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20A LED Driver with Accurate $\pm 3\%$ Full Scale Current Sensing Adapts to Multitude of Applications

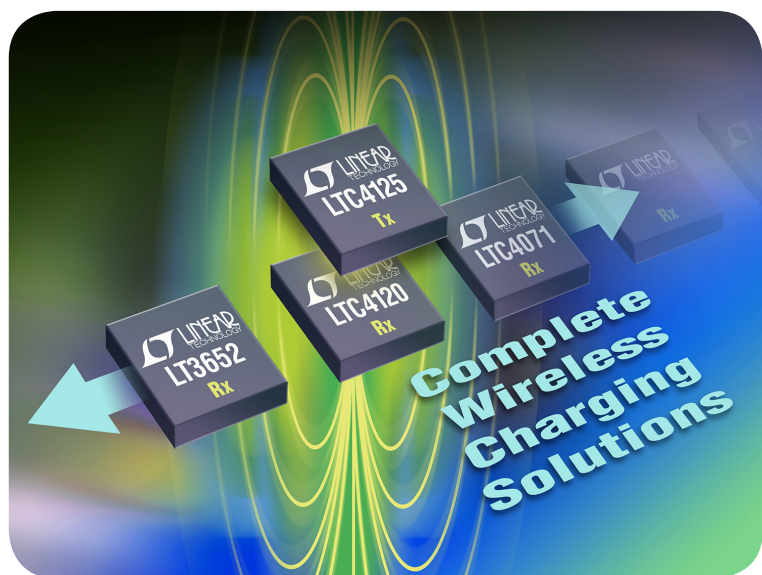
Josh Caldwell and Walker Bai

Rapidly evolving LED lighting applications are replacing nearly all traditional forms of illumination. As this transformation accelerates, power requirements for LED drivers increase, with higher currents making it more challenging to maintain current sensing accuracy without sacrificing efficiency. LED drivers must do this while managing current delivery to multiple independent LED loads at high speeds, and be able to connect parallel drivers with accurate current sharing.

Some high power LEDs have unique mechanical and electrical considerations, where the anode is electrically tied to the thermally conducting backtab. In a traditional LED driver with a step-down regulator configuration, where thermal management is achieved by cooling the chassis, the anode connection to the backtab creates a mechanical-electrical design challenge. The backtab must have good thermal conductivity to the heat sink, but also be electrically isolated from it if the voltage at the tab is different from the chassis. Since it is difficult for LED manufacturers to change processing or packaging, the LED driver itself must meet this design challenge.

One option is to use a 4-switch positive buck-boost LED driver, but the additional switching MOSFETs add system complexity and cost. An inverting buck-boost topology uses only one set of switching power MOSFETs, and allows the anode heat sink to be tied directly—electrically and

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The LTC4125 5W AutoResonant wireless power transmitter features foreign object detection and completes linear wireless charging solutions (see page 31).

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SINGAPORE TEST FACILITY EXPANDS TO BOOST PRODUCTION CAPACITY

In February, Linear opened the company's third semiconductor test facility in Singapore. The additional space for staff, equipment and materials will allow the company to more than double its production capacity of analog circuits and μ Module[®] (power module) products. This strengthens Linear's ability to meet the growing demand for high performance analog integrated circuits worldwide.

The new 87,000 square foot facility is located beside Linear Technology's current 191,000 square foot facility in Singapore. The company's Singapore test operation, started 27 years ago in 1989, has sophisticated capabilities for high volume testing of the company's numerous products, including many package types, tape and reel, as well as pack and ship to customers worldwide. The location also includes Linear's Singapore Design Center and the area sales office supporting Singapore, Malaysia, India and Australia/New Zealand.

Continued Expansion

Over the years, Linear has continued to expand its Singapore test operations, with expansion of its first building in 1997 and a second five-story building completed in 2005. This third major expansion, adding an additional 87,000 square foot test facility, is now complete. With head count of nearly a thousand employees today, Linear has a highly experienced team, capable of testing the most high performance analog ICs. The facility provides test capability for over 90 percent of the company's global demand.

Over the past decade, Linear's products have grown in sophistication and complexity. This has paralleled the company's increasing participation in the key electronics growth markets of industrial and automotive. Industrial, at 44 percent of the company's business in the most recent fiscal year, is a broad market that includes industrial process control, factory automation, robotics, instrumentation and medical, among others.

Linear has also enjoyed significant growth in its automotive business, reaching 20 percent of the company's business. This market is driven by the increasing use of electronic systems, replacing mechanical and other systems, in all aspects of the car, from safety and navigation to electronic steering and braking and many systems under the hood. This technical transformation has resulted in analog and power devices that are increasingly complex, and require sophisticated test systems, now installed in the company's Singapore facility. These test systems enable Linear to provide the high quality and reliability demanded by industrial and automotive manufacturers.



Linear's Singapore test facility expands to boost production capacity.

In addition to test capability for the company's analog and power ICs, the Singapore facility has extensive test capability for Linear's growing line of μ Module power products. These are complete power systems-in-package with integrated inductor, MOSFET, DC/DC regulator ICs and supporting components. Each μ Module product is thoroughly tested using Linear's stringent electrical, package and thermal reliability tests. The new Singapore expansion provides the company with additional capacity for testing μ Module products to meet growing demand.

Also located in Singapore is the company's reliability testing center. This is a fundamental part of Linear's operations, focusing on ensuring superior product quality for automotive and other demanding markets.

Grand Opening

In February, Linear's management team was in Singapore for the opening of the expanded test facility. They toured the new facility and spent time with the Singapore operations team.

Robert Swanson, Linear Technology co-founder and Executive Chairman, who flew to Singapore for the opening, said, "The facilities in Singapore are vital

components of our global manufacturing operations. Given the excellent conditions for growth in the region, as well as the skill and dedication of our employees here, Singapore will remain as the headquarters and focal point for all Linear Technology operations in Asia. We will continue to enhance our capabilities here to deliver advanced technology solutions to rapidly growing markets around the world."

Lothar Maier, Chief Executive Officer of Linear Technology, added, "I have high confidence in our Singapore test infrastructure and the talent base we've cultivated here over many years, and we expect to grow it. Our advanced test operations here ensure that our customers in the demanding and fast growing automotive and industrial markets continue to receive the highest quality products."

Complete Manufacturing Capability

Linear's Singapore test operation is just one part of the company's advanced manufacturing operations. These include two wafer manufacturing facilities, located in Milpitas, California and Camas, Washington, as well as a wafer sort and package assembly operation in Penang, Malaysia. These facilities ensure that Linear customers

receive the highest quality products in the shortest possible lead times.

CONFERENCES & EVENTS

Sensor+Test 2016, Nuremberg Exhibition Centre, Nuremberg, Germany, May 10–12, Booth 241, Hall 1—Showcasing Linear's broad line of high performance ICs, including SmartMesh IP™ solutions. There will be working demo applications from European customers using Linear's products. www.sensor-test.de/welcome-to-the-measurement-fair-sensor-test-2016/

Internet of Things World 2016, Santa Clara Convention Center, Santa Clara, California, May 10–12—Linear's Dust Networks® wireless sensor network products. <https://iiotworldevent.com/>

Space Tech Expo, Pasadena Convention Center, Pasadena, California, May 24–26, Booth 8025—Showcasing products for space and harsh environments. www.spacetechexpo.com/

NXP FTF Technology Forum, JW Marriott, Austin, Texas, May 16–19—Power management ICs and μ Module products. www.nxp.com/support/classroom-training-events/nxp-fff-tech-forum:NXP-FTF-TECH-FORUM-HOME

Wireless Japan 2016, Tokyo Big Sight, Japan, May 25–27, Booth 1233—Demonstrating Linear's Dust Networks wireless sensor network products and their ecosystem in Japan. www.wjexpo.com

Sensors Expo & Conference, McEnery Convention Center, San Jose, California, June 21–23, Booth 940—Presenting Linear's energy harvesting family and low power wireless sensor networks. www.sensorsexpo.com/

IEEE Nuclear and Space Radiation Effects Conference, DoubleTree and Oregon Convention Center, Portland, Oregon, July 11–15, Booth 33—Showcasing products for space and harsh environments. www.nsrec.com/ ■

To meet high performance demands, the LT3744 can be configured as a synchronous step-down or inverting buck-boost controller to drive LED loads at continuous currents exceeding 20A. The supply input for the LT3744 is designed to handle 3.3V to 36V.

(LT3744, continued from page 1)

mechanically—to the chassis ground, eliminating the need for electrical isolators on the heat sink, and simplifying the mechanical design of the system.

To meet high performance demands, the LT[®]3744 can be configured as a synchronous step-down or inverting buck-boost controller to drive LED loads at continuous currents exceeding 20A. The supply input for the LT3744 is designed to handle 3.3V to 36V. As a step-down converter, it regulates LED current from 0V up to the supply voltage. As an inverting buck-boost converter, the LT3744 can accurately regulate LED currents with output voltages from 0V down to -20V.

Full-range analog current regulation accuracy is 3%, and even at 1/20th scale, it is better than ±30%. The LT3744 has three independent analog and digital control inputs with three compensation and gate drive outputs for a wide range of LED configurations. By separating the inductor current sense from the LED current sense, the LT3744 can be configured as a buck or inverting buck-boost. For ease of system design, all input signals are referenced to board ground (SGND, signal ground), eliminating the need for complex discrete level-shifters.

In the inverting buck-boost configuration, the total LED forward voltage can be higher than the input supply voltage, allowing high voltage LED strings to be driven from low voltage supplies. When PCB power density calls for spreading the component power

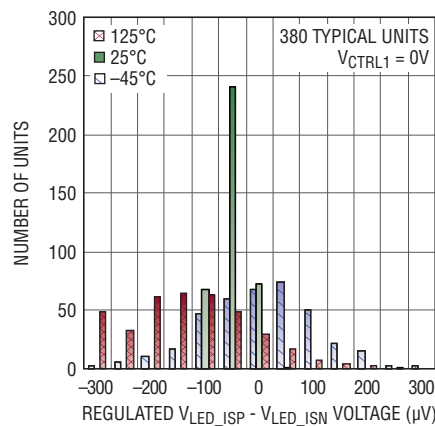


Figure 1. The LED current regulation amplifier in the LT3744 has a typical offset of ±300µV with $V_{CTRL1} = 0V$.

dissipation, the LT3744 can be easily paralleled with other LT3744s to drive high pulsed or DC currents in LED loads.

HIGH ACCURACY CURRENT SENSING

The LT3744 features a high accuracy current regulation error amplifier, which achieves accurate analog dimming down

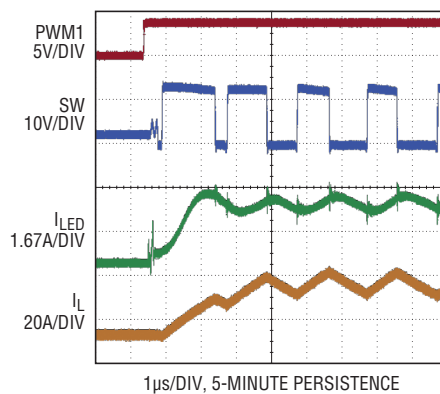


Figure 3. The LT3744 features flicker-free LED dimming.

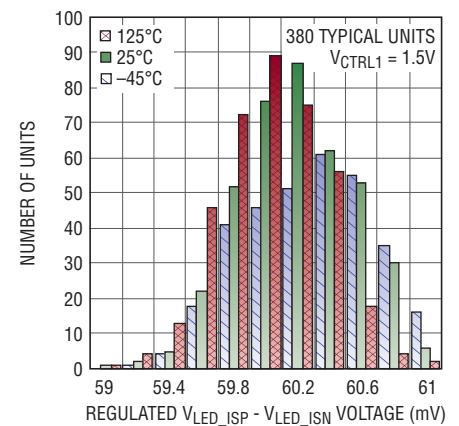


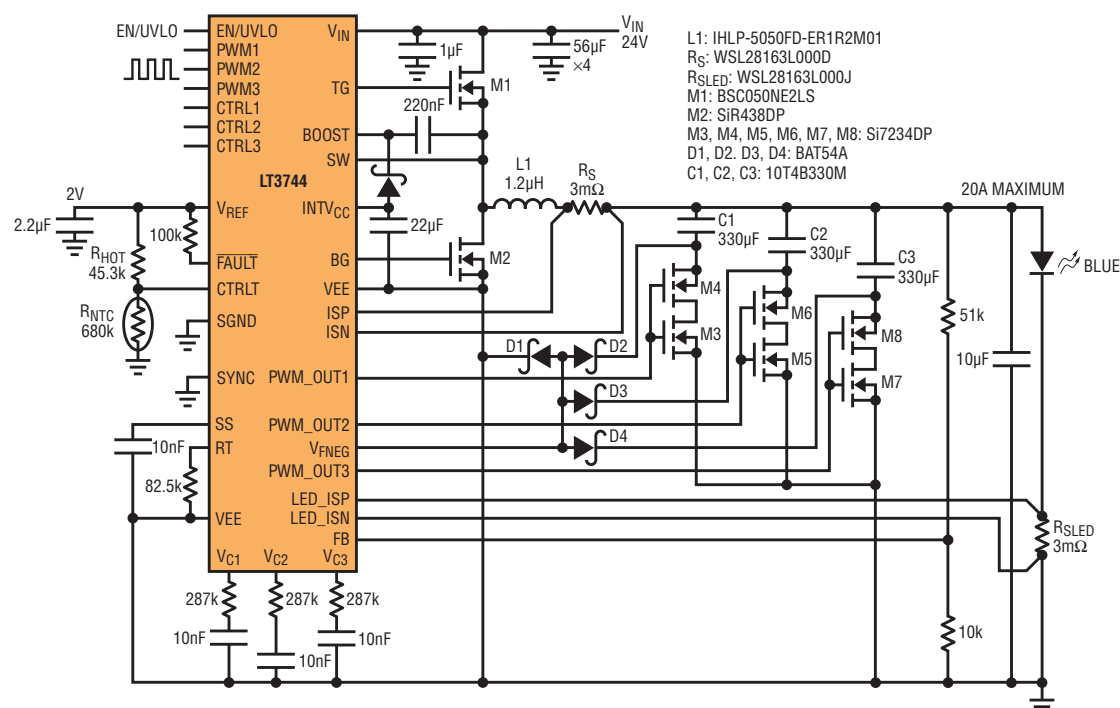
Figure 2. At full current, the LED current regulation loop has a typical accuracy of ±1.7% with $V_{CTRL1} = 1.5V$.

to 1/20th of the total current control range. This is critical in applications where the total digital PWM dimming range is limited—or in applications where very high dimming range is required. As an example, with a 100Hz PWM dimming frequency and a 1MHz switching frequency, the LT3744 is capable of 1250:1 PWM dimming, which can be combined with 20:1 analog dimming to extend the total dimming range to 25,000:1.

Figure 1 shows the production consistency of the LT3744 with regard to offset voltage over temperature, in this case 380 typical units when the analog control input is at 0V. With the low offset of the error amplifier, the control loop is capable of a typical accuracy of ±10% at 1/20th scale analog dimming. The distribution of the regulated voltage across the LED current sensing pins with the control input equal to 1.5V is shown in Figure 2. The accuracy at full range is better than

In projection systems, reducing the turn-on time of the light source reduces timing constraints. With a reduction in timing constraints, the image refresh rate can increase, allowing higher resolution images and a reduction in the rainbow effect from fast-moving white objects. The LT3744 is capable of transitioning between the different output current states in less than three switching cycles.

Figure 4. The LT3744 is capable of driving a single LED with three different current levels.



$\pm 3\%$, which corresponds to $\pm 1.8\text{mV}$ on the 60mV full-scale regulation voltage.

FLICKER-FREE PERFORMANCE

One of the most important metrics in LED driver performance is in the recovery of the LED current during PWM dimming. The quality of the end product is highly dependent on the behavior of the driver in the first few switching cycles after the rising edge of the PWM turn-on signal. The LT3744 uses proprietary PWM, compensation and clock synchronization technology to provide flicker-free performance—even when driving LEDs to 20A .

Figure 3 shows a 5-minute capture of the LED current recovery with a 12V supply delivering 20A to a red LED. The switching frequency is 550kHz , the inductor

is $1\mu\text{H}$, the PWM dimming frequency is 100Hz with an on-time of $10\mu\text{sec}$ ($1000:1$ PWM dimming). Roughly $30,000$ dimming cycles are shown, with no jitter in the switching waveform—every recovery switching cycle is identical.

HIGH SPEED DIMMING BETWEEN THREE DIFFERENT REGULATED CURRENTS

In projection systems, reducing the turn-on time of the light source reduces timing constraints. With a reduction in timing constraints, the image refresh rate can increase, allowing higher resolution images and a reduction in the rainbow effect from fast-moving white objects. The LT3744 is capable of transitioning between the different output current states in less than three switching cycles.

The LT3744 features three regulated current states, allowing color-mixing system designers to sculpt the color temperature of each LED. Color mixing delivers high color accuracy, corrects inaccurate LED colors, and eliminates variations in production systems. While the LT3743 has low and high current states, the LT3744 features three current states so that all three RGB LED colors can be mixed with each other at their own light outputs to independently correct the other colors.

Figure 4 shows a 24V input/ 20A output, single LED driver with three different regulated currents—determined by the analog voltages on the CTRL and the digital state of the PWM pins. Note that since R_S is only used for peak inductor current and absolute overcurrent protection,

Within miniature “pocket” or smartphone projection systems, total solution space and cost are paramount. The LT3744 combines switched output capacitor technology with a floating gate driver to create a complete RGB solution from a single LED driver, a significant space savings over multi-IC drivers.

it does not need to be a high accuracy resistor—which reduces system cost.

PWM dimming between the three different current states is shown in Figures 5 and 6. In Figure 5, the PWM signals are sequentially turned on and off. PWM₃ has the highest priority and PWM₁ has the lowest. This allows rapid, single input signal transitions to change the output current. As shown in Figure 6, there can be any arbitrary interval between the PWM input signals.

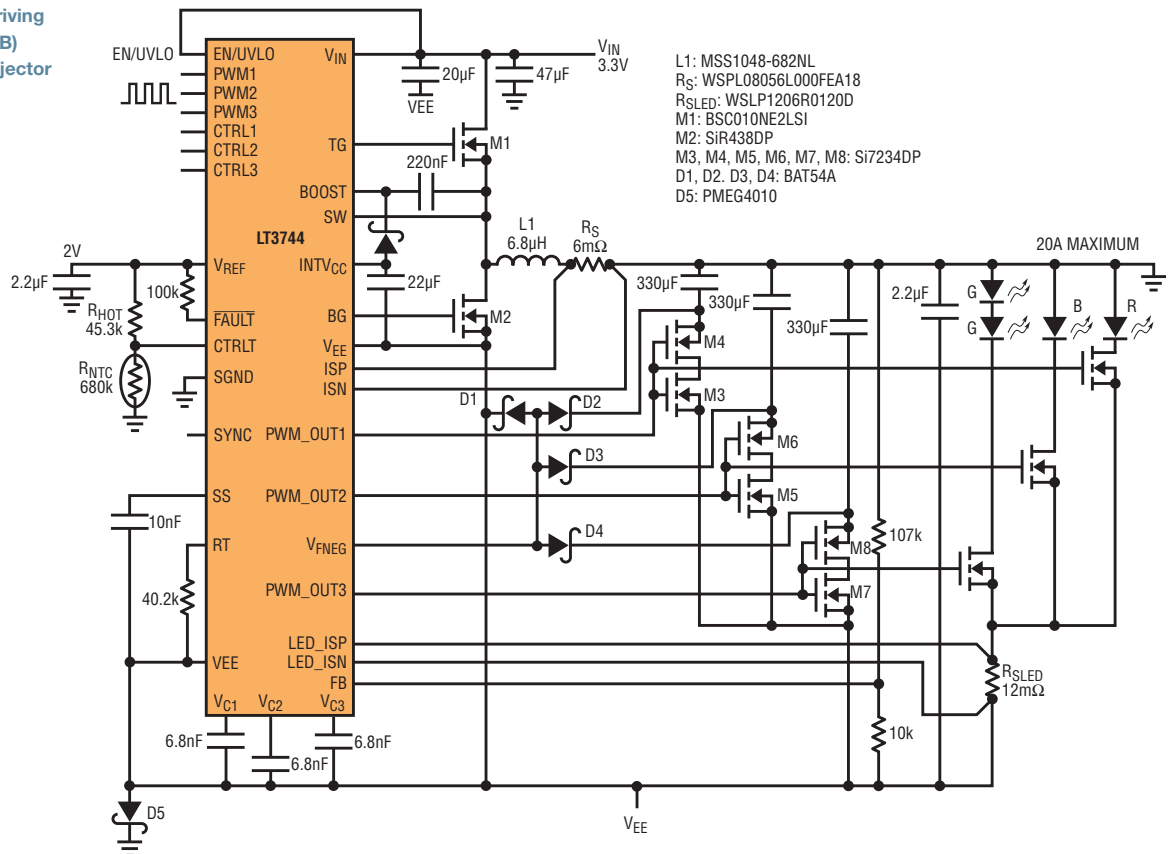
A COMPLETE RGB LED SOLUTION FOR POCKET OR SMARTPHONE PROJECTORS

Within miniature “pocket” or smartphone projection systems, total solution space and cost are paramount. In these applications, PCB space is extremely limited and the total volume of the driver solution (including component height) must be minimized. Using only one LED driver for all three LEDs drastically reduces space—allowing use of larger batteries or higher power LEDs for improved battery lifetime and projected lumens.

The LT3744 combines switched output capacitor technology with a floating gate driver to create a complete RGB solution from a single LED driver. The LT3744 uses a unique gate driver for the PWM output pins. The negative rail of the driver floats on the V_{FNEG} pin, allowing it to pull down the gates of all of the switches that are off to negative voltages. This ensures that the switches in-series with the output capacitors do not turn on in any condition. This driver allows up to a 15V difference between any string of LEDs.

Each LED can be turned on sequentially, with a time delay in between, or with any

Figure 7. The LT3744 is capable of driving all three color component (R, G and B) LEDs in a pocket or smartphone projector from a single Li-ion battery.



In addition, with the three independent analog control inputs, each LED can operate at a different regulated current. When the LT3744 is configured as an inverting buck-boost, a single lithium-ion battery can drive three independent LED strings using only a single controller.

Summary of Linear's high power LED driver-controller family

	LT3741	LT3743	LT3744	LT3763	LT3791
V_{IN} range	6V–36V	6V–36V	3.3V–36V	6V–60V	4.7V–60V
LED output range	0V–34V	0V–34V	–20V–36V	0V–55V	0V–52V
Topology	buck	buck	buck and inverting buck-boost	buck	buck-boost
LED current regulation accuracy	±6%	±6%	±3%	±6%	±6%
$\frac{1}{10}$ scale LED current accuracy	±60%	±60%	±17%	±60%	±35%
Full-scale LED current sense	50mV	50mV	60mV	50mV	100mV
Common anode connection for LEDs			☑		
LED fault indication			☑	☑	☑
Low side LED PWM gate driver(s)	0	2	3	1	1
Individual LED current states	1	2	3	1	1

pattern input into the PWM digital inputs. In addition, with the three independent analog control inputs, each LED can operate at a different regulated current. When the LT3744 is configured as an inverting buck-boost, a single lithium-ion battery can drive three independent

LED strings using only a single controller. Figure 7 shows a 3.3V/5A inverting tri-color buck-boost LED driver designed specifically for RGB pocket projectors.

324W 2-LED DRIVER USING TWO PARALLEL LT3744 LED DRIVERS

A significant limiting factor in any high power/high current controller design is power density in the PCB. PCB power density is limited to roughly 50W/cm² to prevent excessive temperature rise within the power path components. In extreme cases, where an LED load requires more power than a single driver can support (while remaining within power density limits), multiple converters can be paralleled to spread the load.

An efficient high current LED driver-controller, with modern power MOSFETs, can provide roughly 200W (at a solution size of approximately 4cm²) and limit all power path component temperatures to under 80°C. For LED loads higher than 200W, the LT3744 can be paralleled with other LT3744s to limit the temperature rise

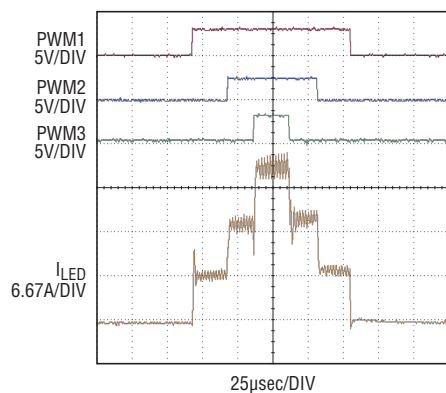


Figure 5. The LT3744 transitions between any of three regulated current states and off in less than three switching cycles.

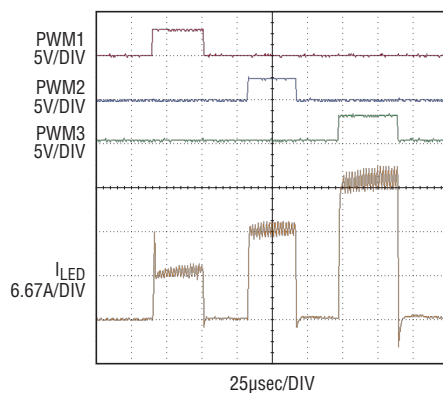


Figure 6. The different current states can be turned on at any time—with or without time in between each state.

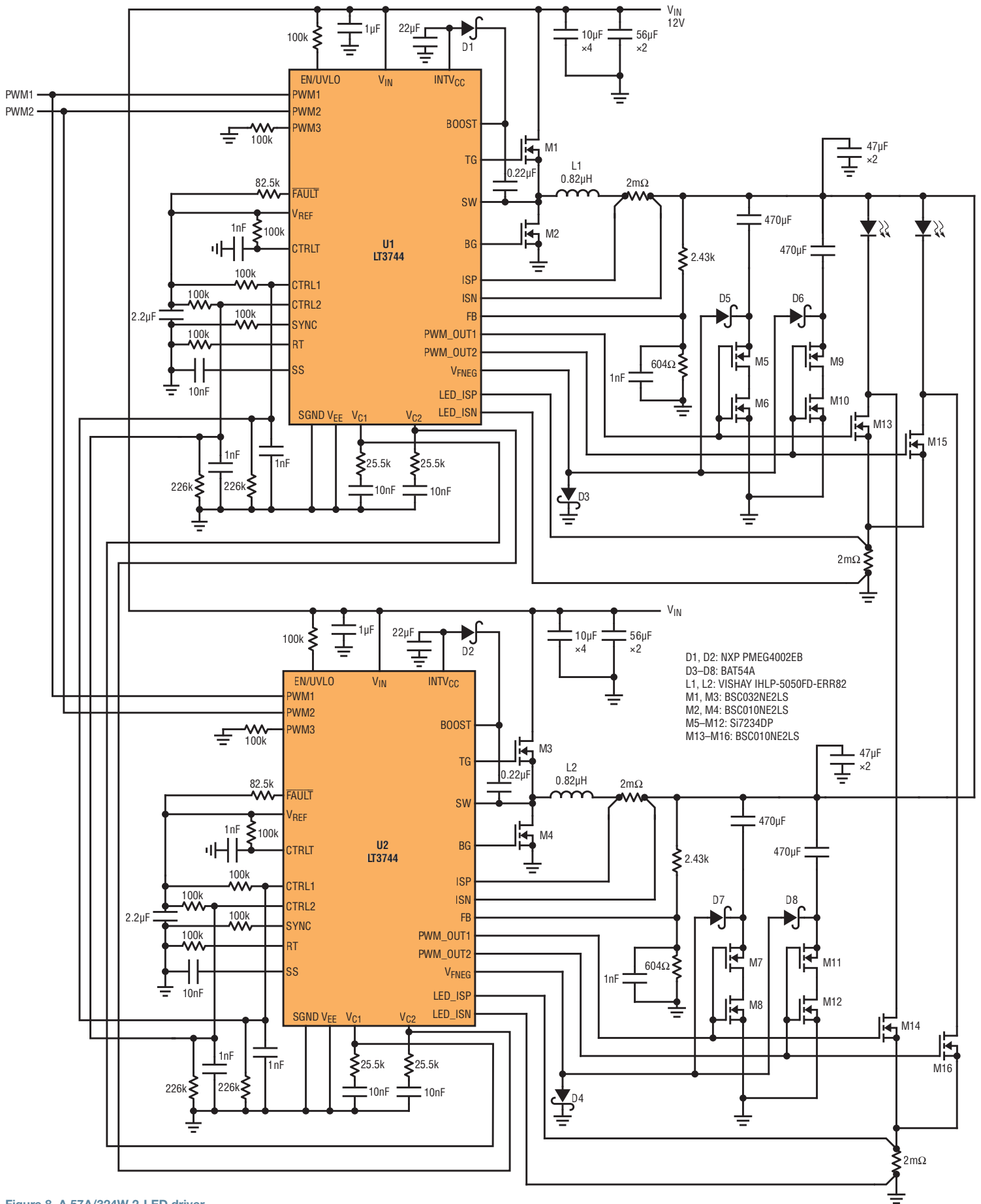


Figure 8. A 57A/324W 2-LED driver

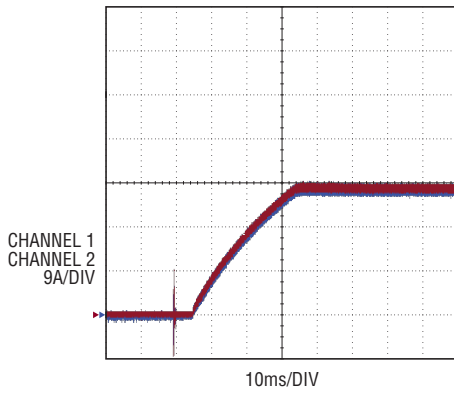


Figure 9. LED current sharing during start-up

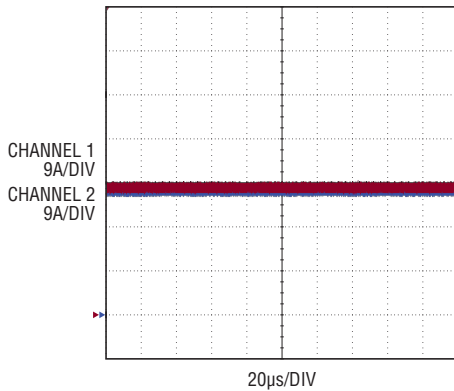


Figure 10. DC LED current sharing at full load—showing very little variation between the two parallel drivers

in any particular component. All compensation outputs should be paralleled, allowing current sharing between each regulator.

Figure 8 shows a 324W converter using two Linear DC2339A demo boards connected in parallel. Each of the parallel

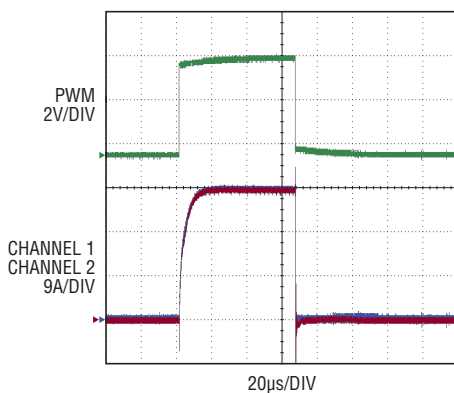
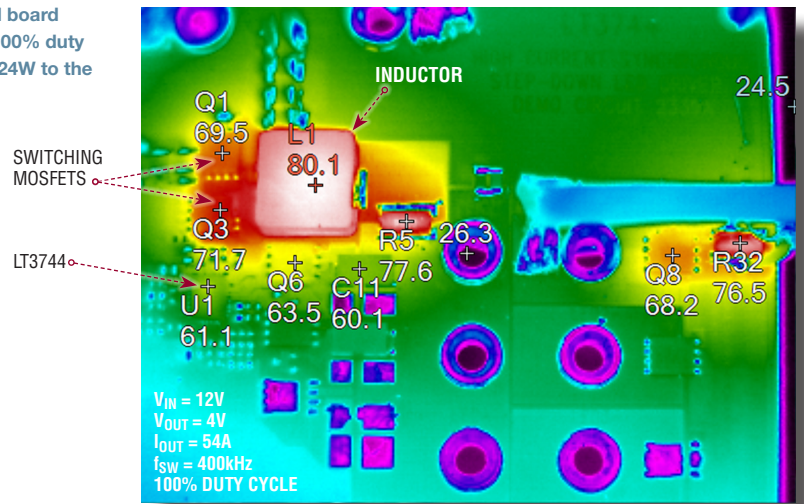


Figure 12. The LT3744 features excellent LED current sharing between parallel drivers during PWM dimming.

Figure 11. Parallel board temperatures at 100% duty cycle delivering 324W to the LED



controllers in this design produces 27A—for a total of 54A at 6V. By tying the corresponding compensation outputs together, both controllers behave in unison to provide a smooth, well behaved start-up and accurate DC regulation.

Figure 9 shows the LED current start-up behavior of each board. Note that the regulated current provided by each board is identical throughout the entire start-up sequence. In DC regulation, without PWM dimming, Figure 10 shows excellent current sharing between the two application boards (the waveforms are directly on top of each other). Figure 11 shows that the temperature rise above ambient of the board at 100% duty cycle is about 55°C. Component L1 is the

inductor, Q1 and Q3 are the switching power FETs, R5 is the inductor current sense resistor, R32 is the LED current sense resistor, and U1 is the LT3744.

In this application, two independent LED strings can be PWM dimmed at the full 54A. When PWM dimming, Figure 12 shows that the LED current is completely shared between the two drivers. In this test, the rise time of the current in the LED from 0A to 54A is 6.6µs. The electrical connection from the output of each driver to the LED must be carefully balanced to avoid added inductance in either path—which reduces the effective rise time.

Figure 13 shows the temperature rise in each demo board with a 50% PWM-dimmed LED current of 54A. To

Figure 13. Parallel board temperatures at 50% PWM dimming delivering 54A pulses to the LED

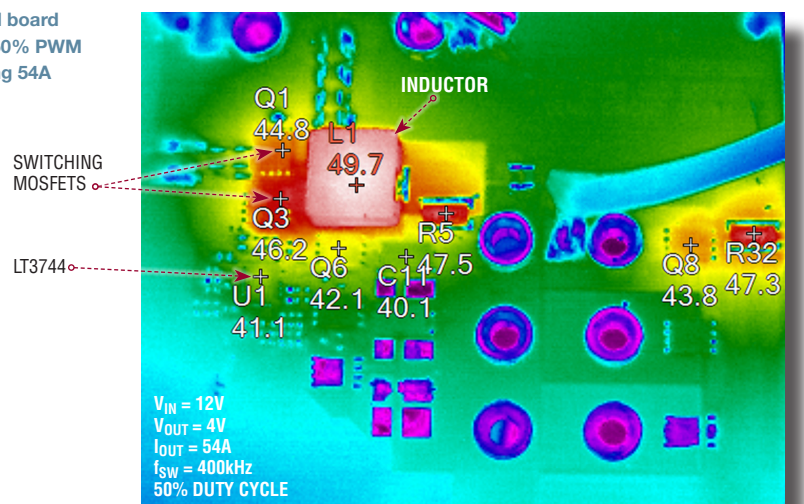
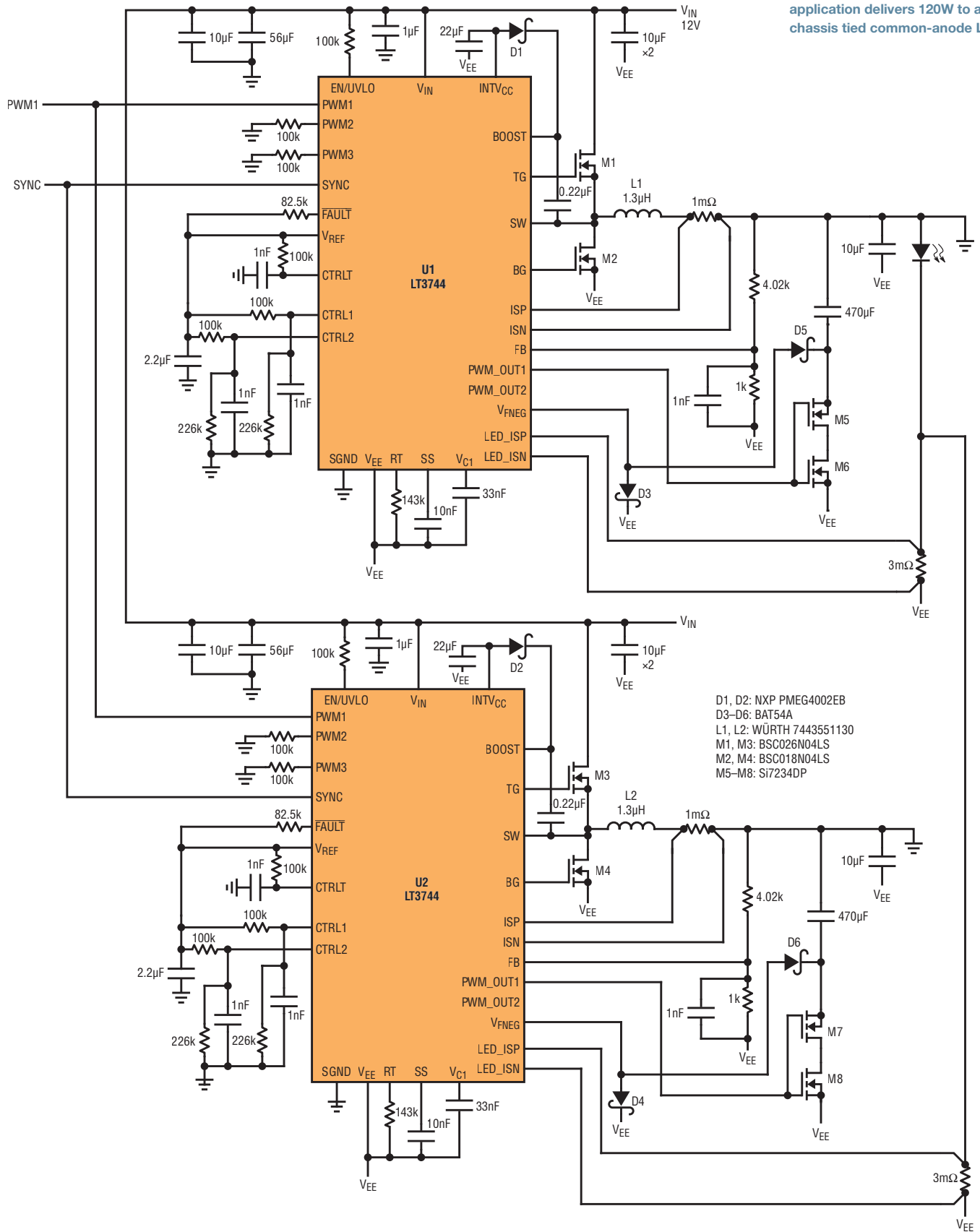


Figure 14. This parallel inverting application delivers 120W to a chassis tied common-anode LED.



By regulating the LED current directly and level-shifting all input signals, the LT3744 is capable of producing negative voltages, allowing low voltage battery operated systems to drive multi-LED strings with a simple 2-switch solution.

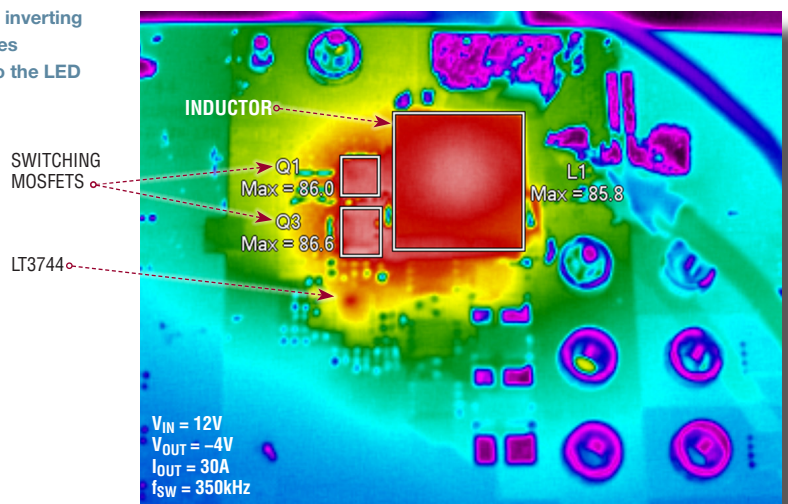
minimize the inductance from each of the demo boards to the LED, the parallel LED driver boards were mounted directly on top of each other. A more optimized layout would feature both drivers mounted on a single board, with the driver layouts mirroring each other, reflected across their mutual connection to the LED. Whenever designing the conduction path from a LED driver to a high current LED, careful attention should be placed on the total inductance. Since inductance is a function of wire length, the longer the wire, the longer the current recovery in the LED—no matter how fast the driver.

INVERTING BUCK-BOOST, 120W LED DRIVER WITH TWO PARALLEL LT3744s

Inverting buck-boost applications have the same thermal concerns as non-inverting converters, with the additional design challenge of increased inductor current. For low input voltages and high LED voltages, the average current in the inductor could be very high. For example, if the input is 3.3V and the output is one green LED—which has a forward voltage of 6V at 20A—the peak inductor current is 70A. The inductor used in the design should have a saturation current at least 20% higher—in this case, greater than 80A.

Since this current flows in the switching MOSFETs, the MOSFETs must be rated for greater than 80A. By placing two LT3744 inverting buck-boost converters in parallel, the peak switched current is cut in half, reducing the requirements of the power path components.

Figure 15. Parallel inverting board temperatures delivering 120W to the LED



In the inverting buck-boost topology, the inductor current is delivered to the load only during the synchronous FET conduction time. If the two parallel converters are allowed to run at their free-running frequencies, there is noticeable beat frequency apparent in the LED current ripple resulting from the slight switching frequency differences. To avoid this, each converter uses the same R_T resistor value, but they are synchronized using an external clock. In the application in Figure 14, the converters are designed to run at a non-synchronized frequency of 300kHz—with a 350kHz synchronizing clock.

Figure 15 shows the component temperature rise when delivering 30A to the LED in a parallel inverting buck-boost application.

CONCLUSION

With features including high current regulation accuracy, a floating PWM gate driver, and level shifted input signals, the LT3744 can be configured to drive LEDs

in a wide range of applications. The LT3744 has the capability to be used as the single driver in an RGB projection system, drastically reducing total solution space—making it possible to produce high lumen video projection from a smartphone.

Through the use of three current regulation states, the LT3744 gives system designers freedom to sculpt LED color, producing more faithful video images. By regulating the LED current directly and level-shifting all input signals, the LT3744 has the capability to produce negative voltages, allowing low voltage battery operated systems to drive multi-LED strings with a simple 2-switch solution. The LT3744 can be easily paralleled with other LT3744s to efficiently deliver extremely high current to an LED, while maintaining current accuracy and sharing even when PWM dimming. Paralleling the LT3744 lowers board temperatures, reduces inductor currents and expands supported LED power to hundreds of watts. ■

Multi-Output Clock Synthesizer with Integrated VCO Features the Low Jitter Required to Drive Modern High Speed ADC and DAC Clock Inputs

Chris Pearson

The latest high performance ADCs cannot realize their potential without an ultralow jitter high speed clock signal. The LTC6951 satisfies the requirements of top ADCs by producing a clock signal up to 2.7GHz with an impressively low wideband noise floor. Figure 1 compares the LTC6951's measured ADC SNR results to other ADC clock sources.

The quantity and performance requirements for low jitter clocks in electronic systems continues to increase with system complexity and performance. This may result in a costly array of parts, including VCOs, PLLs, clock distribution devices and synchronization components to support the clock signals. The LTC[®]6951, on the other hand, *decreases* complexity and cost by integrating a high performance PLL/VCO, and distributing five ultralow jitter clock outputs. Additionally, the LTC6951 supports several software-based synchronization methods: EZSync[™], ParallelSync[™] and EZ204Sync[™] (aka EZParallelSync[™]).

The latest trend in high speed converter digital interfaces is the adoption of the JESD204B standard. Previous generation clocking devices are often incompatible with the JESD204B standard due to different synchronization and output divider requirements. The LTC6951 accounts for these differences, making it capable of supporting JESD204B subclass 1. The LTC6951 introduces Linear's unique reference alignment synchronization method known as ParallelSync, which allows parallel LTC6951s to clock multiple JESD204B devices.

THE INNER WORKINGS OF THE LTC6951

Referring to Figure 2, the LTC6951 features two different configurations based on the setting of the RAO (Reference Aligned Output) register bit. The desired synchronization method determines which configuration is selected. The LTC6951 is divided into three main circuit blocks: the phase-locked loop (PLL) and voltage controlled oscillator (VCO) section, the clock distribution section and the digital control section.

The PLL section works in conjunction with the external reference and the internal 4GHz to 5.4GHz VCO to generate the desired VCO frequency (f_{VCO}) as follows:

$$\text{for RAO} = 0: \quad f_{VCO} = \frac{f_{REF} \cdot N}{R} \quad (1)$$

$$\text{for RAO} = 1: \quad f_{VCO} = \frac{f_{REF} \cdot N \cdot P \cdot MO}{R} \quad (2)$$

Figure 1. LTC6951 performance advantage

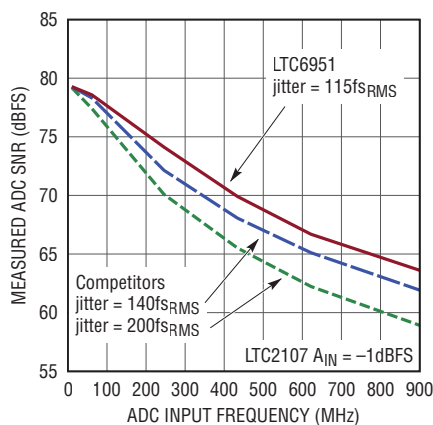
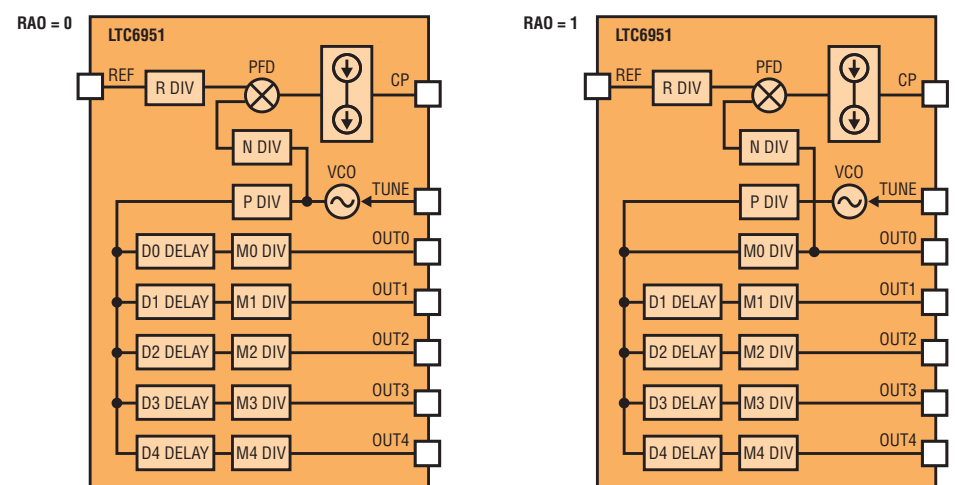


Figure 2. LTC6951 block diagram



The LTC6951 produces clock frequencies up to 2.7GHz with the lowest wideband noise floor in the industry for a clock distribution device. This allows the LTC6951 to directly clock high speed ADCs with very challenging SNR and clock-to-clock skew targets.

where f_{ref} is the reference input frequency, R is the reference input divide value, N is the PLL feedback divide value, P is the prescaler divide value, and Mo is the output divider value. When $RAO = 0$, N is the VCO feedback divide value. When $RAO = 1$, the LTC6951 is in reference aligned output mode and $N \cdot P \cdot Mo$ is the VCO feedback divide value. Reference aligned output mode allows the user to align the outputs of one or multiple LTC6951s to the reference input.

The clock distribution section receives a signal at f_{VCO}/P , where P is the P-divider value. After the P-divider, the clock signal is distributed to five separate channels. When $RAO = 0$, each of the five channels can independently delay the first synchronized clock edge by any integer from 0 to 255 P-divider clock cycles. When $RAO = 1$, OUT0's delay option is disabled. After the delay function, each channel can independently divide the frequency from a list of divider values that range from 1 to 512. The output signal from the dividers is sent to a buffer that determines the output signal type. Four channels produce an ultralow noise differential CML clock signal capable of output frequencies up to 2.7GHz. The fifth channel creates a differential LVDS output that can produce clock frequencies up to 800MHz.

The third and final section is the digital control section, which controls the various synchronization functions and is discussed in detail in the "Synchronization Methods" section of this article. The digital control section includes a standard

Summary of Linear's clock generation and distribution devices

	LTC6950	LTC6951	LTC6954	LTC6957
Internal PLL				
Internal VCO				
Output fMAX (MHz)	1400	2700	1800	300
Outputs	5	5	3	2
Max output divide ratio	63	2048	63	1
EZSync				
ParallelSync				
JESD204B Subclass 1 compatible				
PC-based design, simulation and demo board control	ClockWizard™	LTC6951 Wizard	LTC6954_GUI	

4-wire serial interface and a pin to monitor the status of certain register bits.

PERFORMANCE

There is a trade-off between using filtered ADC clocks for optimal SNR performance or unfiltered ADC clocks for optimal clock-to-clock skew performance. There are several applications with challenging clock jitter and clock-to-clock skew requirements. Examples include JESD204B converters, and multi-arrayed systems such as medical scanners and smart array antennas. Filtering multiple clocks for performance while accounting for variations in filter delays to meet skew requirements can be problematic. The LTC6951 addresses these design challenges by providing multiple CML clock outputs with $115f_{S_{RMS}}$ jitter and $\pm 20ps$ clock skew. For larger arrayed clock systems requiring multiple LTC6951s, $\pm 100ps$ clock skew can be achieved.

To determine the jitter requirement for an ideal ADC clock input, refer to Equations 3 and 4. Equation 3 calculates the total clock jitter required to achieve a desired SNR level at a known full scale analog input frequency. Equation 4 determines the ADC clock input jitter requirement after removing the ADC aperture jitter from the total clock jitter. The ADC aperture jitter number is usually provided in the ADC data sheet. Equation 3 and Figure 1 highlight that as an ADC's analog input frequency increases, lower jitter clocks are required to achieve optimal SNR performance. For a more in-depth discussion of clock jitter requirements for ADCs refer to the LTC6951 data sheet.

$$t_{J(TOTAL)} = \frac{10^{-\frac{SNR_{dB}}{20}}}{2 \cdot \pi \cdot f_{IN}} \quad (3)$$

$$t_{J(CLK_IN)} = \sqrt{t_{J(TOTAL)}^2 - t_{J(APERTURE)}^2} \quad (4)$$

f_{IN} = ADC analog input frequency

Table 1. Synchronization selection table

	EZSync Standalone	EZSync Multichip	ParallelSync	EZ204Sync (EZParallelSync)
Architecture	Standalone	Clock Distribution	Reference Distribution	Reference Divide and Distribution
Jitter	Ultralow	Low	Ultralow	Ultralow
Timing requirements	Easy	Easy	Moderate	Easy
Phase alignment (all outputs)	Yes, at Time 0*	Yes, at Time 0*	Yes, at Time 0*	Yes, phases aligned per LTC6951 sync

*Time 0 alignment implies all outputs requiring synchronization are phase aligned on the same sync event.

Figure 3. EZSync Standalone

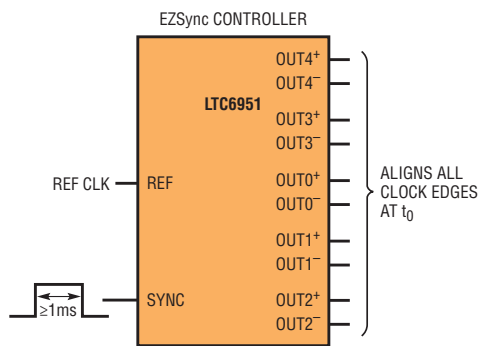
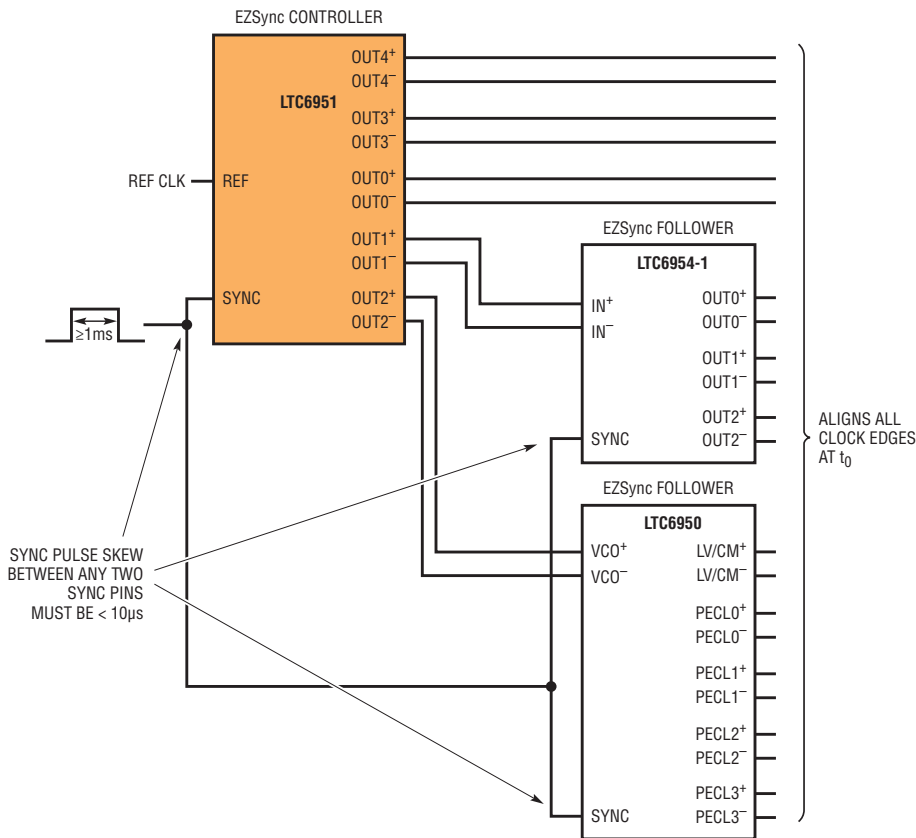


Figure 4. EZSync Multichip



SYNCHRONIZATION METHODS

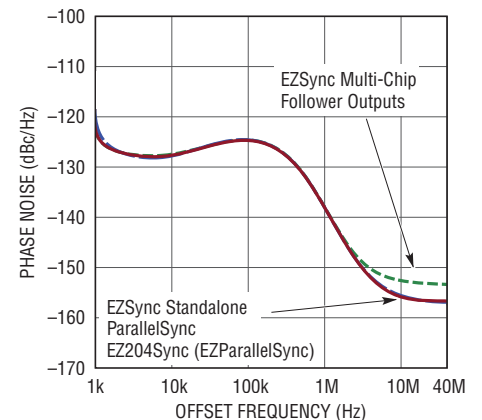
The LTC6951 provides three synchronization methods: EZSync, ParallelSync and EZ204Sync (or EZParallelSync). The advantages and disadvantages of each method are summarized in Table 1 and in the descriptions below.

EZSync Standalone (Figure 3) synchronizes the LTC6951's five outputs after toggling the LTC6951's sync pin or the SPI register SSYNC bit. This method showcases the best jitter, clock skew performance and easiest synchronization method.

EZSync Multichip (Figure 4) increases the number of synchronized clock outputs by using the LTC6951 as an EZSync CONTROLLER. This method maintains the simple EZSync synchronization timing requirements. However, for FOLLOWER devices (Figure 4), such as the LTC6950 and LTC6954, the clock jitter performance becomes additive in nature, as shown in Equation 5 and Figure 5. Clock skew performance depends on several factors, including board trace length differences between EZSync devices, FOLLOWER propagation delays, and individual EZSync device skew performance. The EZSync clock skew performance can be optimized using the LTC6951 output delay SPI bits.

$$t_{J(EZSyncTOTAL)} = \sqrt{t_{J(EZSyncCNTRLR)}^2 + t_{J(EZSyncFLLWR)}^2} \quad (5)$$

Figure 5. Phase comparison



ParallelSync synchronization (Figure 6) increases the number of synchronized clock outputs by distributing the reference to multiple LTC6951s. This method maintains the LTC6951 jitter performance provided by the EZSync Standalone method, since the out of band reference input noise is removed by the LTC6951 loop filter, as shown in Figure 5. The synchronization timing requirements are a function of the reference frequency (refer to Figure 6 for SYNC to REF timing diagram). The clock skew performance depends on board trace length differences between the reference distribution circuit and the LTC6951, reference clock skew and individual LTC6951 output skews. The clock skew performance can be optimized using the LTC6951 output delay SPI bits.

ParallelSync synchronization uses the LTC6951's Reference Aligned Output mode (RAO = 1 in Figure 2), which provides a known latency between the falling edge of the sync input signal and the starting edge of all LTC6951 outputs. Figure 8's ParallelSync timing diagram explains how outputs from one or multiple LTC6951's can be programmed to begin at a desired point in time.

EZ204Sync (or EZParallelSync) (Figure 7) is a simple multichip synchronization method targeted at, but not limited to, JESD204B applications requiring CLOCK and SYSREF signals. EZ204Sync maintains the jitter performance of ParallelSync, but with easier implementation. This is accomplished by using an EZSync distribution device to act as an external R-divider to the PLL/VCO reference inputs, as shown in Figure 7.

The outputs of all PLL/VCOs are phase aligned. However, this architecture allows the phase alignment of the multiple PLL/VCO devices to take place on any R-divider cycle. As a result, phase alignment of each LTC6951 is performed independently, enabling the user to

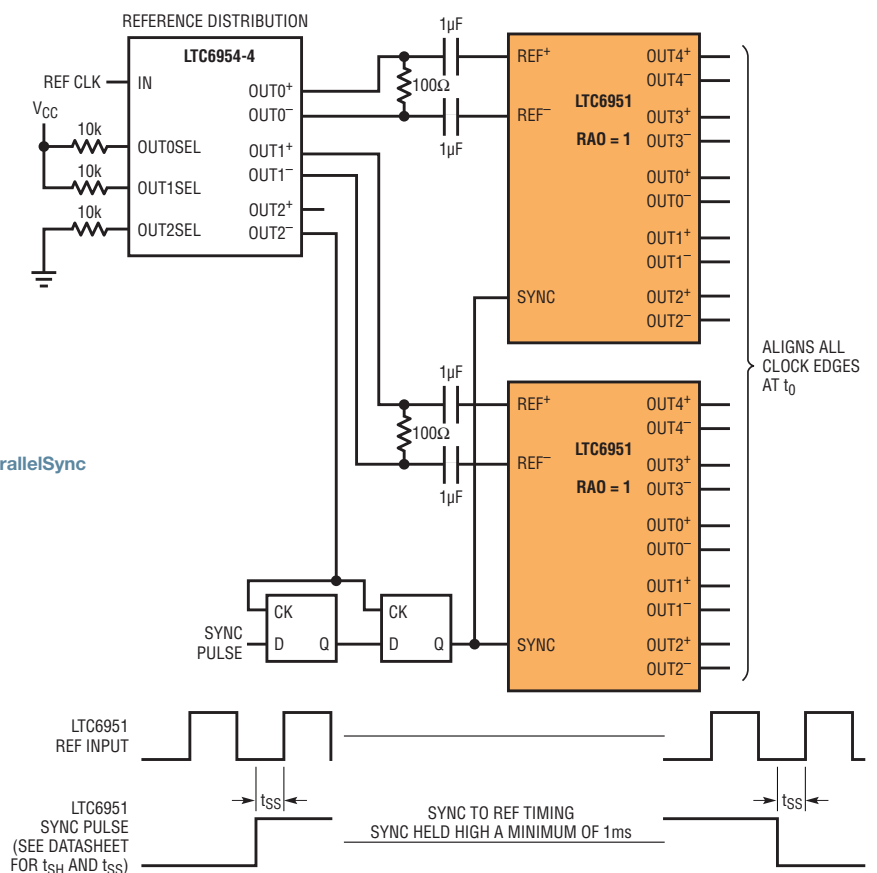


Figure 6. ParallelSync

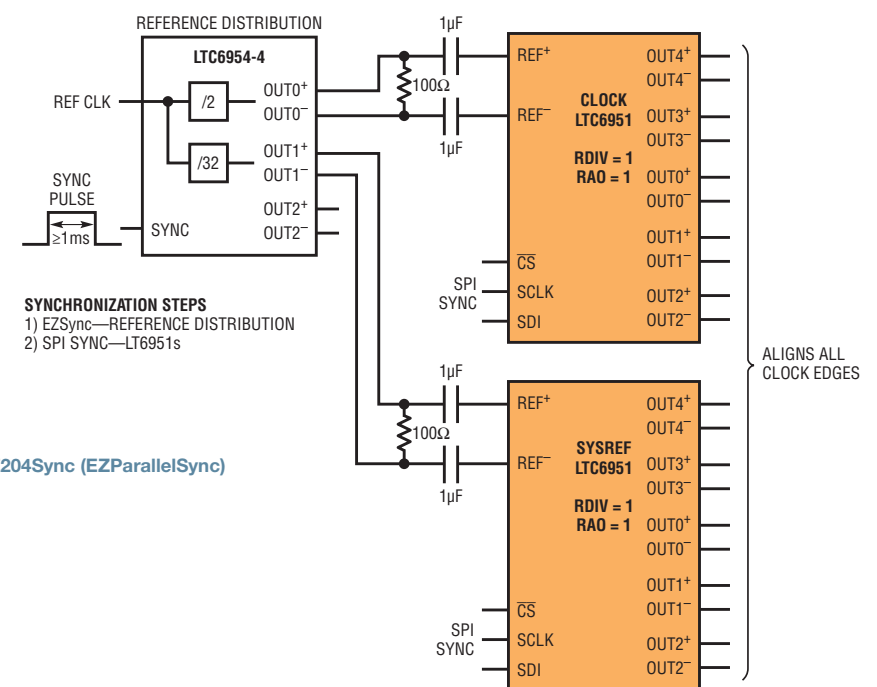


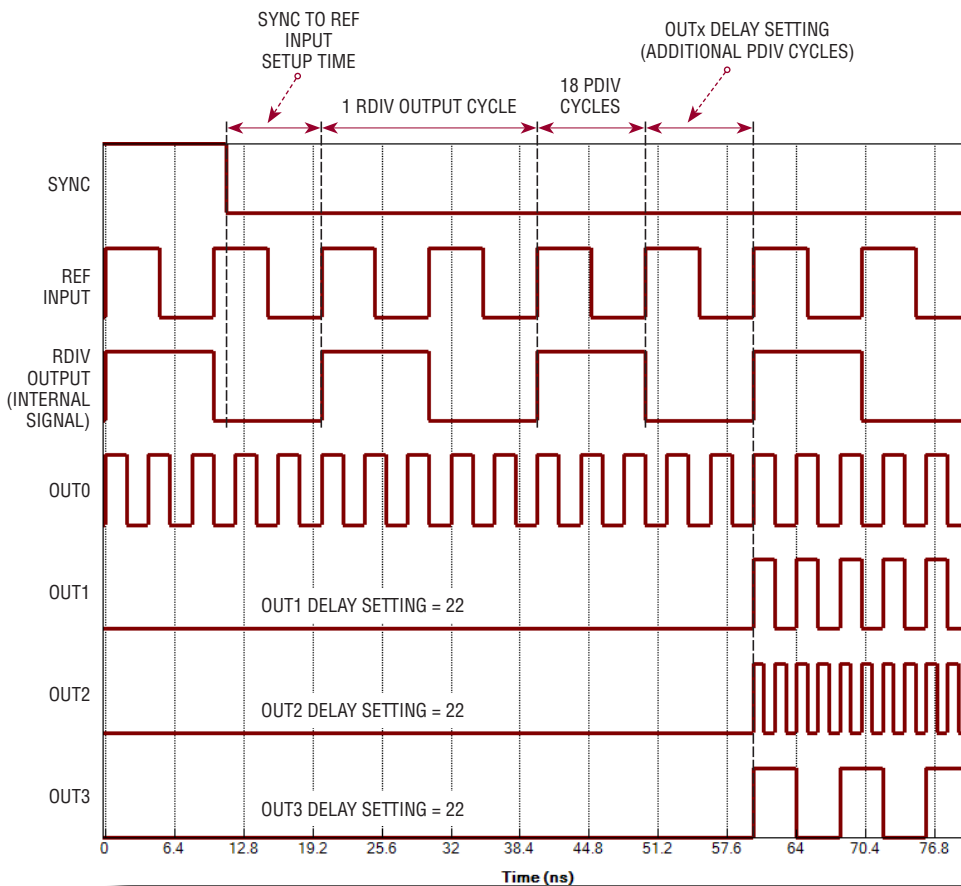
Figure 7. EZ204Sync (EZParallelSync)

power on and off individual LTC6951s without requiring resynchronization of all LTC6951s. This ability to synchronize

individual LTC6951s independently is ideal for JESD204B subclass 1 applications.

The LTC6951's variety of synchronization methods allows designers to optimize for ease of synchronization, clock jitter and the number of clocks required.

Figure 8. ParallelSync timing diagram



NOTES:

1. SYNC RISING EDGE (NOT SHOWN) ALIGNS RDIV OUTPUT TO REF INPUT
2. RDIV = 2
3. PDIV CYCLE = 500ps (NOT SHOWN)

JESD204B INTERFACE

JESD204 is a serial data converter digital interface that has undergone two major revisions since its original 2006 specification. The original goal of JESD204 was to simplify and lower the cost of the digital interface by reducing the number of converter output pins, FPGA pins and the board area consumed by routing multiple ADCs to an FPGA. The latest revision, JESD204B, added the ability to establish deterministic latency between a logic device and the data converters. Over the past few years, a large percentage of the new converter ICs and FPGAs have adopted the JESD204B interface.

To enable deterministic latency, JESD204B added two new subclasses, subclass 1 and subclass 2. Subclass 1 is the preferred method when converter clocks are faster than 500MSPs.

JESD204B subclass 1 added the alignment signal SYSREF. From the clock IC's perspective, SYSREF is phase aligned to the clock signal, and can range from a single pulse to several pulses at an integer multiple of the converter clock period. As a result, many existing clock devices did not have the divider range to support the JESD204B clock and SYSREF signals.

Over the past few years a large percentage of the new converter ICs and FPGA have adopted the JESD204B interface. The LTC6951 is JESD204B subclass 1 capable, due to the LTC6951 output divider ranging from 1 to 512.

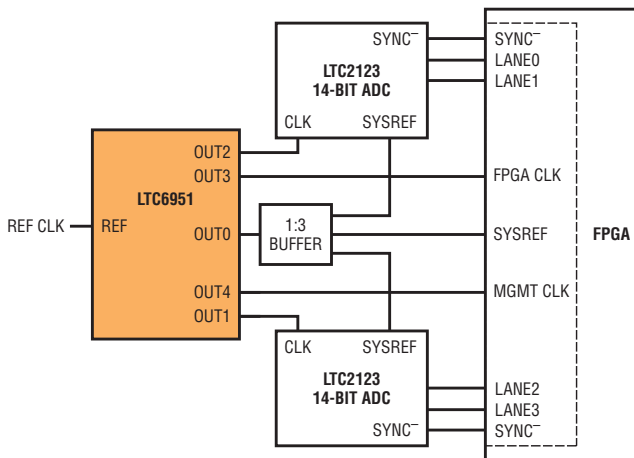


Figure 9. LTC6951 EZSync: JESD204B subclass 1 example

The LTC6951 is JESD204B subclass 1 capable, due to the LTC6951 output divider range extending from 1 to 512. In addition to Figure 7's EZ204Sync example, Figure 9 provides an EZSync Standalone example of a LTC6951 clocking two JESD204B converters. Figure 10 shows a ParallelSync example of multiple LTC6951s clocking several JESD converters.

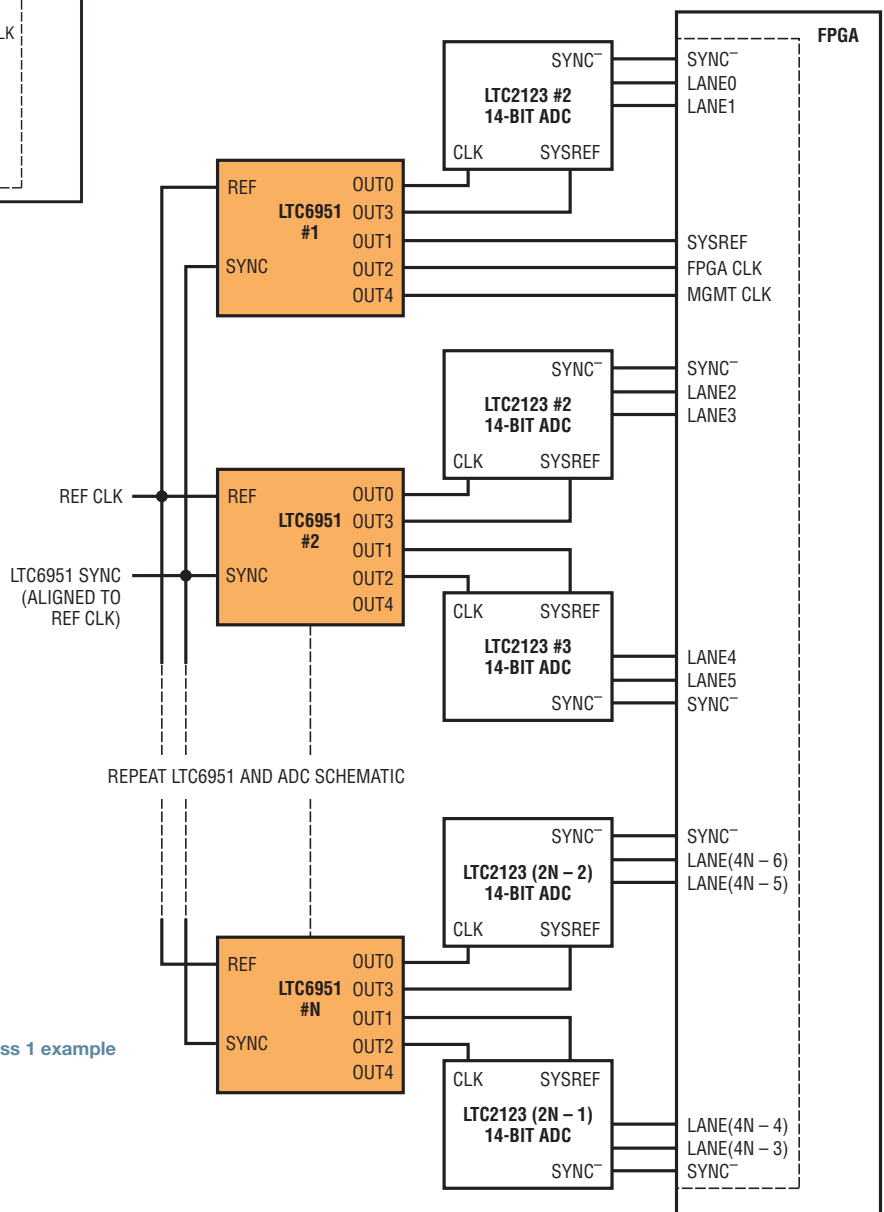


Figure 10. LTC6951 ParallelSync: JESD204B subclass 1 example

For initial evaluation, the LTC6951Wizard provides register settings files that are based off the LTC6951 data sheet examples and typical application circuits.

TOOLS

The LTC6951 demo board (www.linear.com/product/LTC6951#demoboards) and the LTC6951Wizard™ greatly simplify evaluation and design. These tools can:

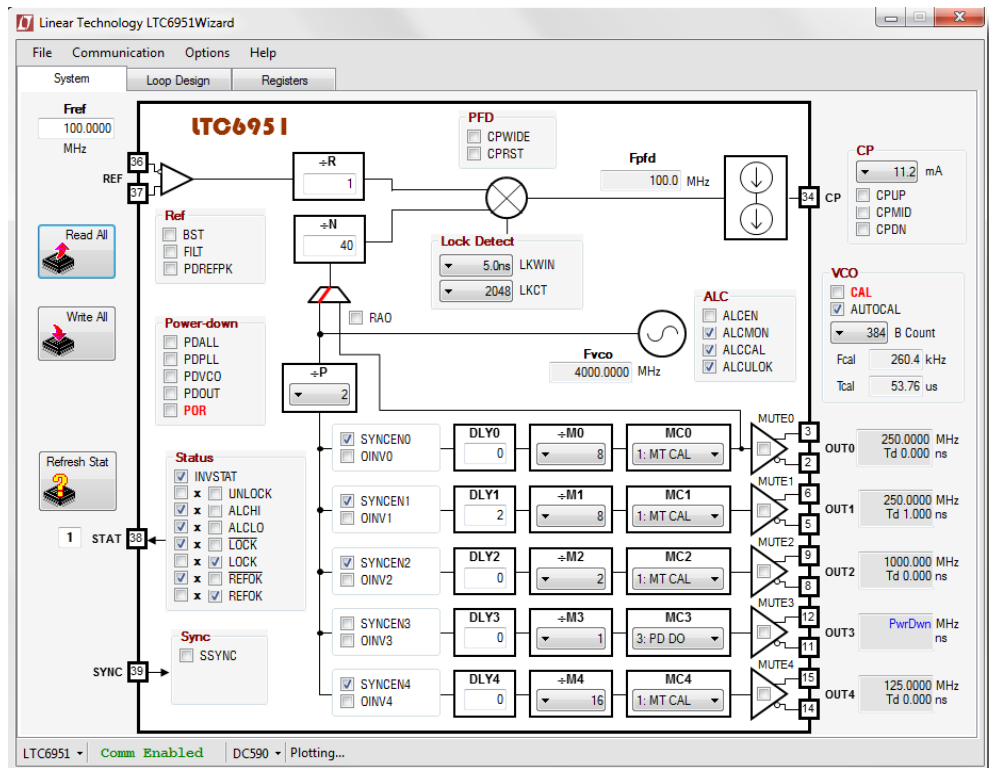
- Read/write to the LTC6951 SPI registers (Figure 11)
- Calculate registers settings and design loop filters based on a frequency plan (Figure 12)
- Simulate time and frequency domain response based on register settings and loop filter design (Figure 12)

For initial evaluation, the LTC6951Wizard provides register settings files that are based on the LTC6951 data sheet examples and typical application circuits. To evaluate a custom frequency plan, the LTC6951Wizard provides a Help file with step-by-step examples using the LTC6951Wizard to calculate register settings, design the loop filter and program the LTC6951 SPI registers. Download the LTC6951Wizard at www.linear.com/LTC6951Wizard.

CONCLUSION

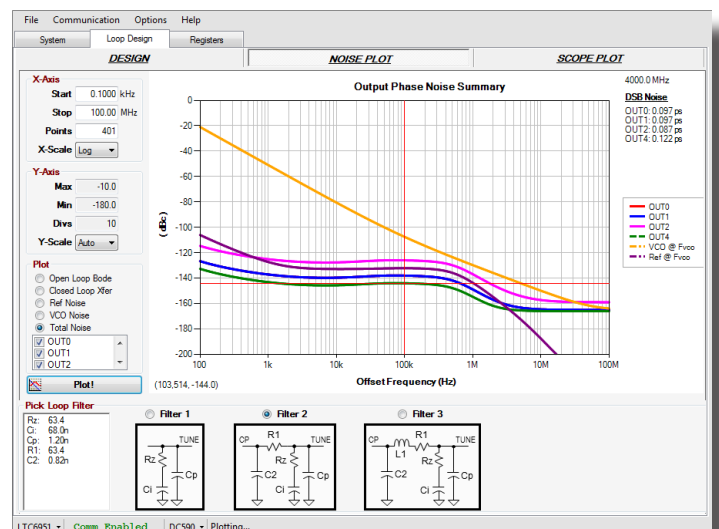
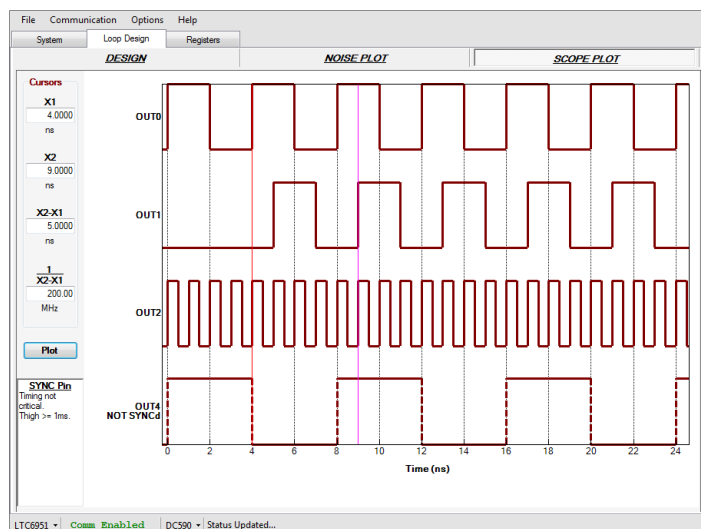
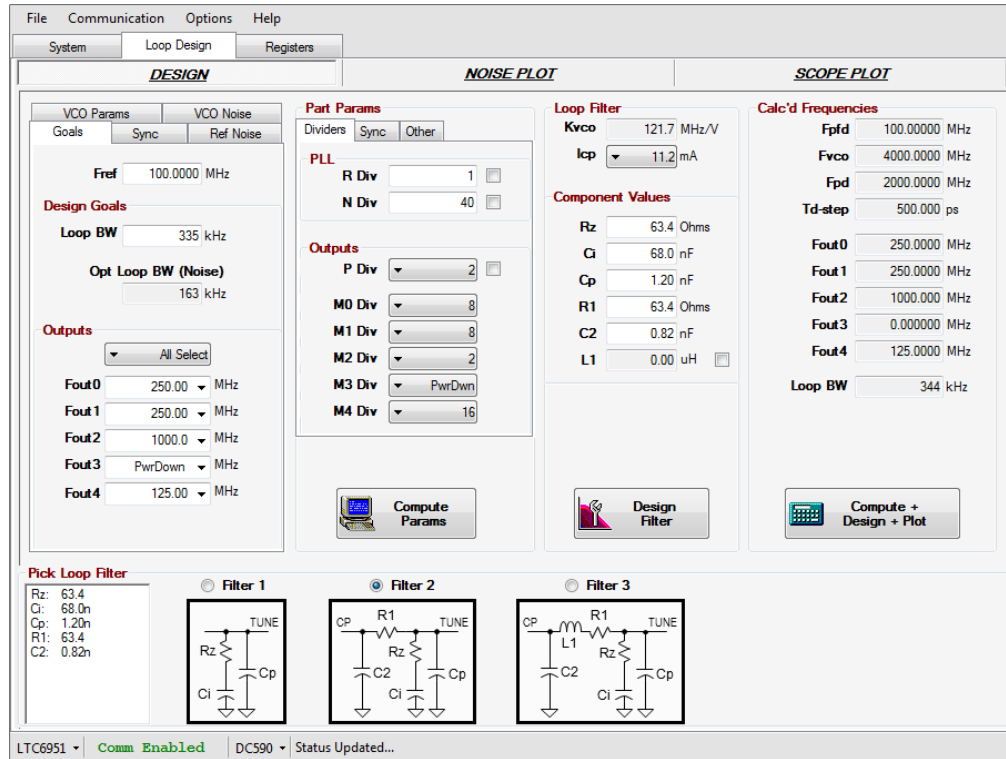
The LTC6951 produces clock frequencies up to 2.7GHz with the lowest wideband noise floor in the industry for a clock distribution device. This allows the LTC6951 to directly clock high speed ADCs with very challenging SNR and clock-to-clock skew targets. The LTC6951's variety of synchronization methods allows designers to optimize for ease of synchronization, clock jitter and the number of clocks required. The LTC6951 supports JESD204B subclass 1 converter clock schemes. To further simplify design, the LTC6951Wizard is provided to guide the user through design, simulation and evaluation of the LTC6951. ■

Figure 11. LTC6951Wizard settings



To evaluate a custom frequency plan, the LTC6951Wizard provides a Help file with step-by-step examples using the LTC6951Wizard to calculate register settings, design loop filter and program the LTC6951 SPI registers.

Figure 12. LTC6951Wizard loop filter design and simulation



1.5A, Negative Regulator Expands Family of Current-Reference Linear Regulators

Dawson Huang

The LT3080, introduced in 2007, represented a new linear regulator architecture featuring a current source as reference and a voltage follower for the output amplifier. This new architecture has a number of advantages, including easy regulator paralleling for increased output current and operation down to zero output voltage. Since the output amplifier always operates at unity gain without a resistor-setting divider, bandwidth and absolute regulation are constant across the output voltage range. Transient response is independent of output voltage and regulation can be specified in millivolts rather than as a percent of output.

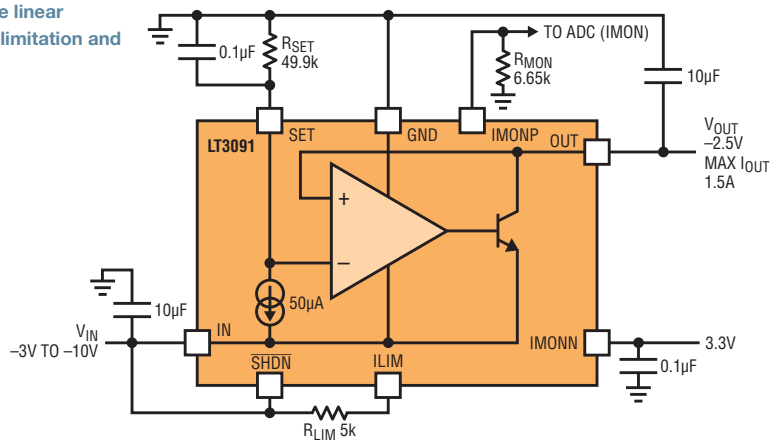
Table 1 summarizes the family of devices that use this architecture. The LT3091, the latest addition to this family, is a 1.5A low dropout negative linear regulator featuring adjustable current limit and current monitor. The LT3091 is similar to the other negative linear regulator in

the family, the LT3090, but with more than double the LT3090's current rating.

The LT3091 is useful in high current, negative voltage applications requiring low noise or precision output. It features fast transient response, high PSRR and low output noise. Low dropout helps

keep it from overheating when supporting loads up to 1.5A. Built-in protection includes reverse output protection, internal current limit with foldback and thermal shutdown with hysteresis. This versatile negative regulator architecture can operate down to zero volts out and as a negative floating regulator.

Figure 1. 1.5A, negative linear regulator with current limitation and monitor



HOW IT WORKS

The negative output voltage is set with a $-50\mu\text{A}$ precision current source driven through a single resistor R_{SET} from ground to the SET pin. The internal follower amplifier forces the output voltage to match the negative voltage of the SET pin. With this architecture, all of the internal operating current flows in from the output pin. Only a $20\mu\text{A}$ load is required to maintain regulation at all output voltages. Figure 1 shows the basic hookup for the LT3091. It provides 1.5A of output current, can be adjustable to zero output voltage, and features both positive and negative monitors for output current. It is also reverse protected, when output voltage is lower than input.

The current limit can be reduced below 1.5A by connecting an external resistor R_{LIM} between ILIM and IN pins,

Table 1. Some of Linear's regulators featuring the current reference architecture

	LT3091	LT3090	LT3081	LT3080
Output current	1.5A	600mA	1.5A	1.1A
I_{SET}	$-50\mu\text{A}$	$-50\mu\text{A}$	$50\mu\text{A}$	$10\mu\text{A}$
Adjustable current limit/current monitor	Yes/Yes	Yes/Yes	Yes/Yes	No/No
LDO (low dropout)	Yes	Yes	No	Yes
Positive/Negative voltage	Negative	Negative	Positive	Positive

This regulator is easy to parallel to increase output current. It can be used for power supplies capable of sinking and sourcing current.

as shown in Figure 1. This function can effectively protect the load and limit the temperature of the IC.

With 3.3V feeding the IMONN pin, the IMONP pin sources current equal to $\frac{1}{4000}$ of the output current. This current source is measured by tying a resistor, R_{MON} , to ground in series with the current source and reading the voltage across the resistor. With the IMONP pin tied to V_{IN} , the IMONN pin sinks current equal to $\frac{1}{2000}$ of the output current. In this way, positive or negative output current can be monitored with minimal components, no additional sense resistors or amplifiers required.

PARALLELING DEVICES FOR MORE CURRENT

Paralleling LT3091s is easy with this new current source reference regulator. Paralleling is useful for increasing output current or spreading heat. Since the LT3091 is set up as a voltage follower, tying all the SET pins together makes the outputs the same voltage. If the outputs are at the same voltage, only a few milliohms of ballast, $R_{OUT1,2}$, are required to allow them to share current.

Figure 2 shows a schematic of two LT3091s paralleled to obtain 3A output. The set resistor, R_{SET} , now has twice the set current flowing through it, so the output is $-100\mu\text{A}$ times R_{SET} . The $10\text{m}\Omega$ output resistors, $R_{OUT1,2}$ ensure ballasting at full current. There is no limit to the number of devices that can be paralleled for higher current.

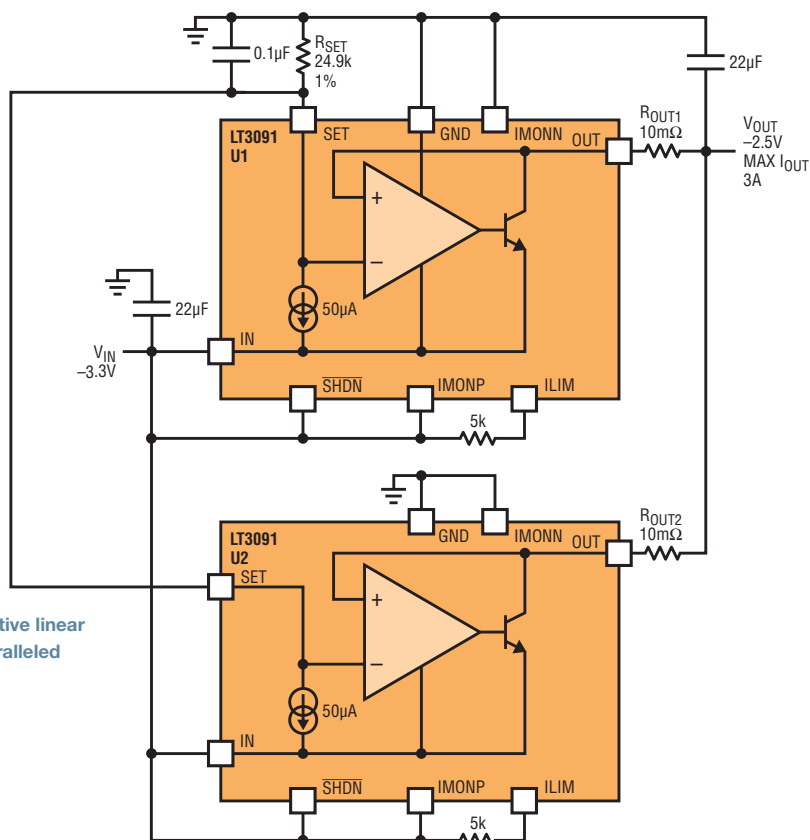


Figure 2. 3A negative linear regulator with paralleled LT3091

Figure 3. Thermal performance of two paralleled LT3091s

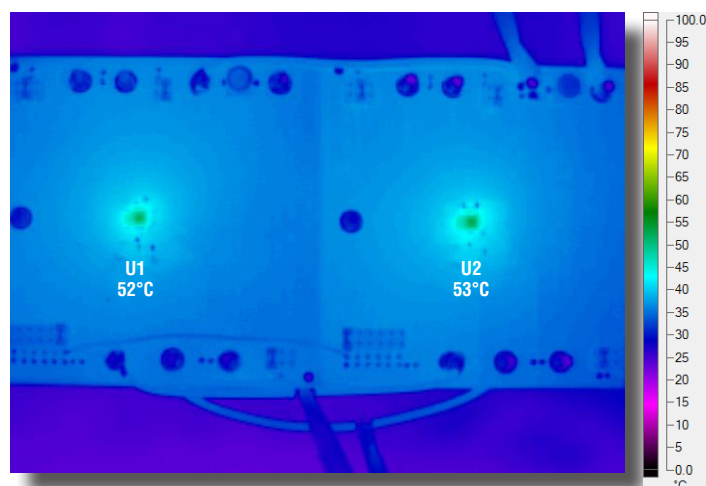


Figure 3 shows the thermal distribution of the design of Figure 2—U1 and U2 reach similar temperatures, indicating equally shared current.

LOW NOISE POSITIVE-TO-NEGATIVE CONVERTER

Inverting converters generate a negative voltage from a positive input, and feature low output ripple. If combined with a high bandwidth LDO such as the LT3091, the overall converter can have very high transient response with even lower noise.

Figure 4 shows a low noise coupled-inductor positive-to-negative converter. The inverting converter is based on LT3581, a PWM DC/DC converter with built-in power switch. Its 4mm × 3mm DFN package and tiny externals can be combined with the LT3091 in a compact

and quiet solution. Figure 5 shows the transient response of the two output voltages. Figure 6 shows the thermal performance of the entire system.

LOW NOISE POSITIVE AND NEGATIVE POWER SUPPLY

A high current positive-to-positive-and-negative converter can be built with a positive 1.5A LT3081 linear regulator and its negative 1.5A linear counterpart, the LT3091. The LT8582 is a dual-channel PWM DC/DC converter with internal switches in an available 7mm × 4mm DFN package. It can generate both a positive and a negative output from a single input.

Figure 7 shows a 1.5A 12V-to-±3.3V low noise power supply using the LT8582, LT3081 and LT3091.

Figure 8 shows the transient response

of the negative rail. Figure 9 shows the temperature of the entire system.

This setup can be used as an operational amplifier power supply—where a high speed operational amplifier requires a low noise, high speed ±3.3V power supply.

CONCLUSION

The LT3091 is a 1.5A, low dropout, current reference negative linear regulator. This regulator is easy to parallel to increase output current. It also features fast transient response, high PSRR and low output noise, making it ideal as a post regulator. It can be used for power supplies capable of sinking and sourcing current. ■

Figure 4. 1.5A low noise and fast transient positive-to-negative converter

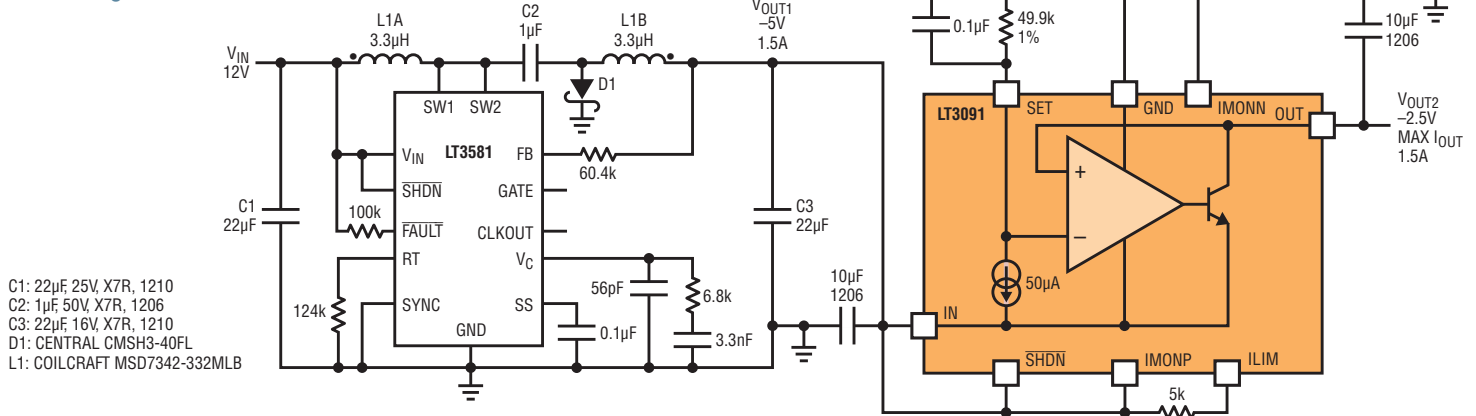


Figure 5. Transient response for positive-to-negative converter

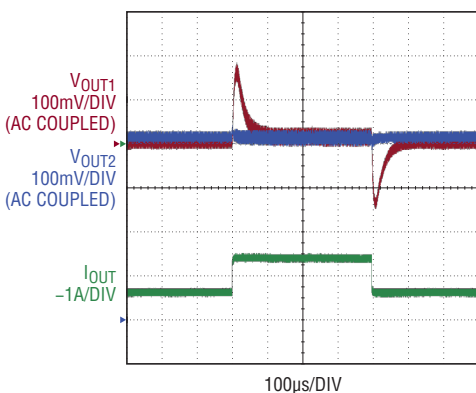
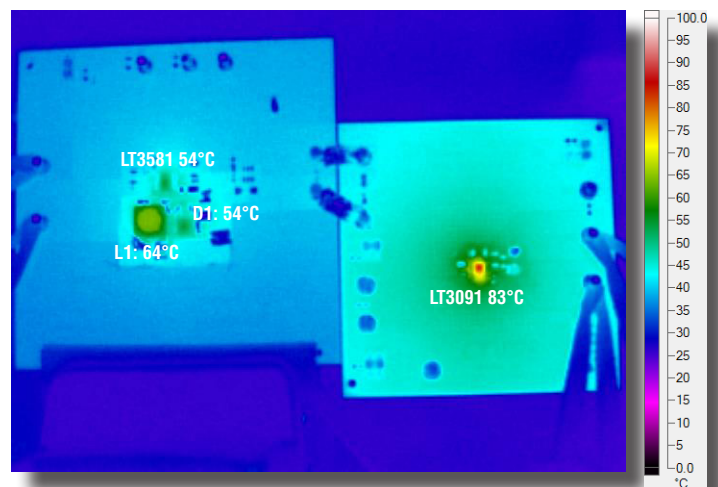


Figure 6. Thermal image for positive-to-negative converter



The LT3091 is useful in high current, negative voltage applications requiring low noise or precision output. It features fast transient response, high PSRR and low output noise, making it ideal as a post regulator. Low dropout helps keep it from overheating when supporting 1.5A loads.

Figure 7. 12V to $\pm 3.3V$ low noise power supply

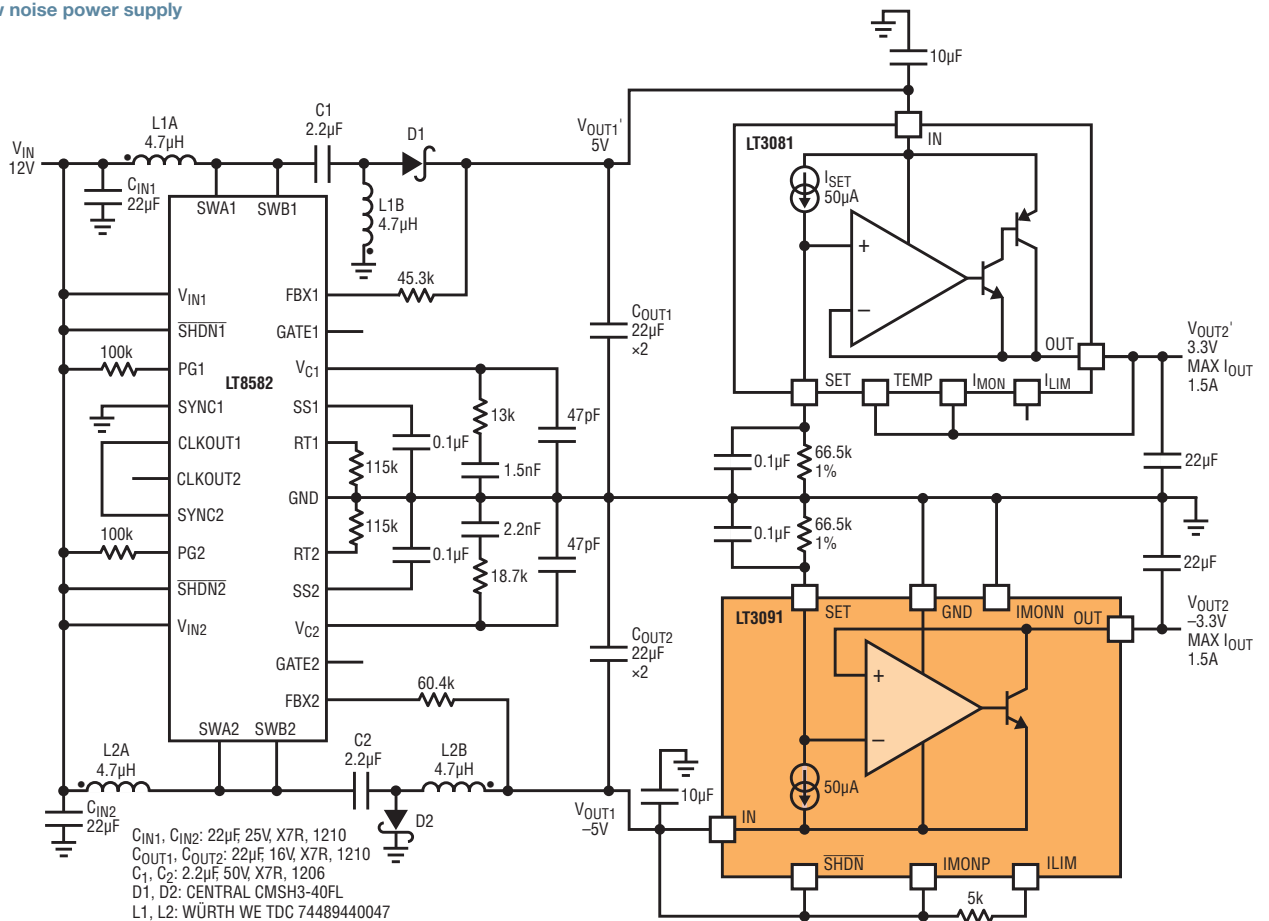


Figure 8. Transient response at V_{OUT2} load transient

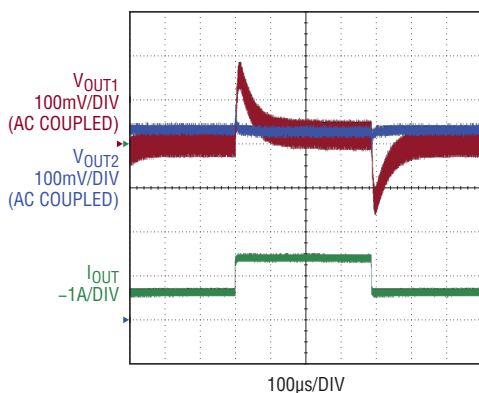
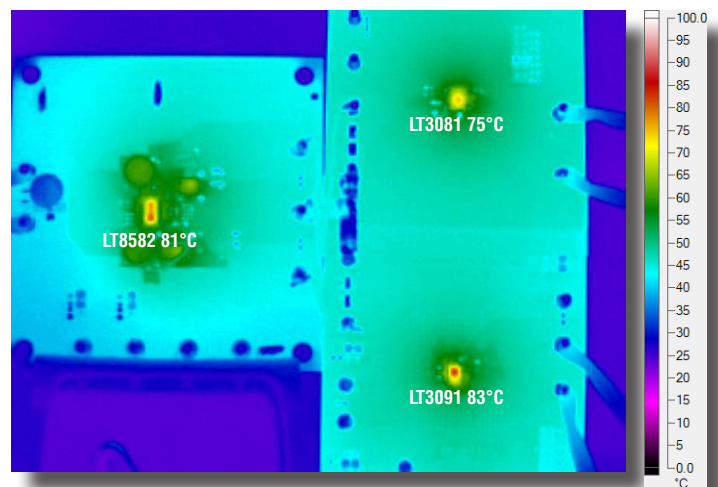


Figure 9. Thermal image for 12V to $\pm 3.3V$ low noise power supply



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Nearly all circuit simulations require a voltage source. This video reveals some of the undiscovered talents of the not-so-humble LTspice® voltage source, specifically exploring the power of the behavioral voltage source. A behavioral voltage source outputs a voltage according to any number of circuit parameters, and it can be used to unleash the real mathematical power of LTspice.

www.linear.com/solutions/6106

SELECTED DEMO CIRCUITS

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

Buck Regulators

- **LT8602:** Automotive quad buck regulator (5.5V–42V to 5V at 1.5A, 3.3V at 2.5A, 1.8V at 1.8A, 1.25V at 1.8A) www.linear.com/solutions/5835
- **LTC3649:** High voltage monolithic synchronous buck regulator with cable drop compensation (4V–60V to 5V at 4A) www.linear.com/solutions/7117

- **LTM4622:** Dual step-down regulator (3.6V–20V to 3.3V & 1.2V at 2.5A) www.linear.com/solutions/5847
- **LTM4675:** Paralleled μ Module buck regulator with digital interface (10V–14V to 1V at 72A) www.linear.com/solutions/5833

Boost Regulators

- **LT3095:** Dual low noise, low ripple bias generator (3V–20V to 5V & 15V at 50mA) www.linear.com/solutions/6001
- **LT8331:** 120V boost converter (36V–72V to 120V at 60mA) www.linear.com/solutions/6022

SEPIC Regulator

- **LT8331:** 48V SEPIC converter (36V–72V to 48V at 165mA) www.linear.com/solutions/6019

Buck-Boost Regulator

- **LTM8055:** Paralleled synchronous buck-boost regulator with accurate current limit (7V–36V to 12V at 12A) www.linear.com/solutions/5617

4-Quadrant Converter

- **LT8714:** Synchronous four quadrant converter with power good indication (10V–14V to –5V to 5V at –5A to 5A) www.linear.com/solutions/6004

Operational Amplifier

- **LTC6268-10:** Oscilloscope differential probe www.linear.com/solutions/6058

SELECTED MODELS

To search the LTspice library for a particular device model, press F2. Since LTspice is often updated with new features and models, it is good practice to update to the current version by choosing Sync Release from the Tools menu.

Buck Regulators

- **LT8641:** 65V, 3.5A synchronous step-down Silent Switcher® with 2.5 μ A quiescent current www.linear.com/LT8641
- **LTM4650:** Dual 25A or single 50A DC/DC μ Module regulator www.linear.com/LTM4650

Inverting Buck Regulator

- **LTC7149:** 60V, 4A synchronous step-down regulator for inverting outputs www.linear.com/LTC7149

Isolated Flyback Converter

- **LTM8068:** 2.8V to 40V input isolated μ Module DC/DC converter with LDO post regulator www.linear.com/LTM8068

Charge Pumps

- **LTC3265:** Low noise dual supply with boost and inverting charge pumps www.linear.com/LTC3265

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.

Hot Swap Controller

- **LTC4281:** Hot swap controller with I²C compatible monitoring www.linear.com/LTC4281

PoE Powered Device

- **LT4276A:** LTPoE++[®]/PoE+/PoE PD forward/flyback controller www.linear.com/LT4276

Ideal Diode-OR Controller

- **LTC4371:** Dual negative voltage ideal diode-OR controller and monitor www.linear.com/LTC4371

Op Amp

- **LT6375:** $\pm 270V$ common mode voltage difference amplifier www.linear.com/LT6375

Comparator

- **LTC6754:** High speed rail-to-rail input comparator with LVDS compatible outputs www.linear.com/LTC6754

Voltage Reference

- **LT6657:** 1.5ppm/ $^{\circ}C$ drift, low noise, buffered reference www.linear.com/LT6657 ■

Power User Tip

AC ANALYSIS USING THE STEP COMMAND

In LTSpice, AC analysis involves computing the AC complex node voltages as a function of frequency using an independent voltage or current source as the driving signal. The small signal analysis results are plotted in the waveform viewer as magnitude and phase over frequency.

AC analysis in LTSpice has a number of settings: the x-axis scaling (linear, octave or decade), number of simulation points and frequency range. For example, if you want to see how your circuit performs from 100Hz to 1MHz with 1,000 points per decade you would edit your simulation command to the following:

```
.ac dec 1K 100 1Meg
```

Repeated AC Analysis with Parameter Sweeps

AC analysis usually involves using fixed parameters to calculate the small signal AC response of a circuit, but you may want to refine your design by viewing the response under varying parameters. This can be accomplished by stepping the parameter of interest using a .step command. For example, you could sweep a capacitance logarithmically through the range of

10pF to .5nF with 30 points per octave using the .step directive (press S to insert a spice directive in the schematic editor):

```
.step oct param C 10p .5n 30
```

The schematic for this case and its resulting waveform are shown below.

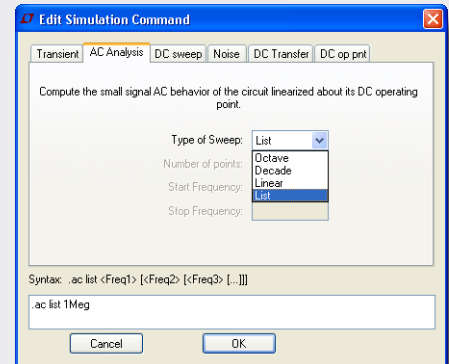
Note that using a .step command with AC analysis can drastically increase simulation time, so carefully choose the values, ranges, increments, and frequency range for each parameter sweep.

Single Frequency Analysis with a Swept Parameter

LTSpice offers an elegant solution for holding frequency constant and performing small signal analysis over a varying parameter. It is as simple as using the 'list' AC Analysis option in the simulation command, and specifying the frequency at which you want to perform the analysis, in this case, 1MHz:

```
.step oct param C 10p .5n 30
.ac list 1Meg
```

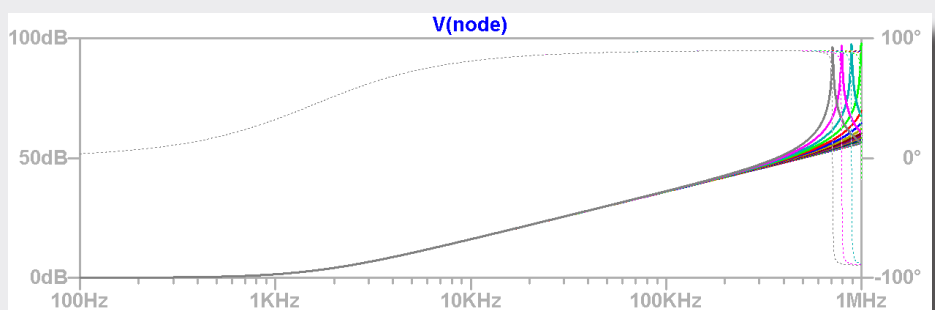
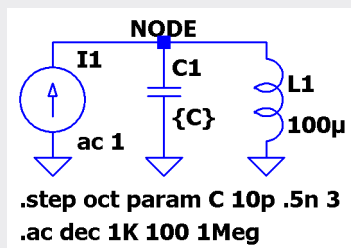
The beauty of single frequency analysis with a .step command is that the resulting plot shows magnitude and phase as a function of parameter sweep, not frequency. Below is the result of a simulation using a single frequency analysis where the x-axis is the capacitance sweep as defined in the .step function.



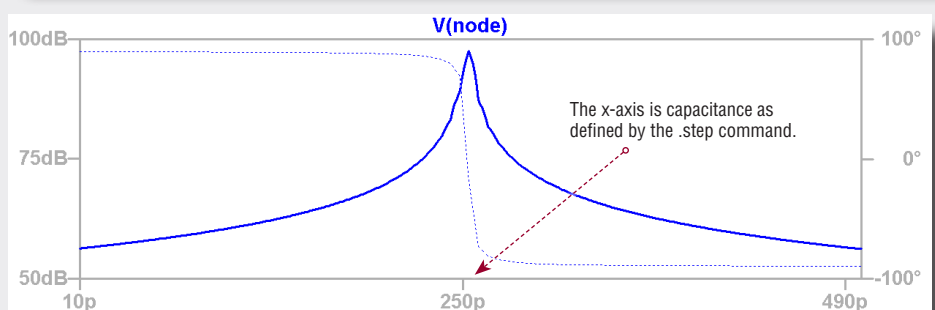
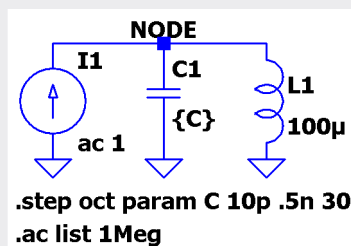
AC analysis commands can be edited using the Edit Simulation Command dialog.

Happy simulations!

Repeated AC analysis with stepped capacitance



Single frequency analysis with swept capacitance



Easy Balanced Load Sharing for Three or Four Supplies, Even with Unequal Supply Voltages

Vladimir Ostrerov and Chris Umminger

Using multiple small power supplies is often more economical and more reliable than using a single large power supply. For instance, separate batteries can be used for higher reliability. In a multi-supply system, it is important that the load is equally shared; otherwise, one supply may attempt to carry the entire load. This article shows how to easily load balance three or four supplies by cascading LTC4370 circuits.

The LTC4370 controller enables current sharing between two supplies with a modest difference between the output voltages, as shown in Figure 1. To perfectly balance the current in both sides, the controller regulates the gate-source voltage of an N-channel MOSFET in whichever side has the higher voltage. This creates a voltage drop across the MOSFET's $R_{DS(ON)}$ plus the current sense resistor.

The LTC4370 can compensate for a voltage difference between two rails of up to 0.5V. If the voltage difference of the two supplies is somewhat less than 0.5V, the

LTC4370 can regulate its output to match the lower value rail, set by adding an appropriate resistor on the RANGE pin.

BALANCING THE LOAD BETWEEN THREE SUPPLIES WITH TWO CASCADED LTC4370s

Figure 2 shows a 3-input, 12V system delivering 10A. Notice that one LTC4370 (U1) performs equal current sharing between supplies V_1 and V_2 , while the second LTC4370 (U2) implements a 2:1 relation between the output current of U1 and the current of a third supply, V_3 . Thus, each supply contributes one third

of the total load current equally. The output voltage at the load is less than the minimum of the supply voltages V_1 , V_2 and V_3 . Because there are two stages of cascading, it is possible to have as much as 1V difference between V_3 and V_1 or V_2 , if the difference between V_1 and V_2 is already at the 0.5V limit.

BALANCING THE LOAD BETWEEN FOUR SUPPLIES

Cascading three LTC4370 controllers (Figure 2) allows four supplies to share the load. In the first stage, U1 and U2 force equal sharing between a pair of supplies, where the output current of U1 is $I_{12} = I_1 + I_2$, and the output current of U2 is $I_{34} = I_3 + I_4$. A third LTC4370, the second stage, keeps $I_{12} = I_{34}$. Thus, each supply contributes one fourth of the total load current. The two stages, as above, allow the possibility of as much as 1V difference between the four supply voltages.

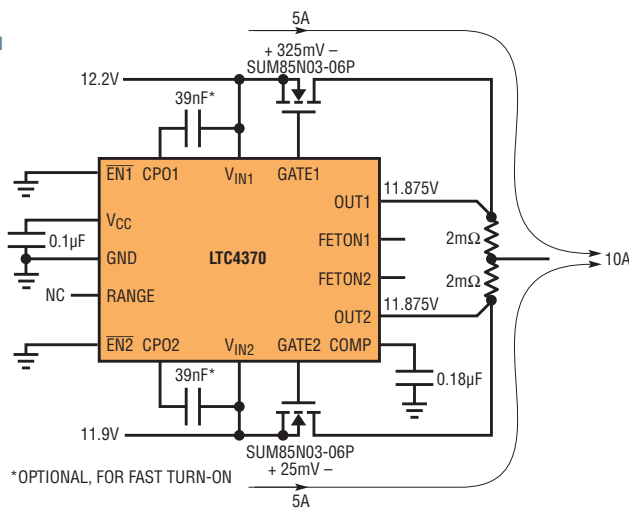
LIMITATIONS

The main error sources that affect perfect current sharing are:

- LTC4370 error amplifier input offset, $\pm 2\text{mV}$ (maximum)
- Sense resistor tolerance, worst-case for 1% resistors is 2% overall.

Sharing error attributed to the error amplifier input offset decreases with increasing sense voltage, but power dissipation increases. For the simple LTC4370 circuit with two supplies, this error is expressed as an imbalance in the supplies' sharing of current:

Figure 1. The LTC4370 current-balancing controller enables balanced load sharing between two supplies, even when their voltage outputs are different.



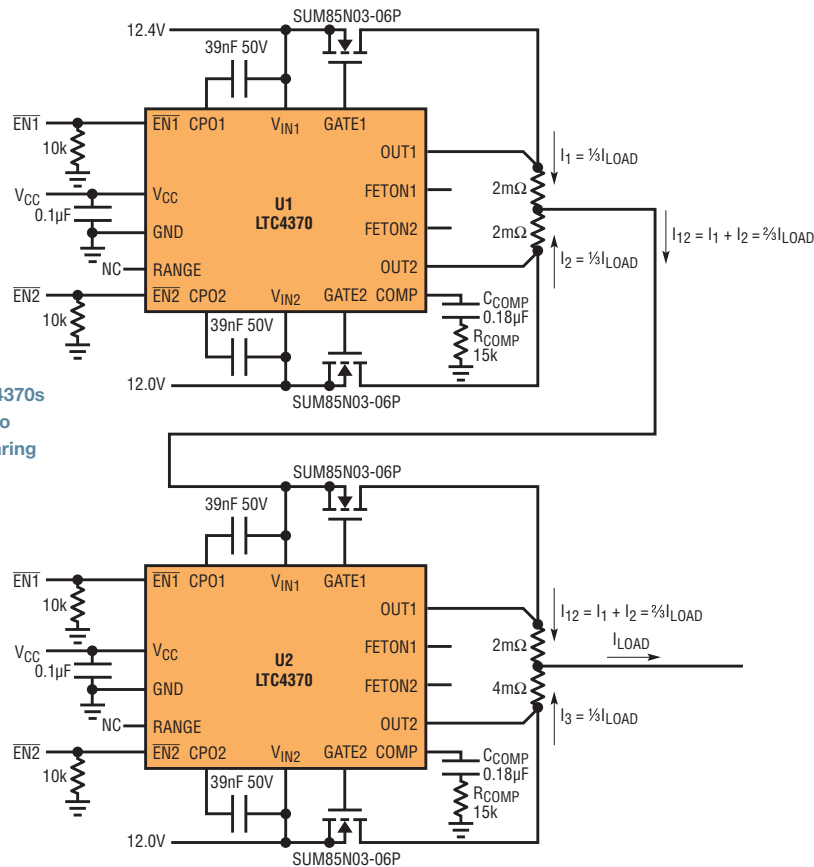


Figure 2. Two LTC4370s can be cascaded to enable current sharing of three supplies.

$$\Delta I = |I_1 - I_2|$$

Using the worst-case errors, above, the error is:

$$\Delta I \leq \left(\frac{2\text{mV}}{R_{\text{SENSE}}} + 0.01 \cdot I_{\text{LOAD}} \right) [A]$$

For the circuit of Figure 2, where ideal load sharing means the load is distributed into $\frac{1}{3}I_{\text{LOAD}}$ and $\frac{2}{3}I_{\text{LOAD}}$, it is easier to estimate the worst-case imbalance via an expression of the maximum and minimum current of each supply:

$$I_{\text{MAX}} = \left(0.672 \cdot I_{\text{LOAD}} + \frac{2\text{mV}}{3.01 \cdot R_{\text{SENSE}}} \right) [A]$$

$$I_{\text{MIN}} = \left(0.328 \cdot I_{\text{LOAD}} + \frac{2\text{mV}}{3.01 \cdot R_{\text{SENSE}}} \right) [A]$$

CONCLUSION

By cascading the shared output of one LTC4370 with another LTC4370, three or more supplies can be efficiently controlled to provide equal current to the load. With errors on the order of the sense resistor tolerance, the voltage drop is minimal. ■

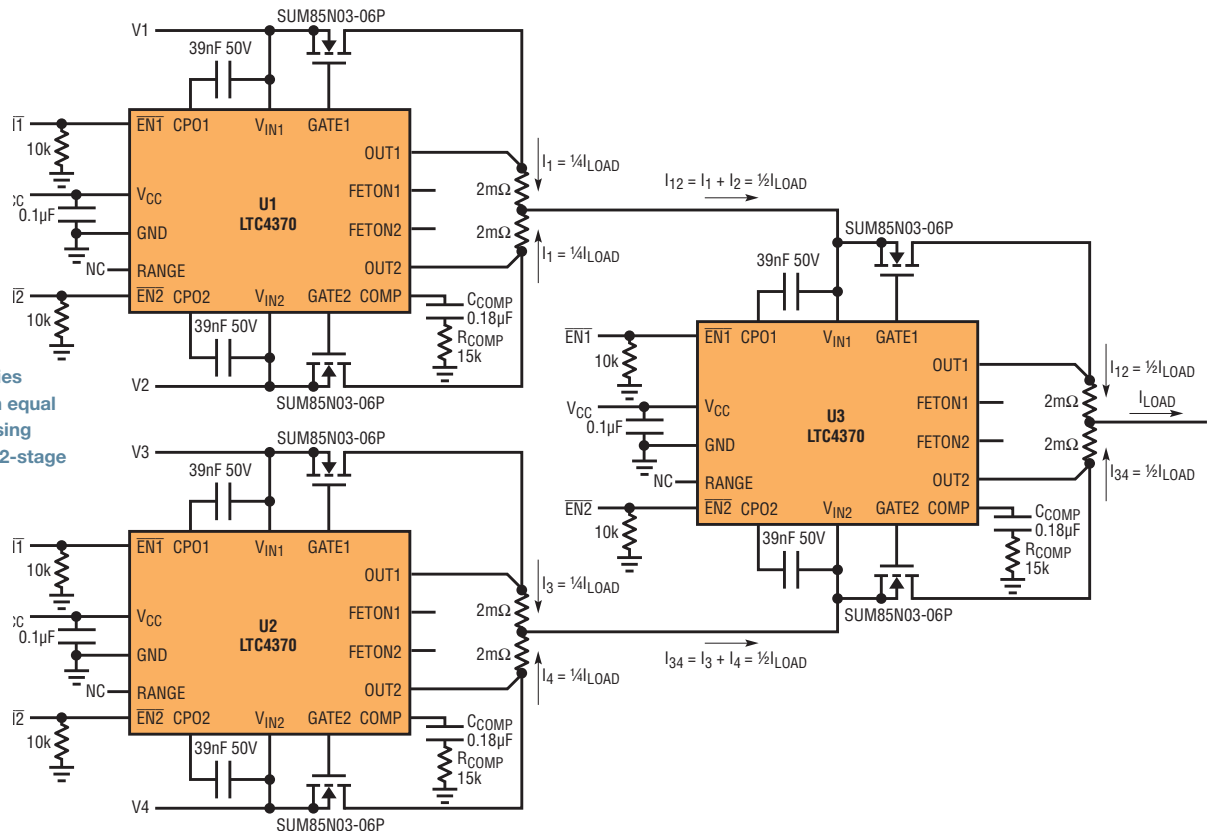


Figure 3. Four supplies can each support an equal share of a load by using three LTC4370s in a 2-stage cascade.

Design Once; Use Twice: Monolithic SEPIC/Boost Regulators with Wide V_{IN} Range Satisfy Requirements of Both Consumer and Commercial Vehicles

Molly Zhu

Automobile manufacturers continually add electronic control units (ECUs) to support increasing numbers of performance, comfort and safety features. ECU power either comes from a single lead-acid battery in consumer vehicles, or from two batteries in commercial vehicles. Ideally, an ECU can run off either, enabling a single design for both consumer and commercial vehicles. This requires that ECU power ICs support an input range covering both configurations—namely 3.5V to 60V. Furthermore, the power ICs should feature ultralow quiescent current, preserving the vehicle's battery run time when the engine is off, but always-on systems remain engaged.

The LT8495 and LT8494 are high voltage switching regulators that meet these requirements when configured as SEPIC or boost converters. Both parts operate over 2.5V to 60V input, and have low quiescent current to extend the battery life. The quiescent current of the LT8495 is 9 μ A, and is 7 μ A for the LT8494. The parts are available in 20-lead QFN and 20-lead TSSOP packages.

The LT8494 and LT8495 are similar, but the LT8495 adds power-on reset and watchdog timers. It is designed specifically for microcontrolled applications, where reliability and safety are critical. The

supply voltage is monitored by power-on reset, and the software/hardware activities are supervised by watchdog timers. These functions are integrated in the LT8495, simplifying designs with enhanced safety and reliability.

DUAL SUPPLY PINS

The input voltage of the LT8494/LT8495 can be as high as 60V for SEPIC topologies, and 32V for boost circuits with the 60V ride-through voltage. The internal power switch driver must be in the 2.4V~34V (typical) range to enable the LT8494/LT8495, but the minimum operating V_{IN} range can be reduced to 1V. The

integrated power switch drivers can operate from either of two supplies: V_{IN} or BIAS. This allows the part to optimize efficiency and reduces the minimum input voltage requirement. The LT8494/LT8495 automatically chooses the lower supply of the two, provided it is in the operation range. This selection is made on-the-fly as V_{IN} or BIAS voltages change. After initial start-up, the part can draw current from BIAS if it is lower than V_{IN} .

A typical application of a boost converter using the LT8494 is shown in Figure 1. The BIAS pin is connected to ground instead of the output since the input

Figure 1. The LT8494 in a 750kHz, 48V boost converter

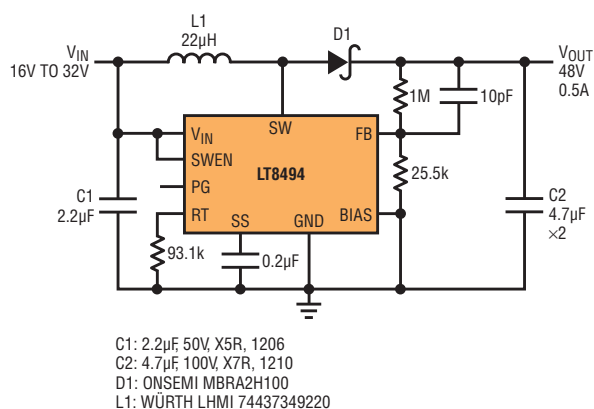
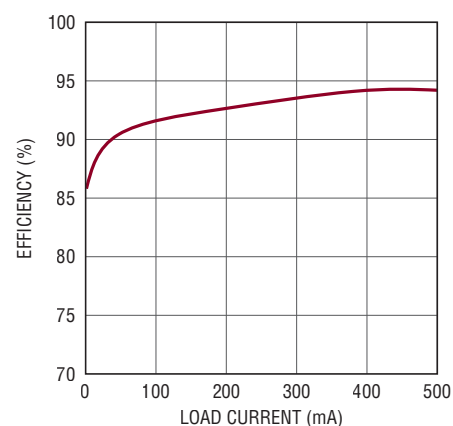


Figure 2. Efficiency of the circuit in Figure 1



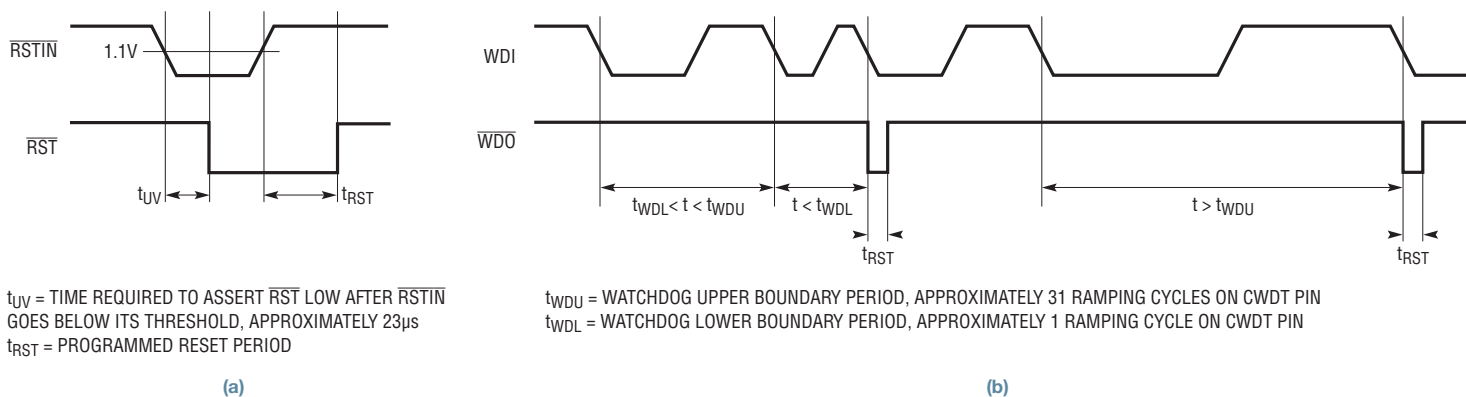


Figure 3. POR (a) and watchdog (b) timing

voltage is always lower than the output. The efficiency is given in Figure 2. At very light load, the efficiency of the LT8494 is slightly higher than that of the LT8495 because the LT8494 is not supporting a watchdog function.

WATCHDOG TIMER AND POR FUNCTIONS

The LT8495 is similar to the LT8494, but it adds integrated power-on reset (POR) and watchdog timer functions to enhance system safety in automotive applications. The POR monitors the supply voltages, while the watchdog timer monitors the software and hardware functions.

The LT8495 monitors the output via the \overline{RSTIN} pin voltage. During normal operation, if the voltage of the \overline{RSTIN} is below its threshold, the \overline{RST} pin is asserted low. Once the \overline{RSTIN} rises above its threshold, the \overline{RST}

pin is released after the reset delay time. The reset delay time, t_{RST} , is programmable through the cap on the CPOR pin.

The LT8495's watchdog timer includes an independent enable pin (WDE), and can operate without the V_{IN} supply. If the time between the negative edges on the WDI is too long or too short, the WDO pin is pulled low for the reset delay time, t_{RST} , before it is released. The window time of WDI can be programmed through the cap on CWDT pin. The timing diagrams of the POR and watchdog timer are shown in Figure 3.

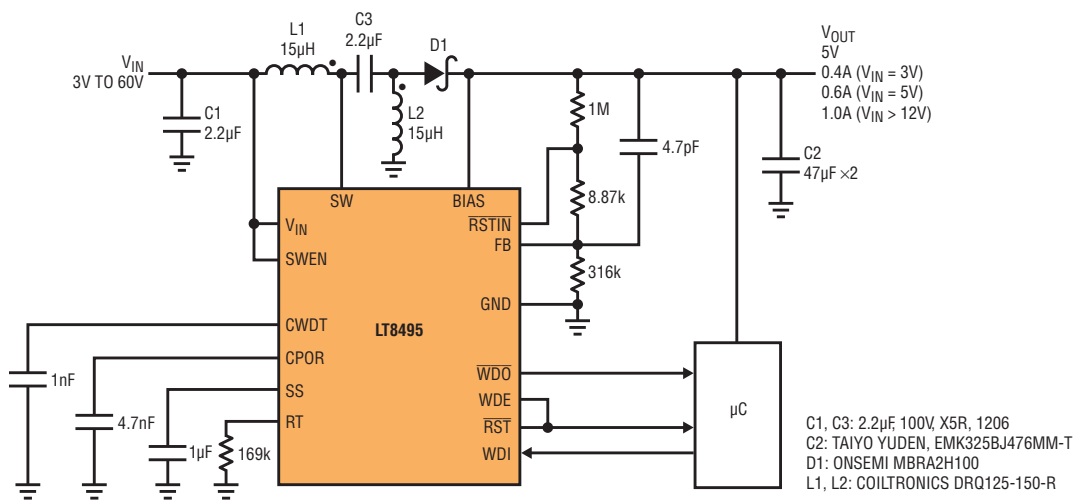
Figure 4 shows the LT8495 configured as a SEPIC converter with a 3V–60V input voltage and 5V output. The max load current increases with the input voltage until reaching the full load current of 1A at 12V input. The output voltage is monitored

by the \overline{RSTIN} pin, and the watchdog timer supervises the microcontroller.

CONCLUSION

The LT8494 and LT8495 are monolithic boost/SEPIC switching regulators with input voltage ranges of 1V to 60V after start-up. Both parts can automatically select the lower supply pins, V_{IN} or BIAS, to improve efficiency. The LT8495 features an integrated power-on reset and a watchdog timer to monitor the microcontroller's activity. Their wide input voltage ranges, high efficiency, low quiescent current and programmable timing make them ideal for industrial and automotive applications. ■

Figure 4. The LT8495 in a 450kHz, 5V output SEPIC converter with POR and watchdog timer



New Product Briefs

±270V COMMON MODE DIFFERENCE AMPLIFIER FEATURES 97dB MIN CMRR, ±35PPM MAX GAIN ERROR

The LT6375 is a unity-gain difference amplifier with integrated precision matched resistors, which precisely level shifts and buffers small difference signals while rejecting up to ±270V common mode. The A-grade version achieves unprecedented performance: CMRR is 97dB (min), initial gain error is 35ppm (max), gain drift is 1ppm/°C (max) and gain nonlinearity is 2ppm (max) with a common mode divide ratio of 25:1. The common mode divide ratio is selectable from 7:1 to 25:1, enabling the designer to select the ratio with the best performance for a given common mode input range.

At the heart of the LT6375 is a high precision Over-The-Top® amplifier which operates with inputs both within and above the 3.3V to 50V supply voltage. This permits the combination of a wide input range and low voltage supply. Use of a low voltage supply limits power consumption and protects downstream circuitry from high voltage.

“The LT6375 combines a high precision, wide voltage range Over-The-Top amplifier with configurable precision matched resistors,” says Maziar Tavakoli, Design Manager, Signal Conditioning Products. “With seven different divider ratios to choose from, precision, noise

and speed can be optimized for specific input range requirements. For example, if the input common mode range is ±80V, a resistor divider ratio of seven can be selected to achieve lower noise, lower offset and wider bandwidth than is achievable with a ratio of 20.”

The LT6375 includes many other useful features, including rail-to-rail outputs, low supply current and a shutdown mode. It is available in a 4mm × 4mm 12-lead DFN and a 4mm long MSOP package with 12 leads. Both packages include skipped leads for extra spacing of high voltage input signals.

42V QUAD SYNCHRONOUS STEP-DOWN DC/DC CONVERTER DELIVERS 93% EFFICIENCY & OPERATES FROM 3V TO 42V INPUTS

The LT8602 is a 42V input capable, high efficiency quad output synchronous monolithic step-down switching regulator. Its quad channel design combines two high voltage 2.5A and 1.5A channels with two lower voltage 1.8A channels to provide four independent outputs, delivering voltages as low as 0.8V.

Its synchronous rectification topology delivers up to 93% efficiency while Burst Mode® operation keeps quiescent current under 30µA (all channels) in no-load standby conditions, making it ideal for always-on systems.

For noise-sensitive applications, the LT8602 utilizes its pulse-skipping mode to minimize switching noise and meet the CISPR25, Class 5 EMI requirements. Switching frequency can be programmed from 250kHz to 2.2MHz and is synchronizable throughout this range.

The LT8602's 60ns minimum on-time enables 16V V_{IN} to 0.8V V_{OUT} step-down conversions while switching at 2MHz, enabling designers to avoid critical noise-sensitive frequency bands such as AM radio, while using a very compact solution footprint.

Its 3V to 42V input voltage range makes it ideal for automotive applications that must regulate through cold-crank and stop-start scenarios with minimum input voltages as low as 3V and load dump transients in excess of 40V. Each channel of the LT8602 maintains a minimum dropout voltage of only 200mV (at 1A) under all conditions, enabling it to excel in scenarios such as automotive cold-crank. Programmable power-on reset and power good indicators for each channel ensure overall system reliability.

The LT8602's 40-lead thermally enhanced 6mm × 6mm QFN package and high switching frequency keep external inductors and capacitors small, providing a compact, thermally efficient footprint.

5W AutoResonant WIRELESS POWER TRANSMITTER FEATURES FOREIGN OBJECT DETECTION, COMPLETES LINEAR CHARGING SOLUTIONS

The LTC4125 is a wireless power transmitter that complements Linear’s wireless receiver ICs in wireless charging solutions. The LTC4125 is a high performance monolithic full bridge resonant driver, capable of delivering up to 5W of power wirelessly to a companion receiver. It functions as the transmit circuit component in a complete wireless power transfer system comprised of transmit circuitry, transmit coil, receive coil and receive circuitry.

The LTC4125 wireless power transmitter improves on a basic transmitter by providing three key features:

- The AutoResonant™ function maximizes available receiver power
- The optimum power search algorithm maximizes overall wireless power system efficiency
- Foreign object detection (FOD) ensures safe and reliable operation when working in the presence of conductive foreign objects.

The LTC4125 automatically adjusts its drive frequency to match the LC network resonant frequency. AutoResonant switching enables the device to deliver maximum power from a low voltage input supply (3V to 5.5V) to a tuned receiver such as Linear’s LTC4120 wireless receiver and battery charger via loosely coupled coils.

Wireless power receivers can also be designed with the LTC4071 shunt battery charger or the LT3652HV multi-chemistry battery charger. To optimize system efficiency, the LTC4125 employs a periodic transmit power search and adjusts the transmission power based on the receiver load requirements. The device stops delivering power in a fault condition, or if a conductive foreign object is detected.

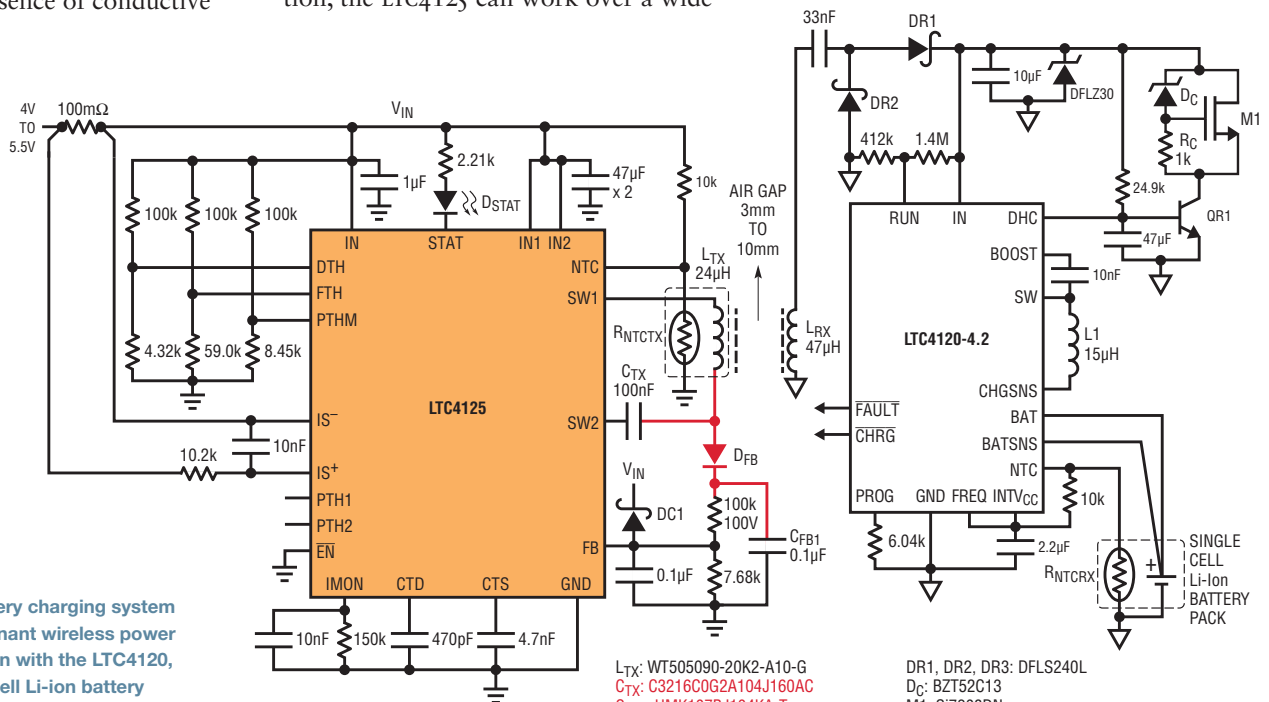
It is surprisingly easy to design an entirely analog wireless power system using the LTC4125. The transmit power optimization and foreign object detection features in the LTC4125 require no direct communication between the transmitter and receiver circuits. Even without digital communication, the LTC4125 can work over a wide

range of transmit-to-receive coil coupling factors—no complicated signal processing hardware and software is needed.

The LTC4125 includes a programmable maximum current limit and an NTC input as additional means of foreign object and overload protection. Applications include handheld instruments, industrial/military sensors for harsh environments, portable medical devices and electrically isolated devices. LTC4125-based systems enable robust, standalone solutions capable of large transmission distances up to 10mm, which also tolerate poor coil coupling due to misalignment.

The LTC4125 is housed in a low profile (0.75mm) 20-pin 4mm × 5mm QFN package with backside metal pad for excellent thermal performance. ■

A complete wireless battery charging system using LTC4125 AutoResonant wireless power transmitter in combination with the LTC4120, forming a 200mA single cell Li-ion battery charger. The LTC4125 drives a 24µH transmit coil at 103kHz, with 530mA input current threshold, 119kHz frequency limit and 41.5°C transmit coil surface temperature limit.



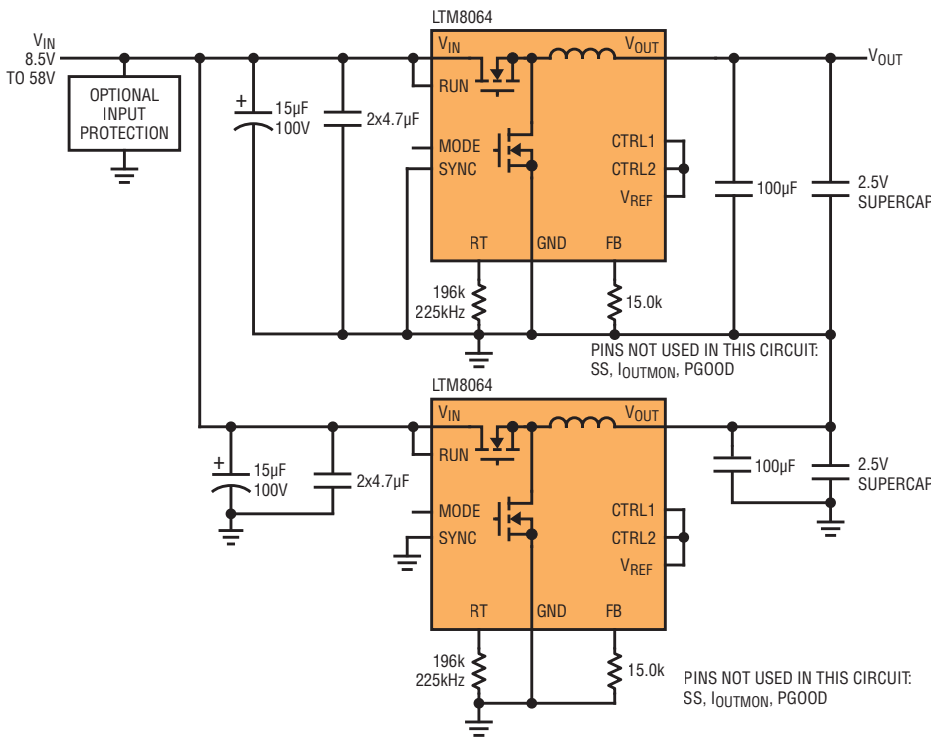
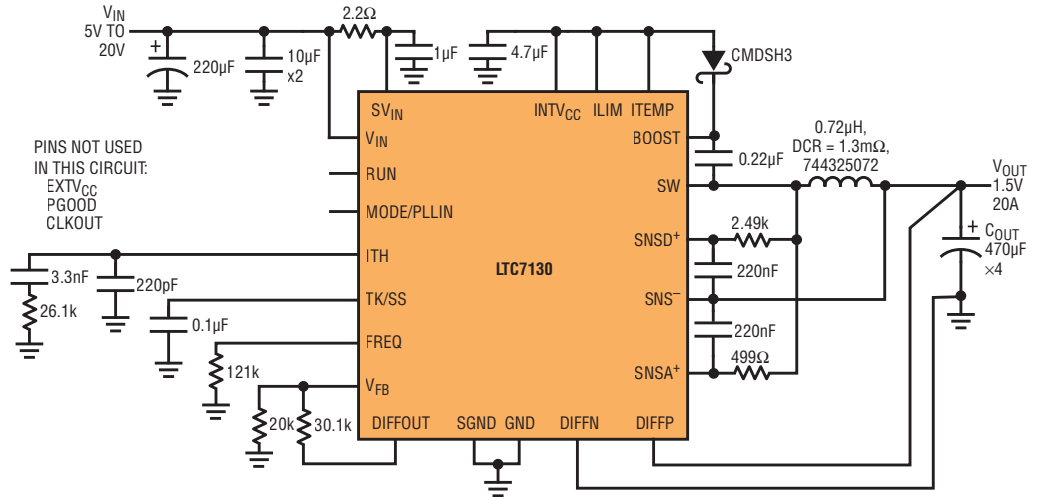
- LTX: WT505090-20K2-A10-G
- CTX: C3216C0G2A104J160AC
- CFB1: HMK107BJ104KA-T
- DC1: CDBQR70
- DSTAT: LTST-C193KGKT-5A
- D_{FB}: BAS521-7
- RNTCTX: NTHS0603N02N1002J
- RED INDICATES HIGH VOLTAGE PARTS

- DR1, DR2, DR3: DFLS240L
- DC: BZT52C13
- M1: S17308DN
- QR1: PMBT3904M
- RNTCRX: NTHS0402N02N1002F
- L_{RX}: PCB COIL AND FERRITE: B67410-A0223-X195 OR 760308101303
- L1: LPS4018-153ML

LTC7130 HIGH EFFICIENCY, 1.5V/15A STEP-DOWN CONVERTER WITH VERY LOW OUTPUT RIPPLE

The LTC7130 is a current mode synchronous step-down monolithic converter that can deliver up to 20A continuous load current. It employs a unique architecture which enhances the signal-to-noise ratio of the current sense signal, allowing the use of a very low DC resistance power inductor to maximize efficiency in high current applications. This feature also reduces the switching jitter commonly found in low DCR applications. The LTC7130 includes a high speed differential remote sense amplifier and a programmable current sense limit that can be selected from 10mV to 30mV to set the output current limit up to 20A. In addition, the DCR temperature compensation feature limits the maximum output current precisely over temperature.

www.linear.com/solutions/7216



STACK TWO LTM8064s TO CHARGE AND ACTIVELY BALANCE SUPERCAPACITORS (OR BATTERIES)

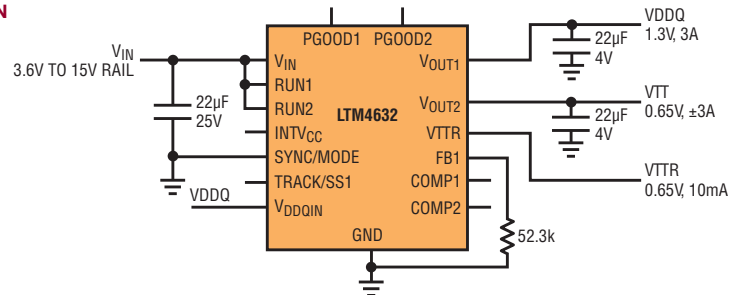
The LTM[®]8064 is a 58V input, 6A, constant-voltage, constant current (CVCC), step-down µModule (power module) regulator. Included in the package are the switching controller, power switches, inductor and support components. Operating over an input voltage range of 6V to 58V, the LTM8064 supports an output voltage range of 1.2V to 36V. CVCC operation allows the LTM8064 to accurately regulate its output current up to 7A when sourcing and 9.1A when sinking over the entire output range. The output current can be set by a control voltage, a single resistor or a thermistor. To set the switching frequency, simply place a resistor from the RT pin to ground. A resistor from FB to ground sets the output voltage. Only the bulk input and output filter capacitors are required to finish the design.

www.linear.com/solutions/7150

LTM4632 3.6V TO 15V INPUT, 1.5V/3A VDDQ, 0.75V/±3A VTT AND 10mA VTTR DESIGN

The LTM4632 is an ultrathin triple output step-down µModule (power module) regulator to provide complete power solution for DDR-QDR4 SRAM. Operating from a 3.6V to 15V input voltage, the LTM4632 supports two ±3A output rails, both sink and source capable, for VDDQ and VTT, plus a 10mA low noise reference VTTR output. Both VTT and VTTR track and are equal to VDDQ/2. Housed in a 6.25mm × 6.25mm × 1.82mm LGA package, the LTM4632 includes the switching controller, power FETs, inductors and support components. Alternatively, the power module can be configured as a two phase single ±6A output VTT. Only a few ceramic input and output capacitors are needed to complete the design.

www.linear.com/solutions/7189



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