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## High Accuracy ( $\pm 1^\circ C$ ) Temperature Sensors Improve System Performance and Reliability

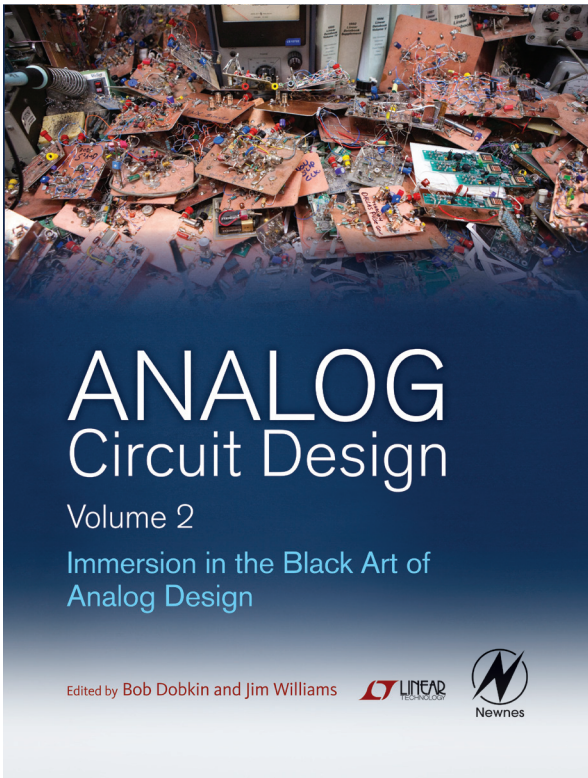
Christoph Schwoerer and Gerd Trampitsch

The march toward increasingly dense computing power has amplified the challenges related to heat. In many systems, the capabilities of the cooling system are a significant limitation to overall performance. Standard cooling components—bulky heat sinks and power-hungry noisy fans (or expensive quiet ones)—impose size limitations on tightly packed electronics. The only way to maximize performance, minimize cooling requirements, and ensure the health of the electronics is with accurate, precise and comprehensive temperature monitoring throughout the system.

With this in mind, Linear Technology has developed a family of highly accurate temperature monitors that can be easily distributed throughout a system. Included in this family:

- The LTC<sup>®</sup>2997 accurately measures either its own temperature or the temperature of an external diode.
- The LTC2996 adds monitoring functionality by comparing the measured temperature with a high and a low temperature threshold and communicating any temperature excess via open drain alert outputs.
- The LTC2995 combines the LTC2996 with a dual supply voltage monitor, allowing it to measure temperature, compare temperature to configurable thresholds, and supervise two supply voltages.

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Analog Circuit Design, Volume 2 now available. See page 3.

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## THE LTC2997 IS A TINY HIGH PRECISION TEMPERATURE SENSOR

The LTC2997 in a 2mm × 3mm 6-pin DFN package is perfectly suited to measure temperature of an FPGA or microprocessor as shown in Figure 1.

To this end, the LTC2997 sends measurement currents to the temperature monitoring diode of the FPGA or microprocessor and generates a voltage proportional to the temperature of the diode on its V<sub>PTAT</sub> output. LTC2997 also provides a 1.8V reference voltage at the V<sub>REF</sub> output, which can be used as reference voltage for the onboard ADC in the FPGA or microprocessor. The measurement error in this configuration with external sensor element is *guaranteed* to  $\pm 1^\circ\text{C}$  over the wide temperature range from  $0^\circ\text{C}$  to  $100^\circ\text{C}$  and to  $\pm 1.5^\circ\text{C}$  from  $-40^\circ\text{C}$  to  $125^\circ\text{C}$ ; *typical* temperature measurement error is far better, as shown in Figure 2.

Tying the D<sup>+</sup> pin to V<sub>CC</sub> configures the LTC2997 to use its own internal temperature sensor. The V<sub>PTAT</sub> voltage has a slope of 4mV/K and is updated every 3.5ms.

## OPERATING PRINCIPLES

The LTC2997 achieves impressive accuracy by measuring the diode voltage at multiple test currents and using the measurements to remove any process-dependent errors and series resistance errors.

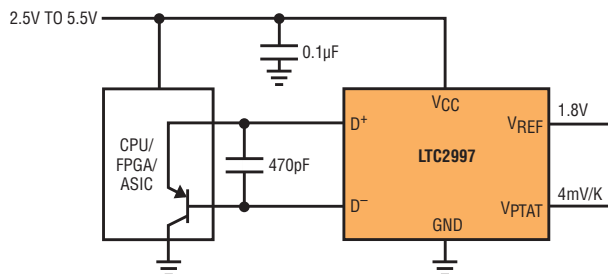
The diode equation can be solved for T, where T is temperature in Kelvin, I<sub>S</sub> is a process dependent factor on the order of  $10^{-13}\text{A}$ , η is the diode ideality factor, k is the Boltzmann constant and q is the electron charge:

$$T = \frac{q}{\eta \cdot k} \cdot \frac{V_D}{\ln\left(\frac{I_D}{I_S}\right)}$$

This equation has a relationship between temperature and voltage, dependent on the process-dependent variable I<sub>S</sub>. Measuring the same diode (with the same value I<sub>S</sub>) at two different currents yields an expression that is independent of

(continued on page 4)

Figure 1. Remote CPU temperature sensor



# Linear in the News

## ANALOG CIRCUIT DESIGN BOOK SEQUEL PUBLISHED

The much anticipated *Analog Circuit Design, Volume 2* has just been published by the Newnes Press imprint of Elsevier Science & Technology Books. Edited by industry gurus, Bob Dobkin and the late Jim Williams, the new volume, *Analog Circuit Design, Volume 2, Immersion in the Black Art of Analog Design*, extends the reach of the first volume, at 1250 pages, covering a broad range of analog circuit design techniques.

The book includes an extensive power management section, covering such topics as power management tutorials, switching regulator design, linear regulator design, powering illumination devices and automotive and industrial power design. Other sections of the book span a wide array of topics in data conversion, signal conditioning and high frequency/RF. This volume also features an extensive section of circuit collections with numerous hands-on examples across a variety of application areas.

Readers of *Analog Circuit Design, Volume 2* will be treated to the insight, technique and fascinating design approaches of Bob Dobkin, Jim Williams, Carl Nelson, Bob Widlar and many others. For more information, go to [www.linear.com/designtools/acd\\_book.php](http://www.linear.com/designtools/acd_book.php) To purchase *Analog Circuit Design, Volume 2*, click on the Elsevier link for a 30 percent discount on the cover price or go to the Amazon link at the bottom of the page.

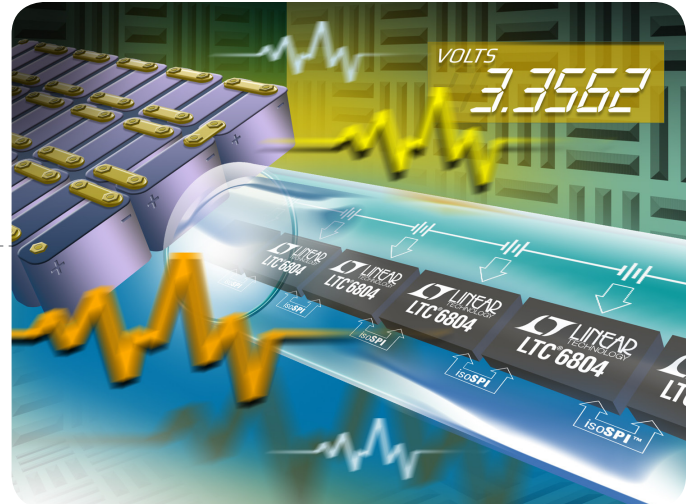
## NEXT GENERATION BATTERY STACK MONITOR FOR HYBRID/ELECTRICS

Linear has just announced its next-generation battery stack monitor for hybrid/electric vehicles, the LTC6804, at press conferences in Europe, Asia and the US. This device can measure up to 12 series-connected battery cells at voltages up to 4.2V with 16-bit resolution and better than 0.04% accuracy. This high precision is maintained over time, temperature and operating conditions by a subsurface Zener voltage reference similar to references used in precision instrumentation. When stacked in series, the LTC6804 enables measurement of every battery cell voltage in large high voltage systems.

“The LTC6804 combines 30 years of analog experience with hard-earned lessons in automotive battery management,” stated Mike Kultgen, design manager for Linear Technology.

Multiple LTC6804s can be interconnected over long distances and operated simultaneously using Linear’s proprietary 2-wire ISO-SPI™ interface. The LTC6804 operates with a companion device, the LTC6820 ISO-SPI transceiver, which enables bidirectional transmission of the serial peripheral interface (SPI) bus across an isolated barrier up to 100 meters.

For more information, visit [www.linear.com/product/LTC6804](http://www.linear.com/product/LTC6804) and [www.linear.com/product/LTC6820](http://www.linear.com/product/LTC6820).



## CONFERENCES & EVENTS

**Car-Ele Japan 2013, 5th Annual Automotive Electronics Technology EXPO, Tokyo Big-sight, Japan, January 16-18, 2013, East Hall 2, Booth E11-49**—Focus on automotive applications solutions, including LTC6804 battery management system. More info at [www.car-ele.jp/en](http://www.car-ele.jp/en)

**Advanced Automotive Battery Conference, Pasadena Convention Center, California, February 4-8, 2013, Booths 300-301**—Presenting Linear’s battery management solutions. Erik Soule will present “Measuring the EV Battery Stack.” More info at [www.advanced-autobat.com/conferences/automotive-battery-conference-2013/index.html](http://www.advanced-autobat.com/conferences/automotive-battery-conference-2013/index.html)

**APEC 2013, Applied Power Electronics Conference, Long Beach Convention Center, California, March 17-21, 2013, Booths 1111 & 1113**—Presenting Linear’s broad line of high performance power solutions. Brian Shaffer will present “Advancements in Energy Harvesting Transducers & the Challenges They Present for Power Management Solutions.” More info at [www.apec-conf.org/](http://www.apec-conf.org/)

**Electronica China 2013, Shanghai New International Expo Centre, China, March 19-21, 2013, Hall E1, Booth 1332**—Linear will showcase its high performance analog and power management portfolio. More info at [www.electronicachina.com/en/home](http://www.electronicachina.com/en/home) ■

The LTC2997 in a 2mm × 3mm 6-Pin DFN package is perfectly suited to measure temperature of an FPGA or microprocessor via the processor's temperature measuring diode. The measurement error in this configuration is *guaranteed* to ±1°C over the temperature range from 0°C to 100°C and to ±1.5°C from -40°C to 125°C.

(LTC299x continued from page 2)

$I_S$ . The value in the natural logarithm term becomes the ratio of the two currents, which is process independent:

$$T = \frac{q}{\eta \cdot k} \cdot \frac{V_{D2} - V_{D1}}{\ln\left(\frac{I_{D2}}{I_{D1}}\right)}$$

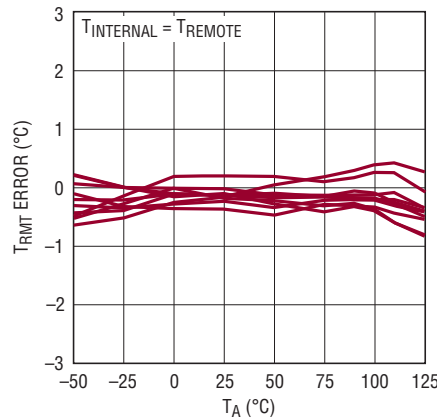
Resistance in series with the remote diode causes a positive temperature error by increasing the measured voltage at each test current. The composite voltage equals:

$$V_D + V_{ERROR} = \eta \frac{kT}{q} \cdot \ln\left(\frac{I_D}{I_S}\right) + R_S \cdot I_D$$

where  $R_S$  is the series resistance.

The LTC2997 removes this error term from the sensor signal by subtracting a cancellation voltage (see Figure 3a). A resistance extraction circuit uses one additional measurement current ( $I_3$ ) to determine the series resistance in the measurement path. Once the correct value of the resistor is determined  $V_{CANCEL}$  equals  $V_{ERROR}$ . Now the temperature to voltage converter's input signal is free from errors due to series

Figure 2. Temperature error vs temperature (LTC2997 at same temperature as remote diode)



resistance and the sensor temperature can be determined using currents  $I_1$  and  $I_2$ .

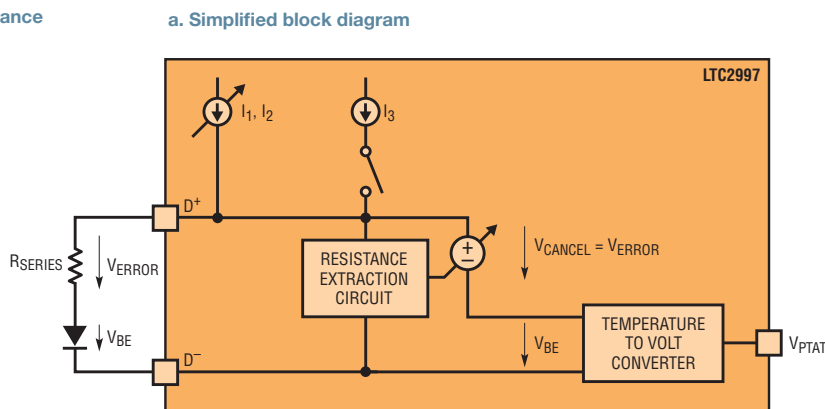
Series resistance up to 1k typically causes less than 1°C of temperature error as indicated in Figure 3b, which makes LTC2997 the ideal device to read out diode sensors that are several meters away from the temperature management system. Indeed, the maximum distance is limited more by the line capacitance than by the line resistance.

Capacitances larger than 1nF start to impact the settling of the sensor voltage at the various sense currents and therefore introduce additional temperature reading errors. For example, a 10m long CAT 6 cable has about 500pF of capacitance.

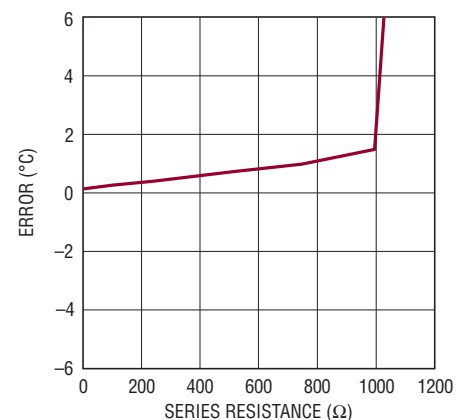
Unlike many remote diode sensors, the LTC2997 accurately tracks fast changing temperatures due to its short update time (3.5ms) and its robust temperature measurement algorithm in the face of temperature variations, even during a measurement interval. Figure 4 shows the step response of the LTC2997's internal sensor when the entire device is dipped into boiling water immediately after sitting in ice water.

The LTC2997 has many advantages over its digital counterparts when applied in temperature regulation loops. Its fast response time and analog output temperature eliminate much of the complexity required by digital systems. For example, Figure 5 shows the LTC2997 in a heater that regulates at 75°C. In this application, the

Figure 3. Series resistance cancellation



b. Temperature error vs series resistance



The LTC2997 has many advantages over its digital counterparts when applied in temperature regulation loops. Its fast response time and analog output temperature eliminate much of the complexity required by digital systems.

Figure 4. LTC2997 internal sensor thermal step response

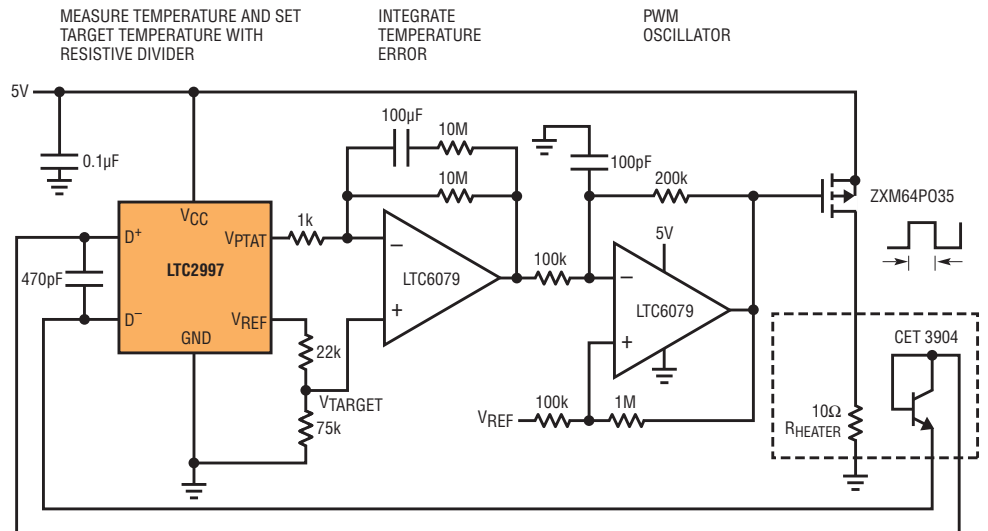
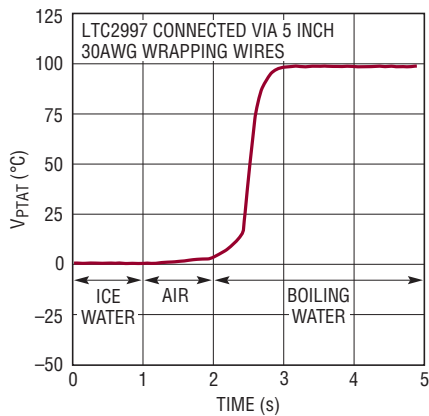


Figure 5. 75°C analog PWM heater controller

reference voltage is used to generate—by means of a resistive divider—a target voltage of 1.392V ( $= [75 + 273.15]K \cdot 4mV/K$ ).

The first micropower rail-to-rail amplifier, the LTC6079, integrates the difference between the  $V_{PTAT}$  output of the LTC2997 and the target voltage. The integrated error signal is converted to a pulse width modulated signal by the PWM oscillator, which in turn drives the switch of the PMOS, controlling the current through the heating resistor.

The LTC2997 can also be used to build a Celsius thermometer (Figure 6), a Fahrenheit thermometer (Figure 7), a thermocouple thermometer with cold junction compensation (Figure 8), or in countless other applications where accurate and fast temperature measurements are required.

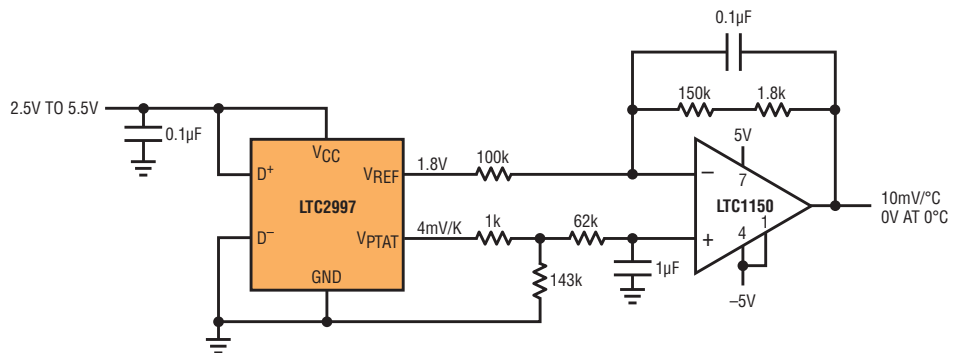


Figure 6. Celsius thermometer

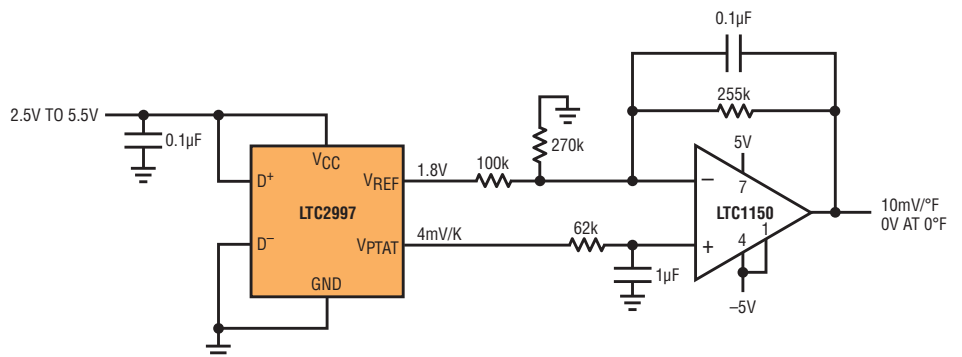


Figure 7. Fahrenheit thermometer

Unlike many remote diode sensors, the LTC2997 accurately tracks fast changing temperatures due to its short update time (3.5ms) and its robust temperature measurement algorithm in the face of temperature variations, even during a measurement interval.

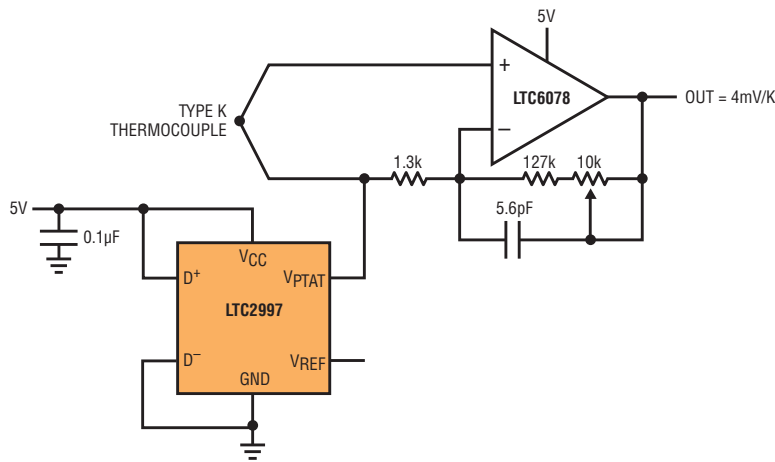


Figure 8. Thermocouple thermometer with cold junction compensation

### THE LTC2996 TEMPERATURE MONITOR

The LTC2996 adds threshold inputs  $V_{TH}$  and  $V_{TL}$  to the LTC2997 and continuously compares  $V_{PTAT}$  to these thresholds to detect overtemperature (OT) or undertemperature (UT) conditions. The threshold input voltages can be conveniently set by resistive dividers from the built-in reference voltage, as depicted in Figure 9.

If the temperature of the remote diode in Figure 9 increases above  $70^{\circ}\text{C}$ , the  $V_{PTAT}$  voltage exceeds the high temperature threshold at  $V_{TH}$ . The LTC2996 detects this overtemperature condition and alerts the temperature control system by pulling the OT pin low. In the same way, a temperature falling below  $-20^{\circ}\text{C}$  is communicated via the UT pin. Note that the LTC2996 pulls on the open drain alert outputs only if the temperature exceeds the corresponding threshold for five consecutive update intervals of 3.5ms each. The OT and the UT pin have internal weak 400k pull-up resistors to  $V_{CC}$ —no external resistors are required in many applications.

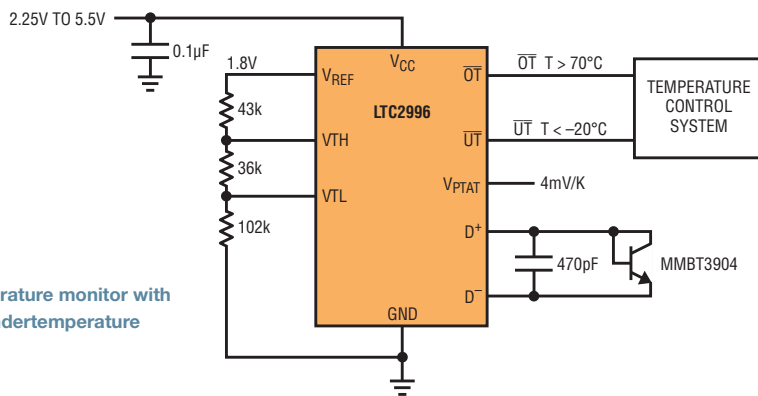


Figure 9. Remote temperature monitor with overtemperature and undertemperature thresholds

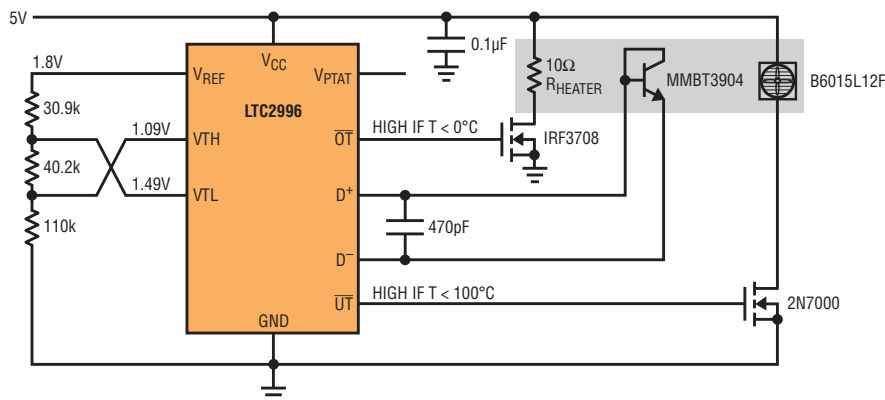


Figure 10. Bang-bang controller maintains temperature between  $0^{\circ}\text{C}$  and  $100^{\circ}\text{C}$

The LTC2996 can be used to implement a bang-bang controller, keeping the temperature of a sensitive device (e.g., a battery) in a certain desirable temperature range, as shown in Figure 10.

In this application, the undertemperature input threshold is set to  $100^{\circ}\text{C}$ , whereas the overtemperature input threshold is set to  $0^{\circ}\text{C}$ . This seemingly upside down arrangement is linked to the fact that OT and UT are pulled low when a threshold is exceeded. Therefore, in this

The LTC2996 adds threshold inputs  $V_{TH}$  and  $V_{TL}$  to the LTC2997 and continuously compares  $V_{PTAT}$  to these thresholds to detect overtemperature (OT) or undertemperature (UT) conditions.

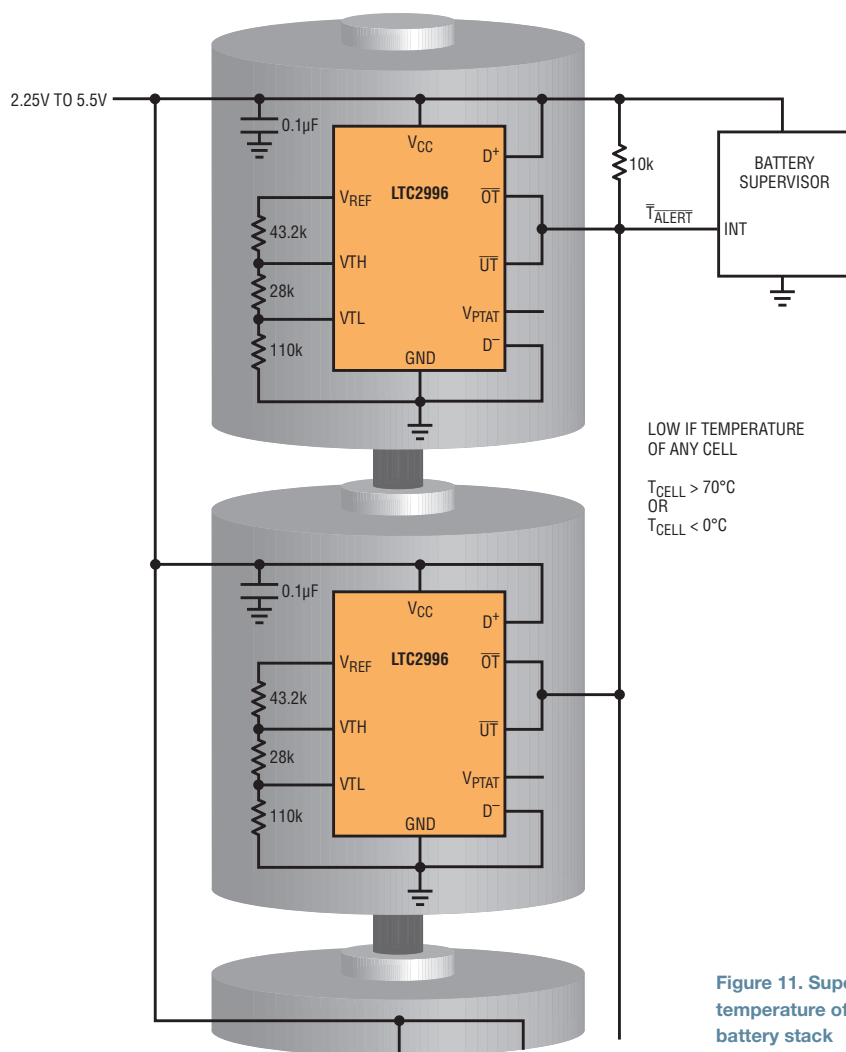


Figure 11. Supervising temperature of cells in a battery stack

configuration, UT and OT both pull the gates of the NMOS transistors low while the temperature remains within the desired range (over the overtemp and under the undertemp), and the heating resistor and the cooling fan are turned off. If the temperature rises above  $100^{\circ}\text{C}$ , the undertemperature open drain output UT is released high and the fan

is switched on. Similarly, a temperature below  $0^{\circ}\text{C}$  turns on the heater.

In the context of batteries, the LTC2996 can also be used to supervise the temperature of a large battery composed of several different cells. A damaged, shorted or worn out cell typically heats up, and can, in worst case, catch fire. The LTC2996 supervises the temperature

of each cell individually with minimal additional wiring, as shown in Figure 11.

In fact, if the cells are connected in series (battery stack) only three additional lines— $V_{CC}$ , GND and an alert output—are required to monitor whether the temperature of any cell leaves the desired operating range. If the cells are connected in parallel, and a battery with a terminal voltage between 2.25V and 5.5V (e.g., Li-ion) is monitored, even a single additional line—the alert output—is sufficient to supervise the temperature of each cell.

#### THE LTC2995 COMBINES A TEMPERATURE AND A DUAL VOLTAGE MONITOR / SUPERVISOR

In addition to temperature monitoring, nearly every electronic system requires multisupply voltage supervision. To serve this need, the LTC2995 combines the LTC2996 with a dual voltage supervisor, monitoring two supply lines for overvoltage and undervoltage conditions as shown in Figure 12.

The LTC2995 adds two additional high and low voltage inputs per channel, which are continuously compared to an internal 500mV reference. As soon as the voltage at either  $V_{H1}$  or  $V_{H2}$  falls below 500mV, the LTC2995 flags an undervoltage condition by pulling the UV output pin low. Similarly, an overvoltage condition is indicated by pulling the OV pin low if either  $V_{L1}$  or  $V_{L2}$  rise above 500mV.

To prevent spurious resets due to noise on the monitored supply voltages, the LTC2995's lowpass filter causes the

To prevent spurious resets due to noise on the monitored supply voltages, the LTC2995's lowpass filter causes the output of the comparator to be integrated before asserting UV or OV. Any transient at the input of the comparator must be of sufficient magnitude and duration before the comparator triggers the output logic.

output of the comparator to be integrated before asserting UV or OV. Any transient at the input of the comparator must be of sufficient magnitude and duration before the comparator triggers the output logic. Furthermore, the LTC2995 has an adjustable timeout period ( $t_{UOTO}$ ) that holds UV and OV asserted after any faults have cleared. This delay minimizes the effect of input noise with a frequency above  $1/t_{UOTO}$ . The timeout period ( $t_{UOTO}$ ) is adjustable by connecting a capacitor,  $C_{TMR}$ , between the TMR pin and ground in order to accommodate a variety of applications.

The LTC2995 includes temperature measuring and monitoring features that provide more flexibility than the LTC2997 and LTC2996. While the latter devices always switch to external mode if an external diode is connected, requiring  $D^+$  to be connected to  $V_{CC}$  to measure the internal diode, the LTC2995 provides an additional diode select (DS) pin, allowing switching between the internal and an external diode on the fly. If the DS pin is left floating, the LTC2995 goes into "ping-pong" mode, where it alternates between

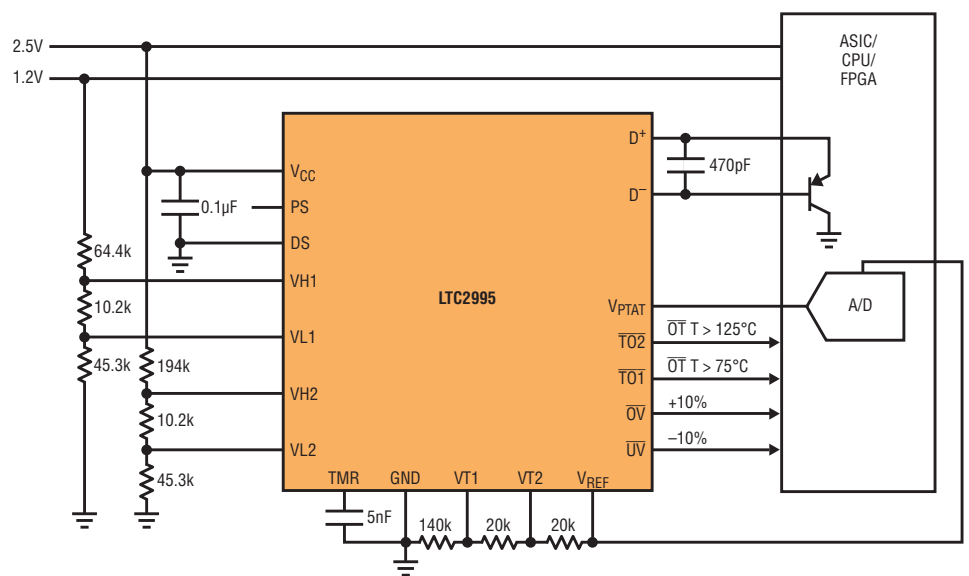
internal and external diode measurement with a period of about 20ms.

Finally, the LTC2995 can configure its two temperature thresholds both as overtemperature or both as undertemperature limits using the polarity select (PS) pin. This feature allows systems to react in levels to changes in temperature. As an example you might want to get a warning if the temperature rises above  $75^{\circ}\text{C}$  (e.g., to switch on a fan) and an alert if it increases above  $125^{\circ}\text{C}$  (e.g., to switch off the system) as depicted in Figure 12.

## CONCLUSION

Linear Technology's new family of accurate temperature sensors/monitors can use an internal or external diode as a sensor and produce analog outputs proportional to measured temperature. The family ranges from a tiny temperature sensor to a combined temperature and dual voltage supervisor that can signal out-of-range conditions. These devices make it easy to build analog temperature control loops or to monitor temperatures (and voltages) with minimum complexity. ■

Figure 12. Dual OV/UV  $\pm 10\%$  supply and  $75^{\circ}\text{C}/125^{\circ}\text{C}$  OT/OT remote temperature monitor



## If You Need Digital Output

The LTC2990 and the LTC2991 feature digital I<sup>2</sup>C output and control as well as voltage and current monitoring functions. For more information, go to [www.linear.com/2990](http://www.linear.com/2990) or [www.linear.com/2991](http://www.linear.com/2991).



# 2.7V to 40V Monolithic Buck-Boost DC/DC Expands Input Capabilities, Regulates Seamlessly through Automotive Cold-Crank and Load-Dump Transients

John Canfield

Handheld devices, industrial instruments and automotive electronics all demand power supply solutions that can support an expansive range of input voltages resulting from automotive input voltage transients, resistive line drops and a wide variety of power sources. As a further design challenge, applications often require a variety of regulated voltage rails, including some that fall within the input voltage range. The LTC3115-1 buck-boost DC/DC converter, with its wide 2.7V to 40V input and output voltage capability, high efficiency, small footprint and seamless transition between step-up and step-down modes of operation, easily meets the requirements of such applications.

For automotive electronics, the LTC3115-1 provides uninterrupted operation through load dump transients and even the harshest cold-crank conditions. Its programmable switching frequency optimizes efficiency and supports operation at 2MHz to ensure that switching noise and harmonics are located above the AM broadcast band. The LTC3115-1 employs a proprietary low noise PWM control algorithm that minimizes electromagnetic emissions over all operating conditions even during transitions between the step-up and step-down modes of operation and over the full range of load current. An internal phase-locked loop allows switching edges to be synchronized with an external clock for further control of EMI in noise-sensitive applications.

An accurate RUN pin provides a programmable input undervoltage lockout threshold with independent control of hysteresis. By consuming only 30µA of quiescent current in Burst Mode® operation and 3µA in shutdown, the LTC3115-1 reduces standby current drain on automobile batteries to negligible levels.

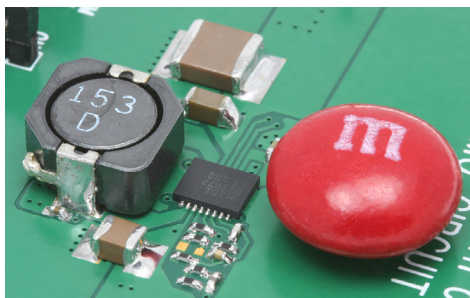


Figure 1. 5V regulator with wide 2.7V to 40V input range

The LTC3115-1 is also well suited for handheld devices, which are required to interface to an expanding array of power sources. While it was once common for portable devices to be powered by a dedicated AC adapter or a single power source, many must now be compatible with a variety of inputs including automotive, USB, Firewire and unregulated wall adapters. Next generation military radios and support electronics are an extreme example, requiring the capability to operate from all available power sources for emergency use and to minimize the number of battery varieties carried in the field.

Additionally, in an effort to reduce design overhead, many product families utilize a single power supply design that is shared across multiple versions of a product. This requires that the common power supply support the widest range of possible input voltages that will be seen by any device within the family. With its wide 2.7V to 40V input and output voltage ranges, internal power switches and high efficiency the LTC3115-1 has the features and flexibility required for these demanding applications.

## 5V, 2MHz MINIATURE SIZE AUTOMOTIVE SUPPLY

The proliferation of electronic subsystems in automobiles has created demand for small size, high reliability power supplies that can operate under the stringent conditions presented by the automotive environment. The LTC3115-1 is well suited for such applications given its ability to provide a stable well-regulated voltage over automotive operating conditions even when the battery voltage falls below the required output rail due to battery state of charge, line transients induced by switched high current loads and cold-cranking events.

Of commonly utilized power sources, the automotive supply rail presents one of the most challenging inputs to a power supply. Its nominal voltage varies from 10.6V to 15V depending on the state of charge of the battery, the ambient temperature and whether the alternator is charging or idle. Cold-crank conditions can push the rail below 4V and line transients can produce 40V spikes.

Figure 2 shows a 5V automotive supply ideal for use in engine control units and other critical functions including safety, fuel system and drive train subsystems where processors must remain powered without glitch during even the most severe input voltage transients. This application uses a 2MHz switching frequency to minimize its footprint and eliminate interference with the AM broadcast band.

The  $V_{CC}$  rail provides power to the internal circuitry of the LTC3115-1 including the power device gate drivers and is ordinarily powered from the input rail via an internal linear regulator. In this application, diode D1 bypasses the internal linear regulator and delivers power to the  $V_{CC}$  rail directly from the regulated output to improve efficiency and output current capability. This is particularly advantageous in applications with higher switching frequencies, given that the increased gate drive current is provided more efficiently from the converter's output rail than through the internal linear

regulator. Figure 3 shows the efficiency of this application circuit with a 500mA load for input voltages from 3.3V to 40V.

### RIDING THROUGH AUTOMOTIVE LOAD-DUMP AND INDUCTIVE LINE TRANSIENTS

Of commonly utilized power sources, the automotive supply rail presents one of the most challenging inputs to a power supply. Its nominal voltage varies from 10.6V to 15V depending on the state of charge of the battery, the ambient temperature and whether the alternator is charging or idle. In addition to the variability in its nominal voltage, the automotive power rail is also subject to a wide range of dynamic disturbances induced by changes in engine RPM, transitioning loads such as power windows, wipers and air conditioning, and inductive transients in the wiring harness.

However, the most extreme conditions occur during a load-dump transient which can produce voltages in excess of 120V for a duration of hundreds of milliseconds.

A load-dump transient occurs when the alternator is charging the vehicle's battery and an electrical open-circuit causes a momentary disconnection of the battery from the alternator. Until the voltage regulator can respond, the full alternator charging current is applied directly to the automotive power bus, raising its voltage to potentially dangerous levels. Such a transient could be caused through a physical disconnection of the battery by a mechanic working on the vehicle, but could also result from a faulty connection in the battery cable or corrosion at the battery terminals.

Automotive electronics must also be designed to survive a double-battery jump start, where they are subjected to 24V for extended durations as the vehicle is jump started using a series-connected second battery or from a commercial vehicle with a dual battery electrical system. An additional overvoltage condition on the automotive bus is caused by alternator voltage regulator failure and is often

Figure 2. A 5V, 2MHz automotive supply with cold-crank capability

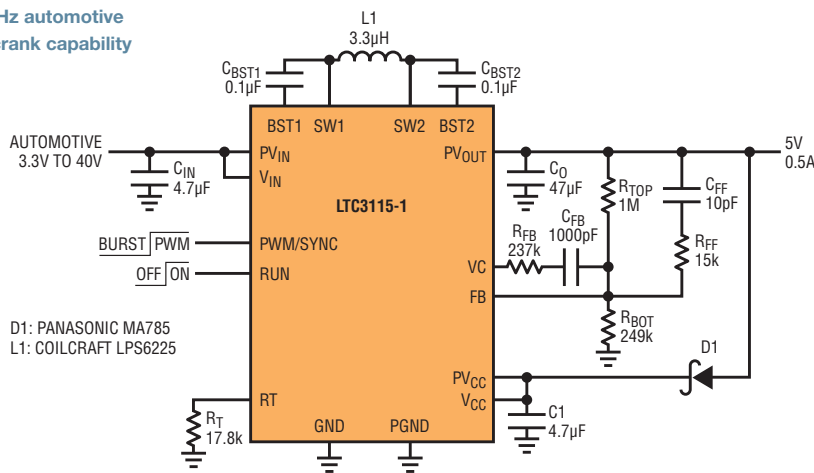
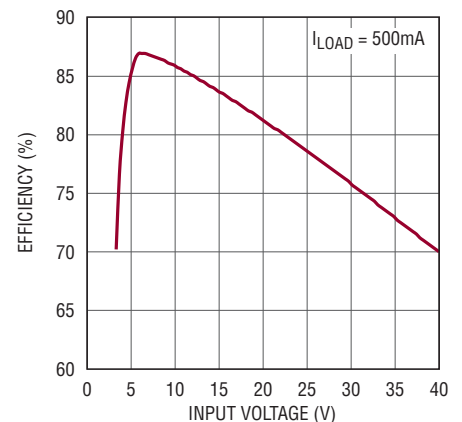


Figure 3. 5V, 2MHz automotive supply efficiency versus  $V_{IN}$



Typically, automotive electronics located downstream from passive protection networks must survive up to a 40V transient without damage. Critical systems must survive high level transients, and function seamlessly through such transients without interruption. The LTC3115-1 can maintain uninterrupted regulation of a 5V supply rail through a 13.8V-to-40V momentary line transient with 1ms rise and fall times.

included in the battery of tests conducted by automotive electronics OEMs. Such a malfunction can result in full application of the alternator charge current to the battery and an overvoltage of approximately 18V for extended durations.

The automotive power rail is also polluted with short duration overvoltage transients due to rapid load changes produced by switching high power loads such as power doors, fans and cooling fan motors interacting with the significant inductance in the vehicle's wiring harness.

In most vehicles a passive protection network consisting of a lowpass LC filter and transient voltage suppression (TVS) array is used as a first line of defense to clamp the peak excursions of the power bus. Typically, automotive electronics located downstream from the protection network must survive up to a 40V transient without damage. Critical systems must not only survive, but must also function seamlessly through such transients

without interruption. Figure 4 illustrates the ability of the LTC3115-1 to maintain uninterrupted regulation of a 5V supply rail through a 13.8V-to-40V momentary line transient with 1ms rise and fall times.

#### SEAMLESS OPERATION THROUGH AUTOMOTIVE COLD-CRANK TRANSIENTS

High voltage transients are a problem on the automotive power bus, but perhaps the more challenging problem is undervoltage transients. The most severe of these is known as cold crank, which occurs when the engine is initially started.

A typical cold-crank voltage waveform is shown in Figure 5. The initial low voltage plateau is the most extreme and is caused when the starter motor begins turning over the engine from a dead stop. During this phase, the vehicle's bus voltage can fall below 4V. Colder temperatures exacerbate the situation since the higher viscosity of the engine oil results in a higher required torque from the starter

motor. The first plateau is followed by a second somewhat higher voltage plateau, typically near half the nominal battery voltage, as the starter maintains the engine rotation. Once the engine starts, the battery recovers to its nominal voltage.

Safety devices and engine critical components such as the engine control unit and fuel injection system are required to remain operational throughout a cold-crank transient. As shown in Figure 5, the LTC3115-1's buck-boost architecture enables it to maintain output regulation through even the most severe cold-crank transients by automatically and seamlessly switching to boost mode operation during the undervoltage event.

Cold-crank capability for automotive electronics has expanded in importance as cars now include automated fuel-saving, on-demand engine start/stop, whereby the vehicle's engine is turned off during momentary vehicle stops at stoplights or in traffic. Vehicles equipped with on-demand starting are subjected to frequent cranking undervoltage events. As a result, auxiliary electrical components that previously had no need to function through the occasional cold-crank event in a traditional vehicle must now operate through such transients to eliminate any disturbance to infotainment, navigation, dashboard electronics and lighting systems.

Figure 4. A 13.8V to 40V load-dump line transient

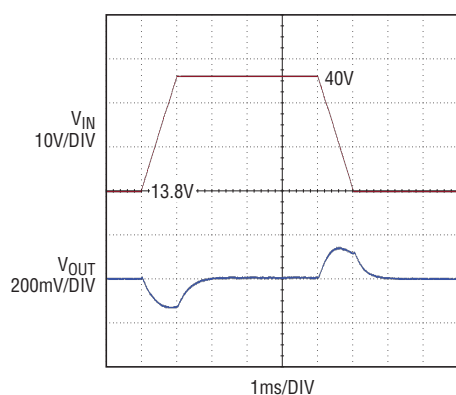
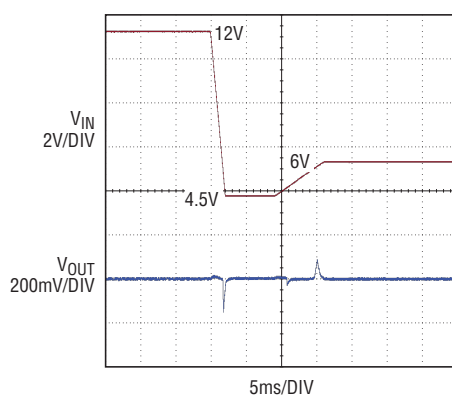


Figure 5. A 12V to 4.5V cold-crank line transient



The LTC3115-1's buck-boost architecture enables it to maintain output regulation through even the most severe cold-crank transients by automatically and seamlessly switching to boost mode operation during the undervoltage event.

### LOW EMI AND NO EMISSIONS IN THE AM BAND

The LTC3115-1 features a low noise forced PWM mode where both switch pins operate at constant frequency for all loads, producing a low noise spectrum, independent of operating conditions. The predictable spectrum and minimal subharmonic emissions help reduce interference and aid in compliance with strict automotive EMI standards.

The LTC3115-1 supports switching frequencies up to 2MHz so that the fundamental switching frequency component, and all of its harmonics, can be located above the AM frequency band to minimize interference with radio reception. Figure 6 shows the spectral emission of the LTC3115-1 over the AM band for the automotive application circuit of Figure 2 operating at no load and with a 500mA load. In both cases the entire range of frequencies

within the AM broadcast band is free from any significant spectral emission.

### HANDLING MULTIPLE POWER SOURCES – UNREGULATED WALL ADAPTER, AUTOMOTIVE INPUT, USB, USB-PD AND FIREWIRE

To increase flexibility and enhance the user's experience, many portable electronic devices are being designed to work from various power sources. These power sources can vary widely in voltage, especially when accounting for connector and cable drops.

Under USB 3.0, the nominal supplied voltage is  $5V \pm 5\%$ , but a fully compliant powered device must be able to operate down to 4V when accounting for allowable cable and connector voltage drops. In addition, a downstream USB power rail is permitted to drop as low as 3.67V under transient conditions such as when additional devices are plugged into the host or powered hub.

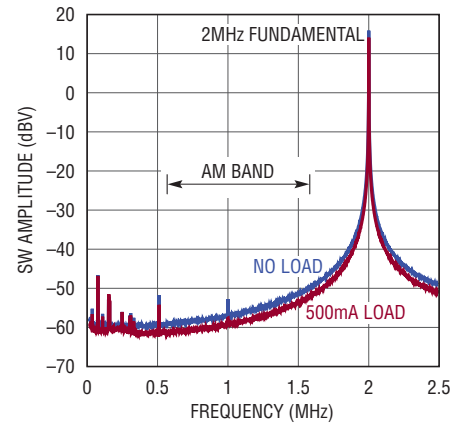


Figure 6. Fixed frequency low noise PWM minimizes emissions across the AM band

The newly approved USB PD (power delivery) specification allows for higher power delivery over USB with support for supply voltages up to 20V. Firewire ports deliver an unregulated power rail with a voltage that varies over a wide range, typically 9V to 26V depending on the class of the power provider.

Figure 7. For high efficiency, this dual input 5V supply uses a LTC4412 low loss PowerPath™ controller and a P-channel MOSFET in the battery path instead of a Schottky diode. An inexpensive Schottky diode is used on the higher voltage input where its voltage drop is insignificant.

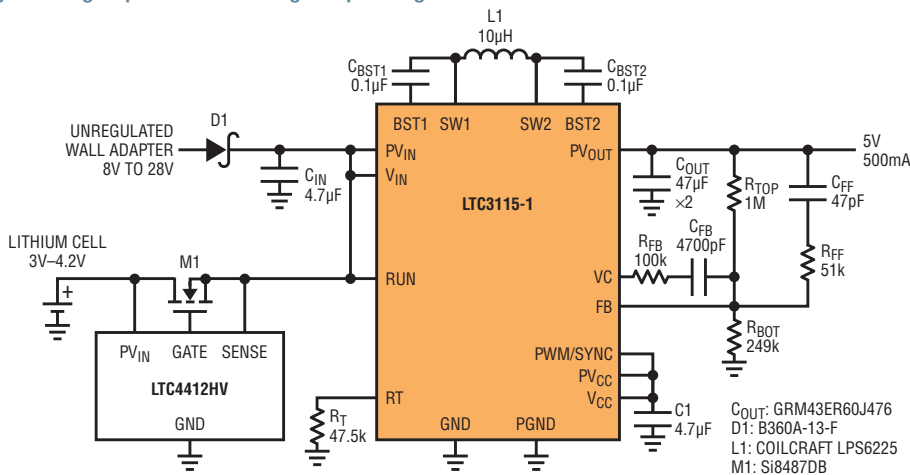
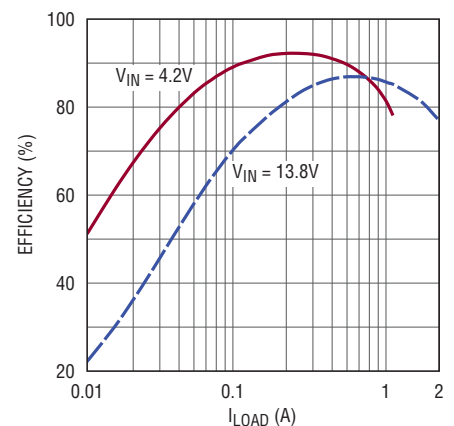


Figure 8. Overall efficiency of the PowerPath and LTC3115-1



The LTC3115-1 features a low noise forced PWM mode where both switch pins operate at constant frequency for all loads, producing a low noise spectrum independent of operating conditions. The predictable spectrum and minimal subharmonic emissions help reduce interference and aid in compliance with strict automotive EMI standards.

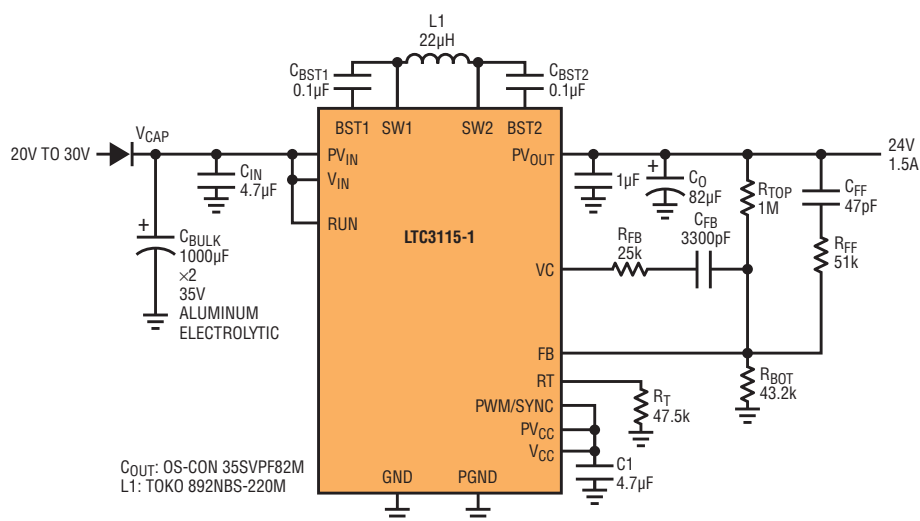


Figure 9. 24V industrial rail restorer with brownout ride-through

The ubiquitous wall adapter remains perhaps the most common source of power for portable devices. A typical wall adapter is simply a transformer followed by a bridge rectifier, offering no active regulation. That task is left to the end device to avoid the effects of cable drop. Unregulated wall adapters are designed to provide rated current at the specified typical output voltage. Being unregulated, the output voltage is a load line function, increasing substantially at lighter loads and decreasing under heavy load. In addition, the AC line voltage is permitted to vary between 105V and 125V, adding an additional 10% variability in the unregulated wall adapter's output. It is not uncommon for a 12V unregulated wall adapter to produce an output voltage of 17V or greater at light load.

The LTC3115-1 operates directly from all of these portable power sources as well

as from a variety of battery chemistries including lithium (single cell or series connected), sealed lead acid, three or more series alkaline cells and even a bank of supercapacitors for backup applications. Multiple power sources can be combined through a Schottky diode-OR circuit.

For higher efficiency, the LTC3115-1 can be combined with an ideal diode PowerPath controller to provide automatic switchover between multiple power sources using the low voltage drop of a power p-channel MOSFET to replace the Schottky diode. Figure 7 shows how the LTC3115-1 can be combined with the LTC4412HV to obtain a dual input—single lithium and unregulated wall adapter—5V supply. In this case, a series PMOS is used on the lower voltage lithium input while an inexpensive Schottky diode is used on the higher voltage input where its

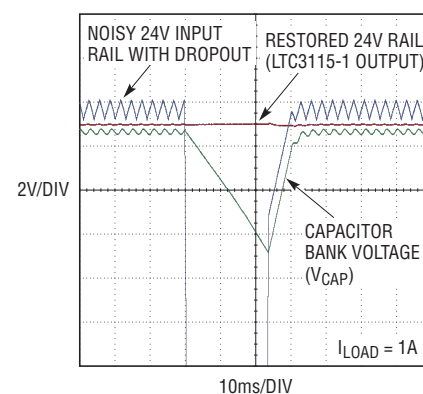


Figure 10. The LTC3115-1 regulates the output rail through input brownouts

voltage drop is insignificant. The overall efficiency of this supply including the converter and PowerPath is given in Figure 8 for each power input.

## 24V INDUSTRIAL RAIL RESTORER AND BACKUP

Industrial control and monitoring systems commonly utilize a 24V bus to power DIN mounted instrumentation such as programmable logic controllers, actuators and sensors. Being subject to high power switching loads and possible fault conditions, this bus can become corrupted with transients and momentary undervoltage transients. In severe cases there may even be momentary interruptions in bus power. Critical rail-powered systems are required to remain powered throughout such events to ensure control and monitoring of critical functions.

(continued on page 16)

# Monolithic Operational Amplifier Works from $\pm 4.75\text{V}$ to $\pm 70\text{V}$ and Features Rail-to-Rail Output Swing and Low Input Bias Current

Michael B. Anderson

Monolithic operational amplifiers have been around since the 1960s, but this ubiquitous device still sees steady improvements in performance. The LTC6090 precision monolithic operational amplifier takes a big step forward by extending the supply voltage to  $\pm 70\text{V}$  without compromising the features that are expected in a precision op amp. The LTC6090 is available in a small 8-lead SO package and a 16-lead TSSOP package. Both packages feature exposed pads to reduce thermal resistance, eliminating the need for a heat sink. An easy interface to low voltage control lines and built-in thermal safety features simplify the task of high voltage analog design.

## HIGH VOLTAGE AND HIGH PERFORMANCE

Operational amplifiers are expected to have low input bias current, low offset, and low noise. The LTC6090 is no exception. Designed with a MOS input stage the input bias current is typically  $3\text{pA}$  at  $25^\circ\text{C}$  and less than  $100\text{pA}$  at  $85^\circ\text{C}$ . This makes it well suited for high impedance applications such as a photodiode amplifier

shown in Figure 1. The low input offset voltage is less than  $1.6\text{mV}$ , and the noise is  $11\text{nV}/\sqrt{\text{Hz}}$  at  $10\text{kHz}$ . The input common mode range is to  $3\text{V}$  of either rail or a range of  $134\text{V}$  across a  $140\text{V}$  supply.

On the output side, precision op amps are expected to maintain precision when driving loads. Again, the LTC6090 does not disappoint. The unity gain stable output drive capability includes a  $10\text{MHz}$  GBW product,

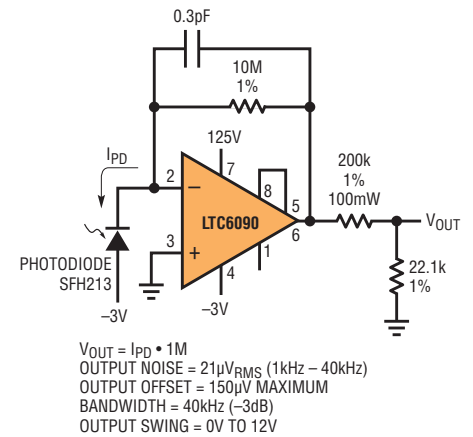


Figure 1. Extended dynamic range 1M transimpedance photodiode amplifier

fast slew rate and rail-to-rail output stage rated for  $\pm 10\text{mA}$  that can drive up to  $200\text{pF}$ . An example shown in Figure 2 is a  $140\text{V}_{\text{P-P}}$   $10\text{kHz}$  sine wave. Figure 3 shows the output swing is well maintained as load current is increased. And the fidelity of the output voltage at  $100\text{V}_{\text{P-P}}$  extends out to  $8\text{kHz}$  as shown in Figure 4.

Figure 2. LTC6090 output voltage  $140\text{V}_{\text{P-P}}$   $10\text{kHz}$  sine wave

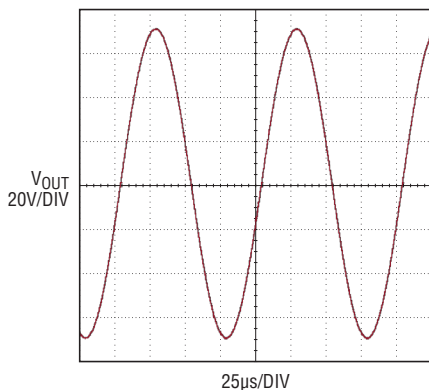


Figure 3. LTC6090 output voltage swing vs load current

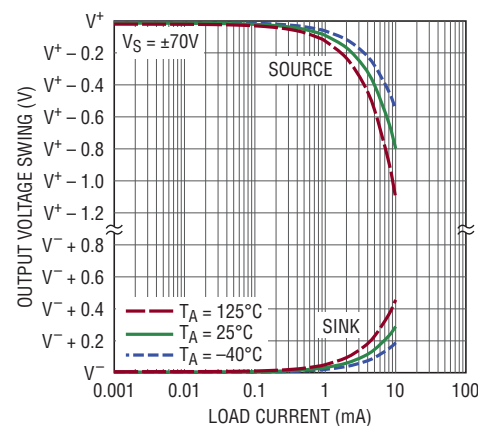
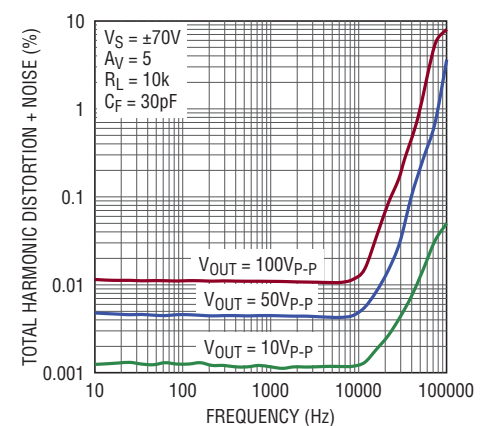


Figure 4. LTC6090 total harmonic distortion plus noise vs. frequency



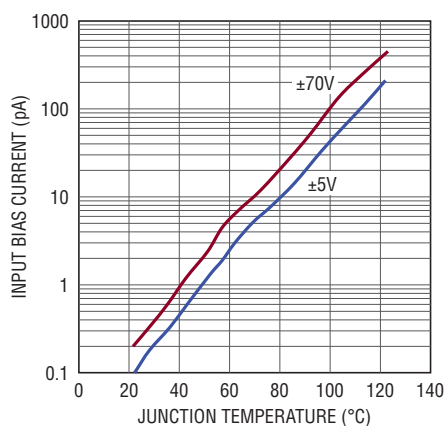
Operational amplifiers are expected to have low input bias current, low offset and low noise. The LTC6090 is no exception. Designed with a MOS input stage, the input bias current is typically 3pA at 25°C and less than 100pA at 85°C. This makes it well suited for high impedance applications.

### HIGH IMPEDANCE APPLICATIONS REQUIRE LOW LEAKAGE CIRCUITS

The low input bias current of the LTC6090 make it an excellent choice for high impedance applications that require high voltage. As shown in Figure 5, input bias current is logarithmically dependent on temperature, doubling for every 10°C increase. In addition, input protection devices sit in an isolated pocket where leakage increases as the voltage on the input pin increases with respect to  $v^-$ . In Figure 5 the input pin is held at mid-supply.

In order to maintain low input bias current, care should be taken during PCB layout. Special low leakage board material can be considered. In critical applications, consider using guard rings. The TSSOP package with exposed pad has guard ring pins that can be used to protect the input pins from leakage currents. An example PCB layout of an inverting amplifier is shown in Figure 6.

Figure 5. LTC6090 input bias current versus junction temperature

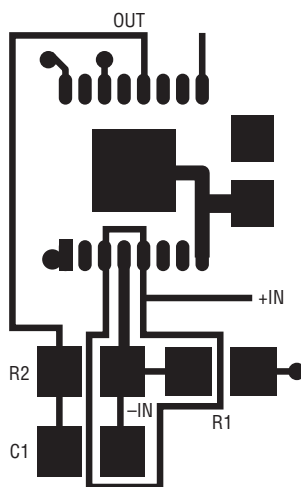


Note that the solder mask should be pulled back over the guard ring to expose the PCB metal. It is important that the PCB be clean and moisture free. Consider cleaning it with a solvent and rinsing any residue with tap water, then baking the board to remove any moisture. We have also found that thoroughly washing the board using soap and tap water (without solvent) yields good results.

### INTERFACING LOW VOLTAGE CONTROL LINES TO A HIGH VOLTAGE OP AMP

The low voltage control lines on the LTC6090 can be interfaced as low as the negative supply rail, or as high as 5V below the positive supply rail. The COM pin acts as a common to interface to the low voltage control lines, and can be connected to the low voltage system ground or left to float. The output disable, OD, and overtemperature, TFLAG, pins are now referred to the low voltage

Figure 6. PCB guard ring example layout

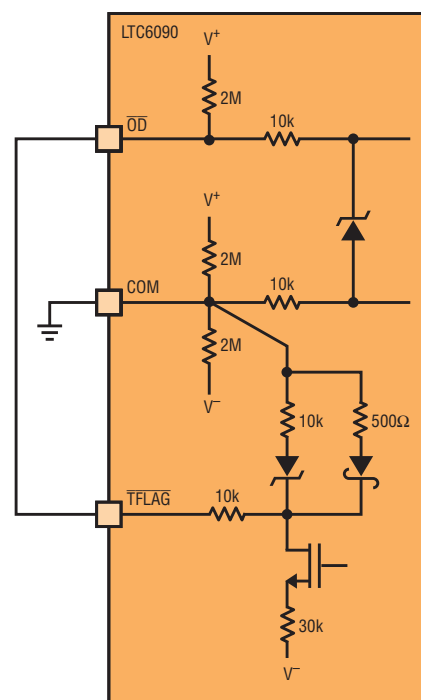


system ground. COM, OD and TFLAG pins are protected with diodes and resistors as shown in Figure 7. If left floating the COM pin will be pulled above mid-supply by the OD pin internal pull-up resistor to 21V when the supplies are  $\pm 70V$ .

### THERMAL PROTECTION: USE $\overline{OD}$ AND $\overline{TFLAG}$

At 140V total supply voltage and 2.7mA typical quiescent current, the LTC6090 consumes 378mW of power. Add a load and the power can exceed a watt, making good thermal design a priority. Both packages, the SO and TSSOP, feature an exposed pad on the bottom of the

Figure 7. The low voltage interface configured to automatically disable the output stage when the junction temperature of the die reaches 145°C



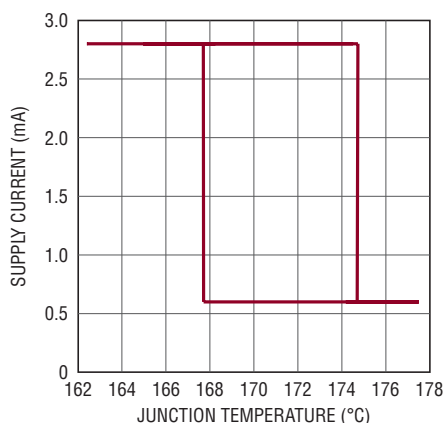
package, which is internally connected to the negative supply rail,  $v^-$ , and must be connected to the negative power plane. Connect as much PCB metal as practical to the exposed pad—the thermal resistance of the package is proportional to the amount of metal soldered to the exposed pad. In a best case scenario the thermal resistance,  $\theta_{JA}$ , of the SO package is  $33^{\circ}\text{C}/\text{W}$ . For  $1\text{W}$  of power, the junction temperature of the die increases  $33^{\circ}\text{C}$  above ambient temperature.

An important feature designed to protect the LTC6090 from exceeding  $150^{\circ}\text{C}$  junction temperature shuts down the output stage when the junction temperature gets too high. This is accomplished by connecting the overtemperature pin to the output disable pin. The overtemperature pin, or  $\overline{\text{TFLAG}}$  pin, is an open drain pin that pulls low when the junction temperature of the die reaches  $145^{\circ}\text{C}$ . The  $5^{\circ}\text{C}$  built-in hysteresis releases the  $\overline{\text{TFLAG}}$  pin when the junction temperature reaches  $140^{\circ}\text{C}$ . The output disable pin, or OD pin, is an active low pin that turns off the output stage and lowers the quiescent current

of the device to  $670\mu\text{A}$  when pulled low with respect to the COM pin. When these two pins are tied together, the LTC6090 is disabled if the junction temperature of the die reaches  $145^{\circ}\text{C}$ . Note that these pins can float and be tied together.

An additional thermal safety feature shuts off the output stage when the junction temperature of the die reaches approximately  $175^{\circ}\text{C}$ . The  $7^{\circ}\text{C}$  of hysteresis enables the output stage when it returns to approximately  $168^{\circ}\text{C}$  as shown

Figure 8. LTC6090 thermal shutdown hysteresis plot



in Figure 8. Note that Figure 8 shows the junction temperature. This feature is intended to prevent the device from thermal catastrophic failure. Operating the LTC6090 above its absolute maximum junction temperature of  $150^{\circ}\text{C}$  can reduce reliability and is discouraged.

## CONCLUSION

The LTC6090 features the high performance specs of a low voltage precision amplifier, but with the ability to work with  $\pm 70\text{V}$  for high voltage applications. These features include high gain, low input bias current, low offset and low noise for a precision front end. A rail-to-rail output stage can drive a  $200\text{pF}$  load capacitor and  $\pm 10\text{mA}$  of load current, making this part suitable for precision high voltage applications such as high impedance amplifiers. Easily interfaced control lines for disabling the output and a thermal shutdown function are simple to implement. Small 8-lead SO and 16-lead TSSOP packages both have exposed pads to reduce thermal resistance, eliminating the need for a heat sink. ■

(LTC3115-1 continued from page 13)

In addition, many devices must remain operating for a period of time after bus failure in order to initiate a controlled shutdown. The LTC3115-1 application shown in Figure 9 is a  $24\text{V}$  rail restorer application that maintains a clean and well-regulated  $24\text{V}$  output rail from a noisy input supply rail, which can fluctuate above and below the regulation target. In addition, as shown in the waveforms of Figure 10, this supply is able to maintain regulation of its  $24\text{V}$  output through momentary interruptions in bus power.

## CONCLUSION

The flexibility and high efficiency of the LTC3115-1 make it perfectly suited to meet the demanding needs of the next generation of automotive electronics and

portable devices, especially those operated from multiple power sources. Its internal power switches and programmable switching frequency minimize the power solution footprint, supporting the increasing demand for miniaturization of electronic devices in the portable and automotive arenas. Low Burst Mode operation and shutdown quiescent currents prolong battery life and facilitate use in always-active automotive applications.

The LTC3115-1 is ideal for noise-sensitive applications, given its low noise, fixed frequency PWM mode, which produces a predictable and well controlled EMI spectrum with switching edges that can be synchronized to a system clock. Internal soft-start minimizes inrush current during

start-up and an internal divider in the control path reduces the impact of input voltage variations, and makes the loop easier to compensate in applications with widely varying input voltages. A programmable input undervoltage lockout allows the input voltage at which the part is enabled to be set by the user, and provides for independent control of the hysteresis. The LTC3115-1 also features complete disconnect of the output from the input in shutdown, and is fully protected with output short-circuit protection and overtemperature shutdown. ■



# Bus Buffers Simplify Design of Large, Noisy I<sup>2</sup>C Systems

Rajesh Venugopal

The I<sup>2</sup>C bus and its derivatives—such as SMBus, PMBus, the DDC bus of HDMI and IPMB bus of ATCA—are used in a variety of large systems to transfer vital system information. These bus specifications have gained wide acceptance due to ease of use. The I<sup>2</sup>C bus is a digital serial 2-wire bus consisting of a single clock (SCL) and single data (SDA) line. The I<sup>2</sup>C protocol employs open drain pull-downs to drive the bus low, and resistors or current sources to pull the bus high. The maximum allowed pull-up current and bus capacitance are 4mA and 400pF, respectively.

The original I<sup>2</sup>C specification limited the maximum bus operating frequency to 100kHz; it is now 400kHz. As systems grew larger, bus buffers were introduced to buffer bus capacitance and solve several other common I<sup>2</sup>C issues. Early bus

buffers degraded certain I<sup>2</sup>C specifications in a manner that can be unacceptable in large noisy systems. The LTC4313 and LTC4315 family of bus buffers offers the benefits of traditional bus buffers while maintaining compliance to all I<sup>2</sup>C voltage

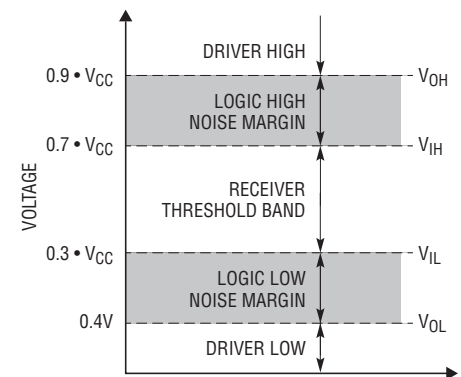


Figure 1. I<sup>2</sup>C bus voltage specifications and resulting noise margins

specifications. This makes it the preferred choice for use in large noisy systems.

Figure 1 shows the I<sup>2</sup>C specification requirements for logic high and logic

Table 1. A list of LTC4313 and LTC4315 features and benefits

FEATURE	BENEFITS
I <sup>2</sup> C Buffers	<ul style="list-style-type: none"> <li>Break up bus capacitance, which allows large I<sup>2</sup>C compliant systems to be built, by keeping the capacitance of each section &lt; 400pF</li> </ul>
High $V_{IL}$	<ul style="list-style-type: none"> <li>High logic-low noise margin up to <math>0.3 \cdot V_{CC}</math></li> <li>Operation with noncompliant I<sup>2</sup>C devices</li> </ul>
Automatic Buffer Turn-Off Voltage Adjustment	<ul style="list-style-type: none"> <li>Compatible with devices whose RTA turn-on voltage is lower than <math>0.3 \cdot V_{CC}</math></li> <li>Interoperable with other LTC buffers</li> </ul>
Level Translation	<ul style="list-style-type: none"> <li>Provides I<sup>2</sup>C communication between buses with voltages from 1.4V to 5.5V</li> </ul>
Rise Time Accelerators (RTAs)	<ul style="list-style-type: none"> <li>Reduce rise time</li> <li>Allow larger bus pull-up resistors for better logic low noise margin</li> <li>Selectable RTA pull-up current strength</li> </ul>
Disconnection and Recovery from Stuck Bus	<ul style="list-style-type: none"> <li>Free masters to resume upstream communications</li> <li>Generates up to 16 clock pulses and a stop bit on the stuck buses to get the bus to release high</li> </ul>
Fall Time Control	<ul style="list-style-type: none"> <li>Minimizes transmission line effects in systems</li> </ul>
Hot Swapping	<ul style="list-style-type: none"> <li>Waits for bus idle or stop bit before making a connection</li> <li>Precharges bus to minimize disturbance</li> </ul>

The LTC4315 and LTC4313 are high noise margin bus buffers that solve a number of problems associated with large I<sup>2</sup>C systems. They provide capacitance buffering, level translation for bus supplies ranging from 1.4V to 5.5V, high logic-low noise margins up to  $0.3 \cdot V_{CC}$  and reject noise above  $0.3 \cdot V_{CC}$  when the bus is a logic high.

low voltages on the bus. For I<sup>2</sup>C compliance, driven logic low signals must be below an output low level ( $V_{OL}$ ) of 0.4V. Logic high signals require the bus to be pulled up above an output high level ( $V_{OH}$ ) of  $0.9 \cdot V_{CC}$ , where  $V_{CC}$  is the bus supply voltage. I<sup>2</sup>C compliant receivers must interpret any voltage below an input low level ( $V_{IL}$ ) of  $0.3 \cdot V_{CC}$  as a logic low and any voltage above an input high level ( $V_{IH}$ ) of  $0.7 \cdot V_{CC}$  as a logic high. These requirements yield a logic low noise margin of  $0.3 \cdot V_{CC} - 0.4V$  and a logic high noise margin of  $0.2 \cdot V_{CC}$ .

Over time, as systems grew larger, bus capacitances increased well beyond 400pF. Bus buffers were introduced to break the large I<sup>2</sup>C bus into smaller segments and to drive the capacitance associated with each segment.

A higher operating frequency coupled with increasing bus capacitance also required a decrease in signal rise times. Rise time accelerators (RTAs) were incorporated into the bus buffers to reduce bus rise times—by sourcing strong pull-up currents into the bus during these transitions.

In addition, bus buffer products offered by Linear Technology also incorporated several additional features like SDA, SCL Hot Swap, precharge and stuck bus recovery to improve robustness of I<sup>2</sup>C systems and voltage level translation to ease communication across voltage domains.

The downside of buffer and RTA insertion into a bidirectional I<sup>2</sup>C bus is the introduction of

deviations from the I<sup>2</sup>C specification. There are three reasons for this:

- First, buffers require a scheme to differentiate an externally driven logic low from their own driven low. This is required to prevent locking the bus into a permanent low state. As a result, some buffers drive  $V_{OLs}$  above the 0.4V I<sup>2</sup>C specification and require all other devices to drive below 0.4V. Others drive an output  $V_{OL}$  that is a small offset higher than the driven input  $V_{OL}$ .
- Second, to maximize RTA operating range, Linear Technology bus buffers turn off their pull-down devices and turn on their RTAs at voltages slightly higher than the I<sup>2</sup>C  $V_{OL}$ .
- Third, all buffers capacitively load the bus when they are active and need to be turned off at as low a voltage as possible in order to reduce bus rise time.

As a result, most existing bus buffers detect a logic low only if the bus voltage is  $< 0.6V$ . Most buffers turn on their RTAs at 0.8V. Some buffers drive a noncompliant  $V_{OL} > 0.4V$ . All these result in reducing the logic low

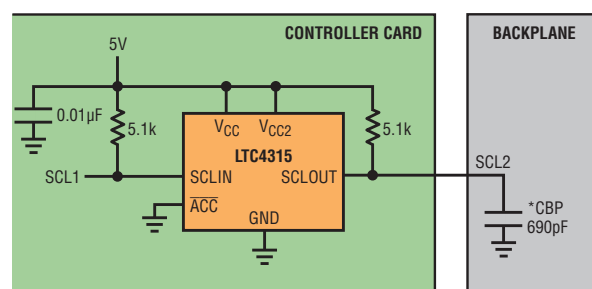
noise margin from  $(0.3 \cdot V_{CC} - 0.4V)$  to 0.2V or even lower, and slowing the bus rising edge by the capacitive load of the buffers when they are active.

As systems grew, the compressed logic low noise margin of existing buffers increased the bus' susceptibility to noise. Typically larger systems require a bus buffer that restores logic low noise margin to the I<sup>2</sup>C specification, namely a fast buffer that is active until the bus voltage crosses the  $V_{IL}$  value of  $0.3 \cdot V_{CC}$  and does not load the bus.

An additional requirement in large systems is backward compatibility with buffer products whose RTAs turn on below  $0.3 \cdot V_{CC}$  or with products that drive a noncompliant  $V_{OL}$  of 0.6V. An adjustable RTA current is also advantageous, especially in large systems where multiple RTAs can be activated simultaneously. Large RTA currents result in sharp edges and raise concerns about unwanted effects like inductive ringing and EMI.

The LTC4315 (12-pin) and the LTC4313 (8-pin) parts specifically solve these problems while retaining the beneficial features of other Linear Technology bus buffer

**Figure 2. The LTC4315 driving the parasitic backplane capacitance in a large system. Only the SCL pathway is shown for simplicity.**



\*LARGE PARASITIC BACKPLANE CAPACITANCE

In extended I<sup>2</sup>C systems, long PCB traces and large backplanes with long cables generate large parasitic bus capacitances. The LTC4315's high noise margin buffers can drive these capacitances without degrading signal integrity or reducing operating frequency.

products. Table 1 lists the key features of these products. This document references the LTC4315, but all text applies to the LTC4313 as well, unless otherwise noted. The LTC4315 has a high  $0.3 \cdot V_{CC}$  guaranteed minimum  $V_{IL}$ , ensuring a high logic-low noise margin. The LTC4315 is interoperable with devices that drive a high  $V_{OL} > 0.4V$  and with products whose RTAs turn on at voltages below  $0.3 \cdot V_{CC}$ . The LTC4315 allows user selection of the RTA current level in order to control bus rise rates. The LTC4315 retains capacitance buffering, Hot Swap, precharge, stuck bus recovery and level translation features of other Linear Technology bus buffers. Since its buffers do not load the bus, the LTC4315 is capable of operation up to 1MHz and is compatible with the I<sup>2</sup>C standard mode and fast mode, SMBus and PMBus specifications. In summary, LTC4315 provides all the benefits of the existing buffers without compromising any I<sup>2</sup>C specification.

### CAPACITANCE BUFFERING AND NOISE REJECTION IN LARGE SYSTEMS

In large I<sup>2</sup>C systems, long PCB traces and large backplanes with long cables cause large parasitic bus capacitances. As shown in Figure 2, the LTC4315's high noise margin buffers can drive these large capacitances without degrading signal integrity or reducing operating frequency.

Another issue of large I<sup>2</sup>C systems, like the one in Figure 2, is noise susceptibility. Noise and signal coupling in the cable and between PCB traces can disrupt input and output clock and data signals, causing system level failures. A particularly

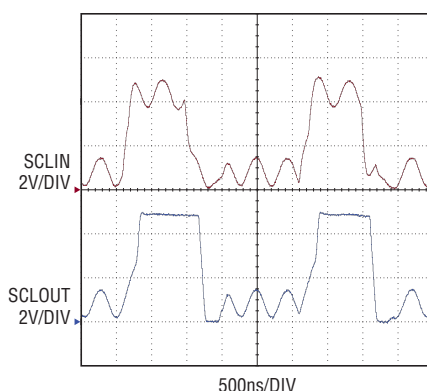


Figure 3. The LTC4315 transmits a clean logic high at SCLOUT even when a noisy 400kHz I<sup>2</sup>C signal is applied to SCLIN.

extreme example of a noisy SCL waveform is shown in Figure 3 to illustrate the robust noise rejection the LTC4315 features.

Figure 3 shows the LTC4315's handling of sinusoidal noise superimposed on a 400kHz square wave at its input. The noise applied to the logic high state is not propagated to the other side as long as that bus voltage does not drop below  $0.33 \cdot V_{MIN}$ . The logic high state of SCLOUT is not affected by noise on SCLIN.

For the LTC4315, logic high noise margin is

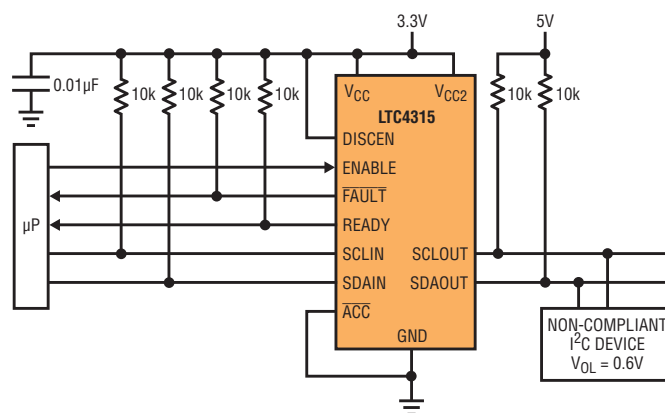
$V_{OH} - 0.33 \cdot V_{MIN}$ , where  $V_{MIN}$  is the lower of the  $V_{CC}$  and  $V_{CC2}$  voltages. For all versions of the LTC4313,  $V_{MIN}$  defaults to  $V_{CC}$ .

In Figure 3, when the SCLIN voltage drops below  $0.33 \cdot V_{MIN}$ , SCLOUT tracks SCLIN. No output glitches occur as the input crosses the  $V_{IL}$  level of  $0.33 \cdot V_{MIN}$ . Assuming a worst-case DC  $V_{OL}$  of 0.4V on the bus, the LTC4315's logic low noise margin is  $0.33 \cdot V_{MIN} - 0.4V = 1.25V$ . These noise suppression features make the LTC4315 a solid choice for large, noisy I<sup>2</sup>C systems. Ideally, system designers of large, noisy I<sup>2</sup>C systems should use LTC4315s on all boards for maximum noise immunity.

### OPERATION WITH NON-COMPLIANT I<sup>2</sup>C DEVICES

Figure 4 shows the LTC4315's compatibility with devices that drive non-compliant  $V_{OL}$ s—in this case 0.6V. The LTC4315 passes the 0.6V to the microprocessor where it is interpreted as a logic low. The high buffer turn-off voltage of the LTC4315—1.089V in this circuit—yields a logic low noise margin of 489mV.

Figure 4. The LTC4315 communicating with a noncompliant I<sup>2</sup>C device.



The LTC4315 detects RTA current from other devices and turns off its buffers to prevent contention between its buffers and other RTAs. This permits the LTC4315 to be interoperable with any combination of all older Linear Technology bus buffers, whose RTAs turn on at voltages  $< 0.3 \cdot V_{CC}$ .

### INTEROPERABILITY WITH OTHER LINEAR TECHNOLOGY BUFFERS

In large systems older Linear Technology buffers might be present on the same bus with the LTC4315. These older buffers may have RTAs that turn on at voltages below the LTC4315 buffer turn-off voltage of  $0.3 \cdot V_{CC}$ . Glitch-free operation under these circumstances is critical for system integrity. The LTC4315 detects RTA current from other devices at bus voltages below  $0.3 \cdot V_{CC}$  and turns off its buffers to prevent contention between its buffers and other RTAs, to facilitate interoperability.

Figure 5 shows the LTC4315 operating in a dynamic system that changes as cards are plugged into or out of the backplane. For simplicity, a single 3.3V supply is chosen and only the SCL pathway is shown. Cards have buffers at their edges in order to shield the I<sup>2</sup>C devices on the card from the large backplane capacitance and to keep the card capacitances isolated from each other and to aid in hot swapping. The cards in the

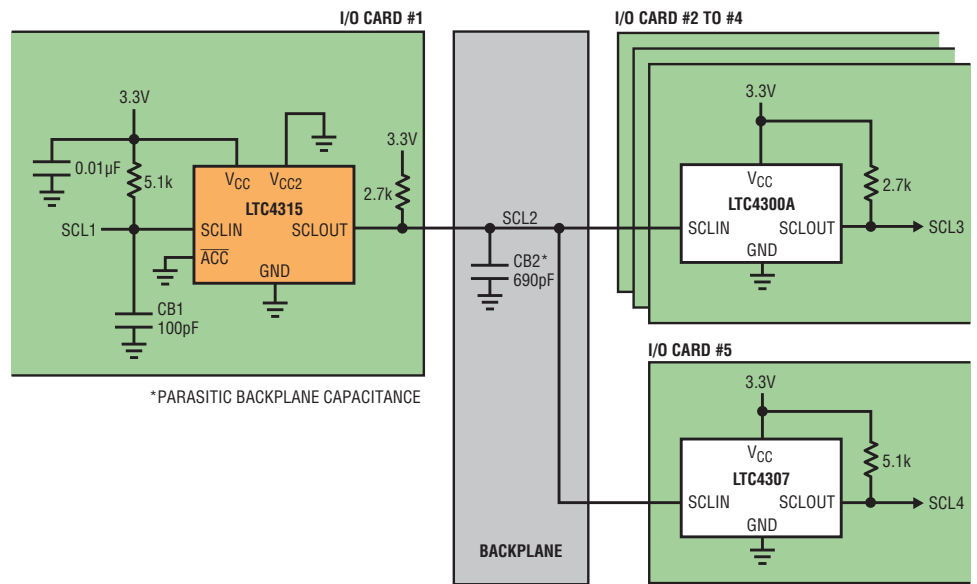


Figure 5. The LTC4315 operating with multiple LTC4300As and LTC4307s in a cascaded application.

application shown have LTC4300A or LTC4307 buffers on their edges. The RTAs of these products turn on at 0.6V and 0.8V, respectively, while the LTC4315's buffers turn off at  $0.3 \cdot V_{CC}$  (~1V).

Figures 6–9 track backplane and card SCL waveforms in this system as its configuration changes. Figure 6 shows the SCL waveforms for the system configuration shown in Figure 5, where three LTC4300As and one LTC4307 operate with one LTC4315. In Figure 7, the LTC4307 is

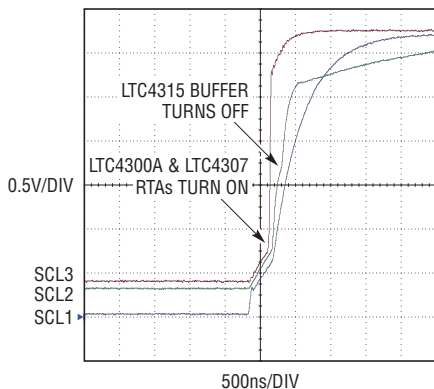


Figure 6. SCL waveforms of one LTC4315 operating with three LTC4300As and one LTC4307.

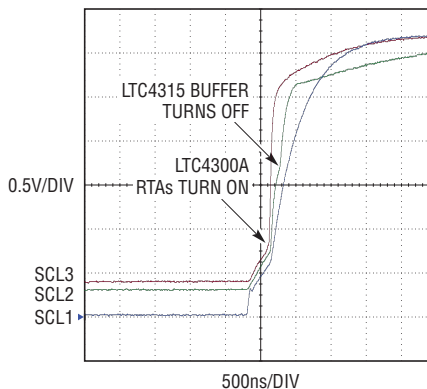


Figure 7. SCL waveforms of one LTC4315 operating with three LTC4300As.

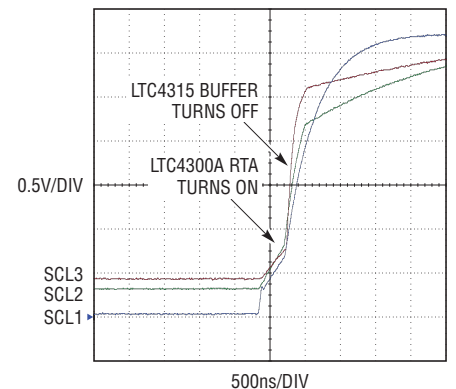


Figure 8. SCL waveforms of one LTC4315 operating with one LTC4300A.

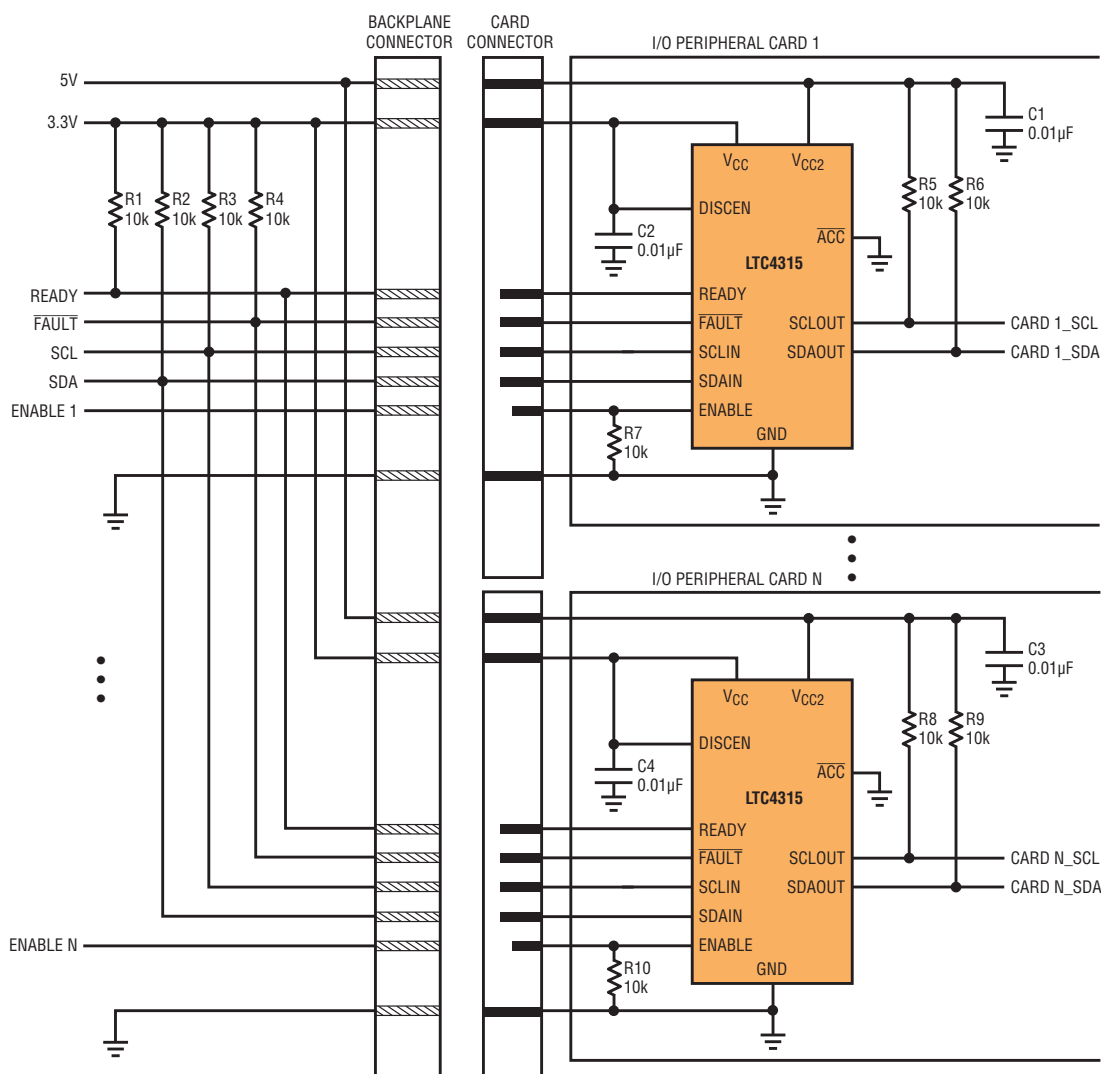


Figure 10. The LTC4315 in an I<sup>2</sup>C Hot Swap application with staggered pin lengths in the connector.

swapped out, leaving three LTC4300As and one LTC4315. In Figure 8, two more LTC4300As are swapped out, leaving one

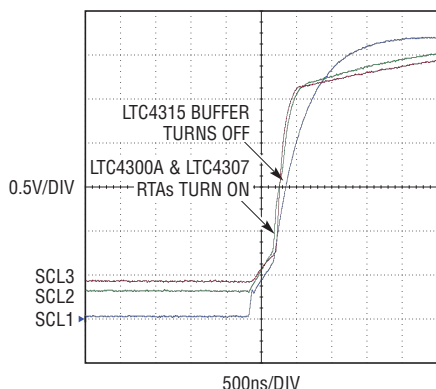


Figure 9. SCL waveforms of one LTC4315 operating with one LTC4300A and one LTC4307.

LTC4315 and one LTC4300A. Finally in Figure 9, the LTC4307 is reconnected, making the system one LTC4307, one LTC4300A and one LTC4315. The SCL waveforms remain monotonic during the entire sequence of events due to the automatic adjustment of the LTC4315 buffer turn-off voltage in response to varying amounts of LTC4300A and LTC4307 RTA current.

Figures 6–9 illustrate the interoperability of the LTC4315 with various combinations of LTC4300As and LTC4307s in a moderately complex system. As a general rule, the LTC4315 is interoperable with any number or combination of older Linear Technology buffers. Nevertheless, given

the varying number and variety of buffers that can interact with each other, interoperability cannot be tested and hence guaranteed under all circumstances. Useful guidelines on card capacitances, bus pull-up resistances and buffer combinations to ensure interoperability in large systems are provided in the LTC4315 data sheet.

### HOT SWAP AND CAPACITANCE BUFFERING

I/O cards with LTC4315s on their edges can be hot swapped into a live backplane as shown in Figure 10. The corresponding waveforms are shown in Figure 11. Communication at the backplane end is not disrupted during hot plug because

Circuits on a card that has an LTC4315 on its edge drive only the  $< 10\text{pF}$  input capacitance of the LTC4315. The LTC4315 drives the large combined capacitance of backplane and all the cards that plug into it. The LTC4315 can drive up to  $1.2\text{nF}$  of capacitance on its SDA and SCL pins. This capacitance buffering feature, combined with RTAs, permits  $400\text{kHz}$  operation in large systems.

the LTC4315's small input capacitance causes minimal disturbance during connection to the backplane. Furthermore the LTC4315 precharges its clock and data lines to  $1\text{V}$  before they contact the backplane, minimizing the voltage step on the backplane bus. The LTC4315 waits for a stop bit or bus idle condition to enable its buffers, ensuring that a partial message is not transmitted across its buffers. When hot plugging into a live backplane, a staggered connector should be used. Make ENABLE the shortest pin with a pull-down resistor to GND on the card,  $V_{CC}$  and GND the longest pins and SCL and SDA medium length pins. This ensures that the part is powered up and SDA and SCL pins are precharged to  $1\text{V}$ , before they connect to the backplane. Holding ENABLE low during this period ensures correct operation of the stop bit and bus idle circuitry and allows any transients associated with card insertion to settle before the LTC4315 is activated.

Figure 11 shows waveforms when the LTC4315 is hot plugged into a live backplane using a staggered connector.  $V_{CC}$  and

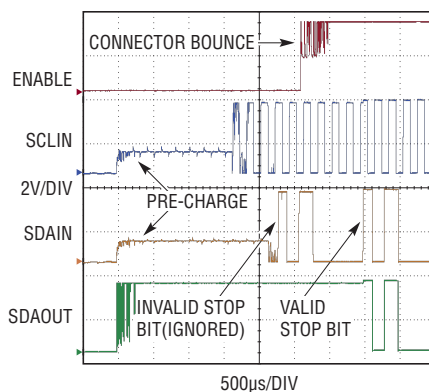


Figure 11. Waveforms during an LTC4315 Hot Swap event into a live backplane using a staggered connector.

$V_{CC2}$ , as the longest pins, have already contacted the backplane and are powering the LTC4315 and the output buses. At this time SDAIN and SCLIN are precharged to  $1\text{V}$  by the LTC4315. Once SDAIN and SCLIN contact the backplane, they are driven by backplane circuitry. Stop bits at the input are ignored by the LTC4315 as ENABLE is low. The outputs of the LTC4315 idle high (SCLOUT not shown), until a stop bit is detected at the input after ENABLE has been asserted high and is stable. The LTC4315

buffers turn on at this time and establish a connection between the input and output. Partial messages are not propagated across the LTC4315. If a staggered connector is not used, ENABLE should be held low until all transients associated with card insertion into a live system die out.

Circuits on a card that has an LTC4315 on its edge drive only the  $< 10\text{pF}$  input capacitance of the LTC4315. The LTC4315 drives the large combined capacitance of the backplane and all the cards that plug into it. The LTC4315 can drive up to  $1.2\text{nF}$  of capacitance on its SDA and SCL pins. This capacitance buffering feature, combined with RTAs, permits  $400\text{kHz}$  operation in large systems.

### RISE TIME ACCELERATORS

The RTAs of the LTC4315 can be configured either in the current source mode ( $\overline{\text{ACC}}$  open), slew limited switch mode ( $\overline{\text{ACC}}$  grounded) or disabled ( $\overline{\text{ACC}}$  high). In the current source mode the RTAs source a constant  $2.5\text{mA}$  current into the bus. In the slew controlled switch mode, the RTAs turn on in a controlled manner and source current into the buses, making them rise at a typical rate of  $40\text{V}/\mu\text{s}$ . To selectively disable RTAs only on the outputs, ground  $V_{CC2}$  and either ground  $\overline{\text{ACC}}$  or leave  $\overline{\text{ACC}}$  open. The LTC4313 comes with 3 different versions of RTAs. The LTC4313-1 RTAs are slew controlled switches, the LTC4313-2 RTAs are  $2.5\text{mA}$  current sources and the LTC4313-3 has no RTAs.

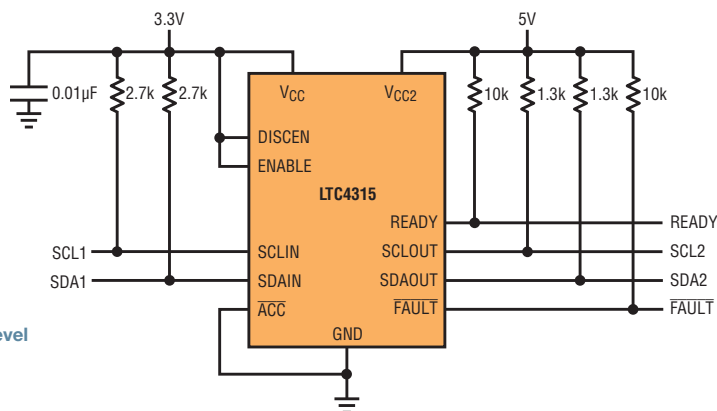


Figure 12. The LTC4315 in a level translating application.

The LTC4315 and LTC4313 disconnect stuck buses and allow I/O cards to be hot swapped into and out of live systems. They level translate signals down to 1.4V and provide user-selectable RTA current that permits operation at frequencies up to 1MHz.

### LEVEL TRANSLATION

The circuit shown in Figure 12 illustrates the level translation feature of the LTC4315. The operating ranges for the LTC4315 supplies are  $V_{CC}$  from 2.9V–5.5V and  $V_{CC2}$  from 2.25V–5.5V. Tying the input bus to  $V_{CC}$  and the output bus to  $V_{CC2}$  permits level translation between 2.9V–5.5V inputs and 2.25V–5.5V outputs.

The example shown in Figure 12 translates a 3.3V input to a 5V output. Level translation to voltages lower than the minimum allowed  $V_{CC}$  and  $V_{CC2}$  values imposes other constraints. Level translation to output voltages less than 2.25V requires  $V_{CC2}$  to be tied low to disable output RTAs. Level translation to input voltages less than 2.9V requires all RTAs to be disabled by tying ACC high for the LTC4315 or using the LTC4313-3. This prevents overdriving of the input bus by the RTA. Under these conditions, level translation to a bus voltage of 1.4V is possible. The buffer turn-off voltage in both cases is  $0.3 \cdot V_{CC}$  and a high logic-low noise margin is maintained.

### STUCK BUS DETECTION AND RECOVERY

Occasionally, slave devices get confused and get stuck in a low state. The LTC4315 monitors the output I<sup>2</sup>C bus to see if clock and data have been simultaneously high at least once in 45ms. If this condition is not detected, the LTC4315 asserts the FAULT flag low.

If DISCEN is tied high, the LTC4315 also disconnects the input and output sides and generates clock pulses on SCLOUT in an attempt to free the stuck bus. Clocking

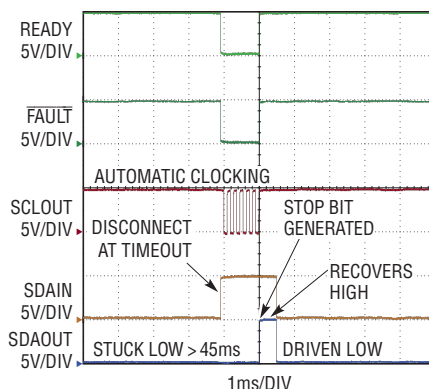


Figure 13. Bus waveforms during an SDAOUT stuck low and recovery event.

is stopped when data releases high or 16 clocks have been generated. After the final clock pulse, a stop bit is generated to reset the bus for further communication. When a stuck bus releases high, connection is reestablished when a stop bit or bus idle condition is detected on both buses. No user intervention is required.

Figure 13 shows the waveforms during an SDAOUT stuck low and recovery event with DISCEN tied high. In Figure 13, the FAULT flag is asserted low after the 45ms timeout period and the input and output sides are disconnected. This causes SDAIN to release high. Clock pulses are generated on SCLOUT. SDAOUT releases high before 16 clock pulses have been generated. Clock pulsing is stopped and a stop bit is generated. As SDAOUT recovers and a stop bit is detected, connection is reestablished and signals propagate from the input to the output. If SDAOUT stays low, an input to output connection can be forced by toggling ENABLE low, then high.

If automatic stuck bus disconnection is not desired, this feature can be disabled in the LTC4315 by tying DISCEN low. In this case, during a stuck bus event, the FAULT flag is asserted low, but no stop bit or clock generation occurs and the input and output sides stay connected. Stuck bus disconnection and output clocking cannot be disabled in the LTC4313.

### CONCLUSION

The LTC4315 and LTC4313 are high noise margin bus buffers that solve a number of problems associated with large I<sup>2</sup>C systems. They provide capacitance buffering, level translation for bus supplies ranging from 1.4V to 5.5V, high logic-low noise margins up to  $0.3 \cdot V_{CC}$  and reject noise above  $0.3 \cdot V_{CC}$  when the bus is a logic high. Their high bandwidth buffers and integrated RTAs enable operation at frequencies up to 1MHz. The buffers can drive noncompliant buses with parasitic capacitance as large as 1.2nF. They disconnect stuck buses and allow I/O cards to be hot swapped into and out of live systems. These buffers are interoperable with noncompliant I<sup>2</sup>C devices that drive a high  $V_{OL}$  and with legacy buffers whose RTAs turn on at low voltages. The LTC4315 and LTC4313 ease practical design issues associated with large I<sup>2</sup>C bus systems. ■

# Ideal Diode and Hot Swap Controller Enables Supply Redundancy and Isolates Faults

Chew Lye Huat

Schottky diodes are used in a variety of ways to implement multisource power systems. For instance, high availability electronic systems—such as  $\mu$ TCA network and storage servers—employ power Schottky diode-OR circuits in redundant power systems. Diode ORing is also used in systems with alternate power sources, such as an AC wall adapter and a backup battery feed. The problem is that the Schottky diodes consume power due to the forward voltage drop—the resulting heat must be dissipated with dedicated copper area on the PCB, or by heat sinks bolted to the diode, both of which require significant space.

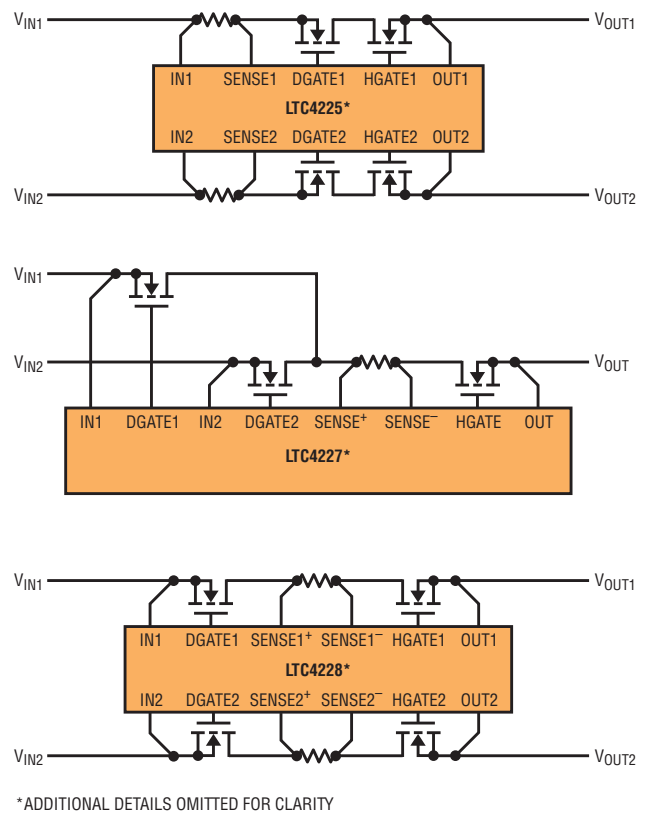
The family of products comprising the LTC4225, LTC4227 and LTC4228 minimize power loss by using external N-channel MOSFETs for pass elements, minimizing the voltage drop from the supply to the load when the MOSFETs are turned on. When an input source voltage drops below the output common supply voltage, the appropriate MOSFET is turned off, thereby matching the function and performance of an ideal diode.

As shown in Figure 1, by adding a current sense resistor and configuring two MOSFETs back-to-back with separate gate control, the LTC4225 enhances the ideal diode performance with inrush current limiting and overcurrent protection. This allows the boards to be safely inserted and removed from a live backplane without damaging the connector. The LTC4227 can be used with the current sense resistor and the Hot Swap MOSFET added

Figure 1. An overview of different configurations with sense resistor and external N-channel MOSFETs for the LTC4225, LTC4227 and LTC4228

after the parallel-connected ideal diode MOSFET to save one MOSFET. By configuring the sense resistor between the ideal diode and Hot Swap MOSFET, the LTC4228 improves on the LTC4225 by recovering more quickly from input brownouts to preserve the output voltage.

The LTC4225-1, LTC4227-1 and LTC4228-1 feature a latching circuit breaker, while the LTC4225-2, LTC4227-2 and LTC4228-2 provide automatic retry after a fault. Both options are available in 24-pin, 20-pin and 28-pin 4mm  $\times$  5mm QFN and SSOP packages for LTC4225, LTC4227 and LTC4228, respectively.



## IDEAL DIODE CONTROL

The LTC4225 and LTC4228 function as an ideal diode by monitoring the voltage between IN and OUT pins (IN and SENSE<sup>+</sup> pins for LTC4227) with an internal gate drive amplifier, which drives the DGATE pin. The amplifier quickly pulls up the DGATE pin, turning on the MOSFET for ideal diode control, when it senses a large forward voltage drop (Figure 2).

An external capacitor connected between the CPO and IN pins provides the charge needed to quickly turn on the ideal diode MOSFET. An internal charge pump charges up this capacitor at device power-up.



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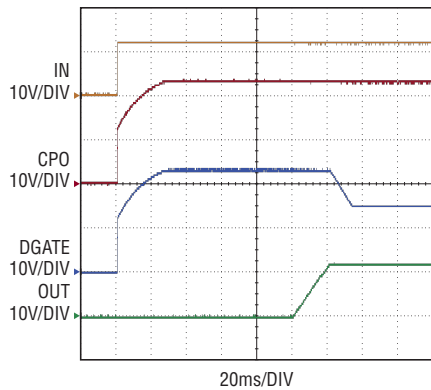


Figure 2. Ideal diode controller CPO and DGATE pull up when IN supply turns on

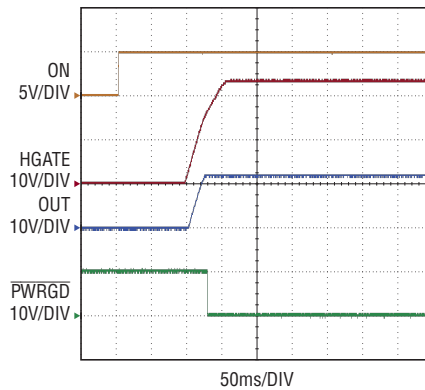


Figure 3. Hot Swap controller HGATE starts up and PWRGD pulls low after 100ms delay when ON toggles high

The DGATE pin sources current from the CPO pin and sinks current into the IN and GND pins. The gate drive amplifier controls DGATE to servo the forward voltage

drop across the sense resistor and the two external N-channel MOSFETs to 25mV.

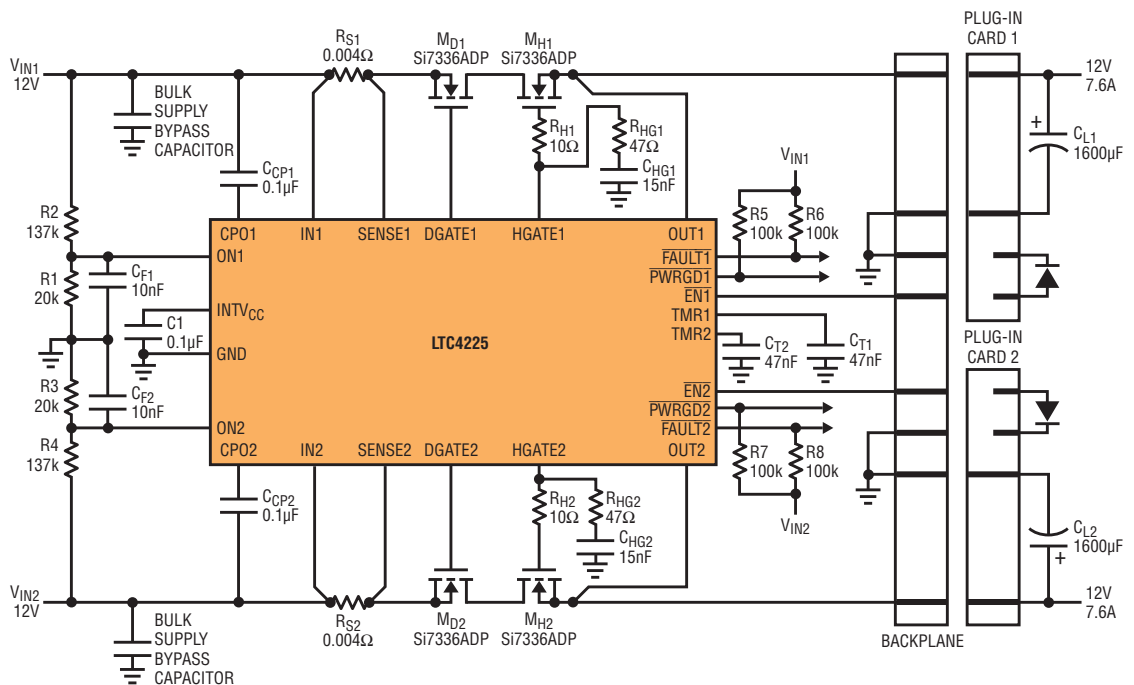
If the load current causes more than 25mV of voltage drop, the gate voltage

rises to enhance the MOSFET used for ideal diode control. In the case of an input supply short-circuit when the MOSFETs are conducting, a large reverse current starts flowing from the load toward the input. The gate drive amplifier detects this failure condition as soon as it appears and turns off the ideal diode MOSFET by pulling down the DGATE.

### HOT SWAP CONTROL

Pulling the ON pin high and the  $\overline{\text{EN}}$  pin low initiates a 100ms debounce timing cycle. After this timing cycle, a 100 $\mu\text{A}$  current from the charge pump ramps up the HGATE pin. When the Hot Swap MOSFET turns on, the inrush current is limited at a level set by an external sense resistor connected between the IN and SENSE pins for LTC4225 (SENSE+ and

Figure 4. The LTC4225 in a  $\mu\text{TCA}$  application to supply 12V power to two  $\mu\text{TCA}$  slots



If the main supply loses power, the controller reacts quickly to turn off the ideal diode MOSFET in the main supply path and turn on the MOSFET in the redundant supply path, providing a smooth supply switchover to the output load. The Hot Swap MOSFETs remain on so they do not affect the supply switchover.

SENSE<sup>-</sup> pins for LTC4227 and LTC4228). An active current limit amplifier servos the gate of the MOSFET so that 65mV appears across the current sense resistor. If the sense voltage exceeds 50mV for more than a fault-filter delay configured at the TMR pin, a circuit breaker trips and pulls HGATE low. Inrush current can be further reduced, if desired, by adding a capacitor from HGATE to GND. When the MOSFET's gate overdrive (HGATE to OUT voltage) exceeds 4.2V, the PWRGD pin pulls low (Figure 3).

### COMBINING THE IDEAL DIODE AND HOT SWAP CONTROL

In a typical  $\mu$ TCA application with redundant supplies (Figures 4 and 9), the outputs are diode-ored at the backplane, so cards can be removed or inserted without

powering down the system. The LTC4225 and LTC4228, which both include dual ideal diode and Hot Swap controllers, are ideal for these applications—they provide smooth supply switchover between two supplies and overcurrent protection.

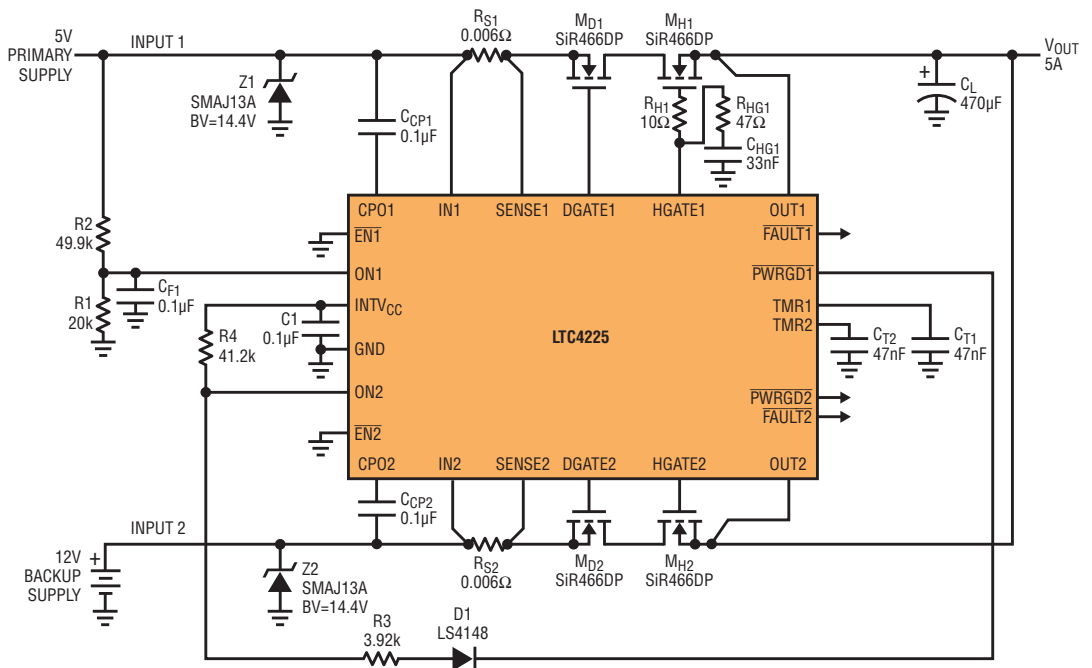
If the main supply loses power, the controller reacts quickly to turn off the ideal diode MOSFET in the main supply path and turn on the MOSFET in the redundant supply path, providing a smooth supply switchover to the output load. The Hot Swap MOSFETs remain on so they do not affect the supply switchover. The controller turns off a Hot Swap MOSFET when the respective ON pin is pulled low or  $\overline{\text{EN}}$  pin is pulled high. When an overcurrent fault is detected at the output, the gate of the Hot Swap MOSFET is pulled down quickly,

after which the output is regulated in current limit until the fault filter delay set by the TMR pin capacitor times out. The Hot Swap MOSFET is turned off and the  $\overline{\text{FAULT}}$  pin is latched-low to indicate a fault. The electronic circuit breaker is reset by pulling the ON pin below 0.6V.

### PRIORITIZING A POWER SUPPLY

In a traditional diode-ored multisupply system, the input supply with the higher voltage is passed to the output, while the lower voltage supply is shut out. This simple solution satisfies the needs of applications where the priority of the supplies is not simply a matter of the higher voltage supply winning. Figure 5 shows a backup supply system where the 5V primary supply (INPUT1) is passed to the output whenever it is available, while the 12V backup

Figure 5. LTC4225 for 2-channel power prioritizer with IN1 as the prioritizing input



In a typical  $\mu$ TCA application with redundant supplies, the outputs are diode-ORed at the backplane, so cards can be removed or inserted without powering down the system. The LTC4225 and LTC4228, which both include dual ideal diode and Hot Swap controllers, are ideal for these applications—they provide smooth supply switchover between two supplies and overcurrent protection.

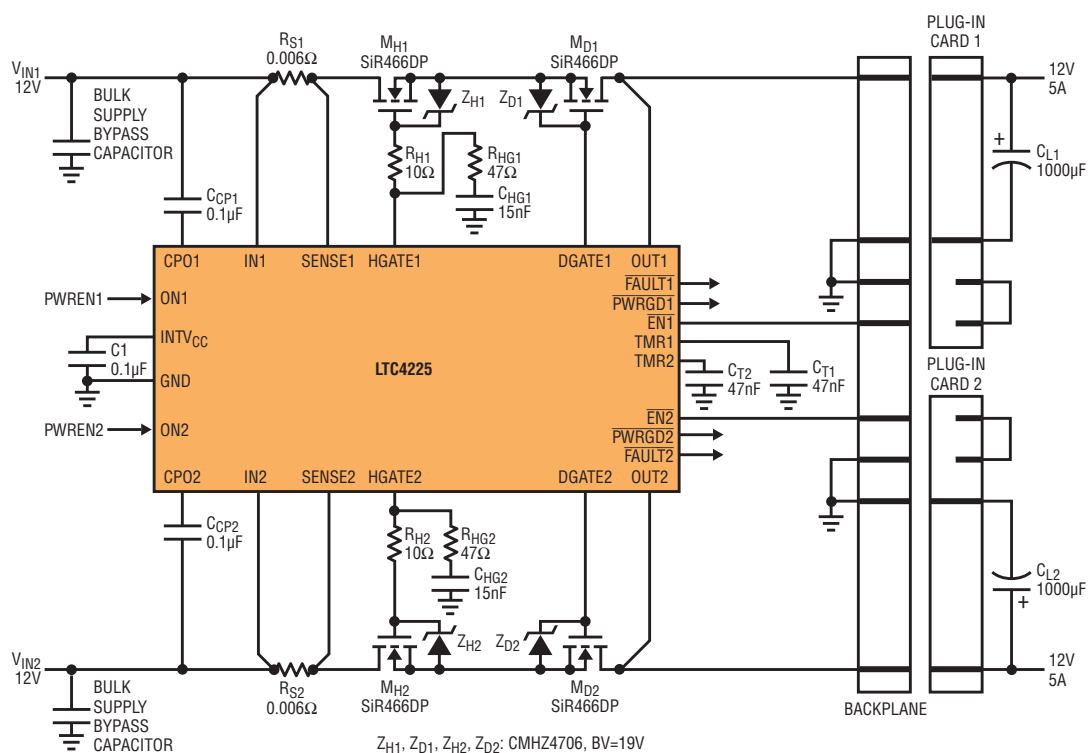


Figure 6. LTC4225 for application with the Hot Swap MOSFET on the supply side and the ideal diode MOSFET on the load side

supply (INPUT2) is called on only when the primary supply fails to deliver.

As long as INPUT1 is above the 4.3V UV threshold set by the R1-R2 divider at the ON1 pin,  $M_{H1}$  is turned on, connecting INPUT1 to the output. When  $M_{H1}$  is on,  $\overline{PWRGD1}$  goes low, which in turn pulls ON2 low and disables the IN2 path by turning  $M_{H2}$  off. If the primary supply fails and INPUT1 drops below 4.3V, ON1 turns off  $M_{H1}$  and  $\overline{PWRGD1}$  goes high, allowing ON2 to turn on  $M_{H2}$  and connect the INPUT2 to the output. The ideal diode MOSFETs  $M_{D1}$  and  $M_{D2}$  prevent backfeeding of one input to the other under any condition.

### SWAPPING THE DIODE AND HOT SWAP FET ON SUPPLY AND LOAD SIDE

The LTC4225 allows applications with back-to-back MOSFETs to be configured with the MOSFET on the supply side as the ideal diode and the MOSFET on the load side as the Hot Swap control (Figure 4) or vice versa (Figure 6). In Figure 6, an external Zener diode clamp may be required between the GATE and SOURCE pins of the MOSFET to prevent it from breaking down if the MOSFET's gate-to-source voltage is rated for less than 20V. In either arrangement, LTC4225 smoothly switches between supplies with its ideal diode ORing between the IN and OUT pins.

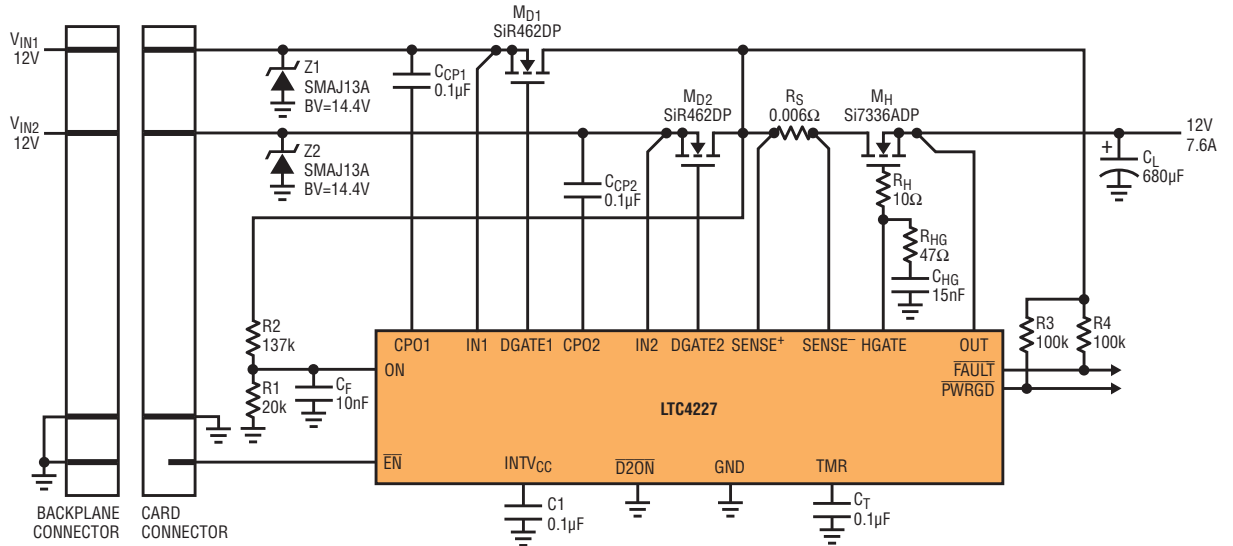
### DUAL IDEAL DIODE AND SINGLE HOT SWAP CONTROL

Figure 7 shows a LTC4227 application where the sense resistor is placed after dual supply ideal diode MOSFETs connected in parallel, which is then followed by a single Hot Swap MOSFET. Here, the LTC4227 regulates an overloaded output at 1× the current limit before fault timeout, instead of 2×, as in the LTC4225 diode-OR application. As a result, power dissipation is reduced during an overload condition.

The LTC4227 also features the  $\overline{D2ON}$  pin, which allows the IN1 supply to be easily prioritized. For example, Figure 8 shows a simple resistive divider connecting IN1 to the  $\overline{D2ON}$  pin, so that the

Tight 5% circuit breaker threshold accuracy and fast acting current limit protect the supplies against overcurrent faults. The LTC4228's fast recovery from input brownouts preserves the output voltage in the face of such events.

Figure 7. LTC4227 for card-resident diode-OR application with Hot Swap control



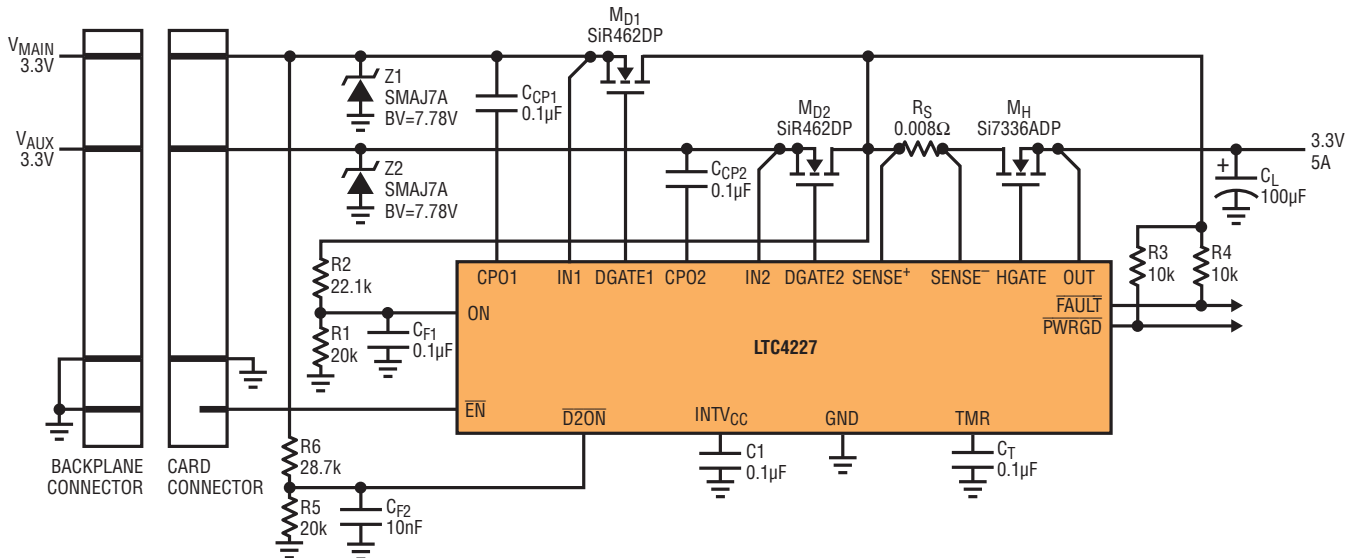
IN1 supply is prioritized until IN1 falls below 2.8V, wherein  $M_{D2}$  is turned on and the diode-OR output is switched from the main 3.3V supply at IN1 to the auxiliary 3.3V supply at IN2.

### FASTER OUTPUT RECOVERY FROM INPUT COLLAPSE

In the LTC4225  $\mu$ TCA application shown in Figure 4, if one of the input supplies collapses to ground momentarily

while the other supply is not available, HGATE is pulled low to turn off the Hot Swap MOSFET as the IN supply drops below the undervoltage lockout threshold. When the input supply recovers, HGATE is allowed to start up to

Figure 8. Plug-in card IN1 supply controls the IN2 supply turn-on via  $\overline{D2ON}$  of LTC4227



The LTC4225, LTC4227 and LTC4228 enable ideal diode and Hot Swap functions for two power rails by controlling external N-channel MOSFETs. They feature fast reverse turn-off, smooth supply switchover, active current limit and status and fault reporting.

turn on the MOSFET. As it takes a while to charge up HGATE and the depleted output capacitance, the output voltage may brown out during this period.

In this situation, the LTC4228 offers an advantage over the LTC4225 by recovering more quickly to preserve the output voltage. As shown in Figure 9, the sense resistor is placed in between the ideal diode and Hot Swap MOSFET, allowing the SENSE<sup>+</sup> pin voltage to be held up by the output load capacitance temporarily when the input supply collapses.

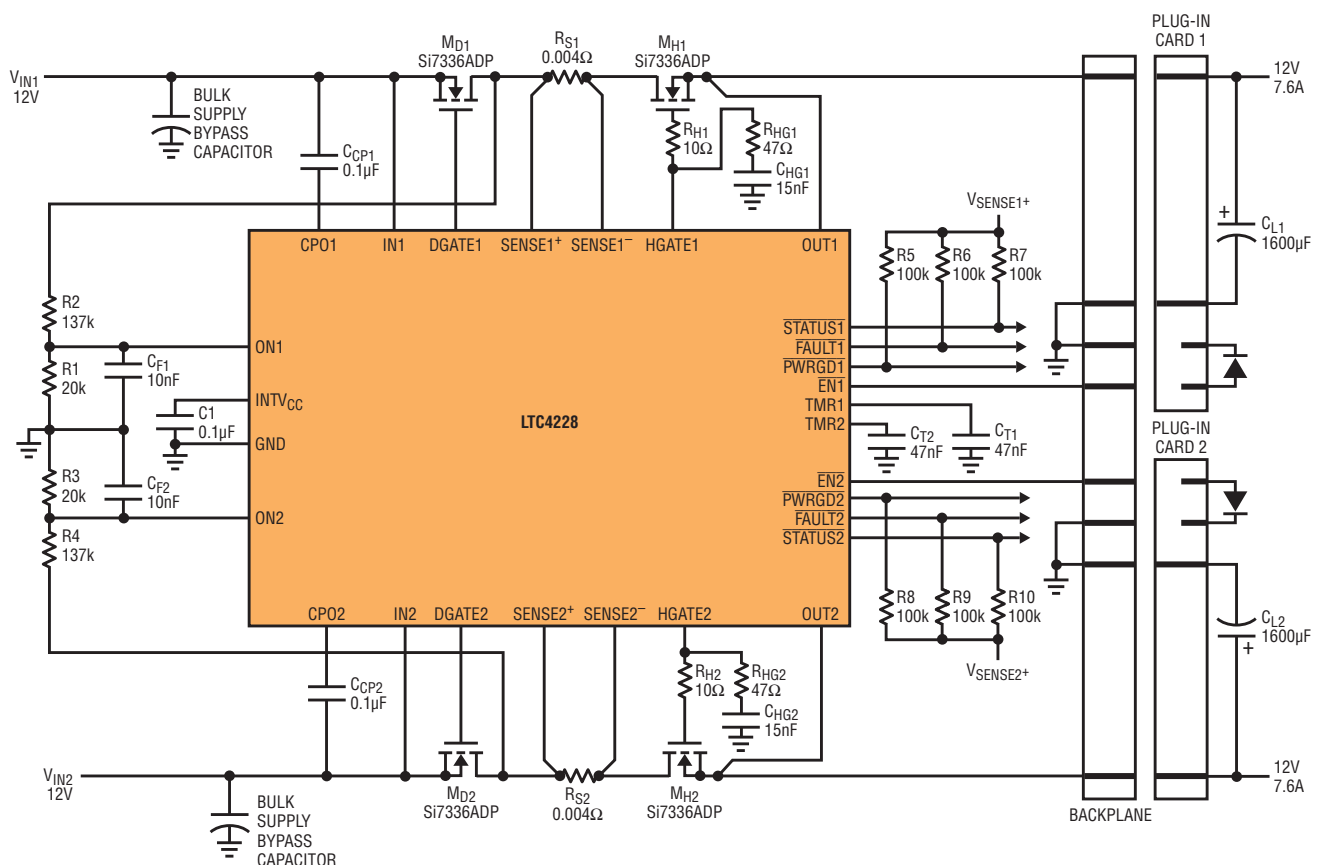
This prevents the SENSE<sup>+</sup> voltage from entering into undervoltage lockout and turning off the Hot Swap MOSFET. As the input supply recovers, it charges up the depleted load capacitance and instantly provides power to the downstream load, since the Hot Swap MOSFET remains on.

### CONCLUSION

The LTC4225, LTC4227 and LTC4228 enable ideal diode and Hot Swap functions for two power rails by controlling external N-channel MOSFETs. They feature fast reverse turn-off, smooth

supply switchover, active current limit and status and fault reporting. Their tight 5% circuit breaker threshold accuracy and fast acting current limit protect the supplies against overcurrent faults. The LTC4228's fast recovery from input brownouts preserves the output voltage in the face of such events. ■

Figure 9. LTC4228 for  $\mu$ TCA application to supply 12V power to two  $\mu$ TCA slots



# What's New with LTspice IV?

Gabino Alonso

 Follow @LTspice on Twitter for up-to-date information on models, demo circuits, events and user tips: [www.twitter.com/LTspice](http://www.twitter.com/LTspice)

## DEMO CIRCUITS

### Step-Down Regulators

- **LT<sup>®</sup>3641**: Dual high voltage buck with POR and WDT (7V–42V to 5V at 1A & 1.8V at 0.8A) [www.linear.com/LT3641](http://www.linear.com/LT3641)
- **LT3976**: 3.3V Step-down converter (4.3V–42V to 3.3V at 5A) [www.linear.com/LT3976](http://www.linear.com/LT3976)
- **LT8300**: 100V  $\mu$ Power isolated flyback converter (22V–75V to 5V at 0.25A) [www.linear.com/LT8300](http://www.linear.com/LT8300)
- **LTC3626**: 2.5V, 1MHz step-down converter with average input current limit & monitor (3.6V–20V to 2.5V at 2.5A) [www.linear.com/LTC3626](http://www.linear.com/LTC3626)
- **LTC3839**: Fast transient step-down converter with differential R<sub>SENSE</sub> sensing (4.5V–14V to 1.5V at 40A) [www.linear.com/LTC3839](http://www.linear.com/LTC3839)
- **LTC3861**: High current, dual output synchronous buck converter with DCR current sensing (4V–14V to 1.2V at 25A & 1.8V at 25A) [www.linear.com/LTC3861](http://www.linear.com/LTC3861)
- **LTM<sup>®</sup>8029**:  $\mu$ Power high voltage buck converter (5.6V–36V to 5V at 600mA) [www.linear.com/LTM8029](http://www.linear.com/LTM8029)

### LED Drivers, Battery Chargers and Negative & Inverting Regulators

- **LT3791**: 98% efficient 100W buck-boost LED driver (15V–58V to 33V LED at 3A) [www.linear.com/LT3791](http://www.linear.com/LT3791)
- **LT3959**: Wide input voltage range boost converter (2V–10V to 12V at 0.5V–2A) [www.linear.com/LT3959](http://www.linear.com/LT3959)
- **LT8611**: Negative converter with 1A output current limit (3.8V–42V to –3.3V at 1A) [www.linear.com/LT8611](http://www.linear.com/LT8611)
- **LT8611**: CCCV Li-ion battery charger (3.8V–42V to 4.1V at 1A) [www.linear.com/LT8611](http://www.linear.com/LT8611)

## NEW MODELS

### Switching Regulators

- **LT3761**: 60V input LED controller with internal PWM generator [www.linear.com/LT3761](http://www.linear.com/LT3761)
- **LT3791-1**: 60V input 4-switch synchronous buck-boost controller [www.linear.com/LT3791-1](http://www.linear.com/LT3791-1)
- **LT3959**: Wide input voltage range boost/SEPIC/inverting converter with 6A, 40V switch [www.linear.com/LT3959](http://www.linear.com/LT3959)

- **LT8300**: 100V input  $\mu$ Power isolated flyback converter with 150V/260mA switch [www.linear.com/LT8300](http://www.linear.com/LT8300)
- **LTC3122**: 15V, 2.5A synchronous step-up DC/DC converter with output disconnect [www.linear.com/LTC3122](http://www.linear.com/LTC3122)
- **LTC3633A**: Dual channel 3A, 20V monolithic synchronous step-down regulator [www.linear.com/LTC3633A](http://www.linear.com/LTC3633A)
- **LTC3861-1**: Dual, multiphase step-down voltage mode DC/DC controller with accurate current sharing [www.linear.com/LTC3861-1](http://www.linear.com/LTC3861-1)

### Linear Regulators

- **LTC3026-1**: 1.5A low input voltage VLDO™ linear regulator [www.linear.com/LTC3026-1](http://www.linear.com/LTC3026-1)

### Overvoltage & Overcurrent Protection and Timing

- **LT4363-1**: High voltage surge stopper with current limit [www.linear.com/LT4363](http://www.linear.com/LT4363)
- **LTC4359**: Ideal diode controller with reverse input protection [www.linear.com/LTC4359](http://www.linear.com/LTC4359)
- **LTC6905**: 17MHz to 170MHz resistor set SOTV–23 oscillator [www.linear.com/LTC6905](http://www.linear.com/LTC6905)
- **LT3957A**: Boost, flyback, SEPIC and inverting converter with 5A, 40V switch [www.linear.com/LT3957A](http://www.linear.com/LT3957A) ■

## What is LTspice IV?

LTspice<sup>®</sup> IV is a high performance SPICE simulator, schematic capture and waveform viewer designed to speed the process of power supply design. LTspice IV adds enhancements and models to SPICE, significantly reducing simulation time compared to typical SPICE simulators, allowing one to view waveforms for most switching regulators in minutes compared to hours for other SPICE simulators.

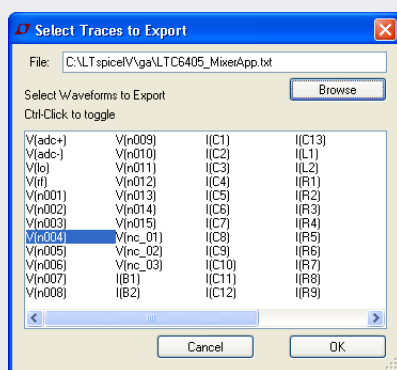
LTspice IV is available free from Linear Technology at [www.linear.com/LTspice](http://www.linear.com/LTspice). Included in the download is a complete working version of LTspice IV, macro models for Linear Technology's power products, over 200 op amp models, as well as models for resistors, transistors and MOSFETs.

### IMPORTING AND EXPORTING DATA IN LTSPICE IV

The LTspice IV waveform viewer is a handy way to perform basic measurements, but there are times when you need to export data from, or import data into LTspice to further evaluate a circuit.

#### To export waveform data to an ACSII text file:

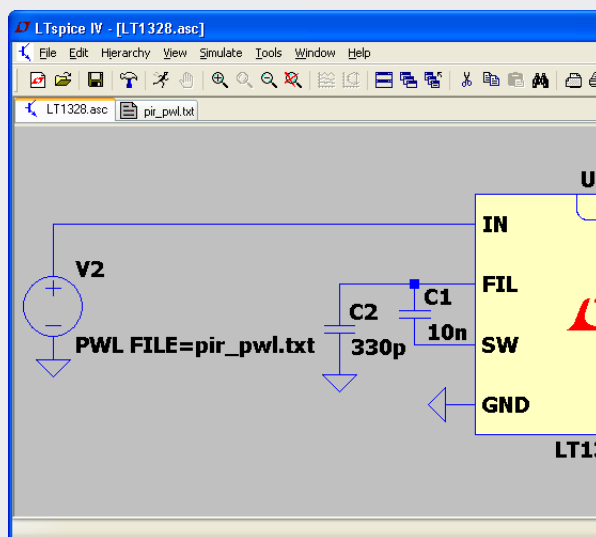
1. Click to select the waveform viewer
2. Choose Export from the File menu.
3. Select the traces you want exported



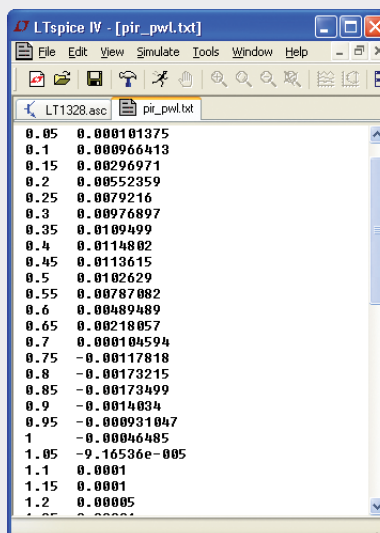
4. Click browse to specify the file location and name to save the text file.

Once this file is created you can analyze it further in applications like Microsoft Excel or MATLAB. Note that some applications like MATLAB expect imported files to contain only data, with no header information. If you need to remove the header, open the text file in a text editor or Excel and delete the header information.

To import waveform data into LTspice IV you must attach a text file as a piecewise linear (PWL) function in a voltage or current source.

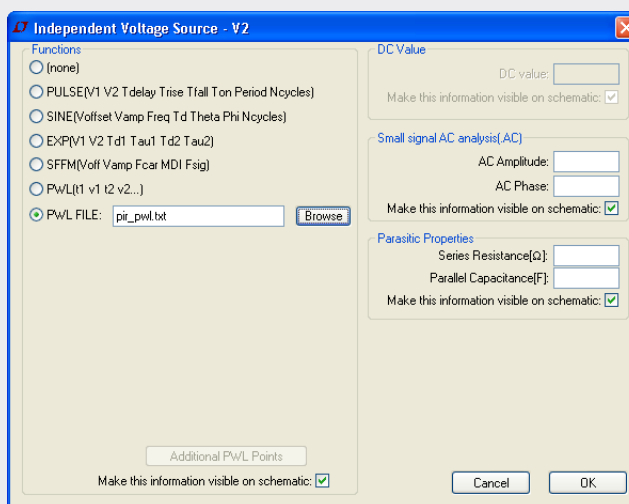


The imported file must contain a list of two-dimensional points that represent time and value data pairs in a tab or comma delimited format—with no header information. The PWL function connects the dots in the data, constructing a waveform based on straight-line segments between the points defined in the text file.



To add a text file as a PWL function to a voltage or current source:

1. Right-click the symbol in the schematic editor
2. Choose advance
3. Select PWL FILE: and click Browse to choose the text file.



The PWL statement is discussed in more depth in the previous issue of this magazine at [cds.linear.com/docs/LT%20Journal/LTJournal-V22N3-2012-10.pdf](http://cds.linear.com/docs/LT%20Journal/LTJournal-V22N3-2012-10.pdf).

*Happy simulations!*

# 20V, 2.5A Synchronous Monolithic Buck with Current and Temperature Monitoring

K. Bassett

Increases in digital IC integration, coupled with advances in printed circuit board layout and assembly techniques, continue to push system performance and power density higher. Many of these systems, powered from a 12V rail or battery stack, utilize point-of-load regulators to maximize power chain efficiency while maintaining a small form factor. The LTC3626 synchronous, monolithic step-down regulator is ideally suited for these operating environments, given its ability to provide a flexible, highly efficient DC/DC conversion while occupying a very small footprint.

The LTC3626 is capable of supplying 2.5A of output current over an input voltage range of 3.6V to 20V from a tiny, 3mm × 4mm, 20-pin QFN package. Its patented controlled on-time architecture yields outstanding transient response and enables high step-down ratios at high switching frequencies, minimizing board footprint.

The LTC3626 integrates a number of easy-to-use, but powerful, features that would normally require additional ICs and design time to implement. Specifically, with the addition of just a couple of passive components, the LTC3626 can be configured to provide accurate measures of its output current, input current, and on-die temperature. It can be just as easily programmed to limit each measured parameter.

These built-in features expand the designer's insight into the performance of the system and increase the level of control with remarkably little extra design investment. Additionally, optional internal loop compensation is available to minimize the design effort.

The LTC3626 also includes user-selectable Burst Mode operation or forced-continuous mode, resistor-programmable switching frequencies from 500kHz to 3MHz, power good status output, output tracking capability, and external clock synchronization.

## CURRENT MONITOR AND LIMIT

One way to measure the overall performance of a system is to monitor the current at the output of the power supply. Supply current monitoring *also* informs designers if downstream ICs are operating as expected—useful in design and debug, and during normal operation.

The LTC3626 makes it easy to monitor the supply current by producing a fraction of its average output current at its IMON<sub>OUT</sub> pin, specifically, the current at the IMON<sub>OUT</sub> pin is equal to the average output current divided by 16,000.

Figure 1 shows the typical performance of the output current measurement for an ambient temperature range of -40°C to 85°C. Figure 2 shows the error between the actual average output

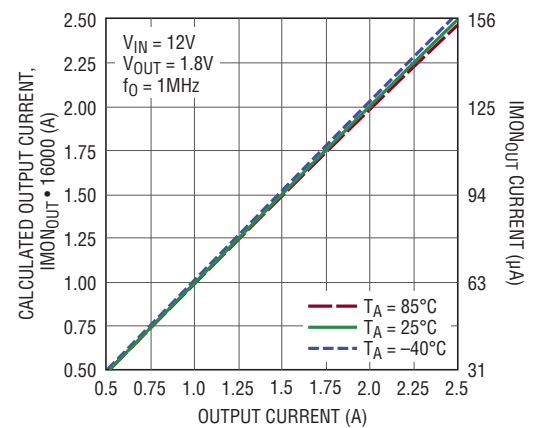
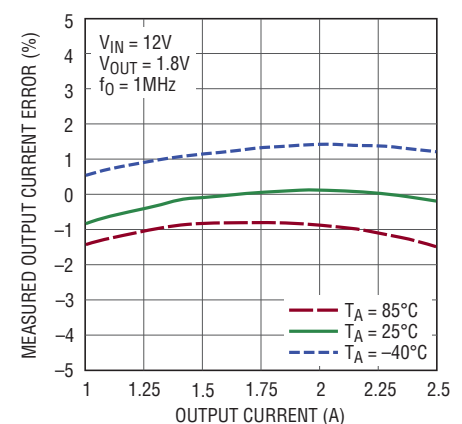


Figure 1. Output current monitor vs output current

current and the average output current as measured by the LTC3626.

The current at the IMON<sub>OUT</sub> pin can be measured directly or converted to a voltage by placing a resistor from the IMON<sub>OUT</sub> pin to ground. Converting the output of the IMON<sub>OUT</sub> pin to a voltage makes it easy to scale the output for digitization via a microcontroller or standalone ADC. Figure 3 shows the LTC3626 configured to run with

Figure 2. Output current monitor error vs output current





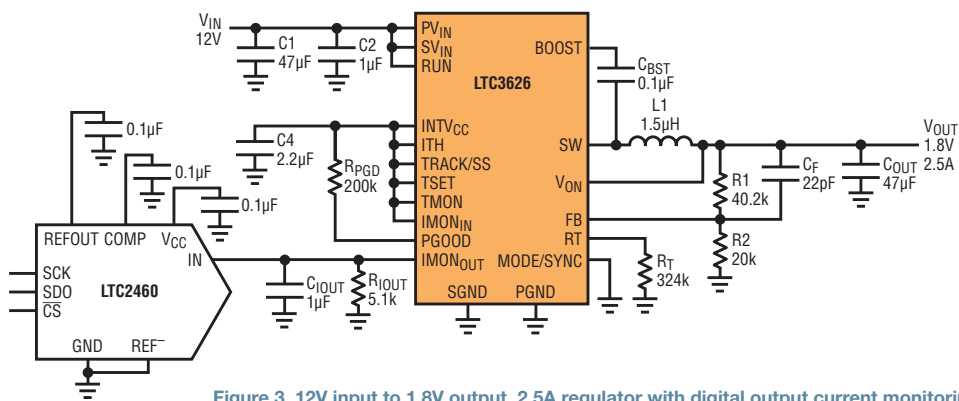


Figure 3. 12V input to 1.8V output, 2.5A regulator with digital output current monitoring

the output current monitor activated while the LTC2460, 16-bit ADC, digitizes the result for digital processing.

The LTC3626 also features an easily programmed average output current limit. Specifically, the LTC3626 contains an on-chip current limit amplifier with a reference of approximately 1.2V. To program an average output current, simply size the resistor from IMON<sub>OUT</sub> to ground such that the resultant voltage is 1.2V for the current at which the limit should be activated.

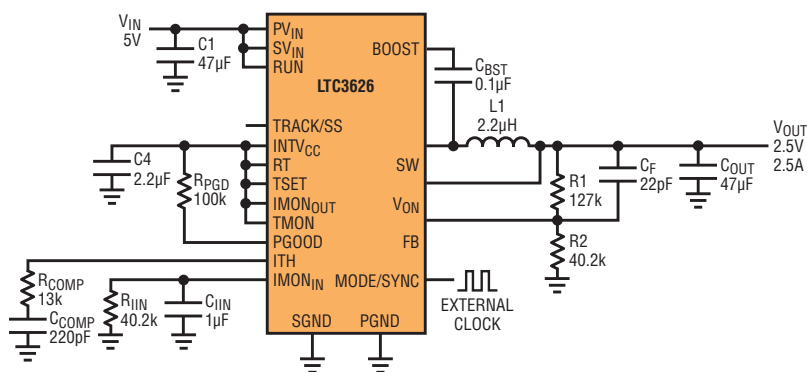
Similar to the average output current, the LTC3626 produces an estimate of the average input current at the IMON<sub>IN</sub> pin. That is, the current at the IMON<sub>IN</sub> pin is an estimate of the average input current divided by 16,000. Just like the average output current, the LTC3626 offers a simple mechanism to program a limit for the average input current. This feature

is useful for applications that must limit the average current drawn from the input supply. Figure 4 shows the LTC3626 configured to limit the average input current to 475mA while producing an output voltage of 2.5V from a 5V input voltage.

### TEMPERATURE MONITOR AND LIMIT

The LTC3626 produces an estimate of the on-die temperature at the TMON pin. This feature can be used to determine the quality of the ground connection to the QFN exposed pad made during assembly. The exposed pad for the QFN is intended to provide a low impedance electrical connection to the board as well as good thermal contact. Visual inspection of this critical connection can be difficult, and a poor exposed pad connection may not be apparent by simple observation of the regulated output voltage even though the on-die temperature may be far

Figure 4. 5V Input to 2.5V output at 1MHz synchronized frequency with input current monitor and 475mA input current limit



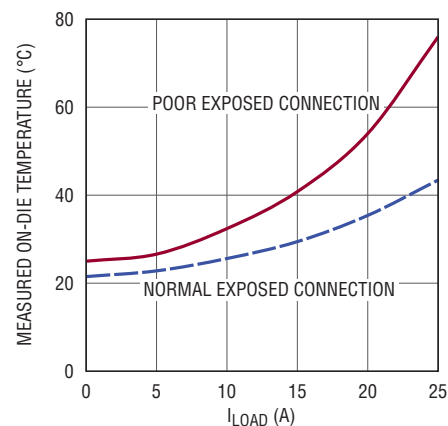
too high for reliable, long-term part operation. Measurement of the TMON pin however gives the user insight into the exposed pad connection and hence the internal part operating environment.

As an example, Figure 5 shows data taken on two parts, one with a good exposed pad connection to the PCB, the other with a poor exposed pad connection. Though both parts regulate to the expected output voltage, it is clear from the internal temperature measurement that the internal operating environment is very different between the two parts. If placed in a system with an ambient operating temperature of say 70°C, the device with the poor exposed pad connection will clearly exceed the maximum allowed junction temperature of 125°C and will thus have compromised long-term reliability.

### CONCLUSION

The continuous push for higher performance and power density faced by today's system designers require small, flexible, and efficient point-of-load converters to maximize overall power chain efficiency. The LTC3626's combination of wide input voltage range, output current capability, flexible feature set, and very small form factor make it ideal for many of today's point-of-load regulator applications. ■

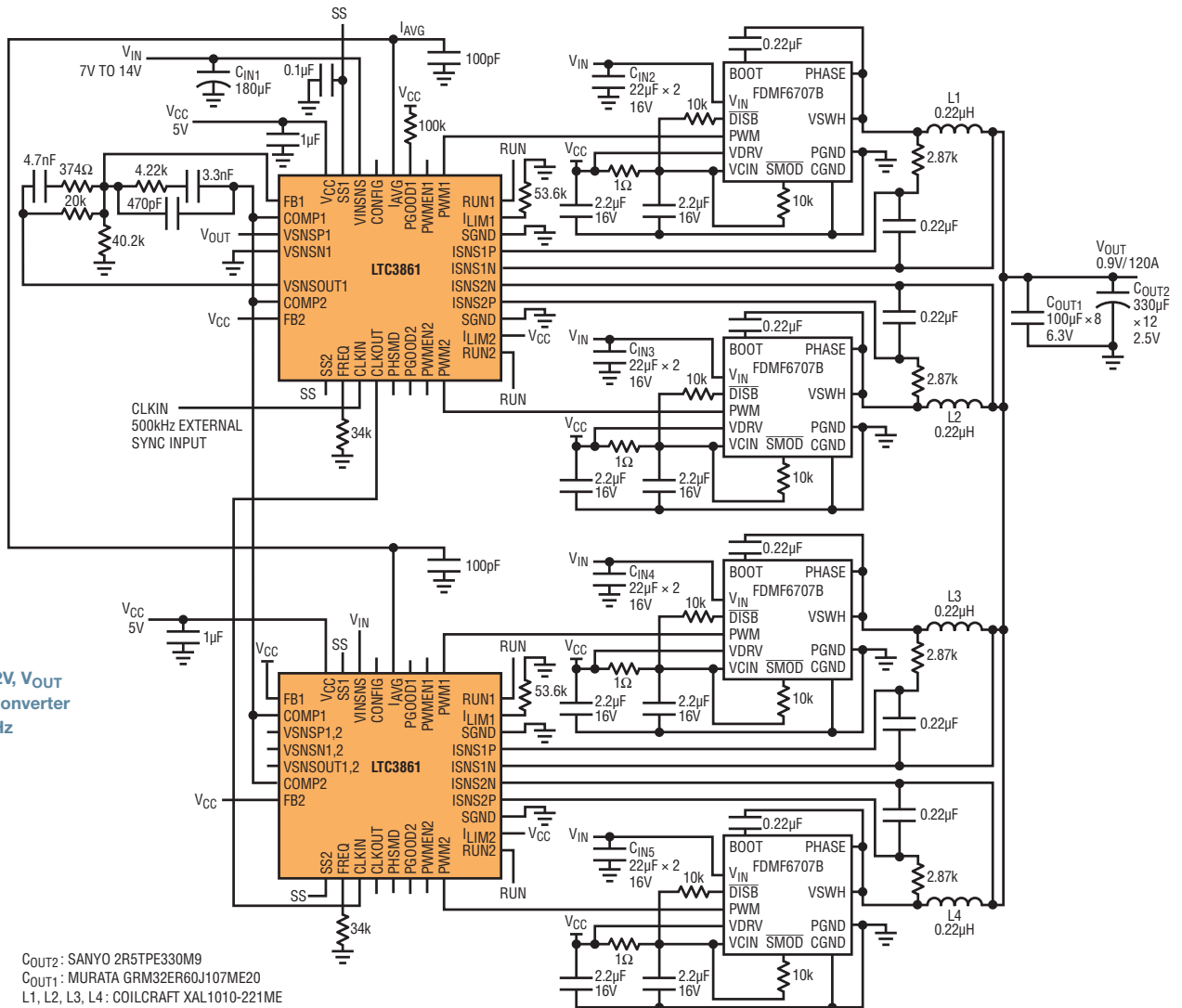
Figure 5. It is easy to determine the quality of the exposed pad connection by examining temperature measurements made by the LTC3626.



# Sub-Milliohm DCR Current Sensing with Accurate Multiphase Current Sharing for High Current Power Supplies

Muthu Subramanian, Tuan Nguyen and Theo Phillips

The increasing functional complexity of electronic devices, combined with the desire for higher microprocessor computational speed and the quest for eco-friendly electronics, places stringent requirements on power supplies. High current supplies are expected to operate at top efficiency. In order to minimize conduction losses, power supplies are placed closer to the load, and multiple power stages are used on the same board. Individual power stages have had to shrink in size to fit the available board area. To achieve the best performance per board area, controllers must work with external power stages such as power blocks, DrMOS or external gate drivers with MOSFETs.



The LTC3861 uses a constant-frequency voltage mode architecture, combined with a very low offset, high bandwidth error amplifier and a remote output sense differential amplifier per channel for excellent transient response and output regulation.

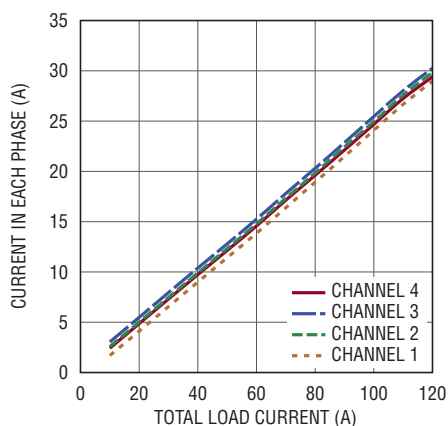


Figure 2. Current sharing between the four phases with varying load current

The LTC3861 is a multiphase dual output synchronous step-down DC/DC controller that can operate with power blocks, DrMOS and external gate drivers. It is flexible enough to operate as a dual output, 3+1 output, or up to a 12-phase single output step-down converter.

The LTC3861 uses a constant-frequency voltage mode architecture, combined with a very low offset, high bandwidth error amplifier and a remote output sense differential amplifier per channel for excellent transient response and output regulation. The error and differential amplifiers have a gain bandwidth of 40MHz, high enough not to affect the main loop compensation and transient behavior, especially when all ceramic low ESR output capacitors are used to minimize output ripple. The differential amplifiers sense the resistively divided feedback voltage differentially over the full output range from 0.6V to  $V_{CC} - 0.5V$ , ensuring that the LTC3861 sees the actual output voltage,

independent of any offsets between power ground and the controller's ground.

In a voltage mode control loop, the error amplifier output is compared to a sawtooth ramp, which directly controls the converter duty cycle. The output voltage of the error amplifier depends on the magnitude of the error signal between the differentially sensed output voltage and the amplifier reference voltage. The 600mV reference has an accuracy of  $\pm 0.75\%$  over a 0°C to 85°C temperature

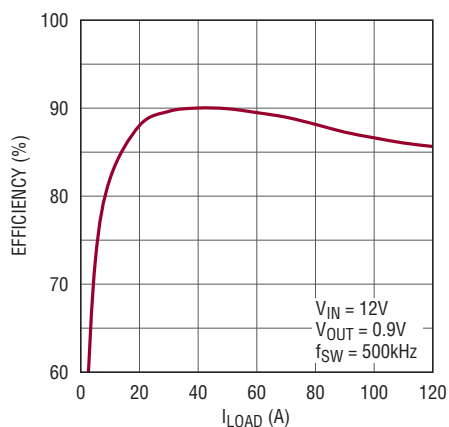


Figure 4. 4-phase, 0.9V/120A converter efficiency

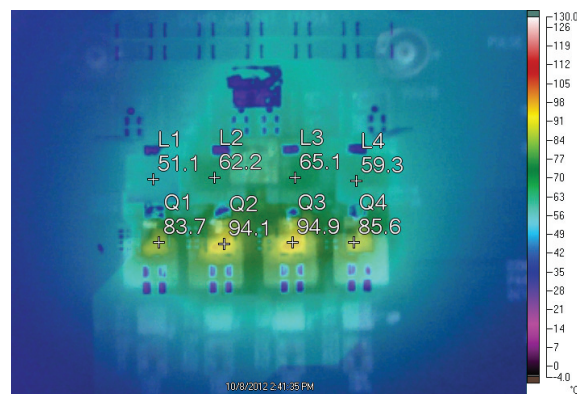


Figure 3. Thermal image at 0.9V/120A, 400 FPM,  $f_{SW} = 500kHz$

range. This, combined with the low offset of the amplifiers, guarantees a total output regulation accuracy of  $\pm 1.3\%$  over a  $-40^{\circ}C$  to  $125^{\circ}C$  temperature range.

The LTC3861 achieves outstanding line transient response using a feedforward correction scheme, which instantaneously adjusts the duty cycle to compensate for changes in input voltage, significantly reducing output overshoot and undershoot. This scheme makes the DC loop gain independent of the input voltage. The converter has a minimum on-time of 20ns, which is suitable for high step-down ratio converters operating at high frequencies. The operating frequency is resistor programmable from 250kHz to 2.25MHz, or can be synchronized to an external clock through an onboard PLL.

#### MULTIPHASE CURRENT SHARING

The controller allows the use of sense resistors or lossless inductor DCR current sensing to maintain current balance between phases and to provide overcurrent protection. In multiphase operation, the LTC3861 incorporates an auxiliary current

In multiphase operation, the LTC3861 incorporates an auxiliary current share loop, which is activated by configuring the FB pin and by adding an external capacitor on the  $I_{AVG}$  pin. The maximum current sense mismatch between phases is  $\pm 1.25\text{mV}$  over the  $-40^\circ\text{C}$  to  $125^\circ\text{C}$  temperature range. The current sharing accuracy between the four phases at full 120A load current is  $\pm 2.15\%$ .

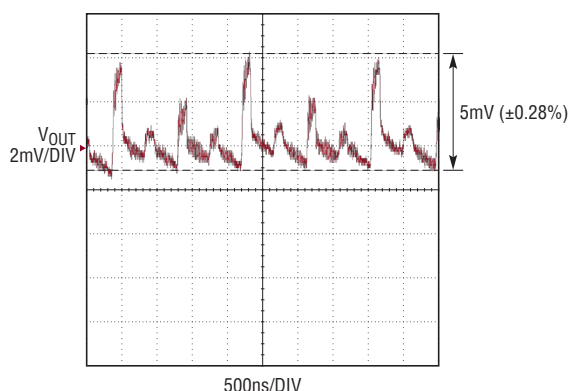


Figure 5. Steady state voltage ripple

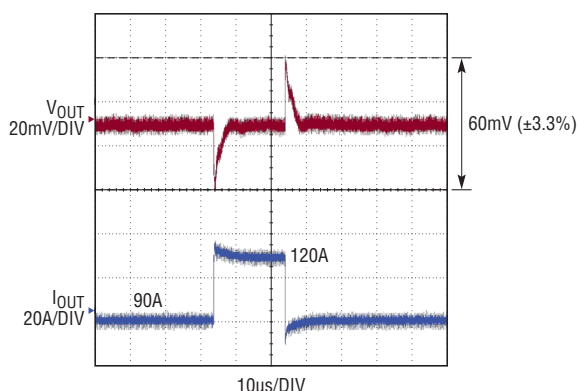


Figure 6. 30A Load step transient response from 90A to 120A

share loop, which is activated by configuring the FB pin and by adding an external capacitor on the  $I_{AVG}$  pin. The voltage on the  $I_{AVG}$  pin corresponds to the instantaneous average inductor current of the master phase. Each slave phase integrates the difference between its inductor current and the master's. A resistor connected to the ILIM pin sets the threshold for the positive and negative overcurrent fault protection comparator. The maximum current sense mismatch between phases is  $\pm 1.25\text{mV}$  over  $-40^\circ\text{C}$  to  $125^\circ\text{C}$  temperature range.

#### CIRCUIT PERFORMANCE

Figure 1 shows a high efficiency 12V to 0.9V/120A 4-phase step-down converter with low DCR sensing. An inductor with  $\text{DCR} = 0.45\text{m}\Omega$  is used in the design. The current sharing accuracy between the four phases at full 120A load current

is  $\pm 2.15\%$ . Figure 2 shows the current sharing between phases as a function of varying load current.

Figure 3 shows the thermal image at 120A load, and the hottest spot occurs on the MOSFETs of channels 2 and 3. The efficiency at full 120A load is close to 86%, as illustrated in Figure 4. Figure 5 shows the steady state voltage ripple as approximately  $\pm 0.3\%$  of output voltage. Load step transient analysis was performed by stepping the load from 75% to 100% of full load. This resulted in a 30A load step from 90A to 120A. The peak to peak voltage overshoot and undershoot during a load step was 60mV, which is about  $\pm 3.3\%$  of output voltage.

#### CONCLUSION

The LTC3861 is a voltage mode controller with accurate current sharing of up to 12 phases in parallel. Since it has a 3-state PWM output instead of a built-in gate driver output, the controller can be placed further from high current paths. Because output voltage is differentially sensed, offsets between power ground and the LTC3861's ground do not affect load regulation.

The LTC3861 works with DrMOS, power blocks, and external MOSFETs with an LTC4449 gate driver. It is used in high current distributed power systems, DSP, FPGA, and ASIC supplies, datacom and telecom systems, and industrial power supplies. The LTC3861 is available in a 36-pin  $5\text{mm} \times 6\text{mm}$  QFN package. In addition, the LTC3861-1 is a pin-compatible drop-in replacement for the LTC3860, available in a 32-pin  $5\text{mm} \times 5\text{mm}$  QFN package. ■



The LTC3883 uses a proprietary inductor DCR auto-calibration function, which enables output current read back accuracy within 3%, regardless of inductor DCR tolerance.

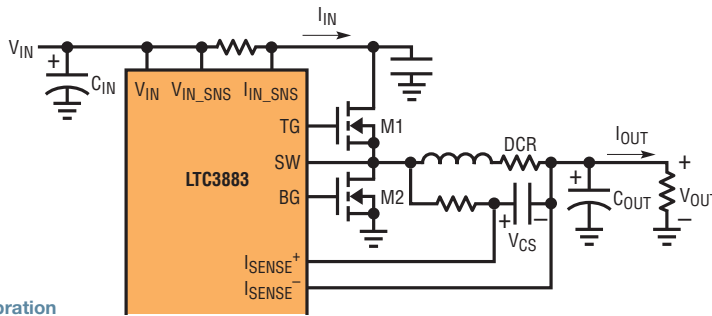


Figure 3. DCR auto calibration

The LTC3883 features input current sensing via a resistor in series with the input side of the buck converter—a 5mΩ sense resistor as shown in Figure 1. The sense voltage is translated into a power stage input current by the LTC3883's 16-bit internal ADC. An internal sense resistor senses chip's supply current at  $V_{IN}$ , so it can provide both the chip and the power stage's input current measurements.

### INDUCTOR DCR AUTO CALIBRATION

The problem with the conventional inductor DCR current sensing is that the tolerance of the DCR can be as large as  $\pm 10\%$ , greatly limiting the current read back accuracy. To solve this problem, the LTC3883 uses a proprietary inductor DCR auto-calibration function. Figure 3 shows the simplified diagram of this circuit.

The LTC3883 accurately measures the input current,  $I_{IN}$ , the duty cycle,  $D$  and calibrates the real DCR value based on the relation:

$$DCR_{CALIBRATED} = V_{CS} \cdot \frac{D}{I_{IN}}$$

With this auto-calibration method, the output current read back accuracy can be within 3%, regardless of inductor DCR tolerance.

### 1.2V/60A 3-PHASE DIGITAL POWER SUPPLY

The LTC3883 has an analog current control loop, which makes it ideal for PolyPhase® operation. Figure 4 shows an example of a 3-phase single output circuit, with one LTC3883 and one LTC3880 for a 7V to 14V input, 1.2V/60A output application. The LTC3880 is a 2-phase synchronous buck controller with digital power system management. The interconnection between these two chips is straightforward and easy. Note how the input current sense resistor of the LTC3883 is used to sense the total input current for all three phases.

Figure 5 shows the dynamic current sharing for a load step transient. All the three phases can share the current evenly.

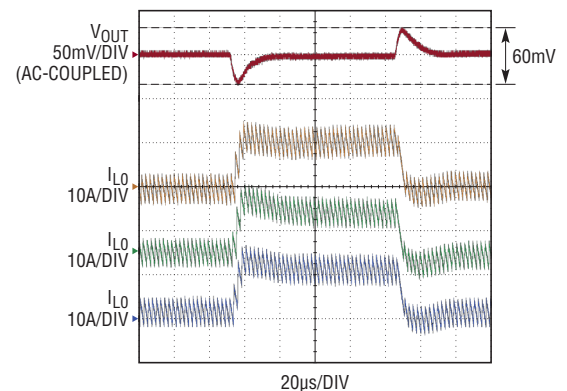
### LTPOWERPLAY DEVELOPMENT

All digital power management functions can be controlled by LTpowerPlay, PC-based software compatible with all of Linear Technology's digital power products. With LTpowerPlay, designers can easily program and control the entire power system without writing a line of code. It is easy to configure any chip on the bus, verify the system's status, read the telemetry, check fault status, control supply sequencing.

### CONCLUSION

The LTC3883 combines a best-in-class analog DC/DC controller with complete digital power management functions and precision data converters for unprecedented performance and control. Multiple LTC3883s can be used with other Linear Technology PMBus products to optimize multirail digital power systems. Powerful LTpowerPlay software simplifies the development of complex power systems. The LTC3883 can be used for telecom, computing, data storage, and other applications. ■

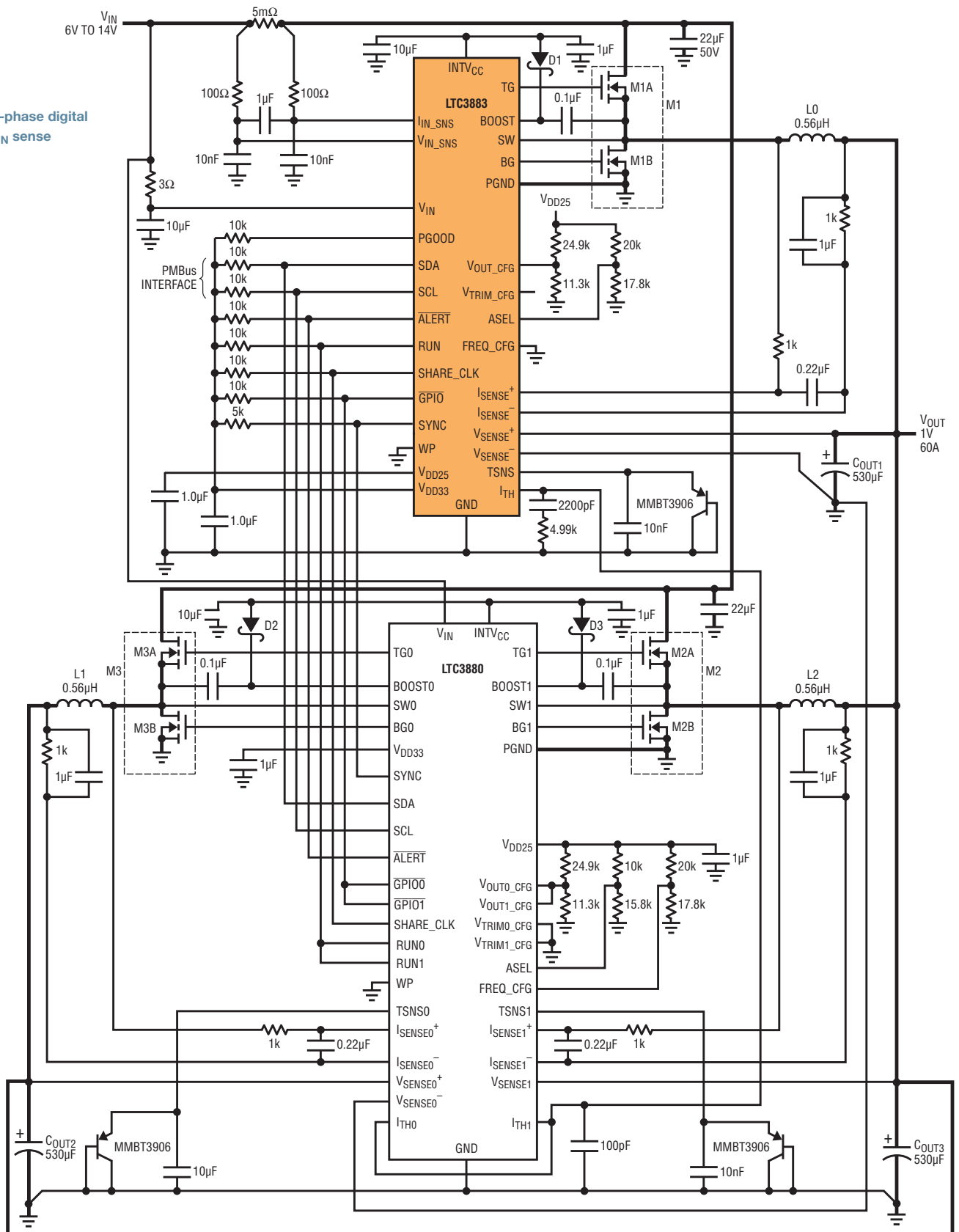
Figure 5. Transient performance of a 30A load step for 3-phase power supply



LTpowerPlay

LTpowerPlay™ software is available for free at [www.linear.com/ltpowerplay](http://www.linear.com/ltpowerplay)

Figure 4. 1.0V/60A 3-phase digital power supply with  $I_{IN}$  sense

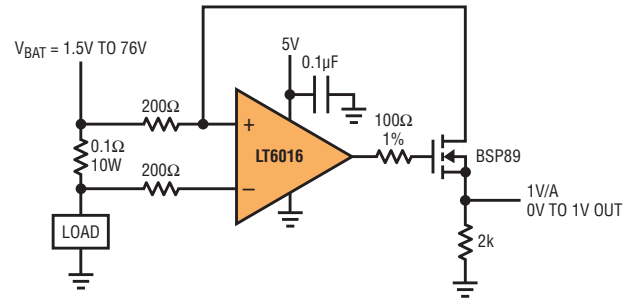


D1-D3: CENTRAL CMDSH-3TR  
L0-L2: COILCRAFT XAL7070-301ME

M1, M2, M3: FAIRCHILD FDMS3620S  
C<sub>OUT1</sub>, C<sub>OUT2</sub>, C<sub>OUT3</sub>: 330μH SANYO 4TPF330ML, 2x 100μF AVX 12106D107KAT2A

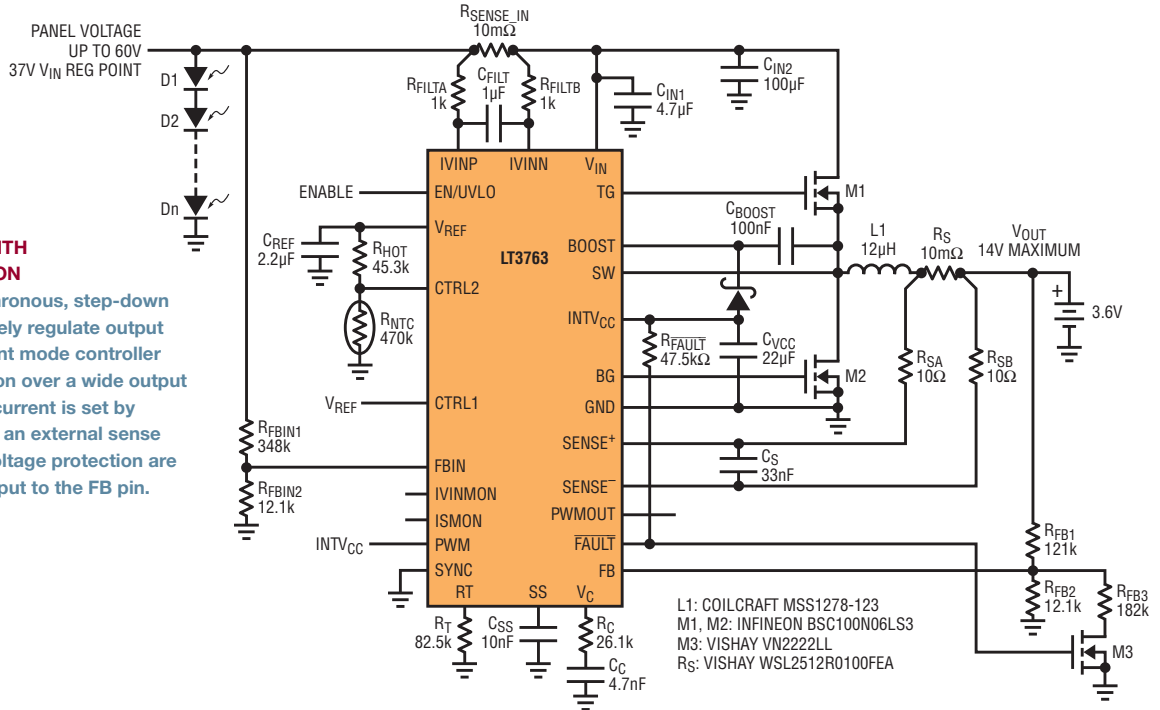
**PRECISION HIGH VOLTAGE HIGH SIDE LOAD CURRENT MONITOR**

The LT6016/LT6017 are dual and quad rail-to-rail input operational amplifiers with input offset voltage trimmed to less than 50µV. These amplifiers operate on single and split supplies with a total voltage of 3V to 50V and draw only 315µA per amplifier. The Over-The-Top® input stage of the LT6016/LT6017 is designed for added protection in demanding environments. The input common mode range extends to inputs up to 76V above V- independent of V+.



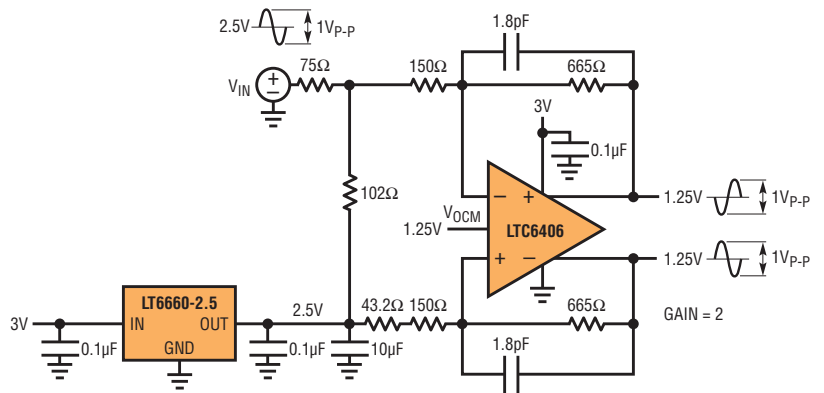
**70W, SOLAR ENERGY HARVESTER WITH MAXIMUM POWER POINT REGULATION**

The LT3763 is a fixed frequency, synchronous, step-down DC/DC controller designed to accurately regulate output currents up to 20A. The average current mode controller will maintain inductor current regulation over a wide output voltage range from 0V to 55V. Output current is set by analog voltages on the CTRL pins and an external sense resistor. Voltage regulation and overvoltage protection are set with a voltage divider from the output to the FB pin.



**A 133MHz DIFFERENTIAL AMPLIFIER WITH EXTERNAL GAIN SET, IMPEDANCE MATCHING TO A 75Ω SOURCE AND LEVEL SHIFTING**

Complete single-ended 75Ω input impedance to differential out, level shifting 2.5V input to 1.25V differential common mode, single-ended to differential gain of 2 using external resistors circuit example.



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