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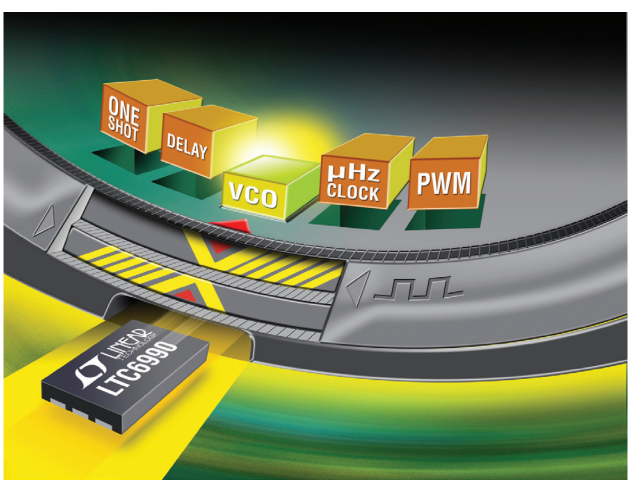
IN THIS ISSUE

TimerBlox: Function-Specific ICs Quickly and Reliably Solve Timing Problems

Andy Crofts

Your design is nearly complete, but a nagging timing requirement has suddenly cropped up. It might call for a variable frequency oscillator, a low frequency timer, a pulse-width modulator, a controlled one-shot pulse generator, or an accurate delay. Regardless of the requirement, you need a quick, reliable, stable solution—there is no time to develop code for a microcontroller. You could build something out of discrete components and a comparator or two, or maybe the good old 555 timer could do the job, but will the accuracy be there? Will it take up too much room on the board? What about time to test and specify the bench-built timer?



TimerBlox devices solve timing problems

There is a better way. Linear Technology's TimerBlox® family of silicon timing devices solves specific timing problems with minimal effort. TimerBlox devices easily drop into designs with a fraction of the design effort or space requirements that a microcontroller or discrete-component solution would demand. It only takes a few resistors to nail down the frequency or time duration you require. That's it, no coding or testing required. Complete solutions are tiny, composed of a 2mm × 3mm DFN, or a popular 6-lead SOT-23, plus a couple of resistors and decoupling cap.

A TOOLBOX OF TIMERBLOX DEVICES

All TimerBlox devices use Linear's silicon oscillator technology, featuring low component count, vibration-immunity, fast start-up, and ease-of-use. Each TimerBlox device is purpose-built to solve a specific timing problem (see Table 1), so the performance

(continued on page 2)

In this issue...

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(LTC699x, continued from page 1)

of each device is specified for its intended application, eliminating the guesswork involved with configuring and applying do-it-all timers.

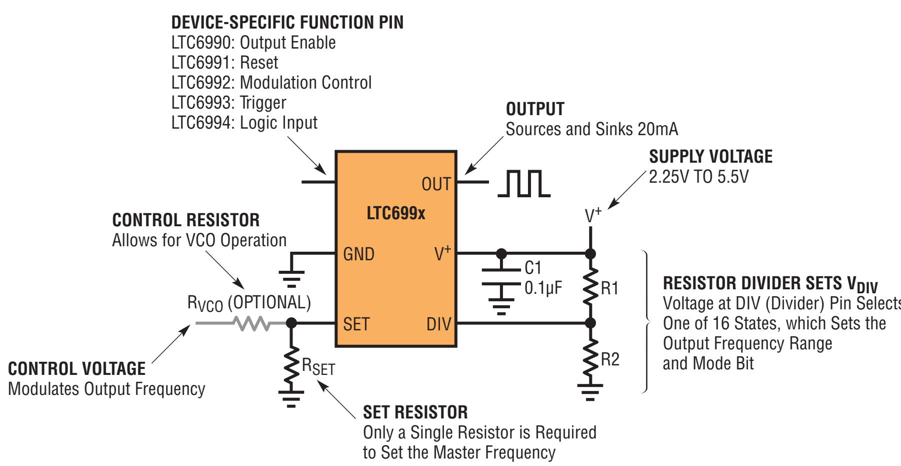
Because each TimerBlox device is designed to perform a specific timing function, the most significant design decision is choosing the proper part number. To further simplify design, five of the six package pins in all TimerBlox devices share the same name and function—with the remaining pin unique to the device function. Figure 1 details the function of each pin (SOT-23 shown).

Each Timerblox device offers eight different timing ranges and two modes of operation (which vary for each device). The operational state is represented by a 4-bit DIVCODE value, which is set by the voltage on the DIV pin. For the ultimate in simplicity, a resistor divider can be used to set the DIVCODE. For example, Figure 2 shows how changing the voltage at the DIV pin sets the functionality of the LTC6992 by selecting a DIVCODE from 0–15. The MSB of DIVCODE is a "mode" bit, in this case selecting the output polarity. The remaining bits choose the frequency range.

Once the proper DIVCODE has been determined, the frequency or timing duration is fine-tuned by a simple calculation for R_{SET}. The set resistor establishes the frequency of an internal silicon oscillator master clock. The resulting circuit has guaranteed accuracy over the full 2.25V–5.5V supply range and –40°C to 125°C temperature range.

(continued on page 4)

Figure 1. All TimerBlox devices share common pin functions



Linear in the News

APEC SHOW

Linear will have a booth at APEC, the Applied Power Electronics Conference and Exposition, held in Fort Worth, Texas, March 6-10. At the booth (151 and 152), Linear will showcase a broad range of power management solutions, including:

- Energy harvesting solutions
- Power µModule® regulators
- Digital power products
- LED drivers
- Linear regulators
- Switching regulators

The booth will be staffed by Linear's power experts and technical field staff. Info at www.apec-conf.org.

AUTOMOTIVE SHOWS

Linear Technology is rapidly growing its commitment to the automotive electronics market. This parallels the increase in the electronics content in cars, as well as new innovations in hybrid and electric vehicles. Linear's products for automotive now cover most electronics systems including navigation and entertainment, safety systems, security, electronic steering and braking, LED lighting, engine control and battery management systems for hybrid/electric vehicles.

Linear plans to participate with booths at the following automotive events in the coming months:

International Automotive Electronics Technology Expo, Tokyo Bigsight Convention Center, Japan, January 19–21: At this show, Linear will showcase its LTC6802 family of battery management ICs for hybrid/electric vehicles, as well as H-grade power management ICs for automotive applications and power µModule regulators. Information at www.car-ele.jp/carele/en.

Advanced Automotive Batteries Conference, Pasadena Convention Center, Pasadena, California, January 24–28: Linear will showcase the company's innovative battery management IC family. including the LTC6802, a highly integrated multicell battery monitoring IC capable of precisely measuring the voltages of up to 12 series-connected battery cells. Using a novel stacking technique, multiple LTC6802s can be placed in series without opto-couplers or isolators. Stacked LTC6802s enable precision measurement of all battery cell voltages, independent of battery string size, within 13ms. Linear will also show the companion LTC6801 independent multicell battery stack monitor and other devices in the family. Info at www.advancedautobat.com/automotive-battery-conference-2011/index.html.

SAE 2011 Hybrid Vehicle Technology Symposium, Hilton Anaheim, Anaheim, California, February 9–11: At this automotive-focused conference, Linear will showcase its growing family of battery stack monitors for hybrid/electric vehicles. This conference will focus on technology advances and platform strategies for hybrid/electric vehicles, plug-in hybrid electric vehicles and all-electric vehicles. Info at www.sae.org/events/training/symposia/hybrid.

EVENTS IN CHINA

IIC China Conference & Exhibition, Shenzhen Convention & Exhibition Center, Shenzhen, China, February 24–26: IIC China is attended by design engineers and technical managers in China. It is China's largest showcase of IC application technologies and high-end components. At Linear's booth (2C15), visitors will gain an overview of the company's products across a range of diverse applications. Info at www.english.iic-china.com.

Electronica & Productronica China 2011, Shanghai New International Expo Center, Shanghai, China, March 15–17: This is the 10th anniversary of Electronica & Productronica. The show focuses on the latest technology breakthroughs in growth-oriented markets, including telecommunications, industrial, automotive and IT products, and consumer electronics. Linear will be in Hall E2, booth 2466. More info at e-p-china.com/en/home.

At both IIC China and Electronica & Productronica, Linear will showcase the following:

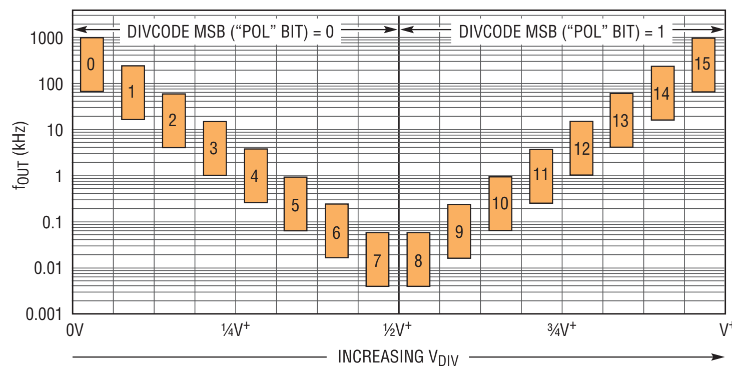
- Automotive electronic solutions
- Battery management systems for hybrid/electric vehicles
- Wireless communications solutions
- Industrial & medical solutions
- Instrumentation
- Energy harvesting/ Nanopower solutions
- High power LED drivers
- High voltage step-down (buck) regulators
- TimerBlox product family
- Power µModule regulators ■

The LTC6990 can easily be used as a voltage-controlled frequency modulator. Although this technique can be used with other silicon oscillators, they typically are limited in accuracy and suffer from poor supply rejection. The LTC6990 does not have these limitations.

(LTC699x, continued from page 2)

For an even easier design process, download "*The TimerBlox Designer*" from www.linear.com/timerblox—a free Excel-based tool that generates component values, schematics, and timing diagrams automatically.

Figure 2. LTC6992 Frequency Range and "POL" Bit vs DIVCODE



VOLTAGE-CONTROLLED OSCILLATOR CAN BE USED FOR FIXED FREQUENCY OR FREQUENCY MODULATION

The LTC6990 is a resistor-programmable oscillator featuring 1.5% accuracy and an output enable function to force the output low or into a high-impedance state. The output frequency is determined by the N_{DIV} frequency divider and R_{SET} (which replaces V_{SET}/I_{SET}):

$$f_{OUT} = \frac{1\text{MHz} \bullet 50\text{k}}{N_{DIV}} \bullet \frac{I_{SET}}{V_{SET}}$$

where N_{DIV} = 1, 2, 4, …, 128

While it can be used as a fixed-frequency oscillator, the LTC6990 can easily be applied as a frequency modulator. A second SET-pin resistor, R_{VCO}, allows a control voltage to vary I_{SET} and change the output frequency. Although this technique can be used with other silicon oscillators, they typically are limited in accuracy and suffer from poor supply rejection. The LTC6990 does not have these limitations because of three important enhancements:

- V_{SET} (the SET pin voltage) is regulated to 1V and is accurate to ±30mV over all conditions. This allows R_{VCO} to establish an accurate VCO gain.
- V_{SET} is GND-referenced, allowing for a GND-referenced control voltage that is easy to work with.
- All TimerBlox devices allow for a wide 16:1 timing range within each N_{DIV} setting, but only the LTC6990 uses a small 2× step through divider settings. That allows for maximum overlap between ranges to accommodate any 8:1 range of VCO frequencies (or 16:1 with a reduced-accuracy extended range). And since each TimerBlox device has eight different timing ranges, the LTC6990 still maintains a large 4096:1 total frequency range.

Figure 3 shows the LTC6990 configured as a VCO that translates a 0V to 3.3V control

Figure 3. LTC6990 voltage-controlled oscillator

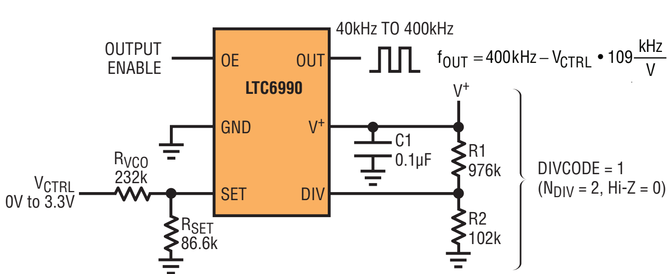
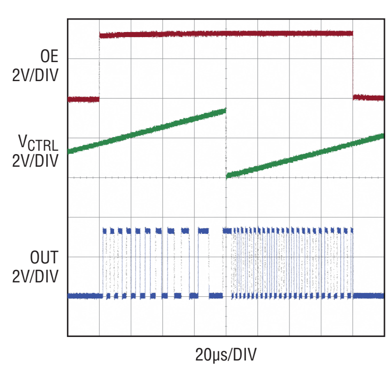


Figure 4. Performance of the voltage-controlled oscillator shown in Figure 3



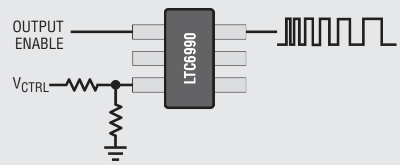
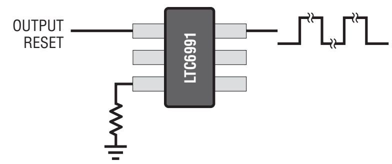
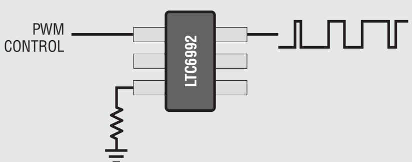
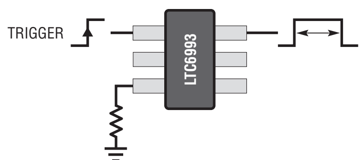
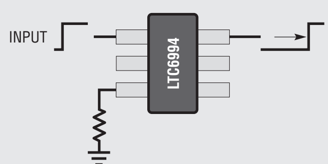
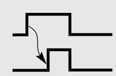
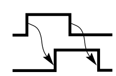
DEVICE	FUNCTION	OPTIONS		RANGE
	Voltage-Controlled Silicon Oscillator	Configurable frequency gain and voltage range		488Hz to 2MHz
	Low Frequency Oscillator	Period range from 1ms to 9.5 hours		29µHz to 977Hz
	Voltage-Controlled PWM	LTC6992-1	0%–100% Duty Cycle	3.8Hz to 1MHz
		LTC6992-2	5%–95% Duty Cycle	
		LTC6992-3	0%–95% Duty Cycle	
		LTC6992-4	5%–100% Duty Cycle	
	One-Shot	LTC6993-1	Rising-Edge Triggered	1µs to 34 sec
		LTC6993-2	Rising-Edge Re-Triggerable	
		LTC6993-3	Falling-Edge Triggered	
		LTC6993-4	Falling-Edge Re-Triggerable	
	Delay	LTC6994-1	 1-Edge Delay	1µs to 34 sec
		LTC6994-2	 2-Edge Delay	

Table 1. TimerBlox family members

voltage into a 40kHz to 400kHz frequency. Due to the LTC6990's high modulation bandwidth, the output responds quickly to control voltage changes, as can be seen in Figure 4.

LOW FREQUENCY SOLUTIONS

The LTC6991 picks up in frequency where the LTC6990 leaves off, with an enormous 29µHz to 977Hz range (a period range of 1ms to 9.5 hours). It incorporates a fixed 10-stage frequency divider and a programmable 21-stage divider.

Since the applications for frequency modulation are rare at such low frequencies, the emphasis for this part is on covering as wide a range as possible. Therefore, the LTC6991 uses large 8× steps between N_{DIV} settings. The trade-off is a smaller 2× overlap between ranges. The output interval relationship is:

$$t_{OUT} = \frac{N_{DIV} \bullet R_{SET}}{50k} \bullet 1.024ms$$

where $N_{DIV} = 1, 8, 64, \ldots, 2^{21}$

The LTC6991 is designed to handle long duration timing events. In place of an output enable, it includes a similar reset function. The RST pin can truncate the output pulse or prevent the output from oscillating at all, but it has no effect on the timing of the next rising edge. This function allows the LTC6991 to initiate an event with a variable duration, perhaps controlled by another circuit. Otherwise, if RST is inactive, the LTC6991 produces a square wave.

Figure 5 shows how a simple camera intervalometer can be constructed from the LTC6991 and a handful of discrete

Figure 5. An LTC6991-based camera intervalometer

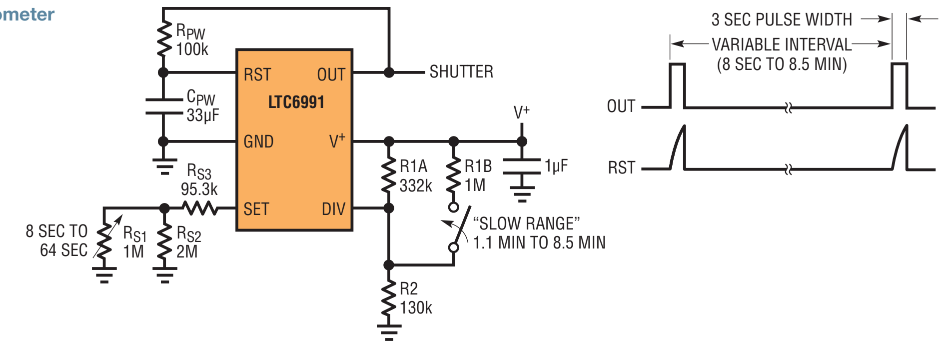
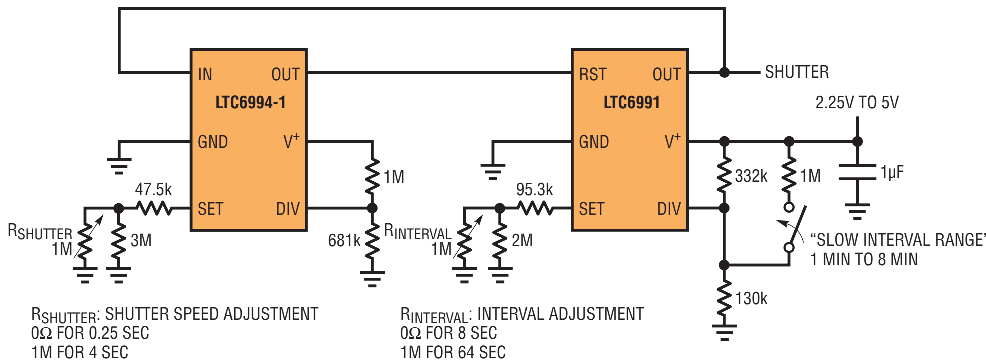


Figure 6. An upgraded camera intervalometer—the LTC6994-1 is added to allow shutter speed adjustment



components. An intervalometer is used in time-lapse photography to capture images at specific intervals. The shutter rate might range from a few seconds to a few hours. In this example, the photographer can choose any interval between 8 seconds and 8.5 minutes.

An RC delay from OUT to RST allows for a 3-second shutter pulse before resetting the output. Potentiometer R_{S1} varies the total resistance at the SET pin from 95.3k to 762k to adjust the period from 8 seconds to 64 seconds, with DIVCODE set to 4 by R1A and R2. Closing the SLOW RANGE switch changes the DIVCODE to 5, increasing N_{DIV} by 8× to extend the interval up to 8.5 minutes.

Figure 7. Measured transfer function of the LTC6992 family

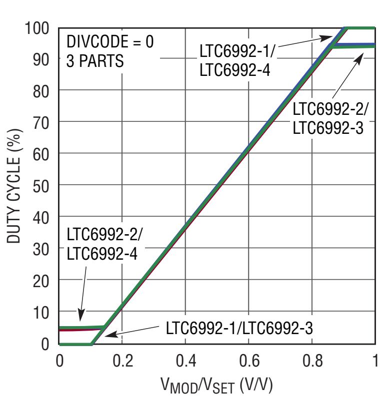


Figure 6 shows how easy it is to add timing functions on top of each other using TimerBlox devices. Here the LTC6994-1 is added to the intervalometer in Figure 5 to create an intervalometer with shutter-speed adjustment.

PULSE-WIDTH MODULATOR

The LTC6992 TimerBlox oscillator features pulse-width modulation—the ability to control output duty cycle with a simple input voltage. The LTC6992 makes quick work of a technique that is useful for many applications: light dimming, isolated proportional control, and efficient load control, to name a few.

The MOD pin accepts a control voltage with a range of 0.1V to 0.9V that linearly regulates the output duty cycle. The 0.1V "pedestal" ensures that an op-amp or other input driver is able to reach the bottom of the control range. The duty cycle is given by:

$$DutyCycle = \frac{V_{MOD}}{0.8 \bullet V_{SET}} - \frac{1}{8} \approx \frac{V_{MOD} - 100mV}{800mV}$$

The output frequency is governed by the simple relationship shown below. The total frequency range of the LTC6992 covers 3.8Hz to 1MHz, using 4× divider steps in the eight N_{DIV} settings.

$$f_{OUT} = \frac{1MHz \bullet 50k}{N_{DIV} \bullet R_{SET}}$$

where N_{DIV} = 1, 4, 16, …, 16384

The LTC6992-1 allows for the full duty cycle range, covering 0% (for $V_{MOD} \le 0.1V$) to 100% (for $V_{MOD} \ge 0.9V$). At the extremes, the output stops oscillating, resting at GND (0% duty) or V+ (100% duty). Some applications (such as coupling a control signal across an isolation transformer) require continuous oscillation. For such applications, choose the LTC6992-2, which limits the output duty cycle to 5% min and 95% max. The LTC6992-3 and LTC6992-4 complete

The LTC6992 makes quick work of producing a voltage-controlled PWM signal—useful for many applications: light dimming, isolated proportional control and efficient load control, to name a few.

the family by limiting the duty cycle at only one extreme. Figure 7mV shows the measured response for the LTC6992 family.

Figure 8 shows a typical circuit. With the frequency divider (N_{DIV}) set to 1 and R_{SET} = 200k, this PWM circuit is configured for a 250kHz output frequency. Figure 9 demonstrates the circuit in action for both the LTC6992-1 and the LTC6992-2. The high modulation bandwidth allows the output duty cycle to quickly track changes in the modulation voltage.

ONE-SHOT EVENTS

Of course, not all timing applications require a stable frequency oscillator output. Some circuits require an event-triggered fixed-duration pulse, like that produced by the LTC6993 monostable (one-shot) pulse generator, which offers eight different logic functions and a huge 1µs to 34-second timing range. The one-shot duration t_{OUT} is established by R_{SET}:

$$t_{OUT} = \frac{N_{DIV} \bullet R_{SET}}{50k} \bullet 1\mu s$$

where N_{DIV} = 1, 8, 64, …, 2^{21}

The LTC6993 is triggered by a rising or falling transition on its TRIG pin, which initiates an output pulse with pulse width t_{OUT}. Some variations include the ability to "retrigger" the pulse, extending the output pulse duration with additional trigger signals. And each version can be configured to produce logic high or low output pulses using the MSB of the DIVCODE. Table 2 summarizes the different options.

Figure 10 shows a basic circuit, with the DIVCODE set to 3 (N_{DIV} = 512, POL = 0) by a resistor divider and a 97.6k R_{SET} defining a

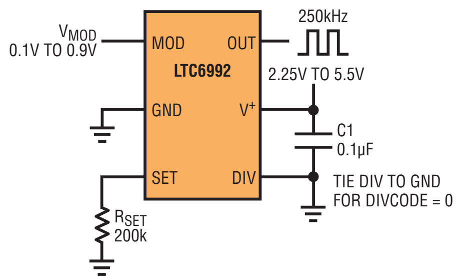


Figure 8. An LTC6992 pulse-width modulator

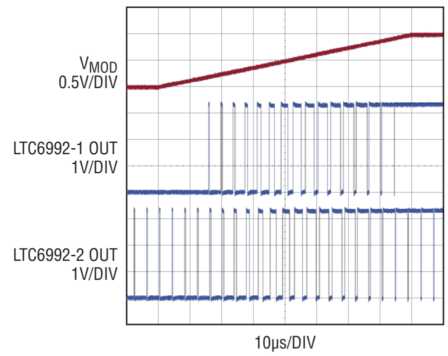


Figure 9. Performance of the PWM shown in Figure 7

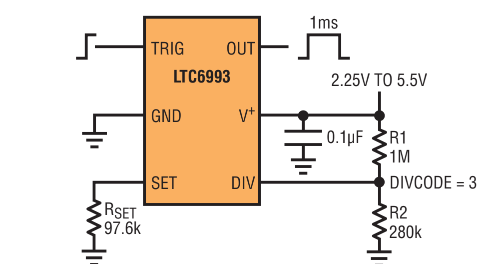


Figure 10. An LTC6993 monostable pulse generator (one-shot)

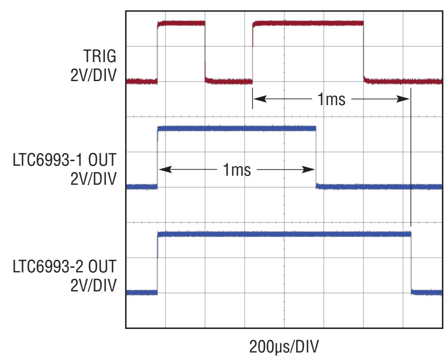


Figure 11. The LTC6993 non-retriggerable and retriggerable functionality

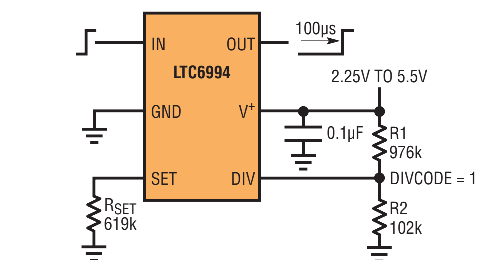


Figure 12. LTC6994 delay interval generator

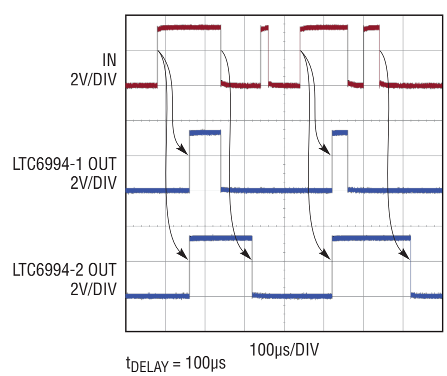


Figure 13. LTC6994 single and double-edge delay functionality

The LTC6993 is triggered by a rising or falling transition on its TRIG pin, which initiates an output pulse with pulse width t_{OUT}. Some variations include the ability to "retrigger" the pulse, extending the output pulse duration with additional trigger signals.

1ms output pulse width. To demonstrate the difference between retriggerable and non-retriggerable functionality, Figure 11 shows the results of using either the LTC6993-1 or LTC6993-2 in this circuit.

THE LTC6994 FOR PROGRAMMABLE DELAY AND PULSE QUALIFICATION

The LTC6994 is a programmable delay or pulse qualifier. It can perform noise filtering, which distinguishes its function from a delay line. The LTC6994 is available in two versions, as detailed in Table 3. The LTC6994-1 delays the rising or falling edge of the input signal. The LTC6994-2 delays any input transition, rising or falling, and can invert the output signal.

The LTC6994's programmable delay (denoted as t_{DELAY} below) can vary from 1µs to 34 seconds, accurate to ±3% in most conditions.

$$t_{DELAY} = \frac{N_{DIV} \bullet R_{SET}}{50k\Omega} \bullet 1\mu s$$

where $N_{DIV} = 1, 8, 64, \ldots, 2^{21}$

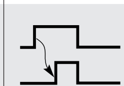
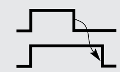
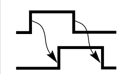
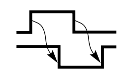
The output will only respond to input changes that persist longer than the delay period. This operation is well suited for pulse qualification, switch debouncing, or guaranteeing minimum pulse widths. The basic circuit in Figure 12 is configured for a 100µs delay. Figure 13 demonstrates the difference between the LTC6994-1, which delays either the rising or falling transition, and the LTC6994-2, which delays transitions in both directions. Both versions will reject narrow pulses, but the LTC6994-2 preserves the original signal's pulse width.

In addition to this type of noise filtering, the LTC6994 is useful for delay matching, generating multiple clock phases, or doubling the clock frequency of the input signal, as shown in Figure 14.

Table 2. LTC6993 options

DEVICE	INPUT POLARITY	RE-TRIGGER
LTC6993-1	Rising-Edge	No
LTC6993-2	Rising-Edge	Yes
LTC6993-3	Falling-Edge	No
LTC6993-4	Falling-Edge	Yes

Table 3. LTC6994 options

DEVICE	DELAY FUNCTION
LTC6994-1	 or 
LTC6994-2	 or 

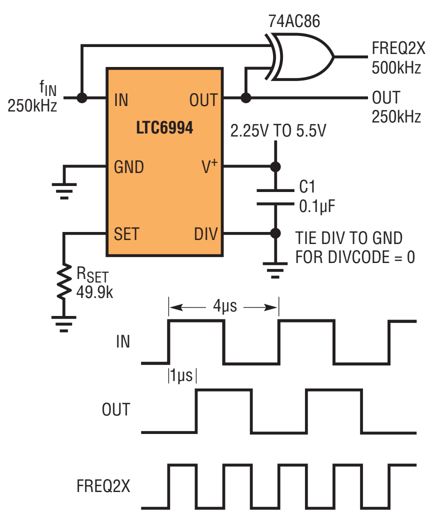


Figure 14. 90° phase-shifted (quadrature) signal generator and frequency doubler

MOTOR SPEED ALARM

There is no limit to how TimerBlox devices can be combined to easily produce esoteric timing functions. For instance, the design in Figure 15 combines one shots and delay blocks with a VCO to produce a high/low motor speed alarm. The circuit sounds a high frequency tone if a motor is spinning too fast and a low frequency tone if too slow.

The input is taken from a motor shaft encoder or other rotational sensor and used to trigger a one shot to produce a 1ms pulse per revolution.

The *fast alarm threshold* can be set between 10,000 rpm and 1500 rpm which, in time, is one pulse every 6ms to 40ms. Re-triggerable one shot, U3, is adjusted for a time interval equal to the warning threshold value. If it is continually re-triggered and not allowed to time out, then the motor is turning too fast.

For time-filtering, a delay timer, U4, is programmed by the same threshold adjust voltage to delay an output signal until the motor has exceeded the threshold speed for 100 revolutions (600ms to 4000ms). The delayed

More Online

Learn more about TimerBlox devices at www.linear.com/timerblox. There you can find data sheets, *TimerBlox Designer* software, even an introductory video about the products.

> The output of the LTC6994 will only respond to input changes that persist longer than the delay period. This operation is well suited for pulse qualification, switch debouncing, or guaranteeing minimum pulse widths.

output signal enables an LTC6990 oscillator to produce a 5kHz warning tone.

The *slow alarm threshold* can be set between 1200 rpm and 120 rpm or one pulse every 50ms to 500ms. The delay timer, U5, pulses its output if allowed to time out because the motor speed is too slow. This output re-triggers one shot U6 and keeps its output high as long as the speed remains too slow.

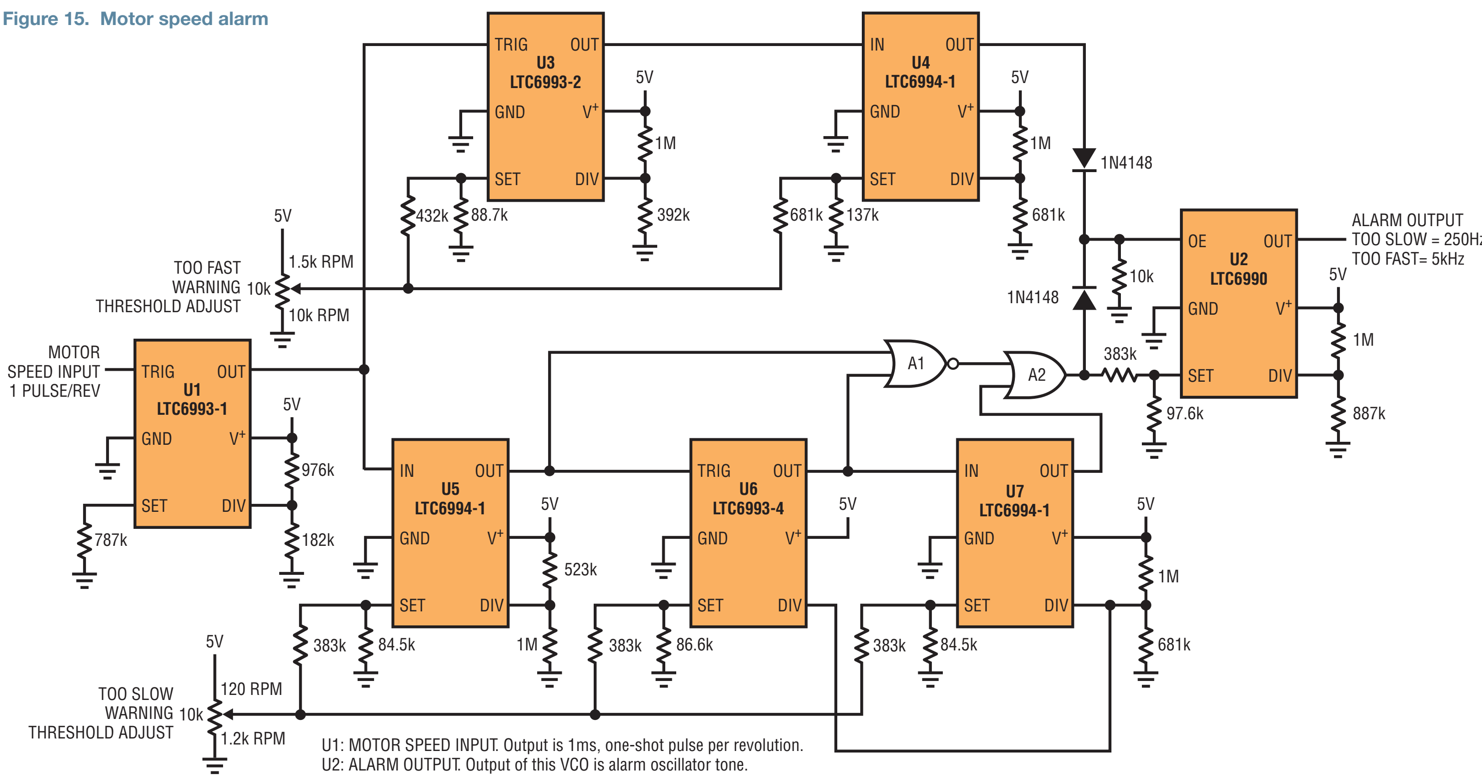
Another time filter is created with delay block U7 which sounds a lower frequency alarm if the motor remains too slow for 10 revolutions (500ms to 5000ms). Two OR gates are used to detect when the motor has stopped completely.

CONCLUSION

The Linear Technology TimerBlox family of silicon oscillators fills a designer's toolbox with simple and dependable timing solutions that require minimal design effort to produce accurate and reliable circuits. Several of the five core products are available in multiple versions to cover more applications and reduce the need for external components.

Each part is designed to be as flexible as possible with a 2.25V to 5.5V supply range, up to –40°C to 125°C temp range and wide timing ranges. In addition, the parts are offered in a small 2mm × 3mm DFN or a low-profile SOT-23 (ThinSOT™) package when a leaded package is required. ■

Figure 15. Motor speed alarm



U1: MOTOR SPEED INPUT. Output is 1ms, one-shot pulse per revolution.
U2: ALARM OUTPUT. Output of this VCO is alarm oscillator tone.

FAST SPEED SENSOR
U3: RETRIGGERABLE ONE SHOT. Output stops pulsing if rpm > fast threshold.
U4: DELAY TIME FILTER. If rpm too fast for 100 cycles, ouput alarm is sounded.

SLOW SPEED SENSOR
U5: DELAY TIMER. Output never pulses if rpm > slow threshold.
U6: RETRIGGERABLE ONE SHOT. If triggered output goes high and stays high if rpm below threshold.
U7: DELAY TIME FILTER. If rpm too slow for 10 cycles, output alarm is sounded.
A1, A2: Logic to sound alarm if motor too slow or stopped.

Battery Charger's Unique Input Regulation Loop Simplifies Solar Panel Maximum Power Point Tracking

Jay Celani

Advances in battery technology and device performance have made it possible to produce complex electronics that run for long periods between charges. Even so, for some devices, recharging the batteries by plugging into the grid is not possible. Emergency roadside telephones, navigation buoys, and remote weather monitoring stations are just a few applications that have no access to the power grid, so they must harvest energy from their environment.

Solar panels have great potential as energy harvesting power sources—they just need batteries to store the harvested power and to provide carry-though during dark periods. Solar panels are relatively expensive, so extracting maximum power from the panels is paramount to minimizing the panel size. The tricky part is a balancing of solar panel size with required power. The characteristics of solar panels require careful management of the panel's output power versus load to effectively optimize the panel's output power for various lighting conditions.

For a given illumination level, a solar panel has a specific operating point that produces the maximum amount of power (see Figure 1). Maintaining this peak-power point during operation as lighting conditions change is called maximum peak power tracking (MPPT). Complex algorithms are often used to perform this function, such as varying the panel's load periodically while directly measuring panel output voltage and output current, calculating panel output power, then forcing the point of operation that provides the peak output power as illumination and/or temperature conditions change. This type of algorithm generally requires complex circuitry and microprocessor control.

In Depth

For an in-depth discussion of the maximum power point tracking feature of the LT3652, see "Designing a Solar Cell Battery Charger" in the December 2009 issue of *LT Magazine*. You can find this article and the LT3652 data sheet at www.linear.com/3652.

There exists, however, an interesting relationship between the output voltage of a solar panel and the power that the panel produces. A solar panel output voltage at the maximum power point remains relatively constant regardless of illumination level. It follows that forcing operation of the panel such that the output voltage is maintained at this peak power voltage (V_{MP}) yields peak output power from the panel. A battery-charger can therefore maintain peak power transfer by exploiting this V_{MP} characteristic instead of implementing complex MPPT circuitry and algorithms.

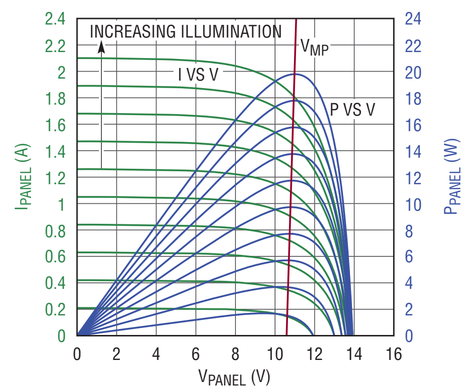


Figure 1. Current vs voltage and power vs voltage for a solar panel at a number of different illumination levels. The panel output voltage at the maximum power point (V_{MP}) remains relatively constant regardless of illumination level.

A FEW FEATURES OF THE LT3652 BATTERY CHARGER

The LT3652 is a complete monolithic step-down multi-chemistry battery charger that operates with input voltages as high as 32V (40V abs max) and charges battery stacks with float voltages up to 14.4V. The LT3652 incorporates an innovative input regulation circuit, which implements a simple and automatic method for controlling the charger's input supply voltage when using poorly regulated sources, such as solar panels. The LT3652HV, a high voltage version of the charger, is available to charge battery stacks with float voltages up to 18V.

The LT3652 is a versatile platform for simple and efficient solar-powered battery charger solutions, applicable to a wide variety of battery chemistries and configurations. The LT3652 is equally at home in conventionally powered applications, providing small and efficient charging solutions for a wide variety of battery chemistries and stack voltages.

Input Regulation Loop Maintains Peak Power Point for Solar Panels

The LT3652 input regulation loop linearly reduces the output battery charge current if the input supply voltage falls toward a programmed level. This closed-loop regulation circuit servos the charge current, and thus the load on the input supply, such that the input supply voltage is maintained at or above a programmed level. When powered by a solar panel, the LT3652 implements MPPT operation by simply programming the minimum input voltage level to that panel's peak power voltage, V_{MP}. The desired peak-power voltage is programmed via a resistor divider.

If during charging, the power required by the LT3652 exceeds the available power from the solar panel, the LT3652 input regulation loop servos the charge current lower. This might occur due to an increase in desired battery charge current or drop in solar panel illumination levels. In either case the regulation loop maintains the solar panel output voltage at the programmed V_{MP} as set by the resistor divider on VIN_REG.

The input regulation loop is a simple and elegant method of forcing peak power operation from a particular solar panel. The input voltage regulation loop also allows optimized operation from other types of poorly regulated sources, where the input supply can collapse during overcurrent conditions.

Integrated, Full-Featured Battery Charger

The LT3652 operates at a fixed switching frequency of 1MHz, and provides a constant-current/constant-voltage (CC/CV) charge characteristic. The part is externally resistor-programmable to provide charge current up to 2A, with charge-current accuracy of ±5%. The IC is particularly suitable for the voltage ranges associated with popular and inexpensive "12V system" solar panels, which typically have open-circuit voltages around 25V.

The charger employs a 3.3V float voltage feedback reference, so any desired battery float voltage from 3.3V to 14.4V (or up to 18V with the LT3652HV) can be programmed with a resistor divider. The float-voltage feedback accuracy for the LT3652 is ±0.5%. The wide LT3652 output voltage range accommodates many battery chemistries and configurations, including up to three Li-ion/polymer cells in series, up to four $LiFePO_4$ (lithium iron phosphate) cells in series, and sealed lead acid (SLA) batteries containing up to six cells in series. The LT3652HV, a high-voltage version of the charger, is also available. The LT3652HV operates with input voltages up to 34V and can charge to float voltages of 18V, accommodating 4-cell Li-ion/polymer or 5-cell $LiFePO_4$ battery stacks.

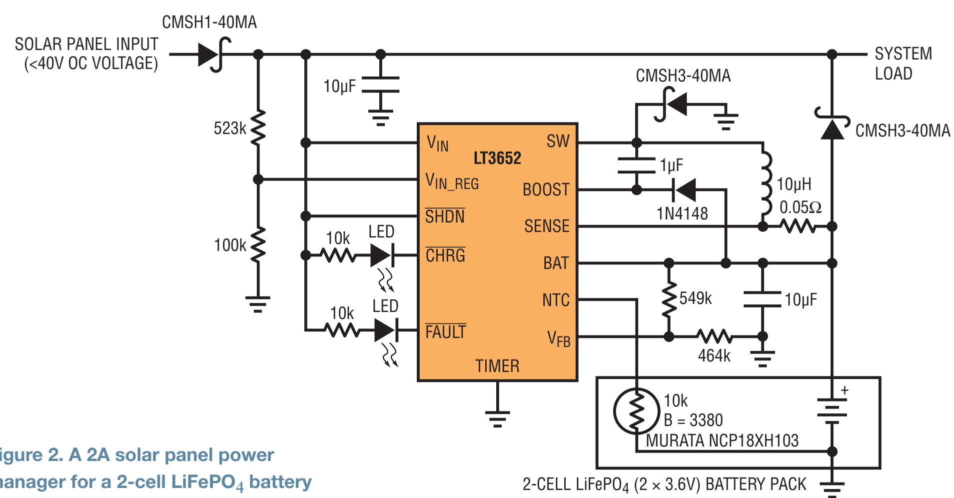


Figure 2. A 2A solar panel power manager for a 2-cell $LiFePO_4$ battery with 17V peak power tracking

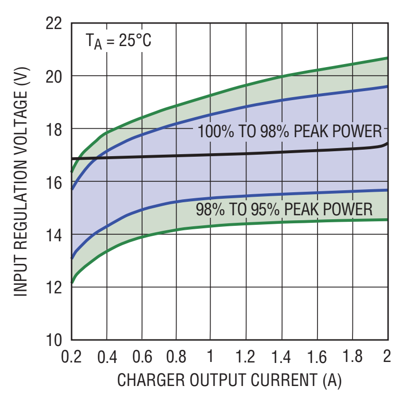


Figure 3. A 17V input voltage regulation threshold tracks solar panel peak power to greater than 98%

The LT3652 incorporates an innovative input regulation circuit, which implements a simple and automatic method for controlling the charger's input supply voltage when using poorly regulated sources, such as solar panels.

The LT3652 contains a programmable safety timer used to terminate charging after a desired time is reached. Simply attaching a capacitor to the TIMER pin enables the timer. Shorting the TIMER pin to ground configures the LT3652 to terminate charging when charge current falls below 10% of the programmed maximum (C/10), with C/10 detection accuracy of ±2.5%. Using the safety timer for termination allows top-off charging at currents less than C/10. Once charging is terminated, the LT3652 enters a low-current (85µA) standby mode. An auto-recharge feature starts a new charging cycle if the battery voltage falls 2.5% below the programmed float voltage. The LT3652 is packaged in low-profile, 12-lead 3mm × 3mm DFN and MSOP packages.

Energy Saving Low Quiescent Current Shutdown

The LT3652 employs a precision-threshold shutdown pin, allowing simple implementation of undervoltage lockout functions using a resistor divider. While in low-current shutdown mode, the LT3652 draws only 15µA from the input supply. The IC also supports temperature-qualified charging by monitoring battery temperature using a single thermistor attached to the part's NTC pin. The device has two binary coded open-collector status pins that display the operational state of the LT3652 battery charger, CHRG and FAULT. These status pins can drive LEDs for visual signaling of charger status, or be used as logic-level signals for control systems.

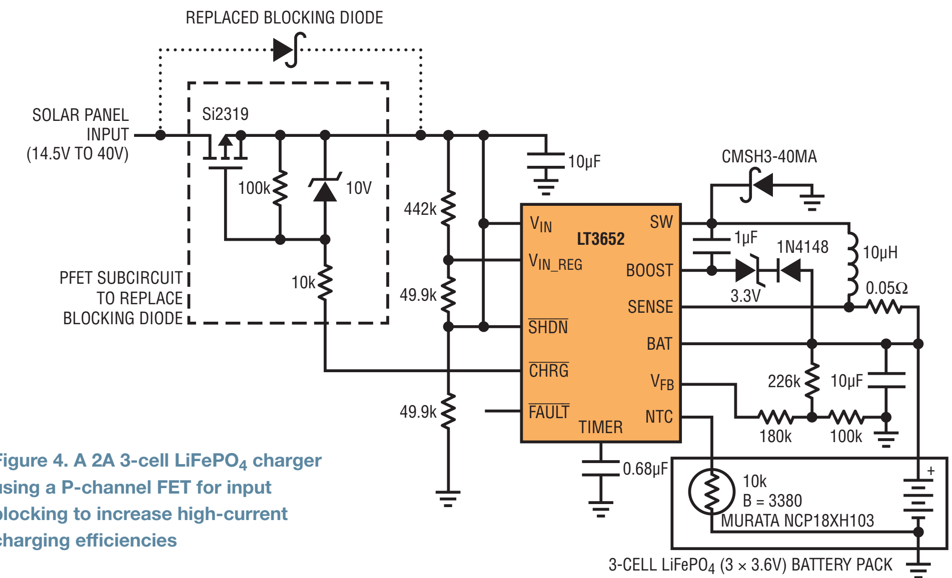
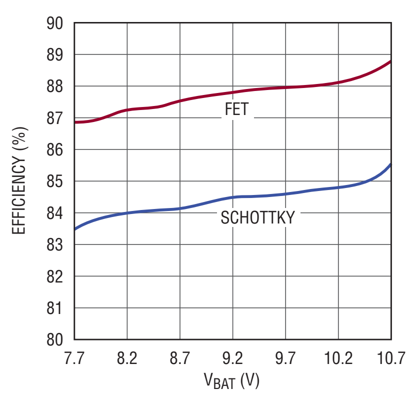


Figure 4. A 2A 3-cell $LiFePO_4$ charger using a P-channel FET for input blocking to increase high-current charging efficiencies

SIMPLE SOLAR POWERED BATTERY CHARGER

Figure 2 shows a 2A 2-cell $LiFePO_4$ battery charger with power path management. This circuit provides power to the system load from the battery when the solar panel is not adequately illuminated and directly from the solar panel when the power required for the system load is available. The input voltage regulation loop is programmed for a 17V peak power input panel. The charger uses C/10 termination, so the charge circuit is disabled when the required battery charge current falls below 200mA. This LT3652 charger also uses two LEDs that provide status and signal fault conditions. These binary-coded pins signal battery charging, standby or shutdown modes, battery temperature faults and bad battery faults.

Figure 5. Comparative efficiencies for blocking Schottky diode vs blocking FET as battery voltage rises for 15V to 10.8V 3-cell $LiFePO_4$ charger



The input voltage regulation point is programmed using a resistor divider from the panel output to the VIN_REG pin. Maximum output charge current is reduced as the voltage on the solar panel output collapses toward 17V, which corresponds to 2.7V on the VIN_REG pin. This servo loop thus acts to dynamically reduce the power requirements of the charger system to the maximum

When powered by a solar panel, the LT3652 implements maximum power point tracking (MPPT) operation by simply programming the minimum input voltage level to that panel's peak power voltage, V_{MP}. The specific desired peak-power voltage is programmed via a resistor divider.

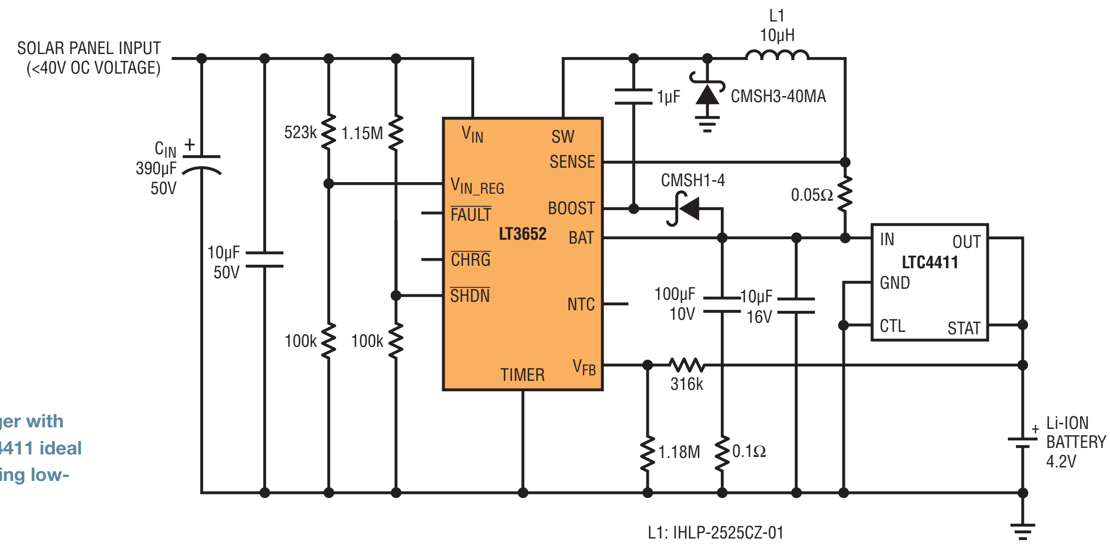


Figure 6. A solar powered, 2A Li-ion charger with ideal diode output pass element; the LTC4411 ideal diode IC prevents reverse conduction during low-light conditions

power that the panel can provide, maintaining solar panel power utilization close to 100%, as shown in Figure 3.

WANT BETTER EFFICIENCY? REPLACE THE BLOCKING DIODE WITH A BLOCKING FET

The LT3652 requires a blocking diode when used with battery voltages higher than 4.2V. The voltage drop across this diode creates a power loss term that reduces charging efficiency. This term can be greatly reduced by replacing the blocking diode with a P-channel FET, as shown in Figure 4.

Figure 4 shows a 3-cell $LiFePO_4$ 2A charger with a float voltage of 10.8V. This charger has an input voltage regulation threshold of 14.5V and is enabled by the SHDN pin when $V_{IN} \geq 13V$. Charge cycle termination is controlled by a 3-hour timer cycle. The blocking diode normally used in series with the input supply for reverse voltage protection is replaced by a FET. A 10V Zener diode clamp is used to prevent exceeding the FET maximum V_{GS}. If the specified V_{IN} range does not exceed the maximum V_{GS} of the input FET, this clamp is not required.

During the high-current charging period of a normal charge cycle ($I_{CHG} > C/10$), the $\overline{CHRG}$ status pin is held low. In the charger shown in Figure 4, this $\overline{CHRG}$ signal is used to pull the gate of the blocking FET low, enabling a low-impedance power supply path that eliminates the blocking diode drop to improve conversion efficiency. Figure 5 shows that the addition of this blocking FET improves efficiency by 4% compared to operation with a blocking Schottky diode.

Should the timer be used for termination, the body diode of the FET provides a conduction path once charge currents of < C/10 is achieved, and the $\overline{CHRG}$ pin becomes high-impedance. If desired, a blocking Schottky diode can be left in parallel with the blocking FET to improve conversion efficiency during the top-off portion of the timer-controlled charge cycle. Use of a FETKEY as the blocking element also increases top-off efficiency.

SCARED OF THE DARK? USE AN IDEAL DIODE FOR LOW-LIGHT APPLICATIONS

When the LT3652 is actively charging, the IC provides an internal load onto the switching loop to ensure closed-loop operation during all conditions. This is accomplished by sinking 2mA into the BAT pin whenever a charging cycle is active. In a solar-panel-powered battery charger, low-light conditions can make the input solar panel voltage collapse below the input regulation threshold, causing

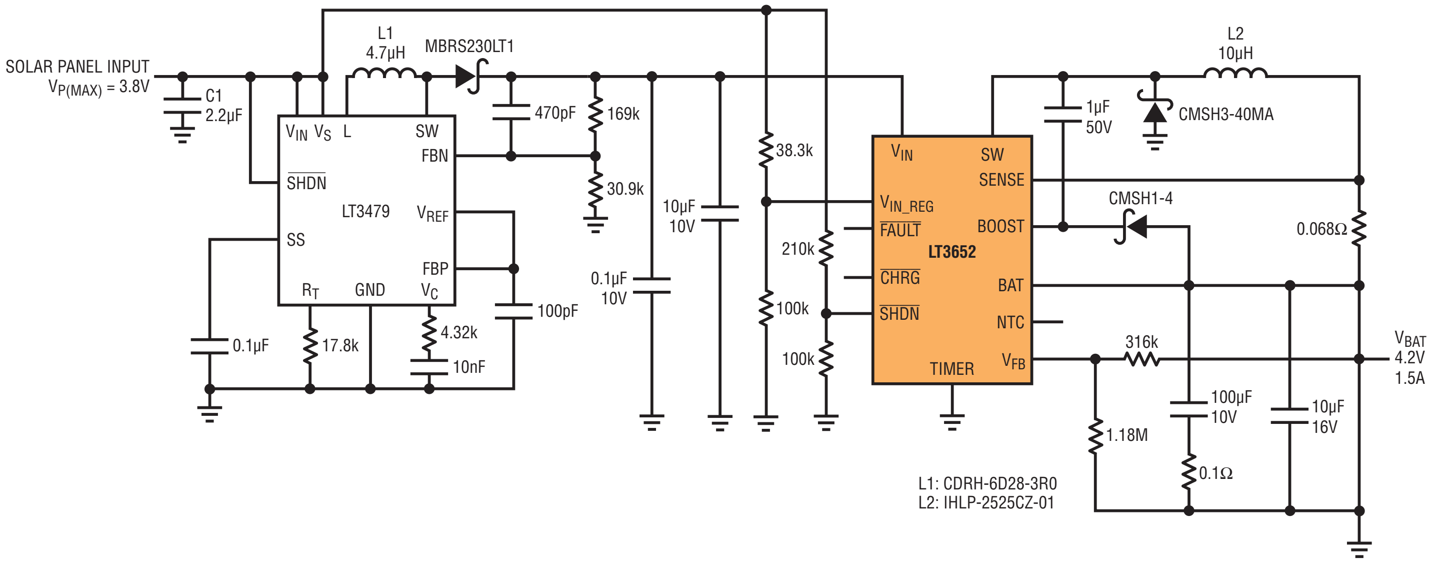


Figure 7. Low-voltage solar panel powers 1.5A single cell Li-ion buck/boost battery charger. The LT3479 boosts the solar panel's 3.8V output to operate an LT3652 charger. The LT3652's closed loop operation includes the boost converter, thus regulating the LT3479's input to the solar panel's V_{MP} of 3.8V.

output charge current to be reduced to zero. If the charger remains enabled during this condition (i.e., the panel voltage remains above the UVLO threshold), the internal battery load results in a net current drain from the battery. This is undesirable for obvious reasons, but this condition can be eliminated by incorporating a unidirectional pass element that prevents current backflow from the battery.

Linear Technology makes a high-efficiency pass element IC, the LTC4411 ideal diode, which has an effective forward drop close to zero. The effect on overall charger efficiency and final float voltage is negligible due to the extremely low forward drop during conduction.

Figure 6 shows an LT3652 solar-powered battery charger that employs low-light reverse protection using an LTC4411 ideal-diode IC. During a low light condition, should the panel voltage collapse below the input regulation threshold, the LT3652 reduces battery charge current to zero. In the case where the input voltage remains above the UVLO threshold, the charger remains enabled but is held in a zero charge current state. The LT3652 attempts to sink 2mA into the BAT pin; however, the LTC4411 prevents reverse conduction from the battery.

NEED TO STEP-UP? NO PROBLEM. A 2-STAGE BUCK-BOOST BATTERY CHARGER

The LT3652 can be used for step-up and step-up/step-down charger applications by incorporating a front-end step-up DC/DC converter. The front-end converter generates a local high-voltage supply for the LT3652 to use as an input supply. The LT3652 input regulation loop functions perfectly when wrapped around both converters.

Figure 7 shows a low-voltage solar panel powered 1.5A single-cell Li-ion charger with a 4.2V float voltage. This charger is designed to operate from a solar panel that has a peak power voltage of 3.8V.

An LT3479 switching boost converter running at 1MHz is used on the front-end to create an 8V supply, which is used to power the LT3652. This charger operates with input voltages as low as the input regulation threshold of 3.8V, up to 24V, the maximum input voltage for the LT3479. When input voltages approach 8V (or higher), the LT3479 boost converter no longer regulates, ultimately operating at 0% duty cycle and effectively shorting the input supply through the pass Schottky diode to the LT3652. Because the input regulation loop monitors the input to the LT3479, when the input voltage collapses toward the input regulation threshold, the LT3652 scales back charge current, reducing the current requirements of the LT3479 boost converter. The input voltage servos to the regulation point, with the boost converter and LT3652 charger combination extracting the peak power available from the solar panel.

NEED MORE CHARGE CURRENT? USE MORE LT3652s

Multiple LT3652 chargers can be used in parallel to produce a charger that exceeds the charge current capability of a single LT3652. In the application shown in Figure 8, three 2A LT3652 charger networks are connected in parallel to yield a 6A 3-cell Li-ion charger with a float voltage of 12.3V that uses C/10 termination. This charger is solar power compatible, having an input regulation threshold of 20V. This charger also implements an input blocking FET to increase charging efficiencies.

The three LT3652 charger ICs share a common float voltage feedback network

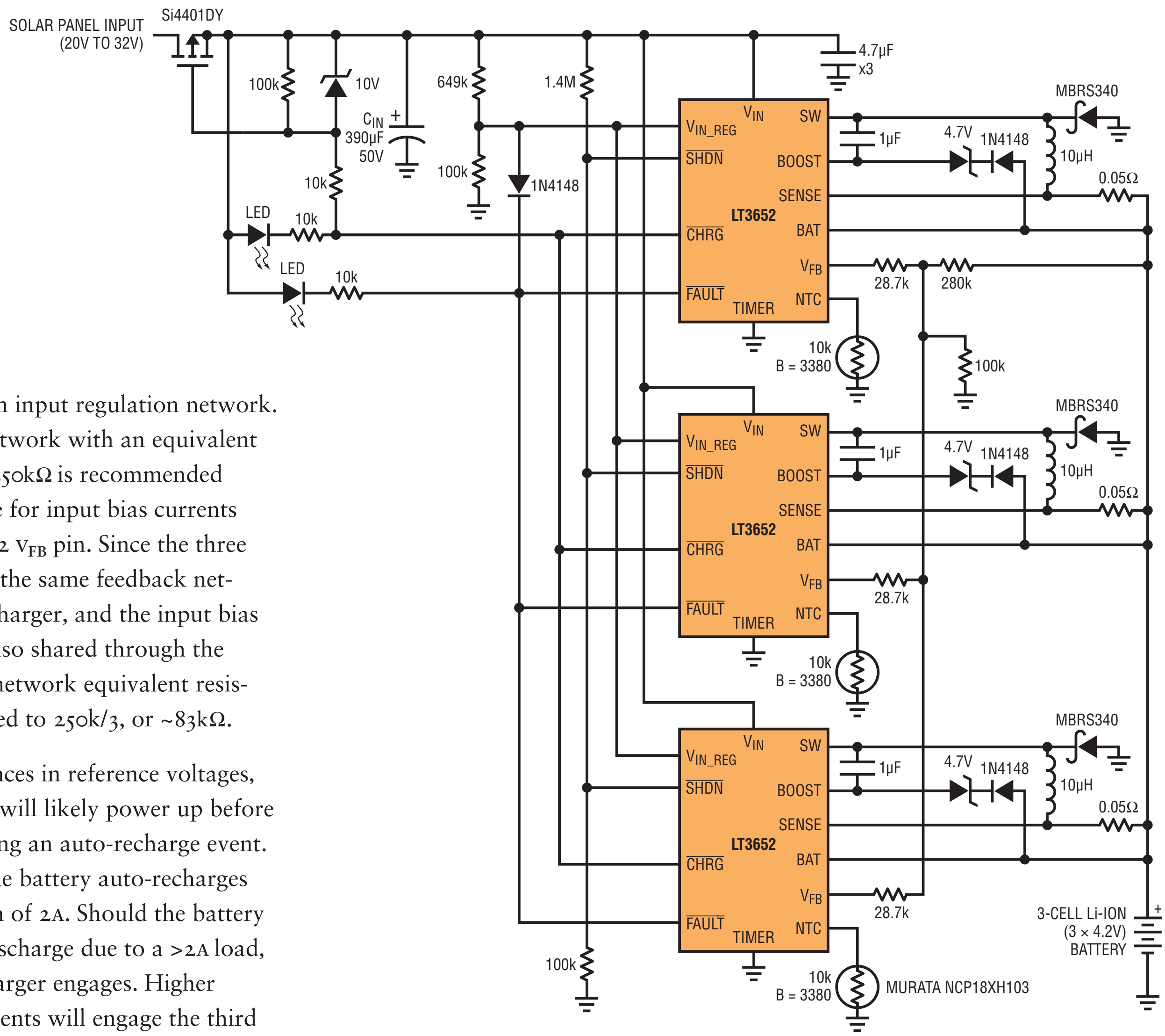


Figure 8. A 6A 3-cell Li-ion battery charger using three LT3652 charger ICs

and a common input regulation network. A feedback network with an equivalent resistance of 250kΩ is recommended to compensate for input bias currents into the LT3652 V_{FB} pin. Since the three LT3652s share the same feedback network in this charger, and the input bias currents are also shared through the network, the network equivalent resistance is reduced to 250k/3, or ~83kΩ.

Due to tolerances in reference voltages, one of the ICs will likely power up before the other during an auto-recharge event. In this case, the battery auto-recharges at a maximum of 2A. Should the battery continue to discharge due to a >2A load, the second charger engages. Higher discharge currents will engage the third charger IC, allowing the charger to produce the full 6A system charge current. The $\overline{\text{CHRG}}$ pins on all of the LT3652s are tied together to enable the input blocking FET, so the FET is low-impedance regardless of which order the ICs auto-restart.

The NTC and status functions are shared by all three LT3652s, with each IC using a dedicated NTC thermistor. The open collector status pins of the ICs are shorted together, so engaging any or all of the individual chargers lights the $\overline{\text{CHRG}}$ status indicator. Likewise, an NTC fault in any of the ICs lights the $\overline{\text{FAULT}}$ status indicator. The individual LT3652 NTC functions are slaved to each other via a diode connected from the common $\overline{\text{FAULT}}$ pins to the common VIN_REG pins of all three ICs. This diode pulls the VIN_REG pin below the VIN_REG threshold should any of the ICs trigger an NTC fault, which disables all output charge current until the temperature fault condition is relieved.

CONCLUSION

The LT3652 is a versatile platform for simple and efficient solar-powered battery charger solutions, applicable to a wide variety of battery chemistries and configurations. The LT3652 is equally at home in conventionally powered applications, providing small and efficient charging solutions for a wide variety of battery chemistries and stack voltages.

Solar-powered charger solutions maintain panel utilization close to 100%, reducing solution costs due to minimized panel area. The compact size of the IC, coupled with modest external component requirements, allows construction of stand-alone charger systems that are both tiny and inexpensive, providing a simple and efficient solution to realize true grid-independence for portable electronics. ■

Two High Power Monolithic Switching Regulators Include Integrated 6A, 42V or 3.3A, 42V Power Switches, Built-in Fault Protection and Operation up to 2.5MHz

Matthew Topp and Joshua Moore

Power supply designers looking to shrink applications and simplify layout often turn to monolithic switching regulators. Monolithics simplify power supply layout by including the power switch on the die—no external FETs or precision sense resistors are needed. Monolithics can also operate at substantially higher switching frequencies than their controller-only counterparts, thus reducing the size and number of external passive components. The benefits of monolithic regulators are clear, but they traditionally have one major limitation: as the required power level goes up, the likelihood of finding a suitable monolithic regulator diminishes. Two new high power monolithics, the LT3579 and LT3581, solve this problem by integrating 6A (42V) and 3.3A (42V) power switches, respectively.

The LT3579 and LT3581 are highly flexible parts and can be configured in boost, SEPIC, inverting, or flyback configurations. They also offer many unique performance and fault protection features. When configured as high power boost converters, these parts can survive output overloads with only a few additional external components. They can also be configured to provide hot-plug and reverse input voltage protection. In addition, a novel master and slave power switch design allows high voltage charge pump circuits to be made with low power dissipation and few components.

Both parts can be programmed to free-run from 200kHz to 2.5Mhz or can be synchronized with an outside clock source. The parts also provide a clock output pin, enabling the ICs to synchronize other switching regulators. The LT3579 comes in a 4mm × 5mm QFN and 20-lead TSSOP package, and the LT3581 comes in a 4mm × 3mm DFN and 16-lead MSE package.

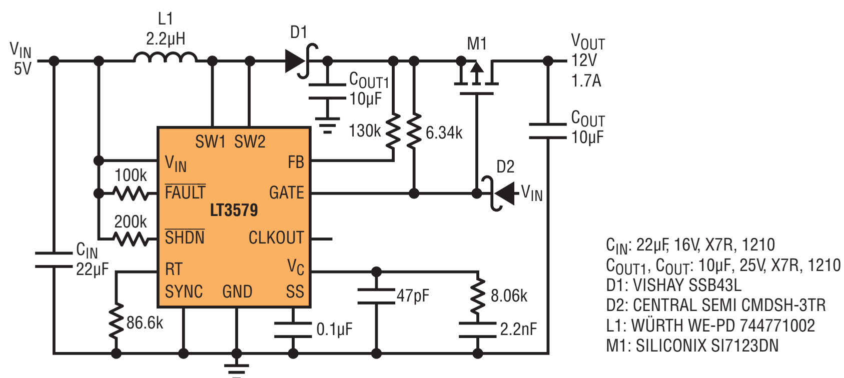


Figure 1. This 5V to 12V boost converter can survive the infamous metal file test where a wire attached to the output is dragged across the jagged surface of a grounded metal file

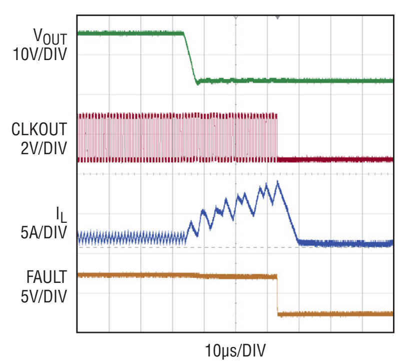


Figure 2. Operating waveforms for Figure 1 circuit during brutal metal file test

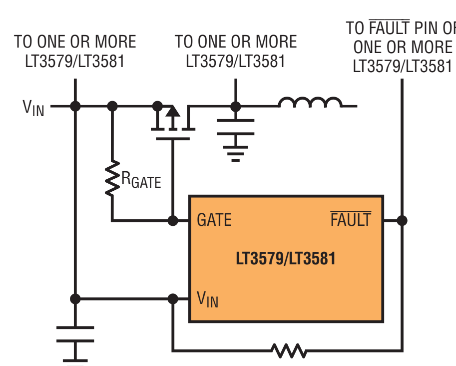


Figure 3. Input disconnect schematic

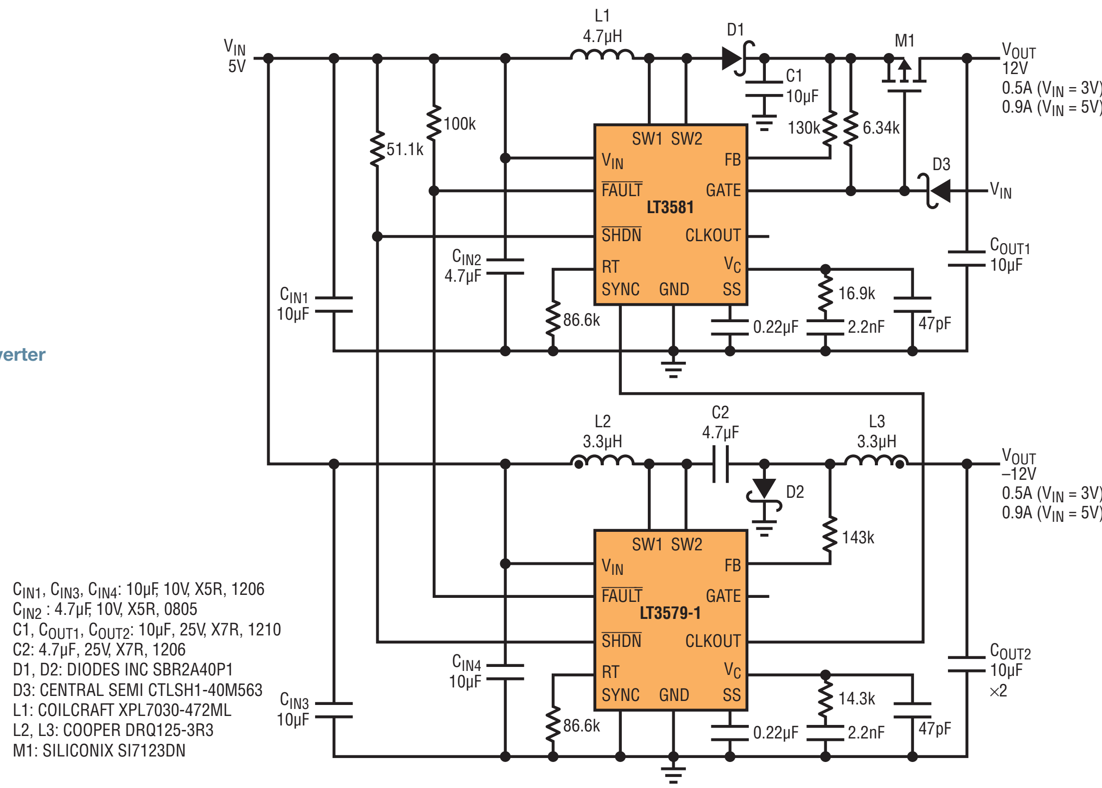


Figure 4. A 3V–5V input to ±12V output converter

FAULT PROTECTION FEATURE: CURRENT OVERLOADS

Most high power boost converters cannot survive an output overload condition because of the inherent DC pathway that exists from the input to output through the inductor and rectifying diode. An output overload or short causes the current in this pathway to increase and run away, thus damaging anything in this pathway or connected to it. The LT3579 and LT3581 include features that protect against such fault events.

Figure 1 shows an LT3579 configured as a 5V input to 12V output boost converter with output short protection. An external PFET, diode, and resistor are all it takes to implement robust output short protection. In fact, this circuit can survive the infamous "file test," where a wire tied to the output is swiped across the surface of a metal woodworking file tied to ground. Figure 2 shows the operating waveforms during this normally destructive test—the LT3579 survives this brutal test without any problems.

These parts also protect against several other types of fault conditions, including overcurrent conditions, overvoltage on V_{IN}, and over-temperature inside the part.

In systems where multiple LT3579s/LT3581s are incorporated to produce multiple rails, a single PFET and resistor can be used on the input side to protect all the rails from a current overload. Figure 3 shows how to set this up. Simply tie the FAULT pins of all ICs together and connect to a single pull-up resistor. The fault control scheme is designed so that if one part goes into fault, it pulls its FAULT pin low, causing the other parts to go into fault as well. Switching activity in all parts stops and all enter into a time-out period. This time-out period allows the components in the system to cool down. Only after the last part exits the time-out period do all parts attempt to restart. To

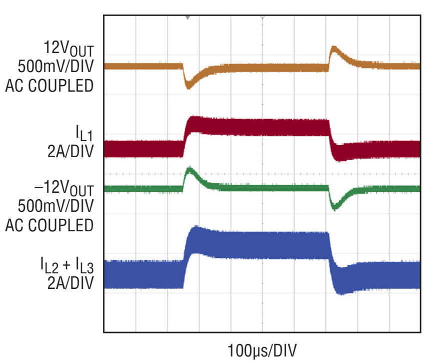


Figure 5. Load step from 0.25A to 0.75A between +12V and −12V rail, with 5V input

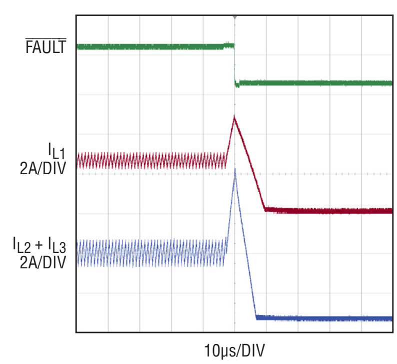


Figure 6. Transient short between rails with 5V input, 0.9A load before short

> The LT3579 and LT3581 include features that protect against a number of fault events including output overloads or shorts, overcurrent conditions, overvoltage on V_{IN}, and over-temperature inside the part.

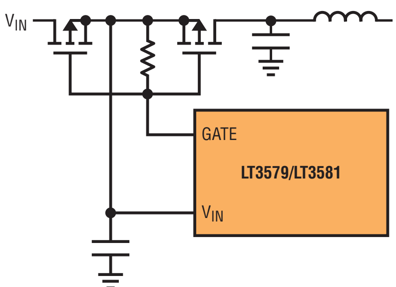


Figure 7. Recommended connections for hot plug, reverse input voltage, and input overvoltage events

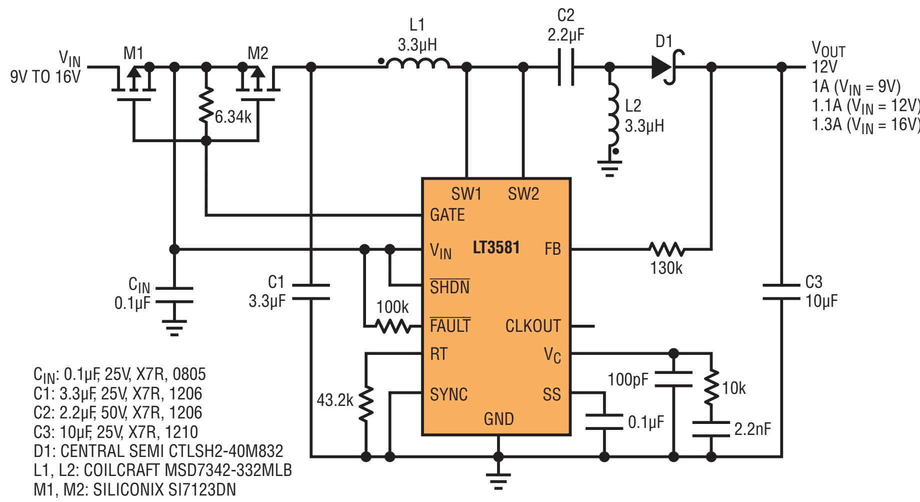


Figure 8. A 9V–16V input to 12V output SEPIC with hot plug, reverse input voltage, and input overvoltage protection

isolate a fault to only one part, simply do not connect the $\overline{\text{FAULT}}$ pins together.

The LT3579 and LT3581 can be easily mixed within a system while maintaining all overload and protection features. Figure 4 shows the LT3579-1 configured as an inverting converter working together with an LT3581 configured as a boost converter. Together, these converters generate a regulated ±12V output at up to 0.9A running off a 3V–5V input, with overload and over-temperature protection. The LT3579-1 is used because it features low input ripple (see page 19 for more about this feature of the LT3579-1). Figure 5 shows the load step response. This system not only accommodates output shorts and overloads between each rail to ground, but it can also tolerate these conditions between the rails as shown in Figure 6.

FAULT PROTECTION FEATURES: HOT PLUG, REVERSE INPUT VOLTAGE, AND INPUT OVERVOLTAGE

The GATE pin, SS pin and related circuitry can also be used to protect against hot plug, reverse input voltage, and input overvoltage events. Figure 7 shows one way to set this up. Hot plug protection is

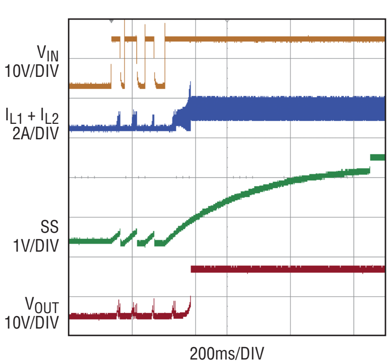


Figure 9. Operating waveforms for a hot plug event

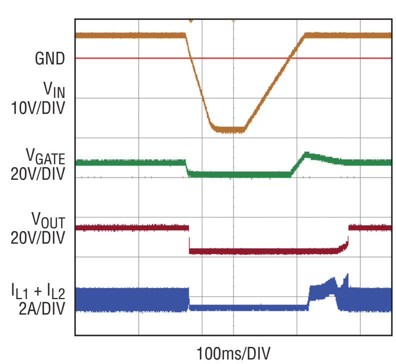


Figure 10. Operating waveforms for a negative V_{IN} transient

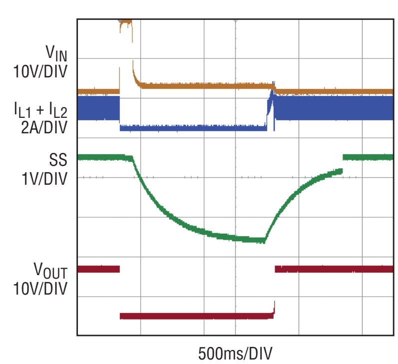


Figure 11. Operating waveforms for a V_{IN} overvoltage transient

Packed with the latest features and some of the highest power levels of any monolithic converters in the industry, the LT3579 and LT3581 venture into applications once reserved for controllers with external FETs.

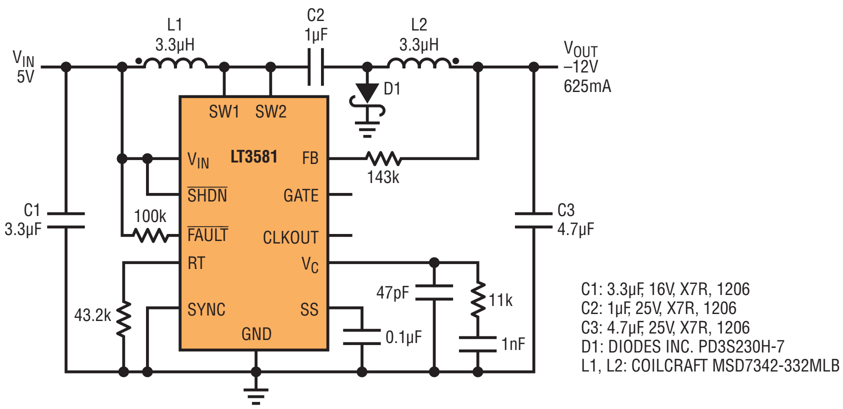


Figure 12. A 5V input to –12V output inverting DC/DC converter

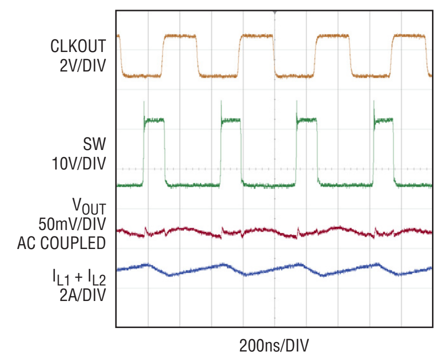


Figure 13. High operating frequency results in low output ripple, even at maximum load

useful for limiting the surge current when the input to the power supply is suddenly stepped from low voltage to normal. In a boost converter, there is a DC path from the input to the output capacitors of the circuit. Since these capacitors are initially discharged, large surge currents are possible if this feature is not used.

Figure 8 shows a circuit designed to handle all these potentially dangerous conditions. Figure 9 shows the operating waveforms during a hot plug event, Figure 10 shows the waveforms during a negative V_{IN} transient, and Figure 11 shows the result of a V_{IN} overvoltage transient. The LT3579/LT3581 survives all these fault conditions and when the fault is removed, resumes a normal start-up cycle.

HIGH POWER AND HIGH SPEED

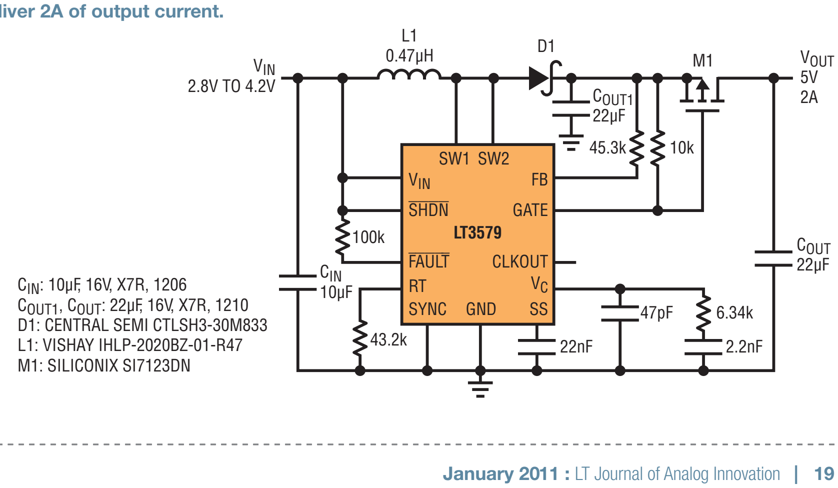
The combination of high current capability and high switching frequency make the LT3579/LT3581 useful in a wide range of applications. Not only can the parts be set for an internal oscillator frequency between 200kHz and 2.5MHz, but the parts can synchronize to an external clock. The CLKOUT pin on the parts is designed to drive the SYNC pins of other switching regulators. The LT3579 and LT3581 also encode die temperature information into the duty cycle of the CLKOUT signal, making thermal measurements simple.

Figure 12 shows a 2MHz, 5V input to −12V output inverting converter with 625mA of output current capability using the LT3581. Due to the high switching frequency, external components are small. The amount of output ripple is also very low, as shown in Figure 13. Figure 14 shows a 2.8V to 4.2V input to 5V output boost running at 2MHz using the LT3579. This circuit is configured to survive output overloads and can deliver up to 2A of output current.

USE THE LT3579-1 FOR EVEN MORE POWER AND SPEED

The LT3579-1 is nearly identical to the LT3579 with one exception: the CLKOUT pin has a 50% duty cycle that does not vary

Figure 14. Li-ion battery to 5V output boost running at 2MHz can deliver 2A of output current.



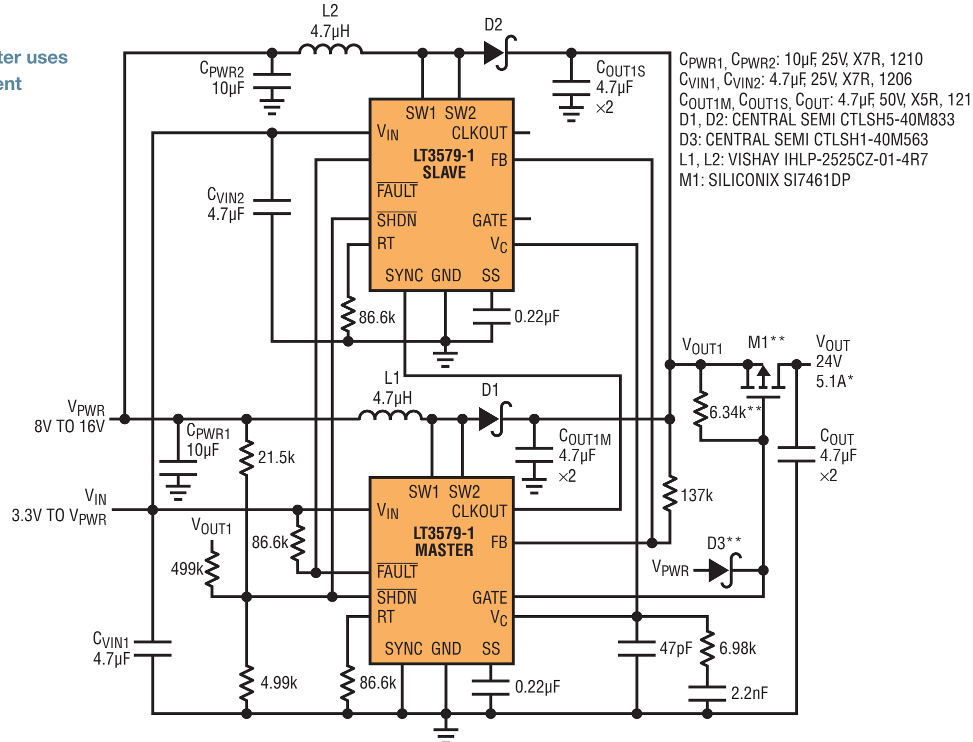


Figure 15. Dual phase 8V–16V input to 24V boost converter uses two LT3579-1s and can deliver up to 5.1A of output current

*MAX OUTPUT CURRENT

	V_{PWR} = 8V	V_{PWR} = 12V	V_{PWR} = 16V
V_{IN} = 3.3V TO 5V	2.4A	3.7A	5.1A
V_{IN} = V_{PWR}	2.2A	3.1A	3.9A

**OPTIONAL FOR OUTPUT SHORT CIRCUIT PROTECTION

with die temperature and is 180° out of phase with its own internal clock whether the part free runs or is synchronized. This difference allows for the construction of a dual phase converter in the boost, SEPIC, or inverting configurations.

A major benefit of out-of-phase operation is an inherent reduction in input and output ripple. Figure 15 shows an 8V–16V input to 24V output dual-phase boost converter capable of delivering up to 5.1A of output current. Each part operates at 1MHz, but because the outputs operate out of phase the effective switching frequency of the converter is 2MHz. Figure 16 shows the output ripple at maximum load, Figure 17 shows the transient load response, and Figure 18 shows the efficiency. This circuit features output short circuit protection, which is easily removed if not needed.

MASTER AND SLAVE SWITCHES

Both the LT3579 and LT3581 have a novel master/slave switch configuration. To implement current mode control, the master switch (SW1 pin) has a current comparator to monitor the current. The slave switch (SW2 pin) has no current comparator and simply operates in phase with the master. For most applications, simply tie SW1 and SW2 pins together to get a 6A or 3.3A total current limit for the LT3579 and LT3581, respectively. Since it may be desirable in some situations to have a lower current limit with an easy way to upgrade to a higher current in the future, these parts can operate using only the master switch. To do this, simply float the slave switch pins. As a result, the LT3579 becomes a 3.4A part and the LT3581 becomes a 1.9A part.

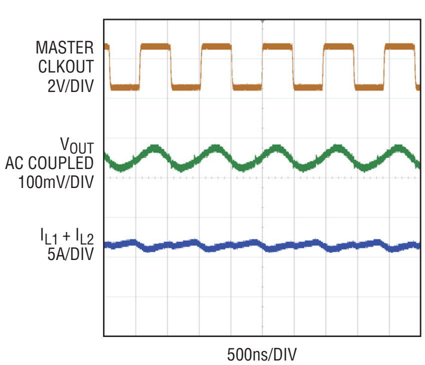


Figure 16. Output ripple at maximum load for the dual phase circuit shown in Figure 15

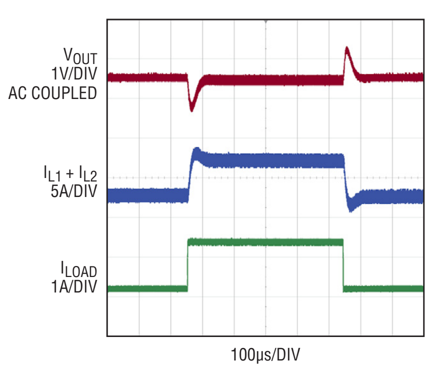


Figure 17. Transient load response for the dual phase circuit shown in Figure 15

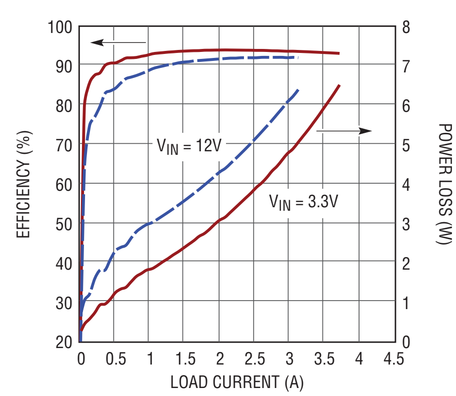


Figure 18. Converter efficiency reaches 93% for the dual phase circuit shown in Figure 15

The master/slave architecture provides a clear advantage when creating high voltage charge pump circuits. It is common practice to create high voltage rails by building a boost converter and adding charge pump stages to double or even triple the boost converter's output voltage.

At higher power levels, it becomes necessary to dampen the current spikes inherent in these charge pump circuits. Figure 19 shows a traditional approach, which uses high power resistors within the charge pumps. Without these resistors, the current spikes would cause the switching regulator to false trip, causing erratic and unstable operation. The problem is that these resistors add to the component count and generate additional heat.

Figure 20 shows a better solution in which the master/slave switch configuration eliminates the need for the high power resistors. All current spikes caused by the charge pump stages are only seen by the slave switch, eliminating the possibility of false tripping.

BEST IN CLASS SPECIFICATIONS

With so many new features, it is easy to overlook that the LT3579 and LT3581 include all the standard features available in many modern Linear Technology switching regulators. Both parts feature a wide input operating voltage range. The LT3579 can operate from 2.5V to 16V and survive transients to 40V. The LT3581 can operate from 2.5V to 22V with transients to 40V. Both parts have built-in programmable soft-start and automatic frequency foldback. Single pin feedback enables both positive and negative output voltages. Each part has an accurate comparator/reference for the $\overline{\text{SHDN}}$ pin, allowing the pin to be used as a programmable undervoltage lockout.

CONCLUSION

Packed with the latest features and some of the highest power levels of any monolithic converter in the industry, the LT3579 and LT3581 venture into applications once reserved for controllers. Monolithic converters can operate at clock speeds far beyond the ability of controllers, resulting in solution sizes unachievable by controller solutions. Advanced fault protection features make it possible to produce compact and rugged solutions without additional ICs.

A new master and slave switch architecture not only allows adjustment of the current limit but also significantly eases the design of high voltage boost plus charge pump circuits. These new features are simple to implement, yet stay out the way if not required. The LT3579, with a 6A, 42V switch comes in a 4mm × 5mm QFN or 20-lead TSSOP package. The LT3581, with a 3.3A, 42V switch comes in a 3mm × 4mm DFN or 16-lead MSE package. ■

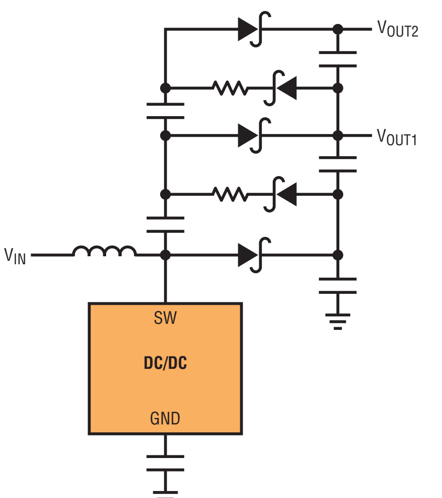


Figure 19. Traditional method for building high power boost plus charge pump circuits

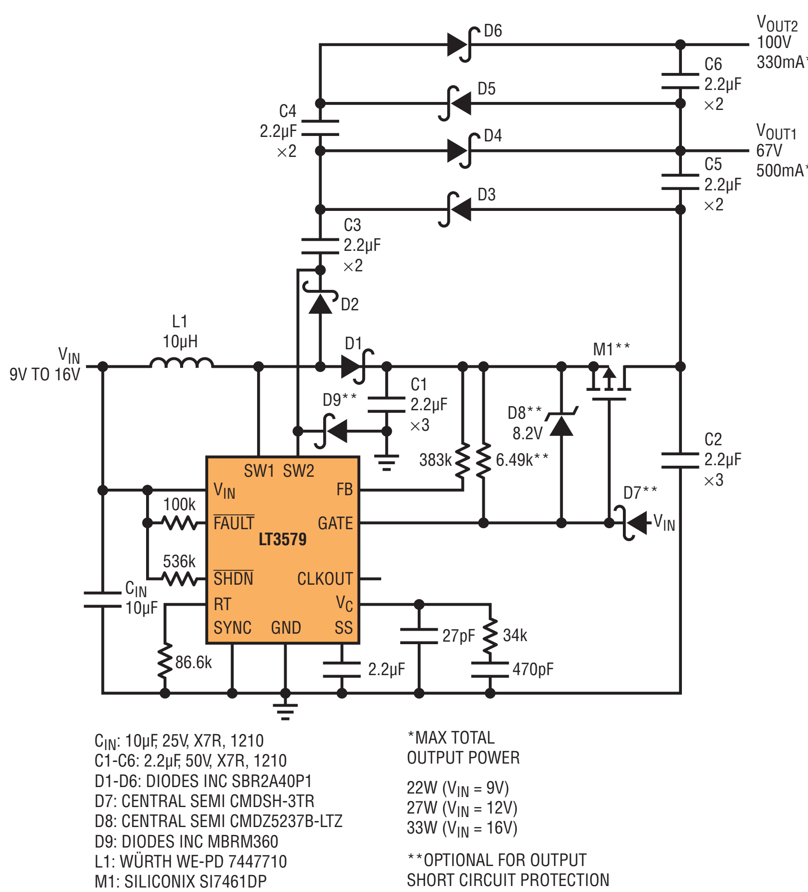


Figure 20. Master and slave switches of the LT3579/LT3581 allow a cooler running, simpler method for building boost plus charge pump circuits.

I²C System Monitor Combines Temperature, Voltage and Current Measurements for Single-IC System Monitoring

David Schneider

The limit on the complexity of large integrated circuits is dominated by how much power they can dissipate. The trend in µprocessors and FPGAs is toward packing more features into smaller ICs, run at ever-lower voltages. The resulting rise in power dissipation makes it increasingly difficult to monitor and control sources of heat. Where it was once suitable to have a single chassis temperature monitor to deduce the health of the system, modern electronic systems produce many high power, point sources of heat that would go undetected with a simple chassis monitor.

LTC2990 Features

- Measures Voltage, Current and Temperature
- Measures Two Remote Diode Temperatures
- ±1°C Accuracy, 0.06°C Resolution
- ±2°C Internal Temperature
- 15-Bit ADC Measures Voltage and Current
- 3V to 5.5V Supply Operating Voltage
- I²C Serial Interface with Four Selectable Addresses
- Internal 10ppm Voltage Reference
- 10-Lead MSOP Package

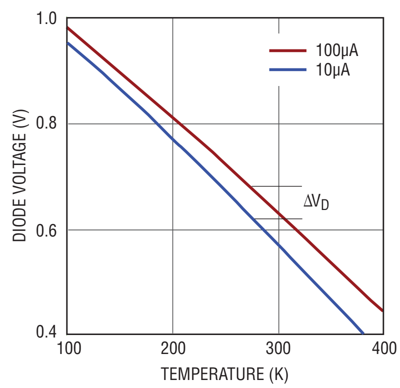


Figure 1. Diode voltage V_D vs temperature T(K) for different bias currents

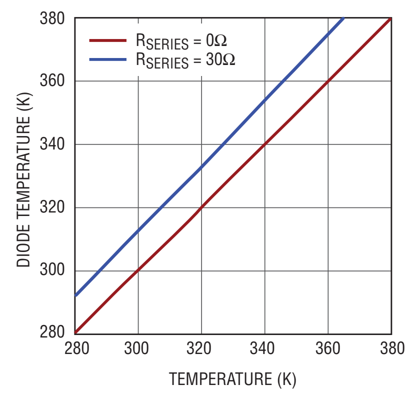


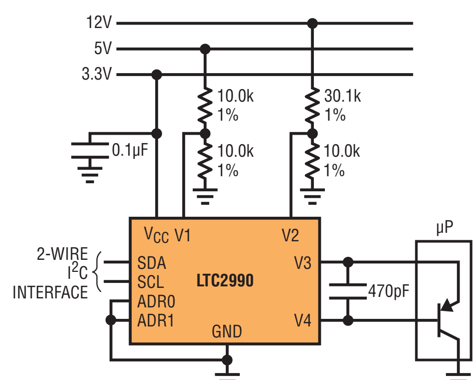
Figure 2. Reported uncompensated diode temperature T_D(K) vs temperature T(K) with series resistance

Even PC processors feature dedicated secondary fans in order to keep specific die junction temperatures below an acceptable level. One line of defense against overheating is to increase fan speeds, while another is to temporarily disable the heat source. In telecommunication systems and other always-on applications, it is not acceptable to disable the system, so the only line of defense is to increase cooling.

One problem with reactive cooling is that large HVAC systems have lag—they require time to reduce the ambient temperature. Moreover, microprocessors and FPGAs are embedded in chassis with surrounding thermal mass, which take even longer to respond to a request for cooling. Therefore it is important to monitor not only the temperature, but also the rate of temperature change in order to apply the correction before temperatures escalate to dangerous levels. An integrated power and temperature monitoring system can use changes in power consumption to anticipate changes in temperature.

The LTC2990 measures ambient and remote temperature, plus voltage and current, so the measurements are easily combined. Temperature sensors can be diodes or transistor sensors—remote sensor diodes are available as substrate diodes in large microprocessors and

Figure 3. Single LTC2990 accurately monitors three voltage rails and microprocessor temperature (via substrate diode)



VOLTAGE, CURRENT AND TEMPERATURE CONFIGURATION:
CONTROL REGISTER: 0x58

T_{AMB}	REG 4, 5	0.0625°C/LSB
V1 (+5)	REG 6, 7	0.61mVLSB
V2(+12)	REG 8, 9	1.22mV/LSB
$T_{PROCESSOR}$	REG A, B	0.0625°C/LSB
V_{CC}	REG E, F	2.5V + 305.18µV/LSB

It is important to monitor not only the temperature, but also the rate of temperature change in order to apply corrections before temperatures escalate to dangerous levels. An integrated power and temperature monitoring system can use changes in power consumption to anticipate changes in temperature.

FPGAs. The I^2C serial interface provides four addresses accommodating up to four LTC2990s on the same bus.

PRINCIPLE OF OPERATION

Measuring the absolute temperature of a diode is possible due to the relationship between current, voltage and temperature described by the classic diode equation:

$$I_D = I_S \bullet e^{(V_D/\eta \bullet V_T)}$$

or

$$V_D = \eta \bullet V_T \bullet \ln \frac{I_D}{I_S} \qquad (1)$$

where I_D is the diode current, V_D is the diode voltage, η is the ideality factor (typically close to 1.0) and I_S (saturation current) is a process dependent parameter. V_T can be broken out to:

$$V_T = \frac{k \bullet T}{q}$$

where T is the diode junction temperature in Kelvin, q is the electron charge and k is Boltzmann's constant. V_T is approximately 26mV at room temperature (298K) and scales linearly with Kelvin temperature. It is this linear temperature relationship that makes diodes suitable temperature sensors. The I_S term in the equation above is the extrapolated current through a diode junction when the diode has zero volts across the terminals. The I_S term varies from process to process, varies with temperature, and by definition must always be less than I_D. Combining all of the constants into one term:

$$K_D = \frac{\eta \bullet k}{q}$$

where $K_D = 8.62^{-5}$, and knowing $\ln(I_D/I_S)$ is always positive because I_D is always greater than I_S, leaves us with the equation that:

$$V_D = T(KELVIN) \bullet K_D \bullet \ln \frac{I_D}{I_S}$$

where V_D appears to increase with temperature. It is common knowledge that a silicon diode biased with a current source has an approximately –2mV/°C temperature relationship (Figure 1), which is at odds with the equation. In fact, the I_S term increases with temperature, reducing the $\ln(I_D/I_S)$ absolute value yielding an approximately –2mV/deg composite diode voltage slope.

To obtain a linear voltage proportional to temperature we cancel the I_S variable in the natural logarithm term to remove the I_S dependency from the equation 1. This is accomplished by measuring the diode voltage at two currents I_1, and I_2, where $I_1 = 10 \bullet I_2$),

Subtracting we get:

$$\Delta V_D = T(KELVIN) \bullet K_D \bullet \ln \frac{I_1}{I_S} - T(KELVIN) \bullet K_D \bullet \ln \frac{I_2}{I_S}$$

Combining like terms, then simplifying the natural log terms yields:

$$\Delta V_D = T(KELVIN) \bullet K_D \bullet \ln(10)$$

and redefining constant

$$K'_D = K_D \bullet \ln(10) = \frac{198\mu V}{K}$$

yields

$$\Delta V_D = K'_D \bullet T(KELVIN)$$

Solving for temperature:

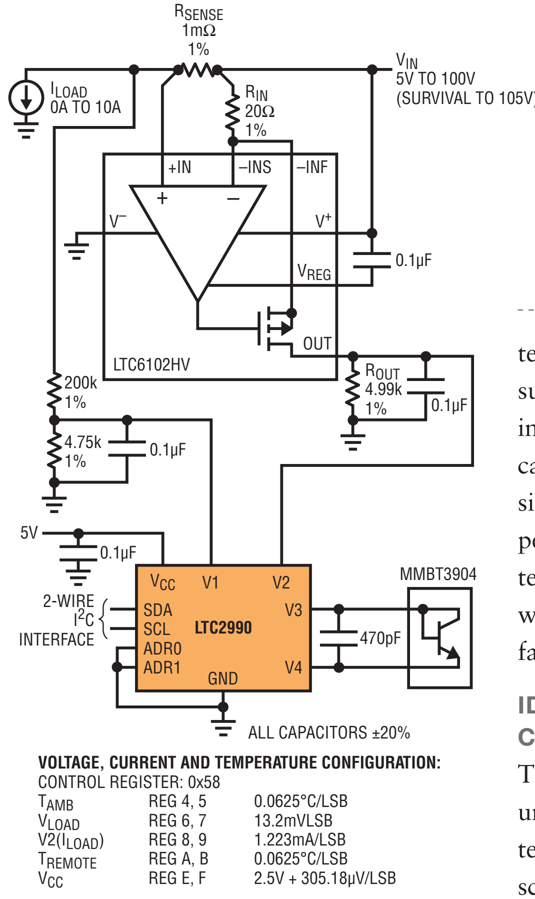
$$T(KELVIN) = \frac{\Delta V_D}{K'_D}$$

means that is we take the difference in voltage across the diode measured at two currents with a ratio of 10, the resulting voltage is 198µV per Kelvin of the junction with a zero intercept at 0 Kelvin.

Table 1. Recommended transistors to be used as temperature sensors

MANUFACTURER	PART NUMBER	PACKAGE
Fairchild Semiconductor	MMBT3904	SOT-23
Central Semiconductor	CMPT3904 CET3904E	SOT-23 SOT883L
Diodes, Inc.	MMBT3904	SOT-23
On Semiconductor	MMBT3904LT1	SOT-23
NXP	MMBT3904	SOT-23
Infineon	MMBT3904	SOT-23
Rohm	UMT3904	SC-70

Figure 4. High voltage current sensing



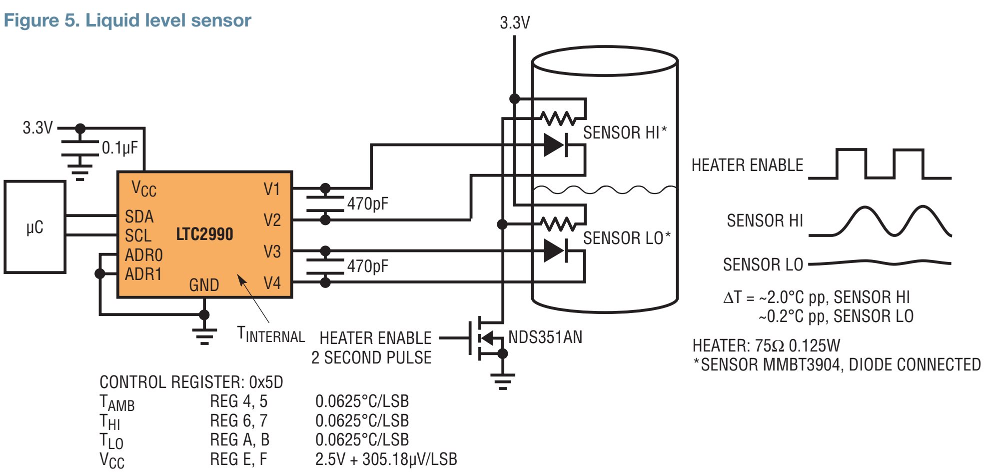
Thus, the equation describes a perfectly linear, monotonically increasing temperature result provided that the current ratio is constant, but arbitrary to the absolute value of the currents. The two independent diode voltages measured at I_1 and I_2 both have negative temperature dependence (~2mV/°C), but the diode voltage at the larger bias current has a slightly smaller negative slope, yielding a positive composite ΔV_D term (Figure 1). Another way to think of it is that when the junction is biased at a higher current, it is more probable (by a factor of $\ln(I_1/I_2)$ that a thermally generated carrier will have sufficient energy to exceed the diode junction energy barrier. Using this method, common diodes and transistors can be used as temperature sensors over an operating range of –55°C to 150°C, typically limited by packaging materials.

One complication with the method described above is the effect of series resistance with the sensor diode. At 193µV/°C slope, it does not take much series resistance to yield artificially high temperature readings due to the additional voltage drop (the temperature would always report falsely high). This series resistance can be in the form of copper traces and junction contact resistances. Moreover, this resistance can have a temperature coefficient (copper is 3930ppm/°C) yielding a temperature dependent additive term. To combat this, multiple ΔV_D measurements are made at multiple operating points, so the series resistance can be calculated and compensated. The LTC2990 simplifies all of these complications, compensates for them and converts the diode temperature straight to a digital result, where it can be read over the I²C interface to a host microcontroller or FPGA.

IDEALITY FACTOR AND COMPENSATION

The LTC2990 can report temperature in units of degrees Celsius or Kelvin. Kelvin temperature is valuable when fine-tuning scaling calibration factors (η) of various manufacturers' devices. Since absolute temperature is measured by silicon diodes, the gain or slope of a sensor extrapolates to absolute zero, or 0 Kelvin. An ideality factor error of +1%, or 1.01, represents a temperature error of 273.15 • 0.01 ≈ 2.7°C at 0°C. At 100°C (398.15K), a 1% error in ideality factor translates to an error of approximately 4°C. The LTC2990 is factory calibrated for an ideality factor of 1.004, which is typical of the popular MMBT3904 NPN transistor. Transistor sensors are made of ultra-pure materials, inherently hermetic, small and inexpensive, making them very attractive for –55°C to 125°C applications. The linearity of transistor sensors eliminates the need for linearization in contrast to thermocouples, RTDs and thermistors. The semiconductor purity and wafer-level processing limits device-to-device variation, making these devices interchangeable (typically < 0.5°C) for no additional cost. Several manufacturers

Figure 5. Liquid level sensor



supply suitable transistors—some recommended sources are listed in Table 1.

If a target sensor ideality factor differs from 1.004, it can be compensated in the following manner:

$$T_{ACTUAL}(K) = \frac{T_{MEAS}(K) \bullet \eta_{SENSOR}}{1.004}$$

where T_{ACT} and T_{MEAS} are in Kelvin degrees. To perform the scaling in Celsius degrees:

$$T_{ACTUAL}(°C) =$$

$$\left(T_{MEAS}(°C) + 273.15\right) \bullet \frac{\eta_{SENSOR}}{1.004} - 273.15$$

TEMPERATURE MONITORING APPLICATIONS

Figure 3 illustrates a typical application where the LTC2990 is configured to measure a substrate diode, which monitors the microprocessor temperature and three system power supply voltages (12V, 5V and 3.3V). To extend the measurement range of the voltage inputs, resistive voltage dividers are used for the 5V and 12V voltages. For this application the 0.1% accuracy of the LTC2990 introduces negligible gain error over what is produced by the resistor divider network.

The 14-bit resolution also allows the use of larger voltage divider networks while maintaining high resolution. For example, compare the LTC2990 to a device with a 10-bit dynamic range that can measure 12V to 2% accuracy. The LTC2990 can measure a 192V signal with the same LSB weight (11.72 mV) as the 10-bit part and maintain 2% accuracy, again dominated by the 1% precision of the external voltage divider network components.

Figure 6. Fan/air filter/temperature alarm

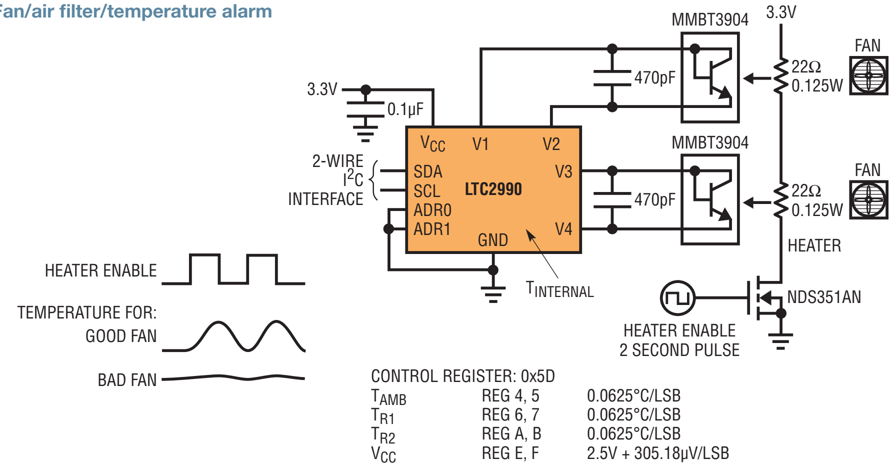


Figure 4 shows an example of high voltage monitoring. The LTC6102HV is optimized for accurate high-side current sensing. Using a voltage divider for current sensing would result in large gain errors, > 4%, and low resolution for the current sensing function. By attenuating the common-mode voltage with a voltage divider, the differential voltage is attenuated by the same factor. By making the sense resistor larger to increase the gain, the power-loss scales with the square of sense voltage.

Liquid Level Sensing

Figure 5 illustrates a simple application that uses temperature measurement to indicate liquid level. A heater is pulsed, and the temperature sensor is monitored for a corresponding change in temperature. The measurement indicating the liquid level threshold is actually a combined thermal conductivity and heat capacity measurement, which is proportional to the change in temperature.

In operation, the remote temperature is measured and stored for reference, after which the heater is switched on, and given a few seconds to heat the surroundings. The temperature is again measured and compared with the first temperature. If the temperature difference is greater than a preset threshold, the sensor is determined to be above the liquid level. If the sensor is submerged in the liquid, the relatively larger heat capacity of the liquid prevents the temperature from rising quickly. The smaller the discernable temperature change, the less heater power is required for detection. For this

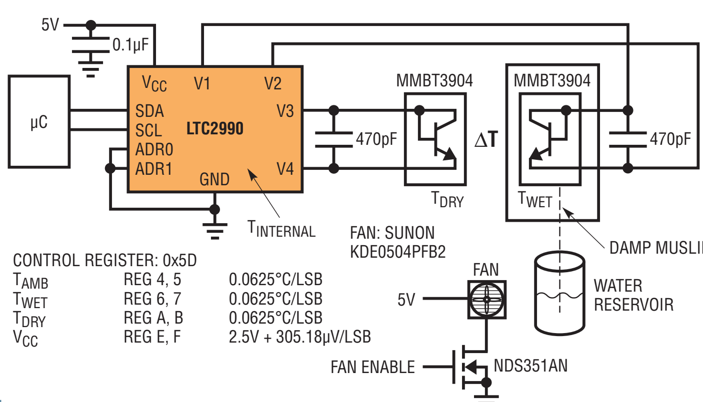


Figure 7. Wet bulb psychrometer

application, filtering the remote temperature sensor can trade time for power.

Airflow Measurement

Airflow can also be measured by monitoring temperature. Figure 6 illustrates a method using a heater and a temperature sensor similar to the liquid level application. In this application the cooling power of the fan is tested by turning on a small heater and measuring the temperature rise, or the rate of temperature rise with the remote sensor. In the absence of cooling air, both the absolute and the rate of temperature rise increases.

This method can be used to detect faulty fans, or dust buildup on air filters. Whatever the cause, the circuit can signal inadequate cooling conditions. Thermistors are undesirable in this application because their change in resistance is not consistent over a broad operating temperature range.

Temperature monitoring can signal the alarm for overheating, but simple temperature monitoring cannot predict overheating. By measuring power (voltage and current) and cooling capacity, one can predict a problem prior to a catastrophic failure. This is important, because it takes time to correct an over-temperature condition due to the heat capacity of the system and its immediate evironment.

Humidity Measurement

Humidity can also be measured using temperature monitoring as shown in Figure 7. One can implement a humidity sensor in the form of a psychrometer. A psychrometer uses two temperature sensors to detect humidity: one of them is dry and acts as a reference; the other is dampened and exposed to airflow. The cooling effectiveness of the water on the wet sensor is a function of humidity. In a 100% humidity environment, the forced air on the wet sensor yields no evaporation and thus yields no cooling effect. Conversely, in an arid environment, the cooling due to the heat of evaporation can cool the "wet bulb" temperature sensor significantly. The dry temperature sensor reads the same with or without airflow.

The temperature difference function is non-linear, and commonly implemented with lookup tables in a host microprocessor. Thus the temperature difference between the wet and dry temperature sensor in the presence of air movement is an indirect measurement of humidity.

CURRENT SENSING WITH PARASITIC RESISTANCE

The application circuit in Figure 8 uses the LTC2990 as a current monitor. The sense resistor in this application is the parasitic resistance in a buck switching

Figure 8. Current sensing with inductor parasitic resistance

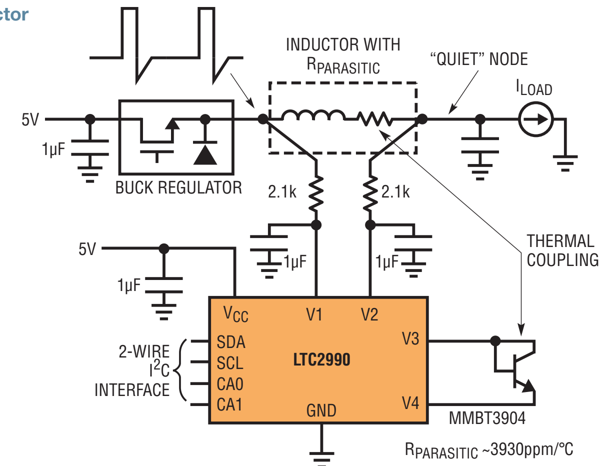


Figure 9. Example pseudo-code for an FIR filter

```
//FIR digital filter example (Moving Average Filter)
#define filter_dim 16

int16 FIR_temp[filter_dim]; //memory allocation scales with filter size!
int8 i = 0;
int8 j;
int32 accumulator;
int16 filtered_data;

// Moving Average filter for ltc2990 temperature
// Reduces noise by factor of sqrt(filter_dim), or in this case ~4

    if((ltc2990_temperature && 0x1000) == 0x1000)
        FIR_temp[i++%filter_dim] = ltc2990_temperature | 0xE000; //sign extend data
    else
        FIR_temp[i++%filter_dim] = ltc2990_temperature & 0x1FFF; //strip off alarms & data_valid

    accumulator=0; //cleared each pass through filter routine

    for(j=0; j<filter_dim; j++)
        accumulator += FIR_temp[j];

    filtered_data = (int16)(accumulator/filter_dim); //could use >>4, where 4 = log2(filter_dim)
```

Temperature sensors can be diodes or transistor sensors. Remote sensor diodes are available as substrate diodes in large microprocessors and FPGAs.

regulator. At the output of the buck regulator is the switching node, which typically toggles between V_{CC} and ground. The average value of this voltage is the output regulated voltage. The load current runs through the power supply inductor, which has a series parasitic resistance. This parasitic resistance is typically small and is minimized in the power supply design to maximize efficiency.

The RC filter across the inductor into the LTC2990 V1 and V2 pins filters out the transitions seen on the switching node. The quiet node is equivalently filtered to maintain circuit balance due to LTC2990 input common-mode sampling currents. Knowing $R_{PARASITIC}$ and V1 – V2, the load current can be calculated. Moreover, V_{CC} is measured by the LTC2990, so load voltage and load current are known; thus load power can be calculated.

Because $R_{PARASITIC}$ is typically copper, it has a temperature coefficient of resistance (TCR) of ~3930ppm/°C. By measuring the inductor temperature, this relatively large error source can be compensated by introducing a temperature dependent gain coefficient inversely proportional to the resistor TCR. Knowing the load power, the inductor temperature and ambient temperature from the LTC2990 internal temperature sensor, you can predict the rise in temperature of the inductor for various load currents. This can be important to avoid inductor core saturation at high temperatures, which can be a potentially catastrophic event to the buck regulator.

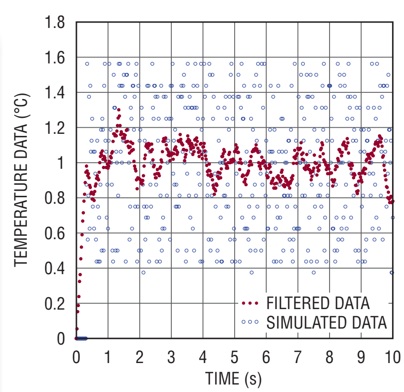
MEASUREMENT ACCURACY AND NOISE

The LTC2990 can measure temperatures at a rate of ~20Hz. This allows the designer to trade resolution and noise performance for speed. At 20Hz, the noise is ~1.2°C peak to peak, or ~0.2°C RMS. For most board level monitoring applications this is excellent performance, though there are applications that require lower noise levels, which can be obtained by controlling the measurement bandwidth. The temperature data output is digital, so this requires the band limiting function to be in the form of a digital filter. Example filters and their simulated performance

Figure 10. Example pseudo-code for an IIR filter

```
//IIR digital filter example (higher averaging for limited ram application)

#define filter_coefficient 16 //a power of 2 here can speed up filter

int8 j;
int16 filtered_data;
static int32 accumulator = 0; //GLOBAL, only cleared at boot time. Does not change with filter growth!

    // implements: filtered_temperature = (filtered_temperature*(filter_coefficient-1) +
    // ltc2990_temperature)/filter_coefficient

    for(j=0;j<(filter_coefficient-1);j++)
        //multiply by repeated add resulting in accumulator = filter_coefficient-1
        accumulator += accumulator;

     //add the latest LTC2990 output to the accumulator once

    if((ltc2990_temperature && 0x1000) == 0x1000)
        accumulator = ltc2990_temperature | 0xE000; //sign extend data
    else
        accumulator = ltc2990_temperature & 0x1FFF; //strip off alarms & data_valid

    accumulator >>= 4;  // where 4 = log2(filter_coefficient)
    filtered_data = (int16)accumulator;
```

Figure 11. Simulated IIR filter response



The LTC2990 serves up the results with 14-bit resolution via I^2C. Its small package size, integrated voltage reference and 1µA shutdown current are ideal for portable electronics applications.

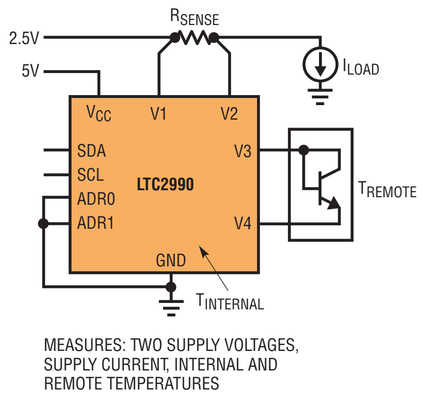


Figure 12. Temperature compensated current sense resistor

for equal over-sampling ratios are illustrated in Figures 9 through 11.

The LTC2990 measurement resolution is 14-bit for voltages and 15-bit for currents. The monitor contains an internal reference with 10ppm/°C stability, requiring no external support components. Ground referenced single-ended voltages can be measured in a range of zero volts to V_{CC} + 0.2V, (4.9V max), and differential voltages in a range of ±300mV with a common mode voltage range of zero volts to V_{CC} + 0.2V, which is suitable for current sensing and bridge circuits.

Scaling single-ended, ground referenced voltages is common practice using standard voltage dividers with precision resistors. Sensing current with high accuracy requires more attention to detail. In the case of current measurements, the external sense resistor is typically small, and determined by the full-scale input voltage of the LTC2990. The full-scale differential voltage is 0.3V. The external sense resistance is then a function of the maximum measurable current, or:

$$R_{EXTERNAL(MAX)} = \frac{0.3V}{I_{MAX}}.$$

THE FINE POINTS OF CURRENT SENSE MEASUREMENT

If you wanted to measure a current range of ±10A, the external shunt resistance would equal 0.3V/10A = 30mΩ. This resistance is fairly small, and one may be tempted to implement this resistor using a thin copper trace on the printed circuit board. The dimension of this resistor is determined by the bulk resistance of the PCB copper, the thickness of the copper clad sheet, the length and width of the copper trace. PCB clad material thickness is specified by weight in units of ounces per square foot. Typical copper thicknesses are ½, 1, and 2 oz, corresponding to 0.7, 1.4 and 2.8 mils thickness, respectively. When multi-layer printed circuit boards are manufactured, via holes are electroplated. This electroplating process, also adds copper thickness to the outer copper layers or the PCB. Even if the thickness of the copper clad on the PCB stock

Figure 13. Current sense connections

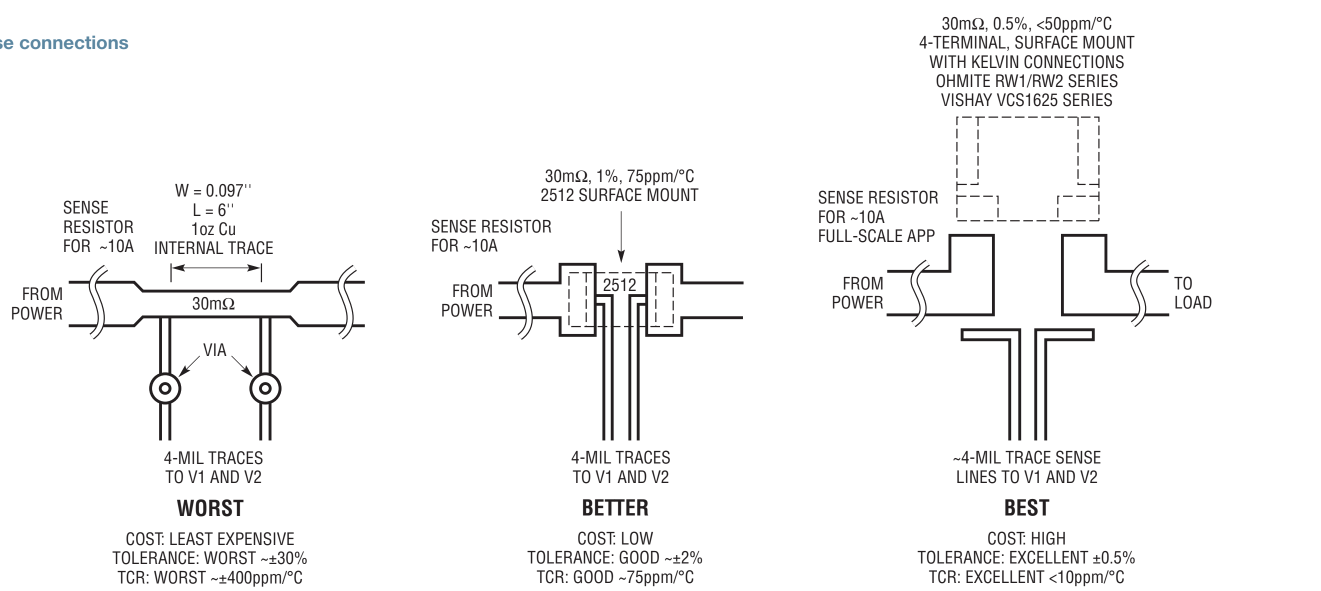


Table 2. Current sense resistor precision comparison table

SENSE RESISTOR TYPE	RESISTANCE TOLERANCE (%)	TCR % FOR 50°C RISE, (ppm)	TOTAL ERROR %, (BITS PRECISION)
Copper Trace • R Not calibrated • TCR Not calibrated	20	20, (3970)	40, (1.3)
2-Terminal Discrete Resistor • R Not calibrated • TCR Not calibrated	2	0.375, (75)	2.375, (5.4)
4-Terminal Precision Discrete Resistor • R Not calibrated • TCR Not calibrated	0.5	0.05, (10)	0.55, (7.5)
Copper Trace • R Calibrated & Compensated • TCR Calibrated & Compensated	0.025	0.5, (3970 ±100)	0.525, (7.5)
2-Terminal Discrete Resistor • R Calibrated & Compensated • TCR Compensated	0.025	0.375, (75)	0.4, (8.0)
4-Terminal Precision Discrete Resistor • R Calibrated & Compensated • TCR Compensated	0.025	0.05, (10)	0.075, (10.4)
4-Terminal Precision Discrete Resistor • R Calibrated & Compensated • TCR Calibrated & Compensated	0.025	0.005, (x ±1)	0.075, (11.7)

material is well controlled, the thickness of the trace will have a manufacturing variable due to plating thickness, when plating the via holes. The copper thickness uncertainty impacts the sense resistor value, and hence the resulting differential volts/amp that the LTC2990 measures.

Copper has a relatively high temperature coefficient of resistance (TCR), with a value of ~3930ppm/K. The TCR of copper also changes with temperature. Assuming that the current through the sense resistor produces negligible self-heating over a –40°C to 85°C temperature range, the copper resistance changes about 50%. If the sense resistor does heat itself, there is a nonlinear current-to-voltage distortion in the measurement. For this reason, there are special sense resistors manufactured with low TCR values (Figure 13). If the temperature rise in the sense resistor is large due to large currents, even small TCRs can yield large measurement errors. The LTC2990 can be used to track the sense resistor temperature so its TCR can be compensated for, improving measurement accuracy.

CONCLUSION

The LTC2990 is able to measure electrical power (via voltage and current) and temperature and serve up the results with 14-bit resolution via I^2C. Combo power and temperature measurements are commonly used for industrial control and fault monitoring applications, including air and fluid flow, liquid level, over/under temperature, power sharing and limiting, redundancy management, alarm generation, nonvolatile memory write/erase protection, and countless others. The small package size, integrated voltage reference and 1μA shutdown current are ideal for portable electronics applications. Remote diode sensors are available in extremely small packages (Central Semiconductor CET3904E: 1.05mm × 0.65mm) allowing for fast thermal response times, taking advantage of the 50ms temperature measurement capabilities of the LTC2990. ■

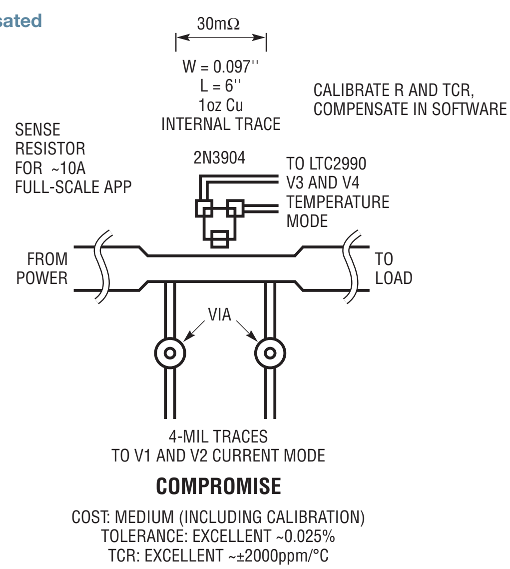


Figure 14. Temperature compensated copper trace resistor

Isolated Data Transmission and Power Conversion Integrated Into a Surface Mount Package

Keith Bennett

Galvanic isolation is used in a variety of industries, most commonly to provide safety against potentially lethal voltages. Isolation is also used to eliminate the effects of noise and common mode voltage differences created by ground loops, or as a level shifter between dissimilar operating voltages. Typically, building an isolated system requires a number of passive and active components on either side of the isolation barrier, in addition to the barrier components themselves. These barrier components can be optical, magnetic, capacitive, RF or even GMR (giant magnetoresistance) devices.

Barrier components are notoriously difficult to use, adding significant design time and cost to isolated systems. With this in mind, Linear Technology has developed a line of µModule® isolators that reduces the design of isolated systems to simply plugging in a module—no complex barrier components are required. In fact, µModule isolators require no external components at all.

Linear Technology µModule isolators use magnetically coupled techniques to provide data and power isolation in a single package. The result is an easy-to-use, low power, robust solution with excellent field immunity. The LTM2881 isolated RS485/RS422 transceiver and LTM2882 dual isolated RS232 transceivers use µModule isolator technology to provide complete transceiver-plus-power solutions in 15mm × 11.25mm × 2.8mm surface mount packages.

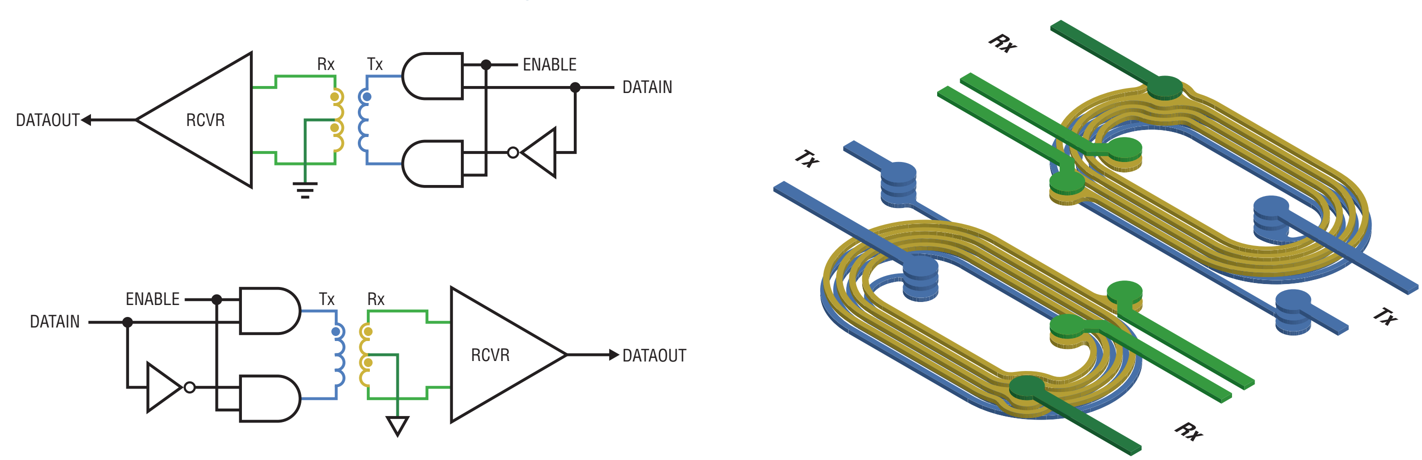
ISOLATED DATA TRANSMISSION

µModule isolators use inductively coupled coils, or coreless transformers, to pass data across the isolation boundary. Electrical and mechanical representations are illustrated in Figure 1. Dedicated integrated circuits perform the data transmission and receiving functions for all channels and both data directions.

Three channels of data are encoded, serialized into a packet, and transmitted across the isolation boundary in each direction. Data transmission in one direction is completely independent of data transmission in the other direction.

The encoding process is initiated when the data changes (edge triggered) on any of the three inputs. The three data inputs consist of one high priority and two low priority channels. A state change on the high priority channel preempts an encoding process initiated by a low priority channel state change. This scheme ensures that the data on the high priority channel is transmitted with no jitter to the output, but in turn produces some amount of timing uncertainty on the

Figure 1. Data isolation equivalent electrical and mechanical configuration



Linear Technology has developed a line of µModule isolators that reduces the design of isolated systems to simply plugging in a module—no complex barrier components are required. In fact, µModule isolators require no external components at all.

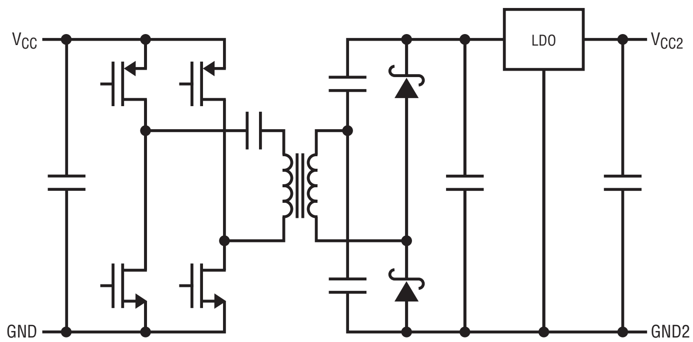


Figure 2. Simplified isolated power conversion stage

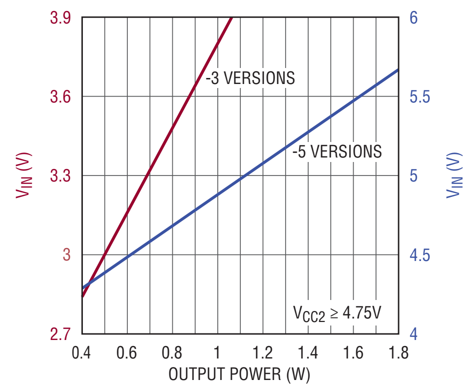


Figure 3. µModule isolator power capability

low priority channels. The high priority channel is assigned to DI to (Y,Z) and (A,B) to RO for the LTM2881, and from T1IN to T1OUT and R1IN to R1OUT for the LTM2882. All remaining channels for these products are low priority. Encoding is completed by sampling all three input data states and transmitting the data across the coreless isolation transformer as a series of pulses.

Each transmission is received as a differential signal, checked for errors, decoded, and clocked to the associated data output. The receiver is connected to a center tapped transformer secondary. This winding arrangement provides common mode rejection since any coupled signals are cancelled by the opposing winding geometry at the receiver input. The error checking process determines if the transmitted data is valid; if not, the outputs are not updated.

The encoding/decoding process supports a minimum data throughput rate of approximately 21Mbps. Edge events occurring during a packet transmission initiate a new capture operation, which is completed at the end of the current transmit cycle.

Data is refreshed at a rate of approximately 1MHz, ensuring DC correctness of all data outputs. If four invalid packets are received in succession then a communication fault is generated. This fault mode forces a high impedance state on certain outputs, for instance RO and DOUT for the LTM2881, and R1OUT and R2OUT for the LTM2882. This fault condition can be easily detected in critical applications.

The coreless transformer is fabricated within the µModule substrate's inner layers. Minimum coil layer separation of 60µm is provided by a 2-ply Bismaleimide-Triazine (BT) high performance resin-based laminate.

ISOLATED POWER TRANSMISSION

Isolated power is generated by more conventional means. The overall power converter consists of a full-bridge square wave oscillator AC-coupled to an isolation transformer primary, rectified with a full wave voltage doubler connected to the transformer secondary, and post regulated by a low-dropout linear regulator (LDO). Figure 2 schematically shows the power conversion stage.

The overall power topology provides a simple, flexible, fault tolerant and relatively efficient design (~65%). Bridge current is monitored and limited to protect the power switches and transformer. The primary and secondary are both AC-coupled, preventing transformer saturation under any condition. All components are integrated within the µModule package; no external decoupling is required for proper operation.

Two input operating voltage ranges, determined by transformer turns ratio, are available: 3V to 3.6V (-3 versions) and 4.5V to 5.5V (-5 versions). Input voltage level is internally sensed, setting the primary current limit to approximately 550mA for -3 part versions and 400mA for -5 part versions. The converter output power capability versus input voltage is shown in Figure 3 for $V_{CC2} \geq 4.75V$.

PARAMETER	CONDITIONS	MIN	TYP	MAX	UNITS
Rated Dielectric Insulation Voltage	1 Minute	2500			V_{RMS}
Maximum Working Insulation Voltage	Continuous	400 560			V_{RMS} V_{PEAK}
Partial Discharge	$V_{PR} = 1050V_{PEAK}$			5	pC
Common Mode Transient Immunity		30			kV/µs
Input to Output (Insulation) Resistance	$V_{IO} = 500V$	10^9	10^{11}		Ω
Input to Output (Barrier) Capacitance	f = 1MHz		6		pF
External Tracking (Creepage) Distance	L/BGA		9.53		mm
External Air Gap (Clearance) Distance	BGA		9.38		mm
Comparitive Tracking Index (CTI)		175			V
Highest Allowable Overvoltage	t = 10s			4000	V_{PEAK}
Minimum Distance Through Insulation		0.06			mm
Isolation Barrier ESD, HBM	(V_{CC2}, GND2) to GND Isolated I/O to GND		±10 ±8		kV kV

Table 1. Key isolation specifications of the LTM2881 and LTM2882

Primary current limit is not active under normal operating conditions.

The transformer comprises a toroidal ferrite core with one high voltage insulated winding and a second low voltage insulated winding. The high voltage winding uses supplementary-rated Teflon-insulated wire, consisting of two independent layers with a total insulation thickness of 76µm. The transformer is completely encapsulated during the µModule molding process, providing additional protection.

ISOLATION BARRIER PERFORMANCE

As detailed above, the isolation barrier consists of two components: data coils insulated by BT substrate, and Teflon insulated windings within the power transformer. The isolation barrier is designed to have a minimum dielectric withstand rating of $2500V_{RMS}$ for sixty seconds, and continuous working voltage of $400V_{RMS}$ or $560V_{PEAK}$.

Key isolation parameters are listed in Table 1, adopted from a wide variety of international standards. Standards relevant to isolation systems and components, and related topics of interest are listed in Table 2.

UL1577 is a component level standard designed to verify that the dielectric withstands voltages of up to $2500V_{RMS}$ under a variety of environmental conditions. The LTM2881 and LTM2882 devices have achieved UL approval up to an operating temperature of 100°C. The dielectric withstand is 100% production tested by applying a DC test voltage of ±4400V ($\approx 2500 \bullet 1.2 \bullet \sqrt{2}$) for one second at each polarity, with all pins shorted on each side of the isolation barrier.

IEC 60747-5-2 is the European equivalent component level standard, requiring a measurement of partial discharge (PD) across the isolation barrier at a voltage related to the rated system working voltage. Tests under a variety of environmental conditions are required for certification, as well as 100% production screening. The LTM2881 and LTM2882 have been characterized for PD and easily meet the requirements of the standard, with less than 5pC at $1050V_{PEAK}$ for a working voltage of $560V_{PEAK}$. Certification to IEC 60747-5-2 is in process.

The rated continuous working voltage is not explicitly defined in any standard; its value is dependent on a variety of environmental operating conditions, including creepage/clearance, test requirements defined within the standards, as well as the operational lifetime. The operating lifetime at the rated working voltage is extrapolated from accelerated lifetime test data. Tests results for the LTM2881 and LTM2882 are shown in Figure 4. Data conforms to the generally accepted Weibull distribution for accelerated dielectric breakdown testing.[1] The plot shows the minimum lifetime at $500V_{RMS}$ is greater than 100 years.

Parameters related to the isolation barrier voltage rating include electrostatic discharge (ESD), surge immunity, and electrical fast transients. One of the major benefits of galvanic isolation is the ability of the isolation barrier to hold off large voltage potentials, eliminating the need for other protection devices such as

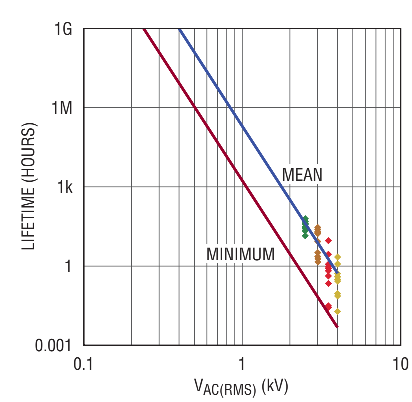


Figure 4. µModule isolator insulation lifetime

Table 2. Standards relevant to isolation systems and components

STANDARD	DESCRIPTION
UL1577	Standard for Safety, Optical Isolators
IEC 60747-5-2 (VDE 0884-10)	Optoelectronic Devices, Essential Ratings and Characteristics
IEC 60664-1	Insulation Coordination for Equipment within Low-Voltage Systems
IEC 60950-1	Information Technology Equipment—Safety
IEC 61010-1	Measurement, Control, Laboratory Equipment—Safety
IEC 60601-1	Medical Electrical Equipment
IEC 61000-4-2	Electrostatic Discharge Immunity
IEC 61000-4-3	Radio Frequency Field Immunity
IEC 61000-4-4	Electrical Fast Transients
IEC 61000-4-5	Surge Immunity
IEC 61000-4-8	Power Frequency Magnetic Field Immunity
IEC 61000-4-9	Pulse Magnetic Field Immunity
CISPR 22	Radiated Emissions - Information Technology Equipment
IEC 60079-11	Intrinsic Safety

transient voltage suppressors. The key is configuring the system in a way that the barrier sees the transient event, which is typically achieved by proper shielding of system interconnects. The isolation barrier easily withstands transient events equal to the dielectric withstand voltage of $2500V_{RMS}$ or $3500V_{PEAK}$, and can withstand much higher voltages for short periods of time as evidenced by the 8kV–10kV barrier ESD ratings, and operating lifetimes at elevated voltages.

The input to output capacitance, or barrier capacitance, is an important parameter impacting many aspects of overall performance. In general, the lower the capacitance the better. The capacitance is a parasitic element and is the parallel combination of data coil and transformer winding capacitance. Typical capacitance is 6pF at 1MHz with the data coils accounting for 1.2pF each and the power transformer 3.6pF. In the case of transients, one or more ESD or body diodes conducts the transient energy to the barrier capacitance and back to ground. A smaller barrier capacitor absorbs more transient voltage, reducing the energy dissipated in the functional IC, thus minimizing the potential for damage.

The magnitude of capacitance also impacts the common mode transient immunity. This parameter is a measure of the component's ability to maintain proper function in the presence of high slew rate signals across the isolation barrier. µModule isolators support a minimum common mode transient rate of 30kV/µs (50kV/µs typical), operating through these transient events error-free while transmitting data. The barrier capacitance displaces a current equal to the capacitance times the slew rate into the application die, potentially disrupting its function by inducing noise or triggering parasitic device structures. Under the extreme conditions needed to produce common mode errors, µModule isolator products do not exhibit any latch-up, instead showing only momentary state changes corrected during the next communication cycle.

ELECTROMAGNETIC COMPATIBILITY

The barrier capacitance also plays a role in the system's electromagnetic compatibility, specifically radiated emissions. Just as transient common mode events inject current through the parasitic barrier capacitance, so do the data and power drive circuits. These drive circuits have fast edge rates which ultimately create a voltage transient on the isolated ground plane (GND2). Most isolated printed circuit board layouts use separate ground planes for the input (GND) and output (GND2) sides. This dual ground plane structure forms a dipole antenna, providing an effective radiator of the common mode voltage created by the parasitic barrier capacitance.

Another way to look at this problem is to consider the currents generated in the parasitic capacitance by the drive circuits. These currents require a return path. If the current is not returned through one of the parallel parasitic capacitors, it will be returned through the capacitance created by a pair of ground planes, or potentially through the capacitance formed between interconnect wires and ground. The radiated emissions can be quite high if not properly mitigated. The most effective technique is to provide a low impedance return path at the frequencies of interest—namely an additional capacitor between the isolated ground planes, or bridge capacitor.

The structures and isolation techniques used in isolator µModule technology are insufficient in themselves to radiate enough power to exceed the Class B limit of CISPR 22. The data coils are essentially small loop antennas, whose

The center tapped receiver coils provide a high level of rejection to external RF and magnetic fields or common mode signals, due to the opposing winding turns.

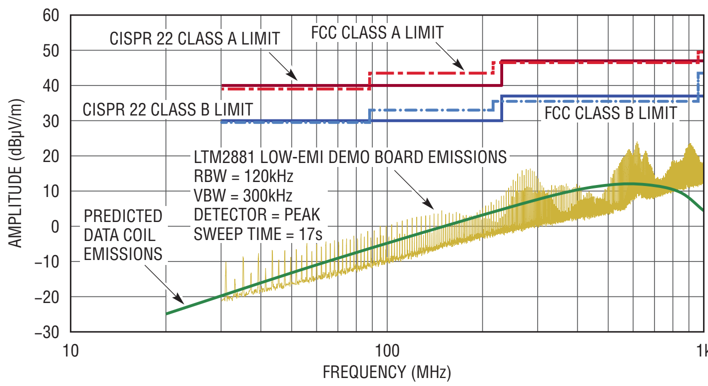


Figure 5. Predicted versus actual total radiated emissions

emissions level can be predicted by solving the radiated power loop antenna equation (1). Figure 5 shows the results of this equation using simulated coil current spectrum data as well as actual measured data, which also includes contributions from the isolated power component.

$$P_{RAD} = 160\pi^6 (I_f)^2 \sum_{n=1}^{N} (r_n/\lambda)^4 \text{ WATTS} \qquad (1)$$

I_f = current at frequency
r_n = radius of nth coil turn in meters
N = Total number of turns
λ = wavelength at frequency

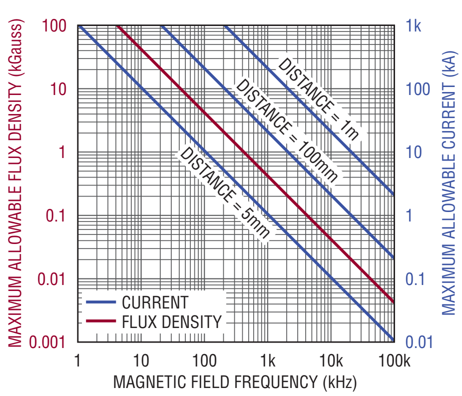
As shown, the emission levels fall far below the required CISPR 22 and related FCC limits.

Several techniques can be used to ensure a design with minimal radiated emissions. The first, as mentioned, is the use of a bridge capacitor, implemented by overlapping a floating plane of printed circuit board copper, typically using an inner layer, over the input and isolated ground planes. This provides a nearly ideal capacitor, and two insulation barriers are created to support the isolation voltage. This technique can be used in combination with discrete capacitors to further reduce emissions below 300MHz, above which frequency the parasitic inductance limits their usefulness. Recommended discrete capacitors are AC safety rated, Y2 type, applied two in series to meet safety standard requirements. Murata's Type GF series of Y2 capacitors meet this requirement.

Additional EMI mitigation techniques include:

- Minimize the size of the isolated ground plane.
- Insure that all signal and power traces have closely coupled return paths to minimize radiation created by these localized loops. Avoid transitioning signals from layer to layer as the image current often cannot follow the same path.
- Add a combination of low ESL and high impedance decoupling capacitors to high current power rails, preventing conducted noise and parasitic ringing from becoming radiated noise.
- Use filtering for all off-board interconnection. This can often be done with ferrite based chip beads and common mode filters. Care must be exercised to ensure the filter components do not compromise the integrity of signals on the associated data lines. The filtering provides a high impedance block to radio frequency signals. Shunt capacitance can also be used to provide a local low impedance return path.
- Reduce the operating supply voltage, or use the lower input voltage version (-3) of the part.
- Low-EMI versions of the LTM2881 and LTM2882 demo boards, DC1746A and DC1747A respectively, are available, leveraging many of these techniques.

Figure 6. Magnetic field immunity



ELECTROMAGNETIC IMMUNITY

By superposition, an inefficient radiator is also an inefficient receiver. The LTM2881 and LTM2882 have been independently evaluated for radio frequency and magnetic field immunity. Table 3 summarizes the applicable test standards with passing field strength levels.

The LTM2881 RS485 transceiver and the LTM2882 dual RS232 transceiver combine desirable data-plus-power isolation features in a robust small-package system. Both devices feature superior transient common mode rejection, magnetic field immunity, ESD and transient barrier withstand, and insulation lifetime.

Passing the test requirements, however, does not give much insight to the system's true immunity level. The external magnetic field required to corrupt data communication can be calculated by equation (2), where V represents the differential receiver threshold voltage. The center tapped receiver coils provide a high level of rejection to external RF and magnetic fields or common mode signals, due to the opposing winding turns. Since the data coils are not completely symmetric, some differential voltage is generated, represented by the net difference in area between the center tap coil turns. The maximum external magnetic field relative to receiver threshold is plotted in Figure 6, taking into account the common mode cancelation.

$$V = \left(-\frac{d\beta}{dt}\right)\sum_{n=1}^{N}\pi(r_n)^2 \text{ VOLTS} \quad (2)$$

β = magnetic flux density in gauss
N = number of turns in receiving coil
r_n = radius of nth coil turn in centimeters

Alternatively, the magnetic field due to an alternating current flowing in a wire some distance away can be calculated. Figure 6 also plots this result for distances of 5mm, 100mm, and 1m away from the device in question. For example, a current of 1000A running at 1MHz in a wire 5mm away would be required to corrupt data transmission at the receiver.

SAFETY STANDARDS

Creepage, clearance, tracking index, and minimum distance through insulation are safety related parameters used in the various equipment level standards and insulation coordination standards to determine proper component application.

TEST	FREQUENCY	FIELD STRENGTH
IEC 61000-4-3 Annex D	80MHz–1GHz	10V/m
	1.4MHz–2GHz	3V/m
	2GHz–2.7GHz	1V/m
IEC 61000-4-8 Level 4	50Hz and 60Hz	30A/m
IEC 61000-4-8 Level 5	60Hz	100A/m (non IEC method)
IEC 61000-4-9 Level 5	Pulse	1000A/m

Table 3. Electromagnetic field immunity

IEC 60664-1 deals specifically with insulation systems and is a reference standard to IEC 60950-1, IEC 61010-1, and IEC 60601-1. These standards define the required creepage, clearance, etc., based on the type of equipment installation and operating environment. The following terms and definitions are used throughout the various standards:

- *Basic Insulation:* Insulation to provide basic protection against electric shock.
- *Supplementary Insulation:* Independent insulation applied in addition to basic insulation in order to reduce the risk of electric shock in the event of a failure of the basic insulation.
- *Double Insulation:* Insulation comprising both basic insulation and supplementary insulation.
- *Reinforced Insulation:* Single insulation system that provides a degree of protection against electric shock equivalent to double insulation. It may comprise several layers that cannot be tested as basic insulation and supplementary insulation.
- *Material Group:* Classification based on an insulating components relative comparative tracking index, a measure of the surface electrical breakdown properties of an insulating material.
- *Pollution Degree:* Numeral characterizing the expected pollution of the microenvironment, degrees include 1, 2 and 3. The level of pollution can result in a reduction of electric strength or surface resistivity of the insulation.
- *Overvoltage Category:* Numeral defining a transient overvoltage condition; categories include I, II, III and IV. Operating category is a function of the highest RMS operating voltage within the system.
- *Creepage:* Shortest distance along the surface of a solid insulating material between two conductive parts.
- *Clearance:* Shortest distance in air between two conductive parts.

A complete interpretation of IEC 60664-1 and related standards as they apply to µModule isolators is beyond the scope of this article. Neverthless, Table 4 summarizes some of the key parameters for

Table 4. Isolation categories

PARAMETER	CONDITION	SPECIFICATION
Basic Isolation Group	Material Group, 175 ≤ CTI < 400	IIIa
	Rated Mains Voltage ≤ $150V_{RMS}$	I–IV
Installation Class	Rated Mains Voltage ≤ $300V_{RMS}$	I–III
	Rated Mains Voltage ≤ $400V_{RMS}$*	I–II

* Range is normally $600V_{RMS}$, limited by devices rated working voltage

µModule isolators often listed on component data sheets. It is worth noting that the creepage and clearance distances of the LTM2881 and LTM2882 modules greatly exceed the requirements for the rated working voltage for all insulation categories, pollution degrees, overvoltage categories, and material groups. For components classified with a Basic Insulation level there is no minimum for distance through insulation. Supplementary and Reinforced Insulation systems require a distance of 400µm, or they must meet the type (conditioned sample) and routine (production) test requirements for partial discharge and/or dielectric withstand. µModule isolators are considered Basic Insulation systems at the rated working voltage.

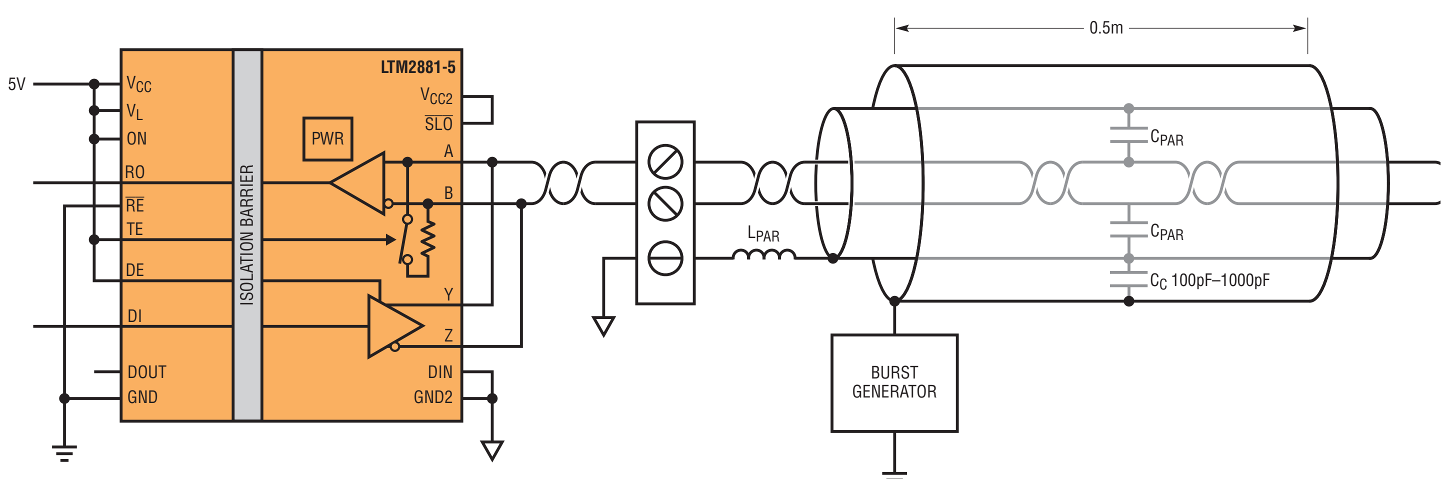
Intrinsic Safety is a standard covering equipment protection in explosive atmospheres. Component requirements are more stringent, and include limits for temperature rise, maximum current, and reactive component energy storage to prevent the generation of sparks. The LTM2881 and LTM2882 are suitable for level of protection "ic" for peak voltages up to 60V. These products meet all of the requirements for protection levels "ia", "ib", and "ic" except for distance through solid insulation.

ESD, EFT AND SURGE

Electrical transients are covered in IEC 61000-4-2 (Electrostatic Discharge Immunity), IEC 61000-4-4 (Electrical Fast Transients), and IEC 61000-4-5 (Surge Immunity). Each of these standards covers transient events that are similar in nature and approximate different real world events such as lighting strikes, conductive circuit interruption, and device handling. The differences between the transients lie in the peak voltages, impulse duration, and repetition rates. In non-isolated systems the addition of protective components is often required to protect against transient events. Proper application of µModule isolators allows the isolation barrier to absorb the transient, eliminating the need for additional protection.

Figure 7 shows a properly configured test set-up to meet the requirements of EFT testing. Surge testing is performed with the signal applied directly to the shield. The transient (burst) generator is capacitively coupled to the shielded I/O lines of the LTM2881. The coupling device is depicted as a second shield with length of 0.5 meters per standard. The return side of the burst generator is tied to the logic side ground. The shield conducts the transient to the isolated ground then across the isolation barrier to the generator return. The parasitic inductance (L_{PAR}) must be minimized or some of the transient is coupled into the signal lines, decreasing the transient immunity effectiveness. The isolation barrier has been tested and is compliant to level 4 (4kV) for both surge and EFT.

Figure 7. EFT test configuration



Electrostatic discharge testing is performed directly from pin to pin of the device. Barrier ESD is performed from any logic side pin to isolated side pin. The LTM2881 and LTM2882 have an ±8kV HBM (human body model) ESD rating from any logic side I/O pin to isolated side I/O pin, and a ±10kV HBM, ±8kV IEC, ESD rating from any isolated side power pin, V_{CC2} or GND2, to logic side power pin, V_{CC}, V_L, or GND.

THE LTM2881 AND LTM2882

Linear Technology's first released µModule isolators are the LTM2881 RS485/RS422 transceiver plus power, and the LTM2882 dual RS232 transceiver plus power. Both offer distinct advantages over alternative solutions including excellent common mode rejection, integrated high efficiency isolated power and low EMI. Furthermore, no external components, including power decoupling capacitors, are required. Each has separate logic power supply inputs for easy interface to low voltage systems ranging from 1.62V to 5.5V.

Two main power supply options are offered, 3.0V to 3.6V and 4.5V to 5.5V, which are completely independent of the logic supply. Devices are available in LGA and BGA packages with ambient temperature ranges of 0°C to 70°C, –40°C to 85°C, and –55°C to 105°C.

The LTM2881, shown in Figure 8, is a 20Mbps transceiver with integrated selectable termination and 250kbps reduced slew rate operating mode. The device includes one uncommitted isolated digital channel from isolated side to the logic side and features ±15kV HBM ESD protection on the RS485 interface pins.

The LTM2882, shown in Figure 9, is a dual channel 1Mbps transceiver featuring one uncommitted isolated digital channel from logic to isolated side and ±10kV HBM ESD protection on the RS232 interface pins.

CONCLUSION

The LTM2881 RS485 transceiver and the LTM2882 dual RS232 transceiver use Linear Technology µModule isolator technology to combine desirable data-plus-power isolation features in a robust small-package system. Both devices feature superior transient common mode rejection, magnetic field immunity, ESD and transient barrier withstand, and insulation lifetime. The core isolation techniques may be applied to a breadth of applications.

Certification to UL1577 has been completed. The certification process has been initiated for IEC 60747-5-2, including routine (production) test support for partial discharge, and certification to CSA (Canadian) Component Acceptance Notice #5A in relation to IEC 60950-1.

Isolation terminology and relevant safety standards have been introduced to aid in the application of Linear Technology µModule isolator products across all industries. Isolation barrier performance is under constant evaluation (i.e., insulation lifetime, partial discharge, etc.) to ensure the highest reliability and performance.

Additional product certifications may be added to further distinguish the products' exceptional isolation characteristics. ■

Figure 8. LTM2881 isolated RS485 µModule transceiver

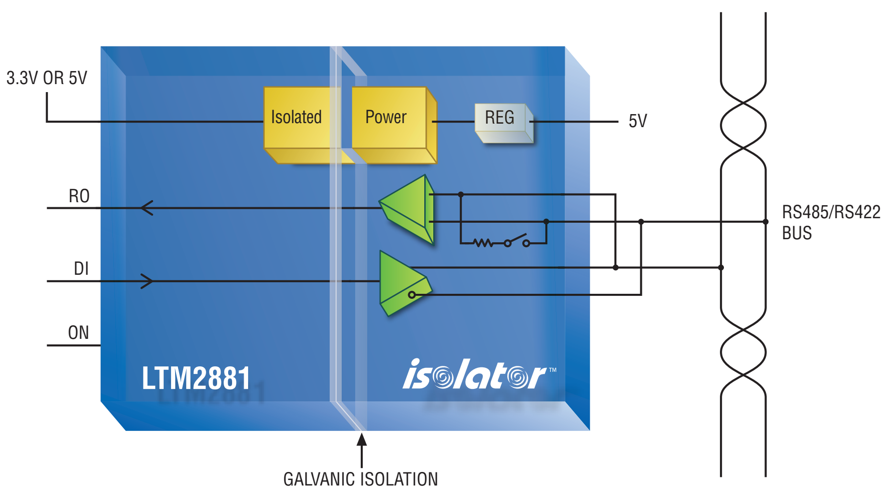
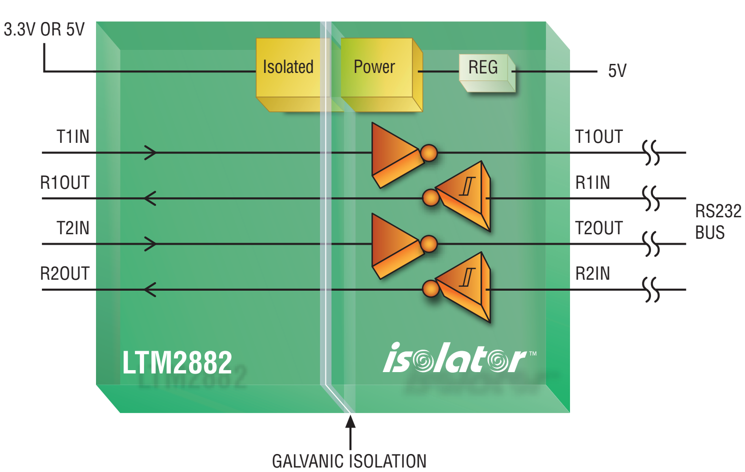


Figure 9. LTM2882 dual RS232 µModule transceiver



Notes

[1] V.Y. Ushakov, Insulation of High-Voltage Equipment, Springer-Verlag, Berlin (2004)

Isolated Power Supplies Made Easy

John D. Morris

The LT3748 is a switching regulator controller specifically designed to simplify the design of isolated power supplies using a flyback topology. No third winding or opto-isolator is required as the LT3748 senses the isolated output voltage directly from the primary-side flyback waveform.

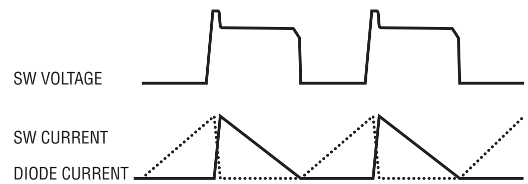


Figure 1. Idealized waveforms for an LT3748-based flyback converter operating in boundary mode

One challenge in designing a flyback converter is that information relating to the output voltage on the secondary side of the transformer must be fed back to the regulator on the primary side in order to maintain regulation. Historically, feedback across the isolation barrier is achieved using opto-isolators or extra transformer windings, though both methods present a number of design problems. Opto-isolator feedback circuits add components, increasing converter size and cost. They also draw power, degrading efficiency and complicating thermal design. Opto-isolators also make it difficult to accurately regulate the output due to their limited dynamic response, inherent nonlinearities, typical variation from unit-to-unit and variation with age. The usual alternative is to add an extra transformer winding, but this may introduce other problems, including bigger, more expensive magnetics or limited dynamic response.

By contrast, the LT3748 infers the isolated output voltage by examining the primary-side flyback pulse waveform. In this manner, neither an opto-isolator nor an extra transformer winding is required to maintain regulation, and the output voltage is easily programmed with two resistors.

The LT3748 features a boundary mode control method (also called critical conduction mode), where the part operates at the boundary between continuous conduction mode and discontinuous conduction mode, as illustrated in Figure 1. Due to the boundary control mode operation, the output voltage can be calculated from the transformer primary voltage when the secondary current is approximately zero. This method improves load regulation without external resistors and capacitors and results in typical line and load regulation of better than ±5% while allowing for a simple and compact solution, as shown by the 12V, 30W demo board in Figure 2.

OUTPUT POWER

Because the MOSFET power switch is located outside the LT3748, the maximum output power is limited primarily by external components—not the LT3748. Output power limitations can be separated into three categories: voltage limitations, current limitations and thermal limitations. The voltage limitations in a flyback design are primarily the MOSFET switch maximum drain to source voltage and the output diode reverse-bias rating. The current limitation on output power delivery is generally constrained by transformer saturation current in higher power applications, although the MOSFET switch and output diode may need to be rated for the desired

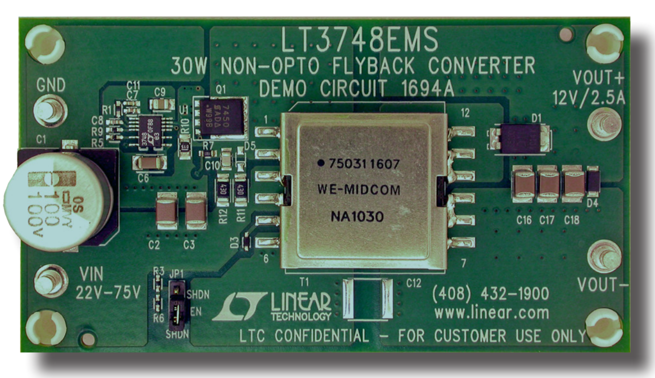


Figure 2. A no-opto-coupler 30W design with an 18V-to-90V input range (actual size)

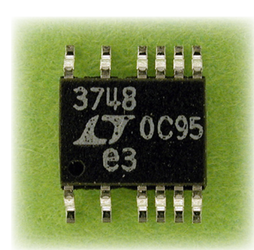


Figure 3. The LT3748 is available in an MSOP-16 package with four pins removed for high voltage operation.

The LT3748 infers the isolated output voltage by examining the primary-side flyback pulse waveform. In this manner, neither an opto-isolator nor an extra transformer winding is required to maintain regulation, and the output voltage is easily programmed with two resistors.

currents, as well. The thermal limitation in flyback applications for lower output voltages is dominated by losses in the output diode, with resistive and leakage losses in the transformer increasing in significance as the output voltage is increased.

OPTIMIZED FEATURES

The LT3748 is capable of driving the vast majority of appropriate MOSFETs at frequencies of up to several hundred kilohertz using its built-in gate driver capable of 1.9A average output current (both rising and falling) and its internal $INTV_{CC}$ low-dropout regulator. In addition, start-up is well controlled with programmable soft-start and undervoltage lockout. Although the LT3748 fits in a compact MSOP-16 package, four pins have been removed to provide sufficient spacing for high voltage operation, as shown in Figure 3.

OVERDRIVING $INTV_{CC}$ WITH A THIRD WINDING

The LT3748 provides excellent output voltage regulation without the need for an opto-coupler or third winding, but for some applications with high input voltages, an additional winding may improve overall system efficiency, particularly at lighter loads. The third winding should be designed to output a voltage above 7.2V but never exceeding 20V. In typical applications over 15W, overdriving the $INTV_{CC}$ pin may improve efficiency by several percent at maximum load and more than 10% at light loads. Figure 4 shows the efficiency of the circuit in Figure 5 with and without the third winding connected.

OVER-CURRENT PROTECTION

The LT3748 has an internal threshold to detect when current in the R_{SENSE} resistor exceeds the programmed range to protect external devices in case of a system fault. This can occur when an inductive output short-circuit causes the output voltage to dip below zero or when the transformer saturation current is exceeded. Regardless of the cause, when the voltage at the SENSE pin exceeds ~130mV—or 30% higher than the programmed maximum current limit in the R_{SENSE} resistor—the SS pin is reset, thus halting switching operation. Once the soft-start capacitor is recharged and the soft-start threshold is reached, switching resumes at the minimum current limit. In output short circuit cases where the reflected output voltage plus the forward diode drop is greater than zero, the LT3748 functions normally and no external components are stressed.

HIGH TEMPERATURE OPERATION

The LT3748 is available in E, I and H grades, and is designed for excellent performance across a wide temperature range. Other than the internal $INTV_{CC}$ regulator,

Figure 4. Efficiency of the LT3748 application in Figure 5 with and without a third winding

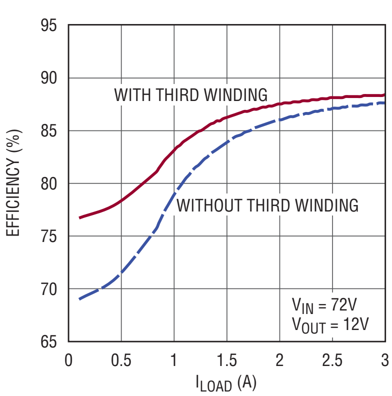


Figure 5. Schematic for the converter pictured in Figure 2. This converter takes an 18V-to-90V input and produces a 2.5A output at 12V.

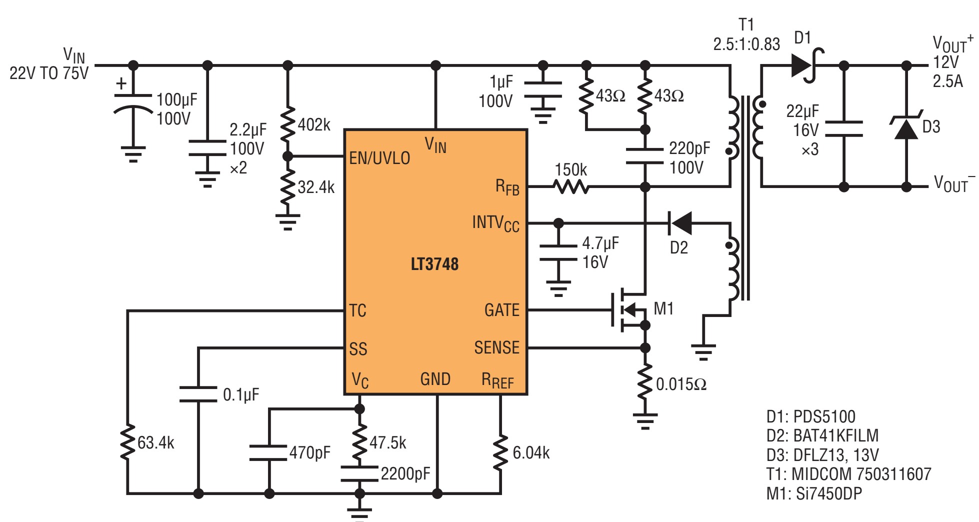
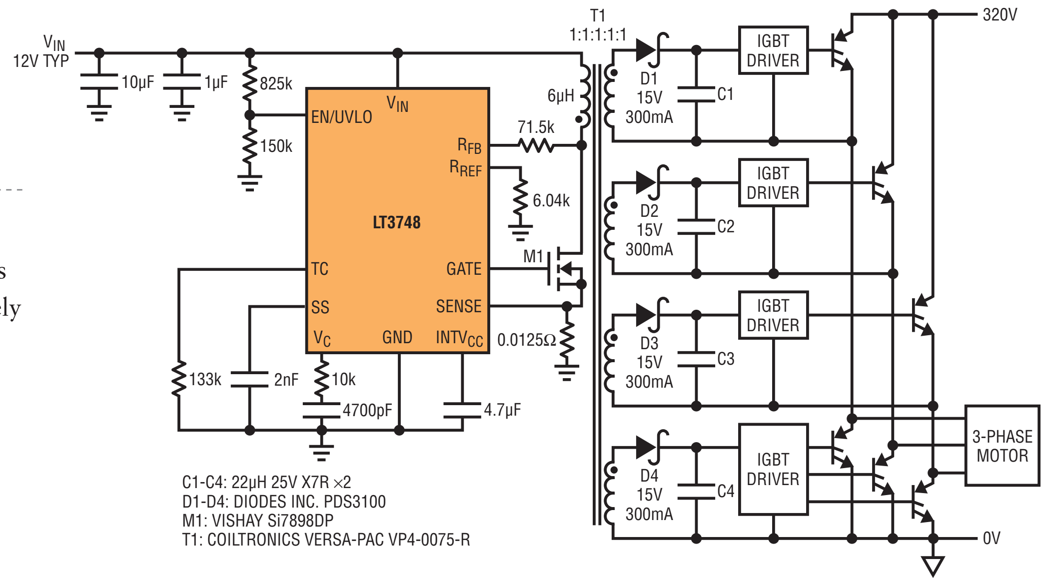


Figure 6. IGBT controller supply for hybrid and electric vehicle applications



the LT3748 dissipates very little power, even at high input voltages, so limitations to thermal performance are almost entirely in the external components, which can be correctly sized or cooled as needed.

12V, 3A OUTPUT FROM 18V–90V INPUT

Figure 5 shows an application that efficiently converts a wide input range to a 12V output. Because the LT3748 is capable of handling up to 100V at its input, no additional interface circuitry is required between the line voltage and the controller. A simple RC snubber is all that is required to protect the 200V Si7450 MOSFET from excessive voltage across the full line and load range. Although a third winding is normally connected to boost efficiency at lighter loads, all regulation is done on the primary winding—a transformer without a third winding would be nearly as efficient at lower input voltages and high output loads.

IGBT CONTROLLER SUPPLY FOR AUTOMOTIVE APPLICATIONS

The LT3748 can easily produce multiple isolated supplies to power IGBTs that drive synchronous motors from high battery voltages in electric or hybrid electric vehicles, as illustrated in Figure 6. A MOSFET with 150V maximum V_{DS} is selected so that any snubbing circuitry is optional and the hysteretic UVLO threshold is set to start switching when V_{IN} equals 10V while allowing V_{IN} to droop to 8V while switching.

HIGH OUTPUT VOLTAGE FOR REMOTE SENSORS

A flyback topology is often the only way to produce a high voltage isolated output for long cable runs or for powering interface equipment. Figure 7 shows a typical application for this style of application with complementary 300V outputs. For the low power levels in this application, an off-the-shelf EP13 transformer is more than sufficient and keeps the total solution size small.

CONCLUSION

The LT3748 simplifies the design of isolated flyback converters by using a primary-side sensing, boundary mode control scheme that precludes the need for an opto-coupler and its related circuitry. The LT3748 also features a wide input range, low internal power dissipation, a 1.9A gate driver and user-programmable protection features that further simplify design and add to its versatility. ■

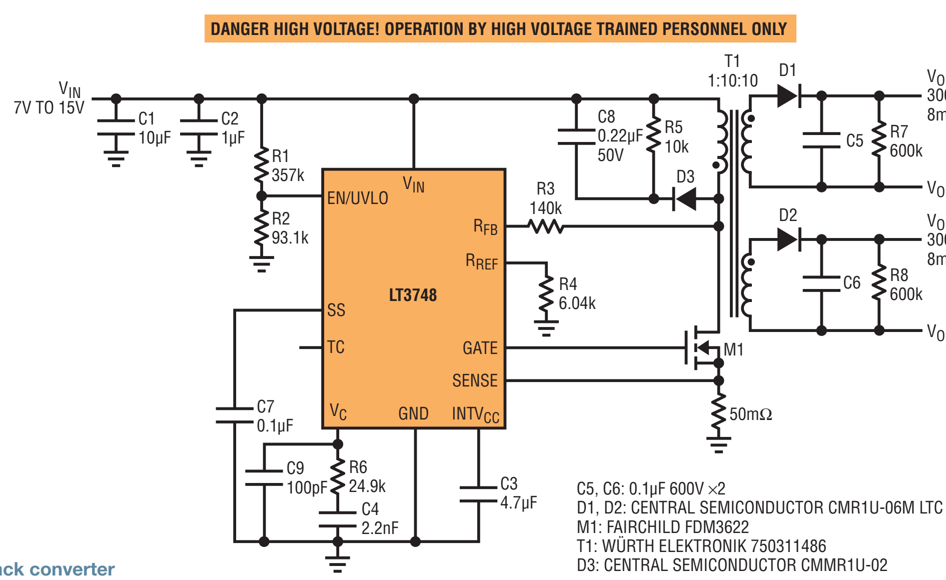


Figure 7. A ±300V isolated flyback converter

Nanopower Buck Converter Runs on 720nA, Easily Fits into Energy Harvesting and Other Low Power Applications

Michael Whitaker

The LTC3388-1/LTC3388-3 integrated synchronous step-down regulator provides a regulated output while consuming a mere 720nA of quiescent current. It accepts inputs up to 20V and can deliver up to 50mA of load current. Eight pin-selectable output voltages are offered: 1.2V, 1.5V, 1.8V, and 2.5V on the LTC3388-1 and 2.8V, 3.0V, 3.3V, and 5.0V on the LTC3388-3. The extremely low quiescent current prolongs battery life for keep-alive circuits in portable electronics and makes it a good fit for energy harvesting applications.

The LTC3388-1/LTC3388-3 (Figure 1) achieves its low quiescent current by entering a sleep state once the output is in regulation. In the sleep state, load current is provided by the output capacitor while the output voltage is monitored. When the output falls below a fixed hysteresis window, the converter wakes up and refreshes the capacitor.

This hysteretic method of providing a regulated output minimizes losses associated with FET switching and makes it possible to efficiently regulate at very light loads. The total quiescent current at V_{IN} in the sleep state is 720nA when V_{IN} is 4V and increases to only 820nA when V_{IN} is 20V. At light loads, the time the buck is active is miniscule relative to the time it sleeps, so the average quiescent current required to maintain regulation approaches the DC sleep quiescent current.

ENABLE AND STANDBY

Two pins, EN and STBY, control enable and standby functions on the LTC3388-1/LTC3388-3. When EN is low, the buck is turned off and only 520nA of quiescent current appears at V_{IN}. When EN is high, the STBY pin places the LTC3388-1/LTC3388-3 in standby. In this mode the buck is prevented from switching, resulting in a quiet supply. The PGOOD pin, which is high when the output is in regulation, remains active while in standby. PGOOD transitioning low can serve as an indicator that the output has fallen and that the LTC3388-1/LTC3388-3 should leave standby mode to refresh the output.

HIGH EFFICIENCY AT LIGHT LOADS

The extremely low quiescent current of the LTC3388-1/LTC3388-3 allows for high efficiency at loads as low as 10µA. This is especially useful for low power systems that spend a long time idling and only periodically wake up to perform a task. Figure 2 shows typical efficiency of the LTC3388-1 for the 1.8V output, which is suitable for powering low power microprocessors.

SUPPORTS ENERGY HARVESTING APPLICATIONS

The LTC3388-1/LTC3388-3 is especially well suited for energy harvesting applications where only low amounts of energy are available. Figure 3 shows the LTC3588-1 piezoelectric energy harvesting power supply harvesting ambient vibration energy with a piezoelectric transducer and producing a 3.3V output. The LTC3388-3 is powered from this output and is configured to provide a –3.3V rail, producing a low power dual output supply. The LTC3388-3's low quiescent current, combined with the LTC3588-1's

(continued on page 43)

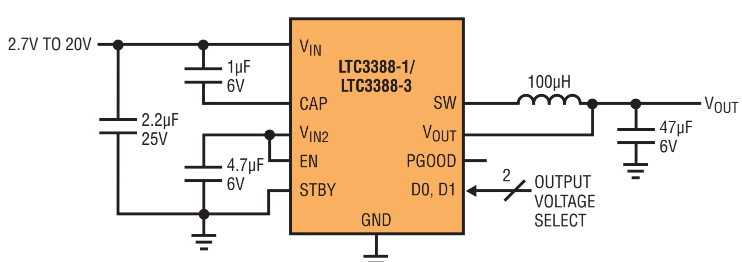


Figure 1: Low quiescent current buck converter

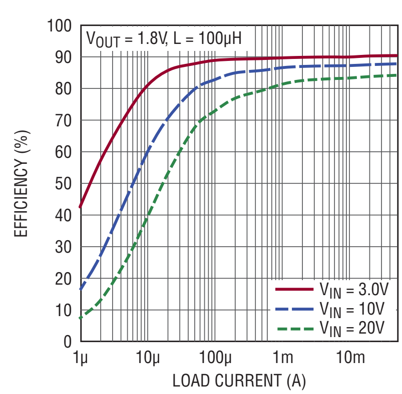


Figure 2: LTC3388-1 Efficiency vs load current for the 1.8V output

Product Briefs

10PPM/°C, 3mV DROPOUT VOLTAGE REFERENCE OPERATES WITH LESS THAN 1μA

The LT6656 is a precision SOT23 voltage reference that operates on only 850nA of supply current. The LT6656 has an initial error of less than 0.05% and a guaranteed temperature drift of less than 10ppm/°C. This combination of precision and ultralow power is ideal for portable, wireless and remote devices. With an output drive capability of 5mA, the LT6656 is suitable for a wide range of applications. For example, the LT6656 could serve as both the supply voltage and the precision reference for a low power, high resolution ADC. The LT6656 can replace low power shunt references, offering better efficiency and regulation in the presence of variable load current and supply voltages. For many applications, the extremely low quiescent current allows the LT6656 to remain in an always-on, stable state.

Building on Linear Technology's extensive family of precision voltage references, the LT6656 is optimized for battery-powered operation. This high performance bipolar device can withstand reverse battery conditions, accept input voltages up to 18V and operate from voltages as low as 3mV above the output voltage. When unpowered, the output is high impedance, avoiding loading on the rest of the circuit. The LT6656 is fully specified for operation from –40°C to 85°C, and is guaranteed functional over the extreme temperature range of –55°C to 125°C.

"The high precision of the LT6656, combined with only 1μA of supply current packaged in a tiny SOT23, demonstrates a significant advance in voltage reference technology," stated Brendan Whelan, design manager for Linear Technology.

2.6A, 2.5MHz STEP-DOWN DC/DC CONVERTER PLUS DUAL LINEAR CONTROLLERS IN 4mm × 5mm QFN OPERATES FROM 4V–36V INPUTS

The LT3694 is a 2.6A, 36V step-down switching regulator with dual linear controllers, packaged in a 4mm × 5mm QFN or TSSOP-20E. The LT3694 operates from a VIN range of 4V to 36V with transient protection to 70V, making it ideal for load dump and cold-crank conditions found in automotive applications. Its internal 3.5A switch can deliver up to 2.6A of continuous output current at voltages as low as 0.75V. Its switching frequency is user-programmable from 250kHz to 2.5MHz, enabling the designer to optimize efficiency while avoiding critical noise-sensitive frequency bands. Each integrated LDO controller has an accurate programmable current limit up to 1A to provide an additional level of reliability. Combined with NPN transistors, they can be used to offer dual low noise outputs in addition to the primary channel. Although the LDO controllers can be powered by independent inputs, powering them from the primary switching output ensures both high efficiency and low noise.

The combination of its 4mm × 5mm QFN package (or thermally enhanced TSSOP-20E) and high switching frequency, which keeps external capacitors and inductors small, provides a compact, thermally efficient footprint.

400mA SYNCHRONOUS STEP-UP DC/DC CONVERTER WITH MAXIMUM POWER POINT CONTROL & 250mV START-UP FOR ENERGY HARVESTING APPLICATIONS

The LTC3105 is a high performance, synchronous boost converter that incorporates maximum power point control (MPPC) and starts up with inputs as low as 250mV. The LTC3105 operates over an extremely wide input range of 0.225V to 5V, making it ideal for harvesting energy from high impedance alternative power sources, including photovoltaic cells, thermoelectric generators (TEGs) and fuel cells.

The LTC3105's internal 400mA synchronous switches maximize efficiency while its Burst Mode® operation offers quiescent current of only 24μA, further optimizing converter efficiency over all operating conditions. A user-programmable MPPC set point maximizes the energy that can be extracted from any power source without collapsing its internal voltage.

The LTC3105 is ideally suited to power wireless sensors and data acquisition applications. Surplus or ambient energy can be harvested and then used to generate system power in lieu of traditional wired or battery power, which may be expensive or impractical. Typically, these applications require very low average power, but require periodic pulses of higher load current. For example, the LTC3105 can be used in wireless sensor applications where the power load is extremely low when the sensor is in standby mode, which is interrupted by periodic high load

The LTC3787 is a high power 2-phase single output synchronous step-up DC/DC controller, which replaces the boost diodes with high efficiency N-channel MOSFETs. This solution eliminates the heat sink normally required in medium to high power boost converters. The LTC3787 can produce a 24V at 10A output from a 12V input at up to 97% efficiency.

bursts, when the circuitry is powered up to take measurements and transmit data.

The LTC3105 offers an auxiliary LDO that delivers up to 6mA of output current to power external microcontrollers and sensors while the main output is charging. Once fully charged, the main output can deliver voltages as high as 5.25V with up to 100mA of output current. It can also regulate V_{OUT} even when V_{IN} is greater than or equal to V_{OUT}, offering further design flexibility. In shutdown, the LTC3105 offers output disconnect, isolating V_{IN} from V_{OUT}, requiring only 10µA of quiescent current.

The combination of the LT3105's 3mm × 3mm DFN package (or MSOP-12) and very small external components offers a very compact solution for energy harvesting applications.

HIGH POWER POLYPHASE SYNCHRONOUS BOOST CONTROLLER ELIMINATES HEAT SINK WITH 97% EFFICIENCY

The LTC3787 is a high power 2-phase single output synchronous step-up DC/DC controller, which replaces the boost diodes with high efficiency N-channel MOSFETs. This solution eliminates the heat sink normally required in medium to high power boost converters. The LTC3787 can produce a 24V at 10A output from a 12V input at up to 97% efficiency. The LTC3787's 135µA standby quiescent current when configured for Burst Mode operation makes it ideal for high power automotive audio amplifiers, as well as industrial and medical applications where a step-up DC/DC converter must deliver high power in a small solution size.

The LTC3787 operates from an input voltage ranging from 4.5V to 38V during start-up, maintains operation down to 2.5V after start-up and can regulate an output voltage as high as 60V. The powerful 1.2Ω onboard N-channel MOSFET gate drivers are capable of slewing large MOSFET gates quickly. The device's current mode architecture, clock output and phase modulation enables easy paralleling of multiple devices for up to 12-phase operation. The LTC3787 has a phase-lockable frequency from 75kHz to 850kHz or a selectable fixed frequency from 50kHz to 900kHz. In applications where the input voltage exceeds the regulated output voltage, the LTC3787 keeps the synchronous MOSFET on continuously so that the output voltage follows the input voltage with minimal power loss. In addition, this device features adjustable cycle-by-cycle current limit and can use a sense resistor or monitor the voltage drop across the inductor (DCR) for current sensing. Furthermore, the LTC3787 has adjustable soft-start, a power good output and maintains ±1% reference voltage accuracy over an operating junction temperature range of –40°C to 125°C. ■

(LTC3388-1/LTC3388-3, continued from page 41)

own low quiescent current results in a complete solution that draws only 1600nA with no load at both outputs.

CONCLUSION

The LTC3388-1/LTC3388-3 monolithic buck converter's extremely low quiescent current makes it ideal for low power applications. A quiescent current of less than a microamp prolongs battery life for keep-alive circuits in portable electronics and enables a new generation of energy harvesting applications. ■

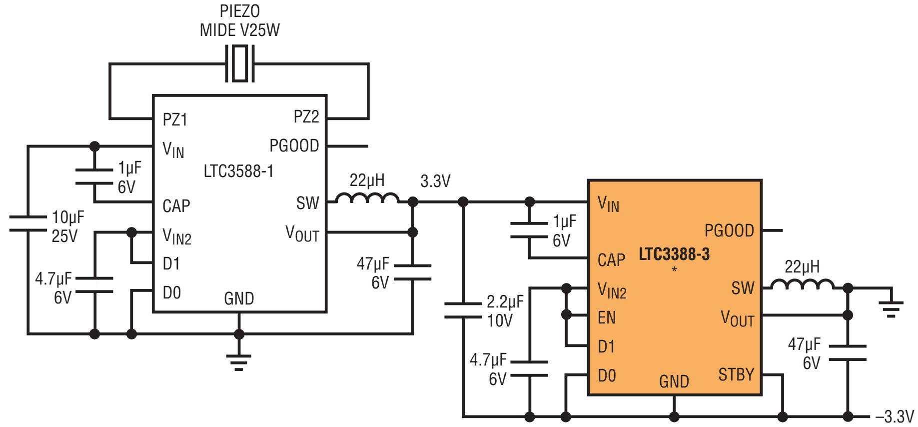
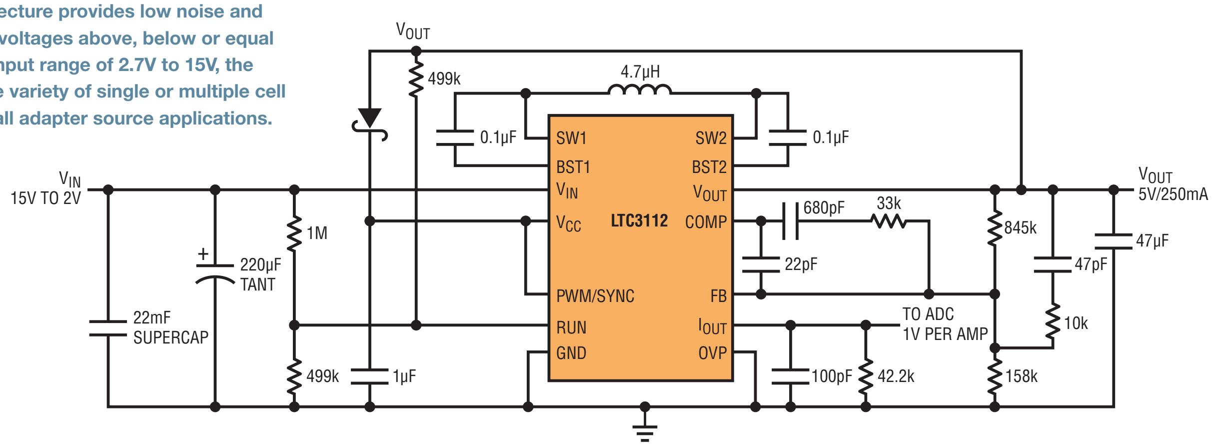


Figure 3: Piezoelectric energy harvester with dual ±3.3V outputs

* EXPOSED PAD MUST BE ELECTRICALLY ISOLATED FROM SYSTEM GROUND AND CONNECTED TO THE –3.3V RAIL.

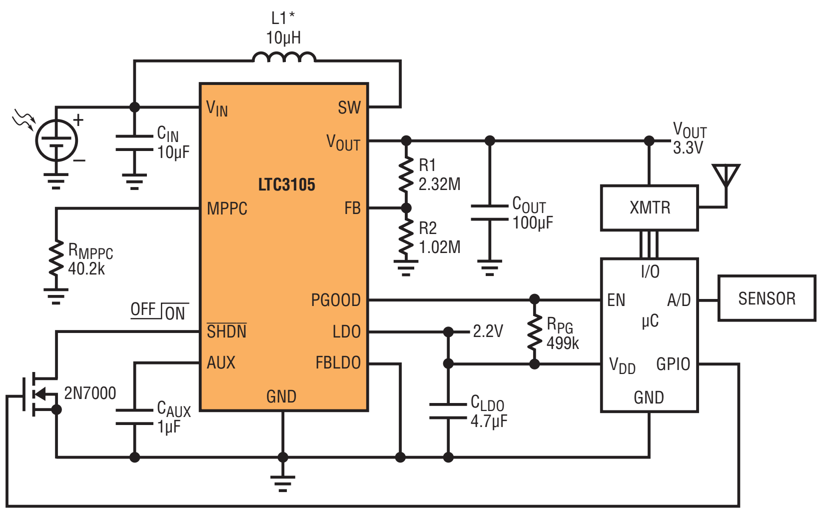
5V BACKUP SUPPLY FROM SUPERCAP

The LTC3112 is a fixed frequency synchronous buck-boost DC/DC converter with an extended input and output range. The unique 4-switch, single inductor architecture provides low noise and seamless operation from input voltages above, below or equal to the output voltage. With an input range of 2.7V to 15V, the LTC3112 is well suited to a wide variety of single or multiple cell battery, backup capacitor or wall adapter source applications.
www.linear.com/3112



SINGLE CELL POWERED REMOTE WIRELESS SENSOR

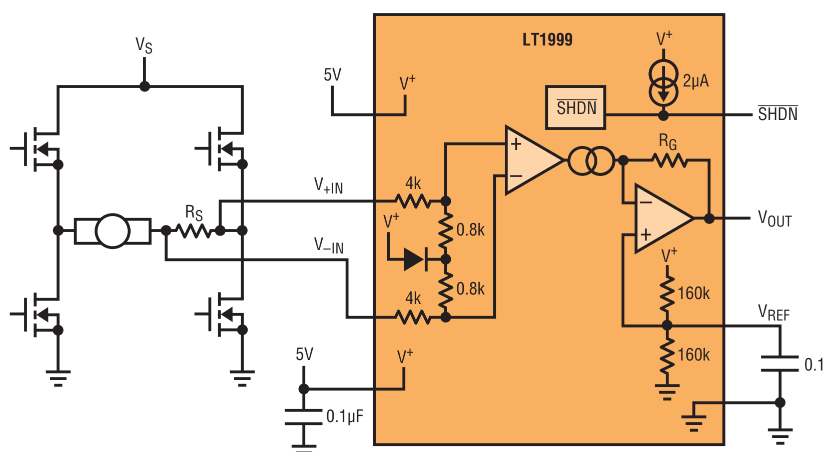
The LTC3105 is a high efficiency step-up DC/DC converter that can operate from input voltages as low as 200mV. A 250mV start-up capability and integrated maximum power point controller (MPPC) enable operation directly from low voltage, high impedance alternative power sources such as photovoltaic cells, TEGs (thermoelectric generators) and fuel cells. A user programmable MPPC set point maximizes the energy that can be extracted from any power source. Burst Mode operation, with a proprietary self-adjusting peak current, optimizes converter efficiency and output voltage ripple over all operating conditions.
www.linear.com/3105



* COILCRAFT MSS5131-103MX

FULL BRIDGE ARMATURE CURRENT MONITOR

The LT1999 is a high speed precision current sense amplifier, designed to monitor bidirectional currents over a wide common mode range. The LT1999 is offered in three gain options: 10V/V, 20V/V, and 50V/V. With a 2MHz bandwidth and a common mode input range of –5V to 80V, the LT1999 is suitable for monitoring currents in H-Bridge motor controls, switching power supplies, solenoid currents, and battery charge currents from full charge to depletion.
www.linear.com/1999



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