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IN THIS ISSUE

Rugged IO-Link Solutions

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Industrial automation systems are growing more interconnected and intelligent to accommodate demands for centralized control, optimized production and reduced cost. IO-Link® is becoming an increasingly popular interface to smart sensors and actuators, combining signaling with power-over-cable technology. The interface electronics must be rugged, power efficient and compact. Two new parts capably meet these requirements. The LTC®2874 is a highly integrated IO-Link master-side physical layer interface (PHY) for four ports. The LT®3669 is a device-side PHY incorporating a step-down regulator and LDO. To appreciate the numerous features of these devices, it helps to review the requirements of IO-Link. This article begins with a brief overview of IO-Link technology, and follows with LTC2874 and LT3669 functions and features.

The LTC3882 POL controller with built-in digital power system management (see page 16)

IO-LINK: POWER AND COMMUNICATION FOR SMART DEVICES

Combining a power feed and a data link inside a cable assembly isn't new,[1] but its presence in the world of industrial automation is. IO-Link[2] emerged in 2009 as a communication interface between automation control systems (masters) and intelligent sensors and actuators (devices). In 2013 it evolved into an international standard for programmable controllers, IEC 61131-9 single-drop digital communication interface for small sensors and actuators (SDCI), whose purpose "extends the traditional digital input and digital output interfaces as defined in IEC 61131-2 towards a point-to-point communication link [enabling] the transfer of parameters to Devices and the delivery of diagnostic

(continued on page 4)

Linear in the News

In this issue...

COVER STORY

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DESIGN IDEAS

LINEAR CELEBRATES TWO ANNIVERSARIES

In August, Linear celebrated the 25th anniversary of the opening of its Singapore test facility, as well as the 20th anniversary of the company's Penang, Malaysia package assembly facility. These two facilities play an important role in Linear's vertically integrated manufacturing process. These facilities help ensure seamless communication between wafer manufacturing and packaging, enabling short and predictable product delivery times.

These state-of-the-art assembly and test operations complement Linear's two US-based wafer manufacturing operations in Camas, Washington and Milpitas, California. Such integrated operations represent a major competitive advantage for customers.

Singapore Test Operation Reaches 25 Years

Linear's Singapore test operation, started in 1989, has sophisticated capabilities for high volume testing capabilities of the company's numerous product types—for both integrated circuits and µModule® products. The manufacturing facility includes capability for high volume testing of many package types, tape and reel, as well as pack and ship capability to customers and distributors. The Singapore location also includes the Singapore Design Center, as well as the area sales office supporting Singapore, Malaysia, India and Australia/New Zealand.

Over the years, Linear has continued to expand its Singapore test operations, with expansion of its first building in 1997/1998 and a second 5-story building completed in 2005. A third major expansion is now underway, planned for completion by the end of next year. With headcount of nearly a thousand employees today, Linear has a highly experienced team, capable of testing the most high performance analog ICs.

Linear's Singapore test facility reaches 25-year milestone.

Penang, Malaysia Package Assembly Marks 20 Years

Started in 1994, Linear's package assembly operation has over 20 years of experience with wafer sort and assembly for a wide range of package types for both ICs and µModule products. Linear has transformed its Penang assembly operation significantly over the years in several phases, adding a second 6-story operations building to the prior facility. The facility now assembles nearly 40 different package types, as well as numerous µModule products. The Penang facility today employs over 1,500 people.

AWARDS

Best of Microwaves & RF Industry Award

Microwaves & RF magazine in June presented Linear with the award for Best Technical Support, as part of their annual Best of Microwaves & RF Industry Awards, highlighting "companies and engineers that rise to the challenge and provide cutting edge value to the industry." In presenting the award, the publication cited Linear's design support and technical documentation, located conveniently on its website. They highlighted the many design support options offered by Linear, including design simulations, quality and reliability information, and technical support.

EE Times China ACE Awards

Linear was recognized by *EE Times China* in September with the Product of the Year Award in the Power Management category for the LTM®4676. The device is a dual 13A or single 26A µModule step-down DC/DC regulator with a serial digital interface. The interface enables system designers and remote operators to command and supervise a system's power condition and consumption. The ability to digitally change power supply parameters reduces time-to-market and down time by eliminating what would have historically required physical hardware, circuit or system bill-of-materials modifications. The LTM4676 simplifies system characterization, optimization and data mining during prototyping, deployment and field operation. Target applications include optical transport systems, datacom and telecom switches and routers, industrial test equipment, robotics, RAID and enterprise systems where the cost of electrical utilities, cooling and maintenance are critical.

EE Times China also selected several other Linear products as ACE Award finalists:

Power Semiconductor/ Voltage Converter category: LTC3300-1 high efficiency bidirectional multicell battery balancer

RF/ Wireless/ Microwave category: LTC5551 300MHz to 3.5GHz ultra-high dynamic range downconverting mixer

Data Conversion/ Driver/ Clock category: LTC2378-20 20-bit, 1Msps, low power SAR ADC

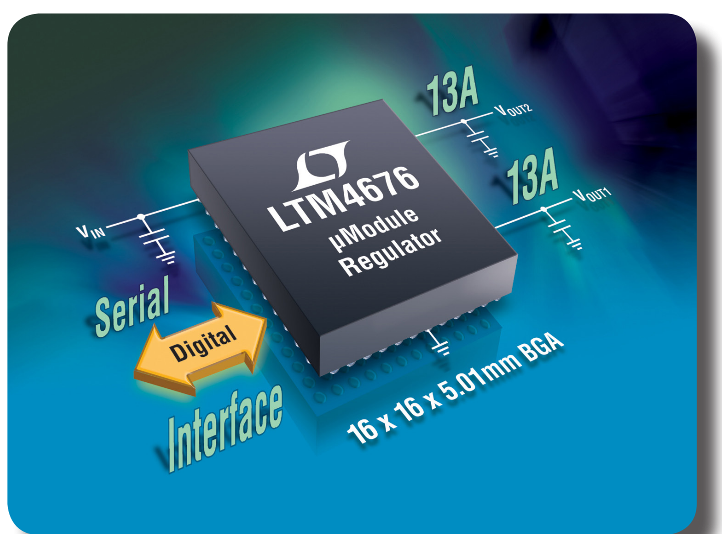
CONFERENCES & EVENTS

Dust Consortium, Tokyo Conference Center Shinagawa, Tokyo, Japan, October 17, 4F-402—Presenting the newly established Dust Consortium, a community of experts in various industries focus on wireless sensor networks, including press conference, study session and reception. More info at www.dust-consortium.jp/

Electronica 2014, Messe München, Munich, Germany, November 11-14, Hall A4, Booths 537 & 538—Linear will exhibit its broad range of analog products, with emphasis on automotive and industrial applications. Linear's Joy Weiss will participate on the *Markt & Technik* panel on "Energy Efficient Semiconductors – How They Will Change Our Lives – From Energy Harvesting to IoT, Smart Production, Smart Buildings, Smart Grids and Beyond" at 3:00 pm, November 12. More info at www.electronica.de/

Energy Harvesting & Storage Conference, Santa Clara Convention Center, Santa Clara, California, November 19-20, Booth L28—Presenting Linear's energy harvesting and Dust Networks® wireless sensor network products. Presentations by Joy Weiss on "Wireless Sensor Network Considerations for the Industrial Internet of Things (IoT)" and James Noon on "Energy Harvesting: Battery Life Extension & Storage." More info at www.idtechex.com/energy-harvesting-usa/eh.asp

Second Annual Analog Guru's Conference, Tokyo Conference Center, Shinagawa, Tokyo, Japan, December 5, 5F in the Large Hall—Presentations by Linear Technology Co-founder and Chief Technical Officer Bob Dobkin; Vice President, Power Management Products, Steve Pietkiewicz; and Dr. A. Kawamoto. More info at http://analog-guru.jp/



Linear was recognized by *EE Times China* in September with the Product of the Year Award in the Power Management category for the LTM4676, a dual 13A or single 26A µModule step-down DC/DC regulator with a serial digital interface.

To solve the problems of inrush current control and fault isolation, the LTC2874 generates L+ power supply outputs using a Hot Swap controller and n-type power MOSFETs. The resistance of the power path is kept low using external components for the MOSFETs and sense resistors, reducing IC heat dissipation and maximizing power efficiency during operation.

(LTC2874/LT3669, continued from page 1)

information from the Devices to the automation system."[3] This technology allows a distributed control system linked by fieldbus networks to operate actuators such as valve terminals; to operate, monitor and collect data from sensors; and to dynamically reconfigure their settings.

While IO-Link is fully described by a protocol stack that includes data link and application layers, it's built upon physical layer interfaces, or PHYs (Figure 1), normally connected by 3-wire cables up to 20m long and terminated by standard M5, M8 or M12 connectors. Two wires (L+ and L–) supply 200mA at 24VDC from master to device, and a third wire is a point-to-point, half-duplex data line (CQ) that operates at up to 230.4kb/s and shares the L– return. Optionally, a fourth wire can serve as a 24V digital line. In specialized configurations, this wire, along with a fifth, supply additional power for actuators.

Inherent to IO-Link systems is backward compatibility. For example:

- IO-Link tolerates unshielded connections, allowing reuse of standard industrial wire in existing installations.
- IO-Link devices can operate without an IO-Link master in a legacy digital switching mode called Standard I/O (SIO). Likewise, IO-Link masters can operate legacy devices using SIO.

A built-in load current on the CQ line at the master side (ILLM) facilitates operation of older sensors with discrete PNP-type outputs, which only drive high.

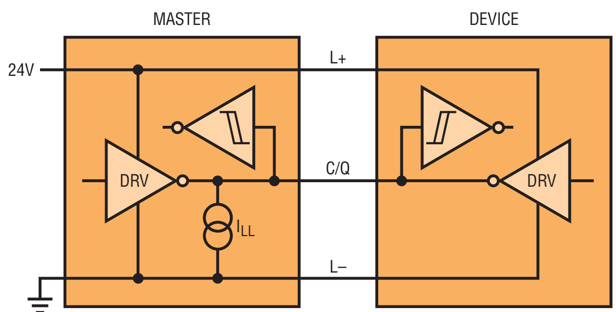


Figure 1. IO-Link physical layer interface (PHY). The device side consists of a high side (and optionally, low side) driver and a receiver. The master side has a push-pull driver, receiver, and a current sink that operates as a load for high side device outputs.

Any overview of IO-Link must introduce the scheme known as wake-up. Before IO-Link communication can commence, an IO-Link master must determine whether a connected device is compatible, and, if it is, identify the highest transmission rate supported: 230.4kb/s (called COM3 mode), 38.4kb/s (COM2), or 4.8kb/s (COM1). This requirement, combined with another—an IO-Link device must start up enabled to operate in SIO mode outside of an IO-Link system—poses a problem: how to gain the attention of an IO-Link device that's dutifully transmitting its sensor output.

The answer is by shouting. The master gains the attention of the device by issuing a wake-up request (WURQ), an 80µs, 0.5A current pulse, which is guaranteed to exceed the drive strength of an IO-Link device so that, upon detecting the pulse, it may stop driving and participate in a signaling exchange of data that informs the master of its maximum communication rate.

Once operating in communication mode, a master and device exchange data asynchronously in frames consisting of 11 bits (Figure 2a). Most of these UART frames are organized into larger units called M-sequences (Figure 2b), which begin with a message sent by the master paired with a reply message from the device.

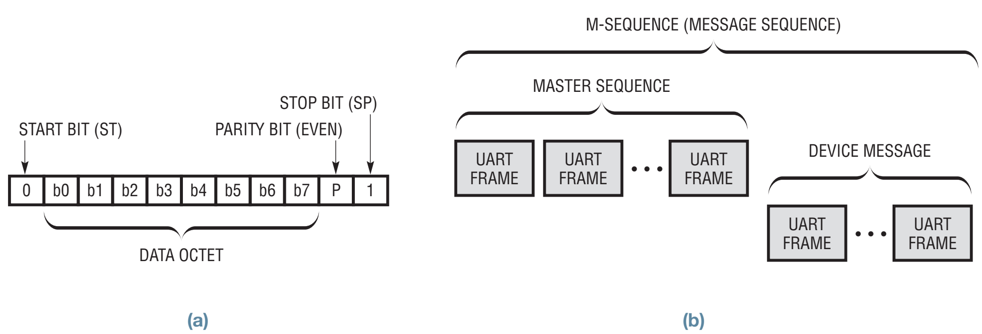
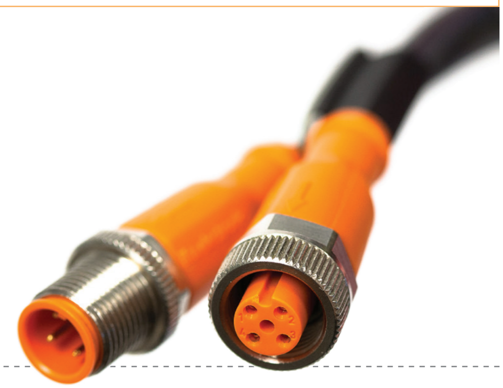


Figure 2. (a) IO-Link UART frames contain 11 bits of data. (b) Cyclic data is organized into paired exchanges of UART frames between master and device called M-sequences.

Two new interface parts target the first I/O technology for communication with sensors and actuators to be adopted as an international standard.



M-sequences transmit process data at predetermined rates in various available formats based on the type of device. Other transmission modes support configuration, maintenance and diagnostic functions.

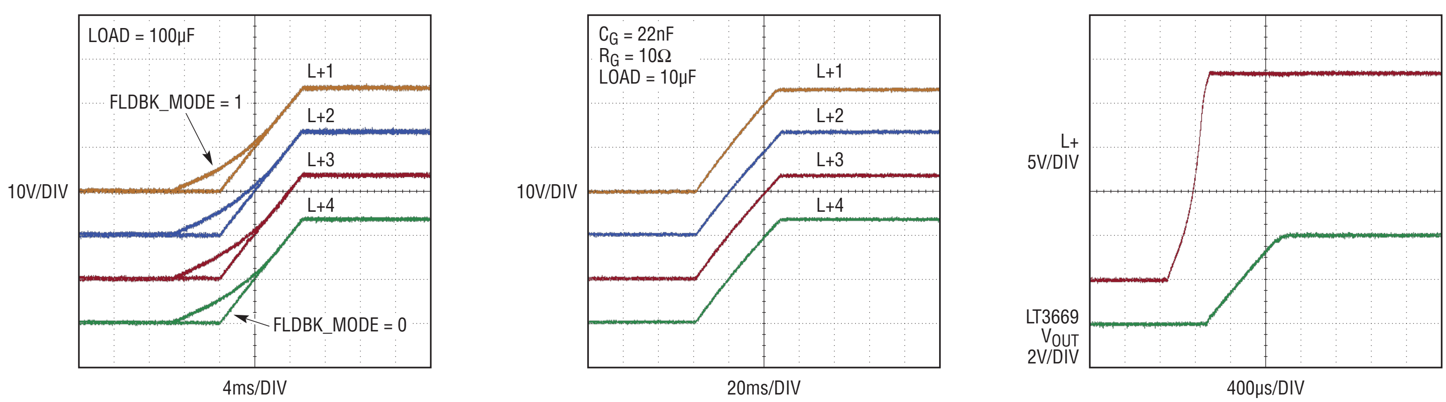
HOT SWAP CONTROLLER PROTECTION AND ADVANTAGES

The IO-Link standard has little to say about the L+ power-over-cable supply, suggesting only that 200mA and perhaps a power switch are needed. But potential problems abound when power is connected to arbitrarily large loads. Although high inrush current shouldn't damage the sturdy connectors used for IO-Link, it can still cause connector sparks and supply droop that can lead to system resets. Although the power-over-cable (POC) requirement of IO-Link (4W minimum) is modest compared to alternative technologies such as Power over Ethernet, anyone who has experienced faults at 24VDC knows they can be disruptive or catastrophic, leading to the question "is something burning?"

To solve the problems of inrush current control and fault isolation, the LTC2874 generates L+ power supply outputs using a Hot Swap controller and n-type power MOSFETs. The resistance of the power path is kept low using external components for the MOSFETs and sense resistors, reducing IC heat dissipation and maximizing power efficiency during operation. This arrangement gives users flexibility in MOSFET selection. Because this application requires the MOSFET to operate in linear mode during current limiting, older planar process MOSFETs such as Fairchild's FQT7N10 are recommended in order to avoid damage-causing hot spots that some newer versions and especially trench transistors can develop in this mode.[4] The controller provides SPI-operated on/off control, current limiting, and a programmable, timed circuit breaker function.

The LTC2874 adds flexibility to inrush current control by raising output supplies in a controlled manner determined either by current limiting (Figure 3a) or, for load independence, by an external RC network (Figure 3b). When enabled by a SPI register bit, the LTC2874 applies foldback behavior to the current limit in order to minimize power dissipation in the MOSFET during start-up and overcurrent conditions. An optional cable-sensing mode keeps the L+ power disabled until a cable is connected to the port.

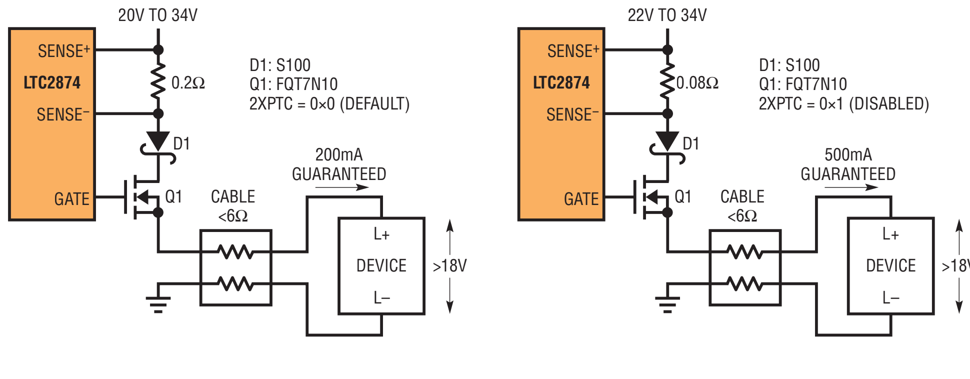
Because IO-Link devices usually require cable-supplied power to operate and communicate, there's normally no way for them to notify their master that power is absent. In such scenarios, master-side diagnostic capabilities are especially valuable. The LTC2874 reports changes to output supply "power good" status—along with a host of other conditions including overtemperature, input



(a) (b) (c)

Figure 3. L+ power supply output start-up (a) in current limit, (b) defined by a GATE resistor-capacitor network, and (c) for LT3669 application circuit configured for 4V buck output.

In IO-Link applications, the LTC2874 and LT3669 simplify wake-up request (WURQ) handling for their respective microcontrollers. On the master side, the LTC2874 generates WURQs of the correct polarity and timing automatically when a SPI register pushbutton bit is set. An interrupt request ($\overline{\text{IRQ}}$) provides a handshake to the microcontroller. On the device side, the LT3669 pulls the $\overline{\text{WAKE}}$ output flag low under certain conditions.



(a) (b)

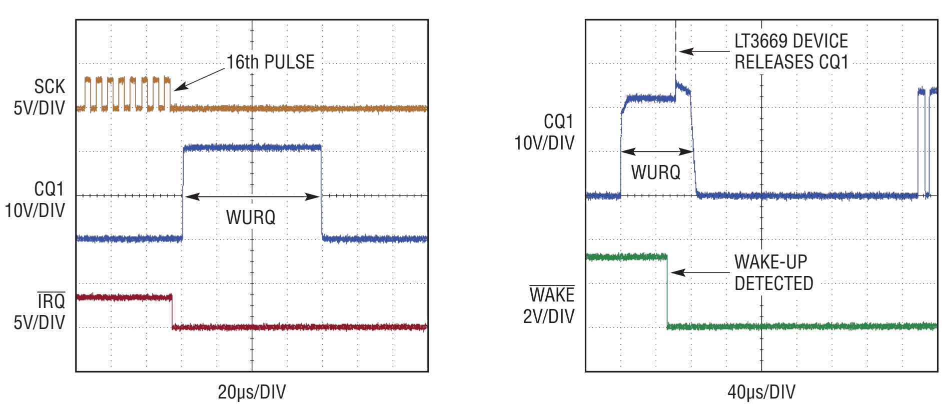
Figure 4. (a) LTC2874 configured for IO-Link-compliant 200mA device supply. Optional D1 provides supply isolation. (b) Alternative configuration for 500mA.

supply voltage level, and output supply overcurrent—to the microcontroller via its SPI port and interrupt request line. These monitoring capabilities enable the software to guide operators toward making faster repairs with less down time.

While L+ outputs must normally supply 200mA, the IO-Link standard requires a boosted current pulse capability at start-up, guaranteeing 400mA for 50ms upon reaching 18V. This requirement can be met indirectly by configuring the sense resistors for higher current and constraining the input supply (Figure 4b). A better approach (Figure 4a) uses the LTC2874's optional SPI-controlled current pulse function to meet the start-up requirement while preserving DC operating margin relative to the safe operating area (SOA) of the MOSFET. In both cases, the optional current-limit foldback helps protect the operating margin at lower output voltages where power dissipation in the MOSFET is highest.

Figure 5. (a) Self-timed 80µs 500mA wake-up request for an unloaded CQ line. (b) LTC2874-generated WURQ overdriving an LT3669 device PHY. Upon notifying its microcontroller that a WURQ pulse was detected, the LT3669 releases CQ1.

(a) (b)



EASY WAKE-UP GENERATION AND DETECTION

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While sensors built with digital IO-Link interface are likely less susceptible to noise than older analog-output models, their wide-swing (24V), single-ended signaling through unshielded wire can produce electromagnetic interference (EMI). The CQ line drivers of both the LTC2874 and LT3669 use slew-rate limiting circuitry to reduce the high frequency content of signaling emissions. Both products also offer a slow edge rate mode.

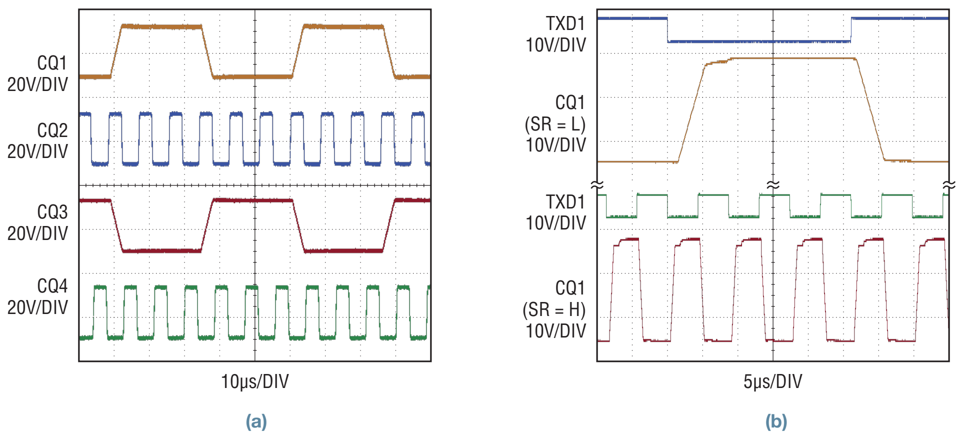


Figure 6. (a) LTC2874 CQ outputs operating with slow edge rate slew control active on two ports. Ports 1 and 3 are shown operating at COM2, or 38.4kb/s, while ports 2 and 4 operate at COM3, or 230.4kb/s. (b) LT3669 CQ1 output with slow and fast edge rate slew control applied for COM2 and COM3 operation, respectively.

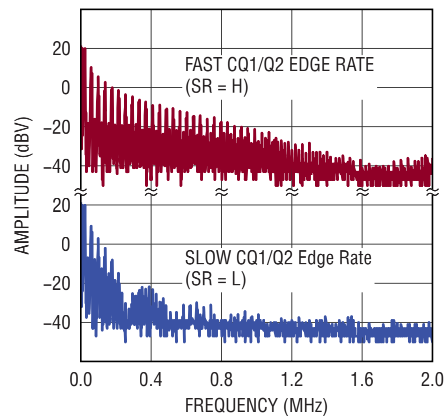


Figure 7. High frequency EMI reduction of LT3669 operating at 38.4kb/s with slow edge rate control (bottom) compared to fast edge rate control (top).

On the device side, the LT3669 pulls the $\overline{\text{WAKE}}$ output flag low (Figure 5b) when either of two conditions persists for more than 75µs:

- CQ1 does not approach its targeted rail within 2.95V while the driver is enabled (TXEN1 high);
- CQ1 is higher than V_{L+} – 2.95V while the driver is disabled (TXEN1 low).

The device side microcontroller can then respond by disabling the driver as needed, handshaking with the LT3669 (by toggling TXD1 while TXEN1 is low) to reset its WAKE state, and listening for a start-up protocol to be initiated by the master. Decision-making and response is left to the microcontroller, which, based on mode and context, must discern between valid WURQ signaling and invalid cases. The LT3669's straightforward approach to detection maximizes flexibility.

CONTROLLED EDGE RATES REDUCE EMISSIONS

While sensors built with digital IO-Link interface are likely less susceptible to noise than older analog-output models, their wide-swing (24V), single-ended signaling through unshielded wire can produce electromagnetic interference (EMI). The CQ line drivers of both the LTC2874 and LT3669 use slew-rate limiting circuitry to reduce the high frequency content of signaling emissions. Both products also offer a slow edge rate mode (Figure 6) that can be selected at lower data rates, suppressing the HF content further. The improvement achieved by the LT3669 slew rate control is shown in Figure 7.

RUGGED INTERFACES TOLERATE ABUSE

Any cable interface risks exposing sensitive electronics to uncontrolled harsh conditions. IO-Link requirements compound the problem, demanding a combination of operating voltage (up to 30V) and guaranteed current (200mA for each L+ output, 100mA DC for each CQ driver output, and 500mA for wake-up request pulses) that, in the event of an overload or shorted output, can result in high power dissipation in the driving MOSFET or IC. Consequently, the LTC2874 and LT3669 are designed to withstand a wide range of operating conditions, abuse and fault modes on their cable interfaces.

The LTC2874 tolerates cable voltages well outside its operating range (for example, 50V above GND for L+ and 50V from opposite rails for CQ) and has multiple ways to protect against an overload. First, current-limiting responds quickly

Table 1. Typical line interface electromagnetic compatibility (EMC) results when data sheet recommendations are followed.

	LTC2874	LT3669	CONDITIONS/NOTES
HUMAN BODY MODEL (ESD)	±8kV	±4kV	Without TVS Clamps
IEC 61000-4-2 (ESD)	±8kV (Level 4)	±6kV (Level 3)	Contact discharge DC1880A/DC1733A demo boards C_{PIN} = 470pF
IEC 61000-4-4 (EFT/Burst)	±4kV (Level 4) ±4kV (Level 4)	±4kV (Level 4) ±4kV (Level 4)	5kHz/15ms 100kHz/0.75ms
IEC 61000-4-5 (Surge)	±2kV (Level 2)	±2kV (Level 2)	1.2/50µs–8/20µs
TVS CLAMP	SM6T36A	SM6T39A	

to prevent damage and reduce power dissipation in the IC or (in the case of the L+ output) MOSFET. The current limit is fixed for CQ outputs and resistor-configurable for L+ outputs. If the overcurrent condition persists after a predefined timeout (mode-specific for CQ, programmable for L+), a circuit breaker function disables the output. After allowing a programmable time for cooling, the LTC2874 auto-retry function optionally re-enables the output. The pattern repeats, pulsing the output at a safely low duty cycle until either the overload is removed or a controller intervenes. Additionally, the IC has built in protection against overtemperature and supply overvoltage conditions.

The LT3669 is similarly well protected. It is reverse polarity protected and tolerates up to ±60V between any combination of L+, CQ1, Q2 and GND pins. This high voltage protection allows the use of standard TVS diodes for additional surge protection while still enabling operation with L+ voltages of up to 36V. This feature is especially attractive for devices operating in SIO mode above the operating voltage range of IO-Link.

The CQ1 and Q2 drivers are current-limited to a value defined by an external resistor. In the case of heavy loads or short circuits, additional high speed current limit clamping and a pulsing scheme keep power dissipation at a safe level. During pulsing, the on-time depends on the voltage level of the active outputs and the off-time is fixed (2.2ms typical), resulting in a duty cycle that adjusts downward as the output dissipates more power, keeping the IC safe and optimizing the time to drive heavy loads fully.

Like its master-side counterpart, the LT3669 has precise built in thermal shutdown and supply overvoltage protection. For junction temperatures above 140°C (typical), both line drivers are disabled while the LDO and V_{OUT} outputs continue to operate. Short-circuit flags $\overline{SC1}$ and $\overline{SC2}$ report a thermal shutdown event to the microcontroller.

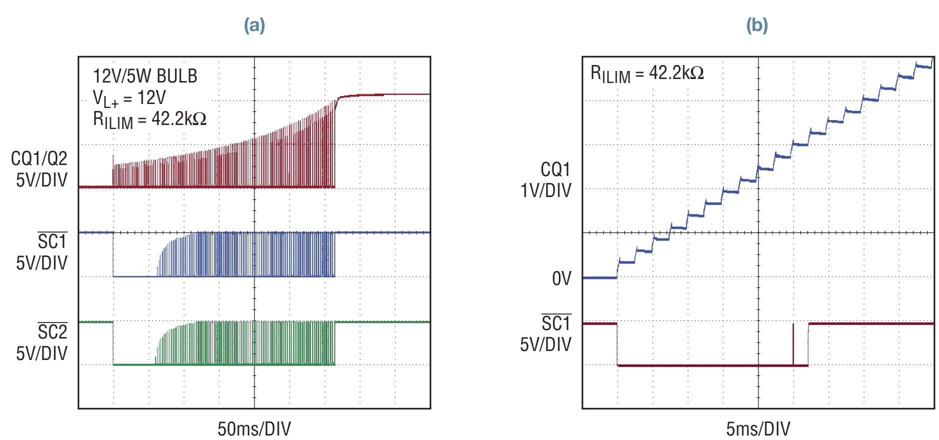
The cable interfaces of both the LTC2874 and LT3669 have built-in protection against electrostatic discharge and are easy to protect against a high level of electromagnetic interference (EMI) using standard TVS clamps (Table 1).

DRIVING HEAVY LOADS

While IO-Link drivers normally see capacitive loading of at most 4nF when connected by cable to another IO-Link PHY, the LTC2874 and LT3669 can drive more than 100mA (up to 250mA for the LT3669) for compatibility with legacy sensors and a variety of industrial loads. For example, this drive strength is sufficient to operate miniature incandescent lamps used in 12V and 24VDC systems.[5]

Turning on an incandescent lamp is nontrivial for an IC driver. Common tungsten

Figure 8. (a) LT3669 lighting a 12V 5W lamp and (b) driving a 470µF load. Short-circuit flags $\overline{SC1}$ and $\overline{SC2}$ are active if the driver's voltage is within 2.95V from the rail opposite the targeted one while the drivers are externally enabled.



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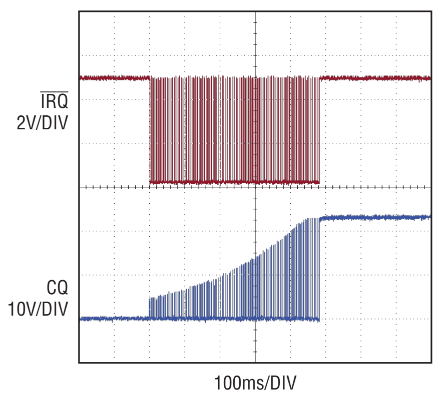


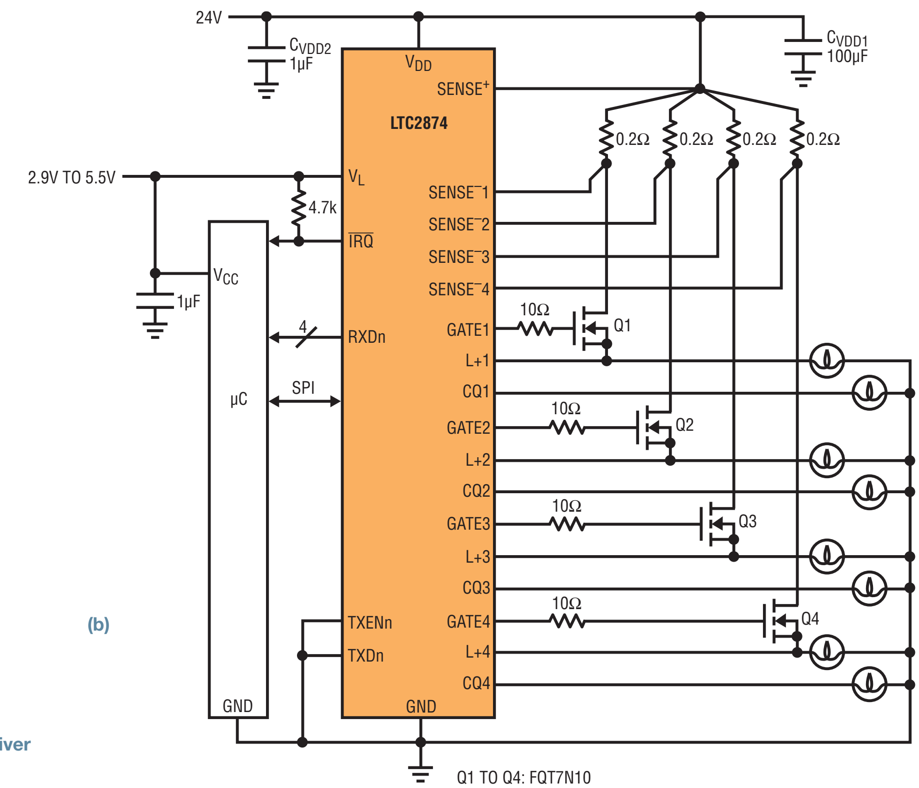


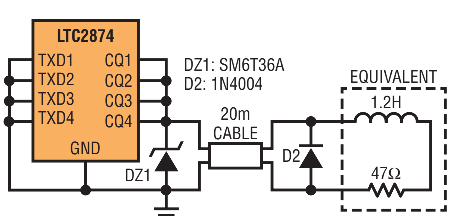
Figure 9. (a) LTC2874 turning on a 24V 2W lamp (b) octal lamp driver

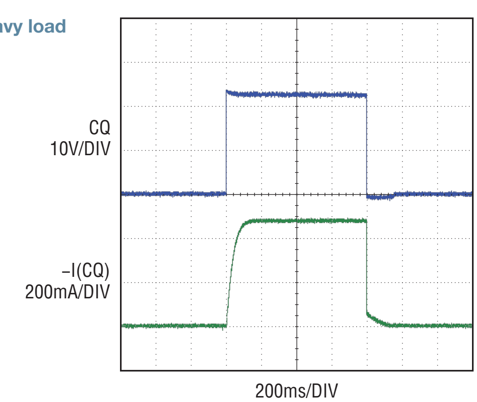
filaments are about 15 times more conductive when cold compared to when glowing hot. Consequently, while lighting a bulb, the driver must cope with a near short-circuit condition without overheating.

The LT3669 protects itself under such conditions by pulsing the output to limit the driver power dissipation. Figure 8a shows a 12V 5W bulb being turned on by the combined output of both LT3669 drivers (up to 500mA combined driving capability), and illustrates the variable load during this process. As the filament heats up, an increasing portion of the voltage is transferred to the lamp. Diagnostic flags $\overline{\text{SC1}}$ and $\overline{\text{SC2}}$—which pull low to indicate short-circuit conditions on the CQ1 and Q2 drivers, respectively—track the progress toward fully driving the light bulb.

The case of driving a large capacitor (Figure 8b) similarly flags a short-circuit condition at the start of the charging phase but only while the driver's voltage is less than 2.95V from the rail opposite the targeted one. Proper processing of these short-circuit flags allows the

Figure 10. Four dotted LTC2874 CQ outputs driving a heavy load





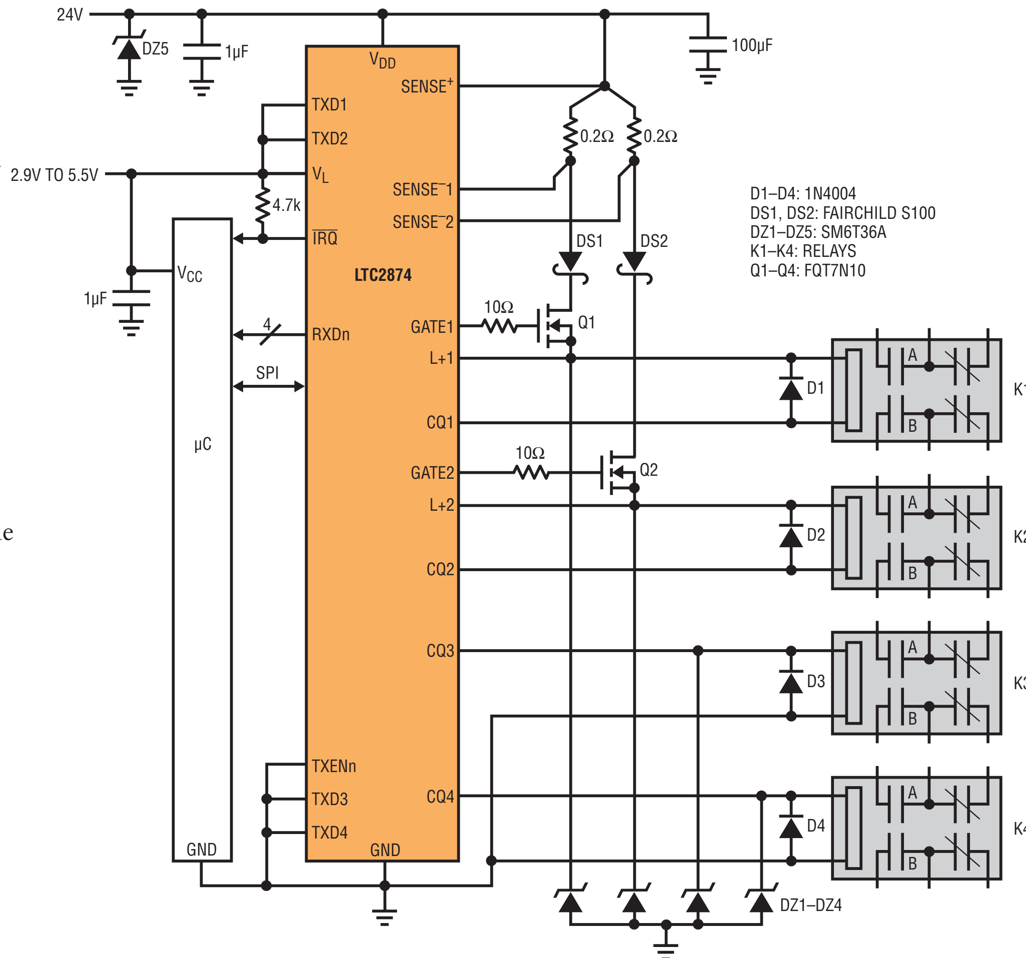
The cable interface of the LTC2874 and LT3669 can drive a variety of 12V and 24V relays. The CQ outputs can operate either high side or low side. In the case of the LTC2874, using the L+ power supply outputs as high side relay drivers, the CQ pins can sense the state of each relay, providing a handshake to the microcontroller via either the RXD outputs or the SPI bus. The LTC2874 can operate eight relays when driving with both CQ and L+ pins.

microcontroller to distinguish between real short circuits and heavy loads.

The LTC2874, too, can drive large loads without damage from overheating. Protective pulsing defined by the built-in circuit breaker and auto-retry timers will successfully turn on 1W miniature lamps. Larger lamps can be driven using more aggressive microcontroller-defined timing (Figure 9a) by connecting CQ drivers in parallel, or even by operating the L+ power supply outputs (configured for sufficient current) as high side drivers. Relying on all individual outputs, the LTC2874 can operate eight lamps (Figure 9b). Higher DC current is available when outputs are combined (Figure 10).

Driving unterminated, sometimes inductive, cable-connected industrial loads commonly produces ringing. The receivers of both parts contain programmable (LTC2874) or mode-specific (LT3669) noise suppression filters to ensure that

Figure 12. SPI-operated quad "ice cube" relay driver demonstrating both low side and high side operation.



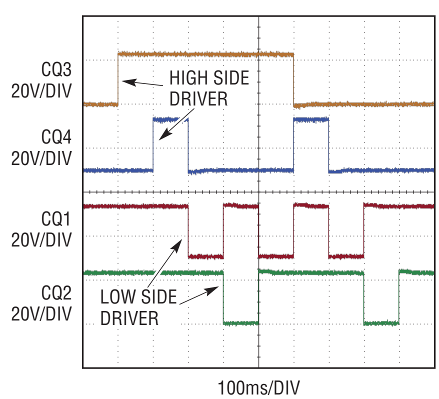
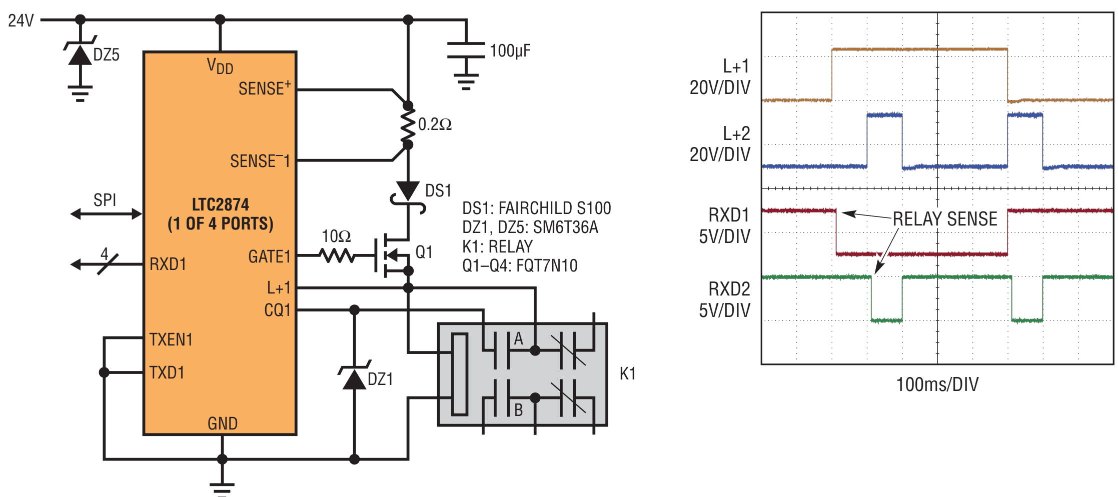


Figure 11. Each CQ output guarantees twice the current required to operate a Potter and Brumfield (Tyco) KRPA-11DG-24.

The LTC2874 and LT3669 are designed to withstand a wide range of operating conditions, abuse and fault modes on their cable interfaces.

Figure 13. When L+ outputs operate relays, the CQ lines can sense the state of each relay.



microcontrollers see clean transitions, whether switching in SIO mode or communicating at the fastest IO-Link rate (COM3).

DRIVING RELAYS

The cable interface of the LTC2874 and LT3669 can drive a variety of 12V and 24V relays (Figure 11). The CQ outputs can operate either high side or low side (Figure 12). In the case of the LTC2874, using the L+ power supply outputs as high side relay drivers, the CQ pins can sense the state of each relay (Figure 13), providing a handshake to the microcontroller via either the RXD outputs or the SPI bus. The LTC2874 can operate eight relays when driving with both CQ and L+ pins.

EFFICIENT AND FLEXIBLE POWER CONVERSION KEEPS TINY SENSORS COOL

Sensors typically incorporate a transducer that converts a physical parameter to an electrical signal, a microcontroller that performs analog-to-digital conversion and signal processing, and a PHY interface that level shifts to the high voltage at the cable interface. Typically, transducers operate from 3.3V to 15V and microcontrollers operate from 1.8V to 5V. Given the IO-Link L+ typical operating voltage of 24V, it's clear that some sort of power conversion is required for proper operation of these lower voltage sensor parts.

While a simple linear regulator is capable of this task, internal power dissipation limits its application to smaller loads. For example, for an LDO generating 5V from 24V, at 10mA the pass transistor dissipates 190mW, which is

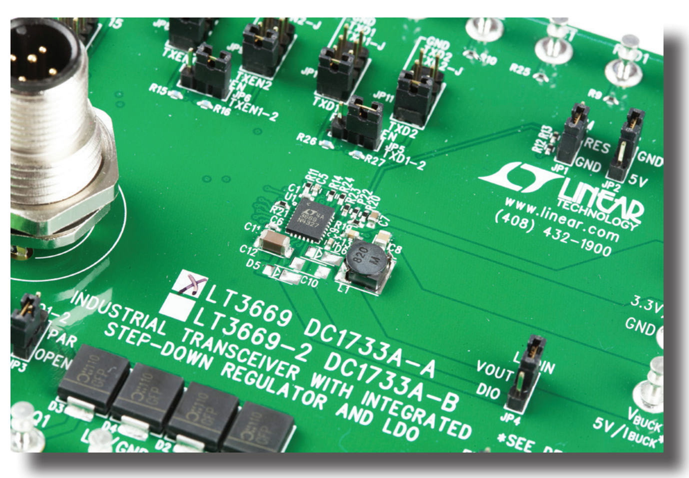


Figure 14. Compact device-side IO-Link PHY and dual power supply solution using the LT3669

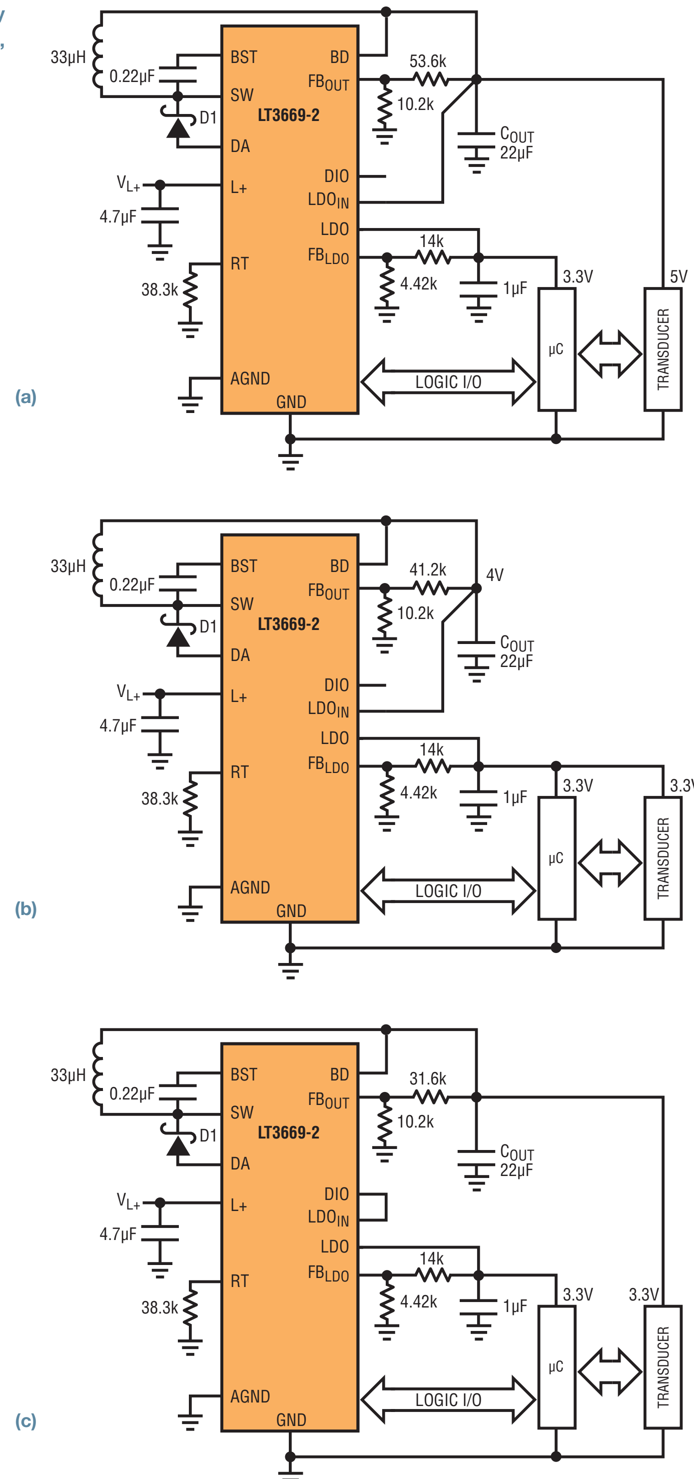
Sensors offer a wide breadth of physical measurement capabilities, and with that just as many varied power requirements. It is impossible to meet this range of requirements with just a switching regulator or LDO. Both are built into the LT3669 and LT3669-2, allowing these devices to meet most power requirements without additional converters.

tolerable, but at 100mA the wasted power increases to 1.9W, which would significantly raise the die temperature.

At these power levels, a switching regulator offers a clear advantage: by reducing the internal power dissipation, the sensor can operate reliably at much higher ambient temperatures. Both the LT3669 and LT3669-2 integrate a step-down switching regulator in addition to an LDO. The LT3669-2 targets applications requiring medium to high power levels for the sensor's low voltage circuitry. With this in mind, it does not incorporate the catch diode, keeping that external. With an external catch diode, it typically achieves 78% efficiency for 24V-to-5V conversion at its rated load current of 300mA, corresponding to 423mW of internal power dissipation. Although efficiency falls to 69% at 100mA, the internal power dissipation is still only 225mW, 8 times lower than the linear regulator equivalent. For less power demanding circuitry, the LT3669 (Figure 14) reduces cost and area by integrating the catch diode, attaining slightly lower efficiency of 64% at its maximum load current of 100mA.

Sensors offer a wide breadth of physical measurement capabilities, and with that just as many varied power requirements. It is impossible to meet this range of requirements with just a switching regulator or LDO. By having both built into the LT3669 and LT3669-2, these devices can meet most power requirements without additional converters, saving significant space, design time and cost.

Figure 15. Various power supply configurations for the LT3669-2, with pin LDO_{IN} connected to the buck regulator output in (a) and (b) for best efficiency and to pin DIO in (c).

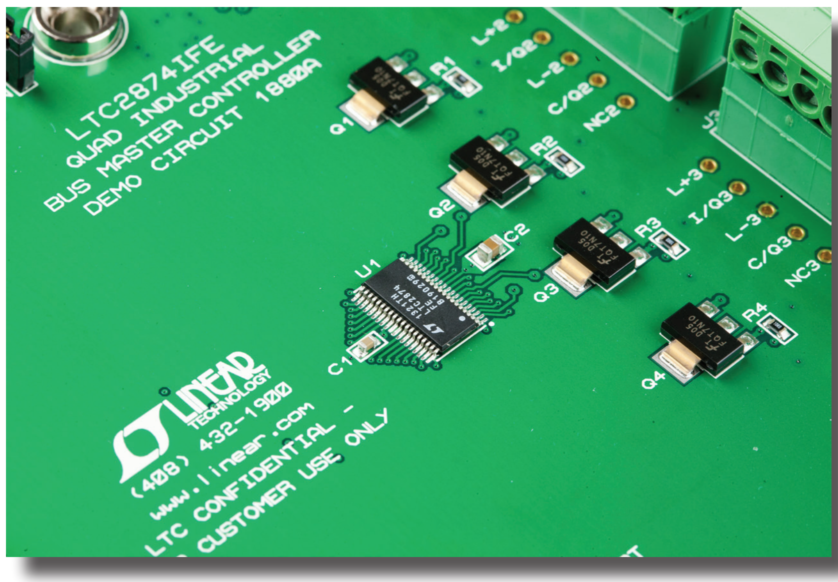


The LDO delivers up to 150mA of load current, depending on the setup. With a dedicated input pin LDO_{IN}, it can be configured to take power from any power source from 2.25V to 40V. The LDO can operate either from the switching regulator output, or separately. Figure 15 shows a number of possible supply configurations. Connecting the LDO input pin to the output of the switching regulator (Figures 15a and 15b) yields the highest efficiency. If this isn't possible, the LDO's input pin can take power from L+ indirectly by connecting it to DIO (an internal diode connects between L+ and DIO) to preserve reverse polarity protection, as shown in Figure 15c. In this case the LDO's maximum load current is reduced due to current limit foldback.

BUILDING LARGER MULTIPORT MASTERS

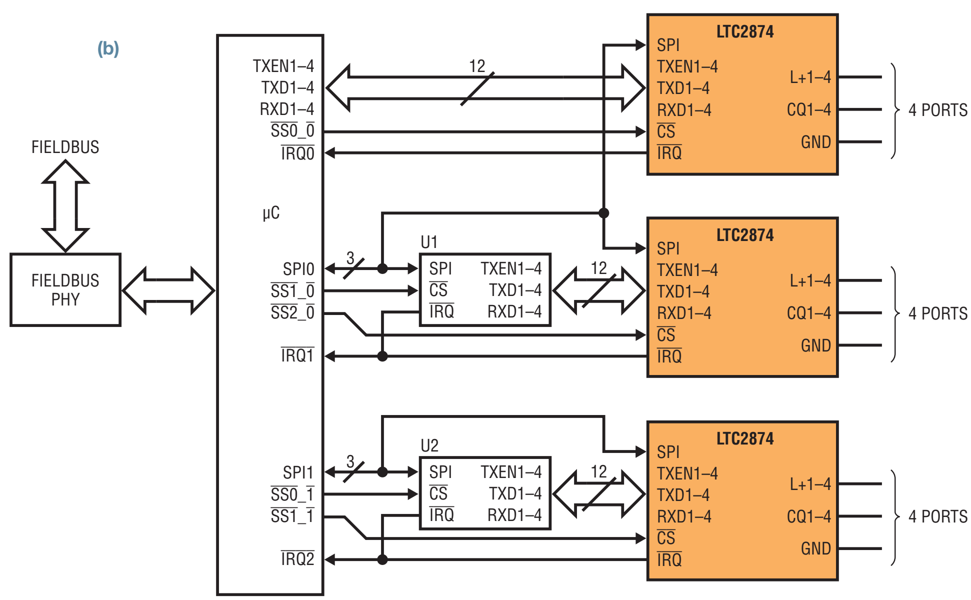
The dense integration of a quad IO-Link master PHY into QFN (Figure 16a) and TSSOP packages makes the LTC2874 ideal for building larger multiport masters. For example, a 12-port master is shown in Figure 16b. Four ports connect to the microcontroller's built-in UARTs; the rest are serviced via SPI port expanders (U1, U2), where their UARTs are implemented using dedicated ARM microcontrollers running optimized code. This system is extendable, limited only by the bandwidth and capabilities of the primary microcontroller. Linear Technology's demonstration circuit DC2228A (Figure 17a), a multiport master built in this way, supports connections to eight IO-Link devices such as the DC2227A (Figure 17b).

Figure 16. (a) Dense integration enables compact multiport masters to be built using the 4-port LTC2874. (b) Master power and communications PHY for 12 ports.

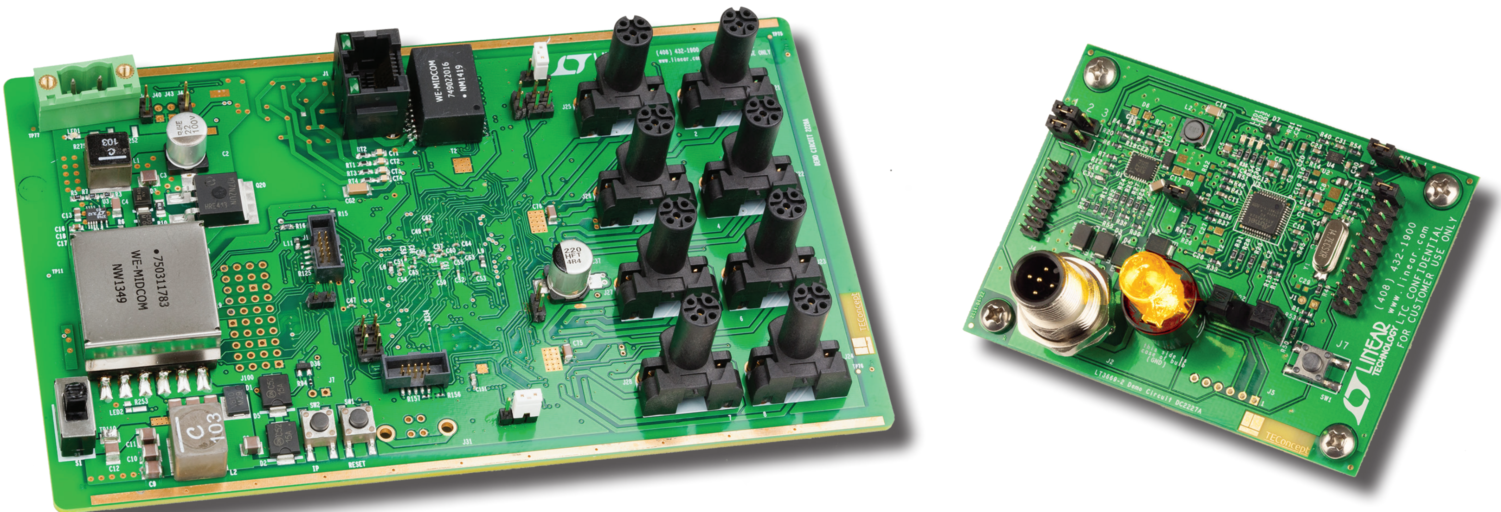


(a)

(b)



The dense integration of a quad IO-Link master PHY into QFN and TSSOP packages makes the LTC2874 ideal for building larger multiport masters.



(a) (b)

Figure 17. IO-Link application demonstration circuits (a) DC2228A, an 8-port master built with LTC2874 and powered optionally by 90W Power over Ethernet (LTPoE++™), and (b) DC2227A, a device-side sensor application built with LT3669-2, a high precision temperature sensor, a photoelectric sensor, and a 28V 100mA incandescent lamp

IEC 61131-2 SUPPORT

The cable interfaces of both parts are, as part of the IO-Link definition, loosely compatible with IEC 61131-2, an older standard specifying digital I/O in programmable logic controller (PLC) applications.[6] This compatibility includes the optional second driver Q2 on the LT3669. Additionally, the LTC2874's built-in current-sinking loads have a setting that meets the requirements for Type-1 inputs while keeping power dissipation to a minimum.

COMPLETE IO-LINK COMPATIBLE POWER AND SIGNALING INTERFACE

Both sides of an IO-Link application, each with its own microcontroller, are shown in Figure 18. The master-side LTC2874 supports four such ports. The device-side LT3669 guarantees 100mA at the 5V switched output, the 3.3V LDO output, and both driver outputs. Connector pin 2 is optional, supported only at the device side.

CONCLUSION

The LTC2874 and LT3669 offer unmatched integration and flexibility for building IO-Link systems. The LTC2874 includes power, signaling, control and diagnostic capabilities for four ports, simplifying the design of larger multiport masters. The LT3669 includes a spare driver (Q2), LDO, and a step-down regulator that helps minimize temperature rise in compact sensor assemblies. The wide operating ranges of these devices (8V to 34V for the LTC2874, and 7.5V to 40V for the LT3669), allow them to drive a variety of industrial loads. Both parts are ruggedized for the harsh environment of 24V automation. ■

The LTC2874 and LT3669 offer unmatched integration and flexibility for building IO-Link systems. The LTC2874 includes power, signaling, control and diagnostic capabilities for four ports, simplifying the design of larger multiport masters. The LT3669 includes a spare driver (Q2), LDO, and a step-down regulator that helps minimize temperature rise in compact sensor assemblies.

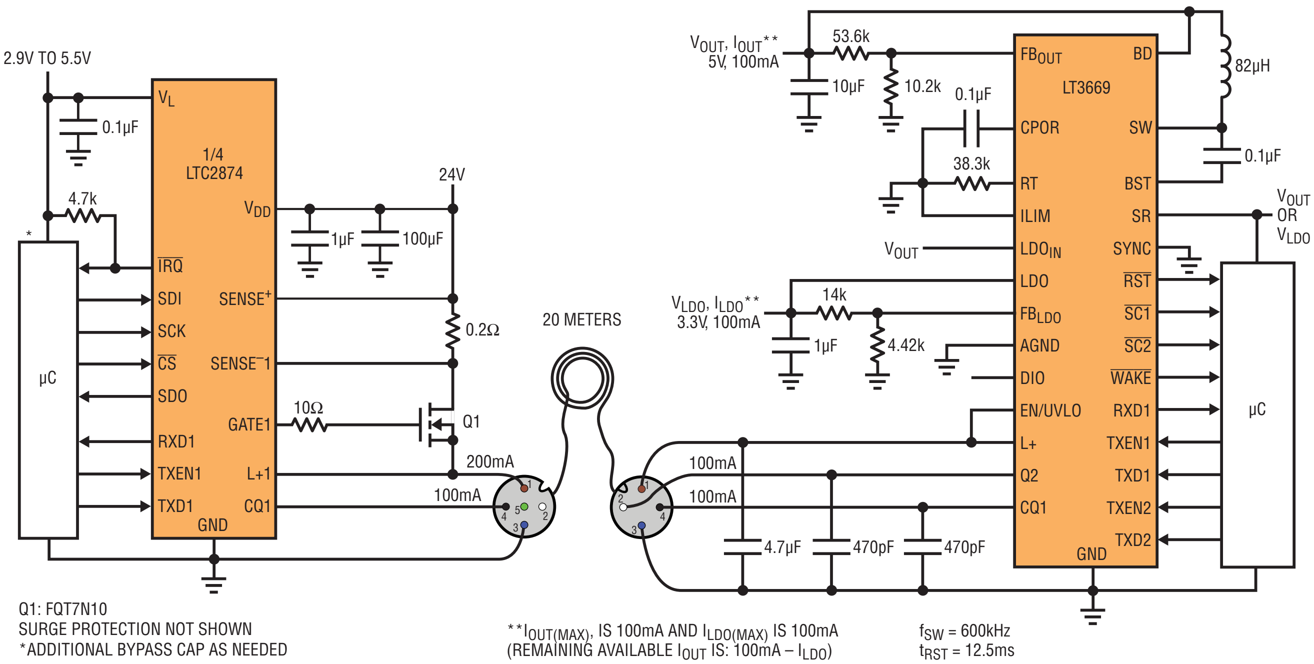


Figure 18. Complete 24V 3-wire power and signaling interface to sensor or actuator. One of four available master ports is shown.

Notes

[1] Tsun-kit Chin and Dac Tran, "Combine power feed and data link via cable for remote peripherals," *EE Times*, November 10, 2011.

[2] www.io-link.com. IO-Link is a registered trademark of PROFIBUS User Organization (PNO).

[3] IEC 61131-9 ed.1.0

[4] Paul Schimel, "MOSFET Design Basics You Need To Know," Parts 1 and 2, *Electronic Design*, April 4 and April 21, 2010.

[5] "Safely Light Miniature Incandescent Lamps Using LTC2874," Kevin Wrenner, January 2014. http://www.linear.com/solutions/4534

[6] IEC 61131-2, Third edition, 2007-07.

High Step-Down Ratio Controller Combines Digital Power System Management with Sub-Milliohm DCR Sensing and Accurate PolyPhase Load Sharing

James A. McKenzie

The increasing complexity of electronics, particularly large computing systems, has exerted pressure on power supplies to improve efficiency, transient response, monitoring and reporting functionality, and digital control. High efficiency is paramount in distributed systems, where high step-down ratios from intermediate voltage busses are used to create local low voltage supplies sourcing high currents. Sensitive low voltage subsystems require accurate output voltage regulation single-cycle load step response. Such needs are frequently met with PolyPhase® designs located in close proximity to their point of load.

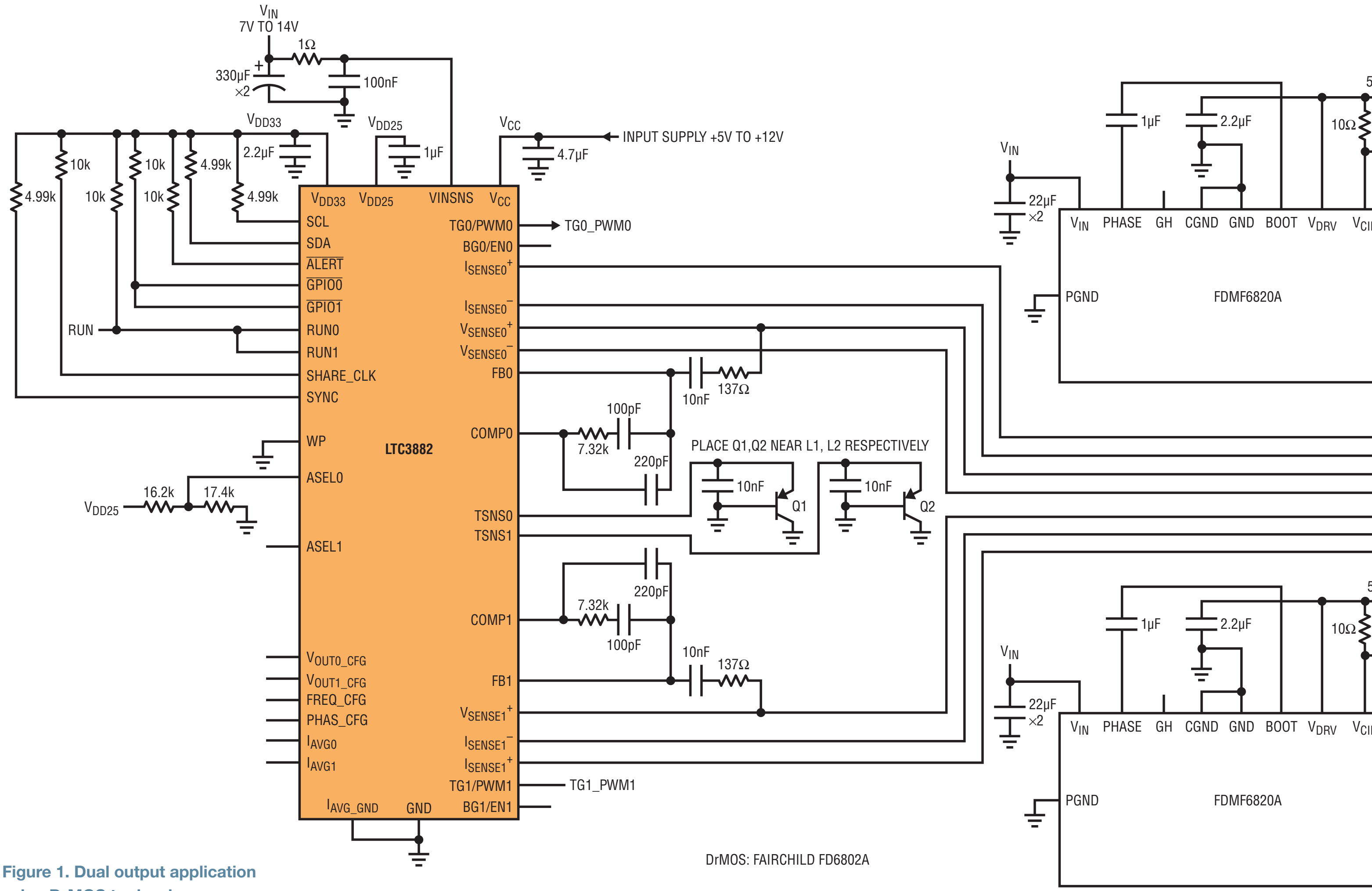
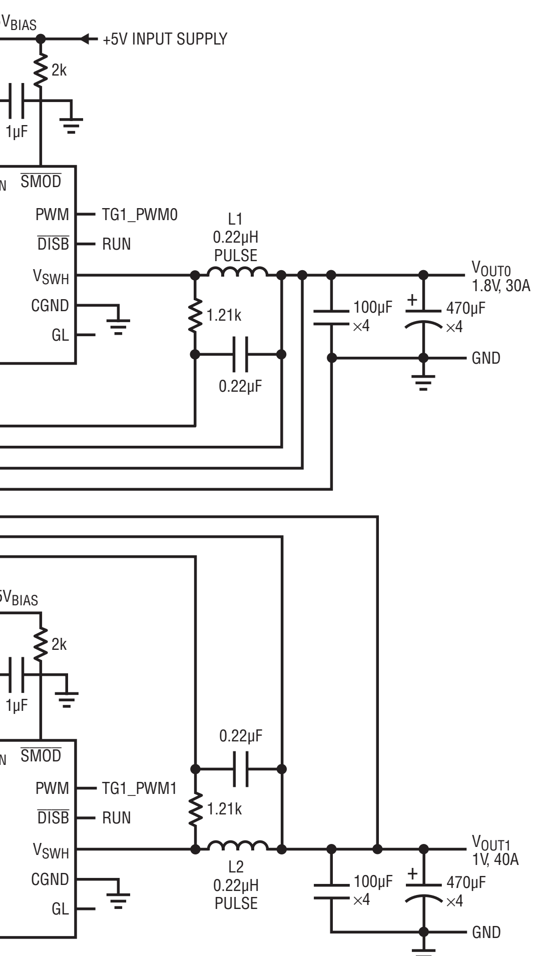


Figure 1. Dual output application using DrMOS to develop over 90W of output power

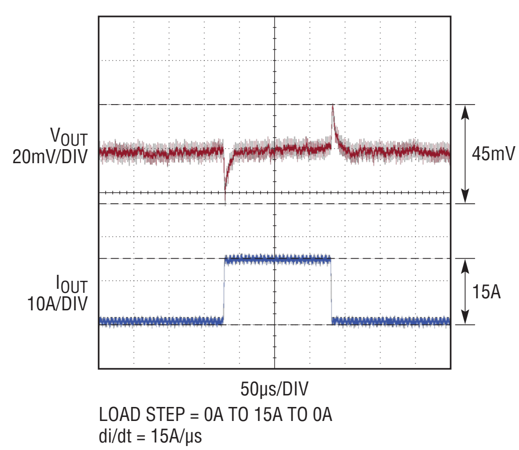
The LTC3882 satisfies the broad demands placed on the modern power supply. It is a dual channel DC/DC synchronous step-down PWM controller with PMBus-compliant serial interface. Each channel can produce independent output voltages from 0.5V to 5.25V. Up to four LTC3882s can operate interleaved in parallel, creating single-output rails containing up to eight phases.

Higher system complexity translates into demand for nontraditional features from the power subsystem. Host systems can have dozens of local voltage rails delivering a wide range of power levels. The power subsystem must be capable of accurately reporting key operating parameters and providing rapid, autonomous fault response.



The LTC3882 satisfies the broad demands placed on the modern power supply. It is a dual channel DC/DC synchronous step-down PWM controller with PMBus-compliant serial interface. Each channel can produce independent output voltages from 0.5V to 5.25V. Up to four LTC3882s can operate interleaved in parallel, creating single-output rails containing up to eight phases. Multiples of 6- or 8-phase designs can also be developed when power or reliability dictate higher phase counts. Once its onboard EEPROM is programmed, the LTC3882 can operate autonomously without host support, even during a fault condition. The LTC3882 is available in a 40-lead 6mm × 6mm QFN package. Figure 1 shows a typical solution.

Figure 2. Load step response of Figure 1 circuit



ARCHITECTURE FOR HIGH PERFORMANCE LOAD STEP RESPONSE AND REGULATION

To support high step-down ratios and fast load transient response, the LTC3882 uses a constant frequency, leading-edge modulation voltage mode architecture. This architecture is combined with a very low offset, high bandwidth voltage error amplifier and proprietary internal feedforward compensation. The low output impedance of a true voltage amplifier allows implementation of flexible Type III loop compensation. Internal feedforward compensation instantaneously adjusts duty cycle for changes in input voltage, significantly reducing output overshoot or undershoot. It also creates constant modulator gain independent of input voltage, Each LTC3882 PWM channel provides five selectable PWM control protocols for interfacing to power stage designs that have 3.3V-compatible control inputs. The user can choose the optimum type of power stage for the design requirements: discrete FET drivers, DrMOS devices or power blocks. These can be mixed and matched on a per channel basis.

Figure 3. Transient response with AVP enabled

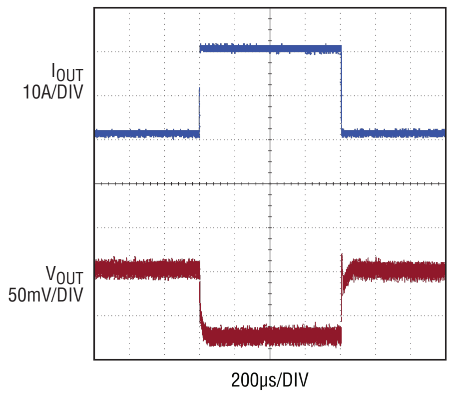
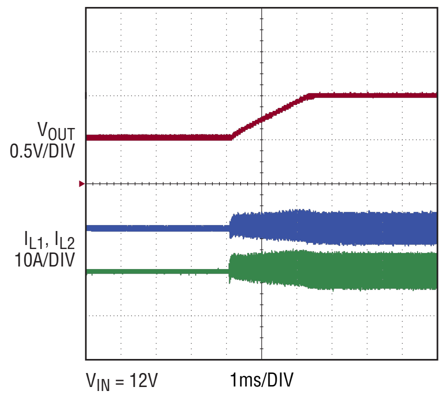


Figure 4. Continuous conduction mode start-up with output prebiased



affording more aggressive loop compensation with improved transient response.

Both channels feature remote output voltage sense. Channel 0 has a corresponding negative sense input for ground offsets. The remote negative sense for channel 1 is the package ground paddle. A separate control loop yields exceptional DC and dynamic PolyPhase load sharing. This high performance architecture can deliver excellent load transient response. Figure 2 shows a typical output transient for an LTC3882 power supply.

Leading-edge modulation affords fast, single-cycle response to output load steps and does not restrict minimum duty cycle. PWM output control pulses can become vanishingly small with this scheme, and minimum on-time is normally limited by the power stage design, not the controller. This, plus feedforward compensation, facilitates robust operation at high step-down ratios. The LTC3882 operates with input power bus voltages from 3V to 38V. Stable operation with no pulse-skipping at step-down ratios approaching 25:1 is possible, even at higher switching frequencies.

For compact solutions, stable operation is possible using only ceramic output capacitors, and the LTC3882 features programmable active voltage positioning (AVP), allowing further optimization of ESR and reduction in output capacitor size. Figure 3 shows a typical example of AVP operation.

Depending on the needs of the application, peak efficiency or solution size can be prioritized by choosing an optimal operating frequency. The LTC3882's 250kHz to 1.25MHz programmable switching frequency supports optimization of inductor size and output current ripple. The LTC3882 can also serve as a shared PWM clock master or accept an external clock input for synchronization to another system time base. For very small magnetic-component footprints, a higher frequency version is available. Contact Linear Technology for details.

As shown in Figure 4, the LTC3882 has the ability to start into a prebiased output without perturbing it, regardless of its soft-start parameter programming or inductor current operating mode (continuous or discontinuous).

LOW DCR SENSING FOR HIGH POWER

At relatively high output currents, conversion efficiency must be maximized to limit heat production and minimize related cooling costs due to conduction losses. Some conduction losses occur in the current sensing element used for detecting output overload and other functions. In a step-down topology, the sense element is key to efficiency because it continuously sees the full DC load current plus additional current ripple.

The LTC3882 monitors critical supply parameters with an internal 16-bit ADC. Digital readback via PMBus is available for input and output voltages, output currents, duty cycles and temperatures. The LTC3882 tracks, maintains and provides peak values for these parameters.

Figure 5. 2-channel efficiency and loss using FDMF5820A DrMOS power stage

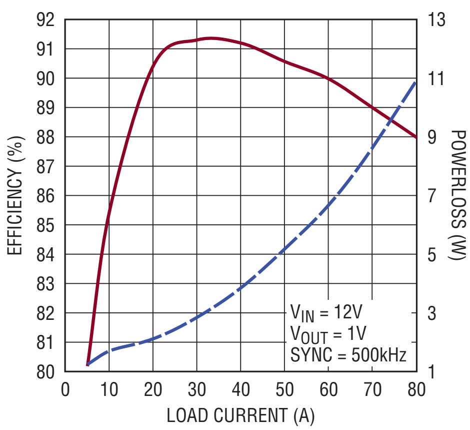
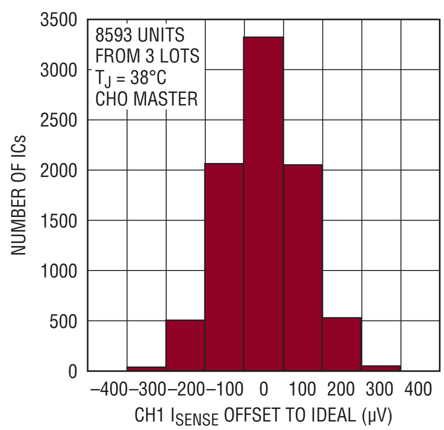


Figure 6. Typical slave I_{SENSE} offset to ideal (master)



The LTC3882 supports conventional sense resistor topologies as well as low DCR sense schemes that can produce a full-scale voltage of only a few tens of millivolts. Trimmed internal auto-zeroed gain amplifiers maintain fast and accurate supervisor detection of output overcurrent conditions. The classical fixed ramp voltage mode PWM architecture allows large signal control of the duty cycle and eliminates noise concerns that could be created by low DCR designs using current-based control schemes. Typical efficiency and loss for a LTC3882 power supply built with Fairchild FDMF5820A DRMOS devices is shown in Figure 5.

DIGITAL ENHANCEMENTS IMPROVE OUTPUT ACCURACY

The LTC3882 contains an optional digital output servo function. When enabled, the 16-bit ADC output for channel voltage is used to servo to the desired average output value. In this case, the converter has an impressive typical output error of only ±0.2% and a worse case error over temperature of ±0.5%. These tolerances are guaranteed over an output voltage range of 600mV to 5V.

ACCURATE LOAD CURRENT SHARING

For PolyPhase operation, the LTC3882 features a separate current sharing loop that provides accurate load balancing, an improvement over conventional voltage mode converters. Channels are designated as control masters or as slaves by pin strapping. The IAVG pin on the master channel provides a voltage analog of its instantaneous output current. A filter capacitor of 100pf to 200pf is added to this line, which is then routed to all slave phases. The slaves use this information and the primary COMP control voltage from the master to match their own output current to that of the master. Figure 6 shows the typical cumulative current sense offset of a slave phase. For low DCR sensing, this translates into typical DC current matching of better than 2% at full output power. Figure 7 shows that this matching is maintained dynamically through high speed load steps.

WIDE SELECTION OF POWER STAGES

Each LTC3882 PWM channel provides five selectable PWM control protocols for interfacing to power stage designs that have 3.3V-compatible control inputs. The user can choose the optimum type of power stage for the design requirements: discrete FET drivers, DRMOS devices or power blocks. These can be mixed and matched on a per channel basis, allowing optimization of power subsystem partitioning, size and cost, according to the power delivery needs of each rail.

There are many reasons to consider use of a power systems management (PSM) controller. PMBus commands can be issued to the LTC3882 to set output voltage, margin voltages, switching frequency, output on/off sequencing and other operating parameters. The LTC3882 supports over 100 PMBus commands, both standard and custom.

ACCURATE OPERATING PARAMETER TELEMETRY

The LTC3882 monitors critical supply parameters with an internal 16-bit ADC. Digital readback via PMBus is available for input and output voltages, output currents, duty cycles and temperatures. The LTC3882 tracks, maintains and provides peak values for these parameters.

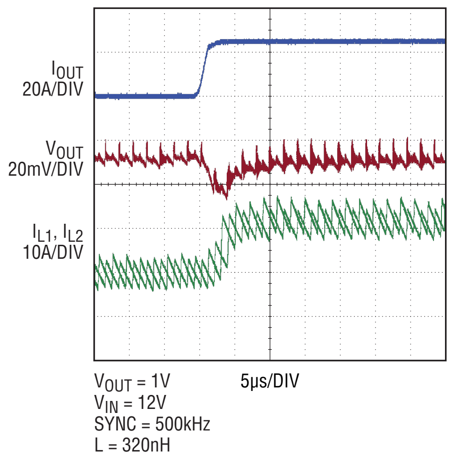
Beyond basic supply parameter telemetry, the LTC3882 can report a wide range of internal and external status information to the system host over the PMBus.

FAST, PROGRAMMABLE FAULT RESPONSE

Faults can be detected and communicated using a shared fault bus between LTC3882s as well as other Linear Tehnology PSM family members, such as the LTC3880. The LTC3882 provides a standard open-drain $\overline{\text{ALERT}}$ output with compliant ARA response for notification of a wide range of fault conditions to the bus host. The LTC3882 implements high speed, low level hardware responses to critical faults to protect the power stage and downstream system load. PMBus commands can then be used to configure higher-level responses, mask faults to the system, and determine which faults are propagated to the shared fault bus. This provides flexibility in dynamically managing fault handling at the system level, even after hardware has been designed and fabricated.

The LTC3882 includes extensive logging capability that records the state of converter operating conditions immediately prior to a fault. This log can be enabled and stored to internal EEPROM to provide a black box recorder function for in-system diagnosis or subsequent remote debugging of abnormal events.

Figure 7. Dynamic load balancing during an output transient



USING DIGITAL PROGRAMMABILITY TO ADVANTAGE

There are many reasons to consider use of a power systems management (PSM) controller. PMBus commands can be issued to the LTC3882 to set output voltage, margin voltages, switching frequency, output on/off sequencing and other operating parameters. In total, the LTC3882 supports over 100 PMBus commands, both standard and custom. A principal benefit of this programmability is reduced design cost and faster time to market.

Once a fundamental hardware macro design is complete, many variations can quickly be created, brought to operation, and verified as needed by simply adjusting digitally programmable parameters inside the LTC3882 controller. Adjustments can continue beyond production release as needed, including fully synchronized resequencing/retiming of power rails. Combined with optional external resistor programming of key supply parameters, this kind of flexibility can avoid risky, costly PCB spins or hand-wired modifications due to last-minute changes in requirements or evolving system use.

Final configurations can be stored to internal EEPROM using a variety of means, including custom factory programming. Once a configuration is stored, the controller powers up autonomously to that state without burdening the host for additional programming. However, even after a final EEPROM configuration is loaded, optional external programming resistors can be used to modify a few key operating parameters: output voltage, frequency, phase and bus address.

Once designed, the multiple addressing schemes supported by the LTC3882 allow the system to communicate with devices globally or selectively at the rail, device or individual channel level, depending on control and monitoring requirements. PMBus then facilitates sophisticated high level system operations, such as energy-efficient application load balancing, local phase shedding, fault containment/redundancy or interactive preventive maintenance. These functions would simply not be cost-effective or even possible with conventional power supply components in large systems.

Once designed, the multiple addressing schemes supported by the LTC3882 allow the system to communicate with devices globally or selectively at the rail, device or individual channel level, depending on control and monitoring requirements.

DESIGN DEVELOPMENT SUPPORT

Linear Technology offers an array of free software tools to assist with design, development and debug of LTC3882-based power supplies. LTpowerCAD™ provides recommendations for component values and performance estimates specific to the target application. This PC-based tool guides the user through the entire PWM design process, reducing development effort and reducing cycle time. It shows real-time results of feedback loop stability, and the design can be exported to LTspice® for additional design verification. PCB layout examples can also be provided.

LTpowerPlay™ is a PC-based tool with a GUI that supports a wide range and combination of Linear Technology PSM products. The LTC3882 PMBus command and feature set is consistent with other devices in the Linear PSM family. It operates seamlessly with these devices for flexibility and system-level optimization of power management design. LTpowerPlay provides a comprehensive, cohesive PMBus development environment with full configuration, internal EEPROM programming, fault logging and real-time telemetry data/graphing. This can be especially helpful to power supply designers needing to quickly bring up a large, complex power subsystem. The tool can communicate with custom designs and standard demo circuits, such as the DC1936A. Both of these tools and other design reference materials are available at www.linear.com.

Proven firmware examples for use with the LTC3882 are available to qualified customers. Contact Linear Technology for details.

CONCLUSION

The LTC3882 is a high performance PSM voltage mode buck controller capable of very accurate output voltage regulation, supporting up to eight phases with well balanced current sharing. It can be used with discrete FET drivers, DrMOS devices or power blocks. An onboard 16-bit ADC provides accurate telemetry of all critical operating parameters. It features sophisticated fault management, reporting, sharing and storage. With its internal EEPROM for settings and optional external resistor configuration, the LTC3882 can operate independently or under PMBus bus control in complex, managed power subsystems. Applications include high current distributed power systems, servers, network storage, intelligent high efficiency power regulation and industrial systems such as ATE and telecom. ■

What's New with LTspice IV?

Gabino Alonso

New Blog Article: "Modeling Safe Operating Area Behavior of N-Channel MOSFETs" by Dan Eddleman
www.linear.com/solutions/5239

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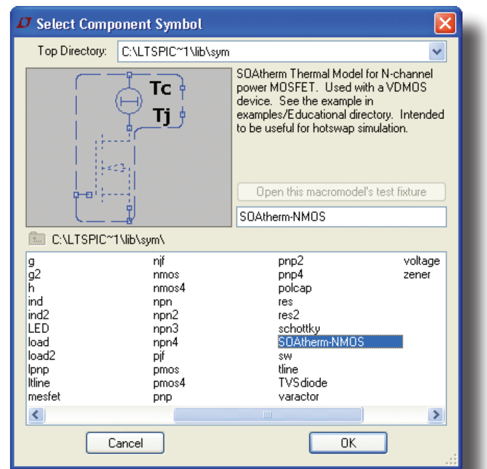
BLOG BY ENGINEERS, FOR ENGINEERS

Check out the LTspice blog (www.linear.com/solutions/LTspice) for tech news, insider tips and interesting points of view regarding LTspice.

Modeling Safe Operating Area Behavior of N-Channel MOSFETs by Dan Eddleman

www.linear.com/solutions/5239—Verifying that a Hot Swap design does not exceed MOSFET's safe operating area (SOA) is challenging. Fortunately, thermal behavior and SOA can now be modeled in LTspice.

The new SOAtherm-NMOS symbol included in LTspice contains a collection of MOSFET thermal models that can be used to verify that the maximum die temperature is not exceeded. The SOAtherm provides MOSFETs' junction and case temperatures in °C (represented as voltage in waveform viewer) and does not influence the electrical behavior of the circuit simulation. Even though using the SOAtherm-NMOS symbol/models is as easy as placing the symbol on top of the NMOS in an LTspice schematic and editing the component attributes, this blog provides a step-by-step tutorial and highlights some design considerations.



Easily model the thermal behavior of MOSFETs in LTspice using the SOAtherm NMOS symbol.

SELECTED DEMO CIRCUITS

For a complete list of example simulations utilizing Linear Technology's devices, please visit www.linear.com/democircuits.

Buck Switching Regulators

- **LT3840:** High efficiency synchronous buck converter (4.5V–60V to 3.3V at 20A) www.linear.com/LT3840
- **LT8620:** 5V 2MHz buck converter (5.5V–65V to 5V at 2A) www.linear.com/LT8620
- **LTC3607:** Dual monolithic synchronous buck regulator (4.5V–15V to 1.8V, 600mA & 3.3V, 600mA) www.linear.com/LTC3607
- **LTC3622:** Dual monolithic synchronous buck regulator (5V–17V to 3.3V, 1A & 5V, 1A) www.linear.com/LTC3622
- **LTC3875 & LTC3874:** High efficiency, 4-phase buck supply with sub-milliohm DCR sensing (4.5V–14V to 1V, 120A) www.linear.com/LTC3875
- **LTM4630:** High efficiency 6-phase 80A buck regulator (11V–13V to 0.95V, 80A) www.linear.com/LTM4630

Boost Switching Regulators

- **LTC3769:** High voltage 60V synchronous boost controller (6V–55V to 48V, 1A) www.linear.com/LTC3769

Flyback, Forward and Isolated Controllers

- **LTM8058:** 2kV isolated flyback converter with LDO post regulator (4.3V–29V to 5.7V, 120mA & 5V, 120mA) www.linear.com/LTM8058

LED Drivers

- **LT3796-1 & LTC1541:** SEPIC LED driver with 100:1 analog dimming (8V–20V to 35V string, 1A) www.linear.com/LT3796
- **LT3797:** Triple LED boost controller (2.7V–40V to 3x 50V LED strings, 1A) www.linear.com/LT3797

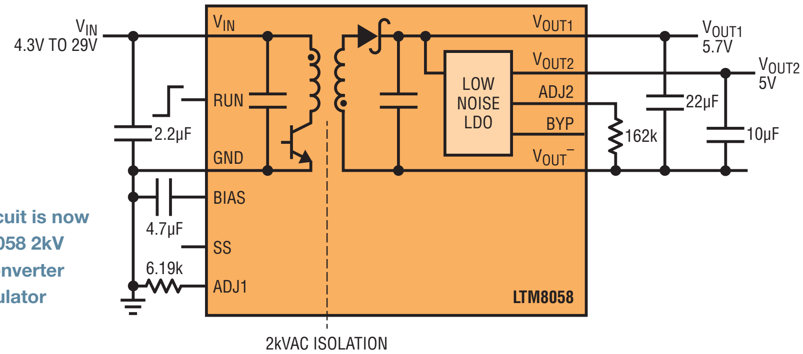
Wireless Power

- **LTC4120:** Wireless power receiver with 800mA buck battery charger www.linear.com/LTC4120

What is LTspice IV?

LTspice® 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. 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.



Demonstration circuit is now available for LTM8058 2kV isolated flyback converter with LDO post regulator

SELECTED MODELS

To search the LTspice library for a particular device model, choose Component from the Edit menu or press F2. LTspice is updated often with new models, so be sure to keep your installation of LTspice current by choosing Sync Release from the Tools menu.

- **LTC3807:** Low IQ, synchronous step-down controller with 24V output voltage capability www.linear.com/LTC3807
- **LTM4634:** Triple output 5A/5A/4A step-down DC/DC µModule regulator www.linear.com/LTM4634

Buck-Boost Switching Regulators

- **LTC3114-1:** 40V, 1A synchronous buck-boost DC/DC converter with programmable output current www.linear.com/LTC3114-1

Flyback, Forward and Isolated Controllers

- **LT8310:** 100V input forward converter controller www.linear.com/LT8310

Current Sense Amplifiers

- **LT6119:** Current sense amplifier, reference and comparators with POR www.linear.com/LT6119-1

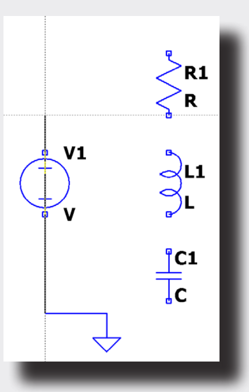
Hot Swap Controllers

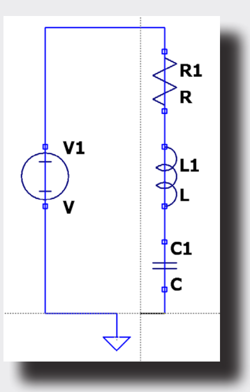
- **LTC4231:** Micropower Hot Swap controller www.linear.com/LTC4231 ■

Power User Tip

CONNECTING THE DOTS

Sometimes the simplest things elude us. Typically, after placing components in an LTspice schematic you select draw wires (F3), left click to start a wire, left click again to change direction or join, repeat until your circuit is complete and then right click to cancel. But did you know you can draw wires through components like resistors and the wire will automatically be cut so that the components are in series with the wire? Drawing a wire straight through several components is an easy way to connect components in series.

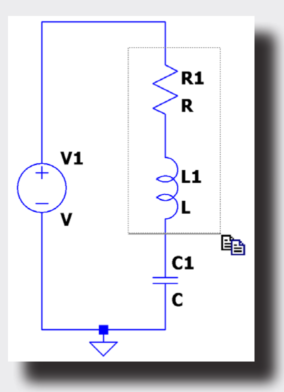


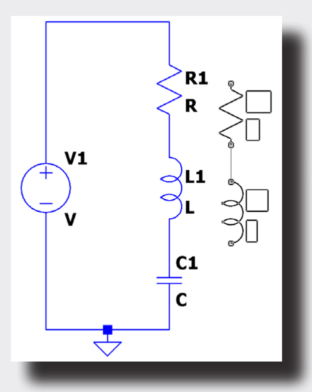


COPY AND PASTE BETWEEN SCHEMATICS

Another feature not commonly understood is how to copy and paste between schematics using the duplicate command. To copy objects from one schematic to another, in the source schematic, invoke the duplicate command (F6 or Ctrl + C)—the crosshair pointer changes to the duplicate symbol, . Left-click to select the object you want to duplicate, or select a group of objects by dragging a box around them.

Once the object or section is copied, simply click in the target schematic window (or the tab) and click again to paste. In Windows, both schematics must be in the same invocation of LTspice.





Happy simulations!

Increasing Output Voltage and Current Range Using Series-Connected Isolated µModule Converters

Jesus Rosales

Linear Technology's isolated µModule® converters are compact solutions for breaking ground loops. These converters employ a flyback architecture whose maximum output current varies with input voltage and output voltage. Although their output voltage range is limited to a maximum of 12V, one can increase the output voltage or the output current range. The solution simply involves connecting the secondary side of two or more isolated µModule converters in series.

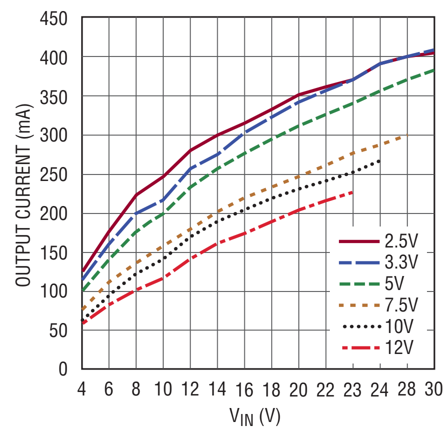


Figure 1. Typical maximum output current vs input voltage

The LTM®8057 and LTM8058 UL60950-recognized 2kV AC isolated µModule converters are used here to demonstrate this design approach, which can also be applied to the LTM8046, LTM8047 and LTM8048. Let's assume an output of 10V at 300mA is desired from a 20V input. Reviewing the maximum output current curve from Figure 1, we notice that a single LTM8057 is insufficient to meet the output current requirement under these conditions.

However, upon noticing that a single LTM8057 can deliver 300mA at 5V from a 20V input, a solution becomes apparent. Since the output voltage is isolated from the input, the outputs of two LTM8057s set at 5V can be connected in series to achieve a 10V output at 300mA (Figure 2).

The same circuit in Figure 2 can also be used to increase the output voltage range when more than 12V is needed. By adjusting the feedback resistors to provide a 7.5V nominal output voltage, the combined output voltage has increased to 15V. The output current capability for

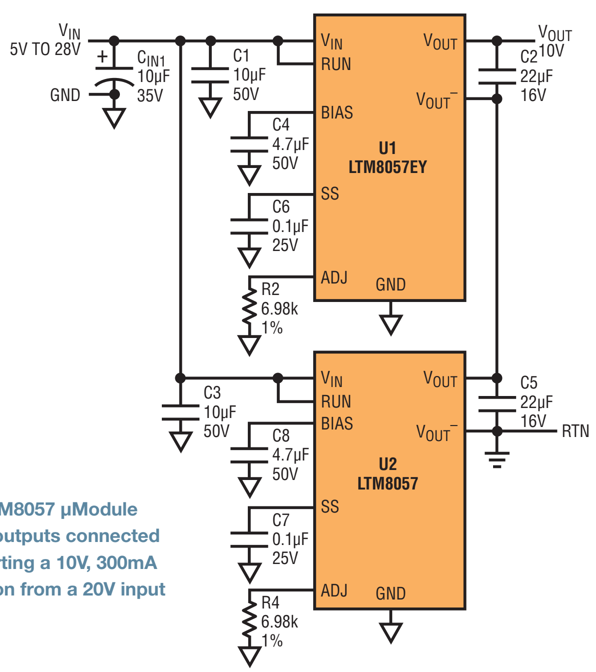


Figure 2. Two LTM8057 µModule regulators with outputs connected in series, supporting a 10V, 300mA output application from a 20V input

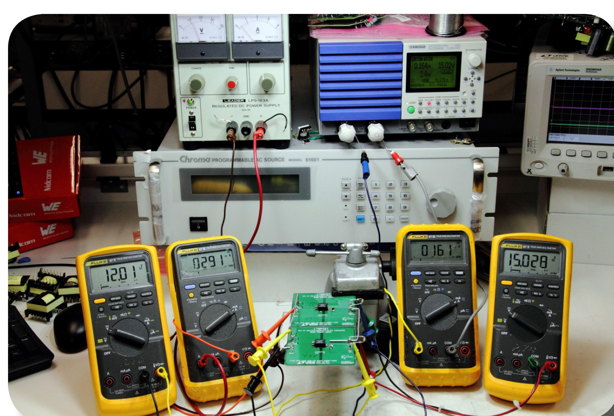


Figure 3. Two LTM8057 µModule regulators with outputs connected in series deliver more than 160mA at 15V output, 12V input.

The output capabilities of isolated µModule converters can be increased by adding one or more isolated µModule converters with the outputs tied in series while preserving the output noise characteristics.

the 15V is the same as that of the individual 7.5V µModule regulator (Figure 3).

The circuit shown in Figure 2 supports a third option: providing positive and negative outputs with a common return. The return node for both outputs is the common connection in the middle of the output stack. With this approach the circuit in Figure 2 would have 5V and –5V outputs. Each output can be of different magnitude, since the output voltages for each converter are determined independently.

LOW OUTPUT NOISE SERIES-CONNECTED CONVERTERS

The low output spectrum noise advantage of the LTM8058 with its integrated LDO post regulator can be maintained with series-connected outputs. Figure 4 shows the schematic for two LTM8058s with V_{OUT2}, the output of the LDO connected in series for 10V output. Figures 5 and 6, respectively, show the output noise spectrum of the LTM8058 under a 100mA load at 10V with the LDO outputs connected in series (Figure 4 schematic) and the flyback outputs connected in series.

Linear Technology's isolated µModule converters provide a simple and compact solution for isolated power at regulated output voltages. The LTM8057 and LTM8058 solutions shown here successfully demonstrate that the output capabilities of isolated µModule converters can be increased by adding one or more isolated µModule converters with the outputs tied in series while preserving the output noise characteristics. ■

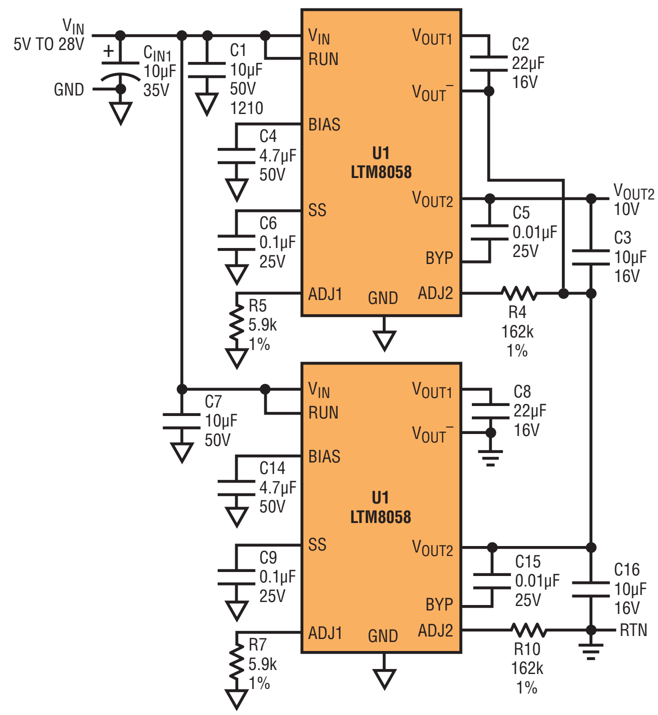


Figure 4. Two LTM8058 µModule regulators connected with V_{OUT2} in series for 10V output

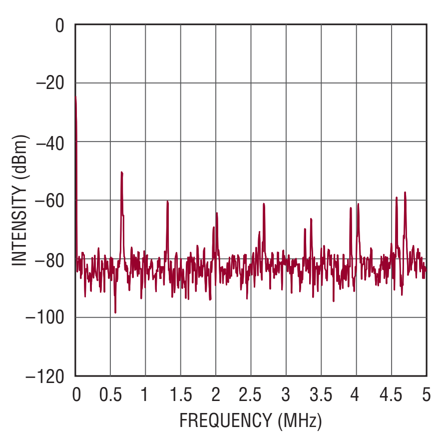


Figure 5. Noise spectrum for two LTM8058s with the LDO outputs connected in series under a 100mA, 10V output load

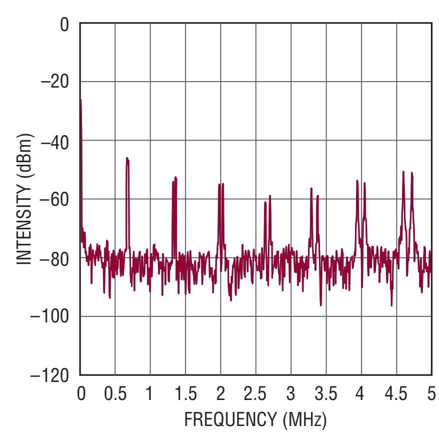


Figure 6. Noise spectrum for two LTM8058s with the flyback outputs connected in series under a 100mA, 10V output load

12V/100A Hot Swap Design for Server Farms

Dan Eddleman

As data centers servicing the cloud grow in speed and capacity, backplane supplies are called on to deliver currents that push the performance boundaries of Hot Swap components. Hot Swap solutions allow boards to be inserted and removed from a live backplane without disturbing the power distributed to other boards. A typical Hot Swap solution uses a series MOSFET to manage the flow of power between the backplane and the board—preventing glitches and faults from disrupting power to the rest of the system.

The challenges of designing robust Hot Swap solutions multiply with increasing current demands. With load currents at 100A, simply determining power dissipation requirements is no longer sufficient. Designers must pay careful attention to the MOSFET safe operating area (SOA) and understand Kelvin current sensing techniques for multiple sense resistors. This article shows how to address these issues using the example of a 12V/100A solution based on the LTC4218 Hot Swap controller.

12V/100A HOT SWAP DESIGN

Figure 1 shows the LTC4218 Hot Swap controller managing power to a board that contains up to 1000µF of bypass capacitance, draws up to 100A of load current and is hot plugged into a 12V backplane supply.

Supporting the 100A load current without excessive power dissipation in the MOSFETs M1 and M2 requires that the PG (power good) signal disable the load until the output is fully powered. Typically, this is implemented by controlling the $\overline{\text{RESET}}$ signal of downstream circuitry with the Hot Swap controller's PG signal. In the circuit of Figure 1, if the effective load resistance is greater than 10Ω during start-up (while PG is low), the output powers up normally. If the output resistance is low during start-up (such as might occur during an output short-circuit fault), the LTC4218 detects this condition and turns off the series MOSFET.

During start-up, the circuit's current limit threshold is reduced by pulling the LTC4218's ISET pin low through R4 until the PG signal transitions high. R4's 3k resistance lowers the current limit threshold to roughly 13% of the normal operating current limit. Any fault conditions that sink extra current beyond that level during start-up cause the TIMER to activate and shut off the MOSFET. (The relatively small components M3, M4, R6, R7, and C4 work together to effectively

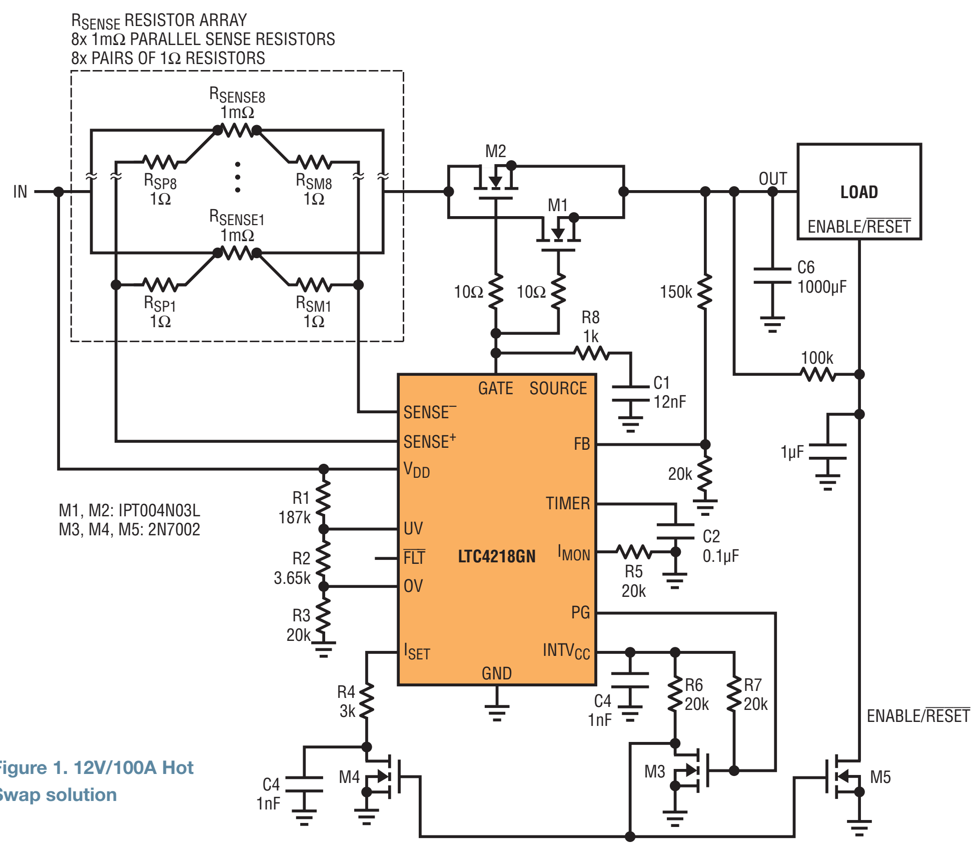


Figure 1. 12V/100A Hot Swap solution

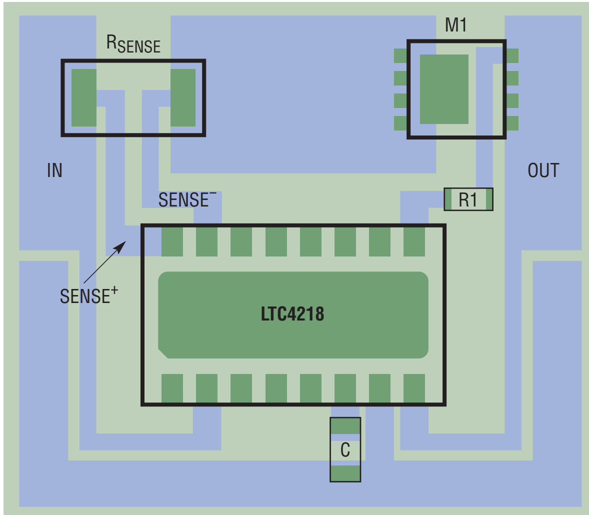


Figure 2. Kelvin sensing with single sense resistor

connect R4's 3k resistance between ISET and ground when the PG pin is pulling low.)

The output ramp rate during start-up is set by the LTC4218's 24μA pull-up current into C1 and the gates of MOSFETs M1 and M2. The result is an output ramp rate of 2V/ms. Because the load circuitry is disabled by the PG signal, the current at start-up is dedicated to charging the capacitance downstream of the Hot Swap circuit, represented by C6 in Figure 1. Ramping the 1000μF of capacitance at 2V/ms requires 1000μF • (2V/ms)=2A of current. This is far below the start-up current limit threshold set by R4 at 16A or 13% of the normal operating current limit. This allows plenty of margin for inaccuracies in the current sensing. Exceeding this current limit threshold for even a short time during start-up indicates a fault condition at the output, and the LTC4218 responds by turning off MOSFETs M1 and M2.

MOSFET SAFE OPERATING AREA

In this application, the entire SOA can be satisfied by M1 or M2 alone. It is unwise to assume that current and SOA share equally among MOSFETs during start-up or output overload faults that cause significant drain to source voltages across the MOSFETs. Either MOSFET should be able to support the entire SOA of the application.

On the other hand, when the MOSFET is fully enhanced during normal operation, its behavior is similar to a resistor and it is safe to assume that current shares more equally. In this application, two MOSFETs are used to reduce the power dissipation during normal operation, not to satisfy transient safe operation area requirements. At 100A, the power dissipated by a single 1mΩ MOSFET is $I^2R = (100A)^2 \bullet 1m\Omega = 10W$. If the current shares equally at 50A, the power in each MOSFET is a more reasonable $I^2R = (50A)^2 \bullet 1m\Omega = 2.5W$.

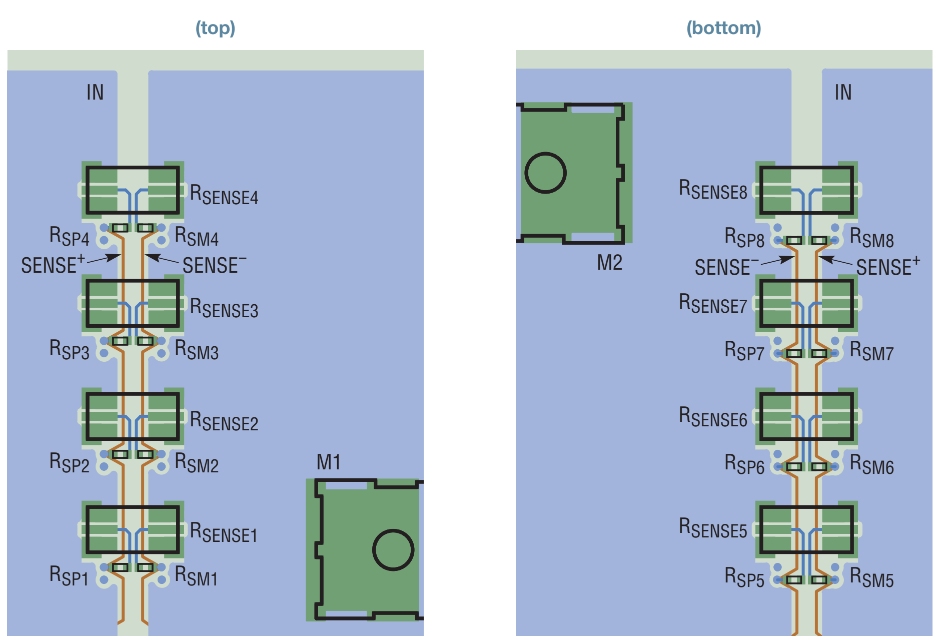
PROPER KELVIN SENSING WITH MULTIPLE SENSE RESISTORS

At these current levels, properly monitoring the voltage across the sense resistance can be challenging. With the LTC4218's 15mV current sense threshold, a 100A current limit requires less than 0.15mΩ of sense resistance, usually achieved using parallel resistors in a Kelvin sensing scheme.

When a single sense resistor is used in Hot Swap (or other current sense) applications, it is common practice to use separate low current Kelvin traces between the sense pins of the IC and the sense resistor. An example layout of Kelvin connections to a current sense resistor is shown in Figure 2. The low current Kelvin sense paths directly between the sense resistor and the LTC4218 SENSE⁺ and SENSE⁻ pins eliminate errors due to the voltage drops that occur when high currents pass through the resistive PCB copper.

In this 100A application, though, it is necessary to implement the sense resistance with multiple parallel sense resistors. Eight 1mΩ resistors in parallel is a reasonable choice, as it results in a typical

Figure 3. Kelvin sensing layout for eight parallel resistors uses top and bottom of board



Modern servers utilize load currents that bring new challenges to Hot Swap design. Two areas of concern are MOSFET safe operating area, and the Kelvin sensing techniques for multiple sense resistors. The 12V/100A LTC4218 Hot Swap controller solution shown here specifically addresses these design points.

current limit of 8 • (15mV/1mΩ) = 120A, providing a comfortable margin above the 100A delivered to the load.

Nevertheless, multiplying the number of sense resistors multiplies the layout challenges; the straightforward layout shown for a single resistor in Figure 2 no longer suffices. Current rarely shares equally among the sense resistors—it is not unusual to see a 50% difference in current between several low value sense resistors in high current applications. The resistors placed more closely to MOSFETs M1 and M2 conduct a greater proportion of the load current than the sense resistors placed farther away, due to the finite resistance of the PC board copper planes showing up in series with the sense resistors. If possible, the preferred layout is to place an equal number of sense resistors on the top and the bottom of the PC board. This minimizes the parasitic voltage drops caused by the lateral current flow through the copper planes required to reach the farthest sense resistor.

Even with an optimal PC board layout, it is necessary to use a resistor network to average the voltages sensed across the individual 1mΩ resistors. In this 12V/100A application, the SENSE$^+$ and SENSE$^-$ pins of the LTC4218 are joined to the eight 1mΩ sense resistors with an array of 1Ω resistors as shown in Figure 1. The resulting voltage between the SENSE$^+$ and SENSE$^-$ pins is the average of all of the voltages across the 1mΩ sense resistors, effectively Kelvin sensing the eight 1mΩ resistors. An example layout is shown in Figure 3.

LAB RESULTS

Of course, calculations and circuit simulations are no substitute for benchtop testing, especially when working with high current Hot Swap solutions. Figure 4 shows an oscilloscope waveform of this design starting up into a 100Ω resistor followed by a 100A load step after the ENABLE/$\overline{\text{RESET}}$ signal transitions high. Note that the ENABLE/$\overline{\text{RESET}}$ in this setup drives the 4V ON signal of an electronic load box rather than the 12V level from M5 and R10 shown in Figure 1.

The waveform in Figure 4 is typical of proper operation when no faults are present. The 12V input supply ramps up first. Then, the LTC4218 charges the 1000µF output capacitor at 2V/ms. Finally, the 100A load turns on when the ENABLE/$\overline{\text{RESET}}$ output transitions high, signaling that the MOSFETs M1 and M2 are fully enhanced.

Figure 5 shows the LTC4218 turning off MOSFETs M1 and M2 when a short circuit occurs on the output. 100ms after the input voltage rises, the circuit begins to charge the output node. The LTC4218 limits the charging current to the 16A start-up current limit threshold and quickly detects the short-circuit. This solution responds properly and shuts off power to the load to avoid any disruption (and damage) to other components in the system.

CONCLUSION

Over the years, the designers of Hot Swap solutions have had to continually address fresh challenges posed by ever increasing supply currents. Some issues are not new, such as the power dissipation requirements that result from high current, but today's current levels have pushed some new design issues to the fore, such as MOSFET safe operating area, and the Kelvin sensing techniques for multiple sense resistors. The 12V/100A LTC4218 Hot Swap controller solution shown here specifically addresses these design points. ■

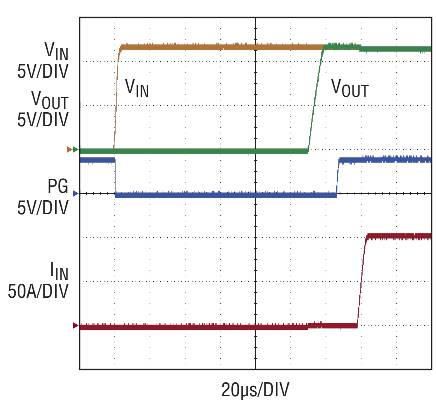


Figure 4. Normal start-up

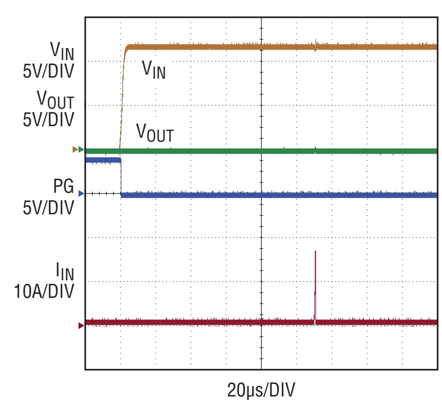


Figure 5. Start-up into a short circuit

Compensate for Wire Drop to a Remote Load

Philip Karantzalis

A common problem in power distribution systems is degradation of regulation due to the wire voltage drop between the regulator and the load. Any increase in wire resistance, cable length or load current increases the voltage drop over the distribution wire, increasing the difference between voltage at the load and the voltage programmed by the regulator. Remote sensing requires routing additional wires to the load. No extra wiring is required with the LT6110 cable/wire drop compensator. This article shows how the LT6110 can improve regulation by compensating for a wide range of regulator-to-load voltage drops.

THE LT6110 CABLE/WIRE COMPENSATOR

Figure 1 shows a 1-wire compensation block diagram. If the remote load circuit does not share the regulator's ground, two wires are required, one to the load and one ground return wire. The LT6110 high side amplifier senses the load current by measuring the voltage, V_{SENSE}, across the sense resistor, R_{SENSE}, and sinks a current, I_{IOUT}, proportional to the load current, I_{LOAD}. I_{IOUT} scale factor is programmable with the R_{IN} resistor from 10µA to 1mA. Wire voltage drop, V_{DROP}, compensation is accomplished by sinking I_{IOUT} through the R_{FA} feedback resistor to increase the regulator's output by an amount equal to V_{DROP}. An LT6110 cable/wire voltage drop compensation design is simple: set the $I_{IOUT} \bullet R_{FA}$ product equal to the maximum cable/wire voltage drop.

The LT6110 includes an internal 20mΩ R_{SENSE} suitable for load currents up to 3A; an external R_{SENSE} is required for I_{LOAD} greater than 3A. The external R_{SENSE} can be a sense resistor, the DC resistance of an inductor or a PCB trace resistor. In addition to the I_{IOUT} sink current, the LT6110 IMON pin provides a sourcing current, IMON, to compensate current-referenced linear regulators such as the LT3080.

COMPENSATING CABLE VOLTAGE DROPS FOR A BUCK REGULATOR

Figure 2 shows a complete cable/wire voltage drop compensation system consisting of a 3.3V, 5A buck regulator and an LT6110, which regulates the voltage of a remote load connected through 20 feet of 18 AWG copper wire. The buck regulator's 5A output requires the use of an external R_{SENSE}.

The maximum 5A I_{LOAD} through the 140mΩ wire resistance and 25mΩ R_{SENSE} creates an 825mV voltage drop. To regulate the load voltage, V_{LOAD}, for $0A \le I_{LOAD} \le 5A$, $I_{IOUT} \bullet R_{FA}$ must equal 825mV. There are two design options: select I_{IOUT} and calculate the R_{FA} resistor,

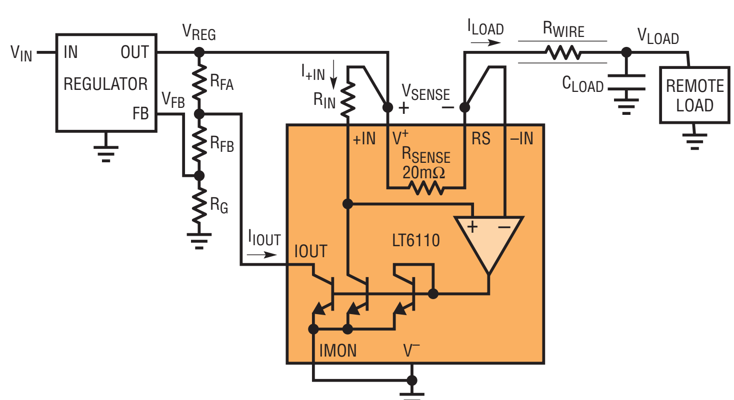


Figure 1. No extra wires are required to compensate for wire voltage drop to a remote load

For precise load regulation, an accurate estimate of the resistance between the power source and load is required. If R_{WIRE}, R_{SENSE} and the resistance of the cable connectors and PCB traces in series with the wire are accurately estimated, the LT6110 can compensate for a wide range of voltage drops to a high degree of precision.

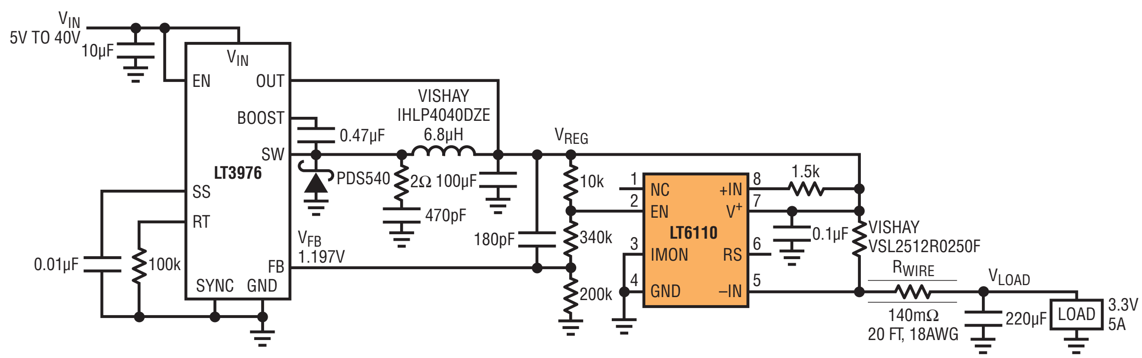


Figure 2. Example of a high current remote load regulation: a 3.3V, 5A buck regulator with LT6110 cable/wire voltage drop compensation

or design the regulator's feedback resistors for very low current and calculate the R_{IN} resistor to set I_{IOUT}. Typically I_{IOUT} is set to 100µA (the I_{IOUT} error is ±1% from 30µA to 300µA). In the Figure 2 circuit the feedback path current is 6µA (V_{FB}/200k), the R_{FA} resistor is 10k and the R_{IN} resistor must be calculated to set $I_{IOUT} \bullet R_{FA}$ = 825mV.

$$I_{IOUT} = V_{SENSE}/R_{IN}$$
$$I_{IOUT} \bullet R_{FA} = V_{DROP}$$

and

$$R_{IN} = R_{FA} \bullet \frac{R_{SENSE}}{R_{SENSE} \bullet R_{WIRE}}$$

so for R_{FA} = 10k, R_{SENSE} = 25mΩ and R_{WIRE} = 140mΩ, R_{IN} = 1.5k.

Without cable/wire drop compensation the maximum change in load voltage, ΔV_{LOAD}, is 700mV (5 • 140mΩ), or an error of 21.2% for a 3.3V output. The LT6110 reduces ΔV_{LOAD} to only 50mV at 25°C, or an error of 1.5%. This is an order of magnitude improvement in load regulation.

PRECISION LOAD REGULATION

A modest improvement in load regulation with the LT6110 only requires a moderately accurate R_{WIRE} estimation. The load regulation error is the product of two errors: error due to the wire/cable resistance and error due to the LT6110 compensation circuit. For example, using the Figure 2 circuit, even if the R_{SENSE} and R_{WIRE} calculation error is 25%, the LT6110 still reduces V_{LOAD} error to 6.25%.

For precise load regulation, an accurate estimate of the resistance between the power source and load is required. If R_{WIRE} ,R_{SENSE} and the resistance of the cable connectors and PCB traces in series with the wire are accurately estimated, the LT6110 can compensate for a wide range of voltage drops to a high degree of precision.

Using the LT6110, an accurate R_{WIRE} estimation and a precision R_{SENSE}, the ΔV_{LOAD} compensation error can be reduced to match the regulator's voltage error over any length of wire.

CONCLUSION

The LT6110 cable/wire voltage drop compensator improves the voltage regulation of remote loads, where high current, long cable runs and resistance would otherwise significantly affect regulation. Accurate regulation can be achieved without adding sense wires, buying Kelvin resistors, using more copper or implementing point-of-load regulators—common drawbacks of other solutions. In contrast, compensator solutions require little space while minimizing design complexity and component costs. ■

New Product Briefs

USB µMODULE ISOLATOR WITH POWER PROTECTS HUBS & PERIPHERAL PORTS

The LTM2884 is a USB µModule isolator that combines USB data communications and USB power, and guards against ground-to-ground differentials and large common mode transients. The rugged interface and isolation makes the LTM2884 ideal for systems implementing USB in harsh industrial or medical environments where protection from ground differences is required. The LTM2884 separates grounds by isolating a pair of USB signal transceivers using internal inductive signal isolation, providing $2500V_{RMS}$ isolation plus superior common mode transient rejection of >30kV/µs.

The LTM2884 features an integrated, low EMI, external or bus powered, DC/DC converter that powers the isolated transceiver and provides up to 2.5W of isolated power for USB peripherals or hub/host controllers. The unique automatic bus speed detection feature allows the LTM2884 to be used in hub/host/bus isolation applications. Integrated downstream facing pull-down resistors and upstream facing pull-up resistors are automatically configured to match the speed of the downstream device, enabling the LTM2884 to monitor and report bus speeds to the host. With $2500V_{RMS}$ of galvanic isolation, integrated power and USB 2.0 compatible transceivers, the LTM2884 requires no external components and is a complete µModule solution for isolated USB communications.

The LTM2884 is suitable for a wide range of applications, including host, hub and peripheral device isolation, as well as USB inline bus isolation. The ±15kV ESD-protected transceivers operate at USB 2.0 full speed (12Mbps) and low speed (1.5Mbps). A suspend mode monitors for inactivity and reduces V_{BUS} current to less than 2.0mA. The integrated DC/DC converter is capable of supplying 2.5W when connected to an external high voltage supply or 1W when connected to the USB V_{BUS} supply.

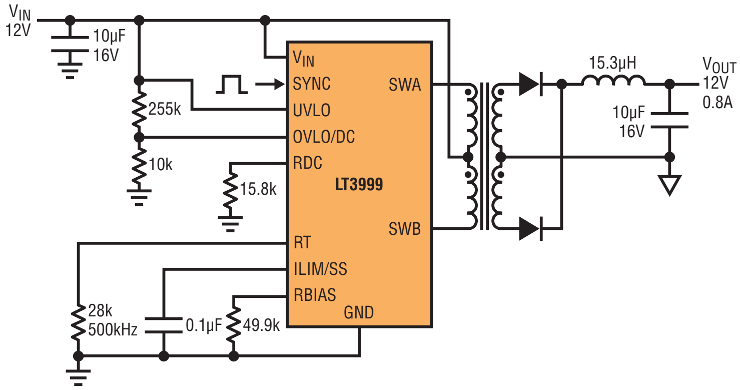
The LTM2884 is available in a compact 15mm × 15mm × 5mm surface mount BGA package; all integrated circuits and passive components are housed in this RoHS-compliant µModule package. The LTM2884 is available in commercial, industrial and automotive versions, supporting operating temperature ranges from 0°C to 70°C, –40°C to 85°C and –40°C to 105°C respectively.

16-CHANNEL, 16-BIT ±10V SOFTSPAN DAC DRIVES 10mA & 1000pF LOADS

The LTC2668-16 is a 16-channel, 16-bit voltage output digital-to-analog converter (DAC) with SoftSpan™ outputs, each of which can be independently configured for one of five selectable unipolar and bipolar output ranges up to ±10V. Each rail-to-rail DAC output is capable of sourcing or sinking 10mA with guaranteed load regulation and is stable driving capacitive loads as large as 1000pF. This makes the LTC2668 ideal for driving a variety of demanding loads in applications such as optical modules, programmable logic controllers (PLCs), MRI and X-ray imaging, automatic test equipment, laser etch equipment, spectrum analyzers and oscilloscopes.

The LTC2668 offers many space-saving features in a compact 6mm × 6mm QFN package, nearly 50% smaller footprint than alternative 16-channel DACs. The LTC2668 can be operated from a single 5V supply, or from dual bipolar supplies depending on the output voltage range requirement. The device includes a precision 2.5V 10ppm/°C max reference to generate the five SoftSpan output ranges, or it can be driven with an external reference. A convenient 16:1 high voltage analog multiplexer enables the user to monitor circuit integrity or perform in-circuit calibration, saving significant board real estate. The LTC2668 supports an A/B toggle function for generating an AC bias or for applying dither to a system. Configuration of the LTC2668 is handled via a SPI-compatible serial interface which can be powered from an independent 1.8V to 5V digital supply.

The LTC2668 is offered in both 16-bit and 12-bit versions and is available in commercial, industrial and automotive (–40°C to 125°C) temperature grades. The DC2025A evaluation board for the LTC2668 family is available at www.linear.com/demo or via a local Linear Technology sales office. The demo board is supported by the Linduino™ firmware development system, using the DC2026A. For more information, visit www.linear.com/product/LTC2668 and www.linear.com/solutions/linduino. ■



LT3999 12V TO 12V, 10W LOW NOISE ISOLATED DC/DC CONVERTER

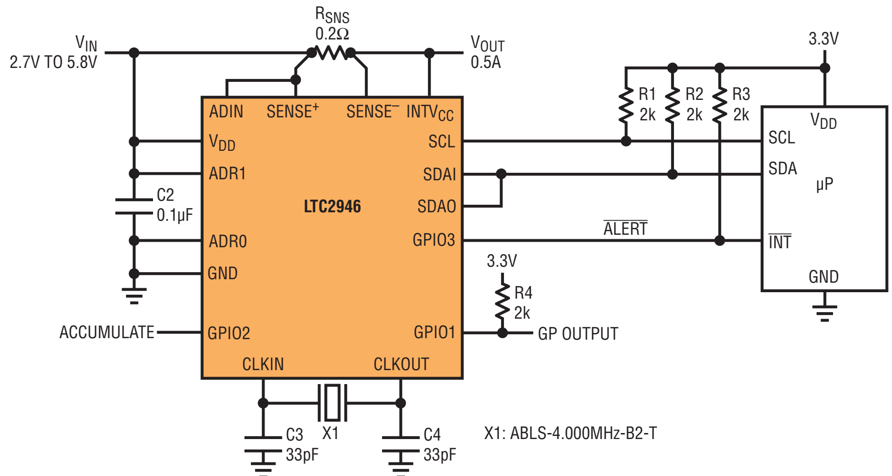
The LT®3999 is a monolithic, high voltage, high frequency DC/DC transformer driver providing isolated power in a small solution footprint..

www.linear.com/solutions/5377

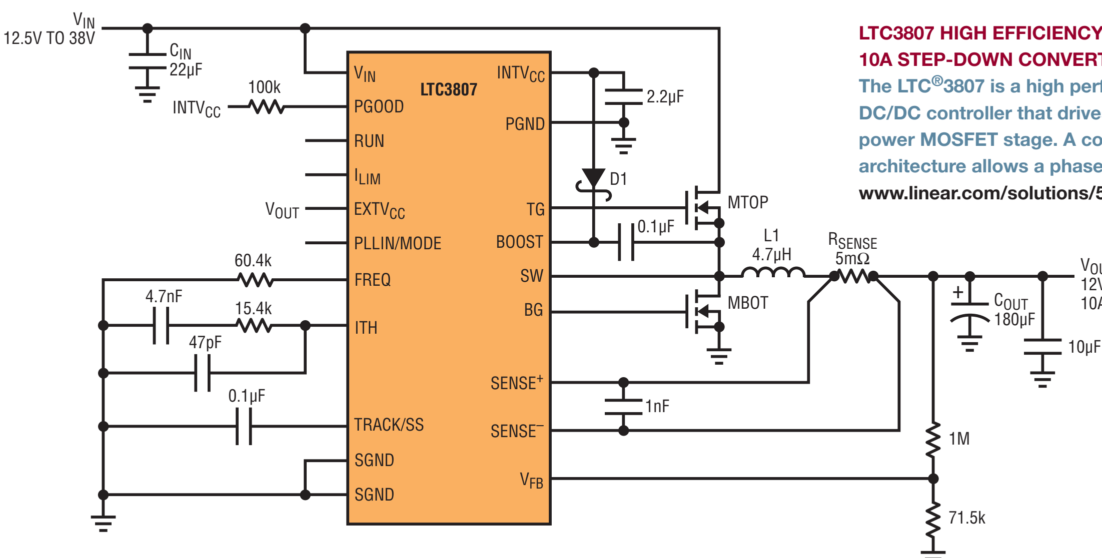
LTC2946 BIDIRECTIONAL POWER MONITOR WITH ENERGY AND CHARGE MONITOR IN FORWARD PATH

The LTC®2946 is a rail-to-rail system monitor that measures current, voltage, power, charge and energy. It features an operating range of 2.7V to 100V and includes a shunt regulator for supplies above 100V. The current measurement common mode range of 0V to 100V is independent of the input supply. A 12-bit ADC measures load current, input voltage and an auxiliary external voltage. Load current and internally calculated power are integrated over an external clock, or crystal or internal oscillator time base for charge and energy. An accurate time base allows the LTC2946 to provide measurement accuracy of better than ±0.6% for charge and ±1% for power and energy. Minimum and maximum values are stored and an overrange alert with programmable thresholds minimizes the need for software polling. Data is reported via a standard I²C interface.

www.linear.com/solutions/5393



POWER FOR REVERSE PATH = $CODE_{ADIN} \times CODE_{VDD}$ TO BE PERFORMED BY µP
CA[7] = 1, SEE TABLE 3



LTC3807 HIGH EFFICIENCY 12V OUTPUT AT 10A STEP-DOWN CONVERTER

The LTC®3807 is a high performance step-down switching regulator DC/DC controller that drives an all N-channel synchronous power MOSFET stage. A constant frequency current mode architecture allows a phase-lockable frequency of up to 750kHz.

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