LINEAR TECHNOLOGY

Journal of
Analog Innovation

November 2015

Volume 25 Number 3

IN THIS ISSUE

Control Individual LEDs in Matrix Headlights with Integrated 8-Switch Flicker-Free Driver

Keith Szolusha

LEDs combine design flexibility with practical, robust circuitry, enabling automotive designers to produce striking headlight designs matched by exceptionally long life and performance. Automobile designers are increasingly incorporating LEDs in lighting because they can be arranged in distinctive eye-catching designs—helping distinguish new models from old, or high end from economy.

There is no question that automobile LED lighting has arrived, but it has not yet reached its full potential. Future models will feature more LED lights, including new shapes and colors, and more control over the individual LEDs. Simple strings of LEDs will give way to *matrices* of LEDs that can be individually dimmed via computer control, enabling unlimited real-time pattern control and animation. The future has arrived: Linear Technology's LT®3965 matrix LED driver makes it easy to take the next step in automotive lighting design.

The LT3965: limitless control of automotive matrix headlights and lighting systems

I²C CONTROL OF EIGHT POWER SWITCHES WITH A SINGLE IC

A basic LED headlight design operates with uniform LED current, and thus, uniform brightness. But this leaves much of the LEDs' potential on the table. Matrix headlights take advantage of the innate abilities of LEDs by enabling control of the brightness of individual LEDs within LED strings.

It is not difficult, in theory, to address the individual LEDs in a matrix via computer-controlled power switches, allowing individual LEDs to be turned on or off, or PWM dimmed,

(continued on page 4)

In this issue...

Linear in the News

LINEAR TECHNOLOGY CO-FOUNDERS RECEIVE ACE LIFETIME ACHIEVEMENT AWARD

Linear Technology co-founders Bob Swanson and Bob Dobkin received UBM Canon's *EDN* and *EE Times* ACE Lifetime Achievement Award at a ceremony at the Embedded Systems Conference in Santa Clara, California in July. The award is presented annually to individuals for their contributions to the electronics industry, selected by a panel of academic and business leaders, and editors of *EDN* and *EE Times*.

Bob Swanson and Bob Dobkin founded Linear Technology 34 years ago, with a goal of building unique high performance analog ICs. The company now employs 4,865 people in over 50 locations worldwide. Linear's name has become synonymous with innovative, high quality analog solutions in a broad range of application areas.

EDN Senior Technical Editor Steve Taranovich stated, "Bob Swanson and Bob Dobkin are unique as individuals in their decades-deep contributions to integrated electronics, as well as their longevity in Silicon Valley. They are also exceptional as a team because of their unprecedented continuity of management at a semiconductor company, as well as their refreshing style of management, amplifying Linear Technology's engineering talent. For these reasons and many more, *EE Times* and *EDN* chose to honor Bob Swanson and Bob Dobkin with the 2015 ACE Lifetime Achievement Award."

Steve Taranovich continued, "The talents and experiences of these two leaders, in my estimation, have brought about a corporate culture unlike most of the companies in the electronics business today. This culture encourages innovation and strongly values and recognizes the company's engineering talent so that when a good idea emerges, management recognizes it and 'gets out of the way' to allow the engineer to bring it to fruition."

The following comments are excerpted from the *EDN* interview with Bob Swanson and Bob Dobkin: www.linear.com/46876.

Bob Swanson: "If you were an Analog Aficionado, Linear Technology looked like a bunch of great technical guys just doing analog and they wanted to be part of that. After 34 years, we are still the same. We can hire as many good people as we can afford to hire. So the great thing we have going for us is that we have a disproportionate share of really innovative people. We leverage that because the world needs innovative analog solutions."

Linear Technology co-founders Bob Swanson and Bob Dobkin received UBM Canon's *EDN* and *EE Times* ACE Lifetime Achievement Award at a ceremony at the Embedded Systems Conference.

Bob Dobkin: "One the things we do is to hire engineers who want to innovate and build products. And then we don't get in their way. So they build products, they like what they are doing, and that works well within Linear."

Bob Dobkin: "If you do some products right, they will sell for over 30 years. If we do some products as well as they can be done, you never have to do them again."

Bob Swanson: "Obviously we have great products, but competitors have great products too. In this analog-challenged world, we have been so good at transferring our knowledge to customers. I will occasionally see the big customers at social events. They always tell me how much they depend upon our design and field people. Our field people are brilliant FAEs."

Bob Swanson: "One of the things that Bob Dobkin told me was that power was analog. So take an automobile with hundreds of processors—every one of them needs a power supply. And it is typically a power supply that is way more difficult than it was 20 years ago. The challenge in this 'explosion of electronics' in the automobile seems to me to be as much about solving analog issues as digital issues."

Bob Swanson: "Smart, happy people probably can be innovators. I tell this story—about five or six years ago somebody asked Steve Jobs: 'You guys are acknowledged to be the best at R&D and innovation, and you've got the smallest R&D budget.' And he said, 'All you need is a handful of real innovators and you can be successful. And I've got a handful of really good innovators and that's all I need.' So R&D is not an arms race. R&D is about having innovators. Going from 100 engineers to 200 does not automatically double your innovation. If you have 25 innovators and you can get two or three more a year, you're in good shape."

Bob Dobkin: "One way we are unique is that the engineering group comes up with the product ideas. We don't go and do a marketing survey. Our engineers visit customers and figure out new products. We're excited to work on things that the customers want."

Steve Taranovich concluded: "During this interview with these two industry icons, I sensed that they know their place in the industry and in their company, and effectively use the talent of their employees in a way that I personally have never seen in my 42 years in electronics. They are strong, talented and intelligent leaders, but with a touch of humility and compassion for their employees from which other companies can learn a great deal. The book entitled, *The Company That No One Leaves* gives wonderful insight into one of the key reasons this company has had such success over the last 34 years." www.linear.com/46751

AWARDS

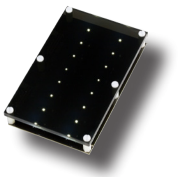
- The LTC®2983 digital temperature measurement IC received the *EDN/EE Times* Analog Ultimate Product ACE Award.
- The LTC2000 16-bit, 2Gsps DAC received the Best Product Award from *EDN China* in the Analog and Mixed Signal IC category.

CONFERENCES & EVENTS

The Wireless Congress: Systems & Applications, Konferenzzentrum, Munich, Germany, Nov. 17–18—Presenting energy harvesting and wireless sensor networks. Joy Weiss presents "Low Power Wireless Sensor Networks for IoT." www.wireless-congress.com

Energy Harvesting & Storage Conference, Santa Clara Convention Center, Santa Clara, California, Nov. 18–19, Booth N28—Presenting energy harvesting and wireless sensor networks. Ross Yu on "Low Power Wireless Sensor Networks for IoT"; Tony Armstrong on "Energy Harvesting: Battery Life Extension & Storage." www.idtechex.com/energy-harvesting-usa

3rd Annual Analog Gurus Conference, Tokyo Conference Center Shinagawa, Tokyo, Japan, Nov. 18—Linear's analog gurus present. CTO Bob Dobkin on "Inside Precision Voltage References," Steve Pietkiewicz, VP, Power Management products on "High Performance µModules®" and Bob Reay, VP, Mixed Signal products on "High Precision Temperature Measurement." ■



When combined with a suitable constant-current LED driver, the matrix dimmer LED driver allows the individual LEDs to be computer-controlled in headlights, daytime running lights, brake and tail lights, side-bending lights, and other trim lighting.

(LT3965, continued from page 1)

to create unique patterns and functions. Each LED (or segment of LEDs) requires either its own converter or its own shunt power switch. It is possible to build a matrix driver with traditional driver/converter ICs that include a serial communications feature, but once more than two or three switches are needed for a matrix of LEDs, designing a discrete component solution becomes challenging, involving a matrix of components that exceeds the size of the LED matrix.

The LT3965 I^2C 8-switch matrix LED dimmer makes it easy to control large or small LED matrices (up to 512 LEDs). Figure 1 shows the LT3965 in action on Linear's demonstration circuit DC2218.

Its highly integrated design (Figure 2) minimizes component count. The individually addressable channels of the LT3965 can be used to control LED matrices in many ways, including:

- Each LT3965 can control eight dimming channels—eight LEDs or eight clusters—within a string of LEDs.
- The eight channels can control the individual red, green, blue and white light on two RGBW LED modules for adjustable brightness or changing color of dashboard or trim lighting.
- Multiple LT3965s can be individually addressed on a single communications bus to multiply the strings in a large array.
- The LT3965 can control multiple LEDs per channel, or channels can be combined to efficiently control a single LED at higher current.

When combined with a suitable constant-current LED driver, the matrix dimmer LED driver allows the individual LEDs to be computer-controlled in headlights, daytime running lights, brake and tail lights, side-bending lights, dashboard display and other trim lighting. The LT3965's built-in automatic fault detection protects individual LEDs in case of a failure and reports failures to the microcontroller.

The 60V LT3965 includes eight integrated 330mΩ power switches, which can be connected to one or more LEDs. The power switches act as shunt devices by turning off or PWM dimming the LEDs on a particular channel. The switches create eight individually controlled brightness channels (up to 256:1 dimming ratio) and eight fault-proof segments of an LED string.

The LT3965 can handle a string current of 500mA when all eight power switches are on at the same time (all LEDs off). The switches can be connected in parallel and run at 1A through four channels of LEDs as shown later in this article. Regardless of the number of LEDs or current, the LED string must be driven by a properly designed converter that has the bandwidth to handle the fast transients of the matrix dimmer. Some reference designs are included in this article.

LT3797 BOOST-THEN-DUAL-BUCK MODE DRIVES TWO STRINGS, 16 LEDs AT 500mA WITH TWO LT3965s

The eight shunt power switches of the LT3965 control the brightness of eight channels of LEDs at 500mA. The string voltage of the 8-LED matrix dimmer system can be between 0V and 26V, depending on how many LEDs are on or off at a given time. The recommended converter topology to drive these LEDs is a 30V step-down converter with high bandwidth and little or no output capacitor. This step-down topology requires that 9V–16V automotive input is "pre-boosted" to a 30V rail from which the step-down regulators can operate.

The triple output LT3797 LED controller conveniently serves as a single-IC solution for both the "pre-boost" and step-down functions—it can be configured as a step-up voltage regulator on one channel, followed by step-down LED drivers on the other two channels. Each of two step-down LED drivers can drive a string of matrix-dimmed LEDs. This topology has a number of advantages, most notably, regardless whether the LED string voltages are above or below the battery voltage, the circuit continues to function optimally.

Figure 3 shows the schematic of the demonstration board shown in Figure 1, a boost-then-dual-buck mode LT3797 and LT3965 matrix dimming headlight system with 16 LEDs at 500mA. Each LED can be individually controlled to be on, off or PWM dimmed down to 1/256 brightness. The 350kHz switching frequency of the LT3797 is outside the AM band (good

Demonstration circuit DC2218 features a complete matrix LED dimmer system with LT3797 boost-then-dual-buck mode LED drivers and two LT3965 matrix dimmers that drive 16 LEDs at 500mA from a car battery. The board operates a matrix headlight with an attached I²C microcontroller via DC2026, the Linduino One demo circuit.

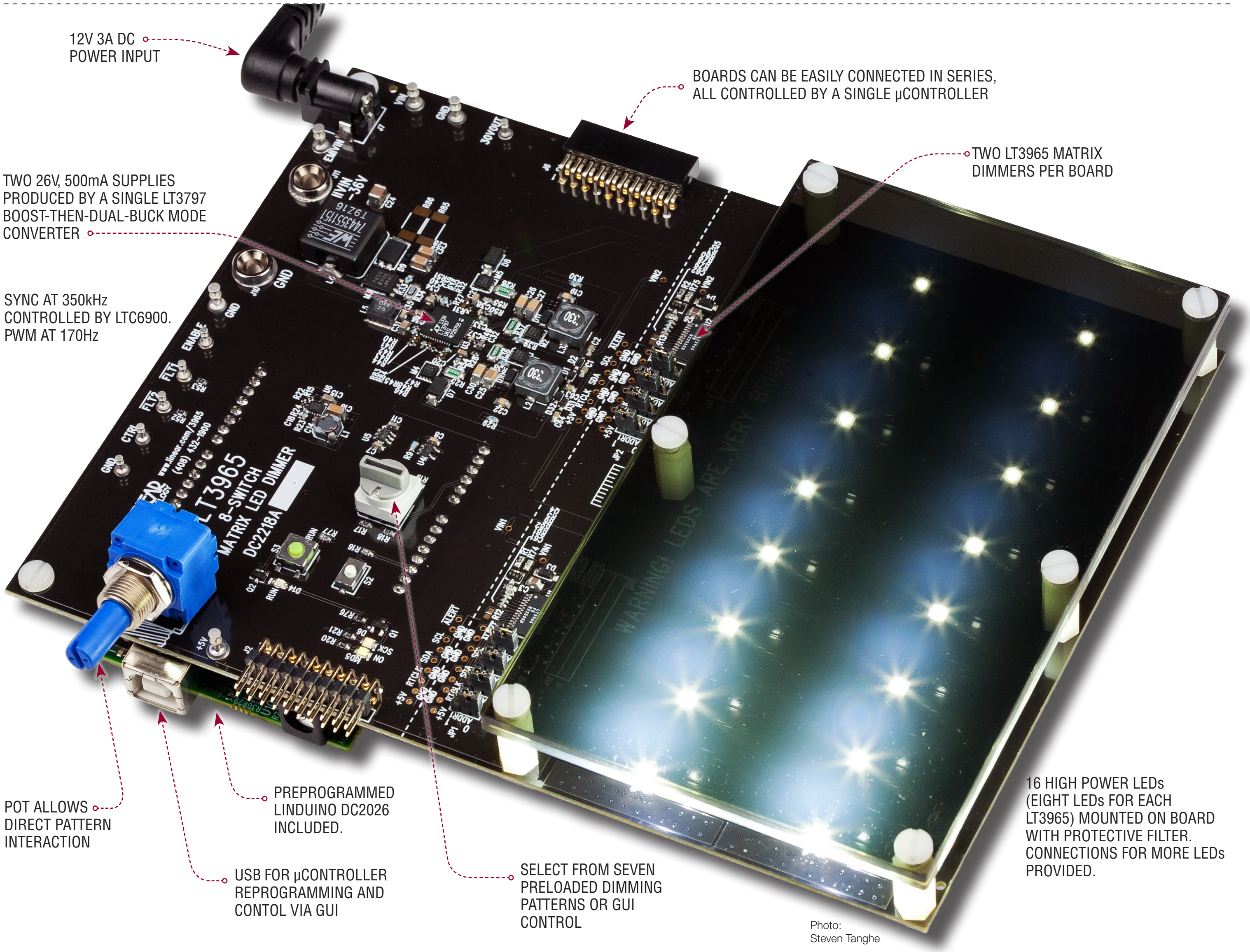
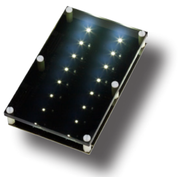


Figure 1. LT3965 LED matrix dimmer demonstration circuit DC2218 run as a Linduino™ shield (DC2026). This demonstration circuit runs headlight, turning light, tail light and trim patterns and can be evaluated with Linear's graphical user interface via a USB cable.

for EMI) and the resulting 170Hz PWM dimming frequency of the LT3965, generated from the same 350kHz clock, is above the visible range. With the system properly synchronized, the LT3797 and LT3965 matrix headlight operates flicker-free.

The LT3797 buck mode converters are optimized for extremely fast transients with little or no output capacitor and properly compensated control loops. These >30kHz bandwidth converters tolerate fast LED transients as the LEDs are turned on and off and PWM dimmed at will. A filter capacitor placed on the LED sense resistor replaces a pole in the control system that is lost when the output capacitor is reduced or removed for the fast transient performance of the matrix dimmer.



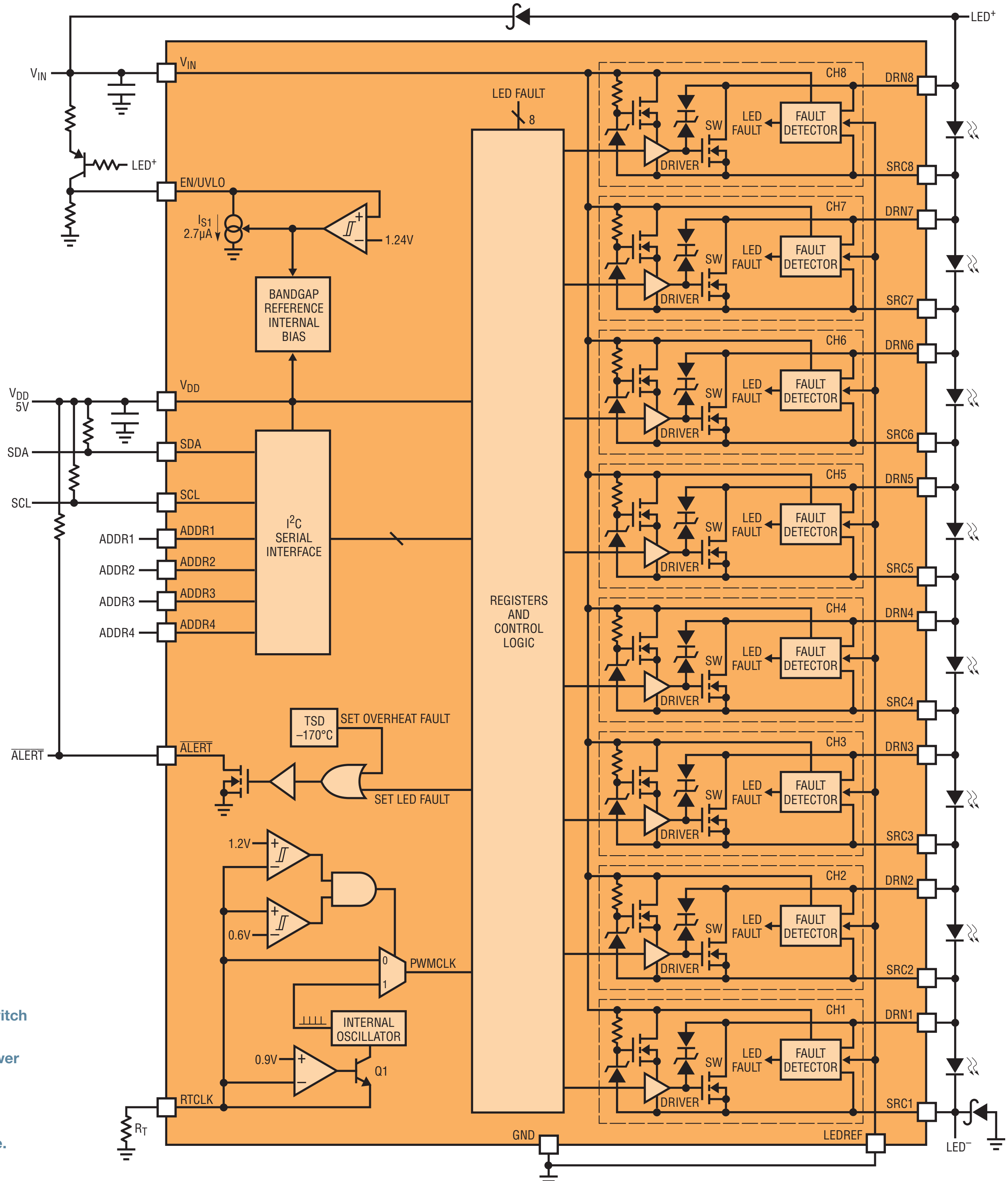


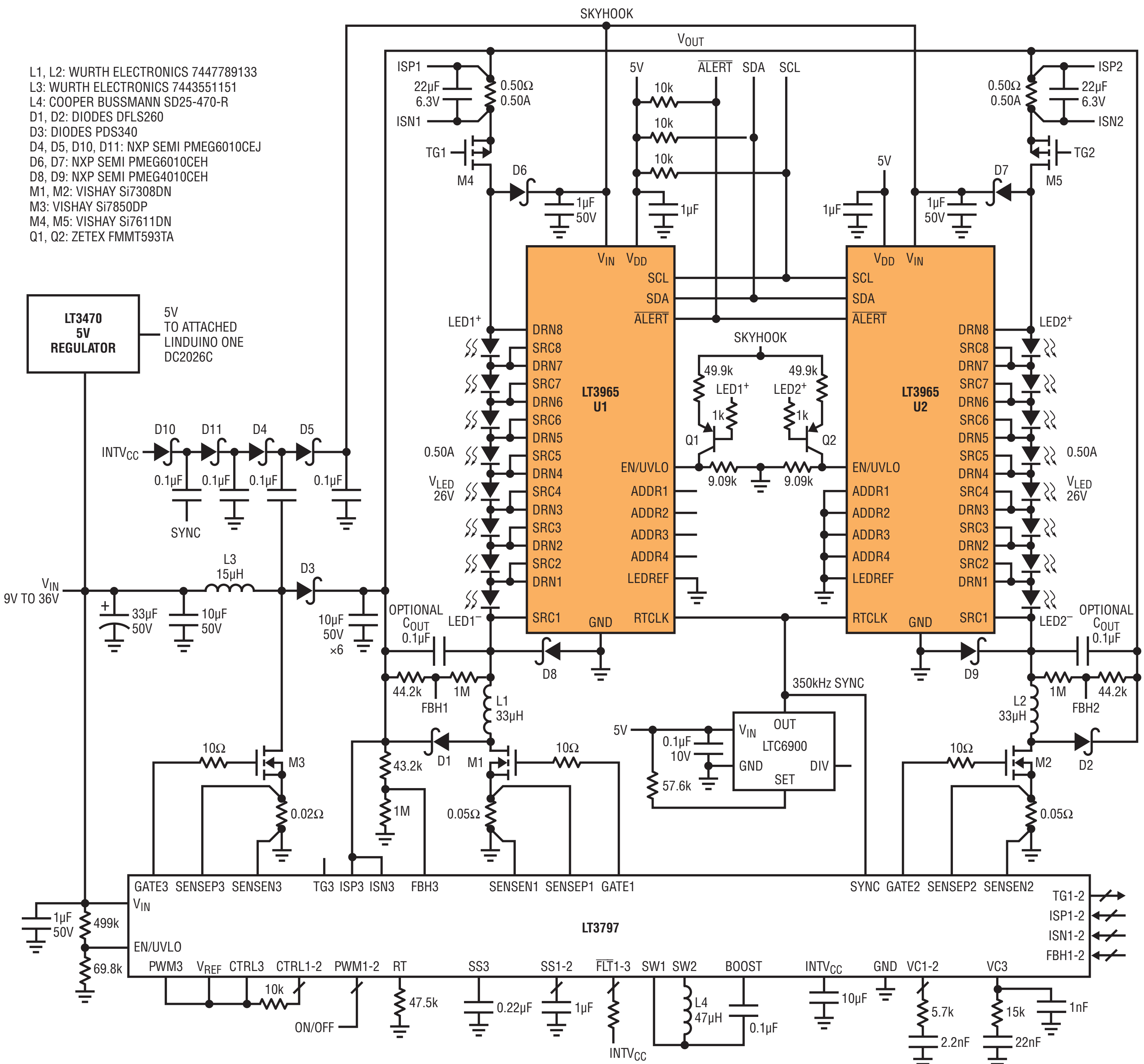
Figure 2. LT3965 60V 8-switch LED matrix dimmer block diagram reveals eight power NMOS shunt switches for brightness control, a fault flag and I²C serial communications interface.

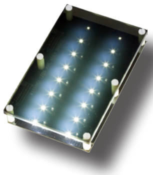
A charge pump from the switch node is used to power the LT3965 V_{IN} pin more than 7V above the LED+ voltage to enable the top channel NMOS to be fully enhanced when driven. The low $R_{DS(ON)}$ NMOS switches in the LT3965 enable high power operation without the IC getting hot, even when all eight shunt switches are on, turning the entire LED string off. In this case, the LT3797 LED driver survives the virtual output short created by all eight shunt switches without any issues, and is ready to quickly regulate 500mA through the next LED that is turned on.

Demonstration circuit DC2218 (Figure 1) features the system shown in Figure 3 and operates a matrix headlight with an attached I²C microcontroller via DC2026, the Linduino™ One demo circuit. DC2218, operated as a large Linduino shield, has up to 400kHz serial code that

The LT3965 I²C 8-switch matrix dimmer, LED driver eases the control of large or small LED matrices (up to 512 LEDs). Its highly integrated design minimizes component count, and built-in fault detection protects individual LEDs in case of a failure and reports failures to the microcontroller.

Figure 3. LT3965 matrix LED dimmer system with LT3797 boost-then-dual-buck mode LED drivers and two LT3965 matrix dimmers that drive 16 LEDs at 500mA from a car battery. I²C serial communications control the brightness of individual LEDs and check for LED and channel faults.





generates different headlight patterns and interfaces with Linear Technology's graphical user interface (Figure 4).

Within the GUI shown in Figure 4, LED brightness and fault protection functions can be examined with ALL CHANNEL MODE and SINGLE CHANNEL MODE commands, as well as FAULT CHECK read and write commands to check for open and short LEDs. Flicker-free operation, fault protection and transient operation can be examined with this demonstration circuit system. DC2218 can be plugged directly into a 12V DC source and it can be controlled by a personal computer running the GUI or reprogrammed from a simple USB connection.

1A MATRIX LED DRIVER USING PARALLEL CHANNELS

The LT3965 can be used to drive matrices of 1A LED channels. It is easy to connect the power switches of the LT3965 in parallel so that two power switches split 1A of LED current and each LT3965 controls four 1A channels. One way to use parallel power switches for higher current is to run each of the anti-phase parallel switches for only 50% of the PWM period. By alternating and running 1A through a single NMOS power switch for half the time, the effective heating is about equal to running 500mA through the same NMOS all of the time.

Figure 5 shows a 1A matrix headlight system using eight LEDs driven by two LT3965s and another boost-then-dual-buck mode LT3797. When PWM dimming, the LT3797 uses a unique 1/8-cycle phasing of the eight switches, as shown in Figure 6. In this 1A matrix system, LT3797 channels are combined in parallel pairs, so

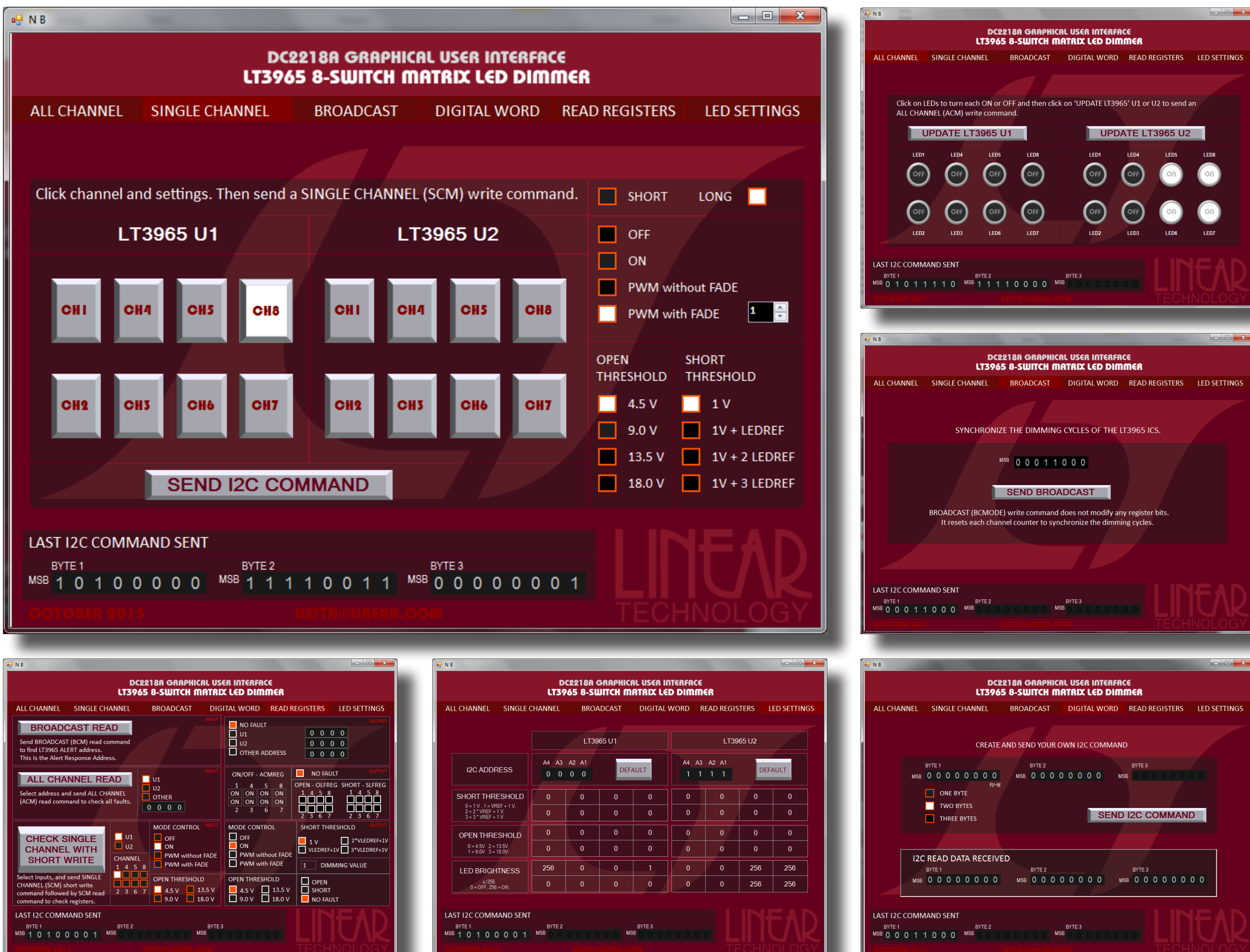
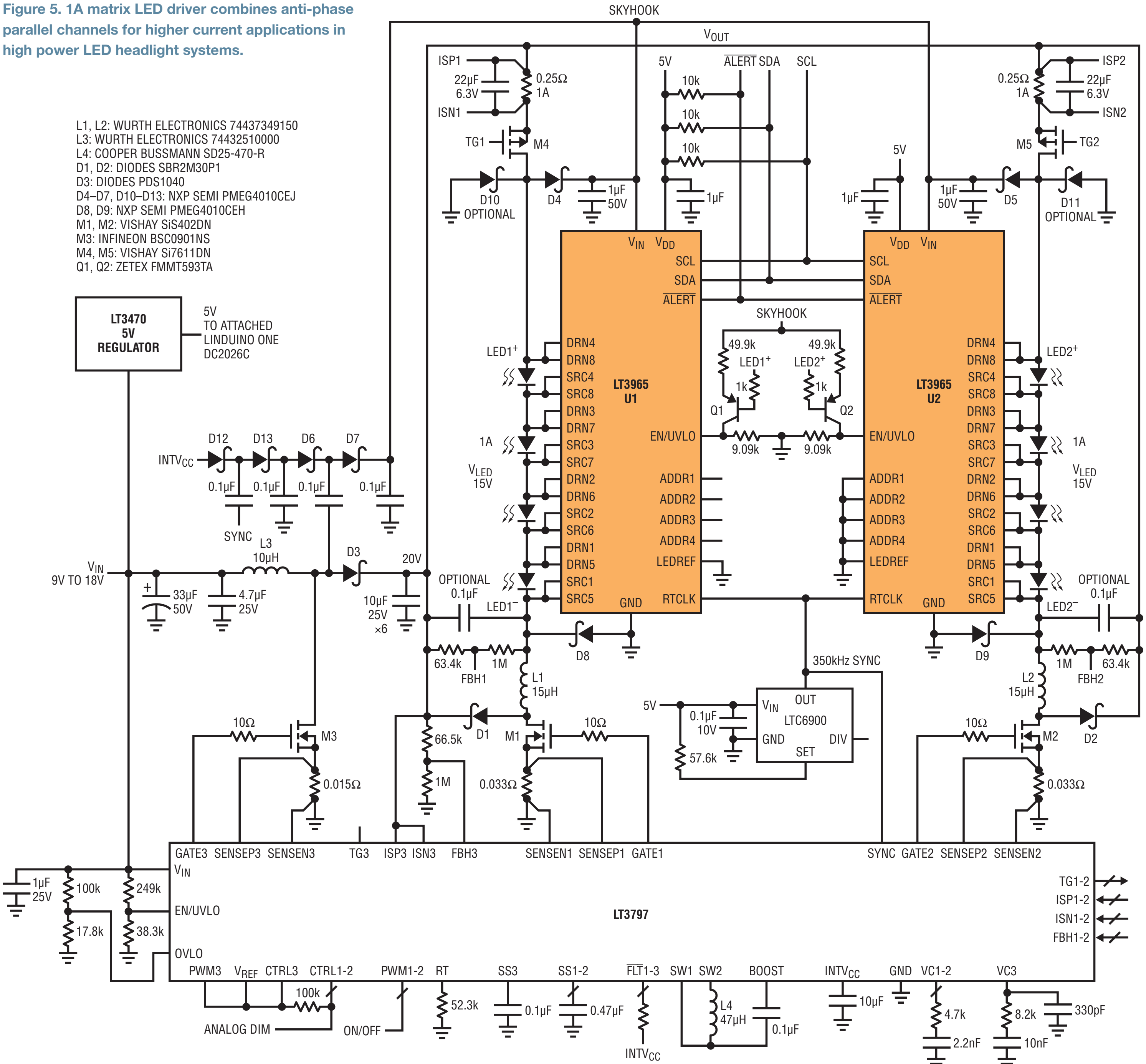
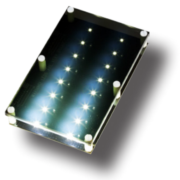


Figure 4. The PC-based interface allows designers to access control and monitoring of the LEDs driven by the LT3965.

The LT3965 can be used to drive matrices of 1A LED channels. It is easy to connect the power switches of the LT3965 in parallel so that two power switches split 1A of LED current and each LT3965 controls four 1A channels.

Figure 5. 1A matrix LED driver combines anti-phase parallel channels for higher current applications in high power LED headlight systems.





Turning a high number of LEDs on or off presents a significant current load step to the DC/DC converter. The converters presented here handle these transients with grace, with a small output capacitor and high bandwidth. An ACM write transitioning a high number of LEDs produces no visible flicker or significant transient on the LED current.

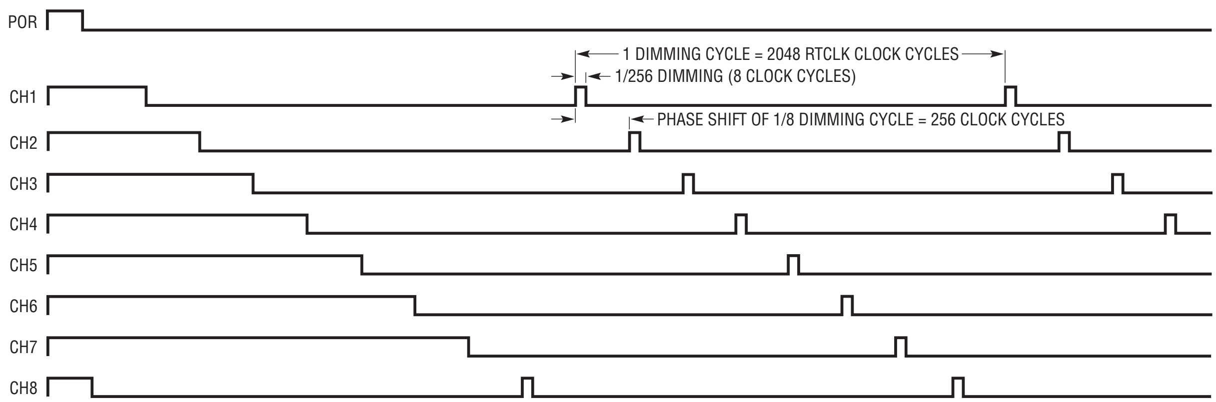


Figure 6. 1/8 PWM flicker-free phasing of the eight LT3965 power switches limits transients during PWM dimming brightness control.

that paired channels are anti-phase, 180° from each other; specifically pairing channels 8 and 4, 7 and 3, 6 and 2, and 5 and 1. Parallel channels alternate shunting, effectively doubling the PWM frequency, with the advantage of spreading out the shunted current and heat. For this to work properly, the maximum duty cycle for any single shunt power switch is 50%, because two anti-phase switches that are *on* 50% of the time (each shunting an LED 50% of the time) turns the LED *off* 100% of the time.

Each LT3965 controls the brightness of four 1A LEDs that are driven by two 1A buck mode LT3797 channels (from the LT3797-boosted 20V channel). This high power, robust system can be expanded to power more LEDs with more LT3965s or higher current LEDs with more channels in parallel. It is possible to drive two LEDs per channel at 1A and drive up the power of this flexible headlight system.

MORE THAN ONE LED PER CHANNEL

The LT3965 can support one to four LEDs per channel. Although it can be advantageous to individually control every single LED for fault protection or high resolution patterns, it is not always necessary. Using more than one LED per channel reduces the number of matrix dimmers in a system and is enough to accomplish the patterns or dimming required for some designs. Segments of headlights, signal lights and tail lights can have up to four LEDs with the same brightness. Emergency LED lights can have sets of three and four LEDs that blink and wave with the same pattern.

The circuit in Figure 7 demonstrates a two-LED-per-channel system—it has the same number of LEDs as the circuit in Figure 3, but uses only a single LT3965 matrix dimmer instead of two.

When an I^2C command tells the LT3965 to turn on, off, or dim a channel, it affects the two LEDs that are controlled by that channel's shunt power switch. To stay within the voltage limitations of the LT3965, the 16 LEDs at 500mA still need to be split into two series LED strings as they are in Figure 2. The same LT3797 circuit in Figure 2 can be used, but only a single LT3965 controls the brightness of the two strings. This demonstrates how each NMOS shunt power switch inside the LT3965 can be configured independently of the others, allowing an endless variety of matrix designs.

ALL CHANNEL MODE AND SINGLE CHANNEL MODE I^2C COMMANDS WITH FLICKER-FREE PWM AND FADE

The I^2C instruction set of the LT3965 includes 1-, 2- and 3-word commands. These commands are sent over the serial data line (SDA) alongside the master-generated clock line (SCL) at up to 400kHz speed. The master microcontroller sends all channel mode (ACM) or single channel mode (SCM) write commands to control the brightness, fade, open-circuit threshold and short-circuit threshold of the LED channels and LT3965 addresses.

Broadcast mode (BCM), ACM and SCM read commands request that the LT3965s report the content of their registers, The LT3965 can support one to four LEDs per channel. Segments of headlights, signal lights and tail lights can have two to four LEDs with the same brightness. Emergency LED lights can have sets of three and four LEDs that blink and wave with the same pattern.

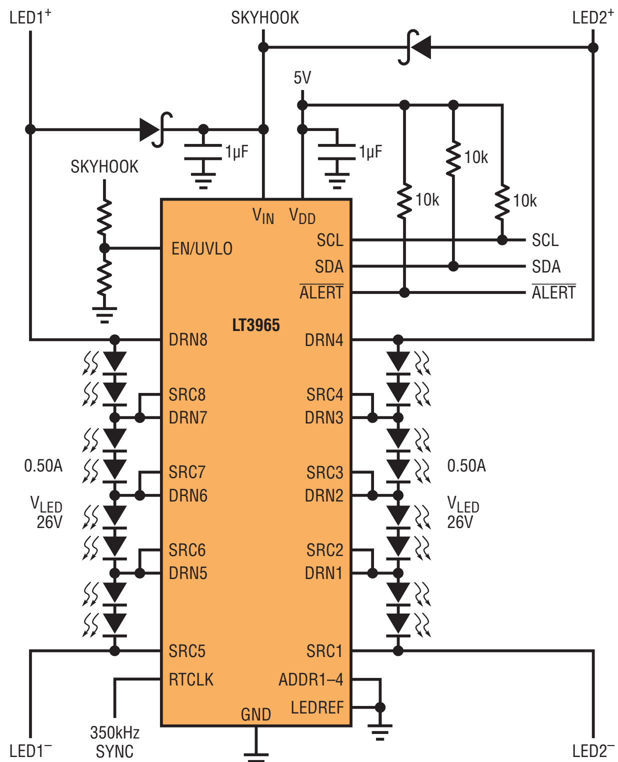


Figure 7. The flexible LT3965 can drive LED channels on independent LED strings and can drive between one and four LEDs per channel. (Complete driver circuit is similar to Figure 3, but with only one LT3956, as shown here.)

including open and short registers for fault diagnostics. The LT3965 asserts an ALERT flag when there is a new fault. The micro can respond to the fault by determining which LT3965 reported the fault, as well as the type and channel of fault. In the case that multiple LT3965 ICs are reporting faults, the LT3965s can sequence fault reporting to the master to prevent overlap errors. This makes the alert response system reliable and conclusive. A complete list of the registers and command set is given in the LT3965 data sheet.

ACM write commands instantly turn all of the eight channels of a single LT3965 address on or off with just two I²C words—the channels transition on or off at the same time. Turning a high number of LEDs on or off presents a significant current voltage load step to the DC/DC converter. The converters presented here handle these transients with grace, with little or no output capacitor and high bandwidth.

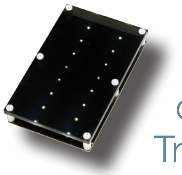
As shown in Figure 8, an ACM write transitioning a high number of LEDs produces no visible flicker or significant transient on the LED current of other channels. The high bandwidth buck mode converter built around the LT3797 is the reason for such a small and controlled transient.

Single channel mode writes produce relatively small and fast single-LED transients. SCM writes are used to set the brightness of only one channel at a time to ON, OFF, or PWM dimming with or without fade. PWM dimming values between 1/256 and 255/256 are communicated in 3-word writes while ON and OFF can be communicated in shorter, 2-word commands. A fade bit on a single SCM write command enables the LT3965 to move between two PWM dimming levels with internally determined logarithmic fade and no additional I²C traffic. The open and short thresholds of each channel can be set between one and four LEDs with SCM write commands.

SHORT AND OPEN LED FAULT PROTECTION FOR EACH CHANNEL

Short- and open-circuit protection is an inherent benefit of the matrix dimmer. Each channel's NMOS power switch can shunt out between one and four series LEDs. Traditional LED strings have protection against the entire string being open or shorted and only some ICs have output diagnostic flags to indicate these fault conditions. In contrast, the LT3965 protects against, *and rides through,* individual channel shorts and opens, keeping operational channels alive and running while recording and reporting the fault conditions.

When a fault occurs within a string, the LT3965 detects the fault and asserts its ALERT flag, indicating to the microcontroller that there is an issue to be addressed. If the fault is an open-circuit, the LT3965 automatically turns on its



Short- and open-circuit protection is an inherent benefit of the matrix dimmer. Each channel's NMOS power switch can shunt out between one and four series LEDs. Traditional LED strings have protection against the entire string being open or shorted and only some ICs have output diagnostic flags to indicate these fault conditions. In contrast, the LT3965 protects and rides through individual channel shorts, keeping operational channels alive and running while recording and reporting the fault conditions.

corresponding NMOS power switch, bypassing the faulty LED until a full diagnosis occurs or until the fault is removed.

The LT3965 maintains registers of open and short faults for each channel and returns the data to the microcontroller during I^2C fault read commands. The command set includes reads that leave the status register unchanged and those that clear the fault registers, allowing user-programmable fault diagnostics. Registers can be read in the various modes allowed for writes, SCM, ACM, BCM:

- Single channel mode (SCM) reads return the open and short register bits for a single channel. SCM reads also check the open and short threshold register, the mode control, and the 8-bit PWM dimming value for that channel.
- All channel mode (ACM) reads return the open and short register bits for all channels of a given address without clearing the bits, as well as the ACM ON and OFF bits for all eight channels.
- In more complex systems with many LT3965 matrix dimmers sharing the same bus, a broadcast mode (BCM) read first requests which, if any, LT3965 address has asserted the fault flag.
- The ACM and SCM reads can be used to check and clear faults *and* to read all of the registers for a robust I^2C communications system.

UP TO 16 ADDRESSABLE LT3965s ON THE SAME BUS

Every LT3965 features four user-selectable address bits, enabling 16 unique bus addresses. Every ACM and SCM I^2C command is sent to the shared communications bus, but action is only taken by the addressed LT3965. BCM commands are followed by all ICs on the bus. The 4-bit address architecture allows a single microcontroller and a single I^2C 2-line communications bus to support up to $8 \times 16 = 128$ individually controllable channels. With the LT3965, for all but the most ambitious lighting displays, all individual LEDs in an automobile's headlight, tail light and trim lights can be controlled by a single I^2C communications bus and a single microcontroller. Given that each channel can be connected to up to four LEDs, one relatively easy-to-implement system can support matrix dimming for up to 512 LEDs.

CONCLUSION

The LT3965 matrix LED dimmer controls eight LED-brightness channels on a single LED string, giving lighting designers unlimited access to sophisticated and striking automotive lighting designs. The I^2C communications interface allows a microprocessor to control the brightness of individual LEDs in the string. Fault protection in the I^2C interface ensures LED lighting system robustness. The channels of the matrix dimmer are versatile: each channel can control multiple LEDs; channels can be combined to support higher current LEDs; or high LED-count systems can be produced with up to 16 matrix dimmer ICs on the same communications bus. Take the next step in designing automotive headlights, tail lights, front, side, dash and trim lights—the future is now. ■

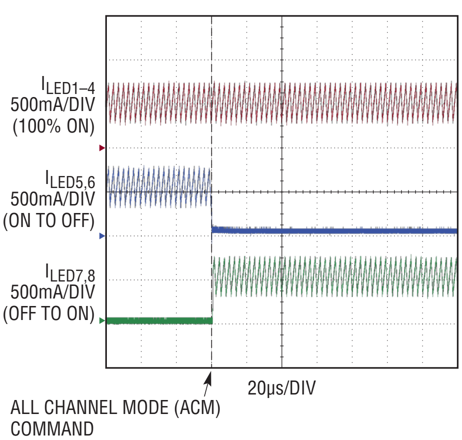


Figure 8. The LED matrix driver designs shown in this article feature minimal to no cross-channel transient effects. For instance, transitioning half the channels—here, simultaneously turning on two and turning off two—has little to no transient effect on the other four, untouched channels. The non-transitioned channels remain flicker free.

CAN Bus Transceivers Operate from 3.3V or 5V and Withstand ±60V Faults

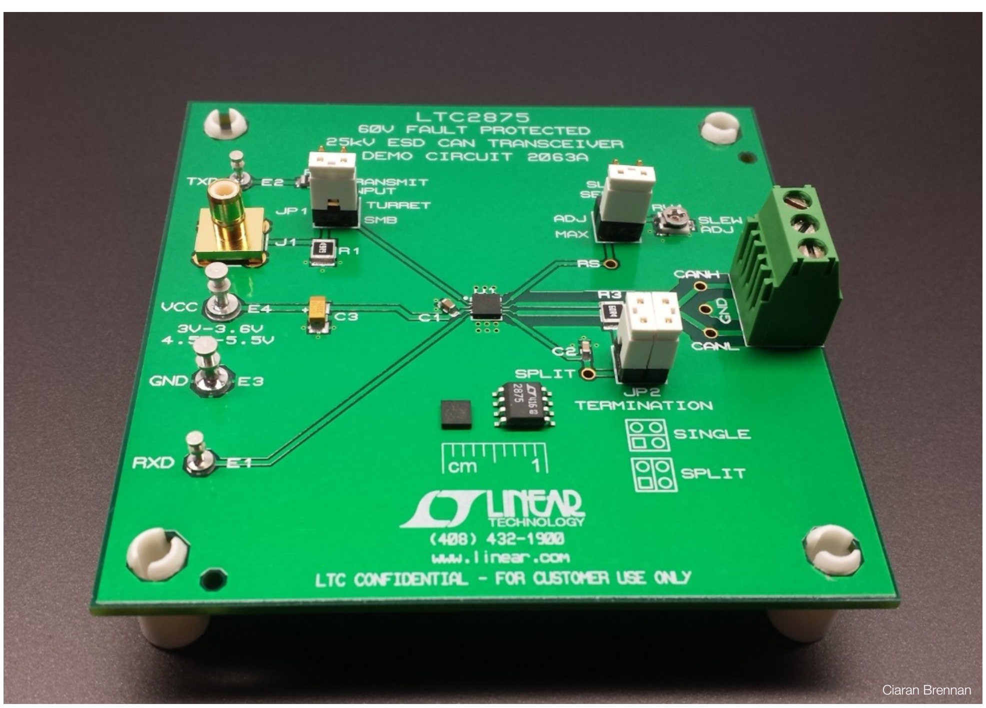
Ciaran Brennan

The LTC2875 is a robust CAN bus transceiver that features ±60V overvoltage and ±25kV ESD tolerance to reduce failures caused by electrical overstress. These transceivers introduce several new capabilities for high voltage tolerant CAN bus transceivers: operation from 3.3V or 5V supply voltages, up to 4Mbps data rate, ±36V common mode voltage range, continuously variable slew rate and availability in 3mm × 3mm DFN packages.

The CAN bus forms the backbone of many automotive, commercial and industrial data communications systems. CAN bus networks are used in a wide variety of applications, including automotive and transportation electronics, industrial control systems, supervisory control and data acquisition systems, building automation and security, HVAC control, and other custom networked systems. Robustness to electrical overstress is an important attribute for CAN bus transceivers used in these applications, which risk exposure to wiring faults, ground voltage faults and lightning induced surge voltages.

However, few CAN transceivers capable of operating from 3.3V supplies are available, and until now, none offer the high voltage tolerance and wide common mode operating range of the LTC2875. Many customers have requested a robust CAN bus transceiver with the performance and the expanded capabilities demanded by contemporary network applications. The LTC2875 transceiver is Linear Technology's response to these requests.

Figure 1. LTC2875 demo circuit with DFN and SO packages in foreground



3.3V OR 5V OPERATION

Most high voltage tolerant CAN bus transceivers can operate only from a 5V supply, but 5V is rarely used by most modern digital circuits. The CAN bus transceiver may be the only 5V component in the system. A high voltage tolerant CAN bus transceiver that operates from a 3.3V supply reduces design time and cost by eliminating the need for a dedicated 5V supply.

The LTC2875 maintains compatibility with the ISO 11898-2 CAN bus standards when operating from a 3.3V supply, driving the full specified differential bus voltage V_{OD} and maintaining the same receiver input threshold voltages. The only difference between 3.3V and 5V operation is that the common mode bus voltage is reduced to 1.95V while operating at 3.3V, which falls below the range of 2V to 3V specified by ISO 11898-2. This minor shift in common mode voltage falls within the minimum common mode voltage range of –2V to 7V specified in the standard (and is truly inconsequential to the ±25V common mode voltage range of the LTC2875 when operating at 3.3V), allowing the LTC2875

The LTC2875 provides a continuously variable slew rate over an approximate 20-to-1 range. The lowest slew rate is appropriate for data rates of 200kbps or less. The slew rate is programmed by a single resistor in series with the chip enable pin RS.

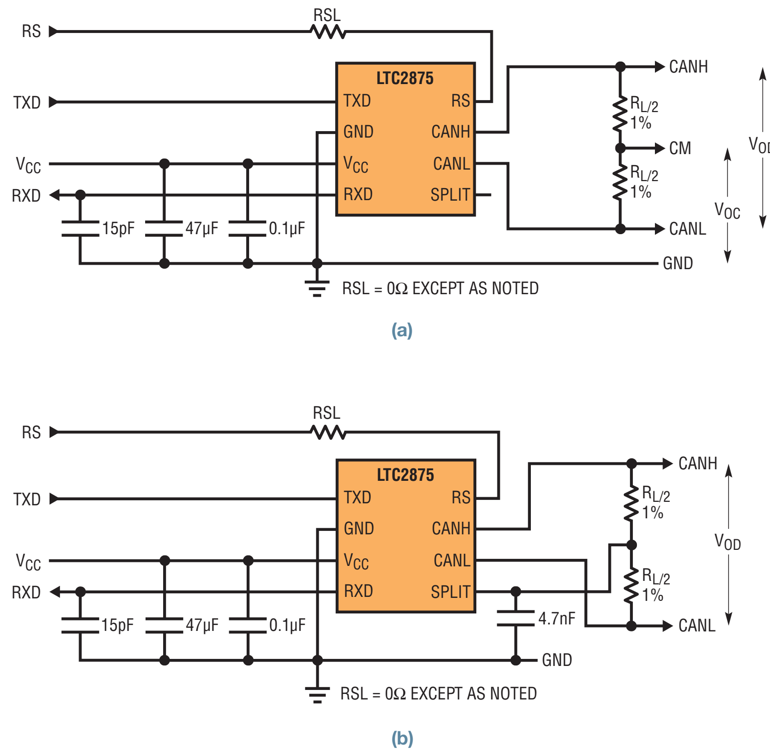


Figure 3. Single resistor termination (a) and split termination (b)

to communicate seamlessly with any other ISO11898-2 compliant transceivers. The LTC2875 is fully interoperable with other transceivers on the same bus that are powered by 5V when operating from either a 3.3V or 5V supply.

4 Mbps DATA RATE WITH HIGH SYMMETRY DRIVER AND CONTINUOUS SLEW RATE CONTROL

Modern CAN bus systems may operate at data rates that exceed the capabilities of existing high voltage tolerant transceivers. For example, Linear Technology's LT1796 CAN transceiver operates at a maximum of 125kbps. The LTC2875 offers similar high voltage tolerance to this predecessor, but can communicate 32 times faster, up to 4Mbps.

Not all systems require a high data rate. In applications where lower data rates suffice, the system designer may prefer a CAN bus driver with low electromagnetic

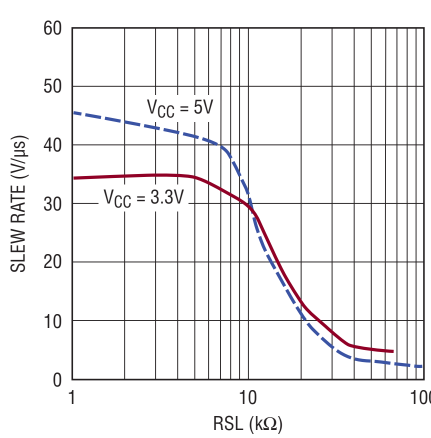


Figure 2. Slew rate vs slew control resistor RSL

emissions (EME) slew controlled transitions. The LTC2875 provides a continuously variable slew rate over an approximate 20-to-1 range. The lowest slew rate is appropriate for data rates of 200kbps or less. The slew rate is programmed by a single resistor in series with the chip enable pin RS, as plotted in Figure 2.

Considerable design effort was made to keep the switching symmetry of the CAN transmitter highly symmetrical (or more accurately, anti-symmetrical) between the CANH and CANL outputs, because any asymmetry between the switching waveforms of the two outputs produces a change in the common mode voltage. While the electromagnetic fields produced by the differential voltage along a twisted

The LTC2875 transceivers operating from a 3.3V supply can interoperate with other CAN transceivers operating from a 5V supply on the same bus. The only major difference between operating at 3.3V and 5V is that the common mode voltages are ~1.95V and ~2.5V, respectively.

pair largely cancel and produce little EME, the electromagnetic fields of the common mode voltage on the pair add together and may produce significant EME, particularly if the twisted pair is unshielded. Therefore, good CAN transmitter switching symmetry results in lower EME.

The LTC2875 provides two features to reduce the EME produced by fluctuations of the common mode voltage during switching: variable slew rate control and split termination. The transmitter slew rate can be programmed by a single resistor in series with the enable pin RS. Reducing the slew rate reduces the high frequency content of the switching waveforms. Split termination entails dividing the terminator resistor at each end of the bus into two equal, series resistors of half the termination resistance value, with the center point of the resistors biased at the DC common mode voltage supplied by the SPLIT pin and a decoupling capacitor (Figure 3). Split termination provides a low impedance load for the common mode signal while maintaining the proper termination for the differential signals. The low impedance common mode loading helps suppress common mode voltage fluctuations.

The effectiveness of the split termination in reducing EME from the common mode voltage fluctuations is illustrated in Figure 4. In this figure, the voltages at the CANH and CANL terminals and the common mode voltage are recorded for an LTC2875 transmitting at 1Mbps over a 10-meter unshielded twisted pair, with V_{CC} = 3.3V, the slew rate set to maximum, and 120Ω termination resistors placed on each end of the cable.

The FFT power spectra of the common mode voltage waveforms are also shown in Figure 4. The results using split termination and those using single resistor termination are both shown. The waveforms with the single resistor termination show a larger magnitude of common mode transients during the switching transition, as well as a damped oscillation after the dominant to recessive transition. This damped oscillation is the result of the inductance of the line interacting with line and transceiver capacitance after the transceiver switches to its high impedance recessive state.

In this example, the common mode voltage in the recessive state with the single resistor termination is loaded only by the four 40kΩ input resistors of two LTC2875 devices, one on each end of the cable, for a parallel resistance of 10k. By contrast, the common mode voltage

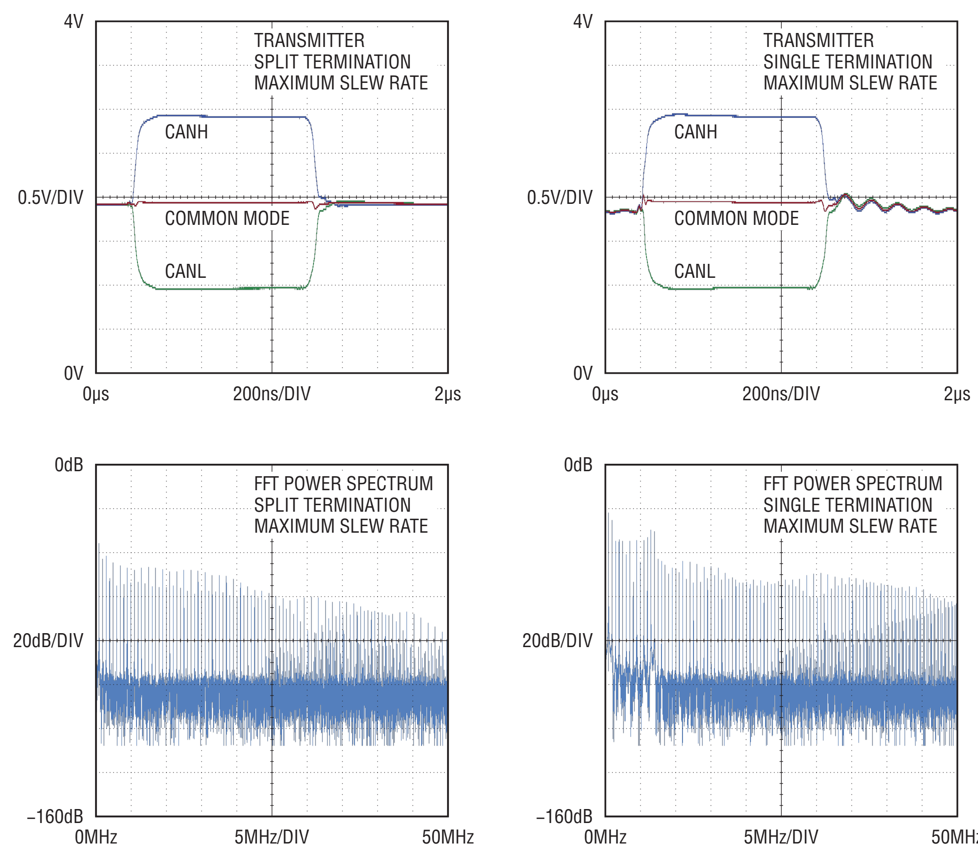


Figure 4. Transmitter waveforms and FFT power spectrum plots of the common mode voltage for split and single bus terminations on 10m unshielded twisted pair cable; V_{CC} = 3.3V, 1Mbps

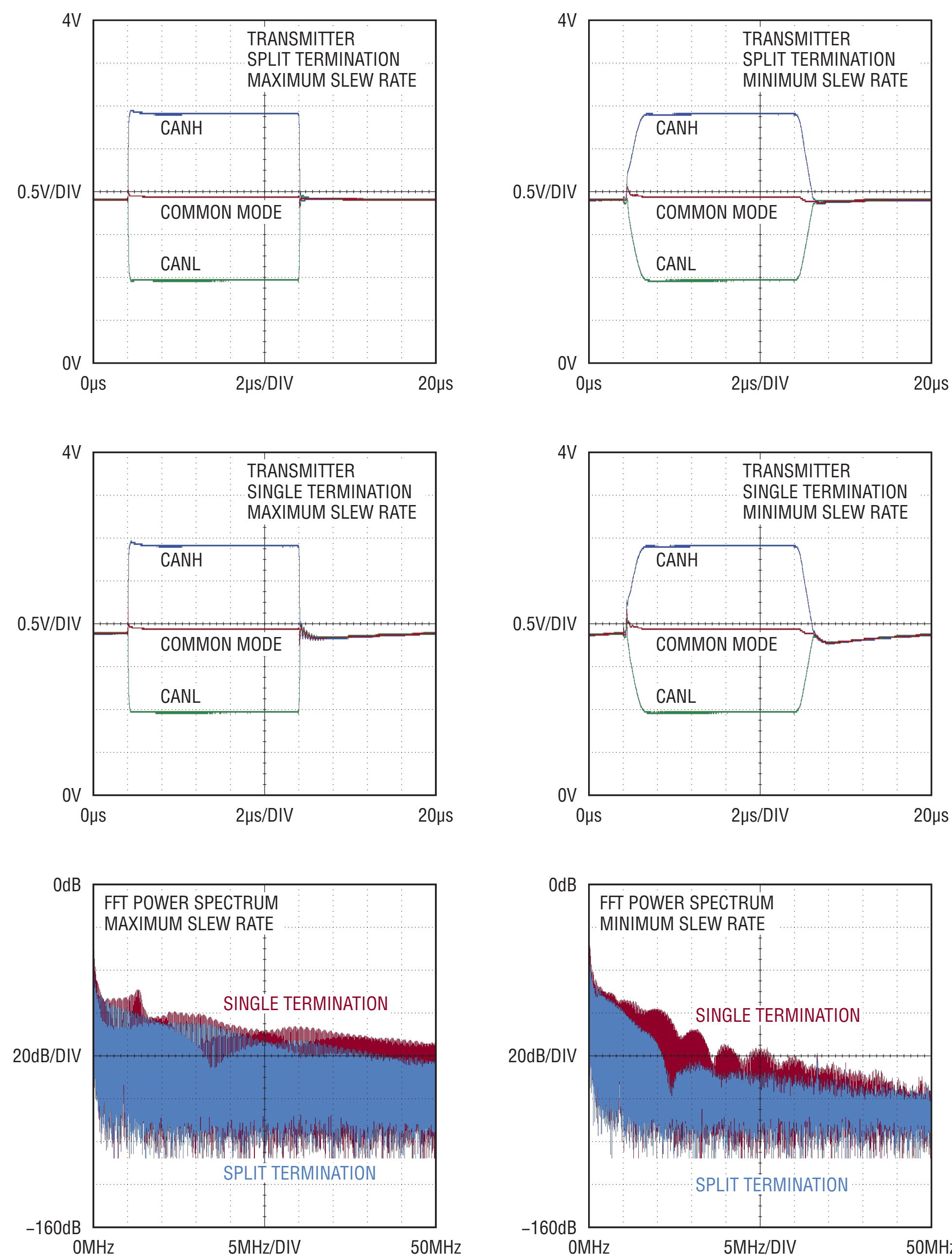
The use of the split termination results in a significant reduction in common mode noise across the frequency spectrum when transmitting at 100kbps. At these lower data rates, further reductions in the common mode noise spectrum can be obtained by setting the LTC2875 to its minimum slew rate.

in the split termination case is also loaded by the four 60Ω split termination resistors, for a parallel resistance of 15Ω, in series with two parallel 4.7nF capacitors. The common mode voltage FFT power spectrum is lower in amplitude across a wide range of frequencies for the split termination compared to the single resistor termination.

For transmitting at a lower data rate, a slower slew rate may be used for additional reduction in common mode EME. Figure 5 illustrates four cases with minimum and maximum slew rates, combined with split or single resistor termination. These measurements were performed with the same test configuration as those shown in Figure 4, except that the data rate was reduced to 100kbps and waveforms at both the minimum and maximum slew rates were recorded.

As in the 1Mbps waveforms of Figure 4, the use of the split termination results in a significant reduction in common mode noise across the frequency spectrum when transmitting at 100kbps. At these lower data rates, further reductions in the common mode noise spectrum can be obtained by setting the LTC2875 to its minimum slew rate. In this example, combining both the split termination and the minimum slew rate reduces the common mode noise power by 20dB or more over most of the recorded spectrum, compared to the single resistor termination combined with the maximum slew rate.

Figure 5. Transmitter waveforms and FFT power spectrum plots of the common mode voltage for four combinations of termination and slew rate; V_{CC} = 3.3V, 100kbps, 10m unshielded twisted pair cable



Another technique to reduce EME from common mode voltage fluctuations is using a common mode choke. The choke increases the source impedance of the common mode signal, and in conjunction with capacitors added between CANH and CANL and GND, forms a lowpass filter that attenuates high frequency noise.

REDUCING EME WITH A COMMON MODE CHOKE

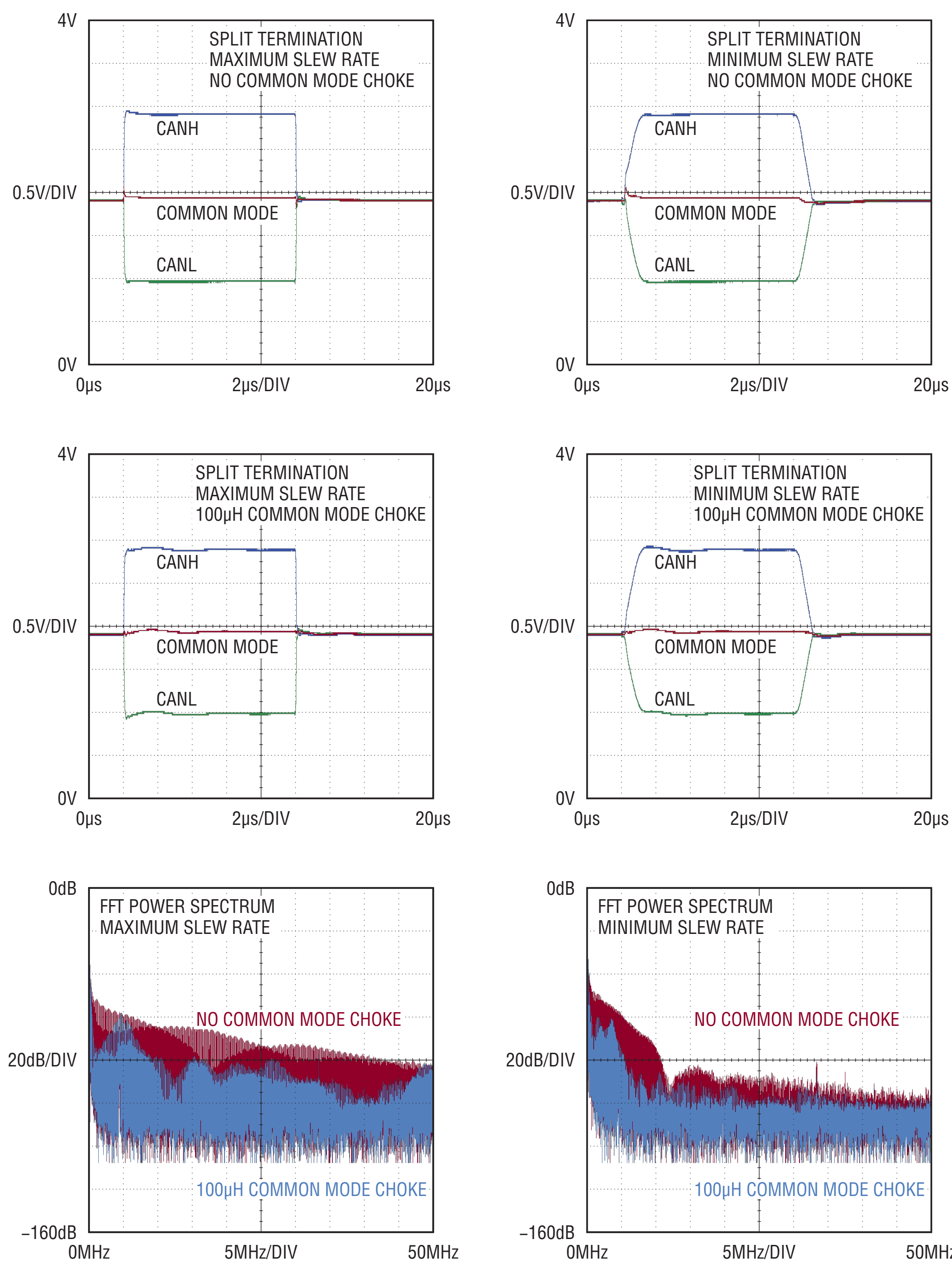
Another technique to reduce EME from common mode voltage fluctuations is using a common mode choke. The choke increases the source impedance of the common mode signal, and in conjunction with capacitors added between CANH and CANL and GND, forms a lowpass filter that attenuates high frequency noise. The effectiveness of a 100µH common mode choke in conjunction with two 33pF capacitors in reducing the common mode noise is shown in Figure 6. In this example, V_{CC} = 3.3V, split termination was employed, the twisted pair cable was 10 meters long and the data rate was 100kbps.

MIXED 3.3V AND 5V OPERATION

The LTC2875 transceivers operating from a 3.3V supply can interoperate with other CAN transceivers operating from a 5V supply on the same bus. The only major difference between operating at 3.3V and 5V is that the common mode voltages are ~1.95V and ~2.5V, respectively. The common mode of the bus therefore fluctuates depending on the logical state of the bus.

When all transmitters are in the recessive state, the common mode voltage settles to some intermediate voltage depending on all the resistive loads placed on the bus, including receiver input resistors, and split termination resistors (if present). When a transmitter powered by 5V is dominant, it pulls the common mode voltage toward 2.5V. When a transmitter is powered by

Figure 6. Transmitter waveforms and FFT power spectrum plots of the common mode voltage, with or without common mode choke



An ideal CAN bus transceiver would survive large common mode voltages and continue to send and receive data without disruption. Accordingly, the receiver in the LTC2875 is designed to operate over an expanded ±36V common mode voltage range when operating from a 5V supply, and ±25V when operating from a 3.3V supply.

3.3V, it pulls the common mode voltage toward 1.95V. The common mode voltage fluctuates between 2.5V and 1.95V, resulting in a modest increase in EME.

An example of mixed voltage operation is shown in Figure 7. The experimental setup consists of two LTC2875 transceivers, each connected to the end of a 10-meter twisted pair, with split termination employed. Each transceiver alternates in driving a dominant state on the bus. The waveforms are recorded on the CANH and CANL pins of the near side transceiver.

In the plots shown on the left, both the near and far transceivers are powered by a 3.3V supply. The common mode voltage remains near 1.95V with only minor perturbations. In the plots on the right, by comparison, the near transceiver remains powered by 3.3V, while the far transceiver is powered by 5V. The recessive common mode voltage settles to about 2.23V, the average of 2.5V and 1.95V. When the near side transceiver is dominant, the common mode voltage is pulled down close to 1.95V, whereas when the far side transceiver is dominant, the common mode voltage is pulled close to 2.5V.

The difference in EME resulting from common mode voltage fluctuations can be seen by comparing the FFT power spectra of the common mode voltage recorded at the terminals of the near transceiver. An increase in power of approximately 8dB is observed from 0MHz to 25MHz for the mixed power supply voltage case, with the difference rolling off above that frequency.

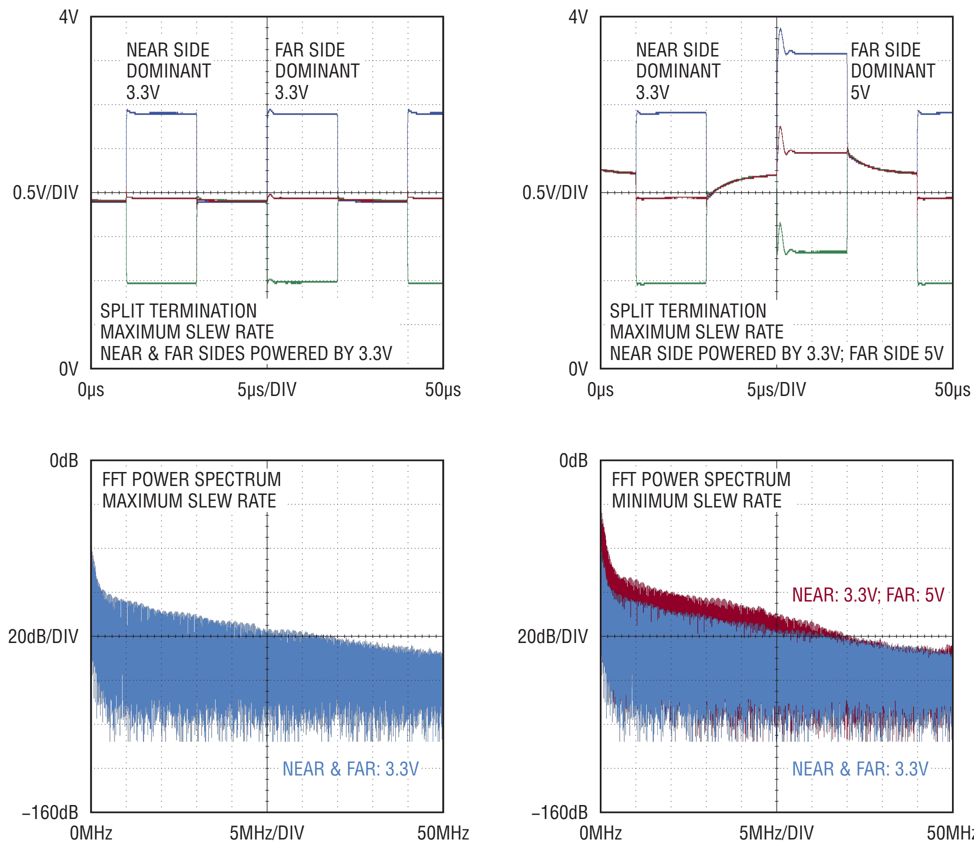


Figure 7. Transmitter waveforms and FFT power spectrum plots of the common mode voltage for two transmitters powered by identical and mixed power supply voltages; 10m unshielded twisted pair cable, 100kbps, maximum slew rate

±36V COMMON MODE VOLTAGE RANGE

Standard CAN bus transceivers operate over a limited common mode voltage range that extends from –2V to +7V. In commercial or industrial environments, ground faults, noise, and other electrical interference can induce common mode voltages that greatly exceed these limits. An ideal CAN bus transceiver would survive large common mode voltages and continue to send and receive data without disruption. Accordingly, the receiver in the LTC2875 is designed to operate over an expanded ±36V common mode voltage range when operating from a 5V supply, and ±25V when operating from a 3.3V supply.

The receiver uses low offset bipolar differential inputs, combined with high precision resistor dividers, to maintain precise receiver thresholds over the wide common mode voltage range. The

The LTC2875 is a groundbreaking ±60V overvoltage tolerant CAN bus transceiver that operates from either 3.3V or 5V supplies. Its industrial robustness is matched by superior performance, application flexibility and excellent EME characteristics.

transmitters operate up to the absolute maximum voltages of ±60V, and will sink or source current up to the limits imposed by their current limit circuitry.

HOT PLUGGING, HOT SWAPPING, AND GLITCH-FREE POWER-UP AND POWER-DOWN

The LTC2875 features glitch-free power-up and power-down protection to meet hot plugging (or hot swap) requirements. These transceivers do not produce a differential disturbance on the bus when they are connected to the bus while unpowered, or while powered but disabled. Similarly, these transceivers do not produce a differential disturbance on the bus when they are powered up in the disabled state while already connected to the bus. In all of these cases the receiver output RXD remains high impedance (with an internal 500k pull-up resistor), while the CANH and CANL outputs remain in the high impedance recessive state.

If the transceiver is powered up in the enabled state, the chip goes active shortly after the supply voltage passes through the transceiver's internal power good detector threshold. The RXD output reflects the state of the bus data when the chip goes active, while the transmitter remains in the recessive state with its outputs high impedance until the first recessive-to-dominant transition of TXD after the chip goes active.

If the transmitter is in the enabled state when the chip is powered down, the chip goes inactive shortly after the supply voltage passes through the transceiver's internal supply undervoltage detector threshold. If the transmitter is in the dominant state at this time, the outputs smoothly switch to the recessive state. Regardless of whether it is outputting a dominant or recessive state, the receiver output RXD smoothly switches to a high impedance state (weakly pulled up through an internal 500k pull-up resistor).

±60V FAULT AND ±25KV ESD TOLERANCE

CAN bus wiring connections in industrial installations are sometimes made by connecting the bare twisted wire to screw terminal blocks. The apparatus containing the CAN bus interface may house circuits powered by 24V AC/DC or other voltages that are also connected with screw terminals. The handling of exposed wires and screw terminals by service personnel introduces the risk of ESD damage, while the possibility of wiring the cables to the wrong screw terminals introduces the risk of overvoltage damage. The high fault voltage and ESD tolerance make the LTC2875 exceptionally resistant to damage from these hazards.

The ±60V fault protection of the LTC2875 is achieved by using high voltage BiCMOS integrated circuit technology. The naturally high breakdown voltage of this technology provides protection in powered-off and high impedance conditions. The driver outputs use a progressive foldback current limit design to protect against overvoltage faults while still allowing high current output drive. The LTC2875 is protected from ±60V faults even with GND open, or V_{CC} open or grounded.

The LTC2875 is protected from electrostatic discharge from personnel or equipment up to ±25kV (HBM) to the A, B, Y and Z pins with respect to GND. On-chip protection devices begin to conduct at voltages greater than approximately ±78V and conduct the discharge current safely to the GND pin. Furthermore, these devices withstand up to ±25kV discharges even when the part is powered up and operating without latching up. All the other pins are protected to ±8kV (HBM).

CONCLUSION

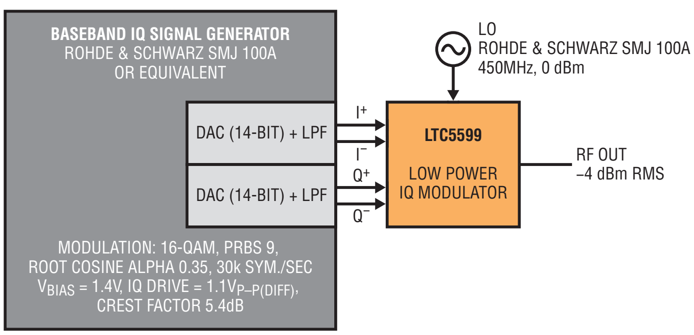
The LTC2875 is a groundbreaking ±60V overvoltage tolerant CAN bus transceiver that operates from either 3.3V or 5V supplies. Its industrial robustness is matched by superior performance, application flexibility and excellent EME characteristics. ■

Low Power IQ Modulator for Digital Communications

Bruce Hemp and Sunny Hsiao

IQ modulators are versatile building blocks for RF systems. The most common application is generating RF signals for digital communication systems. This article illustrates the modulation accuracy of the LTC5599 low power IQ modulator, and shows by simple example how to integrate the device into a digital communication system.

Figure 1. Test setup to measure basic modulation accuracy



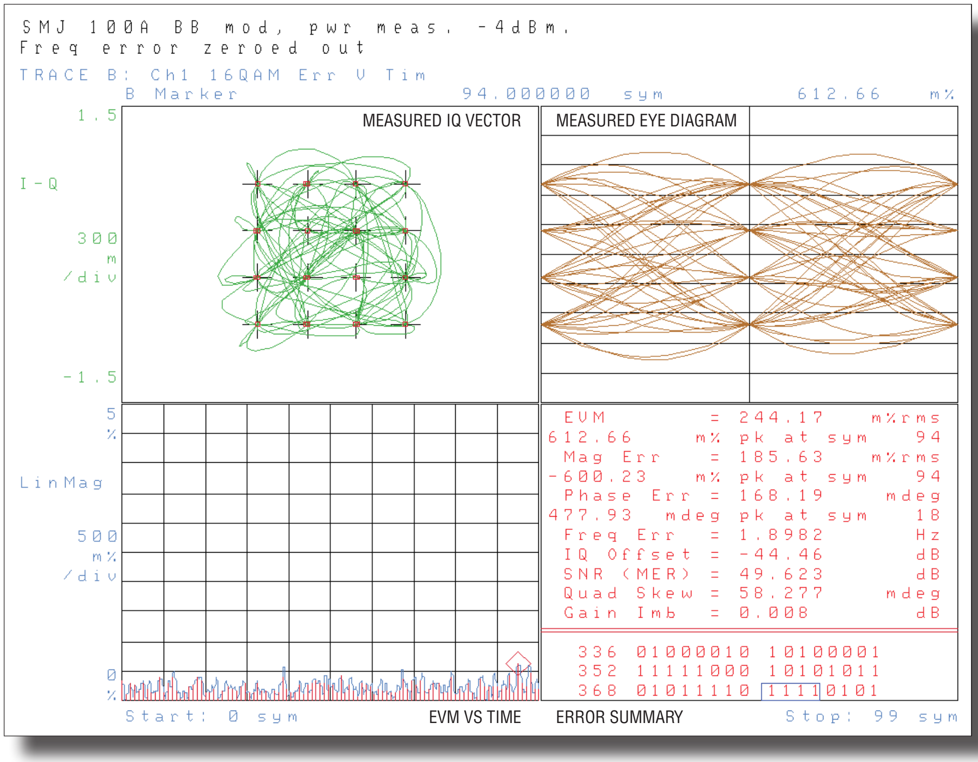
MODULATOR APPLICATIONS

Virtually any type of RF modulation can be generated with IQ modulation, within the center frequency, bandwidth and accuracy capabilities of the modulator device. Table 1 shows some of the applications of the LTC5599.

Table 1. Some possible applications for the LTC5599 low power IQ modulator.

APPLICATION	MOD STD	MODULATION TYPE (REFERENCE 1)	MAX RF BW
Digital wireless microphones	Proprietary	QPSK, 16/32/64-DAPSK, Star-QAM	200kHz
Wireless networking • White-space radios • Cognitive radio	802.11af	OFDM: BPSK, QPSK, 16/64/256-QAM	Up to 4× 6MHz channels
CATV upstream	DOCSIS	16-QAM	6MHz
Military radios (portable, manpack)	Custom	Wide programmability range	—
Software defined radios (SDR)			
Portable test equipment			
Analog modulation	—	AM, FM/PM, SSB, DSB-SC	—
2-way radios • Commercial • Industrial • Public safety	TETRA	π/4-DQPSK, π/8-D8PSK, 4/16/64-QAM	25kHz to 150kHz
	TETRAPOL	GMSK	10kHz, 12.5kHz
	P-25	C4FM, CQPSK	6.25kHz to 12.5kHz
	DMR	4FSK	6.25kHz, 12.5kHz

Figure 2. LTC5599 EVM measured using lab-grade baseband and LO signal generators. Note that the MER measures over 49dB, basically “Broadcast Quality.”



TEST CIRCUIT SHOWN IN FIGURE 1
DUT: LTC5599
REGISTERS[0…8] = [0X31, 84, 80, 80, 80, 10, 50, 06, 00]
FREQUENCY SET TO 450MHz; OTHERWISE ALL DEFAULTS
VSA: AGILENT 89441A, ANALYSIS SPAN = 100kHz
MEASURING FILTER: ROOT COSINE ALPHA 0.35
REFERENCE FILTER: RAISED COSINE

MODULATION ACCURACY AND EVM

The error vector magnitude or EVM is a measure of modulation accuracy in digital radio communication systems. Modulation accuracy is important because any error on the modulated signal can cause reception difficulty or excessive occupied bandwidth. If left unchecked, the receiver could exhibit excessive bit errors, the effective receiver sensitivity could be degraded or the transmit adjacent channel power (ACP) can become elevated.

An error vector is a vector in the I-Q plane between the actual received or transmitted symbol and the ideal reference symbol. EVM is the ratio of the average of the error vector power over the average ideal reference symbol vector power. It is frequently expressed in either dB or percentage.

Figure 1 is a test setup example showing the modulation accuracy attainable with the LTC5599 low power direct quadrature modulator. Figure 2 shows the results. In this test, precision lab equipment generates a 30k symbol/second 16-QAM baseband (120kbps), and 450MHz LO input signal to the modulator. A vector signal analyzer (VSA) examines the modulator output.

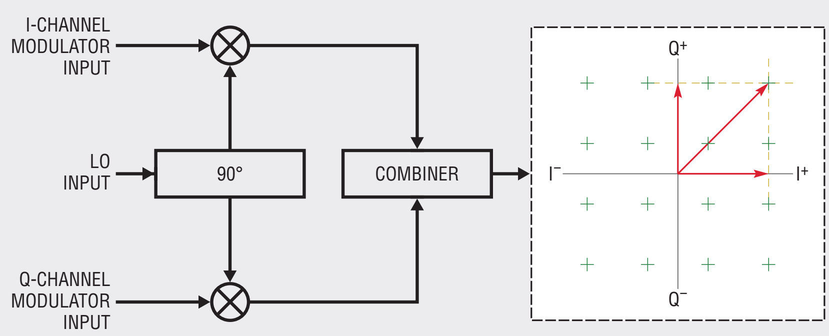
In Figure 2, the EVM vs time results show EVM uniformly low across all symbols, while the error summary shows EVM approximately 0.24% RMS, and 0.6% peak. This is indeed excellent performance, shown by a modulation error ratio (MER) of 49.6dB.

The LTC5599 has internal trim registers that facilitate fine adjustments of I and

What’s an IQ Modulator?

An IQ modulator is a device that converts baseband information into RF signals. Internally, two double-balanced mixers are combined as shown below. By modulating with both in-phase (I) and quadrature (Q) inputs, any arbitrary output amplitude and phase can be selected.

By targeting specific points in amplitude and phase, high order modulation is created. Shown below is 16-QAM. There are four possible I values, which decodes into two bits. Likewise for the Q axis. So each symbol can convey four bits of information.

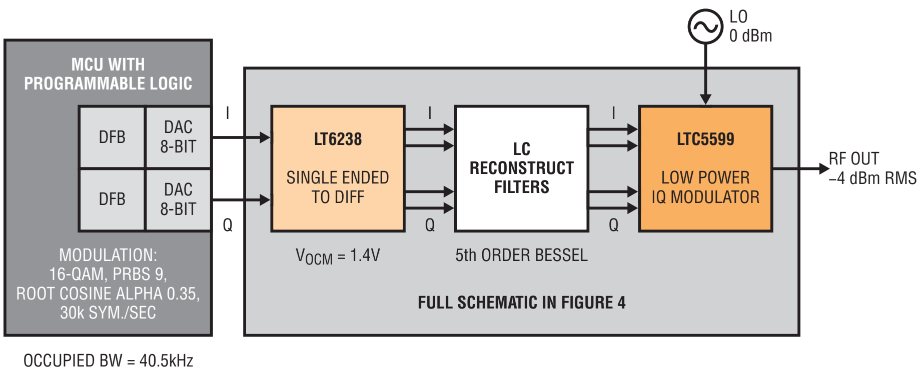


Fundamental architecture of an IQ modulator

Q DC offset, amplitude imbalance, and quadrature phase imbalance to further optimize modulation accuracy—results are even better if trim registers are adjusted.

In many ways, this test demonstrates the *best-case* capabilities of the modulator without optimization: baseband bandwidth is large, DAC accuracy and resolution are superb and digital filtering is nearly ideal.[1] While these test results are useful for measuring the true performance of the modulator, practical low power wireless implementations necessitate some compromises, as discussed below.

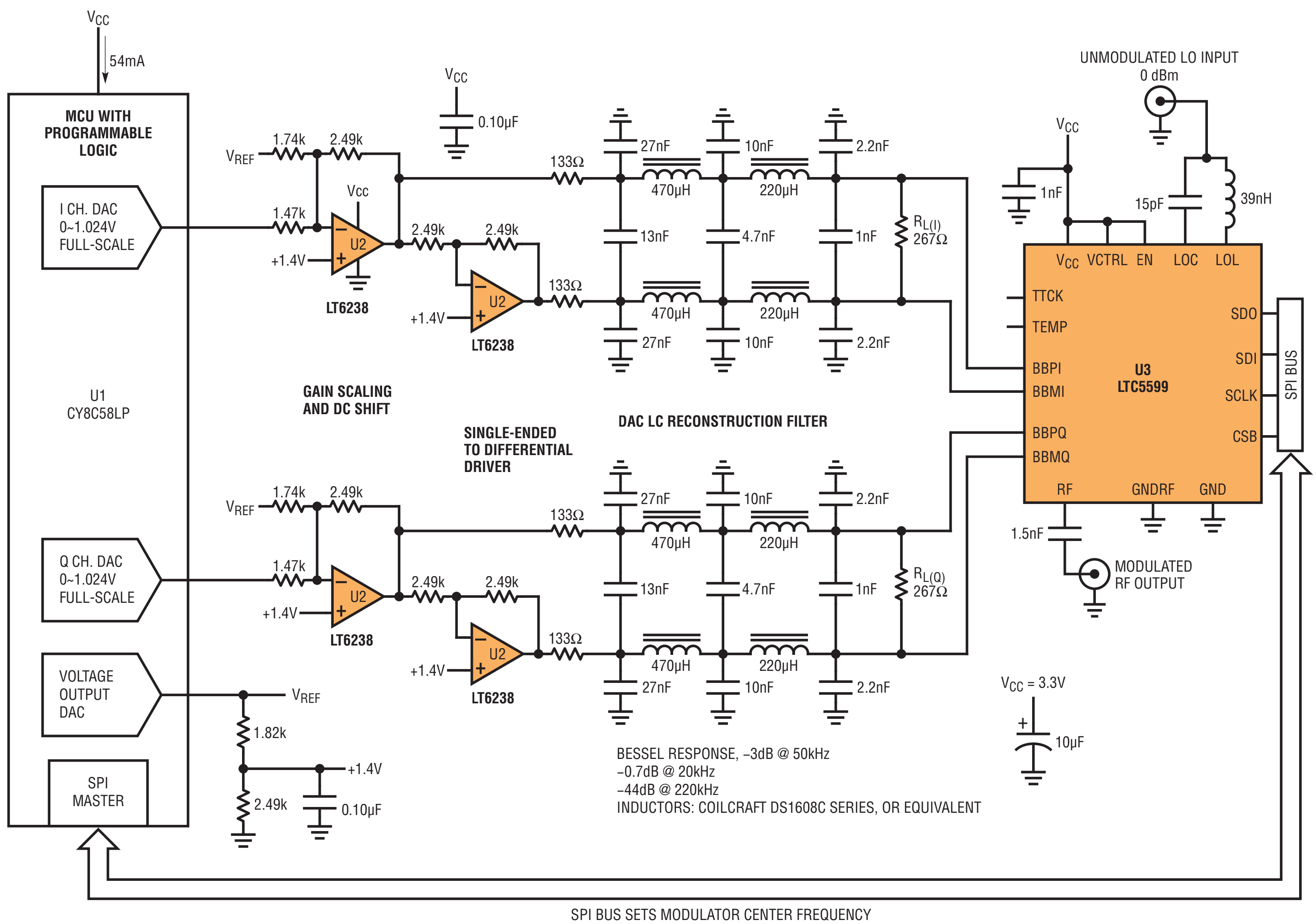
Figure 3. Transmit exciter block diagram. (Full schematic is in Figure 4.)



DRIVING FROM PROGRAMMABLE LOGIC OR AN FPGA

Many FPGAs and programmable devices support digital filter block (DFB) functionality, an essential building block for digital communications. Raw transmit data is readily IQ mapped and digitally filtered. Figure 3 shows an example of how a device such as the Cypress PSoC 5LP can be utilized to drive IQ modulators such as the LTC5599.

Figure 4. Driving an IQ modulator with programmable logic and DACs. The passive Bessel filter attenuates DAC images and provides lowest RF output noise floor, while imposing negligible symbol error vector.



Digital interpolation is used to increase the DAC clock frequency, and hence the DAC image frequencies. This lowers the filter order requirement of the LC reconstruct filter, which serves to attenuate DAC images to acceptable levels, while minimizing phase error and wideband noise.

Figure 4 shows the complete circuit. The differential baseband drive to the modulator, as opposed to single-ended baseband drive, offers the highest RF output power and lowest EVM. The LTC6238 low noise amplifier, U2, converts the DAC single-ended I and Q outputs to differential.[2] Input amplifier U2 gain is designed to scale the DAC out voltage range to the modulator input voltage range, after the 2:1 attenuation effect of filter terminating resistors $R_{L(I)}$ and $R_{L(Q)}$ is taken into account. The input amplifier U2 is also designed to supply the required input common mode voltage for the IQ modulator—important for maintaining proper modulator DC operating point and linearity.

Classical LC filter synthesis methods are used for the DAC reconstruction lowpass filter (LPF) design. Some of the filter shunt capacitance is implemented as common mode capacitors to ground. This also reduces common mode noise, which can find its way to the modulator output. If active filters are used here, the final filter stage before the modulator should be a passive LC roofing filter for lowest broadband RF noise floor.

Table 2, Figure 5 and Figure 6 show the performance results. In this case, EVM is limited by the digital accuracy of the baseband waveforms, here determined by the number of U1 FIR filter taps (63), and by the DAC resolution (eight bits). For this reason, EVM does not substantially improve when IQ modulator impairments are adjusted out, as shown in Table 2. For lower EVM, use more FIR filter taps and higher resolution DACs.

When comparing the results shown in Figures 2 and 5, we see the price paid for replacing a high grade lab signal generator with a circuit composed of programmable logic and op amp filters. EVM increased from 0.24% RMS to 0.8% RMS. The increased EVM is primarily due to the fact that the waveforms generated by the programmable logic IC are not as accurate as the lab instrument. Such is the case in a real world implementation, but Figure 5 shows a fairly decent eye diagram, and a summary measurement that shows the modulation accuracy is sufficient for most applications.

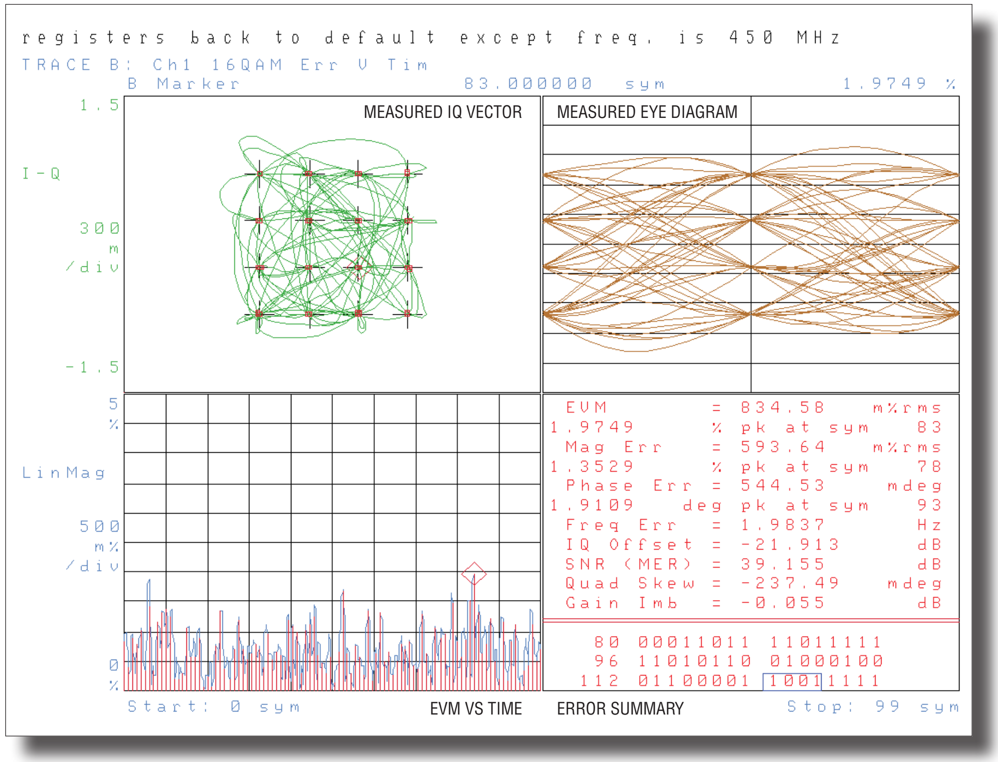


Figure 5. EVM measurement detail. Two IC devices replace the lab signal generator. It's not perfect, but is usually 'good enough.'

In Figure 6 we see the output spectrum is quite clean. The amplitude of the DAC image spurs, relative to the desired signal, is estimated by sin(x)/x, where $x = \pi f/f_{CLK}$, plus attenuation afforded by the DAC LC reconstruct filter. For lowest adjacent channel power, a long FIR filter (many taps) is essential, as is a low phase noise LO.

Table 2. EVM performance. Even with a 63-tap FIR filter design and 8-bit dual-DACs, the 0.8% RMS EVM achievement is entirely adequate for most applications.

TX FIR FILTER DESIGN	INTERPOLATION FACTOR	SYMBOL RATE (ksps)	DATA RATE (kbps)	EVM (% RMS)	EVM (% PEAK)	NOTES
63-tap RRC, α = 0.35	8	30	120	0.8	2.0	LTC5599 Unadjusted (MER = 39.1dB)
				0.8	1.8	LTC5599 Adjusted (MER = 39.8dB)

Linear Technology's LTC5599 IQ modulator is a versatile RF building block, offering low power consumption, high performance, wide frequency range and unique optimization capabilities. It simplifies radio transmitter design without sacrificing performance or efficiency.

Figure 6. Output spectrum. In this design, the closest image spurs are about 70dB down, reasonably good for most systems. Modulator RMS output power measures –4dBm. Harmonic filtering is still required.

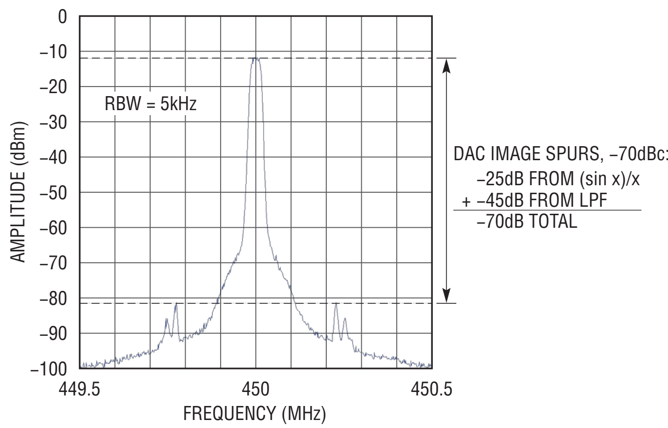


Table 3. Output noise density levels off at approximately 17dB over kTB.

FREQUENCY OFFSET (MHz)	RF OUTPUT NOISE DENSITY (dBM/Hz)
+6	–156.7
+10	–156.8
+20	–156.8

Higher frequency span sweeps show no visible spurious products except for the harmonics of the carrier, which must be filtered as usual.

Low output noise floor is also important in many cases, such as when a transmitter and receiver are duplexed or co-located, when high PA gain is used, or when multiple transmitters run simultaneously. Table 3 shows the measured output noise density for the system of Figure 3, while transmitting at a modulated carrier frequency of 460MHz. The low U2 op amp noise, combined with the 5th order roll-off of the LC reconstruct filter, keeps the baseband noise contribution as low as possible.

Total current consumption at 3.3V measures 96mA, as summarized in Table 4. The majority of the DC power is consumed by U1, the programmable logic device, for which each DFB is specified to typically consume 21.8mA at the 67MHz clock frequency of this application.[3] In summary, the DFBs account for 81% of the digital power consumption. Clearly the key to reduced current consumption for the digital section is optimization of the DFB architecture, which is beyond the scope of this article.[4]

Table 4. Total power consumption

STAGE	DESCRIPTION	ICC (mA)	POWER (mW)
U1	CY8C58LP Programmable System on Chip	54	178
U2	LT6238 Quad Op Amp	13	43
U3	LTC5599 Low Power IQ Modulator	29	96
	Total:	96	317

CONCLUSION

Linear Technology's LTC5599 IQ modulator is a versatile RF building block, offering low power consumption, high performance, wide frequency range and unique optimization capabilities. It simplifies radio transmitter design without sacrificing performance or efficiency. ■

Notes

1 Test equipment FIR filters are synthesized in software, so hundreds or thousands of filter taps are feasible and preferred, since signal quality is most important, and delay is inconsequential. In contrast, a real-time wireless application typically requires trade-offs between filter delay and EVM/ACP.

2 For lower symbol rate applications, the LTC1992 low power fully differential input/output amplifier/driver could also be used for this purpose, offering improved DC accuracy and lower DC power consumption in exchange for a higher transmit noise floor within the channel passband.

3 In this example, the minimum DFB clock frequency = 30kHz symbol rate • 8x interpolation • 63 FIR filter taps • 2 cycles for multiply and accumulate (MAC) • 2 cycles for arithmetic logic (ALU) = 60.5MHz.

4 DFBs that are faster and more highly optimized are available from Altera and Xilinx.

References

1 "Digital Modulation in Communications Systems – An Introduction," Application Note 1298, Keysight Technologies

Low Profile Supercapacitor Power Backup with Input Current Limiting

David Salerno

Supercapacitors are increasingly used as backup power sources, due in large part to their continually improving volumetric energy capacity and robust nature. Large output capacitors can strain the load capabilities of an input source, especially when that source is limited by protocol (USB or PCMCIA) or a high source resistance. Input source limitations can complicate designs. The LTC3128 simplifies power backup by adding a programmable accurate input current limit to a complete supercapacitor charger. Figure 1 shows that only a few components are needed to produce a supercapacitor charger with a 3.0A input current limit.

The LTC3128 is a buck-boost DC/DC supercapacitor charger with programmable accurate input current limit (up to 3A) and active balancing, offered in 4mm × 5mm × 0.75mm QFN or 24-lead TSSOP packages. The 1.2MHz switching frequency, along with low resistance, low gate charge integrated switches provide an efficient, compact and low profile solution for charging large output capacitors. The high accuracy (±2%) of the programmable input current limit allows designers to limit the maximum current draw to just below the capability of the input source.

Capacitor voltage monitoring and protection, combined with the integrated active charge balancer, prevents mismatched capacitors from being overvoltaged and keeps capacitors with mismatched leakages in balance. This makes the LTC3128 ideal for backup or pulsed load applications. Supercapacitors, because of their long lifetime, large cycle capability (up to 10 years and 500,000 cycles) and relatively straightforward charging profiles, are ideal for backup solutions.

SUPERCAPACITOR CHARGE TIME AND HOLDUP TIME

When designing a backup system, two of the most important criteria are charge time and holdup time. The charge time determines the minimum amount of time the system needs to be in operation before it can withstand a power failure, and holdup time determines how long a system can maintain operation from its backup source.

Charge time is determined by a combination of programmed input current limit, programmed output voltage, converter efficiency and output capacitance. Figure 2 shows the charge time for a 1F output capacitance at a programmed input current of 3.0A. This curve takes into account V_{IN}, V_{OUT} and the converter efficiency. If the output capacitance is larger or smaller than 1F, the charge time scales proportionally to the output capacitance.

At the end of charging, the LTC3128 dials back the input current to top off the

Figure 1. Complete supercapacitor charging circuit with input current limit

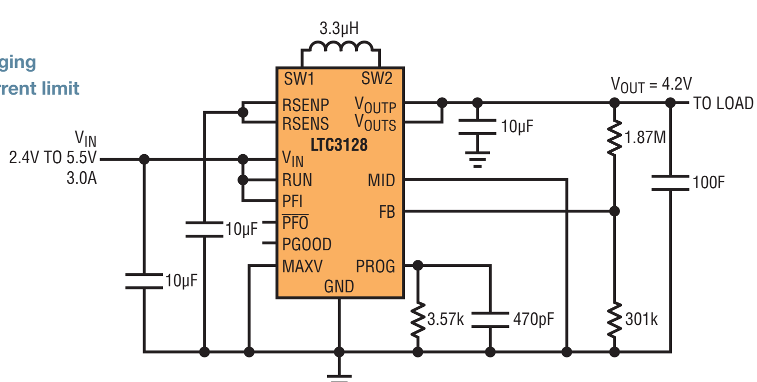
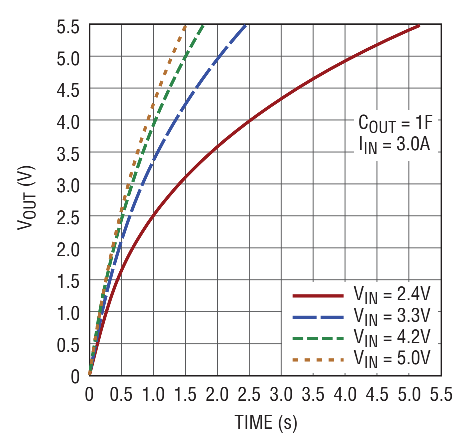


Figure 2. LTC3128 charge time



The active charge balancer uses the inductor of the LTC3128 to efficiently move charge from one capacitor to another to balance them, maintaining the same voltage across each capacitor. Active charge balancing eliminates the high quiescent current and continuous power dissipation of passive balancing.

charge on the output capacitor stack. This is done to prevent chattering in and out of regulation due to the ESR of the output capacitors. Figure 3 shows an example of the charge current being dialed back as the capacitor approaches full charge. The current is typically dialed back at 95% of programmed output voltage, and this is the voltage that should be used for the charge time calculation.

The circuit of Figure 1 charges 100F to 4.2V with a programmed input current of 3.0A and a V_{IN} of 3.3V. Figure 2 shows that it takes 1.3 seconds to charge a 1.0F capacitor to 4.0V (4.0V ≈ 0.95 • 4.2V) from 0V. Since the capacitor in this example is one hundred times larger, it will take roughly 130 seconds to charge a 100F capacitor to 4.0V from 0V.

To determine how long backup power can be provided to the system, the operational voltage range on the output needs to be determined. For this application, the operational output voltage is 4.2V down to 1.0V. The stored energy on the 100F capacitor can be determined as:

$$W = \frac{1}{2}C_{OUT}\left(V_{INITIAL}\right)^2 - \frac{1}{2}C_{OUT}\left(V_{FINAL}\right)^2$$
$$= \frac{1}{2}100 \bullet 4.2^2 - \frac{1}{2}100 \bullet 1.0^2 = 832J$$

where W is the work done in joules, C_{OUT} is the total output capacitance, $V_{INITIAL}$ is the beginning voltage on C_{OUT}, and V_{FINAL} is the minimum voltage C_{OUT} can run down to.

If a secondary boost converter is connected to V_{OUT}, it acts as a constant power draw from the supercapacitor. Figure 4 shows an example of a secondary boost converter being powered by V_{OUT} of the LTC3128. The LTC3122 data sheet shows that for a 12V output with a 100mA load, the average converter efficiency across a 1V to 4.2V input is approximately 80%, resulting in a 1.5W constant power load on the holdup capacitor. The holdup time can be determined by:

$$t_{BACKUP} = \frac{W_{STORED}}{P_{LOAD}} = \frac{832J}{1.5W} = 554.66s$$

where t_{BACKUP} is the holdup time of the system, W_{STORED} is the available stored energy on the output

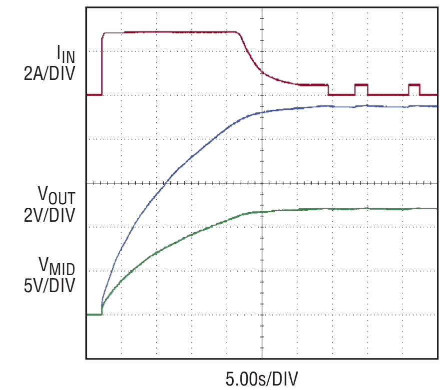


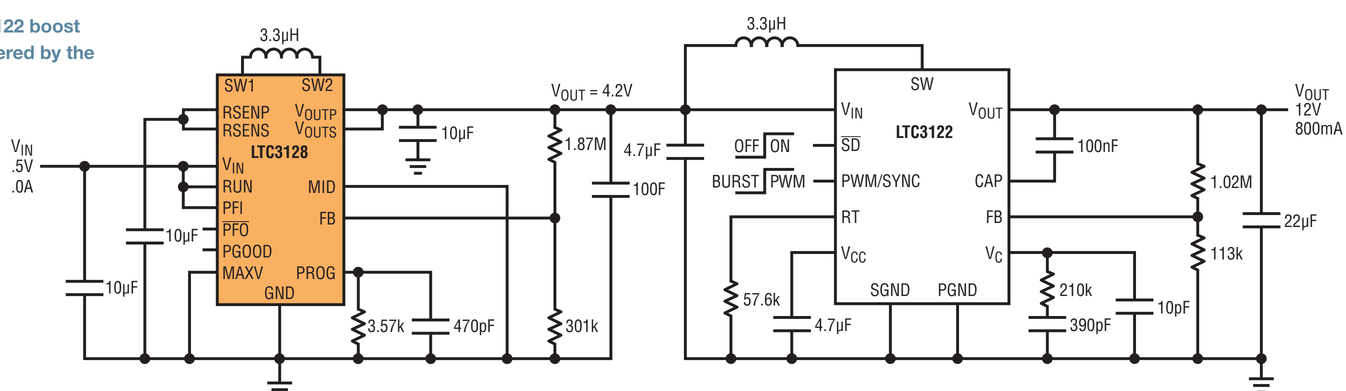
Figure 3. Input current charging profile

capacitor, and P_{LOAD} is the power draw from the secondary converter.

BALANCING SUPERCAPACITORS

Achieving higher output voltages with supercapacitors requires putting two or more cells in series with each other because the maximum voltage for each capacitor is typically specified between 2.3V and 2.7V, depending on the manufacturer and type of capacitor. The life of the capacitor is dependent on the voltage across the capacitor. To extend capacitor lifetime the voltage on the capacitor should be regulated below the rated

Figure 4. LTC3122 boost converter powered by the LTC3128



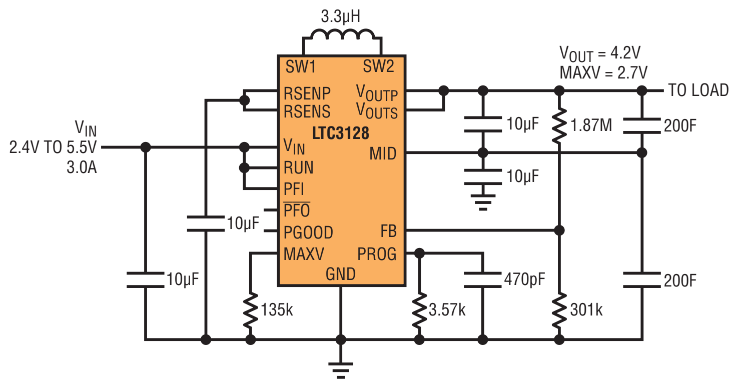


Figure 5. LTC3128 with charge balancer and maximum capacitor voltage protection

maximum voltage. Capacitor vendors typically specify how to derate the voltage on their supercapacitors to extend life.

The LTC3128 integrates a programmable maximum capacitor voltage comparator and an efficient active charge balancer. The maximum capacitor voltage comparators look at the voltage across each individual capacitor and ensure that the programmed voltage is not exceeded while charging. If the maximum programmed capacitor voltage is reached on either capacitor, the LTC3128 halts charging to balance the cells and then resumes charging.

The active charge balancer uses the inductor of the LTC3128 to efficiently move charge from one capacitor to another to balance them, so that the capacitors maintain the same voltage across them. This is important because during a holdup event, if the capacitors are far enough out of balance, the polarity of one of the cells could become reversed, damaging the capacitor. The LTC3128 will only balance the cells if one of the cells has violated its programmed maximum capacitor voltage, or if the output voltage is in regulation and the capacitors are out of balance but the maximum voltage has not been violated.

Active charge balancing eliminates the high quiescent current and continuous power dissipation of passive balancing. Figure 5 shows the LTC3128 configured with 100F of total output capacitance, a programmed output voltage of 4.2V, and a maximum capacitor voltage of 2.7V, each.

POWER RIDE-THROUGH APPLICATION

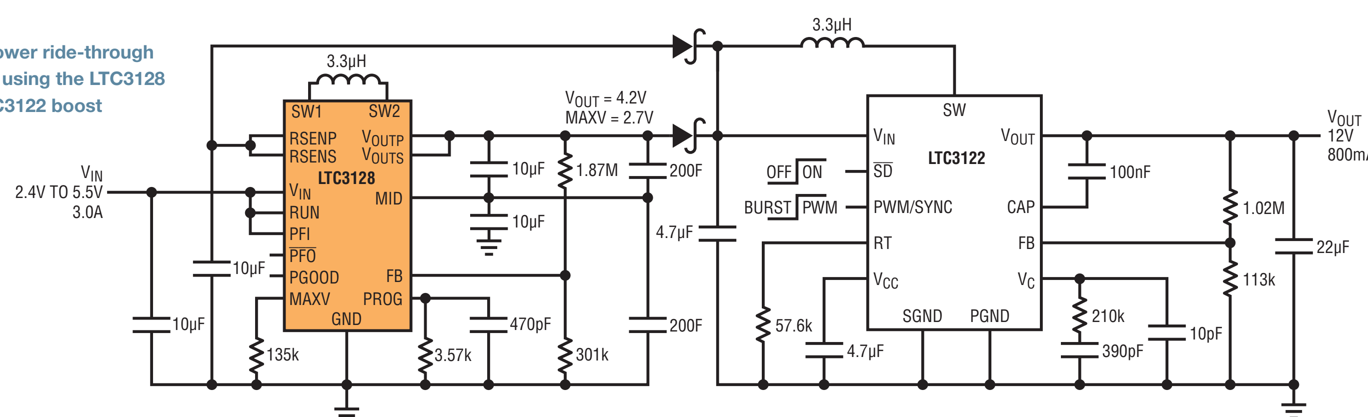
In a backup system, the ability to wait for the storage capacitors to charge before you begin operating is not always an option. A power ride-through application provides a means to power the secondary converter directly from the input supply while simultaneously charging the supercapacitors. The LTC3128 allows the secondary converter to pull its current through a current sense resistor internal to the LTC3128. This allows the secondary converter to draw the required current from the supply, up to 4A, and the LTC3128 will charge the output capacitors with the programmed input current, less the current drawn from the secondary converter. As long as the secondary converter never draws more than the programmed input current, the LTC3128 limits the total current draw from the input supply to the programmed value, while charging the backup capacitors with the remaining available current.

To extend backup time, the LTC3128 draws less than 1μA from V_{OUT} when in shutdown, or less than 2μA when in input UVLO. Figure 6 shows a power ride-through application using the LTC3128 and LTC3122.

CONCLUSION

The LTC3128 3A buck-boost DC/DC supercapacitor charger is a streamlined solution for efficiently charging and protecting supercapacitors in high reliability, long-life applications. It features a ±2% accurate programmable input current limit, programmable maximum capacitor voltage comparators and active charge balancing. ■

Figure 6. Power ride-through application using the LTC3128 and the LTC3122 boost converter



What's New with LTspice IV?

Gabino Alonso

twitter—Follow @LTspice at *www.twitter.com/LTspice*
f—Like us at *facebook.com/LTspice*

BLOG BY ENGINEERS, FOR ENGINEERS

Check out the LTspice® blog (www.linear.com/solutions/LTspice) for tech news, insider tips and interesting points of view.

New Article: "Achieving Low On-Resistance with Guaranteed SOA in High Current Hot Swap Applications" by Dan Eddleman
www.linear.com/solutions/5722

The requirement for live insertion and removal in high current backplane applications demands MOSFETs that exhibit both low on-resistance during steady state operation and high safe operating area (SOA) for transient conditions. Often, modern MOSFETs optimized for low on-resistance are unsuitable for high SOA hot swap applications. This article overviews an application that provides the best of both worlds by utilizing the LTC4234 to satisfy SOA requirements and an external low on-resistance MOSFET reduces the overall power dissipation.

SELECTED DEMO CIRCUITS

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

Buck Regulators

- **LT3697:** 5V step-down converter with cable drop compensation & output current limit (8V–35V to 5V at 6A) www.linear.com/solutions/5476
- **LT8613:** 5V step-down converter with 6A output current limit (5.8V–42V to 5V at 6A) www.linear.com/solutions/5751
- **LT8616:** 5V, 3.3V, 2MHz step-down converter (5.8V–42V to 5V at 1.5A & 3.3V at 2.5A) www.linear.com/solutions/5753
- **LT8640:** 2MHz µPower ultralow EMI buck converter (5.7V–42V to 5V at 5A) www.linear.com/solutions/5635

Buck-Boost Controllers

- **LT8709:** Negative buck-boost regulator with output current monitor and power good (–4.5V to –38V input to –12V output at 5A) www.linear.com/solutions/5719

SEPIC Converter

- **LT8494:** 450kHz, 5V output SEPIC converter (3V–60V to 5V at 1A) www.linear.com/solutions/5848

Isolated Regulator

- **LTM®8057:** 2kV AC isolated low noise µModule regulator (3.1V–29V to 5V at 300mA) www.linear.com/solutions/5206

LED Driver

- **LT3952:** Short-circuit robust boost LED driver (7V–42V to 50V LED string at 333mA) www.linear.com/solutions/5749

SELECT MODELS

To search the LTspice library for a particular device model, choose Component from the Edit menu or 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. The changelog.txt file (see root installation directory) list provides a revision history of changes made to the program.

Linear Regulators

- **LT3042:** 20V, 200mA, ultralow noise, ultrahigh PSRR RF linear regulator www.linear.com/LT3042
- **LT3088:** 800mA single resistor rugged linear regulator www.linear.com/product/LT3088

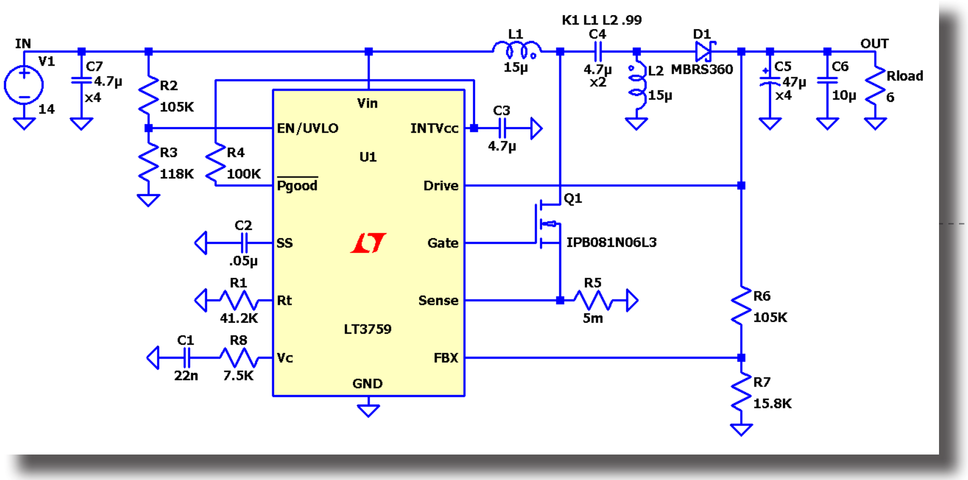
Buck Regulators

- **LT8602:** 42V quad monolithic synchronous step-down regulator www.linear.com/LT8602
- **LTC3887:** Dual output PolyPhase® step-down DC/DC controller with digital power system management www.linear.com/LTC3887
- **LTC7138:** High efficiency, 140V 400mA step-down regulator www.linear.comt/LTC7138
- **LTM4622:** Dual ultrathin 2.5A step-down DC/DC µModule regulator www.linear.com/LTM4622

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.



Be sure to check for recently added demonstration circuit simulations, such as this wide input voltage range boost/SEPIC/inverting controller: 2.5V to 36V input, 12V/2A output SEPIC converter (automotive 12V regulator).

- **LTM4675:** Dual 9A or single 18A µModule regulator with digital power system management www.linear.com/LTM4675
- **LTM4676A:** Dual 13A or single 26A µModule regulator with digital power system management www.linear.com/LTM4676A

Multitopology Controller

- **LT8570:** Boost/SEPIC/inverting DC/DC converter with 65V switch, soft-start and synchronization www.linear.com/LT8570

Surge Stopper

- **LTC7860:** High efficiency switching surge stopper www.linear.com/LTC7860

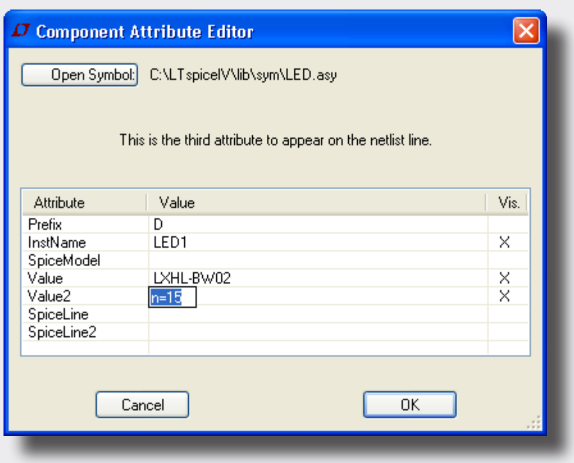
Wake-Up Timer

- **LTC2956:** Wake-up timer with pushbutton control www.linear.com/LTC2956 ■

Power User Tip

TIGHTEN UP YOUR SCHEMATICS: COMBINE MULTIPLE MODEL INSTANCES INTO ONE SYMBOL

When you need multiple instances of a model, it is easy to copy and paste a symbol, but sometimes you can tighten up your schematics by using a single symbol to define multiple instances of same device. For instance, instead of placing four identical capacitor symbols in parallel, use one symbol times four, “x4”. This feat can be accomplished using the M (parallel units) or N (series units) parameters.



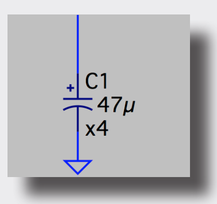
A number of intrinsic devices support the M (parallel units) parameter, such as the capacitor, inductor, diode and MOSFET models. If you are not sure if the model supports the M (parallel units) parameter, try it, and if you do not get an error message, you should be good. The diode (including LED) model is the only intrinsic model that supports N (series units) parameter.

To define multiple instances of a model in a device symbol:

1. Ctrl + right-click the symbol to edit the component attributes.
2. Insert “m=<number>” or “n=<number>” into the Value2 field. Note that non-integer <number> values are allowed.
3. Make the multiple instances visible in your schematic by selecting the Value2 attribute and clicking the Vis column.

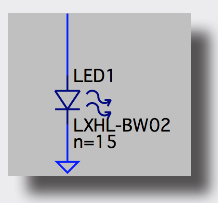
Parallel Capacitors

To match certain electrical schematic standards you can define parallel capacitors either using “m=<number>” or “x<number>” syntax as in “x4”.



Series (String) of LEDs

Diodes are the only intrinsic models that support the N (series units) parameter.



Happy simulations!

Boost 12V to 140V with a Single Converter IC

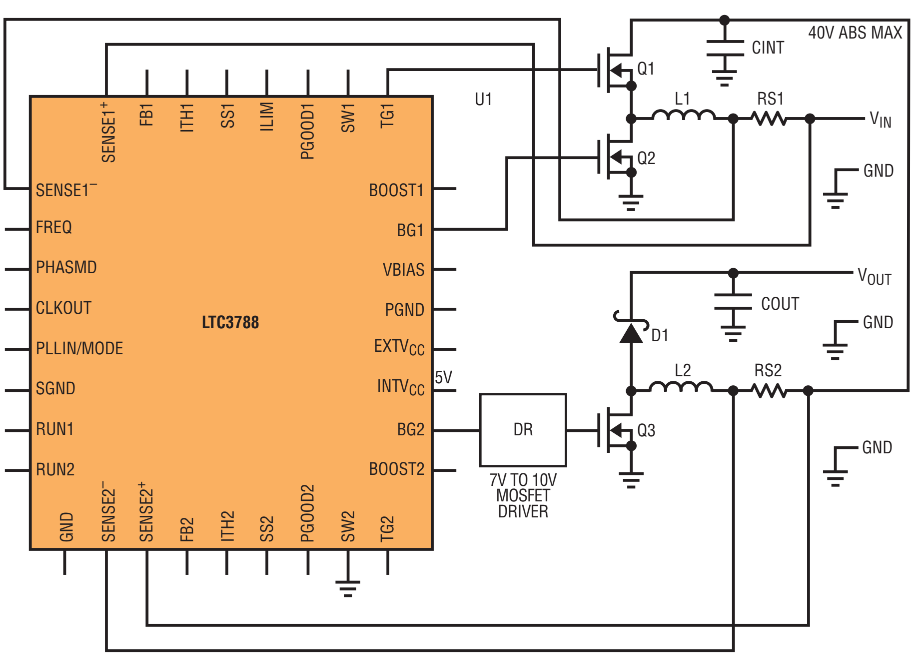
Victor Khasiev

Generating a high voltage from a much lower voltage presents a number of challenges for the classical single stage boost topology. For instance, the maximum duty cycle limitation of a boost controller may not allow the required step-up ratio. Even if it does, there is often a sharp decrease in efficiency at high duty cycles. The duty cycle can be shortened by choosing discontinuous mode of operation, but this leads to high peak input current, higher losses and EMI challenges.

An alternative to a single boost converter is a 2-stage boost converter, where the first stage produces an intermediate voltage and the second stage boosts to the final high voltage. A 2-stage converter can be produced with a single controller IC, such as the LTC3788, a high performance 2-phase dual output synchronous boost controller, which drives all N-channel power MOSFETs.

The LTC3788 can be configured such that the first boost stage takes advantage of its synchronous rectification feature, which maximizes efficiency, reduces power losses and eases thermal requirements. The maximum output voltage of this controller is 60V, when using synchronous rectification. If greater than 60V is required, the second stage can be designed to run non-synchronously, as described below.

Figure 1. Block diagram of LTC3788-based 2-stage boost converter



2-STAGE BOOST PRODUCES 140V FROM 12V

The block diagram in Figure 1 shows the LTC3788 in a 2-stage boost configuration. This block diagram also reveals a few caveats that must be observed in this design:

- The output of the first stage (Q1, CINT) is connected to the input of second stage (RS2, L2). The output of the first stage should not exceed 40V, because the maximum absolute rating of the SENSE pins is 40V.
- The gate drive voltage of 5V is suitable for logic level MOSFETs, but not for high voltage standard MOSFETs, with typical gate voltages of 7V to 12V. The external gate driver DR, controlled by the BG2 signal can be used as shown here to drive high voltage standard MOSFETs.
- To generate an output voltage above maximum limit of 60V, the synchronous rectification MOSFET is replaced by a single diode D1.

Figure 2 shows the complete solution. Transistors Q1, Q2 and inductor L1 compose the first stage, which generates an intermediate bus voltage of 38V. The first stage employs synchronous rectification for maximum efficiency. The output of the first stage is connected as input to the second stage, comprised

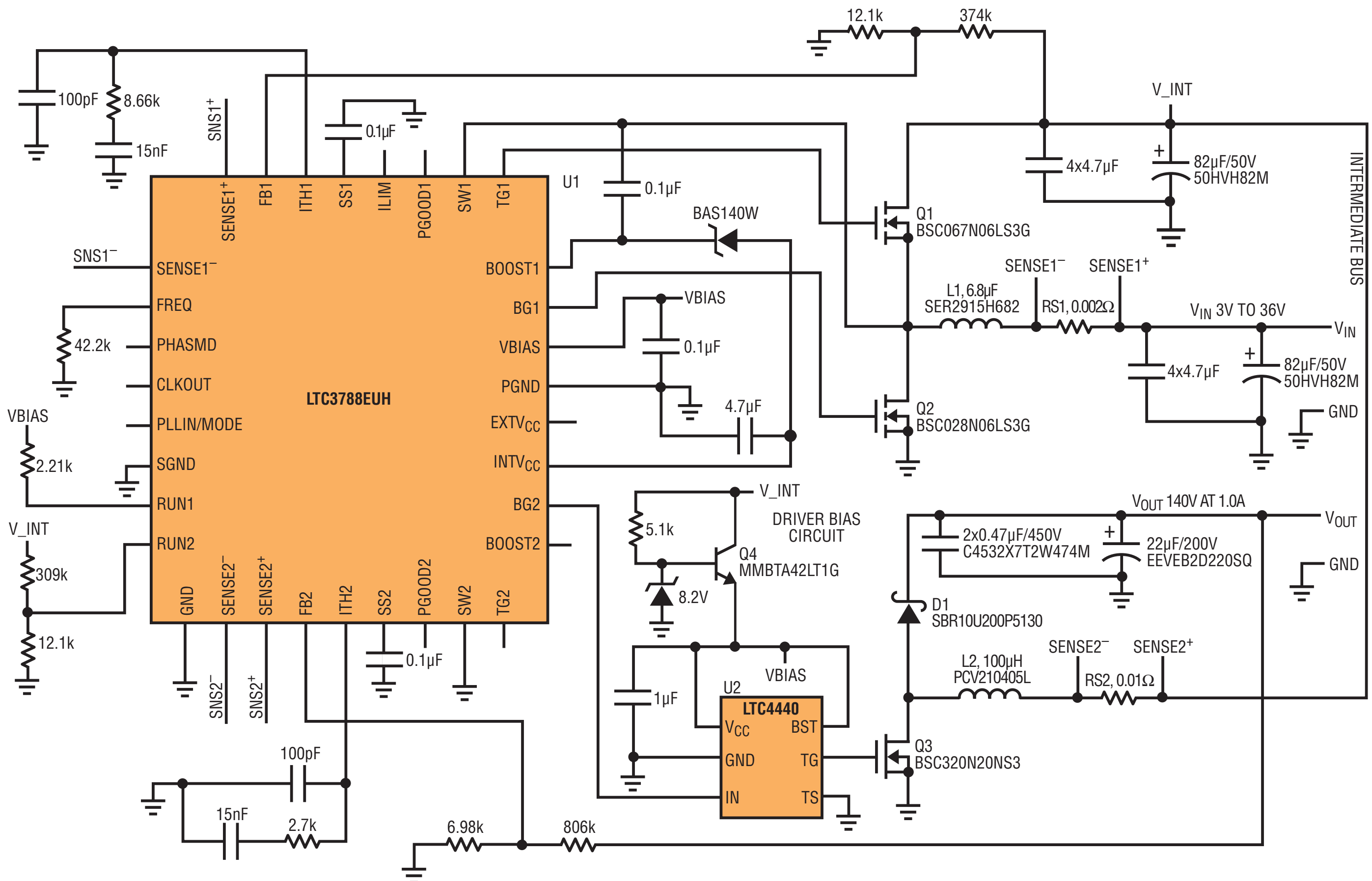


Figure 2. Full schematic of 2-stage 140V output, 1A boost converter

of Q3, D1, L2. The output of the second stage produces 140V at 1A.

Transistor Q3 is a standard level MOSFET, driven by the LTC4440. Here, an LDO, based on transistor Q4, biases the gate driver, but a switching regulator can be employed instead (such as one built around the LTC3536) to further increase overall efficiency.

This solution features an input voltage range from 3V to 36V, nominal 12V. To decrease components' thermal stress, the output current should be reduced when the input voltages fall below 10V. Figure 3 shows measured efficiency, and Figure 4 shows the start-up waveforms. A 93% efficiency is shown with V_{IN} = 24V and with the 140V output loaded from 0.4A to 1A. This converter can operate at full load with no airflow.

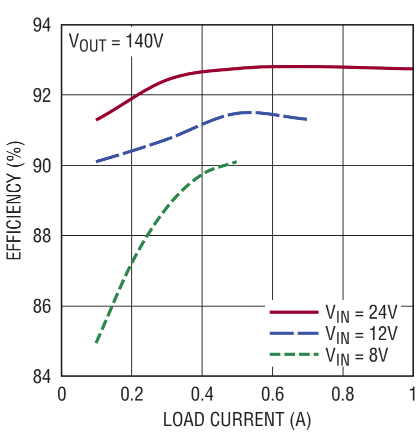


Figure 3. Efficiency of the 2-stage converter in Figure 2

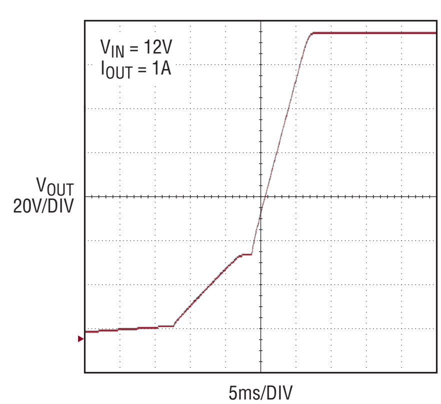


Figure 4. Start-up waveforms

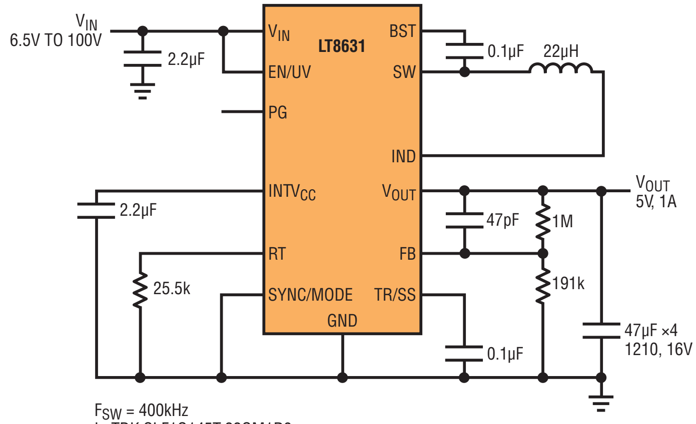
CONCLUSION

LTC3788 is a high performance 2-phase dual output synchronous boost controller, suitable for high power, high voltage applications. Its dual outputs can be used in tandem to achieve extremely high step-up ratios to high voltages. ■

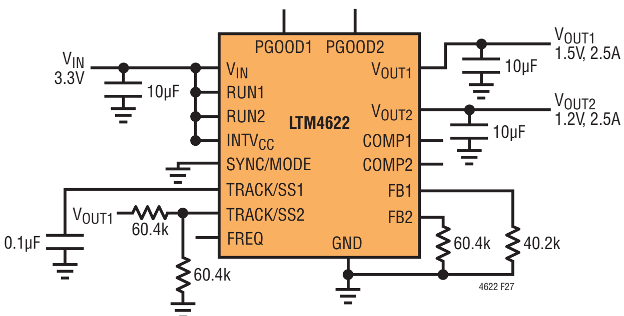
100V INPUT, 5V OUTPUT, LOW RIPPLE 1A STEP-DOWN CONVERTER

The LT8631 is a current mode PWM step-down DC/DC converter with internal synchronous switches that provides current for output loads up to 1A. The wide input range of 3V to 100V makes the LT8631 suitable for regulating power from a wide variety of sources, including automotive and industrial systems and 36V to 72V telecom supplies. Low ripple Burst Mode® operation enables high efficiency operation down to very low output currents while keeping the output ripple below 10mV$_{P-P}$. Resistor programmable 100kHz to 1MHz frequency range and synchronization capability enable optimization between efficiency and external component size. The soft-start feature controls the ramp rate of the output voltage, eliminating input current surge during start-up, while also providing output tracking. A power good flag signals when the output voltage is within ±7.5% of the regulated output. Undervoltage lockout can be programmed using the EN/UV pin. Shutdown mode reduces the total quiescent current to < 5µA. The LT8631 is available in a 20-lead TSSOP package with exposed pad for low thermal resistance and high voltage lead spacing.

www.linear.com/solutions/5855



F_{SW} = 400kHz
L: TDK SLF10145T-220M1R9



ULTRATHIN µModule 3.3V INPUT, 1.5V AND 1.2V OUTPUTS AT 2.5A DESIGN WITH OUTPUT COINCIDENT TRACKING

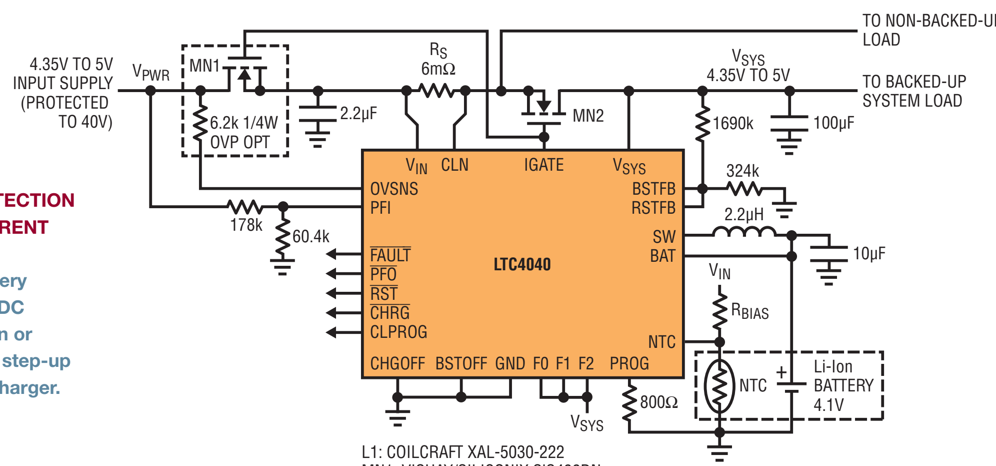
The LTM4622 is a complete dual 2.5A step-down switching mode µModule® (micromodule) regulator in a tiny ultrathin 6.25mm × 6.25mm × 1.82mm LGA package. Included in the package are the switching controller, power FETs, inductor and support components. Operating over an input voltage range of 3.6V to 20V, the LTM4622 supports an output voltage range of 0.6V to 5.5V, set by a single external resistor. Its high efficiency design delivers dual 2.5A continuous, 3A peak, output current. Only a few ceramic input and output capacitors are needed.

www.linear.com/solutions/5841

5V BACKUP APPLICATION WITH OVERVOLTAGE PROTECTION AND NON-BACKED-UP-LOAD OPTION (CHARGE CURRENT SETTING: 2.5A, INPUT CURRENT LIMIT SETTING: 4A)

The LTC4040 is a complete 3.5V to 5.5V supply rail battery backup system. It contains a high current step-up DC/DC regulator to back up the supply from a single-cell Li-Ion or LiFePO$_4$ battery. When external power is available, the step-up regulator operates in reverse as a step-down battery charger.

www.linear.com/solutions/5821



L1: COILCRAFT XAL-5030-222
MN1: VISHAY/SILICONIX SiS488DN
MN2: VISHAY/SILICONIX SIR424DP-T1-GE3

Linear Technology Corporation
1630 McCarthy Boulevard, Milpitas, CA 95035
(408) 432-1900