the inputs of the receiver are floating or shorted.

Bus pin protection on all parts exceeds ±15kV for ESD strikes with no latchup or damage. Driver outputs are protected from damage and excessive power dissipation with current limiting and thermal protection circuits, ensuring bullet-proof operation.

The LTC2856-1 and LTC2856-2 provide half-duplex operation, while the others in the family are full-duplex in a selection of pinouts. Specified over commercial and industrial temperature ranges from −40°C to 85°C, these parts are available in MSOP packages as well as tiny 3mm × 3mm leadless DFN packages.

This latest family of RS485 transceivers compliments Linear Technology's LTC2859 and LTC2861 RS485 transceivers which have similar features plus an integrated switchable termination resistor. The new parts are ideally suited for use at bus nodes not requiring switchable termination resistors, offering outstanding performance in a small footprint.

300MHz Low Distortion, Low Noise Differential Amplifier Drives 12-Bit and 14-Bit ADCs

The LT6402 is a 300MHz low distortion, low noise differential amplifier/ADC driver available in fixed voltage gains of 6dB (LT6402-6), 12dB (LT6402-12) and 20dB (LT6402-20). It meets the demanding requirements of communications transceiver applications and can be used as a differential ADC driver, a general-purpose differential gain block, or other applications requiring differential drive.

The LT6402 can operate in data acquisition systems required to function at frequencies from DC to 300MHz. Exceptionally low input-referred noise and low distortion make the LT6402 an excellent solution for driving high speed 12-bit and 14-bit ADCs. At 20MHz, the LT6402-20's input referred noise and third harmonic distortion measure 1.9nV/√Hz and −81dBc (2Vp-p), respectively. This input referred noise measurement includes the internal gain and feedback resistors.

At the inputs of the LT6402, the signals can be differential or single-ended with virtually no difference in performance. The only external components required by the LT6402, when used as an ADC driver, are the power-supply bypass capacitors. DC levels at the inputs can be set inde-

### Table 1. RS485 New Part Selection Guide

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Max Data Rate (Mbps)</th>
<th>Duplex</th>
<th>Low-Power Shutdown Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>LTC2856-1</td>
<td>20</td>
<td>Half</td>
<td>Yes</td>
</tr>
<tr>
<td>LTC2856-2</td>
<td>0.25</td>
<td>Half</td>
<td>Yes</td>
</tr>
<tr>
<td>LTC2857-1</td>
<td>20</td>
<td>Full</td>
<td>No</td>
</tr>
<tr>
<td>LTC2857-2</td>
<td>0.25</td>
<td>Full</td>
<td>No</td>
</tr>
<tr>
<td>LTC2858-1</td>
<td>20</td>
<td>Full</td>
<td>Yes</td>
</tr>
<tr>
<td>LTC2858-2</td>
<td>0.25</td>
<td>Full</td>
<td>Yes</td>
</tr>
</tbody>
</table>
higher output ripple than pulse skip mode. Burst Mode ripple can be 10 to 20 times larger than pulse skip ripple for a given set of conditions.

**Output Voltage Programmability**
The LTC3549 output voltage is externally programmed via a simple resistive divider to any value above the 0.611V internal reference voltage, and is capable of 100% duty cycle. In dropout, the output voltage is determined by the input voltage minus the voltage drop across the internal P-channel MOSFET and the inductor resistance.

**Fault Protection**
The LTC3549 protects against output overvoltage, output short circuit and excessive power dissipation conditions. When an overvoltage condition at the output (>10% above nominal) is sensed, the top MOSFET is turned off until the fault is removed.

If the output is shorted to ground, reverse current in the synchronous switch is monitored to prevent inductor-current runaway. If the synchronous switch current is too high, the top MOSFET remains off until the synchronous switch current falls to a normal level.

When the junction temperature reaches approximately 160°C, the thermal protection circuit turns off the power MOSFETs allowing the part to cool. Normal operation resumes when the die temperature drops to 150°C.

**Applications**

**1.5V/600mA Step-Down Regulator Using Ceramic Capacitors**
Figure 3 shows an application of the LTC3549 using ceramic capacitors. This particular design supplies up to a 250mA load at 1.5V with an input supply between 1.8V and 3.1V. Ceramic capacitors have the advantages of small size and low equivalent series resistance (ESR), allowing very low ripple voltages at both the input and output. Because the LTC3549’s control loop does not depend on the output capacitor’s ESR for stable operation, ceramic capacitors can be used to achieve very low output ripple and small circuit size. Figures 4 and 5 show the transient response to a 20mA to 250mA load step for the LTC3549 in pulse skip mode, and Burst Mode operation.

**Conclusion**
The LTC3549’s wide 1.6V to 5.5V range allows it to operate from various power sources that range from a 5V AC wall adapter to two series alkaline batteries. Features such as soft-start, Burst Mode operation/pulse skip mode selection and overvoltage protection add application flexibility to this 2mm × 3mm device.
NEW DEVICE CAMEOS

supplies while drawing as little as 1μA of quiescent current.

The ultralow supply current and low operating voltage are combined with excellent amplifier specifications—input offset voltage of 500µV maximum with a typical drift of only 1μV/°C, input bias current of 90pA maximum, open loop gain of 100,000 and the ability to drive 500pF capacitive loads—making the LTC6003/LT6004/LT6005 amplifiers ideal when excellent performance is required in battery powered applications.

The single LT6003 is available in the 5-pin TSOT-23 and tiny 2mm × 2mm DFN packages. The dual LT6004 is available in the 8-pin MSOP and 3mm × 3mm DFN packages. The quad LT6005 is available in the 16-pin TSSOP and 5mm × 3mm DFN packages. These devices are specified over the commercial, industrial and automotive temperature ranges.

LTC3427, continued from page 29

Even though the total solution cost is low and the area required is small, efficiency is not sacrificed. Figure 3 shows that peak efficiencies for this converter of up to 94% are attainable from fully charged batteries. High efficiency is maintained over a wide output load range from 200mA down to a few mA due to the miserly quiescent current required to operate this converter. Figure 4 illustrates the effect of fixed frequency switching on the VOUT ripple over a wide range of loads, which minimizes the spectrum of EMI for noise sensitive applications. These waveforms are for a 4.7µF output capacitor. The ripple can be reduced by increasing this value.

There is always a trade off between solution size and efficiency. For applications where board space concerns are more critical, substantial space savings can be achieved by the use of surface mount chip inductors. In a typical application with a load current of 50mA to 100mA, a sacrifice of 3%–4% in efficiency can yield a board space savings of 25%–30% by using tiny chip coils such as the Murata LQH2MC series.

Lithium-Ion to 5V, 1W Converter

For 5V applications where board space is at a premium. Figure 5 illustrates a single lithium-ion battery to 5V converter with a maximum output current of 200mA. As in the previous example, with careful board layout and component selection, this converter solution should only occupy 45mm² of board space. Further significant board space savings are possible with the use of tiny chip inductors. As illustrated in Figure 6, peak efficiencies of up to 93% are attainable from a fully charged battery. Adding an optional low current Schottky diode across the synchronous rectifier (SW node to VOUT) can increase efficiency by as much as 2%, though this negates the output disconnect feature.

Conclusion

The LTC3427 in the compact 2mm × 2mm DFN package is the industry’s smallest, high efficiency, low noise, synchronous boost converter with true output disconnect and soft start. With few external components required, it is not necessary to sacrifice performance to achieve the smallest possible power converter solution. The LTC3427 is the ideal choice for low voltage, low power converter applications, especially those challenged with severe space constraints or noise sensitivity.
MyLinear (www.linear.com/mylinear)

MyLinear is a customizable home page to store your favorite LTC products, categories, product tables, contact information, preferences and more. Creating a MyLinear account allows you to...

- Store and update your contact information. No more reentering your address every time you request a sample!
- Edit your subscriptions to Linear Insider email newsletter and Linear Technology Magazine.
- Store your favorite products and categories for future reference.
- Store your favorite parametric table. Customize a table by editing columns, filters and sort criteria and store your settings for future use.
- View your sample history and delivery status. Using your MyLinear account is easy. Just visit www.linear.com/mylinear to create your account.

Purchase Products (www.linear.com/purchase)

Purchase products directly from Linear Technology either through the methods below or contact your local LTC sales representative or licensed distributor.

Credit Card Purchase — Your Linear Technology parts can be shipped almost anywhere in the world with your credit card purchase. Orders up to 500 pieces per item are accepted. You can call (408) 435-5723 or email orders@linear.com with questions regarding your order.

Linear Express — Purchase online with credit terms. Linear Express is your new choice for purchasing any quantity of Linear Technology parts. Credit terms are available for qualifying accounts. Minimum order is only $250.00. Call 1-866-546-3271 or email us at express@linear.com.

Product and Applications Information

At www.linear.com you will find our complete collection of product and applications information available for download. Resources include:

- Data Sheets — Complete product specifications, applications information and design tips
- Application Notes — In depth collection of solutions, theory and design tips for a general application area
- Design Notes — Solution-specific design ideas and circuit tips
- LT Chronicle — A monthly look at LTC products for specific end-markets
- Product Press Releases — New products are announced constantly
- Solutions Brochures — Complete solutions for automotive electronics, wireless infrastructure, industrial signal chain, handheld or battery charging applications.

Product Selection

The focus of Linear Technology’s website is simple—to get you the information you need quickly and easily. With that goal in mind, we offer several methods of finding the product and applications information you need.

Part Number and Keyword Search — Search Linear Technology’s entire library of data sheets, Application Notes and Design Notes for a specific part number or keyword.

Sortable Parametric Tables — Any of Linear Technology’s product families can be viewed in table form, allowing the parts to be sorted and filtered by one or many functional parameters.

Applications Solutions — View block diagrams for a wide variety of automotive, communications, industrial and military applications. Click on a functional block to generate a complete list of Linear Technology’s product offerings for that function.

Design Support

Packaging (www.linear.com/packaging) — Visit our packaging page to view complete information for all of Linear Technology’s package types. Resources include package dimensions and footprints, package cross reference, top markings, material declarations, assembly procedures and more.

Quality and Reliability (www.linear.com/quality) — The cornerstone of Linear Technology’s Quality, Reliability & Service (QRS) Program is to achieve 100% customer satisfaction by producing the most technically advanced product with the best quality, on-time delivery and service. Visit our quality and reliability page to view complete reliability data for all of LTC’s products and processes. Also available is complete documentation on assembly and manufacturing flows, quality and environmental certifications, test standards and documentation and failure analysis policies and procedures.

Lead Free (www.linear.com/leadfree) — A complete resource for Linear Technology’s Lead (Pb) Free Program and RoHS compliance information.

Simulation and Software

Linear Technology offers several powerful simulation tools to aid engineers in designing, testing and troubleshooting their high performance analog designs.

LTspice/SwitcherCAD™ III (www.linear.com/swcad) — LTspice / SwitcherCAD III is a powerful SPICE simulator and schematic capture tool specifically designed to speed up and simplify the simulation of switching regulators. LTspice / SwitcherCAD III includes:

- Powerful SPICE simulator specifically designed for switching regulator simulation
- Complete and easy to use schematic capture and waveform viewer
- Macromodels for most of Linear Technology’s switching regulators as well as models for many of LTC’s high performance linear regulators, op amps, comparators, filters and more.
- Ready to use demonstration circuits for over one hundred of Linear Technology’s most popular products.

FilterCAD — FilterCAD 3.0 is a computer-aided design program for creating filters with Linear Technology’s filter ICs.

Noise Program — This program allows the user to calculate circuit noise using LTC op amps and determine the best LTC op amp for a low noise application.

SPICE Macromodel Library — A library includes LTC op amp SPICE macromodels for use with any SPICE simulation package.

www.linear.com