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Finally, High Voltage Current Sensing Made Easy

by Brendan Whelan, Glen Brisebois, Albert Lee and Jon Munson

High Voltage Ability, Flexibility and Accuracy

The LT6100 and LTC6101 are high voltage precision high-side current sense amplifiers. Their simple architectures make them flexible and easy to use, while careful design has made them reliable and robust.

Key features include high supply range, user-configurable gains, low input current, high PSRR and low offset voltage. These features make the LT6100 and LTC6101 perfect for precision industrial and automotive sensing applications as well as current-overload protection circuits.

The LT6100 operates to 48V, is the simpler of the two to use, requiring almost no external components, draws little power, and is tolerant of several abnormal conditions such as split inputs, power off, and reverse battery.

The LTC6101 is the higher speed of the two, operates to 70V, and is more flexible, having external resistors set the gain. Both parts are available in a variety of small packages.

How Current Sensing Works

Current sensing is commonly accomplished in one of two ways. One method is magnetic, where a structure is created using permeable materials to couple an m-field to a coil or Hall-effect sensor. While non-intrusive to the measured circuit, a coil type pickup is intrinsically unable to provide any DC information (though exotic "flux-gate" techniques are possible), and Hall sensors generally lack the accuracy and sensitivity for most DC measurements.

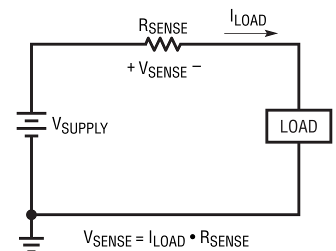

Figure 1. Typical high-side current-sense circuit

The alternative is the introduction of a known "sense" resistance in the load path, thereby creating a small voltage drop that is directly proportional to the load current. Generally, the preferred connection for a sense resistor is in the supply side of the circuit, so that common grounding practices can be retained and load faults can be detected. In the case of positive supply potentials, this connection is commonly referred to as a "high-side" sense configuration, as shown schematically in Figure 1. This means that the sense voltage is a small difference on a large common-mode signal from the perspective of the sense amplifier, which poses unusual demands on the implementation to preserve accuracy and dynamic range.

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Issue Highlights

Monitoring the current on the high side of a high voltage load is a traditionally complex problem. Typical grow-your-own solutions use operational or instrumentation amplifiers, but these are commonly limited in operational voltage range and/or require a number of additional components. Simpler, integrated solutions often lack versatility and/or precision. Neither makes for an ideal solution.

Enter the LT6100 and LTC6101, two high voltage precision high-side current sense amplifiers. They boast simple architectures that make them flexible and easy to use, and careful design that makes them reliable and robust.

See our cover article for more about these breakthrough devices.

Linear Technology in the News...

Linear Completes Solid Quarter

On April 19, Linear Technology announced revenue for its third fiscal quarter of $290,734,000, an increase of 39% over the third quarter of the previous year. Included in the current quarter's revenue is royalty revenue of $40,000,000, which represents past royalties receivable under terms of a settlement and license agreement with another company. Linear Technology expects to earn further royalties, dependent on sales of licensed products, quarterly from July 2005 through June 2013. Linear also reported net income for the quarter of $121,633,000 or $0.39 diluted earnings per share, an increase of 42% over the third quarter last year.

According to Lothar Maier, CEO, "Linear Technology completed a solid quarter, further enhanced by the settlement and license agreement. The Company continues to be cash flow positive and profitable, as evidenced by the 42% return on sales. The license agreement confirms the strength of our intellectual property. We continue to lead the market with high performance analog technology and innovative products."

Products in the News

Linear ADCs Make Waves in Germany... The April issue of the German publication, *Elektronik Journal* features a cover article on Linear Technology's LTC2220 high speed ADC family. The issue included an in-depth article on the product family, which delivers industry-leading performance.

Product of the Week... The April 18 issue of *EE Times* featured Linear Technology's LT5527 RF downconverting active mixer as Product of the Week. The publication highlighted the product's ability to streamline 3G basestation design.

Review of the Week... In its April 11 issue, *EE Times* featured Linear Technology's LTC3780 high performance buck-boost switching regulator controller in its product Review of the Week. *EE Times* states in the article, "The major breakthrough is a device that is the only true buck-boost controller today. That is, it's one that generates a glitch-free output as it switches seamlessly from the buck to boost mode and vise versa. The chip also maintains extremely high system efficiency over a wide input-voltage range."

Featured Devices

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

Compact Power Solutions

The LTC3442 is a 1.2A buck-boost converter that is ideal for mini disk drive applications, and certainly for other buck-boost apps as well. The LTC3442 extends battery life with 95% efficiency and fits into tight spaces with its 3mm × 4mm DFN package. (Page 8)

The LTC3808 synchronous DC/DC controller packs many features required by the latest electronic devices into a low profile (0.8mm tall), 3mm × 4mm leadless DFN package, or a leaded SSOP-16 package. The LTC3808 can provide output voltage as low as 0.6V and output current as high as 7A from a wide, 2.75V to 9.8V, input range, making it a good fit for battery powered and distributed DC power systems. (Page 11)

RS232 Transceivers

Six new devices comprise a family of small-footprint RS232 transceivers that operate at up to 1Mbps over a supply range of 1.8V to 5.5V. The wide supply range permits operation directly from two alkaline, NiCd, or NiMH battery cells, while a separate VL supply pin eliminates interfacing problems in mixed-supply systems. (Page 14)

Low Voltage Hot Swap Controller

The LTC4216 is a low voltage Hot Swap controller that allows a board to be safely inserted and removed from a live backplane. The LTC4216 is designed to meet the latest low voltage board supply requirements with its unique feature of controlling load voltages from 0V to 6V. It also features an adjustable soft-start, important for the large load capacitors typical in low voltage applications. (Page 17)

Design Ideas and Cameos

The Design Ideas start on page 29, including a temperature-to-frequency converter that runs on two AA batteries. an LDO linear regulator that betters switchers in efficiency, and a compact DDR memory solution. Three New Device Cameos appear on page 37.

LT6100 and LT6101, continued from page 1

Traditional grow-your-own solutions use operational or instrumentation amplifiers, but these are commonly limited in the voltage range of operation and/or require a number of additional components to perform the voltage translation function to create a ground-referenced readout signal. Far better and simpler solutions are attainable by using the LT6100 and LTC6101, which solve most high side current sensing requirements.

For an index of these and other current sense solutions, see Table 1. For specific applications where the current sensing is performed within dedicated chips or chip sets, see Table 2.

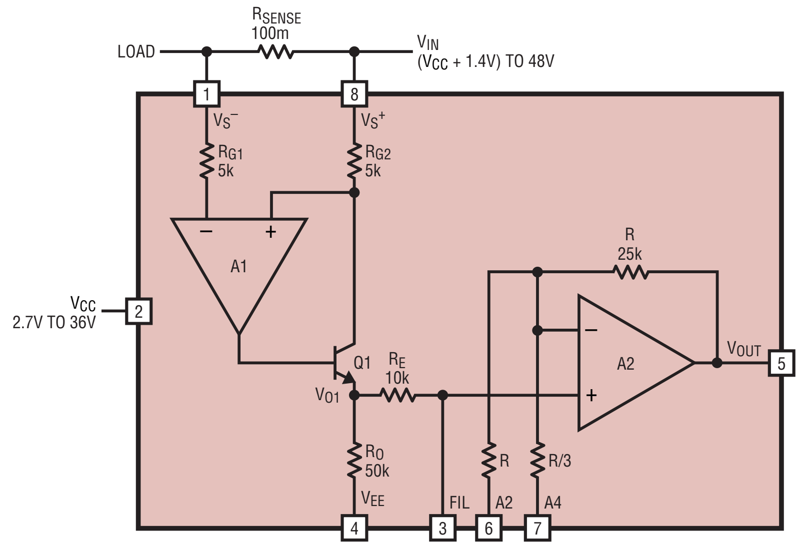

Figure 2. LT6100 simplified schematic

Watch Out for Sources of Current Sensing Error

As with any sensor design, there are several potential sources of error to consider. The accuracy of the circuit depends largely on how well the value of the sense resistor is known. The sense resistor itself has defined tolerances and temperature dependencies that introduce errors. Stray resistance in the measurement path or large dI/dt loops can also add errors. It is important to properly implement Kelvin connections to the sense resistor to minimize these effects.[1]

After sense resistance, the most significant source of error is the voltage offset of the sense amplifier, since it generates a level-independent uncertainty in the measurement. This is particularly important for preserving accuracy at current levels that are substantially below the maximum design value. In some applications it is desirable to calibrate out the static component of this term (in software, for example), but this may not always be practical.

An additional error source to consider is the tolerance of any resistors that may be required for setting scale factors. This can contribute to full-scale uncertainty along with the sense resistor and Kelvin connection tolerances. For the LT6100, scaling resistors are all provided on-chip, so the tolerances are well defined and accounted for in the data sheet specifications. In the case of the LTC6101, the scaling accuracy is set strictly by the user's choice of resistors, thereby allowing optimization for particular requirements.

LT6100 Theory of Operation

Figure 2 shows a simplified schematic of the LT6100 sensing across a $100m\Omega$ sense resistor. The differential voltage across the sense resistor is imposed upon internal resistor R_{G2} by the action of the op amp A1 through Q1's collector. The resulting current through R_{G2} is thus $I = V_{SENSE}/R_{G2}$, and this current flows through Q1 and R_O. The voltage which appears across R_O is $R_O \bullet V_{SENSE}/RG2$. But R_O is ten times the value of R_{G2}, so the voltage is simply $10 \bullet V_{SENSE}$. This gives rise to the LT6100's inherent gain of 10 up to this point. The next stage involving op amp A2 gives the designer the flexibility of selecting further gain by grounding or floating pins A2 and A4 or connecting them to the output. Gains of 1, 1.25, 2, 2.5, 4, and 5 can be set here, for overall gains of 10, 12.5, 20, 25, 40, and 50. Series resistor R_E is provided between the two stages to allow simple low pass filtering by adding a capacitor at the FIL pin.

LTC6101 Theory of Operation

Figure 3 shows a simplified schematic of the LTC6101 in a basic current-sense circuit. As before, a sense resistor, R_{SENSE}, is added in series with the system supply at the positive (high side) of the supply. The internal amplifier of the LTC6101 acts as a voltage follower, driving its inverting

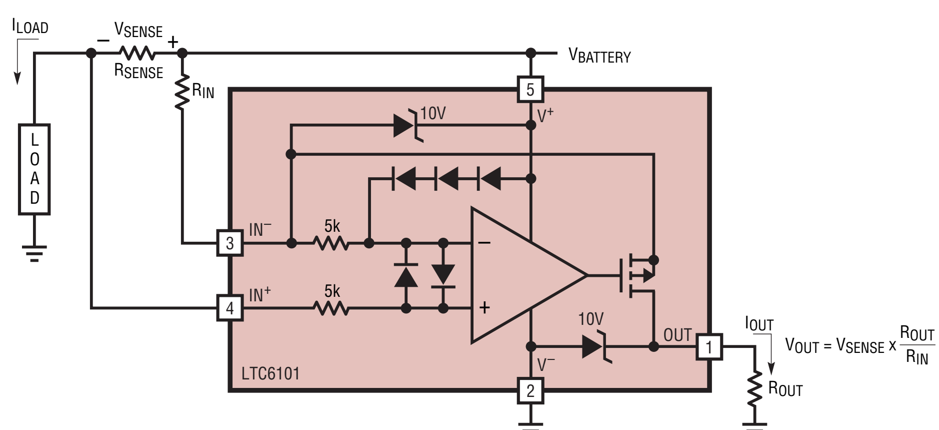

Figure 3. LTC6101 simplified schematic

[1] This topic is covered in depth in "Using Current Sensing Resistors with Hot Swap Controllers and Current Mode Voltage Regulators" in *Linear Technology* Magazine, September, 2003, pp. 34–35.

input (IN^-) to the same voltage as its non-inverting input (IN^+). This sets a voltage across R_{IN} that is equal to the voltage across R_{SENSE}:

$$V_{R(IN)} = V_{SENSE}$$

The current in R_{IN} is therefore:

$$I_{IN} = \frac{V_{SENSE}}{R_{IN}}$$

The amplifier inputs are high impedance, so this current does not flow into the amplifier. It is instead conducted through an internal MOSFET to the OUT pin, where it flows through R_{OUT} to ground. The output voltage is then:

$$V_{OUT} = I_{IN} \bullet R_{OUT},$$

and the gain is:

$$\frac{V_{OUT}}{V_{SENSE}} = \frac{R_{OUT}}{R_{IN}}$$

Substitute:

$$V_{SENSE} = R_{SENSE} \bullet I_{SENSE}$$

to yield the desired ratio of output voltage to sense current:

$$\frac{V_{OUT}}{I_{SENSE}} = \frac{R_{OUT} \bullet R_{SENSE}}{R_{IN}}$$

As with most current-sense solutions, the input and output voltages, as well as output current, are dictated by the application. In order to allow compatibility with most circuits, the LTC6101 supports input voltages between 0V and 500mV. This makes it suitable for most applications that use a small series sense resistor (or shunt). The LTC6101's output may be required to drive a comparator, ADC, or other circuitry. The output voltage can swing from 0V, since it is open-drain, to 8V. The output current may be set as high as 1mA, allowing useful speed and drive capability. The external gain resistors, R_{IN} and R_{OUT}, allow a wide range of gains to work in concert with these circuit constraints.

Table 1. Use this index of publications to find detailed applications information for current sensing solutions.

Publication	Hi Side/Low Side	Uni/Bi Directional	V_{OS} (CMRR)	Input Voltage/Feature
LT6100 Data Sheet	Hi Side	Uni	300	48V
LT6101 Data Sheet	Hi Side	Uni	300	60V
LT1787 Data Sheet	Hi Side	Bi	75µV	60V, 70µA
LT1990 Data Sheet, pp. 1, 16	Both	Bi	(80dB)	±250V
LT1991 Data Sheet, pp. 1, 19–22	Both	Bi	(80dB)	±60V
LT1995 Data Sheet, p. 20	Both	Bi		Hi Speed
LTC2054 Data Sheet, p. 12	Hi Side	Bi	3µV	60V
LTC2054 Data Sheet, p. 1	Low Side	Uni	3µV	–48V
LT1494 Data Sheet, p. 1, 16	Hi Side	Uni, Bi	~1mV	36V
LTC2053 Data Sheet, p. 13	Hi Side (Both possible)	Uni	10µV	5V
LTC6800 Data Sheet, p. 1	Hi Side (Both possible)	Uni	100µV	5V
LTC6943 Data Sheet p. 1	Both	Uni	(120dB)	18V
LT1620 Data Sheet	Both	Uni	5mV	36V, power
LT1366 Data Sheet, p.1	Hi Side	Uni	200µV	36V
LT1797 Data Sheet, p. 1	Low Side	Uni	1mV	–48V, fast
InfoCard 27				Various circuits
LT1637 Data Sheet, p. 13	Hi Side	Uni	~1mV	44V, Over-The-Top
LT1490A Data Sheet, p. 1	Hi Side	Bi	~1mV	12V, Over-The-Top
Design Note 341	Low Side	Uni	~1µV	–48V, Direct ADC
Linear Technology Magazine Aug. 2004, p. 33	Low Side	Bi	2.5µV	Direct ADC
Design Note 297	Hi Side	Uni	2.5µV	Direct ADC
LTC1966 Data Sheet, pp. 29, 32	Both (AC)			RMS Current
Application Note 92	Hi Side	Uni	various	Avalanche PDs

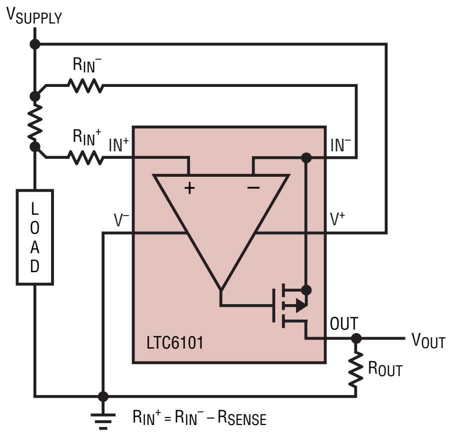

Figure 4. Second input resistor minimizes error due to input bias current

Input Precision: A Quick Comparison

Both the LT6100 and LTC6101 are very precise. They boast 300µV maximum input offset (500µV and 535µV, respectively, over temperature). Neither part draws supply current from the input sense pins. The LT6100 draws 5µA from its Over-The-Top® inputs, while the LTC6101 provides a separate supply pin (V+) to be connected to the sensed supply directly and draws only 100nA bias current at its inputs. This makes the LTC6101 ideal for very low current monitoring. In addition, the LTC6101 sense input currents are well matched so a second input resistor, R_{IN+} (Figure 4), may be added to cancel the effect of input bias. In this way the LTC6101 effective input bias error can be reduced to less than 15nA. The LT6100 provides these matched resistors internally, reducing its effective input bias current error to below 1µA.

Features

The LT6100: Robust and Easy to Use

The LT6100 tolerates a reverse battery on its inputs up to –50V, while guaranteeing less than 100µA of resultant fault current. In addition, it can also be used to sense across fuses and MOSFETs as shown in Figure 5. The LT6100 has no problem when the fuse or MOSFET opens because it has high voltage pnp's and a unique input topology that features full high impedance differential input swing capability to ±48V. This allows direct sensing of fuse or MOSFET voltage drops, without concern for the fuse or MOSFET open circuit condition.

Another unique benefit of the LT6100 is that you can leave it connected to a battery even when it is unpowered. When the LT6100 loses power, or is intentionally powered down, both sense inputs remain high impedance (see Figure 6). This is due to the implementation of Linear Technology's Over-The-Top input topology at the front end. In fact, when powered down, the LT6100 inputs actually draw less current than when powered up. Powered up or down, it represents a benign load.

The LTC6101: Delivers Accuracy and Speed in High Voltage Applications

The LTC6101 boasts a fully specified operating supply range of 4V to 60V, with a maximum supply voltage of 70V. Applications that require high operating voltages, such as motor control and telecom supply monitoring, or temporary high-voltage survival, such as with automotive load dump conditions, benefit from this wide supply range. The accuracy is preserved across this supply range by a high typical PSRR of 140dB.

The fast response time of the LTC6101 makes it suitable for overcurrent-protection circuits. The typical response time is less than 1µs for the output to rise 2.5V on a 5V output transition. The LTC6101 can detect a load fault and signal a comparator or microprocessor in time to open a switch in series with the load before supply, load or switch damage occurs.

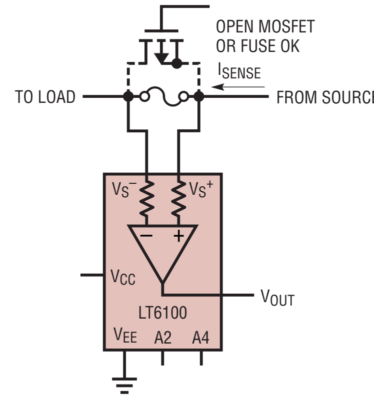

Figure 5. Sense across a MOSFET or fuse without worry. LT6100 inputs can split while remaining high Z.

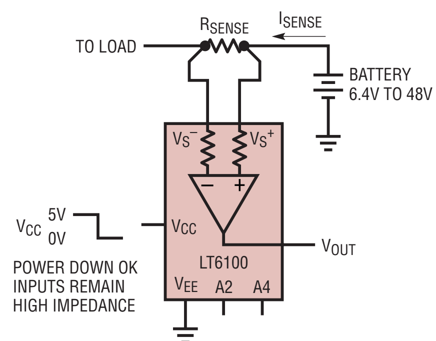

Figure 6. Remove power from the LT6100 with no need to disconnect the battery. The LT6100 inputs remain high Z.

The architecture of the LTC6101 is the key to its flexibility. The gain is completely controlled by external resistors (R_{IN} and R_{OUT}, Figure 3). This is convenient because most applications specify a small maximum shunt voltage (to minimize power loss), which must be matched to either a specific comparator threshold or a desired ADC resolution. This requires that gain be

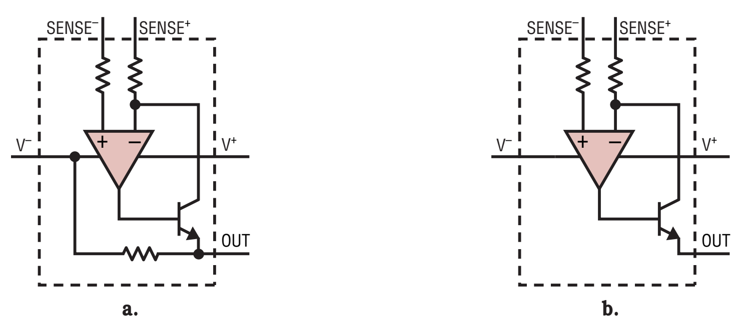

Figure 7. The LT6101 achieves unparalled versatility in high side current sensing applications by allowing the user to select the gain via external R_{IN} and R_{OUT} resistors. In most architectures, some or all of these resistors are internal to the device, as shown here. Fixed gain devices, such as in (a), limit flexibility. Those with fixed input resistors, as in (b), limit gain and speed.

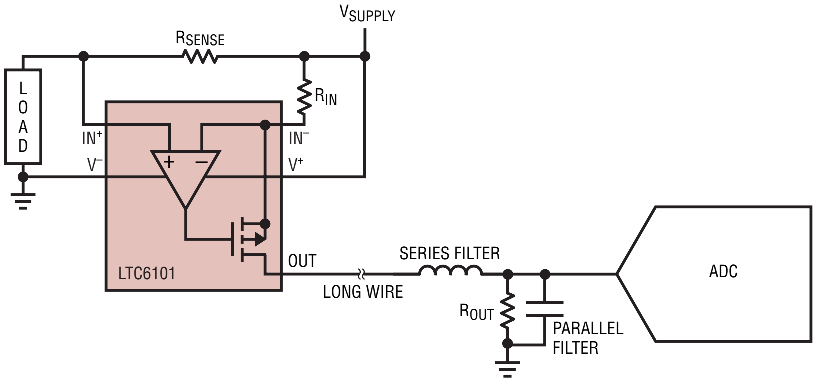

Figure 8. Open drain output enhances remote sensing accuracy.

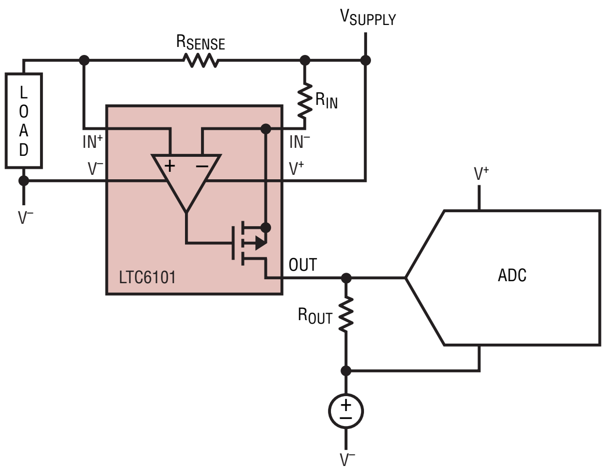

Figure 9. Output reference level shifted above V⁻

carefully set to maintain performance. In solutions where the gain resistors are not user-selectable (Figure 7a), the gain will be fixed, and may not be set to an appropriate value. Another approach is to include internal input resistors (Figure 7b), which allows user-configured gain, but may force the use of a very large output resistor in order to get high gain (10-100 or more). A large output resistor will cause the output to be slower and more susceptible to system noise, and may be too high an impedance to drive a desired ADC. The LTC6101 avoids these problems by allowing the application designer to choose both R_{IN} and R_{OUT}. R_{IN} can be quite small, its value limited only by the gain error due to stray board resistance and the 1mA maximum output current specification. Therefore high gain and high speed can be achieved even with small V_{SENSE} and R_{OUT} requirements. Gain accuracy is determined only by the accuracy of the external resistors.

In addition, the open-drain output architecture provides an advantage for remote-sensing applications. If the LTC6101 output must drive a circuit that is located remotely, such as an ADC, then the output resistor can be placed near the ADC. Since the open-drain output is a high-impedance current source, the resistive drop in the output wire will not affect the result at the converter. System noise that is coupled onto the long wire can be easily reduced with a series filter placed before R_{OUT}, or with a simple capacitor in parallel with R_{OUT}, with no loss of DC accuracy (Figure 8). The output may also be level shifted above V^- by terminating R_{OUT} at a voltage that is held higher than V^- (figure 9), provided that the maximum difference between V_{OUT} and V^- does not exceed the maximum specified output of the LTC6101.

Table 2. Linear Technology offers ICs for application-specific current-sensing solutions. Use this table to find publications that cover specific applications.

Publication	Application
LTC4060 Data Sheet	NiMH/NiCd charger
Linear Technology Magazine Mar. 2003, p. 24	Battery chargers
Linear Technology Magazine May 2004, p. 24	Battery gas gauge
Application Note 89	5V, TEC Controller
Application Note 66, Application Note 84	Switch Mode Power
LT Chronicle Jan. 2003, p. 7	Automotive Temp
Design Note 1009	Photo Flash
Design Note 312	VRM9.x
Design Note 347	Bricks
LTC4259, LTC4267 Data Sheet	Power over Ethernet
Design Solution 43	Altera FPGAs

Applications

Micro-Hotplate Current Monitor

Materials science research examines the properties and interactions of materials at various temperatures. Some of the more interesting properties can be excited with localized nano-technology heaters and detected using the presence of interactive thin films.

While the exact methods of detection are highly complex and relatively proprietary, the method of creating localized heat is as old as the light bulb. Figure 10 shows the schematic of the heater elements of a Micro-hotplate from Boston Microsystems (www.bostonmicrosystems.com). The physical dimensions of the elements are tens of microns. They are micromachined out of SiC and heated with simple DC electrical power, being able to reach 1000°C without damage.

The power introduced to the elements, and thereby their temperature, is ascertained from the voltage-current product with the LT6100 measuring the current and the LT1991 measuring the voltage. The LT6100 senses the current by measuring the voltage across the 10Ω resistor, applies a gain of 50, and provides a ground referenced output. The I to V gain is therefore 500mV/mA, which makes sense given the 10mA full scale heater current and the 5V output swing of the LT6100. The LT1991's task is the opposite, applying precision attenuation instead of gain. The full scale voltage of the heater is a total of 40V (±20), beyond which the life of the heater may be reduced in some atmospheres. The LT1991 is set up for an attenuation factor of 10, so that the 40V full scale differential drive becomes 4V ground referenced at the LT1991 output. In both cases, the voltages are easily read by 0V–5V PC I/O cards and the system readily software controlled.

White LED Current Controller

Figure 11 shows the LT6100 used in conjunction with the LT3436 switch mode power converter to efficiently drive a white LED with a constant current. By closing the switch on pin A2 of the LT6100, its gain is adjusted between 40 (open) and 50 (closed).

The FB pin of the LT3436 is a control pin referenced to a 1.2V set point. When the FB pin is above 1.2V, the LT3436 stops operation; when below 1.2V, the LT3436 continues operation. The output voltage (>1.2V) is usually regulated by applying a resistive divider from the output voltage back to the FB pin to close the feedback loop. To achieve a constant output current, rather than a constant output voltage, the feedback loop must convert the load current to a voltage. Enter the LT6100.

It senses the LED current by measuring the voltage across a 30mΩ resistor, applies a gain, and feeds the resulting voltage back to the FB pin.

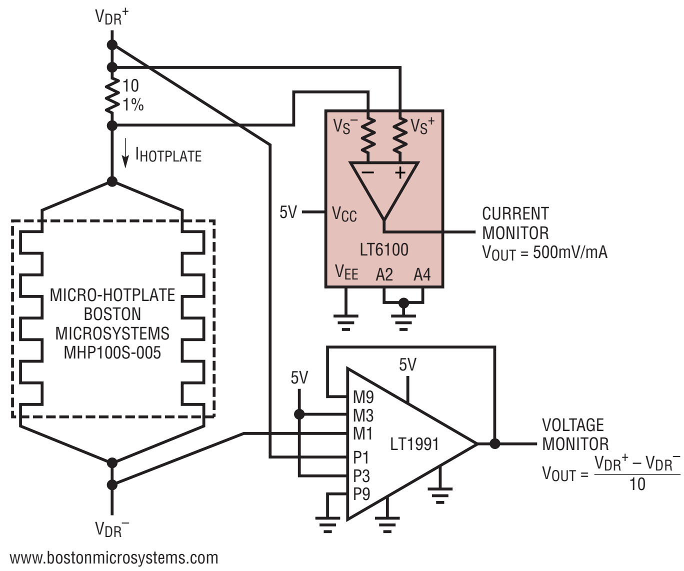

Figure 10. LT6100 and LT1991 monitor the current and voltage through a wide range of drive levels applied to a Microhotplate.

The 1.2V set point at the LT3436 can be referred back across the sense resistor by dividing by the LT6100 gains of 40 and 50. This gives 30mV and 24mV respectively. Dividing by the

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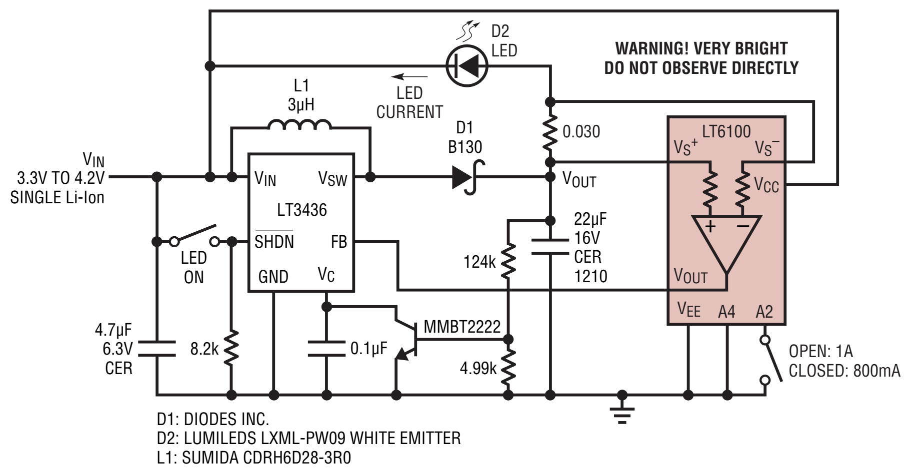

Figure 11. 1Amp/800mA white LED current controller

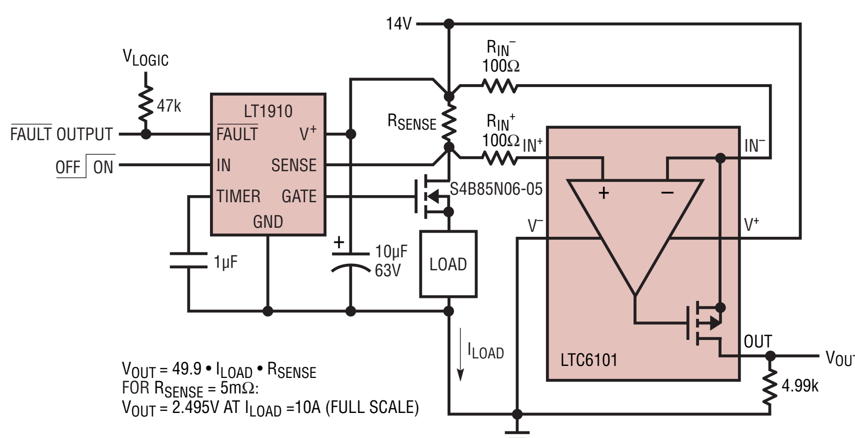

Figure 12. Automotive smart-switch with current readout

Versatile Buck-Boost Converter Offers High Efficiency in a Wide Variety of Applications

by Dave Salerno

Introduction

Miniature hard disk drives are a popular storage medium for MP3 music files, digital photographs and other data stowed in the latest portable electronics. Likewise lithium-ion batteries are popular for these same devices, which presents a minor problem in that mini disk drives typically require a 3.3V supply, which is right in the middle of the lithium-ion battery's operating range (3.0V-to-4.2V). This requires a converter that can both step down a fully-charged Li-Ion battery and step up the same battery as it discharges to sub-3.3V levels.

The LTC3442 is a 1.2A buck-boost converter that is ideal for mini disk drive applications, and certainly for other buck-boost appliations as well. The LTC3442 extends battery life with 95% efficiency and fits into tight spaces with its 3mm × 4mm DFN package. It builds upon previous LTC buck-boost offerings by adding programmable automatic Burst Mode® operation, switching frequency and average input current limiting.

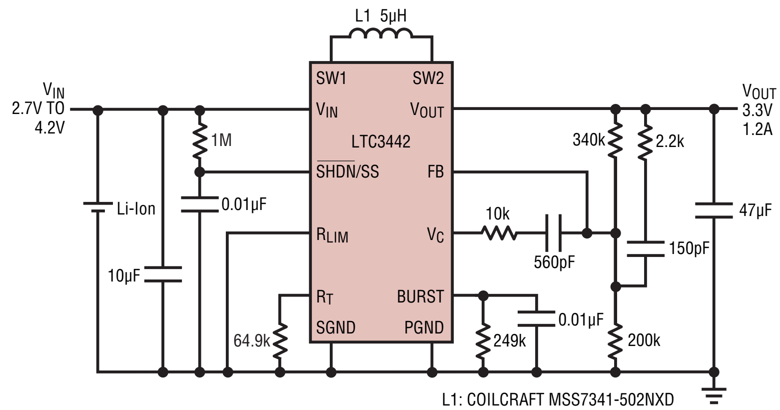

Figure 1. Li-Ion to 3.3V converter delivers 1.2A with automatic Burst Mode operation.

Features

The LTC3442 buck-boost converter uses the same fixed frequency, four-switch architecture as the LTC3440 and LTC3441, allowing it to use a single inductor to regulate the output voltage with input voltages than can be greater or less than the output. This provides an excellent solution for Li-Ion to 3.3V applications, with higher efficiency, smaller size and lower cost than SEPIC designs. Programmable automatic Burst Mode operation enables the converter to change operating modes without external intervention, for the best efficiency in portable applications. The transition point from fixed frequency PWM mode to Burst Mode operation is easily programmed with a single resistor. In addition, programmable average input current limit allows the user to limit the current drawn from the power source. This feature is useful in USB applications, where the allowable current draw is limited to 500mA maximum. The four internal 100mΩ MOSFET switches provide high efficiency, even at peak currents up to 3A. Programmable switching frequency and soft-start provide flexibility for many different applications. Output disconnect, which prevents any unwanted current flow between V_{IN} and V_{OUT} during normal operation or shutdown, is an inherent feature of the 4-switch architecture.

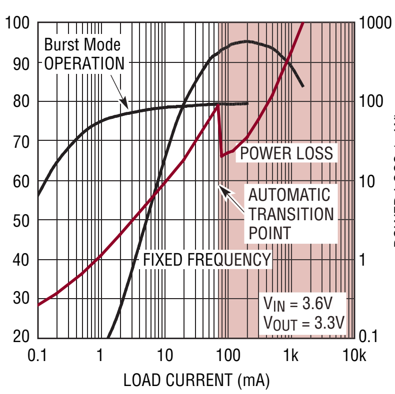

Figure 2. Efficiency vs load for the converter in Figure 1

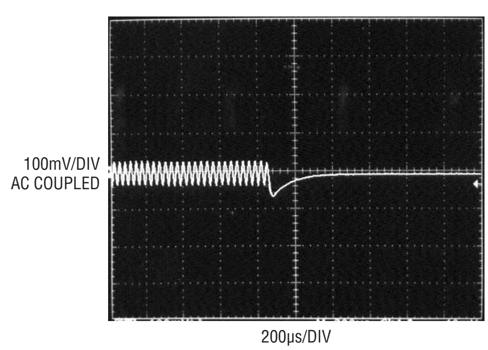

Figure 3. Output voltage during the automatic transition between Burst Mode operation and Fixed Frequency operation

4W, Li-Ion to 3.3V Converter with Automatic Burst Mode Operation is Ideal for Dynamic Load Applications

A typical Li-ion to 3.3V application circuit is shown in Figure 1. It provides efficient, well-regulated 3.3V output power at currents up to 1.2A with very low ripple, even as the battery voltage varies from 4.2V down to less than 3V. The automatic Burst Mode feature enables it to maintain high efficiency, even as the load becomes very light. This is ideal for applications such as miniature disk drives in portable devices, which require currents up to an amp during spin-up, a few hundred milliamps during read and write cycles, but much less current during idle times, or when the device goes to sleep. Figure 2 shows

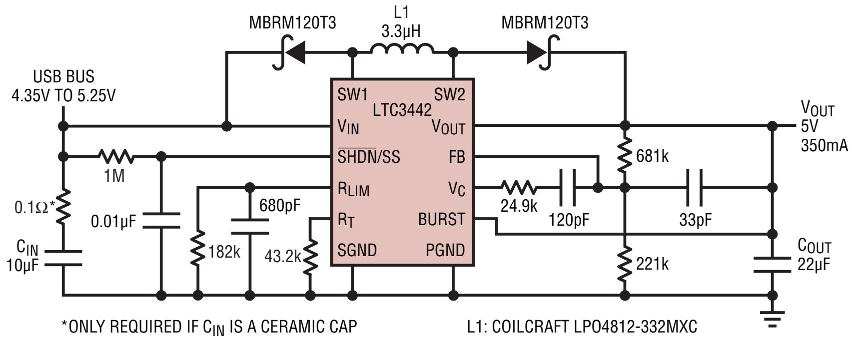

Figure 4. A 5V converter with average input current limit for USB applications

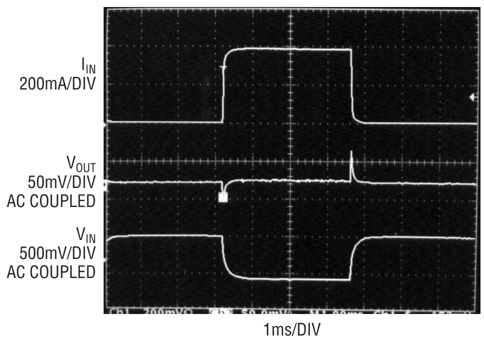

Figure 5. Step load regulation of the USB converter in Figure 4

the converter efficiency, peaking at 95%. Maintaining regulation when the input voltage drops below 3.3V allows all the energy in the battery to be used. It also allows the converter to maintain regulation during load transients, when the battery ESR may cause the input voltage to drop below 3.3V momentarily. In contrast, step-down designs lose output regulation when the battery voltage approaches or dips below 3.3V.

Automatic Burst Mode operation allows the converter to change operating modes as the load current varies, maintaining high efficiency, without any commands required from a host. By mirroring a small fraction of the output current and averaging it on the BURST pin, a voltage is produced that is proportional to the average load current. When this voltage exceeds an internal threshold of 1.12V, the converter operates in fixed frequency mode. When the BURST voltage drops below a threshold of 0.88V, the converter transitions to Burst mode operation. Therefore, raising the value of the resistor on the Burst pin lowers the load current at which Burst mode is entered (values above 250K are not recommended). (Note that the operating mode can be manually controlled by the host at any time by driving the Burst pin above or below these thresholds.)

Another feature of the LTC3442 is an adaptive hold circuit that keeps the VC pin and the compensation network charged to the correct voltage during Burst Mode operation, for a smooth transition back to fixed frequency operation. Figure 3 shows the output voltage as the converter switches automatically from Burst Mode operation to fixed frequency mode, in response to an increase in load. If desired, the operating mode can be forced by driving the Burst pin high (for fixed frequency operation) or low (for Burst Mode operation).

1MHz USB to 5V Converter with Average Input Current Limit

An increasing number of portable electronic devices and computer peripherals are operated with USB power. Although this is convenient for the user, it brings with it some challenges for the designer of the USB powered device. The voltage regulator tolerance of the host, combined with voltage drops in bus-powered hubs and USB cables, cause the 5V available at the end of the USB cable to be poorly regulated, varying from 4.35V to 5.25V (with transients down to 4.0V). Figure 4 shows a low profile (1.2mm), USB to 5V converter using the LTC3442 for high-power bus-powered functions. It accepts the poorly regulated USB input, and delivers 5V with 2% regulation and less than $20mV_{P-P}$ ripple. Figure 5 illustrates the circuit's ability to maintain tight regulation during line

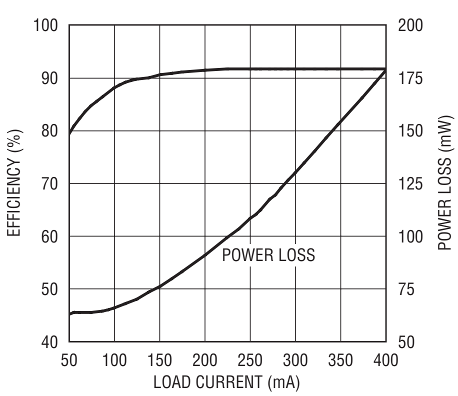

Figure 6. Efficiency vs load for the 5V USB converter in Figure 4

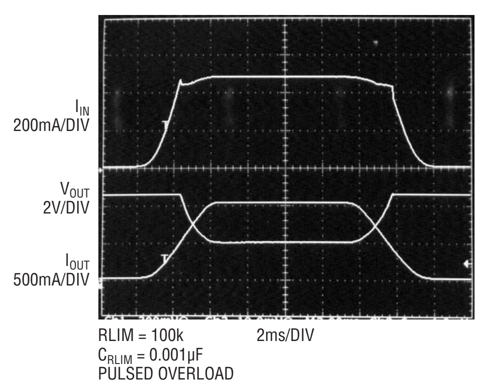

Figure 7. Input current limit overload response of USB converter.

and load transients. In this example, a step load has caused the USB–supplied current to increase by 400mA, resulting in a 600mV drop in the USB input voltage, while V_{OUT} exhibits only a 60mV disturbance.

The converter efficiency is as high as 92% at 1MHz, as shown in Figure 6. Note that in this example, the Burst pin is pulled high for fixed frequency operation.

One of the restrictions placed on users of the USB bus is a maximum allowed current draw of 500mA. To guarantee that this limit is not exceeded, USB powered solutions often employ additional current limiting circuitry, increasing size and cost. The LTC3442 solves this problem by including a programmable average input current limit, which works by mirroring a small fraction of the input current and averaging it on the RLIM pin, using an external RC network. The RLIM voltage is also connected to an internal amplifier with a 1V reference. When the RLIM voltage reaches 1V, the amplifier clamps the VC pin, lowering the output voltage as needed to prevent the input current from increasing any further. In the example of Figure 4, the input current is limited to less than 500mA in the event of an overload. The current limit response time is set by the filter capacitor on the RLIM pin. Figure 7 illustrates the circuit's response to an overload, with V_{OUT} dropping as I_{OUT} increases and the USB input current is clamped to 0.5A.

In this application, Schottky diodes are required to limit the peak voltage on the switch nodes and also provide a small efficiency improvement. Note that since the diodes are back-to-back, the output disconnect feature of the LTC3442 is maintained. The resistor in series with the input filter capacitor damps any oscillation or overshoot resulting from the input capacitor resonating with the USB cable inductance when the cable is first attached. This damping resistor is only required if a ceramic input capacitor is used. When using a tantalum capacitor, the ESR of the capacitor provides damping,

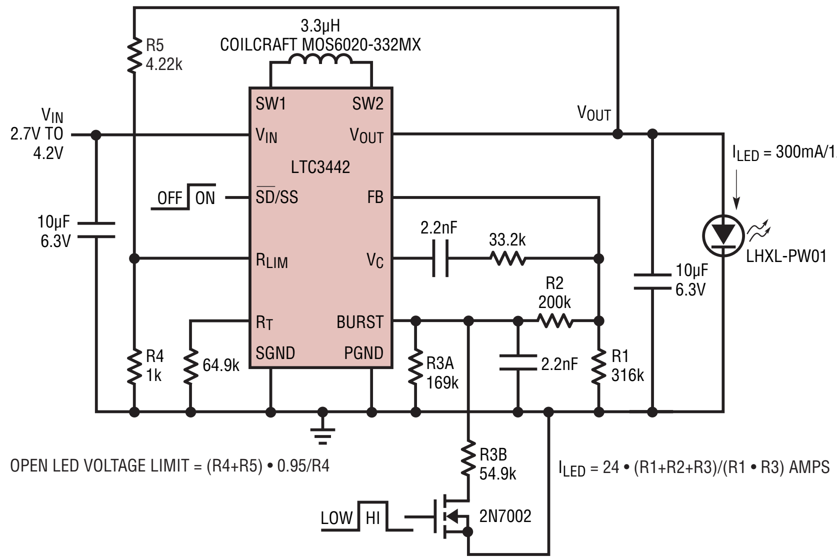

Figure 8. Constant current white LED driver for Li-Ion-powered applications

eliminating the need for an external resistor.

High Efficiency, Constant Current White LED Driver

High current white LEDs are being used in many new applications, including flashes for cell phone cameras. These applications demand a small, high efficiency solution, capable of supplying a regulated LED current, which may need to be set anywhere from a few hundred milliamps to over 1A , while being powered from a Li-ion battery. With typical white LED voltages ranging from 3V to 4V, a buck-boost converter is necessary to maximize Li-ion battery life.

Most LED drivers must use a current sensing resistor to regulate the LED current. This approach lowers efficiency and requires added board real estate, since the resistor must be sized to handle the high peak current in the LED. A unique solution for this application is shown in Figure 8, where the LTC3442 is configured as a fixed frequency constant current source. By utilizing the output current mirror at the BURST pin, normally used for automatic Burst Mode operation, no current sense resistor is required. In this application, the feedback loop is closed on the sensed average output current, rather than the output voltage. With essentially lossless current sensing, 94% efficiency is achieved, as shown in Figure 9. The LED current can be easily programmed or changed quickly, as in a pulsed flash, by changing the resistance on the BURST pin. It can also be turned on and off by means of the shutdown input. Figure 10 illustrates the response to a

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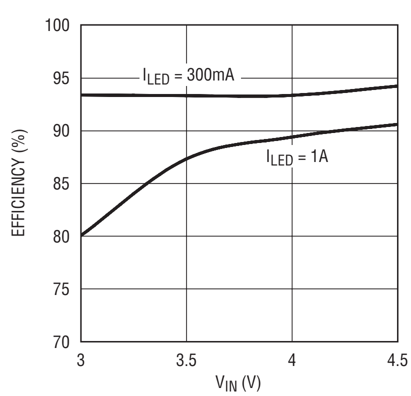


Figure 9. Efficiency vs load for the high current LED driver in Figure 8

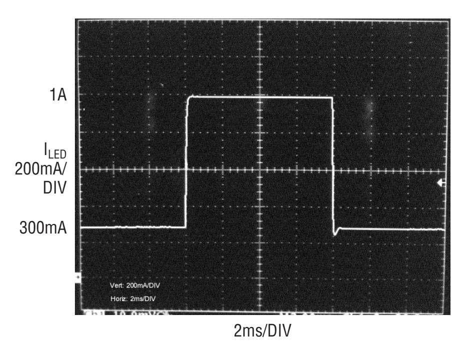


Figure 10. Step response of the LED constant current driver in Figure 8 for flash applications

Low EMI, Output Tracking, High Efficiency, and Too Many Other Features to List in a 3mm x 4mm Synchronous Buck Controller

by Lin Sheng

Introduction

The LTC3808 synchronous DC/DC controller packs many features required by the latest electronic devices into a low profile (0.8mm tall), 3mm × 4mm leadless DFN package, or a leaded SSOP-16 package. The LTC3808 can provide output voltages as low as 0.6V and output currents as high as 7A from a wide, 2.75V to 9.8V, input range, making it an ideal device for battery powered and distributed DC power systems. It also includes important features for noise-sensitive applications, including a phase-locked loop (PLL) for frequency synchronization and spread spectrum frequency modulation to minimize electromagnetic interference (EMI).

The LTC3808 improves battery life and saves space by delivering high efficiency with a low operating quiescent current. The LTC3808 also takes advantage of No R_{SENSE}™ current mode technology by sensing the voltage across the main (top) power MOSFET to improve efficiency and reduce the size and cost of the solution. Its adjustable high operating frequency (300kHz–750kHz) allows the use of small surface mount inductors and ceramic capacitors for a compact power supply solution.

The LTC3808 offers flexibility of start-up control with a fixed internal start-up time, an adjustable external soft-start, or the ability to track another voltage source. It also includes other popular features, such as a Power Good voltage monitor, current mode control for excellent AC and DC line and load regulation, low dropout (100% duty cycle) for maximum energy extraction from a battery, output overvoltage protection and short circuit current limit protection.

How It Works

Figure 1 shows a step-down converter with an input of 5V and an output of 2.5V at 5A. Figure 2 shows its efficiency versus load current. The LTC3808 uses a constant frequency, current mode architecture to drive an external pair of complementary power MOSFETs. During normal operation, the top P-channel MOSFET is turned on every oscillator cycle, and is turned off when the current comparator trips. The peak inductor current at which the current comparator trips is determined by the voltage on the I_{TH} pin, which is driven by the output of the error amplifier. The V_{FB} pin receives the output voltage feedback signal from an external resistor divider. This feedback signal is compared to the internal 0.6V reference voltage by the error amplifier. While the top P-channel MOSFET is off, the bottom N-channel MOSFET is turned on until either the inductor current starts to reverse, as indicated by a current reversal comparator, or the beginning of the next cycle.

The LTC3808 can provide output voltages as low as 0.6V and output currents as high as 7A from a wide, 2.75V to 9.8V, input range, making it an ideal device for battery powered and distributed DC power systems.

Selectable Operation Modes in Light Load Operation

The LTC3808 can be programmed for three modes of operation via the SYNC/MODE pin: high efficiency Burst Mode operation, forced continuous conduction mode or pulse skipping mode at low load currents. Burst Mode operation is enabled by connecting the SYNC/MODE pin to V_{IN}. In this mode, the peak inductor current is clamped to about one-fourth of the maximum value and the I_{TH} pin is monitored to determine whether the device will

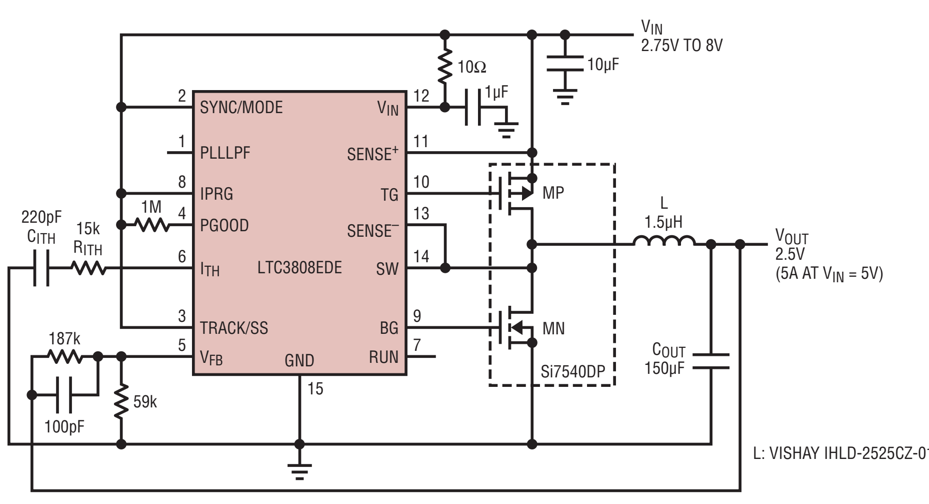


Figure 1. A 550kHz, synchronous DC/DC converter with 5V input and 2.5V output at 5A

go into a power-saving SLEEP mode. When the inductor's average current is higher than the load requirement, the voltage at the I_{TH} pin drops as the output voltage rises slightly. When the I_{TH} voltage goes below 0.85V, the device goes into SLEEP mode, turning off the external MOSFETs and much of the internal circuitry. The load current is then supported by the output capacitors, and the LTC3808 draws only 105µA of quiescent current. As the output voltage decreases, I_{TH} is driven higher. When I_{TH} rises above 0.925V, the device resumes normal operation.

Tying the SYNC/MODE pin to a DC voltage below 0.4V (e.g., GND) enables forced continuous mode which allows the inductor current to reverse at light loads or under large transient conditions. In this mode, the P-channel MOSFET is turned on every cycle (constant frequency) regardless of the I_{TH} pin voltage so that the efficiency at light loads is less than in Burst Mode operation. However it has the advantages of lower output ripple and no noise at audible frequencies.

When the SYNC/MODE pin is clocked by an external clock source to use the phase-locked loop or is set to a DC voltage between 0.4V and several hundred millivolts below V_{IN} (e.g., V_{FB}), the LTC3808 operates in PWM pulse skipping mode at light loads. In this mode, cycle skipping occurs under light load conditions because the inductor current is not allowed to reverse. This mode, like forced continuous operation, exhibits low output ripple as well as low audible noise as compared to Burst Mode operation. Its low-current efficiency is better than forced continuous mode, but not nearly as high as Burst Mode operation. Figure 3 shows the efficiency versus load current for these three operation modes.

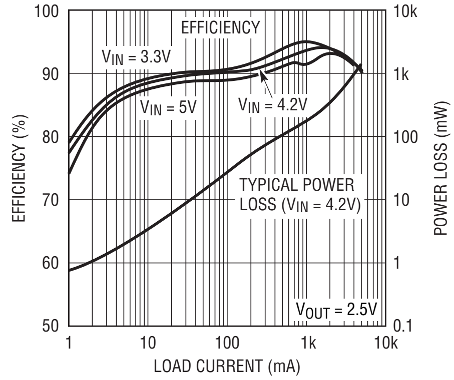


Figure 2. Efficiency and power loss vs load current of the circuit in Figure 1

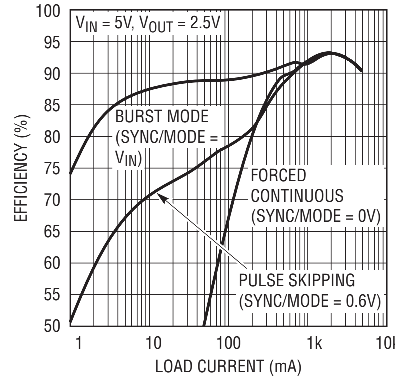


Figure 3. Efficiency vs load current in three operation modes for the circuit in Figure 1

Shutdown and Start-Up Control

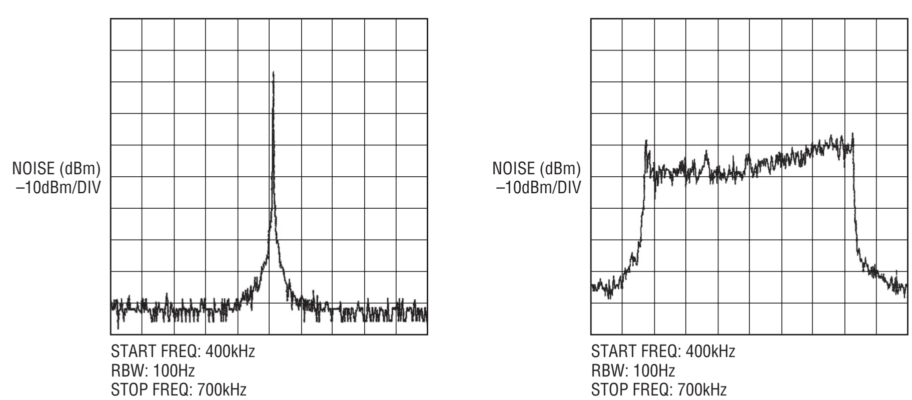
The LTC3808 is shut down by pulling the RUN pin below 1.1V. In shutdown, all controller functions are disabled while the external MOSFETs are held off, and the chip draws less than 9µA. Releasing the RUN pin allows an internal 0.7µA current source to pull up the RUN pin to V_{IN}. The controller is enabled when the RUN pin reaches 1.1V. Alternatively, the RUN pin can be driven directly from a logic output.

The start-up of V_{OUT} is based on the three different connections on the TRACK/SS pin. When TRACK/SS is connected to V_{IN}, the start-up of V_{OUT} is controlled by the internal soft-start, which rises smoothly from 0V to its final value in about 1ms. A second start up mode allows the 1ms soft-start time to increase or decrease by connecting an external capacitor between the TRACK/SS pin and the ground. When the controller is enabled by releasing the RUN pin, TRACK/SS pin is charged up by an internal 1µA current source and rises linearly from 0V to above 0.6V. The error amplifier compares the feedback signal V_{FB} to this ramp instead of the internal soft-start ramp, and regulates V_{FB} linearly from 0V to 0.6V.

In this case, the LTC3808 regulates the V_{FB} to the voltage at the TRACK/SS pin. Therefore, in the third mode, V_{OUT} of LTC3808 can track an external voltage V_X during start-up if a resistor divider from V_X is connected to the TRACK/SS pin. For coincident tracking during startup, the regulated final value of V_X should be larger than that of V_{OUT}, and the resistor divider on V_X would have the same values as the divider on V_{OUT} that is connected to V_{FB}.

Selecting an Operating Frequency

The choice of operating frequency f_{OSC} is generally a trade-off between efficiency and component size. Low frequency operation improves efficiency by reducing MOSFET switching losses (both gate charge and transition losses). Nevertheless, lower frequency operation requires more inductance for a given amount of ripple current.



a. Without SSFM **b. With SSFM**

Figure 4. Spread spectrum modulation of the controller operating frequency lowers peak EMI as seen in this comparison of the V_{OUT} spectrum without spread spectrum modulation (a) and with spread spectrum modulation (b).

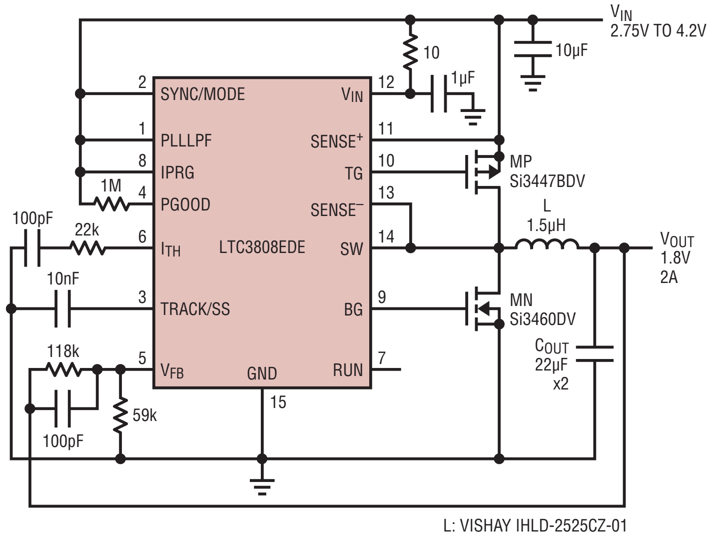


Figure 5. A 750kHz, synchronous single cell Li-Ion to 1.8V/2A converter with external soft-start and a ceramic output capacitor

The internal oscillator for the LTC3808's controller runs at a nominal 550kHz frequency when the PLLLPF pin is left floating and the SYNC/MODE pin is a DC voltage and not configured for spread spectrum operation. Pulling the PLLLPF to V_{IN} selects 750kHz operation; pulling the PLLLPF to GND selects 300kHz operation.

Alternatively, the LTC3808 can phase-lock to a clock signal applied to the SYNC/MODE pin with a frequency between 250kHz and 750kHz, and a series RC filter must be connected between the PLLLPF pin and ground as the loop filter. In this case, pulse-skipping mode is enabled under light load conditions to reduce noise.

Spread spectrum frequency modulation reduces the amplitude of EMI by spreading the nominal 550kHz operating frequency over a range of frequencies between 460kHz and 635kHz with pseudo random pattern (repeat frequency of the pattern is about 4kHz). Spread spectrum frequency modulation is enabled by biasing the SYNC/MODE pin to a DC voltage above 1.35V and V_{IN} – 0.5V. An internal 2.6µA pull-down current source at SYNC/MODE can be used to set the DC voltage at this pin by tying a resistor with an appropriate value between SYNC/MODE and V_{IN}. A 2.2nF filter cap between PLLLPF and ground and a 1000pF cap between SYNC/MODE and PLLLPF are needed in this mode. Figure 4 shows the frequency spectral plots of the output (V_{OUT}) with and without spread spectrum modulation. Note the significant reduction in peak output noise (>20dBm).

Power Good Monitor and Fault Protection

A window comparator monitors the feedback voltage and the open-drain PGOOD output is pulled low when the feedback voltage is not within 10% of the reference voltage of 0.6V.

The LTC3808 incorporates protection features such as programmable current limit, input undervoltage lockout, output overvoltage protection and programmable short circuit current limit.

Current limit is programmed by the IPRG pin. The maximum sense voltage across the external top P-channel MOSFET or a sense resistor is 125mV when the IPRG pin is floating, 85mV when IPRG is tied low and 204mV when IPRG is tied high.

To protect a battery power source from deep discharge, an internal undervoltage lockout circuit shuts down the device when V_{IN} drops below 2.25V to reduce the current consumption to about 3µA. A built-in 200mV hysteresis ensures reliable operation with noisy supplies.

During transient overshoots and other more serious conditions that may cause the output to rise out of regulation (>13.33%), an internal overvoltage comparator will turn off the top P-channel MOSFET and turn on the synchronous N-channel MOSFET until the overvoltage condition is cleared.

In addition, the LTC3808 has a programmable short circuit current limit protection comparator to limit the inductor current and prevent excessive MOSFET and inductor heating. This comparator senses the voltage across the bottom N-channel MOSFET and keeps the P-channel MOSFET off until the inductor current drops below the short circuit current limit. The maximum short-circuit sense voltage is about 90mV when the IPRG pin is floating, 60mV when IPRG is tied low and 150mV when IPRG is tied high.

Single Cell Li-Ion to 1.8V/2A Application

Figure 5 shows a step-down application from 3.3V to 1.8V at 2A. The circuit operates at a frequency of 750kHz, so a small inductor (1.5µH) and ceramic output capacitor (two 22µF caps) can be used. A 10nF capacitor at TRACK/SS sets the soft-start time of about 6ms. The $R_{DS(ON)}$ of the P-channel MOSFET determines the maximum average load current that the controller can drive. The Si3447BDV in this case ensures that the output is capable of supplying 2A with a low input voltage.

Conclusion

The LTC3808 offers flexibility, high efficiency, low EMI and many other popular features in a tiny 3mm × 4mm DFN package or a small 16-lead narrow SSOP package. For low voltage portable or distributed power systems that require small footprint, high efficiency and low noise, the LTC3808 is an excellent fit.

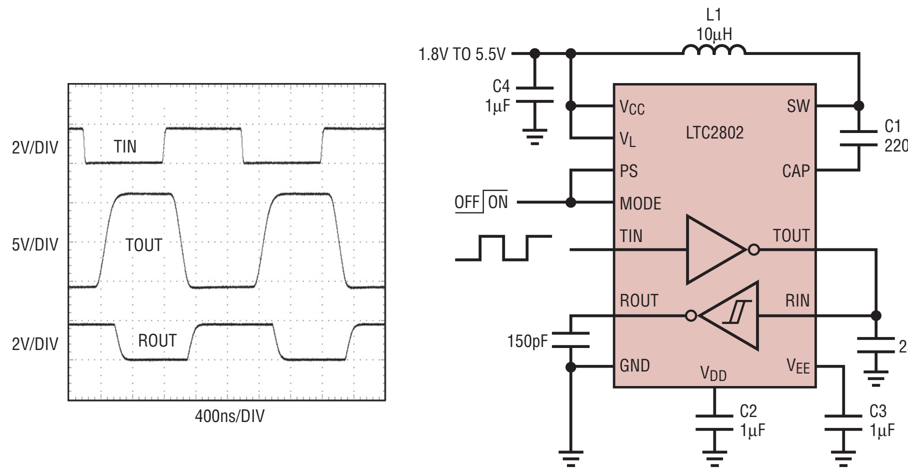
For more information on parts featured in this issue, see http://www.linear.com/designtools

Tiny RS232 Transeivers Run Directly from Alkaline, NiMH or NiCd Batteries

by Kevin Wrenner and Troy Seman

Introduction

Six new devices comprise a family of small-footprint RS-232 transceivers that operate at up to 1Mbps over a supply range of 1.8V to 5.5V. The LTC2801 and LTC2802 are single transceivers available in 4mm × 3mm DFN packages, and the LTC2803 and LTC2804 are dual transceivers available in 5mm × 3mm DFN packages. The LTC2803-1 and LTC2804-1 are dual transceivers offered in 16-pin SSOP packages. The wide supply range permits operation directly from two alkaline, NiCd, or NiMH battery cells, while a separate VL supply pin eliminates interfacing problems in mixed-supply systems.



a. b.

Figure 1. Operating waveforms at 1.8V and 1Mbps with driver and receiver fully loaded (a) and transmitter loopback mode test circuit (b)

1Mbps and 250kbps Data Rate

All of the devices are capable of driving standard RS232 loads (2.5nF/3kΩ) at 100kbps, and 1nF/3kΩ at 250kbps. The faster parts, the LTC2802, LTC2804 and LTC2804-1, can also drive 250pF/3kΩ at 1Mbps. Waveforms for a single transceiver operating at 1Mbps and 1.8V in a transmitter-loopback configuration are shown in Figure 1.

Achieving the higher signaling rate—50× the rate provided for in the original standard—necessitates slewing the driver faster than the standard's 30V/µs limit. The slower parts, the LTC2801 and LTC2803, are fully RS232 compliant. Output levels of all parts are RS232 compliant at their rated data rates even at 1.8V supply.

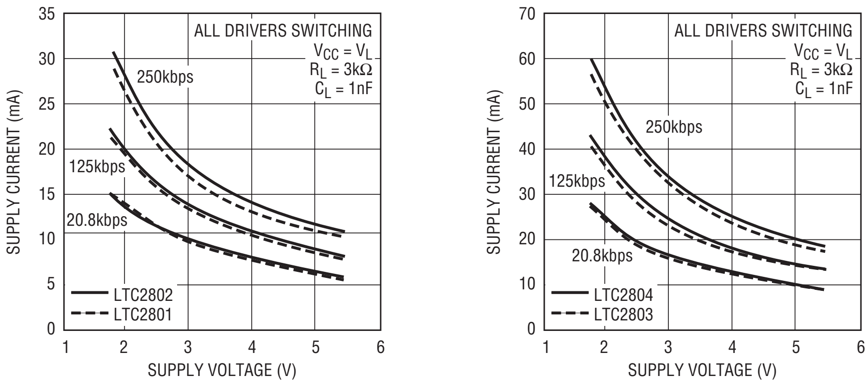
Figure 2 shows the relationship of supply current to supply voltage required to drive 1nF/3kΩ loads at various data rates. Figure 3 shows the supply current sensitivity to data rate at 1.8V.

More Features

Up to four operating modes are available, depending on the part (Table 1). The DFN parts have two power-saving modes. In Shutdown mode, current draw on each supply is reduced below 1µA. Receiver and driver outputs are high impedance, eliminating any problem associated with powering

Table 1. Feature summary

	LTC2801	LTC2802	LTC2803	LTC2803-1	LTC2804	LTC2804-1
Drivers and Receivers	1 + 1	1 + 1	2 + 2	2 + 2	2 + 2	2 + 2
Package	12-lead 4mm × 3mm DFN	12-lead 4mm × 3mm DFN	16-lead 5mm × 3mm DFN	16-lead SSOP	16-lead 5mm × 3mm DFN	16-lead SSOP
100kbps for R_L=3kΩ, C_L=2.5nF	✓	✓	✓	✓	✓	✓
250kbps for R_L=3kΩ, C_L=1nF	✓	✓	✓	✓	✓	✓
1Mbps for R_L=3kΩ, C_L=250pF		✓			✓	✓
30V/µs Maximum Slew Rate	✓		✓	✓		
Shutdown	✓	✓	✓	✓	✓	✓
Receiver(S) Active	✓	✓	✓		✓	
Driver Disable	✓	✓	✓		✓	



a.

b.

Figure 2. Supply current vs supply voltage for single (a) and dual (b) transceiver

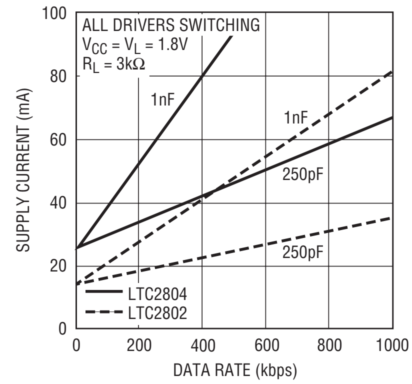


Figure 3. Supply current vs data rate (single and dual transceiver)

down a part connected to a receiver output. Receiver(s) Active mode is like Shutdown except receivers are biased at low current. With only 15µA current draw, one or two receivers can listen for a wake-up signal. Besides the Normal full-duplex operating mode, a Driver(s) Disabled mode is available to support line sharing and half-duplex operation.

These parts have built-in measures that permit reliable operation in the sometimes-harsh environment encountered in RS232 interfaces. All device pins are protected against electrostatic discharge (ESD) events without damage or latch-up. Interface pins have additional protection, tolerating repeated 10kV human body model discharges. Both driver and receiver outputs are current limited.

Dual Regulator

Each device in the LTC2801 family drives RS232 compliant output levels over its entire input supply range using an integrated dual regulator (Figure 4) that replaces the charge pump voltage multiplier found in many RS232 integrated circuits. Excellent line and load regulation is achieved with a constant frequency (1.2MHz typical) boost regulator that generates a positive supply of 7V and a coupled inverting charge pump that generates a negative supply of –6.3V. Like its charge pump voltage multiplier counterpart, regulator switching varies according to the driver loading. The regulator operates in a pulse skipping mode when driver activity/loading is low. Because all its Schottky diodes

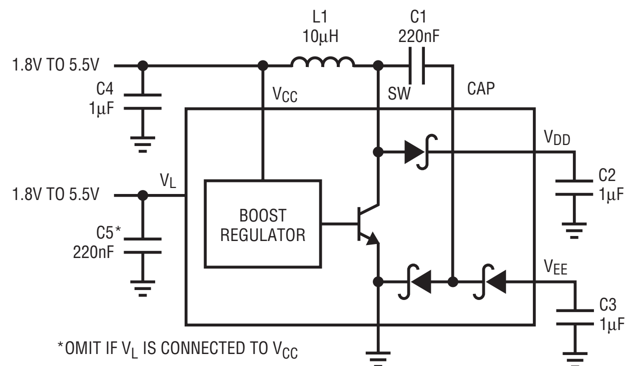


Figure 4. Dual regulator and recommended biasing

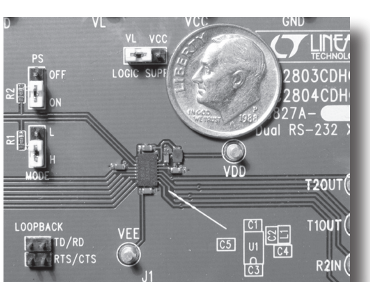


Figure 5. Example board layout with 5mm × 3mm DFN package

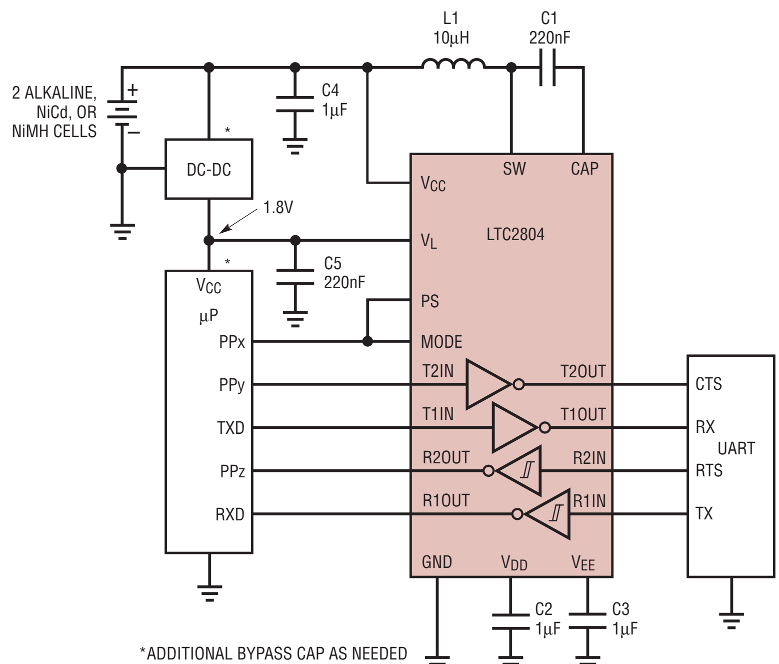


Figure 6. Diagnostic port operating directly off unregulated battery

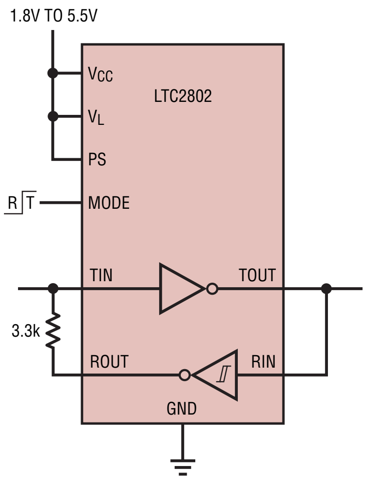


Figure 7. Half-duplex mode on RS232 interface. The logic interface shares a single wire, too.

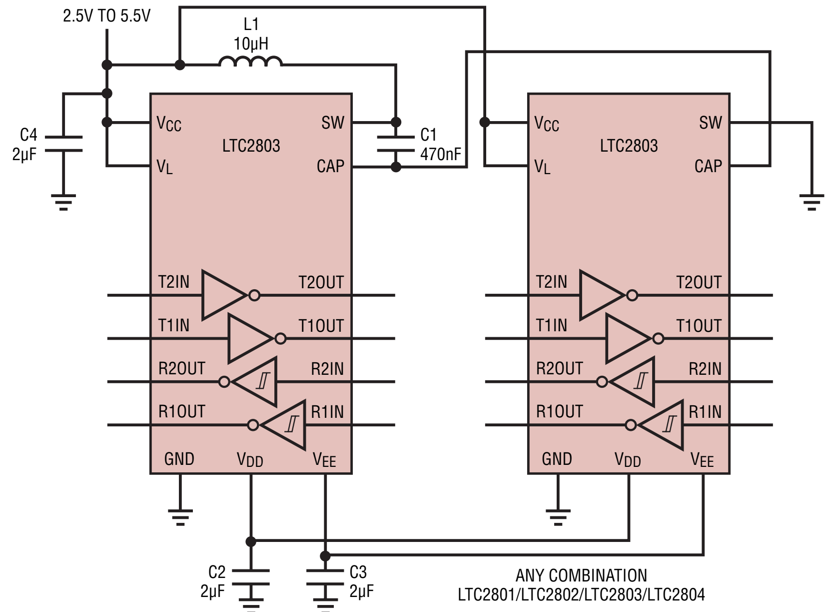


Figure 8. Quad transceiver with reduced component count

are integrated, the regulator requires only five external components: one small inductor and four tiny ceramic capacitors (Figure 5).

Battery-Operated Microcontroller Interface

The advantage of the VL interface logic supply feature can be seen in Figure 6, which shows a battery-operated RS232 interface to a diagnostic port on a 1.8V microprocessor. For maximum efficiency, the LTC2804 is operated directly off the battery voltage. The VL pin is connected to the microprocessor's regulated 1.8V supply, setting the RxOUT high level and the TxIN and control input threshold voltages, which are automatically scaled. This configuration can extend battery life while eliminating the need for level translators.

Half-Duplex on Shared Line

RS232 transceivers are often used in configurations outside the scope of the original standard. Figure 7 shows an LTC2802 configured to signal half-duplex over a single RS232 interface wire. The logic interface, too, shares a single wire between driver and receiver. With PS kept high, the MODE input serves as a low-latency driver enable that can switch between transmit and receive modes within 2µs. Using a switchable terminator in the remote device can help avoid degrading output levels and increasing power consumption.

Quad Transceiver

Dual transceivers are commonly used to provide a bidirectional interface that includes a data line and a hardware handshaking control signal. If two such ports are needed, two dual transceiver devices can share one device's regulator (Figure 8). Tie both device's CAP pins together, connecting in parallel the inverting charge pump Schottky diodes from both devices. The negative supply level is improved due to a reduction in the combined diode's forward voltage. The second device's unused SW pin should be grounded. This configuration eliminates one set of external components.

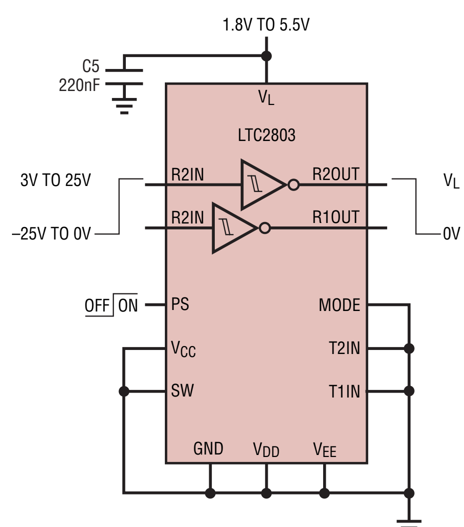


Figure 9. Inverting level translator

Adjustable Level Translator

Any RS232 transceiver is a bidirectional level translator. With the regulator and drivers disabled, the receiver(s) can provide simple unidirectional level translation with the output high level defined by the VL supply (Figure 9). This makes a useful 3V-to-5V or 5V-to-1.8V inverting translator capable of 1Mbps. A static dual translator consumes 120µA current. If hysteresis is not required, the MODE and PS pin connections can be reversed to obtain a lower power version (15µA static) capable of 100kbps.

Conclusion

The LTC2801 family's wide input range of 1.8V to 5.5V enables these parts to provide RS232 interfaces with fully compliant output levels using a broad range of power sources. The small footprint required by each part and its external components (Figure 5), independent logic interface supply, and power saving features, make this family of parts an attractive choice for designing low cost standardized signaling interfaces into modern consumer electronics.

Authors can be contacted at (408) 432-1900

Low Voltage Hot Swap Controller with Inrush Current Control

by Chew Lye Huat

Introduction

The LTC4216 is a low voltage Hot Swap controller that allows a board to be safely inserted and removed from a live backplane. The LTC4216 is designed to meet the latest low voltage board supply requirements with its unique feature of controlling load voltages from 0V to 6V. It also features an adjustable soft-start that provides both inrush current limiting and current slew rate control at start-up, important for the large load capacitors typical in low-voltage applications.

When a board is plugged into a backplane, the inrush currents can be large enough to create a glitch on the load supply causing other boards on the bus to malfunction. The LTC4216 provides a low circuit breaker trip threshold (25mV) with adjustable response time and analog current limiting for dual level overcurrent protection. It also includes a high side gate drive for an external N-channel MOSFET. Figure 1 shows a circuit using the LTC4216 as a Hot Swap controller for a 1.8V load supply.

Controlling Load Voltages Down to Zero Volts

The LTC4216 can control load voltages as low as 0V as it provides two separate pins: SENSEP pin for controlling the load voltages from 0V to 6V and V_{CC} pin for powering the device's internal circuitry with a minimum of 2.3V. An RC network shown in Figure 1 can be connected at the V_{CC} pin to ride out supply glitches during output-shorts or adjacent board transients. These supply glitches can potentially trigger the device into an undervoltage lockout condition, causing its internal latches to reset.

Output Voltage Monitoring

The output voltage is monitored through a resistive divider connected at the feedback (FB) pin, and an FB comparator with a 0.6V reference. The FB comparator has a built-in glitch filter to ride out any unwanted transients appearing on the FB pin. When the FB pin voltage exceeds 0.6V, it signals the $\overline{\text{RESET}}$ high after a power-good delay set by an external capacitor at the TIMER pin. The delay is given by:

$$\frac{1.253V \cdot C_{TIMER}}{2\mu A} = 0.6265 \cdot C_{TIMER}\left(\frac{ms}{nF}\right)$$

Soft-Start Controls Inrush Current Slew Rate

The LTC4216 features a soft-start function that controls the slew rate of the inrush current during power-up (Figure 2). The rate is controlled by an external capacitor connected from the soft-start (SS) pin to ground. A built-in Analog Current Limit (ACL) amplifier servos the GATE pin to track the rate of SS ramp-up during power-up. There are two slopes in the SS ramp-up profile: a 10µA pull-up for a normal ramp-rate, and a 1µA pull-up for a slow ramp rate. The slow SS ramp rate allows the gate of the external MOSFET to be turned on with a small inrush current step. When the load current starts flowing through the external sense resistor, SS reverts back to a normal ramp rate. At the end of the SS ramp-up, the GATE is servoed to limit the load current to 40mV across the sense resistor during startup. If the voltage across the sense resistor drops below 40mV due to reduced load current, the ACL amplifier shuts off and GATE ramps further with a 20µA pull-up.

Inrush Control with a GATE Capacitor

Figure 3 shows an alternative approach from the soft-start method to limit the inrush current during power up for a large load capacitor. An external capacitor, C4, is connected from the GATE pin to ground to limit the inrush current by slewing the GATE pin voltage. With a GATE pull-up

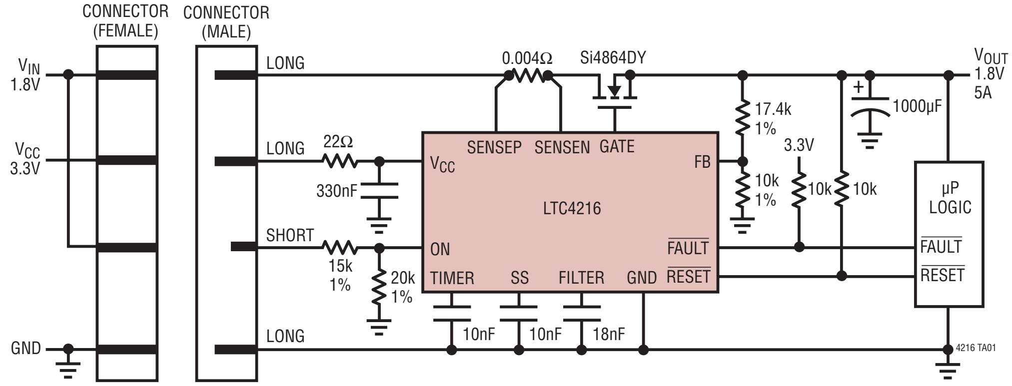


Figure 1. A 1.8V Hot Swap application

current of 20µA, the GATE slew rate is given by:

$$\frac{dV_{GATE}}{dt} = \frac{20\mu A}{C4 + C_{ISS}}$$

where C_{ISS} is the external MOSFET's gate input capacitance. The inrush current flowing into the load capacitor, C_{LOAD}, is limited to:

$$I_{INRUSH} = C_{LOAD} \bullet \frac{dV_{GATE}}{dt} = \frac{C_{LOAD}}{C4 + C_{ISS}} \bullet 20\mu A$$

For the application shown, C_{LOAD} = 470µF, C4 = 22nF and C_{ISS} = 3nF, I_{INRUSH} = 376mA. If C_{LOAD} is very large and I_{INRUSH} exceeds the analog current limit, the GATE servos to control the inrush current to 40mV/R_{SENSE}.

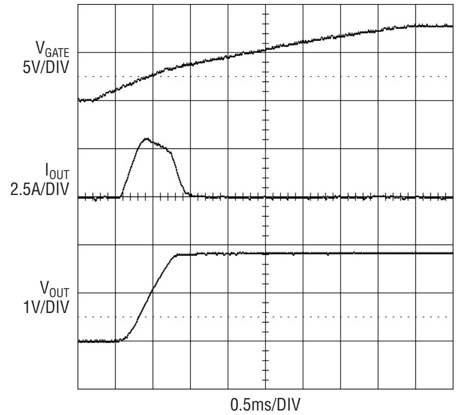


Figure 2. Power-up with soft-start for inrush control

Electronic Circuit Breaker

The load current is sensed by monitoring the voltage across an external sense resistor, R_{SENSE}, connected between SENSEP and SENSEN pins in Figure 1. The Electronic Circuit Breaker (ECB) trips at 25mV across the sense resistor during an overload condition. The response time is adjustable through an external capacitor connected from the FILTER pin to ground. Whenever the ECB trip threshold is exceeded, the FILTER pin charges up the external capacitor with a 60µA pull-up. Otherwise, it is pulled down by a 2.4µA current. When the FILTER pin voltage exceeds 1.253V, the ECB trips and the GATE pin is pulled down to ground immediately to disconnect the board from the backplane supply. The $\overline{FAULT}$ pin is also pulled low whenever the ECB trips. In order to reconnect the board, the ON pin must be pulled below 0.4V for at least 100µs to reset the ECB, or the V_{CC} pin voltage must be below 2V for more than 200µs.

Analog Current Limiting Protects Against Severe Overcurrent Fault

In addition to an Electronic Circuit Breaker (ECB), the LTC4216 includes an Analog Current Limit (ACL) amplifier that does not require an external compensation capacitor at the GATE pin. The amplifier's stability is compensated by the large gate input capacitance (C_{ISS} ≥ 1nF) of the external MOSFET used. The GATE pin is servoed to limit the load current to 40mV/R_{SENSE}. The ACL threshold (40mV) is 1.6 times higher than the ECB trip threshold (25mV) to provide dual level current sensing. When the output is in current limit, it exceeds the ECB trip threshold causing the FILTER pin to charge up the external capacitor with a 60µA pull-up. If the condition persists long enough for the FILTER pin voltage to reach its threshold, the GATE is pulled low and $\overline{FAULT}$ is latched low. If the voltage across the sense resistor exceeds 40mV during an overload condition, the ACL amplifier pulls the GATE down in an attempt to control the load current. For a mild short terrm overload, the ACL amplifier can immediately control the load current. However, in the event of a severe overload, the load current may overshoot as the MOSFET has large gate overdrive initially. The GATE is quickly discharged to ground followed by the ACL amplifier taking control.

Normal Power-Up Sequence

Figure 4 shows a normal power-up sequence with a large capacitor load in Figure 1. When the V_{CC} pin voltage rises above 2.1V and the ON pin is greater than 0.8V, the LTC4216 starts the first timing cycle. A 2µA current source charges an external capacitor (C1) connected from the TIMER pin to ground. When TIMER pin voltage rises above 1.253V, the TIMER pin is pulled

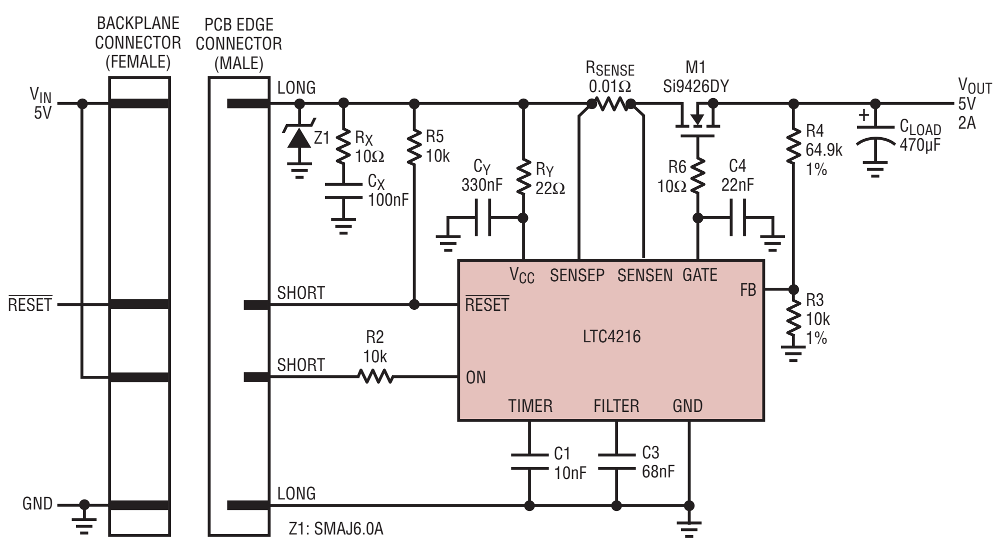


Figure 3. Application with an external GATE capacitor to enhance inrush control

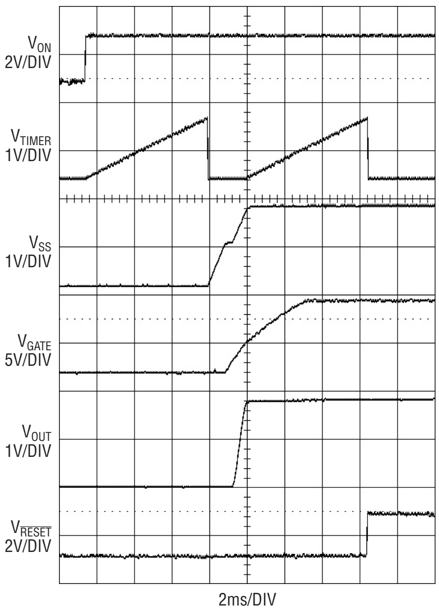


Figure 4. Power-up sequence with load

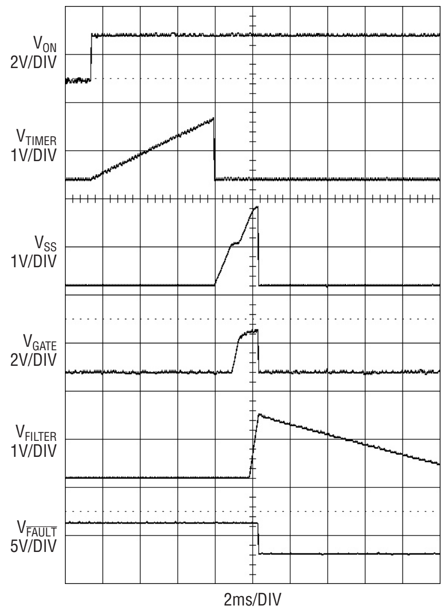


Figure 5. Power-up with short at 1.8V output

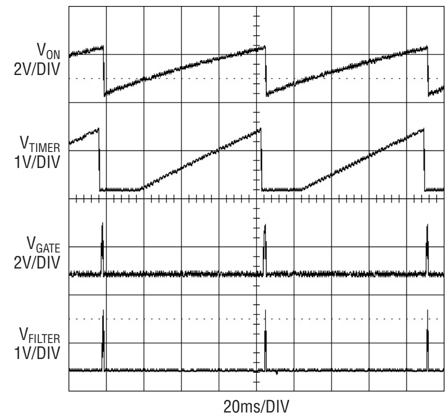


Figure 7. Auto-retry with short at 5V output

low and C1 is discharged. After this, the Electronic Circuit Breaker (ECB) is enabled and a GATE ramp-up cycle begins. GATE is held low initially by the ACL amplifier until SS switches from the 10µA pull-up to the 1µA pull-up for a slower ramp rate. The slew rate of the inrush current is in control as GATE ramps up gradually, tracking the SS ramp rate. SS reverts back to a normal ramp rate when the load current starts flowing through the sense resistor. At the end of the SS ramp, GATE continues to ramp up with a 20µA pull-up if the output is not in current limit. The second timing cycle starts when the FB pin voltage exceeds 0.6V. $\overline{\text{RESET}}$ goes high after a complete timing cycle, indicating that power is good.

Power-Up into an Output-Short Sequence

Figure 5 shows power-up with a short at the output in Figure 1. After the initial timing cycle, GATE ramps up and the external MOSFET is turned on. The load current rises due to the output short, causing the voltage across the sense resistor to rise above 25mV. The FILTER pin charges up the external capacitor with a 60µA pull-up while the output is in current limit. The output current is limited to $40mV/R_{SENSE}$ as the GATE regulates. When the FILTER pin voltage rises above 1.253V, the Electronic Circuit Breaker trips and both GATE and SS are pulled low. The device latches-off and $\overline{\text{FAULT}}$ is pulled low, indicating a fault condition. The FILTER capacitor discharges through a 2.4µA pull-down until the device resets.

Auto-Retry Application

Figure 6 shows an application that automatically tries to power up the board after the Electronic Circuit Breaker (ECB) has been tripped due to a shorted load supply output. The ON pin is shorted to the $\overline{\text{FAULT}}$ pin and is pulled up by a 200kΩ resistor (R_{AUTO}) to the load supply. A 1µF capacitor (C_{AUTO}) connected from the lower end of R_{AUTO} to ground sets the auto-retry duty cycle. The LTC4216 will retry as long as the short persists. R_{AUTO} and C_{AUTO} must be selected to keep the duty cycle low in order to prevent overheating in the external N-channel MOSFET.

Figure 7 shows the auto-retry cycle when the 5V output is shorted to ground. The ECB is tripped when the FILTER pin voltage rises above 1.253V after the first timing cycle. This causes the $\overline{\text{FAULT}}$ pin to be pulled

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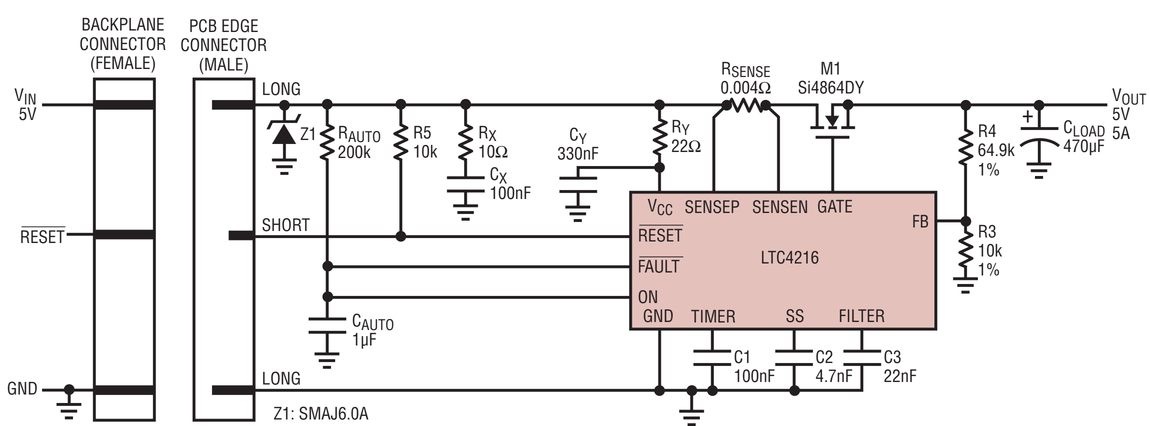

Figure 6. Auto-retry application

Monolithic Synchronous Step-Down Regulator Drives 8A Loads with Few External Components

by Joey M. Esteves

Introduction

The LTC3418 is a monolithic synchronous, step-down switching regulator that is capable of delivering 8A of output current for microprocessor and I/O supplies, point of load regulation, and automotive applications. Internal power MOSFET switches, with only 35mΩ on-resistance, allow the LTC3418 to reduce component count while achieving high efficiency. Operating at switching frequencies as high as 4MHz conserves additional space by permitting the use of smaller inductors and capacitors. The LTC3418's ability to track another voltage supply also allows it to be used in dual-supply systems that require power supply sequencing during start-up.

The LTC3418 employs a constant frequency, current-mode architecture that operates from an input voltage range of 2.25V to 5.5V and provides an adjustable output voltage from 0.8V to 5V while delivering up to 8A of output current. The switching frequency can be set between 300kHz and 4MHz by an external resistor. The LTC3418 can also be synchronized to an external clock, where each switching cycle begins at the falling edge of the external clock signal. Since output voltage ripple is inversely proportional to the switching frequency and the inductor value, a designer can take advantage of the LTC3418's high switching frequency to use smaller inductors without compromising the output voltage ripple. Lower inductor values translate directly to smaller case sizes, reducing the overall size of the system. OPTI-LOOP® compensation allows the transient response to be optimized over a wide range of loads and output capacitors, including ceramics. For increased thermal handling, the LTC3418 is offered in a 5mm × 8mm

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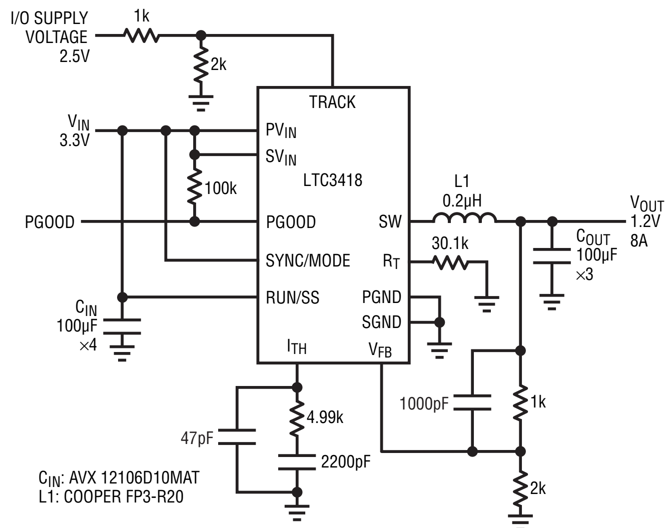

Figure 1. A 1.2V, 8A step-down regulator running at 2MHz, which allows the use of tiny capacitors and inductors. This particular configuration operates at a single frequency in forced continuous mode, which simplifies EMI filtering.

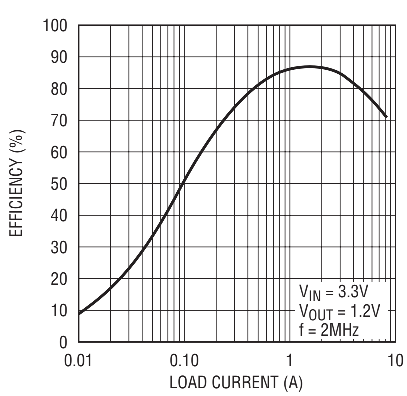

Figure 2. Efficiency vs Load Current

DESIGN IDEAS

Simple Converter Drives Luxeon White LEDs from Batteries

by Michael Nootbaar

Introduction

The high output 1W white LEDs from Luxeon and Nichia provide illumination levels close to 12W incandescent levels while dissipating only 1W and lasting for 50,000 hours or more. These devices promise enormous power savings and reduced maintenance cost for many lamp applications. However, these LEDs must be driven with a constant current to maintain proper brightness. The forward voltage drop varies between 2.8V and 4.0V over process and temperature extremes. The circuit used to drive the LED must compensate for this forward voltage variation while maintaining constant current drive. Existing boost circuits generally use voltage feedback switching converters with extra circuitry to sense output current rather than voltage. This results in complex circuits with poor efficiency.

The LTC3490 provides a simple solution for boosting a single or dual cell battery voltage to the necessary LED forward voltage and regulating the current through the LED load.

The LTC3490 provides a simple solution for boosting a single or dual cell battery voltage to the necessary LED forward voltage and regulating the current through the LED load. The high frequency (1.3MHz) operation allows small inductor and capacitor values. The current sensing resistor and loop compensation components are internal, reducing the component count. The LTC3490 is a synchronous converter eliminating the rectifier diode and its associated efficiency loss. The only required components are the boost inductor and an output filter capacitor. The shutdown and dimming functions add a few resistors, and an input capacitor is recommended in certain conditions.

Circuit Description

The LTC3490 is a synchronous boost converter. Its block diagram is shown in Figure 1. It will start up with input voltage as low as 0.9V using a low voltage startup circuit. When the output voltage exceeds 2.3V, the boost circuits turn on and the startup circuit shuts off. The boost converter is a fixed frequency, current mode architecture.

The LED current is sensed with an internal 0.1Ω resistor on the high side, which allows the LED cathode to be grounded. A sense amplifier compares this voltage to a reference current flowing through a ratiometrically matched 19.2Ω resistor. The sensed voltage dif-

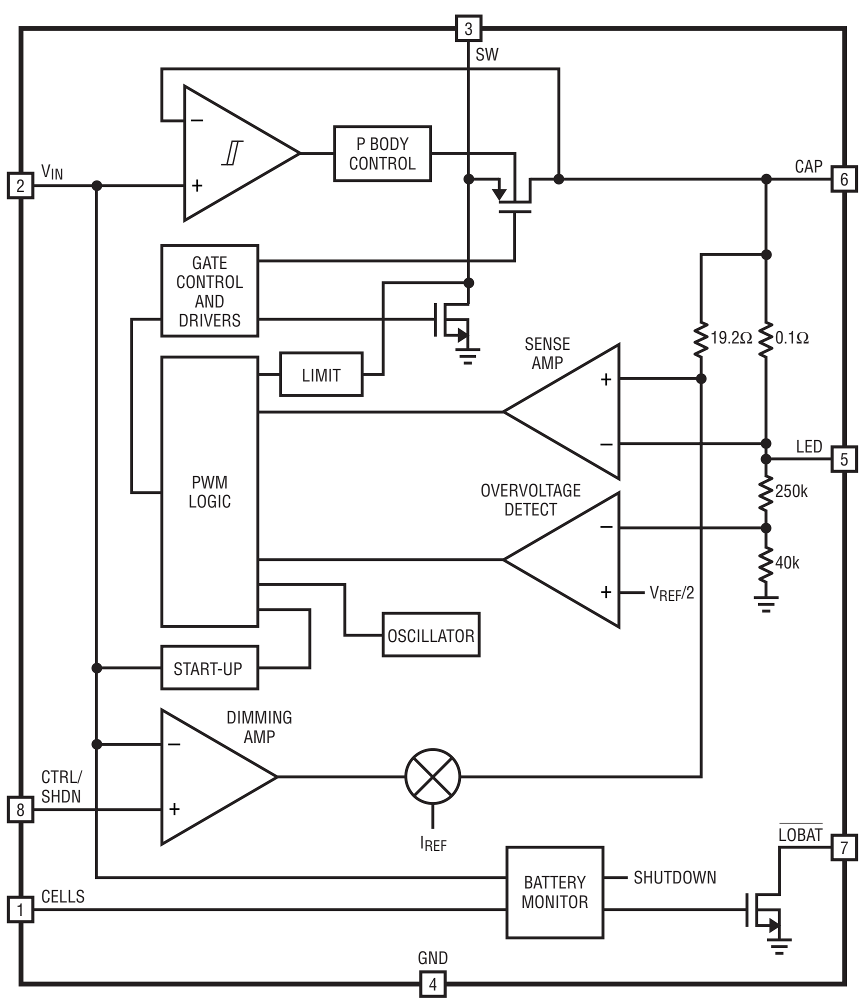

Figure 1. LTC3490 block diagram

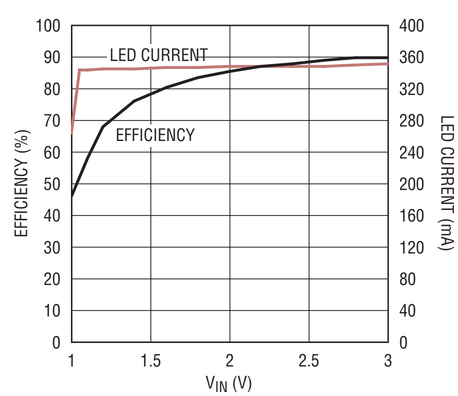

Figure 2. LTC3490 efficiency

ference is integrated and used to set the PWM controller. The LED current is therefore constant regardless of the LED forward voltage.

The LTC3490 is up to 90% efficient in dual cell applications and over 70% in single cell applications (Figure 2). The dual cell and single cell circuits are shown in Figures 3 and 4, respectively.

Overvoltage Protection

Output overvoltage protection is required because the current sensing controller can drive the output voltage to damaging levels if there is no load. This occurs if the LED is removed from the circuit or has failed. As long as the output current is below 350mA, the output voltage continues to climb and would damage the LTC3490 without overvoltage protection. The overvoltage detector forces the LTC3490 into shutdown when the output voltage is greater than 4.5V. The overvoltage detector remains on and will restore normal operation when the output drops below 4.5V.

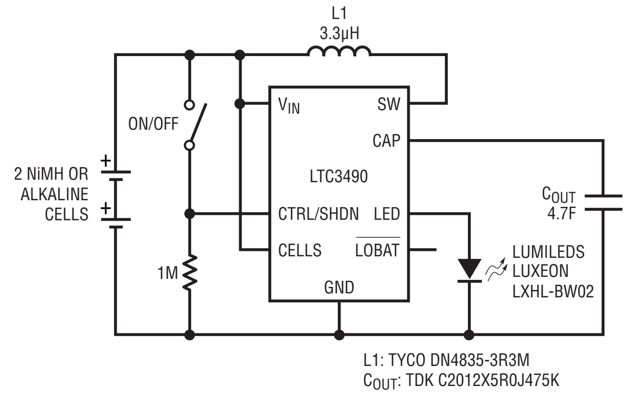

Figure 3. Minimum component 2-cell circuit

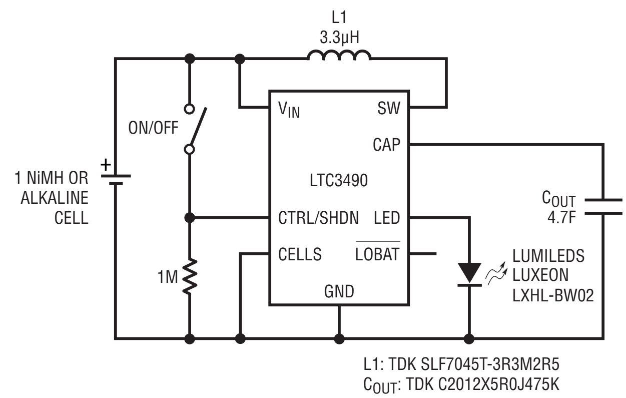

Figure 4. Minimum component 1-cell circuit

Dimming Function

The LTC3490 allows the LED current to be gradually reduced using the CTRL/SHDN pin. The CTRL/SHDN input has three functions: shutdown, dimming control and constant current output. The pin is ratiometric to V_{IN}, which allows simple resistor dividers for setting current values. When CTRL/SHDN is below 0.2 • V_{IN}, the part is in shutdown and draws minimal current. When CTRL/SHDN is greater than 0.9 • V_{IN}, the part is in constant 350mA mode. When CTRL/SHDN is between 0.2 • V_{IN} and 0.9 • V_{IN}, the LED current varies linearly between 0mA and 350mA.

Low Battery Detection

The LTC3490 provides two levels of low battery detection. These levels are set by the CELLS pin, indicating the number of battery cells. The low battery detection is set at 1.0V when the CELLS pin is low, and at 2.0V when the CELLS pin is tied to V_{IN}. This corresponds to single cell and dual cell operation, respectively. When the battery voltage drops below the detection level, an open drain output on the $\overline{\text{LOBAT}}$ pin is pulled low. This output can be used to drive an indicator or can be fed back to the CTRL/SHDN pin to lower the LED current to extend remaining battery time.

There is also an undervoltage lockout, which shuts down the LTC3490 when the battery voltage drops below 0.8V/cell. This prevents excessive battery current (single cell) and cell reversal in unevenly discharged NiMH cells (dual cell).

Battery Reality Check

Batteries have a phenomenon called discharge recovery. When a load is removed from a nearly discharged battery, the terminal voltage recovers to surprisingly high voltages. Thus when a nearly discharged battery trips the LTC3490 dead battery shutdown, the reduction in current draw allows the battery to recover. This turns the LTC3490 back on, putting the load back on the battery. The battery voltage drops, triggering shutdown again. This phenomenon causes LTC3490 to turn the LED current on and off rapidly. The observed effect is that the average LED current slowly drops as the battery nears the end of its charge.

Conclusion

The LTC3490 provides a simple solution to driving the high output white LEDs from alkaline or NiMH batteries. It offers high efficiency with a low parts count.

For further information on any of the devices mentioned in this issue of *Linear Technology*, use the reader service card or call the LTC literature service number:

1-800-4-LINEAR

Ask for the pertinent data sheets and Application Notes.

Monolithic Step-Down Regulator Withstands Rigors of Automotive Environments and Consumes Only 100µA of Quiescent Current

by Rich Philpott

Introduction

Automobile electronic systems place high demands on today's DC/DC converters. They must be able to precisely regulate an output voltage in the face of wide temperature and input voltage ranges—including load dump transients in excess of 60V, and cold crank drops to 4V. The converter must also be able to minimize battery drain in always-on systems by maintaining high efficiency over a broad load current range. Similar demands are made by many 48V nonisolated telecom applications, 40V FireWire peripherals, and battery-powered applications with auto plug adaptors. The LT3437's best in class performance meets all of these requirements in a small thermally enhanced 3mm × 3mm DFN package.

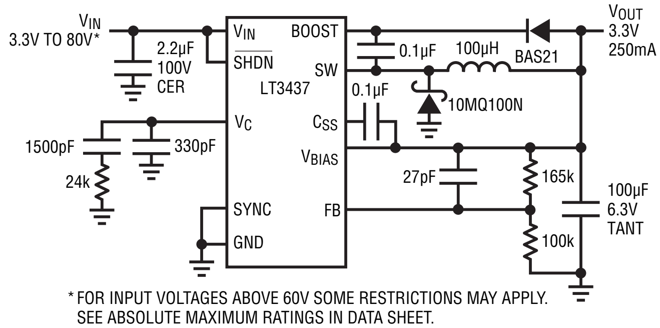

Figure 1. 14V to 3.3V step-down converter with 100µA no load quiescent current

Features of the LT3437

The LT3437 is a 200kHz fixed frequency, 500mA monolithic buck switching regulator. Its 3.3V-to-80V input voltage range makes the LT3437 ideal for harsh automotive environments. Micropower bias current and Burst Mode operation help to maintain high efficiency over the entire load range and result in a no load quiescent current of 100µA for the circuit in Figure 1. The LT3437 has an undervoltage lockout and a shutdown pin with an accurate threshold for a <1µA shutdown mode.

External synchronization can be implemented by driving the SYNC pin with a logic-level input. The SYNC pin also doubles as burst mode defeat for applications where lower output ripple is desired over light load efficiency. A single capacitor provides soft-start capability which limits inrush current and output voltage overshoot during startup and recovery from brown-out situations. The LT3437 is available in either a low profile 3mm × 3mm 10-pin DFN or 16-pin TSSOP package both with an exposed pad leadframe for low thermal resistance.

Brutal Input Transients

Figure 2 shows the LT3437's reaction to the lethal input transients that are possible in an automotive environment. Here, the input voltage rises from a nominal 12V to 72V in a 100ms load dump pulse, then drops to 4V in a 150ms cold crank pulse. The 200kHz fixed frequency and current mode topology of the LT3437 allow it to take it all in stride—response to the input transients are less than 1% of the regulated voltage. The fuzziness seen on the output voltage is due to the ESR of the output capacitor and the change in inductor current ripple as the input voltage transitions between levels. The fuzziness can be

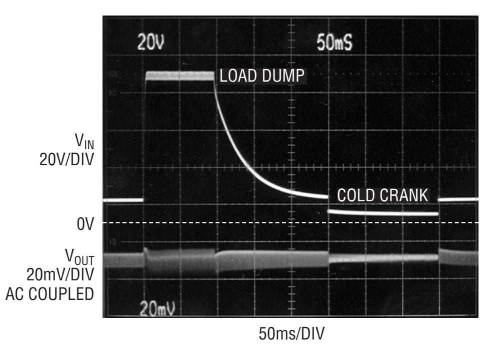

Figure 2. Output voltage response to load dump and cold crank input transients

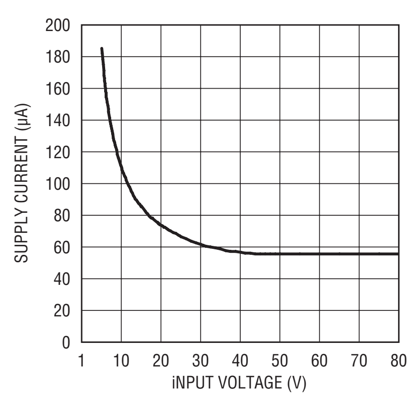

Figure 3. Supply current vs input voltage for circuit in Figure 1

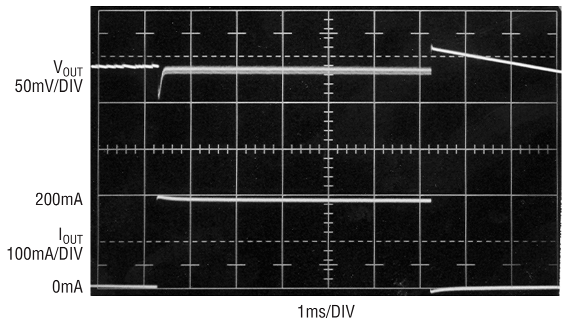

Figure 4. Output voltage response for 0mA-to-200mA load step

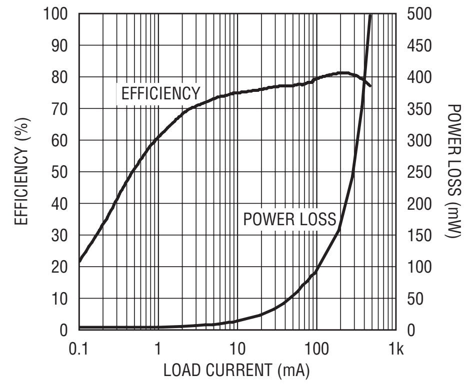

Figure 5. Efficiency vs load current for the circuit in Figure 1

eliminated by changing the output capacitor type from tantalum to a more costly ceramic.

Low Quiescent Currents

Today's automotive applications are migrating to always-on systems, which require low average quiescent current to prolong battery life. Loads are switched off or reduced during low demand periods, then activated for short periods. Quiescent current for the application circuit in Figure 1 is less than 1µA in shutdown mode, and a mere 100µA (Figure 3) for an input voltage of 12V under a no load condition. The LT3437 provides excellent step response from a no-load to load situation as shown in Figure 4. Automatic Burst Mode operation ensures efficiency over the entire load range as seen in Figure 5. Burst Mode operation can be defeated or enabled on the fly if lower ripple is desired over light load efficiency.

Soft-Start Capability

The rising slope of the output voltage is determined by the output voltage and a single capacitor. Initially, when the output voltage is close to zero, the slope of the output is determined by the soft-start capacitor. As the output voltage increases, the slope is increased to full bandwidth near the regulated voltage. Since the circuit is always active, inrush current and voltage overshoot are minimized for startup and recovery from overload (brown-out) conditions. Figure 6 illustrates the effect of several soft-start capacitor values.

Conclusion

The LT3437's wide input range, low quiescent current, robust design, and available small thermally enhanced packages make it an ideal solution for all automotive and wide input voltage, low quiescent current solutions.

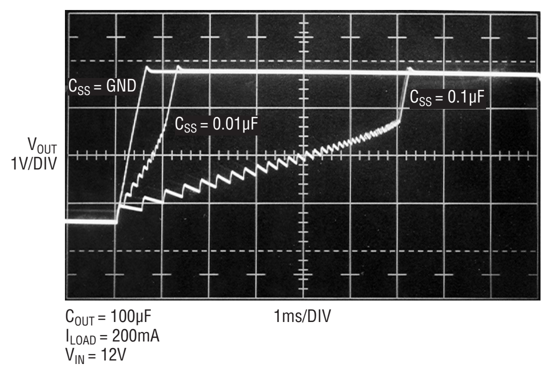

Figure 6. Output voltage soft-start

LTC3442, continued from page 10

pulse input for a flash application. The entire solution is only 2mm high.

This circuit also features overvoltage protection, preventing excessive output voltage in the event that the current path to the LED becomes open-circuited. By connecting the RLIM pin to a resistive divider on V_{OUT}, the RLIM input acts as an overvoltage comparator with a 1.0V reference. Raising RLIM above 1.0V pulls down on the VC pin, limiting the output voltage. By making the value of the divider resistors relatively small, the current sourced by the input current mirror to RLIM has a negligible effect on the overvoltage threshold.

Conclusion

Linear Technology's LTC3442 synchronous buck-boost converter, with automatic Burst Mode operation and programmable input current limit, simplifies the system power design in a wide variety of applications. The buck-boost architecture and 100mΩ internal switches provide a robust, high efficiency solution with high current capability, while the automatic Burst Mode feature maximizes runtime in portable Li-Ion powered devices with widely varying load requirements. Programmable soft-start and switching frequency, as well as external compensation, make the LTC3442 a very flexible solution. The high level of integration in a 3mm × 4mm DFN package, and the ability to operate efficiently at over 1MHz using low profile inductors and all ceramic capacitors, helps the designer save precious board real estate and meet the stringent height requirements of today's miniature, portable applications.

Small DFN Electronic Circuit Breaker Eliminates Sense Resistor

by SH Lim

Introduction

Traditionally, an Electronic Circuit Breaker (ECB) comprises a MOSFET, a MOSFET controller and a current sense resistor. The LTC4213 is a new electronic circuit breaker that does away with the sense resistor by instead using the $R_{DS(ON)}$ of the external MOSFET. The result is a simple, small solution that offers significant low insertion loss advantage at low operating load voltage. The LTC4213 features two circuit breaking responses to varying over load conditions with three selectable trip thresholds and a high side drive for an external N-channel MOSFET switch.

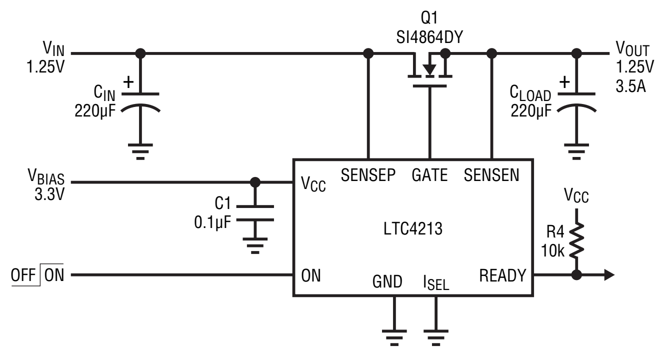

Figure 1. The LTC4213 in an electronic circuit breaker application

Overcurrent Protection

The SENSEP and SENSEN pins monitor the load current via the $R_{DS(ON)}$ of the external MOSFET, and serve as inputs to two internal comparators—SLOWCOMP and FASTCOMP—with trip points at V_{CB} and $V_{CB(FAST)}$, respectively. The circuit breaker trips when an over-current fault causes a substantial voltage drop across the MOSFET. An overload current exceeding $V_{CB}/R_{DS(ON)}$ causes SLOWCOMP to trip the circuit breaker after a 16µs delay. In the event of a severe overload or short circuit current exceeding $V_{CB(FAST)}/R_{DS(ON)}$, the FASTCOMP trips the circuit breaker within 1µs, protecting both the MOSFET and the load.

When the circuit breaker trips, the GATE pin is pulled down immediately to disconnect the load from the supply. In order to reset the circuit breaker fault, either the ON pin must be taken below 0.4V for at least 80µs or the bias V_{CC} must be taken below 1.97V for at least 80µs. Both of the comparators have a common mode input voltage range from ground to V_{CC} + 0.2V. This allows the circuit breaker to operate even under severe output short circuit conditions where the load supply voltage collapses.

Flexible Overcurrent Setting

The LTC4213 has an I_{SEL} pin to select one of these three over-current settings:

- ❑ I_{SEL} at GND, V_{CB} = 25mV and $V_{CB(FAST)}$ = 100mV
- ❑ I_{SEL} left open, V_{CB} = 50mV and $V_{CB(FAST)}$ = 175mV
- ❑ I_{SEL} at V_{CC}, V_{CB} = 100mV and $V_{CB(FAST)}$ = 325mV

I_{SEL} can be stepped dynamically. For example, a higher over-current threshold can be set at startup and a lower threshold can be selected after the supply current has stabilized.

Overvoltage Protection

The LTC4213 can provide load overvoltage protection (OVP) above the bias supply. When $V_{SENSEP} > V_{CC}$ + 0.7V for 65µs, an internal OVP circuit activates with the GATE pin pulling low and the external MOSFET turning off. The OVP circuit protects the system from an incorrect plug-in event where the V_{IN} load supply is much higher than the V_{CC} bias voltage. The OVP circuit also cuts off the load from the supply during any prolonged over voltage conditions. The 65µs delay prevents the OVP circuit from triggering due fast transient noise. Nevertheless, if fast over voltage spikes are threats to the system, an external input bypass capacitor and/or transient suppressor should be installed.

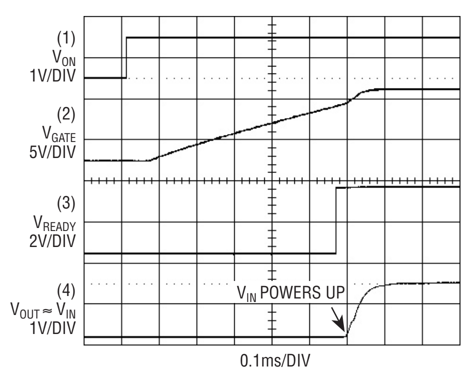

Figure 2. Normal power-up sequence

Typical Electronic Circuit Breaker (ECB) Application

Figure 1 shows the LTC4213 in a dual supply ECB application. An input bypass capacitor is recommended to prevent transient spikes when the V_{IN} supply powers-up or the ECB responds to overcurrent conditions. Figure 2 shows a normal power-up sequence. The LTC4213 exits reset mode once the V_{CC} pin is above the internal under voltage lockout threshold and the ON pin rises above 0.8V (see trace 1 in Figure 2). After an internal 60µs de-bounce cycle, the GATE pin capacitance is charged up from ground by an internal 100µA current source (see trace 2). As the GATE pin and the gate of MOSFET charges up, the external MOSFET turns on when V_{GATE} exceeds the MOSFET's threshold. The circuit breaker is armed when V_{GATE} exceeds ΔV_{GSARM}, a voltage at which the external MOSFET is deemed fully enhanced, and $R_{DS(ON)}$ minimized.

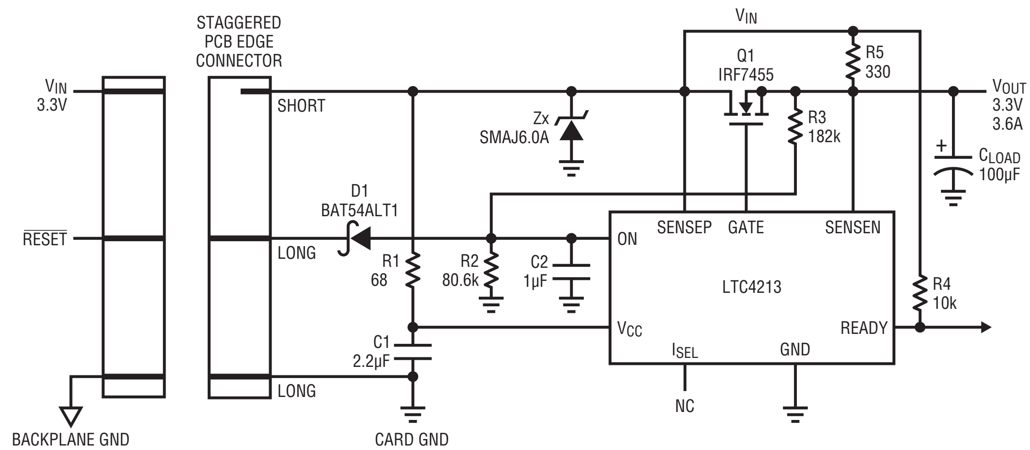

Figure 3. The LTC4213 in a Hot Swap application

Then, 50µs after the circuit breaker is armed and the READY pin goes high (see trace 3), the V_{IN} supply starts to power-up. To prevent power-up failures, the V_{IN} supply should rise with a ramp-rate that keeps the inrush current below the ECB trip level. Trace 4 shows the V_{OUT} waveform during the V_{IN} supply power-up. The gate voltage finally peaks at $\Delta V_{GSMAX} + V_{SENSEN}$. The MOSFET gate overdrive voltage is ΔV_{GSMAX} which is higher than the ΔV_{GSARM}. This ensures that the external MOSFET is fully enhanced and the R_{DSON} is further reduced. Choose the MOSFET with the required R_{DSON} at V_{GS} approximately equal to ΔV_{GSMAX}. The LTC4213 monitors the load current when the gate overdrive voltage exceeds ΔV_{GSARM}.

Typical Hot Swap Application

Figure 3 shows the LTC4213 in a single supply Hot Swap application where the load can be kept in shutdown mode until the Hot Swap action is completed. Large input bypass capacitors should be avoided in Hot Swap applications as they cause large inrush currents. Instead, a transient voltage suppressor should be employed to clip and protect against fast transient spikes.

In this application, the backplane starts with the $\overline{RESET}$ signal held low. When the PCB long trace makes contact the ON pin is held below 0.4V by the D1 schottky diode. This keeps the LTC4213 in reset mode. The V_{IN} supply is connected to the card when the short trace makes contact. The V_{CC} pin is biased via the R1-C1 filter and V_{OUT} is pre-charged by resistor R5. To power-up successfully, the R5 resistor should provide sufficient initial start up current for the shutdown load circuit and the 280µA sinking current source at SENSEN pin. On the other hand, the R5 resistor value should limit the load surge current during board insertions and fault conditions. When $\overline{RESET}$ signals a high at the backplane, capacitor C2 at the ON pin charges up via the R3/R2 resistive divider. When ON pin voltage exceeds 0.8V, the GATE pin ramps up. The GATE voltage finally peaks and the external MOSFET is fully turned on to reduce the voltage drop between V_{IN} and V_{OUT}. The LTC4213 monitors the load current when the gate overdrive voltage exceeds ΔV_{GSARM}.

Conclusion

The LTC4213 is a small package, No R_{SENSE} Electronic Circuit Breaker that is ideally suited for low voltage applications with low MOSFET insertion loss. It includes selectable dual current level and dual response time circuit breaker functions. The circuit breaker has wide operating input common-mode-range from ground to V_{CC}.

LTC4216, continued from page 19

low by an internal N-channel device and C_{AUTO} is discharged to ground. The GATE pin is pulled immediately to ground to disconnect the board. When the ON pin goes below 0.4V for more than 100µs, the ECB is reset. The internal N-channel device at the $\overline{FAULT}$ pin is switched off and R_{AUTO} starts to charge C_{AUTO} slowly towards the load supply.

When the ON pin rises above 0.8V, the LTC4216 attempts to reconnect the board and start the first timing cycle. With a dead short at the 5V output in Figure 6, the ECB trips when the FILTER pin voltage exceeds 1.253V after the first timing cycle. The entire cycle is repeated until the short is removed. The duration of each cycle is given by the time needed to charge C_{AUTO} to within 0.8V of the ON pin voltage, after the $\overline{FAULT}$ pin is pulled low and the first timing cycle delay. With R_{AUTO} = 200kΩ, C_{AUTO} = 1µF and C1 = 100nF, the cycle time is 85ms. The external MOSFET is on for about 2ms giving a duty cycle of 2.3%.

Conclusion

The LTC4216 Hot Swap controller is designed to handle very low supply voltages, down to 0V. Its adjustable soft-start function controls the inrush current slew rate at start-up, important with the large load capacitors used in low voltage systems. The analog current limit amplifier, the electronic circuit breaker with low trip threshold of 25mV and adjustable response time provides dual level overcurrent protection.

900mA Li-Ion Charger in 2mm×2mm DFN is Thermally Regulated for Faster Charge Time

by David Kim

Introduction

It can be tough to design a high performance linear Li-Ion battery charger for cell phones, MP3 players and other portable devices. The overriding design problem is how to squeeze the charger onto ever-shrinking boards, while managing the heat inherently generated by the charge process. The typical solution is to lower the maximum charge current to a sub-optimal value to avoid overheating, thus increasing charge time.

The LTC4059 is designed to shorten charge time even while squeezing the charger into the smallest spaces. The LTC4059 is a 2mm × 2mm DFN package constant-current/constant voltage Li-Ion linear charger with a built-in 900mA MOSFET, accurate charge current monitor output and thermal regulation control. Thermal regulation in this device is different, and much better, than the thermal shutdown found in most chargers. Thermal feedback control allows a designer to maximize the charge current, and thus decrease charge time without the risk of damaging the LTC4059 or any other components. Figure 1 shows a typical application.

Figure 2 shows a complete 2.5mm x 2.7mm charging circuit that includes the LTC4059 and two passive components. The internal MOSFET architecture requires no blocking diode or external sense resistor.

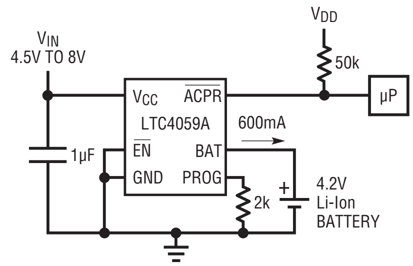

Figure 1. Simple and tiny Li-Ion battery charger offers thermal regulation for improved charge time.

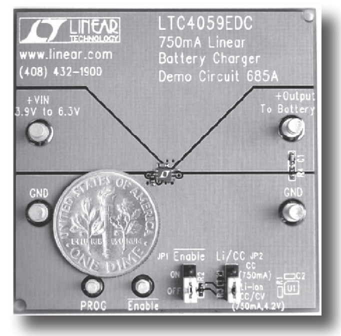

Figure 2. Chargers do not get smaller than this (2.5mm x 2.7mm).

In addition to its miniscule size, the LTC4059 includes other important features for the latest cellular phones, wireless headsets, digital cameras, wireless PDAs and MP3 players. Supply current in shutdown mode is very low—10μA from the input supply, and under 1μA from the battery when the input supply is removed. It also has the capability of charging single cell Li-Ion batteries directly from a USB port.

Constant Current/ Constant Voltage/ Constant Temperature

The LTC4059 uses a unique architecture to charge a battery in a constant-current, constant-voltage or constant temperature fashion. In a typical operation, to charge a single cell Li-Ion battery, the user must apply an input voltage of at least 4.5V to the Vcc pin along with a 1% resistor connected from PROG to GND (using the formula R_{PROG} = 1000 • 1.21V/I_{CHG}) and EN pin under 0.92V. When all three conditions are met, the charge cycle begins in constant-current mode with the current delivered to the battery equal to 1210V/R_{PROG}.

If the power dissipation of the LTC4059 and/or high ambient temperature results in the device junction temperature rising to near 115°C, the part enters constant temperature mode and the thermal feedback loop of the LTC4059 decreases the charge current to regulate the die temperature to approximately 115 °C. This feature allows the user to program a charge current based on typical operating conditions and eliminates the need for the complicated thermal over-design necessary in other linear chargers. Typically, the thermal feedback loop conditions are temporary as the

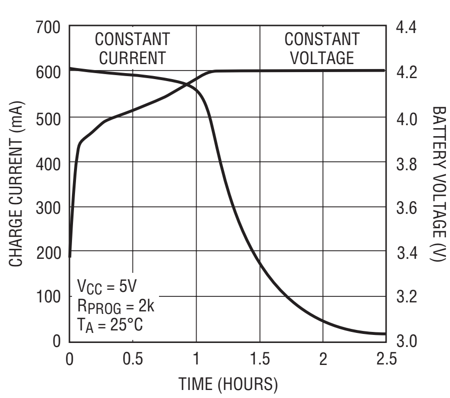

Figure 3. Complete charge cycle (800mAh Battery)

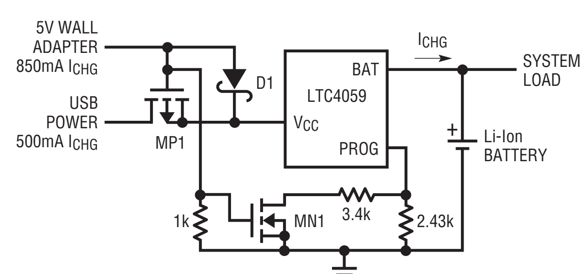

Figure 4. Charger that combines both wall adapter and USB power inputs

battery voltage rises with its charge (resulting in lower power dissipation across the MOSFET) but it is the worst case situation that one must account for when determining the maximum allowable values for charge current and IC temperature.

Once the die temperature drops below 115 °C, the LTC4059 returns to constant-current mode straight from constant temperature mode. As the battery voltage approaches the 4.2V float voltage, the part enters constant-voltage mode. In constant-voltage mode LTC4059 begins to decrease the charge current to maintain a constant voltage at the BAT pin rather than a constant current out of the BAT pin (Figure 3).

Regardless of the mode, the voltage at the PROG pin is proportional to the current delivered to the battery. During the constant current mode, the PROG pin voltage is always 1.21V indicating that the programmed charge current is flowing out of the BAT pin. In constant temperature mode or constant voltage mode, the BAT pin current is reduced. The charge current at any given charge cycle can be determined by measuring the PROG pin voltage using the formula $I_{CHRG} = 1000 \bullet (1.21V/R_{PROG})$.

Using the battery voltage and the PROG pin voltage information, the user can determine the proper charge termination current level (typically 10% of the full-scale programmed charge current). Once the desired charge current level is reached, the user can terminate the charge cycle simply by pulling up the EN pin above 1.2V.

Board Layout

Properly soldering the exposed metal on the backside of the LTC4059 package is critical for minimizing the thermal resistance. Properly soldered LTC4059 on a 2500mm^2 double sided 1oz copper board should have a thermal resistance of approximately 60°C/W. When the LTC4059 is not properly soldered (or does not have enough copper), the thermal resistance rises, causing the LTC4059 to enter constant-temperature mode more often, thus resulting in longer charge time. As an example, a correctly soldered LTC4059 can deliver over 900mA to a battery from a 5V supply at room temperature. Without a backside thermal connection, this number could drop to less than 500mA.

Li$\overline{CC}$, $\overline{ACPR}$

Two versions of the part are available, depending on the needs of the battery chemistry. The LTC4059 has a Li$\overline{CC}$ pin, which disables constant-voltage operation when it is pulled up above 0.92V. In this mode, the LTC4059 turns into a precision current source capable of charging Nickel chemistry batteries. In the LTC4059A, the Li$\overline{CC}$ pin is replaced by an $\overline{ACPR}$ pin, which monitors the status of the input voltage with an open-drain output. When V_{cc} is greater than 3V and 150mV above the BAT pin voltage, the $\overline{ACPR}$ pin will pull to ground; other wise the pin is forced to a high impedance state.

Combining Wall Adapter and USB Power

Figure 4 shows an example of combining wall adapter and USB power inputs. In this circuit, MP1 is used to prevent back conduction into the USB port when a wall adapter is present and D1 is used to prevent USB power loss through the 1K pull-down resistor. The 2.43k resistor sets the charge current to 500mA when the USB port is used as input and the MN1 and 3.4k resistor is used to increase the charge current to 850mA when the wall adapter is present.

Conclusion

The LTC4059 is industry's smallest single cell Li-Ion battery charger capable of up to 900mA charge current. The thermal regulation feature of LTC4059 allows the designer to maximize the charge current and shorten the charge time without the risk of damaging the circuit. The small circuit size, thermal protection, low supply current and low external component count make LTC4059 an ideal solution for small portable and USB devices.

LT6100, LTC6101, continued from page 7

sense resistor of 30mΩ gives set point currents of 1A and 800mA.

Monitor the Current of Automotive Load Switches

With its 60V input rating, the LTC6101 is ideally suited for directly monitoring currents on vehicular power systems, without need for additional supply conditioning or surge protection components.

Figure 12 shows an LT1910-based intelligent automotive high-side switch with an LTC6101 providing an analog current indication. The LT1910 high-side switch controls an N-channel MOSFET that drives a controlled load, and uses a sense resistance to provide overload detection (note the surge-current of lamp filaments may cause a protection trip, thus are not recommended loads with the LT1910). The sense resistor is shared by the LT6101 to provide the current measurement.

The LTC6101 supplies a current output, rather than a voltage output, in proportion to the sense resistor voltage drop. The load resistor for the LTC6101 may be located at the far end of an arbitrary length connection, thereby preserving accuracy even in the presence of ground-loop voltages.

Conclusion

The LT6100 and LTC6101 are precise high side current sensing solutions. Although very similar in obvious respects, each has its unique advantages. The LT6100 draws much less power, can be powered down while maintaining high Z characteristics, and has nearly indestructible inputs. The LTC6101 can withstand up to 70V, is infinitely gain configurable, and provides an open drain output.

600mA Switching Converter Reduces Noise by Automatically Shifting to a Linear Regulator at Light Loads

by Kevin Soch

Introduction

High efficiency, low ripple current, and a small footprint are critical power supply design requirements for cell phones, MP3 players and other portable devices. The LTC3448 delivers excellent performance in each of these areas. It is a high efficiency, monolithic, synchronous buck regulator using a constant frequency, current mode architecture. It achieves very low ripple by automatically shifting to linear regulator operation at load currents below 3mA, and pulse skipping operation at moderate load currents. This is a critical feature in applications such as cell phones, where low power supply noise is required while in standby. Its built-in 0.35Ω switches provide for up to 96% efficiency. Finally, it fits into 0.1in^2 (see Figure 1) due to its 8-lead 3mm × 3mm DFN or MSOP package, 1.5MHz or 2.25MHz switching frequency, internal compensation, and minimum number of small external components.

Features

The LTC3448 automatically shifts gears to maintain high efficiency and low noise over a wide range of load currents. For normal loads, it operates as a current mode constant frequency converter, which yields well-defined ripple frequencies. At moderate load currents, it transitions into pulse skipping mode for decreased output ripple. At load currents below 3mA, it automatically shifts to linear regulator operation to maintain <5mV$_{P-P}$ noise and reduce the quiescent supply current to 32µA.

No external sense resistor is required to detect the load current. Simply tie the MODE pin to V_{OUT}. The LTC3448 uses a patent pending process where it monitors the behavior of the switcher to determine the load

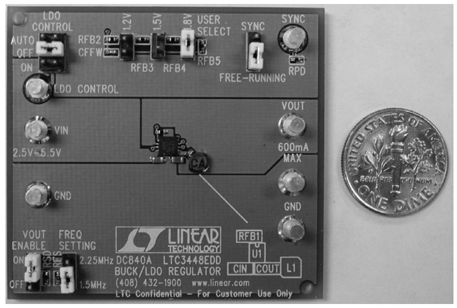

Figure 1. The LTC3448 regulator occupies less than 0.1in^2 of board space.

current, and enters linear regulator operation when appropriate. The crossover between switcher mode and linear regulator mode can also be controlled externally by driving the MODE pin high or low.

The LTC3448 has a 2.5V to 5.5V input voltage range, perfect for single Li-Ion battery-powered applications, and is available with an adjustable output voltage. Its 100% duty cycle provides low dropout operation, extending battery life in portable systems. Low output voltages are easily supported with the 0.6V feedback reference voltage.

Switching frequency is selectable at either 1.5MHz or 2.25MHz, or can be synchronized to an external clock applied to the SYNC pin. The high switching frequency allows the use of small surface mount inductors and capacitors. The LTC3448 also saves space with an internal synchronous switch, which eliminates the need for an external Schottky diode and increases efficiency.

continued on page 32

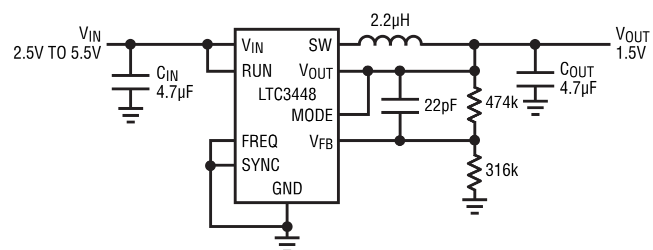

Figure 2. LTC3448 minimum component implementation.

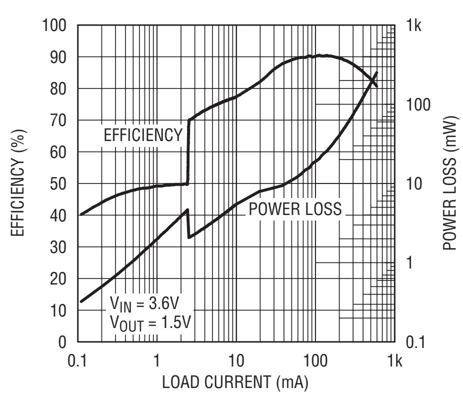

Figure 3. Overall efficiency and power loss as a function of load current. Part is operating in automatic linear regulator mode with V_{IN} = 3.6V and V_{OUT} = 1.5V.

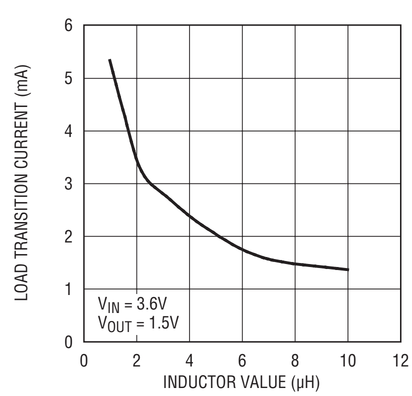

Figure 4. Switching-to-linear-regulator crossover load current depends on inductor value. V_{IN} = 3.6V, V_{OUT} = 1.5V.

Single Converter Provides Positive and Negative Supplies

by Jesus Rosales

Charge coupled device (CCD) imagers, LCDs, some op amps and many other circuits require both a positive and negative power supply. Typically, two DC/DC converters are used—one for the positive supply and the other for the negative—but the additional ICs and related circuitry add cost and complexity. There are single converter topologies that develop plus/minus supplies, but usually the second output suffers from poor regulation. In addition, in order to produce a second output of different amplitude, odd transformer turns ratios or post regulators become necessary, which also increases cost, complexity and efficiency losses.

The LT3472 dual DC/DC converter simplifies the design of dual, positive and negative, supplies by combining two switchers that have independent control loops and ±34V output ranges. Figure 1 shows a circuit using the LT3472 that produces two independently regulated power supplies from a single Lithium-ion cell: a 15V, 25mA supply, and a –8V, 35mA supply. A useful application for this could be for amplifier circuits which need to output true zero volts with only a single positive supply available. A low current negative supply and boosted positive supply rail permits full amplifier output swing from 0V to $V_{BATTERY}$.

The Schottky rectifying diodes are integrated into the LT3472, which shrinks and simplifies the solution. Each supply requires only one resistor to set its output voltage. The LT3472 works well with input voltages as high as 16V. The LT3472 also includes an output sequencing feature which allows the negative supply to ramp up only after the positive one has reached 88% of its final value, providing for a controlled turn on as demonstrated in Figure 2. In situations where inrush current is a problem, the LT3472 offers a capacitor-programmable soft start feature that allows the designer to individually program the ramp rate of each output. This feature allows the designer to reduce inrush current to any arbitrary level. Figure 3 shows the supply efficiency.

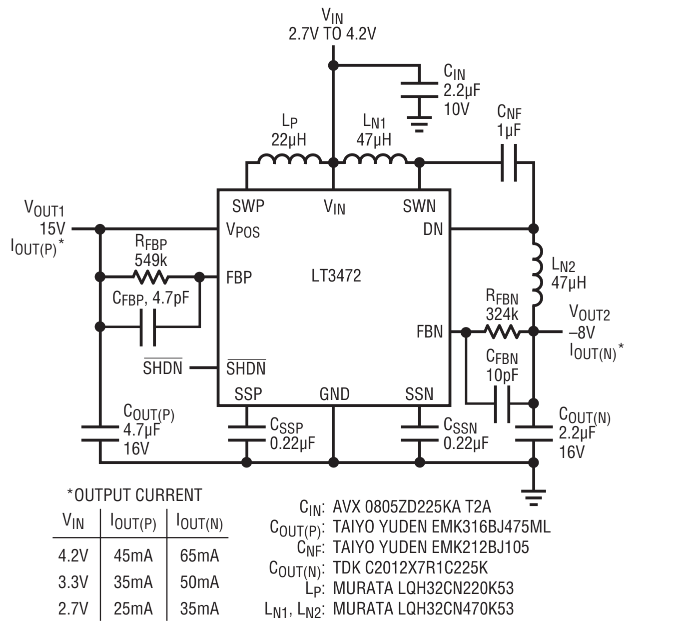

Figure 1. A 1.1MHz, 2.7V–4.2V to 15V, 25mA and –8V, 35mA converter/inverter.

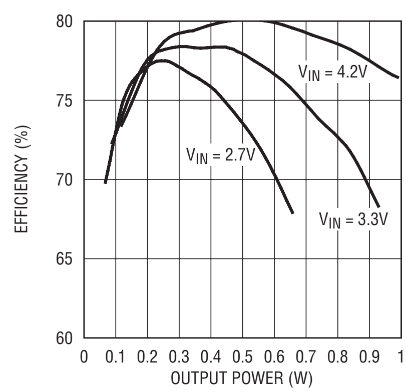

Figure 3. Efficiency for both outputs loaded at 10% load increments

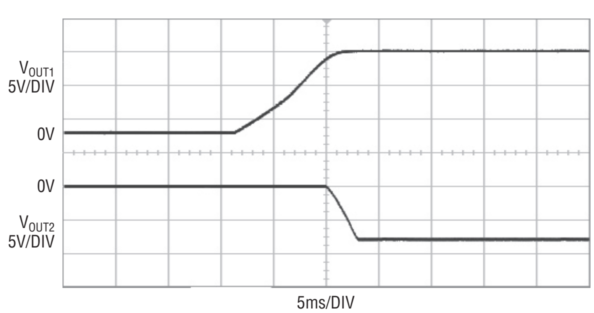

Figure 2. Start up sequence

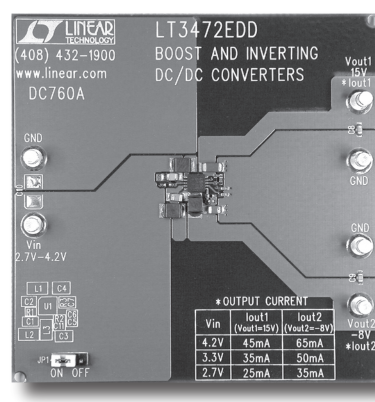

Figure 4. The compact layout of a dual output converter/inverter

LDO Linear Regulators Rival Switchers for Efficiency

by Tom Gross

Introduction

Switching power supplies owe much of their popularity to their efficiency, even when the distinction is not necessarily deserved. For instance, when low voltage input supplies are available, and currents are around an amp or so, a less complex low dropout linear regulator can match the efficiency of a switcher. Furthermore, if the design is limited to all surface mount applications, with heat sinking provided by the board, a linear regulator can provide switcher-like efficiency over a fairly wide range of input voltages.

For example, a linear regulator provides excellent efficiency in a 1.8V-to-1.2V application. Even at 2A of output current, only 1.2W of power is dissipated. This is sufficiently low enough for a multi-layer board to provide adequate heat sinking.

Thermal Limitations

While efficiency is always quoted as a benchmark for switching regulators, power loss is often more important. Power loss sets the size of the heat sink, and the size of the heat sink is—more than any other component—directly related to the size of the board.

Linear regulators are about simplicity, so their advantages are clearest in designs where no more than the multi-layer circuit board is needed to provide heat sinking. To a first approximation, a multi layer board can dissipate power at 40°C per watt. If we want to limit the regulator maximum temperature to 125°C, 1W of dissipation allows an ambient temperature of 85°C. An ambient temperature of 85°C is a conservative design number that satisfies the requirements of most industrial applications.

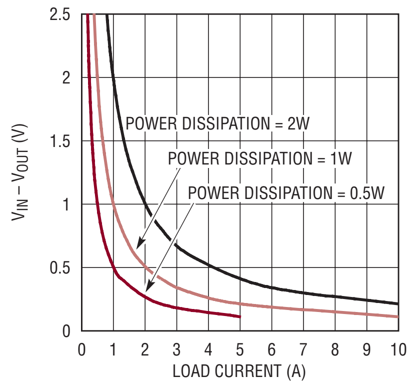

Figure 1. Various power dissipation limits shown as a function of load current and input-to-output differential voltage.

At low input and output voltages, linear regulators offer excellent regulation, and in many cases, deliver efficiency rivaling that of switching regulators. In all cases a linear regulator circuit is simpler and less costly.

The amount of output current that the linear regulator can deliver depends on the input-to-output differential voltage and the power loss limitations. For instance, in a 2.5V-to-1.5V design, the 1V differential voltage allows for 1A of load current to meet the 1W dissipation requirement (see Figure 1). If the differential voltage is only 0.7V, as in a 2.5V-to-1.8V regulator, the maximum load current increases to over 1.4A.

Figure 1 shows that there is a wide range of power combinations that can be filled under these circumstances. In surface mount designs, power loss correlates directly to board area as power is usually dissipated through the metal layers. With this in mind, Figure 1 covers a range of linear regulator applications that compare well with switching regulators—which are very efficient at high input-to-output differential voltages, but rarely have better than 75%–80% efficiency at low input-to-output differential voltages.

For instance, consider a low dropout regulator regulating 1.8V-to-1.2V at one amp. With an input-to-output differential of 0.6V, the maximum amount of output current available increases to over 1.5A, at one watt of power dissipation (see Figure 1).

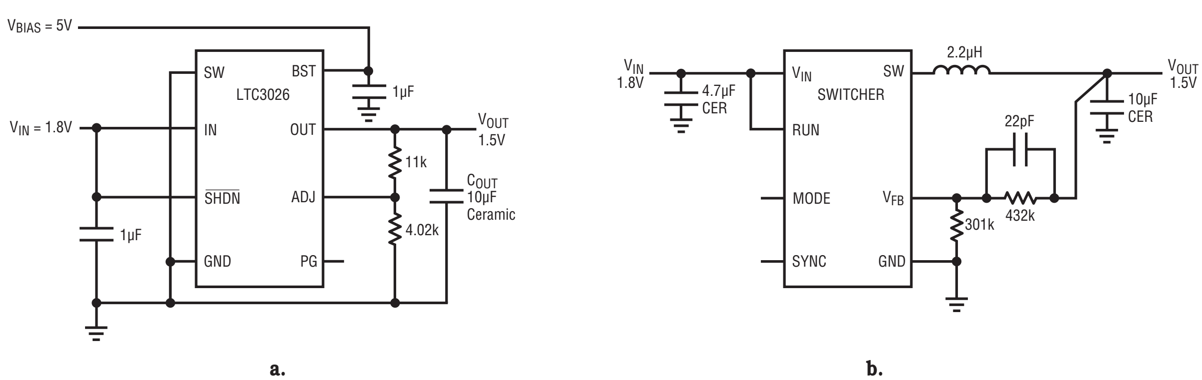

Figure 2. Two 1.5V output DC/DC converters. The first (a) is a typical linear regulator using the LTC3026 with an external bias supply. The second (b) is a typical 1.5V switching regulator application. In circuit (a), if an external bias supply is not present, the LTC3026 can generate its own bias with an internal boost converter and an external inductor (10 µH, 150mA).

Increasing the maximum power dissipation to 2W, allows well over 3A of output current. The efficiency of a switching regulator operating under these conditions is typically 75%. The added complexity and cost of a switching regulator makes a linear regulator look even better.

Comparison of a Switcher and Linear Regulator in the Same Application

Compare the two different topologies in a 1.8-to-1.5 volt application. In this design, the power dissipation is low enough that even three amps of output current do not exceed our 1W power limitation. Figure 2a shows a 1.5A application using the LTC3026 CMOS linear regulator. A comparable step-down switching regulator circuit is shown in Figure 2b. Figure 3 compares the efficiencies and power losses of both circuits. As shown, the switching converter is more efficient at low load currents, but the linear regulator efficiency matches, then surpasses, the switcher efficiency as the load current increases. The same is true for the power losses. The linear regulator fares better as load current increases.

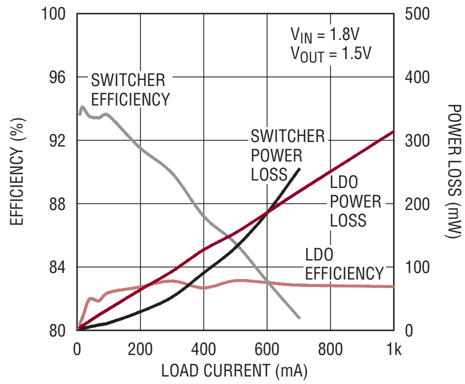

Figure 3. Efficiency and power loss of the LTC3026 linear regulator compare favorably to that of a switching regulator. The LDO maintains good efficiency to 1.5A.

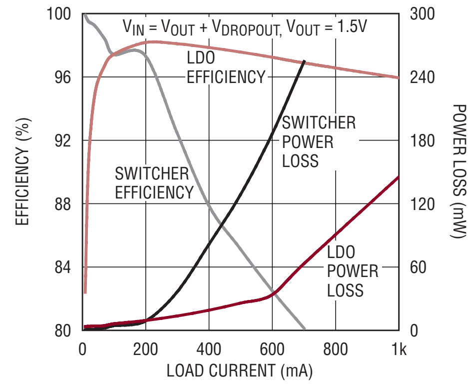

Figure 4. At the lowest input-to-output differential voltage, $V_{IN} = V_{OUT} + V_{DROPOUT}$ and V_{OUT} = 1.5V, the efficiency and power losses of the linear regulator fare even better compared to those of the switching regulator.

As the input-to-output differential voltages decrease, such as occurs in battery-powered applications, the linear regulator efficiency compares even more favorably to the switcher (see Figure 4). For instance, at 500mA of load current, where the dropout voltage of the LTC3026 is only 60mV, the linear regulator is over 97% efficient, whereas the switcher efficiency is around 85%. In this case, the linear regulator beats the switcher in all aspects—efficiency, power loss, size, simplicity and cost.

Conclusion

At low input and output voltages, linear regulators offer excellent regulation, and in many cases, deliver efficiency rivaling that of switching regulators. In all cases a linear regulator circuit is simpler and less costly. In applications where the board can adequately dissipate the power, linear regulators can handle a reasonable range of inputs and output voltages.

LTC3448, continued from page 29

Minimum Component 1.5V Step-Down Implementation

Figure 2 shows a typical application using a minimum number of external components. The loop compensation is integrated into the device, and the optional 22pF feed-forward capacitor improves the transient response. The switching frequency is 1.5MHz as shown (FREQ pin to ground) but it can be set to 2.25MHz by connecting the FREQ pin to V_{IN}. Figure 3 shows the efficiency and power loss as a function of load current.

By connecting the MODE pin to V_{OUT}, the part automatically transitions from a switching regulator to a linear regulator at low load currents. In the circuit of Figure 2, the transition occurs when the load current drops below approximately 3mA. The transition load value has an inverse relationship to the inductor value, as shown in Figure 4, but is independent of other external component values, and largely independent of the values of V_{IN} and V_{OUT}. The device transitions back into switching regulator mode when the load current exceeds 10mA, regardless of inductor value.

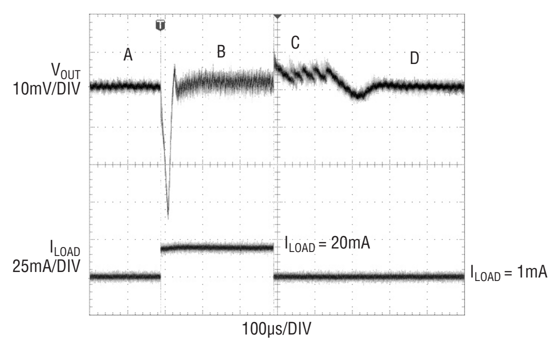

Figure 5. The load transient response of the circuit in Figure 2. The transitions from linear regulator behavior to switching behavior and back are shown. In the region labeled A, load current is 1mA and the part is operating as a linear regulator. In the region labeled B, the load current has increased to 20mA and the switcher has turned on in pulse skipping mode. In the region labeled C, the load has decreased to 1mA, but the part has not yet transitioned back into linear regulator operation, thus the lower frequency pulse skipping behavior. In region D, the part is again operating as a linear regulator, with greatly reduced output noise.

Figure 5 shows the load transient response when the load is increased from 1mA to 20mA and then back to 1mA. The difference in ripple between the pulse skipping operation and linear regulator operation can be clearly seen.

Instrumentation Amplifier with Clock-Tunable Sampling Eliminates Errors in Acquisition Systems

by Jon Munson

Introduction

The LTC2053 is a highly popular precision instrumentation amplifier for differentially acquiring DC or low-frequency signals—it's popularity is mainly due to its offset uncertainty below 10µV worst case and DC common-mode rejection of 116dB. It owes its high performance to a switched-capacitor front-end that drives a Zero-Drift (ZD) operation amplifier (shown in Figure 1). The LTC2053 incorporates a fixed-frequency timing generator to coordinate the switched-capacitor activity. The nominal input sampling rate, f_S, is 3kHz, which is not necessarily ideal for all applications.

Enter the LTC2053-SYNC. It offers all the features of the LTC2053 plus the ability to set the sampling rate with an external clock. The sampling rate is an eighth of the external clock frequency, and is guaranteed to operate over a 2-octave range above and below the nominal rate of 24kHz (i.e. 12kHz to 48kHz).

Tuning Input Performance by External Clocking

The LTC2053 input structure includes CMOS switches and two 1000pF capacitors. Since charge transfers balance the capacitor voltages on each sampling cycle, the overall behavior is that of an Infinite-Impulse-Response (IIR) function that approximates a first-order lowpass filter (LPF). The sample rate and corner frequency of the LPF behavior is related to the LTC2053-SYNC external clock by the following relationships:

$$f_S = \frac{f_{CLK}}{8} \text{ and } f_{3dB} \approx \frac{f_{CLK}}{72}$$

In the center of the clock frequency range of the LTC2053-SYNC:

$$f_{3dB} = \frac{24kHz}{72} = 330Hz$$

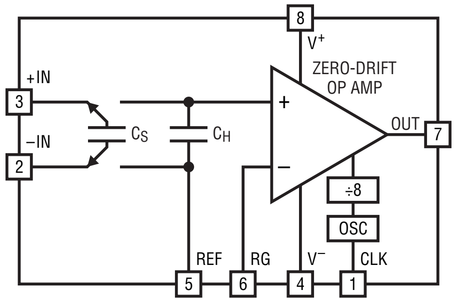

Figure 1. LTC2053-SYNC instrumentation amplifier includes an external clock input for sample rate control.

By varying the clock frequency, the 3dB rolloff characteristic is tunable over a range of 150Hz–700Hz. This property can be used to avoid attenuation of a desirable signal component, improve rejection of an undesired component, or most importantly, provide frequency placement of Nyquist input-sampling aliases.

Tuning Output Performance by External Clocking

The bandwidth of the internal ZD op-amp is much wider than the first Nyquist zone established by the switched capacitor front-end, so the LTC2053 output naturally reproduces a classical sample-and-hold "stair-case" waveform, including any attendant alias frequency energy.

In DC applications of the LTC2053, the alias energy is negligible, simply looking like an insignificant spurious "clock noise" (for example, about $8\mu V_{RMS}$ output at f_S with a gain of 250 connection). Sampling theory indicates that the alias level is proportional to signal amplitude and increases with signal frequency. This simply means that larger sampling steps occur for more rapidly varying signal waveforms, such that post-filtering may be needed to minimize error in the downstream signal-processing chain.

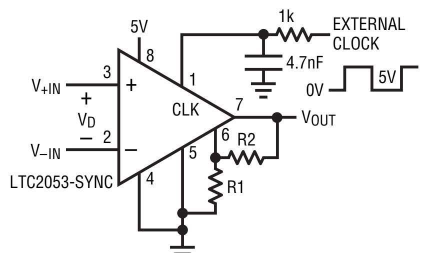

Figure 2. Recommended clock source coupling to minimize digitally-induced ground noise.

For acquisition systems with integrating analog-to-digital conversion (ADC), simply configuring the ZD op-amp with heavily capacitive feedback is ordinarily sufficient to minimize error. In systems with sample-and-hold ADC technology, management of the Nyquist energy and/or sampling transients is important. One technique is to filter the LTC2053 output with added components, and another is to synchronize the input sampling with the ADC sample-and-hold rate (or a sub-harmonic thereof). The LTC2053-SYNC offers improved performance in either case by allowing the input sampling rate to be externally controlled. In the filtered case, raising the sampling rate can help ease the filter requirements, and thus reduce cost. In a synchronized mode the need for special filtering is often completely eliminated, since LTC2053-SYNC sampling transients can be arranged to never coincide with the ADC sample-and-hold aperture.

Using the External Clock Signal

The external clock input allows for slaving of the oscillator that generates the various sampling controls internal to the LTC2053-SYNC. The input sampling is performed at a rate that is an eighth of the clock signal due to the multiphase nature of the internal sequencing. If the clock pin is left not

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Temperature-to-Frequency Converter Runs for Years on Two AA Batteries

by Cheng-Wei Pei

Introduction

There are many advantages in converting temperature to frequency, including the ability to transmit encoded temperature readings over isolated channels. A frequency carrier allows complete electrical and thermal isolation of the temperature measurement circuit, because transmission can occur via capacitive, inductive or optical coupling. A simple edge counter on the receiving end is all that is needed to demodulate the signal for highly accurate temperature reading.

Figure 1 shows a simple battery-operated temperature monitor that outputs a frequency proportional to temperature. The beauty of the circuit lies in its simplicity and low power draw: a mere 27µA typical at room temperature, and 50µA max over the industrial temperature range—low enough to run from a pair of 1800mAH AA batteries for over four years. The circuit maintains operation with supply voltages as low as 2.5V.

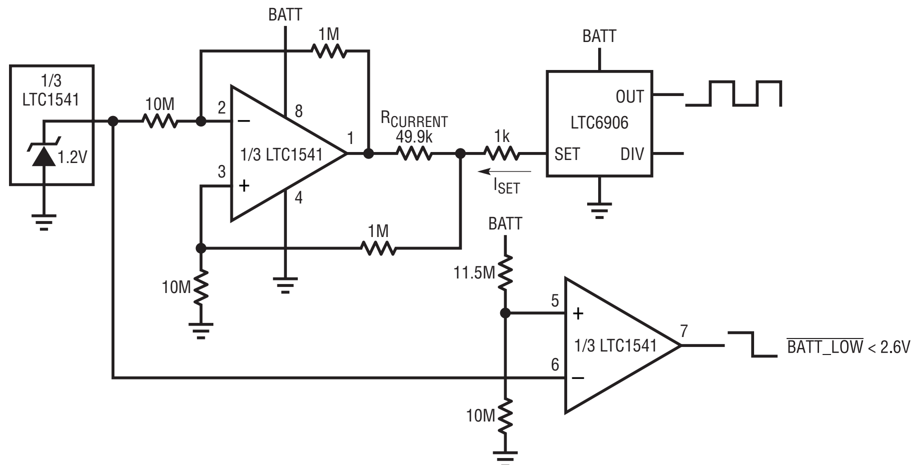

Figure 1. The micropower circuit shown draws 50µA max quiescent current (27µA typical at room temperature) and contains only two components (not counting external resistors). The circuit runs on supply voltages from 2.5V–5.5V, and can be powered by CMOS logic gates or microprocessor outputs.

Circuit Description

Figure 1 contains a current source (using the amplifier section of an LTC1541 micropower op amp, comparator and reference) driving the SET pin of an LTC6906 micropower oscillator. A 1.2V reference voltage is attenuated by 10 and forced across the 49.9kΩ resistor ($R_{CURRENT}$), which creates a constant current source regardless of the voltage at the SET pin. The temperature monitoring function is not readily apparent from the schematic, because the LTC6906 clock output is temperature independent in common usage. The trick is to take advantage of the unique architecture of the LTC6906 with constant current drive of the SET pin. The output of the LTC6906 is determined by the following equations:

$$\text{FREQUENCY} = \frac{I_{SET}}{V_{SET} \bullet 10\text{pF}}$$

$$V_{SET} = 26\text{mV} \bullet \ln\left(\frac{I_{SET}}{82 \times 10^{-18}}\right) - 2.3\text{mV}(T - 27)$$

V_{SET} depends on temperature, but only in the 2.3mV term.

In a typical application of the LTC6906, the temperature dependence of V_{SET} is irrelevant, because a resistor to ground, R_{SET}, sets the output frequency. Thus:

$$I_{SET} = \frac{V_{SET}}{R_{SET}}$$

$$\text{FREQUENCY} = \frac{V_{SET}/R_{SET}}{V_{SET} \bullet 10\text{pF}} = \frac{1}{R_{SET} \bullet 10\text{pF}}$$

Here, though, the LTC6906 finds itself in an atypical application. We *want* to bring out the temperature dependence of V_{SET}, so I_{SET} is held constant in the circuit shown in Figure 1. The temperature dependence on V_{SET} causes the frequency to change with temperature (as shown in Figure 2):

$$\text{FREQUENCY} = \frac{I_{SET}/10\text{pF}}{26\text{mV} \bullet \ln\left(\frac{I_{SET}}{82 \times 10^{-18}}\right) - 2.3\text{mV}(T - 27)}$$

The DIV pin and the amount of current sunk by the current source set the frequency range of the circuit in Figure 1. This current can be adjusted by changing the value of $R_{CURRENT}$, with the equation:

$$I_{SET} = \frac{0.12\text{V}}{R_{CURRENT}}$$

As shown, the current source is designed to sink 2.4µA from the SET pin of the LTC6906, and the DIV

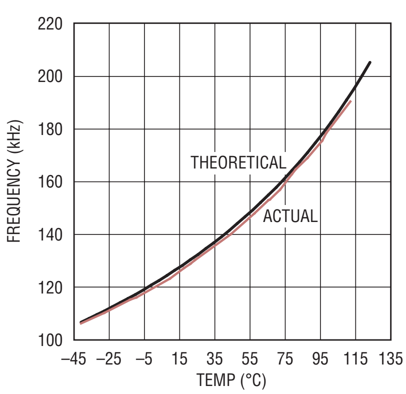

Figure 2. A graph of output frequency versus temperature. The slight bow in the circuit comes from the 1/(1 – T) dependence of the frequency, and is repeatable with part-to-part variations.

pin is left unconnected. This gives an output range of approximately 110kHz–170kHz over the –40°C to 85°C industrial temperature range.

A larger I_{SET} current would move the frequency range to higher frequencies, within the capabilities of the LTC6906. Higher output frequencies, though, come at the cost of higher quiescent current. The output of the LTC6906 should also be buffered or isolated with a resistor if the LTC6906 is driving more than 50pF of capacitance or supplying over 1mA of load current. Heavier loads dissipate more power in the IC, which causes additional heating of the part and possible skewing of the ambient temperature measurement results.

The 1kΩ resistor at the SET pin serves to isolate the sensitive pin from any stray capacitance, and does not affect the temperature performance of the circuit. The use of an isolation resistor along with a guard ring minimizes errors due to board leakage currents.

The comparator section of the LTC1541 is used in Figure 1 as a low battery monitor. The supply voltage is divided and compared to the 1.2V reference, and the output of the comparator goes low if the supply voltage drops below 2.6V.

Circuit Performance

Figure 2 compares the theoretical temperature versus frequency plot of the circuit in Figure 1 (with I_{SET} = 2.4µA) with actual measurements taken from a circuit in the lab. The graph shows a monotonic curve that agrees well with theory, and the architecture of the LTC6906 ensures that the circuit performance is repeatable with part-to-part variations, thus simplifying calibration.

The low quiescent current of the LTC6906, even at high output frequencies, is low enough that the dissipated quiescent power does not affect the temperature reading of the circuit. At 50µA quiescent current with a 3V power supply voltage (two AA batteries in series), the LTC6906 dissipates 150µW, which adds approximately 24.8m°C to the junction temperature. At room temperature (27°C), this represents less than 0.1% error in the temperature-to-frequency conversion.

The other possible source of error is the current source, where an input reference drift over temperature would change the value of the current, and thus the frequency. The LTC1541's internal reference drift is less than 0.1% over the industrial temperature range, which ultimately contributes less than 0.01% of error to the temperature circuit (considering the 0.1 voltage gain of the current source).

Output Transmission

Though the temperature measurement circuit discussed in this article is extremely low power, the circuit components necessary to transmit the output frequency over isolated channels may not be. There are many ways to transmit information over isolated channels, and some of them require significantly more current than the 50µA of the temperature circuit.[1] Optical sources (IR diodes, photo transistors, etc.) and RF power amplifiers can require many milliamps of quiescent operating current. One way to mitigate the significant loss of these measurement devices is to gate the power to the system on and off, which keeps the average power very low.

If the temperature measurement function is not needed continuously, the low power and high supply rejection of the LTC6906 and LTC1541 allow the circuit to be powered by a CMOS logic gate or microprocessor output pin. The system diagram shown in Figure 3 features CMOS gates that enable and disable the temperature monitoring circuit and its buffer/transmission circuitry. Using this method, the average power consumption of the temperature monitor circuit alone can be reduced to nanoamps or picoamps. Even if 10mA of current is required to drive external transmission and logic circuitry, if the system is only active 1% of the time, the average current will be 100µA. A circuit with 100µA of average current will operate on a pair of AA batteries for over two years.

If more frequent transmission is necessary, and the 1 millisecond turn-on time of the LTC6906 would make circuit timing too complex, the 50µA quiescent current of the temperature monitoring circuit is low enough that it can always stay on, regardless of the status of the transmission circuitry. The CMOS logic would then be designed to enable and disable only the output buffer/transmission circuitry.

Conclusion

The LTC6906 micropower oscillator and the LTC1541 combination amplifier, comparator, and reference can combine to create a robust, accurate, and repeatable temperature-to-frequency monitor that runs off of low-voltage power supplies and can be electrically and thermally isolated from other electronic circuits.

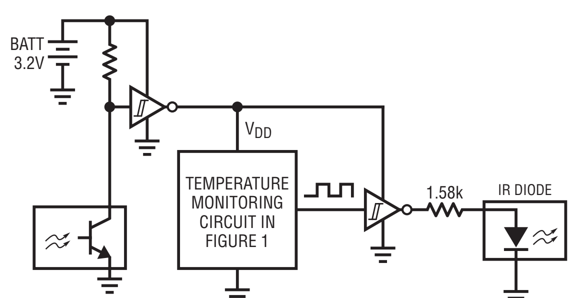

Figure 3. CMOS logic shown gating the power supply of the temperature monitoring circuit and the transmission circuitry (an LED). The circuit may draw milliamps in its "on" state, but reducing the "on" duty cycle can significantly lower the average dissipated power.

Notes

[1] Keep in mind that any high current circuit elements dissipate power, and therefore generate heat. Maintain enough distance between these components and the LTC6906 to prevent errors in the ambient temperature measurement.

Compact DDR Memory Power

by Jason Leonard

Introduction

The LTC3776 is a high efficiency, 2-phase dual DC/DC synchronous controller that provides a complete power solution for DDR memory. Its first output is designed to supply the I/O power V_{DDQ}, while the second output, which has symmetric source and sink load current capability, provides the bus termination power V_{TT}. The LTC3776 features a No R_{SENSE} constant frequency current mode architecture that requires no current sense resistors or Schottky diodes. It operates from a wide input supply from 2.75V to 9.8V, making it ideal for $3.3V_{IN}$ and $5V_{IN}$ applications. The LTC3776's two channels operate out-of-phase, reducing the required input capacitance, while its high operating frequency of up to 850kHz allows the use of small inductors and capacitors. The LTC3776 is available in a tiny 4mm x 4mm QFN package or in a 24-lead narrow SSOP package.

3.3V to 2.5V/1.25V Dual Step-Down DC/DC Converter

Figure 1 illustrates a design solution for a 3.3V to 2.5V (V_{DDQ}) and 1.25V (V_{TT}) step-down DC/DC converter. This circuit can source up to 3A of load current on the V_{DDQ} supply and can sink or source up to 3A on the V_{TT} supply. The 2.5V regulation point is set by the R1-R2 resistor divider. The V_{TT} voltage is internally programmed to regulate to half the voltage on the V_{REF} pin via an internal resistor divider. Thus, to achieve the $V_{TT} = V_{DDQ}/2$ DDR memory requirement, the V_{DDQ} output can be simply tied to the V_{REF} pin, without requiring any additional external resistors. The $V_{TT} = V_{DDQ}/2$ requirement is met even during startup as illustrated in Figure 2. Figure 3 shows the efficiency for this circuit. Since the V_{DDQ} output voltage is adjustable, the LTC3776 is compatible with all generations of DDR memory.

Adjustable, Synchronizable or Spreadable Frequency

The LTC3776 offers three selectable operating frequencies—300kHz, 550kHz, or 750kHz—or it can be synchronized to an external clock source between 250kHz and 850kHz using the LTC3776's phase-locked loop. This allows the switching frequency of both the V_{DDQ} and V_{TT} output to be synchronized not only to each other, but also to a system clock. Alternatively, the LTC3776 can be programmed to enter spread spectrum modulation mode, in which the frequency is randomly varied between 450kHz and 580kHz to reduce conducted and radiated electromagnetic interference (EMI) (See "Dual Switcher with Spread Specturm Reduces EMI" in *Linear Technology* Magazine, December 2004, page 9).

Conclusion

The LTC3776 is a dual step-down DC/DC controller that provides both the V_{DDQ} and V_{TT} supplies with a single IC. It requires few external components and enables a small, easy-to-use, highly efficient solution that makes the LTC3776 the ideal choice for DDR memory power.

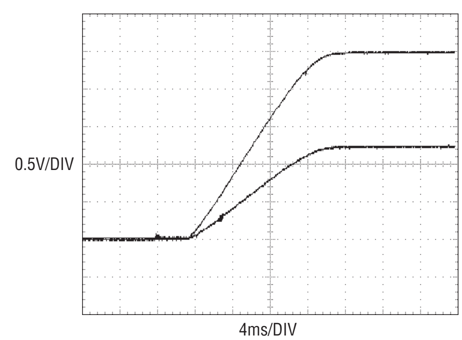

Figure 2. Startup waveforms for the circuit in Figure 1

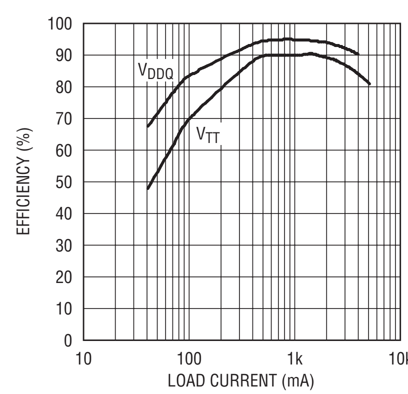

Figure 3. Efficiency versus load current for the circuit in Figure 1

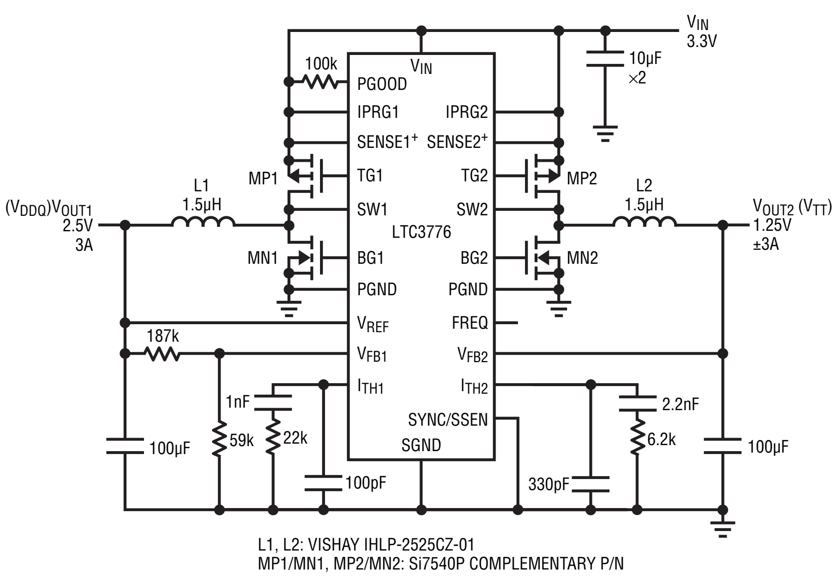

Figure 1. Complete DDR power solution using the LTC3776

New Device Cameos

Dual Low Dropout, Low Noise, Micropower Regulators with Independent Inputs Work in Tracking Supplies

The LT3027 and LT3028 are dual low dropout, low noise, micropower regulators with independent inputs. The LT3027 has two regulators capable of providing 100mA of output current, whereas the LT3028 combines a 100mA and a 500mA regulator. Typical dropout voltage for the 100mA regulator is 300mV at the rated output current; the 500mA regulator of the LT3028 has a typical dropout voltage of 320mV. Each regulator has its own independent input, allowing for flexibility in power management. Quiescent current for each of the regulators is less than 30µA, ideal for use in battery-powered systems. Both regulators also feature an independent shutdown state, lowering quiescent current to less than 0.1µA. Quiescent current is well controlled in dropout.

The LT3027 and LT3028 are capable of operating with the voltage at the ADJ pin above the regulated output voltage. This allows for the regulators to be used with power supply control devices that sequence, track, or ratio multiple supplies, such as the LTC2923. The LT3027 and LT3028 regulators also feature low noise operation with the addition of an external 0.01µF bypass capacitor. Over the 10Hz to 100kHz bandwidth, output voltage noise is reduced to $20\mu V_{RMS}$. The 100mA regulators can operate with as low as 1µF of capacitance on the output while the 500mA regulator requires 4.7µF, though the use of the external bypass capacitor necessitates larger output capacitors. Small ceramic capacitors can be used on these devices without the need for added series resistance as is common with other regulators. Internal protection circuitry on the regulators includes reverse-battery protection, current limiting and thermal limiting.

Both regulators are adjustable with an output voltage range of 1.22V to 20V. The LT3027 is packaged in thermally enhanced 10-lead MSOP and DFN (3mm × 3mm) packages and the LT3028 is available in thermally enhanced 16-lead TSSOP and DFN (5mm × 3mm) packages.

Synchronous DC/DC Converter Features Low EMI and Programmable Output Tracking

LTC3809 and LTC3809-1 are low power, synchronous step-down DC/DC converters that can deliver high efficiency with a low quiescent current. Each can provide output voltages as low as 0.6V and output currents as high as 7A from a wide, 2.75V to 9.8V, input range, making them ideal devices for single lithium-ion cell, other multi-cell and distributed DC power systems. LTC3809 and LTC3809-1 also take advantage of No R_{SENSE}™ current mode technology by sensing the voltage across the main (top) power MOSFET to improve efficiency and reduce the size and cost of the solution. Both include other popular features, such as current mode control for excellent AC and DC line and load regulation, low dropout (100% duty cycle) for maximum energy extraction from a battery, output overvoltage protection and short circuit current limit protection.

LTC3809's adjustable high operating frequency (300kHz–750kHz) allows the use of small surface mount inductors and ceramic capacitors for a compact power supply solution. It also includes important features for noise-sensitive applications, including a phase-locked loop (PLL) for frequency synchronization and spread spectrum frequency modulation to minimize electromagnetic interference (EMI). Spread spectrum modulation minimizes the need for EMI shields and filters in applications such as navigation systems, wireless LANs, data acquisition boards and industrial/military radio devices by spreading the nominal operating frequency (550kHz) over a range of frequencies between 460kHz and 635kHz.

LTC3809-1 operates at a fixed frequency of 550kHz. It also offers flexibility of start-up control with a fixed internal start-up time, an adjustable external soft-start, or the ability to track another voltage source. This flexibility of start-up control not only reduces the inrush current surge and prevents output voltage overshoot, but also provides the ability of output tracking in multiple power supply systems.

Both LTC3809 and LTC3809-1 are available in a low profile (0.8mm height), tiny 3mm × 3mm leadless DFN package or a 10-pin MSOP exposed pad package.

Dual Synchronous, 400/800mA, 2.25MHz Step-Down DC/DC Regulators in a 10-Lead MSOP

The LTC3548 is a dual, constant frequency, synchronous step-down DC/DC converter, intended for low power applications. It operates within a 2.5V to 5.5V input voltage range and has a fixed 2.25MHz switching frequency, making it possible to use capacitors and inductors that are under 1.2mm in height. The LTC3548 is the latest in the LTC3407 and LTC3407-2 family of dual regulators and features improved Burst Mode ripple and two outputs of 400mA and 800mA. It is available in a small MS10 package, allowing two DC/DC Regulators to occupy less than 0.2 square inches of board real estate.

The outputs of the LTC3548 are independently adjustable from 0.6V to 5V. For battery-powered applications that have input voltages above *and* below the output voltage, the LTC3548 can be used in a single inductor, positive buck-boost converter configuration. Two built-in 0.40Ω switches allows up to 400mA and 800mA of output current at high efficiency. Internal compensation minimizes external components and board space.

Efficiency is extremely important in battery-powered applications, and the LTC3548 keeps efficiency high with an automatic, power saving Burst Mode operation, which reduces gate charge losses at low load currents. With no load, both converters together draw only draw 40µA, and in shutdown, the device draws less than 1µA, making it ideal for low current applications.

The LTC3548 uses a current-mode, constant frequency architecture that benefits noise sensitive applications. Burst Mode operation is an efficient solution for low current applications, but sometimes noise suppression is a higher priority. To reduce noise problems, a pulse-skipping mode is available, which decreases the ripple noise at low currents. Although not as efficient as Burst Mode operation at low currents, pulse-skipping mode still provides high efficiency for moderate loads. In dropout, the internal P-channel MOSFET switch is turned on continuously, thereby maximizing the usable battery life.

A Power-On Reset output is available for microprocessor systems to insure proper startups. Internal undervoltage comparators on both outputs pull the $\overline{\text{POR}}$ output low if the output voltages are not above –8.5% of the regulation. The $\overline{\text{POR}}$ output is delayed by 262,144 clock cycles (about 117ms) after achieving regulation, but is pulled low immediately when either ouput is out of regulation.

The small size, efficiency, low external component count, and design flexibility of the LTC3548 make it an ideal DC/DC converter for portable devices.

LTC2053-SYNC, continued from page 33

connected, then the internal oscillator free-runs at approximately 24kHz and the sampling rate is thus about 3kHz. When an external clock is applied, the internal oscillator's feedback is overdriven and all timing is then based on the external frequency. To minimize digital ground-noise transients at the LTC2053-SYNC, the use of an RC coupling network at the external clock input pin is recommended, as shown in Figure 2.

Conclusion

The LTC2053-SYNC offers a means to utilize the exceptional low frequency precision of the LTC2053 sampling architecture in those difficult signal acquisition situations where sampling artifacts may be otherwise difficult or impractical to manage. The external clocking feature allows controlling the sampling rate over at least a 2-octave range to optimize performance and reduce (or eliminate) antialias filter complexity.

LTC3418, continued from page 20

QFN package with an exposed pad to facilitate heat sinking.

The LTC3418 can be configured for either Burst Mode, pulse skip or forced continuous operation. Burst Mode operation provides high efficiency over the entire load range by reducing gate charge losses at light loads. In the LTC3418, the burst clamp is adjusted by varying the DC voltage at the Sync/Mode pin within a 0V–1V range. The voltage at this pin sets the minimum peak inductor current during each switching cycle in Burst Mode operation. If the minimum peak inductor current delivers more energy than is demanded by the load current, the internal power switches skip switching cycles to maintain regulation. Burst Mode operation provides an efficient solution for light-load applications, but sometimes noise suppression takes priority over efficiency. Forced continuous operation, though not as efficient as Burst Mode operation at light loads, maintains a steady frequency, making it easier to reduce noise and RF interference.

Voltage tracking is enabled by applying a ramp voltage to the TRACK pin. When the voltage on the TRACK pin is below 0.8V, the feedback voltage regulates to this tracking voltage. When the tracking voltage exceeds 0.8V, tracking is disabled and the feedback voltage regulates to the internal 0.8V reference voltage.

A High Efficiency 1.2V/8A Step-Down Regulator with All Ceramic Capacitors

Figure 1 shows a 1.2V step-down switching regulator that can be used as a core supply voltage for microprocessors. It uses all ceramic capacitors and tracks an I/O voltage of 2.5V. This circuit provides a regulated 1.2V output at up to 8A from a 3.3V input. Efficiency for this circuit is as high as 87% and is shown in Figure 2. The switching frequency for this circuit is set at 2MHz by an external resistor, R_{OSC}. Operating at a frequency this high allows the use of a lower valued and physically smaller inductor. During start-up, the output of the LTC3418 coincidentally tracks the I/O supply voltage. Once the I/O supply voltage exceeds 1.2V, tracking is disabled and the LTC3418 regulates its output voltage to 1.2V.

Ceramic capacitors offer low cost and low ESR, but many switching regulators have difficulty operating with them. The LTC3418, however, includes OPTI-LOOP compensation, which allows it to operate properly with ceramic input and output capacitors. The problem that many switching regulators have when using ceramic capacitors is that their ESR is too low, which leads to loop instability. That is, the phase margin of the control loop can drop to inadequate levels without the aid of the zero that is normally generated from the higher ESR of tantalum capacitors. The LTC3418 allows loop stability to be achieved over a wide range of loads and output capacitors with the proper selection of compensation components at the I_{TH} and V_{FB} pins.

Conclusion

The LTC3418 is a monolithic, synchronous step-down DC/DC converter that is well suited to applications requiring up to 8A of output current. Its high switching frequency and internal low $R_{DS(ON)}$ power switches allow the LTC3418 to provide a small solution size with high efficiency.

DESIGN TOOLS

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

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

CD-ROM

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

Brochures

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

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SALES OFFICES

NORTH AMERICA

NORTHWEST AREA

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

Denver
Phone: (303) 926-0002

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

Sacramento
Phone: (408) 432-6326

Salt Lake City
Phone: (801) 731-8008

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

SOUTHWEST AREA

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

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

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

CENTRAL AREA

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

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

Columbus
Phone: (614) 488-4466

Detroit
Phone: (248) 374-2243

Indiana
Phone: (317) 581-9055

Kansas
Phone: (913) 829-8844

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

Wisconsin
Phone: (262) 859-1900

NORTHEAST AREA

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

Connecticut
Phone: (860) 228-4104

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

SOUTHEAST AREA

Atlanta
Phone: (770) 888-8137

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

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

Fort Lauderdale
Phone: (954) 986-9810

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

Huntsville
Phone: (256) 885-0215

Orlando
Phone: (407) 688-7616

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

Tampa
Phone: (813) 634-9434

ASIA

CHINA

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

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

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

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

JAPAN

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

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

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

KOREA

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

SINGAPORE

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

TAIWAN

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

EUROPE

FINLAND

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

FRANCE

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

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

GERMANY

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

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

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

ITALY

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

SWEDEN

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

UNITED KINGDOM

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

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

www.linear.com