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IN THIS ISSUE

Combined Voltage and Current Control Loops Simplify LED Drivers, High Capacity Battery/Supercap Chargers & MPPT* Solar Applications

Xin (Shin) Qi

* Maximum Power Point Tracking

The rapid expansion of constant-current/constant-voltage (CC-CV) applications, especially in LED lighting and high capacity battery and supercapacitor chargers challenges power supply designers to keep pace with the increasingly complicated interplay of current and voltage control loops. A switch-mode converter designed specifically for CC-CV offers a clear advantage, especially when the supply has limited power, or its power is allocated among several competing loads.

The LTC4155 is a monolithic switching battery charger that efficiently delivers 3.5A charge current in a compact PCB footprint. See page 13.

Consider, for instance, the challenge of charging a supercapacitor in a minimum amount of time from a *power-limited* supply. To maintain constant input power, the controlled charging current must decrease as the output (supercapacitor) voltage increases. The LT®3796 solves the problem of power limited or constant current/constant voltage regulation by seamlessly combining a current regulation loop and two voltage regulation loops to control an external N-channel power switch. The inherent wired-OR behavior of its three transconductance error amplifiers summed into the compensation pin, V_C, ensures that the correct loop (that is, the one closest to regulation) dominates.

(continued on page 4)

In this issue...

Linear in the News

LINEAR RECEIVES PRESTIGIOUS AWARDS

Over the past several months, Linear Technology received several significant awards for products, system solutions, and for manufacturing quality and delivery. Here are the highlights:

Electronic Products 2011 Product of the Year Award: LTC5569 RF Mixer

Electronic Products honored Linear with the selection of the LTC®5569 dual broadband RF mixer as Product of the Year. From thousands of products, the editors of *Electronic Products* selected those they felt are among the most outstanding. The selection is based on a significant advance in technology or its application, innovation in design, or gain in price/performance.

The editors stated, "In order to make LTE, a 4G (fourth-generation) high data-rate wireless technology attractive to the carrier for deployment, base station manufacturers worldwide are trying to build a multiband, multimode platform that is easily field configured for use in any frequency band and standard to make the deployment cost attractive. The 26.8dBm IIP3 LTC5569 dual-broadband RF mixer accomplishes this by combining 26.8dBm IIP3, 300mW/ch, and a wide 300MHz to 4GHz frequency range. So a receiver such as that based on the LTC5569, is capable of working in all of the 700MHz, 880MHz, 1.7GHz, 1.8GHz, 1.9GHz, 2.4GHz, and 2.6GHz bands. In addition, within each band, the receiver must receive signals that are 60MHz wide, compared to the previous 20MHz wide without sacrificing performance. The LTC5569 meets both of these requirements with outstanding performance."

EN-Genius Network Awards Linear for Products of the Year & the Decade

EN-Genius Network, formerly *AnalogZone*, selected Linear Technology's µModule® family as Best Product of Our Decade. According to the editor, "The concept of the µModules allows the product designer to come to the decisions about power management quite late in the development cycle—simplifying the final product choice.

"Linear has also extended the concept to a family of seventeen 'System in a Package' (SiP) signal chain receiver modules, the first of which, the LTM®9001, we reviewed here. The SiPs, which feature 12-/14-/16-bit solutions, not only simplify circuit design for the less than sure RF engineer out there but they also bypass export regulation control of some individual ADCs.

"All-in-all the µModule concept has been a spectacularly successful commercial and technological story for Linear. We are delighted to congratulate them on their achievement and to recognize them as the Product of Our Decade."

EN-Genius Network also selected Linear's LTC6946 373MHz to 5.79GHz Integer-N synthesizer as Product of the Year for the Best Integer-N Synthesizer. The publication commented, "The parts are a welcome addition to Linear's RF arsenal and will prove to be equally attractive to designers who do not have to cope with large bandwidth issues straight away."

China Electronics Awards

Several major electronics publications in China presented Linear with awards:

- **EDN China:** Innovation Award, Excellent Product Award for the LTC4000 high voltage controller and power manager.
- **China Electronic Market:** Editor's Choice Award for the Most Competitive Power Product: LTC4000
- **EEPW Editor's Choice Awards:** Best Analog Product: LTC6803 battery stack monitor for hybrid/electric vehicles Best Amplifier: LT1999 high voltage bidirectional current sense monitor
- **Electronic Products China:** Annual Award: LTM8047/8048 isolated µModule DC/DC converter

Enics Manufacturing Award

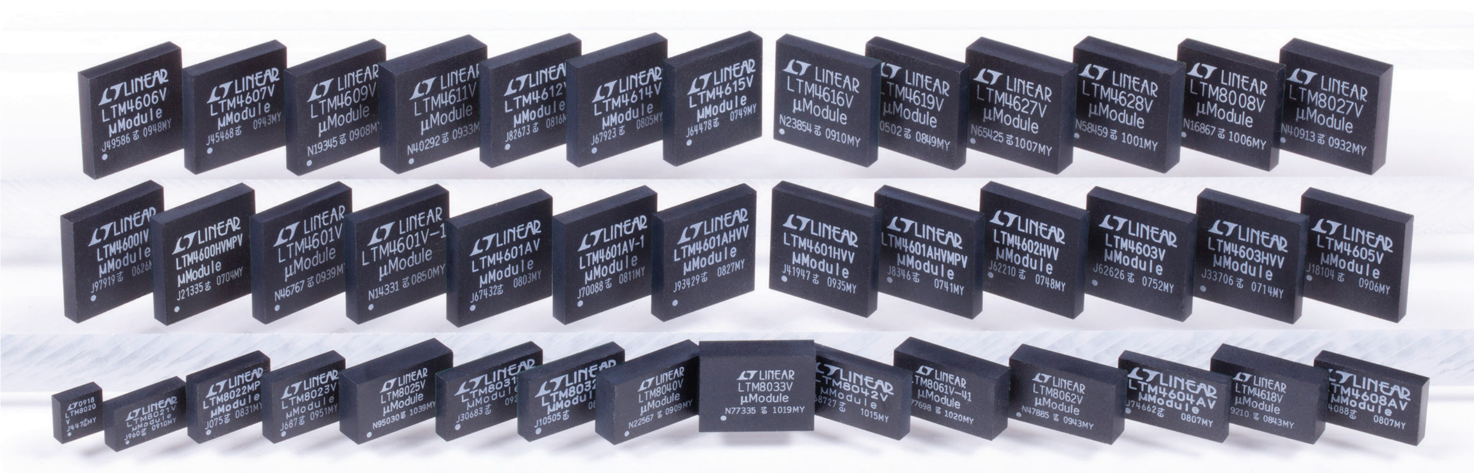
Enics, one of the largest providers of electronics manufacturing services, named the best suppliers of the year, and honored Linear as the Best Component Manufacturer at the annual Enics Fair in Zurich, Switzerland.

LINEAR'S STRONG PATENT PORTFOLIO RECOGNIZED

Ocean Tomo announced the leading companies in patent assets. According to Ocean Tomo's ranking, Linear Technology's patent portfolio received an IPQ score of 123—the highest of any major analog semiconductor company. Ocean Tomo claims to rate patent assets objectively based on proven statistical methodology. This reinforces the value of Linear's growing patent portfolio and the company's strong analog intellectual property.

CONFERENCES & EVENTS

Power Systems Show 2012, Tokyo Big Sight, Tokyo, Japan, July 11–13, Booth 6B-301—Linear will showcase power products, including µModule products and FPGA power management solutions. More info at www.jma.or.jp/tf/en11/electronics/index.html.



EN-GENIUS NETWORK AWARDS LINEAR FOR PRODUCTS OF THE YEAR & THE DECADE

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(LT3796, continued from page 1)

The additional, standalone current sense amplifier can be configured for any number of functions, including input current limit and input voltage regulation.

The LT3796's wide V_{IN} range (6V to 100V) and rail-to-rail (0V to 100V) output current monitoring and regulation allow it to be used in a wide variety of applications from solar battery chargers to high power LED lighting systems. The fixed switching frequency, current-mode architecture results in stable operation over a wide range of supply and output voltages. The LT3796 incorporates a high side current sense, enabling its use in boost, buck, buck-boost or SEPIC and flyback topologies.

HIGH POWER LED DRIVER WITH ROBUST OUTPUT SHORT CIRCUIT PROTECTION

Figure 1 shows the LT3796 configured as a boost converter to drive a 34W LED string from a wide input range. The LED current is derated at low input voltages to prevent external power components from overheating. The front-end current sense amplifier monitors the input current by converting the input current to a voltage signal at the CSOUT pin with

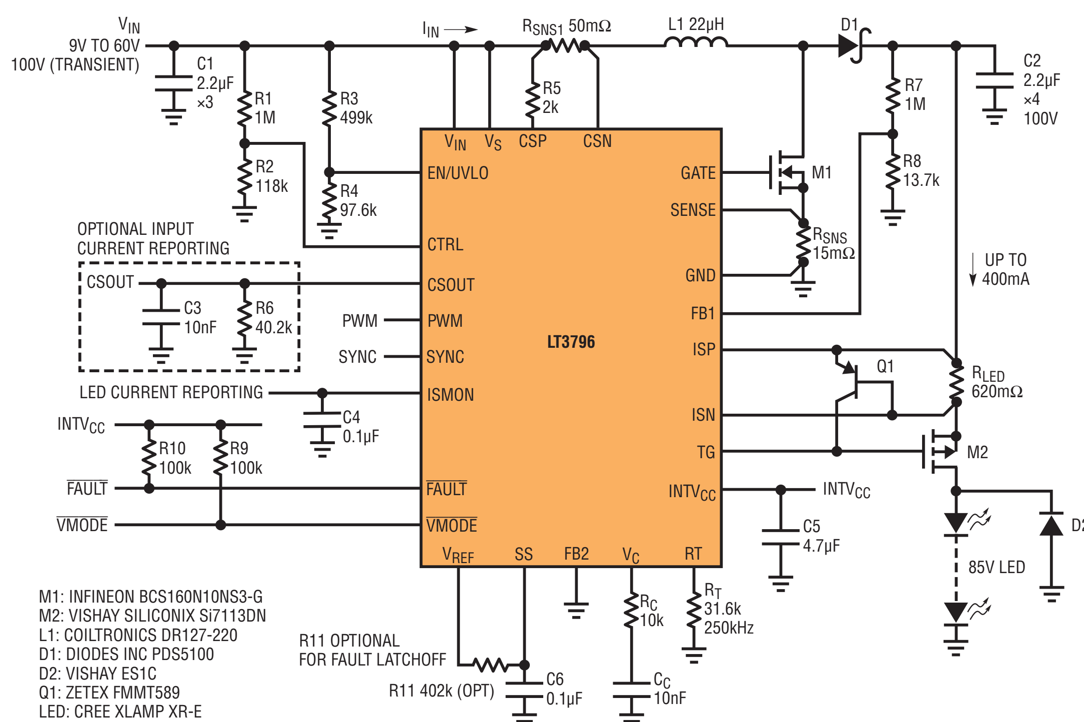
$$V_{CSOUT} = I_{IN} \bullet R_{SNS1} \bullet \frac{R6}{R5}$$

The resistor network at the FB1 pin provides OPENLED protection, which limits the output voltage and prevents the ISP pin, ISN pin and several external components from exceeding their maximum rating. If an LED fails open or if the LED string is removed from the high power driver, the FB constant voltage loop takes over and regulates the output to 92.5V. The $\overline{\text{VMODE}}$ flag is also asserted to indicate an OPENLED event.

The LT3796 includes short-circuit protection independent of the LED current sense. The short-circuit protection feature prevents the development of excessive switching currents and protects the power components. The protection threshold (375mV, typ) is designed to be 50% higher than the default LED current sense threshold.

Figure 1. A 34W LED driver with robust output short-circuit protection.

LTspice IV
circuits.linear.com/558



The LT3796 solves the problem of power limited, or constant-current/constant-voltage regulation by seamlessly combining a current regulation loop and two voltage regulation loops to control an external N-channel power switch.

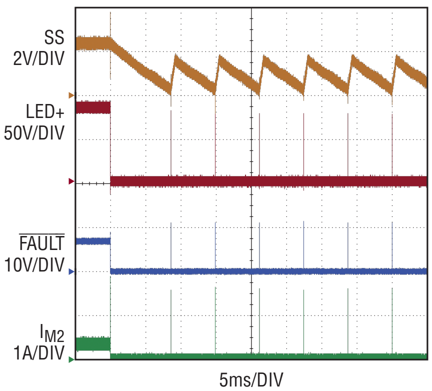


Figure 2. Short LED protection: hiccup mode (without R11 in Figure 1)

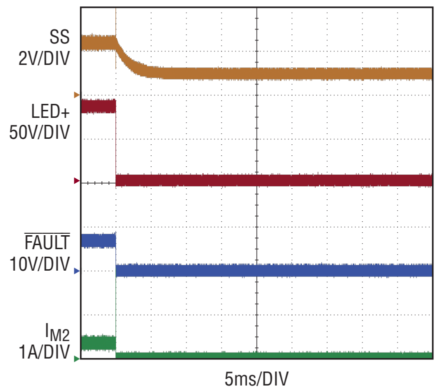


Figure 3. Short LED protection: latchoff mode (with R11 in Figure 1)

Once the LED overcurrent is detected, the GATE pin drives to GND to stop switching, the TG pin is pulled high to disconnect the LED array from the power path and the $\overline{\text{FAULT}}$ pin is asserted. The Schottky diode D2 is added to protect the drain of PMOS M2 from swinging well below ground when shorting to ground through a long cable. The PNP helper Q1 is included to further limit the transient short-circuit current.

If there is no resistor between the SS pin and V_{REF} pin, the converter enters hiccup mode and periodically retries as shown in the Figure 2. If a resistor is placed between V_{REF} and SS pin to hold SS pin higher than 0.2V during LED short, then the LT3796 enters latchoff mode with GATE pin low and TG pin high, as shown in Figure 3. To exit latchoff mode, the EN/UVLO pin must be toggled low to high.

LED DRIVER WITH HIGH PWM DIMMING RATIO

Using an input referred LED string allows the LT3796 to act as a buck mode controller as shown in Figure 4. The 1MHz operating frequency enables a high PWM dimming ratio. The OPENLED regulation voltage is set to

$$1.25\text{V} \bullet \frac{R3}{R6} \bullet \left(\frac{R5}{R4}+1\right)$$

through the independent current sense amplifier at CSP, CSN and CSOUT pins. During the PWM off phase, the LT3796 disables all internal loads to the V_C pin

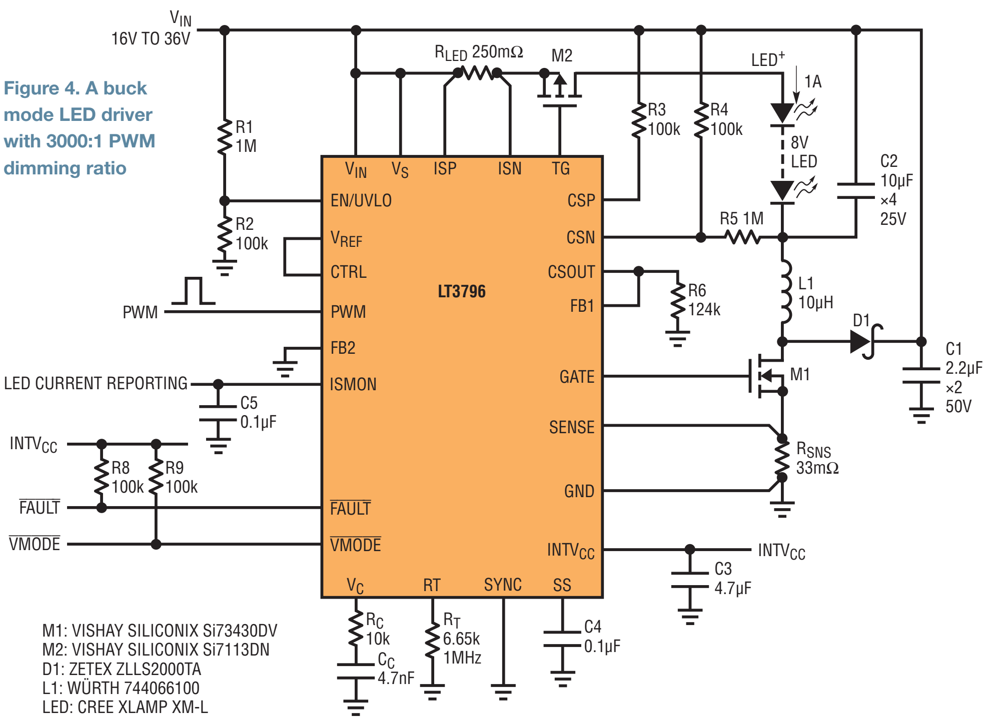
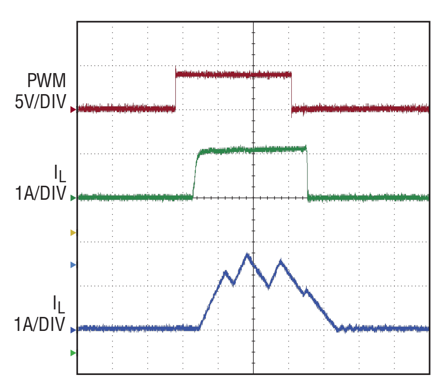


Figure 4. A buck mode LED driver with 3000:1 PWM dimming ratio

Figure 5. 3000:1 PWM dimming ratio of the circuit in Figure 4 at V_{IN} = 24V and PWM = 100Hz



Voltage drops in wiring and cables can cause load regulation errors. These errors can be corrected by adding remote sensing wires, but adding wires is not an option in some applications. As an alternative, the LT3796 can adjust for wiring drops, regardless of load current, provided that the parasitic wiring or cable impedance is known.

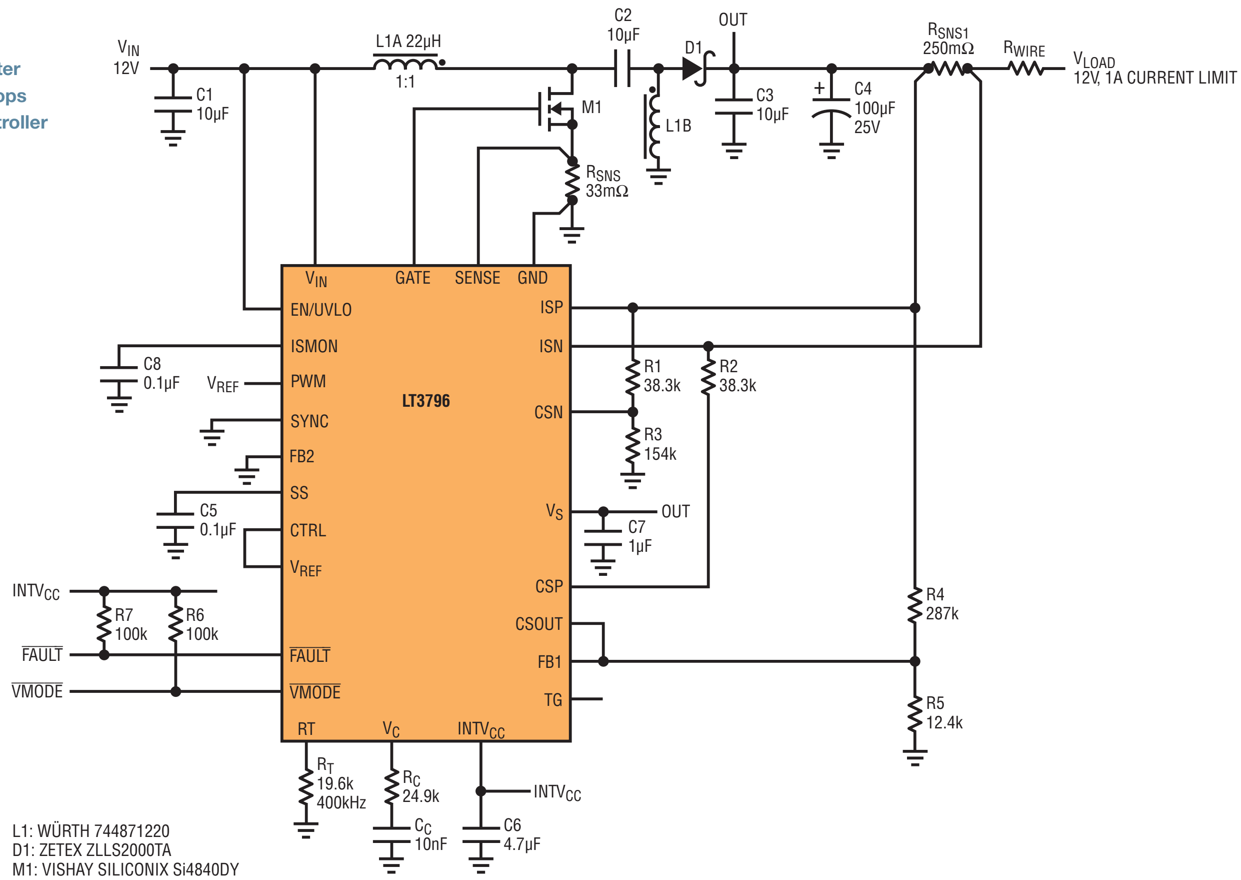


Figure 6. This SEPIC converter compensates for voltage drops in the wire between the controller and the load (R_{WIRE})

and preserves the charge state. It also turns off the PMOS switch M2 to disconnect the LED string from the power path and prevent the output capacitor from discharging. These features combine to greatly improve the LED current recovery time when PWM signal goes high. Even with a 100Hz PWM input signal, this buck mode LED driver can achieve a 3000:1 dimming ratio as illustrated in Figure 5.

SEPIC CONVERTER WITH R_{WIRE} COMPENSATION

Voltage drops in wiring and cables can cause load regulation errors. These errors can be corrected by adding remote sensing wires, but adding wires is not an option in some applications. As an alternative, the LT3796 can adjust for wiring drops, regardless of load current, provided that the parasitic wiring or cable impedance is known.

Figure 6 shows a 12V SEPIC converter that uses the R_{WIRE} compensation feature. R_{SNS1} is selected to have 1A load current limit controlled by the ISP, ISN pins. The resistor network R1–R5, along with the LT3796's integrated current sense amplifier (CSAMP in Figure 7), adjusts the OUT node voltage (V_{OUT}) to account for voltage drops with respect to the load current. This ensures that V_{LOAD} remains constant at 12V throughout the load range.

Figure 7 shows how the LT3796's internal CSAMP circuit plays into the operation. The LT3796's voltage loop regulates the FB1 pin at 1.25V so that I_3 stays fixed at 100µA for R5 = 12.4k. In Figure 7, V_{OUT} changes

The LT3796 in a 28-lead TSSOP package performs tasks that would otherwise require a number of control ICs and systems. It offers a reliable power system with simplicity, reduced cost and small solution size.

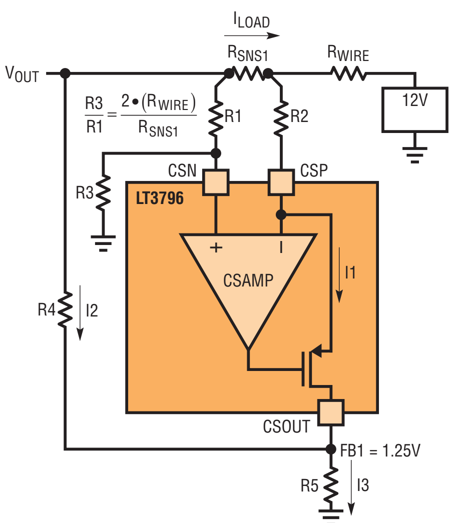


Figure 7. R_{WIRE} voltage drops are compensated for via the LT3796's CSAMP circuit

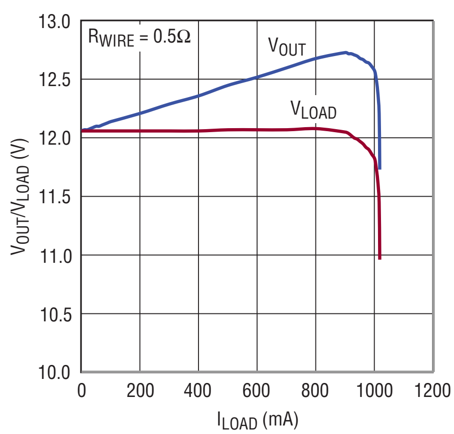


Figure 8. Measured V_{LOAD} and V_{OUT} with respect to I_{LOAD}

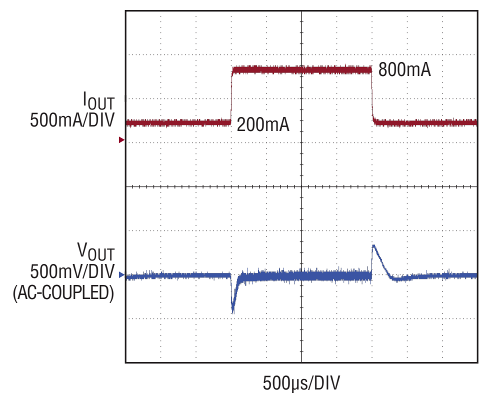


Figure 9. Load step response of the circuit in Figure 6

with current I_2 as $V_{OUT} = 1.25V + I_2 \bullet R4$. If the change of $I2 \bullet R4$ can offset the change of $I_{LOAD} \bullet (R_{SNS1} + R_{WIRE})$, then V_{LOAD} will stay constant.

Referring to Figure 7, the divider R1/R3 from V_{OUT} sets the voltage regulated at CSP by the current I_1 flowing in R2. I_1 is conveyed to the FB1 node where it sums with I_2.

As the output current increases, I_1 decreases due to the increasing voltage drop across R_{SNS}; its decrease must be compensated by a matching increase in the current I_2 to maintain the constant 100µA into FB2. This increase in I_2 with output current is what gives V_{OUT} the positive load regulation characteristic. The positive load regulation is just what is needed to compensate for the cable drop.

The measured V_{LOAD} and V_{OUT} with respect to I_{LOAD} are shown in Figure 8. Clearly, V_{LOAD} is independent of I_{LOAD} when I_{LOAD} is less than the 1A current limit. When I_{LOAD} approaches 1A, the current loop at ISP and ISN pins begins to interfere with the voltage loop and drags the output voltage down correspondingly. The load transient response is shown in Figure 9.

SOLAR PANEL BATTERY CHARGER

Solar powered devices rely on a highly variable energy source, so for a device to be useful at all times, energy from solar cells must be stored in a rechargeable battery. Solar panels have a maximum power point, a relatively fixed voltage at which the panel can produce the most power. Maximum power point tracking (MPPT) is usually achieved by limiting a converter's output current to keep the panel voltage from straying from this value. The LT3796's unique combination of current and voltage loops make it an ideal MPPT battery charger solution.

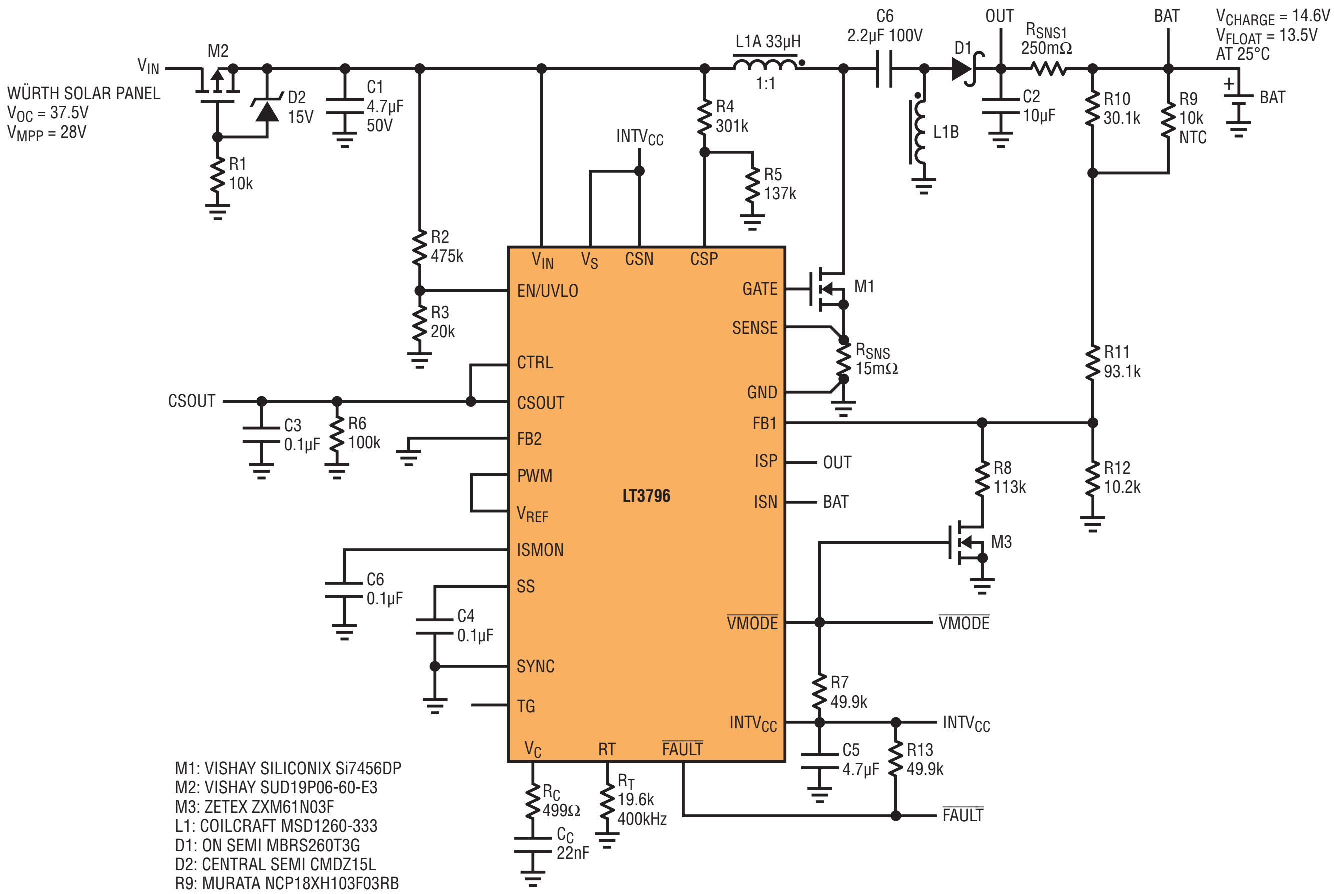


Figure 10. A solar panel battery charger maximum power point tracking (MPPT)

Figure 10 shows a solar panel to sealed lead acid (SLA) battery charger driven by the LT3796. The charger uses a three-stage charging scheme. The first stage is a constant current charge. Once the battery is charged up to 14.35V, the charging current begins to decrease. Finally, when the required battery charge current falls below 100mA, the built-in C/10 termination disables the charge circuit by pulling down $\overline{\text{VMODE}}$, and the charger enters float charge stage with V_{FLOAT} = 13.5V to compensate for the loss caused by self-discharge.

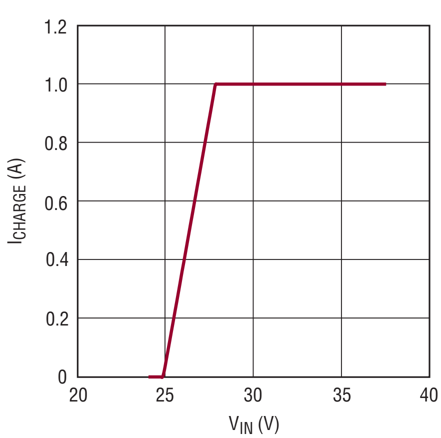


Figure 11. I_{CHARGE} vs V_{IN} for the solar charger in Figure 10

The charging current is programmed by the resistor network at the CSP and CSOUT (CTRL) pins as follows,

$$V_{CTRL} = R6 \bullet \left(\frac{V_{IN} - V_{INTVCC}}{R4} - \frac{V_{INTVCC}}{R5} \right),$$

$$\text{FOR } V_{IN} \geq V_{INTVCC} \left(1 + \frac{R4}{R5} \right)$$

$$V_{CTRL} = 0V,$$

$$\text{FOR } V_{IN} < V_{INTVCC} \left(1 + \frac{R4}{R5} \right)$$

Maximum power point tracking is implemented by controlling the maximum output charge current. Charge current is reduced as the voltage on the solar panel output falls toward 28V, which corresponds to 1.1V on the CTRL pin and full charging current, as shown in Figure 11. This servo loop thus acts to dynamically reduce the power requirements of the charger system to the maximum power that the panel can provide, maintaining solar panel power utilization close to 100%.

SUPERCAPACITOR CHARGER WITH INPUT CURRENT LIMIT

Supercapacitors are rapidly replacing batteries in a number of applications from rapid-charge power cells for cordless tools to short term backup systems for microprocessors. Supercapacitors are longer lasting, greener, higher performance and less expensive over the long run, but charging supercapacitors requires precise control of charging current and voltage

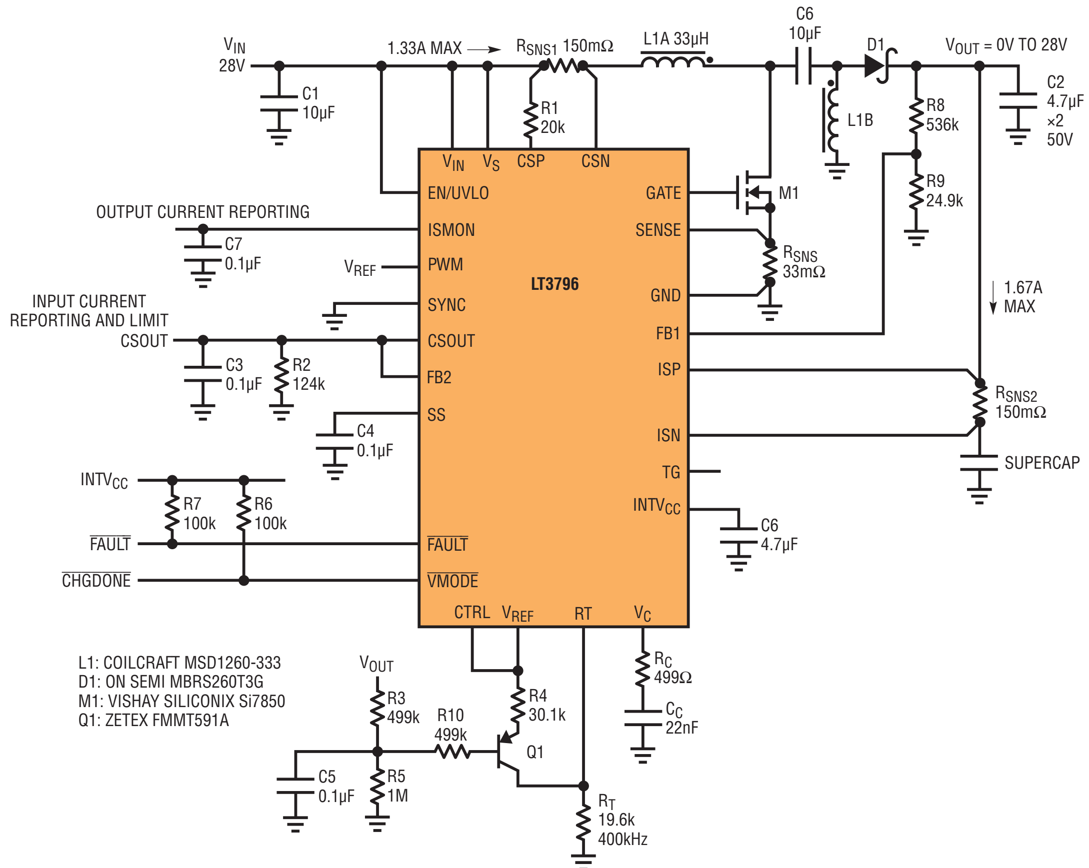


Figure 12. A 28V/1.67A supercapacitor charger with input current limit

limiting to prevent any system-wide damage or damage to the supercapacitor.

Some applications require that the input current is limited to prevent the input supply from crashing. Figure 12 shows a 1.67A supercapacitor charger with 28V regulated output voltage and 1.33A input current limit. The input current is sensed by R_{SNS1}, converted to a voltage signal and fed to the FB2 pin to provide input current limit.

In each charging cycle, the supercapacitor is charged from 0V. The feedback loop from V_{OUT} to the RT pin through R3, C5, R5, R10, R4, and Q1 to R_T works as frequency foldback to keep regulation under control. In Figure 13, the input current and output charging current are plotted against output voltage for this charger, showing the LT3796 maintaining the output current regulation until the input current moves close to the 1.33A input current limit.

CONCLUSION

The LT3796 is a versatile step-up DC/DC controller that combines accurate current and voltage regulation loops. Its unique combination of a single current loop and two voltage loops makes it easy to solve the problems posed by applications that require multiple control loops, such as LED drivers, battery or supercapacitor chargers, MPPT solar battery chargers, and step-up or SEPIC converters with input and output current limit. It also includes a number of fault protection and reporting functions, a top gate driver and current loop reporting.

The LT3796 in a 28-lead TSSOP package performs tasks that would otherwise require a number of control ICs and systems. It offers a reliable power system with simplicity, reduced cost and small solution size. ■

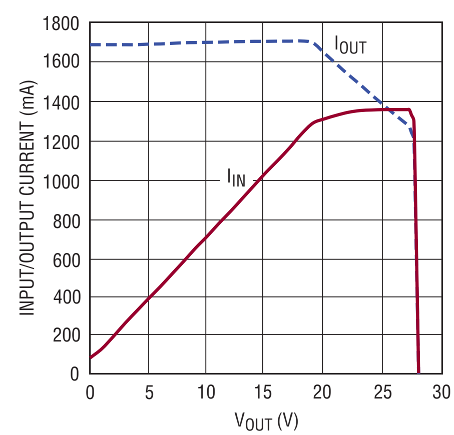


Figure 13. Input/output current vs output voltage for 28V/1.67A supercapacitor charger in Figure 12

Pushbutton On/Off Controller Includes Optional Automatic Turn-On When Handheld Device is Plugged In

Vui Min Ho

It is well-known that most mechanical pushbutton switches bounce when pressed, and that a debounce circuit is required to produce a clean, usable signal from the pushbutton. There are many debounce solutions available—common ones use flip-flops or R-S latches—but designing and implementing a debounce circuit is not as trivial as it might seem, especially for handheld devices.

Because a pushbutton debounce circuit must remain on all the time, a low supply current is critical for battery-powered handheld devices. Additionally, the circuit should be capable of accepting power from any available standby supply voltage without requiring a linear regulator. Furthermore, the pushbutton input should be able to withstand high ESD levels during operation since it is usually connected where contact with the human finger is possible. And finally, the circuit must be small enough to fit into whatever little space is left on the printed circuit board.

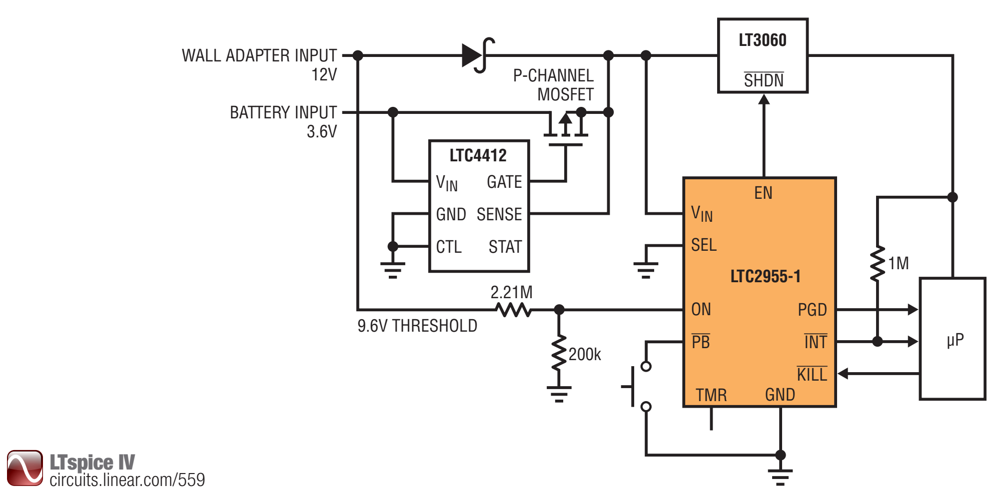
The LTC2955 pushbutton controller covers all of these requirements. It generates a latched enable output from the noisy pushbutton input. The enable output comes in both active high (LTC2955-1) or active low (LTC2955-2) options, allowing it to drive the on/off input of any system or regulator.

The LTC2955 features a voltage monitor pin (ON) that can be used for automatic system turn-on when the device is plugged into a secondary supply such as a wall adapter or car battery. This is a common feature found in handheld devices where, if you plug in the wall adapter or charger cable, the device automatically powers up by itself without a press of the on/off switch.

The LTC2955 is designed to interface with a microprocessor via the LTC2955's $\overline{\text{INT}}$ (interrupt) output pin and $\overline{\text{KILL}}$ input pin. The LTC2955's $\overline{\text{INT}}$ output alerts the microprocessor that the pushbutton is pressed, allowing the microprocessor to perform any power-down tasks. Once these tasks are complete, the microprocessor can communicate—via the $\overline{\text{KILL}}$ pin—that the system is ready to be switched off. The user can also force the system to power-down if the microprocessor fails to respond to the interrupt signal ($\overline{\text{KILL}}$ pin remains high). This is the familiar user-holds-the-button-down for a duration greater than the defined power-off period. The power-off period is adjustable through the capacitor at the TMR pin and it can be made as long as required to prevent accidental turn-off.

The LTC2955 is also designed with blanking times after each pushbutton event, during which all inputs are ignored. This prevents the EN output from turning on and off continuously if the pushbutton is held down or stuck low. These blanking times ensure sufficient time for the voltage regulator to fully charge up or discharge its output and allow the system or microprocessor time to perform power on/off tasks. In addition, the power-down debounce time is adjustable using an external capacitor. This allows the designer to extend the power-down

Figure 1. Pushbutton on/off control for battery-powered device, with automatic turn-on when the device is plugged in



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time in cases where some systems need more time to perform power-down tasks.

The LTC2955 minimizes components by operating directly from inputs as low as a 1.5V single-cell battery up to a 36V multicell stack—with no additional boost regulator or LDO required. The low quiescent current of 1.2µA extends the battery life. The device is available in a space-saving 10-lead 3mm × 2mm DFN package and 8-lead ThinSOT™ package.

HANDHELD WITH AUTOMATIC TURN-ON WHEN PLUGGED IN

Figure 1 shows a typical LTC2955-1 application for a handheld device. The 3.6V supply is produced directly from the handheld's battery; the 12V secondary supply comes from a wall adapter. Both the 3.6V and 12V inputs are connected to the LT3060 regulator input via diode-OR so that either supply can power the system. The LTC4412 is an ideal diode controller that controls the P-channel MOSFET to reduce the voltage drop across the diode connected to the 3.6V supply.

The LTC2955-1 ON pin monitors the 12V input through the resistive divider R1 and R2. When the user plugs in the wall adapter, the 12V supply becomes present. The LTC2955-1 detects that the ON pin is high and pulls the EN (enable) pin high after a 32ms debounce time and turns on the voltage regulator, applying power to the system. This allows automatic system turn-on when the user plugs in the wall adapter. The system can also be turned on by pressing the pushbutton. The LTC2955 alerts the microprocessor that the 12V supply is present or absent by pulling the PGD output pin high or low, respectively.

PUSHBUTTON PIN ESD PROTECTION

The LTC2955 $\overline{PB}$ (pushbutton) input is protected to ESD levels of up to ±25kV HBM with respect to ground. This protection level exists during all modes of operation including power-down, power-up or when the supply is disconnected from the battery. When the pushbutton pin is hit with an ESD strike during operation, the part remains in its current logic state. The device does not reset or latch up and there is no need to cycle the supply to recover.

VERSATILE PUSHBUTTON INPUT

The LTC2955 requires only a few external components for most applications, as shown in Figure 1. Except for the logic-level pins used to interface with the microprocessor, most of the pins can withstand a maximum voltage of 36V, precluding the need for external supplies or resistor dividers. Designs remain flexible in the face of high input supply voltages, especially when no typical board-level supply (e.g., 5V) is available.

The $\overline{PB}$ input is designed to operate in harsh and noisy environments. The pin

Figure 2. LTC2955-1 waveforms

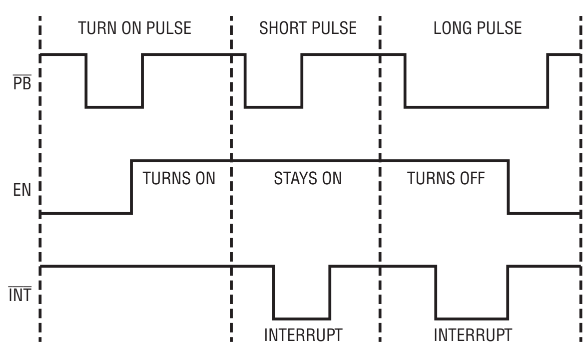
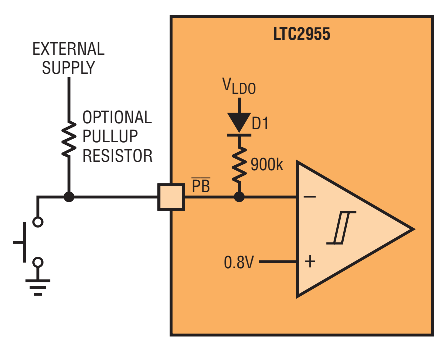


Figure 3. Pushbutton input



The $\overline{PB}$ input is designed to operate in harsh and noisy environments. The pin can withstand both positive and negative voltages up to ±36V. This allows for long cable runs between the pushbutton switch and the LTC2955, where even if the input rings, it will not cause damage to the part.

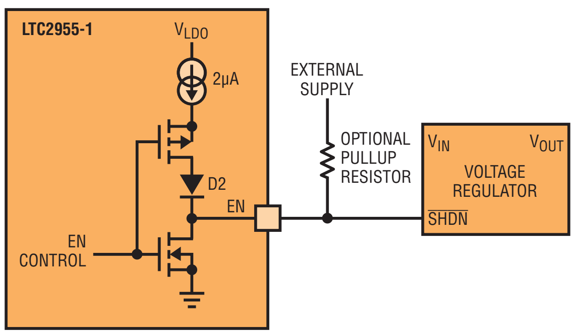


Figure 4. LTC2955-1 EN output

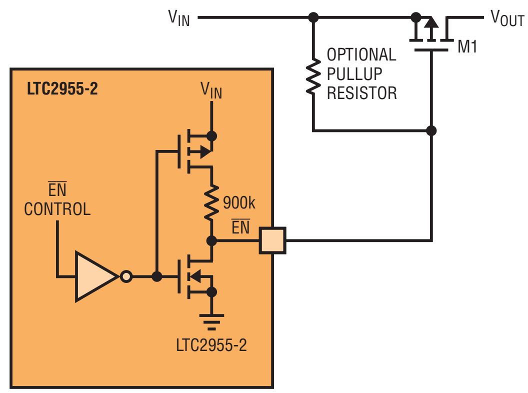


Figure 5. LTC2955-2 $\overline{EN}$ output

can withstand both positive and negative voltages up to ±36V. This allows for long cable runs between the pushbutton switch and the LTC2955, where even if the input rings, it will not cause damage to the part.

Figure 3 shows the pushbutton pin connection and internal circuitry. The internal 900k pull-up resistor allows connection of the pin directly to the pushbutton switch (with the other terminal grounded) without requiring an external pull-up resistor. If an external pull-up resistor is desired in applications where the pushbutton switch is leaky, this optional pull-up resistor can be tied to any voltage up to the 36V maximum as shown. The internal diode D1 blocks the external supply current from flowing into the device, preventing unnecessary current consumption.

VERSATILE ENABLE OUTPUT

Figure 4 shows the LTC2955-1 active high EN pin driving the SHUTDOWN input of a voltage regulator. The LTC2955-1 EN pin pulls high to 4.3V with an internal 2µA pull-up current in active mode. If a higher V_{OH} voltage is required, an optional external pull-up resistor can be added to pull this pin above 4.3V as shown. The diode D2 blocks the external supply current from flowing into the device. The EN pin can be pulled high up to 36V.

Figure 5 shows the LTC2955-2 active low $\overline{EN}$ pin driving a P-channel MOSFET to control the system supply. The LTC2955-2 $\overline{EN}$ pin pulls high through an internal 900k resistor during the inactive mode. In the active mode with the pin low, this 900k resistor is disconnected from the supply to minimize the quiescent current consumed by the 900k resistor. If a V_{OH} lower than the supply voltage is required, this pin can be tied to the external supply through an optional pull-up resistor as shown.

The ON input and SEL inputs can withstand voltages up to 36V. This makes it easy to connect these pins directly to the high voltage supply without requiring a resistive divider, and thus minimize the quiescent current consumed by the resistive divider.

CONCLUSION

The LTC2955 is a family of micropower (1.2µA), wide input voltage range (1.5V to 36V) pushbutton controllers. These parts lower system cost and preserve battery life by integrating a rugged pushbutton input, a flexible enable output and a simple microprocessor interface that provides intelligent power-up and power-down. The device is available in space-saving 10-lead 3mm × 2mm DFN and 8-lead ThinSOT packages. ■

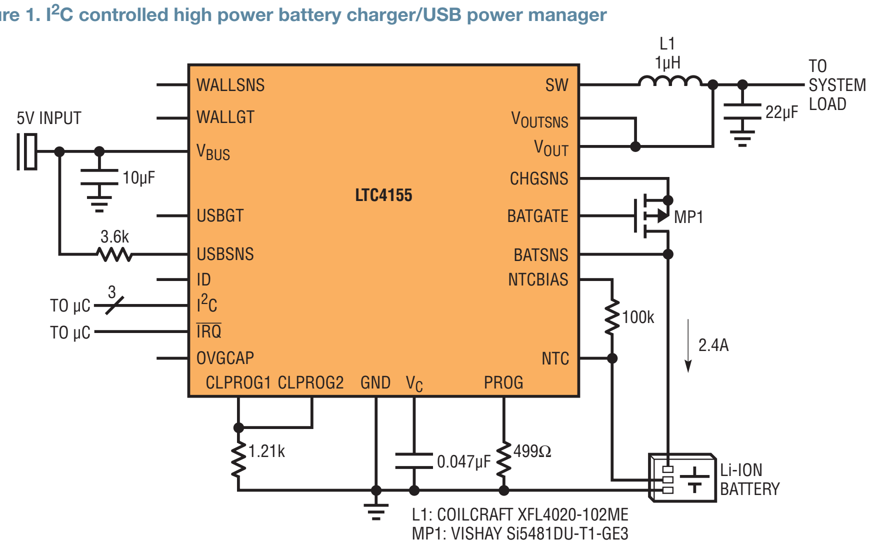
I²C-Controlled Li-Ion Power Management IC with Integrated Power Devices Charges High Capacity Batteries from Any 5V Source While Keeping Cool

David Simmons

Designers of portable electronics are challenged to create devices that do everything while running endlessly on a single battery charge. While it is impossible to fully meet this challenge, each successive generation of batteries at least comes closer to that goal. With devices now sporting large vibrant touch-sensitive displays, multicore CPU and graphics processors, and an assortment of wireless modems for high speed communications anywhere on the planet, high battery capacity is essential. Battery manufacturers have met the demand with light weight, compact cells with capacities to over 30 watt-hours.

While USB has become the dominant standard for device interconnect, synchronization and data exchange, its power delivery capabilities have not kept pace with battery demands. USB 2.0 allows a maximum 2.5W load, while USB 3.0 extends the limit to 4.5W. Even with perfect efficiency and all power going directly to the battery, a full charge cycle via USB would require overnight and then some. Though USB is not suitable as a primary power source for large capacity batteries, it still has great value as an opportunistic power source to charge when and where possible, and to prevent battery drain when the device is tethered to a traditional computer.

Figure 1. I²C controlled high power battery charger/USB power manager



THE BEST OF BOTH WORLDS

The LTC4155 is a monolithic switching battery charger that delivers 3.5A charge current efficiently in a compact PCB footprint. Figure 1 shows the required components in a typical application. The 2.25MHz switching frequency allows for a small inductor and bypass capacitors to minimize the overall PCB footprint.

High efficiency (Figure 2) even at multi-amp charge rates is critical not only to make optimal use of available input power, but also to control power dissipation inside the portable device. The combination of high power dissipation and marginal thermal performance in a tightly enclosed space can make a device with a less efficient charging solution too warm to hold comfortably. To help keep things cool, the LTC4155's integrated power switches feature an on-resistance well under 100mΩ.

While the LTC4155's power switches are sized to handle higher currents than available from USB, the LTC4155 remains fully USB compatible for opportunistic charging. Input current is automatically measured internally and limited to any of sixteen I²C user-selectable values. Of these settings, three correspond to guaranteed maximum limits of 100mA and 500mA for USB 2.0 and 900mA for USB 3.0. Automatic input current limiting can also be used with AC adapters or other sources by choosing any of the other current limit settings up to a maximum of 3A.

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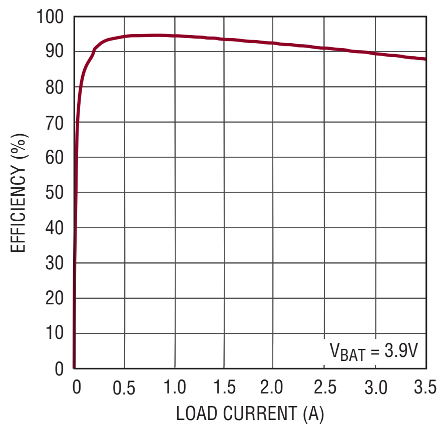

Figure 2. Switching regulator efficiency

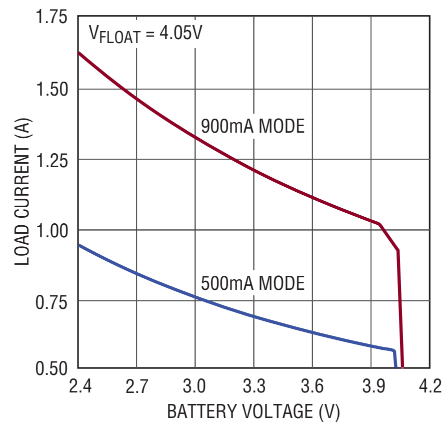

Figure 3. USB-compliant load current available before discharging battery

The LTC4155 supports a pin-programmable power-on default input current. For high power applications that do not require USB compatibility, a single resistor connected to the CLPROG1 pin programs a default power-on input current. This resistor is chosen to correspond to an initial current limit most appropriate to the particular application, intended power source capability, etc. After power-up, the input current limit can be modified under I²C control to any of the sixteen other available settings up to 3A.

For USB applications, the CLPROG1 and CLPROG2 pins can be connected together to program the LTC4155 to enforce USB current limit rules. The input current limit will default to 100mA upon application of external power. After successful enumeration with the USB host controller, the input current limit setting can be increased under I²C control to 500mA or 900mA as appropriate. Figure 3 shows the available current to the system load and battery charger. Note that the switching regulator output current is higher than the USB-limited input current. If the system detects that the power source is an AC adapter, dedicated USB charger, or other non-USB source, the input current limit setting can be increased under I²C control to any other setting up to 3A.

SEAMLESS HANDLING OF MULTIPLE INPUT CONNECTORS

The LTC4155 optionally accepts input from two power sources, solving the challenge of intelligently routing power from two different physical connectors to the product. When both input sources are connected simultaneously, the decision of which source to use is based on a user-programmable priority. As long as each input voltage is within the valid operating range, either one may be selected without concern for which voltage is higher than the other. This allows, for instance, a 4.5V/2A AC adapter to be favored over a 5V/500mA USB port. If the USB connection is removed and a 5V/3A AC adapter is connected to the same port, the input source priority can be modified over I²C to switch to the new higher power source.

The LTC4155 supports independent I²C programmable input current limits for each of its two power inputs. When the higher priority input source is disconnected, charging can continue uninterrupted, with automatic reduction to the new lower maximum input current limit. No immediate attention is required from the system microcontroller.

Depending on the external components selected for the input multiplexer, overvoltage and reverse voltage protection up to ±77V can be easily implemented if required for the application. Additionally, the LTC4155 can produce a USB On-The-Go 5V current-limited supply to the USB connector using no additional external components.

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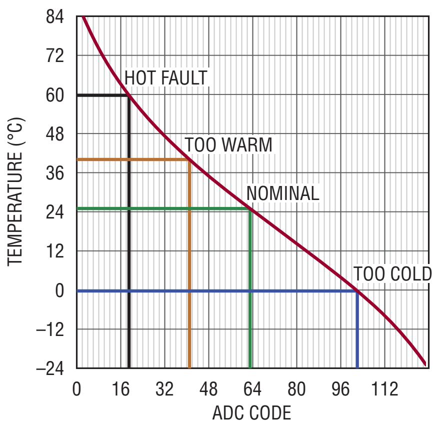


Figure 4. Transfer function of the LTC4155 battery temperature data converter, with the autonomous charger cut-out temperature thresholds highlighted.

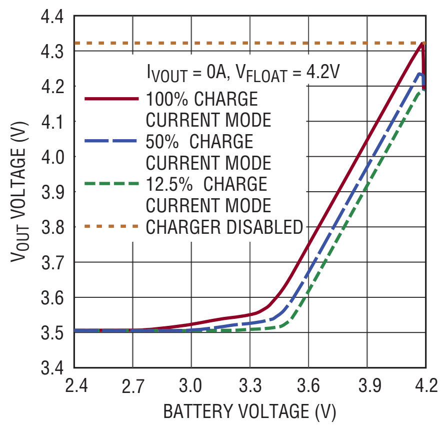


Figure 5. V_{OUT} voltage vs battery voltage

EXTENSIVE PROGRAMMABILITY AND TELEMETRY FOR ADVANCED CHARGING ALGORITHMS

The LTC4155 provides continuous I²C status reporting, allowing system software to have a complete view of the state of input power sources, fault conditions, battery charge cycle state, battery temperature, and several other parameters.

Key charge parameters can be changed under I²C control to implement customized charge algorithms. Unlike microcontroller-based or other programmable charge algorithms, all possible LTC4155 settings available under software I²C control are intrinsically safe for the battery. Float voltage can never be programmed above 4.2V or below 4.05V. Similarly, battery charge current is programmble to one of 15 possible settings, but software may never increase the limit above the level set by the designer—via a programming resistor chosen to match the battery capacity and maximum charge rate.

Continuous battery temperature data is available to system software to dynamically adapt system or charger behavior to manage extreme operational corners. For instance, float voltage and/or charge current may be reduced under I²C control to increase the battery safety margin at high ambient temperatures. Similarly, charge current or total system load current can be reduced in response to high temperature to reduce additional heating within the product enclosure.

Like all other aspects of battery charger programmability, the LTC4155 implements an intrinsically safe charging solution without (or despite) any software intervention. Battery charging is always paused when the cell temperature falls below 0°C or rises above 40°C. Additionally, a fault interrupt may be optionally generated whenever cell temperature rises above 60°C. Figure 4 shows the transfer function of the LTC4155 battery temperature data converter, with the autonomous charger cut-out temperature thresholds highlighted.

POWERPATH INSTANT-ON OPERATION

Dead batteries can be especially troublesome in a traditional power architecture where most of the portable product is connected directly to the battery. When the battery voltage is too low for the system to run, the product may appear to be unresponsive even minutes after being connected to a source of input power—possibly generating unnecessary support phone calls. The problem is further compounded when the battery capacity is very large relative to the available charging current (e.g., a USB-powered system with a large capacity battery).

Linear Technology PowerPath™ products such as the LTC4155 decouple the system power rail from the battery to enable instant-on operation and solve

The LTC4155 features automatic reduction of input current when the input voltage begins to drop to an unacceptable level. At high charge current levels, this can happen when connections are made through undersized wire, to an undersized adapter, through connectors with mild corrosion, or other conditions outside the usual design envelope.

the two most vexing problems caused by deeply discharged batteries.

The first problem is that charge current and system load become indistinguishable when the system power rail is connected directly to the battery. When the battery is deeply discharged, battery manufacturers recommend a greatly reduced initial charge current until the cell voltage reaches a safer level. This trickle charge current must be programmed to a safe level for the battery assuming minimum or no system load current.

Secondly, in a direct-connect battery system, if the system is operational during trickle charging, a significant portion of the charge current intended for the battery is shunted to the system rail. The resulting reduced battery charge current extends recovery time proportionately. A sizable system load can cause the net battery current to reverse, further discharging the battery. For the duration of this low battery condition, the portable system may not be able to respond to the user due to insufficient voltage on the system power supply rail. The duration of unresponsiveness is multiplied by at least a factor of 10 because of the reduced power available to the common-connected battery and system power rail.

The LTC4155 delivers 3.5V to the system rail when the battery is deeply discharged to enable instant start-up. As the battery voltage rises during the precharging phase, the LTC4155 seamlessly and automatically transitions to a higher efficiency mode to speed charging and minimize heat production. Figure 5 shows the voltage available to the system power rail as a function of battery voltage.

The LTC4155 battery charge current is programmed independently from the input current limit to decouple battery charge current constraints from input power constraints. The input current limit can be programmed based only on the limitations of the input supply. Similarly, the battery charge current can be programmed based only on the battery capacity. The LTC4155 always enforces input current limit and prioritizes power to the system load over battery charging if necessary.

ROBUST IN THE FACE OF NON-IDEAL SOURCES

The LTC4155 features automatic reduction of input current when the input voltage begins to drop to an unacceptable level. At high charge current levels, this can happen when connections are made through undersized wire, to an undersized adapter, through connectors with mild corrosion, or any number of conditions outside the usual design envelope.

Without intervention, the input voltage to the IC would continue to drop, eventually falling below the undervoltage lockout threshold. The IC would then shut down, allowing the input voltage to recover and restart the whole cycle. The LTC4155 makes the best of a bad situation. As the input voltage falls to 4.3V, the LTC4155 smoothly reduces its input power by whatever amount is necessary to prevent further decay of the input voltage. In this mode the current delivered to the system load and battery is less than the programmed amount, but more than would be available if the input voltage oscillation were allowed to continue. Additionally, the LTC4155 produces an I^2C status report and optional interrupt signal to alert the system that corrective or diagnostic action may need to be undertaken by the end user to restore maximum charge current capability.

CONCLUSION

The LTC4155 combines high current capability and efficiency with a small monolithic PCB footprint, ideal for portable devices with large lithium batteries where board space is at a premium, and heat and charge time are the enemy. USB-compatible input current limit settings further extend versatility to allow opportunistic charging from ubiquitous but lower power sources. Extensive telemetry allows for custom behavior based on changing environmental or application conditions without compromising autonomous battery safety. Uninterrupted power is delivered to the system rail despite common problems such as a deeply discharged battery or a resistive undersized input power cable. The LTC4155 is available in a 28-lead 4mm × 5mm QFN package. ■

15V, 2.5A Monolithic Buck-Boost DC/DC Converter with 95% Efficiency and Low Noise Operation

Eddy Wells

Power-hungry handheld devices and industrial instruments often require multicell or high capacity batteries to support their ever-increasing processing needs. A wide voltage range, high efficiency buck-boost DC/DC converter is the ideal solution for longer battery run times and handling multiple input sources. The LTC3112 is a 2.2V to 15V input capable 2.5A buck-boost converter. The extended voltage range allows conversion from a variety of power sources such as one, two or three Li-ion cells, lead acid batteries, supercapacitors, USB cables and wall adapters to output voltages programmed between 2.5V and 14V.

The LTC3112 features the latest generation buck-boost PWM control scheme, effectively eliminating jitter when crossing the barrier between buck and boost operation. Safeguards such as current limit, overvoltage protection, thermal shutdown, and short-circuit protection provide robust operation in harsh environments.

For demanding applications where component size or conversion efficiency is critical, the LTC3112's 750kHz default switching frequency can be synchronized between 300kHz and 1.5MHz. For designs where output current needs to be controlled or measured, an output current monitor pin is available. Selectable Burst Mode® operation extends the operating life when the battery-powered device is idle.

The LTC3112-based converter shown in Figure 1 can generate 30W of power with a 12V output. The solution footprint is less than 200mm², which cannot be matched by a controller-based buck-boost or complex dual-inductor SEPIC design at similar power levels. The main external components are limited to the input and output filter caps and the power inductor. The LTC3112 is offered in a thermally enhanced 16-lead 4mm × 5mm DFN or 20-lead TSSOP package.

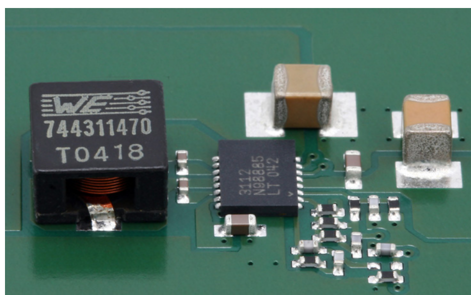


Figure 1. LTC3112 based 30W solution

OPERATION FROM MULTIPLE INPUT SOURCES

The LTC3112's wide operating range allows devices to be powered from multiple input sources. Figure 2 shows an application where the LTC4412 PowerPath controller (TSOT-23 package) provides a low loss selection between two input sources. The LTC4412 maintains a 20mV forward voltage across the selected P-channel MOSFET, keeping losses to a minimum. In this circuit, the LTC4412 automatically switches the greater of a single Li-ion cell or 12V wall adapter to the input of the LTC3112.

Efficiency curves based on the two input sources are given in Figure 3. Peak efficiencies of greater than 90% are achieved with either input. Selectable Burst Mode operation (dashed lines) with 50µA of typical sleep current extends high efficiency operation for more than two decades of load current.

A feedforward network (C_{FF}, R_{FF} of Figure 2) connected between the V_{IN} and FB pins provides improved transient response when the wall adapter voltage is applied. Feedforward values were selected by first measuring the voltage change in voltage at COMP as V_{IN} transitions from 3.6V to 12V. A 380mV change at COMP was observed, optimal values for V_{IN} and R_{FF} can now be calculated as follows:

$$C_{FF} = \frac{\Delta V_{COMP}}{\Delta V_{IN}} \bullet (C_{FB} + C_P) = 33pF$$

$$R_{FF} = \frac{R_{FB} \bullet C_{FB}}{C_{FF}} = 681k$$

V_{OUT} regulation is maintained within 300mV or 6% during the 15µs transition with a 47µF output cap (Figure 4) and 500mA load. A falling V_{IN} edge is about 10-times slower, resulting in an even smaller transient.

A 3.6V input, 5V output load step response using the compensation components of Figure 2 is shown in Figure 5. In this case, a 250mA to 1A load step results in only a 250mV transient on V_{OUT} with a 47µF output capacitor. Figures 4 and 5 illustrate how the LTC3112's loop

The LTC3112 features the latest generation buck-boost PWM control scheme, effectively eliminating jitter when crossing the barrier between buck and boost operation.

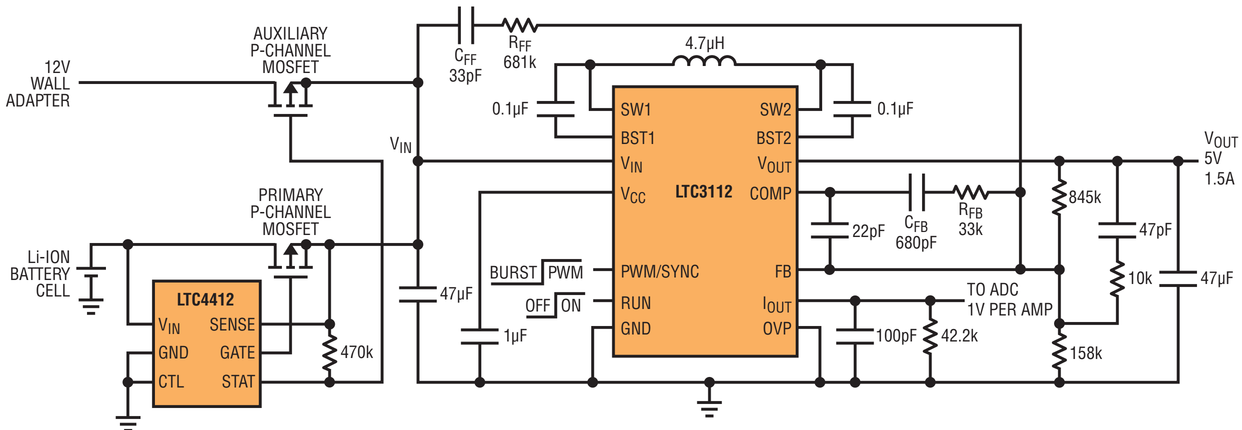


Figure 2. LTC4412 PowerPath controller selects highest voltage input to power the LTC3112 converter

response can be configured to provide excellent response to both input voltage and output current load steps.

5V BACKUP SUPPLY

To protect data, some data systems require a short period of time to backup data when the primary power source fails. A bank of supercapacitors is often used to provide the required burst of energy. The LTC3112's wide input voltage range and ability to buck or boost make it ideal for such an application, as shown in Figure 6.

In this circuit, a stack of supercapacitors totaling 22mF is charged to 15V while the primary power source is active. A lower ESR electrolytic or ceramic cap is placed in parallel to minimize V_{IN} ripple. The V_{CC} supply pin is back-driven from the 5V output in this example, allowing the LTC3112's gate drive circuits to operate efficiently with an input voltage from 15V down to 2.2V. Available energy at the input is given by:

$$E_{IN} = \frac{1}{2} \cdot C_{IN} \cdot \left[(V_{INITIAL})^2 - (V_{FINAL})^2\right]$$
$$= \frac{22mF}{2} \cdot \left[15^2 - 2.2^2\right]$$
$$= 2.4J$$

The results of the backup event are shown in Figure 7. A resistive network from V_{IN}, V_{OUT} and GND is used to drive

Figure 3. 5V output efficiency from a single Li-ion cell (3.6V) or wall plug (12V)

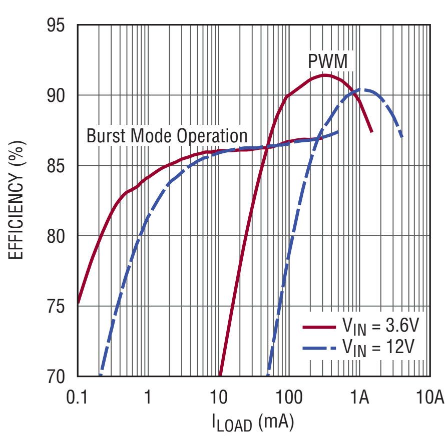


Figure 4. 3.6V to 12V input step and resulting V_{OUT} transient

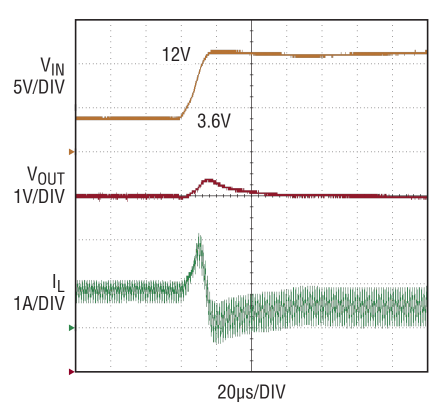
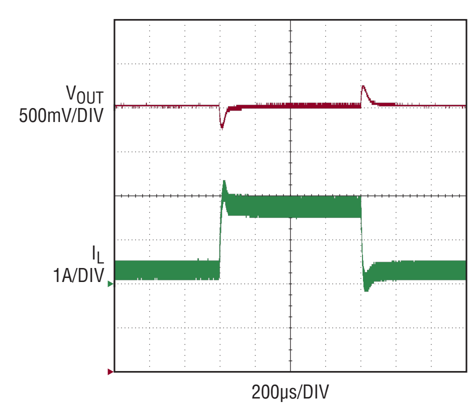


Figure 5. 250mA to 1A load step and resulting V_{OUT} transient



The LTC3112's ability to support large load currents make it ideal for handheld devices with increased processing power. Solution size and conversion efficiency benefit from 50mΩ N-channel MOSFET switches and thermally enhanced packages.

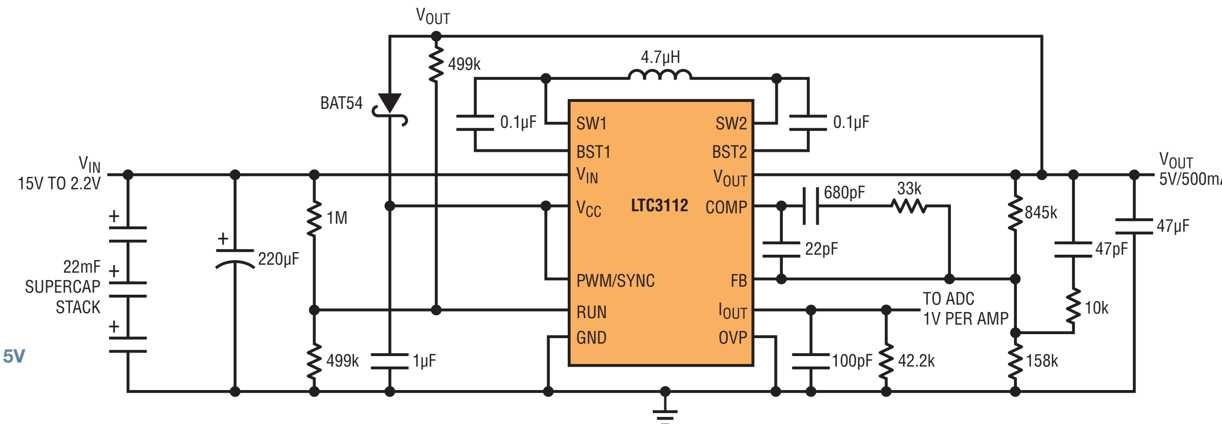


Figure 6. Backup Supply for 5V rail runs down to V_{IN} = 2.2V

the RUN pin to provide a clean shutdown of V_{OUT}. In this example, a constant 250mA load is drawn from the LTC3112 resulting in the V_{IN} capacitors maintaining regulation for 1.7 seconds, and an average conversion efficiency of 88% including the supercapacitor losses.

$$
\begin{aligned}
E_{OUT} &= I_{OUT} \bullet V_{OUT} \bullet t \\
&= 250\text{mA} \bullet 5\text{V} \bullet 1.7\text{s} \\
&= 2.1\text{J}
\end{aligned}
$$

The prior example can be easily scaled depending on the voltage rating of the supercapacitors and the energy required for backup. The I_{OUT} pin (Figure 6) can be monitored by an ADC to measure load current during the backup event. An important consideration in design is the maximum output current capability of the buck-boost converter. As shown in Figure 8, the LTC3112 is able to support up to 4A of load current when $V_{IN} >> V_{OUT}$. As the converter transitions from buck to boost mode, the maximum load current drops accordingly.

Figure 7. Supercap discharge performance during power supply backup event

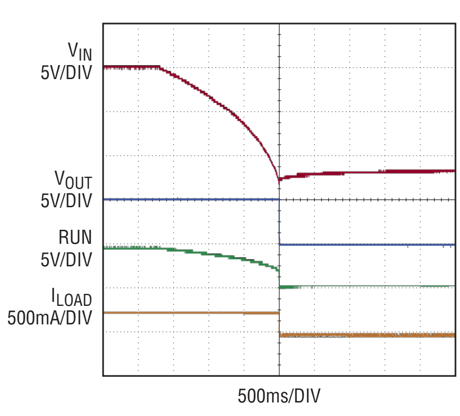
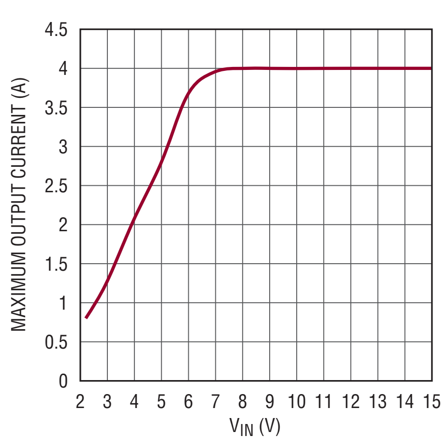


Figure 8. Maximum output current versus V_{IN} with V_{OUT} = 5V and V_{CC} back-fed



SUMMARY

The LTC3112 produces low noise buck-boost conversion in a range of applications requiring an extended input or output voltage range. The LTC3112's ability to support large load currents make it ideal for handheld devices with increased processing power. Solution size and conversion efficiency benefit from 50mΩ N-channel MOSFET switches and thermally enhanced packages. To provide longer run times, a low Burst Mode quiescent current extends high efficiency over several decades of load current. Features such as synchronized switching frequency, programmable output voltage, a load current monitor and external loop compensation allow the LTC3112 to be tailored for a specific application. ■

Novel Current-Sharing IC Balances Two Supplies with Ease

Pinkesh Sachdev

Failure is not an option. That's the likely motto for the architects of today's always-up electrical infrastructure—think telecommunications networks, the Internet and the electrical grid. The problem is that the bricks of this infrastructure, from the humble capacitor to the brainy blade-servers, have a limited lifetime usually ending at the most Murphy of moments. The usual workaround to the mortality problem is redundancy—backup systems ready to take over whenever a critical component fails.

For instance, high availability computer servers typically ship with two similar DC supplies feeding power to each individual board. Each supply is capable of taking on the entire load by itself, with the two supplies diode-ORed together via power diodes to create a single 1 + 1 redundant supply. That is, the higher voltage supply delivers power to the load, while the other supply idly stands by. If the active supply voltage drops or disappears, due to failure or removal, the once lower-voltage supply becomes the higher voltage supply, so it takes over the load. The diodes prevent back-feeding and cross-conduction between supplies while protecting the system from a supply failure.

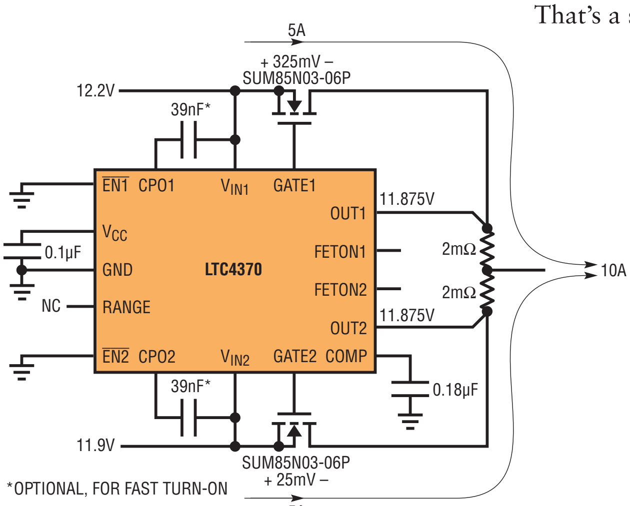


Figure 1. The LTC4370 balancing a 10A load current between two diode-ORed 12V supplies. Sharing is achieved by modulating the MOSFET voltage drops to offset the mismatch in the supply voltages.

The diode-OR is a simple winner-take-all system where the highest voltage supply sources the entire load current. The lower voltage supply remains idle until called into action. Although easy to implement, the 1 + 1 solution is inefficient, wasting resources that could be better used to improve overall operating efficiency and lifetime. It is far better for the supplies to share the load in tandem, offering several advantages:

- Supply lifetimes are extended if each takes on half the load, spreading the supply heat and reducing thermal stresses on supply components. A rule of thumb for the lifetime of electronics is that the failure rate of components halves for every 10°C fall in temperature. That's a significant dependability gain.
- Because the lower voltage supply is always operational, there is no surprise when transitioning to a backup supply that might have already silently failed—a possibility in a simple diode-OR system.
- It is possible in a load-sharing system to parallel smaller at-hand supplies to build a larger one.
- The recovery dynamics on supply failure are smoother and faster, since the supply changes are on the order of less and more, not off and on.
- A DC/DC converter formed by two supplies running at half capacity has better overall conversion efficiency than a single supply running near full capacity.

METHODS OF CURRENT SHARING

Connecting the outputs of multiple power supplies allows them to share a common load current. The division of the load current among the supplies depends on the individual supply output voltages and supply path resistances to the common load. This is known as droop sharing. To prevent back-feeding of a supply and to isolate the system from a faulting supply, diodes can be inserted in series with each supply. Of course, this added diode voltage drop affects the balance of the load sharing.

The LTC4370 introduces a new paradigm for current sharing, where the contributions from individual supplies are under full active control, but no share bus, with its extra wires, is required. Complete control is as easy to implement as a simple diode-OR droop sharing system, but the traditional passive diodes are replaced with adjustable diodes, with turn-on voltages that can be adjusted to achieve actively balanced current sharing.

Droop sharing is simple but sharing accuracy is poorly controlled, and the series diodes present a voltage and power loss. A more controlled way of current sharing is to monitor the supply current, compare it to an average current required from each supply, then adjust the supply voltage (through its trim pin or feedback network) until the supply current matches the required value. This method requires wires to every supply—a share bus—to signal the current contribution required from each. The current sharing loop compensation is customized to accommodate the power supply loop dynamics. Controlled current sharing requires careful design and access to all of the supplies—not possible in some systems.

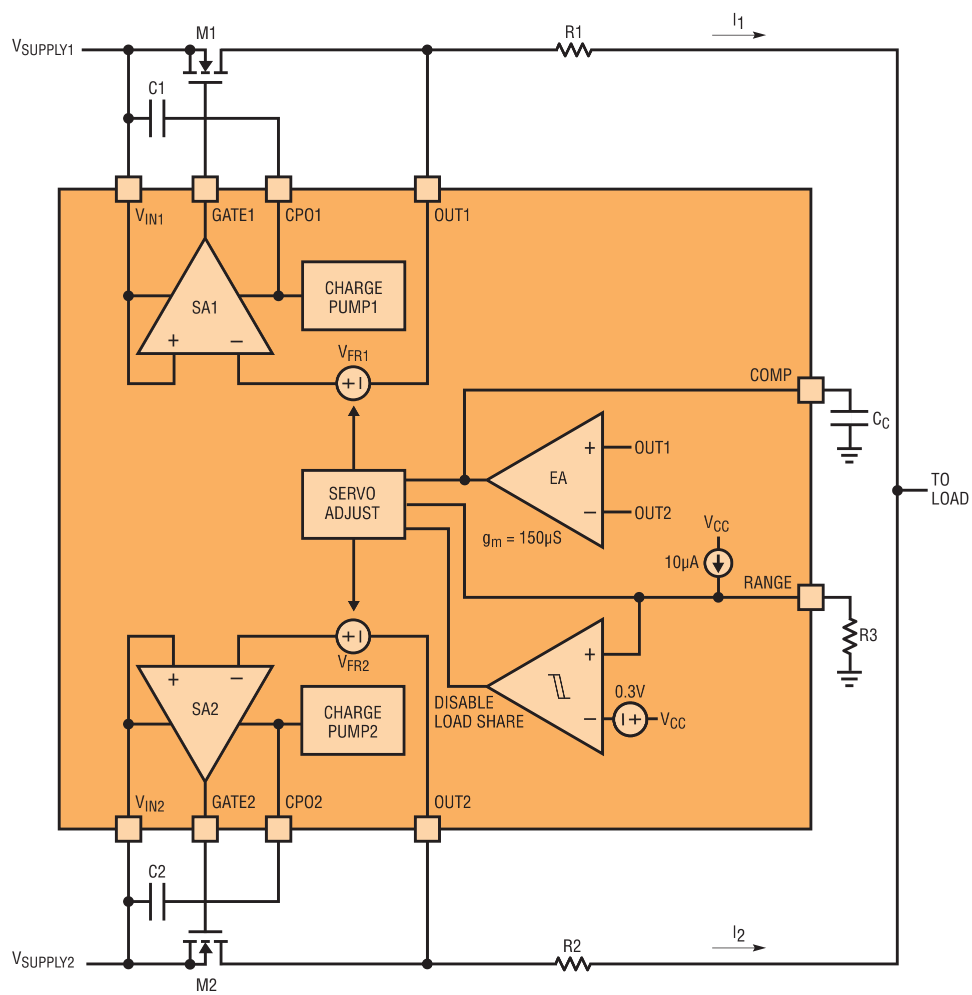
This article introduces a new method of current sharing, allowing active control of individual supply contributions, but with the simplicity of droop sharing. In this system, the diodes are replaced with adjustable diodes with turn-on voltages that can be adjusted to achieve balanced current sharing. This produces better sharing accuracy than droop sharing and the power spent in the adjustable diodes is the minimum required to achieve sharing, far less than that lost in a traditional diode. Because no sharing bus is required, it offers simpler supply-independent compensation and portable design. Supplies with difficult or no access to their trim pins and feedback networks are ideal for this technique.

THE CURRENT SHARING CONTROLLER

The LTC4370 features Linear Technology's proprietary adjustable-diode current sharing technique. It balances the load between two supplies using external N-channel MOSFETs that act as adjustable diodes whose turn-on voltage can be modulated to achieve balanced sharing. Figure 1 shows the LTC4370 sharing a 10A load between two 12V supplies

Figure 2 shows the device internals that affect load sharing. Error amplifier EA monitors the differential voltage between the OUT1 and OUT2 pins. It sets the forward regulation voltage V_{FR} of two servo amplifiers (SA1, SA2), one for each supply. The servo amplifier modulates the gate of the external MOSFET (hence its resistance) such that the forward drop across the MOSFET is equal to the forward regulation voltage. The error amplifier sets

Figure 2. Load-sharing-related internals of the LTC4370



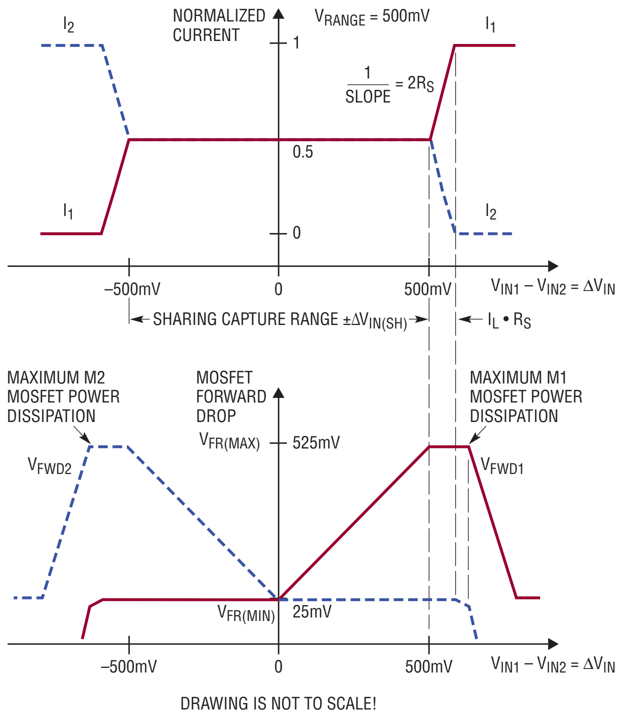


Figure 3. Current sharing characteristic of the LTC4370 method as the supply voltage difference varies.

the V_{FR} on the lower voltage supply to a minimum value of 25mV. The servo on the higher voltage supply is set to 25mV plus the difference in the two supply voltages. In this way both the OUT pin voltages are equalized. OUT1 = OUT2 implies $I_1 \bullet R_1 = I_2 \bullet R_2$. Hence, $I_1 = I_2$ if $R_1 = R_2$. A simple adjustment to different-valued sense resistors can be used to set up ratiometric sharing, i.e., $I_1/I_2 = R_2/R_1$. Note that the load voltage tracks 25mV below the lowest supply voltage.

The MOSFET in conjunction with the servo amplifier behaves like a diode whose turn-on voltage is the forward regulation voltage. The MOSFET is turned off when its forward drop falls below the regulation voltage. With increasing MOSFET current, the gate voltage rises to reduce the on-resistance to maintain the forward drop at V_{FR}. This happens until the gate voltage rails out at 12V above the source. Further rise in current increases the drop across the MOSFET linearly as $I_{FET} \bullet R_{DS(ON)}$.

Given the above, when the error amplifier sets the forward regulation voltage of the servo amplifier, it is functionally equivalent to adjusting the turn-on voltage of the (MOSFET-based) diode. The adjustment range runs from a minimum of 25mV to a maximum set by the RANGE pin (see "Design Considerations" below).

The controller can load share supplies from 0V to 18V. When both supplies are below 2.9V, an external supply in the range 2.9V to 6V is required at the V_{CC} pin to power the LTC4370. Under reverse current conditions the gate of the MOSFET is turned off within 1µs. The gate is also turned on in under a microsecond for a large forward drop. The fast turn-on, important for low voltage supplies, is achieved with a reservoir capacitor on the integrated charge pump output. It stores charge at device power-up and delivers 1.4A of gate pull-up current during a fast turn-on event.

The $\overline{EN1}$ and $\overline{EN2}$ pins can be used to turn off their respective MOSFETs. Note that current can still flow through the body diode of the MOSFET. When both channels are off, the device current consumption is reduced to 80µA per supply. The FETON outputs indicate whether the respective MOSFET is on or off.

THE CURRENT SHARING CHARACTERISTIC

Figure 3 shows the current sharing characteristic of the LTC4370, adjustable-diode method. There are two plots, both with the supply voltage difference, $\Delta V_{IN} = V_{IN1} - V_{IN2}$, on the x-axis. The top plot shows the two supply currents normalized to the load current; the lower shows the forward voltage drops, V_{FWDx}, across the MOSFETs. When both supply voltages are equal ($\Delta V_{IN} = 0V$), the supply currents are equal, and both forward voltages are at the minimum servo voltage of 25mV. As V_{IN1} increases above V_{IN2} (positive ΔV_{IN}), V_{FWD2} stays at 25mV, while V_{FWD1} increases exactly with ΔV_{IN} to maintain OUT1 = OUT2. This is turn keeps $I_1 = I_2 = 0.5I_{LOAD}$.

There is an upper limit to the adjustment on V_{FWD} set by the RANGE pin. For the example in Figure 3, that limit is 525mV, set by the RANGE pin at 500mV. Once V_{FWD1} hits this limit, sharing becomes imbalanced and any further rise in V_{IN1} pushes OUT1 above OUT2.

The break point is $V_{FR(MAX)} - V_{FR(MIN)}$, where more of the load current comes from the higher voltage supply. When $OUT1 - OUT2 = I_{LOAD} \bullet R_{SENSE}$, the entire load current transfers over to I_1. This is the operating point with the maximum power dissipation in MOSFET M1, since the entire load current flows through it with the maximum forward drop. For example, a 10A load current causes 5.3W (= 10A • 525mV) dissipated in the MOSFET. For any further rise in ΔV_{IN}, the controller ramps down the forward

The LTC4370's novel approach to load-sharing power supplies results in easy design, especially with supplies that don't lend themselves to on-the-fly tweaking. Inherent diode behavior protects supplies from reverse currents and the system from faulting supplies.

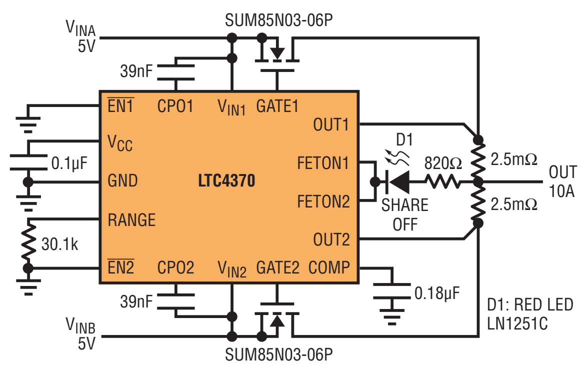


Figure 4. 5V diode-OR load share with status light. Red LED D1 lights up whenever any MOSFET is off, indicating a break in sharing.

drop across M1 to the minimum 25mV. This minimizes power dissipation in the MOSFET for large V_{IN} when the load current is not being shared. The behavior is symmetric for negative ΔV_{IN}.

The sharing capture range in this example is 500mV and is set by the RANGE pin voltage. With this range the controller can share supplies that have a tolerance of ±250mV. This translates to the following: ±7.5% tolerance on a 3.3V supply, ±5% on a 5V, and ±2% on a 12V supply.

DESIGN CONSIDERATIONS

These are some of the high level considerations for a load share design.

MOSFET Choice — Ideally the MOSFET's $R_{DS(ON)}$ should be small enough that the controller can servo the minimum forward regulation voltage of 25mV across the MOSFET with half of the load current flowing through it. A higher $R_{DS(ON)}$ prevents the controller from regulating 25mV. In this case, the unregulated drop is $0.5I_L \bullet R_{DS(ON)}$. As this drop rises, the sharing break point (now defined by $V_{FR(MAX)} - 0.5I_L \bullet R_{DS(ON)}$) occurs earlier, shrinking the capture range.

Since the MOSFET dissipates power, up to $I_L \bullet V_{FR(MAX)}$ as in Figure 3, its package and heat sink should be chosen appropriately. The only way to dissipate less power in the MOSFET is by using more accurate supplies or by forgoing sharing range.

RANGE Pin — The RANGE pin sets the sharing capture range of the application, which in turn depends on the accuracy of the supplies. For example, a 5V system with ±3% tolerance supplies would need a sharing range of 2 • 5V • 3% or 300mV (higher supply is 5.15V while lower is 4.85V). The RANGE pin has a precise internal pull-up current of 10µA. Placing a 30.1k resistor on the RANGE pin sets its voltage to 301mV and now the controller can compensate for the 300mV supply difference (see Figure 4).

Leaving the RANGE pin open (as shown in Figure 1) gives the maximum possible sharing range of 600mV. But when servo voltages approach the diode voltage, currents can flow through the body diode of the MOSFET causing loss of sharing. Connecting RANGE to V_{CC} disables load share to transform the device into a dual ideal-diode controller.

Compensation — The load share loop is compensated by a single capacitor from the COMP pin to ground. This capacitor must be 50× the input (gate) capacitance of the MOSFET, C_{ISS}. If fast gate turn-on is not being used (CPO capacitors absent) then the capacitor can be just 10× C_{ISS}.

Sense Resistors — The sense resistors determine the load sharing accuracy. Accuracy improves as resistor voltage drops increase. The maximum error amplifier offset is 2mV. Therefore, a 25mV sense resistor drop yields a 4% sharing error. The resistance can be lowered if power dissipation is more important than accuracy.

CONCLUSION

Balancing load currents between supplies is a historically difficult problem, conjuring visions of juggling on a tightrope. When power modules or bricks don't offer built-in support, some designers will spend significant time designing a well-controlled system (and redesigning it whenever the supply type changes); others will settle for crude resistance-based droop sharing.

The LTC4370 takes a completely different approach to load-sharing supplies than any other controller. It eases design, especially with supplies that don't lend themselves to on-the-fly tweaking, and it can be ported to various types of supplies. Inherent diode behavior protects supplies from reverse currents and the system from faulting supplies. The LTC4370 provides a simple, elegant and compact solution to a complicated problem. ■

What's New with LTspice IV?

Gabino Alonso

New Video: Evaluating Electrical Quantities

NEW HOW-TO VIDEOS

Evaluating Electrical Quantities
video.linear.com/115

The LTspice IV waveform viewer provides visual analysis of circuit performance and performs basic measurements. Sometimes, though, you need a more in depth numerical analysis of circuit performance. For this, .MEASURE statements allow you to perform direct measurements such as:

- rise, fall and time delay
- average, RMS, min, max and peak-to-peak
- find X when Y occurs
- derivative and integral evaluations

This new video shows an example of how to use .MEASURE statements for numerical analysis.

What is LTspice IV?

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

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

NEW DEMO CIRCUITS

µModule Regulators

- **LTM8047:** 725V DC isolated low noise µModule regulator (3.1–29V to 5V at 280mA) www.linear.com/LTM8047
- **LTM8048:** 725V DC isolated low noise µModule regulator with LDO post regulator (3.5V–30V to 5V at 120mA & 5.7V at 120mA)

Monolithic Switching Regulators

- **LTC3103:** Solar-powered buck supply with Li battery backup (3.2V–15V to 2.2V at 300mA) www.linear.com/LTC3103
- **LTC3115-1:** 12V 1MHz buck-boost regulator with undervoltage lockout (10V–40V to 12V at 1.4A) www.linear.com/LTC3115-1

Switching Regulator Controllers

- **LT3798:** Isolated no opto-coupler flyback controller with active power factor correction (PFC) ($90V_{AC}$–$265V_{AC}$ to 24V at 2A) www.linear.com/LTC3798
- **LT8582:** 1.5MHz +5V to ±12V dual converter (5V to ±12V at 550mA) www.linear.com/LT8582
- **LTC3765/LTC3766:** Active clamp forward converter (18V–72V to 12V at 12.5A) www.linear.com/LTC3765, www.linear.com/LTC3766
- **LTC3838:** Dual output, 350kHz, step-down converter with differential DCR output sensing (4.5V–38V to 1.2V at 15A & 1.5V & 15A) www.linear.com/LTC3838
- **LTC3839:** 2MHz, 2-phase, step-down converter with differential R_{SENSE} sensing (4.5-14V to 3.3V at 25A) www.linear.com/LTC3839
- **LTC3866:** High efficiency, 1.5V/30A step-down converter with very low DCR Sensing (4.5V–20V to 1.5V at 30A) www.linear.com/LTC3866

LED Drivers

- **LT3799-1:** Offline isolated flyback LED controller with active power factor correction (PFC) ($277V_{AC}$ to 3A/36V) www.linear.com/LTC3799-1

MACRO MODELS

µModule Regulators

- **LTM8026:** 36V input, 5A CVCC step-down µModule regulator www.linear.com/LTM8026
- **LTM8029:** 36V input, 600mA step-down µModule converter with 5µA quiescent current www.linear.com/LTM8029

Monolithic Switching Regulators

- **LT3692A:** Monolithic dual tracking 3.5A step-down switching regulator www.linear.com/LT3692A
- **LT3973:** 42V, 750mA step-down regulator with 2.5µA quiescent current and integrated diodes www.linear.com/LT3973
- **LT3988:** Dual 60V monolithic 1A step-down switching regulator www.linear.com/LT3988
- **LT3992:** Monolithic dual tracking 3A step-down switching regulator www.linear.com/LT3992
- **LT8610:** 42V, 2.5A synchronous step-down regulator with 2.5µA quiescent current www.linear.com/LT8610
- **LT8611:** 42V, 2.5A synchronous step-down regulator with current sense and 2.5µA quiescent current www.linear.com/LT8611

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

- **LTC3600:** 15V, 1.5A synchronous rail-to-rail single resistor step-down regulator www.linear.com/LTC3600
- **LTC3630:** High efficiency, 65V 500mA synchronous step-down converter www.linear.com/LTC3630

Switching Regulator Controllers

- **LT3798:** Isolated no opto-coupler flyback controller with active power factor correction (PFC) www.linear.com/LT3798
- **LTC3861:** Dual, multiphase step-down voltage mode DC/DC controller with accurate current sharing www.linear.com/LTC3861

LED Drivers

- **LT3791:** 60V 4-switch synchronous buck-boost LED driver controller www.linear.com/LT3791
- **LT3796:** 100V constant-current and constant-voltage controller with dual current sense www.linear.com/LT3796

Inductorless Converters

- **LTC3260:** Low noise dual supply inverting charge pump www.linear.com/LTC3260
- **LTC3261:** High voltage, low quiescent current inverting charge pump www.linear.com/LTC3261

Differential Amplifiers & ADC Drivers

- **LTC6362:** Precision, low power rail-to-rail input/output differential op amp/ SAR ADC driver www.linear.com/LTC6362

System Supervisor, Monitor and Control

- **LT4363-2:** High voltage surge stopper with current limit www.linear.com/LT4363
- **LTC2960:** 36V Nano-current two input voltage monitor www.linear.com/LTC2960
- **LTC2955-1/-2:** Pushbutton on/off controller with automatic turn-on www.linear.com/LTC2955 ■

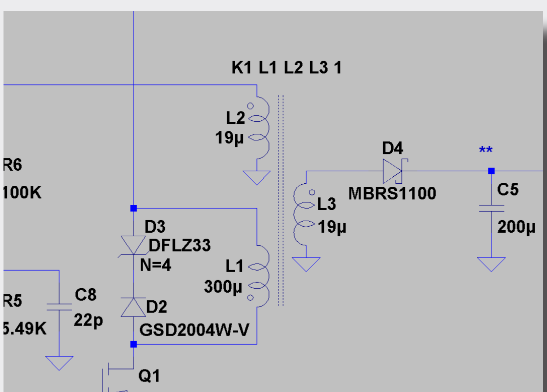
Power User Tip

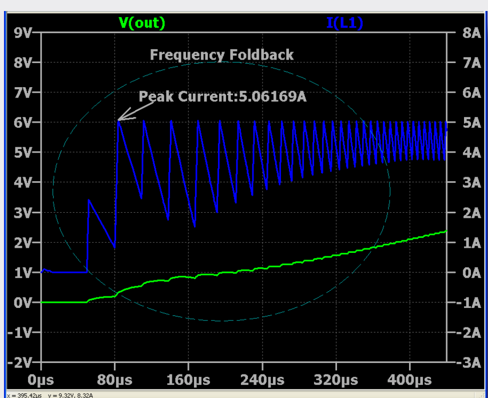
ANNOTATING SCHEMATIC AND WAVEFORM PLOTS

Adding informative comments to a schematic using text is very useful. However, there are times when adding a line, rectangle, circle or arc to a schematic can better illustrate a circuit. A classic example is highlighting a transformer core using two lines. These graphical annotations are available under Draw in the Edit menu. If you do not want these graphical annotations to snap to the grid, you can hold down the Ctrl key while positioning.

Waveform plots can be annotated with text, arrows, lines, boxes and circles. These annotations are effective for illustrating a particular result in your plot to a colleague. Plot annotations along with Move and Drag can be found under Notes & Annotations under Plot Setting menu. Note that if you annotate a plot you will need to save your annotations via a Plot Setting file (available under Plot Setting menu); otherwise they will not be saved.

Happy simulations!





Examples of graphical annotations added to a schematic and a waveform plot.

24V, 15A Step-Down Regulator in Sub-1mm Height Package Pushes Monolithic Performance Limits

Stephanie Dai

Monolithic switching regulators and switching controllers together dominate the DC/DC converter market. Generally, there is little overlap in their respective applications. Controller-based solutions are favored for high performance, higher power applications where minimal power loss and top thermal performance are priorities. In contrast, monolithic regulators are favored in lower power applications where compact size is the main requirement. Controllers typically offer more features than monolithic solutions, but are at a significant solution-size disadvantage. The light footprint of monolithic regulators usually comes at a cost of features and increased power loss, and their reliance on integrated MOSFETs places practical limits on power.

The LTC3613 monolithic regulator blurs the line drawn between applications for controllers and monolithic regulators by combining a high performance fully featured controller with onboard low $R_{DS(ON)}$ MOSFETs.

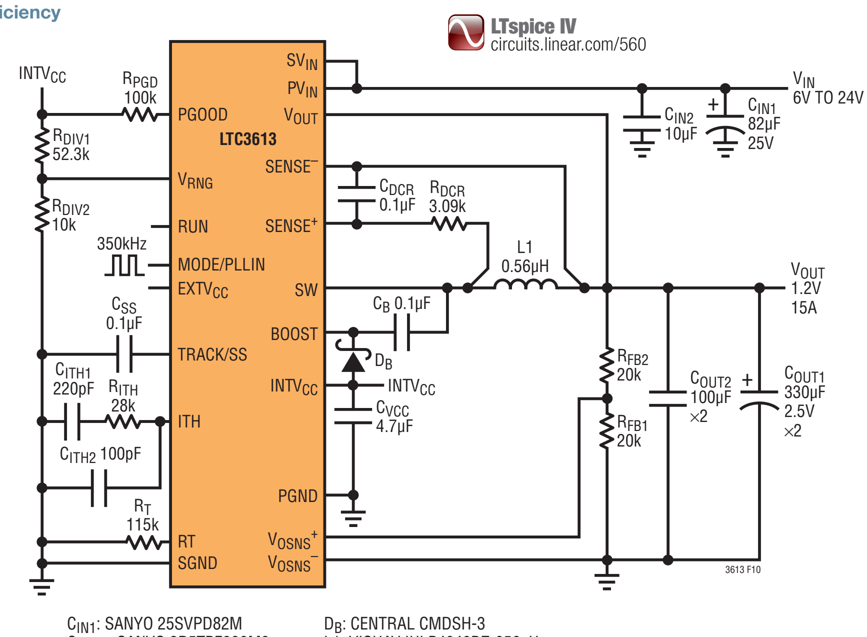
FEATURES

The LTC3613 can accept an input voltage between 4.5V to 24V and supports output voltages between 0.6V to 5.5V. The onboard top and bottom MOSFETs feature low $R_{DS(ON)}$, around 7mΩ and 5mΩ, respectively, keeping power dissipation low and allowing the LTC3613 to deliver up to 15A of adjustable load current.

The LTC3613 features true remote differential output voltage sensing. This allows for accurate regulation of the output with maximum load currents and shared ground planes. This feature is critical for low output voltage applications, where even small voltage offsets caused by parasitic IR drops on board traces can cost several percentage points in regulation accuracy. Remote differential output sensing and the LTC3613's accurate internal reference combine to offer excellent output regulation accuracy over line, load and temperature: ±0.25% at 25°C, ±0.67% from 0°C to 85°C and 1% from –40°C to 125°C.

The LTC3613 has a low minimum on-time of 60ns, allowing for high step-down ratios at high switching frequencies. Because of its sophisticated controlled on-time, valley current mode architecture, the on-time is controlled so that the switching frequency is constant over steady state conditions under line and load. It also allows the LTC3613 to recover from a large load step in only a few short cycles. This architecture yields well balanced current sharing among multiple LTC3613s, which can be easily paralleled for high power applications. It also includes a phase-lock loop (PLL) for synchronization to an

Figure 1. 24V input to 1.2V output using inductor DCR sensing to minimize solution size and cost and to maximize efficiency



	LTC3608	LTC3609	LTC3610	LTC3611	LTC3613
$PV_{IN(MAX)}$	18V	32V	24V	32V	24V
$I_{LOAD(MAX)}$	8A	6A	12A	10A	15A
Frequency Sync					✓
Precise Differential Output Sensing	±1%	±1%	±1%	±1%	±0.67%
Accurate Current Sensing	Bottom FET $R_{DS(ON)}$	Bottom FET $R_{DS(ON)}$	Bottom FET $R_{DS(ON)}$	Bottom FET $R_{DS(ON)}$	R_{SENSE} or DCR sensing
MOSFET $R_{DS(ON)}$ Top/Bottom	10mΩ/8mΩ	18mΩ/13mΩ	12mΩ/6.5mΩ	15mΩ/9mΩ	7.5mΩ/5.5mΩ
Package	7mm × 8mm × 0.9mm 64-pin	7mm × 8mm × 0.9mm 64-pin	9mm × 9mm × 0.9mm 52-pin	9mm × 9mm × 0.9mm 52-pin	7mm × 9mm × 0.9mm 56-pin

Table 1. High power monolithic regulator family

external clock, especially beneficial for high current, low output voltage applications where interleaving of paralleled phases can minimize output voltage ripple.

The LTC3613 includes several safety and protection features including overvoltage protection and current-limit foldback. If the output exceeds 7.5% of the programmed value, then it is considered an overvoltage (OV) condition, the top MOSFET is immediately turned off and the bottom MOSFET is turned on indefinitely until the OV condition is cleared. A power good output monitor is also available which flags if the part is outside a ±7.5% window of the 0.6V reference voltage. In the case of an output short circuit, if the output fails by more than 50%, then the maximum sense voltage is reduced to about one-fourth of its full value, limiting the inductor current level to one-fourth of its maximum value.

The LTC3613 offers precise control of the output during start-up and shutdown sequencing though its output voltage tracking and soft-start features. An external V_{CC} input pin is also available, allowing for bypassing of its internal LDO for an efficiency benefit in high power applications.

The LTC3613 can be configured to sense the inductor current through a series sense resistor, R_{SENSE}, or via an inductor DCR sensing network. The tradeoffs between the two current sensing schemes are largely matters of cost, power consumption and accuracy. DCR sensing owes its increasing popularity to its lower expense and power loss compared to a sense resistor scheme. Even so, the tight tolerances of current-sensing resistors provide the most accurate current limit.

Figure 1 shows a typical application of the LTC3613, configured for DCR sensing in a high step-down solution, 24V to 1.2V, and synchronized to a 350kHz external clock. Figure 2 shows the efficiency and Figure 3 shows transient performance.

Figure 2. Efficiency of the regulator in Figure 1

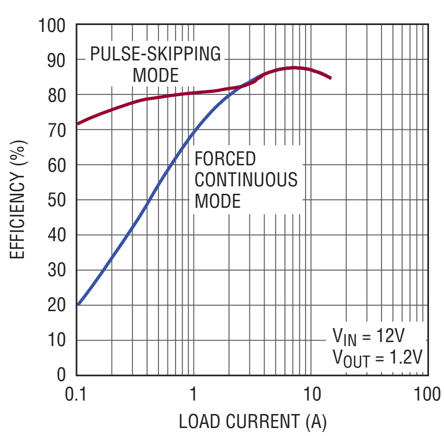
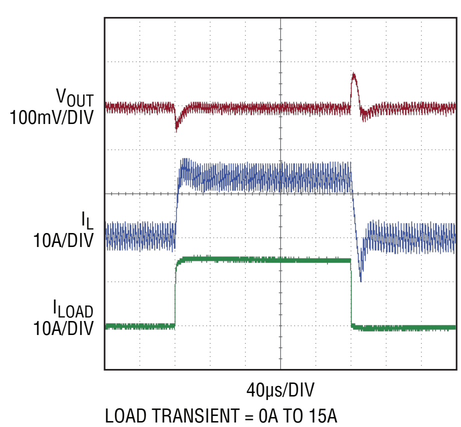


Figure 3. Load transient response of the circuit in Figure 1



CONCLUSION

The LTC3613 offers far more design flexibility than a typical monolithic switching regulator by including a variety of user-programmable features such as soft-start, programmable frequency, external clock synchronization, adjustable current limit and selectable light load operating modes. Its critical safety features such as overvoltage protection and programmable current limit with foldback current limiting further improve the robustness of the part. An external V_{CC} input is provided for high power applications. Its compact solution size, extensive feature set and high performance capabilities extend its range of use compared to traditional monolithics, making it suitable for an expanding range of applications. ■

Step-Down Converter Delivers 25A at 12V Output from Inputs Up to 60V

Victor Khasiev

The LTC3890 (dual outputs) and LTC3891 (single output) step-down DC/DC controllers directly accept inputs from 4V to 60V. This wide input range covers input voltages for single or double battery automotive environments, eliminating the need for snubbers and voltage suppression circuitry typically required to protect ICs during load dumps. This range also encompasses 48V telecom applications. If no galvanic isolation is required between the input and output voltages, the LTC3890 and LTC3891 can replace expensive and bulky transformer-based converters. Compared to a transformer-based solution, an LTC3890 or LTC3891 step-down converter increases efficiency, reduces power loss in the supply lines, simplifies layout and significantly reduces the bill of materials.

HIGH EFFICIENCY 2-PHASE CONVERTER PRODUCES 12V AT 25A

Figure 1 shows the LTC3890 in a 2-phase single output step-down converter configuration that delivers 25A at 12V, which can be scaled up to 75A by adding more LTC3890 ICs to increase the number of power phases. For lower output current, the single-phase LTC3891 can be used. Implementing a 2-phase converter simply requires tying together the independent channel pins of the LTC3890, namely, FB1 and FB2, TRACK/SS1 and TRACK/SS2, RUN1 and RUN2, ITH1 and ITH2.

Although the ITH pins are connected together, each is terminated to a separate 47pF capacitor to compensate

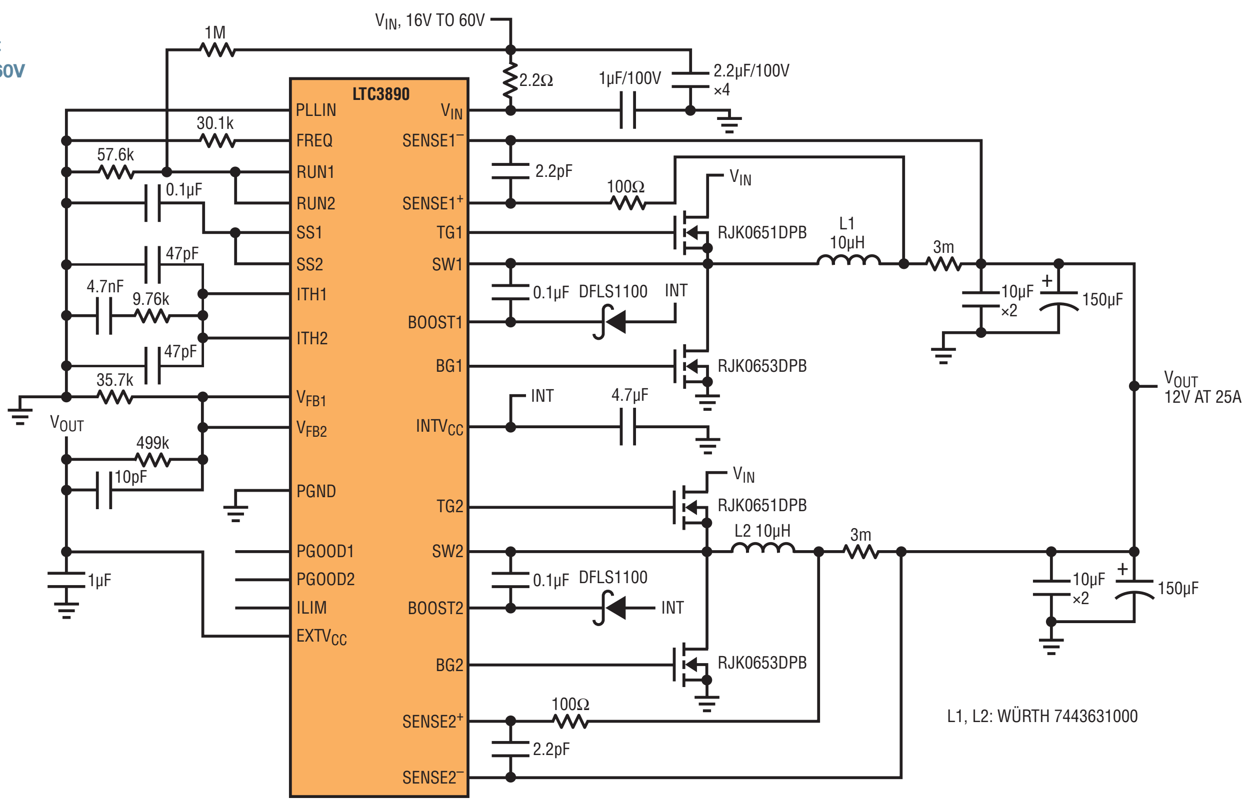


Figure 1. High efficiency converter produces 25A at $12V_{OUT}$ from inputs up to 60V

The LTC3890 dual output, synchronous step-down converter can be easily configured as a single output, dual phase converter for high input voltage, high output current automotive and telecom applications.

for possible noise from interconnecting traces. A relatively low switching frequency, around 150kHz, and a relatively high phase inductance of 10µH are used to reduce switching losses at high input voltages. The output voltage is fed to the EXTVCC pin to reduce losses associated with biasing the chip and internal gate drivers at high input voltages.

CIRCUIT PERFORMANCE

Efficiency is shown in Figure 2, measured without cooling air flow. Efficiency peaks close to 98% in the middle of the load range and declines to 96% at the 25A maximum load. Figure 3 shows the average input current vs input voltage at no load in Burst Mode operation. The value of this current is below 0.5mA. Figure 4 shows a thermal map of the board with no air flow present at V_{IN} = 20V and V_{OUT} = 12V at 25A (300W).

COMPONENT SELECTION

Two values define selection of the inductor: RMS current (IRMS) and saturation current (IPK):

$$I_{RMS} = \sqrt{(I_{PH})^2 + \frac{\Delta I^2}{12}}$$

$$\Delta I = \frac{(V_{IN} - V_{OUT}) \bullet D}{L \bullet f}$$

$$D = \frac{V_{OUT}}{V_{IN}}$$

$$I_{PH} = k \bullet \frac{I_{OUT}}{2}$$

$$I_{PK} = I_{PH} + \frac{\Delta I}{2}$$

where f is the switching frequency and k is a coefficient defined by the current imbalance between the phases. For converters based on the LTC3890, k = 1.08, assuming current sense resistors with a 1% tolerance.

Selection of power MOSFETs and input/output capacitors is described in detail in the LTC3890 data sheet. It is important to note that the typical internal V_{CC} voltage and, consequently, the MOSFET gate voltage is 5.1V. This means that logic level MOSFETs must be used in the design.

CONCLUSION

The LTC3890 dual output, synchronous step-down converter can be easily configured as a single output, dual phase converter for high input voltage, high output current automotive and telecom applications. ■

Figure 2. Efficiency at V_{IN} = 20V, 36V and 50V

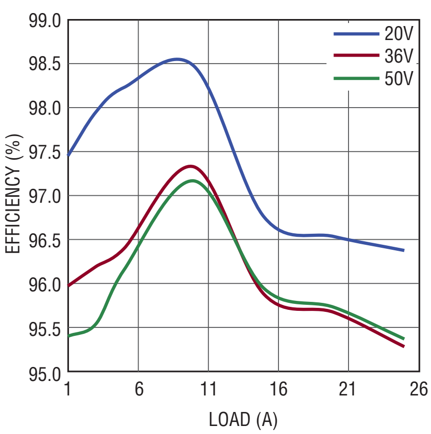


Figure 3. Average input current vs input voltage at no load. V_{OUT} is 12V.

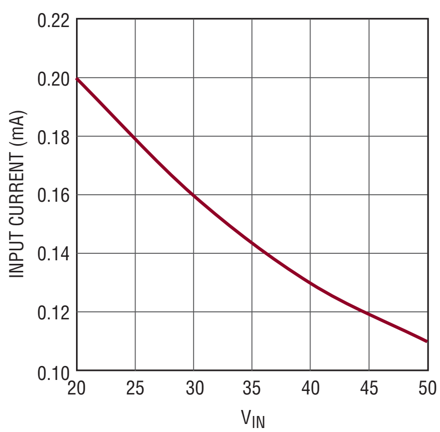
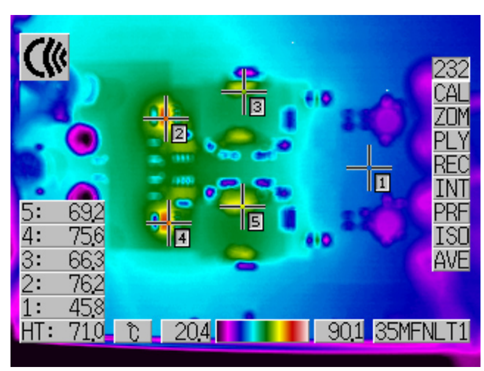


Figure 4. Temperature hot spots with no air flow



1.5A Rail-to-Rail Output Synchronous Step-Down Regulator Adjusts with a Single Resistor

Jeff Zhang

The LTC3600 features a wide output range with tight regulation over the entire range. In most regulators, the lowest output voltage is limited to the reference voltage. The LTC3600, however, uses a novel regulation scheme with a precision 50μA current source and a voltage follower, creating an adjustable output from "0V" to close to V_{IN}. It also features constant loop gain, independent of the output voltage, giving excellent regulation at any output and allowing multiple regulators to be paralleled for high output currents.

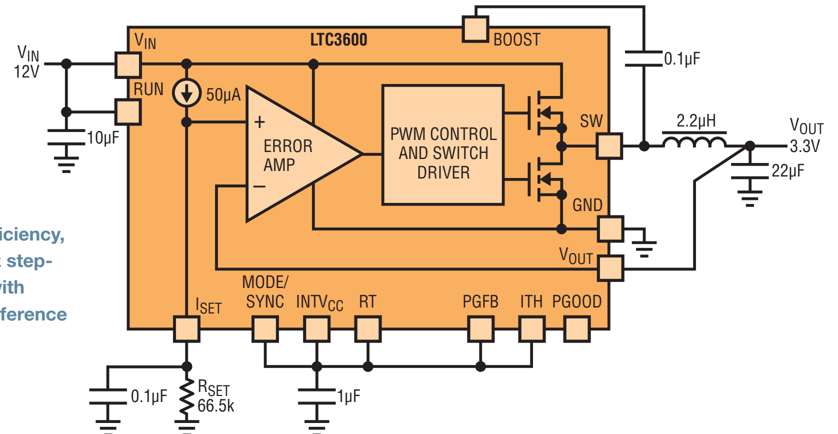


Figure 1. High efficiency, 12V to 3.3V 1MHz step-down regulator with programmable reference

OPERATION

The LTC3600 is a current mode monolithic step-down buck regulator with excellent line and load transient responses. The 200kHz to 4MHz operating frequency can be set by a resistor or synchronized to an external clock. The LTC3600 internally generates an accurate 50μA current source, allowing the use of a single external resistor to program the reference voltage from 0V to 0.5V below V_{IN}. As shown in Figure 1, the output feeds directly back to the error amplifier with unity gain. The output equals the reference voltage at the I_{SET} pin. A capacitor can be paralleled with R_{SET} for soft-start or to improve noise while an external voltage applied to the I_{SET} pin is tracked by the output.

Figure 2. 0A to 1.5A load step response of the Figure 1 schematic

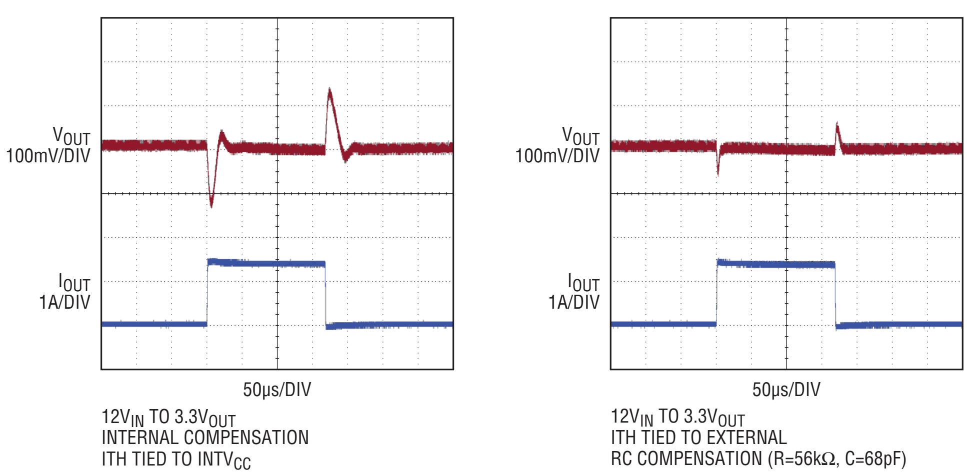
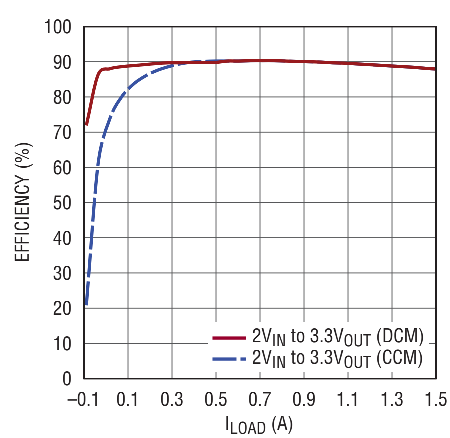


Figure 3. Efficiency of 12V input to 3.3V output regulator in CCM and DCM mode



Internal loop compensation stabilizes the output voltage in most applications, though the design can be customized with external RC components. The device also features a power good output, adjustable soft-start or voltage tracking and selectable continuous/discontinuous mode operation. These features, combined with less than 1μA supply current in shutdown, V_{IN} overvoltage protection and output overcurrent protection, make this regulator suitable for a wide range of power applications.

APPLICATIONS

Figure 1 shows the complete LTC3600 schematic in a typical application that generates a 3.3V output voltage from 12V input. Figure 2 shows the load step transient response using internal compensation and with external compensation. Figure 3 shows the efficiency in CCM and DCM modes. Furthermore, the LTC3600 can be easily configured to be a current source, as shown in Figure 4. By changing the R_{SET} resistance from 0Ω to 3kΩ, the output current can be programmed from 0A to 1.5A.

CONCLUSION

The LTC3600 uses an accurate internal current source to generate a programmable reference, expanding the range of output voltages. This unique feature gives the LTC3600 great flexibility, making it possible to dynamically change the output voltage, generate current sources, and parallel regulators for applications that would be difficult to implement using a standard DC/DC regulator configuration. ■

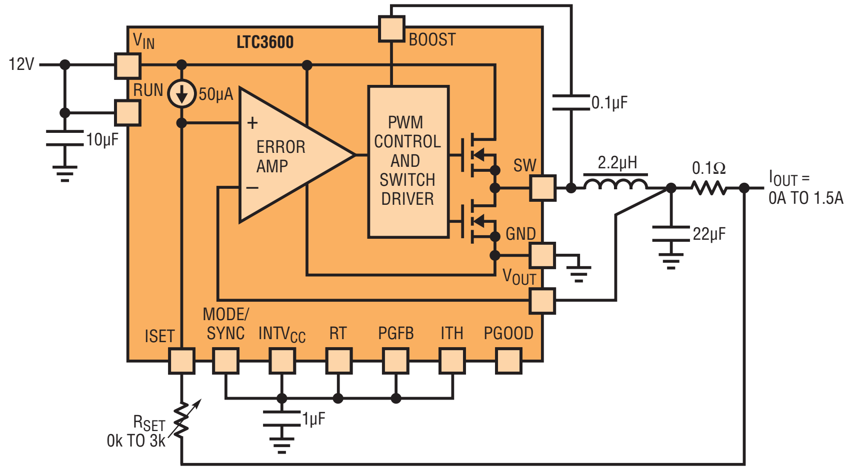
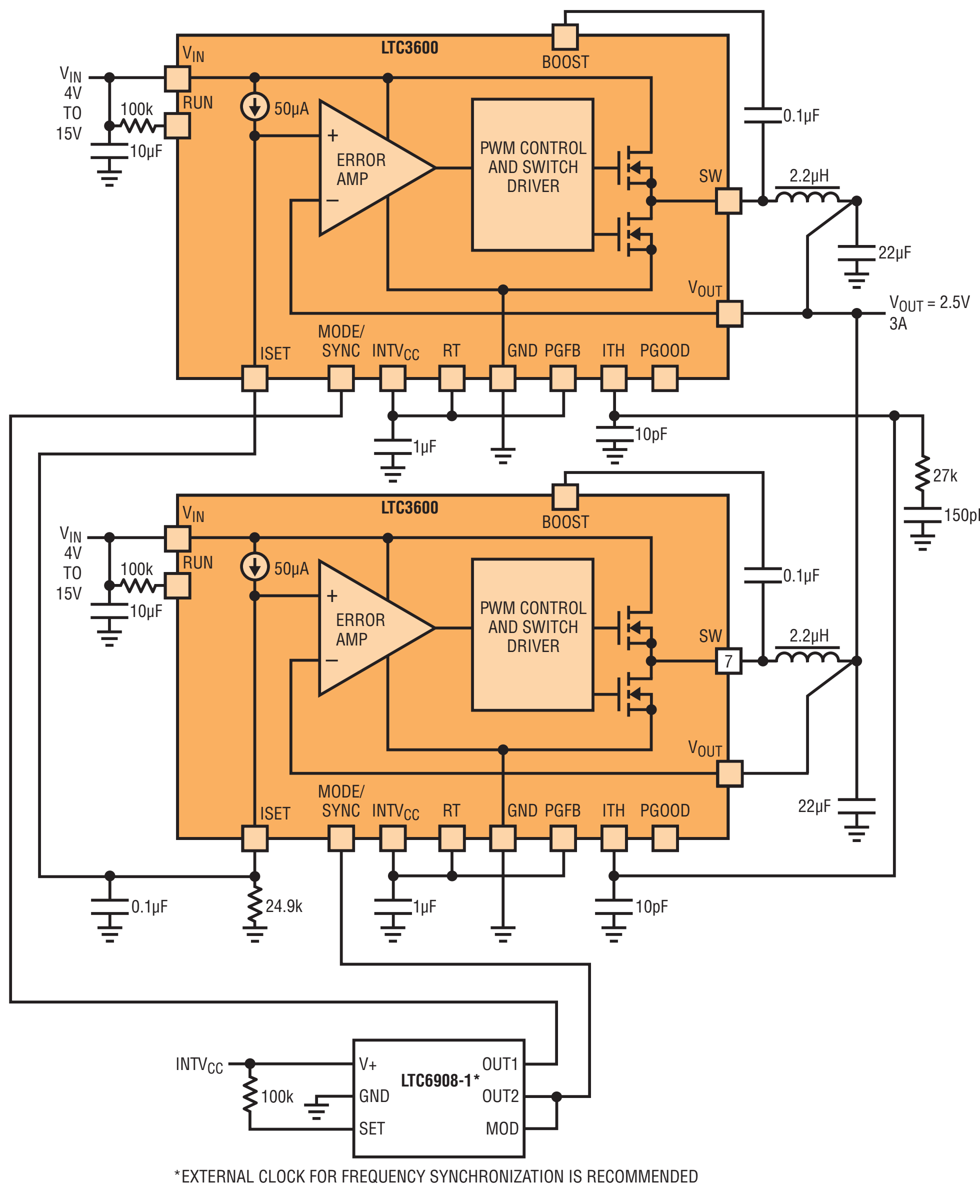


Figure 4. The LTC3600 as a programmable 0A to 1.5A current source

Figure 5. 15V to 2.5V, 3A dual phase regulator



LOW NOISE ±12V POWER SUPPLY FROM A SINGLE-ENDED 15V INPUT SUPPLY

The LTC3260 is a low noise dual polarity output power supply that includes an inverting charge pump with both positive and negative LDO regulators. The charge pump operates over a wide 4.5V to 32V input range and can deliver up to 100mA of output current. Each LDO regulator can provide up to 50mA of output current. The negative LDO post regulator is powered from the charge pump output. The LDO output voltages can be adjusted using external resistor dividers.

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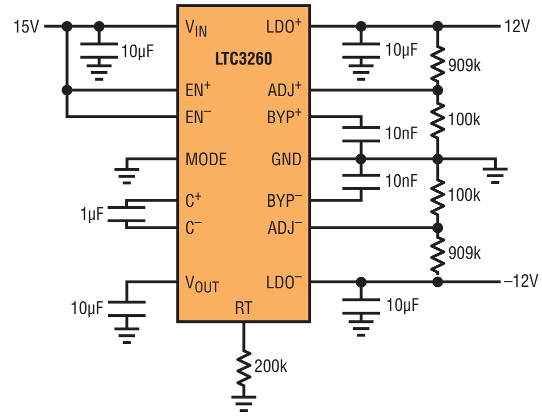

OVERVOLTAGE REGULATOR WITH 250V SURGE PROTECTION

The LT4363 surge stopper protects loads from high voltage transients. It regulates the output during an overvoltage event, such as load dump in vehicles, by controlling the gate of an external N-channel MOSFET. The output is limited to a safe value, allowing the loads to continue functioning. The LT4363 also monitors the voltage drop between the SNS and OUT pins to protect against overcurrent faults. An internal amplifier limits the voltage across the current sense resistor to 50mV. In either fault condition, a timer is started inversely proportional to MOSFET stress. Before the timer expires, the FLT pin pulls low to warn of an impending power-down. If the condition persists, the MOSFET is turned off. The LT4363-1 remains off until reset, whereas the LT4363-2 restarts after a cooldown period.

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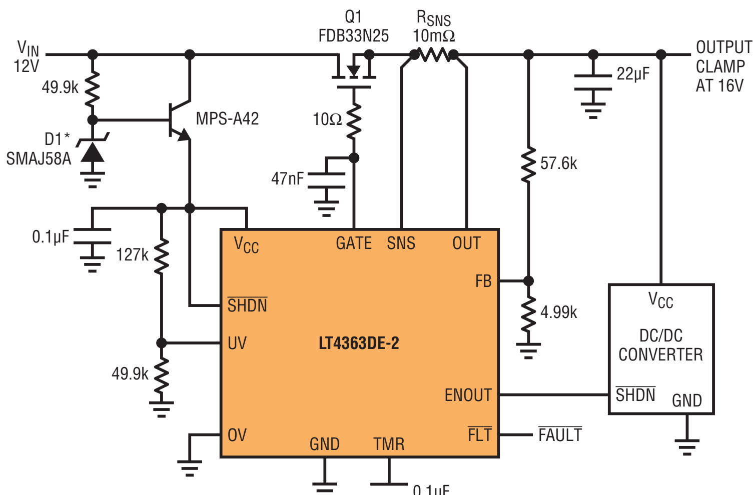

*DIODES INC.

36V INPUT, 5.6A TWO 2.5V SERIES SUPERCAPACITOR CHARGER

The LTM8026 is a 36V input, 5A constant-voltage, constant-current (CVCC) step-down µModule regulator. Included in the package are the switching controller, power switches, inductor and support components. Operating over an input voltage range of 6V to 36V, the LTM8026 supports an output voltage range of 1.2V to 24V. CVCC operation allows the LTM8026 to accurately regulate its output current up to 5A over the entire output range. The output current can be set by a control voltage, a single resistor or a thermistor. Only resistors to set the output voltage and frequency and the bulk input and output filter capacitors are needed to complete the design.

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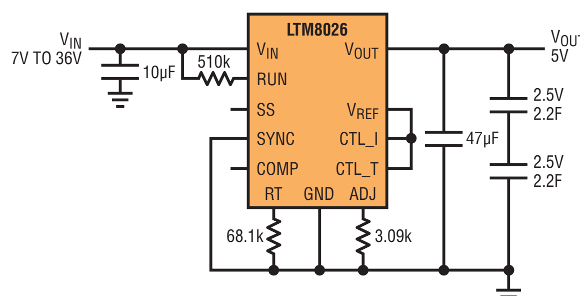

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