LINEAR TECHNOLOGY

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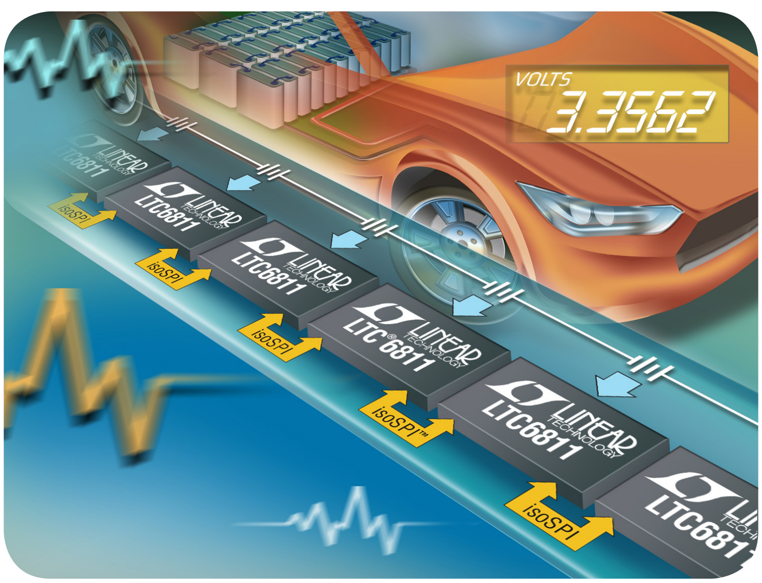
IN THIS ISSUE

The Evolution of High Voltage Digital Power System Management

Hellmuth Witte

The LTC®3886 takes inputs up to 60V and produces two 0.5V-to-13.8V outputs—enabling it to easily drop into industrial, server and automotive environments as an intermediate or point-of-load (POL) supply. Other controllers with similarly impressive input/output ranges cannot match the LTC3886's digital management capabilities. Its I²C-based PMBus-compliant serial interface allows power supply designers to configure, monitor, control and expand capabilities via PC-based, graphical LTpowerPlay® and then store optimal production settings in the LTC3886's onboard EEPROM. No board changes are required, since capabilities and optimization settings (including compensation) can be changed via software.



The LTC6811 ushers in Linear's fourth generation of multicell battery stack monitors. See page 2 for more about this powerful device.

This 2-channel PolyPhase® DC/DC synchronous step-down switching regulator controller employs a constant-frequency, current-mode architecture, with accurate input and output current sensing and programmable loop compensation, and is available in a 52-lead (7mm × 8mm) QFN package. Accurate voltage and current sensing, adjustable compensation and dedicated PGOOD pins make the LTC3886 ideal for industrial applications that demand versatile power system design, control, monitoring, programming and accuracy.

FLEXIBLE FEATURE SET

Figure 1 shows a generalized schematic of a LTC3886. The 100kHz to 750kHz PWM switching frequency range, and low $R_{DS(ON)}$ integrated N-channel MOSFET gate drivers support a plethora of external components and enable power capability and system cost optimization. The

(continued on page 4)

In this issue...

Linear in the News

LINEAR TECHNOLOGY ANNOUNCES FOURTH GENERATION AUTOMOTIVE BATTERY STACK MONITOR

Electric and hybrid vehicles can require tens or hundreds of series-connected battery cells, with battery stacks up to 1000V or higher. A battery management system in this high voltage environment must be able to reject common mode voltage fluctuations so that it can accurately monitor and control each cell in the strings.

High voltage battery stacks in vehicles face challenging operating conditions, with significant electrical noise and wide operating temperatures. Battery management electronics are expected to maximize operating range, lifetime, safety and reliability, while minimizing cost, size and weight.

In November, Linear announced the LTC6811, Linear Technology's latest multicell battery stack monitor, incorporating an ultrastable voltage reference, high voltage multiplexers, 16-bit delta-sigma ADCs, and a 1Mbps isolated serial interface. The LTC6811 can measure up to 12 series-connected battery cells at voltages with better than 0.04% accuracy. With eight programmable third order lowpass filter settings, the LTC6811 provides outstanding noise reduction. In the fastest ADC mode, all cells can be measured within 290µs.

The LTC6811 battery stack monitor was announced by Linear at press meetings worldwide. Linear's technical team presented the attributes of this advanced automotive device and its contribution to improved efficiency, reliability and safety in the next generation of electric and hybrid/electric vehicles.

For large battery packs, multiple LTC6811s can be interconnected and operated simultaneously, using Linear Technology's proprietary 2-wire isoSPI™ interface. This built-in interface provides electrically isolated, high RF noise immune communication for data rates up to 1Mbps. Using twisted pair, many LTC6811s can be connected in a daisy chain to a single host processor, enabling measurement of hundreds of cells in high voltage battery stacks.

The LTC6811 is the fourth generation of Linear's road-proven battery monitor ICs, designed to surpass the environmental, reliability and safety requirements of automotive and industrial applications. The LTC6811 is fully specified for operation from –40°C to 125°C. It has been engineered for ISO 26262 (ASIL) compliant systems, with extensive fault coverage via its redundant voltage reference, logic test circuitry, cross-channel testing, open wire detection capability, a watchdog timer and packet error checking on the serial interface.

Safety and Reliability

The LTC6811 enables high reliability, high stability and high measurement accuracy systems, built for years of operation in environments of high voltages, extreme temperatures, hot plugging and electrical noise. The LTC6811 supports automotive functional safety, as defined by the ISO 26262 standard, which systematically addresses potential hazards in an automobile caused by the malfunctioning behavior of electronic and electrical systems. This requires that the system must continuously confirm the proper operation of key electronics, such as the cell voltage measurement electronics.

Accuracy

To achieve outstanding accuracy, the LTC6811 includes a dedicated sub-surface Zener voltage reference, offering outstanding long term stability and accuracy, over time and operating conditions. This enables the LTC6811 to measure every battery cell to within less than 1.2mV of error.

Added Functionality

The LTC6811 is designed to operate at the most critical location in the battery system: directly connected to the battery cells. The LTC6811 can monitor battery current and temperature sensors, and closely correlate these values to cell measurements.

The LTC6811 offers very flexible general purpose I/O that can operate as digital inputs, digital outputs or as analog inputs. When operated as analog inputs, the LTC6811 can measure any voltage from V^- to 5V with the same measurement accuracy as the cell measurements. The LTC6811 allows cell measurements to be synchronized with these external signals or with the 12-cell stack voltage. The LTC6811 has built-in capability, through the digital I/O, to control I^2C or SPI slave devices. This enables the LTC6811 to control more complex functions, such as multiplexers for expanded analog inputs or EEPROM to store calibration information.

For more information, visit www.linear.com/product/LTC6811-1

Linear CTO Bob Dobkin presents at the Third Annual Analog Gurus Conference in Tokyo.

THIRD ANNUAL ANALOG GURUS CONFERENCE HELD IN TOKYO

On November 18, Linear held the Third Annual Analog Gurus Conference in Tokyo. Nearly 400 attendees heard presentations from analog experts, including:

- Professor Akira Hyogo, Professor/ Vice President Faculty of Science & Technology, Tokyo University of Science
- Bob Dobkin, Co-Founder & Chief Technical Officer, Linear Technology
- Steve Pietkiewicz, Vice President Power Management Products, Linear Technology
- Bob Reay, Vice President, Mixed Signal Products, Linear Technology

Conference attendees received signed copies of the just published Japanese edition of *Analog Circuit Design, Volume 2, Immersion in the Black Art of Analog Design, Part 1—Power Management*, edited by Bob Dobkin and Jim Williams.

CONFERENCES & EVENTS

CAR-ELE Japan, 8th International Automotive Electronics Technology Expo, Tokyo, Japan, January 13–15, Booth W8-13—Presenting Linear's automotive solutions, including LED lighting, collision avoidance and improved audio. www.car-ele.jp/en/Home/

European Advanced Automotive & Industrial Battery Conference (AABC Europe 2016), Mainz, Germany, January 25–28—Presenting Linear's battery management systems. Participating in three technology-focused symposia covering lithium-ion chemistry, lithium-ion engineering and EC capacitor developments, and an application-focused symposia with two parallel tracks focusing on high volume and industrial/specialty automotive. www.advancedautobat.com/conferences/automotive-battery-conference-Europe-2016/index.html

Embedded World, Nuremberg, Germany, February 23–25, Booth 310, Hall 4A—Showcasing demos of Linear's latest products and solutions, focusing on electronic systems, distributed intelligence, the Internet of Things, e-mobility and energy efficiency. www.embedded-world.de/en

WEKA Batterie Forum, Munich, Germany, March 9–10—Presenting Linear's battery management system products with live demos. www.elektroniknet.de/termine/?schid=10260&date=201603

Power Supply Anwenderforum, Munich, Germany, March 9–10—Presenting Linear's µModule® portfolio and showcasing live demos. www.elektroniknet.de/termine/?schid=10260&date=201603

APEC 2016, Long Beach Convention Center, Long Beach, CA, March 20–24, Booth 1233—Showcasing Linear's broad line of high performance power management products. www.apec-conf.org/ ■

The LTC3886's regulation and supervision accuracy reduces total system costs with fewer output capacitors, while still meeting the tight input voltage requirements of downstream ICs.

(LTC3886, continued from page 1)

LTC3886 can readily accommodate a wide variety of industrial, medical, and point-of-load applications due to a flexible programmable feature set that addresses the specific application at hand.

ADAPTABILITY THROUGH PROGRAMMABILITY

The following parameters of the LTC3886 are configurable and storable in the onboard EEPROM via the I²C/SMBus interface:

- Output voltage, overvoltage, undervoltage and overcurrent limit
- Input ON/OFF voltage, input overvoltage and input overcurrent warning
- Digital soft-start/stop, sequencing, margining
- Control loop compensation
- PWM switching frequency and phasing
- Fault response and fault propagation via the FAULT pins
- Device address

Switching frequency, device phasing and output voltage are also programmable with external configuration resistors. In addition, all 128 possible addresses are resistor selectable.

POWER GOOD, SEQUENCING AND PROGRAMMABLE FAULT RESPONSE

The dedicated PGOOD pin for each channel simplifies enabling event-based sequencing across multiple LTC3886s and other power system management ICs. The LTC3886 also supports time-based sequencing. After waiting the TON_DELAY amount of time following the RUN pin going high, a PMBus command to turn on, or the V_{IN} pin voltage rising above a preprogrammed voltage, the outputs are enabled.

Time-based power off sequencing is handled in a similar way. To assure proper time based sequencing, simply connect all SHARE_CLK pins together and connect together the RUN pins of all the power system management ICs. The LTC3886 FAULT pins are configurable to indicate a variety of faults including OV, UV, OC, OT, timing faults and peak current faults. In addition, the FAULT pins can be pulled low by external sources, indicating a fault in some other portion of the system. The fault responses of the LTC3886 are configurable and allow the following options:

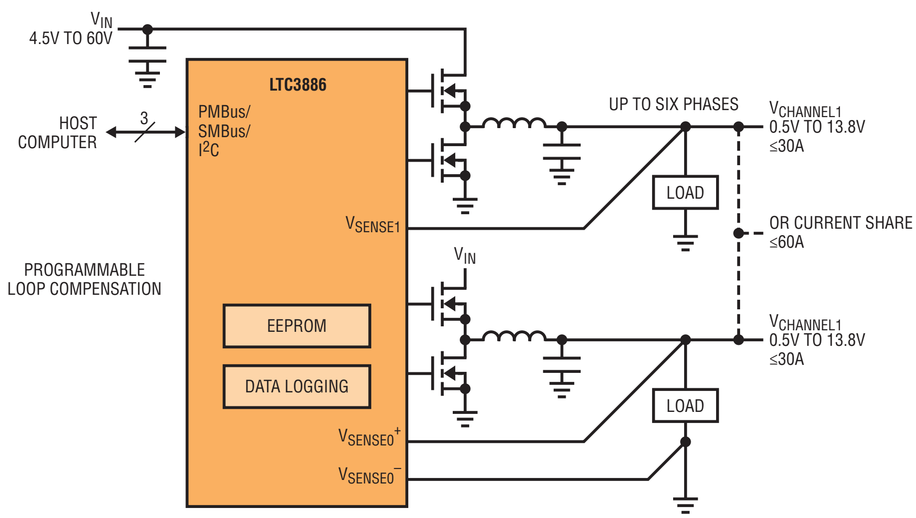
- Ignore
- Shut Down Immediately—latchoff
- Shut Down Immediately—retry indefinitely at the time interval specified in MFR_RETRY_DELAY

Table 1. Summary of Linear's power system management controllers and PSM µModule regulators

	µMODULE REGULATORS			CONTROLLERS					
	LTM4675	LTM4676A	LTM4677	LTC3880	LTC3882	LTC3883	LTC3884	LTC3886	LTC3887
V_{OUT} range (V)	0.5–5.5	0.5–5.5	0.5–5.5	0.5–4.0, ch0 0.5–5.4, ch1	0.5–5.3	0.5–5.4	0.5–5.4	0.5–13.2	0.5–5.5
V_{IN} range (V)	4.5–17	4.5–17	4.5–17	4.5–24	3.0–38	4.5–24	4.5–38	4.5–60	4.5–24
V_{OUT} accuracy (%)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Input current sense	calibrated	calibrated	calibrated	inferred					inferred
I_{OUT} max (A)	dual 9 or single 18	dual 13 or single 26	dual 18 or single 36	30/phase[1]	40/phase[1]	30/phase[1]	30/phase[1]	30/phase[1]	30/phase[1]
DCR sensing	NA	NA	NA	low	ultralow	low	very low	low	low
Digitally adjustable loop compensation									

[1] Controller maximum I_{OUT} depends on external components

Figure 1. The LTC3886 is versatile and flexible. It features wide input and output ranges and and it is highly customizable via PMBus. Accurate telemetry is also available over the digital bus. All features can be controlled via LTpowerPlay.



FAULT LOGGING AND TELEMETRY

The LTC3886 supports fault logging, which stores telemetry and fault status data in a continuously updated RAM buffer. After a fault event occurs, the buffer is copied from RAM to EEPROM and becomes a persistent fault log, which can be read back at a later date to determine what caused the fault.

EXTV$_{CC}$ PIN FOR MAXIMUM EFFICIENCY

The EXTV$_{CC}$ pin is provided to minimize application power loss and supports voltages of 5V to 14V. It enables designs with optimal circuit efficiency and minimal die temperature, and enables the LTC3886 to efficiently supply its own bias power from the output voltage.

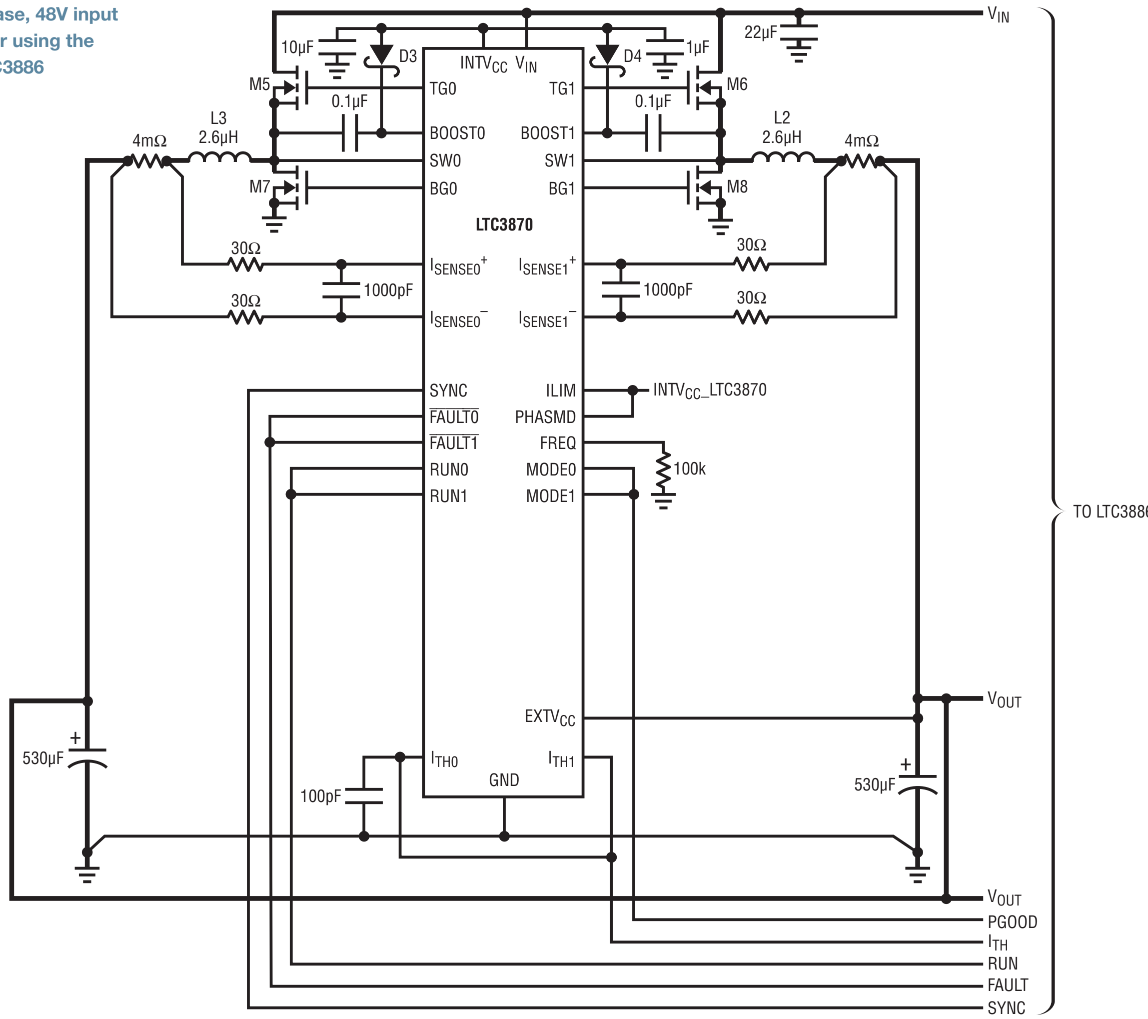
ACCURACY AND PRECISION

Modern applications require supply voltage regulation and supervision with stringent tolerances. These requirements are met with a high speed analog control loop and an integrated 16-bit ADC and 12-bit DACs. The output voltage accuracy of the LTC3886 is guaranteed at ±0.5% over the full operating temperature. In addition, the output voltage overvoltage and undervoltage comparators have less than ±2% error over temperature. The LTC3886's regulation and supervision accuracy reduces total system costs with fewer output capacitors, while still meeting the tight input voltage requirements of downstream ICs.

The unique high side 60V input current sense amplifier measures the input current with less than ±1.2% error over temperature. The output current is guaranteed accurate to ±1.5% over temperature. The internal die temperature measurement of the LTC3886 is guaranteed accurate to 0.25°C, and the external temperature telemetry has less than ±1°C error.

Figure 2. LTpowerPlay

Figure 3. High efficiency 425kHz 4-phase, 48V input to 5V output, 50A step-down converter using the LTC3870 phase expander with the LTC3886

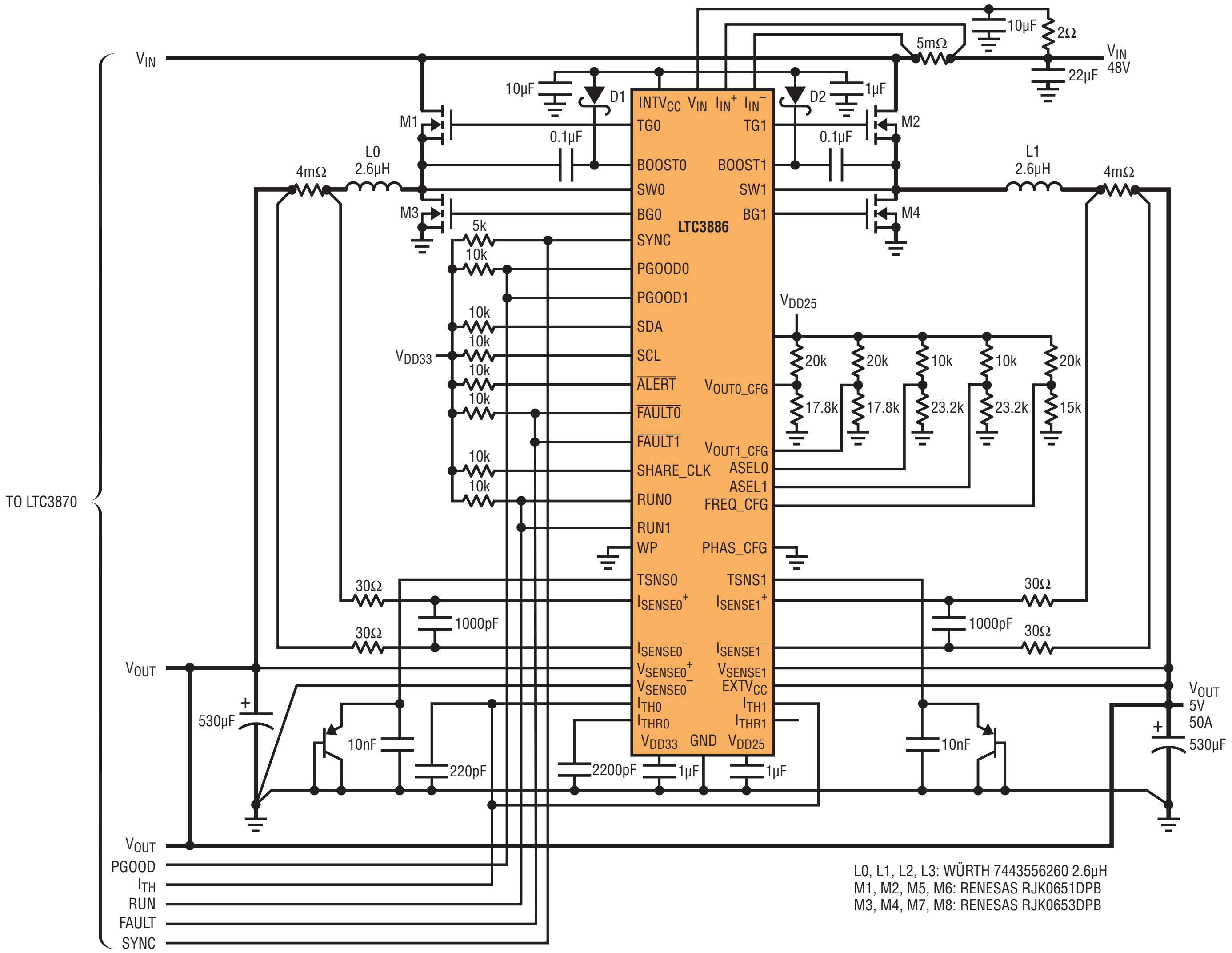


EXPANSION

State of the art power management systems require increasing power and control, but must fit into dwindling board space. Parallel multiphase rails are the best solution for high power requirements because they enable high power density and efficient expandability. The LTC3886 supports accurate PolyPhase® current sharing for up to six phases between multiple LTC3886s. This allows system designers to add power stages as needed. In addition, the dual-phase LTC3870 PolyPhase expander IC mates seamlessly with the LTC3886 to create 6-phase PolyPhase rails at a lower price point. Figure 3 shows a 4-phase solution. Figure 4 shows the dynamic current sharing among the phases.

The LTC3870 requires no additional I²C addresses, and it supports all programmable features as well as fault protection. When configuring a PolyPhase rail with multiple LTC3886/LTC3870s, the user simply shares the SYNC, ITH, SHARE_CLK, FAULTn, PGOODn and ALERT pins of all the channels connected to the rail. The relative phasing of all the channels should be set to be equally spaced. This phase interleaving results in the lowest peak input current and lowest output voltage ripple, and reduces input and output capacitor requirements.

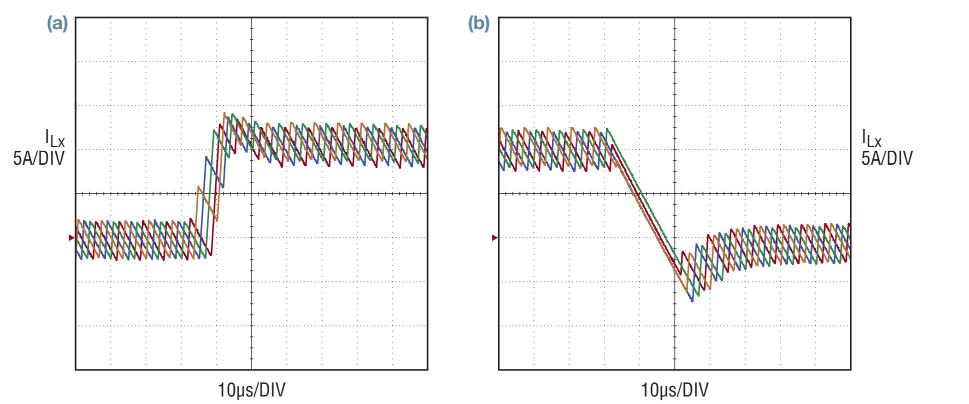
System architects often fragment the power system to meet functional and board space requirements: the LTC3886/LTC3870 PolyPhase rail simplifies fragmentation by breaking up the power and control components, allowing them to be easily placed in available spaces. Fragmentation also spreads the heat of the power supply system over the PCB, simplifying overall thermal extraction and reducing hot zones.



PROGRESSION

Figure 2 shows a screen from LTpowerPlay, a powerful Windows-based software development tool with graphical user interface (GUI) that fully supports the LTC3886. LTpowerPlay enhances evaluation when connected to demo boards and directly to application hardware. LTpowerPlay provides unparalleled development, diagnostic and debug features. Telemetry, system fault status and PMBus command values are all readily accessible through the GUI. The LTC3886 and other power system management ICs can be uniquely configured with ease using LTpowerPlay. Complete information is available at: http://www.linear.com/ltpowerplay.

Figure 4. Dynamic current sharing for the 4-phase circuit shown in Figure 3; load step (a) rising and (b) falling.



The LTC3886 offers programmable loop compensation to assure loop stability and optimize the transient response of the controller without any external component changes. Gone are the days of painstakingly soldering and unsoldering multitudes of components to achieve the ideal compensation. A few clicks of a mouse using LTpowerPlay, and the LTC3886 can have optimal compensation.

ADJUSTABLE COMPENSATION

The LTC3886 offers programmable loop compensation to assure loop stability and optimize the transient response of the controller without any external component changes. Gone are the days of painstakingly soldering and unsoldering multitudes of components to achieve the ideal compensation. A few clicks of a mouse using LTpowerPlay, and the LTC3886 can have optimal compensation. The control loop is fine-tunable quickly and painlessly, regardless of last minute component substitutions or variations. This empowers designers to squeeze the maximum performance out their systems by removing unnecessary output capacitors while saving board space and cost.

The process of programming loop compensation is summarized in Figures 5, 6 and 7. The error amplifier g_m (Figure 5) is programmable from 1.0mmho to 5.73mmho using bits[7:5] of the MFR_PWM_COMP command, and the compensation resistor R_{TH}, inside the LTC3886 is programmable from 0kΩ to 62kΩ using bits[4:0] of the MFR_PWM_COMP command. Only two external compensation capacitors, C_{TH} and C_{THP}, are required in the design and the typical ratio between C_{TH} and C_{THP} is set to a typical value of 10.

By adjusting the g_m and R_{TH} only, the LTC3886 provides a programmable type II compensation network for optimizing the loop over a wide range of output capacitors, and compensation component tolerances. Adjusting the g_m of the error amplifier proportionately changes the gain of the compensation loop over the entire frequency range without moving the pole and zero location, as shown in Figure 6. Adjusting the R_{TH} resistor changes the pole and zero location, as shown in Figure 7. Once the voltage and current ranges of the LTC3886 are determined, changes to the output voltage or current limit do not affect the loop gain. When the output voltage is modified by either changing voltage command, or by margining, the transient response of the circuit remains constant.

ACCURATE TELEMETRY FOR OPTIMIZING SYSTEM EFFICIENCY WITH AN INTERMEDIATE BUS

The LTC3886 has a wide input voltage range of 4.5V to 60V, and an output voltage range of 0.5V to 13.8V. This makes the LTC3886 an excellent choice for efficiently regulating a high voltage input supply voltage down to an intermediate bus voltage. The intermediate bus voltage powers downstream point-of-load converters (POL).

When used as an intermediate bus converter to power downstream power system management POLs, the LTC3886 enables the user to optimize the intermediate bus voltage for maximum efficiency. Since voltage and current telemetry provided by the LTC3886 *and* power system management ICs is so accurate, it is possible to produce accurate *system* efficiency measurements in real time. This, in turn, makes it possible to create an optimization program, in which a microcontroller determines the optimal intermediate bus voltage for various conditions.

Figure 5. Programmable loop compensation

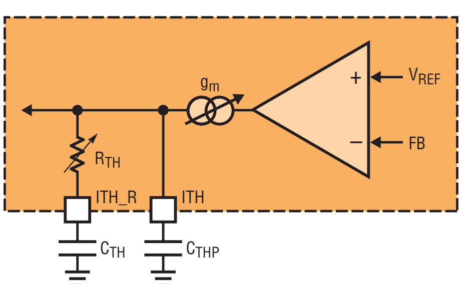


Figure 6. Error amp g_m adjust

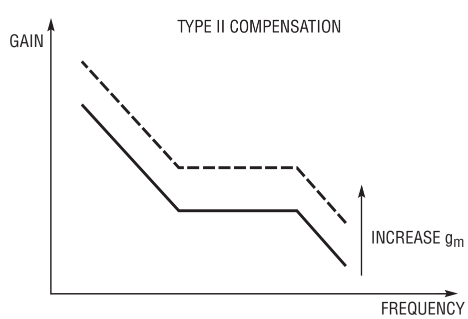
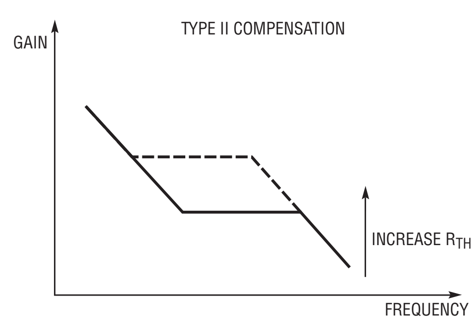


Figure 7. R_{TH} adjust



See the video:
www.linear.com/solutions/5761

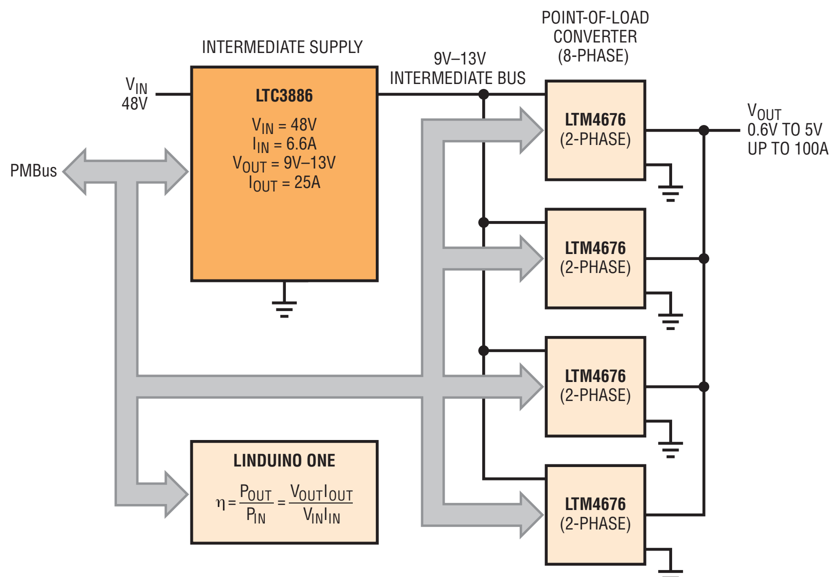
To demonstrate this, a 9V-to-13V LTC3886 output intermediate supply was used to power the input of an LTM®4676 8-phase demonstration circuit configured as a point-of-load converter, as shown in Figure 8. A Linear Technology Linduino® One demonstration board (www.linear.com/solutions/linduino) measured and calculated the total efficiency of the system by reading the accurate voltage and current telemetry from the LTC3886 and LTM4676 via the PMBus. The Linduino application measured the total system efficiency at multiple intermediate bus voltages and modified the intermediate bus voltage for the lowest input power, achieving highest system efficiency, without user intervention.

The efficiency of the LTC3886 vs the intermediate bus voltage is shown in Figure 9. The total system efficiency vs the intermediate bus voltage is shown in Figure 10. The curves represent point-of-load currents of 10A, 20A, 40A, 80A and 100A, with the peak efficiency shifting respective of load current. Higher load currents require a higher intermediate bus voltage to operate at peak efficiency. Setting the intermediate bus voltage at a fixed voltage that is too high lowers the total efficiency of the system at low load currents. Compared to a using a standard fixed 12V intermediate bus voltage, optimizing the intermediate bus voltage with the LTC3886 improves efficiency by 6.2% at 10A of load current, 3.5% at 20A, and 1% at 40A. This technique enables efficiency optimization over the full workload of a system.

SUMMARY

The LTC3886 expands Linear's portfolio of power system management controllers into the high voltage arena. A wide output voltage range of 0.5V to 13.8V, along with accurate voltage and current sensing, adjustable compensation, and dedicated PGOOD pins, gives LTC3886 users maximum design flexibility and performance. The LTC3886 is ideal for industrial applications that demand versatile power system design, control, monitoring, programming and accuracy. ■

Figure 8. The LTC3886 set up as an intermediate bus to drive a power management IC POL converter. Telemetry from the LTC3886 intermediate supply and the POL ICs is used by a Linduino One demonstration circuit to optimize system efficiency by adjusting the intermediate bus voltage as load current changes.



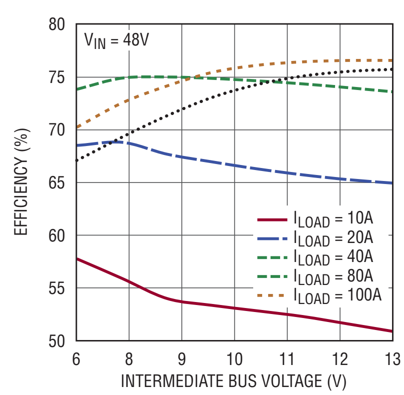


Figure 9. LTC3886 efficiency vs output voltage at various load currents

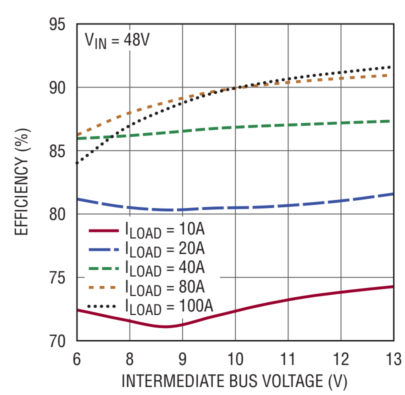


Figure 10. System efficiency

Low I_Q, 60V Monolithic Boost/Sepic/Inverting Converter in ThinSOT or 3mm x 2mm DFN

Owen Jong

The LT8330 monolithic DC/DC converter enables boost, SEPIC or inverting topologies in a low profile 6-lead ThinSOT™ or an 8-lead (3mm × 2mm) DFN package. It meets the demand for small, efficient power supply solutions with a 3V-to-40V input range, internal 1A, 60V switch and 6µA quiescent current. It easily satisfies the requirements of numerous industrial and automotive applications.

NEW FAMILY OF SPACE-SAVING MONOLITHIC CONVERTERS

The LT®8330 is the first in a new family of monolithic boost/SEPIC/inverting converters that take advantage of new design techniques and a new process technology to achieve low output ripple Burst Mode® operation, rugged power switches and fast switching times with low AC losses. The low minimum on- and off-times of the power switch allow a wide range of duty cycles at the high 2MHz switching frequency, reducing the cost and size of the required magnetic components and capacitors.

EASY TO USE

Overall converter design is simplified, and parts count is minimized by using internal compensation. Positive or negative output voltages are easily programmed using a resistor divider from the output to a single FBX pin. Integrated frequency foldback and soft-start allow the output capacitor to be charged gradually toward its final value during start-up while limiting inductor peak currents. Undervoltage lockout can be programmed for the input supply using an accurate EN/UVLO pin threshold.

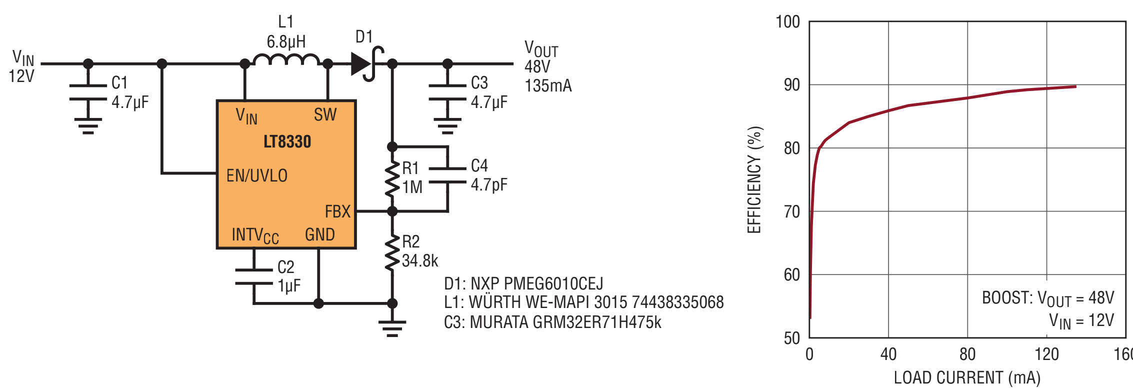


Figure 1. 12V to 48V boost converter and efficiency

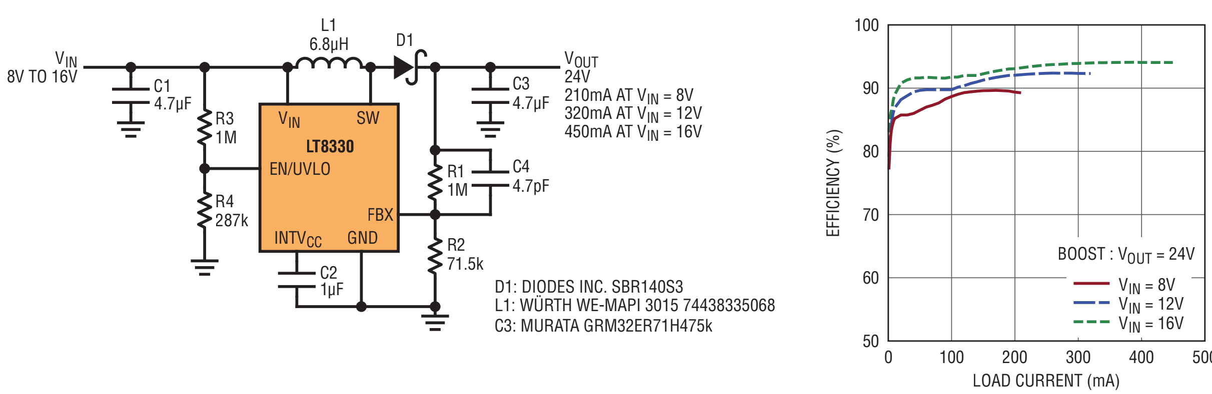


Figure 2. 8V–16V to 24V boost converter and efficiency

Summary of ThinSOT monolothic boost/inverting/SEPIC converters

PART	V_{IN}	I_Q	f_{SW}	POWER SWITCH	PACKAGE
LT8330	3V–40V	6µA	2.0MHz	1A/60V DMOS	ThinSOT–6 3mm × 2mm DFN
LT1615/17	1.1V–15V	20µA	constant off-time	0.3A/36V NPN	ThinSOT–5
LT1613/11	1.1V–10V	3mA	1.4MHz	0.55A/36V NPN	ThinSOT–5
LT1930/31 LT1930A/31A	2.6V–16V	5.5mA	1.2MHz 2.2MHz	1A/36V NPN	ThinSOT–5
LT3467 LT3467A	2.6V–16V	1.2mA	1.3MHz 2.1MHz	1.1A/40V NPN	ThinSOT–6 3mm × 2mm DFN
LT1935	2.6V–16V	3mA	1.2MHz	2A/40V NPN	ThinSOT–5

PIN COMPATIBILITY

The LT8330 is pin compatible with LT3467/67A for those applications requiring higher input voltage or higher switch voltage (LT3467/67A SS pin becomes $INTV_{CC}$ pin).

BOOST CONVERTERS

For applications requiring output voltages greater than the input, the 3V-to-40V input capability and internal 60V/1A power switch make LT8330 an attractive choice for many boost converter applications.

In some of the applications shown here, the converter is operated in discontinuous conduction mode (DCM) to achieve a very high step-up ratio. When configured in continuous conduction mode (CCM), the LT8330 is capable of delivering higher output power.

12V Input to 48V Output Boost

The converter in Figure 1 operates from a 12V input supply to generate 48V at up to 6.5W at 90% peak efficiency.

8V–16V Input to 24V Output Boost

Figure 2 shows a 24V boost converter, powered from an 8V-to-16V input. It is capable of delivering up to 10.8W at an efficiency of 94%.

3V–6V to 48V Boost

Figure 3 shows the LT8330 configured to operate in discontinuous conduction mode (DCM) to achieve a 16:1 step up ratio. This 48V boost converter maintains an efficiency of 75% when loaded at 14mA (for a 6V input voltage).

Figure 3. 3V–6V to 48V boost converter and efficiency

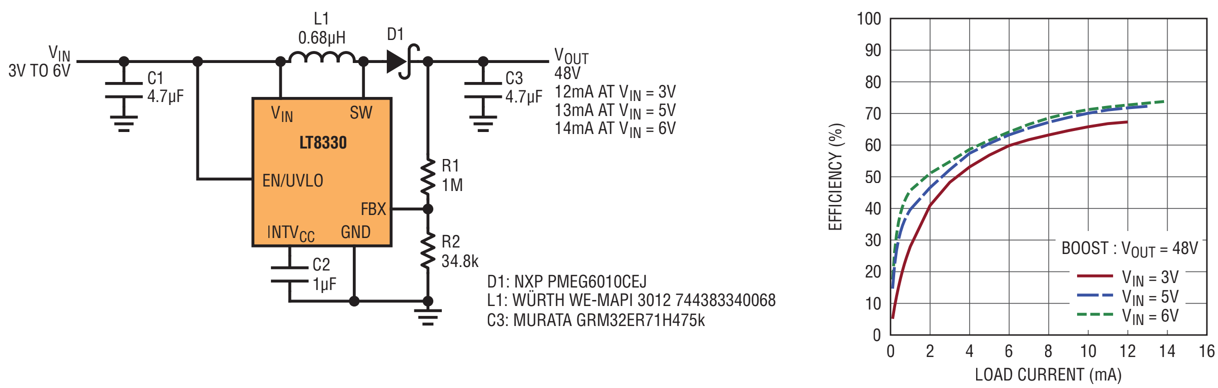
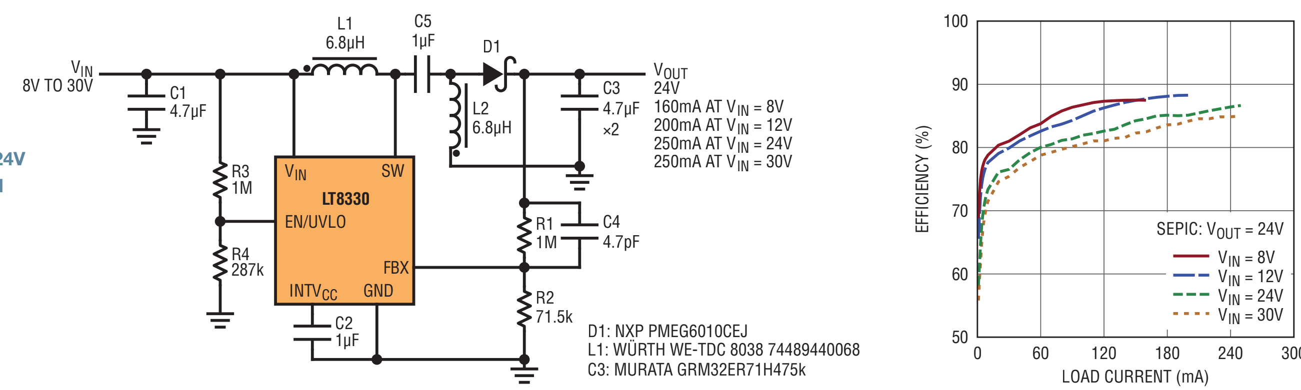


Figure 4. 8V–30V to 24V SEPIC converter and efficiency



The LT8330 is ideal for applications requiring efficient power supply solutions in a compact space. The LT8330's 3V-to-40V input voltage range and 60V/1A rugged power switch enable a wide variety of boost/SEPIC/inverting converter solutions.

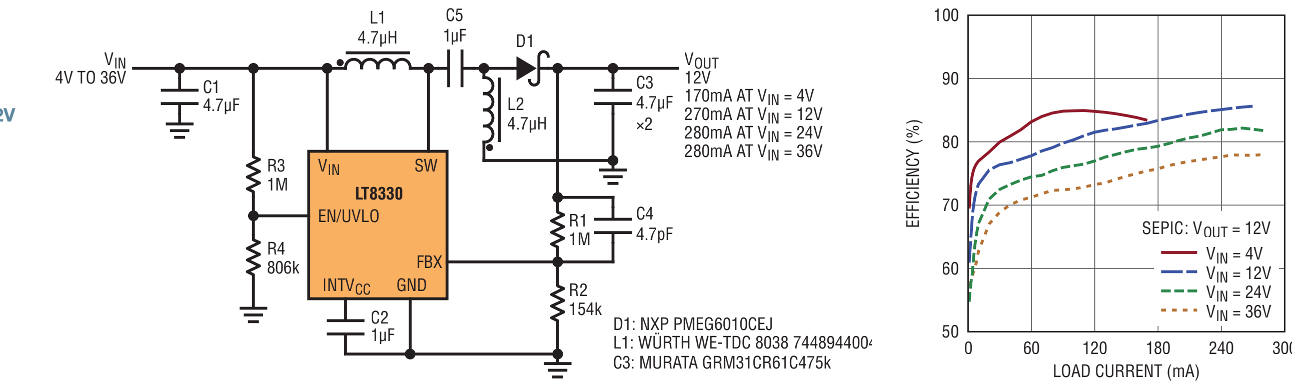


Figure 5. 4V–36V to 12V SEPIC converter and efficiency

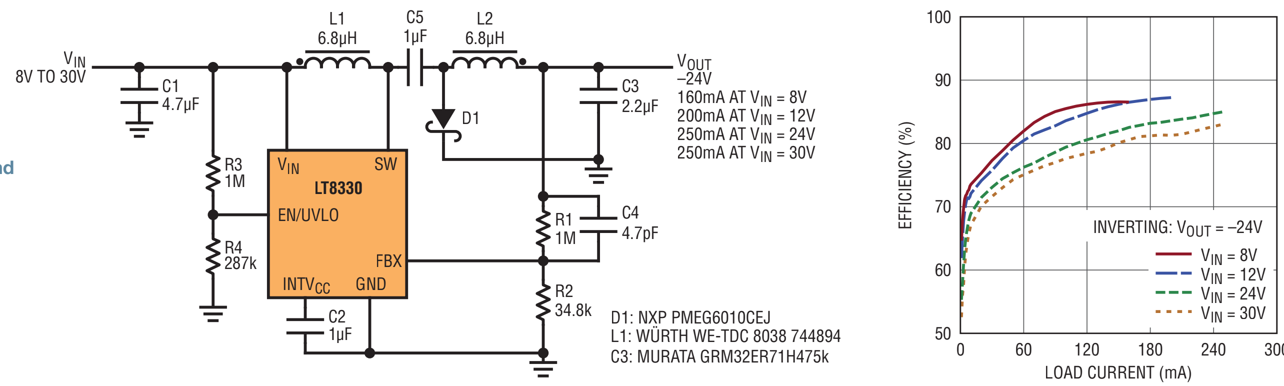


Figure 6. 8V–30V to –24V Cuk converter and efficiency

SEPIC CONVERTERS

Automotive and industrial applications often operate from input voltages that are above and below the required output voltage. For applications where the DC/DC converter is required to both step-up and step-down its input, the SEPIC topology is commonly chosen. The SEPIC topology is also useful for applications that require output disconnect. This feature ensures no output voltage during shutdown and also tolerates output short-circuit faults since there is no DC path from output to input. The high 60V switch rating of the LT8330 and the low minimum on and off times of the power switch allow wide input voltage ranges even at the high 2MHz switching frequency of the LT8330.

8V–30V Input to 24V Output SEPIC

The circuit in Figure 4 shows a 24V SEPIC converter with a wide input range, delivering up to 6W at up to 86.6% efficiency.

4V–36V Input to 12V Output SEPIC

Figure 5 shows another solution with a wide input range, with an operating input voltage that can be as low as 4V while delivering 2W of power at up to 85% efficiency. For input voltages above 24V, the circuit in Figure 5 can supply up to 3.4W.

CUK CONVERTERS

Negative supplies are commonly used in today's electronics. However, many applications only have a positive input voltage from which to operate. The LT8330, when configured in the Cuk inverting topology, can regulate from a positive input voltage that is above or below the magnitude of the negative output voltage.

As with the SEPIC topology, the high 60V switch rating of the LT8330 and the low minimum on and off times of the power switch allow wide input voltage ranges even at the high 2MHz switching frequency of the LT8330.

The LT8330, when configured in the Cuk inverting topology, can regulate from a positive input voltage that is above or below the magnitude of the negative output voltage. The low minimum on- and off-times of the power switch allow wide input voltage ranges even at the high 2MHz switching frequency of the LT8330.

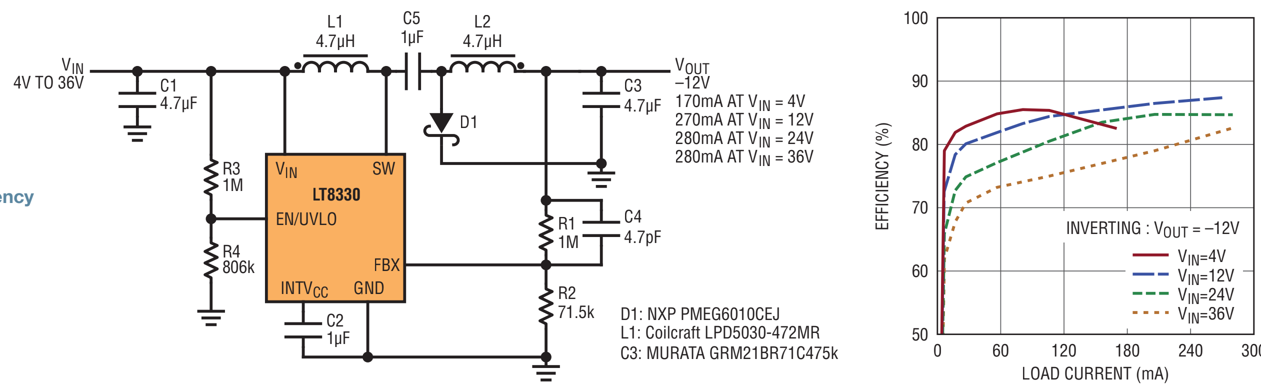


Figure 7. 4V–36V to –12V Cuk converter and efficiency

8V–30V Input to –24V Output Cuk Converter

Figure 6 shows the LT8330 regulating a negative output voltage using the Cuk topology. This circuit delivers up to 6W of power and maintains its efficiency up to 87%.

4V–36V to –12V Cuk Converter

A –12V output CUK converter is shown in Figure 7. This circuit has a wide input range and high efficiency operation— at up to 3.4W, it achieves a peak efficiency of 86%.

8V–40V to ±15V

Figure 8 shows a dual output, +15V/–15V converter. This circuit has a wide input range and high efficiency operation—at up to 4.8W of power, it reaches a peak efficiency of 87%.

CONCLUSION

The LT8330 is ideal for applications requiring efficient power supply solutions in a compact space. The LT8330's 3V-to-40V input voltage range and 60V/1A rugged power switch enable a wide variety of boost/SEPIC/inverting converter solutions. Its low output ripple burst mode capability allows efficiency to be maintained at light loads. The low minimum on- and off-times of the power switch allow operation at 2MHz to reduce component sizing for compact power supply solutions in a tiny, low profile 6-lead ThinSOT, or an 8-lead (3mm × 2mm) DFN. ■

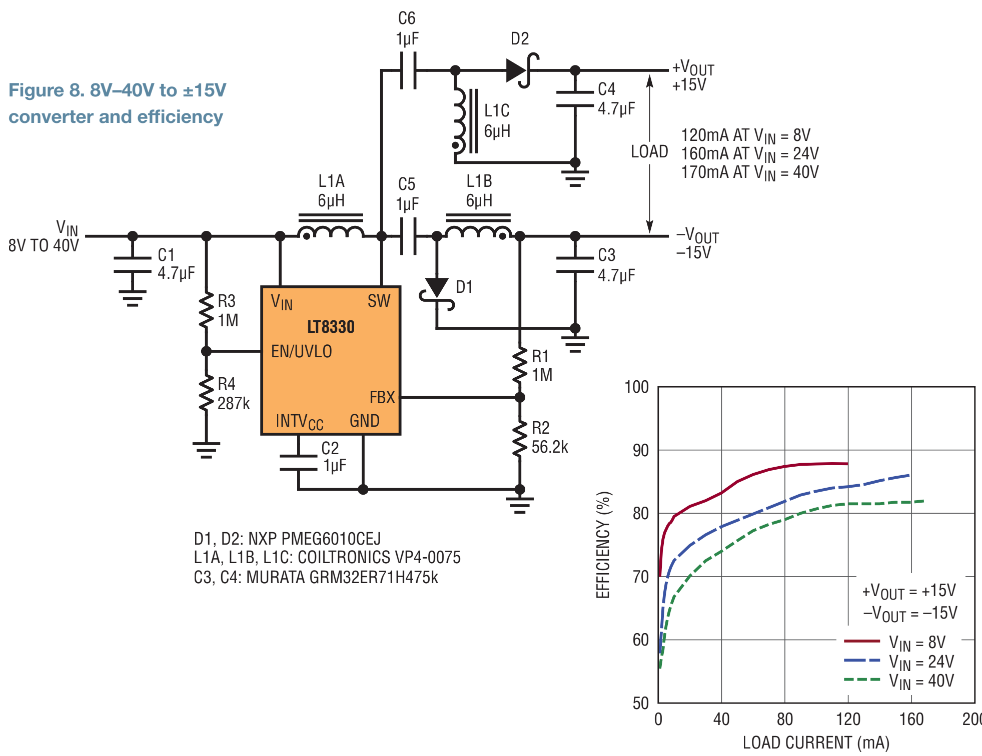


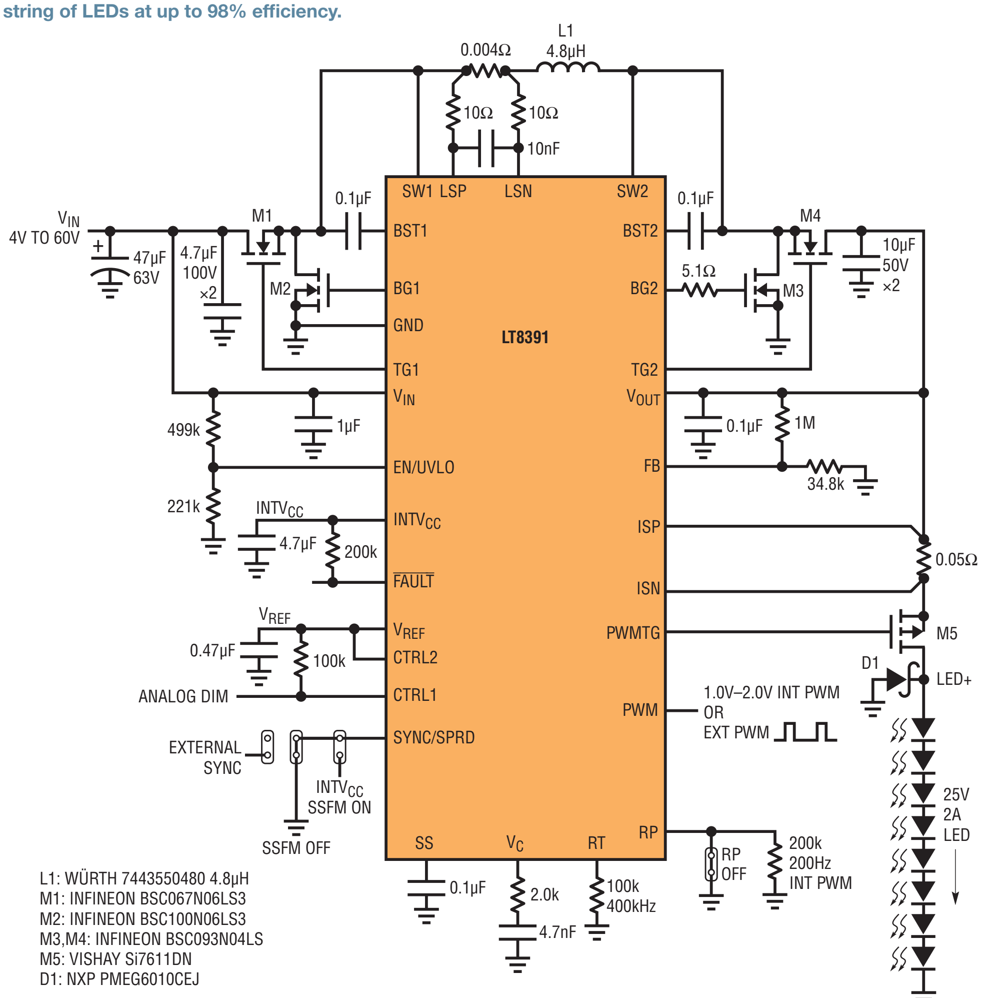
Figure 8. 8V–40V to ±15V converter and efficiency

Buck-Boost LED Driver Reaches 98% Efficiency, Features Internal PWM Dimming and Spread Spectrum without Flicker

Keith Szolusha

Four-switch converters combine two converters (a buck and boost) into a single converter, with the obvious advantage of reduced solution size and cost, plus relatively high efficiency conversion. High performance 4-switch converters have carefully designed control schemes. For instance, for highest efficiency, a 4-switch converter should operate with only two switches when only step-up or step-down conversion is needed, but bring in all four switches as V_{IN} approaches V_{OUT}. A well-designed buck-boost converter gracefully transitions between the three regions of operation—boost, buck and buck-boost—by taking into account the challenge of combining three control loops—2-switch boost, 2-switch buck and 4-switch operation.

Figure 1. LT8391 4V–60V 4-switch synchronous buck-boost LED driver powers a 25V, 2A (50W) string of LEDs at up to 98% efficiency.



The LT8391 60V 4-switch buck-boost LED driver is designed to drive high power LEDs and to flawlessly transition between 2-switch boost, 4-switch buck-boost, and 2-switch buck regions of operation.

A patent-pending 4-switch buck-boost current-sense resistor control scheme provides a simple, yet masterful, method for the IC to run in peak current mode control in all regions of operation with a single sense resistor. It also allows the IC to run in CCM operation under normal load conditions and DCM operation at light load conditions while maintaining cycle-by-cycle peak inductor current control and preventing negative current.

This new generation buck-boost LED driver features spread spectrum frequency modulation and internally generated PWM dimming. These two features work together—the LT8391 supports flicker-free PWM dimming with either internal or external PWM dimming, even when spread spectrum is turned on (technique patent-pending).

The LT8391 60V 4-switch buck-boost LED driver is designed to drive high power LEDs and to flawlessly transition between 2-switch boost, 4-switch buck-boost and 2-switch buck regions of operation.

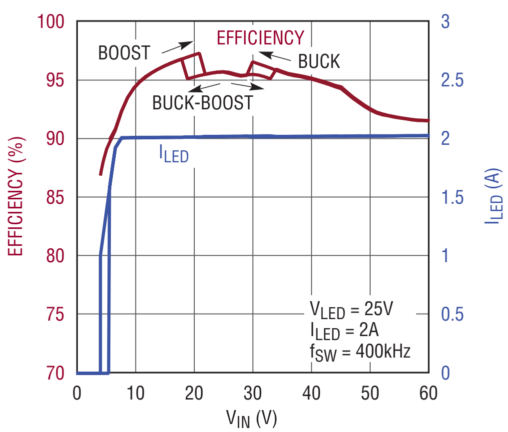
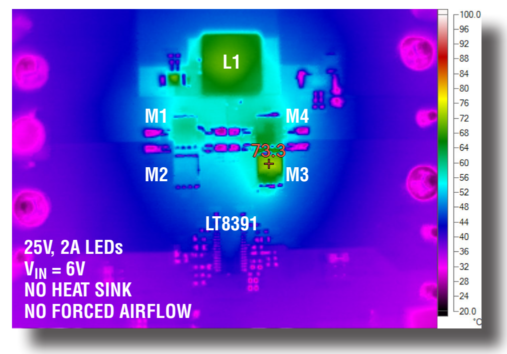


Figure 2. Efficiency and LED current vs input voltage for the 50W LED driver in Figure 1. Efficiency peaks at 98% and doesn't stray far from that peak, ranging from 95% to 97% throughout the typical 9V–16V automotive input range. Also shown, the LT8391 peak inductor current limit can maintain stable output with reduced output power at low V_{IN}.

Figure 3. Thermal imaging of the buck-boost LED driver in Figure 1 shows well contained temperature rise for wide ranging V_{IN}.



98% EFFICIENT, 50W SYNCHRONOUS BUCK-BOOST LED DRIVER

The LT8391 high power buck-boost LED driver in Figure 1 drives 25V of LEDs at 2A from a wide input voltage range. The 60V buck-boost converter operates down to 4V input. When the input voltage is low, input and peak switch currents can be pushed high. When V_{IN} drops enough to hit the peak inductor current limit, the IC can maintain stability and regulate at its peak current limit, albeit at reduced output power, as shown in Figure 2. This is advantageous from a system design perspective: riding through a low V_{IN} cold-crank condition with a reduction of output brightness is a welcome alternative to cranking up the current limit—and sizing up the inductor, cost, board space and input current—just to keep the lights full brightness during transient low V_{IN} conditions.

Efficiency of the 50W LED driver in Figure 1 is as high as 98% at its highest point (Figure 2). Over the typical automotive battery input range of 9V to 16V, the converter operates between 95% and 97% efficiency.

With high power MOSFETs and a single high power inductor, the temperature rise for this converter is low, even at 50W. At 12V input, no component rises more than 25°C above room temperature, as shown by the thermal scans in Figure 3. At 6V input, the hottest component rises less than 50°C with a standard 4-layer PCB and no heat sink or airflow. There is room to increase power output; hundreds of watts are possible with a single stage converter.

The 50W LED driver can achieve 1000:1 PWM dimming at 120Hz without flicker. The high side PWM TG MOSFET provides PWM dimming of a grounded LED string on the output. As a bonus, it acts as an overcurrent disconnect during short-circuit faults. The PWM input pin doubles as the standard logic-level PWM input waveform receiver for external PWM dimming and as a novel analog input that determines the internally generated PWM duty cycle.

The LT8391's novel SSFM reduces average EMI even more than peak EMI. You can see that there is 18dBμV or more reduction of average EMI while there is still about 5dBμV of peak EMI reduction.

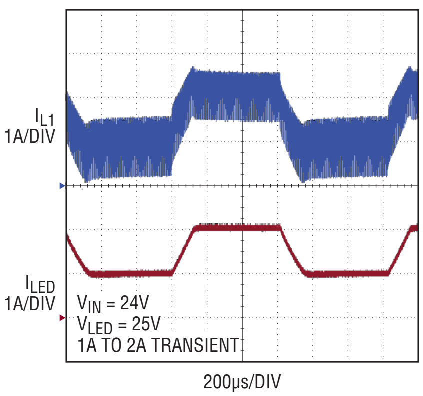


Figure 4. LED current shows a stable response to a CTRL pin driven 1A to 2A

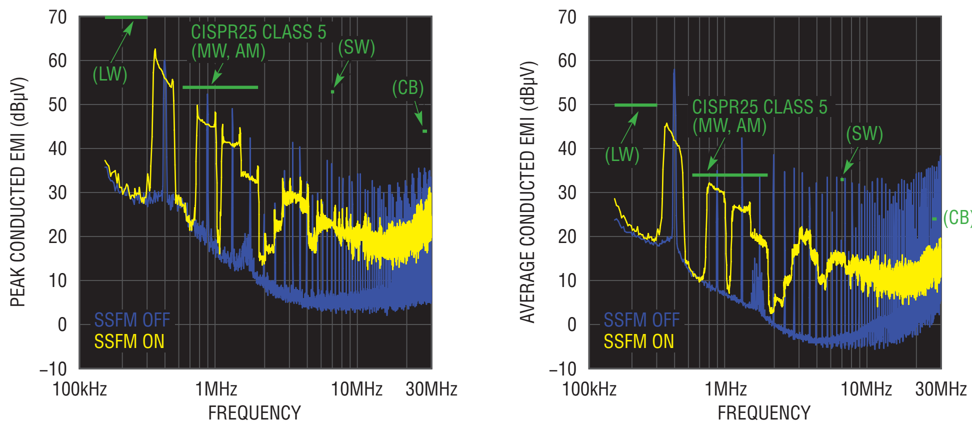


Figure 5. Spread spectrum frequency modulation (SSFM) reduces LT8391 peak and average EMI below CISPR25 limits. Average EMI has even greater reduction than peak EMI with LT8391 SSFM.

INTERNALLY GENERATED PWM DIMMING

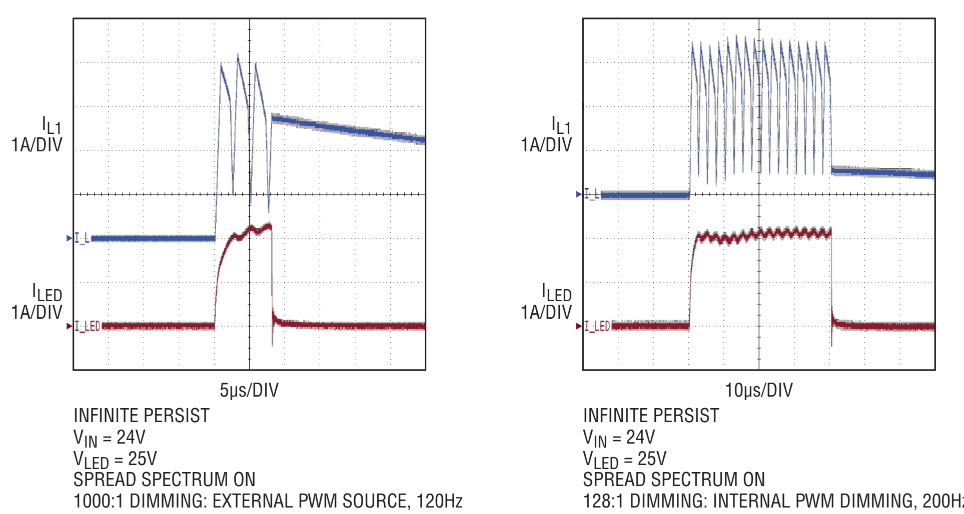
The LT8391 has two forms of PWM dimming: standard external PWM dimming, and internally generated PWM dimming. LT8391's unique internal PWM dimming feature eliminates the need for external components such as clocking devices and microcontrollers to be able to generate a highly accurate PWM dimming brightness control at ratios as high as 128:1.

The IC's internally generated PWM frequency, such as 200Hz, is set by a resistor on the RP pin. The voltage on the PWM pin, set between 1.0V and 2.0V, determines the internal generator's PWM dimming duty cycle for accurate brightness control. The duty cycle of internal dimming is chosen as one of 128 steps and internal hysteresis prevents duty cycle chatter. The better than ±1% accuracy of the internally generated PWM dimming is unchanged in boost, buck and buck-boost regions of operation.

SPREAD SPECTRUM REDUCES EMI

Spread spectrum frequency modulation reduces EMI in switching regulators. Although the switching frequency is most often chosen to be outside the AM frequency band (530kHz to 1.8MHz), unmitigated switching harmonics can still violate stringent automotive peak and average EMI requirements within the AM band. Adding spread spectrum to a 400kHz switch mode power supply can drastically reduce the EMI of high power headlight drivers, within the AM band and other regions such as medium and shortwave radio bands.

Figure 6. Infinite-persist scope traces show PWM dimming and SSFM working together for flicker-free brightness control with both externally and internally generated PWM dimming.



In some converters, spread spectrum and flicker-free LED PWM dimming do not work well together. Linear's patent-pending PWM dimming and spread spectrum operation is designed to run both functions simultaneously with flicker-free operation, even at high dimming ratios.

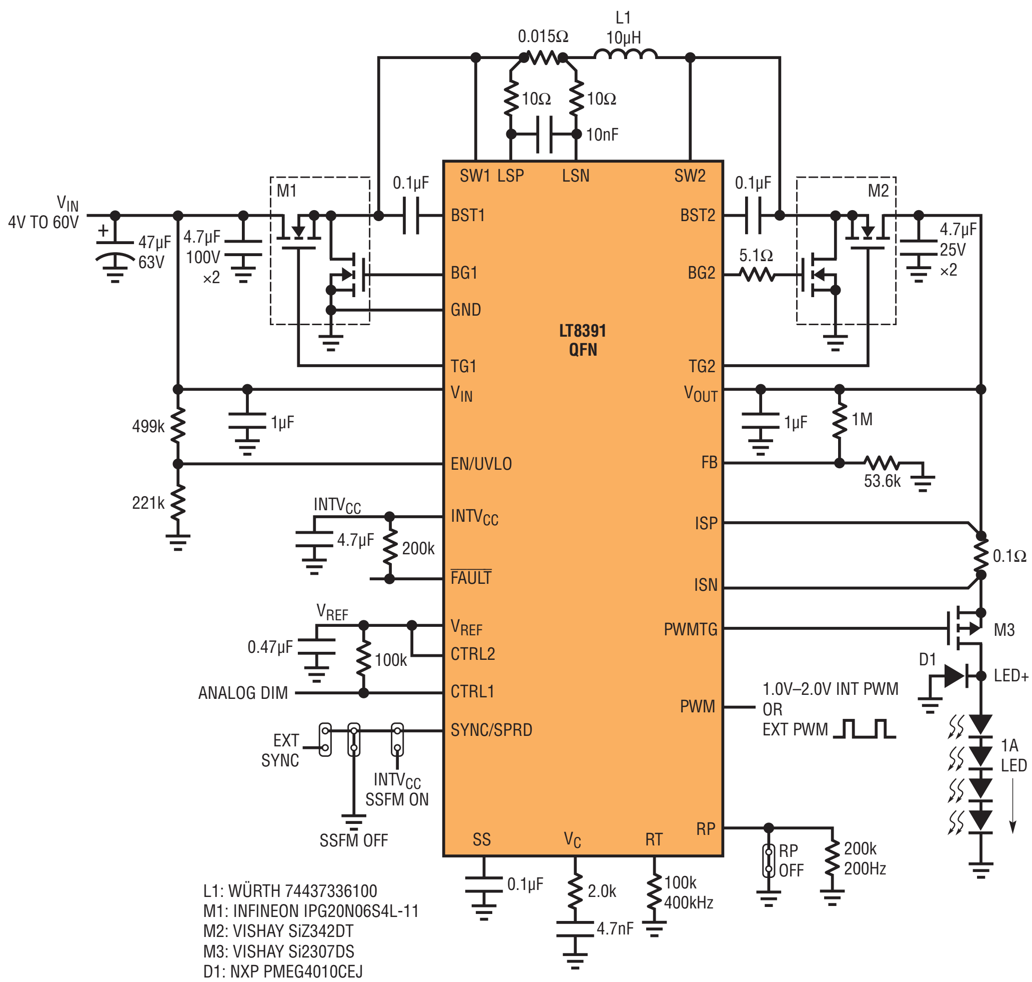
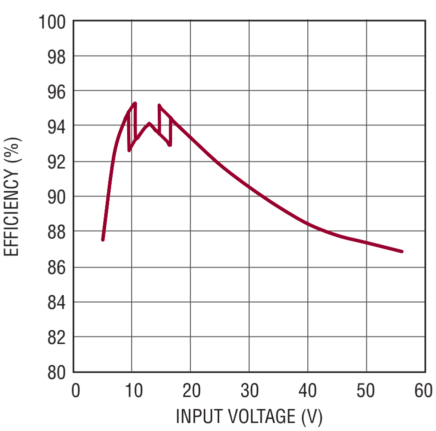


Figure 7. Compact solution featuring the LT8391 in a QFN and dual-package MOSFETs. This 4V–60V input, 4-switch buck-boost converter powers 12V–16V at 1A (16W) LEDs with minimum board space and high efficiency.



When activated, SSFM drops the LT8391's 50W LED driver EMI below both the peak and average EMI requirements of CISPR25 in the AM band (see Figure 5). Average EMI has a more difficult requirement—20dBµV lower than the peak limit. For this reason, the LT8391's novel SSFM reduces average EMI even more than peak EMI. You can see that there is 18dBµV or more reduction of average EMI, while there is still about 5dBµV of peak EMI reduction. Spread spectrum is very useful in limiting the converter's effect on other EMI-sensitive automotive electronics such as radio and communications.

In some converters, spread spectrum and flicker-free LED PWM dimming do not work well together. SSFM, a source of changing switching frequency, can look like noise to the outside world—in order to spread EMI energy, smearing non-spread peak values—but it can work together with PWM dimming for flicker-free operation. Linear's patent-pending PWM dimming and spread spectrum operation is designed to run both functions simultaneously with flicker-free operation, even at high dimming ratios. At 1000:1 PWM dimming with external PWM, and at 128:1 internally generated PWM, spread spectrum continues to operate with flicker-free LED current as shown in the infinite-persist scope photos of Figure 6.

The constant-current and constant-voltage capability of LED drivers make them suitable as battery chargers, especially when the driver also has C/10 detection and reporting.

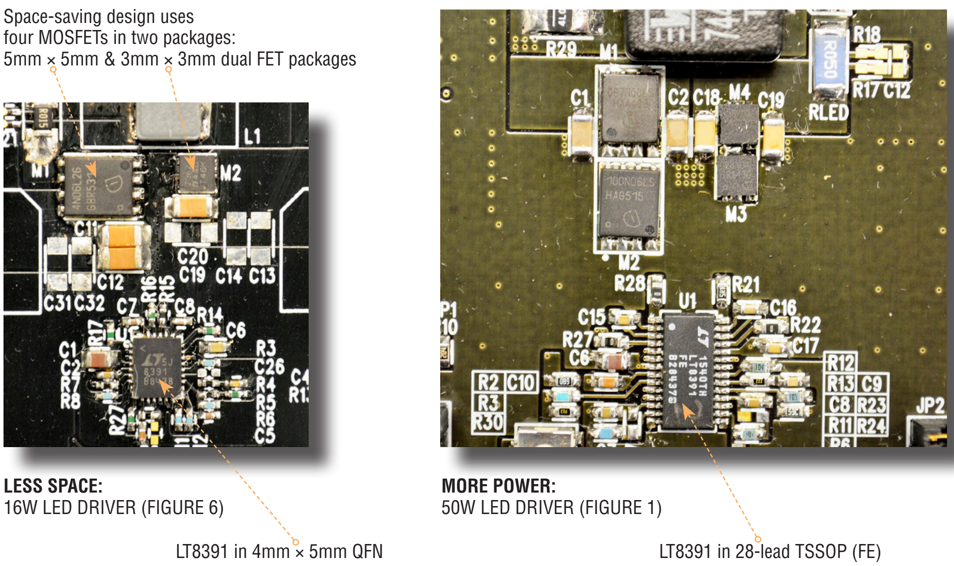


Figure 8. Comparison of the compact solution shown in Figure 6 with the solution of Figure 1. The compact solution, with 5mm × 5mm and 3mm × 3mm dual-package MOSFETs, reduces board space in this 4-switch synchronous buck-boost converter.

QFN PACKAGE AND DUAL PACKAGE MOSFETs FOR COMPACT BUCK-BOOST SOLUTIONS

The LT8391 is available in two package types, a 28-pin leaded FE package, and a smaller 4mm × 5mm QFN. Designers who require access to pins for onboard testing and manufacturing protocols may prefer the 28-pin FE package, but others will be pleased with the small footprint of the QFN. Those that are space-constrained can pair the QFN with a set of 3mm × 3mm or 5mm × 5mm dual package MOSFETs. A synchronous buck-boost controller does not require a lot of board space—very high efficiency can be achieved throughout the main automotive range when dual package MOSFETs are chosen for a very small PCB footprint.

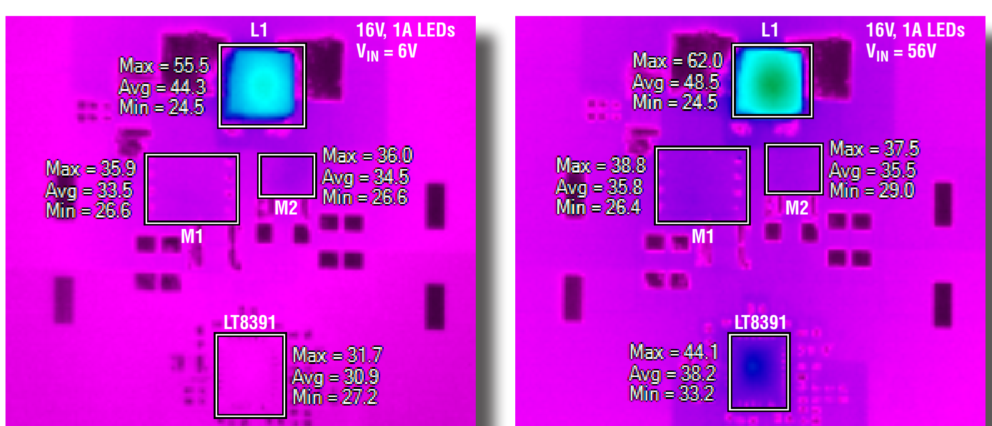
The 4V to 60V input and 16V, 1A buck-boost LED driver shown in Figure 7 uses two such dual-package MOSFETs and the QFN LT8391, achieving greater than 95% peak efficiency. The space savings are shown in Figure 8.

The dual package MOSFETs experience only a 15°C temperature rise at high and low input voltage operating conditions, as shown in Figure 9. The dual package MOSFETs can handle 12V, 2A+ (25W) loads while maintaining high efficiency. To further reduce the solution size, the smaller, 3mm × 3mm, dual-MOSFET packages can be used in both locations. For for a slightly higher power rating, or to accommodate higher voltages, the larger, 5mm × 5mm, packages can be used for both dual MOSFETs.

CONSTANT-CURRENT, CONSTANT-VOLTAGE AND $\overline{C/10}$ FLAG FOR SLA BATTERY CHARGERS

The constant-current and constant-voltage capability of LED drivers make them suitable as battery chargers, especially when the driver also has C/10 detection and reporting. The C/10 detection in LT8391 toggles the state of the FAULT pin and can be used to change the regulated charge voltage of a SLA battery to

Figure 9. The compact system in Figure 6 exhibits only a 15° temperature rise on the dual MOSFETs at both low and high V_{IN}.



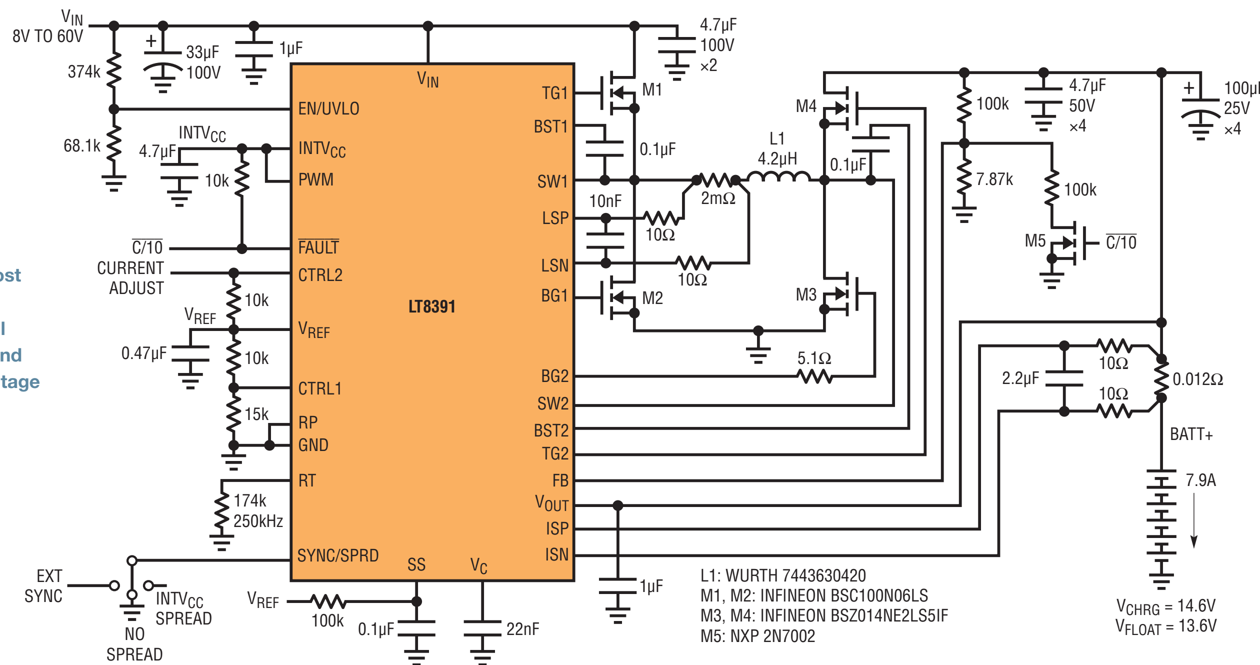


Figure 10. A 7.8A sealed lead-acid (SLA) buck-boost battery charger featuring high efficiency, four small 3mm x 3mm MOSFETs, and both charge and float voltage regulation.

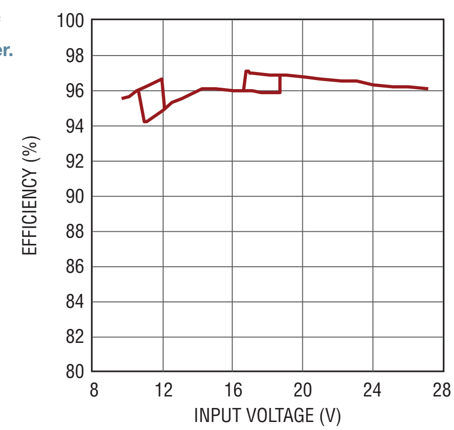


Figure 11. Efficiency of the SLA battery charger.

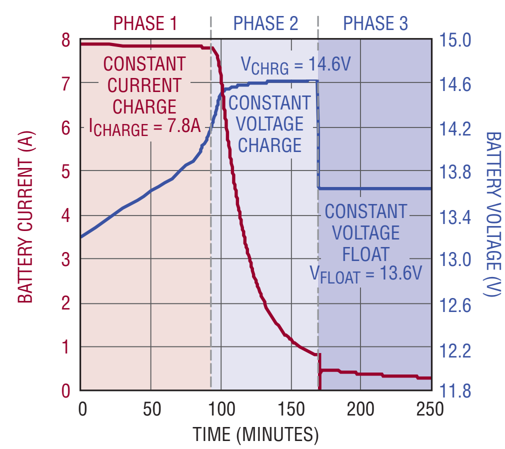


Figure 12. The three charge states of an LT8391 SLA battery charger include constant-current charge, constant-voltage charge and float voltage regulation.

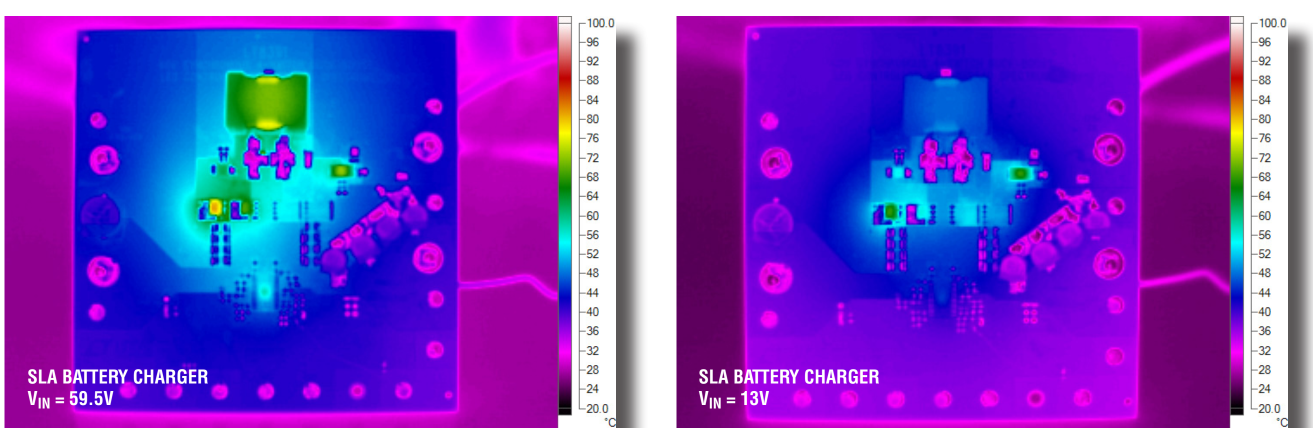


Figure 13. Thermal performance of the SLA battery charger

The 84W AC LED lighting converter powers 15V–25V of LEDs at 120Hz AC currents peaking as high as 6A. A full-wave rectifier converts 24VAC at 60Hz into a 120Hz half-wave at the input of the LT8391. Four-switch conversion allows the LT8391 to move between boost, buck-boost and buck regions of operation and to regulate an AC LED output with high power factor at the input.

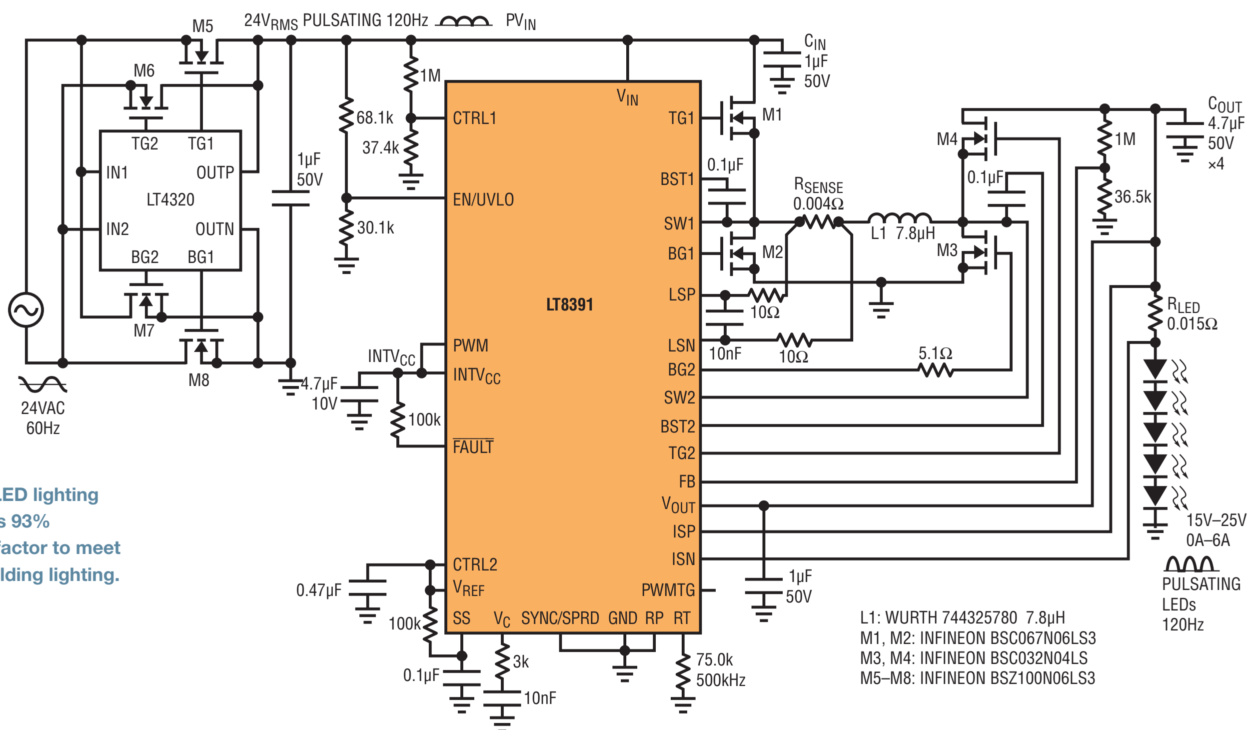


Figure 14. 84W, 120Hz AC LED lighting from 24VAC, 60Hz input has 93% efficiency and 98% power factor to meet green standards in new building lighting.

a different, yet regulated float voltage when the charge current drops off.

The LT8391-based, 7.8A SLA battery charger shown in Figure 10 features 97% peak efficiency (Figure 11), and supports constant-current charge, constant-voltage charge and float voltage maintenance in all three regions of operation—boost, buck and buck-boost.

This charger handles short-circuit, battery disconnect and prevents reverse battery current. DCM operation and the novel peak inductor sense resistor design detect peak current at all times and prevent current from rushing backward through the inductor and switches—a potential pitfall of some 4-switch buck-boost battery chargers that use forced continuous operation.

The charge profile shown in Figure 12 demonstrates the 7.8A constant-current charge state, the constant-voltage charge state and the low current float state of this buck-boost SLA battery charger. Figure 13 shows thermal scans of the charger running at various V_{IN}.

GO GREEN WITH HIGH POWER AC LED BUILDING LIGHTING

High power LED lighting designs for new buildings and structures is both environmentally friendly and robust. With very low failure and replacement rates, LEDs offer excellent color and brightness control while reducing hazardous waste materials and increasing energy efficiency. Halogen lighting that is typically fitted with 24VAC transformers can be replaced by more efficient AC LED lighting using the LT8391.

The 84W AC LED lighting converter in Figure 14 powers 15V–25V of LEDs at 120Hz AC currents peaking as high as 6A. A full-wave rectifier converts 24VAC at 60Hz into a 120Hz half-wave at the input of the LT8391. Four-switch conversion allows the LT8391 to move between boost, buck-boost and buck regions of operation and regulate an AC LED output with high power factor at the input. The waveforms in Figure 15 demonstrate 98% power factor while maintaining 93% efficiency at a very high power. The thermal scan in Figure 16 shows the full wave rectifier.

The LT8391 60V 4-switch synchronous buck-boost LED driver can power large, high power LED strings, and can be used in compact, highly efficient designs. It features spread spectrum frequency modulation for low EMI and flicker-free external and internal PWM dimming.

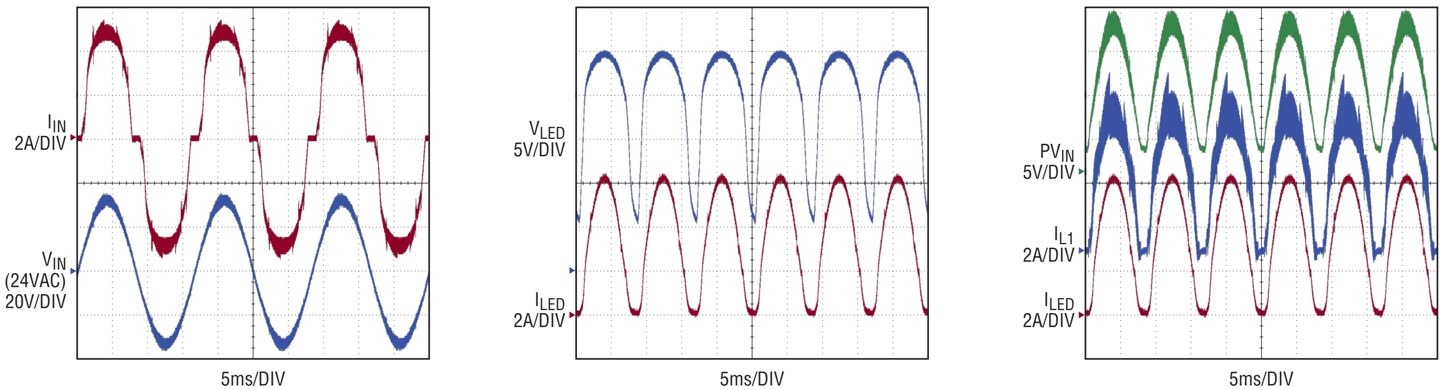
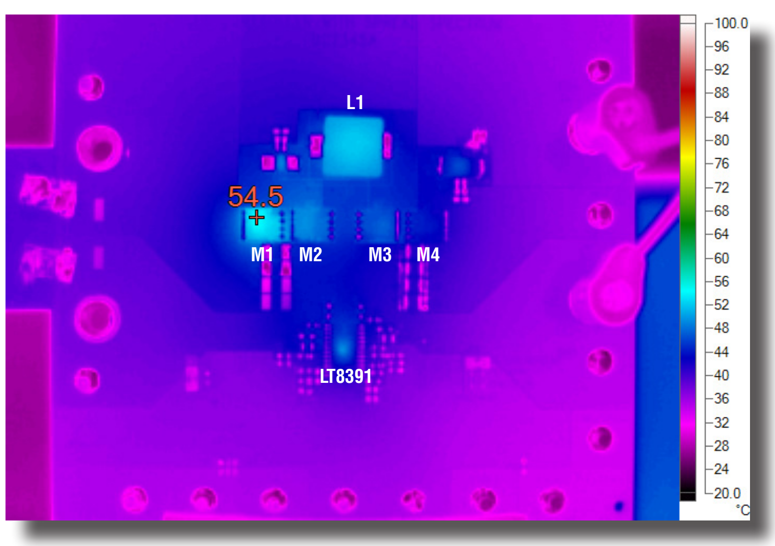


Figure 15. Input current and voltage waveforms for the 84W, 120Hz AC LED driver demonstrate 98% power factor.

CONCLUSION

The LT8391 60V 4-switch synchronous buck-boost LED driver can power large, high power LED strings, and can be used in compact, highly efficient designs. It features spread spectrum frequency modulation for low EMI and flicker-free external and internal PWM dimming. Synchronous switching offers high efficiency through its wide input voltage range, but it also features DCM operation at light loads to prevent reverse current and maintain high efficiency. The constant-current and constant-voltage operation, combined with its C/10 detection, make the LT8391 suitable for high power SLA battery charger applications with both charge and float voltage termination. ■

Figure 16. The LT4320 ideal diode used in the 24VAC LED lighting solution stays cool and keeps efficiency high; discrete components remain below 55°C



What's New with LTspice IV?

Gabino Alonso

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NEW VIDEO: "IMPORTING AND EXPORTING WAV FILES AND PWL TEXT FILES" by Simon Bramble

This video shows how to import and export WAV audio files to and from LTspice®, and how to read a list of piecewise linear values from a text file. www.linear.com/solutions/6087

SELECTED DEMO CIRCUITS

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

Linear Regulators

- **LT3042:** Low noise, high PSRR RF linear regulator (3.8V–20V to 3.3V @ 200mA) www.linear.com/solutions/5638
- **LT3088:** Wide safe operating area linear regulator (1.2V–36V to 1.5V @ 800mA) www.linear.com/solutions/5817

Buck Regulators

- **LT8631:** High voltage buck converter (6.5V–100V to 5V @ 1A) www.linear.com/solutions/5945
- **LT8709:** Negative buck regulator with output current monitor & power good (–16V to –30Vin to –12V @ 8.5A) www.linear.com/solutions/5600
- **LTM4630A:** High efficiency dual 18A buck with output tracking (6V–15V to 3.3 V & 5.0V @ 18A) www.linear.com/solutions/5782

Boost Regulators

- **LT8330:** 48V boost converter (10V–36V to 48V @ 135mA) www.linear.com/solutions/5947
- **LT8570:** Boost converter (5V–10V to 12V @ 125mA) www.linear.com/solutions/5667
- **LT8709:** Negative boost regulator with output current monitor & power good (–4.5V to –9V input to –12V @ 4.5A) www.linear.com/solutions/5596
- **LTC3121:** 5V to 12V synchronous boost converter with output disconnect (1.8V–5.5V to 12V @ 400mA) www.linear.com/solutions/5982

Inverting Regulators

- **LT8330:** Inverting converter (4V–36V to –12V @ 270mA) www.linear.com/solutions/5947
- **LT8709:** Negative inverting regulator with output current monitor & power good (–4.5V to –42V input to 5V @ 4A) www.linear.com/solutions/5598

Buck-Boost Regulator

- **LTM8054:** Buck-boost regulator with accurate current limit & output current monitor (6V–35V to 12V @ 3A) www.linear.com/solutions/5964

Surge Stopper

- **LTC7860:** High voltage surge stopper with timer (3.5V–60V to 3.5V–17V @ 5A) www.linear.com/solutions/5748

Amplifier

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

SELECT 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 Regulator

- **LTM4677:** Dual 18A or single 36A µModule regulator with digital power system management www.linear.com/LTM4677

Boost Regulator

- **LTC3121:** 15V, 1.5A synchronous step-up DC/DC converter with output disconnect www.linear.com/LTC3121

Multitopology Regulators

- **LT8331:** Low I_Q boost/SEPIC/ flyback/ inverting converter with 0.5A, 140V switch www.linear.com/LT8331
- **LT8714:** Bipolar output synchronous controller with seamless four quadrant operation www.linear.com/LT8714

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.

- **LTC3899:** 60V low I_Q, triple output, buck/buck/boost synchronous controller www.linear.com/LTC3899

Hot Swap Controllers

- **LTC4233:** 10A guaranteed SOA hot swap controller www.linear.com/LTC4233

- **LTC4282:** High current hot swap controller with I²C compatible monitoring www.linear.com/LTC4282

LED Driver

- **LT3744:** High current synchronous step-down LED driver www.linear.com/LT3744

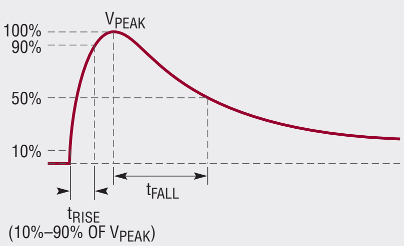
Amplifier

- **LTC6363:** Precision, low power rail-to-rail output differential op amp www.linear.com/LTC6363 ■

Power User Tip

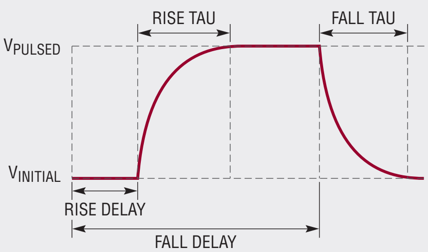
USING TIME-DEPENDENT EXPONENTIAL SOURCES TO MODEL TRANSIENTS

Occasionally there is a need to simulate a circuit's behavior with a specified voltage or current transient. These transients are usually modeled using a double exponential waveform characterized by a peak voltage, a rise time (usually 10%–90%), a fall time to 50% of the peak voltage and a series resistance.



Generalized exponential waveform

LTspice features a double exponential function (EXP) that is ideal for modeling transients via a voltage source. However, it is not as simple as filling in the parameter with t_{RISE}, t_{FALL} and V_{PEAK}. Instead, the EXP function uses standard parameters: Vinital, Vpulsed, Rise & Fall Delay and Raise & Fall Tau time constants.

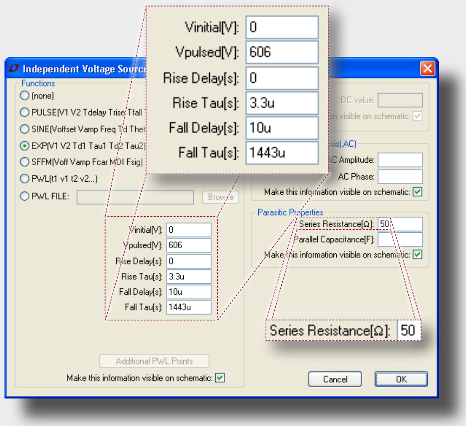


Exp voltage source parameters

For waveforms where t_{FALL}:t_{RISE} > 50:1 and t_{RISE} is defined from 10%–90%, you can use the following conversions for the EXP function parameters, and under the voltage source's parasitic properties, enter the appropriate series resistance or as a separate component:

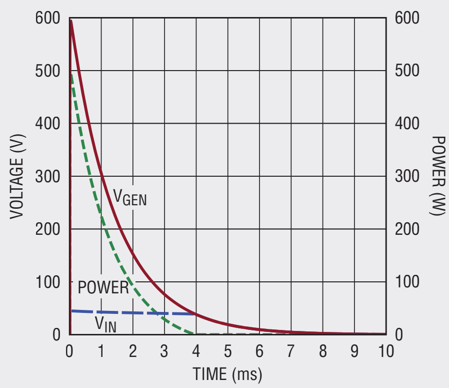
$V_{INITIAL}$ = V1
V_{PULSED} = V2 = V_{PEAK} • 1.01
Rise Delay = Td1 = (0 for no delay)
Rise Tau = Tau1 = t_{RISE}/2.2
Fall Delay = Td2 = t_{RISE}
Fall Tau = Tau2 = t_{FALL} • 1.443

Below is an example of a non-repetitive pulse waveform using EXP function with 10µs rise time, 1,000µs fall time, 600V peak and 50Ω series resistance.

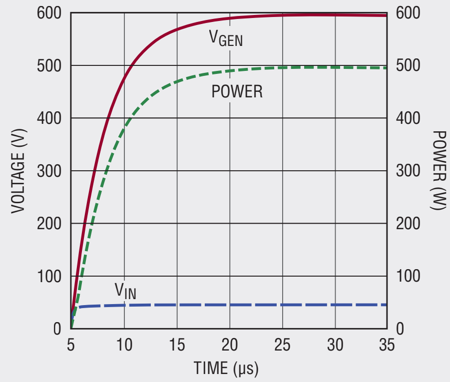


Sample EXP voltage source settings

The waveforms below show the results of the above EXP voltage source with an open circuit, V_{GEN}, and clamped with a TVS clamp, V_{IN}. Also shown is the instantaneous power dissipation (Alt + left-click) of the TVS.



Resulting waveform for an EXP voltage source



Detail of the EXP voltage source rise time

To simulate repeated bursts of transients as in Electrical Fast Transient, LTspice provides an extended syntax for the EXP function that is undocumented and not available in the standard component editor.

`EXP(V1 V2 Td1 Tau1 Td2 Tau2` **`Tpulse Npulse Tburst`**`)`

Where Tpulse is the pulse period, Npulse is the number of pulses per burst and Tburst is the burst period. To add these to your exisitng EXP fuction, edit the EXP text string directly in your schematic by right-clicking it.

The following example shows an example of 75 transients at 200µs intervals which are repeated at 300ms intervals.

`EXP(0 1.10 0 1.16n 1tp 63.5n 200u 75 300m)`

For waveforms where t_{FALL}:t_{RISE} < 50:1, implementing a rising and falling edge with a single EXP function is challenging. Instead, try using two voltage sources in series:

1. A piece wise linear (PWL) function for the rising edge where time1 = 0, value1 = 0, time2 = t_{RISE} (where t_{RISE} is 0%–100%), value2 = V_{PEAK}.
2. An EXP function for the falling edge where $V_{INITIAL}$ = 0, V_{PULSED} = –V_{PEAK}, Rise Delay = t_{RISE}, Rise Tau = (t_{FALL} – t_{RISE}) • 1.443 (falling edge of the waveform), Fall Delay = 1K (places the second exponential beyond the simulation time).

Happy simulations!

Matrix LED Dimmer Enables Accurate Color Control and Pattern Production in RGBW LEDs

Keith Szolusha

RGB LEDs are used in projector, architectural, display, stage and automotive lighting systems that require efficient, bright output. To produce predictable colors from an RGB LED, each of its component LEDs (red, green and blue) requires individual, accurate dimming control. High end systems can use an optical feedback loop to allow a microcontroller to adjust the LEDs for color accuracy. Adding a white LED to an RGB LED to produce an RGBW LED extends the hue, saturation and brightness values available in the color system. Each RGBW LED requires accurate dimming of four component LEDs. Two RGBW LEDs require eight "channels."

One way to drive and dim RGBW LEDs is to use four separate LED drivers, one for each color (R, G, B and W). In such a system, the LED current, or PWM dimming, of each individual LED or string is driven by separate drivers and control signals. In this solution, though, the number of LED drivers increases quickly with the number of RGBW LEDs. Any lighting system with a significant number of RGBW LEDs requires a substantial number of drivers and synchronization of the control signals to those drivers.

A much simpler (and more elegant) approach is to drive *all* of the LEDs with a *single driver/converter* at a fixed current, while using a matrix of shunting power MOSFETs to PWM dim the individual LEDs for brightness control. This is the analog equivalent of the transistors in an LCD display, where the number of switches is allowed to multiply while keeping the number of controllers in check. Furthermore, a single communications bus to control the dimming matrix LED makes RGBW color-mixing LED systems relatively easy to produce, while providing a wide color gamut.

The LT3965 matrix LED dimmer enables such a design, as shown in Figure 1. Each LT3965 8-switch matrix dimmer can pair with exactly two RGBW LEDs, allowing control of the individual brightness of each LED (red, green, blue and white) in PWM steps of 1/256 between zero and 100% brightness. Two-wire I^2C serial commands provide both color and brightness control to all eight channels. I^2C serial code to the LT3965 determines the brightness state of all eight LEDs and can check for open and short LEDs in case of a fault.

MATRIX LED COLOR MIXER WITH LT3952 BOOST-BUCK

The matrix dimmer requires a suitable LED driver to power the string of eight LEDs from a variety of inputs: standard 12V ±10%, 9V–16V (auto) or 6V–8.4V (Li-ion). One such solution is the LT3952 boost-buck[1] LED driver, which both steps-up and steps-down input-to-LED voltage, while providing low ripple input and output current. With little or no output capacitor in its floating output topology, it can react quickly to changes in LED voltage as the individual LEDs are PWM-dimmed on and off to control color and brightness (Figure 2).

The LT3952 500mA boost-buck LED driver shown in Figure 1 pairs with the LT3965 8-switch matrix LED dimmer and two RGBW 500mA LEDs. This new boost-buck topology gracefully operates over the entire range of zero-to-eight LEDs in series, with a voltage of 0V to 25V. The instantaneous series LED voltage changes, determined by which, and how many LEDs are enabled and disabled by the matrix dimmer at any given moment. The 60V OUT voltage of this converter/topology (a sum of V_{IN} and V_{LED}), and the converter duty cycle, are rated for the full input range of 6V to 20V and output range (LED series voltage) of 0V to 25V at 500mA.

This boost-buck floating output voltage topology works well with the LT3965 matrix dimmer. The matrix dimmer controls LED brightness by shunting the LEDs with parallel power MOSFETs.

The LEDs do not need to be connected to ground. As long as the V_{IN} pin of the LT3965 is connected to SKYHOOK, which is at least 7.1V above LED+, all of the shunt MOSFETs work properly. SKYHOOK can be created with a charge pump from the switching converter or it can be supplied with a regulated source that is at least

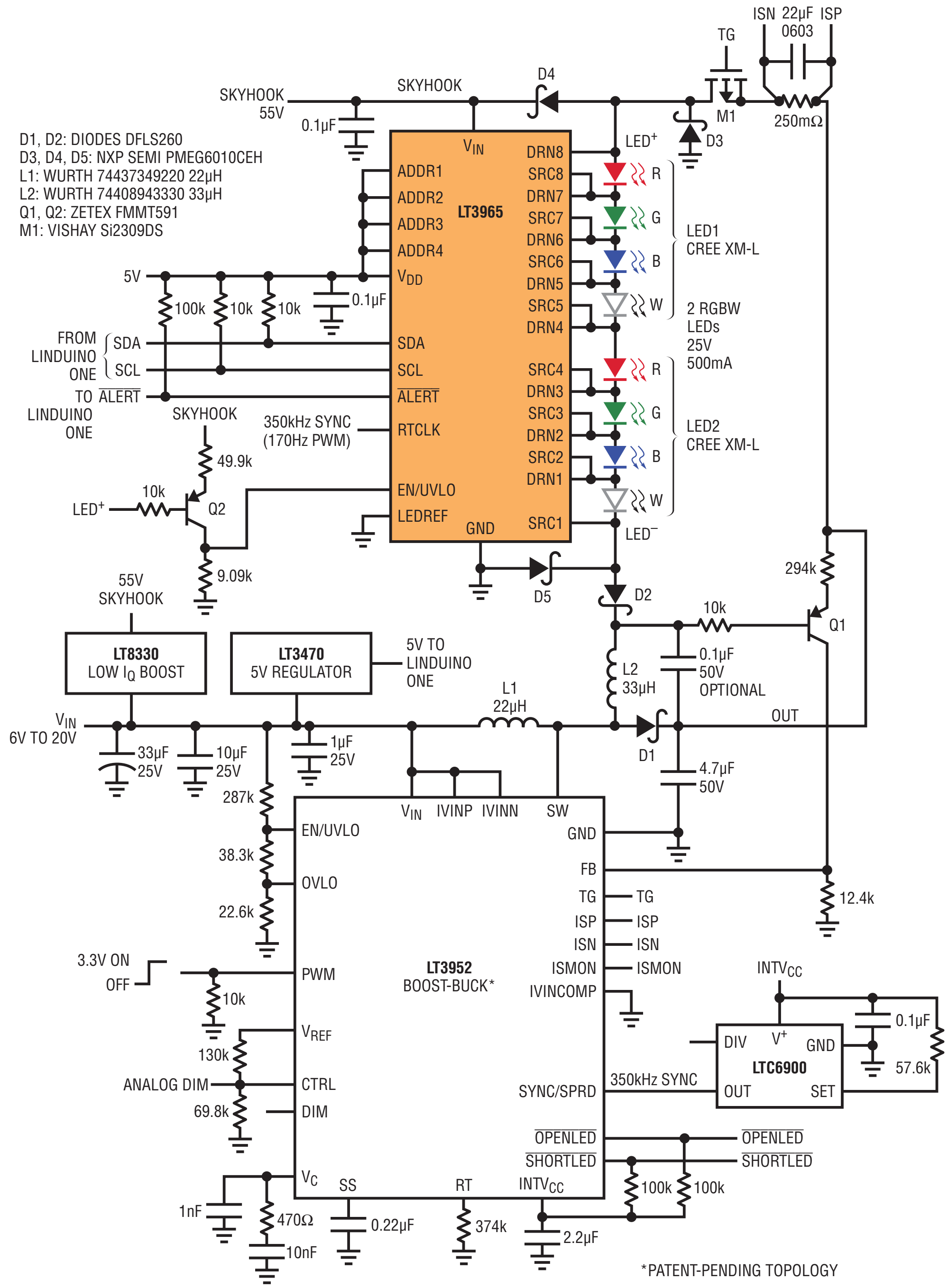


Figure 1. Together with the LT3952 boost-buck LED driver, the LT3965 matrix LED dimmer controls individual colors on two 500mA RGBW LEDs for serial-controlled color and patterns.

7.1V greater than the highest expected LED+ voltage (in this case, 20V V_{IN} max plus 25V LED max). The tiny LT8330 boost converter in a 3mm × 2mm DFN is a good choice to generate SKYHOOK.

An optional external clocking device is used to synchronize the system at 350kHz, which is suitable for automotive environments, relatively efficient and allows the use of compact components. Although this system could just as well run at 2MHz (above the AM band), 350kHz (below the AM band) enables this boost-buck converter to regulate without pulse-skipping when all LEDs are shorted by the matrix dimmer and the LED string voltage drops to 330mΩ • 500mA • 8 = 1.3V. This frequency also supports high dimming ratios without visible LED flicker.

Since each RGBW LED is designed as a single point source, the red, green, blue, and white light combine to produce color variety, with saturation, hue, and brightness control. Each LED can be set in 1/256 steps between zero (0/256) and 100% (256/256). The matrix dimmer

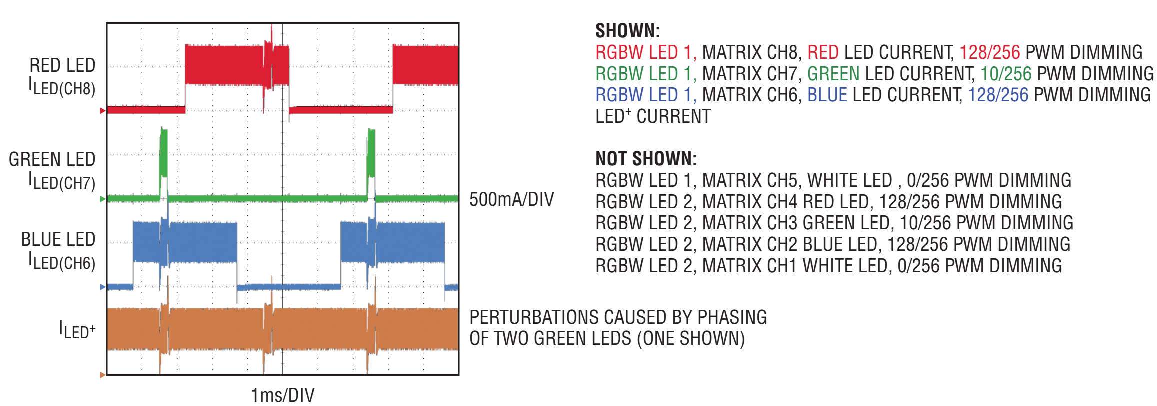


Figure 2. The RGBW 500mA LED currents are PWM dimmed and phased by the LT3965 matrix dimmer to create colors and patterns. The LT3952 boost-buck converter/LED driver easily keeps up with the rapid changes in LED voltage as individual LEDs are PWM dimmed.

An alternative to PWM dimming is to simply reduce the drive current for each LED, but accuracy suffers in this method, allowing only 10-to-1 dimming ratios, and incurring color drift in the LEDs themselves. A matrix approach using PWM dimming outperforms drive-current schemes in color accuracy.

can change PWM dimming levels with or without an internal fade function using a single channel serial command.

ACCURATE 0–256 RGBW COLOR AND BRIGHTNESS CONTROL

RGBW LEDs can produce accurate color and brightness with PWM dimming of the individual component red, green, blue and white LEDs. Individual PWM brightness control can support 256-to-1 or higher dimming ratios. An alternative to PWM dimming is to simply reduce the drive current for each LED, but accuracy suffers in this method, allowing only 10-to-1 dimming ratios, and incurring color drift in the LEDs themselves. A matrix dimming approach using PWM dimming outperforms drive-current schemes in accuracy of color and brightness.

The bandwidth and transient response of the LED driver (the source of the 500mA LED current) affects the color accuracy. With over 10kHz crossover frequency and little or no output capacitor, the compact boost-buck converter reacts quickly to changes in the number of driven LEDs as the matrix dimmer turns its switches on and off.

To illustrate how important this is to accuracy, red, green and blue LEDs are run separately at different PWM duty cycles and measured for light output with an RGB optical sensor. The results in Figure 3 show uniform slopes of each color from 4/256 to 256/256, with a slight change in slope below that. Of course, red, green and blue LEDs are not perfect in their color, so some color from other bands sneaks out even when only one is driven. Overall, this is a highly accurate system.

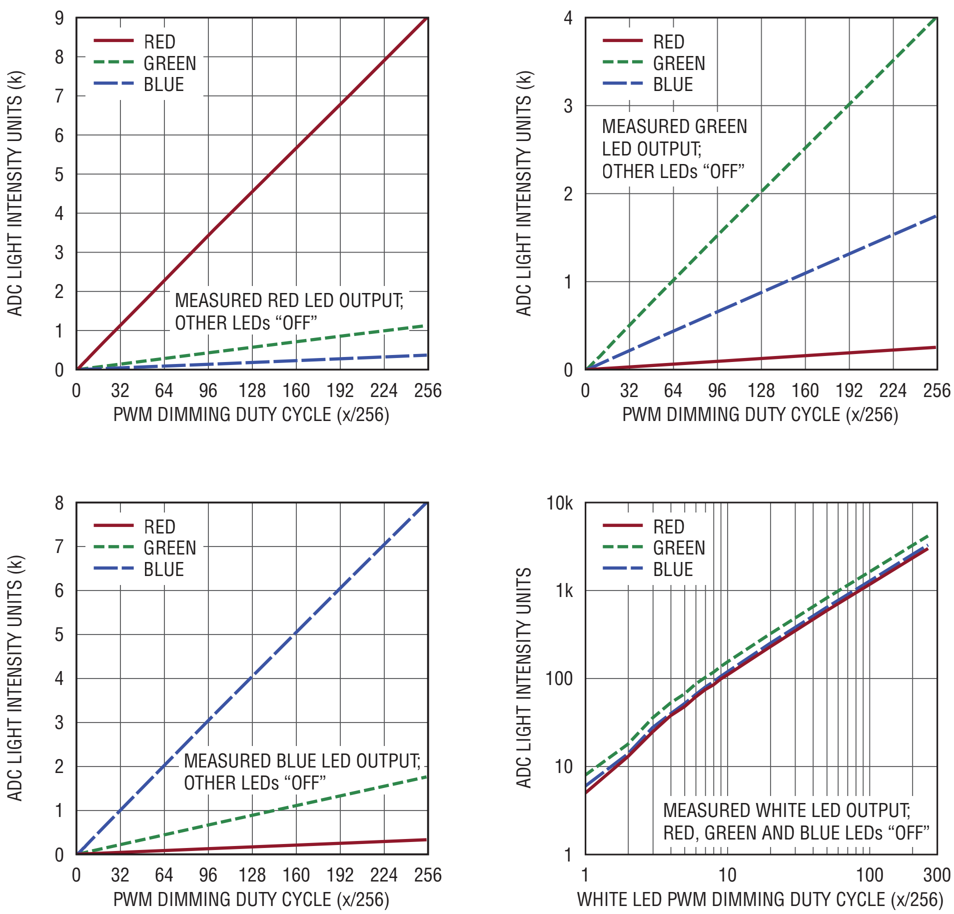
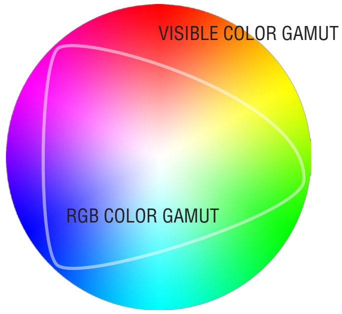


Figure 3. Red, green, blue, and white brightness control versus 0–256 (out of 256) PWM dimming duty cycle controlled by the matrix LED dimmer when paired with the LT3952 boost-buck LED driver in Figure 1.

Accuracy can be improved down to 1/256 using a very high bandwidth (>40kHz) buck converter version of the LT3952 LED driver, but that involves either the expense of adding another step-up converter to create a regulated, greater than 30V output voltage, or having an input voltage source above 30V. Unless a high level of accuracy at low light is necessary, there is little reason to forgo the boost-buck's versatility, simplicity and compact size by adding an extra converter.

The matrix dimmed RGBW LED color mixer system described here achieves a broad color gamut, as shown in Figure 4. Adding additional colors, such as amber, can expand the gamut. RGBWA LEDs

Figure 4. RGB LEDs feature a wide color gamut. Adding white is one way to simplify the algorithmic mixing of specific colors. In some mixing schemes, white is used to change the saturation, while red, green and blue set the hue.



(with an amber LED component) can produce deep yellows and oranges that RGBW LEDs cannot. These LEDs can also be driven with the matrix dimmer, but the eight channels of the matrix dimmer match well to two RGBW LEDs.

The 256-level dimming scheme of the LT3965 easily translates to typical RGB paint programs and common color-mixing algorithms. For instance, if you open a standard PC paint program, you will see that colors are mixed using a 256-value RGB system as shown in Figure 5.

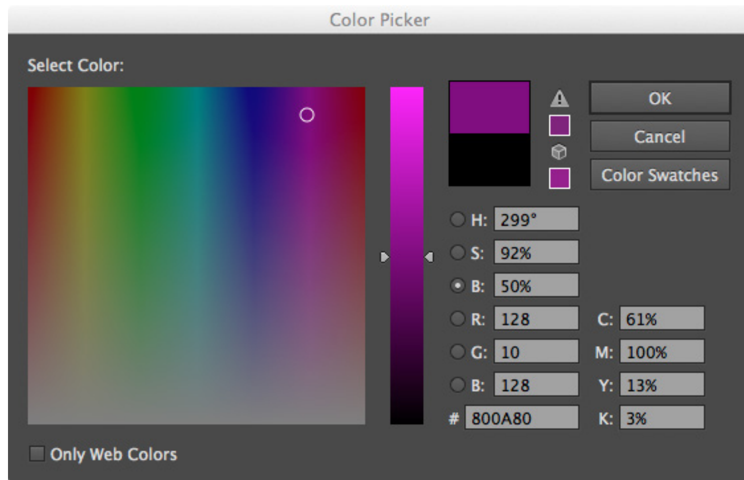
For example, the LED current waveforms in Figure 2 produce purple light from an RGBW matrix LED system controlled by a basic PC-based paint program. Because the design described in this article produces accurate current drive and PWM control, RGBW LEDs can be predictably color-calibrated by adjusting the duty cycles of the component LEDs, easily accounting for inherent variations in LED brightness.

START-UP SEQUENCE WITH LEDs ON OR OFF

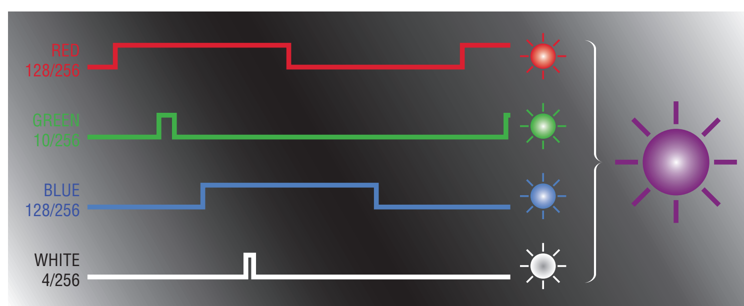
The LT3965 matrix dimmer system can be set to start with all of the LEDs on or off. Starting up with all of the LEDs off allows them to fade on softly or to start at a programmed color and brightness, such as green-blue at 10% brightness. If all of the LEDs start with full 500mA current before the serial communications begin telling the dimmer what to do, then full bright "white" light may be observed before serial communications start.

Figure 5. Colors can be chosen using a standard PC-based color picker. The 0–256 values used by the matrix dimmer can be related to the 0–255 values used in typical RGB systems. For instance, RGB(128,10,128) produces a purple hue. As can be seen in the photograph below, the matrix dimmer can produce predictable colors with a real RGBW LED, simplifying the work of a lighting designer.

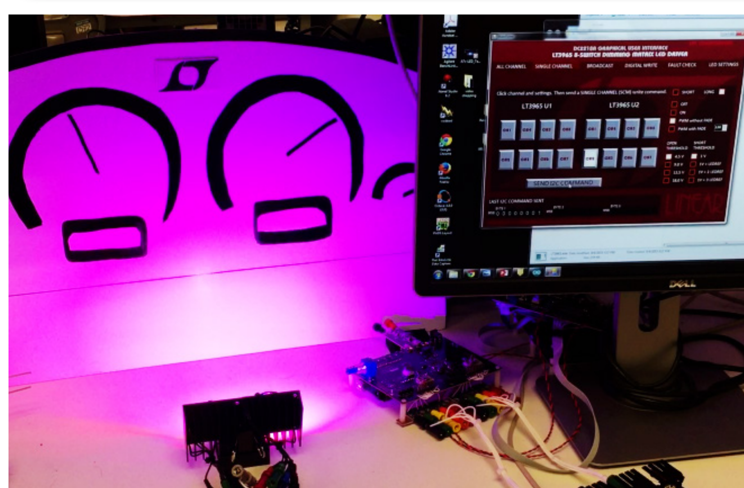
Choose a color.



The RGB values correspond to the LT3965 LED matrix dimming ratios.



Use your PC to set the dimming values, and see the results.

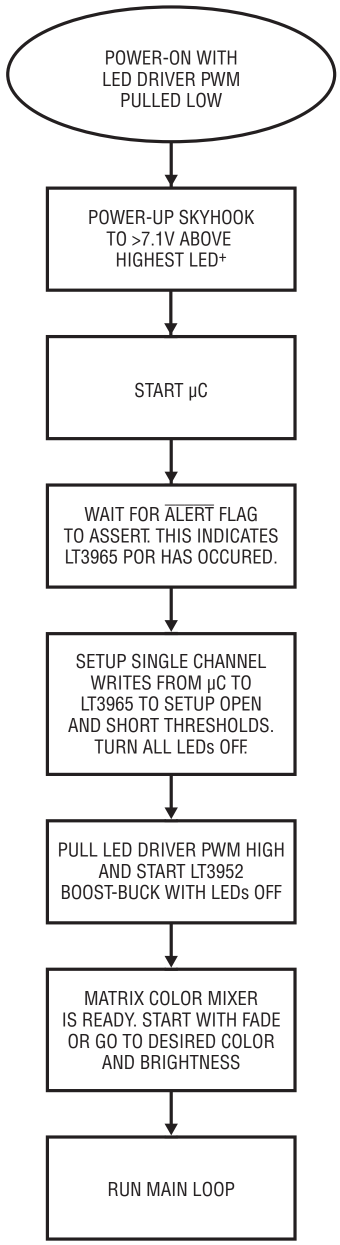


Each LT3965 8-switch matrix dimmer can pair with exactly two RGBW LEDs, allowing control of the individual brightness of each LED (red, green, blue and white) in PWM steps of 1/256 between zero and 100% brightness. A versatile 500mA LED driver, such as an LT3952-based boost-buck,[1] can be used to drive the LEDs.

With either start-up method, the LT3965 should be powered up before it receives I^2C serial communications, or the initial communications may be lost when it performs a power-on reset (POR). The POR occurs when the EN/UVLO pin crosses above the 1.2V threshold. Since this voltage is based on SKYHOOK being at least 7.1V above LED^+, this can occur at any time after a high SKYHOOK voltage is applied, such as 55V from a small boost regulator, or it can happen after a charge-pumped voltage from the LT3952 switch node is high enough to create SKYHOOK. In the case of a charge-pumped SKYHOOK, the LED current may be present before the charge-pumped SKYHOOK, so the LEDs light up before the LT3965 switches can turn the LEDs off. This is a simple solution for a designer who would like the LEDs to turn on full brightness to start.

To start the LEDs off, SKYHOOK must be present at a high voltage before the LT3952 is turned on. As shown in Figure 6, if the PWM pin is held low during start-up, the LT3952 will not start up until it is commanded to do so by an external source, such as the master microcontroller. The microcontroller can send I^2C setup commands to the LT3965 once SKYHOOK is present and set up its switches to the LED OFF position before current is flowing to them. Then, after setup, the LT3952 PWM can be asserted and the current begins to flow through shorted LT3965 switches, with the LEDs off. After this, a fade start can occur, or the LT3965 dimmer can jump to a particular color or brightness.

Figure 6. Start the matrix LED dimmer color mixer with all of the LEDs off using this sequence.



Upon a reset, the PWM of the LT3952 must be pulled low again to turn it off and restart in the LEDs off position. In the case of Figure 1, a simple micropower boost such as an LT8330 can supply 55V from the 6V–20V input. The microcontroller receives a signal that LT3965 is powered up and ready to receive serial communications by asserting the ALERT flag. Before any of the switches are shorted out, zero current through the LEDs shows up as zero voltage across the switches—interpreted as, and reported as, a short-circuit fault. Only after the LT3965 is powered up by SKYHOOK, is the flag asserted.

CONCLUSION

The LT3965 matrix LED dimmer can be paired with the LT3952 boost-buck converter to form an accurate-color RGBW LED color mixer system. It can be used to drive two RGBW LEDs at 500mA with 350kHz switching frequency from a 6V to 20V input. This versatile system can be powered with automotive batteries, 12V power or Li-ion batteries.

High color accuracy results from the fast transient response of the patent-pending boost-buck LED driver topology and predictable dimming control via the 256:1, I^2C-controlled matrix system. It can be set up to start up with all of the LEDs off and can fade to start or jump to a particular color. Although not required, optical feedback (via microcontroller) can be added to improve color accuracy. ■

NOTES

[1] patent-pending topology

High Efficiency 17V, 2A Synchronous Monolithic Step-Down Regulator with Ultralow Quiescent Current in a 3mm × 3mm DFN

Gina Le and Jian Li

Portable power electronic devices require compact power supplies that can deliver high efficiency over wide input and output voltage ranges. Other requirements include low standby current, low dropout operation, output voltage accuracy and a fast loop response to line and load transient. The LTC3624 is a 17V, 2A synchronous monolithic step-down regulator, featuring ultralow quiescent current and high efficiency over a wide V_{IN} and V_{OUT} range—an excellent choice for battery powered equipment, portable instrumentation, emergency radios and general purpose step-down power supplies.

Some of the LTC3624's notable features:

- Wide V_{IN} range: 2.7V to 17V
- Wide V_{OUT} range: 0.6V up to V_{IN} at 2A rated output current
- 95% peak efficiency
- Constant frequency of 1MHz or 2.25MHz
- Ultralow quiescent current of 3.5μA
- Low dropout operation at high duty cycle
- Current mode architecture, allowing excellent line and load transient response.

Despite its small size, the LTC3624 remains flexible, enabling designers to optimize solutions by simply selecting a desired mode or frequency of operation. A user-selectable mode input is provided with the following options: Burst Mode operation provides the highest efficiency at light loads, while pulse-skipping mode provides the lowest output voltage ripple. Forced continuous conduction mode is also available for low EMI and to minimize high frequency noise interference. The mode pin can also be used to synchronize the internal system clock to an external clock within ±40% of the nominal switching frequency. The LTC3624 (1MHz) or LTC3624-2 (2.25MHz), is available in a compact 8-lead DFN (3mm × 3mm) thermally enhanced package.

17V, 2A SYNCHRONOUS STEP-DOWN REGULATOR

LTC3624 can be optimized to operate over wide V_{IN} and V_{OUT} ranges, using just a few small footprint, low cost external components and a single ceramic output capacitor, as shown in Figure 1. The entire solution fits within a 13mm × 12mm footprint, as shown in Figure 2.

HIGH EFFICIENCY OVER A WIDE RANGE OF INPUT AND OUTPUT VOLTAGES AND LOADS

The LTC3624 delivers high efficiency over a wide range of input and output voltages, as shown in Figures 3 and 4. Figure 5 shows the light load efficiency.

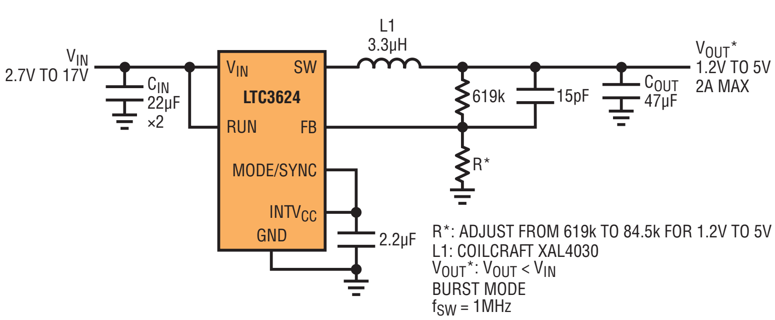


Figure 1. 17V, 2A synchronous step-down regulator featuring the LTC3624

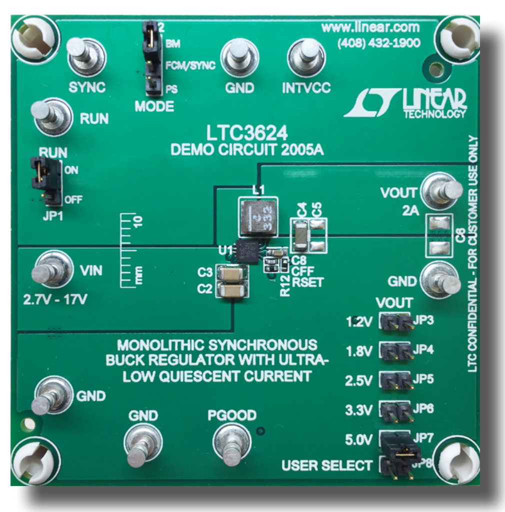


Figure 2. Small total solution size: 13mm × 12mm

LTC3624 can be optimized to operate over wide V_{IN} and V_{OUT} ranges, using just a few small footprint, low cost external components and a single ceramic output capacitor. An entire solution fits within a 13mm × 12mm footprint.

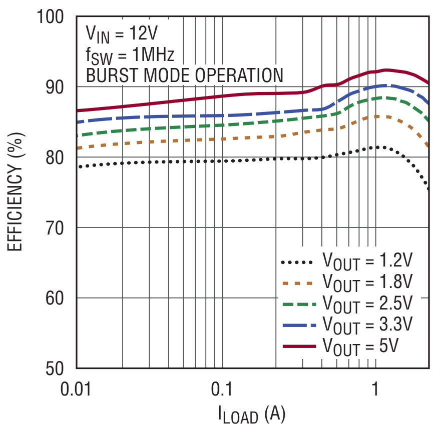


Figure 3. High efficiency is maintained over a wide range of output voltages and loads

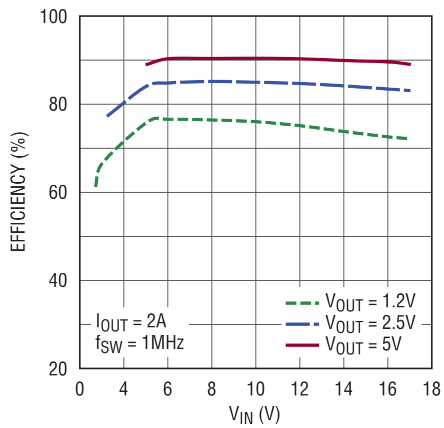


Figure 4. Efficiency also remains high over a wide range of input voltages

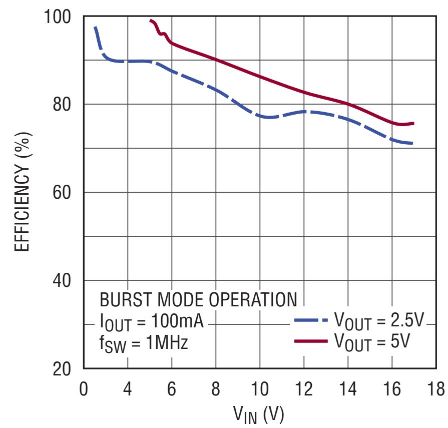


Figure 5. Light load efficiency vs input voltage

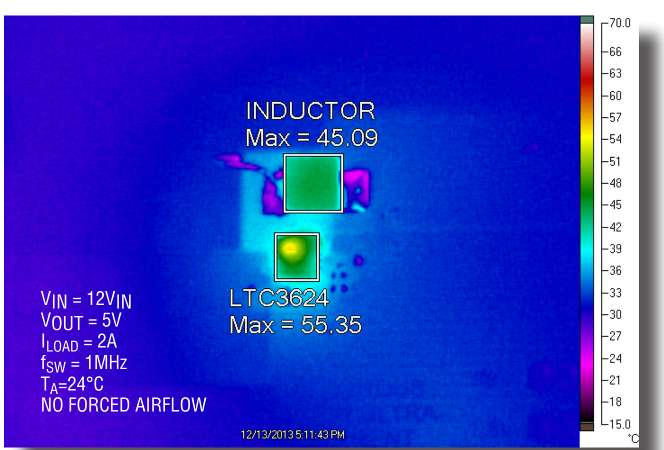
Figure 6 shows the thermal response at 12V input to 5V output, maximum load.

Selecting Burst Mode operation yields the highest efficiency at light load, as switching loss is significantly reduced. Furthermore, LTC3624 uses the integrated high side MOSFET's $R_{DS(ON)}$ as a current sensing element, eliminating the use of an additional sense resistor in the current path, thereby improving overall efficiency.

FAST LOAD TRANSIENT RESPONSE

LTC3624 uses a constant frequency, peak current mode control architecture that yields fast loop response to the sudden changes in load current. The load transient response is shown in Figure 7. Using only one ceramic output capacitor in the design, the output voltage spike at 25% load step is well limited within ±4% of V_{OUT}. For duty cycle of 41.6% and a 50% load step, the output voltage spike is less than ±5% as shown in Figure 8.

Figure 6. Thermal performance



HIGH DUTY CYCLE/LOW DROPOUT OPERATION

Due to the increasing demand in battery powered devices operating at high duty cycle while maintaining V_{OUT} within its regulation window, LTC3624 is designed to operate in low dropout mode.

When the input supply voltage is decreasing toward the output voltages and the duty cycle approaches 100%, if FCM mode is selected, the high side MOSFET is turned on continuously and all active circuits are kept alive. The required headroom voltage for V_{OUT} to maintain regulation at full load is determined by V_{IN} minus nominal V_{OUT}, the voltage drop across the high side MOSFET's $R_{DS(ON)}$ and the output inductor's parasitic DCR.

If Burst Mode operation or pulse skipping mode is selected, the part transitions in and out of sleep mode depending on the output load current, thus reducing the quiescent current and extending the life of the battery. Figure 5 shows the

The LTC3624's small footprint and high power density in a thermally enhanced package make it an excellent choice for portable electronic devices. Despite its small size, the LTC3624 remains flexible, enabling designers to optimize solutions by simply selecting a desired mode or frequency of operation.

Figure 7. Load step transient response for 3V input, 1.2V output

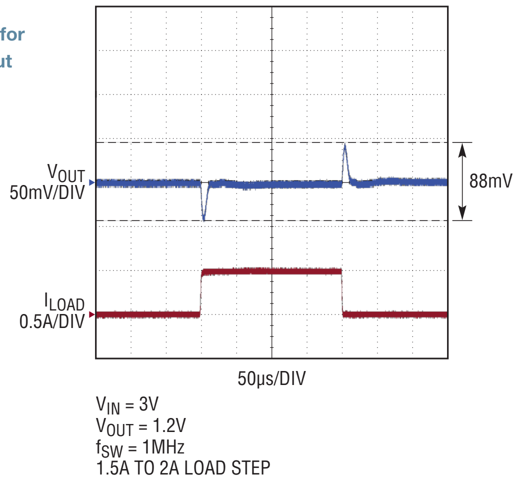
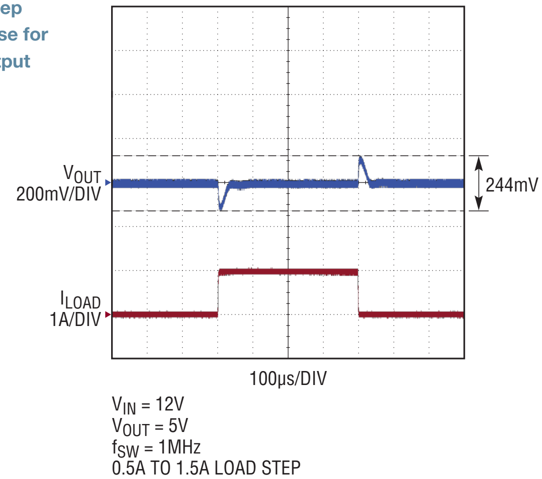


Figure 8. Load step transient response for 12V input, 5V output



minimal energy used to maintain the output near dropout and light loads.

OTHER FEATURES

LTC3624 incorporates other features to keep it functioning properly under fault conditions and allow it to be used in a variety of applications.

Output Overcurrent and V_{IN} Overvoltage Protection

The built-in current limit protects the part from exceeding rated power dissipation if the output is temporarily overloaded. The V_{IN} overvoltage fault limit function protects the internal MOSFET devices from transient voltage spikes. As V_{IN} rises above 19V, the part shuts down both high side and low side MOSFETs and resumes normal operation as V_{IN} drops below 18.5V.

Soft-Start and PGOOD Indicator

An internal 1ms soft-start ramp allows the part to rise smoothly from 0V to its set voltage without a sudden inrush of current. If the output power good signal, PGOOD, is high, the output voltage is within the ±7.5% window of the nominal set voltage, otherwise it stays low. There is a blanking delay of approximate 32 switching cycles to avoid unwanted noise coupled into the PGOOD signal during any disturbance or transient at V_{OUT}.

Frequency Synchronization

Frequency sync capability allows the internal oscillator to be synchronized to an external clock signal applied at MODE/SYNC pin. This is a simple way to program the switching frequency of the part to ±40% of its fixed internal preset frequency.

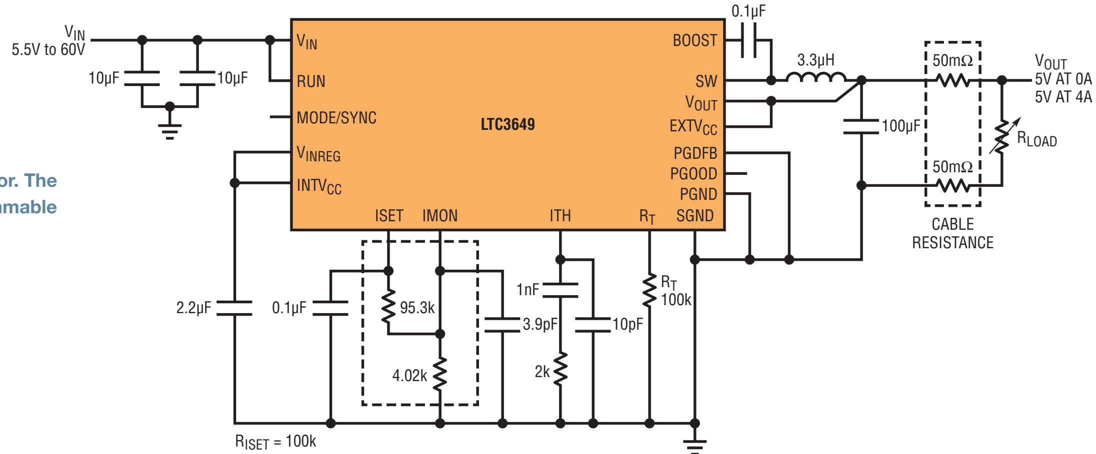
CONCLUSION

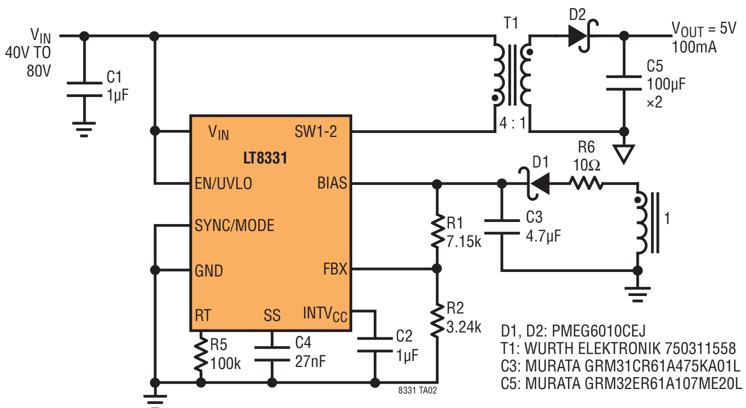
The LTC3624's small footprint and high power density in a thermally enhanced package make it an excellent choice for portable electronic devices. The LTC3624 features ultralow quiescent current, high efficiency, low dropout operation, wide V_{IN} and V_{OUT} ranges and embedded protection functions. It is an attractive option for users seeking to improve a system's overall efficiency, power density and reliability. ■

LTC3649 60V INPUT TO 5V OUTPUT AT 4A WITH CABLE DROP COMPENSATION

The LTC3649 is a high efficiency 60V, 4A synchronous monolithic step-down regulator. The regulator features a single resistor programmable output voltage, internal compensation and high efficiencies over a wide V_{OUT} range.

www.linear.com/solutions/6090





LT8331 40V TO 80V INPUT, 5V ISOLATED OUTPUT CONVERTER

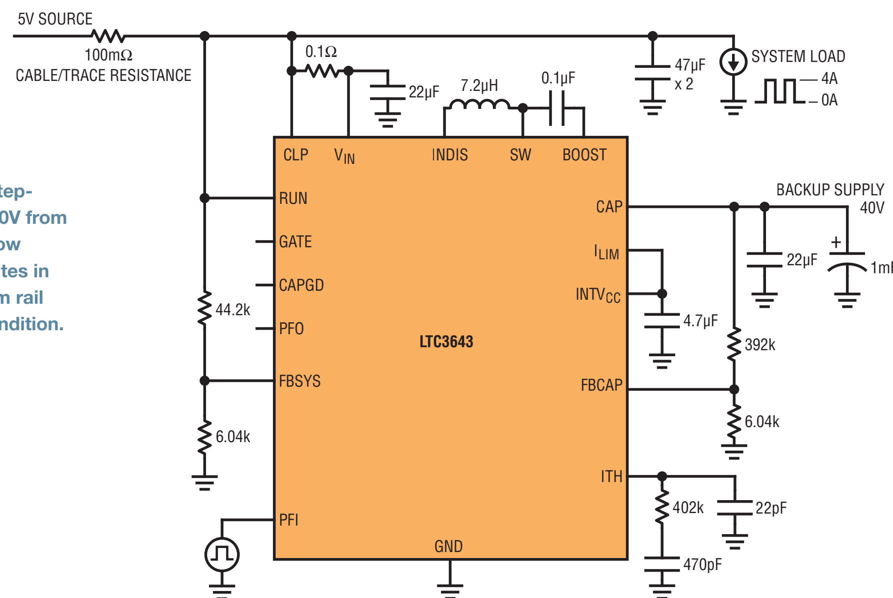
The LT8331 is a current mode DC/DC converter with a 140V, 0.5A switch operating from a 4.5V to 100V input. With a unique single feedback pin architecture, it is capable of boost, SEPIC, flyback or inverting configurations. Burst Mode operation consumes as low as 6µA quiescent current to maintain high efficiency at very low output currents, while keeping typical output ripple below 20mV.

www.linear.com/solutions/6013

LTC3643 TEMPORARY SUPPLY BOOSTER

The LTC3643 is a bidirectional synchronous step-up charger and step-down converter which efficiently charges a capacitor array up to 40V from an input supply between 3V to 17V. When the input supply falls below the programmable power-fail threshold, the step-up charger operates in reverse as a synchronous step-down regulator to power the system rail from the backup capacitor during this power interuption/failure condition.

www.linear.com/solutions/6010



NOTE: DRIVE PFI PIN HIGH WHEN HIGH LOAD IS PRESENT TO MAINTAIN DESIRED VOLTAGE AT THE SYSTEM LOAD

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