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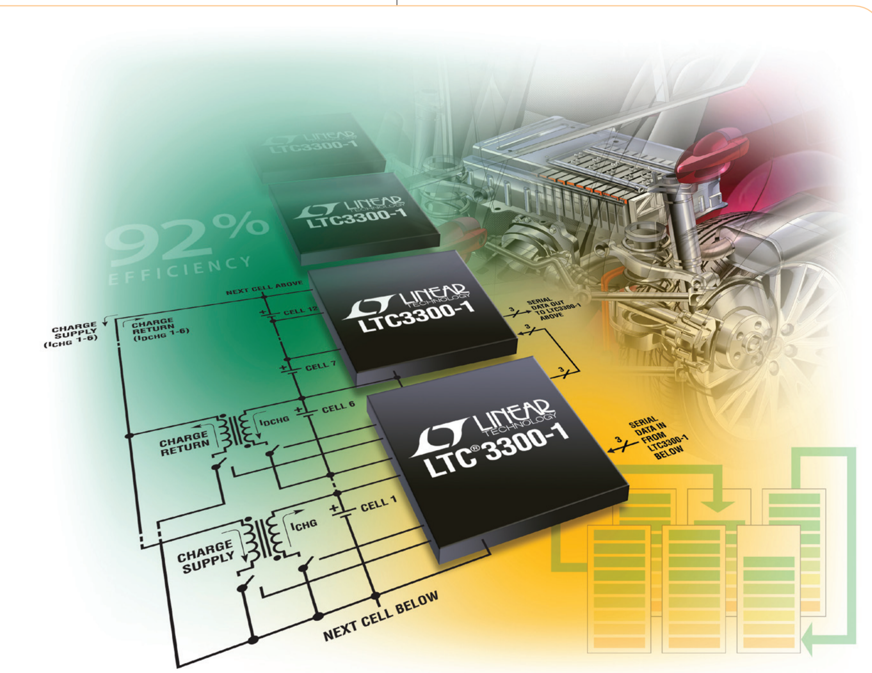
IN THIS ISSUE

Active Cell Balancer Extends Run Time and Lifetime of Large Series-Connected Battery Stacks

Jim Drew

Large stacks of series-connected battery cells are increasingly used to power electric vehicles or store energy in wind and solar power systems. It is not uncommon to have 100 cells connected in series in an electric vehicle, and even more in energy storage units for alternative energy systems. Typically, the stack is treated by the charge-discharge system as a single battery—cells are charged and discharged as a series stack and the state of charge (SoC) of each cell depends on its ability to store and maintain charge. Treating the cell stack as a single battery composed of capacity-matched cells can work well in the short term, but becomes increasingly inefficient in the long run.



The LTC®3300-1 balances the states of charge of individual cells in large battery stacks, increasing capacity, extending run time and prolonging lifetime of the stack

When a battery stack is first constructed, the capacities of its component cells can be well matched, but over time, individual cells lose capacity at different rates due to temperature variations and other factors. In a straightforward stack charge-discharge implementation, the cell with the least capacity—the weakest cell—effectively limits the run time of the stack. When the stack is charged, the weakest cell reaches its full charge voltage before stronger cells, so stronger cells are not charged to capacity. Likewise, when the stack is discharged, the weakest cell reaches its cutoff voltage sooner, limiting run time.

(continued on page 4)

In this issue...

Linear in the News

BREAKING GROUND WITH NEW VIDEOS

Linear's library of video design ideas at www.linear.com has grown to more than 120 presentations by experienced designers and applications engineers, discussing challenging analog design problems and their solutions. The videos cover a broad range of topics—from new packaging that improves the stability of voltage references to energy harvesting applications. The videos provide focused solutions for power management, data conversion, signal conditioning, µModule® integration, and wireless sensor networks.

Linear videos fall into three basic categories:

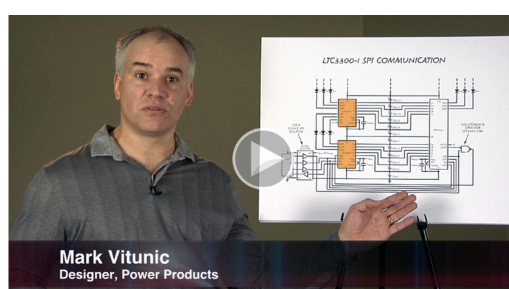
Video Design Ideas

These five to eight minute videos cover significant design challenges and solutions. Following is an example of a recent video topic, one of over 65 produced to date.

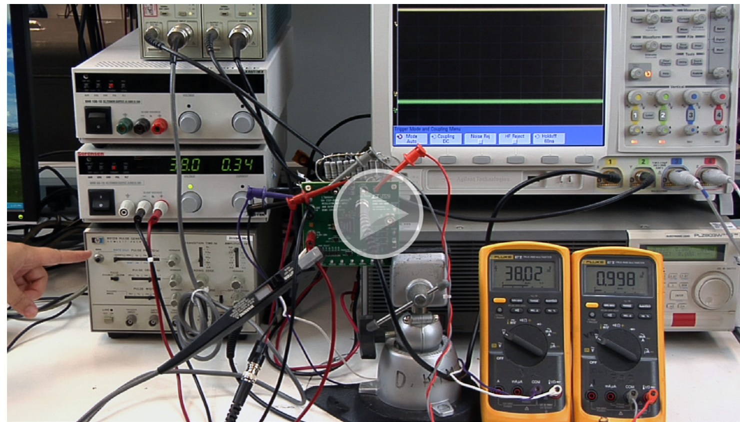
High Efficiency Bidirectional Cell Balancer Maximizes Capacity and Lifetime of Series-Connected Battery Stacks—Large, series-connected strings of batteries are commonly used in electric vehicles, backup power systems and a wide variety of energy storage applications. Maximizing the lifetime and ensuring safe usage of such battery stacks requires accurate measurement and balancing of each cells' state of charge (SoC). Cell aging occurs in all cells and at different rates due to the same factors that cause SoC mismatch. Without capacity compensation, the run time of the battery is limited by the lowest-capacity cell in the stack.

Active balancers such as the LTC3300 have the ability to correct for SoC imbalance and to compensate for cell-to-cell capacity differences. By efficiently redistributing charge from mismatched cells, the LTC3300 maximizes the usable capacity of the battery stack. The LTC3300 provides high current, high efficiency bidirectional cell balancing for series-connected batteries. Each IC can simultaneously charge or discharge up to six series cells. There is no limit to the height of the stack. Balancer-to-balancer communication is achieved through a high noise margin SPI bus, and

Mark Vitunic discusses how to improve battery stack run time and lifetime with active cell balancing



numerous safety features ensure reliable, efficient, high current active balancing. View at video.linear.com/p4691-146.



Video TechClip demonstration of the LTM4641 µModule regulator's overcurrent protection capability

Video TechClips

These are brief videos of one to two minutes, showing a specific aspect of a design solution. For example, video TechClips may demonstrate the thermal properties of a package, the efficiency of a design solution, or the short circuit protection built into a part. One example of a video TechClip:

Demonstration of the LTM®4641 µModule regulator's overcurrent protection capability—The LTM4641 includes output overcurrent protection and thermal shutdown. Once the fault condition has cleared, the LTM4641 automatically resumes operation. The output voltage stays well controlled in all circumstances. View at video.linear.com/p4656-144.

Video Interviews

Interviews cover a broad range of topics, from interviews with Linear Executive Chairman Bob Swanson and CEO Lothar Maier regarding company direction, to analog technology discussions with Chief Technical Officer Bob Dobkin and focused interviews on such topics as wireless sensor networks.

In conjunction with publication of the latest *Analog Circuit Design* book, *Volume 2, An Immersion in the Black Art of Analog Design*, Bob Dobkin has completed two video interviews—one focused on the challenge of analog design and the other a reminiscence on the late staff scientist and writer Jim Williams, who co-edited the book series with Bob Dobkin. You can view his discussion of the challenge of analog design at www.linear.com/designtools/acd_book.php.

Visit www.linear.com to see interviews with Bob Dobkin and other Linear luminaries

LINEAR PRODUCT AWARDS

Several Linear products have recently received significant industry awards:

Best of *Electronic Design*

The LTC5800 SmartMesh® system-on-chip wireless sensor network solution received *Electronic Design's* 2012 Best of Wireless Design Award. In their article on the product award, the editor stated that the SmartMesh LTC5800 and LTP5800 product families from Linear Technology's Dust Networks® product group "let you build complete wireless mesh networks for industrial applications. They're available to implement WirelessHART and IPv6 networks."

Electronic Products Product of the Year

In its annual product of the year awards, *Electronic Products* magazine selected Linear's LT4275 LTPoE++™ powered device controller as a Product of the Year. In their award article in the January 2013 issue, the magazine's editors stated, "The LT4275 powered-device (PD) interface controllers are LTPoE++, PoE+, and PoE-compliant and target applications requiring up to 90W. The existing PoE+ standard limits the maximum PD power delivery to 25.5W, which is insufficient for picocells, base stations, signage, and heated outdoor cameras. The device expands the power budget to 38.7, 52.7, 70, and 90W power levels to accommodate these applications. They deliver power to PD loads using just one IC."

CONFERENCES & EVENTS

Sensors Expo & Conference, Donald E. Stephens Convention Center, Rosemont, Illinois, June 4–6, 2013, Booth 1020—Linear will showcase its line of energy harvesting products, as well as its Dust Networks' wireless sensor network products. Sam Nork will make a presentation: "Use Energy Harvesting to Extend Battery Life in Wireless Sensor Applications" at 11:15 am on June 4. More info at www.sensorsmag.com/sensors-expo. ■

The LTC3300-1 is a fault-protected controller IC for transformer-based bidirectional active balancing of multicell battery stacks. Active bidirectional balancing can transfer charge from the stack to low SoC cells, or transfer charge from high SoC cells to the stack. In this way, the overall capacity of the stack is improved.

(LTC3300-1 continued from page 1)

The capacity of the stack and its run time can be improved by balancing the state of charge between cells within the stack. Figure 1 shows a simplified schematic of a 12-cell balancer using two LTC3300-1 cell balancing controllers.

LTC3300-1 IMPROVES BATTERY STACK RUN TIMES AND LIFETIMES

The LTC3300-1 is a fault-protected controller IC for transformer-based bidirectional active balancing of multicell battery stacks. Active bidirectional balancing can transfer charge from the stack to low SoC cells, or transfer charge from high SoC cells to the stack. In this way, the overall capacity of the stack is improved.

A single LTC3300-1 can balance up to six series connected cells with a common mode voltage range of up to 36V. Multiple LTC3300-1 devices can be connected in series, allowing balancing of long strings of series connected cells. A unique level shifting SPI-compatible serial interface allows multiple LTC3300-1 devices to be connected in series without opto-couplers or isolators.

As the stack is charged, weaker cells operate in discharge mode and stronger cells operate in the charge mode until all cells reach their full SOC. Likewise, during discharge, weaker cells are operated in charge mode while stronger cells are operated in discharge mode until all cells reach their cutoff voltage. This extends the run time of the stack, which reduces the number of charge/discharge cycles and thus extends the life of the batteries within the stack.

With the LTC3300-1, all individual cell balancers can operate simultaneously in any combination of discharge or charge modes, even when multiple LTC3300-1 devices are used. For instance, for a stack of 12 cells, with two LTC3300-1 devices connected in series, charge can be transferred from cell 12 to cell 1 in a single time step by discharging cell 12 and charging cell 1. When compared to other methods of transferring charge between cells, this single time step method is the fastest and most efficient. A single time step can include multiple balancers in discharge or charge modes resulting in optimum balance time.

The LTC3300-1 includes fault protection, including read-back capability, cyclic redundancy check (CRC) communication error detection, maximum on-time volt-second clamps and cell or transformer secondary overvoltage shutdown.

The LTC3300-1 is available in a 48-lead 7mm × 7mm QFN or LQFP package.

HOW TO APPLY THE LTC3300-1

The cell balancer incorporates a boundary mode synchronous flyback transformer power stage that is controlled by the LTC3300-1. There are six sets of control signals within the LTC3300-1 that control the gates of the primary side and secondary side NMOS switches and current sense inputs for each pair of NMOS switches.

The naming convention used for the LTC3300-1 is that the transformer primary is connected across the battery cell and the secondary of the transformer is across the ground reference of the IC to a point six or more cells up the stack. The primary side gate signals are referenced to the next lower cell while the secondary side gates are referenced to the ground reference of the IC, the V⁻ exposed pad.

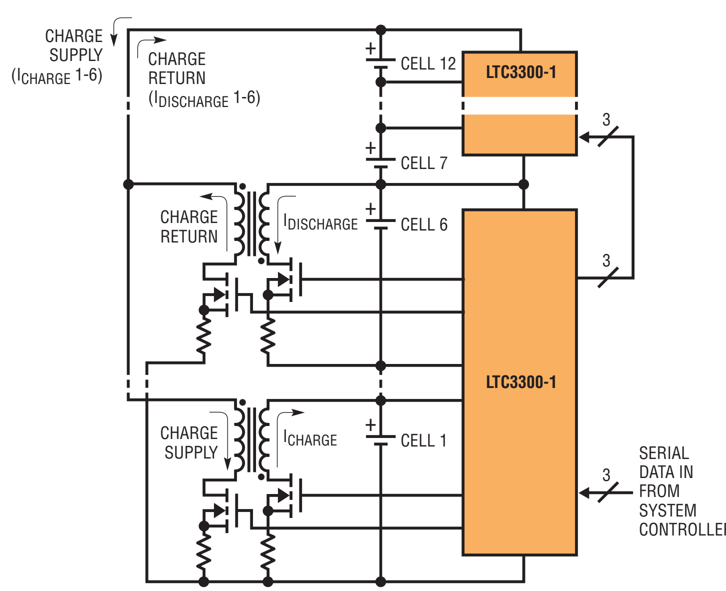


Figure 1. Simplified schematic of how the LTC3300-1 actively balances individual cells in a 12-cell battery stack

With the LTC3300-1, all individual cell balancers can operate simultaneously, in any combination of discharge or charge modes, even when multiple LTC3300-1 devices are used. For instance for a stack of 12 cells, with two LTC3300-1 devices connected in series, charge can be transferred from cell 12 to cell 1 in a single time step by discharging cell 12 and charging cell 1.

During discharge mode (Figure 2) the primary side NMOS is turned on first and remains on until the current signal ramps up to 50mV or the primary max on-time setting is reached. The flux built up in the primary side of the flyback transformer is then transferred to the secondary. The secondary gate signal turns on the secondary side NMOS, and it remains on until the secondary current sense signal ramps down to 0mV or the secondary side max on-time is reached. The cycle repeats until the LTC3300-1 is given a command to stop the discharge mode or encounters a fault such as a watchdog timer timeout, a cell undervoltage (2.0V), a cell overvoltage (5.0V) or a transformer secondary overvoltage caused by a lost connection.

During charge mode (Figure 3) the secondary is turned on first and remains on until the secondary current signal ramps up to 50mV or the secondary max on-time setting is reached. The flux built up in the secondary side of the flyback transformer is then transferred to the primary. The primary gate signal turns on the primary side NMOS and it remains on until the current sense signal ramps down to 0mV or the primary side max on-time is reached. The cycle repeats until the LTC3300-1 is given a command to stop the charge mode or encounters a fault such as a watchdog timer timeout, a cell undervoltage (2.0V), a cell overvoltage (5.0V), or a transformer secondary overvoltage caused by a lost connection.

The average balancing currents are determined by the value of the current sensing resistors ($R_{SENSE(PRI)}$ and $R_{SENSE(SEC)}$), the turns ratio (1:T) from primary to secondary of the flyback transformer, the number of cells within the secondary stack (s) and the transfer efficiency (η) of the power stage.

$$R_{SENSE(PRI)} = \frac{50mV}{2 \bullet I_{DISCHARGE}} \bullet \frac{S}{S+T}$$

$$R_{SENSE(PRI)} = \frac{50mV}{2 \bullet I_{CHARGE}} \bullet \frac{S \bullet T}{S+T} \eta_{CHARGE}$$

The turns ratio of the flyback transformer is selected based on the number of cells across the secondary winding and the maximum reflected voltage on the primary side and secondary side NMOS switches. For a 12-cell secondary, a 1:2 turns ratio from primary to secondary provides a good balance between transfer efficiency and voltage stress on the two NMOS switches. For a larger number of cells across the secondary, a higher turns ratio can be selected and still provide

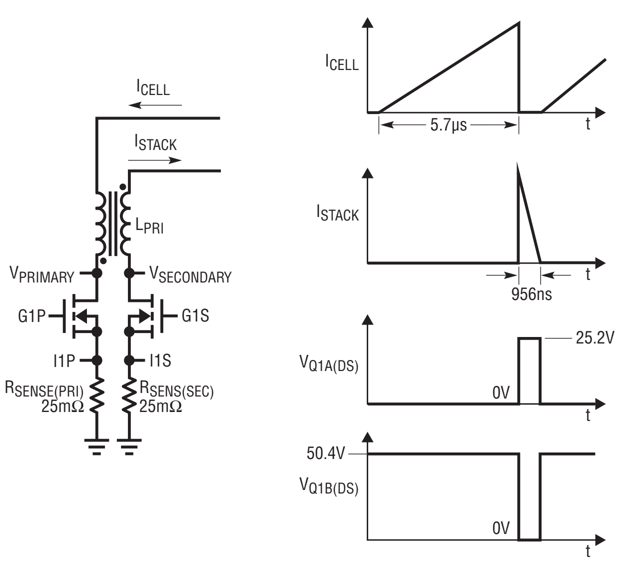


Figure 2. Discharge mode of a single cell in the stack

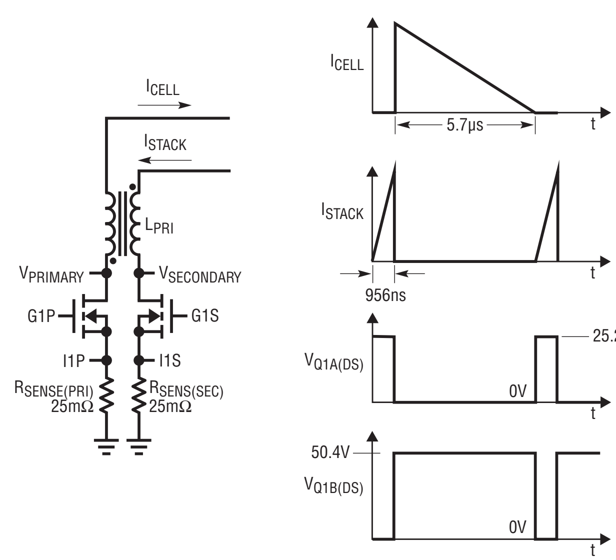


Figure 3. Charge mode of a single cell in the stack

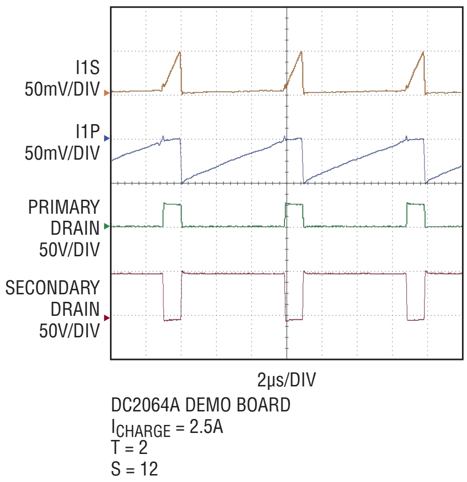
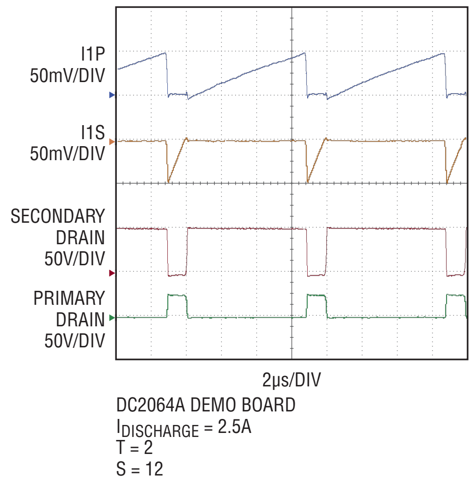


Figure 4. Demonstration circuit DC2064A typical charge mode waveforms for a 2.5A balance current



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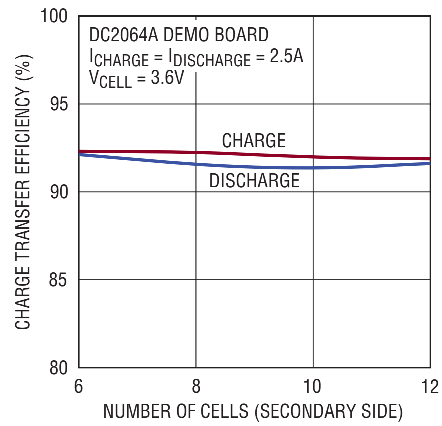


Figure 6. Cell balancer efficiency verses the number of cells across the transformer secondary winding

high transfer efficiency and manageable voltage stress on the NMOS switches.

Once the current sensing resistors and transformer turns ratio are defined, the primary inductance of the flyback transformer is determined. To do so, the operation frequency needs to be defined. The operating frequency is a function of the cell voltage, the current sensing resistor, the inductance of the primary, the number of cells within the stack, and the turns ratio of the transformer. The operating frequency is generally set to approximately 150kHz to reduce interference with other circuitry that may be in the system and to yield reasonable circuit component sizes with high transfer efficiency. The nominal cell voltage is used in this calculation.

$$L_{PRI} = \frac{S}{S+T} \bullet \frac{V_{CELL} \bullet R_{SENSE(PRI)}}{f_{DISCHARGE} \bullet 50mV}$$

$$L_{PRI} = \frac{S}{S+T} \bullet \frac{V_{CELL} \bullet R_{SENSE(SEC)}}{f_{CHARGE} \bullet 50mV \bullet T}$$

In most designs the average charge and discharge currents are set to be equal, which necessitates $R_{SENSE(SEC)} = R_{SENSE(PRI)} \bullet T$

As a result, the charge and discharge frequencies are equal. Note that the frequency of operation is a linear function of the cell voltage: 10% shift in cell voltage results in a 10% shift in the operating frequency.

Selection of the NMOS switches is determined by the peak balancing current and the drain-to-source off-state voltage. The drain-to-source off-state voltage can be estimated using the following expressions:

$$V_{DS(PRI)MIN} > V_{CELL} \bullet \left(1+\frac{S}{T}\right)+\frac{V_{DIODE}}{T}$$

$$V_{DS(SEC)MIN} > V_{CELL} \bullet (S+T)+T \bullet V_{DIODE}$$

Good design practice recommends that the MOSFET breakdown rating be 20% higher than this minimum calculated value to account for voltage spikes due to leakage inductance ringing. Some applications may require a series resistor capacitor snubber in parallel with the drain and source of the NMOS switch to reduce the ringing. These snubber circuits may lower the transfer efficiency but keep the NMOS devices within their safe operating region.

Additional NMOS parameters that need to be considered are the total gate charge (Q_G) and $R_{DS(ON)}$. The product of total gate charge and the operating frequency determines the gate current requirements for the primary and secondary gate drivers. The primary gate drive for cells 1–5 is sourced from the cell above the selected cell. Cell 6 primary gate drive is sourced from the boost circuitry, which gets its energy from C6. All six secondary gate drivers are sourced from the V_{REG} circuitry. When all six balancers are operating, the secondary gate drivers present a load current on V_{REG} of:

$$I_{V(REG)} = 6 \bullet Q_G \bullet f$$

resulting in a power dissipation of:

$$P_{V(REG)} = (V_{C6} - V_{REG}) \bullet I_{V(REG)}$$

The primary gate drivers generate power dissipation in the LTC3300-1 of

$$P_{PRI(DRIVE)} = 2 \bullet V_{CELL} \bullet 6 \bullet Q_G \bullet f$$

The individual primary and secondary gate drive currents should be limited to less than 4mA.

Figure 4 shows typical charge mode waveforms for a 2.5A cell balancer with a secondary of 12 cells and a transformer turns ratio of 1:2. The primary inductance is 3µH, $R_{SENSE(PRI)}$ is 8mΩ, $R_{SENSE(SEC)}$ is 16mΩ and the cell voltage is 3.6V. Figure 5 shows the same cell balancer in discharge mode. Figure 6 shows the cell balancer efficiency for various numbers of cells connected to the secondary.

INTERLEAVING SECONDARIES IN AN 18-CELL CONFIGURATION

Large strings of cells can be accomodated by the LTC3300-1 by interleaving their secondary windings. Figure 7 shows an 18-cell stack with three LTC3300-1 ICs connected in series via the SPI-compatible serial interface. The transformer secondaries of the bottom LTC3300-1 are connected across (cell 1)$^-$ and (cell 12)$^+$ while secondaries of the middle LTC3300-1 are connected across (cell 6)$^+$ and (cell 18)$^+$. The secondaries of the top LTC3300-1 are connected across six cells, (cell 12)$^+$ and (cell 18)$^+$.

The lower two devices have their BOOST and TOS pins tied to their respective V^- pin and $BOOST^+$ pins connected to the cell above the cell connected to their respective C6 pins. The top LTC3300-1 has its BOOST and TOS pins tied to the V_{REG} pin.

A flying capacitor is connected between the $BOOST^-$ and $BOOST^+$ pins along with a series 6.8Ω resistor and diode connected from the $BOOST^+$ pin to cell 6. The V_{MODE} pin of the bottom LTC3300-1 is tied to its V_{REG} pin while all other devices have their V_{MODE} pins tied to their respective V^- pins.

CONCLUSION

The LTC3300-1 actively balances the state of charge of individual cells in multicell, series-connected battery stacks using a transformer-based bidirectional scheme. Active balancing extends the run time of battery stacks, which in turn extends their lifetimes. The LTC3300-1 integrates gate drive circuitry and a robust serial interface with built in watchdog timer, undervoltage and overvoltage protection in a 48-lead QFN or LQFP package. Each LTC3300-1 controls up to six cell balancers while larger stacks can be accommodated with multiple LTC3300-1 ICs connected in series using an SPI-compatible serial interface.

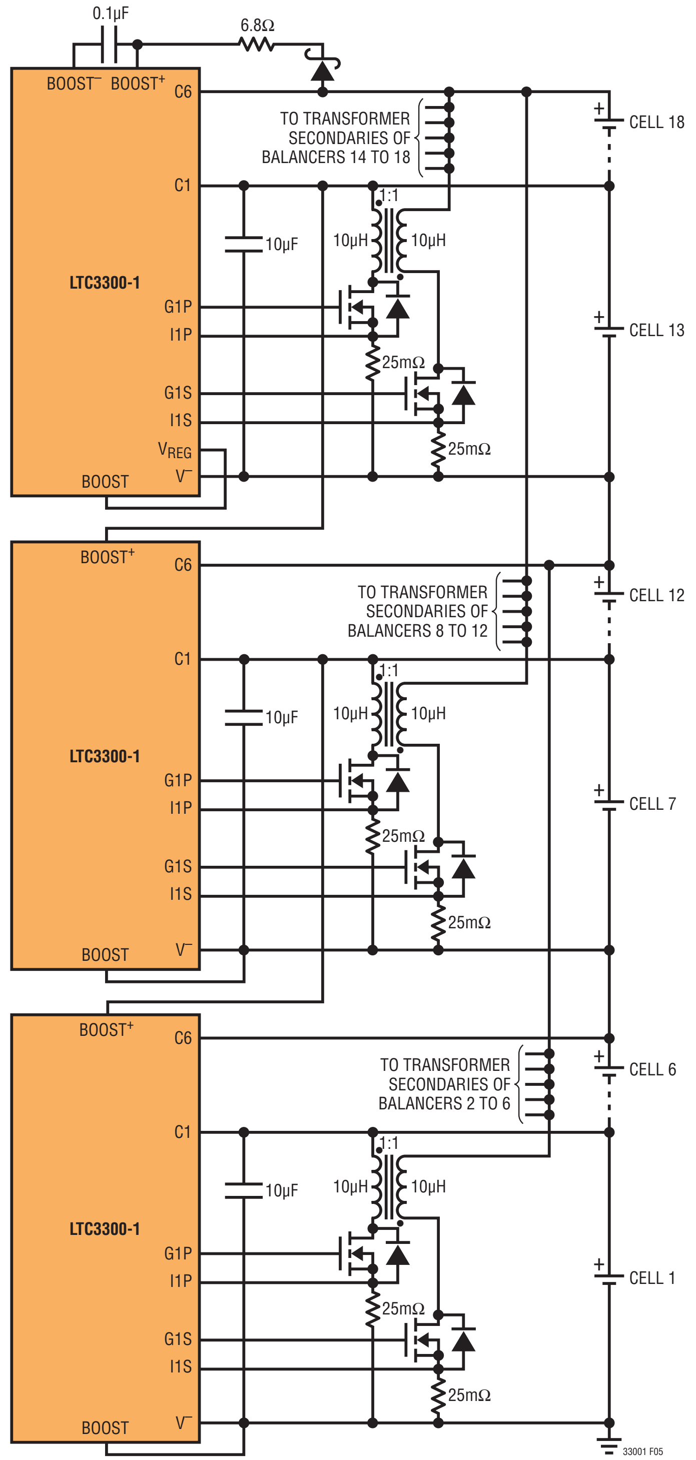


Figure 7. 18-cell active balancer

Visit www.linear.com/LTC3300-1 for data sheets, demo boards and other applications information. ■

High Power Controller Drives High Power LEDs, Regulates Solar Cells, and Charges Batteries, Steps Down 60V Inputs

Luke Milner

The best LED drivers accurately regulate LED current for consistent color reproduction and modulate it rapidly for high contrast dimming. They also recognize and survive short and open circuits, monitor and report current levels, guard against overheating, and protect weak power supplies from excessive load currents. A standard switching converter would require a number of additional expensive amplifiers, references and passive components to fulfill these responsibilities.

In contrast, the LT®3763 LED driver-controller has these functions built in—reducing BOM costs, saving board space and improving reliability. The LT3763 is more than just a high performance LED driver. Its rich feature set simplifies the design of other demanding applications, such as safe charging of a sealed lead-acid batteries, or maximum power point regulation for a solar panel, or a combination of both. The LT3763 performs these tasks with high efficiency, even at input voltages reaching 60V.

DRIVING LEDs

Figure 1 shows the LT3763 configured as a high power LED driver. A potentiometer at the CTRL1 pin permits manual adjustment of the regulated LED current from 0 to 20A. For thermal regulation of the LED current, a resistor with a negative temperature coefficient is mounted near the LED and connected from the CTRL2 pin to GND.

The resistor network at the EN/UVLO pin programs the LT3763 to shut down if the input voltage falls to less than 10V. The resistor network at the FB pin defines an open-circuit condition as when the output reaches 6V, and should that ever happen, the LT3763 automatically reduces the inductor current to prevent overshoot and pulls down the $\overline{\text{FAULT}}$ pin to mark the occasion.

The LT3763 is designed to provide flicker-free LED dimming as shown in Figure 2. This is achieved by pulling PWMOUT low whenever PWM is low and thereby disconnecting the LED, by similarly disconnecting the compensation network at V_C, and resynchronizing internal switching clocks to the PWM pulse. These maneuvers ensure that subsequent pulses are identical, that the inductor current rises as fast as possible to satisfy the programmed LED current level, and that the LED light never flickers.

The LT3763 can be configured as in Figure 3 to deliver 350W with 98% efficiency from a 48V input. An internal regulator supplies the drivers of the TG and BG pins with enough power for each to drive two of the external NMOS power switches. Higher power applications can be built by connecting LT3763s in parallel,

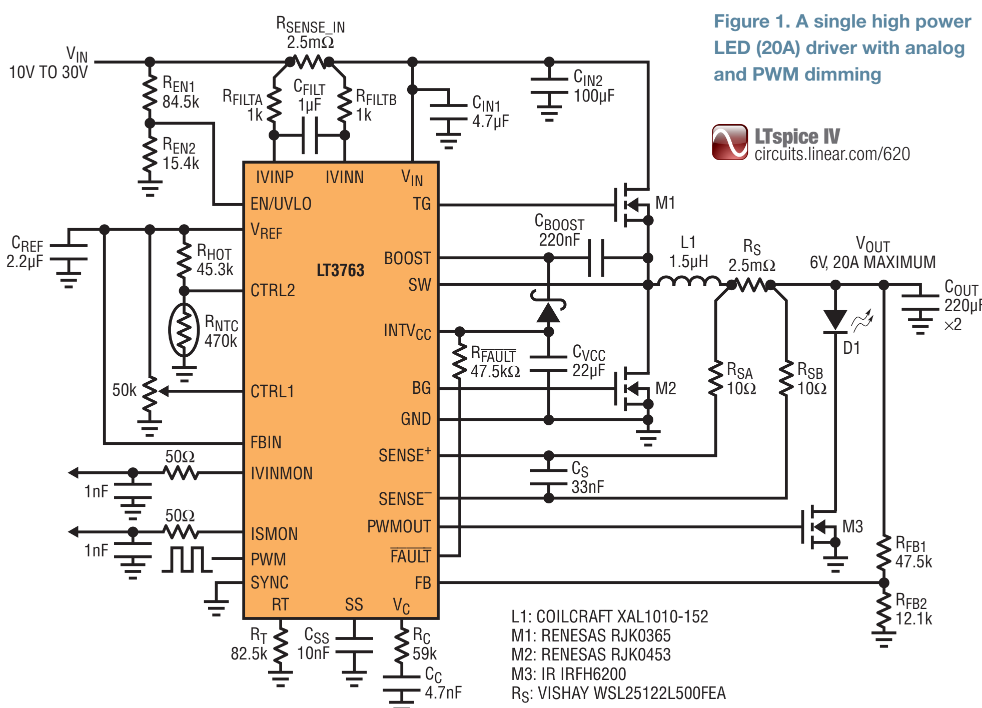


Figure 1. A single high power LED (20A) driver with analog and PWM dimming

The output voltage can be as high as 1.5V less than input voltage, making it possible to charge three sealed lead-acid batteries in series (up to 45V) from a 48V supply with the simplicity of a standard buck converter.

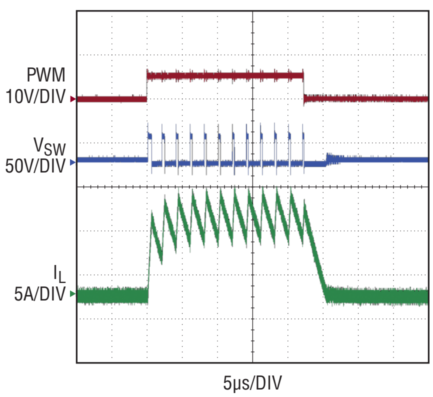


Figure 2. PWM dimming performance of the circuit in Figure 1

so that current is shared equally between the two controllers. This configuration also illustrates how the SYNC pin can be used to synchronize the parallel connected LT3763s to an external clock.

The high output voltage rating of the LT3763 enables 35V at the output with the simplicity of a standard buck converter. The output voltage can be as high as 1.5V less than input voltage, and the configuration in Figure 4 makes use of this feature to charge three sealed lead-acid batteries in series (up to 45V) from a 48V supply.

CHARGING BATTERIES

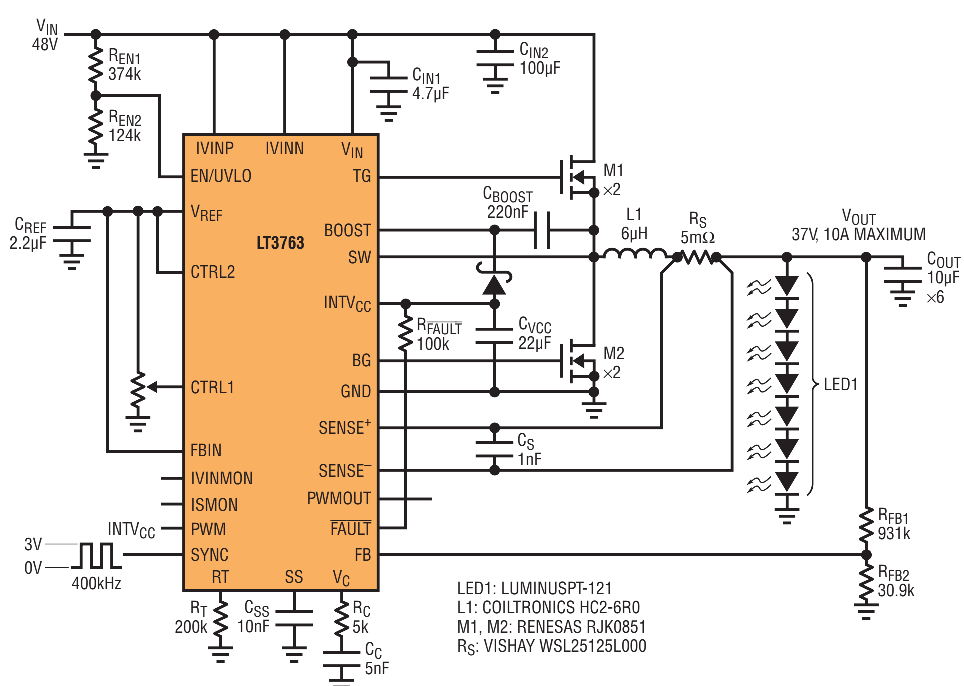
The battery charger shown in Figure 4, like all chargers, must be able to precisely regulate the batteries' rated charging current (constant current mode) until the battery voltages reach the limit set by their chemistry. The charger must maintain that voltage (constant voltage mode) without overshoot until the current drawn by the trickle-charging batteries becomes very small. Once the trickle charge phase is complete, the charger should allow the batteries' voltages to decay to a relaxed level before finally settling at and holding that final voltage indefinitely.

The combined current and voltage regulation loops on the LT3763, and its LED fault handling circuitry, nearly make it a complete battery charger. Only a single additional transistor is required to form a complete battery charging system.

The resistor divider at the FB pin has been designed to program the charging voltage to 45V. As in the case of an open-circuit, when the voltage reaches 45V, the LT3763 automatically reduces the current to prevent overshoot as shown in Figure 5. Subsequently, during trickle charging, the battery draws less current over time. When the charging current reduces to ten percent of the regulated current (C/10 battery specification), the LT3763's open-circuit fault condition is triggered. The resulting high-to-low transition at the $\overline{\text{FAULT}}$ pin is used to turn off the gate of the added transistor M3 and remove the resistor R_{FB3} from the feedback network. The programmed output voltage is thereby lowered, and the LT3763 stops switching to allow the batteries to relax on their own.

When their combined voltage decays to the newly programmed value, the LT3763 begins switching again and provides a sustaining current necessary to maintain the output voltage indefinitely. As an added

Figure 3. 350W white LED driver



The LT3763 is a versatile step-down buck converter that integrates many complex features essential for LED drivers, solar harvesters and battery chargers. A PWM driver and current monitors are included with fault detection, current limiting, input and output voltage regulation.

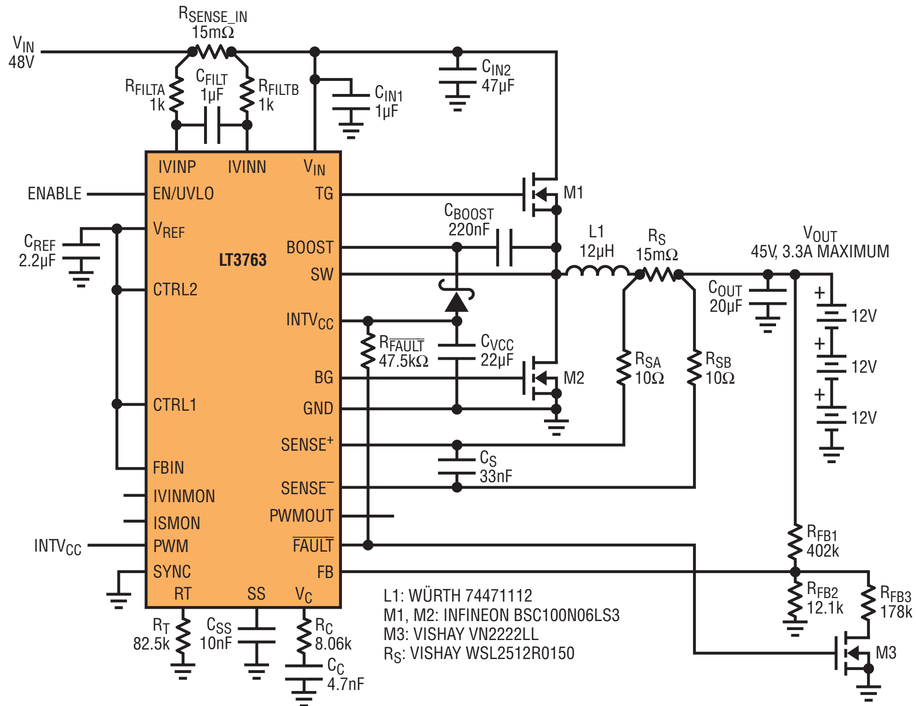


Figure 4. 3.3A, six-cell (36V) SLA battery charger

benefit, the $\overline{\text{FAULT}}$ pin transition serves as a signal that the trickle charging has begun.

REGULATING SOLAR PANELS

A well-designed solar panel power supply requires an intelligent combination of current and voltage regulation. In an optimum design, a converter must sense the voltage on the panel and adjust the current it draws to maintain the input voltage at the panel's maximum power point. If it draws too much current, the voltage of the high impedance panel will collapse. If it draws too little current, available light energy is essentially wasted.

In many common solutions, a solar panel controller designer would use an amplifier to sense the input voltage and adjust the voltage on the current control pin. The LT3763 includes this function at the FBIN pin. Simply tie CTRL1 high, to the 2V reference available at V_{REF}, and add a voltage divider from V_{IN} to FBIN. When the voltage at FBIN falls to nearly 1.205V, the internal amplifier automatically overrides the CTRL1 voltage and reduces the load current. This regulates the input voltage (the voltage of the solar panel) at the maximum power point for the panel. The resistor divider on the FBIN pin is shown in Figure 6 and can be customized to fit the requirements of any solar panel.

In the configuration shown in Figure 6, the converter can generate whatever inductor current, up to 5A, is required to hold the panel voltage at 37V. Input voltage feedback is via the voltage divider at the FBIN pin, which in turn regulates the inductor current to what is actually necessary to hold the panel at peak power in any given light condition.

As shown in Figure 7, the process of charging a battery with a solar panel looks very similar to charging with a low impedance supply as before. The difference is that the regulated inductor current (charge current) is not preset by the designer, but is instead adjusted on the fly via the feedback loop regulating input voltage. This effectively minimizes charge time, since input power is maximized at all times, regardless of panel illumination.

Since the LT3763 has the capability of regulating input voltage and current, as well as output voltage and current, and provides a fault flag with C/10, it can easily be used with a wide variety of solar panels to charge many different types of batteries.

Figure 5. 36V SLA battery charging cycle

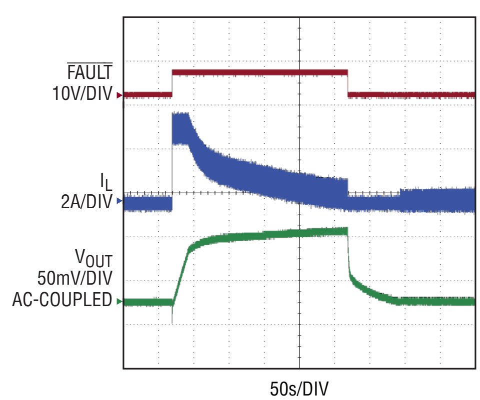
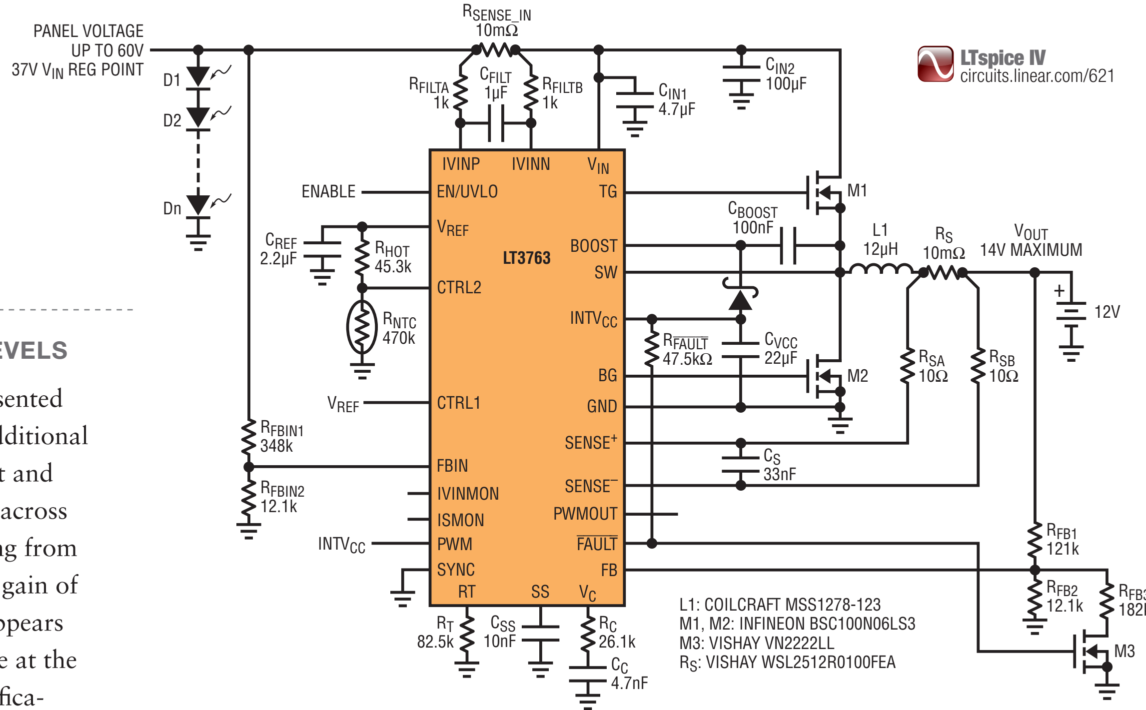


Figure 6. 70W solar energy harvester with maximum power point regulation



MONITORING CURRENT LEVELS

In each of the applications presented here, the LT3763 provides an additional service by monitoring the input and output current levels. Voltages across the IVINP and IVINN pins ranging from 0 to 50mV are amplified with a gain of 20, and the resulting voltage appears at the IVINMON pin. The voltage at the ISMON pin is an identical amplification of the voltage across the SENSE+ and SENSE− pins, as shown in Figure 8.

These signals are helpful in systems that must verify the current provided to LEDs or measure the efficiency of voltage conversion. They can also help to estimate the power provided by a solar panel or to monitor the current trickling into a charging battery as it decays to zero.

Due to the discontinuous input current of a step-down buck converter, a lowpass filter is typically necessary at the IVINP and IVINN pins as shown in Figure 1 and Figure 4. A much smaller filter at the SENSE+ and SENSE− pins may also be useful in filtering high frequency noise, but it is not necessary. Even with these filters, the monitors are fast enough to track reasonably short PWM pulses as shown in Figure 8. Nevertheless, if a designer is more concerned with average current levels than instantaneous current levels, then additional lowpass filters can be easily added to the ISMON and IVINMON pins.

SUMMARY

The LT3763 is a versatile step-down buck converter that integrates many complex features essential for not only LED drivers, but solar harvesters and battery chargers as well. A PWM driver and current monitors are included with fault detection, current limiting, input and output voltage regulation. Due to its high voltage rating, all of these features can be utilized to illuminate long strings of LEDs or charge stacks of batteries. Available in a 28-lead TSSOP package, the LT3763 is a compact, complete, and efficient power system.

Visit www.linear.com/LT3763 for data sheets, demo boards and other applications information. ■

Figure 7. Solar powered SLA battery charging

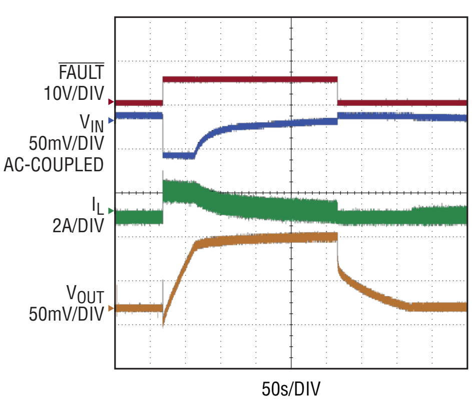
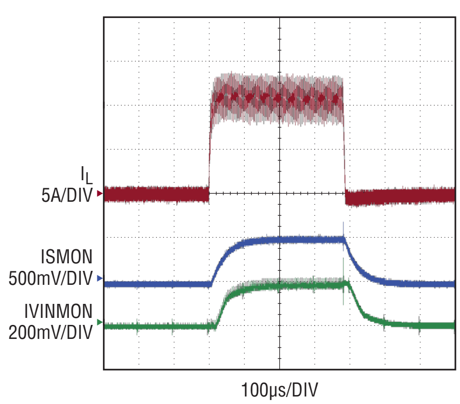


Figure 8. Current monitor outputs in an LED driver application with PWM dimming



40μA I_Q, P-Channel Step-Down Controller Operates from 60V to 3.5V V_{IN} and Maintains High Efficiency at Light Loads

Terry Groom

The LTC3864 is low I_Q step-down DC/DC controller. It controls an external P-channel MOSFET to provide excellent light load efficiency, wide input voltage range (3.5V–60V) including low dropout operation, reliability and functional simplicity in an easy-to-use 12-pin package. The LTC3864 is capable of 100% duty factor operation, allowing continued operation with input supply voltage droop.

This combination of features makes it ideal for automotive applications such as always-on power in an electronic control unit (ECU). Low dropout performance is guaranteed down to 3.5V over the full operating temperature range. The LTC3864 is offered in automotive temperature and reliability grade and has been verified to strict failure mode and effects analysis, or (FMEA) criteria.

HIGH EFFICIENCY PMOS CONTROLLER

The LTC3864 offers high efficiency at full and light load by virtue of a strong 0.9Ω turn-on and 2Ω turn-off gate driver and 40μA low I_Q Burst Mode® operation. Modern automotive always-on applications often require less than 70μA total supply current to prevent battery drain. Burst Mode switching and a low I_Q of only 40μA allows high efficiency at these very low currents.

Figure 1 shows a typical efficiency graph, showing very little decline as the load current is reduced. Light load efficiency is achieved in two ways: first by low frequency Burst Mode switching, and second by low V_{IN} I_Q. In light load Burst Mode operation, the load current is supported by multiple switching pulses generated in a "burst" of activity, with periods of no switching in between bursts.

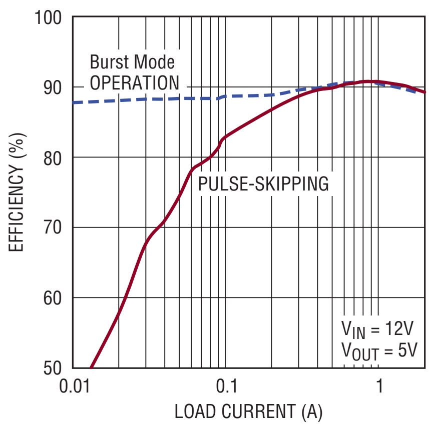


Figure 1. LTC3864 pulse-skip and Burst Mode efficiency

This effectively lowers the switching frequency. Power FET switching losses are a significant loss component when loads are light. Reducing the effective operating frequency reduces switching losses and increases efficiency. The efficiency's lower limit is ultimately determined by the V_{IN} quiescent current, or I_Q, of 40μA, which enables efficient standby operation in always-on power applications.

WIDE V_{IN} OPERATING RANGE

The LTC3864 has a high voltage PMOS gate driver capable of operating continuously up to 60V and down to 3.5V. This input voltage operating range is guaranteed over the full temperature range up to a military grade from –55°C to 150°C. The minimum input voltage operation or undervoltage lockout condition is actually set by the differential voltage from the V_{IN} pin to the CAP pin of 3.5V. This voltage is used to drive the gate of the power FET.

The LTC3864's internal linear regulator maintains 8V between V_{IN} and CAP. When V_{IN} is less than 8V, the VCAP regulator is in dropout and the CAP pin is held at ground. In this condition, the V_{IN} undervoltage is set by the V_{IN}-to-CAP undervoltage. The LTC3864 guarantees a 3.5V minimum from V_{IN} to CAP to assure adequate PMOS switch gate voltage. For low V_{IN} operating conditions, we recommend choosing an external P-channel MOSFET that has a threshold voltage of less than 2V to assure adequate overdrive when approaching minimum V_{IN}.

100% DUTY CYCLE OPERATION

The LTC3864 naturally and easily handles 100% duty factor operation with an external P-channel simply by forcing the gate on. No boost drive or additional circuitry is needed. While there is efficiency loss by using a P-channel at high current as opposed to an N-channel, the simplicity of the solution makes the LTC3864 ideally suited for many low and medium current level applications.

One important function in automotive applications is output voltage

One important function in automotive applications is output voltage dropout during a cold crank condition. With the LTC3864, the output simply tracks the input voltage when it is below the regulation output. The output quickly recovers to the regulation once the cold crank condition is over.

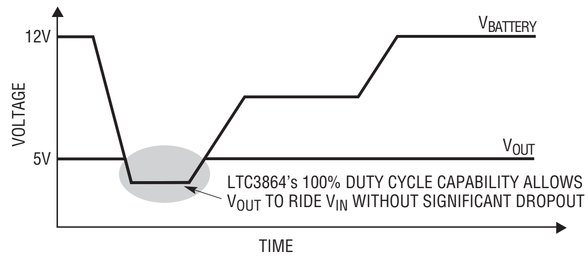


Figure 2. Typical automotive cold crank from 12V to below 5V

dropout during a cold crank condition. Figure 2 shows how the regulated 5V output drops out and recovers during a cold crank condition. The output simply tracks the input voltage under the output regulation voltage. The output quickly recovers to the regulated 5V once the cold crank condition is over.

SOFT-START, FAULT PROTECTION AND RECOVERY

The LTC3864 includes soft-start, tracking, fault protection and recovery features to assure robust operation even under extreme conditions. The SS pin provides both soft-start and tracking features.

To set the soft-start ramp-up time, simply tie a capacitor from the SS pin to ground and the internal 10µA charging current sets the SS voltage ramp from 0 to 0.8V. At 0.8V on the SS pin the output is at the full regulation voltage.

The LTC3864 can track another input source or supply by overdriving the 10µA current and forcing the SS pin input voltage. The output tracks the SS pin until the signal exceeds 0.8V.

Fault protection features include power good, undervoltage lockout, short-circuit recovery and frequency foldback during start-up and short-circuit conditions.

The LTC3864 includes an internal soft-start ramping feature, which sets the maximum output ramping rate under all operational conditions including short-circuit recovery. The internal soft-start ramp sets the minimum output voltage ramp time to approximately 650µs. An external capacitor to the SS pin determines the SS ramp once the internal minimum of 650µs is exceeded.

The internal soft-start ramp also determines the maximum output voltage ramp from a short-circuit recovery. Without this feature, the output recovery would be limited only by current limit. An output recovery rise without soft-start leads to high transient current and possible output voltage overshoot.

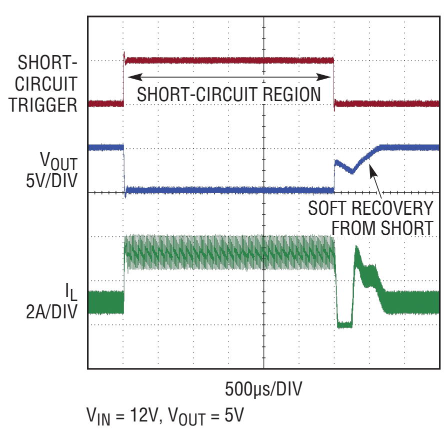


Figure 3. Short-circuit operation including soft recovery from short

Figure 3 shows a short-circuit event including recovery. When the output is shorted, the output drops near zero and the current is regulated to the programmed short-circuit value. The first V_{OUT} rise in recovery is a result of the energy in the inductor being transferred to the output once the short is removed. Next, the internal regulation ramp prevents switching until the ramp exceeds the regulation point, and then ramps monotonically once switching begins. Figure 3 shows a smooth output recovery from a short-circuit without exceeding current limit and without output voltage overshoot.

VERIFIED FAILURE MODE AND EFFECTS ANALYSIS (FMEA)

The LTC3864 is designed to meet the most stringent automotive requirements and to satisfactorily survive an FMEA to adjacent-pin short and pin open operations in a typical configuration. The purpose of this test is to emulate the effects of typical PCB defects and determine if they are destructive. In the test, the LTC3864 was configured for a V_{IN} of 12V and V_{OUT} of 5V with an output load of 1A. Each pin was then systematically opened and adjacent pins shorted and the results measured. In all instances, the LTC3864 recovered when the FMEA conditions were removed. The results can be found in the LCT3864 data sheet.

SIMPLE AND EASY TO USE

The LTC3864 is a nonsynchronous PMOS DC/DC controller and can be used in a variety of low to medium current level applications. Figure 4 shows a typical 5V output automotive application. This is a minimum component count solution. Include input and output capacitors, PMOS switch, nonsynchronous diode, sense resistor, bias caps and compensation and the application is complete.

This 5V, 2A output solution achieves an efficiency of around 90% near maximum load and maintains this high efficiency all the way down through Burst Mode operation at light loads, as shown in Figure 1. The output voltage is programmed using feedback resistors R_{FB2} and R_{FB1} with an optional C_{FF} available to speed up transient response, if desired.

The LTC3864 fits a wide variety of applications where size and light load efficiency are paramount. The output can be programmed from 0.8V up to a maximum of 60V. Output currents typically range up to 5A depending on the application. Figure 5 shows 24V output voltage, 750kHz application with 92% peak efficiency at 1A and greater than 72% at low current efficiency in Burst Mode operation.

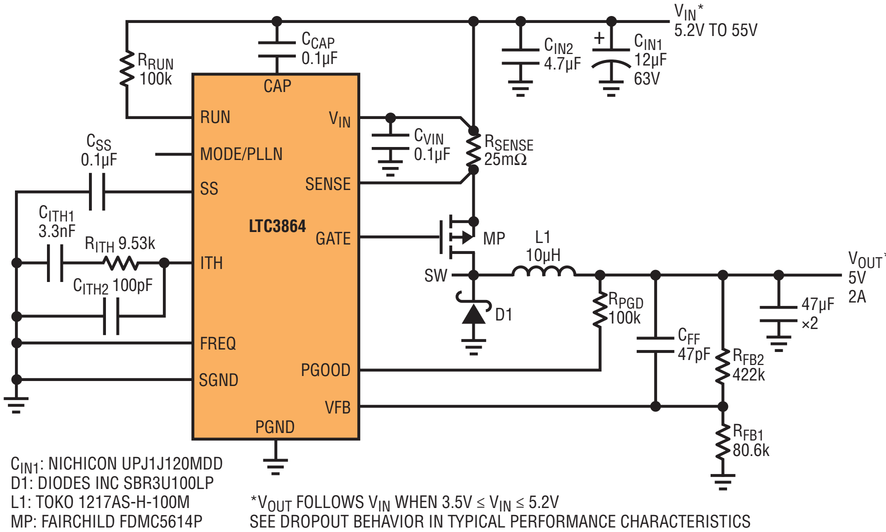


Figure 4. Typical 5V output automotive application

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SUMMARY

The LTC3864 is a versatile, easy-to-use high voltage PMOS controller with excellent light load efficiency. Its 40µA low I_Q Burst Mode operation is suited to applications where standby light load efficiency is important such as in always-on power systems. The 100% duty cycle capability allows the output voltage to ride through severe input voltage droop such as in a cold crank condition. The LTC3864 is designed to operate in low V_{IN} droop conditions where minimum V_{IN} is 3.5V over the full temperature range. The LTC3864 provides high input voltage capability and excellent light load efficiency in a simple and easy-to-use 12-pin package. The LTC3864E and LTC3864I versions operate from –40°C to 125°C junction temperature. The LTC3864H is guaranteed to operate from a –40°C to 150°C operating junction temperature. The LTC3864MP is 100% tri-temperature tested and guaranteed to operate from –55°C to 150°C operating junction temperature.

Visit www.linear.com/LTC3864 for data sheets, demo boards and other applications information. ■

Figure 5. 24V to 60V input, 24V/1A output at 750kHz

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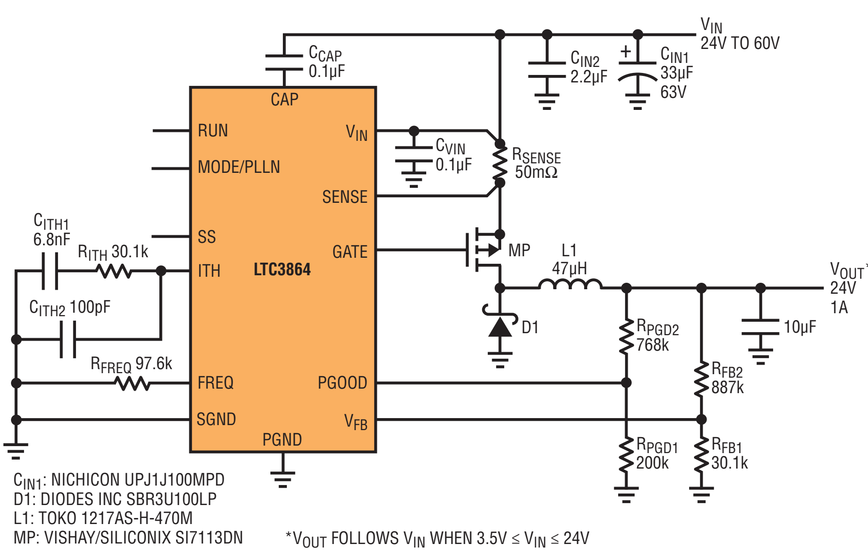

Dual, Fast, Step-Down Controller's External Reference Input Enables Dynamic Voltage Scaling from 0.4V to 5.5V and 0.3% Total Combined Regulation Accuracy

Shuo Chen and Terry Groom

Low voltage, high current systems require accurate differential regulation. It is not uncommon for power supply rails at or below 0.9V to demand 25A or more, with fast transients that look like intermittent electrical shorts to the power supply rail. Such systems typically require power supply regulation accuracy of less than 1% regulated DC and 3% in the face of input transients.

PART NUMBER	REFERENCE VOLTAGE	OUTPUT VOLTAGE	TOTAL COMBINED ACCURACY (GROUND, LINE, LOAD & TEMP)*
LTC3838-1/-2 Ch.1 and LTC3838-1 Ch.2	0.6V Internal	0.6V to 5.5V	< ±0.75% (0°C ≤ T_A ≤85°C) < ±1% (-40°C ≤ TA ≤125°C)
LTC3838-2 Ch.2 (e.g., with ±0.1% Linear Technology Voltage References)	0.6V External	0.6V to 5.5V	< ±0.67% (-40°C ≤ T_A ≤125°C)
	1.5V External	1.5V to 5.5V	< ±0.4% (-40°C ≤ T_A ≤125°C)
	2.5V External	2.5V to 5.5V	< ±0.3%

*external resistor divider error not included

Table 1. Output voltage regulation accuracy over remote power ground deviation (up to ±200mV), input voltage (4.5V to 38V), output current, and temperature

Increasingly, core processors and other large scale digital ICs (such as ASICs and FPGAs) require dynamic voltage scaling—either multiple fixed levels, or a continuously adjusted reference voltage using a servo loop—to deliver power based on the processor demand. The goal is that the system can keep the applied power supply at the minimum voltage necessary for proper operation based on processing demand to conserve energy. One example is LSI's adaptive voltage scaling & optimization (AVSO).

The LTC3838-2 is designed to meet the extreme accuracy requirements through precision differential output sensing, and offer dynamic output voltage scaling using the differential external reference voltage input.

DUAL DIFFERENTIAL V_{OUT} ACCURACY THAT MATTERS

To obtain superior regulation accuracy, power supply designers sometimes bypass a controller's internal error amplifier and instead use a discrete precision reference and external op amps to control the power stage. The problem is that soft-start and many common fault control features such a overvoltage protection might be sacrificed, depending on the technique used.

The LTC3838-2 avoids this trade-off by allowing the use of an external reference for accuracy while preserving valuable fault and protection features. With a precision voltage reference (such as LTC6652) from Linear Technology, or a DAC for programmability, the channel 2 output of the LTC3838-2 can be tightly regulated from 0.4V to 5.5V in applications with currents up to 25A per channel. At a very low 0.6V, the LTC3838-2 is able to achieve a total

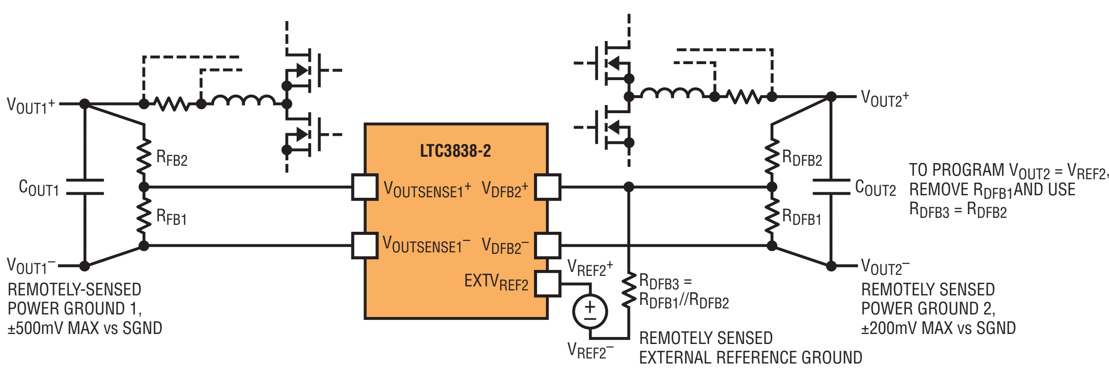

Figure 1. Channel 2 of the LTC3838-2 regulates to an external reference; channel 1 to an internal reference. V_{OUT1} and V_{OUT2} allow remote grounds up to ±500mV and ±200mV, respectively. V_{REF2} is also differentially sensed, but no separate pin for the remote ground of external reference is required.

For differential external reference sensing, the LTC3838-2 has only one pin for external reference input. Channel 2 features a unique feedback amplifier configuration, which eliminates the need for a separate pin to sense the external reference's remote ground. Instead, one additional resistor, equal to the parallel of the two feedback resistors, is used to connect to the remote ground externally.

combined accuracy of ±4mV, or ±0.67%, over all operating conditions including line, load, extreme temperature and remote ground deviation up to ±200mV.

Relative accuracy improves as the reference increases because the absolute error is a smaller percentage out of a larger reference voltage. This contrasts with programming the output voltage by scaling feedback with respect to a fixed lower reference voltage, where the percentage error does not change. For example, with an external reference of 2.5V, the total relative tolerance is less than ±0.3%. The LTC3838-2's dual channels can be configured to single-output applications using channel 2's external reference at such accuracy.

TRACKING DYNAMIC DIFFERENTIAL EXTERNAL REFERENCE

For differential external reference sensing, the LTC3838-2 has only one pin for external reference input. Channel 2 features a unique feedback amplifier configuration, which eliminates the need for a separate pin to sense the external reference's remote ground. Instead, one

Figure 2. A LTC3838-2, 300kHz, 2-phase single-output step-down converter with inductor-DCR sense. This application converts a 4.5V to 14V input to a dynamic 0.4V to 2.5V output at 50A.

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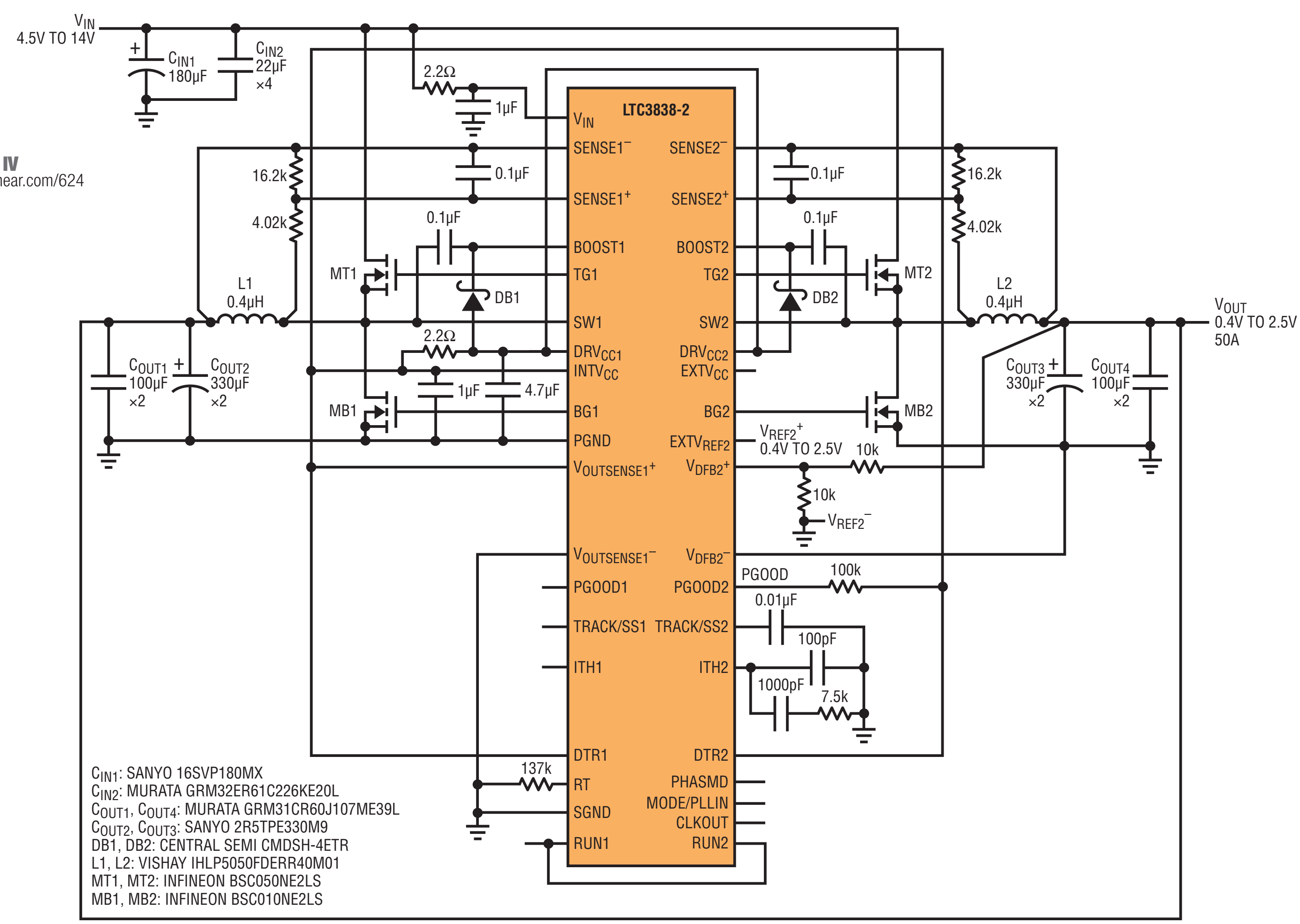


In addition to regulation accuracy, the LTC3838-2 offers wide-bandwidth tracking to a dynamic external reference. Tracking bandwidth is important in applications like dynamic voltage scaling because bandwidth determines how quickly the supply can respond to changes to the programmed external reference.

additional resistor equal to the parallel of the two feedback resistors is used to connect to the remote ground externally. See the LTC3838-2 data sheet for an explanation of how this configuration works.

Figure 2 shows a typical LTC3838-2 application with external reference input. This 2-phase converter is capable of producing 50A over a wide ranging output from 0.4V to 2.5V. For example, at 1.5V this application can achieve 0.4% total combined accuracy for all operating conditions. The high accuracy and superior transient performance make the LTC3838-2 well suited for the most demanding processor applications.

In addition to regulation accuracy, the LTC3838-2 offers wide-bandwidth tracking to a dynamic external reference. Tracking bandwidth is important in applications like dynamic voltage scaling because bandwidth determines how quickly the supply can respond to changes to the programmed external reference.

Figure 3 shows Bode plots from a 350kHz LTC3838-2 step-down converter compensated to an aggressive bandwidth close to 1/3 of the switching frequency without sacrificing stability. This allows the LTC3838-2 to track an external sine wave of 3.5kHz or 1/100 switching frequency at full power, without any noticeable distortion even at the sine wave's very high bandwidth start and stop instants (Figure 4). Careful attention should be paid to the bandwidth requirements for any dynamic system. The wide-bandwidth external-reference-tacking capability, in addition to high speed transient performance, makes the LTC3838-2 ideally suited for the most dynamic supply applications.

LT3838-1 CONTROLLER: INTERNAL REFERENCE ON BOTH CHANNELS

The LTC3838-1 shares the same functions as LTC3838-2, except channel 2 of the LTC3838-1 uses a 0.6V internal reference. Like its predecessors, the LTC3838 and LTC3839, both the LTC3838-1 and -2 use the controlled on-time, valley current mode architecture, which offers superior regulation during fast load transients without the typical switching period response delay of fixed frequency controllers, while still capable of constant frequency switching locked to an external 200kHz to 2MHz clock. They retain all features of the LTC3838, including the proprietary detect transient release (DTR), which improves the transient performance in low output voltage applications. Like the LTC3838, both LTC3838-1 and -2 include a full set of popular features, such as an external V_{CC} power pin, R_{SENSE} or inductor-DCR current sensing, selectable light load operating modes, overvoltage protection and current

Figure 3. Loop gain and closed-loop Bode plots taken with an OMICRON Lab network analyzer on V_{OUT2} of a 350kHz LTC3838-2 step-down converter with external reference ($EXTV_{REF2}$).

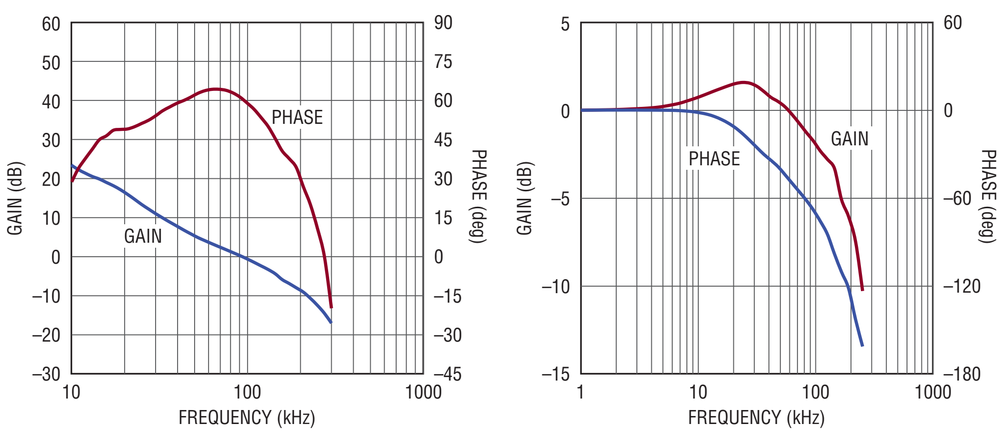
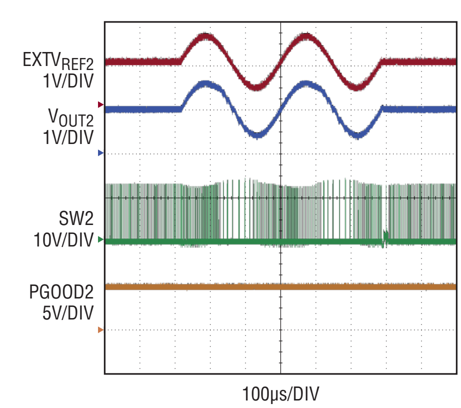


Figure 4. The LTC3838-2 tracks a 1V peak-to-peak, 3.5kHz sine wave external reference.



The LTC3838-1/-2 is the ideal choice for power in applications requiring fast transient performance, dual accurate differential output regulation, and external references for increased V_{OUT} accuracy and programmability down to 0.4V.

limit foldback, soft-start/rail tracking, and PGOOD and RUN pins for each channel.

In addition to the differential remote output sensing on both channels, a significant improvement of the LTC3838-1/-2 over the original LTC3838 is the maximum current sense threshold voltage (i.e., current limit) accuracy. Unlike the LTC3838, which has a continuously variable and two fixed current limit ranges (V_{RNG}), the LTC3838-2 has a fixed V_{RNG} of 30mV (typical) and its tolerance over temperature is ±20%, which is much improved. The LTC3838-1 has the same 30mV and an additional 60mV (typical) V_{RNG} setting whose tolerance is also significantly tighter. Refer to Table 2 for the comparison on the current limit tolerances and V_{RNG} controls of the LTC3838-series 2-channel controllers.

The LTC3838-1/-2 controllers require a minimum V_{IN} pin voltage of 4.5V, but this does not limit the power input to 4.5V. For example, many digital systems have an available regulated 5V rail, which can be used to bias the V_{IN} pin and gate drivers, and to efficiently step down inputs less than 4.5V.

Figure 5 shows the V_{IN} pin connected via diode-OR to the V_{BIAS} 5V rail and to power V_{IN}, 3.3V–14V, rail. This allows the power V_{IN} rail to dynamically switch between a higher voltage and a minimum of 3.3V. When operating with the power V_{IN} supply below 5.5V, this application requires the V_{BIAS} supply to be present at $EXTV_{CC}$ in order to maintain

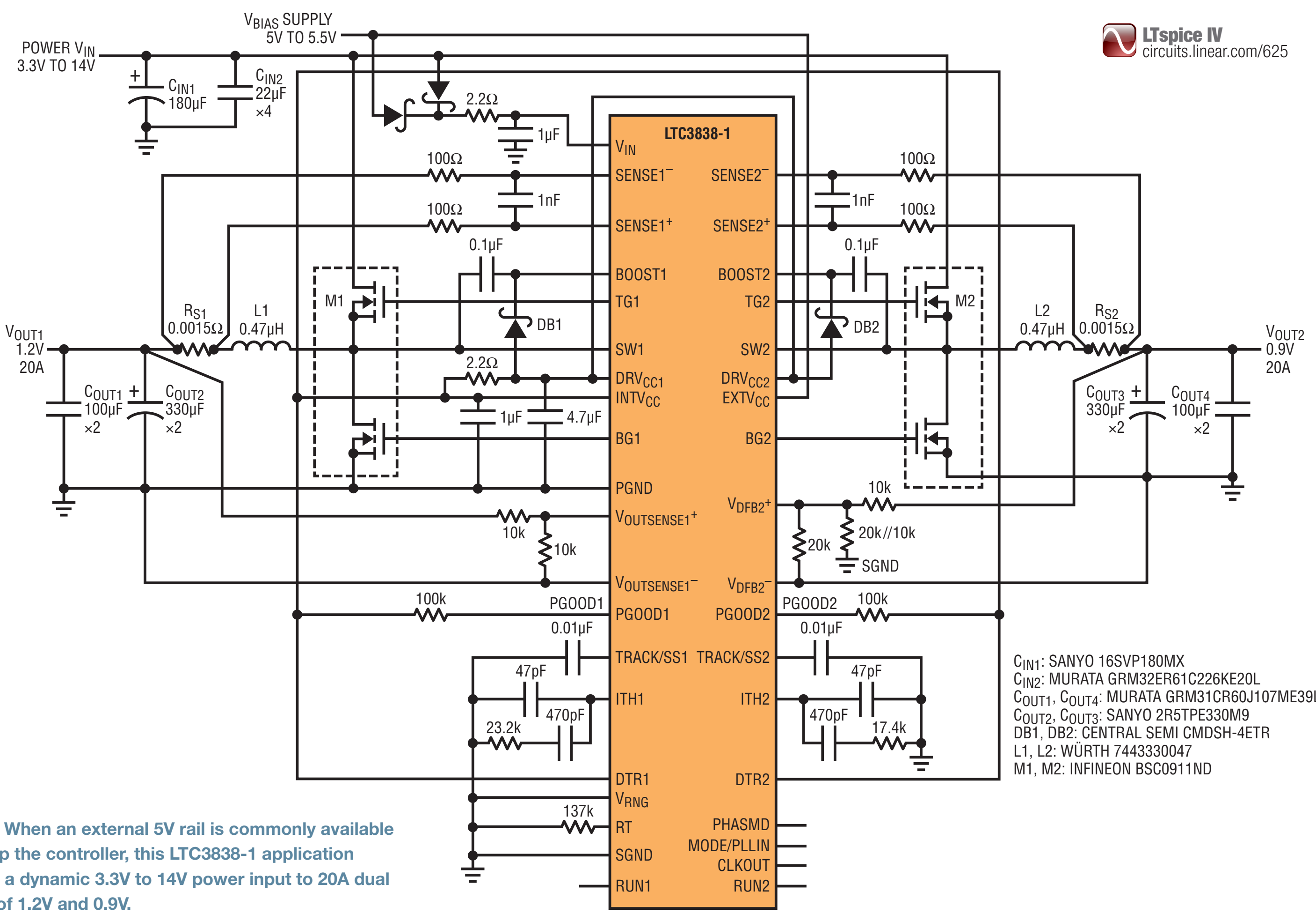


Figure 5. When an external 5V rail is commonly available to bias up the controller, this LTC3838-1 application converts a dynamic 3.3V to 14V power input to 20A dual outputs of 1.2V and 0.9V.

Using an external reference, the LTC3838-2 can achieve total accuracy levels as low as 0.3% under all operating conditions. The external reference feature is designed to accommodate dynamic voltage scaling and track fast external reference inputs with minimum distortion.

Table 2. Maximum Current Sense Threshold Voltage Specifications and Range Controls

PART	V_{RNG} = SGND	V_{RNG} = $INTV_{CC}$	V_{RNG} CONTROL	V_{RNG} PIN(s)
LTC3838 and LTC3839	21mV to 40mV	39mV to 61mV	30mV–200mV continuous & 30mV/50mV fixed	each per channel
LTC3838-1	24mV to 36mV	54mV to 69mV	30mV/60mV fixed	single
LTC3838-2	24mV to 36mV		30mV fixed only	no

DRV_{CC}, $INTV_{CC}$ and V_{IN} pin voltages needed for the IC to function properly. The $EXTV_{CC}$ supply is optional when the power V_{IN} supply is at or above 5.5V.

Note that the power input voltage range of this application cannot be generalized for other frequencies and output voltages, and each application that needs a power input voltage different from the V_{IN} pin voltage should be tested individually for margin of range in which the switching nodes (SW1, SW2) phase-lock to the clock output (CLKOUT).

SUMMARY

The LTC3838-1/-2 is the ideal choice for power in applications requiring fast transient performance, dual accurate differential output regulation, and external references for increased V_{OUT} accuracy and programmability down to 0.4V. Compared to the original LTC3838, the LTC3838-1/LTC3838-2 offers differential output sensing on *both* channels, improved current limit accuracy, and the choice of internal/external reference. Using an external reference, the LTC3838-2 can achieve accuracy levels as low as 0.3% under all operating conditions. The external reference feature is designed to accommodate dynamic voltage scaling and track fast external reference inputs with minimum distortion.

The LTC3838-1 and -2 are offered in 38-pin QFN (5mm × 7mm) packages with exposed pads for enhanced thermal performance.

Visit www.linear.com/LTC3838-1 and /LTC3838-2 for data sheets, demo boards, a variety of applications designs, and for more information about how:

- a 30ns minimum on-time enables high step-down ratios, e.g., from 38V to 0.8V at 350kHz
- 2MHz switching frequency enables applications with tiny power components
- 25A output becomes practical at 2MHz, with 95% peak efficiency (2V-5V V_{OUT}). ■

For More Information…

THE LTC3838/LTC3839, PREDECESSOR TO THE LTC3838-1/-2:

See the article:

- **2MHz Dual DC/DC Controller Halves Settling Time of Load Release Transients, Features 0.67% Differential V_{OUT} Accuracy and is Primed for High Step-Down Ratios** in the *LT Journal of Analog Innovation*, April 2012 (Volume 22, Number 1).

THE LTC3833 SINGLE-CHANNEL CONTROLLER

The LTC3838 series of dual controllers are based on and have all features of the single-channel controller LTC3833. For a full discussion of the features shared with LTC3833, refer to the cover article:

- **Fast, Accurate Step-Down DC/DC Controller Converts 24V Directly to 1.8V at 2MHz** in the *LT Journal of Analog Innovation*, October 2011 (Volume 21, Number 3).

4A Li-Ion Battery Charger Accepts Inputs to 32V

Rick Brewster

Advances in Li-ion battery technologies continue to produce batteries with increased capacity and energy density. Charge/discharge rate capabilities are also rising, sometimes to multiple C rates (C is the standard designator for battery capacity stated in amp-hrs). These technologies are making their way into consumer, automotive, medical and industrial markets. In most cases, the charger must be able to recharge multiple sources over a wide range of input voltages.

High capacity/current batteries require chargers that handle the high currents safely, efficiently and cost effectively. Until now, building a safe high current battery charger required the use of multiple ICs and a host of external components resulting in expensive and bulky solutions. The LT3651 integrated battery charger solves this problem by supporting charge currents up to 4A and accepting input voltages to 32V.

BATTERY CHARGER FEATURES

Charger safety is a significant concern as batteries increase in capacity. The LT3651 includes all of the necessary charge termination and protection features. Charge termination methods include C/10 termination or safety timer termination. Additional protection features include battery temperature monitoring, disabling charging of a battery that is too hot or cold, battery preconditioning for deeply discharged batteries and bad battery detection when in timer mode.

The LT3651 provides an additional PowerPath™ feature that regulates battery charge current in response to total input supply current. With this feature, the battery charger current is reduced if other loads on the input supply increase their current such that the total input supply load exceeds a programmed limit. This allows designers to reduce the input supply requirements to more efficiently manage power. This feature can also be used to enforce a thermal budget by limiting a set maximum input power.

The LT3651 can be programmed via an external resistor for switching frequency, average battery charger current and input current limit (reducing battery charge current to try and maintain constant input current). An external capacitor sets timeout period for timer controlled termination.

The LT3651 operates at high frequency, reducing inductor and filter component size. The frequency is user adjustable, offering the advantage of reduction of power dissipation at higher voltages and control of spectral harmonics.

THE CHARGE CYCLE

Li-ion battery charging typically uses a constant-current/constant-voltage (CC/CV) charging algorithm. A Li-ion battery is initially charged with constant current, generally between 0.5C and 1C, though newer batteries can use higher rates. As the battery voltage approaches the full-charge float voltage, the charger reduces charge current and transitions into constant voltage operation. The LT3651 prevents overcharging of the battery, protecting the battery against damage. There are four variants of the LT3651 supporting 4.1V, 4.2V, 8.2V and 8.4V float voltages.

The LT3651 combines a synchronous buck switcher with a battery charger to efficiently produce high charge current. It provides a CC/CV charging characteristic and adjusts charge current

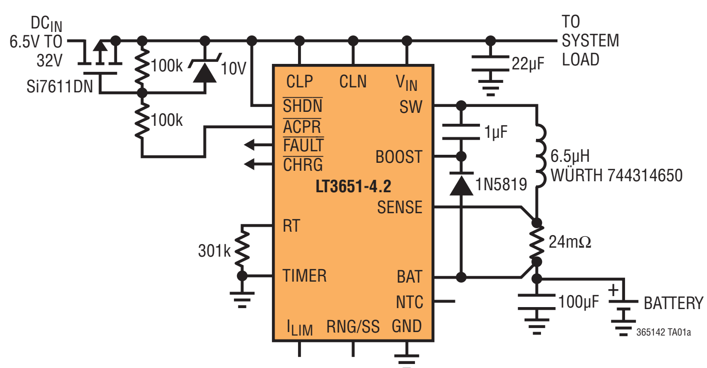


Figure 1. Basic single cell 4A charger

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Charger safety is a significant concern as batteries increase in capacity and usage. The LT3651 includes all of the necessary charge termination and protection features. Charge termination methods include C/10 termination or safety timer termination.

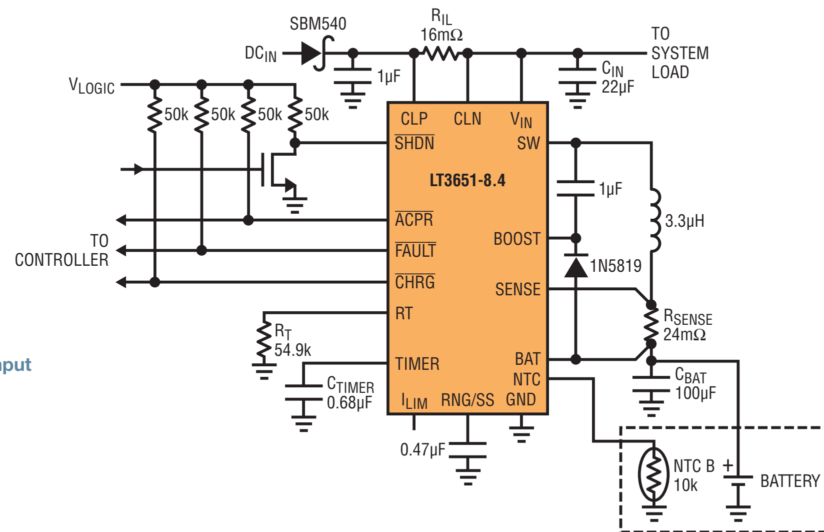

Figure 2. 2-cell Li-ion 9V to 32V charger with input current limit and 3-hour charge timeout

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based on battery voltage. During constant-current operation, the maximum charge current provided to the battery is programmable via a sense resistor, up to a maximum of 4A and adjustable using the RNG/SS pin. Charge current is internally reduced as the battery approaches the full-charge float voltage and the charger transitions to constant voltage charging mode.

A charge cycle terminates by either charge current level or time. Once terminated, the charger is in a low power state, which draws about 85µA from the input supply and less than 1µA from the battery. With both termination modes, charging is restarted when the battery voltage drops to 97.5% of the float voltage (the recharge voltage).

Two pins indicate the charging state. While charging the CHRG pin actively sinks current so an LED from a supply to this pin provides visual indication of charging. The pin transitions to a high impedance upon completion of a charge cycle. A FAULT pin provides additional information about charging disruptions such as a battery out of temperature range fault or a bad battery fault.

A 4A CHARGER WITH INPUT SHORT PROTECTION

Figure 1 shows a basic 4A single-cell Li-ion battery charger that operates from a 6.5V to 32V input. Charging is suspended if the input supply voltage exceeds 32V, but the IC can withstand input voltages as high as 40V without damage. So this application can be used for charging from different inputs inside the 6.5V to 32V range.

The 4A maximum charge current corresponds to 95mV across the 24mΩ external sense resistor. This basic design does not take advantage of the status pins, battery temperature monitoring or safety timer features. The battery charging cycle terminates when the battery voltage approaches 4.2V and the charge current falls to approximately 400mA. A new charge cycle is automatically initiated when the battery voltage falls to 4.1V.

A MOSFET is used as a low loss diode to provide reverse blocking in the event of an input short. This prevents battery discharge through the charger.

WIDE INPUT RANGE, 2-CELL CHARGER

Figure 2 shows a 2-cell 9V to 32V charging application. This could be used in an automotive application where the input needs to tolerate a wide input voltage. This application uses the -8.2 or -8.4 option for charging two Li-ion cells at 4A. This application also uses the input current regulation feature. R_{IL} monitors the current drawn from the supply that supplies both the charge current and system load. It is set such that if the combined input current exceeds 6.3A, charge current is reduced to keep input current from increasing. Often input supply voltages

The LT3651 operates at high frequency, reducing inductor and filter component size. The frequency is user adjustable offering the advantage of reduction of power dissipation at higher voltages and control of spectral harmonics.

are relatively constant. For applications where this is true, then the setup in Figure 2 also limits total input power. For example, with a 12V input supply total input power will be limited to about 75W.

In this application, the safety timer is used for termination, the timer is paused for the duration of a temperature fault, so a battery receives a full-duration charging cycle, even if that cycle is interrupted if the battery is out of the allowed temperature range. The capacitor on the timer pin sets the charge time, in this case it is three hours, so charging continues past the C/10 charge point. At timeout the part goes into standby and reduces battery discharge current to less than 1µA.

The timer also provides for determination of a bad battery. The LT3651 has an automatic precondition mode, which gracefully initiates a charging cycle for deeply discharged batteries. If the battery voltage is below the precondition threshold of 70% of the float voltage (5.8V for the -8.4), the maximum charge current is reduced to 15% of the programmed maximum (0.15C) until the battery voltage rises past the precondition threshold. This current is sufficient to activate any safety circuitry in a battery pack and also provides a small charge current. If the battery does not respond to the precondition current and the battery voltage does not rise past the precondition threshold after 1/8 of the charge cycle (22.5min in this application), full-current charge is not initiated and a battery fault is issued.

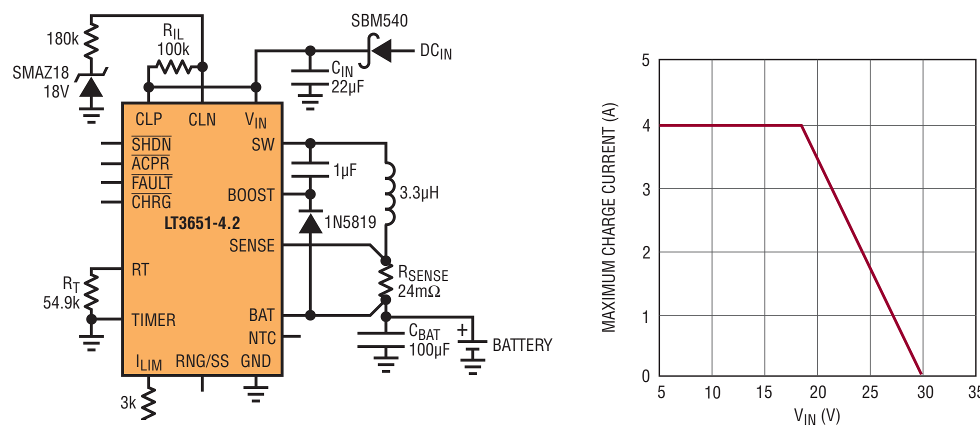

Figure 3. 4A single cell charger with high voltage current foldback

This application also makes use of an external NTC resistor in the battery pack to monitor battery temperature. Under- and overtemperature protection is enabled by connecting a 10k NTC thermistor from the part's NTC pin to ground. This function suspends a charging cycle if the temperature of the thermistor is greater than 40°C or less than 0°C.

The two status pins $\overline{\text{CHRG}}$ and $\overline{\text{FAULT}}$ are used to communicate charger status back to a controller. While the LT3651 does not need a controller to operate, one could be used for additional functionality. The status pins indicate: standby/shutdown; CC/CV charging (>C/10); bad battery detection and temperature fault. Of course in other applications an LED could be placed on these pins for visual indication.

An additional feature of the LT3651 is the ability to withstand input voltages to 40V, which helps in automotive designs.

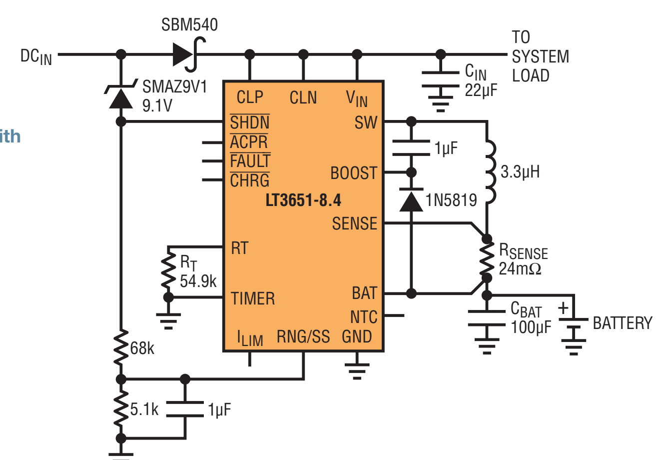

Figure 4. 4A 2-cell charger with low voltage current foldback

The LT3651 is a versatile, compact and easy-to-use solution for charging Li-ion batteries with up to 4A in current and from input supplies up to 32V (40V ride through). High efficiency, built in safety controls and compact size make it an easy fit in a wide variety of applications.

When the input voltage exceeds 32V the output switches are disabled but can ride out the overvoltage condition.

An input diode is used to protect from discharging the Li-ion batteries in the event of an input short. This could be replaced with a MOSFET as in the previous example to improve efficiency.

MORE OPTIONS

The charge current and input current limit control pins can also be used to provide other functionality to a charger application. Figure 3 shows an application where the charge current is diminished with increasing DC_{IN}, a useful feature to control power dissipation of the input source.

Figure 4 shows an application with the inverse feature, where charge current is reduced at lower input voltage, so in the event a supply voltage drops, less load is drawn.

Note in general both the ILIM pin and the RNG/SS pin provide control over charge current and can be changed dynamically to produce additional functionality.

Figure 5 shows an application that offers a maximum power point control (MPPC) feature that regulates input voltage at a constant voltage. This is useful for solar panel applications. It makes use of the input current limit amplifier and reconfigures it for input voltage regulation. The differential CLP-CLN voltage is used to regulate output current. The reference is set with a Zener diode but could be done many ways. The NPNs are used to buffer the CLN input bias current. ILIM is shorted to remove the built-in offset between CLP and CLN. In this case the input regulation is set for 17V, but is adjustable with the 100k/61.9k divider.

SUMMARY

The LT3651 is a versatile, compact and easy-to-use solution for charging Li-ion batteries with up to 4A in current and from input supplies up to 32V (40V ride through). High efficiency, built-in safety controls and compact size make it ideal for a wide variety of applications.

Visit www.linear.com/LT3651 for data sheets, demo boards and other applications information. ■

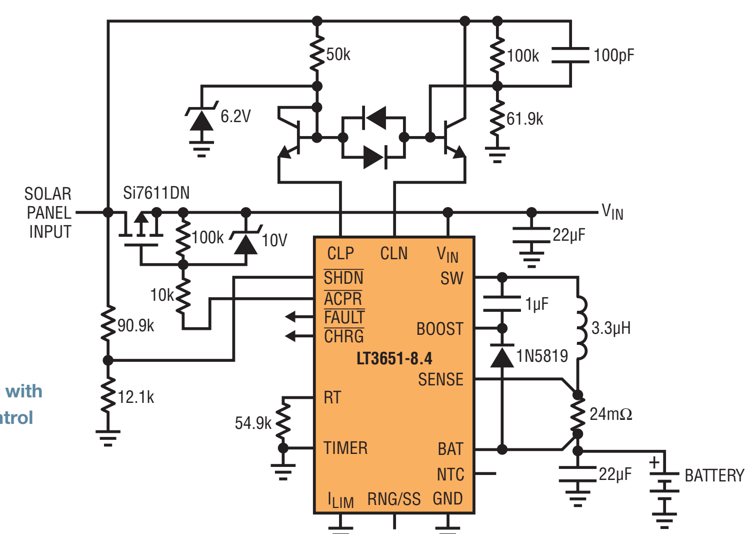

Figure 5. 4A 2-cell charger with maximum power point control

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What's New with LTspice IV?

Gabino Alonso

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

SELECTED DEMO CIRCUITS

Operational Amplifiers

- **LT6016:** Precision high voltage high side load current monitor www.linear.com/LT6016
- **LTC6406:** Differential amplifier with impedance matching and level shifting www.linear.com/LTC6406

Step-Down Regulators

- **LT3763:** 70W, solar powered SLA battery charger with maximum power point regulation (37V–60V to 14V at 5A) www.linear.com/LT3763
- **LTC3646:** High efficiency low quiescent current step-down converter (7V–40V to 5V at 1A) www.linear.com/LTC3646
- **LTM4620A Demo Circuit:** High efficiency single 26A step-down regulator (4.5V–16V to 1V at 26A) www.linear.com/LTM4620A

Linear Regulators (LDO)

- **LT1185:** Negative regulator with 3.5A current limit (6V–16V to −5V at 3A) www.linear.com/LT1185

LED Drivers

- **LTC3783:** Single inductor buck-boost LED driver with analog and PWM dimming (9V–20V to 4× WLEDs at 350mA) www.linear.com/LTC3783

High Side Switches

- **LT1910:** Fault protected high side switch (8V–48V supply) www.linear.com/LT1910

SELECTED DEVICE MODELS

Operational Amplifiers and ADC Driver

- **LT6016:** Dual/quad 3.2MHz, 0.8V/µs low power, Over-The-Top® precision op amp www.linear.com/LT6016
- **LT6236:** Rail-to-rail output 215MHz, 1.1nV/√Hz op amp/SAR ADC driver www.linear.com/LT6236
- **LTC6090:** 140V CMOS rail-to-rail output, pA input current op amp www.linear.com/LTC6090

Step-Down Switching Regulators

- **LT3504:** Quad 40V/1A step-down switching regulator with 100% duty cycle operation www.linear.com/LT3504
- **LTC3646:** 40V, 1A synchronous step-down converter www.linear.com/LTC3646
- **LTC3864:** 60V Low I_Q step-down DC/DC controller with 100% duty cycle capability www.linear.com/LTC3864
- **LTC3890-2:** 60V Low I_Q, dual, 2-phase synchronous step-down DC/DC controller www.linear.com/LTC3890-2
- **LTM4620A:** Dual 13A or single 26A DC/DC µModule regulator www.linear.com/LTM4620A

Buck-Boost Regulators

- **LT8705:** 80V V_{IN} and V_{OUT} synchronous 4-switch buck-boost DC/DC controller www.linear.com/LT8705

LED Driver

- **LT3763:** 60V high current step-down LED driver controller www.linear.com/LT3763

Ideal Diodes and Current Balancing Controllers

- **LTC4353:** Dual low voltage ideal diode controller www.linear.com/LTC4353
- **LTC4370:** Two-supply diode-OR current balancing controller www.linear.com/LTC4370

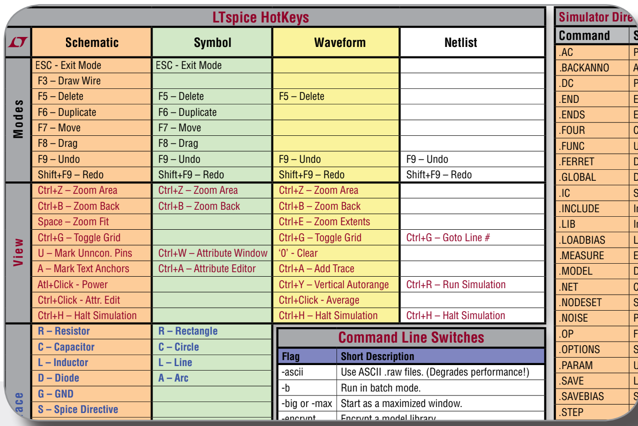
Battery Chargers

- **LTC4009:** High efficiency, multi-chemistry battery charger www.linear.com/4009
- **LTM8061:** 32V, 2A µModule Li-ion/polymer battery charger www.linear.com/LTM8061 ■

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.



	Schematic	Symbol	Waveform	Netlist
Modes	ESC - Exit Mode	ESC - Exit Mode		
	F3 – Draw Wire			
	F5 – Delete	F5 – Delete	F5 – Delete	
	F6 – Duplicate	F6 – Duplicate		
	F7 – Move	F7 – Move		
	F8 – Drag	F8 – Drag		
	F9 – Undo	F9 – Undo	F9 – Undo	F9 – Undo
	Shift+F9 – Redo	Shift+F9 – Redo	Shift+F9 – Redo	Shift+F9 – Redo
View	Ctrl+Z – Zoom Area	Ctrl+Z – Zoom Area	Ctrl+Z – Zoom Area	
	Ctrl+B – Zoom Back	Ctrl+B – Zoom Back	Ctrl+B – Zoom Back	
	Space – Zoom Fit		Ctrl+E – Zoom Extents	
	Ctrl+G – Toggle Grid		Ctrl+G – Toggle Grid	Ctrl+G – Goto Line #
	U – Mark Unncon. Pins	Ctrl+W – Attribute Window	'0' - Clear	
	A – Mark Text Anchors	Ctrl+A – Attribute Editor	Ctrl+A – Add Trace	
	Atl+Click - Power		Ctrl+Y – Vertical Autorange	Ctrl+R – Run Simulation
	Ctrl+Click - Attr. Edit		Ctrl+Click - Average	
	Ctrl+H – Halt Simulation		Ctrl+H – Halt Simulation	Ctrl+H – Halt Simulation
ace	R – Resistor	R – Rectangle		
	C – Capacitor	C – Circle		
	L – Inductor	L – Line		
	D – Diode	A – Arc		
	G – GND			
	S – Spice Directive			

Command Line Switches

Flag	Short Description
-ascii	Use ASCII .raw files. (Degrades performance!)
-b	Run in batch mode.
-big or -max	Start as a maximized window.
-encrypt	Encrypt a model library.

Simulator Dire

Command	S
.AC	P
.BACKANNO	A
.DC	P
.END	E
.ENDS	E
.FOUR	C
.FUNC	U
.FERRET	D
.GLOBAL	D
.IC	S
.INCLUDE	In
.LIB	In
.LOADBIAS	L
.MEASURE	E
.MODEL	D
.NET	C
.NODESET	S
.NOISE	P
.OP	Fi
.OPTIONS	S
.PARAM	U
.SAVE	L
.SAVEBIAS	S
.STEP	

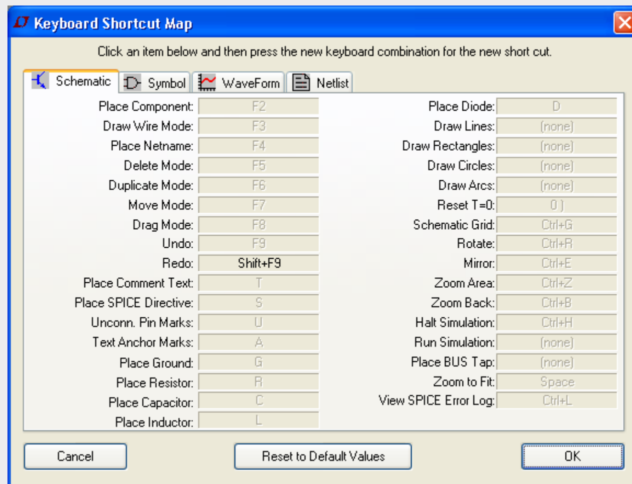
For a complete reference table of Hot Keys, DOT commands and more you can download the LTspice flyer at **www.linear.com/LTspice**.

Power User Tip

KEYBOARD SHORTCUTS

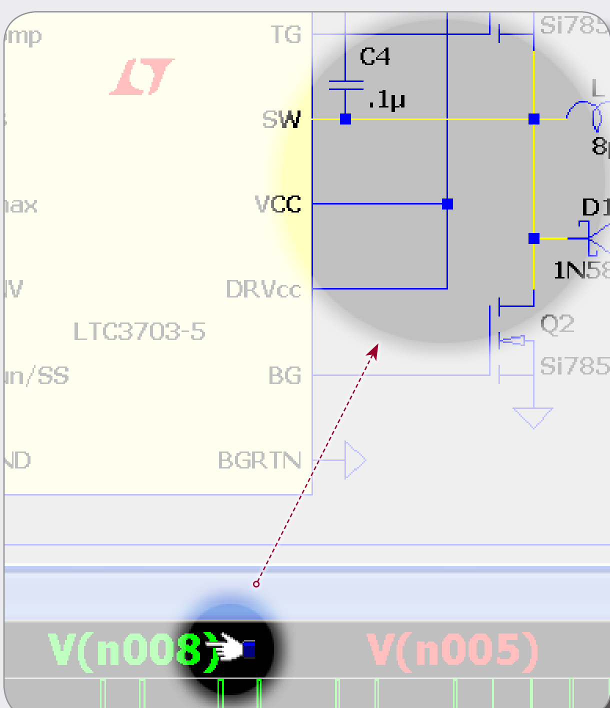
Keyboard shortcuts are an alternate way to invoke one or more commands in LTspice that would otherwise only be accessible by clicking through the menu or toolbar. You can view these shortcuts for the schematic editor by choosing Tools > Control Panel > Drafting Options and clicking Hot Keys. Additional Hot Keys are also available for the Waveform Viewer, Symbol Editor and Netlist Editor.

Hot Keys can be reprogrammed by selecting a command and then pressing the key or key combination for the command. For example, you may want to reprogram the Undo, Redo and Duplicate (Copy) commands to a more traditional key combination. To remove a shortcut, select the command and press Delete.

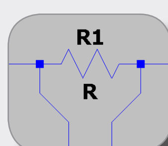


UNDOCUMENTED SHORTCUTS

There are also several undocumented shortcuts in LTspice that may be useful:

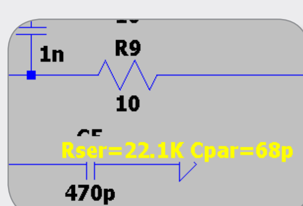


Alt + left-click on a label, V(n008), in the waveform viewer to highlight that particular net in the schematic editor.



To route wires at an angle, hold down Ctrl key as you draw them.

Text with a preceding underscore character, e.g., "_FAULT" is displayed as an overbar, active low, digital signal.



Ctrl + Alt + Shift + H temporarily highlights all hidden text within the schematic. In this example, a series resistor and parallel capacitor are encapsulated and hidden within C5 to simplify layout.

Happy simulations!

Compact Quad Step-Down Regulator with 100% Duty Cycle Operation Withstands 180V Surges

Jonathan Paolucci

Automotive, industrial and distributed applications routinely subject step-down DC/DC converters to a vast assortment of supply voltage transients. High voltage power spikes and input voltage dips can destroy sensitive circuits and jeopardize system reliability. To avoid damage, most applications rely on Tranzorbs or protection circuits that use MOSFETs as pass elements to suppress input voltage transients. If an N-channel MOSFET is used for this purpose, some means of providing gate drive above the input rail is necessary to bias the MOSFET on. Generating this bias is an undesirable complication that most engineers would prefer to avoid.

The LT3504 is a 4-channel monolithic step-down regulator designed for 100% duty cycle operation. Its unique architecture makes available a bias voltage, which is easily adapted to an N-channel protection scheme, allowing the LT3504 to operate continuously through overvoltage transients and dropouts down to 3.2V. Among its many features, the LT3504 includes output voltage tracking and sequencing, programmable frequency, programmable undervoltage lockout, and a power good pin to indicate when all outputs are in regulation.

QUAD 1A STEP-DOWN REGULATOR

Figure 1 shows the complete application circuit for a 4-output, 1A step-down regulator operating over a 3.2V to 30V range. Q1 provides surge protection to 180V. An on-chip boost regulator generates a voltage rail (V_{SKY}) that is 5V greater than the input voltage V_{IN}. Under normal operating conditions ($V_{IN} < 33V$), the V_{SKY} rail supplies gate drive to MOSFET Q1, providing the LT3504 with a low resistance path to V_{SUPPLY}. Additionally, the V_{SKY} pin supplies base drive for the switches in each buck converter channel, which allows for 100% duty cycle and

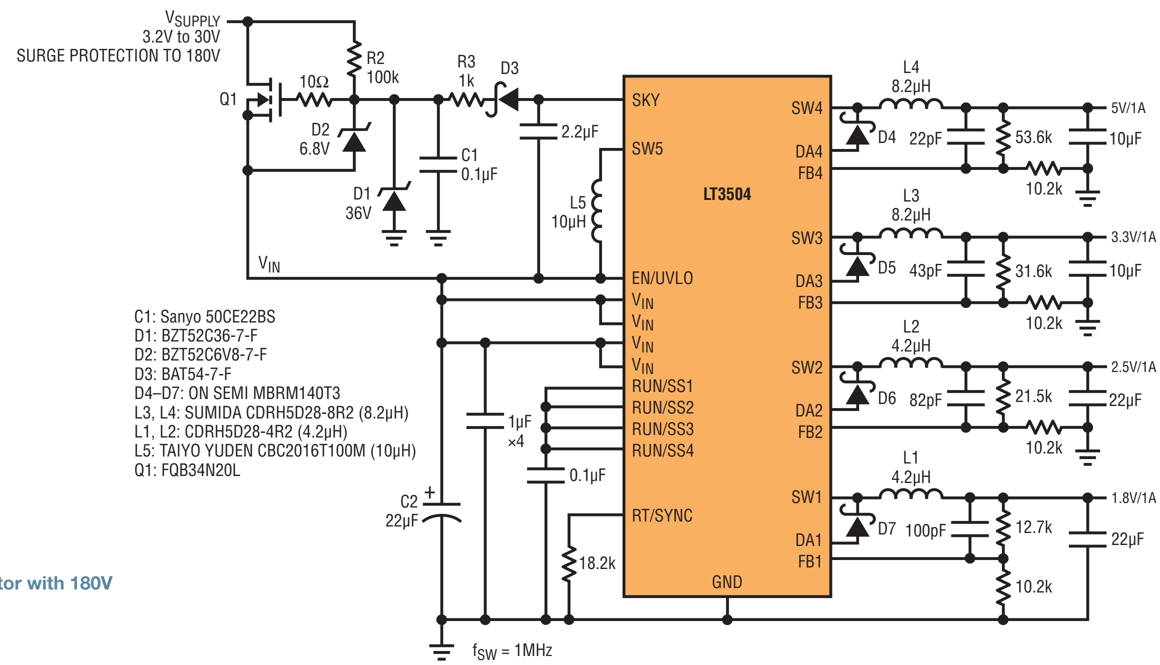


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Figure 1. Complete quad buck regulator with 180V surge protection

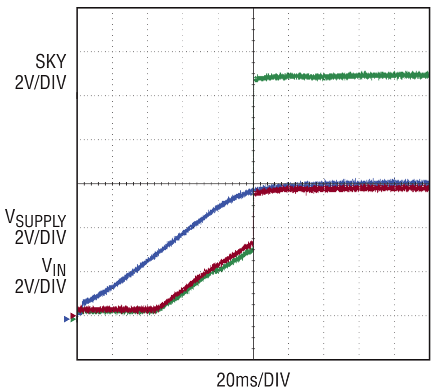


Figure 2. Figure 1's start-up behavior

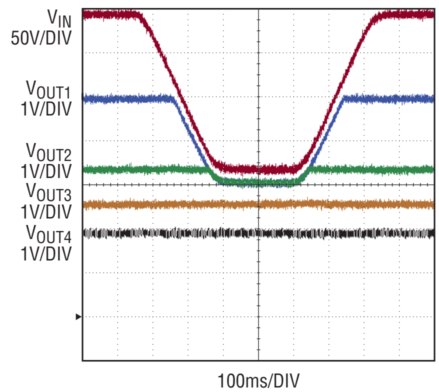


Figure 3. Figure 1's dropout performance

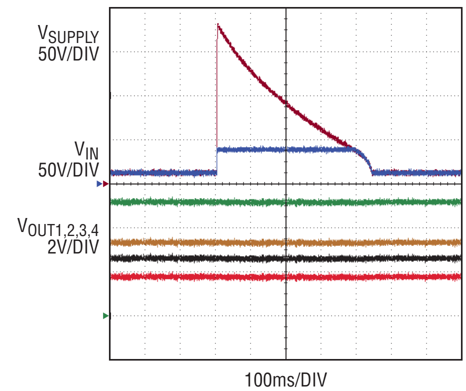


Figure 4. Overvoltage protection withstands 180V surge

eliminates the need for the boost capacitor typically found in buck converters.

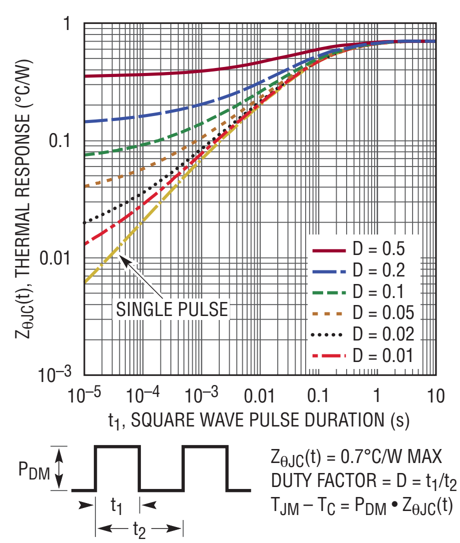
Start-up behavior is shown in Figure 2. Resistor R2 pulls up on the gate of Q1, forcing source-connected V_{IN} to follow approximately 3V below V_{SUPPLY}. Once V_{IN} reaches the LT3504's 3.2V minimum start-up voltage, the on-chip boost converter immediately regulates the V_{SKY} rail 5V above V_{IN}. Diode D3 and resistor R3 bootstrap Q1's gate to the V_{SKY}, fully enhancing Q1. This connects V_{IN} directly to V_{SUPPLY} through Q1's low resistance drain-source path. It should be noted that, prior to the presence of V_{SKY}, the minimum input voltage is about 6.2V. However, with V_{SKY} in regulation and Q1 enhanced, the minimum run voltage drops to 3.2V, permitting the LT3504 to maintain regulation through deep input voltage dips. Figure 3 shows all channels operating down to the LT3504's 3.2V minimum input voltage.

OVERVOLTAGE INPUT TRANSIENT PROTECTION FOR MULTIPLE OUTPUTS

Figure 4 shows the LT3504 regulating all four channels at 1A load through a 180V surge event without interruption. As the supply voltage rises, Zener diode D1 clamps Q1's gate voltage to 36V. The source-follower configuration prevents V_{IN} from rising further than about 33V, well below the LT3504's 40V maximum input voltage rating. The LT3504 uses cycle-by-cycle peak current limiting, as well as catch diode current limit sensing, to protect the part and the external pass device from carrying excessive current during overload conditions.

Bear in mind that significant power dissipation occurs in Q1 during an overvoltage event. The MOSFET junction temperature must be kept below its absolute maximum rating. For the overvoltage transient shown in Figure 4, MOSFET Q1 conducts 0.5A (1A load on all buck channels) while withstanding the voltage difference between V_{SUPPLY} (180V) and V_{IN} (33V). This results in a peak power of 74W. Since the overvoltage pulse in Figure 4 is roughly triangular, average power dissipation

Figure 5. FQB34N20L MOSFET transient thermal response



during the transient event is approximately half the peak power. As such, the average power is given by:

$$P_{AVG}(W) = \frac{1}{2} \cdot P_{PEAK}(W) = 37W$$

In order to approximate the MOSFET junction temperature rise from an overvoltage transient, one must determine the MOSFET transient thermal response as well as the MOSFET power dissipation. Fortunately, most MOSFET transient thermal response curves are provided by the manufacturer (as shown in Figure 5). For a 400ms pulse duration, the FQB34N20L MOSFET thermal response $Z_{\theta JC}(t)$ is 0.65°C/W. The MOSFET junction temperature rise is given by:

$$T_{RISE}(°C) = Z_{\theta JC}(t) \cdot P_{AVG}(W) = 24°C$$

Note that, by properly selecting MOSFET Q1, it is possible to withstand even higher input voltage surges. Consult manufacturer data sheets to ensure that the MOSFET operates within its Maximum Safe Operating Area.

INDUCTIVE SPIKE PROTECTION

Input voltage transients, coupled with low ESR input capacitors, can produce large inductive spikes, which may damage buck converters. These high dV/dt events cause large inrush currents to flow in power connections and filter capacitors, particularly if parasitic inductance and resistance

(continued on page 29)

µModule Regulator Charges Supercapacitor Backup Supply, Supporting LDO Outputs When the Input Supply Fails

Andy Radosevich

The LTM8001 is a µModule regulator that combines a 5A switching regulator with an array of five 1.1A low noise LDOs. The switching regulator can be set for constant current, suitable to charge supercapacitors for power backup. The LTM8001 operates from 6V to 36V inputs. The switching regulator is capable of constant output voltage or constant output current regulation at switching frequencies from 200kHz to 1MHz. The output of the switching regulator can be adjusted from 1.2V to 24V and the outputs of the LDOs are adjustable from 0V to 24V.

The switching regulator is set to regulate output current at 5.6A (typical) to provide a current limit that is above the maximum output current of 5A. The regulated current level can be easily lowered. The inputs for three of the LDOs are hardwired to the output of the switching regulator, but the input to the remaining bank of two LDOs is undedicated, so it can be connected to the switching regulator or elsewhere. The bias inputs to the LDOs are undedicated but are separated into two inputs: one for the bank of three connected to the switching regulator and the other for the remaining bank of two LDOs. The outputs of the LDOs can be operated separately or paralleled for higher output currents.

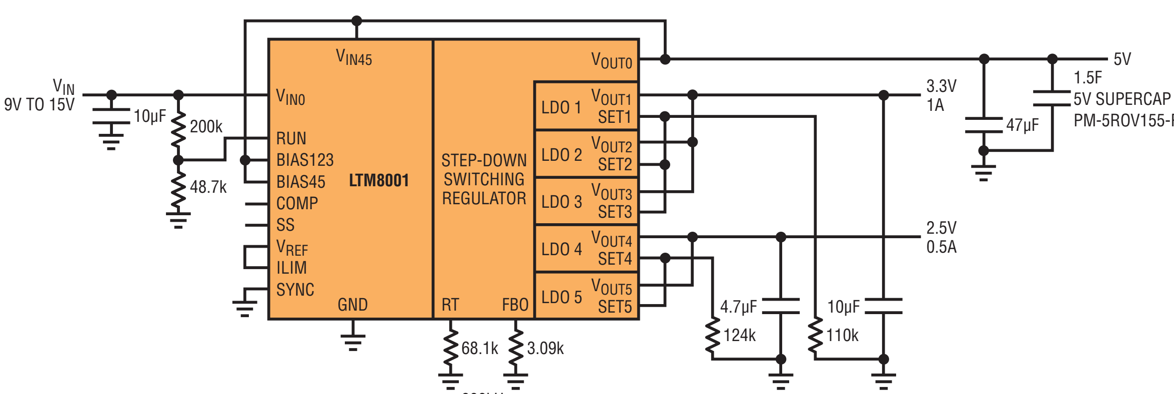
2-OUTPUT REGULATOR WITH SUPPLY RIDE-THROUGH SUPERCAPACITOR

Figure 1 shows the LTM8001 in a dual output application: 3.3V at 1A and 2.5V at 0.5A. This setup also charges a supercapacitor and draws on the supercap to support the outputs in the face of input supply failures.

The switching frequency is 600kHz and the output voltage of the switching regulator is 5V when the supercapacitor is fully charged. The input voltage is from 9V to 15V and the LTM8001 charges the supercapacitor at 5.6A, typical. The resistor divider on the RUN pin programs the circuit to turn on for a 9V or higher input, but also ensures that the switching regulator remains off when back-fed by the supercapacitor when there is an interruption to the input power.

Figure 2 shows LDO V_{BIAS}-to-output dropout voltage vs output current. According to Figure 2, the bias of the higher voltage, 3.3V/1A LDO output must be 1.5V higher than 3.3V, or 4.8V for proper regulation. This means that the LDO outputs remain in regulation during the time the supercapacitor voltage decays 100mV from 4.9V to 4.8V. The 0.07Ω ESR of the PM-5ROV155-R supercapacitor reduces the available voltage from the supercapacitor from 5V to 4.9V while the supercapacitor provides 1.5A to the LDOs. If the supercapacitor is 1.5F and the total

Figure 1. The LTM8001 producing 3.3V at 1A and 2.5V, 0.5A regulated outputs while charging a supercapacitor for backup power.



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The inputs for three of the LDOs are hardwired to the output of the switching regulator, but the input to the remaining bank of two LDOs is undedicated, so it can be connected to the switching regulator or elsewhere. The outputs of the LDOs can be operated separately or paralleled for higher output currents.

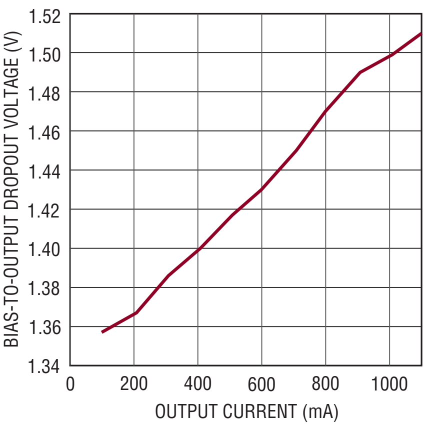

Figure 2. LDO V_{BIAS}-to-output dropout voltage vs output current

output current of the LDOs is 1.5A, the holdup time for the 3.3V LDO output is:

$$
\begin{aligned}
\text{3.3V HOLDUP TIME} &= \frac{C}{I}\Delta V \\
&= \frac{1.5}{1.5}0.1 \\
&= 100\text{ms}
\end{aligned}
$$

Both the LDO bias and LDO input power are connected to 5V from the supercapacitor. Although 5V is non-optimal with

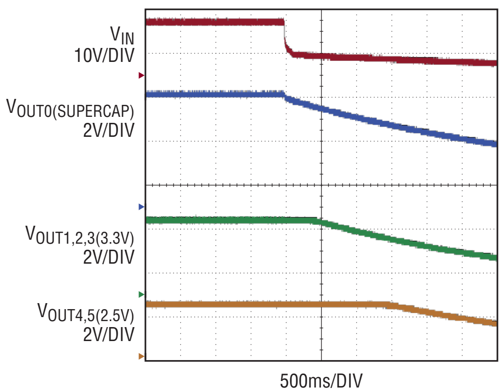

Figure 3. Supercapacitor power backup system holds up the 3.3V output for well over 100ms

regard to power dissipation, it maximizes holdup time if the input supply fails. Power loss is minimized by operating the LDO with inputs that just meet, and do not exceed, the bias dropout requirements of the 3.3V LDO. But the supercapacitor voltage must exceed the input power dropout requirement to meet bias dropout and holdup requirements. To mitigate this increased power dissipation, the LTM8001 parallels LDOs to distribute heat and lower operating temperatures.

Holdup time is longer when the supercapacitor provides bias to the LDOs compared to using a conventional capacitor for that purpose. This avoids detrimental effects of charging a large capacitor directly with the input voltage. Figure 3 shows that the 3.3V output holdup time exceeds 100ms when the supercapacitor is charged to 5V and the LDO outputs are 3.3V at 1A and 2.5V at 0.5A.

CONCLUSION

The LTM8001 makes it easy to design a multiple output voltage regulator circuit featuring supercapacitor backup power. It is possible to achieve significant holdup time without adding large and undesirable capacitance directly to input power.

Visit www.linear.com/LTM8001 for data sheets, demo boards and other applications information. ■

(LT3504 continued from page 27)

is low. External gate network C1 and D2 limits these inrush currents by controlling Q1's gate voltage slew rate. Since V_{IN} follows Q1's gate voltage, the external gate network forces V_{IN} to ramp modestly compared to the abrupt input voltage transient present on V_{SUPPLY}, as shown in Figure 6.

CONCLUSION

The high voltage standoff capability of the series connected MOSFET blocks dangerous spikes from reaching the LT3504. During normal operation, the LT3504's built-in boost regulator permits 100% switch duty cycle operation and serves as an excellent MOSFET gate driver. The LT3504, along with a MOSFET and gate clamp, provides a transient-robust, compact multioutput solution.

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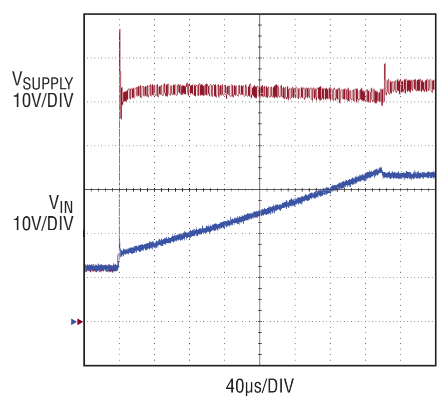


Figure 6. Fast V_{SUPPLY} dV/dt is blocked from V_{IN} by series MOSFET and gate network

New Product Briefs

CONTROLLER REPLACES TWO POWER DIODES WITH MOSFETs TO CONSERVE POWER AND PCB AREA

The LTC4353 is a dual ideal diode controller that replaces power diodes with N-channel MOSFETs to save power, voltage drop, and circuit board space. In high availability redundant supplies and supply holdup circuits for brownout or power-down, high current diode-ORs formed using MOSFETs acting as ideal diodes are more viable and efficient than those using Schottky diodes. The LTC4353 joins the LTC4352, an ideal diode controller for a single low voltage supply. With their unique rapid turn-on feature, both controllers are well suited for low voltage applications where limiting the voltage droop during supply switchover is critical.

The LTC4353 can diode-OR supplies from 0V to 18V. By servoing a 25mV forward drop across the MOSFET, it provides a smooth oscillation-free switchover between supplies. Reverse current through the MOSFET activates a fast turn-off, minimizing shoot-through and fault currents. The LTC4353 can turn on the external MOSFET within a microsecond, faster than most ideal diode controllers. It employs a proprietary technique using an external reservoir capacitor for the integrated charge pump to provide 1.4A of gate pull-up current. A fast turn-on curtails the downward excursion of the ORed voltage, averting nuisance resets in low voltage systems.

Enable pins can hold the MOSFET channel off—turning both off reduces device current consumption. Status outputs indicate when the respective MOSFETs are on. The LTC4353 is available in a compact 4mm × 3mm, 16-pin leadless DFN and a 16-pin MSOP package and operates over a –40°C to 85°C temperature range.

PRECISION 50µV OFFSET OP AMP OPERATES WITH 76V INPUT RANGE

The LT6016 and LT6017 are dual and quad wide input range operational amplifiers. These amplifiers combine high precision with the ruggedness and versatility of Linear Technology's unique Over-The-Top® architecture. Input offset voltage is 50µV max, input bias current is 5nA, and low frequency noise is 0.5µV_{P-P}, making these devices suitable for a wide range of precision industrial, automotive and instrumentation applications.

Over-The-Top inputs provide true operation well beyond the V^+ rail. The LT6016/LT6017 function normally with inputs up to 76V above V^-, independent of whether V^+ is 3V or 50V. Additional fault-tolerant features protect the op amps from reverse supply conditions (up to –50V at V^+), negative transients (up to –25V at V_{IN}), and forced output voltage with no power supplied (up to 50V at V_{OUT}). This robust architecture is especially useful for applications where the amplifier is at the analog interface to another board, and for high side and low side current sensing.

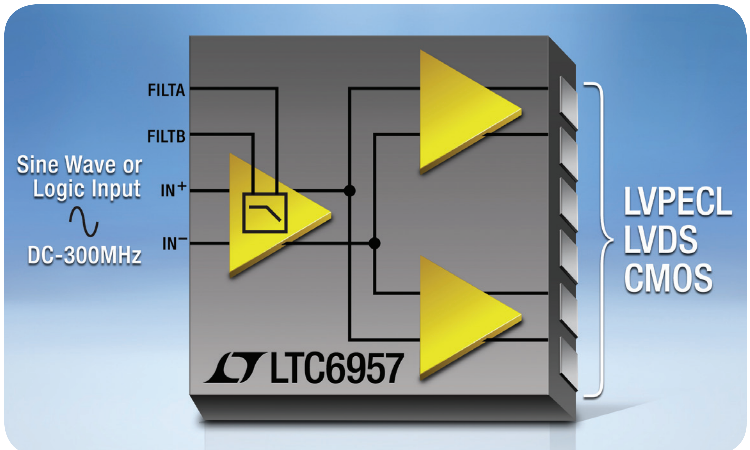
The LT6016 and LT6017 are fully specified over –40°C to 85°C, –40°C to 125°C, and –55°C to 150°C temperature ranges. The dual LT6016 is available in an 8-lead MSOP package; the quad LT6017 in a 6mm × 3mm DFN package.

DUAL OUTPUT SINE WAVE TO LOGIC CONVERTER UTILIZES SELECTABLE INPUT FILTERING FOR LOWEST ADDITIVE JITTER

The LTC6957 is a DC to 300MHz dual output buffer/driver/logic translator, ideal for converting low frequency sine waves into low phase noise logic level signals. Prior solutions were unable to perform this conversion without introducing a significant amount of jitter. The LTC6957 converts any DC to 300MHz reference frequency into dual LVPECL, LVDS or CMOS outputs with exceptionally low additive jitter of 45f_{SRMS} (LTC6957-1) over 12kHz to 20MHz integration bandwidth and less than 150f_{SRMS} total jitter. The device also features a proprietary, selectable, input stage bandwidth-limiting feature, which substantially improves the phase noise for slow slewing signals by up to 3dB–4dB.

While the LTC6957 can be used to convert any signal type to a logic level signal, it particularly excels with sine waves. The selectable, band-limited input stage enables optimal conversion of sine waves with the lowest additive jitter. The device is ideal for systems that distribute system clock references for board level synchronization. It can also be used as a clock driver for analog-to-digital converters (ADCs), digital-to-analog converters (DACs) or DDS (direct digital synthesis) ICs with clock rates up to 300MHz.

The LTC6957 is offered in four output logic signal types: the LTC6957-1 provides two LVPECL outputs, the LTC6957-2 provides two LVDS logic outputs, and the LTC6957-3 and LTC6957-4 offer two CMOS or



The LTC6957 converts any DC to 300MHz reference frequency into dual LVPECL, LVDS or CMOS outputs with exceptionally low additive jitter of $45fs_{RMS}$ (LTC6957-1) over 12kHz to 20MHz integration bandwidth and less than $150fs_{RMS}$ total jitter.

complementary CMOS outputs, respectively, with output skew as low as 2ps (typ). Each device is available in small RoHS-compliant 12-pin MSOP or 3mm × 3mm DFN packages and can be ordered in industrial and automotive grades, supporting operating temperature ranges from –40°C to 85°C and –40°C to 125°C, respectively.

WIDE V_{IN} RANGE, LOW NOISE, 250mA BUCK-BOOST CHARGE PUMP

The LTC3245 is a switched capacitor buck-boost DC/DC converter that produces a regulated output (3.3V, 5V or adjustable) from a 2.7V to 38V input. The device uses switched capacitor fractional conversion to maintain regulation over a wide range of input voltage. Internal circuitry automatically selects the conversion ratio to optimize efficiency as input voltage and load conditions vary. No inductors are required.

The unique constant frequency architecture provides a lower noise output than conventional charge pump regulators. To optimize efficiency at the expense of slightly higher output ripple, the device has pin-selectable Burst Mode operation. Low operating current (20µA with no load, 4µA in shutdown) and low external parts count (three small ceramic capacitors) make the LTC3245 ideal for low power, space constrained automotive and industrial applications. The device is short-circuit and overtemperature protected, and is available in thermally enhanced 12-pin MSOP and low profile 3mm × 4mm 12-pin DFN packages.

SPI/DIGITAL OR I²C µMODULE ISOLATOR PROVIDES THREE ISOLATED POWER RAILS

The LTM2883 is a 6-channel SPI/Digital or I²C digital µModule® isolator with triple rail regulated power for 3.3V and 5V systems. In industrial systems applications, ground potentials can vary widely, often exceeding the tolerable range, which can interrupt communications or even destroy components. The LTM2883 breaks ground loops by electrically separating communication signals, isolating the logic level interface on each side of an internal inductive isolation barrier that withstands a very large common-mode voltage range up to $2{,}500V_{RMS}$. The LTM2883's low EMI isolated DC/DC converter powers the communications interface and provides adjustable 5V, +12.5V, and –12.5V supply outputs, ideal for powering data converters in data acquisition systems. With $2{,}500V_{RMS}$ of galvanic isolation, onboard secondary power and a communications interface operating at up to 20Mbps, the LTM2883 requires no external components and provides a simple µModule solution for isolated data communications.

The LTM2883 is available in two communications interface versions. The LTM2883-I is I²C compliant at up to 400kHz with bidirectional serial data (SDA) plus clock (SCL) and three additional isolated CMOS logic signals that operate at up to 20Mbps. The LTM2883-S is SPI compliant and offers a total of six CMOS digital isolator communication channels. All channels operate at up to 20Mbps and include three forward direction signals ($\overline{CS}$, SCK and SDI) and three reverse direction signals (SDO, DO1 and DO2). When configured for SPI, SPI/Digital or I²C µModule Isolator communications, the maximum clock rate is 8MHz for unidirectional communication or 4MHz for round-trip bidirectional operation.

An onboard 2MHz DC/DC converter powers the LTM2883 and allows each of the three isolated power supply outputs to source up to 20mA over the full operating temperature range. A logic supply pin provides direct interfacing with low voltage microcontrollers down to 1.62V, and an ON pin enables the LTM2883 to be shut down using less than 10µA. Additional features include uninterrupted communications for common mode transients greater than 30kV/µs and rugged ±10kV ESD HBM across the isolation barrier.

The LTM2883 is available in 3.3V or 5V supply voltage versions. The LTM2883 is offered in a 15mm × 11.25mm surface mount BGA package; all integrated circuits and passive components are housed in this RoHS-compliant µModule package. ■

SOLAR POWERED CONVERTER WITH MPPC CHARGES STORAGE CAPACITOR

The LTC3129 is a high efficiency, 200mA buck-boost DC/DC converter with a wide V_{IN} and V_{OUT} range. It includes an accurate RUN pin threshold to allow predictable regulator turn-on and a maximum power point control (MPPC) capability that ensures maximum power extraction from nonideal power sources such as photovoltaic panels.

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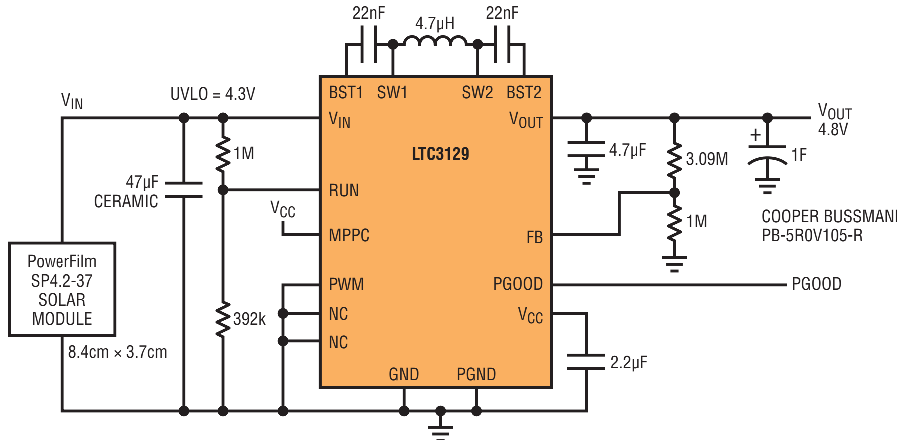

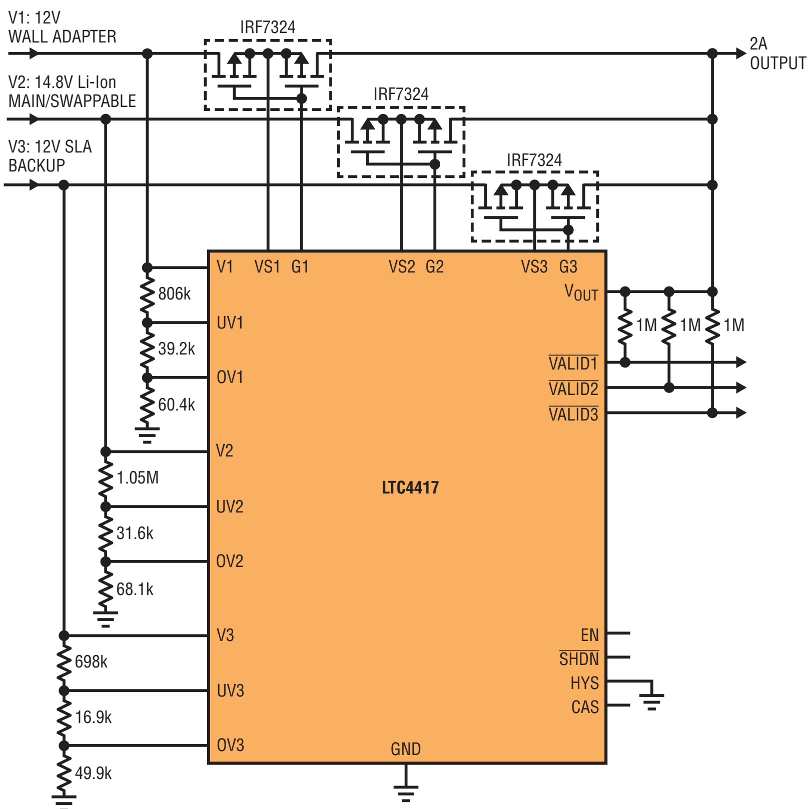

PRIORITY SWITCHING FROM 12V MAIN SUPPLY TO 14.8V BATTERY BACKUP

The LTC4417 connects one of three valid power supplies to a common output based on priority. Priority is defined by pin assignment, with V1 assigned the highest priority and V3 the lowest priority. A power supply is defined as valid when its voltage has been within its overvoltage (OV) and undervoltage (UV) window continuously for at least 256ms. If the highest priority valid input falls out of the OV/UV window, the channel is immediately disconnected and the next highest priority valid input is connected to the common output. Two or more LTC4417s can be cascaded to provide switchover between more than three inputs.

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CHARGE PUMP 12V TO ±5V SUPPLY

The LTC3260 can supply up to 100mA from the inverted input voltage at its charge pump output, V_{OUT}. V_{OUT} also serves as the input supply to a negative LDO regulator, LDO^-. The charge pump frequency can be adjusted between 50kHz and 500kHz by a single external resistor. The MODE pin is used to select between high efficiency Burst Mode operation or constant frequency mode to satisfy low noise requirements.

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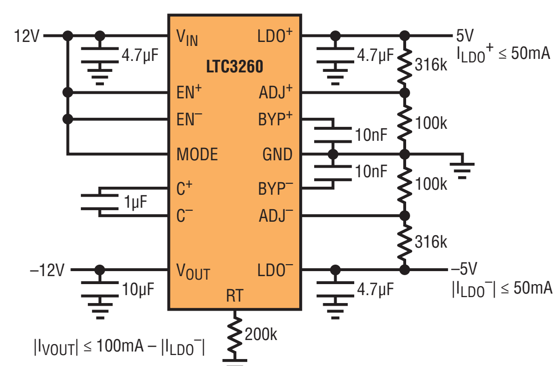

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