IN THIS ISSUE...

Smart Batteries: Not Just for Notebooks Anymore

by Mark Gurries

Introduction

With the backing of Intel and Microsoft, Smart Batteries have become the dominant battery pack solution for products that require an accurate gas gauge to predict battery life. The Smart Battery System (SBS) has simplified the design of standalone battery systems so much that it is showing up in applications outside its usual realm of notebook computers. For instance, the SBS is gaining popularity in backup power systems for mission critical high reliability applications.

The attraction of the SBS is that its modular nature makes easy to design a closed loop battery-charge system, and upgrade components as needed. All of the safety features are taken into account within the battery. This minimizes NRE costs and makes for robust systems, especially important to high reliability battery-backup applications. There is no need to become a battery expert to take advantage of the features of the SBS.

The first part of this article offers an overview of the SBS; the second part describes two of Linear Technology's Smart Battery Chargers.

Figure 1. Simplified schematic of a Smart Battery and Smart Battery Charger. Smart Batteries have an integrated gas gauge, which communicates the condition of the battery, and requests charge (voltage and current) over the SMBus. Charge requests are satisfied by the Smart Battery Charger, which applies the requested voltage and current to the battery terminals. The beauty of the system is that the charger does not need to know the chemistry of the battery. It is up to the gas gauge to maintain the charge algorithms. The modular nature of the SBS allows for any Smart Battery Charger to charge any Smart Battery.

Issue Highlights

With the backing of Intel and Microsoft, Smart Batteries have become the dominant battery pack solution for products that require an accurate gas gauge to predict battery life. The Smart Battery System (SBS) has simplified the design of standalone battery systems so much that it is showing up in applications outside its usual realm of notebook computers.

Our cover article shows how Linear Technology's Smart Battery Charger circuits simplify the design of high performance Smart Battery Systems.

Featured Devices

Below is a summary of the other devices featured in this issue.

Complete PowerPath™ Management Squeezed into 9mm²

The LTC®4413 **dual monolithic ideal diode** makes it possible to build an entire power management solution in a 3mm × 3mm footprint. (Page 7)

Power over Ethernet Simplified

The LTC4267 reduces the complexity and size of a PD by combining an IEEE **802.3af-compliant PD interface with a current mode switching regulator** in a space-saving, low-profile 16-pin SSOP or DFN package. (Page 11)

Tougher than a Crystal Oscillator: An All Silicon Clock

The LTC6905 is an **all silicon clock** that avoids the pitfalls of sensitive and power hungry crystal oscillators. (Page 14)

Wide Range, Digitally Programmable Voltage Gain

The LTC6915 is the simplest, most precise way to obtain **digitally programmable voltage gain**. (Page 16)

Combo Power Supply Sequencer and Supervisor

The LTC2924 is a **complete power supply sequencer and supervisor**

solution for multivoltage-rail systems, such as telecommunications equipment, memory modules, optical systems, networking equipment, servers, and base stations. (Page 20)

High Voltage DC/DC Conversion

The LT®3800 is a feature-packed **high voltage synchronous step-down controller** that helps meet the high-power point-of-load requirements of distributed power systems. (Page 25)

Design Ideas and Cameos

The Design Ideas start on page 29, including a low harmonic distortion, amplitude stable sine wave generator using the LT1968 RMS-to-DC converter. Five New Device Cameos appear on page 37. *LT*

Linear Technology in the News...

Linear Technology Offers All Products in Lead-Free Versions as Part of Broader Commitment to Protecting the Environment

All of Linear Technology's products are now available in lead-free versions as an ordering option. This is part of the company's commitment to meeting the European Community's Reduction of Hazardous Substances (RoHS) guidelines, and represents the latest step in Linear Technology's ongoing commitment to excellence and leadership in protecting the environment.

After evaluating various lead-free alternatives, Linear Technology selected Matte Tin as the optimal plating for lead-free products. The company believes that this provides the best drop-in replacement since it has the lowest reflow temperature of the lead-free alternatives, has excellent solderability performance, and provides excellent quality and reliability. In order to ensure a smooth transition for customers, Linear Technology will continue to offer solder plated products as well, with unique part numbers for both the lead-free and solder plated versions.

In addition to offering lead-free plating, Linear Technology will also provide by mid-2005 an improved plastic mold compound that eliminates antimony trioxide and elemental bromine for a more environmentally friendly packaging alternative. The company's goal is to replace these flame retardants with environmentally friendly alternatives that meet flammability standards, while improving the product reliability.

In early 2002, Linear Technology was certified to ISO 14001 compliance by implementing an environmental management system. The company is dedicated to making an ongoing contribution to environmental excellence in all of its operations.

Electronic Products Magazine Awards Linear Technology "Product of the Year" for Compact Photoflash Capacitor Charger

From the thousands of products introduced in 2004, the editors of Electronic Products have chosen what they feel are among the most outstanding—based on significant advances in technology or its application, a decided innovation in design, or a substantial gain in price-performance.

The LT3468 photoflash capacitor charger is one of these products (see *Electronic Products*, Jan. 2004, p. 84 and *Linear Technology* Magazine, Dec. 2003, p. 1). It enables the use of a Xenon flash lamp in a 3-Mpixel camera phone—providing excellent photographic performance in a small form factor and at a reasonable cost. *LT*

Smart Batteries, continued from page 1

About the Smart Battery System

Figure 1 shows a simplified block diagram of a Smart Battery. The biggest benefit of the Smart Battery System is the highly accurate gas gauge integrated into the battery pack. The gas gauge, as the name implies, indicates how much energy is left in the battery.

An integrated gas gauge can monitor the battery even when the battery is on the shelf, and the gas gauge is calibrated to a single battery, so accuracy is assured. A host-based gas gauge can't match this. Gas gauge measurement techniques have evolved to the point that the latest gas gauges are self-calibrating—error rates are at 1% over the lifetime of the battery. Because the gas gauge knows the battery better than any other circuit can, it is responsible for charge and discharge management.

Smart Battery Chargers

In an SBS Li-ion battery pack, there are built-in MOSFETS that can block charge or discharge current (see Figure 1). The SBS gas gauge can easily prevent over-discharge by turning off the discharge MOSFET when the battery voltage reaches a certain point; but when it comes to charging the bat-

tery, the gas gauge must work with an external charger. Smart Batteries are designed to work with Smart Battery Chargers. A Smart Battery Charger has advantages over a fixed standalone charger, such as:

❏ True Plug and Play operation, independent of battery chemistry and cell-configuration. Any Smart Battery Pack will work with any Smart Battery Charger. Batteries with different chemistries, cell-configurations, and even different charge algorithms can be swapped with no modification to the charger circuit.

❏ Built in safety features. The battery, because of its gas gauge, takes care of itself.

❏ A reliable battery detection system.

❏ Automatic charge management without the need of a host processor.

❏ Any Smart Battery and Smart Charger form a closed loop charge system that requires no

host processor intervention. A host is welcome to gather gas gauge information if required.

To understand how all this is possible, let's see how the Smart Battery system actually works.

How SMBus is used for a Closed Loop Charge Process

The Smart Battery System utilizes the System Management Bus or SMBus standard, which is a based on, and a subset of, the very popular and now recently made public domain two wire I^{2}C serial bus standard. In practice SMBus devices easily coexist with I^{2}C devices on the same bus.

The Smart Battery Standard defines fixed addresses for the battery and charger, and it defines some commands that allow the gas gauge to communicate to the Smart Battery Charger over the SMBus. This forms a closed loop system where the gas gauge determines the charge state of the battery, and evaluates other conditions (such as battery temperature) to see
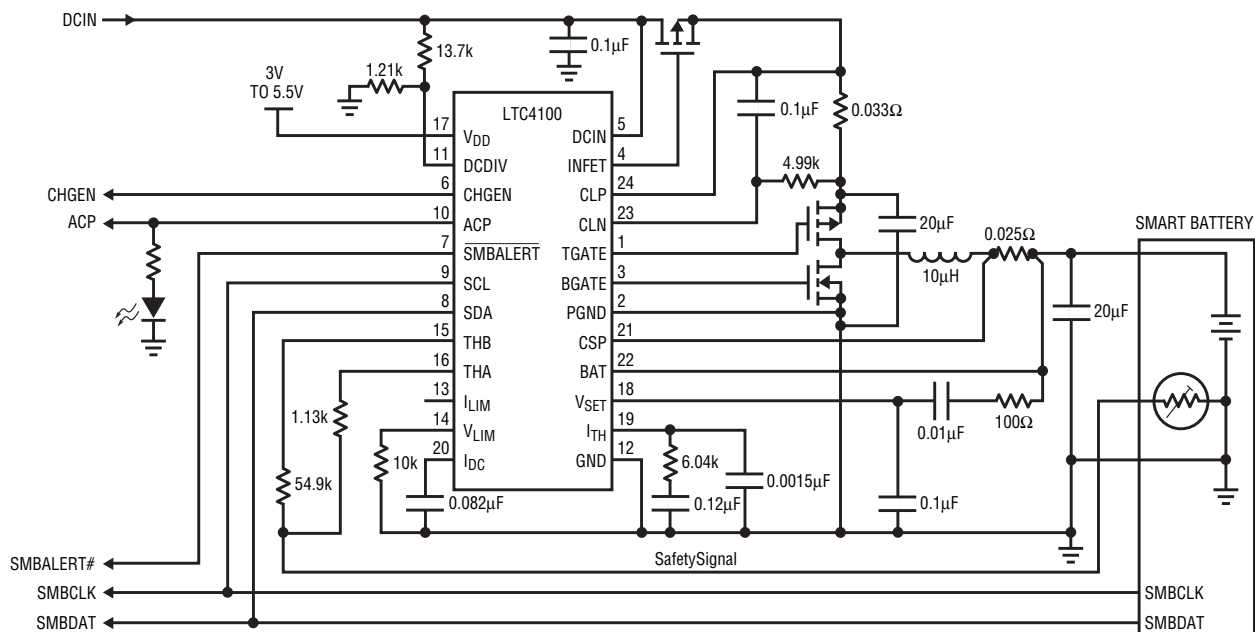

Figure 2. The LTC4100 in a feature-rich, simple and compact 4A Smart Battery charger

if a safe charge can be performed. The gas gauge requests a charge current and voltage from the Smart Charger via the SMBus. Because the gas gauge is in charge, the charger is not burdened with algorithms involving the battery cell configuration or chemistry.

When the gas gauge requests charge, the Smart Charger evaluates the requested charge parameters and does the best job it can to comply with them while at the same time independently evaluating various safety conditions. In order for charge process to happen, *both* the battery and the charger must agree it is safe to proceed. This keeps the loop simple and safe.

Flexible Communications

Although the SMBus standard only allows a single battery and a single charger to exist on a bus, multiple *bus masters* can coexist on the same bus. This allows the "Smarts" of the Smart Battery System to be distributed or augmented.

If you read Smart Battery Specifications, you might come across the terms called levels such as level 2 and level 3. This has nothing to do with sophistication or revision levels. It simply is a way of defining who is primarily responsible for the communication of charge request between the battery and the charger. A level 2 system means the Smart Battery is an SMBus bus master and transmits its charge commands to the charger directly. This is the simplest loop. A level 3 system means any device other than the Smart Battery itself, such as a host, is responsible for sending the commands to the charger. The latter configuration allows for other devices to take more control of the process to implement other unique features beyond those available by default with a level 2 system. Linear technology takes advantage of that capability in the LTC1760 smart charger by building the bus master into the charger. This allows for parallel charge and discharge of dual batteries, which has numerous advantages, explained in the "LTC1760 Dual Smart Battery Charger" section, below.

Safety and Reliability in the SMBus

The SMBus standard incorporates fail-safe mechanisms for SMBus crashes or hangs that allow bus recovery. The charger has watchdog timers that monitor the frequency of charge request commands, and can detect a loss of communication or closed loop operation so that it can pause the charge process and prevent accidental overcharge. For Li-ion batteries this is critically important.

Battery Detection via the Safety Signal

Reliable battery detection and additional safety is achieved by use of the Safety Signal, formerly known as the thermistor signal. The Safety Signal is produced by applying a voltage to a resistor, or thermistor in the Smart Battery via the dedicated SS pin (see Figure 1). A Smart Charger can measure the value of the resistance of the SS pin to ground, and from the resulting value, know if the battery is physically present, and if an NTC thermistor is present, determine if the temperature range is acceptable to allow charge.

The thermistor on the Safety Signal is *not* the same thermistor the gas gauge uses to evaluate temperature. It is a redundant system check that

allows the charger to make its own determination, independent of the gas gauge.

Alarms Warn of Impending Problems

An active safety feature called alarms is available to the Smart Battery. Alarms cover temperature, overcharge and over-discharge fault conditions, and are sent when the battery is close to taking direct action to stop the condition of concern. The gas gauge can send alarms to both the host and the Smart Battery Charger via the SMBus.

Over-Discharge Recovery

Over-discharge presents a special challenge that is fully addressed by the Smart Battery System. What happens if the battery does not have enough charge to support SMBus communications? One cannot attempt to detect the battery via its terminals, since the gas gauge will have already turned off the discharge MOSFET to protect the battery cells. A Smart Battery Charger, though, can use the safety signal to check for the battery pack, regardless of its state of charge.

A Smart Battery Charger, upon detection of a new battery, applies a constant current charge up to 100mA to the battery terminals. This low current quickly charges the cells enough
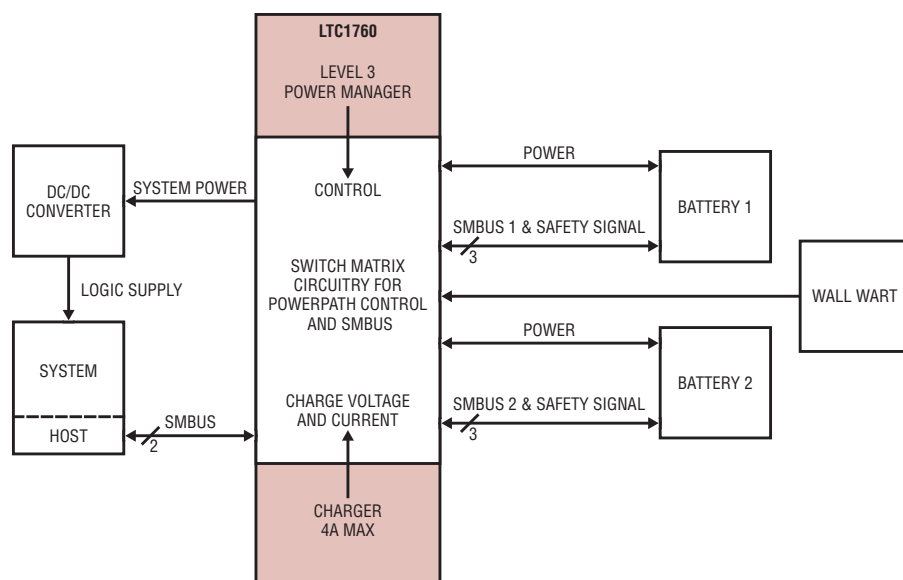
Figure 5. Simplified schematic of a dual battery system using the LTC1760. The LTC1760 acts as a Level 3 bus master, and handles both charge and discharge of the batteries. Even batteries of different chemistries or cell configurations can be used.

to where the gas gauge can come on line and take over the recovery charge process. As soon as the gas gauge sends its first valid charge request commands, the Smart Battery Charger stops applying the wake up charge and immediately implements the requested charge values. A wake up charge is not applied again until a new battery physically takes its place.

As foolproof as this recovery process sounds, there is one more safety issue to address. Consider the case where a new fully-charged Li-ion battery is attached to a Smart Charger, but permanent SMBus communication problems prevent the battery from communicating over the SMBus. The charger would apply the wake up charge indefinitely in the absence of any requests from the gas gauge. This would lead to a potentially dangerous overcharge situation.

To cover this situation, the Safety Signal comes to the rescue again. The resistance of the safety signal can fall into several ranges. Each range defines the acceptable duration of the wake up charge. Batteries thus fall into two categories: those that have the chemistry to receive an indefinite wake up charge and those that can only accept a short 3-minute wake up charge. NiMH batteries fall into the first category where as Li-ion batteries fall into the latter category. In the case of a damaged Li-ion battery, the battery will only receive a short wake up charge, thus preventing the possibility of accidental overcharge. The downside of this important safety feature is that overly discharged batteries *must* be designed to allow SMBus communication to be established within those three minutes regardless of the state of the cells.

Space Saving, Advanced Smart Battery Chargers

As shown above, the Smart Battery System offers advanced capabilities with little required design effort. Linear Technology's Smart Battery Chargers take advantage of Smart Battery System features and add a few of their own, while maintaining compliance to the standard.
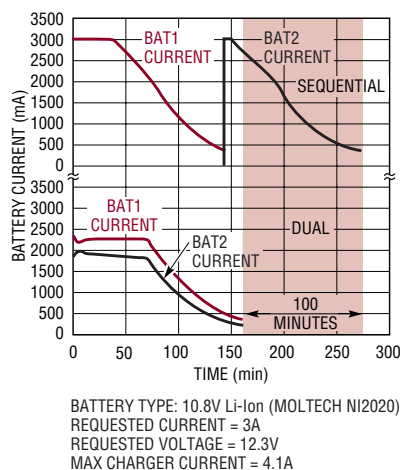

Figure 3. Charging batteries in parallel is almost twice as fast as charging them sequentially.

In an SBS, the charger resides in the system, sharing precious PCB real estate with other devices. Linear Technology has two products that directly address those needs: The LTC4100 single Smart Battery Charger and the LTC1760 dual Smart Battery Charger are switching buck regulators that include features defined in the Smart Battery standard and other important performance enhancements.

One of the most important recent advances in DC/DC converter design is the use of high capacitance and voltage (high C/V) ceramic capacitors. In switching regulator applications, their low ESR allows them to handle large ripple current per µF of capacitance compared to most other types of capacitors, even while remaining inexpensive to buy.

Ceramics have a problem, though. They have piezo-electric properties that can generate audible noise with the PCB acting as a sounding board. There are conditions where audio-frequency signals are generated by typical switching battery chargers. The LTC4100 and LTC1760 are designed to operate outside of the audio range to avoid this problem.

Another challenge is to use smaller inductors, which usually means a reduction in inductance value while still support high currents. Smaller inductance for a given switching frequency means more ripple current and the corresponding increase in capacitor count to handle the higher
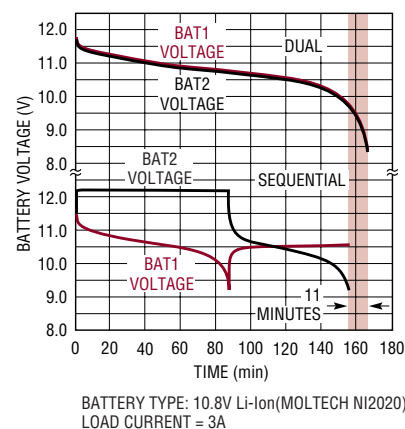

Figure 4. Batteries can run longer when discharged in parallel than they would when discharged sequentially.

ripple current. To keep the ripple current down, the switcher must switch at higher frequencies than before. The LTC4100 and LTC1760 operate at 300kHz, which allows the use of small inductors.

The LTC4100 Single Smart Battery Charger

Single battery applications tend to be systems that are smaller or have lower power requirements. The LTC4100 is a Level 2 (slave) Smart Battery Charger specifically designed to reduce PCB space. It is compliant with both the V1.1 of the Smart Battery Charger and SMBus V1.1 standards. Figure 2 shows a typical application circuit.

The LTC4100 includes a host of features to improve charge times in a variety of applications:

❑ It can charge batteries up to 4A and switch continuously down to zero load current, so as to not make audible noise under any conditions and take full advantage of ceramic capacitors capabilities.

❑ The high 300kHz switching frequency allows the use of small, common, low cost 10µH inductors and ceramic capacitors for bulk C filtering.

❑ Input voltage range is 6V to 32V while output charge voltage range is from 6.4V to 26V.

❑ Precision charge capabilities are assured by the 10-bit current DAC and an 11-bit voltage DAC

with accuracies of 5% and accuracies of 0.8%, respectively.

❏ A topside P-channel MOSFET allows 98% maximum duty cycles, dramatically reducing total part count and IC pin count while providing efficiency greater than 95%.

❏ SMBus accelerators keep the data moving along in high capacitance traces while preventing bus noise from corrupting data. (More information about SMBus accelerators is available in the LTC1694 datasheet).

❏ A user adjustable AC present signal with precision 3% accurate user adjustable trip points.

The LTC4100 also includes important protection features:

❏ A safety signal circuit that rejects false thermistor tripping due to ground bounce caused by the sudden presence of high charge currents

❏ A DC input FET DIODE circuit that prevents battery current from flowing backwards into the wall adapter or DC power source

❏ An ultra fast overvoltage comparator circuit prevents voltage overshoot when the battery is suddenly removed or disconnects itself during charge

❏ An input current limit sensing circuit that is used to reduce

charge current to prevent wall adapter overload as the system power increases.

❏ Many unique features, such as a special current limit and voltage limit system, which prevents SMBus data corruption errors from generating false charge values that would potentially harm the battery.

The LTC1760 Dual Smart Battery Charger

The LTC1760 complies to the Smart Battery System Manager (SBSM) specification V1.0.

The LTC1760 has all the same basic electrical specifications as the
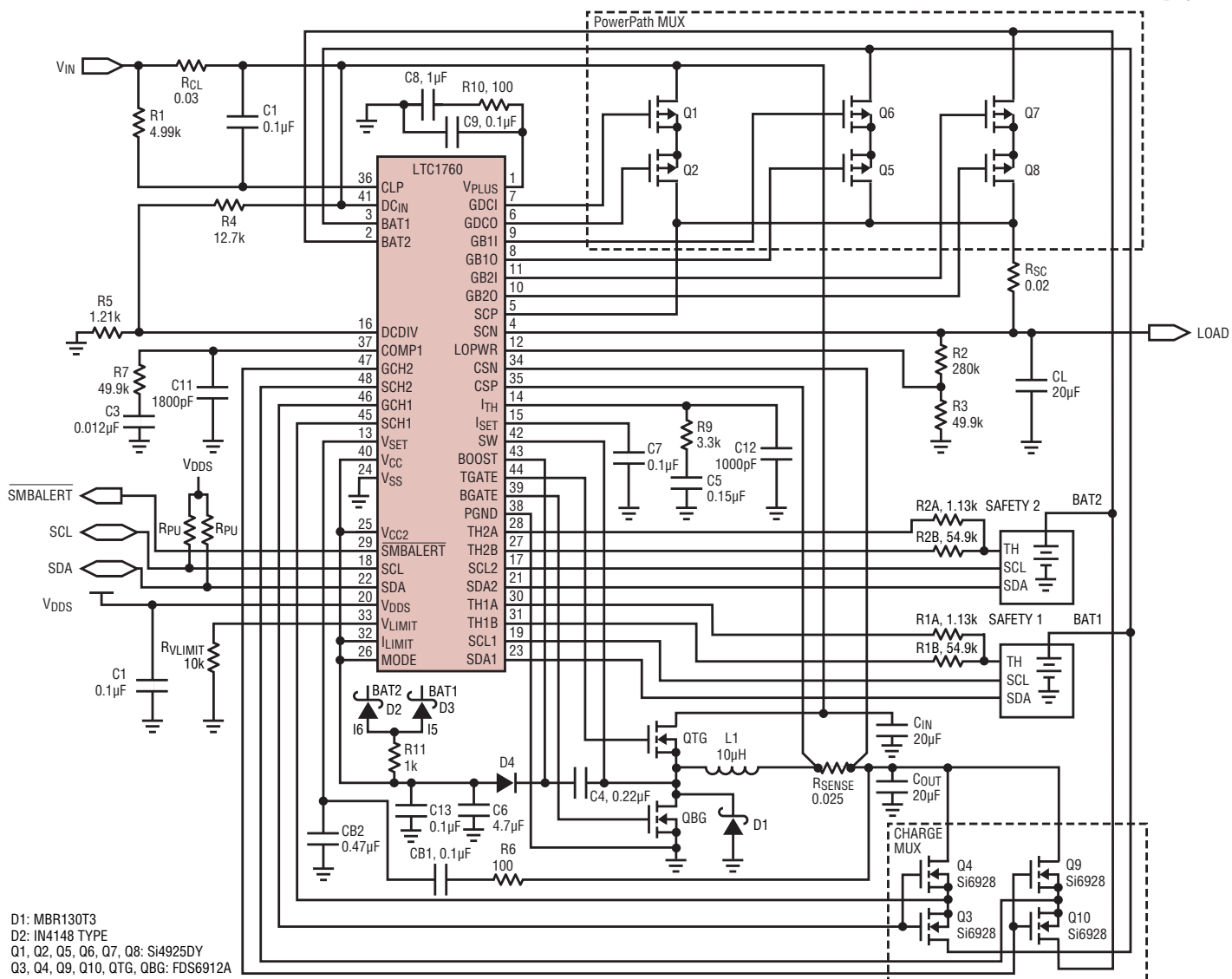
Figure 6. Dual battery charger/controller safely charges and discharges two Smart Batteries in parallel, even two batteries with different chemistries. Parallel charge and discharge is far more efficient and faster than serial charging, and some high power applications require parallel discharge of batteries to supply higher currents than a single battery can offer.

Dual Monolithic Ideal Diodes Provide a Single-Chip Power Management Solution

by Andy Bishop

Introduction

The LTC4413 dual monolithic ideal diode helps reduce the size and improve the performance of handheld and battery operated devices. It packs so many features into a tiny package that it is possible to build an entire power management solution in a 3mm × 3mm footprint. Figure 1 shows how simple it is to build a complete battery-wall-adapter PowerPath™ manager.

Despite its compact size, the LTC4413 includes features that are necessary in demanding applications, including thermal management, short circuit protection, and system-level power management and control.

Two isolated p-channel MOSFET transistors serve as low voltage (2.5V to 5.5V) monolithic ideal diodes. Each ideal diode channel provides a low forward voltage drop (typically as low as 40mV when conducting 10mA) and a low $R_{DS(ON)}$ (below 100mΩ)—important in battery-powered applications.

Furthermore, each channel is capable of providing 2.6A of continuous current from a small 10-pin DFN package. If the load attempts to draw more than 2.6A, the internal current limit threshold is reached. At this point the LTC4413 fixes the output current at the over-current maximum. This causes the output voltage to collapse and the power dissipation within the chip to increase. Current limit protects the internal p-channel MOSFET diodes against shorts and overloads. Sustained overloads that result in excessive die heating are mitigated by thermal shutdown.

System-level power management and control are available through a status signal pin to indicate conduction status, and two active-high disable input pins, which independently control the operation of each of the PowerPath ideal diodes.

The low forward voltage drop, low $R_{DS(ON)}$, and low reverse leakage current of the LTC4413 offer several additional benefits. The tiny forward voltage drop directly results in extended battery life. The low $R_{DS(ON)}$ reduces power dissipation, further enhancing battery performance. The very low reverse leakage current, when compared with a Schottky diode, is

> *"The LTC4413 packs so many features into a tiny package that it is possible to build an entire power management solution in a 3mm × 3mm footprint."*

also beneficial in many applications particularly where leakage current into a battery from a reverse biased Schottky diode could cause damage or failure.

The LTC4413 can be used as a replacement for two LTC4411 monolithic ideal diodes, or it can be used in applications that may have used one LTC4411 along with a Schottky diode, thereby providing an improvement in terms of space and power consumption.

How it Works

Figure 1 shows an application where the LTC4413 is configured as an automatic power switch between a battery and a wall adapter (or other auxiliary power source) to supply continuous power to the load attached to the output.

The operation of this circuit is shown in Figure 2, where the inputs are ramped slowly to illustrate how the LTC4413 functions.

First the battery input at INA is ramped up from 0V while the auxiliary input at INB is left floating (A0). Once the battery voltage exceeds the under voltage lock-out (UVLO) rising threshold of 2.2V (A1), the LTC4413 begins to conduct in forward regulation mode, pulling the output voltage up to within 20mV of the battery voltage (the voltage drop across the LTC4413 depends on the load current). As the battery voltage continues to increase (time interval A1–A2) up to 3.5V, the output voltage follows the battery voltage minus the small forward voltage drop across the LTC4413. During the forward regulation mode of operation (from time A2 to B0), the STAT pin is an open circuit and the 560kΩ resistor pulls the STAT pin voltage up to V_{CC}, indicating that the load current is supplied by the battery connected to INA. Alternatively, this resistor
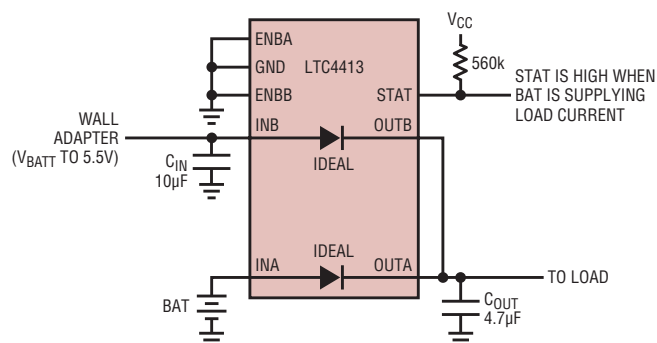

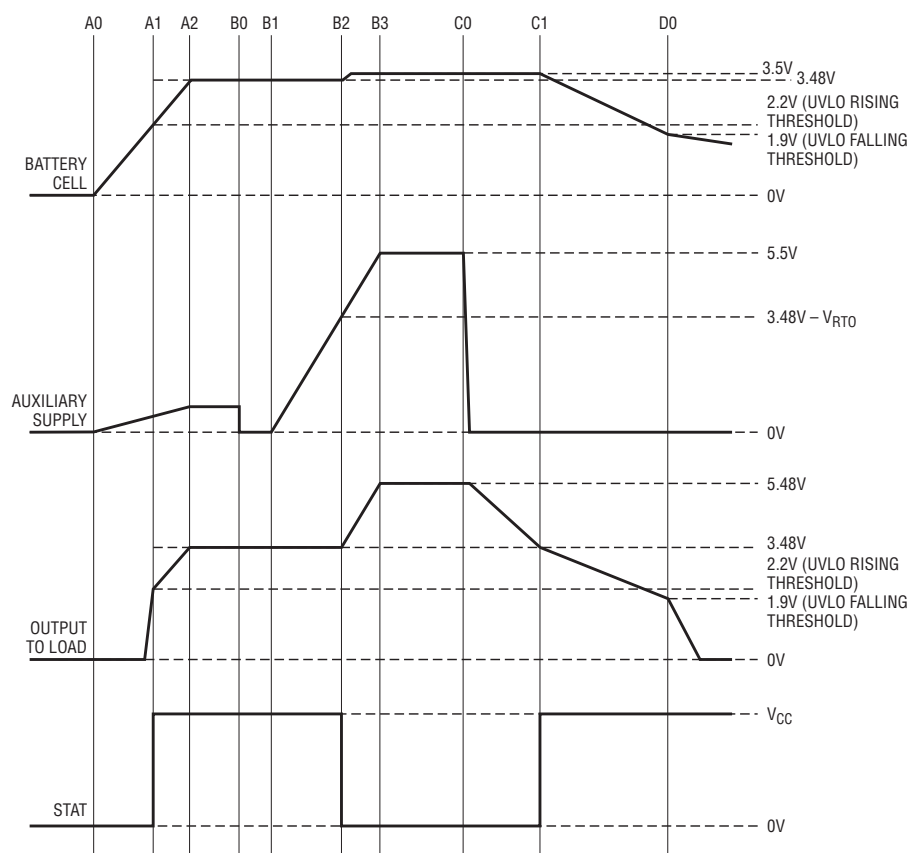**Figure 1. Automatic power switch between a battery and a wall adapter**

Figure 2. Operation waveforms of the LTC4413.

Automatic Dual Battery Load Sharing

A dual battery load sharing circuit is shown in Figure 3. In this schematic an LTC4413 is used to isolate two batteries, perhaps a main and a backup battery, from the load. This circuit takes advantage of the fact that it is more efficient to discharge the batteries in parallel than it is to discharge them sequentially.

Whichever battery has the higher voltage provides the load current until it has discharged to the voltage of the other battery. The load is then shared between the two batteries according to the capacity of each battery. The higher capacity battery provides proportionally higher current to the load.

As the LTC4413 only allows current to flow in one direction, each battery is isolated from the other so that no reverse current can flow from one battery into the other. This eliminates the possibility of a potentially hazardous situation where one battery may uncontrollably discharge curent into the other. The STAT pin may be used to indicate whether the backup battery attached to INA is conducting, thus providing an automatic monitor to indicate when the backup battery is supplying all of the load current.

Multiple Battery Charging

Figure 4 illustrates an application of multiple battery charging using the LTC4413. In this example, one or both of the batteries can be charged from a single battery charger (not shown), regardless of the state of charge of the other battery. This circuit takes advantage of the fact that charging batteries in parallel is more efficient than charging them sequentially.

may be tied to the output as shown in Figures 6, 7 and 8.

Consider next a wall adapter, or other auxiliary supply voltage, applied to pin INB (at time B0). The voltage at INB is then ramped upwards from 0V (starting at time B1). The LTC4413 automatically senses when the voltage at INB is greater than the voltage at the output (at time B2) and reverts to supplying load current from the input applied at pin INB; disconnecting the battery from the load as the voltage at the output rises above the battery voltage at INA. At this point, the STAT pin begins to sink 9µA causing the STAT pin voltage to fall, indicating that the wall adapter at INB is now supplying load current. As the auxiliary voltage continues to rise to 5.5V (B3) the output voltage follows the auxiliary voltage.

When the wall adapter, or auxiliary voltage, is removed (at time C0) and the voltage at INB drops to zero, the output voltage begins to ramp down as C_{OUT} discharges; at a rate depending on the load current. Once the output

voltage drops below the battery voltage (C1) the LTC4413 reverts to supplying load current from the battery. At this time the STAT pin becomes an open circuit, and the 560k resistor pulls the STAT pin voltage to V_{CC} to indicate that the battery is now supplying load current.

As the battery voltage continues to discharge below the under voltage lock-out threshold of 1.9V (at time D0), the LTC4413 turns itself off, and the battery is disconnected from the load. The output voltage then collapses as the load discharges capacitor C_{OUT}.
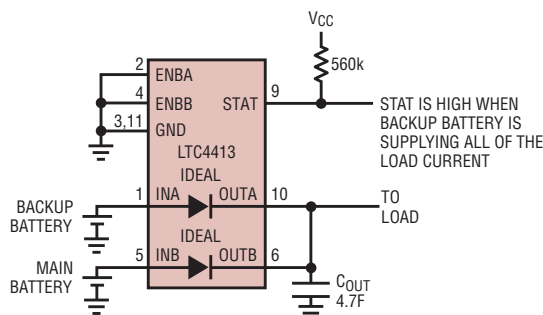

Figure 3. Automatic dual battery load sharing with secondary battery monitor
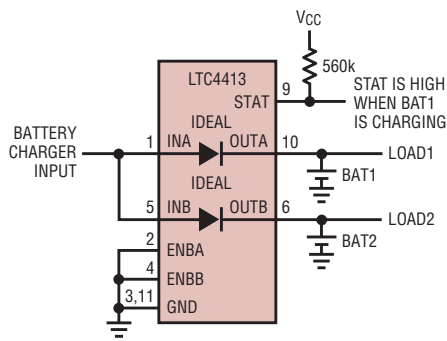
Figure 4. Multiple battery charging

Figure 5. Dual high side power switch

Whichever battery has the lowest voltage receives the full charging current until both battery voltages are the same. Then both batteries are charged simultaneously. One advantage charging multiple batteries in parallel—rather than sequentially—with the LTC4413 is that both batteries are always charged up to the same relative percentage of the cell capacity. So, if the battery charger is suddenly removed in the middle of charging, both batteries are partially charged to the same percentage charge. The enable pins and STAT pin can be used to independently control which of the batteries is charged and monitor if the enabled battery is charging.

Dual High Side Power Switch

Figure 5 illustrates the LTC4413 in use as a dual high side power switch.

When the ENBA pin is a logical low, the LTC4413 turns on ideal diode A, supplying current from INA to the load attached to OUTA. When the ENBB pin is a logical low, the LTC4413 turns on ideal diode B, supplying current from INB to the load attached to OUTB.
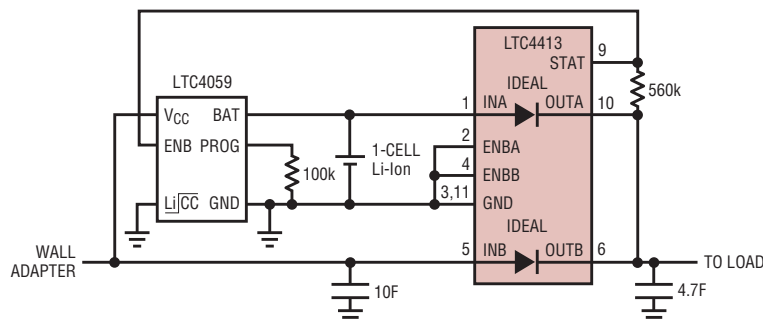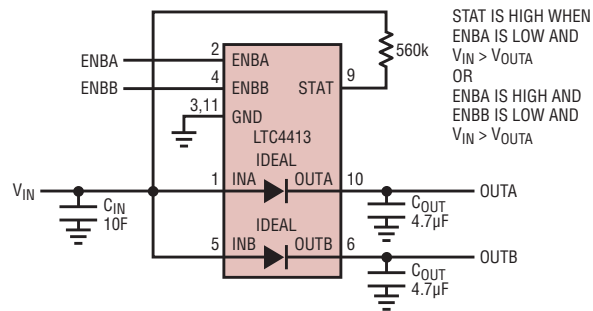
When the ENBA and/or ENBB pins are at a logical high, the LTC4413 turns off the corresponding diode and removes power to that load. If the load at OUTA is powered from another (higher voltage) source, the supply connected to INA remains disconnected from that load; the load connected to OUTB may remain connected to INB independent of the voltage at OUTA and vice versa.

The STAT pin can be used to indicate the conduction STATUS of diode A (if either ENBA is low, or both enable pins are low). Alternatively, the STAT pin can be used to indicate if diode B is conducting (if ENBA is at logic HIGH and ENBB is at logic LOW). If both ENBA and ENBB are logic HIGH, the STAT pin is logic LOW.

Automatic Switchover from a 4.2V Li-Ion Battery to a Wall Adapter and a Battery Charger

Figure 6 illustrates an application where the LTC4413 performs the function of automatically switching a load over from a battery to a wall adapter, while controlling a LTC4059 battery charger.

When no wall adapter is present, the LTC4413 powers the load from the Li-Ion battery at INA, and the STAT voltage is high, thereby disabling the battery charger.

If a wall adapter voltage higher than the battery voltage is connected to INB, the LTC4413 automatically powers the load from the wall adapter. When this occurs, the STAT voltage falls, turning on the LTC4059 battery charger and beginning a charge cycle.

If the wall adapter is removed, the voltage at INB collapses until it is below the battery voltage. When this occurs, the LTC4413 automatically re-connects the battery to the load and the STAT voltage rises, disabling the LTC4059 battery charger.

Dual Battery Load Share with Automatic Switchover to a Wall Adapter

Figure 7 illustrates how to use the LTC4413 to implement a circuit that automatically switches over from a dual battery load share to a wall adapter. As described earlier, with Figure 3, the LTC4413 performs a load sharing function for BAT_A and BAT_B,

Figure 6. Automatic switchover from a 4.2V Li-Ion battery to a wall adapter and battery charger
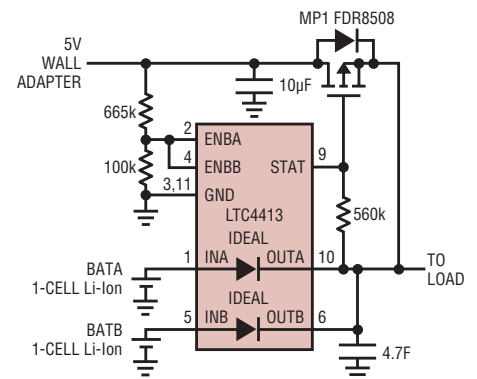

Figure 7. Dual battery load share with automatic switchover to a wall adapter

with the addition of an automatic switchover whenever a wall adapter is applied.

When the wall adapter is connected, both ENBA and ENBB voltages are pulled higher than the turn-off thresholds of 550mV through a user programmable resistive divider. When this occurs, the STAT voltage falls, turning on MP1 so that the wall adapter can provide load current. If the wall adapter is disconnected, the output voltage droops until the ENBA and ENBB voltages fall through their turn-on threshold of 450mV; enabling both ideal diodes. The LTC4413 then connects the higher of BATA or BATB to the load. If the voltage at BATA is highest, the STAT voltage rises, otherwise the STAT voltage remains low.

Automatic Switchover from a Battery to an Auxiliary Supply or to a Wall Adapter

Figure 8 shows automatic switchover from a battery to either an auxiliary supply or to a wall adapter using the LTC4413. This simple circuit handles all combinations of applied power automatically.

Consider two scenarios. In the first, the auxiliary supply is not present and the battery provides load current when the wall adapter is attached. In the second, the auxiliary is present when the wall adapter is attached.

In the first case (aux supply absent), when the wall adapter is applied, the diode in the external PFET (MP1) forward biases pulling the output voltage above the BAT voltage and turning off the ideal diode connected between BAT and the output. This causes the STAT voltage to fall, turning on MP1 and connecting the wall adapter to the load. The load current is then provided by the wall adapter and the battery is disconnected from the load.

When the wall adapter is removed, the output voltage falls until the BAT voltage exceeds the output voltage. When this event occurs the STAT voltage rises, turning off the external

Figure 8. Automatic switchover from a battery to an auxiliary supply or a wall adapter

PFET, and the ideal diode between BAT and the output automatically turns on to provide power to the load.

In the second case (aux supply present), the voltage divider (R5 and R4) pull ENBA higher than its turn-off threshold, disconnecting the battery from the load, and the auxiliary supply provides the load current.

When the wall adapter is applied, the LTC4413 senses the presence of the wall adapter as the ENBB pin voltage is pulled higher than its turn-off threshold; through resistive divider (R2 and R3). When this occurs, the auxiliary is disconnected from the load and the STAT voltage falls, turning on MP1 so that the wall adapter can provide the load current. When the wall adapter is removed, ENBB falls until the auxiliary is enabled and reverts to providing power to the load.

If the auxiliary is removed while the wall adapter is providing load current, the ENBA voltage falls, enabling the ideal diode between BAT and the output. However, if the wall adapter voltage is higher than the BAT voltage, the ideal diode between BAT and the output is reverse biased and no current flows into the battery from the wall adapter (through the LTC4413). When the wall adapter is removed, the output voltage falls until the BAT voltage exceeds the the output voltage. At this point, the ideal diode between

BAT and the output turns-on and the STAT voltage rises, disabling MP1.

When the wall adapter is disconnected while the auxiliary supply is present, the load voltage droops to just below the auxiliary voltage at which point the auxiliary supply begins to source the load current. At this point the STAT voltage rises; disabling MP1. This causes the capacitor C1 to discharge until the ENBA turn-on threshold is reached; this allows the battery to source load current if the output voltage drops below the battery voltage.

If the wall adapter is disconnected when the auxiliary supply is not present, the load voltage drops until the voltage at the ENBA pin (formed by resistive divider R2 and R3) falls below the turn-on threshold of 450mV. When this occurs, the battery is connected to the load and the STAT voltage is pulled high, disabling MP1.

Conclusion

The LTC4413 dual monolithic ideal diode provides a simple and efficient single-IC solution for low-loss PowerPath management. This device is ideal for battery-powered portable devices. It extends battery life, significantly reduce self-heating, and reduces form-factor with its 10-lead 3mm × 3mm footprint and minimal external parts count. *LT*
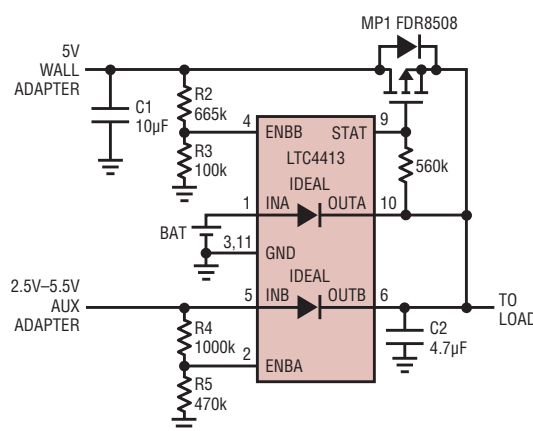
Simplify PoE Implementation with Complete PD Interface and Integrated Switching Regulator

by Kirk Su

Introduction

IEEE 802.3af Power over Ethernet (PoE) is a standard for delivering power over Cat-5 cables, eliminating the need for AC-adapters for equipment plugged into the Ethernet. The two major components in a PoE system are Power Sourcing Equipment (PSE), which deliver power, and Powered Devices (PD), which receive and use the power. A PSE will not deliver power to the load unless it detects a valid signature resistance, which distinguishes a compliant PD from a device that cannot receive power. Once the PD receives power, it must also convert the –48V PoE efficiently to a suitable power supply voltage. Typical PD designs employ two ICs for these tasks. An obvious way to simplify PD designs would be to integrate the interface and DC-DC conversion circuitry into a single device.

The LTC4267 reduces the complexity and size of a PD by combining an IEEE 802.3af-compliant PD interface with a current mode switching regulator. Figure 1 shows a block diagram of the device. The LTC4267 includes the 25kΩ signature resistor, classification current source, thermal overload protection, signature disable and a power good signal, along with an under-voltage lockout (UVLO) optimized for use with the IEEE-required diode bridge. The precision dual-level current limit allows the LTC4267 to charge large load capacitors and interface with legacy PoE systems. The current-mode switching regulator is designed for driving a 6V rated N-channel MOSFET and features programmable slope compensation, soft start, and constant frequency operation, minimizing noise even with light loads. The LTC4267 includes an onboard error amplifier

and voltage reference allowing its use in both isolated and non-isolated configurations. All this functionality is packed into a space-saving, low-profile 16-pin SSOP or DFN package.

PD Implementation Made Simple

Figure 2 presents a complete PD detection and power conversion application—a testimony as to how simple a PD implementation can be. The LTC4267's package size is the smallest in the industry, and many of the circuits that are traditionally implemented with external components have been folded into this device.

During detection, the Power Sourcing Equipment (PSE) identvifies the presence of an IEEE 802.3af-compliant PD by applying two voltages, measuring the corresponding current, then performing a ΔV/ΔI calculation.
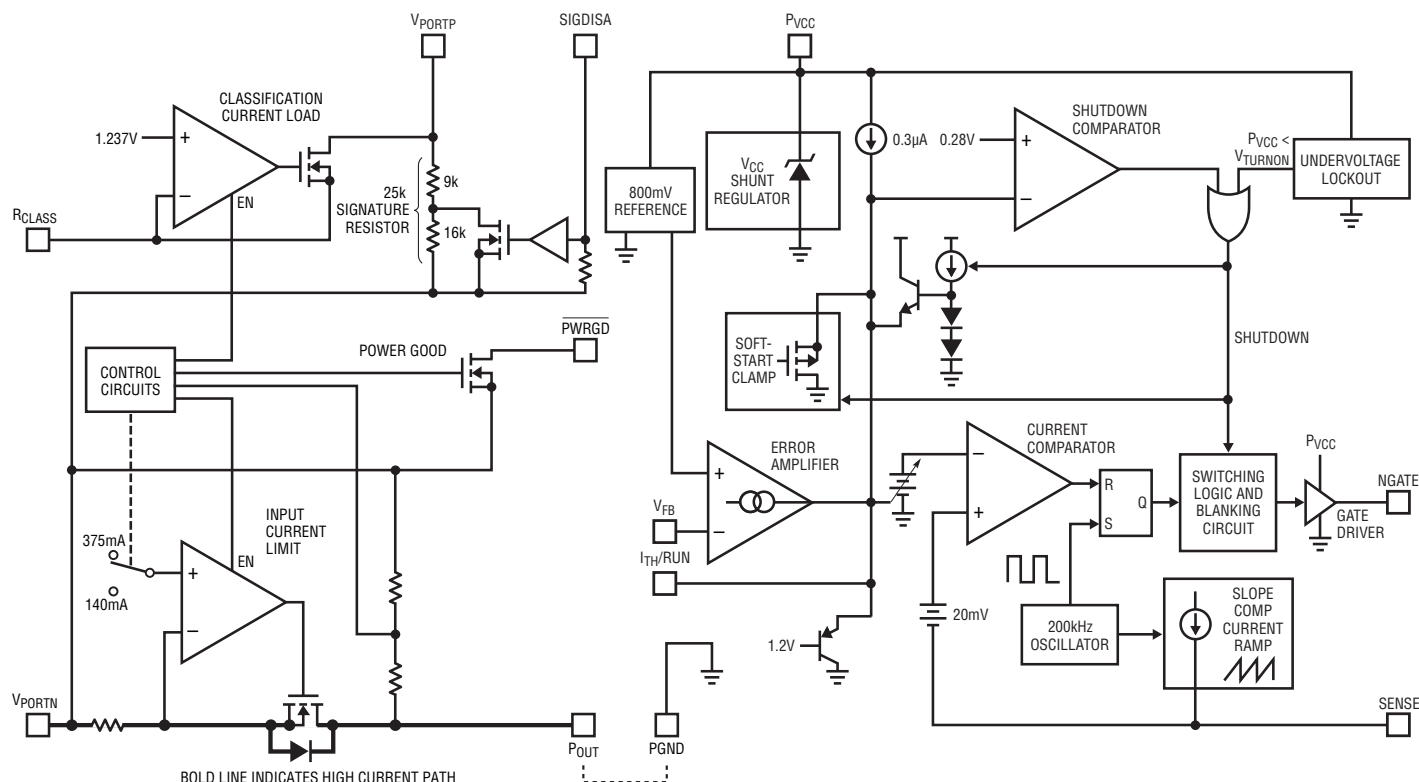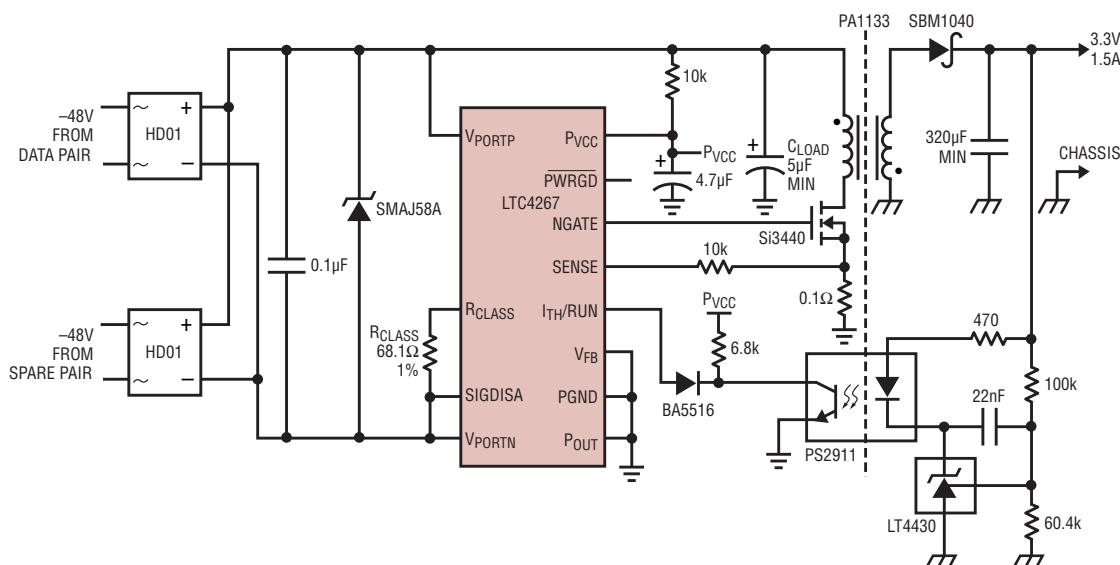

Figure 1. LTC4267 block diagram

Figure 2. A Class 2 PD with 3.3V isolated power supply

A 25kΩ signature resistance signals the PSE that a valid PD is present and is ready to receive power. Most PD detection solutions require one or more external resistors to present a valid signature during detection. One of the benefits of the LTC4267 is an internal, temperature-compensated 25kΩ signature resistor, which is precision trimmed to account for the series resistance of the input diode bridges and all parallel leakage paths. This ensures proper PD detection without the need to size external components.

Another unique feature is the Signature Disable function. When the SIGDISA pin is exercised, the LTC4267 presents a 9kΩ resistance that signals the PSE not to power the PD. This feature simplifies the interface with an external power source such as a wall transformer.

Once the PSE detects the LTC4267, the PSE may classify the PD by detecting a range of load currents. The LTC4267 offers a simple scheme for PD classification: the PD designer programs the classification load current using a single R_{CLASS} resistor or leaves the R_{CLASS} pin open for class 0. During classification, the LTC4267 asserts a precision load current from the V_{PORTP} pin through the R_{CLASS} resistor to notify the PSE of the PD power requirements.

The IEEE 802.3af specifies the classification voltage range to be between –15.5V to –20.5V. However,

the LTC4267 is designed to remain in classification mode from –15.5V to the UVLO turn-on threshold of –36V nominal. IEEE 802.3af does not require this extended classification range, but the added range aids in the PSE-PD power-up stability by maintaining a monotonically increasing V-I characteristic up to the turn-on voltage.

The LTC4267 provides a complete and self-contained dual-current protection without the need for any external components. The LTC4267's unique current limit method ensures PD inter-operability with new and legacy PSEs, and unlike competing products, the LTC4267 does not depend on the PSE to monitor current limit. As the LTC4267 reaches the UVLO turn-on voltage and prepares to delivers power, the LTC4267 limits the inrush current to 140mA nominal until the load capacitor (C_{LOAD} in Figure 2) charges up to within 1.5V of the final value. Once this voltage threshold is reached, the current-limit threshold switches over to 375mA nominal for the remainder of the PD operation. The dual level current limit allows legacy PSEs with limited current sourcing capability to power up the PD while allowing the PD to maximize the power utilization from an IEEE 802.3af-compliant PSE. By maintaining a 375mA current limit once the PD is powered up, the LTC4267 keeps the PD from depending on the PSE for current limit and avoids possible

inter-operability problems. These current-limiting features are controlled by an onboard 100V, 400mA N-channel Power MOSFET and an internal sense resistor.

The LTC4267 presents a Power Good signal once the load capacitor (C_{LOAD} in Figure 2) is charged to within 1.5V of the final value. The Power Good signal may be used to signal to the switching regulator that the PD interface has charged up the load capacitor and is ready to apply power. A 3V hysteresis is included in the power good circuit, allowing the LTC4267 to operate near the current limit point without inadvertently presenting an invalid Power Good.

The thermal shutdown circuit monitors the die temperature, serving as an additional means of self-protecting the LTC4267 and other electronic circuitry from over-current or over-heating conditions. If such an event occurs in either the classification sequence (from the PSE probing exceeding the IEEE-mandated 75ms maximum) or in normal PD operations (from multiple turn on events), the thermal shutdown circuit protects the LTC4267 by disconnecting power to the output load and disabling the classification current until the die returns to a safe operating temperature.

Powering the LTC4267 switching regulator in the simplest case can be achieved with a dropping resistor between V_{PORTP} and P_{VCC}. An internal

shunt regulator maintains the supply at 9.4V, providing the required voltage needed for the gate drive. The LTC4267 can also be powered with a pre-regulator and/or with a separate bias winding on a flyback transformer. Each of these methods offer improved efficiency. The shunt regulator is particularly important when using a flyback methodology since it also serves the vital function of protecting the LTC4267 P_{VCC} pin from seeing too much voltage.

The LTC4267 switching regulator features two ways to enable operation during the initial power-up sequence. The P_{VCC} pin includes an UVLO circuit with hysteresis, and the I_{TH}/RUN pin serves as an enable as well as the compensation point for the internal error amplifier. Once the interface circuit charges the load capacitor, enable the switching regulator operation with the I_{TH}/RUN and P_{VCC} pin. Note that both pins must be enabled for operation to begin. The switching regulator may be disabled by either pulling the P_{VCC} pin below the UVLO turn-off threshold or by pulling the I_{TH}/RUN pin below the 0.28V nominal threshold.

Implementing a robust power-up sequence between the PD Interface circuit and the switching regulator is critical in a successful PD application. The power good signal indicates that the load capacitor is charged and this signal can be used to enable the switching regulator. An N-channel transistor driven by $\overline{PWRGD}$ can be used to disable the switcher by clamping the P_{VCC} or I_{TH}/RUN pins. Disabling the switching regulator until the load capacitor is charged up can also be accomplished with an RC delay on the P_{VCC} pin as shown in Figure 2. The flexibility of the LTC4267 provides the PD designer with the freedom of implementing a controlled power-up sequence in a variety of ways.

The LTC4267 features a soft-start feature that provides an additional 1.4ms delay once the I_{TH}/RUN pin is released. The soft-start feature reduces the switching regulator inrush current and reduces output overshoots. Unlike competing products, there is no minimum external capacitance required to program this delay. The designer may opt to provide additional soft-start delay by employing an external capacitor between I_{TH}/RUN and PGND pins.

An internal error amplifier with a precision voltage reference is integrated into the LTC4267. This feature is particularly desirable in non-isolated power supply applications since the PD designer does not need to add an external amplifier or reference. The internal precision reference provides output voltage accuracy to within ±1.5% over the 0°C to 70°C temperature range. For isolated power supply applications, the internal error amplifier and reference can be disabled by connecting the VFB pin to PGND, and connecting an external error amplifier and opto-isolator to the I_{TH}/RUN pin. Figure 2 shows an example of an isolated power supply using an external amplifier and Figure 3 shows a non-isolated supply that uses the LTC4267's internal error amplifier.

Slope compensation is critical for stabilizing the control loop against sub-harmonic oscillations and is available on the LTC4267 by including an optional resistor between the sense resistor and the SENSE pin of the LTC4267. The SENSE pin monitors the voltage across the sense resistor. It also sources 5µA through the slope compensation resistor, raising the SENSE pin voltage above the sense resistor voltage. This in turn amends the duty cycle of the switching regulator, preventing sub-harmonic oscillation.

Conclusion

The LTC4267 is a self-contained Power over Ethernet PD interface that combines 802.3af PD classification with a switching regulator. It integrates many features that are traditionally implemented with separate components, but it retains the flexibility that external components offer. The result is a compact, easy-to-use, but versatile device. *LT*
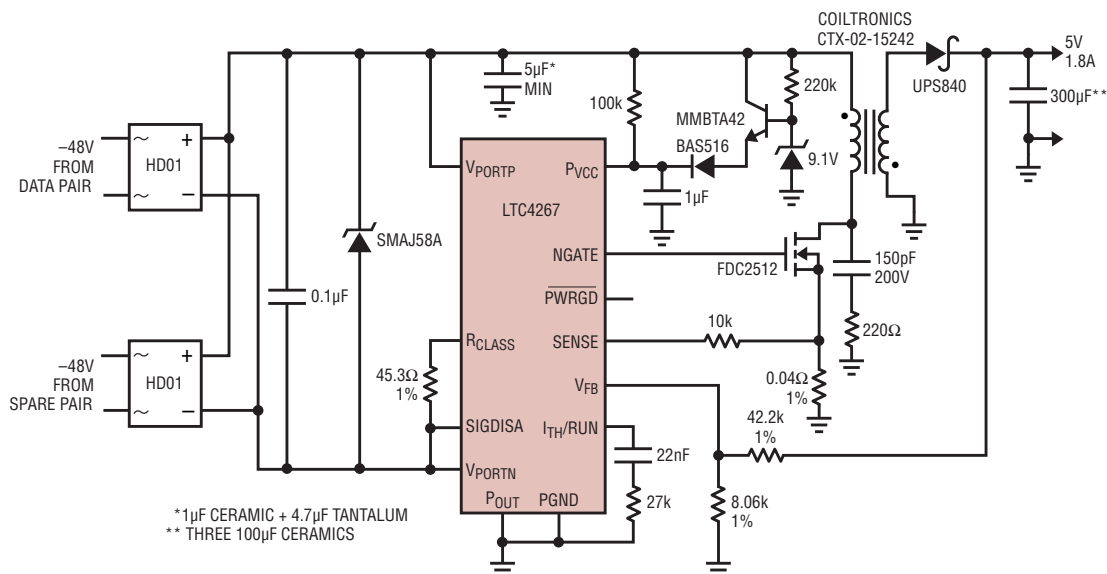

Figure 3. A Class 3 PD with 5V non-isolated power supply

High Accuracy Clock up to 170MHz in a SOT-23

by Albert Huntington

Introduction

Crystal based oscillators are often the default choice for designers looking to clock today's high speed microcontrollers, data converters and programmable logic devices. Crystal oscillators, although convenient, accurate and stable, come at a high price in use—they occupy considerable board space, consume significant power, and are sensitive to environmental factors like shock and temperature extremes. The LTC6905 is an all silicon clock that avoids these pitfalls, making it an alternative to crystal oscillators in applications up to 170MHz.

Accuracy and jitter specifications of the LTC6905 are more than sufficient for most applications, and its power and size advantages allow the LTC6905 to fit in designs where a crystal oscillator could never go.

Device Description

The LTC6905 is a part of Linear Technology's line of resistor controlled SOT-23 oscillators. These resistor controlled oscillators use a single external resistor to accurately set the oscillator frequency, and there is a simple linear relationship between the resistor value and the frequency (see Figure 1). The LTC6905 is pin-compatible with the LTC1799 SOT-23 oscillator, but uses a different control resistor range and a different formula to set the frequency.

The LTC6905 is also available in fixed frequency versions, where the resistor is internal to the part and no external components other than a bypass capacitor are required. Preset devices with master oscillator frequencies of 133MHz, 100MHz, 96MHz and 80 MHz and 1.5% accuracy are available. These devices have an internal divider which makes it possible to produce most popular frequencies between 20MHz and 133MHz. Devices can be customized to output any

Figure 1. A single resistor sets the frequency of this tiny, robust oscillator.

frequency in the range of 2.2MHz to 170Mhz.

The LTC6905 uses an internal feedback loop to accurately match the impedance of a switched capacitor element to the external resistor connected to the R_{SET} pin, thus setting the master oscillator frequency. The voltage level on the DIV pin engages internal dividers to divide this master frequency by 1, 2 or 4 before it is sent to the OUT pin. With fixed frequency devices, the LTC6905-XXX series of parts, the RSET pin is replaced by an output enable pin, which disables the output when it is connected to GND.

The voltage on the R_{SET} pin of the LTC6905 is forced to a bandgap controlled voltage of 1V below the positive supply, independent of the temperature or supply voltage, with a tolerance of less than 5%. This stable R_{SET} voltage makes the LTC6905 ideal for applications where an accurate voltage or current controlled frequency is required.

The frequency range of the master oscillator in the LTC6905 is limited to between 70MHz and 170MHz, which corresponds to external frequency setting resistor values between 10kΩ and 25kΩ. This range is expanded by the internal dividers to between 17MHz and 170MHz, and is limited by the architecture of the high speed master oscillator.

The master oscillator of the LTC6905 is a voltage controlled ring oscillator, and provides a unique jitter profile where the jitter percentage remains relatively constant over

frequency. Traditional relaxation oscillators develop a larger percentage jitter as the frequency increases. The jitter of the LTC6905 actually decreases with increasing operating frequency, making it ideal for high frequency applications.

Fixed Frequency Devices

The LTC6905 can be ordered in a fixed frequency version where the frequency-setting resistor is inside the part. An output enable pin is made available in place of the R_{SET} pin on these devices only. Four versions are available: LTC6905-133, LTC6905-100, LTC6905-96 and LTC6905-80. These four versions collectively offer 12 popular frequencies through the use of their DIV pins. Please see Table 1.

The LTC6905-XXX fixed frequency oscillators offer several advantages that stem from their internal resistor configuration. The parts are less sensitive to external noise that may couple into the R_{SET} pin on the external resistor version of the part. This lack of sensitivity translates into improved jitter of less than 1% at all frequencies and accuracy of better than 1.5% over commercial temperature range. The internal resistor parts are generally more accurate because they are trimmed at one specific frequency and do not have any error term from nonlinearities over the R_{SET} resistor range.

The absence of an R_{SET} pin on the fixed-frequency devices has made room for an output enable pin. This output enable synchronously disables the output drivers when brought low,
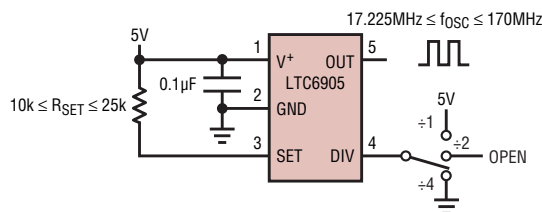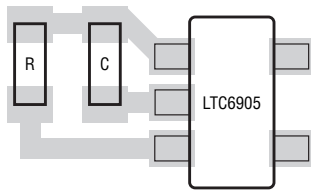
Figure 2. LTC6905 Suggested layout. Note that the bypass capacitor is located adjacent to the device and on the same side of the PC board.

Figure 3. A series resistor on the LTC6905 output pin reduces power supply spikes caused by load capacitance.

Figure 4. The LTC6905 can drive a 50Ω cable with appropriate termination.

and does not produce pulse slivers. Power dissipation is significantly reduced because much of the power is dedicated to driving output capacitance. The internal master oscillator and bias networks remain active in order to facilitate an immediate and accurate frequency output when the output is enabled. If the output enable pin is left floating or pulled to the positive supply, the oscillator is enabled.

Layout Considerations

Because the LTC6905 combines a high frequency oscillator and output stage with a sensitive analog control loop, it is necessary to exercise great care in board layout to maximize accuracy and stability. The bypass capacitor must be placed as close as possible to the LTC6905, preferably on the same side of the board. Even the small inductance and resistance of vias in the pc board can adversely effect part performance. Additionally, the traces to the bypass capacitor should be larger than is indicated by the power consumption of the device. Although the average power consumption is low, driving a capacitively loaded output will induce spikes in the supply current which must be damped by the bypass capacitor.

The R_{SET} pin is the most sensitive input pin, and attempts must be made to shield it from noise coupling or excessive parasitic capacitance. It is recommended that the frequency setting resistor be located as close as possible to the R_{SET} pin, and that the frequency setting resistor be connected to the positive supply as close as possible to the V+ pin. A recommended layout is illustrated in Figure 2. If the bypass capacitor must be situated on the opposite side of the PC board from
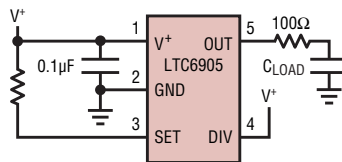
the LTC6905, it is strongly recommended that the connection between the capacitor and the LTC6905 be as short as possible and use multiple, filled vias to minimize series inductance and resistance.

The LTC6905 is specified at an output load of 5pF, which is equivalent to about two standard HC logic inputs. Driving this load at 170MHz is the single largest factor in the power consumption of the LTC6905. The power supply current needed to drive a capacitive load may be calculated as:

$$I_{SUPPLY} = C_{LOAD} \bullet V_{SWING} \bullet F_{OSC}$$

where C_{LOAD} is the 5pF load capacitance, V_{SWING} is the voltage swing, in this case up to 5.5V, and F_{OSC} is the frequency of the oscillator. Driving a 5.5V swing into a 5pF load at 170MHz takes 4.675mA on average.

The majority of this power is expended during the risetime and falltime of the output signal, not while it is in a steady state. The 500ps rise and fall times of the LTC6905 mean that the instantaneous power supply current required during the rise and fall portions of the waveform is much greater than the average. The instantaneous power supply current may be calculated by a similar formula:

$$I_{PEAK} = C_{LOAD} \times V_{SWING} \times \frac{1}{t_{rf}}$$

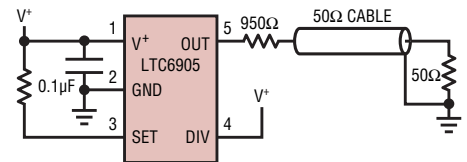where t_{rf} is the rise/fall time of the signal. In this case, 55mA spikes are

generated by driving 5.5V into a 5pF load.

Because of these power supply spikes, and because of the tendency for fast edges to couple into adjacent lines, the layout of the output trace is critical. Capacitance, trace length and loading should be minimized. Additionally, with traces longer than a few centimeters, transmission line effects must be taken into consideration.

Should output loading and coupling problems occur, there are methods to mitigate the effects. A series resistance in the range of 50Ω–1000Ω placed adjacent to the output pin of the device will increase the rise and fall times of the signal being driven into the output load, and therefore reduce power supply spikes and coupling (see Figure 3). A 50Ω cable may be driven using a 950Ω series resistance and a 50Ω termination to ground, though the signal will be attenuated (see Figure 4). A high speed comparator or inexpensive AHC series CMOS logic gate may be placed in the signal path directly after the LTC6905 in order to buffer the output signal and drive heavier loads.

Voltage and Current Controlled Oscillators

The LTC6905 is an ideal candidate for making a voltage or current controlled oscillator. Unlike other resistor controlled parts, where the voltage on R_{SET} varies with power supply and temperature, the LTC6905 maintains

Table 1. LTC6905 family fixed frequency oscillators

DIV Setting	LTC6905-133	LTC6905-100	LTC6905-96	LTC6905-80
V+ (÷1)	133.33MHz	100 MHz	96 MHz	80 MHz
OPEN (÷2)	66.66MHz	50MHz	48MHz	40MHz
GND (÷4)	33.33MHz	25MHz	24MHz	20MHz

Simple, Precise Instrumentation Amplifier Features Digitally Programmable Gains from 1 to 4096

by Michael Kultgen

Introduction

The LTC®6915 is the simplest, most precise way to obtain digitally programmable voltage gain. Any system which needs accurate amplification of small differential voltages and rejection of large common mode signals will benefit from the LTC6915.
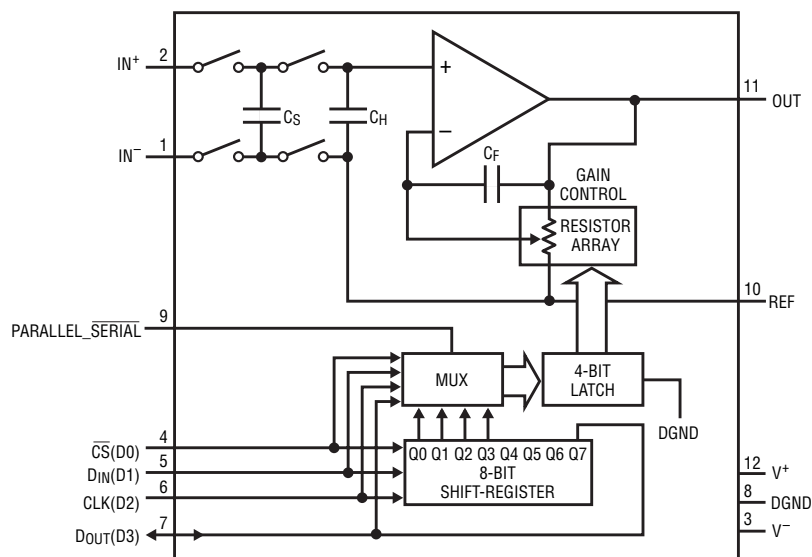
The LTC6915 is an evolution of the LTC2053, a precision rail-to-rail input and output, zero-drift instrumentation amplifier. Due to the amplifier's very low DC errors, very high levels of gain can be taken in a single stage. The LTC2053 uses external resistors to set the gain; the LTC6915 uses a serial port or a parallel port to select internal resistors, and therefore select the gain. The gain can be programmed to 0, 1, 2, 4, 8, 16, 32, 64, 128, 256, 512, 1024, 2048, or 4096. Programmable gain increases the dynamic range of any system. A fixed gain instrumentation amplifier would have about 60dB of useful range. The dynamic range of the LTC6915 is more than 120dB.

Since the high CMRR (typically 125dB) is independent of the gain setting, microvolts of differential signal can be extracted from volts of common mode noise. Furthermore, the common mode level of the differential signal can be any value within the supply rails of the LTC6915.

Other features of the LTC6915 include a flexible digital interface, a Kelvin connected output stage, a wide supply range, a shutdown mode, and a choice of packages.

How it Works

Figure 1 shows a block diagram of the LTC6915. A sophisticated, charge balanced sampling technique impresses the differential input voltage on to a 1000pF internal capacitor. The differential input signal is converted to a single-ended signal referenced to

a. The LTC6915 in a GN16 Package

b. The LTC6915 in a DFN12 Package

Figure 1. The LTC6915 block diagram. The small GN16 package (a) has all control features. The DFN12 package version (b) sacrifices the shutdown and data latching control features for even smaller size.

the "REF" pin of the LTC6915. This single-ended signal is then amplified by a zero-drift op amp connected as a non-inverting gain stage. With OUT connected to SENSE, the gain is set by an integrated precision resistor ladder. For gains up to 1024V/V, the accuracy is guaranteed to be better than ±0.6% over temperature (Figure 2), with a typical gain drift of less than 2ppm. A
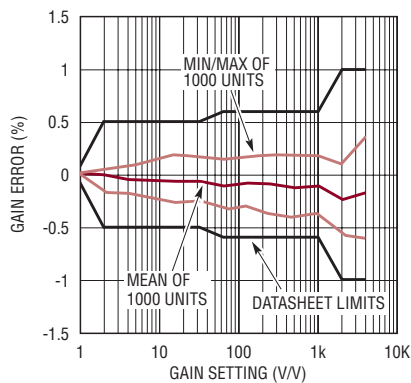
Figure 2. The gain accuracy of the LTC6915 is typically better than 0.5%.

3kHz sampling rate means that signals from DC to 1.5 kHz can be amplified by the LTC6915.

The LTC6915 has the outstanding DC precision inherent in all of Linear Technology's zero-drift amplifiers. The room temperature DC offset is less than ±10µV with less than ±50nV/°C of drift. The 10nA maximum input bias current means there is no additional DC error from source impedances up

to 10kΩ. The high CMRR and PSRR make the LTC6915 immune to fluctuations in power supplies or common mode levels.

The LTC6915 has both a parallel and serial digital interface. Its unique logic design makes it possible to guarantee input high and low thresholds (V_{IH}/V_{IL}) of 2.0 and 0.8 volts for any power supply voltage from 2.7V to ±5.5V. Therefore, microprocessors or FPGAs running on a 2.5V supply can directly interface to the LTC6915 without restriction. The LTC6915 supply can be a single 2.7V up to a split ±5.5V supply without additional level shifting of the digital inputs.

Versatile Serial Control

Connecting the PARALLEL/$\overline{\text{SERIAL}}$ pin to V⁻ puts the LTC6915 in serial control mode. The chip select (CS), clock (CLK), and DATA pins form a simple 3-wire serial input (Figure 3). For daisy chaining (Figure 4), there is also a data out (DOUT) pin. By
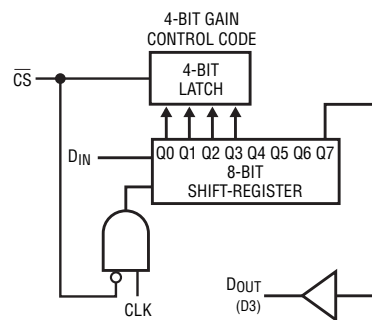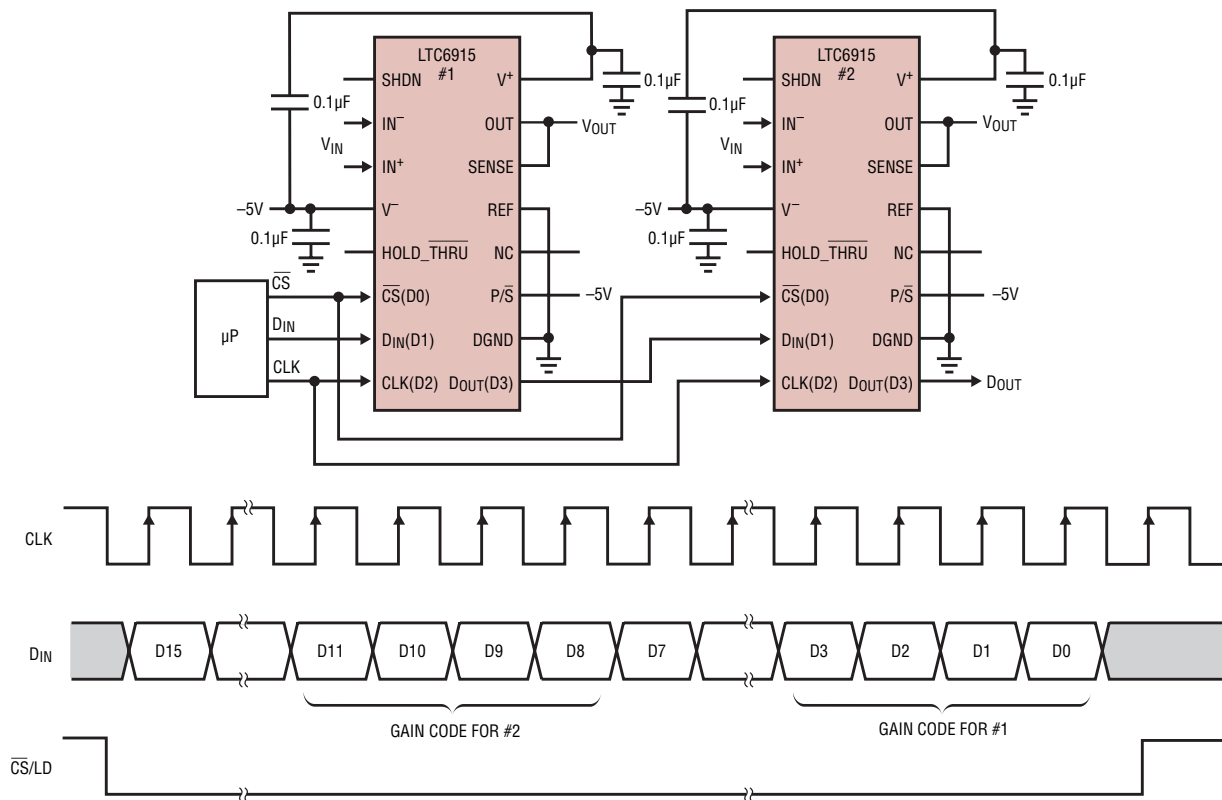

Figure 3. The LTC6915 uses a simple and standard 3-wire serial interface.

using the falling edge of the clock to output data, the LTC6915 is immune to the slow rise and fall times often encountered in optically isolated interfaces. But that does not imply that the LTC6915 is slow. When the DOUT timing is unimportant, data can be input to the LTC6915 as fast as 10MHz!

The internal shift register is eight bits wide; the four LSBs set the gain, and the four MSBs are ignored. This simplifies some software designs be-

GAIN CODE	0000	0001	0010	0011	0100	0101	0110	0111	1000	1001	1010	1011	1100	1101-1111
GAIN	0	1	2	4	8	16	32	64	128	256	512	1024	2048	4096

Figure 4. Two LTC6915s can be connected in a daisy chain. The binary codes for each gain setting are also shown.
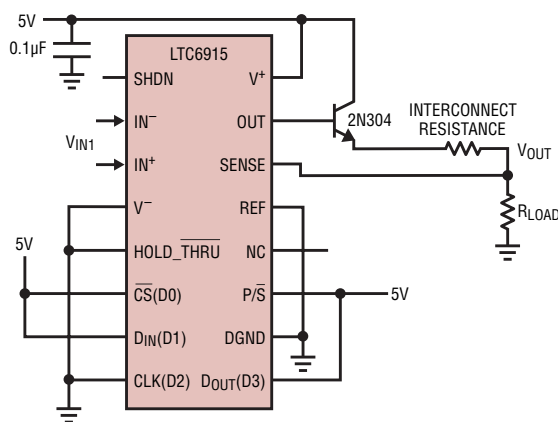
Figure 5. Kelvin sensing at the output maintains precision with increased load drive.

cause the LTC6915 appears to be a "byte wide" device, though it is still an option to load four bits at a time.

Simple Parallel Control

The gain can also be set by simple pin strapping, or through the use of a few spare I/O signals. Just connect the PARALLEL/SERIAL pin to V+ and put the LTC6915 in parallel control mode. Four inputs (D3, D2, D1, D0) directly set the gain of the amplifier as also shown in Figure 4. There is even the ability to "latch" the parallel control bits into the LTC6915 using the HOLD/THRU pin (GN16 package). When this pin goes high, whatever signals are present on D3…D0 are latched into the LTC6915. Any changes in D3 to D0 are ignored until HOLD/THRU is brought low again.

A Flexible Output

The SENSE pin allows clever improvements in the load driving or multiplexing ability of the LTC6915. In Figure 5 a discrete NPN transistor is added to increase the load driving ability. The SENSE pin is Kelvin connected to the load. Gain errors from the V_{BE} of the NPN and the IR drop in the interconnect are eliminated. A precise voltage is delivered to the load. Pin-strapping is used to fix the gain of the amplifier to Code 1011, for a gain of 1024, using the parallel interface option.

In Figure 6 two LTC6915s are connected as a multiplexer. One device is programmed for a gain of 0 (three-stated output) while the other device is programmed for a gain ≥1. Using the serial interface, the gain change of one amplifier, and disabling of the other occurs simultaneously when the CS makes a low to high transition. As a precaution for output shorting, 200Ω resistors are in series with each output in case both amplifiers are ever on simultaneously. The SENSE pin eliminates any error due to the IR drop in the 200Ω resistor during normal operation.

In Figure 7 a software programmable current sink is created using the SENSE pin, an external MOSFET, and the internal gain network. This design can sink a wide range of currents, 0µA to 40.96mA, due to the precision of the internal zero-drift amplifier and the wide range of gain settings. With only 10µV maximum offset voltage error, the circuit operates with an input reference voltage of only 250µV to 500µV. The reference voltage is set by a small regulated current—fixed by the 400mV reference voltage of an
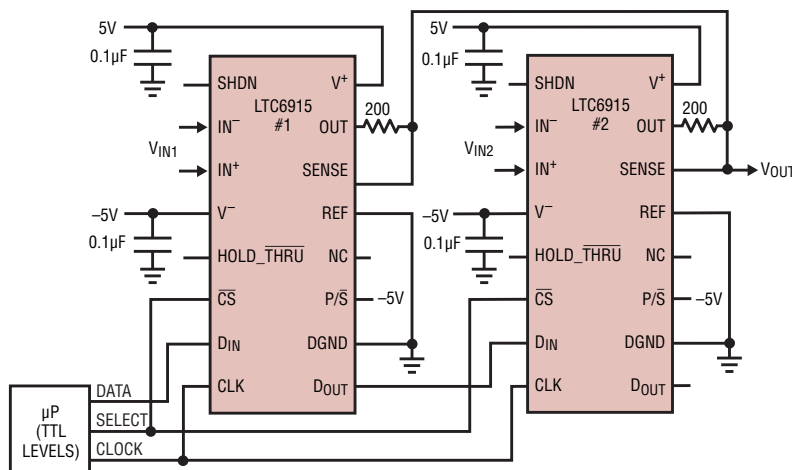

Figure 6. A robust variable gain multiplexer using the high impedance 0 gain setting allows very wide dynamic range in multichannel systems.
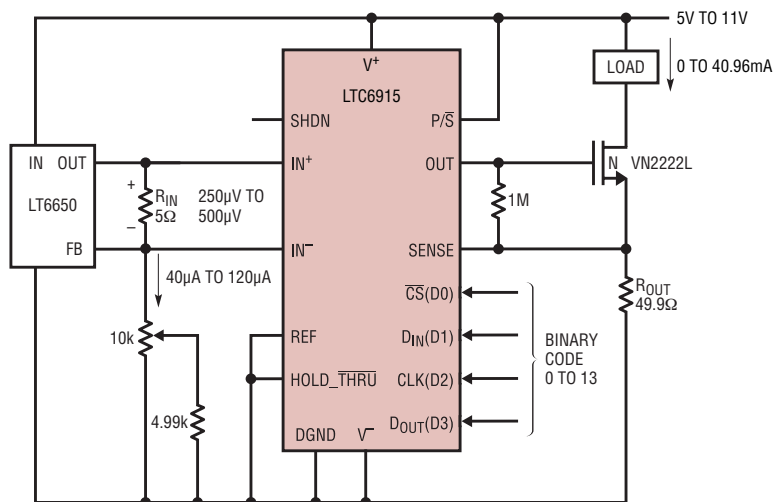

Figure 7. A wide range programmable precision current source takes advantage of the precision of the zero-drift amplifier topology.

LT6650—flowing through a 5Ω input resistor. This small voltage is amplified by the programmed gain of the LTC6915 and forces a current to flow through the 50Ω output resistor via the MOSFET. The voltage compliance of the current sink is determined by the maximum voltage output to the SENSE pin. In this example, the maximum output voltage is only 2.048V, required when the input reference is 500µV and the gain is 4096.

Each successive control code to the LTC6915 increases the output current by a factor of two. Any current level between the binary weighted intervals is achieved by adjusting the input reference voltage. A gain of 1 provides an output current of 5µA to 10µA, and a gain of 4096 outputs 20.48mA to 40.96mA, with better than ±1% typical linearity.

Bridge Amplifier Application

The LTC6915 is ideal for current sensing, thermocouple amplifiers, strain gauges, and many other low frequency and close-to-DC applications. The internal op amp gain bandwidth product is 200kHz with a slew rate of 0.2V/µs and the response time to 0.1% accuracy to a step change in gain can vary between 4ms and 15ms. Figure 8 shows the LTC6915 amplifying a bridge sensor. When in standby the circuit draws less than 100µA. An interrupt to the processor initiates a measurement cycle, turning on the LTC6915 and acquiring a conversion result from the LTC2431 A/D converter.

Conclusion

The LTC6915 instrumentation amplifier combines outstanding precision analog performance with a flexible digital interface. The result is a software programmable gain stage which is precise and easy to use.
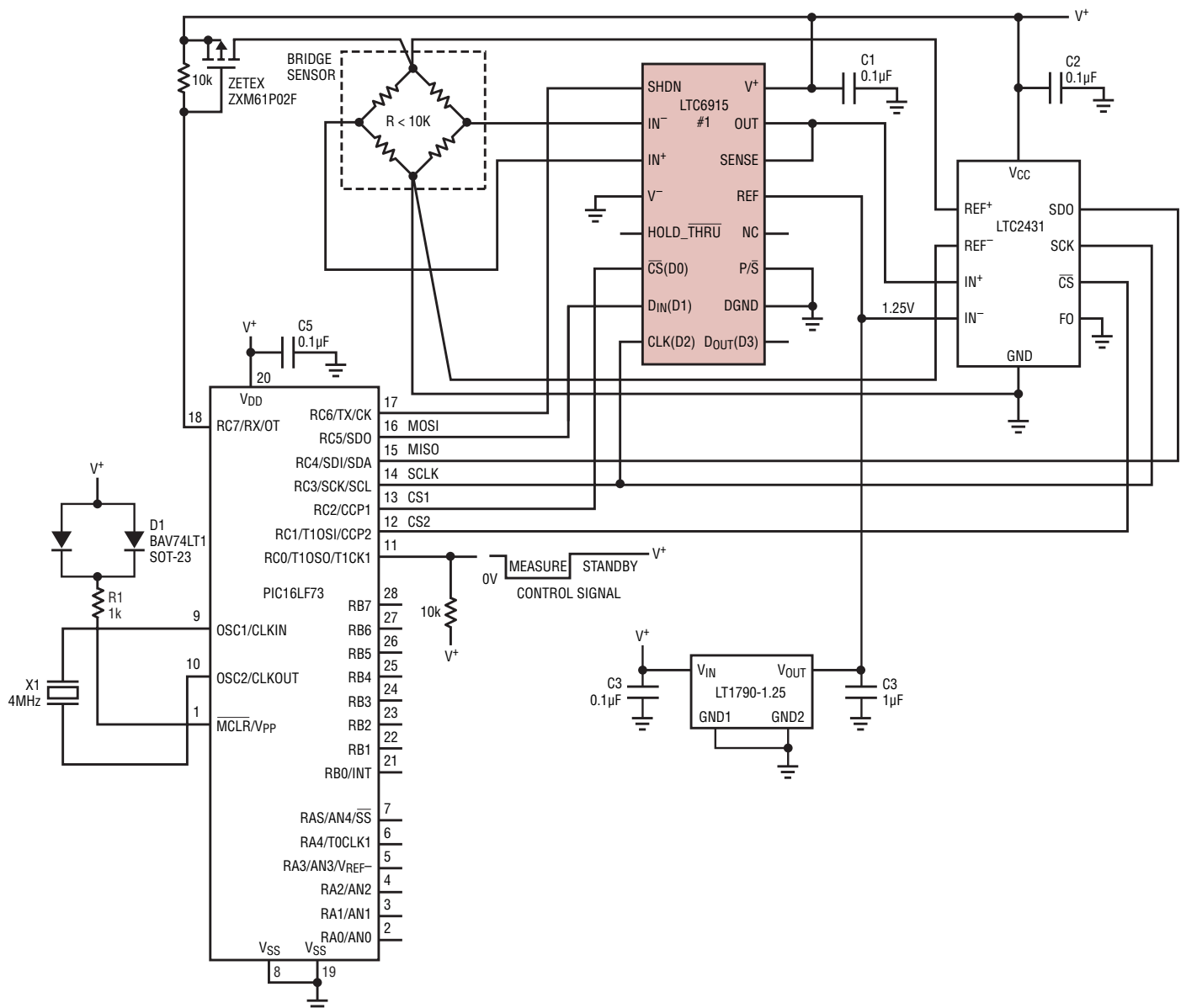

Figure 8. Using the LTC6915 as a direct bridge amplifier in a measurement system with very low standby current

Flexible Power Supply Sequencing and Monitoring

by Jeff Heath and Akin Kestelli

Introduction

The LTC2924 is a complete power supply sequencer and supervisor solution for multivoltage-rail systems, such as telecommunications equipment, memory modules, optical systems, networking equipment, servers, and base stations. The FPGAs and other digital ICs used in these applications require multiple voltage rails that must start up and shut down in a specific order, otherwise the ICs can be damaged. The LTC2924 is a simple and compact solution to power supply sequencing in a 16-pin SSOP package (see Figure 1).

Sure, alternative sequencing solutions are available, but few, if any, can match the ease-of-use, space-saving design, flexibility, and cost effectiveness of the LT2924. For instance, solutions that use discrete components incur a challenging and time-consuming design effort to interface with the digital system, and consume a significant amount of board real estate. Another option, an integrated power supply sequencer, is more expensive and consumes more board space than any LTC2924-based solution, and may require proprietary software and the programming of complicated digital registers. Neither of these options comes close to offering the flexibility across applications that the LTC2924 does. It can be used out-of-the-box, with a few external components, to sequence and supervise just about any type of power supply, converter, or power module.

How it Works

Four power supplies can be easily sequenced using a single LTC2924, and multiple LTC2924s can be just as easily cascaded to sequence any number of power supplies. With slightly reduced functionality, six power supplies can be sequenced with a single LTC2924 (see Figure 5 and "Sequencing Six Supplies with a Single LTC2924" in this article).

The LTC2924 controls the start-up and shutdown sequence, and ramp rates, of four power supply channels via output pins (OUT1–OUT4). Each OUT pin uses a 10µA current source connected to an internal charge pump and a low resistance switch to GND. This combination makes the outputs flexible enough to connect them directly to power supply shutdown pins, or to external N-Channel MOSFET switches. Figure 1a illustrates a typical application for the LTC2924 where four supplies are sequenced using external N-channel MOSFETs, and Figure 1b shows a comparable circuit with four power supplies sequenced using their shutdown pins.
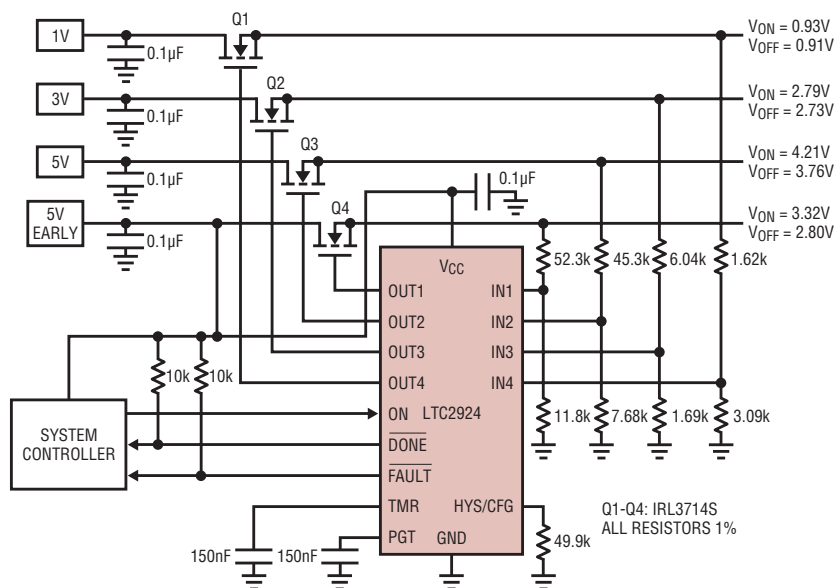

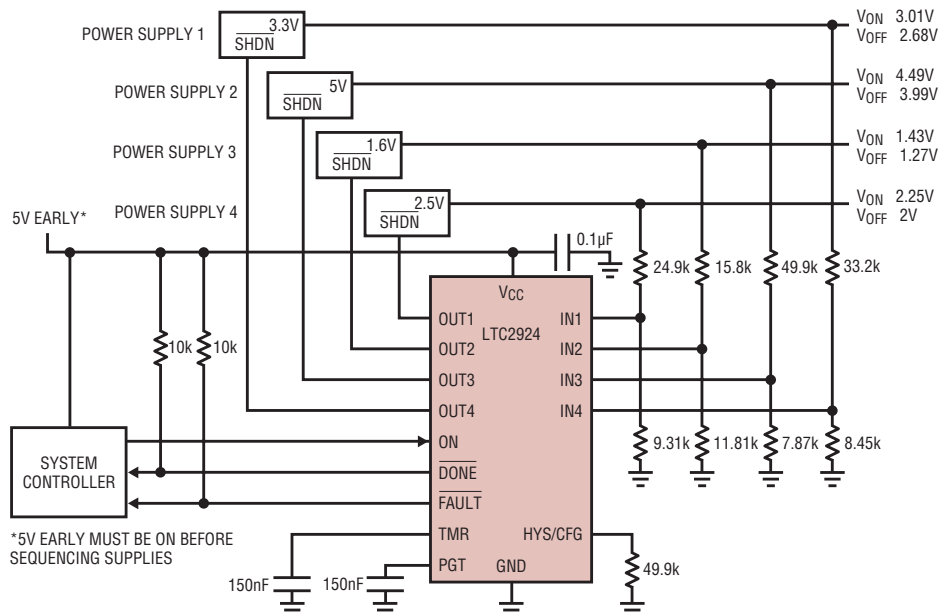**Figure 1a. Typical 4-supply sequencer using external N-channel MOSFETs for voltage control**

Figure 1b. Similar application to Figure 1a, but control is via the converter shutdown pins

The LTC2924's internal charge pump allows the designer to use N-channel MOSFET switches, which are typically lower in cost and $R_{DS(ON)}$ than comparable P-channel MOSFETs. The internal charge pump provides a gate voltage of V_{CC} + 5V, which fully enhances an external logic level MOSFET. The 10µA pull up current source on the output pin allows the implementation of a soft-start (ramped voltage start-up) by including an optional capacitor between the gate of the MOSFET and ground.

The LTC2924 monitors the output voltage of each sequenced power supply via four input pins (IN1–IN4). These inputs use precision comparators and a trimmed bandgap voltage reference to provide better than 1% accuracy. The power ON and power OFF voltage thresholds are set using resistive dividers for each of the four channels. The the power ON threshold and the power OFF threshold is individually selectable on a channel by channel basis (see "Selecting Resistors for the Turn On and Turn Off Voltage Thresholds" in the sidebar for details).

The LTC2924 timer pin (TMR) is used to provide an optional delay between the completion of start-up of one supply, and the start-up of the next power supply. The delay time is selected by placing a capacitor between the TMR pin and ground (delay = 200uS/nF), whereas floating the TMR pin removes any delay. The start-up delay can be different than the shut-down delay. Figure 2 shows a simple circuit where the shut-down delay is half the start-up delay.

The LTC2924 also includes a power good timer (PGT). The LTC2924 starts the PGT as each individual power supply is enabled. If any power supply fails to reach its nominal specified voltage within the allotted time interval, a Power ON fault is detected. The PGT is enabled for the time interval set by a capacitor between the PGT pin and ground. The PGT is disabled by grounding the PGT pin.

The LTC2924 $\overline{DONE}$ pin is used to report the status of the power sequencing to a system controller. The LTC2924 signals the completion of an
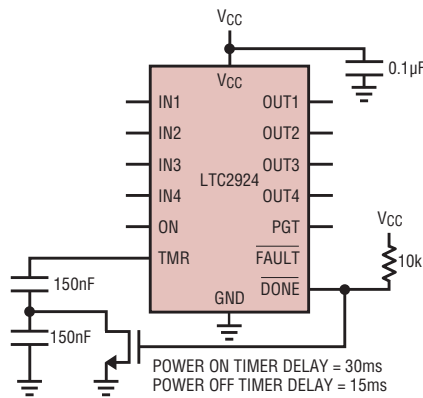

Figure 2. Power ON sequence timer delay longer than power OFF sequence timer delay

entire 4-channel Power ON sequence by pulling down the open-drain $\overline{DONE}$ pin. The completion of a Power OFF sequence is signaled by releasing the $\overline{DONE}$ pin.

The LTC2924 open drain $\overline{FAULT}$ pin is bi-directional. The LTC2924 signals a $\overline{FAULT}$ condition to a system controller by pulling this pin down. Conversely, a system controller can trigger the immediate, simultaneous turn off of all sequenced power supplies by pulling down the $\overline{FAULT}$ pin. This may be used as an alternate way of powering down a system.

Sequencing and Monitoring with the LTC2924

The LTC2924 ON pin is used to initiate Power ON and Power OFF sequences. The ON pin uses the same precision comparator circuits as the four IN pins. The ON pin can either be controlled by a logic level from a system controller, or it can be used to sense the voltage level of an un-sequenced power supply. When the voltage at the ON pin rises above 0.61V, the LTC2924 initiates the Power ON sequence. At this

point the first timer interval occurs. Upon completion of the timer interval, the OUT1 pin is pulled high with its 10µA current source connected to the internal charge pump voltage. Once the voltage of the first power supply reaches its preset threshold—as monitored at the IN1 pin—and after the second delay, the OUT2 enable signal is generated for the subsequent power supply. The sequence repeats until the forth channel is powered up. At this time the $\overline{DONE}$ pin pulls low to signal the completion of the Power ON sequence.

The LTC2924 then enters supervisor mode. The LTC2924 continues to monitor the power supply voltages (at the IN1–IN4 pins). If any of the power supplies fall below the designed OFF voltage, the LTC2924 indicates a fault and all of the OUT pins are pulled low. The fault condition is communicated to the system controller by pulling the $\overline{FAULT}$ pin low.

The Power OFF sequence can be initiated in one of two ways. To turn off all of the power supplies simultaneously, the system controller can pull down on the $\overline{FAULT}$ pin. To sequence off the power supplies, the system controller pulls the ON pin voltage low. The Power OFF sequence is executed in the reverse order of the Power ON sequence, with the supply that was powered up last is powered down first, and the supply that was powered up first is powered down last.

Figure 3 illustrates the power supply up and down sequences for a typical 4-supply application. After the ON pin goes low, the timer delay occurs before the OUT4 pin is pulled low. When the power supply goes below its turn off voltage, there is another timer
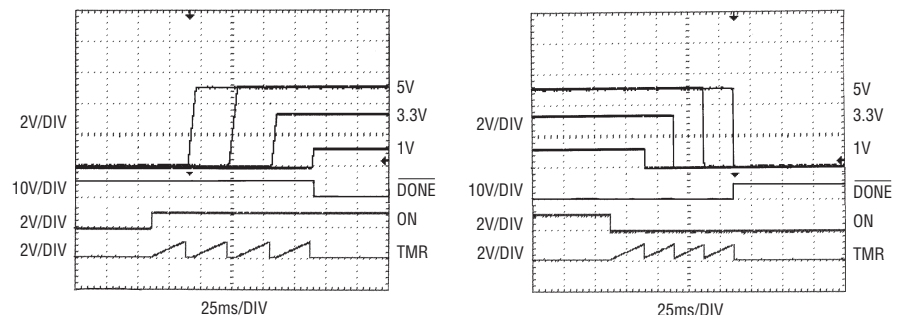

Figure 3. Power up and power down sequences for a typical 4-supply circuit

delay. The sequence repeats until the final power supply has powered down. The LTC2924 signals the end of the Power OFF sequence by releasing the $\overline{\text{DONE}}$ pin.

Cascading the LTC2924 for Eight Supplies and Up

Two or more LTC2924s can be cascaded to fully sequence eight or more supplies. The smart configuration logic in the LTC2924 makes the job of cascading multiple LTC2924 ICs easy. Figure 4 shows three devices configured to sequence 12 supplies. To set the sequence of each of the LTC2924 ICs, the HYS/CFG, $\overline{\text{DONE}}$, and ON pins are connected as shown. See the LTC2924 data shee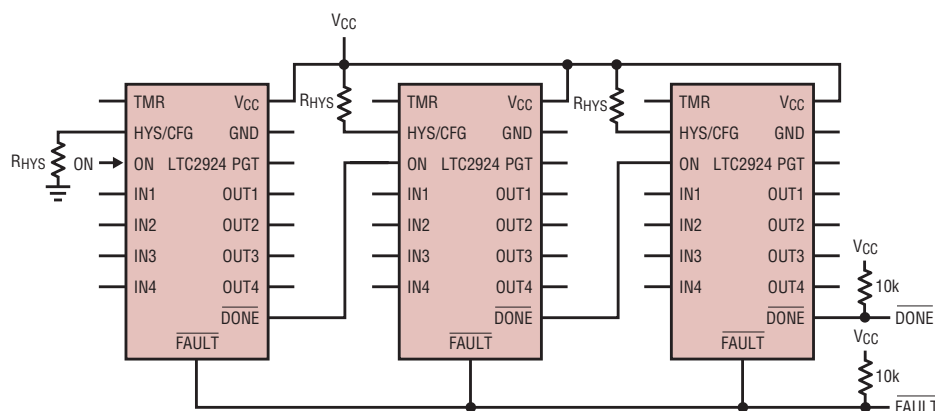t for operational details. To sequence more than 12 power supplies, simply add more LTC2924 ICs in the middle, or 2nd position, in Figure 4. To sequence up to eight power supplies remove the LTC2924 in the middle position.

Figure 4. Cascading LTC2924 ICs to sequence 12 power supplies

Sequencing Six Supplies with a Single LTC2924

Figure 5 shows how to sequence six supplies with one LTC2924. When the system controller releases the TURN OFF node, the first power supply turns on. The ON pin is tied to the output of the first power supply. Once this power supply is powered on, the LTC2924 sequentially starts up power supplies 2 through 5. When the $\overline{\text{DONE}}$ pin is pulled low after the 5th power supply powers ON, the inverted signal allows the 6th power supply to turn on. This inverter can be implemented with a single transistor. The system controller can power off all six power supplies simultaneously by pulling the TURN OFF node low.

Delayed Remote Sensing

Remote sensing is a common configuration in high current applications. Parasitic resistances in the power supply path coupled with high DC currents can result in unacceptable DC voltage drops. The sense pin of a power module is designed to regulate the DC voltage at a point in the power distribution circuitry beyond the parasitic resistance to compensate for the I • R voltage drop. The output voltage of the power module is raised until the desired voltage is reached at sense point.

The problem with this feedback scheme is that many power modules have unalterable maximum output voltages, which, if exceeded, cause the power supply to shut down. This limits the amount of voltage correction available to compensate for parasitic
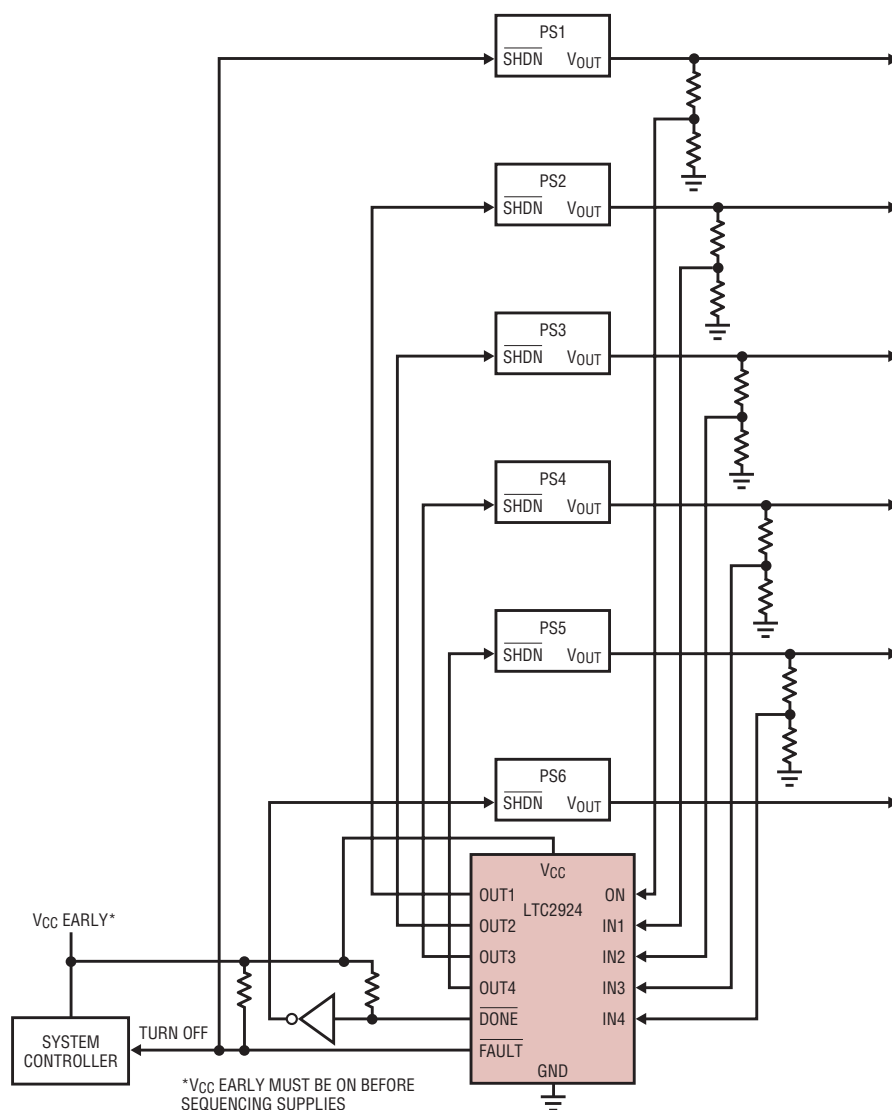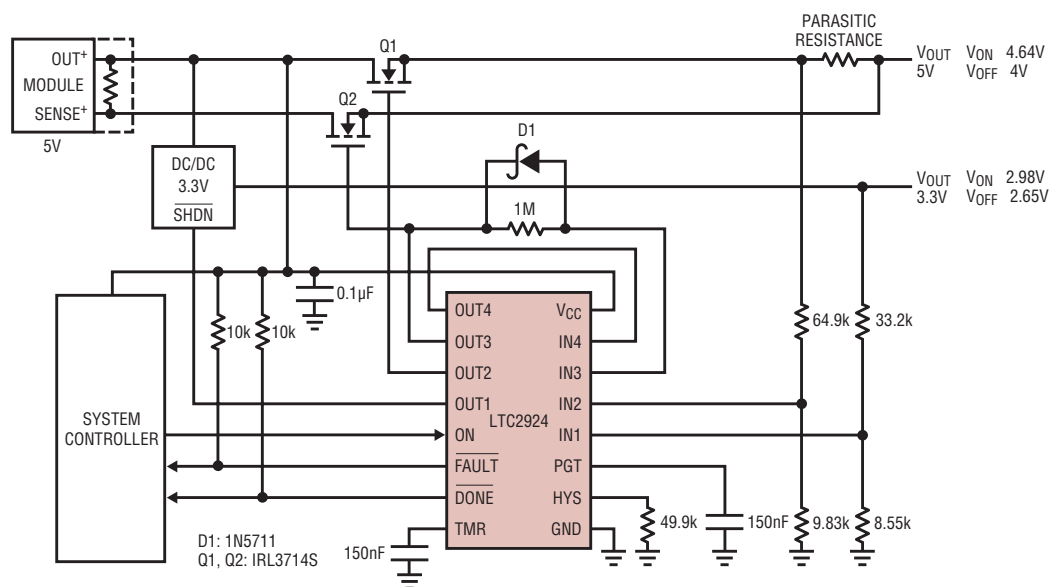

Figure 5. A 6-supply sequencer

Figure 6. Delayed remote sensing

I • R voltage drops. Transient start-up inrush currents, caused by charging power supply bypass capacitors, often exceed the normal DC currents and create a large I • R voltage drop across the parasitic resistance. If the sense pin is connected to the remote sense point, the power module tries to compensate for the additional voltage drop by raising its output voltage, possibly higher than its set maximum. This, off course, causes the power module to shut down before it has even finished starting up. This problem can be avoided by delaying remote sensing until the inrush currents have diminished.

Figure 6 shows how delayed remote sensing can be achieved with the LTC2924. In Figure 6, Channel 1 is a DC-DC converter that receives its input power from the power module. Channel 2 switches on the power module that is being remote sensed and Channel 3 is the remote sense enable. As Figure 7 shows, when the LTC2924 ON pin is pulled HIGH the Power ON sequence is initiated. After the time delay is executed, the DC-DC converter connected to OUT1 is enabled. When the output voltage level on this supply goes above the user-configured threshold voltage the second delay is triggered, and then Q1 is turned on. When the output voltage reaches 4.64V, the 3rd output is en-
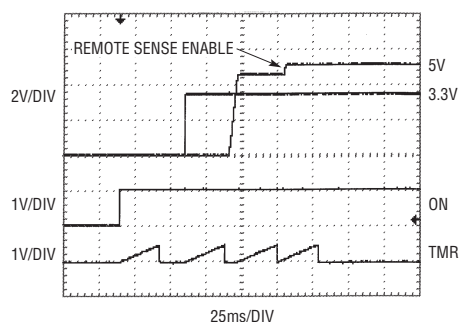

Figure 7. Delayed remote sensing power up sequence

abled after another delay. This enables the remote sensing of the power supply after the initial transient currents have subsided. As Figure 7 illustrates, the output voltage of the power supply increases to the desired level after the remote sensing is enabled.

Power Supply Fault Monitoring and Reporting

The LTC2924 has the capability to monitor the supply levels and report any fault conditions that are detected. If one or more of the following errors are detected, the LTC2924 immediately turns off all supplies and signals a $\overline{FAULT}$ condition by pulling the $\overline{FAULT}$ pin low. The LTC2924 can detect:

❑ **Power ON and Power OFF sequence errors:** The LTC2924 keeps track of each of the supplies during the Power ON sequence, during the time

the power is on, and during the Power OFF sequence. If at any time a power supply output goes low when it should be high, a fault is generated.

❑ **System controller command errors:** The ON pin is the input signal provided by the system controller to direct the LTC2924 power sequencing. By taking this pin HIGH, a Power ON sequence is initiated. Until all the power supplies are powered on, the ON pin must remain HIGH. During the Power OFF sequence the voltage on this pin must remain below 0.61V. If these conditions are not maintained during the Power ON or Power OFF sequencing, the LTC2924 indicates a fault condition.

❑ **Power Good Timer (PGT) Power ON timeout failures:** The PGT is enabled with a single capacitor at the PGT pin with a transfer function of 200µs/nF. If a supply that is being sequenced ON does not reach the desired voltage level within the time set by the PGT, a fault is generated.

❑ **External faults:** The $\overline{FAULT}$ pin can also be used as an input. Pulling the $\overline{FAULT}$ pin low causes the LTC2924 to turn off all power supplies and abort any sequence in progress.

Selecting Resistors for the On and Off Voltage Thresholds

Each of the four channels of the LTC2924 can have its own values of V_{ON}, the turn on voltage threshold, and V_{OFF}, the turn off voltage threshold. Setting the voltages is easy—only two resistors are required at the input pin of each channel, and choosing the resistor values is simple, as described here.

Refer to Figure SB1. The first step is to select a hysteresis current (I_{HYS}). This current is used by all four channels, and is programmed by one resistor, R_{HYS} on the HYS/CFG pin in Figure SB1. The I_{HYS} current is switched in to each IN1-4 pin when each channel is ON. Unless the LTC2924 is being used in a very low power system use 50µA for I_{HYS}. Calculate R_{HYS} from I_{HYS} by the following:

$$R_{HYS} = \frac{0.5V}{I_{HYS}}; 0.5\mu A \leq I_{HYS} \leq 50\mu A$$

or $R_{HYS} = 10k\Omega$ for $I_{HYS} = 50\mu A$

That leaves the two resistors for each channel. For each sequenced power supply, choose V_{ON}, the voltage at which power is considered on during a start up sequence, and $V_{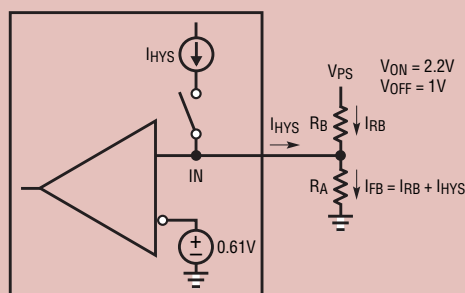OFF}$, the voltage at which power is considered off during a shut down sequence. Referring to Figure SB1, R_B is the resistor connected between the sequenced power supply and the IN pin and R_A is connected between the IN pin and ground. Each resistor can be then calculated by:

$$R_B = \frac{V_{ON} - V_{OFF}}{I_{HYS}}$$

This allows the hysteresis band for each channel to be individually tailored.

$$R_A = \frac{R_B \cdot 0.61V}{V_{ON} - 0.61V}$$

Perform this simple calculation for each channel. For example, if:

$I_{HYS} = 50\mu A$

$$R_{HYS} = \frac{0.5V}{50\mu A} = 10k\Omega$$

Place this resistor between the HYS/CFG pin and ground.

With V_{ON} and V_{OFF} voltages:

$V_{ON} = 2.2V$
$V_{OFF} = 1V$

$$R_B = \frac{V_{ON} - V_{OFF}}{I_{HYS}}$$

$$R_A = \frac{R_B \cdot 0.61V}{V_{ON} - 0.61V}$$

$$R_B = \frac{2.2V - 1V}{50\mu A} = 24k\Omega$$

$$R_A = \frac{24k\Omega \cdot 0.61V}{2.2V - 0.61V} = 9.2k\Omega$$

Repeat the last four calculations for the remaining three channels.

Figure SB1. Designing I_{HYS} feedback resistors

If any of the conditions above are met, the LTC2924 pulls all of the OUT pins low causing all power supplies to turn OFF. The $\overline{FAULT}$ pin is also pulled low to report the event to a system controller. The TMR pin is also pulled high if the fault condition was generated internally. *The fault condition is not reset until all of the IN pins and the ON pins are below 0.61V.*

Conclusion

The LTC2924 fits into a wide variety of power supply sequencing and monitoring applications. With very few external components and a 16-pin narrow SSOP, an LTC2924 based sequencing solution requires very little board space.

The power supply enable pins require no configuration by the designer, yet are versatile enough to directly drive shutdown pins or external N-channel MOSFETs. Soft start of power supplies can be achieved simply by adding a capacitor. If the sequencing of more than four power supplies is required, the LTC2924 can be cascaded to sequence a virtually unlimited number of power supplies. With the addition of a single capacitor, a timer can be enabled and programmed. Adding one more capacitor programs and enables a Power Good Timer (PGT). Power supplies can be turned off in the reverse order of turn on, or they can all be turned off at the same time.

Tailoring the LTC2924 to a specific application requires no software and designs can be fine tuned during system integration simply by changing resistor and capacitor values. Ease of design, low component cost, and a small footprint make the LTC2924 an excellent choice for power supply sequencing and monitoring. ⊿T

High Voltage Step-Down Synchronous Controller Offers Single-Supply Operation, Current Mode Control, and 100µA Burst Mode Operation

by Jay Celani

Introduction

As more features and functions are packed into electronics packages, efficient step-down DC/DC conversion circuits that can handle high input voltages at substantial load currents are increasingly necessary. This is especially true for distributed power systems that have high power point of load requirements. The LT3800 is a feature-packed high voltage synchronous step-down controller that simplifies meeting these high power requirements.

The LT3800 is the core of single-supply DC/DC converter solutions that require few external components and maintain high-efficiencies over wide load ranges. Burst Mode operation and a reverse inductor current inhibit feature maximize efficiencies during light-load and no-load conditions, making the LT3800 ideal for use in applications with supply maintenance requirements. Maintenance requirements are common in automotive applications where a low current standby mode is required in addition to high power operating conditions. Both Burst Mode operation and reverse inductor current inhibit can be disabled if desired.

The LT3800 contains an integrated start-up regulator that powers the IC directly from the input supply for true single-supply operation. The IC uses a 200kHz fixed-frequency current mode architecture and operates with input voltages from 4V to 60V. A precision shutdown pin threshold allows for easy integration of input supply under-voltage lockout (UVLO) using a simple resistor divider, and quiescent currents are reduced to less than 10µA while the IC is in shutdown. Converter output voltage is programmed using a resistor divider, and the IC includes a 1% accurate internal reference. The LT3800 also incorporates a programmable $\Delta V/\Delta t$ soft-start that directly controls the rising rate of the converter output voltage at start-up.

The LT3800 employs continuous high-side inductor current sensing using an external sense resistor. Inductor

> *"The LT3800 is a versatile platform on which to build high-voltage DC/DC converter solutions that use few external components and maintain high-efficiencies over wide load ranges."*

current is limited to the same value in both positive and negative directions, protecting the converter from both source and sink over-current events, and current limit is unaffected by duty-cycle.

A LT3800 DC/DC converter uses standard-level N-channel MOSFETs for main and synchronous switches, employing a bootstrapped supply rail for the main switch MOSFET driver. High current switch-drivers allow the use of low $R_{DS(ON)}$ MOSFETs without the need for gate drive buffers.

The LT3800 is available in a small-footprint thermally-enhanced 16-lead TSSOP package.

Onboard Start-Up Regulator

The LT3800 eliminates the need for an external regulator or a slow-charge hysteretic start scheme through integration of an 8V linear regulator. This regulator generates V_{CC}, the lo-cal supply that runs the IC, from the converter input supply, V_{IN}.

The onboard regulator can operate the IC continuously, provided the input voltage and/or FET gate charge currents are low enough to avoid excessive power dissipation in the part. Forcing the V_{CC} pin above its 8V regulated voltage allows use of externally derived power to minimize power dissipation in the IC, reducing thermal considerations. Using the onboard regulator for start-up then deriving power for V_{CC} from the converter output maximizes conversion efficiencies and is common practice.

The LT3800 has a start-up requirement of $V_{IN} \geq 7.5V$. This assures that the onboard regulator has ample headroom to bring the V_{CC} pin above its UVLO threshold of 6.25V. If V_{CC} is maintained using an external source, such as the converter output, the LT3800 can continue to operate with V_{IN} as low as 4V.

Burst Mode Operation

The LT3800 supports low current Burst Mode operation to maximize efficiency during low-load and no-load conditions. Burst Mode operation is enabled by shorting the BURST_EN pin to SGND, and can be disabled by shorting BURST_EN to either V_{FB} or V_{CC}.

When the peak switch current is below 15% of the programmed current limit, Burst Mode function is engaged. During the Burst interval, switching ceases and all internal IC functions are disabled, which reduces V_{IN} pin current to 20µA and reduces V_{CC} current to 80µA. If no external drive is provided for V_{CC}, all V_{CC} bias currents originate from the V_{IN} pin, giving a
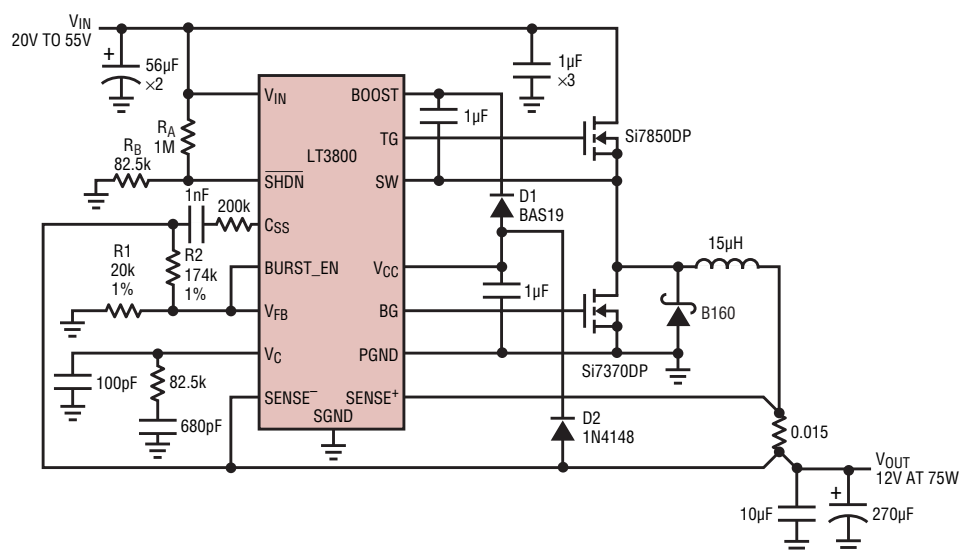
Figure 1. This 20V–55V to 12V 75W DC/DC converter features reverse current inhibit and input under-voltage lockout.

Figure 2. Converter efficiency and power loss for the DC/DC converter in Figure 1

total V_{IN} current of 100μA. An internal negative-excursion clamp on the V_C pin is set 100mV below the switch disable threshold, which limits the negative excursion of the pin voltage during the Burst interval. This clamp minimizes converter output ripple during Burst Mode operation.

Reverse Current Inhibit

The LT3800 contains a reverse-current inhibit feature, which maximizes efficiency during light load conditions. This mode of operation prevents negative inductor current, and is sometimes called "pulse-skipping" mode. This feature is always enabled with Burst Mode operation when the BURST_EN pin is connected to ground. The reverse-current inhibit feature can also be enabled without Burst Mode by connecting the BURST_EN pin to the V_{FB} pin, which is the configuration used for the DC/DC converter shown in Figure 1.
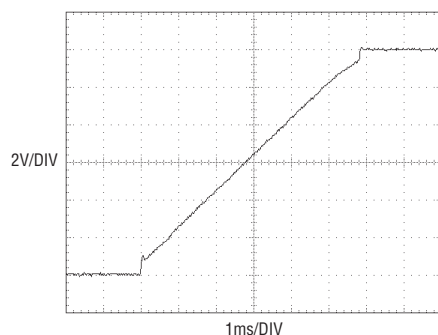
When reverse-current inhibit is enabled, the LT3800 sense amplifier detects inductor currents approaching zero and disables the synchronous switch for the remainder of that switch cycle, simulating the light-load switching characteristics of a non-synchronous converter. Reverse-current inhibit reduces losses associated with inductor ripple currents, improving conversion efficiencies with loads that are less than half of the peak inductor ripple current.

Precision Shutdown Threshold

The LT3800 has a precision-threshold shutdown feature, which allows use of the $\overline{SHDN}$ pin for analog monitoring applications, as well as logic-level controlled applications.

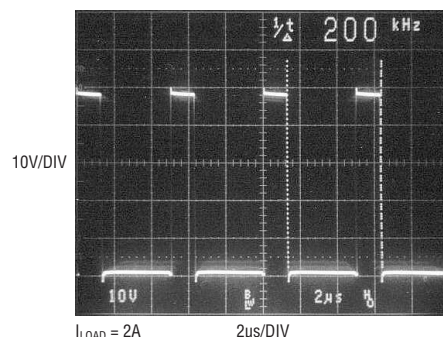Input supply UVLO for sequencing or start-up over-current protection is easily achieved by driving the $\overline{SHDN}$ pin with a resistor divider from the V_{IN} supply. The resistor divider is set such that the divider output puts 1.35V onto the $\overline{SHDN}$ pin when V_{IN} is at the desired UVLO rising threshold voltage. The $\overline{SHDN}$ pin has 120mV of input hysteresis, which allows the IC to resist almost 10% of input supply droop before disabling the converter. The $\overline{SHDN}$ pin has a secondary threshold of 0.5V, below which the IC operates in an ultralow-current shutdown mode with $I_{VIN} < 10$μA. The shutdown function can be disabled by connecting the $\overline{SHDN}$ pin to V_{IN} through a large value pull-up resistor.

Continuous High-Side Inductor Current Sensing

The LT3800 uses a wide common-mode input range current sense amplifier that operates from 0V to 36V. This current sense amplifier provides continuous inductor current sensing via an external sense resistor. A continuous inductor current sensing scheme does not require blanking intervals or a minimum on-time to monitor current, common to schemes
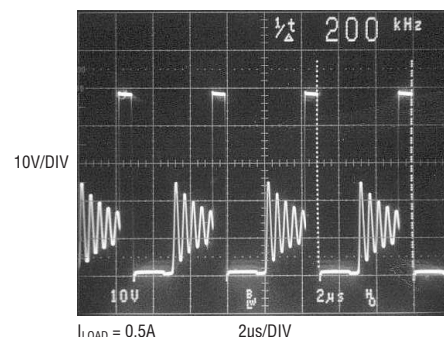

Figure 3. Output soft-start waveform for the DC/DC converter in Figure 1

Figure 4. Switching waveform for the DC/DC converter in Figure 1

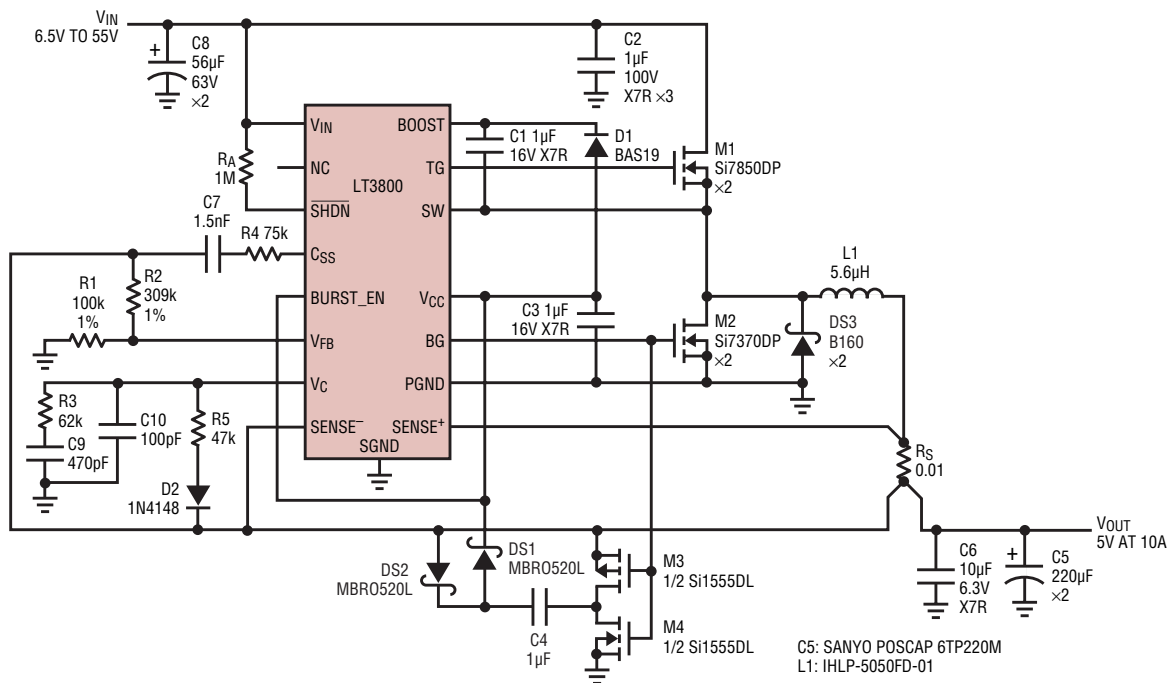Figure 5. Light load switching waveform for the converter in Figure 1

Figure 6. This 6.5V–55V to 5V 10A DC/DC converter features charge pump doubler V_{CC} refresh and current limit foldback.

that sense switch current. The sense amplifier monitors inductor current independent of switch state, so the main switch is not enabled unless the inductor current is below what corresponds to the V_C pin voltage. This turn-on decision is performed at the start of each cycle, and individual switch cycles will be skipped should an over-current condition occur. This eliminates many of the potential over-current dangers caused by minimum on-time requirements, such as those that can occur during startup, short-circuit, or abrupt input transients.

Soft Start

The LT3800 employs an adaptive soft-start scheme that directly controls

Figure 7. Efficiency and power loss for the DC/DC converter in Figure 6

the DC/DC converter output voltage during start-up. The rising rate of this voltage is programmed with a capacitor connected to the converter output. The capacitor value is chosen such that the desired $\Delta V/\Delta t$ of the output results in a 2µA charge current through the capacitor. The soft start function maintains this desired output rising rate up to 95% of the regulated output voltage, when the soft-start circuitry is disabled. The soft-start function is automatically re-enabled if the converter output droops below 70% regulation, so converter recovery is graceful from a short duration shutdown or an output short-circuit condition.

20V–55V to 12V, 75W DC/DC Converter

Figure 1 shows a 20V–55V to 12V 75W converter, configured for reverse current inhibit operation and input UVLO. Power for the IC is obtained directly from V_{IN} through the LT3800's internal V_{CC} regulator at start-up. The main switch bootstrapped supply is refreshed via D1 from the 8V generated on the V_{CC} pin. When the converter output comes up, D2 pulls V_{CC} above regulation, disabling the internal regulator and providing a current path from the converter output to

the V_{CC} pin. With the V_{CC} pin driven from the converter output, V_{IN} current is reduced to 20µA. Using output-generated power in high input voltage converters results in significant reduction of IC power dissipation, which increases overall conversion efficiency, but is critical to reduce IC thermal considerations. Figure 2 shows the conversion efficiency and power loss for this DC/DC converter.

Output voltage is programmed using R1 and R2, and the output is in regulation when the voltage at the V_{FB} pin is 1.231V. V_{IN} UVLO is programmed via R_A and R_B, enabling the LT3800 at 90% of the specified low end of the V_{IN} range, or 18V, which corresponds to 1.35V on the $\overline{SHDN}$ pin. The $\overline{SHDN}$ input has 120mV of hysteresis, so the converter will be disabled if V_{IN} drops below 16V.

The LT3800 soft-start function controls the rising slope of the output at startup such that the $\Delta V/\Delta t$ current through C8 is 2µA, so the converter output will rise at a controlled rate of 2µA/1nF, or 2V/mS. Figure 3 shows the soft-start ramp.

The BURST_EN pin is tied to the V_{FB} pin to disable Burst Mode operation while keeping reverse current inhibit operation enabled. Figure 4 shows continuous current operation when
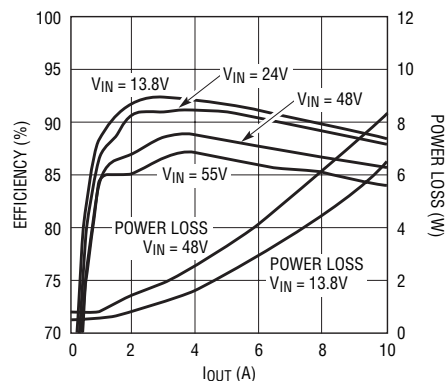
Figure 8. A 9V–38V to 3.3V 10A DC/DC converter with V_{IN} UVLO

C6: SANYO POSCAP 4TPD470M
L1: IHLP-5050FD-01

the load is greater than half of the peak ripple current. With lighter loads, during the switch off interval, as the inductor current approaches zero, the synchronous switch is disabled. The resulting discontinuous switching waveform is shown in Figure 5.

6.5V–55V to 5V, 10A DC/DC Converter

In LT3800 converter applications with output voltages in the 9V to 20V range, back-feeding V_{CC} from the converter output is trivial, accomplished by connecting a diode from the output to the V_{CC} pins. Outputs lower than 9V require step-up techniques to generate back-feed voltages greater than the

Figure 9. Efficiency and power loss for the DC/DC converter in Figure 8

V_{CC} regulated output. The 6.5V–55V to 5V 10A DC/DC converter shown in Figure 6 uses an external Si1555DL MOSFET pair (M3, M4) to create a charge pump doubler that steps up the output voltage. This simple doubler uses the synchronous gate drive (BG pin) as a control signal.

This converter also uses an external current limit foldback scheme. The foldback circuit consists of a single 1N4148 diode (D2) and a 47k resistor (R5). The current limit foldback circuit provides additional control during the first few switch cycles of start-up, and provides reduced short-circuit output current. When the output is at ground, the diode and resistor clamp the VC pin to a value that corresponds to 25% of the programmed maximum current. This circuit is only active with V_{OUT} close to ground, and becomes completely disabled once the output voltage rises above 10% regulation. Figure 7 shows the conversion efficiency and power loss for this converter.

9V–38V to 3.3V, 10A DC/DC Converter

In some DC/DC converter applications, the typical input voltage is moderate, but the converter must

withstand or operate through intermittent high-voltage excursions. This is typical of automotive battery-voltage applications, where high voltage line transients, such as during a load-dump condition, must be accommodated. The 9V–38V to 3.3V 10A DC/DC converter with V_{IN} UVLO shown in Figure 8 is an automotive application that typically operates with V_{IN} = 13.8V, but can operate through V_{IN} excursions from 9V up to 38V. Because the typical line voltage is moderate, the LT3800 can operate directly from the internal V_{CC} regulator without excessive power dissipation, eliminating the need for a step-up scheme to regenerate V_{CC} from the converter output. Figure 9 shows the conversion efficiency and power loss for this circuit.

Conclusion

The LT3800 is a versatile platform on which to build high voltage DC/DC converter solutions that use few external components and maintain high efficiencies over wide load ranges. The integrated start-up regulator facilitates true single-supply operation and Burst Mode function enables efficient solutions to power-supply maintenance requirements. *LT*
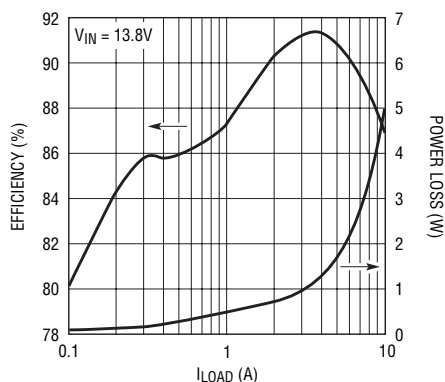
Buck-Boost Converter Minimizes Output Voltage Transients from Very Low to High Output Current

Introduction

by Mark Jordan

Most handheld devices incorporate a low power mode (Burst Mode operation) to save precious battery life during an extended period of inactivity. Transitions from Burst Mode operation, however, can induce transient perturbations in the output voltage, which drain the battery unnecessarily. The LTC3443 Buck-Boost converter minimizes output voltage transient perturbations, and thus realizes the promise of Burst Mode operation to significantly increase battery run time.

The LTC3443 incorporates an adaptive clamp on the VC pin—active during Burst Mode operation—which holds the error amp integrator capacitor to a fixed voltage determined by the input and output voltage. The clamp is removed when the LTC3443 is commanded out of Burst Mode operation. In this way, the compensation capacitors are already close to the nominal steady state voltage at the transition out of Burst Mode operation, so the output voltage transient magnitude and duration is minimized.
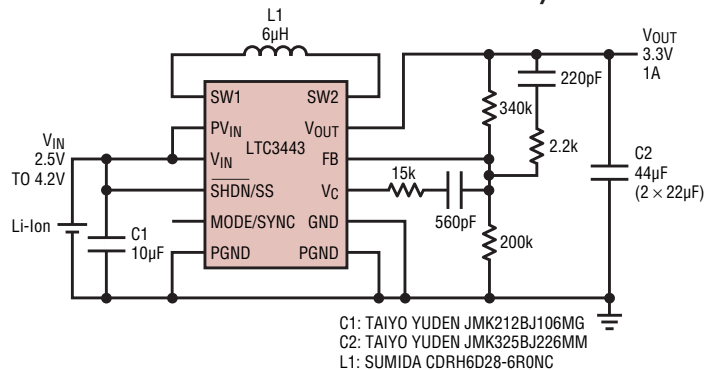
Figure 1. Lithium-Ion to 3.3V converter at 1A utilizing all ceramic capacitors

C1: TAIYO YUDEN JMK212BJ106MG
C2: TAIYO YUDEN JMK325BJ226MM
L1: SUMIDA CDRH6D28-6R0NC

3.3W Li-Ion to 3.3V Converter

A typical application for the LTC3443 is illustrated in Figure 1 with a Li-Ion battery as the input source with the output voltage set to 3.3V at 1A max. Peak efficiency for the application is 96% and 94% during the Buck-Boost region ($V_{OUT} \approx V_{IN}$) when all four switches are commutating. Figure 2 shows the output voltage response when the LTC3443 transitions from Burst Mode operation to fixed frequency operation. The output transient is within 3% of the nominal output voltage. The output ripple during Burst Mode operation is typically 1%. A +1% offset is incorporated in the DC value of the output voltage during Burst Mode operation to better "voltage position" the output in case of an immediate load transient. Figure 3 shows the reverse transition: from fixed frequency operation to Burst Mode operation.

LTC3443 Features

The LTC3443 has an internally trimmed 600kHz oscillator, which can be synchronized from 690kHz to 1.2MHz. The input range is 2.4V to 5.5V and the output range is specified from 2.4V to 5.25V. The output can operate as low at 0.4V with the addition of Schottky diode. The LTC3443 has true output disconnect and inrush current control via a soft start function. The quiescent current in Burst Mode is a mere 28µA, maximizing light load efficiency. During shutdown the supply current is less than 1µa. The LTC3443 is designed to withstand a short circuit by incorporating features such as foldback current limit and thermal shutdown. All of this power and functionality is packed into a tiny 4mm by 3mm thermally enhanced surface mount DFN package. �
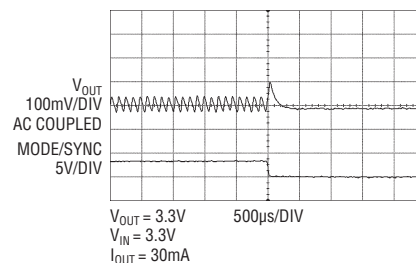
Figure 2. Transient response of the converter in a transition from Burst Mode operation to fixed frequency operation
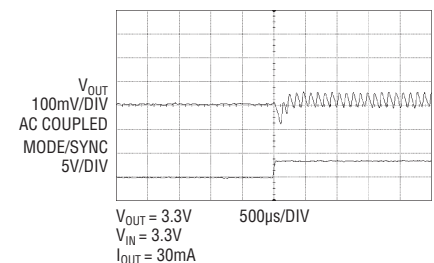
Figure 3. Transient response of the converter in a transition from fixed frequency operation to Burst Mode operation

2-Phase Controller for High Current, High Step-Down Ratio Applications

by Xiaoyong Zhang

Introduction

One of the biggest challenges in designing power supplies for high speed digital systems is achieving high step-down ratios at high load currents, all while maintaining high efficiency and meeting stringent transient response and board space requirements. Designers can easily meet this challenge by using the LTC3709 dual phase, synchronous step-down switching regulator.

The LTC3709 uses a constant on-time with phase locked loops (PLLs), valley current control architecture to deliver very low duty cycles and does not require an output current sense resistor. Figure 1 shows the LTC3709 in a step down circuit that features fast transient response and high efficiency over wide load range.

Figure 1. This high current, 2-phase power supply is efficient and responds quickly to load transients.

High Current *and* High Efficiency

Power losses, and the resulting heat, are significant problems in high current systems, so power supplies must be as efficient as possible. The LTC3709 guarantees high efficiency from light load to heavy load, especially important in high power portable computers (Figure 2).

Much of the efficiency of an LTC3709-based circuit is a result of its 2-phase architecture, which enables supply currents over 30A. The two channels operate out of phase, thus minimizing the input RMS current and the power loss along the input supply path.

The LTC3709 also senses current through the bottom MOSFET, so there is no added power loss from sense resistors, and the powerful onboard synchronous MOSFET drivers effectively suppress conduction losses.

The LTC3709 also offers Stage Shedding™ mode to boost the efficiency at light load. In Stage Shedding mode, the second channel is turned off at light loads, which halves the light load switching losses.

If the load current further drops very low, no reverse inductor current is allowed and the switching frequency drops down as low as necessary to maintain regulation, while keeping the efficiency high.

Constant On-Time Architecture and Fast Transient Response

Modern power supply designs often require a high step down ratio (low duty cycle) and fast operation frequency at the same time. This means a very short on-time feature is indispensable for an excellent controller. Unlike traditional constant frequency controllers that have minimum on-times of several hundreds of nanoseconds, the LTC3709 has a minimum on-time of only 50ns, which makes it a good choice for high current power designs. The constant on-time, valley current control architecture of the LTC3709

has an inherently fast transient response. The LTC3709 responds to a load transient immediately, without the clock latency typical of traditional constant frequency controllers.

Anti-Phase Operation and External Clock Synchronization

The two channels of the LTC3709 operate 180 degrees out of phase. A

Figure 2. The circuit in Figure 1 has high efficiency over a wide load current range.

2A, 40V, SOT-23 Boost Converter Provides High Power in Small Spaces

by Jeff Witt

Introduction
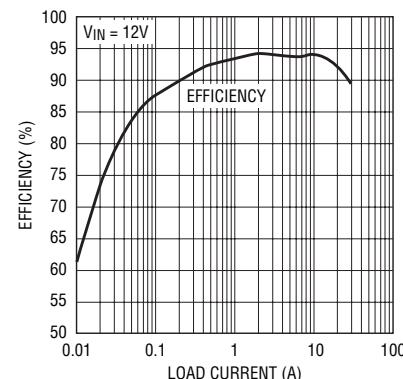
The LT1935 is a current mode boost regulator in a tiny 5-lead ThinSOT package. With its small package, high switching frequency (1.2MHz) and internal 2A, 40V power switch, the LT1935 can deliver high power while occupying very little circuit board space. For instance, from a 5V input, the LT1935 delivers 500mA average and 600mA peak current at 12V (7.2W) using only 100mm^2 of PCB.

The LT1935's power switch drops just 180mV at 2A, minimizing power loss and temperature rise on the circuit board. Current mode control and internal compensation allow the use of small ceramic capacitors, resulting in very low input and output ripple. The input voltage range is 2.3V to 16V. Supply current is less than 1µA in shutdown.

The small size eases system design in many applications. Large digital systems with dense layouts often need point-of-load converters to generate secondary logic supplies. With a minimum input voltage of 2.3V, the LT1935 can convert power from 2.5V, 3.3V or 5V logic rails to a higher output voltage. Even handheld electronics such as cell phones, digital cameras and music players require peak power levels of several watts to drive LEDs, audio amplifiers or large displays. And space is always at a premium in these products.

SOT-23 Boost with 2A Switch

Figure 1 shows the LT1935 generating 5V. Maximum load with V_{IN} = 3.3V is 1A; from 2.5V the maximum load is 600mA. Note that the circuit efficiency remains high even at low input voltage and high load current. The LT1935's bipolar NPN power switch maintains its low forward drop when the input voltage is at its minimum of 2.1V (2.3V max), unlike some MOS devices that suffer increased $R_{DS,ON}$ with low gate drive. The circuit in Figure 1 occupies 80mm^2. Figure 2 shows a 12V circuit that generates 600mA from 5V or 320mA from 3.3V. This higher power circuit requires 100mm^2 of PCB.

Soft-Start Reduces Peak Input Current

During start-up, the input current of an LT1935 circuit can reach 3A. This can cause problems if the input source is current-limited or if other circuits are sensitive to disturbances at V_{IN}. The $\overline{SHDN}$ pin can be used to soft start
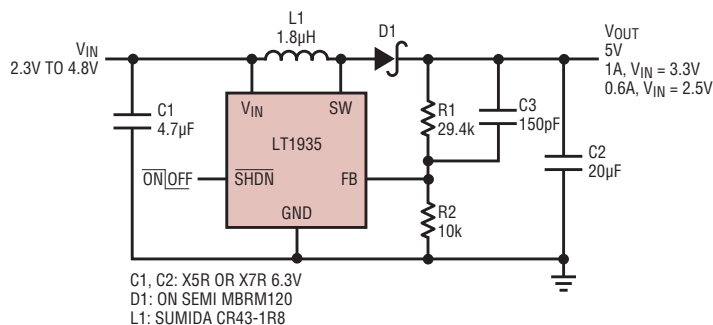

Figure 1. The LT1935 can deliver 1A at 5V from a 3.3V input in a circuit that occupies only 80mm^2.
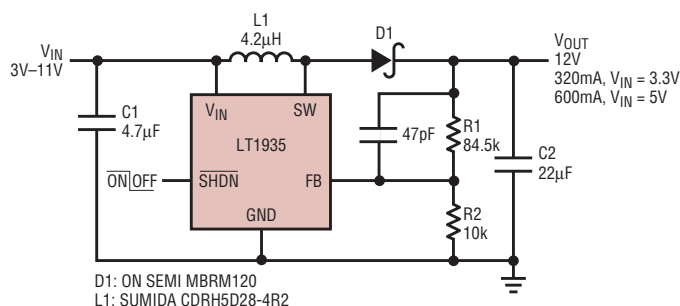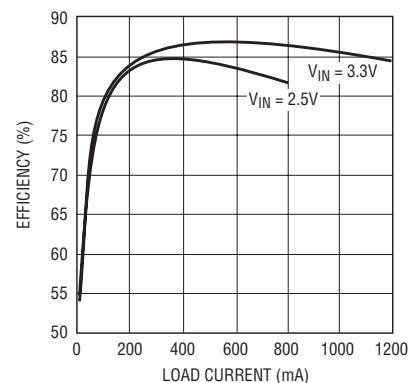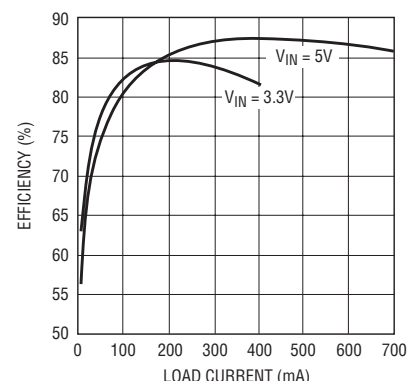

Figure 2. The LT1935 delivers 600mA at 12V from a 5V input. High power density is achieved using the internal 2A, 40V, 90mΩ switch and the high 1.2MHz operating frequency.

the LT1935, reducing the maximum input current during start-up.

The $\overline{\text{SHDN}}$ pin is driven through an external RC filter to create a voltage ramp at this pin. Figure 3 shows the start-up waveforms with and without the soft-start circuit. Without soft-start, the input current peaks at ~3A. With soft start, the peak current is reduced to 1A. By choosing a large RC time constant, the peak start-up current can be reduced to the current that is required to regulate the output, with no overshoot. (The value of the resistor should be chosen so that it can supply 100µA when the $\overline{\text{SHDN}}$ pin reaches 1.8V.)
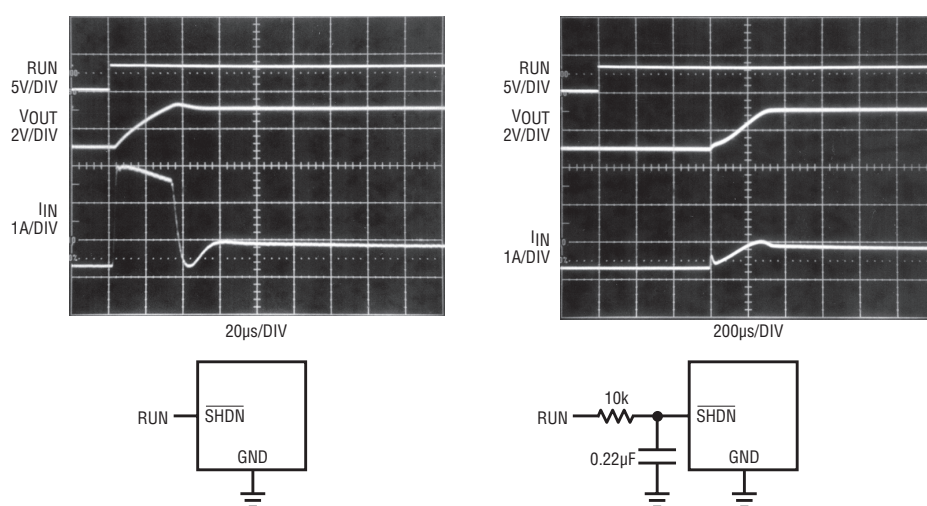

Figure 3. The $\overline{\text{SHDN}}$ pin can be used to soft start the LT1935 reducing the peak input current during start up.

More Power for Larger LCD Panels

TFT LCD display panels continue to grow in size in every type of product from cell phones to televisions. Power requirements grow as well, but the basic need for three supply voltages remains. In Figure 4 the LT1935 produces three outputs using a single inductor. From a 3.3V input, the boost circuit produces the main output of 8V at 450mA. Two discrete charge pumps produce the secondary outputs of 16V and –8V.
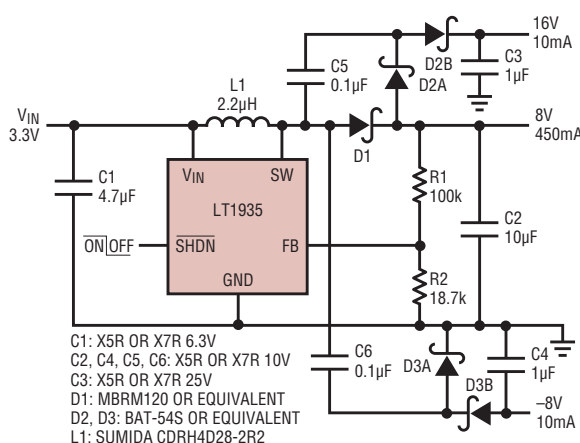
Conclusion

By integrating a high frequency, current mode control with 2A, 90mΩ switch in a SOT-23, the LT1935 delivers outsized power in a small space. The 40V switch rating and the wide input range (2.3V to 16V) allow a wide variety input sources, output voltages and circuit topologies, unlike many regulators with restrictive 5V ratings. *LT*

C1: X5R OR X7R 6.3V
C2, C4, C5, C6: X5R OR X7R 10V
C3: X5R OR X7R 25V
D1: MBRM120 OR EQUIVALENT
D2, D3: BAT-54S OR EQUIVALENT
L1: SUMIDA CDRH4D28-2R2

Figure 4. This TFT-LCD supply produces three outputs using a single inductor.

PLL monitors the switching of the two channels and forces the switching frequency of the second channel to follow that of the first channel. The interleaved operation of two channels minimizes the input RMS current and power loss along the input supply path.

A second PLL is provided for external clock synchronization. The LTC3709 is synchronized by adjusting its on-time, indirectly adjusting its switching frequency. When synchronized, the LTC3709 combines the advantages of constant frequency and constant on-time architectures. The switch-ing frequency stays constant despite the changes of input voltage, output voltage (if programmable) and load current. The LTC3709 can still respond to load transients without clock latency because of the indirect adjustment of switching frequency during synchro-nization. The time constant of the PLL is much longer than the load transient duration, so the switching frequency of the LTC3709 is temporarily altered to take advantage of a constant on-time architecture.

Other Features

The LTC3709 has a differential ampli-fier for remote sensing of both the high and low sides of the output voltage. An output tracking function makes the LTC3709 easy to use in multiple power supplies applications. The LTC3709 also has a short-circuit shutdown timer which is easily defeated.

Conclusion

The LTC3709 employs a constant on-time with PLLs and a valley current control architecture. It has fast tran-sient response, very short minimum on-time and high efficiency from light to full load. The LTC3709 is well suited to high output current, high step-down ratio applications. *LT*

Efficient and Reliable Drive for Synchronous MOSFET Rectifiers

by Goran Perica

Introduction

Many telecom and industrial applications require low voltage, high efficiency isolated power converters. Typical output voltages in these applications are between 1.8V and 12V, thus making a synchronous forward converter a good choice.

Synchronous forward converters require a pair of MOSFETs that rectify the output from the power transformer. The synchronous MOSFET rectifiers can be self-driven, transformer driven, or driven by an integrated MOSFET driver. The most efficient solution is to use a MOSFET driver, like the LTC3900, that is synchronized to the primary PWM controller. The LTC3900 has other advantages, such as protection features not found in other drive methods.

Synchronous Telecom Bus Converter

Figure 1 shows an example of a synchronous forward converter that generates an isolated, semi-regulated 12V output, which in turn is used to

generate all of the non-isolated low voltage rails on a system board. The converter in Figure 1 regulates its output by sensing the input voltage and adjusting its pulse width in order to maintain constant $V_{IN} \cdot T_{ON}$ product. The constant $V_{IN} \cdot T_{ON}$ product results in a constant output voltage. The only variations in output voltage in this type of circuit would be due to circuit parasitic elements like winding resistance, transformer coupling, MOSFET resistance and ramp errors.

The $V_{IN} \cdot T_{ON}$ product is generated by the RAMP pin of the LTC3723 in Figure 1. The input voltage develops current in resistor R1 that charges capacitor C1. When the voltage across capacitor C1 reaches the threshold of Ramp pin, the output pulse is terminated. Figure 2 shows the dependency of output voltage on input voltage and output current. The output voltage variation is well within the requirements for a bus converter. The specification for bus converter allows the output voltage to be proportional

to the input voltage. In other words, there is no requirement for input voltage regulation. This has also led to the term DC-Transformer to be used for bus-converters.

Efficiency is Everything

The main problem with using a bus converter is keeping the size small while processing all of the power required by the system board. Therefore, it is critical to obtain the highest efficiency in order to keep the power density high. For example, 90% efficient converter generating 100W of output power dissipates 11W of heat, which makes it difficult to keep the circuit small. In comparison, a 95% converter dissipates only 5.25W, which simplifies thermal management, and thus shrinks the circuit size.

The only way to obtain such high efficiencies is with synchronous output rectifiers, as shown in Figure 1. All of the switching and power handling components must be optimized in order to achieve the highest possible
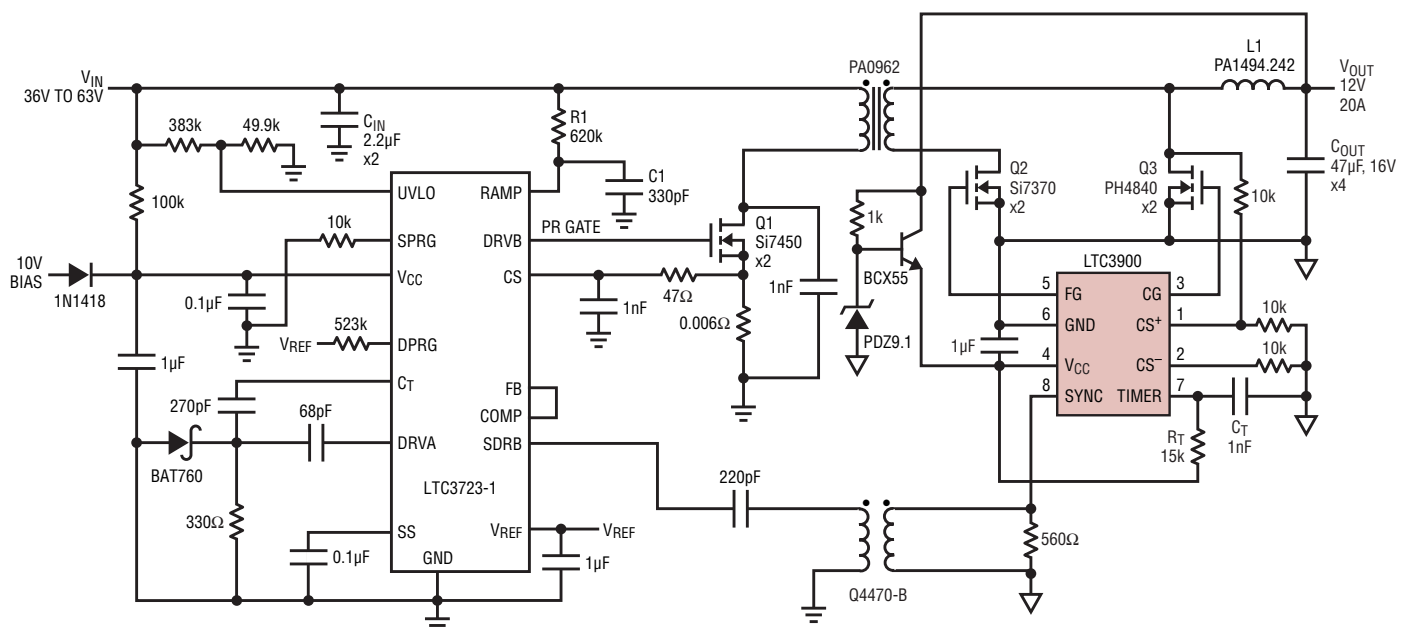
Figure 1. This highly efficient bus converter provides 12V at 20A of isolated, semi-regulated power. The 12V bus can be used by boards to provide low voltage rails via simple, non-isolated converter circuits.

efficiency. Once all of the components have been optimized, the only thing remaining is to provide the converter with precise timing of the synchronous output rectifiers. The LTC3900 synchronous output rectifier controller is not a typical controller. It provides critical timing and protection functions that make the converter in Figure 1 highly reliable and efficient. Efficiency is as high as 94.5% as shown in Figure 3.

LTC3900 Drive and Protection Features

MOSFET switching timing in the circuit of Figure 1 is critical in order to achieve high efficiency. The LTC3723-2 PWM controller generates the appropriate timing delay between the main MOSFET DRVB and synchronous MOSFET SDRB outputs. The synchronous MOSFET driver output, DRVB, is pulse coupled through a small transformer T2. Pulse coupling of the synchronizing signal has the benefit of not requiring the DC levels to be restored on the secondary side of transformer T2. The LTC3900 sync input was designed to accept symmetrical bipolar pulses and to convert these narrow pulses back into appropriate square wave pulses for driving the output synchronous MOSFETs. Another advantage of using pulse coupling is that the coupling transformer can be very small even at low switching frequencies.

One of the problems with driving synchronous MOSFETs has always

Figure 2. The output voltage of the circuit in Figure 1 depends on input voltage and output load. This is a semi-regulated bus supply, intended as input for downstream converters. Even though the output is inexact, its voltage variance remains well within the limits for a bus supply.

been the last pulse that comes from the primary PWM controller following converter shut-down. Depending on the primary controller, the last edge of last synchronizing pulse may leave one of the output MOSFETs turned ON. In that case, the output capacitor may drive a huge reverse current through the output inductor and cause a failure of one of the MOSFETs.

The MOSFET driver circuit LTC3900 has two functions that protect synchronous MOSFETs following PWM shut-down. Figure 4 shows a condition where after the last PWM pulse, the output inductor current has reversed to –25A. The LTC3900 in this case was programmed to turn the forward rectifier MOSFET OFF in order to prevent further reverse current increase. Otherwise, the current could increase far beyond MOSFETs ratings and thus result in MOSFET failure.

As can be seen in Figure 4, the pulse width of the last forward gate pulse can be quite long. The duration of this pulse can be programmed by the Timer function of the LTC3900. The Timer pulse duration doesn't have to be any longer than the normal switching period of primary PWM controller. However, the Timer pulse should not be any shorter than the longest required ON time of the synchronous MOSFETs. If the Timer pulse is too short, the synchronous MOSFET will be turned off too soon and the MOSFETs body diode will have to conduct which will result in far greater power dissipation. A better Timer pulse duration than the one shown in Figure 4 is shown in Figure 5. The Timer dura-

tion programmed in Figure 5 produces reverse current of only –10A, which is well within the ratings of synchronous MOSFET used in this application.

In addition to the Timer function, the LTC3900 also has a reverse current detector. The reverse current detector monitors catch MOSFET Q3 in Figure 1 and terminates the catch MOSFET conduction if current through the MOSFET reverses. In normal operation, the catch MOSFET current creates a negative drain-to-source voltage. If the inductor current reverses, the catch MOSFET drain-to-source voltage becomes positive. If the drain-to-source voltage exceeds a 21mV threshold (10.5mV at CS+

Figure 4. Output inductor reverse current following last PWM pulse keeps increasing until Q3 is turned off. A high reverse current can damage the MOSFET Q3.

Figure 5. The reverse inductor current is reduced with a shorter TIMER period.
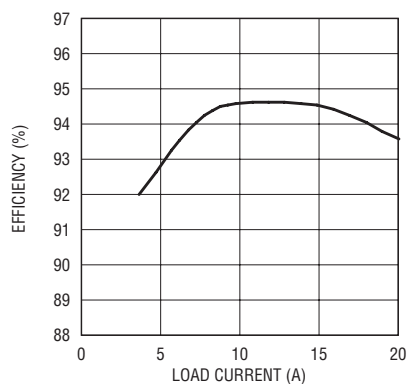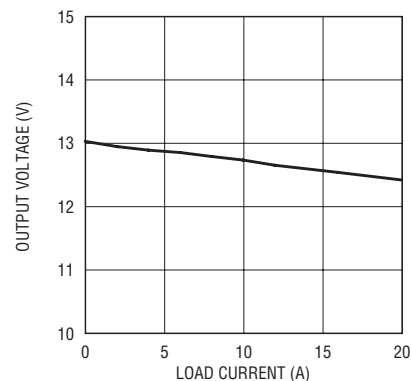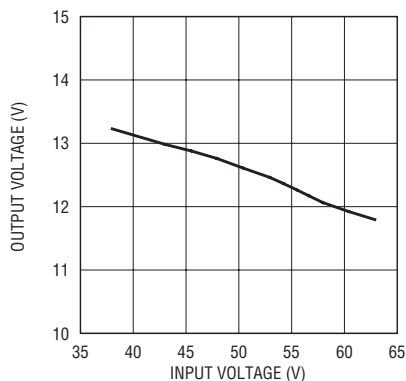

Figure 3. The efficiency of 12V converter is better than 94% over a wide range of loads. High efficiency makes it possible to fit this converter into 35mm by 55mm of space, since thermal management is simplified.

input), the catch MOSFET turns OFF. The 10.5mV current sense threshold of CS+ input is temperature dependent so it can follow the temperature variation of the MOSFET's $R_{DS(ON)}$, as long as it is mounted close to the MOSFET on the PC board. To calculate the amount of reverse current that turns

the catch MOSFET off, use $R_{DS(ON)}$ at room temperature with a 10.5mV current sense threshold. Just as with the Timer function, the catch MOSFET should not be turned off under normal conditions. Therefore, a catch MOSFET with sufficiently low $R_{DS(ON)}$

should be used or voltage divider on the CS+ pin can be added.

Conclusion

The LTC3900 MOSFET is a comprehensive solution for implementing robust, high efficiency, high performance synchronous converters. *LT*

LTC4100 including the SMBus accelerators except it is designed to work with two batteries (see Figure 5). Traditionally, dual battery systems are sequential-discharge systems designed to simply increase total battery run time. Dual-battery systems are increasingly used in parallel-discharge systems to satisfy current requirements beyond the capability of a sequential, battery 1 then battery 2 discharge priority system. The LTC1760 addresses the issue by allowing the safe parallel discharge of two batteries.

It also charges the batteries in parallel. A parallel-charge, parallel-discharge dual-battery system can reduce charge times and increase run times over an equivalent sequential system[1]—see Figures 3 and 4.

The key to allowing the LTC1760 to safely control two batteries in parallel is the utilization of the ideal diode[2] concept where the power MOSFETs are driven to act like diodes as opposed to simple on-off switches.

It is no simple feat to safely juggle the charge and discharge state of multiple batteries and a DC input

power source. Supply continuity is paramount—changing from one power path to another should not interrupt power to the system. This daunting task has historically fallen to the host running custom application software. The LTC1760 avoids the need for complicated software development by operating in a *stand-alone* Level 3 Bus Master mode, thus precluding the need for host intervention. The LTC1760 polls each battery at an accelerated rate so that it can continuously optimize battery charging and PowerPath switching modes between two batteries and a wall adapter. It also has built in crises power management hardware to keep the power flowing even if the SMBus is jammed with traffic.

If there is a feature that will shorten charge times, lengthen run times or make the system more robust, it has been included in the LTC1760:

❑ Proprietary charge algorithms allow parallel charging even for two batteries of different chemistries or cell configuration.

❑ Level 3 capabilities allow the LTC1760 to implement a servo charge current and charge voltage system that eliminates hardware

related losses that would extend charge time (see Figure 7).

❑ A turbo-charge mode maximizes the charge current for the fastest battery charging possible.

❑ Support for full dual battery conditioning, another name for gas gauge calibration for less sophisticated gas gauges.

As sophisticated the LTC1760 is, it remains easy to use. There are only four key parameter choices to make. You can literally drop it into your system, throw some smart batteries and an AC adapter at it, and it will start working right away. A full schematic is shown in Figure 6 (Figure 5 shows a simplified schematic).

Conclusion

The LTC4100 offers a simple and reliable Smart Battery System implementation that uses a single battery. The LTC1760 represents perhaps the most comprehensive single chip dual battery system, providing more control, safety, and automatic crisis management compared to any other solution available today. Both parts offer minimal NRE effort needed to get up and running as a complete battery standalone charger system—no battery expertise required. They are also reduce solution cost, PCB space and part count. *LT*

Figure 7. The LTC1760's servo charge current and voltage system eliminates hardware related inefficiencies, therefore decreasing charge times. This is only one of the many unique performance-enhancing features in the LT1760.

Notes

[1] For a more in depth description of parallel charge, parallel discharge systems, see *Linear Technology* Magazine, December 2001, page 12, "Monolithic Dual Battery Power Manager Increases Run Time and Decreases Charge Time").

[2] For more about ideal diodes, see *Linear Technology* magazine, December 2002, page 1, "Ideal Diode Controller Eliminates Energy Wasting Diodes in Power OR-ing Applications", or any materials describing the LTC4412.
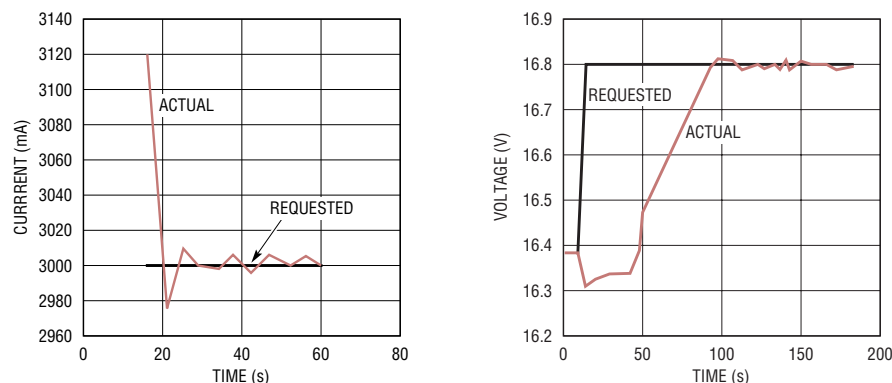
Low-Distortion Sine Wave Oscillator with Precise RMS Amplitude Stability

by Cheng-Wei Pei

Many applications require a frequency and/or amplitude-stable sine wave as a reference for calibration or measurement. Low harmonic distortion is also required for meaningful results in applications such as LVDT signal conditioning, ADC testing, and, of course, harmonic distortion testing. Many sine wave generation techniques simply cannot achieve the low harmonic distortion and amplitude stability required of a precision sine wave reference. The technique shown here generates a sine wave with less than 0.003% distortion and 0.1% amplitude stability.

Figure 1 shows a simple oscillator circuit consisting of a Wien bridge oscillator core and an amplitude stabilization loop. The LT1632 high-speed low-distortion amplifier and its positive feedback RC network generate the oscillations. The amplitude, and amplitude stability, of the sine wave is controlled via a negative feedback loop comprising an LTC1968 RMS-to-DC converter, an LTC2054 buffer, and an LT1632 error amplifier.

The oscillation occurs at a frequency of $1/(2\pi RC)$, where R and C are the positive feedback components of the amplifier. The attenuation of the negative feedback network is approximately 3, to match the attenuation encoun-

> *The LTC1968 true RMS-to-DC converter makes it possible to achieve 0.1% amplitude stability in a simple circuit.*

tered in the positive feedback network. The 2N4338 JFET acts as a variable resistor whose resistance changes according its the gate-source voltage bias. Changing the bias of the JFET adjusts the gain of the oscillator, and thus the amplitude of the resulting sine wave signal. The turn-on and amplitude settling time of this circuit

are dominated by the settling time of the LTC1968, which is typically around 1 millisecond with a 0.01µF averaging capacitor.

The LTC1968 precisely measures the RMS amplitude of the LT1632's output sine wave and gives a DC output that corresponds to the RMS level of the sine wave divided by three. The resistive attenuator at its input allows the LTC1968 output to remain within its low-error region of ≤1V for up to $3V_{RMS}$ output sine waves.

The LTC2054 buffers the output of the LTC1968 for minimal error due to output loading, and the LT1632 error amplifier compares the RMS level of the sine wave with V_{SET}, which sets the desired RMS amplitude. The error amp controls the gate-source voltage bias of the JFET to modulate the amplitude accordingly. As shown, the output amplitude of the sine wave is

$V_{OUT(RMS)} = 3 \cdot V_{SET}$; with $0V \leq V_{SET} \leq 1V$

The 10k-11.5k resistive attenuator at the gate of the JFET compensates for the channel modulation effects of the JFET, which otherwise would cause severe harmonic distortion in the circuit.

As measured with a Hewlett-Packard 3589A Spectrum Analyzer, the harmonic distortion of this circuit with a 100kHz, $1V_{RMS}$ sine wave output is –92dBc (0.0025%). The amplitude stability is better than –60dBc (0.1%). With a $2V_{RMS}$ output, the circuit yields only slightly degraded performance, at –80dBc (0.01%) harmonic distortion and –55dBc (0.18%) amplitude stability.

The LTC1968 can measure the amplitude of sine waves up to 500kHz in frequency with less than 1% absolute error (independent of the amplitude stability of the circuit). Producing higher frequency sine waves using this circuit is possible, up to the 15MHz bandwidth of the LTC1968. ![LT]
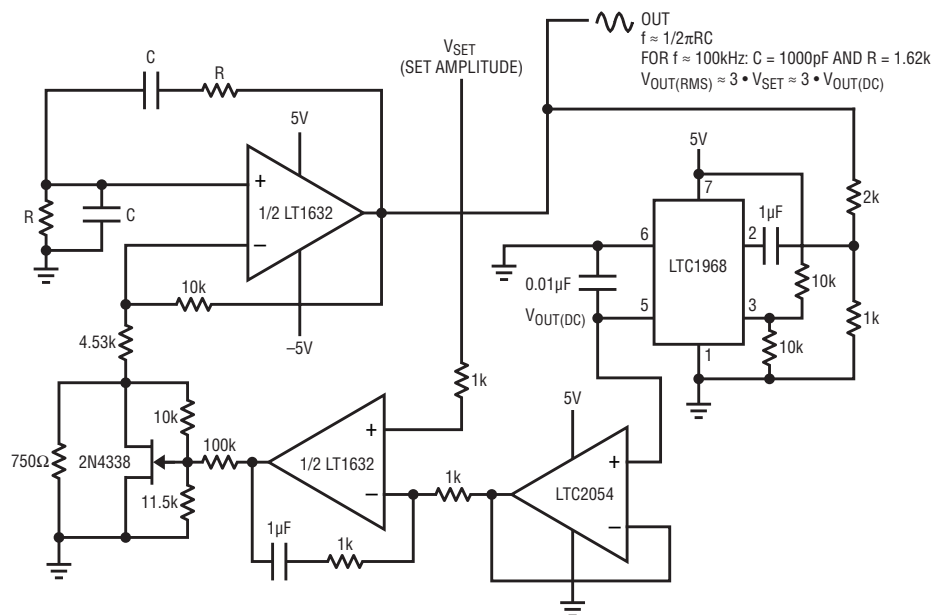

Figure 1. Schematic of the sine wave oscillator, consisting of a low-distortion LT1632-based Wien bridge oscillator core and an LTC1968-controlled amplitude stabilization loop. The output of the LTC1968 equals the RMS level of the sine wave divided by 3.

New Device Cameos

16-Bit Quad DAC with Separate Reference Inputs

The LTC2604 is the latest in Linear Technology's family of 16-bit voltage output DACs that establish excellent performance standards for output drive, crosstalk and noise in single supply, voltage output multiples. High resolution, low power and small size make the LTC2604 ideal for portable instrumentation and industrial process control application. The device's guaranteed monotonic performance is ideal for digital calibration, trim adjust and level setting applications in a wide variety of products.

The rail-to-rail DAC output buffers provide excellent drive capability over a wide supply voltage range of 2.5V to 5.5V. The output can drive capacitive loads up to 1000pF or a maximum current load of 15mA while maintaining excellent linearity within millivolts of both supply rails. The low output offset (9mV max) provides a zero scale voltage much closer to 0V than competitive parts. Low offset drift (5µV/°C) and gain error drift (±5 ppm/°C) makes these parts ideal for use in digital calibration and trim/adjust applications. The low output noise reduces the need for additional output filtering and its 0.1Hz to 10Hz noise (15µV p-p) is much lower than competitive devices.

In addition to separate reference inputs, the LTC2604 also has a Reference Low (REFLO) pin, which allows the zero scale voltage of the DACs to be set higher than 0V. Low DC crosstalk between DACs and separate reference inputs allow true independent control of each of the four DAC output levels. This makes the LTC2604 ideal for "set and forget" type of applications, as an update of one DAC output does not require that the other DAC outputs be re-adjusted.

The LTC2604 family uses a simple SPI/MICROWIRE compatible 3-wire interface that can be operated at a max clock speed of 50MHz. The daisy chain capability allows control of multiple serial devices with a single 3-wire interface. The asynchronous clear function required for servo and control applications is also provided.

The LTC2604 is available in a narrow 16-pin SSOP package, and is one of many pin-compatible devices in a family of compact DACs, making it possible to produce a number of performance options from a single design. This family also includes octal, dual and single DACs that feature superior performance in the smallest available footprints.

Micropower Op Amp has Precision On-Chip Resistors

The LT1996 is a precision micropower op amp with eight on-chip precision resistors packed into a tiny 3mm × 3mm DFN package. It can be configured to hundreds of applications by simply strapping its pins—no external resistors required.

The op amp has an input offset voltage of only 50µV and the supply current is 100µA. The outputs swing to within 40mV of either supply rail, which is critical in low voltage applications. The gain bandwidth product of the op amp is 560kHz, and the LT1996 can operate from any supply voltage between 2.7V and 36V, adding to its versatility.

The eight on-chip precision resistors have excellent matching of 0.05% over temperature, and the matching temperature coefficient is guaranteed less than 3ppm/°C. The nominal resistor values are 450k, 50k, 16.667k and 5.555k. When configured as a difference amplifier, this readily allows gains of 9, 27 and 81. Hundreds of other gains (inverting, noninverting or differential) can be implemented without any external components, and all with excellent precision. An otherwise identical device with different resistor values is also available as the LT1991.

Some of the resistor inputs can be taken well beyond the supply rails, to as high as ±60V. This allows, for example, precise monitoring of signals with a negative 48V common mode while the part is powered by only 5V and ground.

The LT1996 is specified to operate from –40°C to 85°C, comes in standard and A grades, and is available in a 10-lead MSOP as well as a tiny 3mm × 3mm leadless DFN package.

Synchronous Switching Regulator Controller Allows Inputs to 60V

The LTC3703-5 is a synchronous switching regulator controller that can directly step-down input voltages up to 60V, and withstand transients up to 80V, making it ideal for the harsh environments seen in automotive, telecom and industrial applications. The ability to step-down the high input voltage directly allows a simple single inductor topology resulting in a compact high performance power supply—in contrast to the low-side drive topologies that require bulky, expensive transformers.

The LTC3703-5 is similar to its predecessor, the LTC3703, except that it is optimized for logic-level MOSFETs instead of standard-threshold devices. Like the LTC3703, the LTC3703-5 drives external N-channel MOSFETs using a constant frequency, voltage-mode architecture. A high bandwidth error amplifier and patented line feed forward compensation provide very fast line and load transient response. Strong 1Ω gate drivers minimize switching losses even when multiple MOSFETs are used for high current applications.

The LTC3703-5 can also operate as a synchronous step-up regulator eliminating the bulky catch diode and associated heat-sinking required in high current non-synchronous boost converters. Operating as a boost converter, the LTC3703-5 can regulate outputs up to 60V.

Other features include an external clock synchronization input, precise 0.8V 1% reference, programmable current limit, programmable operating frequency (100kHz to 600kHz), and selectable pulse-skip mode operation. The LTC3703-5 is available in 16-pin narrow SSOP and 28-pin SSOP packages.

Low Noise, Synchronous Step-Up DC-DC Converter Connects V_{OUT} to V_{IN} in Shutdown

The LTC3400-1 is an efficient and tiny synchronous step-up DC-DC converter that provides a direct connection from output to input when shut down. This feature is useful in products where the battery power source needs to be monitored while the converter is turned off, or to provide a path for backup power from the main battery.

The LTC3400-1 is pin-for-pin compatible with the LTC3400 family of synchronous step-up regulators. Like the LTC3400 family, it can operate from a single-cell alkaline battery input up to 4.5V and features power conversion efficiency up to 95%. The internal switch and synchronous rectifier are rated at 600mA (min). The output voltage can be programmed from 2.5 to 5.0V with an external resistor divider. The 1.2MHz fixed frequency architecture provides very low V_{OUT} ripple, making it compatible with sensitive measurement applications, and it allows the use of a tiny, low profile inductor and ceramic input and output capacitors.

The LTC3400-1 automatically switches to Burst Mode operation at light loads to reduce battery drain. The current mode PWM architecture of the LTC3400-1 is internally compensated, reducing external parts count. Shutdown quiescent current is less than 1µA.

16-Bit DAC with I²C Interface in a 3mm × 3mm Footprint

The LTC2606 reduces the size and improves performance of compact portable products by integrating a high performance voltage output 16-bit DAC in a 3mm × 3mm 10-pin DFN package. The LTC2606 is ideal for space-constrained applications optimizing board layout. The device's guaranteed monotonic performance is ideal for digital calibration, trim/adjust and level setting applications in a wide variety of products.

The LTC2606's output buffer has excellent drive capability over its entire 2.7V to 5.5V supply voltage range. The DAC output can directly drive capacitive loads up to 1000pF and current loads up to 15mA while maintaining good linearity to within millivolts of both supply rails. The low output offset (9mV max) provides a zero-scale voltage closer to 0V than competitive devices. Low power consumption (270µA supply current and 1µA max shutdown current) makes the LTC2606 ideal for battery-powered applications. The low output noise (15 µV$_{P-P}$ over 0.1Hz to 10Hz) reduces the need for output filtering and is much lower than competitive devices.

The LTC2606 uses a 2-wire I²C serial digital interface that is compatible with both the standard-mode (100kHz max clock speed) and fast-mode (400kHz max clock speed) of operation with 27 selectable I²C slave addresses, which minimizes address conflicts with other I²C components in the system. The device features an asynchronous update pin ($\overline{LDAC}$), which allows the DAC update to be synchronized to a hardware signal. It also allows simultaneous updates and power-up of multiple DACs in a system. A power-on reset sets the LTC2606 to zero-scale on power-up.

The LTC2606 is one of many pin compatible devices in a family of compact DACs, yielding multiple performance options from one design. The LTC2616 and LTC2626 are pin compatible 14-bit and 12-bit DACs; the LTC2606-1, LTC2616-1 and the LTC2626-1 are pin compatible 16-bit, 14-bit and 12-bit DACs which power-up at mid-scale. *LT*

---

the voltage at the R_{SET} pin at 1V below the positive supply. Because the frequency of oscillation is based on the resistance, or V/I at the R_{SET} pin, a stable V at the R_{SET} pin provides the ability to generate an accurate output frequency by injecting an accurate current (I) at the R_{SET} pin.

For stability reasons, it is recommended that the R_{SET} pin be driven by resistors as shown in Figure 5. All
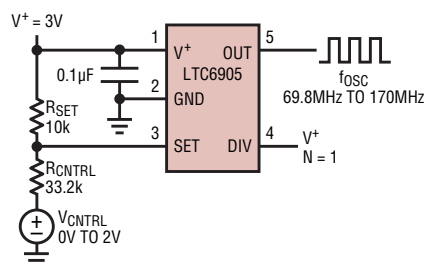

Figure 5. The LTC6905 as a voltage controlled oscillator

modulation of the frequency, whether by voltage or current, relies on modulation of the current input to the R_{SET} pin. Because the R_{SET} voltage is fixed at 1V, the frequency of the output depends to the first degree only on the current into the R_{SET} pin. The master oscillator frequency may be approximated as:

$$F_{OSC} = \frac{10k\Omega}{R_{SET}} \times 170MHz$$

Substituting V_{RSET}/I_{RSET} for R_{SET}, where $V_{RSET}=1V$, we get:

$$F_{OSC} = 10k\Omega \times I_{RSET} \times 170MHz$$

This indicates that a 50µA current into the R_{SET} pin would result in a master oscillator frequency of 85MHz. More applications circuits and information regarding using the LTC6905 as a VCO is available in the data sheet.

The modulation bandwidth of the LTC6905 is dictated by its internal control loop, which is limited to between 700kHz and 2MHz, depending on output frequency. Due to the low modulation bandwidth in relation to the output frequency, it is recommended that the LTC6905 be used as a VCO only in applications where the rate of modulation is less than the output frequency divided by 128.

Conclusion

The LTC6905 and LTC6905-XXX are low power, highly accurate silicon oscillators that can replace crystals in many applications. They offer advantages of lower cost, lower sensitivity to temperature and shock, and ease of frequency modulation—important features in driving microcontrollers, FPGAs and other complex systems. *LT*

DESIGN TOOLS

Databooks

The 2004 set of eleven Linear databooks is available and supersedes all previous Linear databooks. Each databook contains product data sheets, selection guides, QML/space information, package information, appendices, and a complete index to the set.

For more information, or to obtain any of the databooks, contact your local sales office (see the back of this magazine), or visit www.linear.com.

Amplifiers (Book 1 of 2) —
• Operational Amplifiers

Amplifiers (Book 2 of 2) —
• Operational Amplifiers
• Instrumentation Amplifiers
• Application Specific Amplifiers

References, Filters, Comparators, Special Functions, RF & Wireless —
• Voltage References   • Special Functions
• Monolithic Filters   • RF & Wireless
• Comparators   • Optical Communications
• Oscillators

Monolithic Switching Regulators —
• Micropower Switching Regulators
• Continuous Switching Regulators

Switching Regulator Controllers (Book 1 of 2) —
• DC/DC Controllers

Switching Regulator Controllers (Book 2 of 2) —
• DC/DC Controllers
• Digital Voltage Programmers
• Off-Line AC/DC Controllers

Linear Regulators, Charge Pumps, Battery Chargers —
• Linear Regulators
• Charge Pump DC/DC Converters
• Battery Charging & Management

Hot Swap Controllers, MOSFET Drivers, Special Power Functions —
• Hot Swap Controllers
• Power Switching & MOSFET Drivers
• PCMCIA Power Controllers
• CCFL Backlight Converters
• Special Power Functions

Data Converters (Book 1 of 2) —
• Analog-to-Digital Converters

Data Converters (Book 2 of 2) —
• Analog-to-Digital Converters
• Digital-to-Analog Converters
• Switches & Multiplexers

Interface, System Monitoring & Control —
• Interface — RS232/562, RS485, Mixed Protocol, SMBus/I²C
• System Monitoring & Control — Supervisors, Margining, Sequencing & Tracking Controllers

www.linear.com

Customers can quickly and conveniently find and retrieve product information and solutions to their applications. Located at www.linear.com., the site quickly searches our database of technical documents and displays weighted results of our data sheets, application notes, design notes, *Linear Technology* magazine issues and other LTC publications. The LTC website simplifies the product selection process by providing convenient search methods, complete application solutions and design simulation programs for Power, Filter, Op Amp and Data Converter applications. Search methods include a text search for a particular part number, keyword or phrase. And the most powerful, a parametric search engine. After selecting a desired product category, engineers can specify and sort by key parameters and specifications that satisfy their design requirements.

Purchase Products Online

Credit Card Purchases—Purchase online direct from Linear Technology at www.linear.com using a credit card. Create a personalized account to check order history, shipment information and reorder products.

Linear Express Distribution — Get the parts you need. Fast. Most devices are stocked for immediate delivery. Credit terms and low minimum orders make it easy to get you up and running. Place and track orders online. Apply today at www.linear.com or call (866) 546-3271.

Applications Handbooks

Linear Applications Handbook, Volume I—Almost a thousand pages of application ideas covered in depth by 40 Application Notes and 33 Design Notes. This catalog covers a broad range of real world linear circuitry. In addition to detailed, systems-oriented circuits, this handbook contains broad tutorial content together with liberal use of schematics and scope photography. A special feature in this edition includes a 22-page section on SPICE macromodels.

Linear Applications Handbook, Volume II—Continues the stream of real world linear circuitry initiated by Volume I. Similar in scope to Volume I, this book covers Application Notes 40 through 54 and Design Notes 33 through 69. References and articles from non-LTC publications that we have found useful are also included.

Linear Applications Handbook, Volume III—This 976-page handbook includes Application Notes 55 through 69 and Design Notes 70 through 144. Subjects include switching regulators, measurement and control circuits, filters, video designs, interface, data converters, power products, battery chargers and CCFL inverters. An extensive subject index references circuits in Linear data sheets, design notes, application notes and *Linear Technology* magazines.

CD-ROM

The March 2005 CD-ROM contains product data sheets, application notes and Design Notes released through February of 2005. Use your browser to view product categories and select products from parametric tables or simply choose products and documents from part number, application note or design note indexes.

Brochures

Power Management & Wireless Solutions for Handheld Products —The solutions in this product selection guide solve real-life problems for cell phones, digital cameras, PDAs and other portable devices. Circuits are shown for Li-Ion battery chargers, battery managers, USB support, system power regulation, display drivers, white LED drivers, photoflash chargers, DC/DC converters, SIM and smart card interfaces, photoflash chargers, and RF PA power supply and control. All solutions are designed to maximize battery run time, save space and reduce EMI where necessary—important considerations when designing circuits for handheld devices.

Automotive Electronic Solutions—This selection guide features recommended Linear Technology solutions for a wide range of functions commonly used in today's automobiles, including telematics and infotainment systems, body electronics and engine management, safety systems and GPS/navigation systems.

Linear Technology's high-performance analog ICs provide efficient, compact and dependable solutions to solve many automotive application requirements.

Software

SwitcherCAD™ III/LTC SPICE —LTC SwitcherCAD III is a fully functional SPICE simulator with enhancements and models to ease the simulation of switching regulators. This SPICE is a high performance circuit simulator and integrated waveform viewer, and also includes schematic capture. Our enhancements to SPICE result in much faster simulation of switching regulators than is possible with normal SPICE simulators. SwitcherCAD III includes SPICE, macromodels for 80% of LTC's switching regulators and over 200 op amp models. It also includes models of resistors, transistors and MOSFETs. With this SPICE simulator, most switching regulator waveforms can be viewed in a few minutes on a high performance PC. Circuits using op amps and transistors can also be easily simulated. Download at www.linear.com

FilterCAD™ 3.0 —FilterCAD 3.0 is a computer aided design program for creating filters with Linear Technology's filter ICs. FilterCAD is designed to help users without special expertise in filter design to design good filters with a minimum of effort. It can also help experienced filter designers achieve better results by playing "what if" with the configuration and values of various components and observing the results. With FCAD, you can design lowpass, highpass, bandpass or notch filters with a variety of responses, including Butterworth, Bessel, Chebychev, elliptic and minimum Q elliptic, plus custom responses. Download at www.linear.com

SPICE Macromodel Library —This library includes LTC op amp SPICE macromodels. The models can be used with any version of SPICE for analog circuit simulations. These models run on SwitcherCAD III/LTC SPICE.

Noise Program —This PC program allows the user to calculate circuit noise using LTC op amps, determine the best LTC op amp for a low noise application, display the noise data for LTC op amps, calculate resistor noise and calculate noise using specs for any op amp.

World Headquarters

Linear Technology Corporation
1630 McCarthy Blvd.
Milpitas, CA 95035-7417
Phone: (408) 432-1900
FAX: (408) 434-0507
www.linear.com

U.S. Sales Offices

NORTHWEST AREA
Bay Area
720 Sycamore Dr.
Milpitas, CA 95035
Phone: (408) 428-2050
FAX: (408) 432-6331

Denver
Phone: (303) 926-0002

Portland
6700 SW 105th Ave., Ste. 207
Beaverton, OR 97008
Phone: (503) 520-9930
FAX: (503) 520-9929

Sacramento
Phone: (408) 432-6326

Salt Lake City
Phone: (801) 731-8008

Seattle
2018 156th Ave. NE, Ste. 100
Bellevue, WA 98007
Phone: (425) 748-5010
FAX: (425) 748-5009

SOUTHWEST AREA
Los Angeles
21243 Ventura Blvd., Ste. 208
Woodland Hills, CA 91364
Phone: (818) 703-0835
FAX: (818) 703-0517

Orange County
15375 Barranca Pkwy., Ste. A-213
Irvine, CA 92618
Phone: (949) 453-4650
FAX: (949) 453-4765

San Diego
5090 Shoreham Place, Ste. 110
San Diego, CA 92122
Phone: (858) 638-7131
FAX: (858) 638-7231

CENTRAL AREA
Chicago
2040 E. Algonquin Rd., Ste. 512
Schaumburg, IL 60173
Phone: (847) 925-0860
FAX: (847) 925-0878

Cleveland
7550 Lucerne Dr., Ste. 106
Middleburg Heights, OH 44130
Phone: (440) 239-0817
FAX: (440) 239-1466

Columbus
Phone: (614) 488-4466

Detroit
Phone: (248) 374-2243

Indiana
Phone: (317) 581-9055

Kansas
Phone: (913) 829-8844

Minneapolis
7805 Telegraph Rd., Ste. 225
Bloomington, MN 55438
Phone: (952) 903-0605
FAX: (952) 903-0640

Wisconsin
Phone: (262) 859-1900

NORTHEAST AREA
Boston
15 Research Place
North Chelmsford, MA 01863
Phone: (978) 656-4750
FAX: (978) 656-4760

Connecticut
Phone: (860) 228-4104

Philadelphia
3220 Tillman Dr., Ste. 120
Bensalem, PA 19020
Phone: (215) 638-9667
FAX: (215) 638-9764

SOUTHEAST AREA
Atlanta
Phone: (770) 888-8137

Austin
8500 N. Mopac, Ste. 603
Austin, TX 78759
Phone: (512) 795-8000
FAX: (512) 795-0491

Dallas
17000 Dallas Pkwy., Ste. 200
Dallas, TX 75248
Phone: (972) 733-3071
FAX: (972) 380-5138

Fort Lauderdale
Phone: (954) 986-9810

Houston
1080 W. Sam Houston Pkwy., Ste. 225
Houston, TX 77043
Phone: (713) 463-5001
FAX: (713) 463-5009

Huntsville
Phone: (256) 885-0215

Orlando
Phone: (407) 688-7616

Raleigh
15100 Weston Pkwy., Ste. 202
Cary, NC 27513
Phone: (919) 677-0066
FAX: (919) 678-0041

Tampa
Phone: (813) 634-9434

Asia Sales Offices

CHINA
Linear Technology Corp. Ltd.
Unit 2108, Metroplaza Tower 2
223 Hing Fong Road
Kwai Fong, N.T., Hong Kong
Phone: +852 2428-0303
FAX: +852 2348-0885

Linear Technology Corp. Ltd.
Room 902, Peregrine Plaza
1325 Huaihai M. Road
Shanghai, 200031, PRC
Phone: +86 (21) 6375-9478
FAX: +86 (21) 5465-5918

Linear Technology Corp. Ltd.
Room 707, 7th Floor
Beijing Canway Building
66 Nan Li Shi Lu
Beijing, 100045, PRC
Phone: +86 (10) 6801-1080
FAX: +86 (10) 6805-4030

Linear Technology Corp. Ltd.
Rm. 2109, Shenzhen Kerry Centre
2008 Shenzhen Renminnan Lu
Shenzhen, China
Phone: +86 755-8236-6088
FAX: +86 755-8236-6008

JAPAN
Linear Technology KK
8F Shuwa Kioicho Park Bldg.
3-6 Kioicho Chiyoda-ku
Tokyo, 102-0094, Japan
Phone: +81 (3) 5226-7291
FAX: +81 (3) 5226-0268

Linear Technology KK
6F Kearny Place Honmachi Bldg.
1-6-13 Awaza, Nishi-ku
Osaka-shi, 550-0011, Japan
Phone: +81 (6) 6533-5880
FAX: +81 (6) 6543-2588

Linear Technology KK
3F Sakae Members Office Bldg.
4-16-8 Sakae, Naka-ku
Nagoya, 460-0008, Japan
Phone: +81 (52) 269-9510
FAX: +81 (52) 269-9520

KOREA
Linear Technology Korea Co., Ltd.
Yundang Building, #1002
Samsung-Dong 144-23
Kangnam-Ku, Seoul 135-090
Korea
Phone: +82 (2) 792-1617
FAX: +82 (2) 792-1619

SINGAPORE
Linear Technology Pte. Ltd.
507 Yishun Industrial Park A
Singapore 768734
Phone: +65 6753-2692
FAX: +65 6752-0108

TAIWAN
Linear Technology Corporation
8F-1, 77, Nanking E. Rd., Sec. 3
Taipei, Taiwan
Phone: +886 (2) 2505-2622
FAX: +886 (2) 2516-0702

Europe Sales Offices

FINLAND
Linear Technology AB
Teknobulevardi 3-5
P.O. Box 35
FIN-01531 Vantaa
Finland
Phone: +358 (0)9 2517 8200
FAX: +358 (0)9 2517 8201

FRANCE
Linear Technology S.A.R.L.
Immeuble "Le Quartz"
58, Chemin de la Justice
92290 Chatenay Malabry
France
Phone: +33 (1) 41 07 95 55
FAX: +33 (1) 46 31 46 13

Linear Technology
"Le Charlemagne"
140, cours Charlemagne
69286 Lyon Cedex 2
France
Phone: +33 (4) 72 41 63 86
FAX: +33 (4) 72 41 62 99

GERMANY
Linear Technology GmbH
Oskar-Messter-Str. 24
D-85737 Ismaning
Germany
Phone: +49 (89) 962455-0
FAX: +49 (89) 963147

Linear Technology GmbH
Haselburger Damm 4
D-59387 Ascheberg
Germany
Phone: +49 (2593) 9516-0
FAX: +49 (2593) 951679

Linear Technology GmbH
Jesinger Strasse 65
D-73230 Kirchheim/Teck
Germany
Phone: +49 (0)7021 80770
FAX: +49 (0)7021 807720

ITALY
Linear Technology Italy Srl
Via Giovanni da Udine, 34
I-20156 Milano
Italy
Phone: +39 (02) 38093656
FAX: +39 (02) 38093659

SWEDEN
Linear Technology AB
Electrum 204
Isafjordsgatan 22
SE-164 40 Kista
Sweden
Phone: +46 (8) 623 16 00
FAX: +46 (8) 623 16 50

UNITED KINGDOM
Linear Technology (UK) Ltd.
3 The Listons, Liston Road
Marlow, Buckinghamshire SL7 1FD
United Kingdom
Phone: +44 (1628) 477066
FAX: +44 (1628) 478153

Buy online at www.linear.com