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## Sequencer-Supervisor Simplifies Design of Multi-Supply Systems

by Bob Jurgilewicz

### 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 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. When final decisions about the power supplies' operating specifications are determined, calculate the values for a few passive components and populate the empty spaces in the circuit. Changes are easy—no costly rework and testing.

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### 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. *continued on page 3*



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# 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 analog 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 300mAVLDO™ 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  $\pm 2\%$  accuracy, low quiescent and shutdown currents of 100 $\mu$ A and 1 $\mu$ A, 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  $\mu$ Module™ 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. 

LTC2928, continued from page 1

## 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 ( $UV_{TH1}$ ), calculate the ratio for the resistive

divider (R1B, R1A) between supply voltage S1 and ground:

$$\frac{R1B}{R1A} = \frac{UV_{TH1} (V)}{0.5V} - 1$$

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

### Let the LTC2928 Configurator Tool Design It for You

Configuring an LTC2928 application is simple (see “How to Set Up the LTC2928” in this article), but why should you have to do any calculation at all? To make life truly simple, Linear Technology offers free configuration software that calculates all resistor values, capacitor values and required logic connections. The tool also generates schematics and a passive element bill-of-materials. All you need to know are your supply parameters and sequence. The LTC2928 Configurator can be obtained from LTC applications staff members. 

If a negative supply is monitored on the V1 input, tie the VSEL pin to  $V_{CC}$ . 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

$$\frac{R1B}{R1A} = \frac{-UV_{TH1} (V)}{V_{REF}}$$

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  $V_{CC}$  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

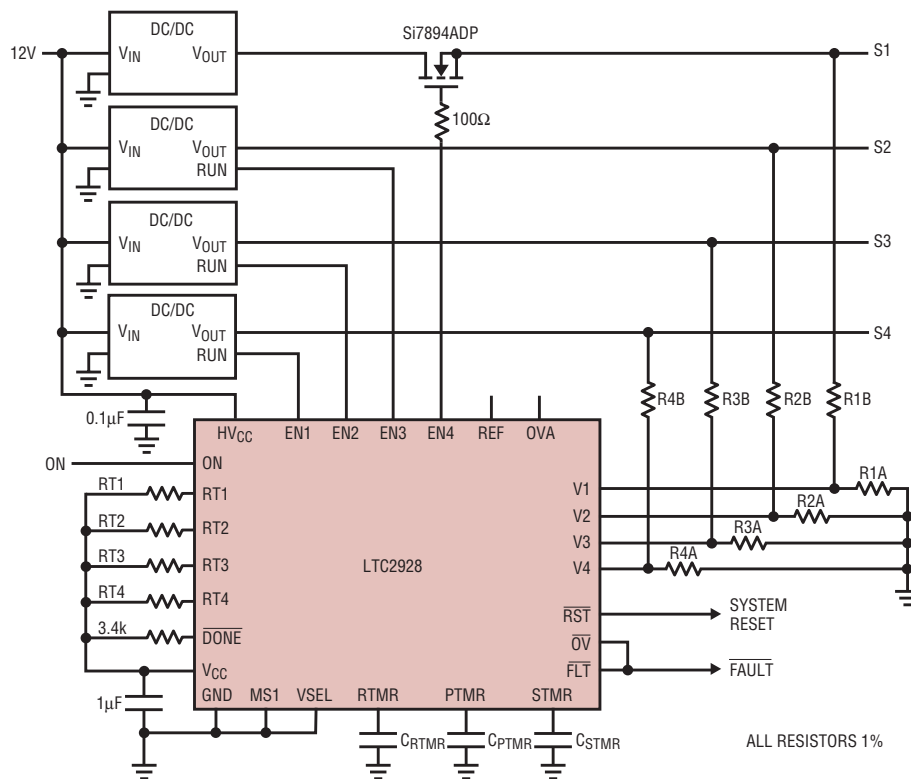
Feature	Available
High Voltage Operation: 7.2V to 16.5V	
Low Voltage Operation: 2.9V to 6V	
Power-Up and Power-Down Sequencing (Positive and Negative Supplies)	
Sequenced Shutdown upon Loss of $V_{CC}$ *	
±1.5% Accurate Under Voltage Comparators	
Over Voltage Comparators	
Sequence Threshold Comparators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

\*see data sheet

Positioning” below. In this generic application, supply S1 is shown to start in time position 5 (TP5). Time position resistor RT1 is connected between V<sub>CC</sub> 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 V<sub>CC</sub>. 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 t<sub>STMR</sub> (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 t<sub>RISE</sub>(S1) to the sequence-up threshold SQ<sub>TH1</sub>. Using three-state



**Figure 1. Generic LTC2928 application**

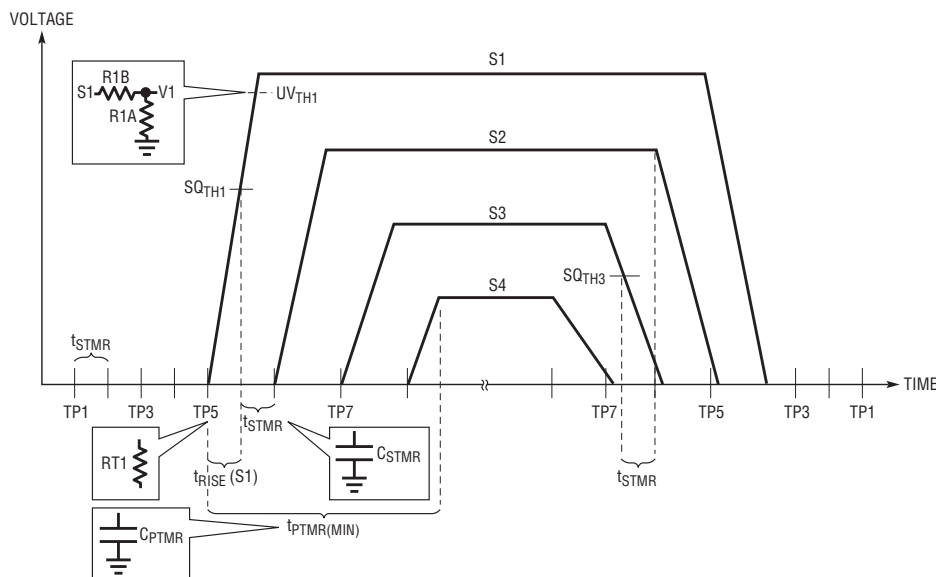
pins SQT1 and SQT2 (not shown), sequence-up thresholds can be set to equal to 100%, 67% or 33% of the configured undervoltage threshold. The time between TP5 and TP6 is seen to be equal to t<sub>RISE</sub>(S1) plus one t<sub>STMR</sub>. The sequence timer delay is set with capacitor C<sub>STMR</sub> 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 C<sub>PTMR</sub> 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



**Figure 2. Generic application waveforms**



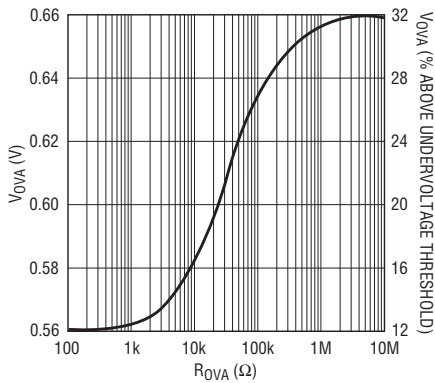


Figure 3. External resistor from OVA to ground

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

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

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

$$t_{PTMR}(\min) = [8 - 4] \cdot t_{STMR} + 4 \cdot t_{RISE} = 4 \cdot t_{STMR} + 4 \cdot t_{RISE}$$

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

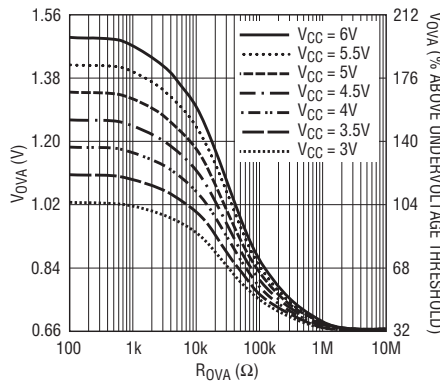


Figure 4. External resistor from OVA to V<sub>CC</sub>

I<sup>2</sup>C interface, such as the LTC2629, to directly drive a programmed voltage to the RT pin(s). Both methods require changing the voltage (V<sub>RT</sub>) 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  $\overline{\text{DONE}}$  signal. During sequencing-up, the  $\overline{\text{DONE}}$  pin is high, so RT1<sub>UP</sub> is selected. When sequencing-down is complete,  $\overline{\text{DONE}}$  pulls low and RT1<sub>DN</sub> is selected. Sequencing-down commences once the ON pin is pulled low.

Table 2. Sequence time position resistors

Position Number	R <sub>T</sub> (kΩ)	Ideal R <sub>T</sub> Pin Set Point (V <sub>RT</sub> / V <sub>CC</sub> ) ±0.005
1	95.3	1/9 = 0.111
2	42.2	2/9 = 0.222
3	24.3	3/9 = 0.333
4	15.0	4/9 = 0.444
5	9.53	5/9 = 0.556
6	6.04	6/9 = 0.667
7	3.40	7/9 = 0.778
8	1.50	8/9 = 0.889

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 I<sup>2</sup>C 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*

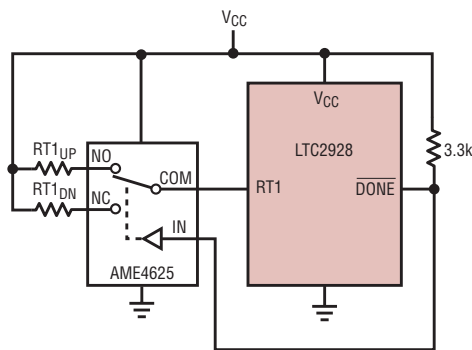


Figure 5. Active sequence positioning using an analog multiplexer

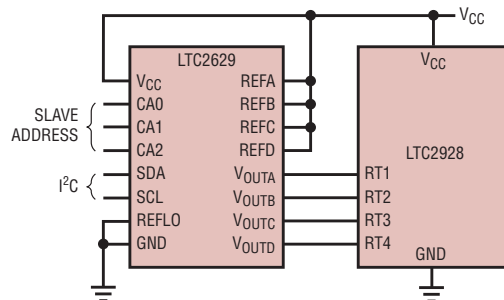


Figure 6. Active sequence positioning using an I<sup>2</sup>C DAC

# 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.

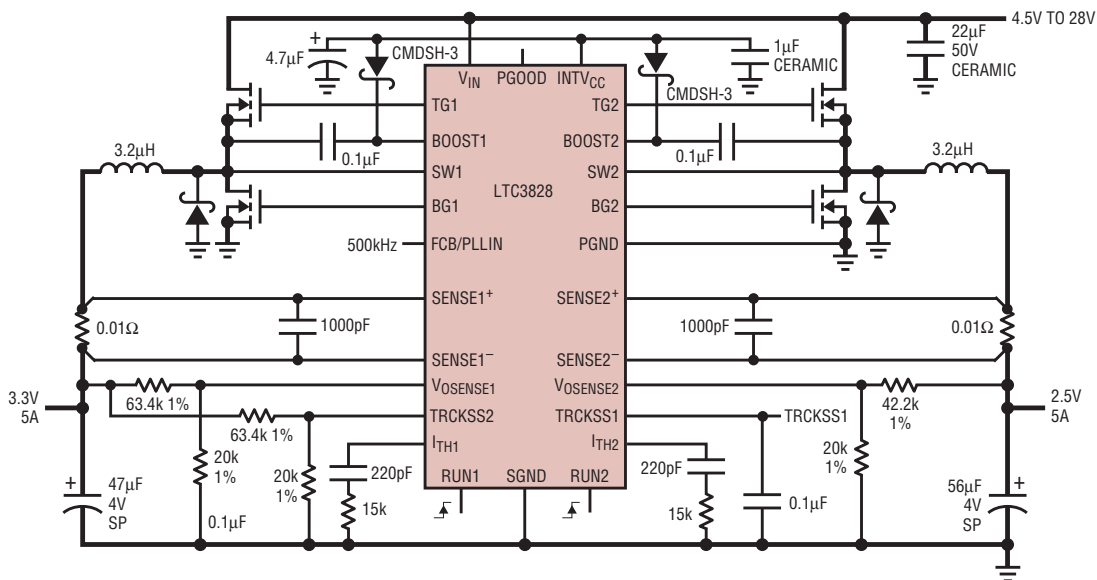


Figure 1. The two outputs of this dual 2.5V/3.3V step-down converter operate out of phase to increase efficiency and reduce size. In this configuration, the channels track each other.

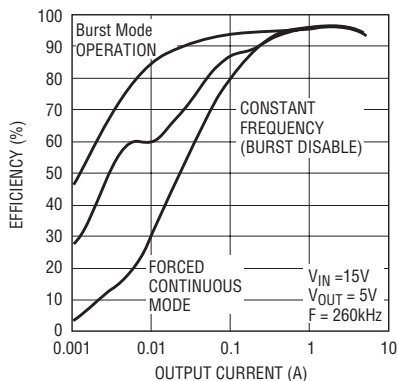


Figure 2. Efficiency of circuit in Figure 1

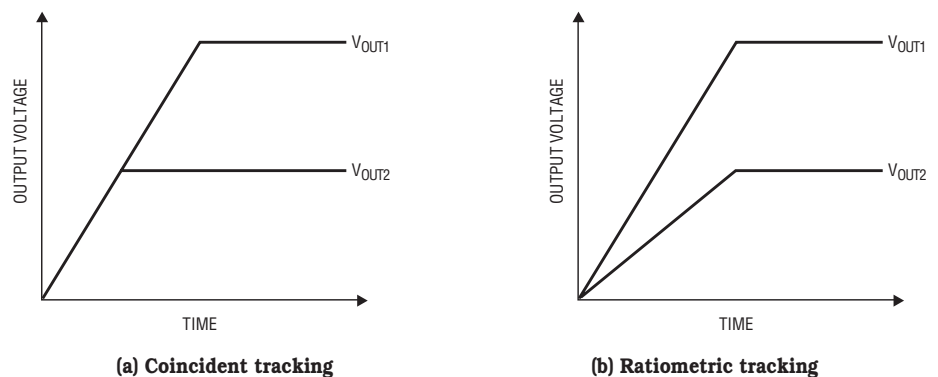


Figure 3. Two different methods of output voltage tracking

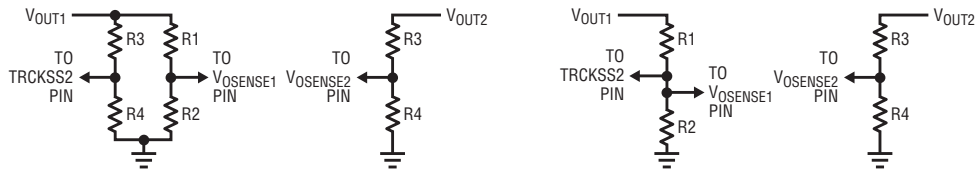


Figure 4. Setups for coincident and ratiometric tracking

### 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  $V_{FB}$  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  $V_{OSENSE}$  follows the TRCKSS voltage. When the TRCKSS voltage is close to the reference voltage, 0.8V, switch S1 is off and  $V_{OSENSE}$  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.

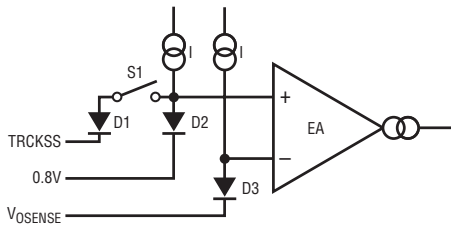


Figure 5. Equivalent input circuit of error amplifier to implement start-up tracking

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  $1.2\mu\text{A}$  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  $450\mu\text{s}$ ). If the voltage at TRCKSS pin is already high, but lower than 0.8V, this channel's  $V_{OSENSE}$  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 tracking 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*

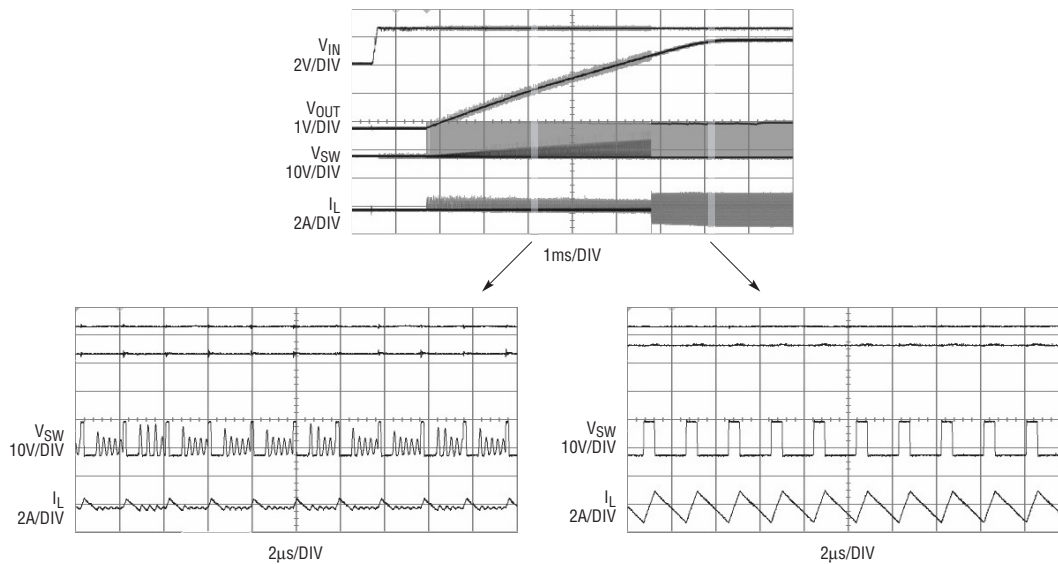


Figure 6. Soft-start waveforms (no negative current)

# Compact Solution for Hot Swap and Supply Monitoring in CompactPCI and PCI Express Systems

by Pinkesh Sachdev

## 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 I<sup>2</sup>C-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.
- ❑ di/dt limited inrush current control prevents supply glitches on backplane due to  $L \cdot di/dt$  drops.
- ❑ Each supply has a circuit breaker with a 20 $\mu$ s filter and a fast current limit at 3 $\times$  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 I<sup>2</sup>C 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  $\times$  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

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***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 I<sup>2</sup>C-compatible interface. This all comes in a 36-pin SSOP package or a space-saving 5mm  $\times$  7mm 38-pin QFN package.***

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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 I<sup>2</sup>C 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



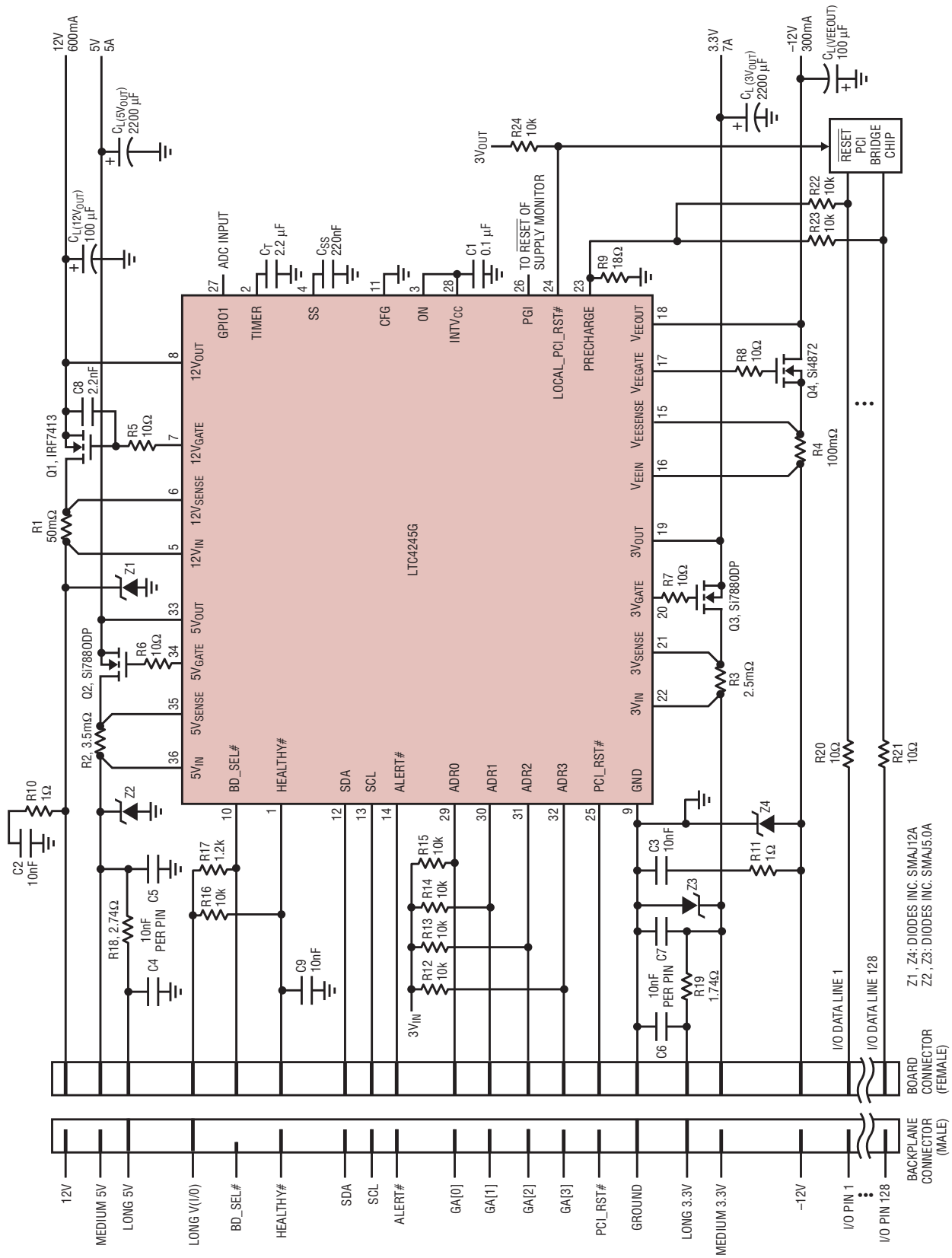
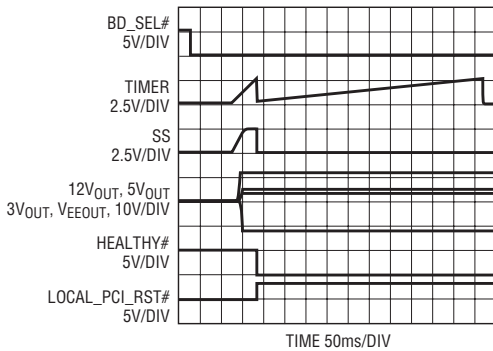


Figure 1. CompactPCI Hot Swap board application using the LTC4245 to control and monitor power on ±12V, 5V and 3.3V supplies. The bus I/O lines are precharged to 1V during insertion and extraction. The CPCI geographical slot address is used to set the I<sup>2</sup>C slave address of the part.



**Figure 2. Typical power-up sequence activated 100ms after BD\_SEL# goes low.**

supply (INTV<sub>CC</sub>) 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.

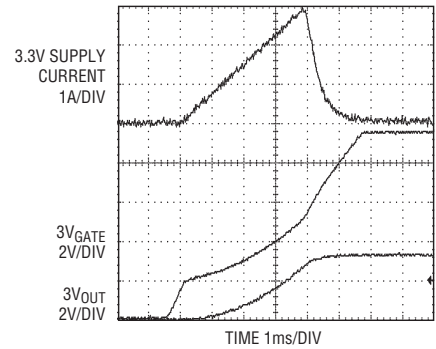
**dI/dt Controlled Soft Start**

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 servos the gate of its external MOSFET so that

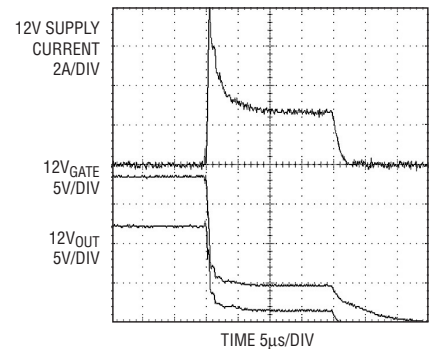
the inrush current never exceeds an internal current limit set by the SS pin voltage. The voltage ramp on the SS pin sets the rate of rise of this internal limit. When the gate voltage reaches the MOSFET threshold voltage, the switch begins to turn on. The amplifier modulates the gate pull-up current 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



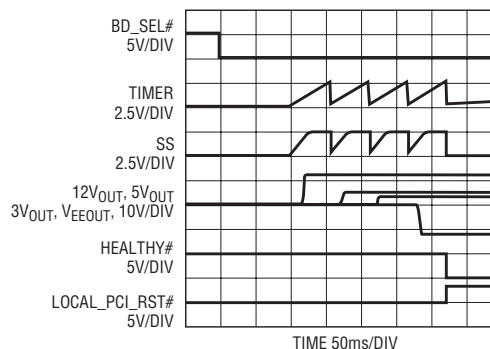
**Figure 3. dI/dt controlled soft-start on 3.3V supply during sequenced turn-on. Inrush current rise rate of 750mA/ms is set by the SS pin capacitor.**



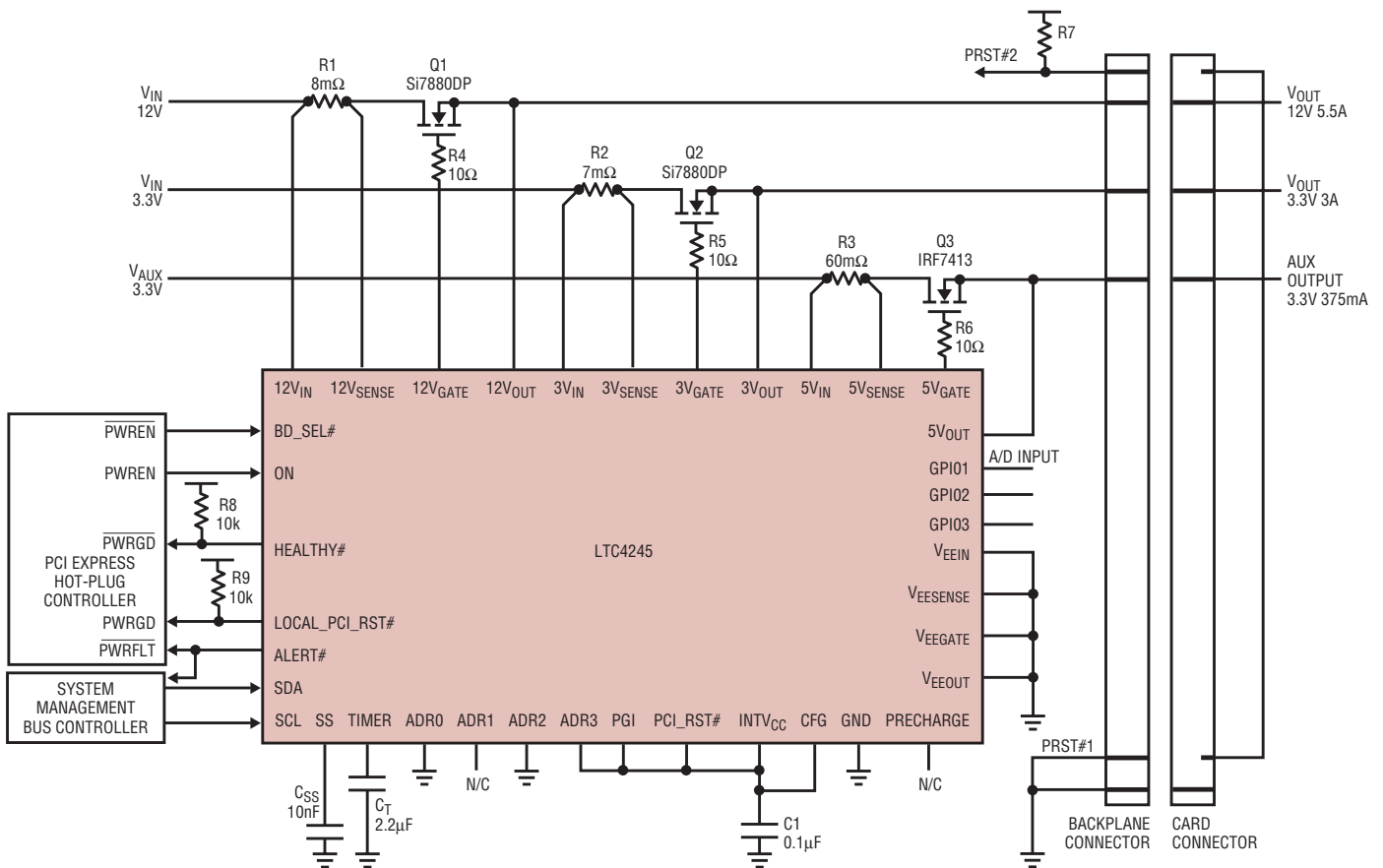
**Figure 4. Fast current limit responds to a short-circuit on 12V output in less than 1µs, by pulling down 12V\_GATE to 12V\_OUT 20µs later, the internal circuit breaker timer expires and all switches are turned off.**

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 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.**

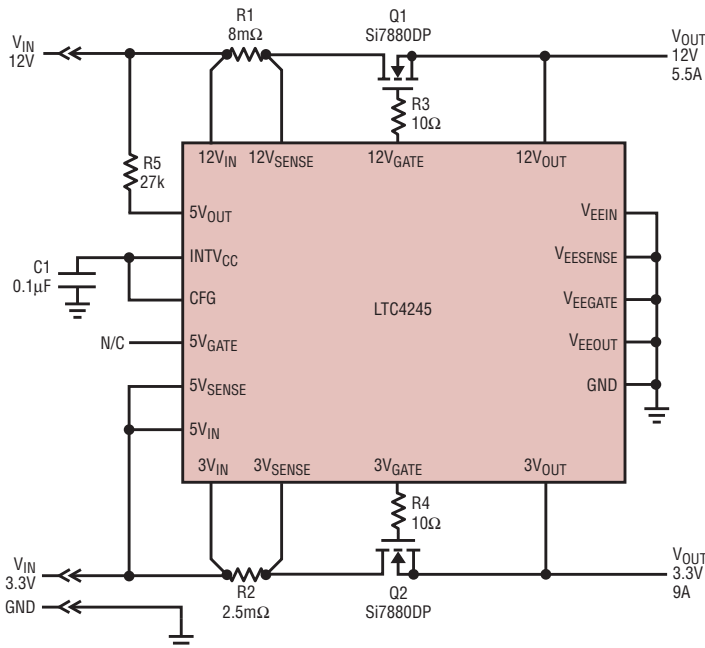


**Figure 6. PCI Express backplane application to hot-plug and monitor 12V, 3.3V main and 3.3V auxiliary power. Tying the CFG pin to INTV<sub>CC</sub> lowers the 5V undervoltage and power bad thresholds to 3.3V levels, while also disabling those functions on the V<sub>EE</sub> pins.**

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.



**Figure 7. A 12V and 3.3V application, similar to Figure 6, but one less 3.3V supply.**

### 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 I<sup>2</sup>C 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

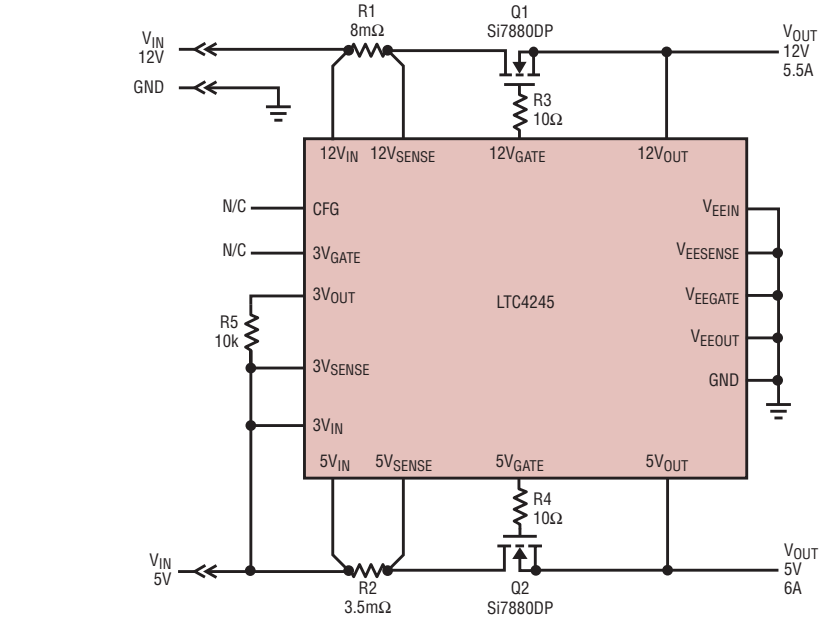
is shown in Figure 5. The most flexible turn-on behavior is afforded by the ON register. For this the ON pin should be set low. Now when BD\_SEL# goes low the switches remain off. The ON register has four bits to control the state of each supply switch. Writing a one to any of these bits turns on that 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 on 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



**Figure 8. A 12V and 5V application. Floating the CFG pin disables the V<sub>EE</sub> undervoltage and power bad functions, allowing those pins to be tied to GND.**

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 INTV<sub>CC</sub>, 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 V<sub>EE</sub> 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, I<sup>2</sup>C interface and numerous other features into a 5mm × 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

by Jesus Rosales

## 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 × 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 25 $\mu$ A input current.

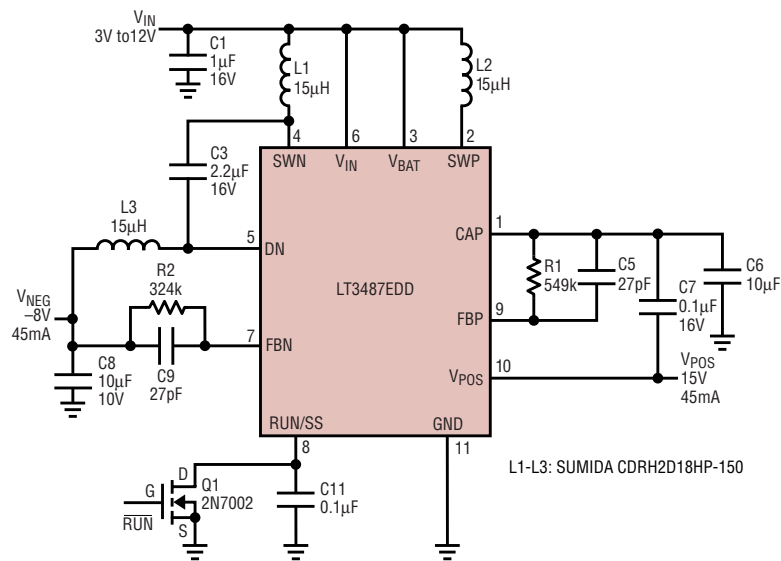


Figure 1. A compact 15V, -8V CCD bias application

## 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  $V_{IN}$  has limited current sourcing capability. The LT3487 has soft-start functionality that clamps the internal  $V_C$  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  $V_{IN}$  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 1.4 $\mu$ A 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

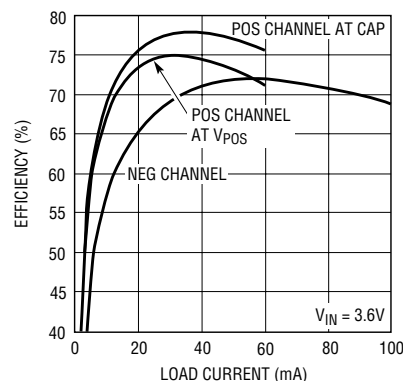


Figure 2. Efficiency of CCD bias application with 3.6V  $V_{IN}$

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 ad-

justable 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  $\mu\text{P}$  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 x 4mm or 20-pin TSSOP. In standby mode it only consumes 25 $\mu\text{A}$  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:  $\pm 1.5\%$  of monitored voltage over temperature
- ❑ Adjustable pushbutton ON/OFF timers
- ❑ Simple interface allows graceful  $\mu\text{P}$  controlled shutdown
- ❑ Extendable house keeping wait time prior to shutdown
- ❑ 200ms reset delay and 1.6s watch dog time out
- ❑  $\pm 8\text{kV}$  HBM ESD on  $\overline{\text{PB}}$  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

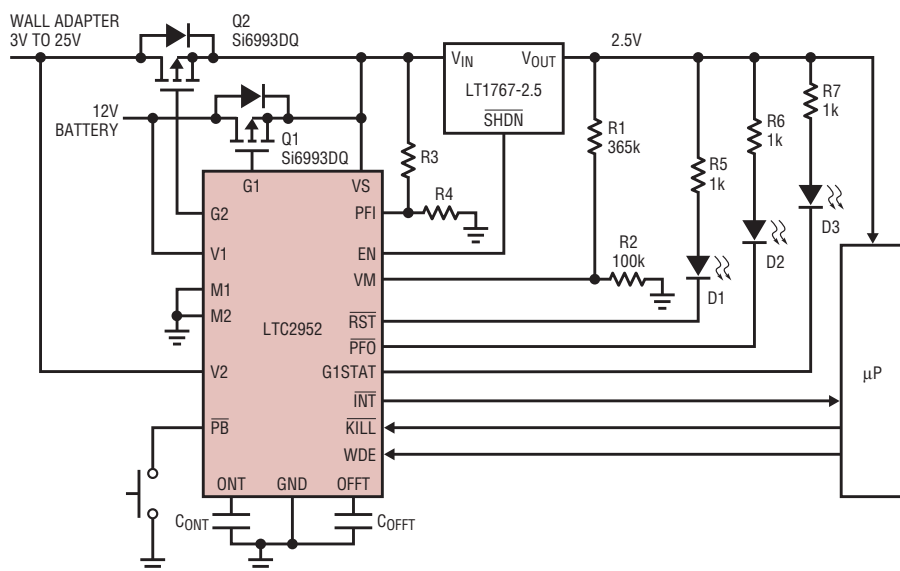


Figure 1. Typical application of LTC2952 with automatic power-ORing between wall adapter and battery and pushbutton control of a DC/DC converter

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  $\overline{PB}$  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  $\mu P$  to ensure proper system power up and power down.

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

The  $\overline{KILL}$ , 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  $\overline{KILL}$  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  $\overline{PB}$  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 3 $\mu A$  internal pull-up current, this current causes both M1 and M2 to pull

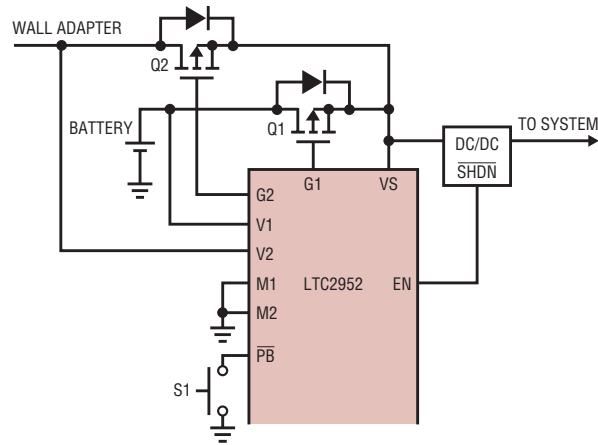


Figure 2. Power path configuration A: pushbutton controller with automatic power-ORing between wall adapter and battery

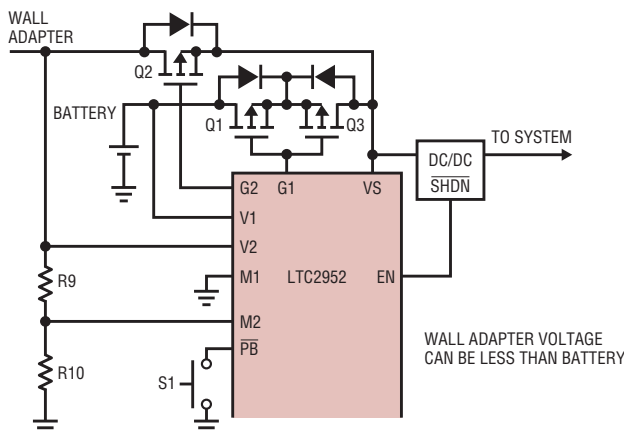


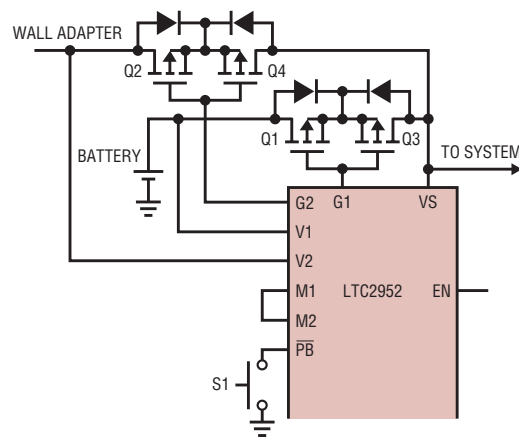
Figure 3. Power path configuration B: pushbutton controller with preferential wall adapter operation and automatic switchover to battery

up above 0.515V (the typical M1 and M2 pins rising threshold). This setup causes the device to operate such that the  $\overline{\text{PB}}$  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.

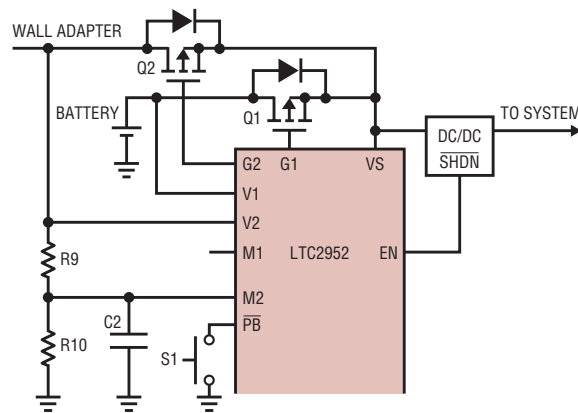
**Configuration D:  
Battery Backup with Pushbutton  
Power Path Controller**

In this configuration the M1 pin is left floating, causing its 3 $\mu\text{A}$  (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



**Figure 4. Power path configuration C: pushbutton control of ideal diode drivers**



**Figure 5. Power path configuration D: battery backup with pushbutton power path controller**

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.

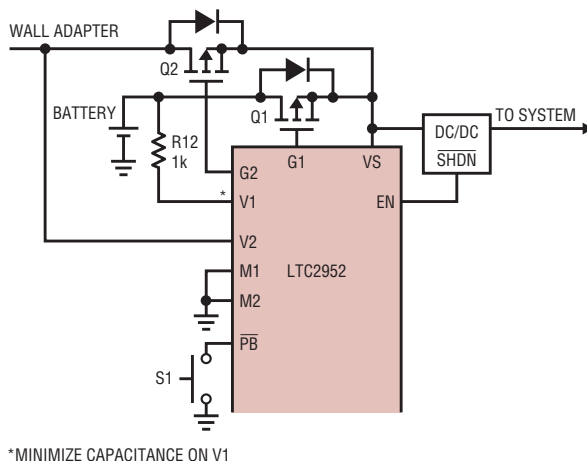
Once power is delivered to the system, the  $\overline{\text{PB}}$  pin can be used to turn off the power. If  $\overline{\text{PB}}$  is used to turn off the power in this configuration, there are two methods to turn the power back

on: a valid pushbutton ON at the  $\overline{\text{PB}}$  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.




**Figure 6. Reverse battery protection on V1**



### 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. 

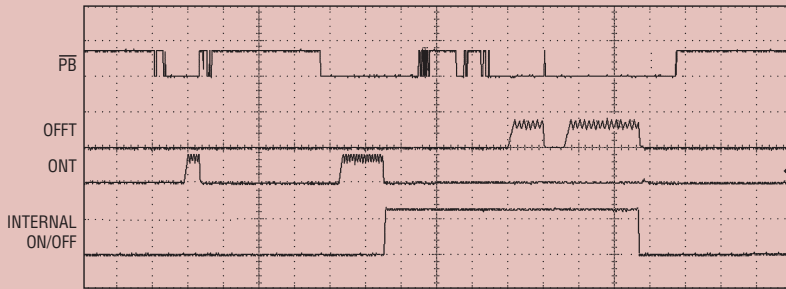


Figure 7. Scope photo of a typical pushbutton bounce

ing 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  $\overline{PB}$  pin must satisfy before it is recognized as a valid pushbutton ON or OFF command.

$$t_{ONT} = C_{ONT} \cdot 9.3[M\Omega]$$

$$t_{OFFT} = C_{OFFT} \cdot 9.3[M\Omega]$$

$C_{ONT}$  and  $C_{OFFT}$  are the ONT and OFFT external programming capacitors respectively.

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

On a release event (rising edge) on the  $\overline{PB}$  pin following a valid push event, the  $\overline{PB}$  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  $\overline{PB}$  signals being debounced into a clean internal ON/OFF signal, and its effect on the state of the  $\overline{INT}$  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

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.

pull up to an internal low voltage supply (4.5V). The  $\overline{PB}$  input comparator has a 0.775V falling trip threshold with 25mV of hysteresis. Due to novel protection circuitry, the  $\overline{PB}$  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  $\overline{PB}$  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  $\overline{PB}$  pin can be increased beyond the fixed internal 26ms by using an external capacitor. Specifically, plac-

### Pushbutton Input

The  $\overline{PB}$  pin is a high impedance input to an accurate comparator with a 10μA

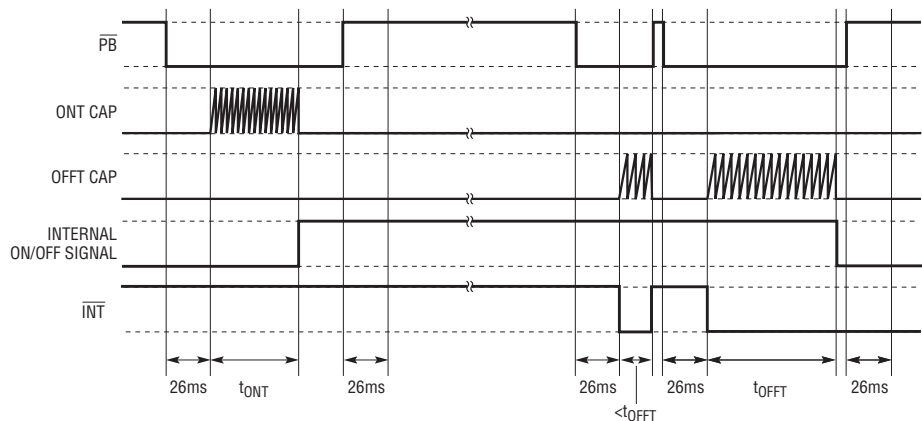


Figure 8. Pushbutton debounce timing

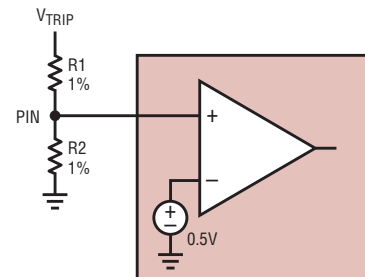


Figure 9. Setting the comparator input trip point

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,  $\overline{\text{KILL}}$  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:

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

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  $\overline{\text{PFO}}$  pin is high imped-

ance. Conversely, when the voltage level at PFI is lower than its falling threshold (0.5V), the  $\overline{\text{PFO}}$  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  $\overline{\text{RST}}$  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  $\overline{\text{RST}}$  pin strongly pulls down to GND. When the voltage level at VM rises above 0.5V, the  $\overline{\text{RST}}$  output pin is held low for a reset time out period (200ms) before turning high impedance.

After the  $\overline{\text{RST}}$  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 watch dog timeout period (1.6s) after the  $\overline{\text{RST}}$  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  $\overline{\text{RST}}$  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  $\overline{\text{RST}}$  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  $\overline{\text{PB}}$  pin or a digital ON/OFF command through the mode input pins (M1/M2).

In this timing sequence, the  $\overline{\text{KILL}}$  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,  $\overline{\text{KILL}}$  On Blanking period, the input to the  $\overline{\text{KILL}}$  pin is ignored and the EN pin remains in its high impedance state. This  $\overline{\text{KILL}}$  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  $\overline{\text{KILL}}$  pin high (t2) indicating that proper power up sequence is completed. Failure to set  $\overline{\text{KILL}}$  pin high at the end of the 500ms  $\overline{\text{KILL}}$  On Blanking period (t3) results in an immediate system shut down (EN pin pulling down). However, in this typical sequence, with the  $\overline{\text{KILL}}$  pin high at the end of the  $\overline{\text{KILL}}$  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  $\overline{\text{INT}}$  pulls low. However, the transition from high to low at the  $\overline{\text{INT}}$  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

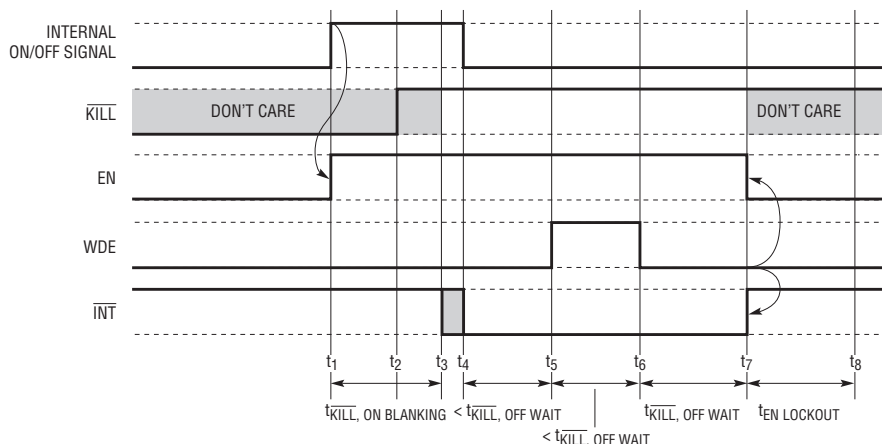


Figure 10. Typical power on and power off sequence

continued on page 26

# Integrated High Voltage Switching Charger/PowerPath Controller Minimizes Power Dissipation and Fits into 2cm<sup>2</sup>

by Tage Bjorklund

## 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 dissipa-

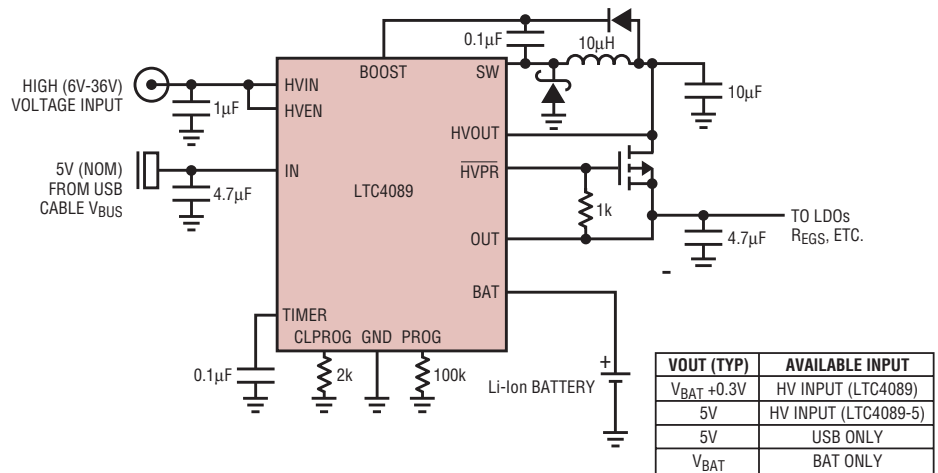


Figure 1. Typical application of the LTC4089

tion, 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 2cm<sup>2</sup> 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  $\overline{HVPR}$  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

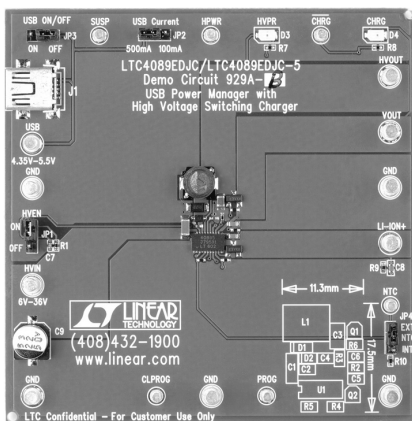
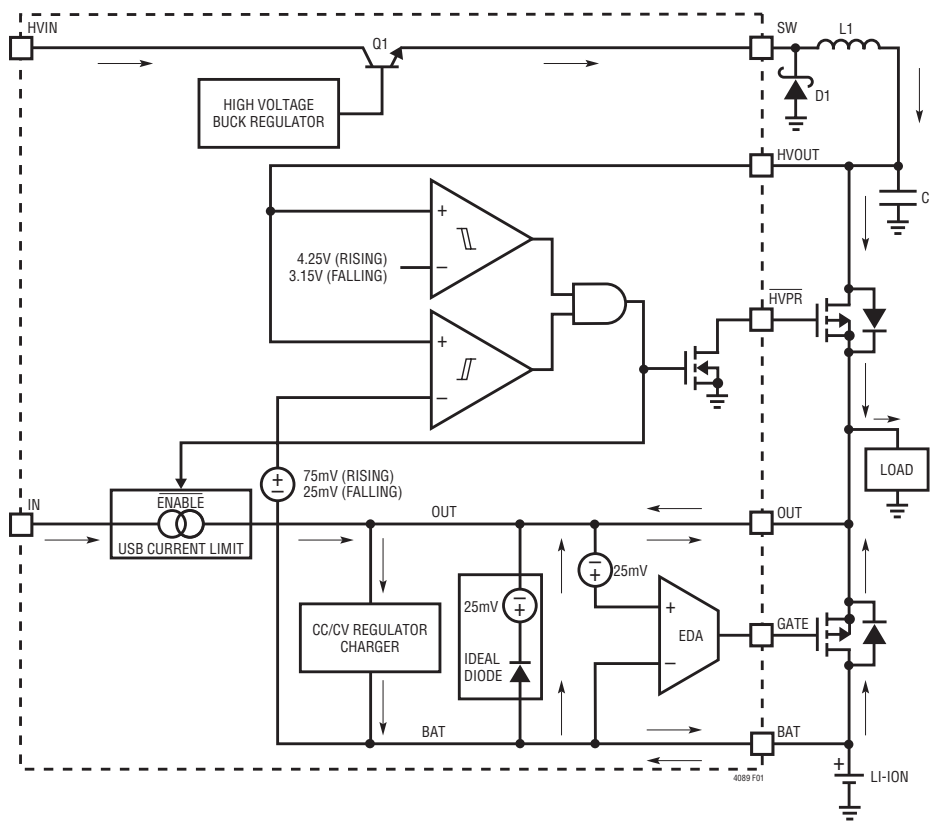


Figure 2. A complete LTC4089/LTC4089-5 USB/high voltage/Li-ion charger application fits into 2cm<sup>2</sup>



**Figure 3. A block diagram of the LTC4089 and LTC4089-5 shows the PowerPath controller, wide-input-range buck regulator and battery charging features.**

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 Saves an Adaptor**

The LTC4089 and LTC4089-5’s input voltage range is 6V to 36V, well within the range of automotive batter-

ies, 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,  $V_{OUT}$ , 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  $V_{OUT}$  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.

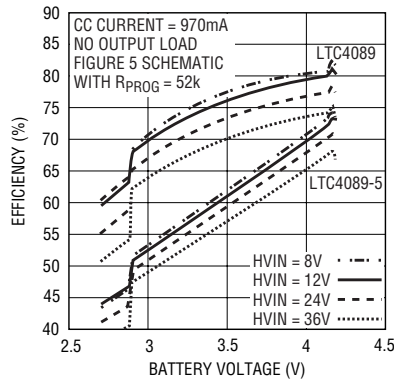
**Table 1. Comparison of traditional dual input charger and LT power manager/charger**

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



- ❑ **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).



**Figure 4.** The efficiency of LTC4089/LTC4089-5 when charging from HVIN

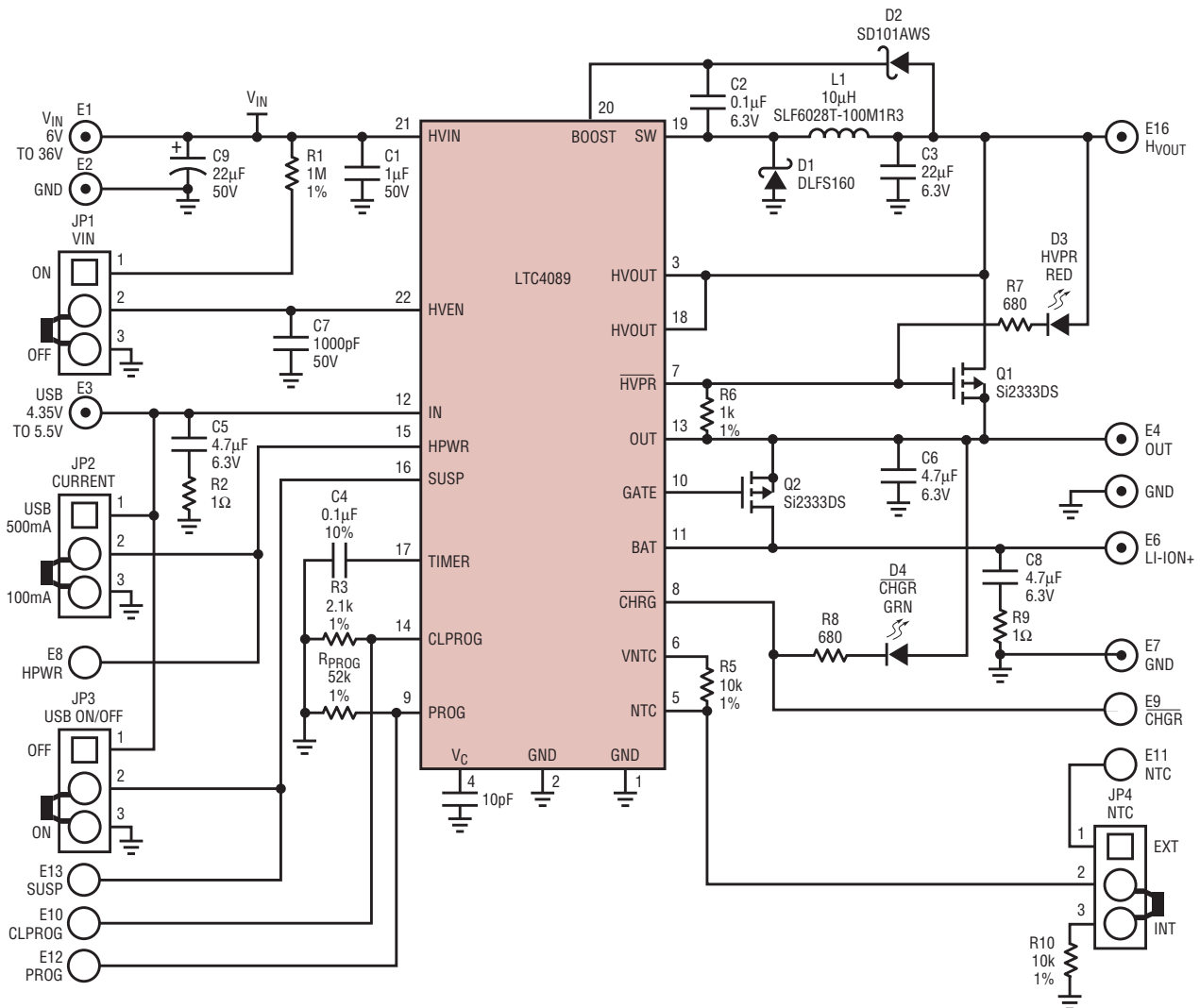
For instance, in Case 1, the system gets the current it needs—anything left over is available to trickle-charge the battery. The removal of the battery (Case 2) doesn't affect the system's available power, which is over 99%

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.



**Figure 5.** The typical application circuit schematic diagram

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 CL-PROG pin (2.1k $\Omega$  for 475mA USB current limit with maximum of 500mA considering component tolerances)
- ❑ **Charge current** is set by a resistor connected to PROG pin (71.5k $\Omega$  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 0.15 $\mu$ F 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

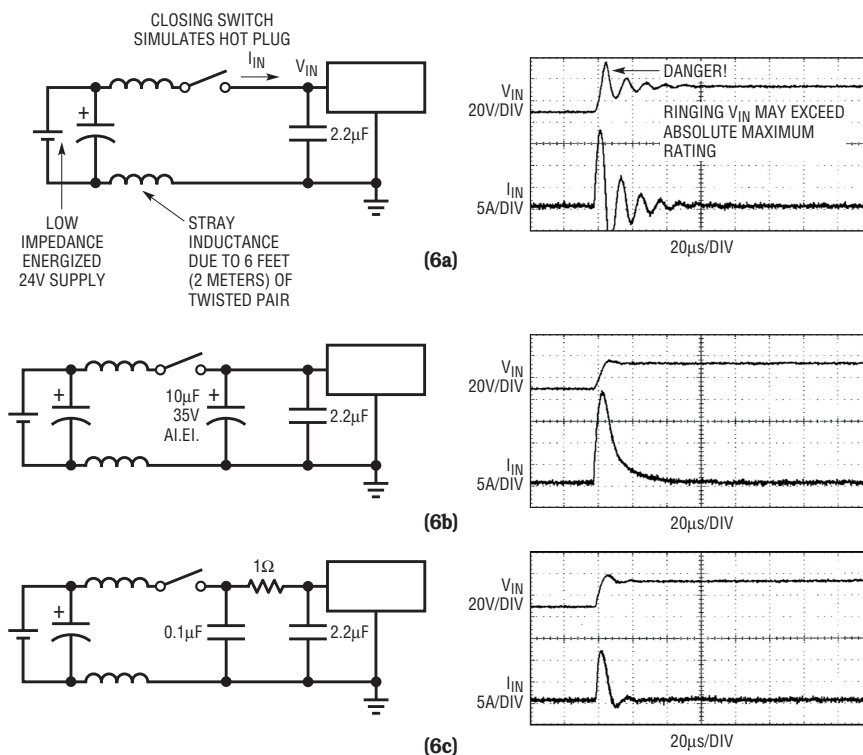
### High Voltage Buck Input Surge Protection

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 can 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 2.2 $\mu$ F 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 1 $\Omega$  resistor is added in series with the input to eliminate the voltage overshoot (it also reduces the peak input current). A 0.1 $\mu$ F 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*



**Figure 6. A well chosen input network prevents input voltage overshoot and ensures reliable operation when the LTC4089/LTC4089-5 is connected to a live supply.**

# Using Transformers in LTspice/SwitcherCAD III

by Mike Engelhardt

## 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 al-

## About LTspice/SwitcherCAD III

LTspice/SwitcherCAD III is a powerful SPICE simulation tool with integrated schematic capture. Unlike many other free simulators, LTSpice is a general purpose tool and not limited. LTSpice includes models for most of Linear Technology's switch-mode DC/DC converters as well as a library of devices for general analog circuit simulation including op amps, comparators, linear regulators and discretes. LTspice/SwitcherCAD III is available for free download at [www.linear.com](http://www.linear.com). 

lows 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

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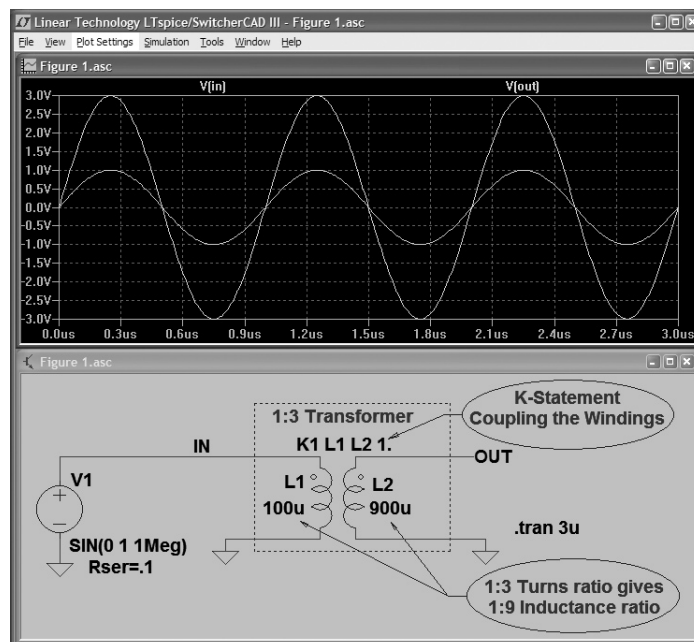


Figure 1. To add a transformer to your LTspice/SwitcherCAD III model, simply draw two inductors and add a "K" statement to couple the inductors.

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:

```
K1 L1 L2 1
K2 L2 L3 1
K3 L3 L4 1
```

LTspice will tell you that this transformer is impossible since it isn't 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:

```
K1 L1 L2 1
K2 L1 L3 1
K3 L1 L4 1
K4 L2 L3 1
K5 L2 L4 1
K6 L3 L4 1
```

In general, the number of mutual inductances in a transformer with N windings is  $N \cdot (N - 1)/2$ . 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

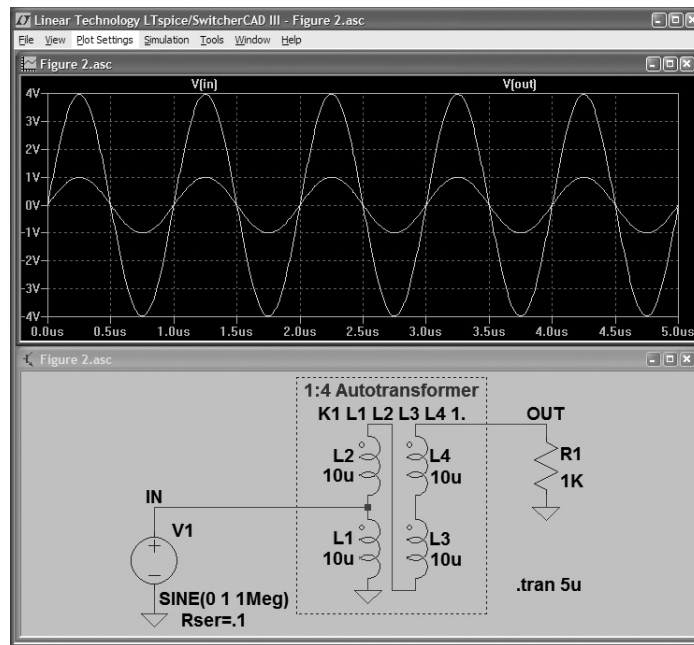
inductance is tedious at best and tends to be error prone. A better approach is to use a single K-statement that mentions all the inductors that are wound on the same core and let LTspice do the work:

```
K1 L1 L2 L3 L4 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:  $L_{LEAK} = L \cdot (1 - K \cdot K)$



**Figure 2.** To add a transformer with more than two windings, add a "K" statement that includes all of the coupled inductors.

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](http://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

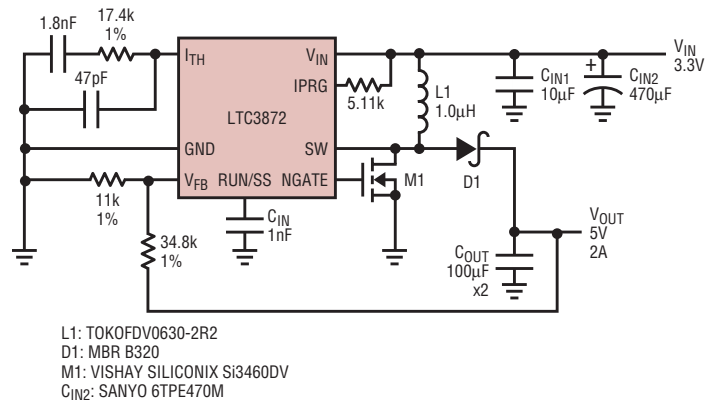
## Introduction

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

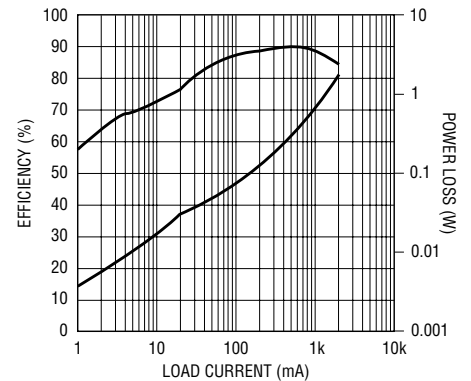
Matching the LTC3872's small size, its 550kHz constant frequency operation allows the use of a small-footprint surface mount inductor and ceramic capacitors. This saves space over boost

controllers that use a constant on-time switching scheme, which can result in a lower operating frequency and physically larger filter components. No  $R_{SENSE}^{TM}$  technology eliminates the need for a separate current-



L1: TOKOFDV0630-2R2  
D1: MBR B320  
M1: VISHAY SILICONIX SI3460DV  
CIN2: SANYO 6TPE470M

**Figure 1.** A 3.3V input, 5V output boost regulator delivering up to 2A. The large input capacitor  $C_{IN2}$  protects against inductive ringing in long traces to the main input supply, which could happen during load transients and startup.

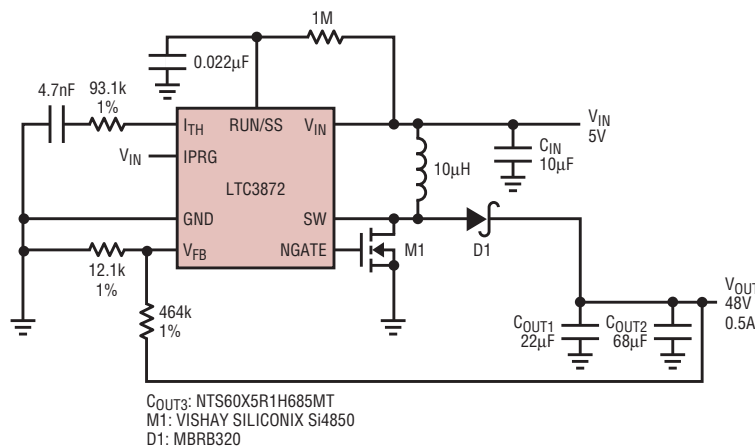


**Figure 2.** Efficiency and Power Loss for the application circuit of Figure 1.

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<sup>®</sup> compensation to accommodate whatever output voltage and filter components are chosen.

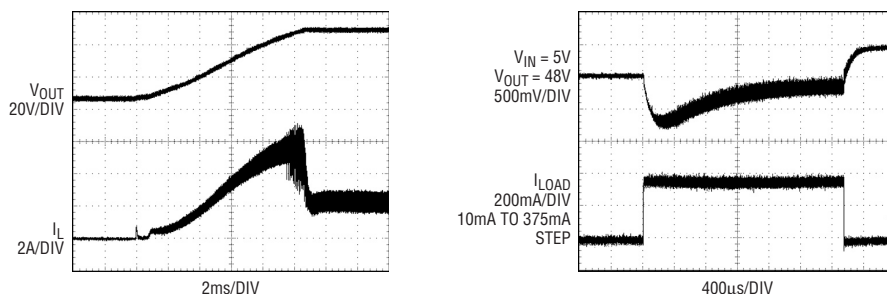
## Light Load Efficiency

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.



COUT3: NTS60X5R1H685MT  
M1: VISHAY SILICONIX SI4850  
D1: MBRB320

**Figure 3.** A 5V input, 48V output boost regulator delivering up to 0.5A



**Figure 4.** Startup and load transient for the circuit of Figure 3

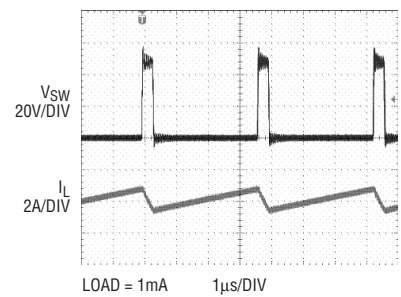
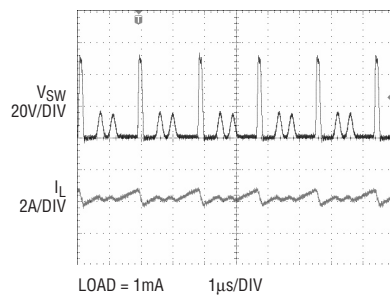
**A 3.3V Input, 5V/2A Output Boost Converter**

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.

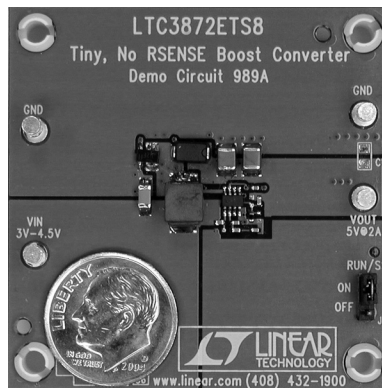
The LTC3872 uses the drain to source voltage of the external N-channel MOSFET to sense the inductor current. Eliminating a separate sense resistor can increase efficiency by 1%–2% at heavy loads. Absent a short circuit at the output, the maximum current that the converter can draw from  $V_{IN}$  is 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



**Figure 5.** At light loads, the circuit of Figure 3 uses pulse skip mode. In this mode operation does not exceed the (80%) maximum duty cycle of the converter at 550kHz. At heavy loads, the maximum duty cycle is extended by allowing the switching frequency to fall.



**Figure 6.** A typical LTC3872 application occupies just 2.25cm<sup>2</sup>.

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<sup>2</sup> (Figure 6). The small solution size and wide input voltage range make it an easy fit for a variety of applications. **LT**

*LTC2952, continued from page 18*

ON/OFF signal is caused by a valid pushbutton OFF.

From the start of the shutdown sequence, the system power turns off in 500ms, unless an edge (a high-to-low or low-to-high transition) at the WDE pin is detected within the 500ms period to extend the wait period for another 500ms. This KILL Wait time (500ms/cycle) is designed to allow the system to finish performing its house keeping tasks before shut down.

Once the µP finishes performing its power down operations, it can either let the KILL Wait time expire on its own or set the  $\overline{\text{KILL}}$  pin low to immediately terminate the KILL Wait time. When the KILL Wait time expires, the LTC2952 sets EN low. This turns off the DC/DC converter connected to the EN pin. In the sequence shown in

Figure 10, the KILL Wait time is reset twice with edges on the WDE pin (t5 and t6) before finally expiring (t7).

When the DC/DC converter is turned off (EN goes low), it can take a significant amount of time for its output level to decay to ground. In order to guarantee that the µP has always powered down properly before it is re-started, another 500ms (Enable Lock Out period) timer is started to allow for the DC/DC converter output power level to power down completely to ground. During this Enable Lock Out period, the EN pin remains in its low state regardless of any transition at the internal ON/OFF signal. At the end of the 500ms Enable Lock Out time (t8) the LTC2952 goes into its reset state, ready for the next turn on sequence. Note that at this reset

state the EN pin remains strongly pulling down.

**Conclusion**

The LTC2952 is a versatile, full featured Power Path Management IC that provides robust pushbutton ON/OFF control with a simple and graceful communication interface to the system microprocessor. Its wide voltage range, gate drive capability and low power fit an extensive number of applications requiring efficient management of two or more power paths. To further complement the requirements of highly reliable systems, the LTC2952 also offers voltage and watchdog monitoring capabilities. **LT**

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# High Voltage Step-Down Controller Delivers High Power with Minimum Number of Components

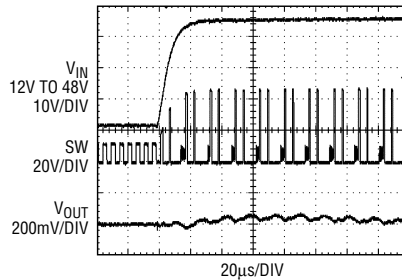
by Stephanie Dai and Theo Phillips

## 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 40 $\mu$ A 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



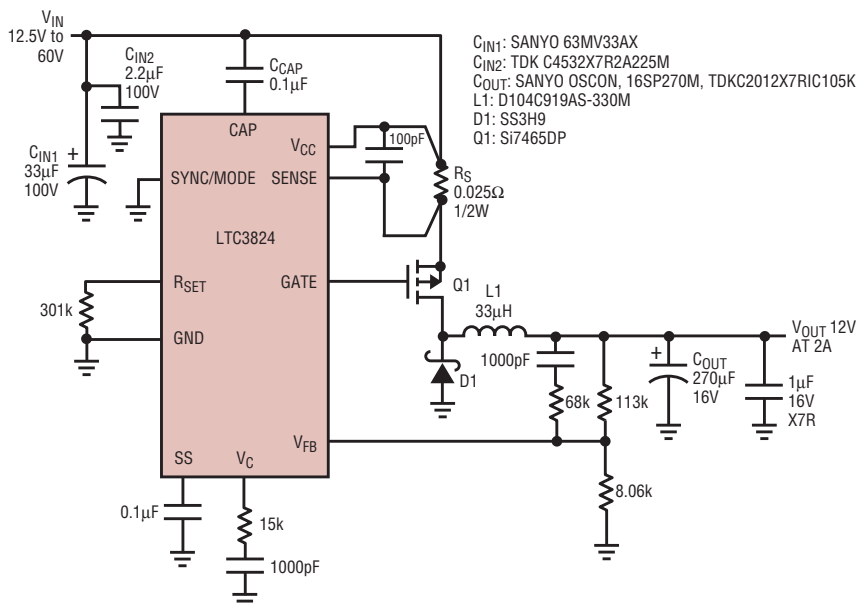
**Figure 1.** The output voltage remains steady regardless of wide swings in the input voltage.

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  $I^2R$  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

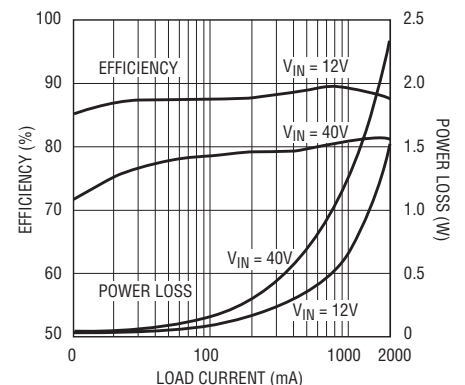
and rapid overvoltage and short circuit protection.

## 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  $V_{OUT}$  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  $R_{SET}$ , or it can synchronize to an ex-



**Figure 2.** A typical LTC3824 application



**Figure 3.** Efficiency for the circuit of Figure 2 is as high as 90% at moderate loads.

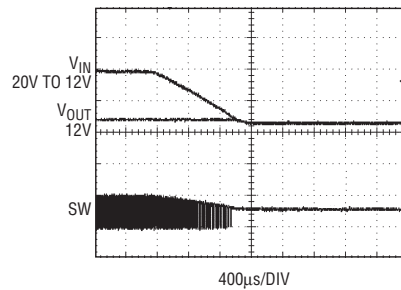


ternal clock from 200kHz to 600kHz. Synchronization facilitates integration into applications using other switching regulators.

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

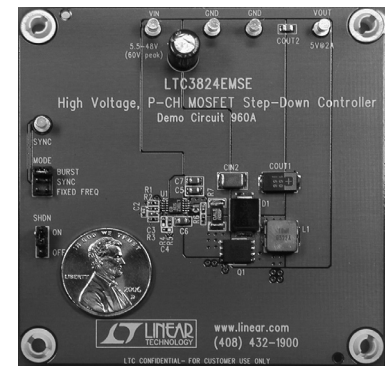
The LTC3827 includes a programmable soft-start time, which requires only a single external capacitor between the SS pin and ground. At high input voltages, a relatively large capacitor prevents inrush currents during start-up. This in turn prevents output overvoltage and sudden drops in  $V_{IN}$ , which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

Short circuit and overvoltage protection are designed to keep the LTC3824 operating normally even



**Figure 4.** When the input voltage drops below the programmed output voltage, the output voltage gracefully tracks the input voltage.

under extreme conditions. In normal operation, the feedback voltage  $V_{FB}$  is regulated to 0.8V. If  $V_{FB}$  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  $V_{FB}$ , 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



**Figure 5.** The LTC3824 comes in a small, thermally enhanced MSE package.

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. **LT**

*LTC3828, continued from page 7*

when the channel 2 feedback voltage is within  $\pm 7.5\%$  window.

The LTC3828 incorporates protection features such as current limit, short circuit current foldback limit, input undervoltage lockout and output overvoltage protection. The current comparators have a maximum sense voltage of 75mV resulting in a maximum MOSFET current of  $75mV / R_{SENSE}$ . If the output falls below 70% of its nominal output level, then the maximum sense voltage is progressively lowered from 75mV to 25mV.

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

$V_{PHSM D}$	GND	OPEN	INTV <sub>CC</sub>
Controller 1	0°	0°	0°
Controller 2	180°	180°	240°
CLKOUT	60°	90°	120°

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  $\pm 50\%$  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 PHSM D 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. **LT**



# 94% Efficient, Low Noise, Step-Up DC/DC Converter in 2mm × 2mm DFN Package Offers Unrivaled Performance and Solution Size

## 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 45mm<sup>2</sup> of board real estate.

## Features

The LTC3427 operates from input voltages as low as 1.8V and provides output voltages ranging from 1.8V

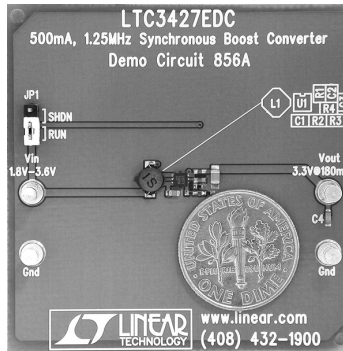


Figure 1. It is possible to fit an entire LTC3427-based boost converter into 45mm<sup>2</sup>.

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

by Bert Hepfinger

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-ringing 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 converter into 45mm<sup>2</sup> of board space. X5R ceramic capacitors are recommended for V<sub>IN</sub> and V<sub>OUT</sub> bypassing.

*continued on page 38*

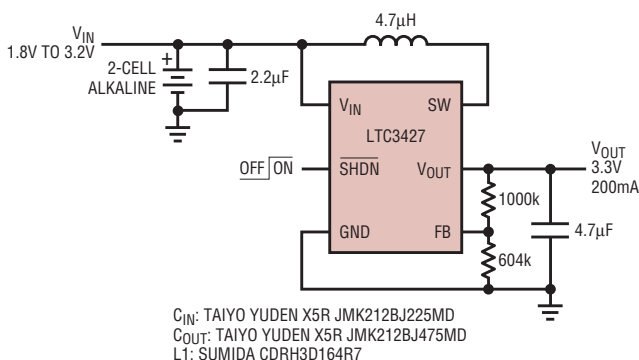


Figure 2. 2-Alkaline cell to 3.3V synchronous boost converter

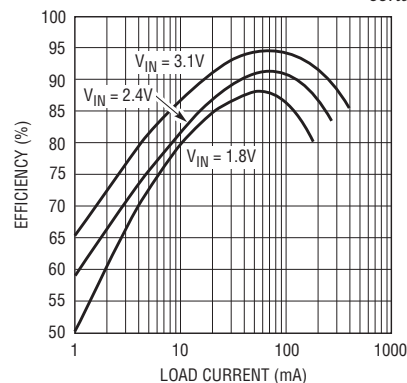


Figure 3. Efficiency vs load current for the converter in Figure 2

# Simple, High Efficiency, Multi-Output, Isolated Flyback Supply with Excellent Regulation

by Ryan Huff

## 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.

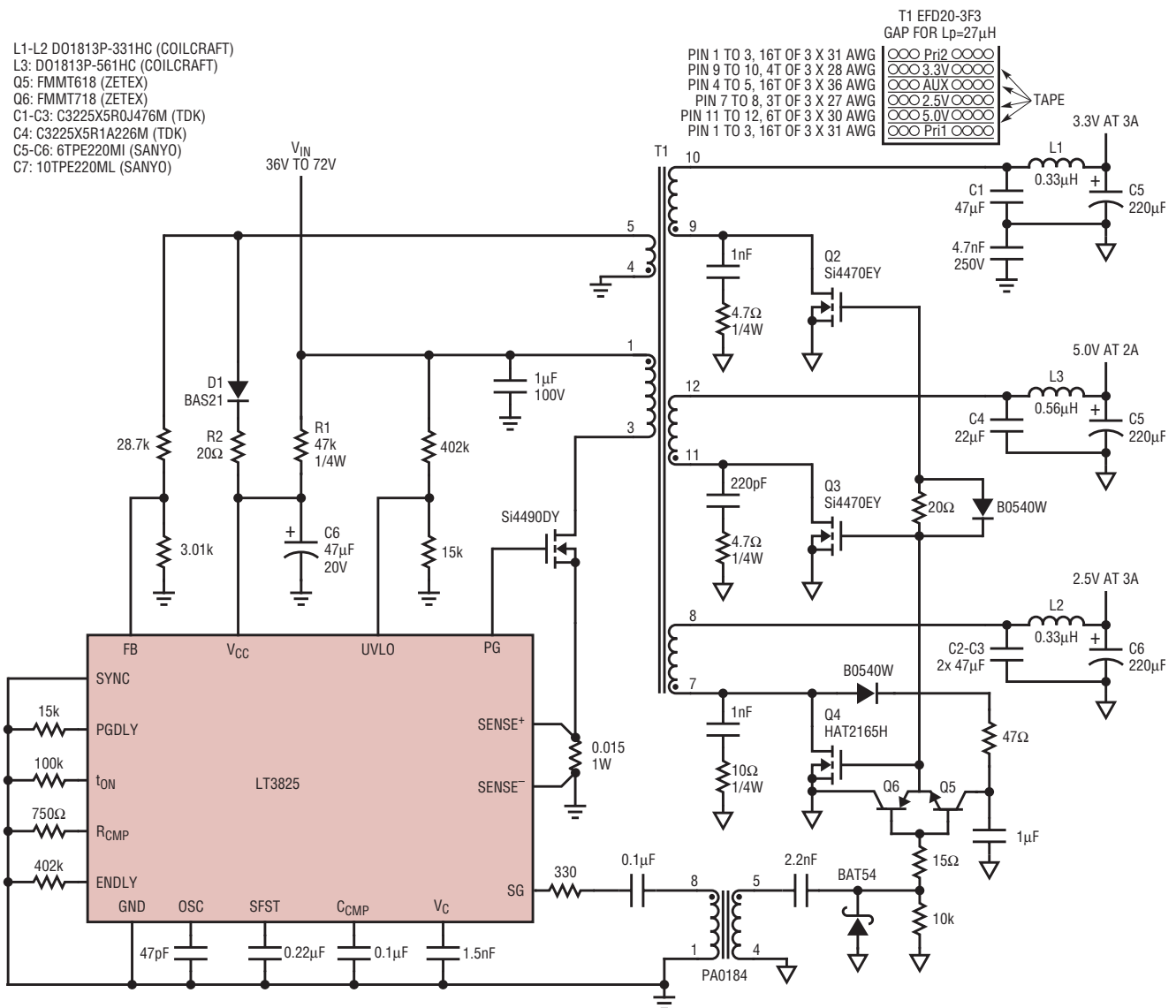


Figure 1. Simple, high efficiency, 36V<sub>IN</sub>-72V<sub>IN</sub> to 2.5V<sub>OUT</sub> at 3A, 3.3V<sub>OUT</sub> at 3A, and 5.0V<sub>OUT</sub> at 2A synchronous flyback

## 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  $\pm 1.6\%$  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  $\pm 3.6\%$ . Figure 4 shows the supply's transient response for a 1.5A-to-3A load step on the 2.5V output at 5A/ $\mu$ s slew rate and 36V input. With this 50% load step, all output voltages remain within  $\pm 2\%$  of their set points.

This circuit also has the advantage of having extremely low ripple on the output voltages; exhibiting less than 10mV<sub>P-P</sub> on all outputs at a switching

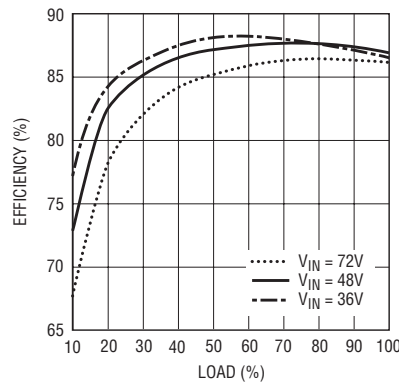


Figure 2. Efficiency of circuit in Figure 1

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 controller 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

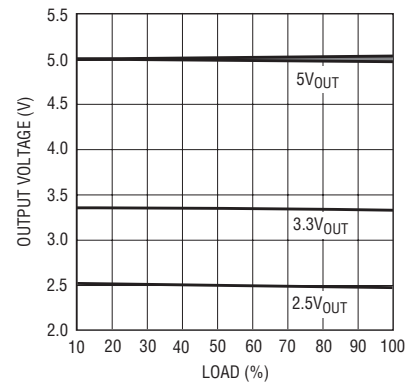


Figure 3. Output voltage regulation of the circuit in Figure 1

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 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

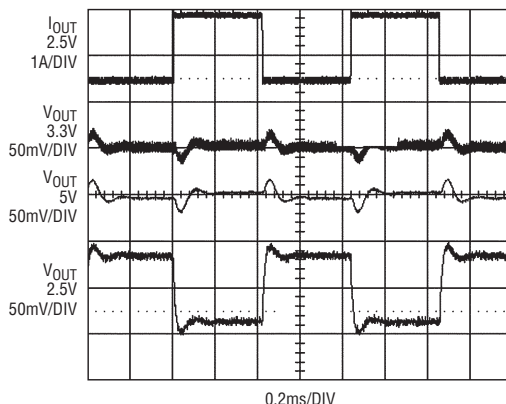


Figure 4. 1.5A to 3A to 1.5A load current step (top trace) on 2.5V output and output voltage responses (bottom traces) of circuit in Figure 1

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<sub>CC</sub> 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. **LT**

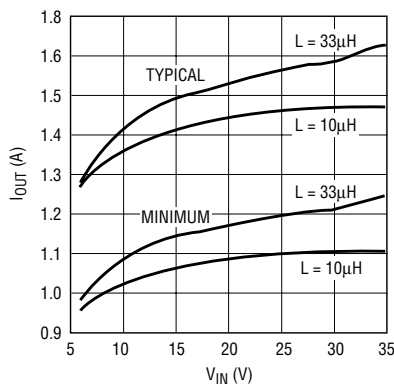
LTC4089, continued from page 22

**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 22µF/6.3V X5R caps measure only 11µF 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 22µF/16V X5R or better 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 22µF/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 10µH inductor



**Figure 7. The high voltage switching regulator's maximum output current for two different value inductors**

and 1.1A for a 33µH 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<sub>PROG</sub>) exceeds the buck output current limit, the buck output voltage collapses to the battery voltage.

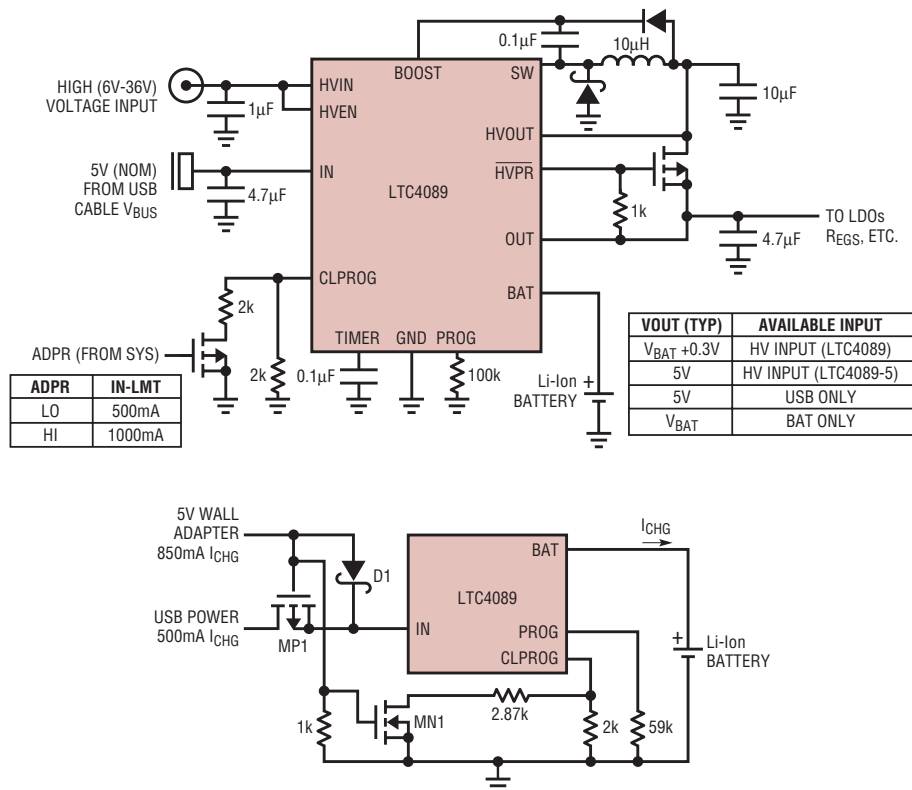
**Accept USB and 5V Adaptor with Different Current Limits**

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 x 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. **LT**



**Figure 8. IN pin accepting USB and 5V Adaptor with different current limits**



# Monolithic Buck Regulator Operates Down to 1.6V Input

by Gregg Castellucci

## 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 2mm × 3mm 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

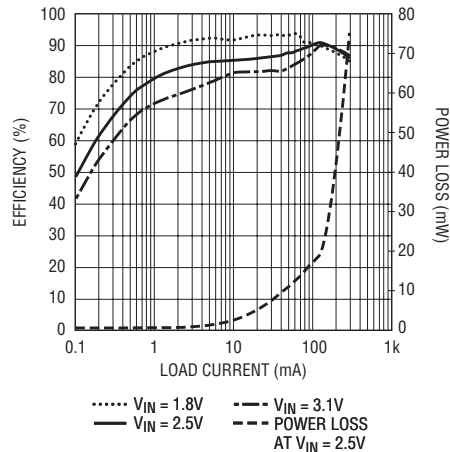


Figure 1. Efficiency vs load current for the LTC3549 in Burst Mode operation

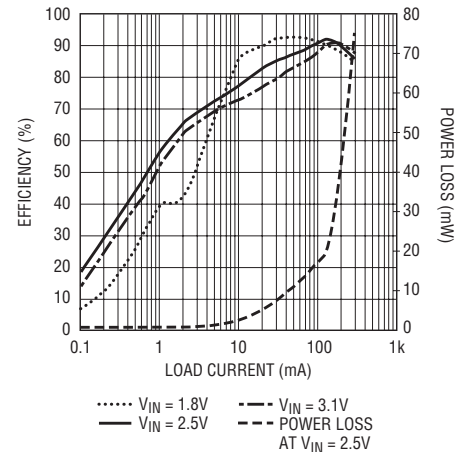


Figure 2. Efficiency vs load current for the LTC3549 in pulse skip mode

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

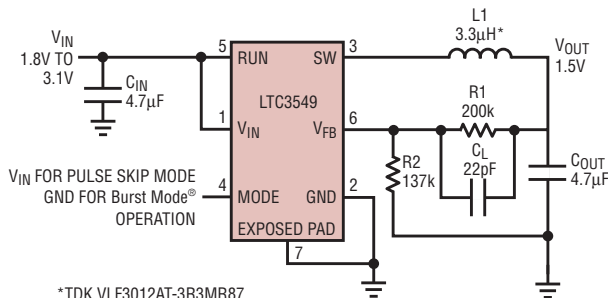
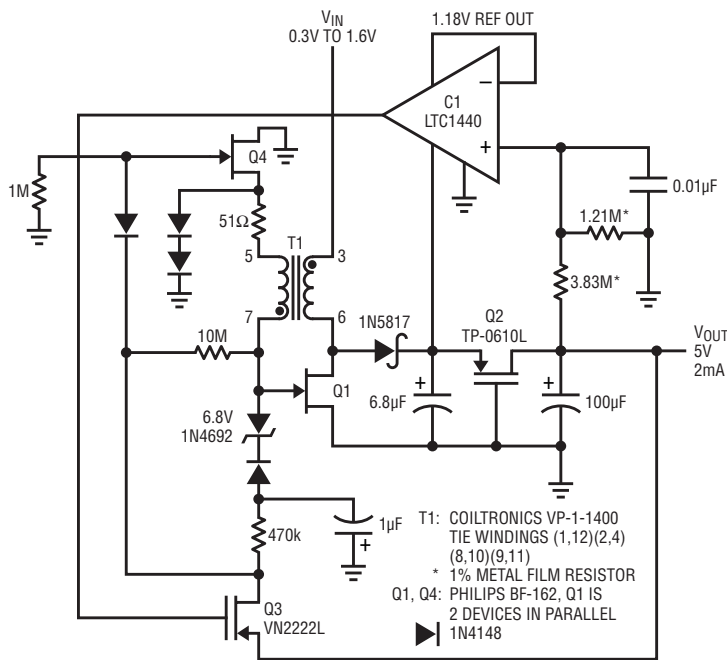



Figure 3. A 1.5V/250mA step down regulator

continued on page 37





Q3's shunt control of Q1 is simple and effective, but results in a 25mA quiescent current drain. Figure 5's modifications reduce this figure to 1mA by series switching T1's secondary. Here, Q3 switches series-connected Q4, more efficiently controlling Q1's gate drive. Negative turn-off bias for Q4 is bootstrapped from T1's secondary; the 6.8V zener holds off bias supply loading during initial power application, aiding start-up. Figure 4 shows minimal penalty imposed by the added quiescent current control circuitry. 

for the latest information on LTC products, visit [www.linear.com](http://www.linear.com)

**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.**

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  $V_{IN}$  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  $V_{CE}$  of less than 210mV.

### $V_{BAT}$ Pin


The  $V_{BAT}$  pin is an innovation that allows output disconnect operation in a wide range of applications.  $V_{BAT}$  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  $V_{BAT}$ . 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  $V_{BAT}$  pin allows the inductors to be powered from a different source than  $V_{IN}$  while still maintaining the disconnect operation. This can be useful in

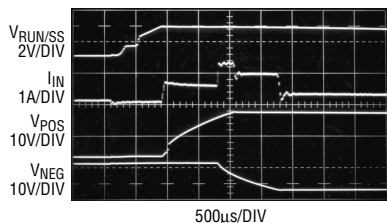
a system using a 2-cell supply where a low voltage boost provides 3.3V for the  $V_{IN}$  supply. By connecting  $V_{BAT}$  as well as the inductors to the 2-cell supply, the positive output is able to stay on as long as possible when the part goes into shutdown.

### Applications

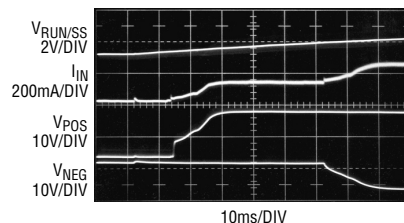
The LT3487 can be used in a CCD bias as well as other applications that require a positive and negative bias such as  $\pm 12V$  data acquisition systems. The boost channel can produce voltages up to 30V as long as the part can meet the required duty cycle. Similarly, the inverting channel can produce 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 3. Startup without soft-start capacitor**



**Figure 4. Startup with 100nF soft-start capacitor**



# 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/disconnect input power from its load simply by toggling the de-bounced pushbutton input.

The LTC2954 operates over a wide 2.7V to 26V input voltage range while consuming only 6µA of supply current and is available in 8-Pin 3mm x 2mm DFN and ThinSOT™ Packages. Two versions of the part are available to

accommodate either positive or negative enable polarities.

## 20Mbps and Slow 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 x 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 (2V<sub>P-P</sub>), 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**

Part Number	Max Data Rate (Mbps)	Duplex	Low-Power Shutdown Mode
LTC2856-1	20	Half	Yes
LTC2856-2	0.25	Half	Yes
LTC2857-1	20	Full	No
LTC2857-2	0.25	Full	No
LTC2858-1	20	Full	Yes
LTC2858-2	0.25	Full	Yes



pendently of the output common mode voltage. These input characteristics often eliminate the need for an input transformer and/or AC-coupling capacitors. This allows DC-coupled operation for applications that have frequency ranges including DC. At the outputs, the common mode voltage is set via the  $V_{OCM}$  pin, allowing the LT6402 to drive ADCs directly.  $V_{OCM}$  is a high impedance input, capable of setting the output common mode voltage anywhere in a range from 1.1V to 3.6V.

The topology of the LT6402 is closed-loop and incorporates three internal amplifiers. Two of the amplifiers are identical and drive the differential outputs. The third amplifier sets the output common mode

voltage. Gain and input impedance are determined by the resistors in the internal feedback network. The low output impedance is based on the inherent output impedance of each feedback amplifier.

The LT6402 includes built-in single-pole output filtering. The user has the choice of using the unfiltered outputs, the filtered outputs (75MHz -3dB lowpass), or modifying the filtered outputs to alter the frequency response with additional components. Numerous lowpass and bandpass filter configurations are easily implemented with just one or two additional components.

The LT6402 operates on a single 5V supply and consumes only 30mA. When 2.0V or greater is applied to

the ENABLE pin, the supply current reduces to 250µA. It comes in a compact 16-lead 3mm × 3mm QFN package. The DC954 demo board has been created for stand-alone evaluation of the LT6402 amplifier. Contact LTC applications for demo boards that combine the LT6402 with one of LTC's high-performance ADCs.

### 1.6V, 1µA Precision Rail-to-Rail Input and Output Op Amps

The LT6003/LT6004/LT6005 are single/dual/quad op amps designed to maximize battery life and performance for portable applications. These amplifiers operate on supplies as low as 1.6V and are fully specified and guaranteed over temperature on 1.8V, 5V and ±8V

LTC3549, continued from page 33

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.

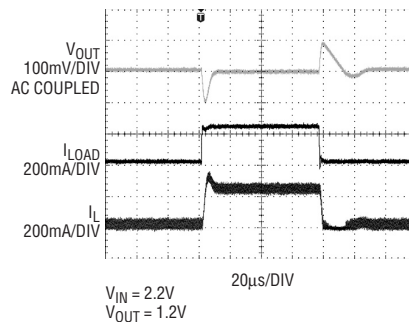


Figure 4. The LTC3549's transient response to a 20mA-to-250mA load step, pulse skip mode.

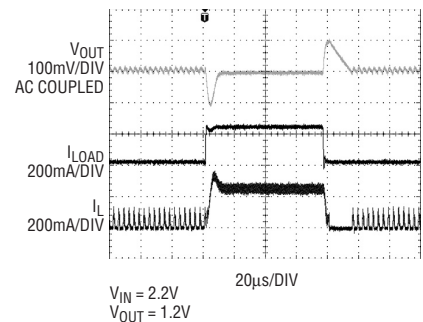


Figure 5. The LTC3549's transient response to a 20mA-to-250mA load step, Burst Mode operation.

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  $V_{IN}$  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. 

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 LT6003/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. 

**For further information on any of the devices or applications described in this issue of *Linear Technology*, please visit:**

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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  $V_{OUT}$  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

**Figure 4. Low  $V_{OUT}$  ripple over a wide range of loads for the circuit of Figure 2**


space savings of 25%–30% by using tiny chip coils such as the Murata LQH2MC series.

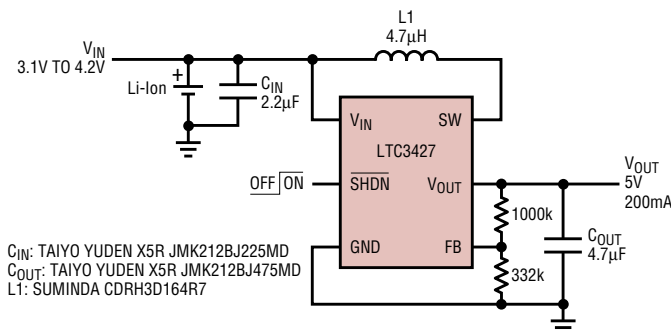
**Lithium-Ion to 5V, 1W Converter**

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 45mm<sup>2</sup> of board space. Further significant board space savings are possible with

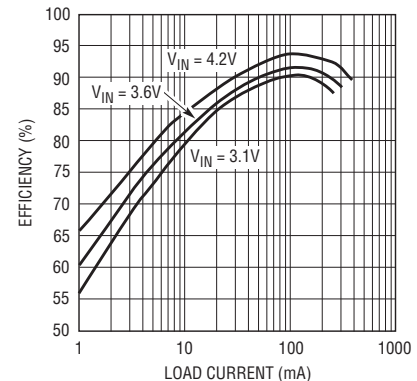
the use of tiny chip inductors. As illustrated in Figure 6, peak efficiencies of up to 93% are attainable from a fully charged battery. Adding an optional low current Schottky diode across the synchronous rectifier (SW node to  $V_{OUT}$ ) can increase efficiency by as much as 2%, though this negates 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. 



**Figure 5. Single Li-ion cell to 5.0V synchronous boost converter**



**Figure 6. Efficiency vs load current for a single lithium ion cell to 5.0V converter**

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