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Fractional-N PLL with Integrated 6GHz+ VCO Delivers Fractional-N Benefits without Complexity or Performance Downsides

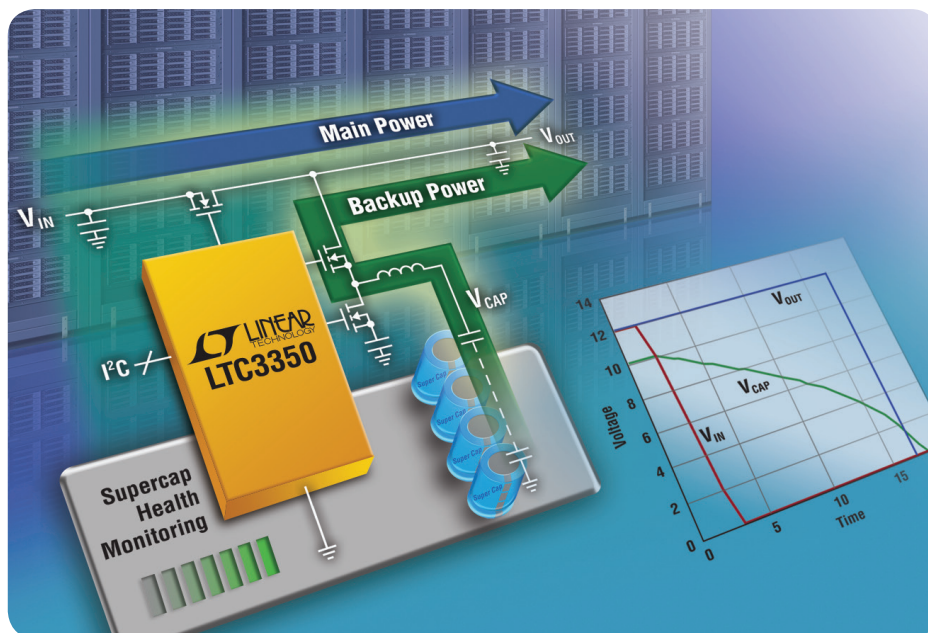
Michel Azarian

Fractional-N synthesizers tempt with a number of advantages over integer-N synthesizers, including frequency agility and overall phase noise performance. Even in light of these advantages, PLL system designers rarely yield to the temptation—complex design, poor spurious performance, and delta-sigma modulator noise

are generally accepted downsides of using fractional-N synthesizers—but the LTC6948 gives system designers the benefits of fractional-N PLLs without the drawbacks. Unlike typical fractional-N synthesizers, this device is easy to use and yields spurious and noise performance on par with integer-N synthesizers.

The LTC6948 integrates a high end 6GHz-plus vco in its 4mm × 5mm package, shrinking the size of the PLL system. Furthermore, PLL system design with the LTC6948 is

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LTC®3350 supercapacitor charger and backup controller ensures uninterrupted power in the event of a main power failure (see page 2).

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NEW POWER PRODUCTS LAUNCHED

Two significant new power management products were announced in May in press meetings in key locations worldwide: the LTC3350 supercapacitor charger and backup controller, and the LT[®]8620 2A, 65V synchronous step-down regulator.

LTC3350 Supercapacitor Charger and Backup Controller

The LTC3350 includes all of the features necessary to provide a complete, stand-alone capacitor-based backup power solution. It is ideal for applications requiring reliable, short-term uninterrupted power in the event of a main power failure. Examples include data backup for solid state drives, power fail alarms in medical and industrial applications, as well as other dying gasp power fail indicators.

The LTC3350 incorporates all PowerPath™ control, capacitor stack charging and balancing, and capacitor health monitoring circuitry necessary to provide a complete, high reliability backup system. The device can charge and monitor a series stack of one to four supercapacitors. The device's synchronous step-down controller drives N-channel MOSFETs for constant current/constant voltage charging, and can run in reverse as a step-up converter to deliver power from the supercapacitor stack to the backup supply rail. Internal balancers eliminate the need for external balance resistors and each capacitor has a shunt regulator for overvoltage protection. All system currents and voltages as well as stack capacitance and ESR are accurately measured using an internal 14-bit ADC and can be read back via I²C interface. Operating parameters such as capacitor charging voltage can be programmed via I²C to optimize system lifetime and performance.

LT8620 Wide Input Voltage Range Synchronous Step-Down Regulator

The LT8620 is the first synchronous high voltage step-down regulator with an input voltage range of 3.4V to 65V, delivering up to 2A to voltages as low as 0.97V. Applications in automotive and commercial vehicles demand power management ICs with increasingly high performance. For example, automotive (12V_{NOM}) or commercial vehicle (24V_{NOM}) applications running from the battery bus require a well regulated output voltage such as 3.3V, since the input voltage can swing from 3.5V in a cold crank or stop/start scenario up to 65V in a load dump scenario. High efficiency is a priority, with a focus on minimizing thermal design considerations while maximizing battery run time in hybrid and electric vehicles. For always-on automotive applications such as security, navigation, safety and environmental control, minimal quiescent current is critical to avoid draining the battery when the car is idle.

The LTC8620's internal synchronous rectification delivers efficiencies as high as 94%, eliminating the need for heat sinks, and Burst Mode[®] operation requires

only 2.5 μ A of quiescent current, reducing battery drain associated with always-on systems. The LT8620's minimum on-time of 30ns enables stepping down from 32V to 2V with a switching frequency of 2MHz. The device operates with only 250mV (at 1A) of dropout under all conditions, ideal for applications that must withstand cold crank or soft-start operating conditions.

AWARDS

Boeing Performance Excellence Award

The Boeing Company presented Linear Technology with a Gold Performance Excellence Award for superior supplier performance over the past year.

Olympus Best Analog IC Supplier Award

Olympus Medical Systems Corporation honored Linear Technology with its Best Analog IC Supplier Award "for a great contribution to product development over the years."

ECN Impact Awards

Winner, Best Integrated Circuit: LTC2378-20—The LTC2378-20 is a 20-bit, 1Msps no latency SAR ADC with industry leading 0.5ppm integral nonlinearity error (INL). A true 20-bit ADC, the LTC2378-20 is able to resolve down to 5 μ V of resolution on a 5V differential input span. The device is the first 20-bit SAR ADC offering extremely stable \pm 0.5ppm (typical) INL error with a guaranteed specification of 2ppm (maximum) over temperature, making it the most accurate ADC in the industry. Applications include seismic monitoring, energy exploration, airflow sensing, silicon wafer fabrication, medical devices, data acquisition systems, automatic test equipment, compact instrumentation and industrial process control systems.

Finalist, Power Sources Category: LT8614—The LT8614 Silent Switcher™ is a 4A, 42V input capable synchronous step-down switching regulator that reduces EMI/EMC emissions by more than 20dB, well below the

CISPR 25 Class 5 limit. Even with switching frequencies in excess of 2MHz, synchronous rectification delivers efficiency as high as 96% while Burst Mode operation keeps quiescent current under 2.5 μ A in no-load standby conditions. This makes it well suited for applications such as automotive "always-on" systems, which need to extend operating battery life. Its 3.4V to 42V input voltage range makes it ideal for automotive and industrial applications.

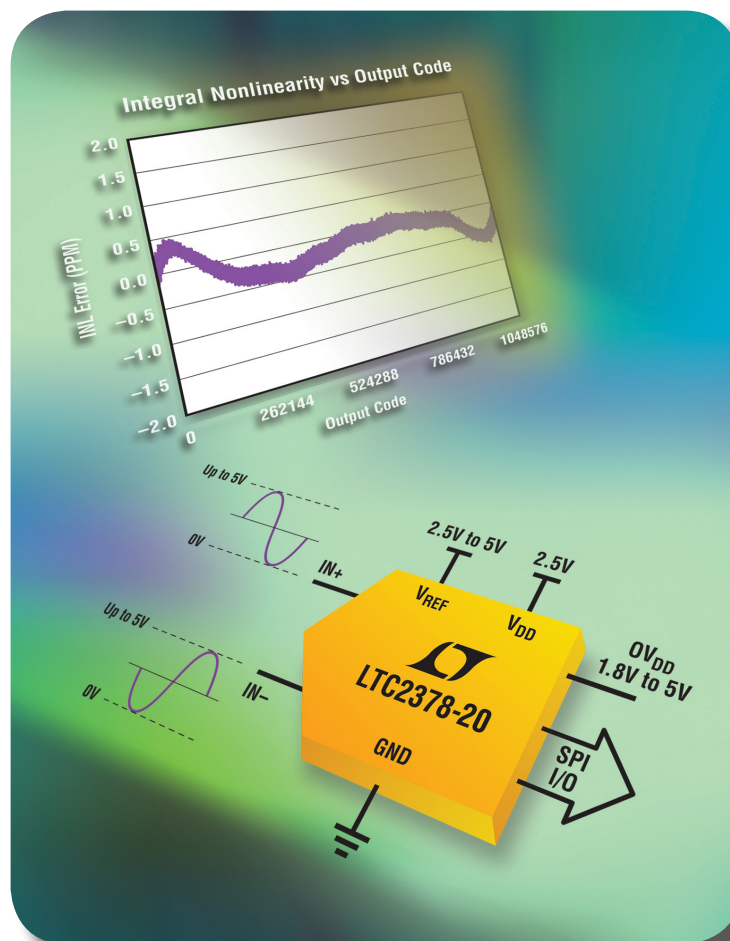
CONFERENCES & EVENTS

LTspice® World Circuit—Join Arrow Electronics and Linear Technology for a free half-day seminar with Mike Engelhardt for both advanced and new users of LTspice. Gain the knowledge to successfully simulate circuit designs and predict circuit behavior for faster, more efficient designs. Offered at multiple locations in the U.S., Europe and Asia, July through September. Schedule &

info at secure.effreg.com/r/ltspice2014
Free LTspice IV download at www.linear.com/solutions/LTspice.

Techno Frontier, Power System Japan 2014, Tokyo Big Sight, Tokyo, Japan, July 23-25, Booth 1F-301—Linear will exhibit power system management, battery management systems and LTspice IV. More info at www.jma.or.jp/tf/en.

The Battery Show/Electric & Hybrid Vehicle Tech Expo, Suburban Collection Showcase, Novi, Michigan, September 16-18, Booth 920—Presenting Linear's battery management system products. More info at www.thebatteryshow.com.



The LTC2378-20 20-bit no-latency serial SAR ADC was named Best Integrated Circuit by ECN magazine. A true 20-bit ADC, it features 1Msps throughput and 0.5ppm INL.

The LTC6948 borrows the high performance phase/frequency detector and VCO from the LTC6946, and adds an 18-bit delta-sigma modulator to the mix to create a world-class fractional-N PLL.

(LTC6948, continued from page 1)

easy with the help of FracNWizard™, a free and sophisticated fractional-N PLL design and simulation tool.

WHO NEEDS A FRACTIONAL-N PLL?

The LTC6946 integer-N PLL (*LT Journal of Analog Innovation*, January 2012) produces a PLL output frequency, $f_{LO(INT_N)}$, that is related to the reference frequency, f_{REF} , as follows:

$$f_{LO(INT_N)} = \frac{f_{REF}}{R} \cdot \frac{N}{O}$$

where R is the reference input divide value, N is the VCO feedback divide value, and O is the output divide value.

Figure 1 shows the LTC6946's simplified block diagram together with the loop filter required to stabilize the loop and an OCXO driving its reference.

The LTC6946 delivers excellent overall performance, but certain applications require that f_{LO} is moved in small frequency steps, $f_{STEP(INT_N)}$, or fine-tuned to track a certain frequency with high resolution. Trying to fit an integer-N PLL into such applications

would require a very small phase/frequency detector rate, $f_{PFD(INT_N)}$, where

$$f_{PFD(INT_N)} = f_{STEP(INT_N)} \cdot O$$

Often, in these situations, f_{PFD} is too small to be practically feasible, but even if it were possible, the in-band phase noise floor, $L_{M(OUT)}$, becomes prohibitively high:

$$L_{M(OUT)} = L_{M(NORM)} + 10 \cdot \log_{10}(f_{PFD}) + 20 \cdot \log_{10}\left(\frac{f_{LO}}{f_{PFD}}\right)$$

where $L_{M(NORM)}$ is the normalized in-band phase noise floor of the PLL.

Combining the two f_{PFD} terms:

$$L_{M(OUT)} = L_{M(NORM)} + 20 \cdot \log_{10}(f_{LO}) - 10 \cdot \log_{10}(f_{PFD})$$

$L_{M(NORM)}$ is fixed for the PLL, so this means that for the same desired f_{LO} , the in-band phase noise floor degrades by $-10 \cdot \log_{10}(f_{PFD})$. In other words, smaller f_{PFD} frequencies make the in-band phase noise floor worse. Figure 2 plots the last equation for an f_{LO} of 6.236GHz while varying f_{PFD} from 10kHz to 100MHz

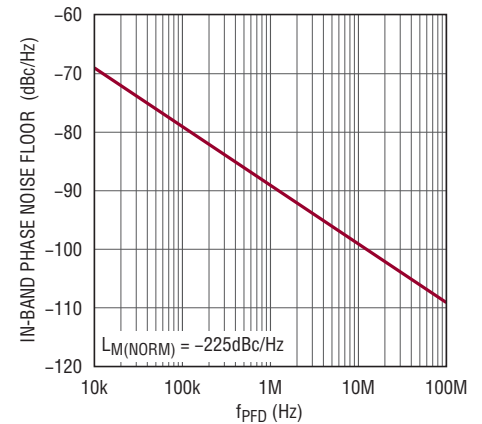


Figure 2. In-band phase noise floor of a PLL at a fixed f_{LO} vs f_{PFD}

and assuming $L_{M(NORM)} = -225\text{dBc/Hz}$, the typical normalized constant for the LTC6948 in fractional mode.

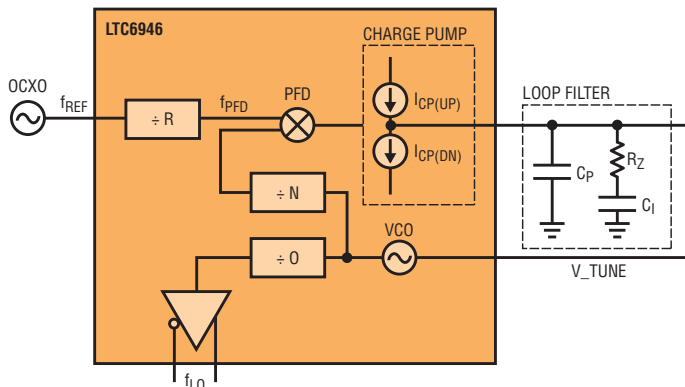
Figure 2 shows that f_{PFD} needs to be as high as possible, but it is strongly limited by $f_{STEP(INT_N)}$, the frequency step size in an integer-N PLL.

Fractional-N PLLs decouple this strong relationship between f_{STEP} and f_{PFD} . Fractional-N PLLs allow for a much smaller f_{STEP} than integer-N PLLs while running at a much faster f_{PFD} .

To further investigate the effect of f_{PFD} on the noise contribution of f_{LO} to a communications channel, the phase noise is integrated from 100Hz to 100MHz offset on both sides of $f_{LO} = 6.236\text{GHz}$ using practical LTC6948 settings in FracNWizard. Figure 3 summarizes the results.

The integrated noise shown in Figure 3 relates directly to the signal-to-noise ratio (SNR) of the communications channel.

Figure 1. Simplified LTC6946 block diagram with external reference clock and loop filter



The LTC6948 employs intelligent noise shaping techniques to minimize the in-band noise contribution from the modulator. It boasts a normalized in-band phase noise floor, $L_{M(NORM)}$, of -225dBc/Hz in fractional-N mode that compares well with its -226dBc/Hz integer-N mode performance. These numbers place the LTC6948 among the PLL elites.

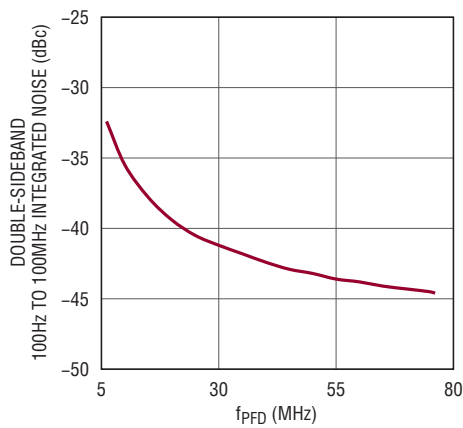


Figure 3. Double-sideband, 100Hz to 100MHz integrated noise at $f_{LO} = 6.236\text{GHz}$

Modern communications channels use complex modulation schemes to maximize data throughput, where an SNR of 40dB or higher is common. Figure 3 shows that a higher f_{PFD} helps meet such requirements.

UNDER THE HOOD OF THE LTC6948

The LTC6948 borrows the high performance phase/frequency detector and VCO from the LTC6946, and adds an 18-bit delta-sigma modulator to the mix to create a world-class fractional-N PLL. Figure 4 shows the block diagram of the LTC6948 along with the loop filter and an OCXO acting as its reference.

For the LTC6948, $f_{LO(FRAC_N)}$ and f_{REF} are related as follows.

$$f_{LO(FRAC_N)} = \frac{f_{REF}}{R} \cdot \frac{N+F}{O}$$

F is the fractional value and is given by

$$F = \frac{NUM}{2^{18}}$$

where NUM is the numerator programmed into the delta-sigma modulator internal to the LTC6948. Its value can be any integer between 1 and $2^{18} - 1$ (or 262,143), meaning $0 < F < 1$

As mentioned above, $f_{STEP(FRAC_N)}$ is small relative to $f_{STEP(INT_N)}$, despite $f_{PFD(FRAC_N)}$ being typically larger than $f_{PFD(INT_N)}$. This allows the designer to choose the highest possible $f_{PFD(FRAC_N)}$ given f_{REF} , taking advantage of the lowered in-band phase noise floor as shown in Figure 2, then verifying that $f_{STEP(FRAC_N)}$ is small enough to provide the desired frequency resolution at $f_{LO(FRAC_N)}$. The following equation relates the step size to the phase/frequency detector rate.

$$f_{STEP(FRAC_N)} = \frac{f_{PFD(FRAC_N)}}{O \cdot 2^{18}}$$

$f_{STEP(FRAC_N)}$ is 2^{18} times smaller than $f_{STEP(INT_N)}$ for the same f_{PFD} . For example, an f_{LO} of 6.236GHz can be generated by the LTC6948 with an f_{PFD} of 50MHz resulting in outstanding in-band phase noise floor with a frequency resolution of 190.7Hz ($= f_{STEP(FRAC_N)}$). That means the

designer can hit any frequency within the VCO range with a maximum error of $\pm(190.7/2 = 95.4\text{Hz})$. A maximum error of 95.4Hz out of $\sim 6.236\text{GHz}$ is 0.015ppm (parts per million) or 15ppb (parts per billion), eclipsing the accuracy of virtually any reference clock. Using a larger than one output divide value, O, further shrinks the absolute step size.

Employing a delta-sigma modulator to perform the fractionalization function in a PLL is the preferred method, because a delta-sigma modulator provides high resolution (such as the 2^{18} steps possible with the LTC6948) while intelligently shaping the quantization noise. In other words, the in-band quantization noise is lowered at the expense of higher out-of-band noise. The out-of-band noise is easy to filter out with the help of the passive components shown in Figure 4. As is shown in the “Design Example: Doppler Radar” below, determining the values of these components is straightforward using the FracNWizard software.

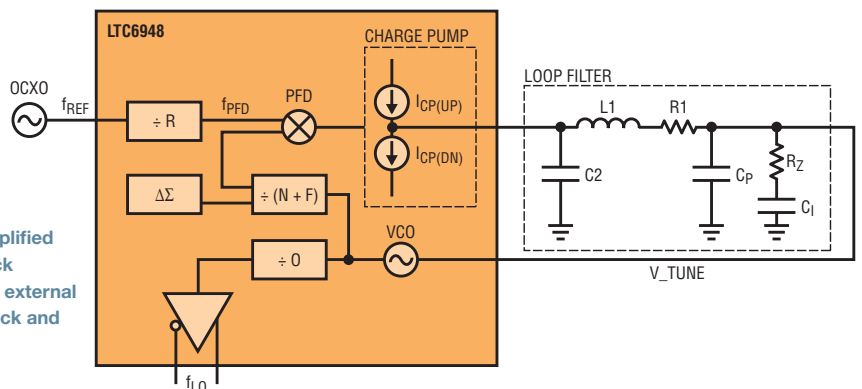


Figure 4. Simplified LTC6948 block diagram with external reference clock and loop filter

A fractional-N PLL has three types of spurious products at its output: reference spurs, integer boundary spurs and fractionalization spurs—troublesome spurs that are unpredictable. The LTC6948 has absolutely no fractionalization (or delta-sigma) spurs.

The delta-sigma modulator inside the LTC6948 can be shut down, making it run as an integer-N PLL.

DON'T PAY THE USUAL PRICE FOR FRACTIONALIZATION

Adding a delta-sigma modulator to a PLL can have serious drawbacks, including poor spurious performance (the most significant), delta-sigma modulator noise and design complexity. This is not the case with the LTC6948, as discussed below.

Spurious Performance Overview

A fractional-N PLL has three types of spurious products at its output.

1. Reference spurs
2. Integer boundary spurs
3. Fractionalization spurs

Troublesome spurs are those that are unpredictable. If the location and magnitude of a spur are known, the system designer can either avoid it, or ensure that it does not corrupt the integrity of the system. If the spur's location and magnitude are random, the designer is left with few good options.

Low Reference Spurs of the LTC6948

Reference (or PFD) spurs are predictable and exist in integer-N PLLs as well. These are located at exactly f_{PFD} and its harmonics away from f_{LO} , centered at f_{LO} . The LTC6948 has excellent reference spur performance. Figure 5 shows the typical performance of the LTC6948 at a $\sim 2.3\text{GHz}$ output.

Figure 5. LTC6948 f_{PFD} spurs for $f_{LO} = 2.378\text{GHz}$

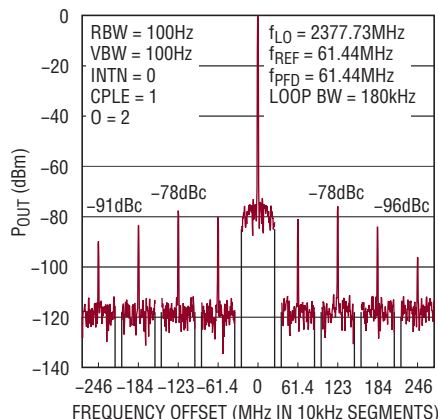


Figure 5 shows that with the LTC6948 set to fractional-N mode and generating an f_{LO} of 2.378GHz , the output spectrum contains reference spurs offset from f_{LO} by 61.44MHz (f_{PFD}), and by the harmonics of f_{PFD} . The LTC6948 reference spurs are relatively low in magnitude compared to other devices. Even the most significant spur, 121.88MHz offset from f_{LO} , is inconsequential—it is too low in energy and too far from f_{LO} to cause harm in most real-world applications.

Low and Predictable Integer Boundary Spurs

Integer boundary spurs are physical phenomena inherent to fractional-N PLLs. The VCO output intermodulates with the f_{PFD} harmonics to create beat frequencies. These beat frequencies appear as spurs around f_{LO} only when they are within or near the passband of the loop bandwidth, BW, of the PLL. In other words,

when F is extremely close to 0 or 1, these spurs are not attenuated by the loop filter and show up in the spectrum of the PLL output. Figure 6 illustrates this with measurements taken using the LTC6948.

As F shifts away from 0 or 1, the integer boundary spurs are attenuated by the loop filter. As F approaches $1/2$, $1/3$, $1/4$, etc., a similar mechanism is in place but at an exponentially lesser extent, so the main integer boundary spurs occur when $f_{PFD} \cdot F < BW$ or $f_{PFD} \cdot (1-F) < BW$.

In most situations, with careful choice of f_{REF} , and possibly using more than one f_{PFD} and/or f_{REF} , a system designer can avoid these spurs, since their position is known beforehand.

Better yet, and in a good portion of applications, the LTC6948's integer boundary spur levels (a maximum of -60dBc in the example shown in Figure 6) are so low that they are likely to be below the channel integrated noise in the system. A -40 to -50dBc double-sideband integrated noise in a communications channel is typically considered high end performance, meaning that a maximum of -60dBc spur is still at least 10dB below the channel noise and should not interfere with the overall system performance.

The reduced levels of integer-boundary spurs in the LTC6948, and even unfiltered inside the loop bandwidth, gives it a competitive advantage over other fractional-N PLLs whose integer-boundary spurs often dominate the channel energy.

Figure 6. LTC6948 integer boundary spurs for $f_{LO} = 2.365\text{GHz}$ ($F = 0.00043$) to $f_{LO} = 2.378\text{GHz}$ ($F = 0.4$)

No Fractionalization Spurs

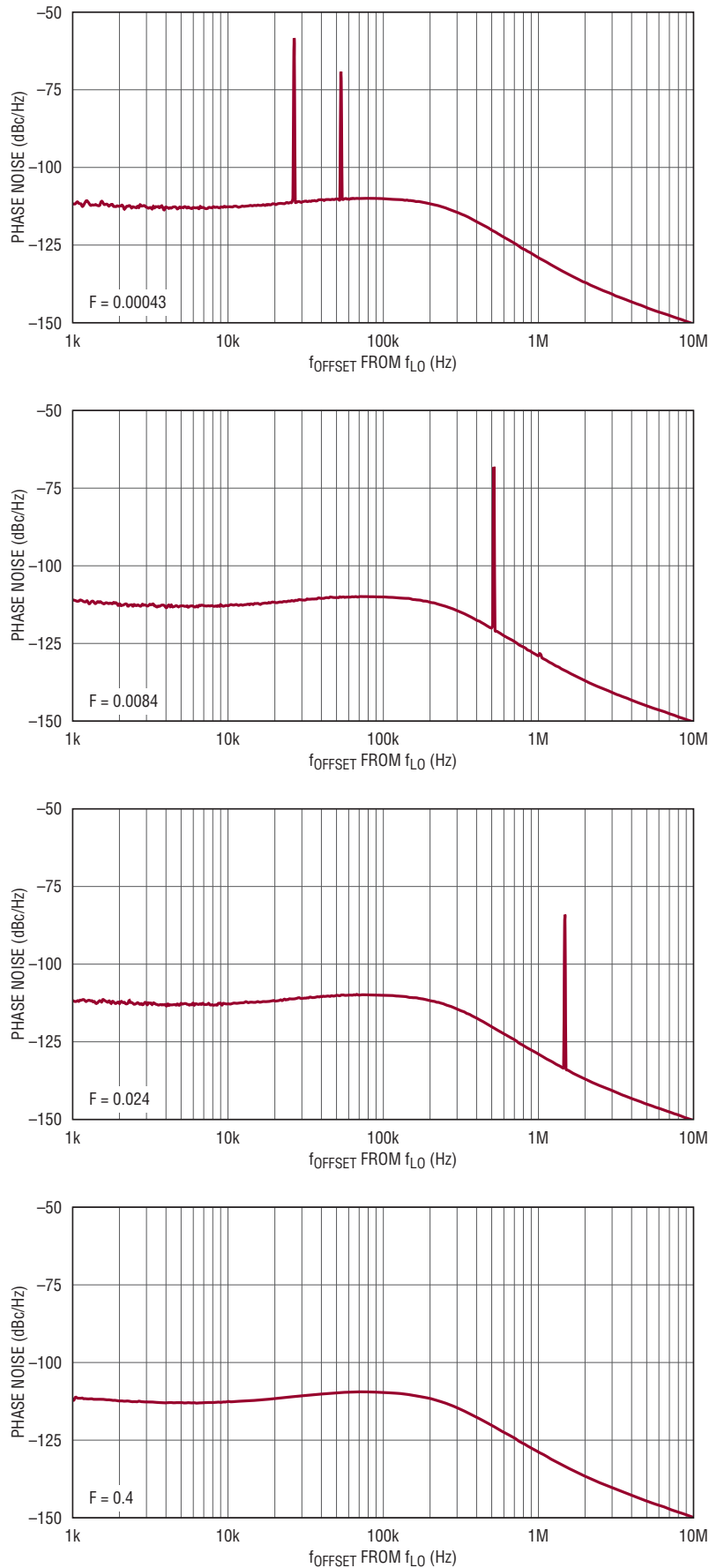
The LTC6948 does not have unpredictable fractionalization spurs, which infest most other fractional-N devices on the market. The stress of dealing with unpredictable spurs is removed from the LTC6948 equation.

Delta-Sigma Noise

The LTC6948 employs intelligent noise shaping techniques to minimize the in-band noise contribution from the modulator. It boasts a normalized in-band phase noise floor, $L_{M(NORM)}$, of -225dBc/Hz in fractional-N mode that compares well with its -226dBc/Hz integer-N mode performance. These numbers place the LTC6948 among the PLL elites.

Easy Design

The radar application described below under “Design Example: Doppler Radar” outlines how simple it is to design-in the LTC6948 with FracNWizard software. The LTC6948 does not use a labyrinth of modes, instead using a straightforward design process. All LTC6948 specifications are readily achievable.



The reference clock can be the most expensive component in the system. Proper and careful selection of the PLL IC avoids degrading the close-in phase noise, ideally dominated by the reference clock. Often overlooked, the 1/f (or flicker) noise of the PLL IC is an important specification that could degrade the close-in phase noise and negatively affect the in-band phase noise.

VCO CALIBRATION TIME

The LTC6948 uses multiple internal VCO sub-bands to cover its entire output frequency range. Each time the LTC6948 is powered up or its frequency is changed, it must be communicated to the IC so it can run an internal search algorithm to apply the correct VCO sub-band.

VCO calibration time should be minimized to limit the PLL lock time. Frequency hopping applications, for example, benefit from fast overall lock times. The LTC6948 can complete its VCO calibration in a little over 10µs as shown in Figure 7. That's a full order of magnitude faster than most alternative devices.

THE OFTEN HIDDEN BUT ALL-IMPORTANT 1/F NOISE

The reference clock can be the most expensive component in the system. Proper and careful selection of the PLL IC avoids degrading the close-in phase noise, ideally dominated by the reference clock. Often overlooked, the 1/f (or flicker) noise of the PLL IC is an important specification that could degrade the close-in phase noise and negatively affect the in-band phase noise. For instance, Figure 8 shows how the 1/f noise corrupts the in-band phase noise when the 1/f noise corner is elevated. Figure 8 assumes a normalized in-band phase noise floor of -225dBc/Hz.

Figure 8 reveals a fact of PLLs that most vendors choose to hide. It shows the strong effect of 1/f noise on the in-band phase noise floor. Even if a PLL IC claims to have an impressive normalized in-band phase noise floor (also known as the figure

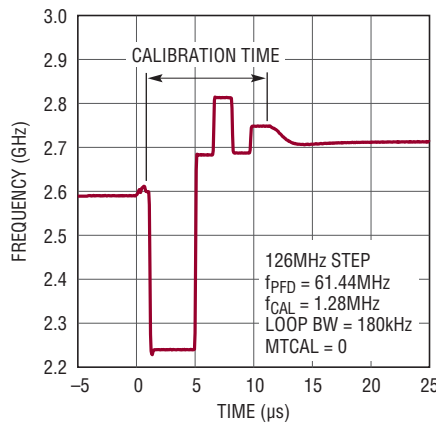


Figure 7. Typical LTC6948 VCO calibration time

of merit), it is likely that the same part lacks 1/f noise performance, devaluing the in-band phase noise specification.

The LTC6948 features an impressive -274dBc/Hz normalized in-band 1/f noise specification (normalized with respect to 1Hz offset from an f_{LO} of 1Hz), which is equivalent to a -134dBc/Hz phase noise level for a 100MHz reference clock at an offset of 100Hz,

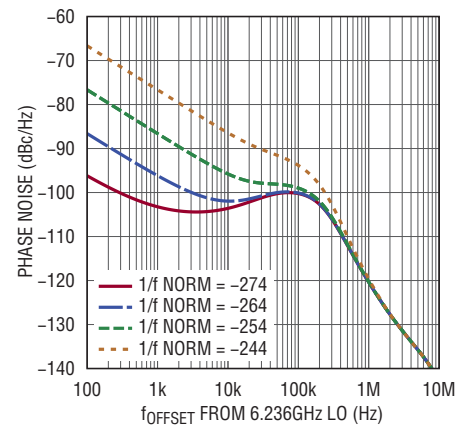


Figure 8. The effect of different normalized in-band 1/f phase noise specifications on the close-in and in-band phase noise performance

challenging the best 100MHz crystal oscillators available on the market.

The following formula shows how to convert the normalized 1/f number ($L_{1/f}$) to an offset phase noise value, $L_{OUT(1/f)}(f_{OFFSET})$, offset by f_{OFFSET} from a certain f_{LO} .

$$L_{OUT(1/f)}(f_{OFFSET}) = L_{1/f} + 20 \cdot \log_{10}(f_{LO}) - 10 \cdot \log_{10}(f_{OFFSET})$$

Table 1. LTC6948 output frequency options

VCO OUTPUT DIVIDER	FREQUENCY RANGE (GHz)			
	LTC6948-1	LTC6948-2	LTC6948-3	LTC6948-4
O_DIV = 1	2.240 to 3.740	3.080 to 4.910	3.840 to 5.790	4.200 to 6.390
O_DIV = 2	1.120 to 1.870	1.540 to 2.455	1.920 to 2.895	2.100 to 3.195
O_DIV = 3	0.747 to 1.247	1.027 to 1.637	1.280 to 1.930	1.400 to 2.130
O_DIV = 4	0.560 to 0.935	0.770 to 1.228	0.960 to 1.448	1.050 to 1.598
O_DIV = 5	0.448 to 0.748	0.616 to 0.982	0.768 to 1.158	0.840 to 1.278
O_DIV = 6	0.373 to 0.623	0.513 to 0.818	0.640 to 0.965	0.700 to 1.065

Doppler radar applications exemplify why 1/f noise performance can be crucial. Doppler radar relies on detecting small frequency shifts inflicted on an incident frequency when reflected by a moving object. The 1/f noise performance of the LTC6948 allows the requisite dynamic range at a 186Hz offset, increasing the chances of locating the 10mph moving object. Because the reflected signal is strongly attenuated, sufficient dynamic range in the radar receiver is key to properly deciphering the signal.

DESIGN EXAMPLE: DOPPLER RADAR

Doppler radar applications exemplify why 1/f noise performance can be crucial. Doppler radar relies on detecting small frequency shifts inflicted on an incident frequency when reflected by a moving object. The frequency shift, Doppler shift, of a reflected electromagnetic wave, f_D , on an incident frequency, f_{LO} , is related to the velocity of the moving object, v , and the speed of light, c , as follows:

$$f_D = 2 \cdot v \cdot \frac{f_{LO}}{c}$$

Modern uses of Doppler radar include tracking slowly moving objects in surveillance applications. A moderately paced object that is moving at 10mph creates an f_D of only 186Hz (assuming $c = 671 \cdot 10^6$ mph) for an $f_{LO} = 6.236$ GHz. As shown in Figure 8, the 1/f noise performance of the LTC6948 allows the requisite dynamic range at a 186Hz

offset, increasing the chances of locating the 10mph moving object. Because the reflected signal is strongly attenuated, sufficient dynamic range in the radar receiver is key to properly deciphering the signal.

Even detection of significantly faster objects benefits from the lower 1/f noise performance of the LTC6948 and its excellent in-band phase noise floor. For instance, a body moving at 200mph has an $f_D = 3.72$ kHz if $f_{LO} = 6.236$ GHz.

Figure 9. The FracNWizard tool determines design parameters for $f_{LO} = 6.236$ GHz using the LTC6948

The screenshot shows the Linear Technology FracNWizard software interface. The interface is divided into several sections: DESIGN, SIMULATE, and a bottom section for filter selection. The DESIGN section includes VCO Params, Design Goals, Recommendations, and Part Params. The SIMULATE section includes Loop Filter, Component Values, and Calc'd Frequencies. The bottom section shows four filter options: Filter 1 (2nd Order), Filter 2 (3rd Order), Filter 3 (4th Order), and Filter 4 (4th Order). Red dashed lines and arrows point from numbered steps (1-8) to specific parts of the interface.

1. Choose Loop Design - Points to the 'Loop Design' tab.

2. Choose the LTC6948-4 - Points to the 'System' dropdown menu.

3. Enter the reference frequency - Points to the 'Fref' field (100.0000 MHz).

4. Enter the desired f_{LO} - Points to the 'Frf' field (6236.0000 MHz).

5. Click Compute Params - Points to the 'Compute Params' button.

6. Choose Filter 3 - Points to the 'Filter 3 (4th Order)' radio button.

7. Click Design Filter - Points to the 'Design Filter' button.

8. Populate the circuit with practical versions of the Component Values shown - Points to the 'Component Values' table.

Component Values Table:

Component	Value	Unit
Rz	71.4	Ohms
Ci	58.0	nF
Cp	2.45	nF
R1	71.4	Ohms
C2	1.64	nF
L1	8.34	uH
R2	0.00	Ohms
C3	0.00	nF

Calc'd Frequencies Table:

Parameter	Value	Unit
Fpfd	50.000000	MHz
Fvco	6236.0001	MHz
Frf	6236.0001	MHz
Fstep	0.1907349	kHz
Max F Error	0.0953674	kHz
Max F Error	0.0152930	ppm
NUMstep	52428.80	counts
Loop BW	173	kHz
OSR	289.017	Hz/Hz
Fcal	1563	kHz
Tcal	8.960	us

Even detection of significantly faster objects benefits from the lower $1/f$ noise performance of the LTC6948 and its excellent in-band phase noise floor. For instance, a body moving at 200mph has an $f_D = 3.72\text{kHz}$ if $f_{LO} = 6.236\text{GHz}$. A radar system equipped with the LTC6948 allows for the best dynamic range at 3.72kHz offset.

Figure 10. The LTC6948-4 circuit with the calculated loop filter components

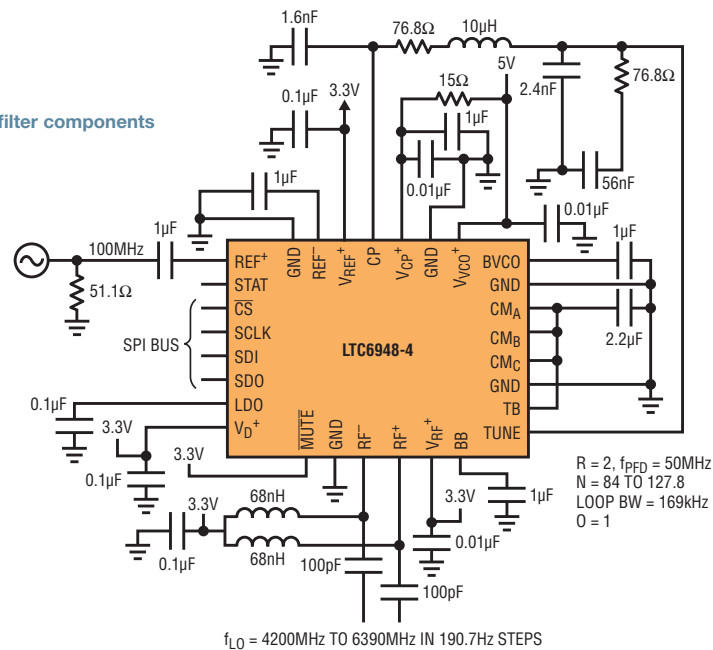


Figure 8 reveals that a radar system equipped with the LTC6948 allows for the best dynamic range at 3.72kHz offset.

Now that we've seen that the performance of the LTC6948 meets the requirements of Doppler radar applications, let's look at the nuts and bolts of the design process.

Picking the PLL

To design a PLL for the Doppler radar application, where f_{LO} is 6.236GHz, choose the version of the LTC6948 that operates at that frequency. Table 1 shows the four available LTC6948 options.

The LTC6948-4 includes a VCO that delivers the desired f_{LO} of 6.236GHz.

Designing the PLL

Download FracNWizard at www.linear.com/FracNWizard and install. The design presented here assumes a 100MHz reference clock—demonstration circuit DC1216A-D from Linear Technology can perform this task. Using FracNWizard (see Figure 9) choose the LTC6948-4, enter the design goals and determine the components required to complete the design.

Simulating and Building the PLL

Demonstration circuit DC1959A-D makes a good starting point. Take the filter component values as determined by FracNWizard (sidebar) and replace components on the DC1959A-D as needed with practical value components. Figure 10 shows the schematic of the 6.236GHz circuit with practical filter component values.

Update the FracNWizard filter component values with the practical values of the passive components. As illustrated in Figure 11, FracNWizard predicts the phase noise performance of the LTC6948-4 at the desired 6.236GHz. It shows how the reference phase noise affects the total output noise, helping you choose the reference clock. FracNWizard also shows how the shaped delta-sigma modulator noise is filtered with the use of the passive filter.

Evaluating the PLL

Apply power to the DC1959 and connect it to a PC via demonstration circuit DC590, a USB serial controller available from Linear Technology. Apply the 100MHz reference clock source to the DC1959 and follow the instructions given in the DC1959 demonstration circuit manual at www.linear.com.

The LTC6948 fractional-N PLL offers the benefits of fractionalization, including frequency agility and overall reduced in-band phase noise, without the usual downsides associated with fractional-N PLLs. Design is simplified by free FracNWizard software, and published specifications, although impressive, are conservative and readily attainable.

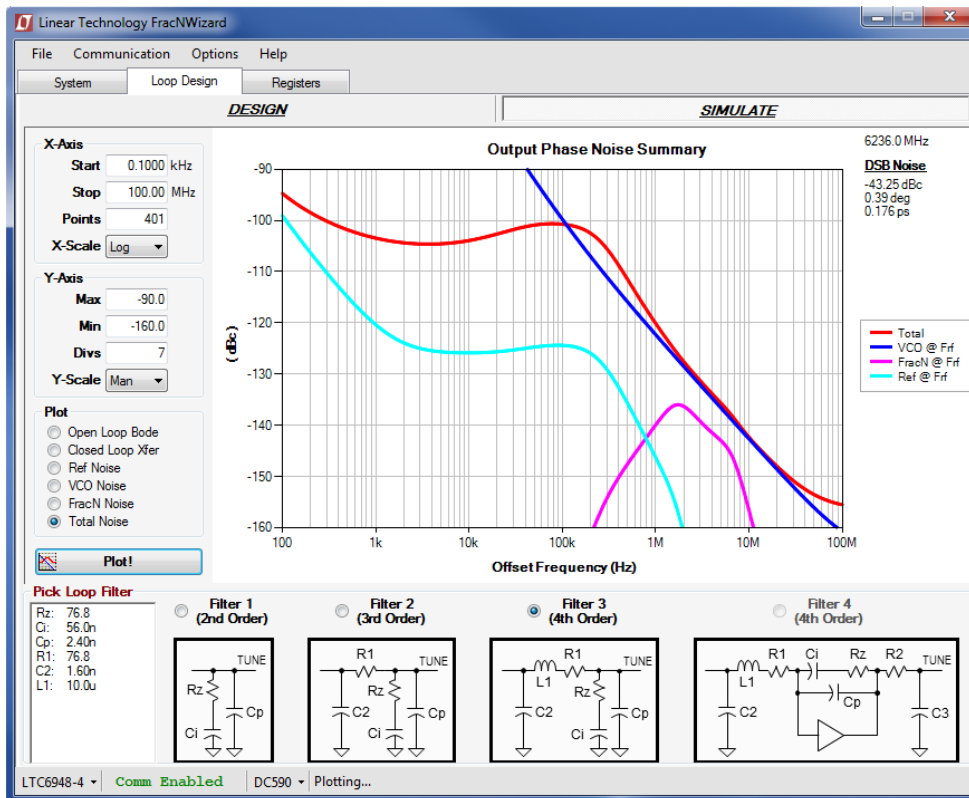


Figure 11. FracNWizard simulation results for $f_{LO} = 6.236\text{GHz}$

Verify the phase noise of our example f_{LO} by connecting the output of the DC1959 to a signal source analyzer, the E5052A from Agilent in this case. Figure 12 shows the result, which aligns closely with the calculated FracNWizard results shown in Figure 11.

That's it. The fractional-N PLL system design is complete.

CONCLUSION

The LTC6948 fractional-N PLL offers the benefits of fractionalization, including frequency agility and overall reduced in-band phase noise, without the usual downsides associated with fractional-N PLLs. Design is simplified by free FracNWizard software, and published specifications, although impressive, are conservative and readily attainable. ■

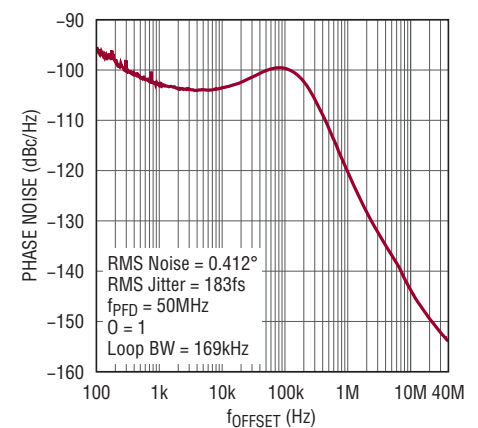


Figure 12. Measured results of $f_{LO} = 6.236\text{GHz}$ at the output of the LTC6948-4

High Performance Portable DC Bench Power Supply: Save Money and Free Up Bench Real Estate by Building Your Own

Keith Szolusha

The bench power supply, along with the soldering iron and handheld multimeter, is a required item in any electronics lab toolbox. Some projects require only a single, constant voltage supply, but more often, properly testing and debugging a project demands a variety of voltages and currents. Significant debugging time can be saved by using a high performance adjustable bench supply to dial in voltage and current at will. Unfortunately, typical universal adjustable bench power supplies are bulky and expensive—at least the better-performing versions—and have a number of limitations. None are truly portable (handheld) due to necessary heat dissipation structures. Furthermore, even high cost supplies do not support zero current or voltage, and cannot match the transient and short performance exhibited by the supply shown here.

Save money and free up benchtop space by building your own high quality bench power supply. The key component to this supply is the LT3081 linear regulator surrounded by a short list of easy-to-get components (see Figure 1). The LT3081's unique current-source reference and voltage-follower output amplifier make it possible to connect two linear regulators in parallel for up to 3A and over 24V of adjustable current and voltage output control. Linear regulators at the output suppress output ripple without requiring large output capacitors, resulting in a truly flat DC output and small size.

In the supply shown here, parallel LT3081s are preceded by a high performance,

Linear Technology's demonstration circuit DC2132A is a high performance, compact, efficient DC bench supply

IMON TOTAL CURRENT MONITOR OUTPUT

0V-24V CONSTANT VOLTAGE
0A-3A CONSTANT CURRENT

1-TURN (OR 10-TURN) POTENTIOMETERS FOR OUTPUT VOLTAGE AND OUTPUT CURRENT ADJUSTMENT

TEMPERATURE MONITOR OUTPUTS

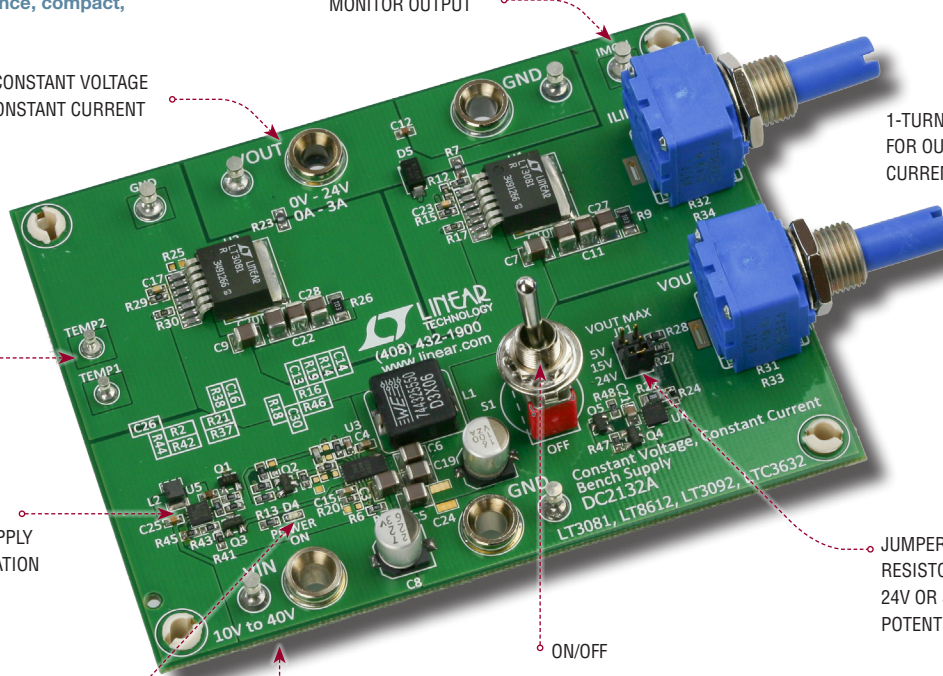
LTC3632
-5V, -8mA SUPPLY FOR 0V OPERATION

JUMPER FOR ADJUSTING V_{OUT} MAXIMUM RESISTOR WITH JUMPER FOR $V_{IN} = 12V, 24V$ OR $36V$ TO MAXIMIZE TURNS OF POTENTIOMETER

LED ON INDICATOR

10V-40V INPUT

ON/OFF



The key component to the supply is the LT3081 linear regulator surrounded by a short list of easy-to-get components. The LT3081's unique current-source reference and voltage-follower output amplifier make it possible to connect two linear regulators in parallel for up to 3A and over 24V of adjustable current and voltage output control. Linear regulators at the output suppress output ripple without requiring large output capacitors, resulting in a truly flat DC output and small size.

synchronous step-down converter, in this case, the 40V, 6A LT8612. No heat sink or fan is required, in direct contrast to linear bench supplies featuring power transistors that require heat sinks and forced airflow (fans) to sufficiently dissipate the heat.

The LT8612 efficiently steps down 10V to 40V at high or low current to a dynamically adaptive output voltage, which remains just above the output voltage of the bench power supply (output of the LT3081 linear regulator). The output of the LT8612 is low ripple and conversion is efficient over the full range of

the bench supply. Power loss across the LT3081 devices is minimized by keeping their input just above dropout. This bench supply includes the uncommon ability to adjust both the voltage and current limit down to zero. A complete schematic of this mixed-mode DC bench supply is shown in Figure 2.

PARALLEL LINEAR REGULATORS STEADY OUTPUT, CONTROL VOLTAGE AND CURRENT

Linear regulators are commonly used at the output of step-down converters to suppress switching power supply ripple

with a minimal efficiency hit. The parallel LT3081 linear regulators shown in Figures 1 and 2 knock down the output ripple of the LT8612 and accurately control constant voltage and constant current output of the power supply. The LT3081 has the unique ability (for linear regulators) to be easily paralleled for higher output currents.

Figures 1 and 2 show how two parallel LT3081s double the supported current of a single LT3081 (1.5A) to 3A. A few parallel connections and two small 10mΩ ballast resistors are all that is needed to accurately share current

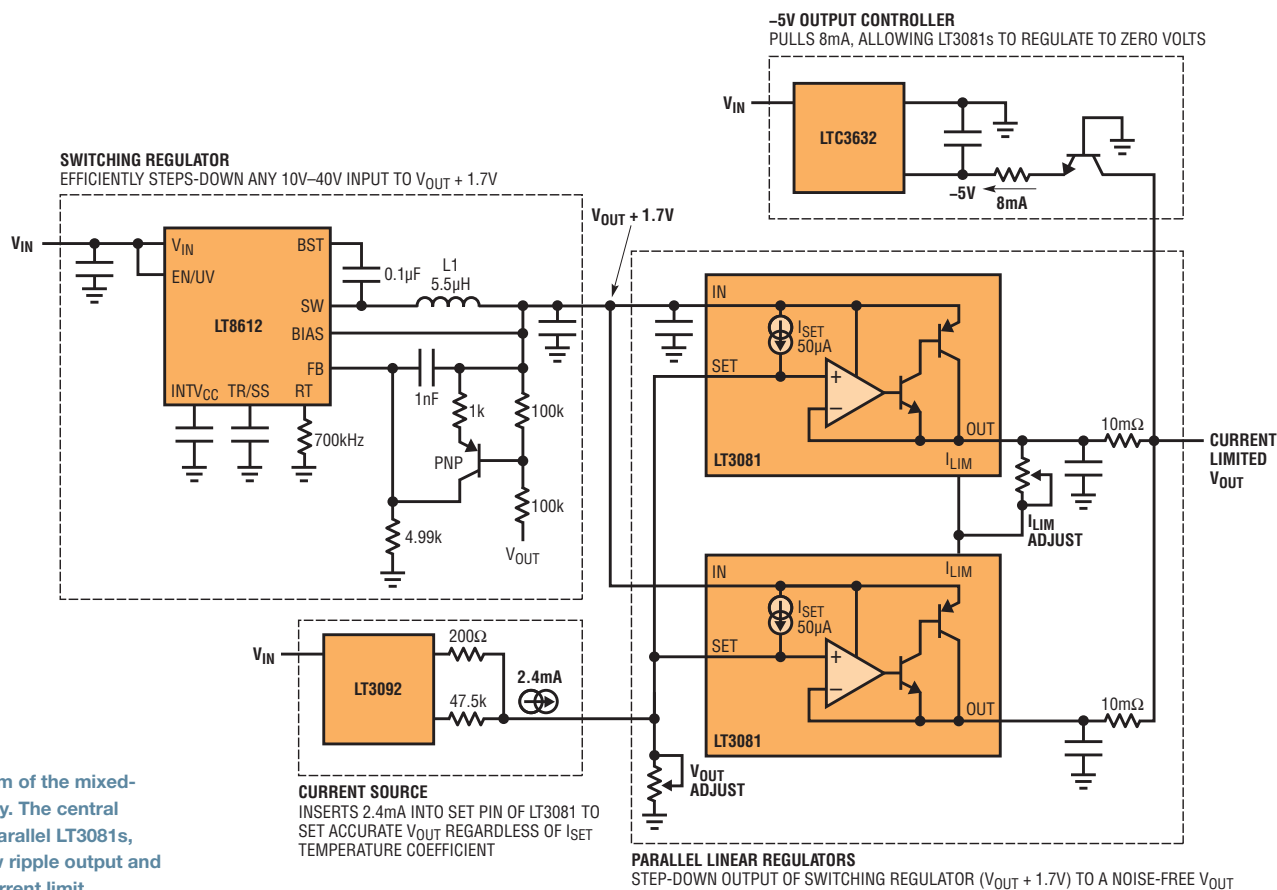


Figure 1. Block diagram of the mixed-mode DC bench supply. The central components are the parallel LT3081s, which produce the low ripple output and set the voltage and current limit.

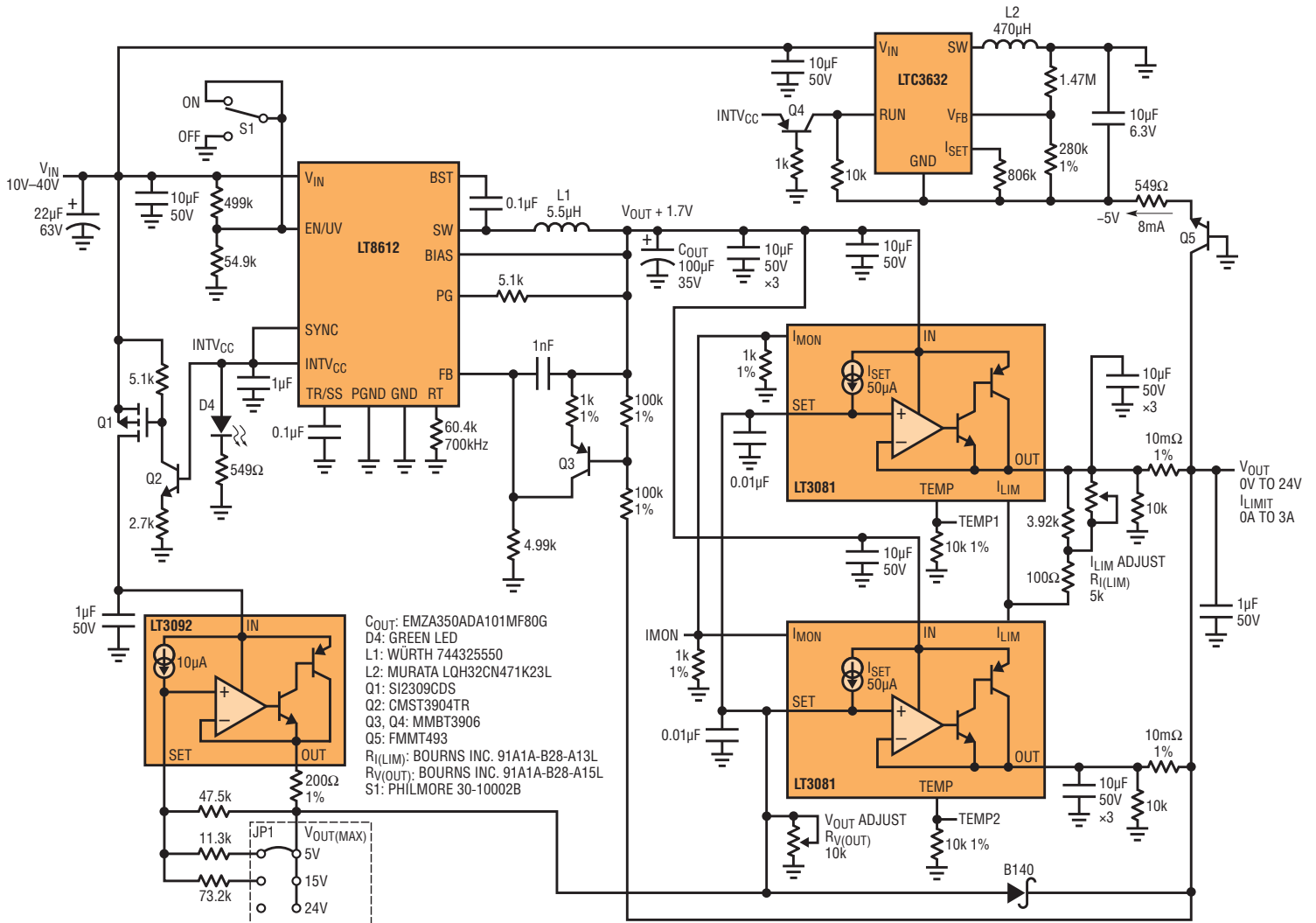
The minimum current limit of the bench power supply is 0A. The LT3081 guarantees 0A output current as long as the ILIM resistor is reduced below 200Ω. The minimum output voltage of the bench power supply is 0V. The LT3081 guarantees 0V output as long as there is 4mA pulled from the output.

between the two without a loss of output voltage accuracy. Readily available, high quality 10k and 5k potentiometers provide the control from 0V–24V and 0V–3A when connected to the SET pin and ILIM pins. Potentiometers with more turns and more accuracy can certainly be used to fancy-up one's bench supply.

The minimum current limit of the bench power supply is 0A. The LT3081 guarantees 0A output current as long as the ILIM resistor is reduced below 200Ω. A small 100Ω resistor is placed in series with the ILIMIT potentiometer to maximize the turning range and still guarantee zero current when two regulators are used in parallel.

The minimum output voltage of the bench power supply is 0V. The LT3081 guarantees 0V output as long as there is 4mA pulled from the output. The best way to do this is to use a negative supply to pull 8mA for the two LT3081s. The LTC3632 –5V regulator easily produces this negative load, dissipates little power and occupies only a tiny bit of board space.

Figure 2. Complete 0V–24V, 0A–3A DC bench supply



Once target voltage is precisely dialed-in, you don't want to see the bench supply voltage drift as load is added, increased or decreased. Ideally, it should maintain a flat regulation profile across the entire range of load currents up to the current limit. The supply shown here fulfills this requirement.

FLAT LOAD REGULATION AND SHARP VI CURVE

Once target voltage is precisely dialed-in, you don't want to see the bench supply voltage drift as load is added, increased or decreased. Ideally, it should maintain a flat regulation profile across the entire range of load currents up to the current limit (Figures 3 and 4).

The supply shown here fulfills this requirement. The LT3081 output remains virtually flat from 0A to 1.5A. Minimum IC heating helps keep load regulation of the bench supply under 50mV for any output voltage, as shown in Figure 3—even with 15mV due to the 10mΩ ballast resistors. A 1.7V drop across the linear regulators while driving 1.5A produces a mere 30°C temperature rise with the DD package, as shown in Figure 5.

Setting the current limit knob should be just as deterministic as the voltage knob. If the current limit is set to 3.0A, the bench supply should enter current limit at exactly 3.0A and never supply higher current. A high performance bench supply must demonstrate a voltage vs current regulation curve that remains flat until it drops off a cliff to 0V when the current limit is reached. Figure 4 shows that

Figure 3. DC bench supply V-I curve shows < 50mV load regulation from 0A to 3A, falling off a cliff above 3.1A.

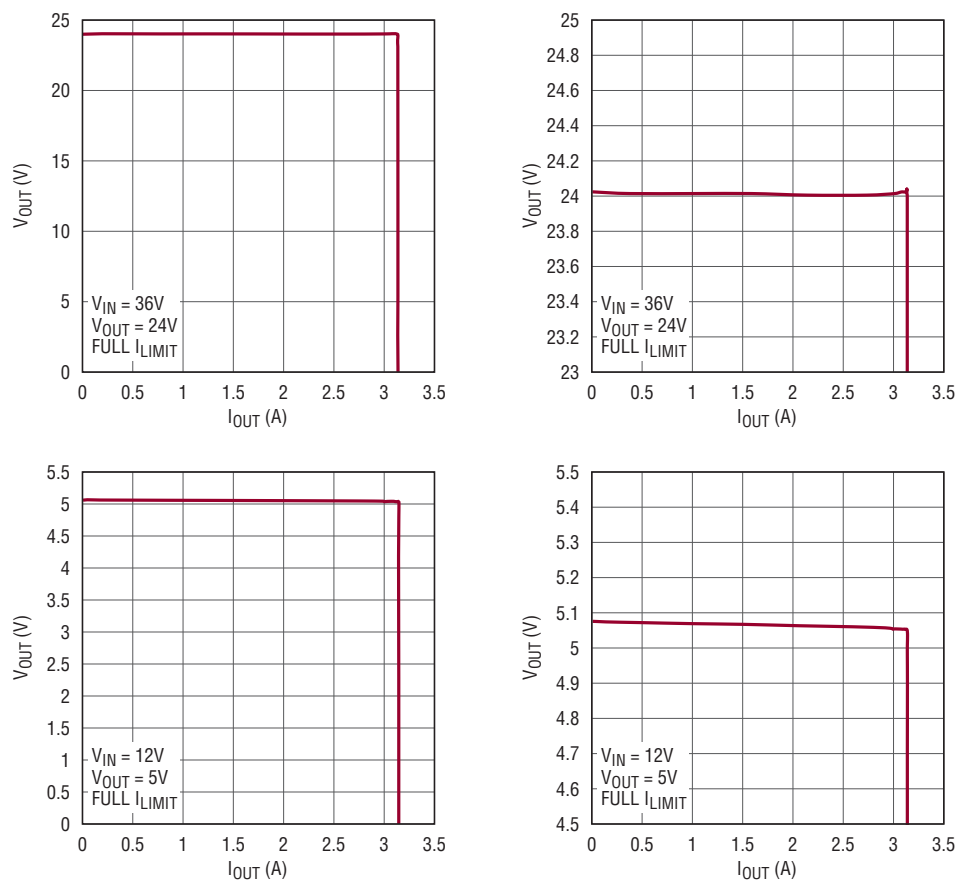
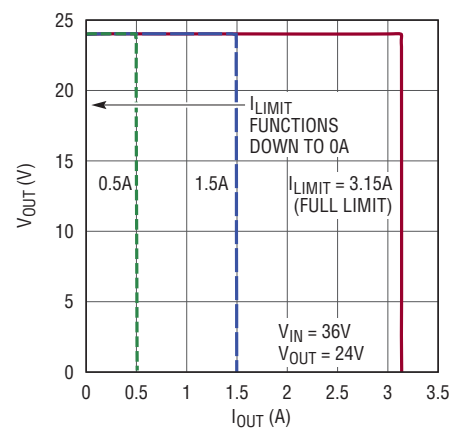


Figure 4. Adjustable current limit moves the cliff of Figure 3 to any value from 3.1A down to 0.0A.



The portable DC bench power supply can produce 0A–3A at any voltage between 0V and 24V from an input voltage of 10V and 40V, with the input at least 5V above the desired output voltage. The input can come from a front-end AC/DC converter, readily available at 19V, 28V and 36V. It can also be a simple 24VAC transformer, a rectifier bridge, and a 10mF capacitor that gives approximately 34V with 1V–2V of ripple.

the bench supply performs as desired, regardless where the current limit is set.

SYNCHRONOUS STEP-DOWN CONVERTER KEEPS OVERALL EFFICIENCY HIGH

The portable DC bench power supply can produce 0A–3A at any voltage between 0V and 24V from an input voltage of 10V and 40V, with the input at least 5V above the desired output voltage. The input can come from a front-end AC/DC converter, readily available at 19V, 28V and 36V. It can also be a simple 24VAC transformer, a rectifier bridge, and a 10mF capacitor that gives approximately 34V with 1V–2V of ripple.

The LT8612 step-down switching converter portion of the power supply drops the AC/DC front-end voltage (10V to 40V) down to any voltage between 0V and just below its input voltage. The low ripple output of the LT8612-based converter is further dropped by 1.7V across the parallel LT3081 linear regulator to the final regulated voltage, with nearly no ripple on the output.

High Efficiency Keeps it Cool

The LT8612 synchronous step-down easily supports 3A and efficiently steps down to outputs as low as 1.7V from inputs up to 40V, even at a relatively high switching frequency, 700kHz, due to low minimum on-time of 40ns. Efficiency is shown in

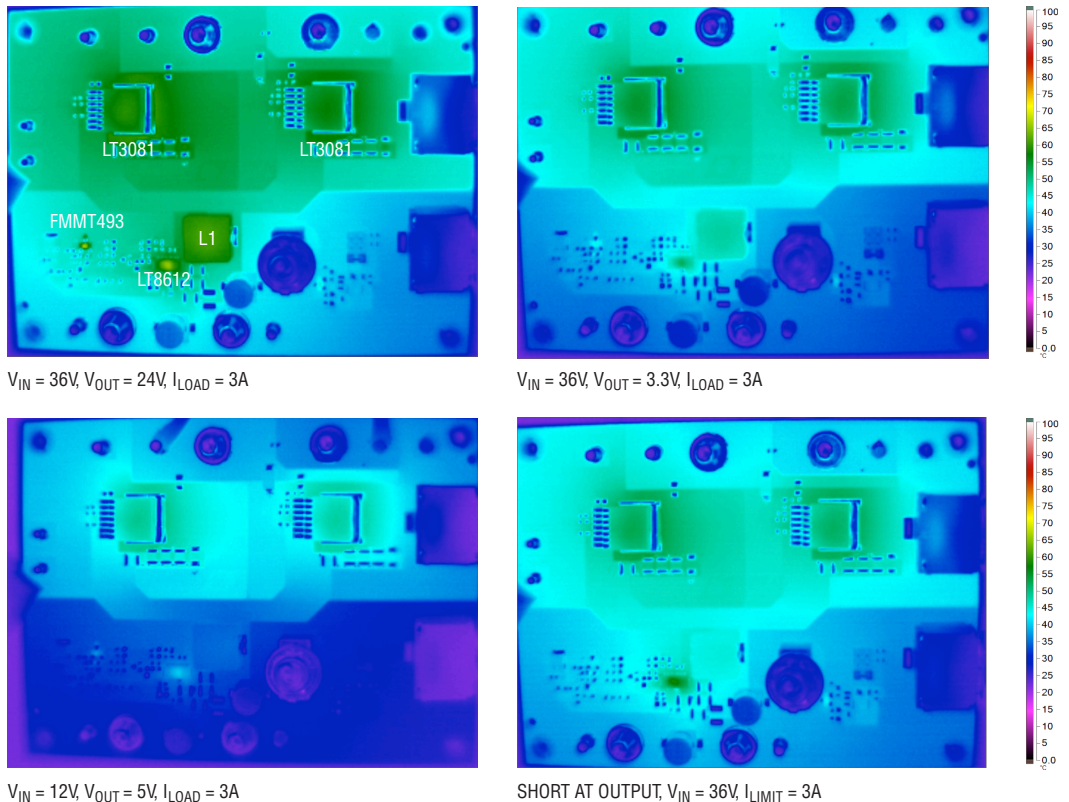
Figure 6. High efficiency at high switching frequency makes it possible to realize a converter with a few small components that remain cool at high power.

Differential Feedback

The LT8612 uses a differential feedback scheme, shown in Figures 1 and 2, to regulate its output (the input to the LT3081 pair) to 1.7V above the bench supply output (the output of the LT3081 pair). The LT3081 works best when its input is at least 1.5V above its output, with 1.7V used here as margin for transients.

Differential feedback continues to operate during output transients and

Figure 5. Thermoscans of bench supply in high power conditions and short-circuit show that the DC bench supply components remain cool without the use of a heat sink or fan.



One way to combat current drift is to use a higher current source to drive the SET pin potentiometer. The LT3092 is an accurate current source that works up to 40V and is used to drive an accurate 2.4mA for a 24V output with a 10k resistor. Its output current is easy to adjust with the change of the set resistor value when a different maximum output voltage is needed.

short-circuits, as shown in Figures 7 and 8. When the output is shorted to GND, the LT8612 output follows it to GND. When the output is suddenly increased with a release of the short or a change in the potentiometer, the LT8612 follows the rising output of the LT3081, striving to stay 1.7V above the quickly changing output. A reasonable-sized 100 μ F output capacitor is enough to provide stability to the LT8612 over a wide range of conditions, while maintaining relatively fast transient response, though it will never move as fast as the linear regulators can.

This setup could be expanded to support 4.5A output current using three parallel LT3081 linear regulators. The switching regulator would need no change, as the LT8612 features 6A peak switch current capability.

ACCURATE CURRENT SOURCE COMBATS I_{SET} TEMPERATURE COEFFICIENT

The output voltage of the bench supply is easily adjusted by hand with a potentiometer that is connected to the SET pins of the LT3081 pair. It seems simple enough that the SET pins each source 50 μ A, and that their sum current, multiplied by an adjustable resistor, can generate the proper output voltage with no additional components. Nevertheless, that current may not be enough for a robust bench power supply solution, since it can drift a bit with LT3081 temperature.

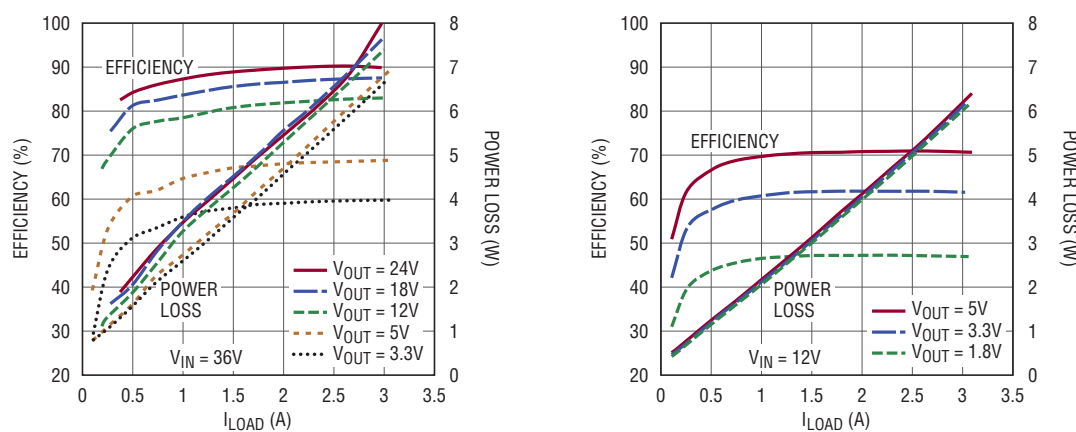
One way to combat the current drift is to use a higher current source to drive the SET pin potentiometer. The LT3092 is an accurate current source that works up to 40V and is used to drive an accurate 2.4mA for a 24V output with a 10k resistor. Its output current is easy to adjust with the change of the set resistor value when a different maximum output voltage is needed. The maximum output

voltage should be 5.5V when a 12V source is used, 15V when a 24V source is used and 24V when a 36V source is used. An input switch is used in the circuit to cut off the supply to the LT3092 when the power switch is turned off. Disconnecting this IC from V_{IN} when the switch is turned off prevents its constant current from charging up an unloaded bench supply output, saving engineers from potentially damaging circumstances.

EASY TURN POTENTIOMETER KNOBS FOR VOLTAGE AND CURRENT

The LT3081 SET and ILIM pin functions make it easy to program the output voltage and current to any level with the simple turn of a potentiometer. Parallel LT3081s share the same SET pin connection and voltage as well as the same ILIM⁺ and ILIM⁻ pin connections. The 10k and 5k potentiometers are chosen to give 0V to 24V and 0A to 3A output ranges (or slightly above for a little headroom.) The potentiometers are easy to source

Figure 6. Efficiency and power loss of DC bench supply for a various input and output conditions



The bench supply shown features single-turn potentiometers with easy-to-turn shafts and right angle PCB connections. The cermet element prevents time and temperature drift with 150ppm/°C rating versus the 1000ppm/°C rating of similar plastic element versions. Less expensive plastic potentiometers are still excellent for use on a standard bench supply, or ten-turn precision potentiometers can be used for very fine trimming of both voltage and current limits.

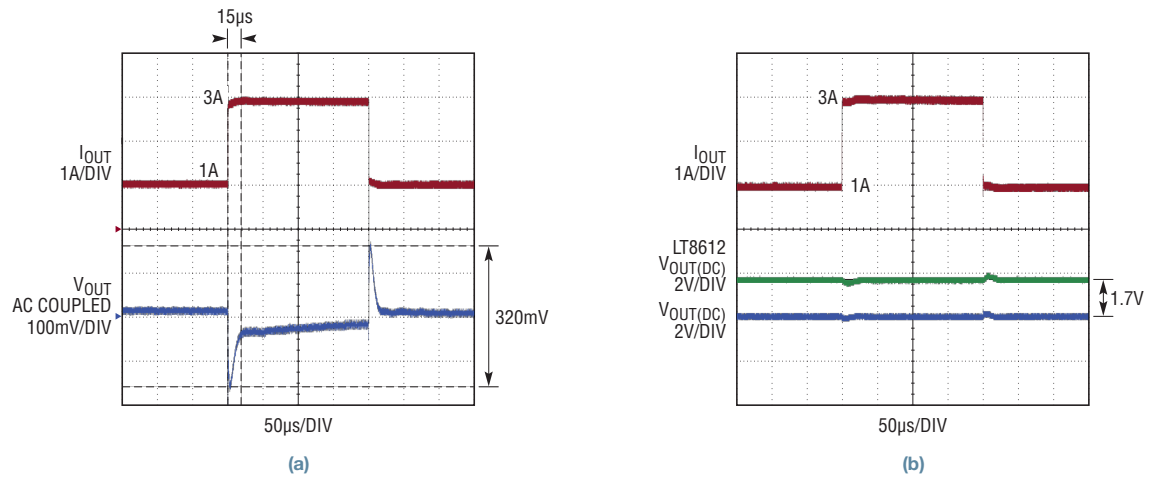


Figure 7. 5V, 1A to 3A output transient response shows (a) low output ripple and (b) LT8612 output tracks LT3081 V_{OUT} through a transient.

and they can be selected from a range of performance and cost parameters.

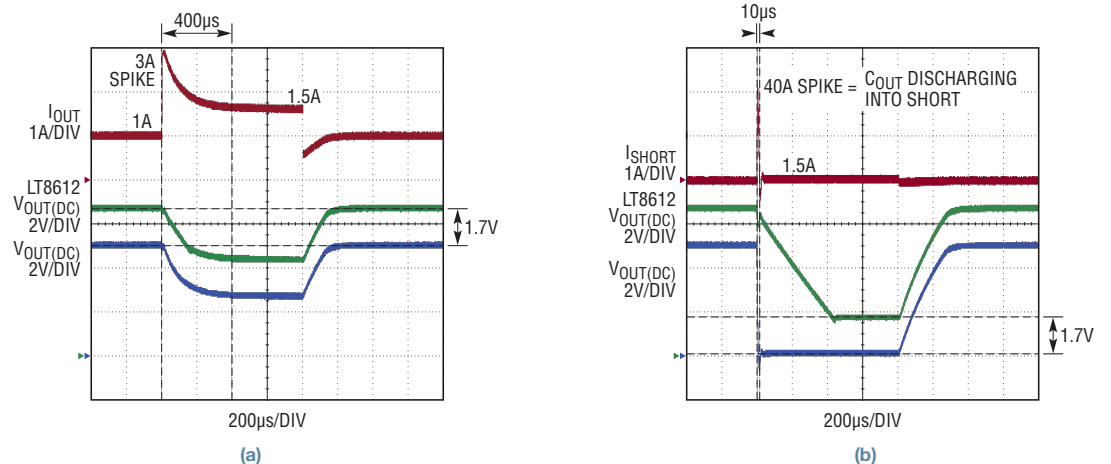
The bench supply shown in the photo on page 12 features single-turn potentiometers with easy-to-turn shafts and right angle PCB connections. They can be mounted on a side hole of a box should you decide to enclose the

PCB in a protective case. The cermet element prevents time and temperature drift with 150ppm/°C rating versus the 1000ppm/°C rating of similar plastic element versions. Less expensive plastic potentiometers are still excellent for use on a standard bench supply, or ten-turn precision potentiometers

can be used for very fine trimming of both voltage and current limits.

If V_{OUT} drift due to I_{SET} temperature coefficient is not an issue, the LT3092 current source can be removed and the 10k potentiometer can be replaced by a 250k pot with similar quality.

Figure 8. 5V output (a) overload transient and (b) short-circuit transient are well tolerated by the DC bench supply.



The most extreme overload condition is a short-circuit, which not only pushes the output over the cliff, but all the way down to ground. The bench supply gracefully maintains its current limit in short-circuit and regulates its LT8612 output to 1.7V, sourcing the limited current through the LT3081 and into the short.

NEGATIVE CONVERTER FOR 0V REGULATION

Although it is trivial to turn the SET potentiometer down to 0V with a short to GND, the LT3081 must have 4mA pulled out of it to run down to 0V. A resistive preload from V_{OUT} to GND only pulls current when V_{OUT} is not equal to zero, so a negative supply is used instead to sink current from a 0V output. The LTC3632 negative regulator is a small -5V source that draws -8mA through a small resistor across -5V and a V_{BE} below ground (-0.6V). Although the LTC3632 turns off when the power switch is turned off, it continues to run when the power is on even when the output voltage is higher than 0V. Caution must be used when choosing the negative current transistor since $-8mA \cdot 24.6V$ drop can be a significant source of heat if the thermal impedance of the transistor is more than $250^{\circ}C/W$ or the negative current is increased to over -10mA.

SHORT-CIRCUIT AND 0A CONTROL

The LT3081 also provides 0A current limit control regardless of the output voltage setting. With its current knob turned all the way up, the bench supply enforces a sharp current limit at just about 3.1A. If the load is increased above this point, its voltage appears to fall off a cliff. A simple turn of the knob moves that sharp current limit cliff down to any other value all the way to 0A, as shown in Figure 4.

The most extreme overload condition is a short-circuit, which not only pushes the output over the cliff, but all the way down to ground. The bench supply gracefully maintains its current limit in short-circuit and regulates its LT8612 output to 1.7V, sourcing the limited current through the LT3081 and into the short.

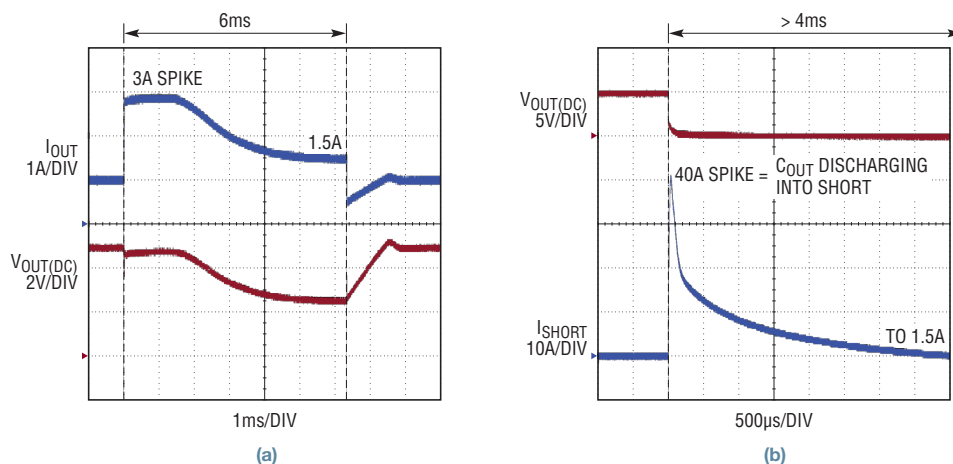
The results of a transient short-circuit are shown in Figure 8, demonstrating the short-circuit regulation of the IC and the

short-lived output capacitor discharge spike. The $< 10\mu s$ short-circuit spike is $1/500$ the duration of a commonly used high power mixed-mode laboratory bench supply (with similar settings) as shown in Figure 9. The long-lasting discharge spike shown in Figure 9 can potentially harm test equipment, a disadvantage of expensive, commonly used universal bench supplies, due to low power transistor speed and/or higher output capacitance.

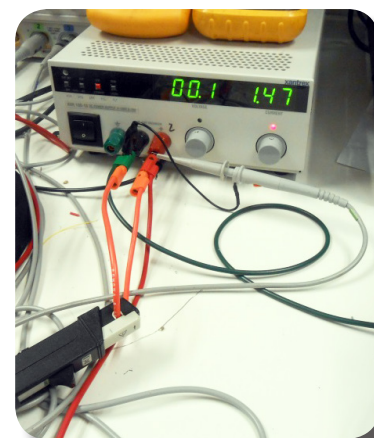
MONITORING THE OUTPUT

Connect a multimeter or a simple analog display to the output to produce an accurate voltage readout. Add another multimeter or display in series with the output for an accurate current readout. If you want to avoid adding additional sensing equipment in series with the output, the IMON terminal can also be used as a voltage-to-current conversion.

Figure 9. Transient results for pricey XH100-10 mixed-mode bench supply, which exhibits slow transient and short-circuit response compared with the DC bench supply described in this article with similar settings (Figure 8).

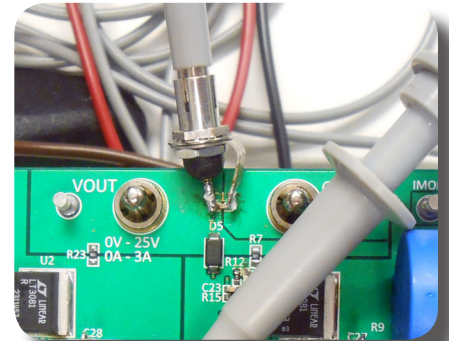
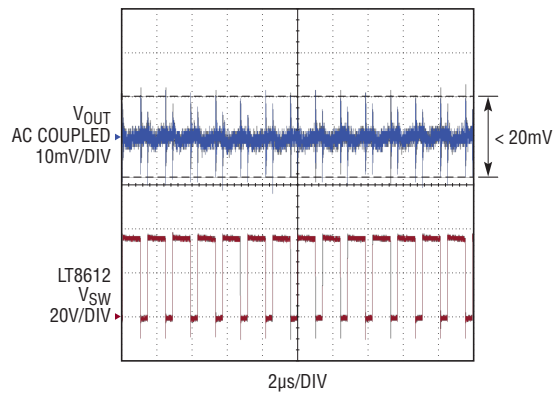


Sorenson XHR100-10 laboratory bench supply in short-circuit with 1.5A limit



This DC power supply is a handy tool for generating a constant voltage or current on-the-fly in the lab. Simply power it up with 10V–40V DC, turn on the switch, and turn the knobs. Since they are small and inexpensive, several of these portable bench supplies can be powered from the same DC input source when multiple circuit outputs and currents are needed.

Figure 10. DC bench supply has low output ripple for a mixed-mode supply with small 60 μ F C_{OUT}.



AC/DC INPUT

This DC power supply is a handy tool for generating a constant voltage or current on-the-fly in the lab. Simply power it up with 10V–40V DC, turn on the switch, and turn the knobs. Since they are small and inexpensive, several of these portable bench supplies can be powered from the same DC input source when multiple circuit outputs and currents are needed.

It's just easy to create a completely self-contained bench supply by adding a simple AC/DC converter on the front end. Figure 11 shows a simple 120V_{AC} to 24V_{AC} (5:1) transformer, a rectifier bridge and a 10mF output capacitor, which combine to produce 34V_{DC} with little ripple. This simple AC/DC converter can be used to produce a maximum bench supply output of 22V.

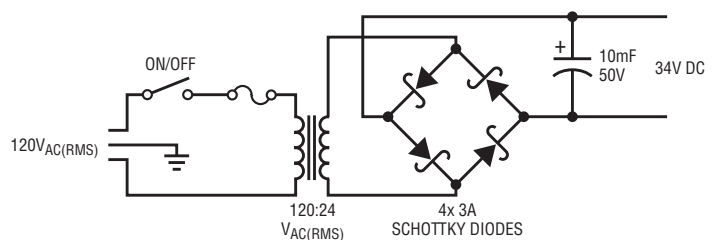
The rectifier bridge should have 3A or higher rated Schottky diodes. If they run too hot, you can still avoid adding a heat sink by replacing the Schottkys with an LT4320 ideal diode bridge controller and four MOSFETs to reduce bridge heating. The size of the 10mF output cap can be changed to adjust for output ripple. At full power, 10mF cap will produce about ± 1 V ripple on the 34V DC input.

You can also piece together a universal bench supply by connecting any universal AC/DC black box converter with a 12V–36V, 3A rating. Any AC/DC converter lifted from an old laptop or purchased from an electronics retailer should work. The only restriction is that the maximum output voltage of the bench supply should remain about 5V below the minimum rating of the input voltage source.

CONCLUSION

Build your own high performance DC bench supply for 0V–24V and 0A–3A constant voltage and current control using a couple parallel LT3081 linear regulators, a synchronous step-down LT8612, an LT3092 current source and a tiny LTC3632 negative supply. The bench supply features low output ripple with low output capacitance, excellent transient response, regulates to 0V and 0A, remains in regulation during short-circuit and stays cool with no bulky heat sinks. It can easily be coupled with an AC/DC converter or it can be powered from a DC source. The complete bench supply solution is low cost, small in size, and easy to build, despite its top shelf performance. ■

Figure 11. Simple combination of a 24V_{AC(RMS)} transformer, rectifier bridge, and capacitor provides AC/DC 34V front-end for a complete solution.



80V Buck-Boost Lead-Acid and Lithium Battery Charging Controller Actively Finds True Maximum Power Point in Solar Power Applications

Tage Bjorklund

In solar power systems, the bulk of the expense is in the panel and batteries. Any cost-effective solar power solution maximizes the capacity usage and lifetime of these components. For instance, a high quality charger increases battery run time, reducing capacity requirements, and extends battery lifetime, minimizing maintenance and replacement costs. Likewise, using a DC/DC controller that extracts the maximum available energy from the solar panel reduces the size and cost of the panels required.

The LT8490 is a charge controller for lead acid and lithium batteries that can be powered by a solar panel or a DC voltage source. It includes true maximum power point tracking (MPPT) for solar panels and optimized built-in battery charging algorithms for various battery types—no firmware development required. 80V input and output ratings enable the LT8490 to be used with panels containing up to 96 cells in series. The power stage uses four external N-channel MOSFETs and a single inductor in a buck-boost configuration. Unlike most charge controllers, the buck-boost configuration allows the charger to operate efficiently with panel voltages that

are below, above or equal to the battery voltage. The minimum panel voltage is 6V.

Batteries live longer and run longer when the charge algorithm is optimized for the battery type. Likewise, a high performing MPPT charger, which tracks the solar panel maximum power point during partial shade conditions, allows the use of a smaller and lower cost solar panel. Creating a discrete-component charger solution to perform all of these duties would be costly and time consuming, typically requiring a microcontroller, a high performance switching regulator and a lengthy firmware development cycle.

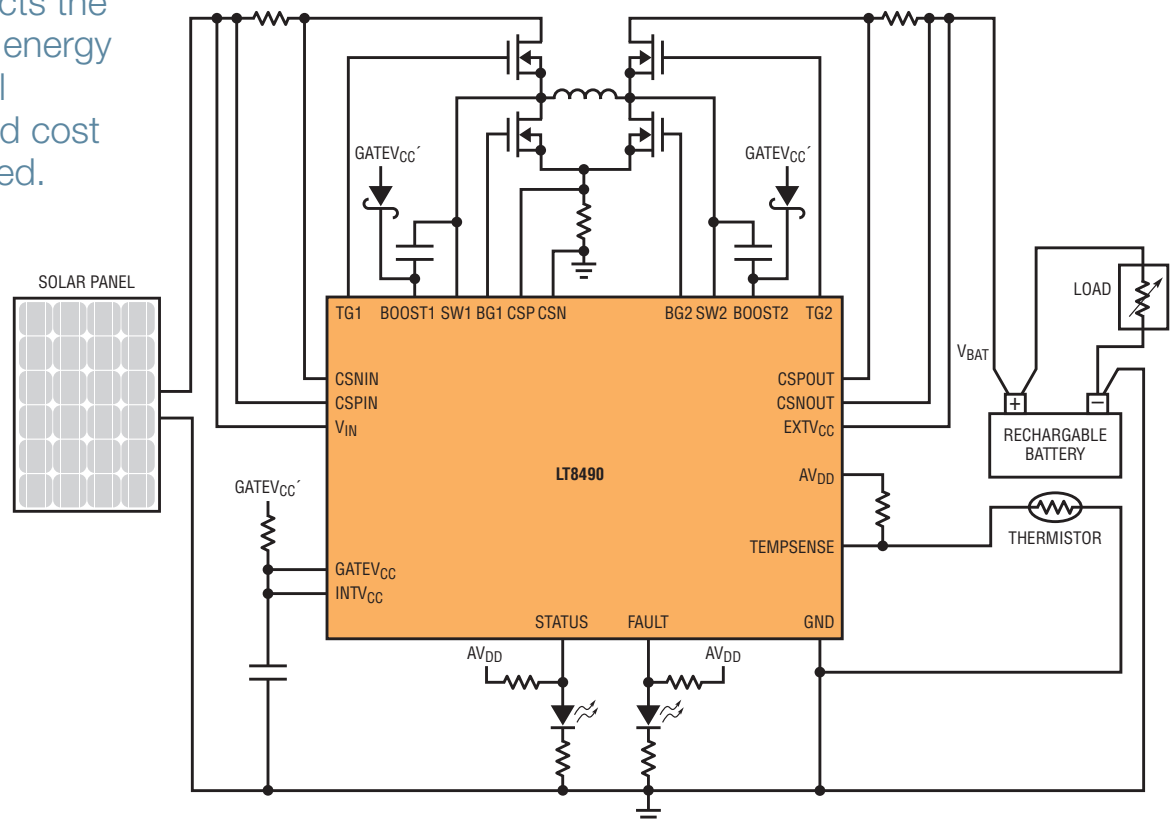


Figure 1. Simplified solar powered battery charger schematic

Dual local maximums are the downfall of the conventional MPPT found in a number of controllers. In contrast, the LT8490 finds the true MPP, yielding twice the charge power—or even higher in other shade conditions.

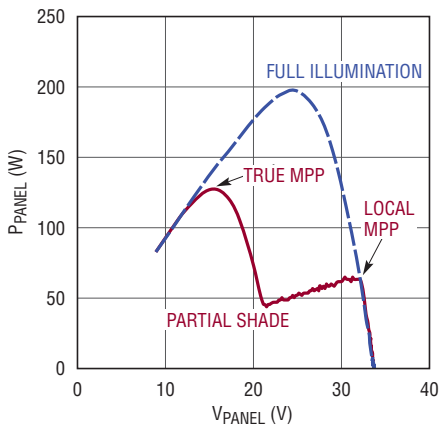


Figure 2. The power curve of a 60-cell 250W solar panel with entire panel illuminated and with a small shadow partly covering one cell (Figure 3)

COMPLETE SINGLE-IC SOLAR POWERED BATTERY CHARGER SOLUTION

The LT8490 is an MPPT battery charger controller with a long list of features including:

- integrated MPPT algorithm (no firmware development required) greatly reduces time to market
- integrated buck-boost controller allows V_{IN} to be above, below or equal to V_{BAT}
- supports lead-acid and lithium-ion batteries
- 6V–80V V_{IN} and 1.3V–80V V_{BAT}

The LT8490 can be powered by a solar panel or any DC voltage source. For a particular battery voltage, a wide range of solar panel types can be used, as the panel voltage can be lower or higher than the battery voltage. The LT8490 accepts panel inputs from 6V to a maximum (cold temperature) open circuit

voltage of 80V; a range corresponding to 16 to 96 series-connected solar cells.

Since the power stage is external, it can be optimized for the application. Charge current limits (and input current limit when a DC voltage source is used) can be configured as needed.

True Maximum Power Point Tracking

When operating from a solar panel, the LT8490 maintains the panel voltage at the panel's maximum power point. Even during partial shade conditions, when more than one local maximum power point appears (an effect of bypass diodes inside the solar panel), the LT8490 detects and tracks the true maximum.

Figure 2 shows the P-V curves for a common 60-cell 250W panel under two different lighting conditions. The maximum power point (200W) occurs at 25V when the panel is fully illuminated. In partial shade (see Figure 3), the available power at a 25V panel voltage drops to 50W, with the new true maximum power point (128W) appearing at 16V. Note that the original 25V/200W power peak actually moves to a local maximum ~32V/63W.

This dual local maximum effect is the downfall of traditional MPPT functions found in a number of controllers, for they follow the initial 25V/200W peak as it shifts to 32V/63W. In contrast, the LT8490 finds the true MPP at 16V/128W, yielding an additional 65W from the panel. It does this by measuring the entire power curve of the panel at regular intervals and locating the true maximum power



Figure 3. The solar panel shaded in top right corner

peak at which to operate. In this case, more than twice as much charge power is extracted, with even greater gains possible in other shade conditions.

Charge Control Functions

Charge algorithms can be configured according to the requirements of each application by adjusting the voltage on two configuration pins. Lead-acid batteries built with AGM, gel and wet cell technologies require slightly different charge voltages for best lifetime, and Li-ion and LiFePO_4 cells have charge requirements that are different from lead-acid batteries. Some of the built-in and configurable charge control functions are:

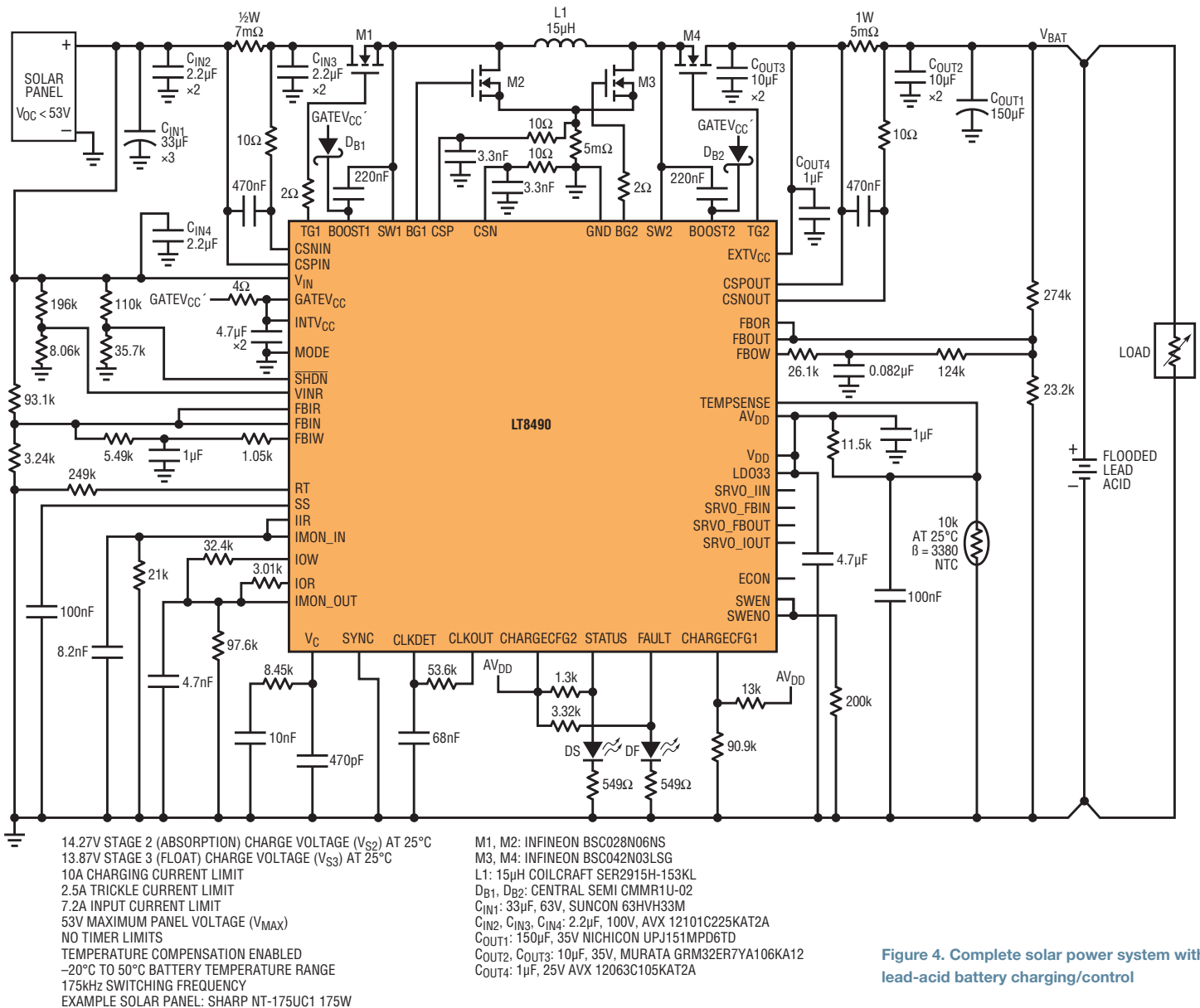


Figure 4. Complete solar power system with lead-acid battery charging/control

- charge voltage temperature compensation (typically for lead-acid batteries) using NTC sensor
- over or under battery temperature stops charge current to protect the battery
- dead battery detection stops the charging, to avoid a hazard
- adjustable trickle charging of a deeply discharged battery reduces risk of damage
- constant current charging that changes to constant voltage charging as the battery voltage reaches its final value

- reduction of charge voltage to a lower float voltage level when the battery is fully charged
- charging time limits can be set when operating from a DC voltage source

CONCLUSION

The LT8490 is a full-featured true MPPT charge controller that can operate from a solar panel or a DC voltage source with a voltage range from 6V to 80V, charging lead-acid or lithium batteries from 1.3V to 80V. The power stage is easily configured by selecting four MOSFETs and

an inductor, allowing the charger to operate with V_{IN} above, below or equal to the battery voltage. All necessary functions are included, with built-in battery charging algorithms and MPPT control, requiring no firmware development. ■

What's New with LTspice IV?

Gabino Alonso



New Video: "SAR ADC Driver Interface"
www.linear.com/solutions/4679

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BLOG

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

New Video on the Blog: "SAR ADC Driver Interface" www.linear.com/solutions/4679

High performance SAR ADCs offer incredible dynamic range and linearity at increasingly faster sample rates, but achieving top performance requires careful attention to the amplifier and interface at the analog inputs. This video shows how to use LTspice to simulate the analog input interface of high performance SAR ADCs. Linear Technology signal chain applications expert Kris Lokere discusses charge kickback, settling time, noise and how to intelligently balance the trade-offs inherent in achieving sometimes conflicting performance goals.

What is LTspice IV?

LTspice® IV is a high performance SPICE simulator, schematic capture and waveform viewer designed to speed the process of power supply design. LTspice IV adds enhancements and models to SPICE, significantly reducing simulation time compared to typical SPICE simulators, allowing one to view waveforms for most switching regulators in minutes compared to hours for other SPICE simulators.

LTspice IV is available free from Linear Technology at www.linear.com/LTspice. Included in the download is a complete working version of LTspice IV, macro models for Linear Technology's power products, over 200 op amp models, as well as models for resistors, transistors and MOSFETs.

SELECTED DEMO CIRCUITS

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

Linear Regulators

- **LT3081:** Wide safe operating area supply using paralleling regulators (2.7–40V to 1.5V, 3A) www.linear.com/LT3081
- **LT3086:** USB supply with cable drop compensation (1.55–40V to 5V, 2.1A) www.linear.com/LT3086

Buck Switching Regulators

- **LT8614:** Ultralow EMI, μ Power buck converter (5.8–42V to 5V, 4A) www.linear.com/LT8614
- **LTC3624:** High efficiency buck regulator with ultralow quiescent current (5.6–17V to 5V, 2A) www.linear.com/LTC3624
- **LTC3875:** High efficiency dual output step-down converter with ultralow DCR sensing and fast transient (4.5–14V to 1V, 30A & 1.5V, 30A) www.linear.com/LTC3875

- **LTM®4633:** Triple 10A step-down μ Module® regulator (4.5–16V to 1.0V, 1.2V & 3.3V, 10A) www.linear.com/LTM4633
- **LTM4676:** Single 26A μ Module buck regulator with digital interface for control & monitoring (4.5–16V to 1V, 26A) www.linear.com/LTM4676

Boost & Inverting Switching Regulators

- **LT8710:** Synchronous boost converter with output current control (4.5–28V to 5V, 6A) www.linear.com/LT8710

- **LT8710:** Synchronous inverting converter with output current control (4.5–28V to –5V, 6A) www.linear.com/LT8710

Flyback, Forward and Isolated Controllers

- **LT8301:** μ Power isolated flyback converter (10–32V to 5V, 0.7A) www.linear.com/LT8301
- **LT8309 & LT3748:** 60W, 12V output, isolated telecom supply (36–72V to 12V, 5A) www.linear.com/LT8309

Overvoltage & Overcurrent Protection

- **LT4364:** 4A, 12V overvoltage output regulator with reverse current protection www.linear.com/LTC4364-1

ADC Drivers

- **LT1637/LT1468/LT5400:** ± 10 V single-ended to ± 5 V fully differential ADC driver for LTC2378-20 using matched resistors www.linear.com/LT1637

SELECT MODELS

To search the LTspice library for a particular Linear Technology device model, choose Edit > Component (or press F2) and enter its part number in the search box or browse to the device/component needed. Since LTspice is often updated with new features and models, it is good practice to update to the current version via the menu command Tools > Sync Release. LTspice's changelog.txt file (in the root installation directory) lists the LTspice revision history.

Linear Regulators

- **LT3065:** 45V input, 500mA low noise, linear regulator with programmable current limit and power good www.linear.com/LT3065

Buck Switching Regulators

- **LT3874:** PolyPhase® step-down synchronous slave controller for LTC3866/LTC3875/LTC3774 with sub-milliohm DCR sensing www.linear.com/LTC3874
- **LTC3624:** 17V, 2A synchronous step-down regulator with 3.5µA quiescent current www.linear.com/LTC3624
- **LTC3870:** PolyPhase step-down slave controller for LTC3880/LTC3883 with digital power system management www.linear.com/LTC3870

- **LTM8058:** 3.1V to 31V input isolated µModule DC/DC converter with LDO post regulator www.linear.com/LTM8058

Boost Switching Regulators

- **LT3048-15:** Low noise bias generator www.linear.com/LT3048-15
- **LTC3784:** 60V PolyPhase synchronous boost controller www.linear.com/LTC3784

Multitopology Switching Regulators

- **LT8471:** Dual multitopology DC/DC converters with 2A switches and synchronization www.linear.com/LT8471
- **LT8710:** Synchronous SEPIC/ inverting/ boost controller with output current control www.linear.com/LT8710

Flyback, Forward and Isolated Controllers

- **LT3752:** Active clamp synchronous forward controllers with internal housekeeping controller www.linear.com/LT3752
- **LT8301:** 42V input micropower no-opto isolated flyback converter with 65V/1.2A switch www.linear.com/LT8301
- **LT8309:** Secondary-side synchronous rectifier driver www.linear.com/LT8309
- **LT8311:** Synchronous rectifier controller with opto-coupler driver for forward converters www.linear.com/LT8311 ■

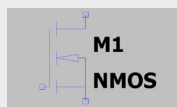
Power User Tip

USE LTspice INTRINSIC SYMBOL FOR THIRD-PARTY MODEL

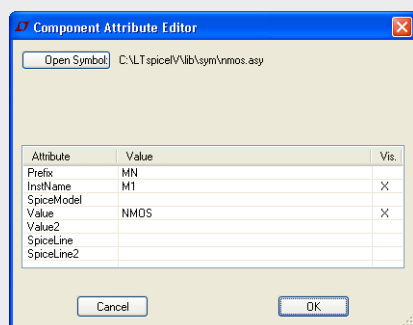
LTspice can automatically create a symbol for a third-party model, or you can associate a third-party subcircuit with an LTspice intrinsic symbol, as long as the third-party .SUBCKT model and the intrinsic symbol share an identical pin/port netlist order.

For example, to add an N-channel MOSFET transistor symbol to a schematic and define it with an IRF_7401 .SUBCKT statement:

1. Add an instance of the N-channel MOSFET transistor symbol to your schematic.



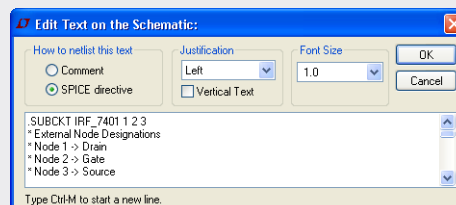
2. Move the cursor over the body of the MOSFET symbol and Ctrl + Right-Click. A dialog box appears.



3. Change Prefix: "MN" to "X". The symbol now netlists as a subcircuit instead of an intrinsic NMOS transistor.
4. Change "NMOS" to be "IRF_7401", corresponding to the name on the .SUBCKT line.

Attribute	Value	Vis.
Prefix	X	
InstName	M1	X
SpiceModel		
Value	IRF_7401	X
Value2		
SpiceLine		
SpiceLine2		

5. Click OK.
6. Either add the .SUBCKT IRF_7401 lines to your schematic or reference the library containing it (.INCLUDE third_party.lib) as a SPICE directive.



Again, this assumes the third-party model you're adding follows popular pin order conventions. When in doubt, use the automatic symbol generation feature because it takes care of any discrepancies with regard to pin and port netlist order. For more about automatic symbol generation, see Help > Schematic Capture > Creating New Symbols > Automatic Symbol Generation.

Happy simulations!

Wireless Precision Temperature Sensor Powers Itself, Forms Own Network, Enabling Easy Deployment in Industrial Environments

Kris Lokere

While the Internet connects people via a worldwide computer network, the Internet of Things (IoT) refers to a growing trend to create relatively simple devices that interconnect and share data independent of computer or human intervention. The IoT has the potential to increase efficiency, improve safety and enable entirely new business models in just about any facet of life or industry. For example, to reliably and efficiently operate an industrial plant, it helps to have as many monitoring (or control) points as possible—more sensors means better monitoring. The device-to-device networking of the IoT simplifies distribution and networking, making it easy to expand the number and reach of sensors throughout a plant.

Exponential increases in the number of sensors can be achieved by eliminating all cabling requirements through the use of robust, wireless, micropower sensors that run for years on a small battery. Better yet, eliminate the need to replace or recharge batteries. Instead, sensors harvest energy from their immediate environment, taking advantage of locally available energy sources, such as light, vibration or temperature gradients.

This article shows how to easily build a high resolution temperature sensor that runs on light energy when available and from a small battery backup when light energy is low. The design also includes a low power radio

module that automatically forms a reliable mesh network to wirelessly connect sensors to a central access point.

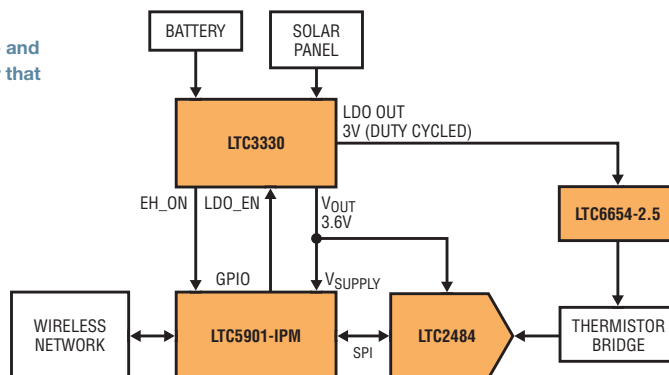
DESIGN OVERVIEW

Figure 1 shows a block diagram of the self-powered wireless temperature sensor. The temperature sensor is based on a thermistor biased by a low noise LT6654 voltage reference. The 24-bit delta-sigma ADC LTC2484 reads the thermistor voltage and reports the result via SPI interface. The LTP™ 5901-IPM radio module takes on a number of tasks: it automatically forms an IP-based mesh network, its built-in microprocessor reads the LTC2484 ADC SPI port and it manages the power sequencing for signal chain components.

The LTC3330 is a low power dual switch-mode power supply that derives power from the solar panel when light is available, reverting to the battery backup when needed to maintain output voltage regulation. The LTC3330 also includes an LDO, which is used to duty cycle power to the temperature sensor.

The entire design has been implemented as Linear Technology demonstration circuit DC2126A. The complete solution, including battery and solar panel, fits inside a small plastic case measuring less than 7 cubic inches as shown in Figure 2.

Figure 1. A wireless temperature sensor is formed by connecting a wireless radio module to an ADC, reference and thermistor. The circuit is powered by an energy harvester that can convert power from a battery or solar panel.



More sensors means better plant monitoring. The achievable number of industrial sensors can be multiplied by eliminating all cabling requirements through the use of robust, wireless, micropower sensors that run for years on a small battery. Better yet, eliminate the need to replace or recharge batteries. Instead, sensors harvest energy from their immediate environment, taking advantage of locally available energy sources, such as light, vibration or temperature gradients.



Figure 2. Entire self-contained, self-powered temperature sensor system fits into an enclosure less than seven cubic inches in volume. Battery, solar panel and wireless-networking controller are included. No external wires or connections are required. Installation is easy: place it somewhere. (a) Front of board showing signal chain, power and control circuitry and wireless mesh network module; (b) back of board with battery; (c) complete solution in enclosure with solar panel installed.

TEMPERATURE MEASUREMENT SIGNAL CHAIN IS ACCURATE AND DRAWS MINIMAL POWER

Figure 3 shows the signal chain—temperature measurement—components of the design, including the thermistor and ADC (with LT6654 precision voltage reference).

Thermistor

A thermistor can read temperatures over a wide range—they are simply resistors with a strongly negative temperature coefficient. For instance, US Sensor KS502J2 has a resistance of 5k at 25°C, and ranges from 88k to 875Ω over the -30°C to 70°C temperature range.

ADC and Accurate Voltage Reference

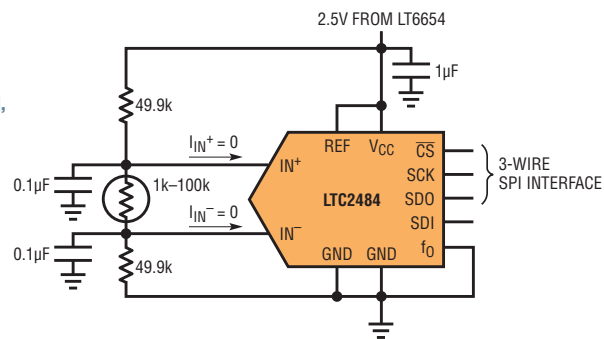
The thermistor is connected in series with two accurate 49.9k resistors, and biased up by the LT6654 precision voltage reference. The LTC2484 delta-sigma ADC measures the resistor divider ratio with 24-bit resolution. The ADC total unadjusted error is 15ppm, which for this thermistor slope corresponds to a temperature uncertainty of less than 0.05°C. This thermistor is specified with an accuracy of 0.1°C,

so we can measure the temperature to that accuracy without any calibration.

The ADC noise is less than $4\mu V_{P-P}$, corresponding to less than a 0.005°C change in temperature. Therefore, with a calibration step, this system could be used to measure temperature to extremely fine resolution.

Because the ADC measures the ratio of thermistor voltage to a reference voltage, strictly speaking, an accurate reference is not required. Nevertheless, it

Figure 3. LTC2484 24-bit ADC reads the thermistor voltage. Because the input common mode voltage remains centered, this Easy Drive™ ADC draws no input current, which makes for an easy and accurate ratiometric reading.



The LTC3330 manages all power for this application. It includes two switch-mode power supplies and a linear regulator in a monolithic package. Here, a buck-boost converter draws power from the battery; a buck converter draws from the solar panel. The LTC3330's internal prioritizer ensures that solar power is used when available, preserving battery charge as much as possible. The LTC3330 also directly accepts AC energy harvesting sources, such as piezo crystals, which generate an AC voltage proportional to vibrational energy.

must be low noise, because variations in reference voltage during the ADC conversion period could produce errors.

The LTC2484 ADC features an Easy Drive™ input structure, meaning that net differential sampling currents during a conversion period are nearly zero. As a result, no measurement errors are induced from input sampling current flowing through the resistive thermistor network, which means no separate op amp buffer is required. Bypass capacitors provide a low impedance path at high frequency.

DUTY CYCLE POWER TO THE SIGNAL CHAIN TO CONSERVE POWER

Few applications require constant temperature monitoring. If one measurement per second or once per minute is enough, it makes sense in this micropower application to minimize the power draw during the mostly idle time. The resistor network draws up to 25µA from the 2.5V reference. To avoid this power loss between measurements, the power supply to the reference is duty cycled to be on only during measurement.

Determine the Required Duty Cycle

The RC time constant at the input of the ADC is about 5ms. By turning on the power 80ms prior to taking a measurement, full settling at the ADC input is ensured. In fact, since both input nodes turn on at the same slope, readings are accurate well before the theoretical settling time. The LT6654 is powered from the 3V LDO output of the LTC3330. The LTP5901-IPM's onboard microprocessor drives the LDO enable pin of the LTC3330 high and low at the correct times before and after performing a temperature reading.

The LTC2484 automatically enters sleep mode when not converting. The 1µA sleep current is low compared to the already low power of the wireless radio. Therefore, it is not necessary to duty cycle the power supply to the ADC. By keeping the ADC permanently powered from the same supply voltage as the LTP5901-IPM, the logic levels at the SPI interface are ensured to be the same.

Refreshing the Temp Reading Each Cycle

After providing a conversion result through the SPI port, the LTC2484 automatically starts a new conversion, and stores the result in its internal register until requested to read it again. This simplifies quick data turnaround in systems that read temperature frequently, but could make for a stale temperature reading in ultralow power applications with a significantly long interval between readings.

To ensure that the communicated temperature reading is always fresh, this application first toggles the \overline{CS} and SCK pins to flush out any stale temperature reading from the ADC register, and automatically starts a new temperature conversion. The microprocessor waits until the conversion is finished and then reads the result through the SPI port. To save power, the system immediately proceeds to shut down the thermistor network (by turning off the LDO), even as the ADC automatically commences to the next temperature reading. This next temperature result is of no consequence, as it is flushed the next time the microprocessor requests a reading.

Table 1. Signal chain current consumption

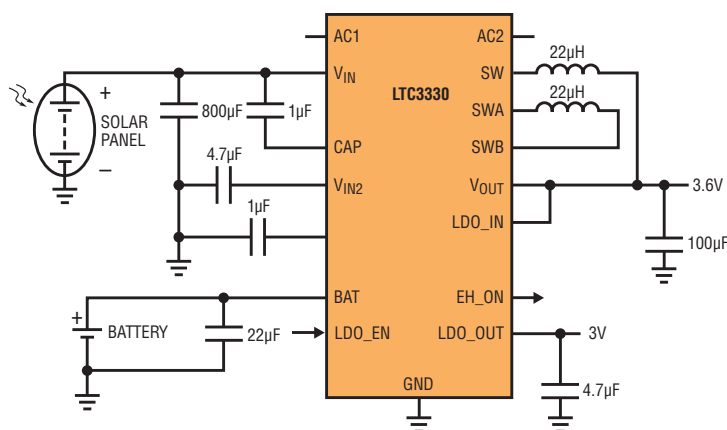
CIRCUIT ELEMENT	CURRENT DRAW WHEN ACTIVE
LT6654 Reference	350µA
Thermistor Network	25µA
LTC2484 ADC	160µA
TOTAL	535µA

Table 2. Average signal chain current consumption based on read frequency

TEMPERATURE READ FREQUENCY	AVERAGE CURRENT
Once per second	170µA
Once per 10 seconds	17µA
Once per minute	2.9µA

The LTP5901-IPM performs two functions in this application: wireless networking and housekeeping. It includes the radio transceiver, embedded microprocessor and networking software. When multiple nodes of LTP5901-IPM are powered up in the vicinity of a network manager, the nodes automatically recognize each other and start forming a highly reliable, low power wireless mesh network. Each node can function as both a source of sensor information and as a routing node to relay data from other nodes toward the manager.

Figure 4. The LTC3330 takes power from the solar panel or battery, automatically prioritizing between the two sources to maintain a regulated output voltage. An additional LDO output is controlled by a logic input pin, which is used to duty cycle power to the temperature sensor. The LTC3330 generates an output flag to indicate whether solar or battery power is being used.



Calculating Signal Chain Power Consumption

The overall power consumption of the temperature sensor circuitry can be estimated by determining the total charge consumed and dividing by the period of temp reading, as follows:

1. Sum the current of the reference ($350\mu\text{A}$), thermistor network ($25\mu\text{A}$), and ADC ($160\mu\text{A}$ when converting) for a total of $535\mu\text{A}$ (Table 1).
2. Determine the total charge consumed by considering how long this current is present. The ADC takes about 140ms for a conversion, with a precursor 80ms for the reference and thermistors to settle. Add some time for the SPI readout, and we are at about 300ms on-time. Consuming a current of $535\mu\text{A}$ during 300ms corresponds to a charge of $160\mu\text{C}$. We should add to this the charge needed to charge up the $4.7\mu\text{F}$ supply bypass capacitor to the voltage reference, because this node is recharged from 0V to 3V with every reading. This $14\mu\text{C}$ of charge brings the total

to $174\mu\text{C}$ per temperature reading.

3. A rate of one temperature reading every 10 seconds works out to an average current consumption of $17\mu\text{A}$. Other examples of average supply current are given in Table 2.

SINGLE POWER IC FOR SOLUTION-WIDE POWER MANAGEMENT

The LTC3330 manages all power for this application, as shown in Figure 4. It includes two switch-mode power supplies and a linear regulator in a small monolithic package.

Two Switch-Mode Converters Handle Battery and Solar Inputs

A buck-boost converter can take power from the battery to maintain a regulated output voltage (set to 3.6V for this application). A separate buck converter can take power from the solar panel to regulate the output voltage to the same level. An internal prioritizer ensures that solar power is used when possible, drawing power from the battery only when needed. For other applications, the LTC3330 also supports

AC energy harvesting sources, such as piezo crystals, which generate an AC voltage proportional to vibrational energy.

The LTC3330 draws less than $1\mu\text{A}$ quiescent current, a good fit for this mostly idle, low power wireless application. The power loss in the operating power supply is a small fraction of the total power—most of the power is available for the work of the temperature sensor and wireless network.

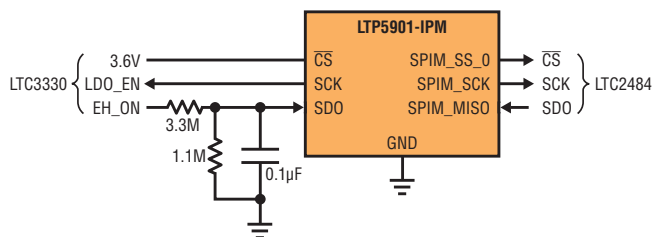
LDO Powers and Duty Cycles Signal Chain

In addition to the two switch-mode power supplies, the LTC3330 includes an LDO with a separate LDO enable pin. This enable feature is handy for this low duty cycle application, where the voltage reference and thermistor network are powered from the LDO to minimize switching noise. The LDO enable feature allows the application to simply toggle power to the signal chain on and off, even as the switch-mode power to the wireless radio is always on.

Even though the wireless radio does not consume much power in between

The LTP5901-IPM includes an ARM Cortex-M3 microprocessor core, which runs the SmartMesh IP networking software. This core is highly programmable via user-supplied application firmware, making it possible to build a wide variety of solutions without any additional microprocessors.

Figure 5. The LTP5901-IPM requires only a few simple connections to manage networking and housekeeping tasks for the application. All wireless networking functions, including firmware and RF circuitry, are built in. A 3-wire SPI master communicates with the LTC2484 SPI port. A GPIO pin (DP2) controls power sequencing to the sensor. The built-in ADC acts as a convenient level translator to read the energy harvesting status flag EH_ON from the LTC3330.



transmissions, it is very important that it always remains biased up, to keep timers running correctly so that the entire network remains time-synchronized. The microprocessor inside the wireless radio sequences the LDO enable pin at the correct times to prepare the signal chain for a temperature reading.

Output Flag Indicates Battery or Solar Panel Draw

The LTC3330 provides an output flag (EH_ON), which tells the system whether power is being drawn from the battery or from the solar panel. It can be informative for the end user to have real-time access to this information. Therefore, we let the microprocessor inside the wireless radio read this output flag and transmit it through the network, along with the temperature data itself.

The logic level for this EH_on output is referred to an internal bias voltage of the LTC3330, which varies depending on operating mode and can be higher than 4V. Rather than connecting that output pin directly to the lower-voltage logic input of the wireless radio, we divide it down and feed it into a built-in 10-bit ADC (part of the microprocessor). In this case, we just

use that ADC as a comparator to indicate which power source the LTC3330 is using.

COMPLETE WIRELESS NETWORK WITH A SINGLE MODULE

The LTP5901-IPM is a complete wireless radio module, including the radio transceiver, embedded microprocessor, and networking software. Only a few connections are required to create a self-forming wireless network and data gathering/communication system with this module, as shown in Figure 5.

Its physical format is a small printed circuit board, which can be easily soldered onto the main board containing the signal chain and power management components.

The LTP5901-IPM performs two functions in this application: wireless networking and housekeeping via microprocessor. When multiple nodes of LTP5901-IPM are powered up in the vicinity of a network manager, the nodes automatically recognize each other and begin forming a wireless mesh network. The entire network is automatically time synchronized, which means that each radio is only powered on during very short, specific time intervals. As a result, each node can function not

only as a source of sensor information, but also as a routing node to relay data from other nodes toward the manager. This creates a highly reliable, low power mesh network, where multiple paths are available from each node to the manager, even though all nodes, including the routing nodes, operate on very low power. A typical range for this radio technology is 100m between nodes, with broader ranges possible in favorable outdoor conditions.

The LTP5901-IPM includes an ARM Cortex-M3 microprocessor core, which runs the SmartMesh IP™ networking software. This core is highly programmable via user-supplied application firmware, making it possible to build a wide variety of solutions without any additional microprocessors. In this example, the LTP5901-IPM's microprocessor manages power sequencing to the temperature sensor by turning the LDO of the LTC3330 on and off to conserve power. The LTP5901-IPM communicates directly to the SPI port of the 24-bit ADC. Finally, the LTP5901-IPM reads the power status output flag (EH_on) from the LTC3330, which indicates whether solar light or battery is used to power the circuit.

A combination of easy-to-use, high performance power management, and wireless networking devices enable the design of self-contained, *completely wireless* sensor products. The time-synchronized wireless mesh network ensures that minimal power is used to reliably transmit data from node to node, and the on-chip microprocessor can further save power by duty cycling power to the sensor circuitry.

Power consumption of the wireless radio can be estimated using the “SmartMesh® Power and Performance Estimator” spreadsheet found at www.linear.com/products/smartmesh_ip. For a typical network of 20 motes, where 10 motes have a direct wireless connection to the manager (1-hop), and 10 others have an indirect connection to the manager (2-hop), average power consumption is about 20µA for the 2-hop nodes and 40µA for the 1-hop nodes. These numbers are for each node reporting temperature once per 10 seconds.

1-hop nodes consume about twice as much power as 2-hop nodes because they transmit not only their own sensor data, but also act as routing nodes to forward the sensor data from some of the 2-hop

nodes. The above-mentioned power levels can be reduced by about a factor of two if the advertising feature is turned off. Once advertising is turned off, the network no longer recognizes new nodes that want to join the network. Other than that, there is no impact on network operation.

OVERALL POWER CONSUMPTION

Total power consumption depends on a number of factors, including how often each sensor measures temperature, and how the nodes are configured in the network. Typical power consumption for a sensor node reporting once per 10 seconds is less than 20µA for the sensor portion and can be 20µA for the wireless radio, for a total average load current of about 40µA.

A small 2-inch by 2-inch solar panel (such as the Amorton series) can generate 40µA at relatively moderate indoor lighting conditions (200-lux); much more in bright light. This application could run entirely on solar power in a variety of environments.

Otherwise, if the circuit must run entirely on battery power, a 2.4Ah AA battery (such as the Tadiran XOL series) could power this application for nearly seven years.

In low or variable light conditions, the circuit automatically toggles back and forth between solar power and battery power, so that any available solar power is used to extend the life of the battery.

CONCLUSION

A combination of easy-to-use, high performance power management, and wireless networking devices enable the design of self-contained, *completely wireless* sensor products. The time-synchronized wireless mesh network ensures that minimal power is used to reliably transmit data from node to node, and the on-chip microprocessor can further save power by duty cycling power to the sensor circuitry. Efficient, highly integrated power management ICs can power the application entirely from a small solar panel, or for many years from a small battery. ■

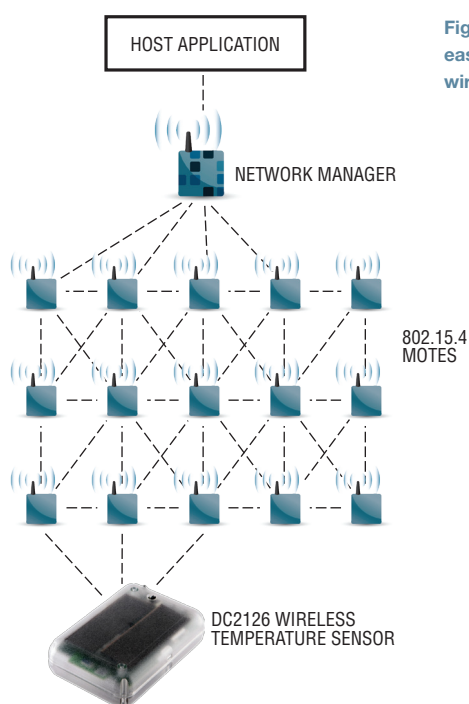


Figure 6. Precision temperature sensor easily drops into robust SmartMesh IP wireless mesh network.

Dual Phase Buck Controller Drives High Density 1.2V/60A Supply with Sub-Milliohm DCR Sensing

Mike Shriver

Designers of low output voltage rails for communication, networking, server and industrial systems are challenged to achieve greater load currents and higher efficiency in diminishing board space. The LTC3774 dual output buck controller eases this burden by interfacing easily with DrMOS devices, providing high efficiency and small size by integrating MOSFET and gate driver in the same package. The LTC3774 can sense current across the inductor's DCR, with values as low as 0.2mΩ, improving efficiency by eliminating the need for a discrete sense resistor. The LTC3774's peak current mode architecture provides cycle-by-cycle current limit, inherent cycle-by-cycle current sharing and easy to design type II compensation.

HIGH EFFICIENCY CONVERTER WITH A SMALL FOOTPRINT

Figure 1 shows a dual phase 1.2V/60A LTC3774 converter operating at a switching frequency of 400kHz. The power stage for each phase is the FDMF6820A DrMOS, which comes in a 6mm × 6mm QFN package, and a 0.3μH single winding ferrite inductor with a typical DCR of 0.325mΩ. The resulting full load efficiency is 89.8%, as shown in Figure 2. The core of the converter has a current density of 50A/in².

DrMOS INTERFACE

The PWM outputs of the LTC3774 are designed to drive DrMOS devices with a 3-state PWM input. When the PWM signal is high, the top FET is on, and when the PWM signal is low, the bottom FET is on. When the PWM signal is floating, both the top FET and bottom FET are off. This state is used to block inductor reverse current when the LTC3774 is set up for either pulse-skipping mode or Burst Mode operation, providing a smooth turn-on into a prebiased output. The PWM outputs of the LTC3774 can

interface with power block devices and gate drivers with external MOSFETs.

DCR SENSING

The ultralow DCR sensing capability is a result of an innovative current sensing technique that improves the signal-to-noise ratio of the current sense signal. The external filter tied to the SNSA+ pin amplifies the AC portion of the DCR-sensed current; the DC current is sensed via the SNSD+ pin, internally amplified and summed with the AC portion. This reconstructed current sense signal seen by the LTC3774's current comparator is effectively amplified by a factor of five, allowing the converter to remain stable and retain current limit accuracy for inductor DCR values as low as 0.2mΩ.

The LTC3774 offers five current limit settings between 10mV and 30mV with a worst-case error over temperature of ±1.25mV. With current mode control, current sharing between phases is tightly balanced, as shown by the thermal image shown in Figure 3. The 1.2V/60A converter operating at full load

produces less than a 1°C temperature difference between the two phases.

The LTC3774 provides accurate output voltage regulation. The output of each phase is sensed with a differential amplifier placed after the feedback divider to compensate for any PCB IR drops. The total regulated feedback voltage accuracy is ±0.75% over temperature. The output voltage range of the LTC3774 is 0.6V to 3.5V.

PolyPhase OPERATION AND IMPROVING ROBUSTNESS

The LTC3774 features CLKIN and CLKOUT pins for PolyPhase operation up to 12 phases. PolyPhase operation reduces ripple current for the input capacitors and in cases where the phases are tied together, reduces output voltage ripple and provides faster load step response.

Further improvements in the reliability of single output, redundant (N + 1), PolyPhase converters can be achieved by placing Hot Swap™ circuits on the input and ideal diode circuits on the output of each phase. If a MOSFET failure occurs, the fault is isolated and the output is protected and continues to regulate. Reliability

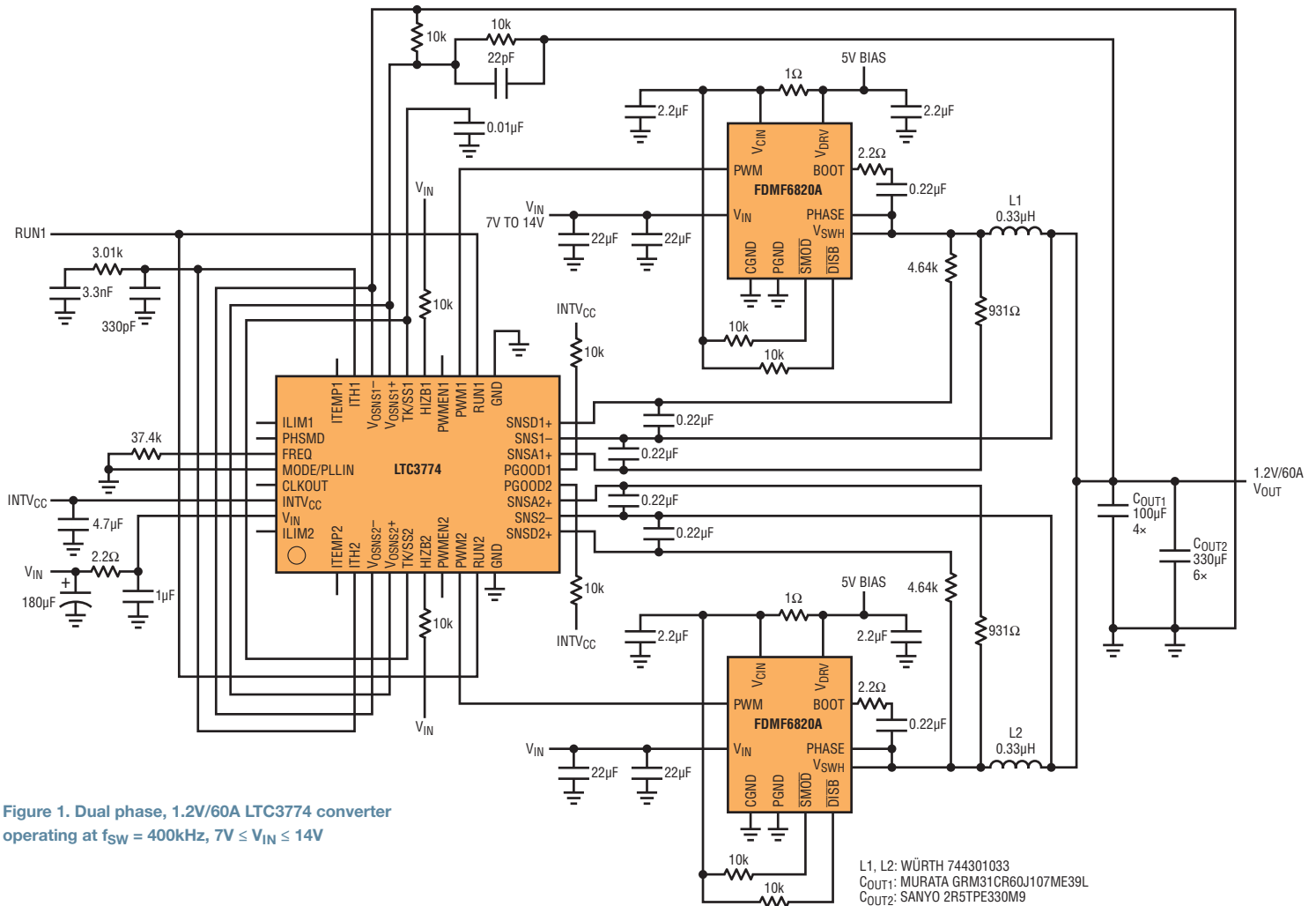


Figure 1. Dual phase, 1.2V/60A LTC3774 converter operating at $f_{SW} = 400\text{kHz}$, $7\text{V} \leq V_{IN} \leq 14\text{V}$

L1, L2: WÜRTH 744301033
 COUT1: MURATA GRM31CR60J107ME39L
 COUT2: SANYO 2R5TPE330M9

is further improved with the LTC3774's HIZB pin, which floats the PWM output when a fault is detected, allowing for a more predictable shutdown of the DrMOS.

Other features include soft recovery from an output overload, optional NTC compensated DCR sensing, a phase-lockable switching frequency range of 200kHz to 1.2MHz and an input voltage range of 4.5V to 38V.

CONCLUSION

The LTC3774 is a high performance dual output buck controller intended for low output voltage, high output current supplies with DrMOS and ultralow DCR inductors. It yields high efficiency, an accurate current limit, a precise $0.6\text{V} \pm 0.75\%$ feedback voltage and fault isolation. ■

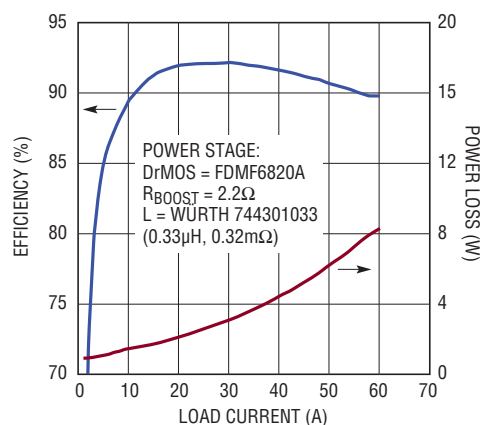


Figure 2. Efficiency and power loss curves for circuit shown in Figure 1. $V_{IN} = 12\text{V}$, $V_{OUT} = 1.2\text{V}$

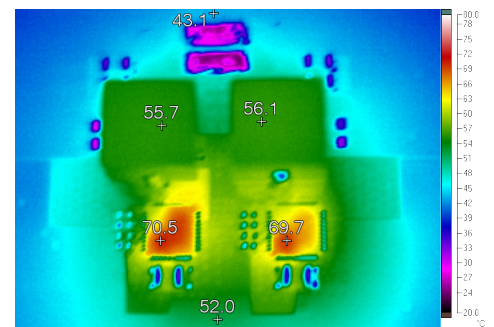


Figure 3. Thermal image of the circuit shown in Figure 1. $f_{SW} = 400\text{kHz}$, $V_{IN} = 12\text{V}$, $V_{OUT} = 1.2\text{V}$, $I_{OUT} = 60\text{A}$, no airflow and 21°C ambient

DC Accurate Driver for 20-Bit SAR ADC Achieves 2ppm Linearity

Guy Hoover

As resolution and sample rates continue to rise for analog-to-digital converters (ADCs), the driver circuitry for the ADC analog input, not the ADC itself, has increasingly become the limiting factor in determining overall circuit accuracy. First, the driver circuitry must buffer the input signal and provide gain. In addition, it must level shift or convert a single-ended signal to a fully differential signal to satisfy the input voltage range and common mode requirements of the ADC. All must be done without adding distortion to the original signal.

This article presents a simple ADC driver circuit that converts a $\pm 10\text{V}$ single-ended input signal into a fully differential signal capable of driving the LTC2377-20 20-bit SAR ADC with a combined linearity error of only 2ppm. Options for providing higher input impedance and a lower overall supply current are also examined.

CIRCUIT DESCRIPTION

The circuit of Figure 1 converts a $\pm 10\text{V}$ single-ended signal into the $\pm 5\text{V}$ fully differential signal required by the LTC2377-20 (U1). The LTC2377-20 is a 20-bit, 500ksps, low power SAR ADC with a typical integral nonlinearity (INL) of $\pm 0.5\text{ppm}$. The voltage at AIN is buffered by U4, which in

turn drives the U5 resistor string, acting as a precision divider. U3 operates in a gain of minus one-half and drives the center of the U5 resistor string to maintain the ADC common mode voltage at $V_{\text{REF}}/2$.

U3 and U4 are LT1468A low offset highly linear op amps. U5 is a LT5400A quad matched resistor network with a guaranteed maximum mismatch of 0.01%. Matched resistor values in U5 are important because any mismatch contributes to both offset and full-scale error in this circuit. For this reason and because of their extremely low voltage coefficient, do not use discrete resistors instead of the LT5400A. R4 provides a quarter-scale shift to the output of U3. R1 and R2 form a divider that biases the noninverting input of U3 at $V_{\text{REF}}/2$.

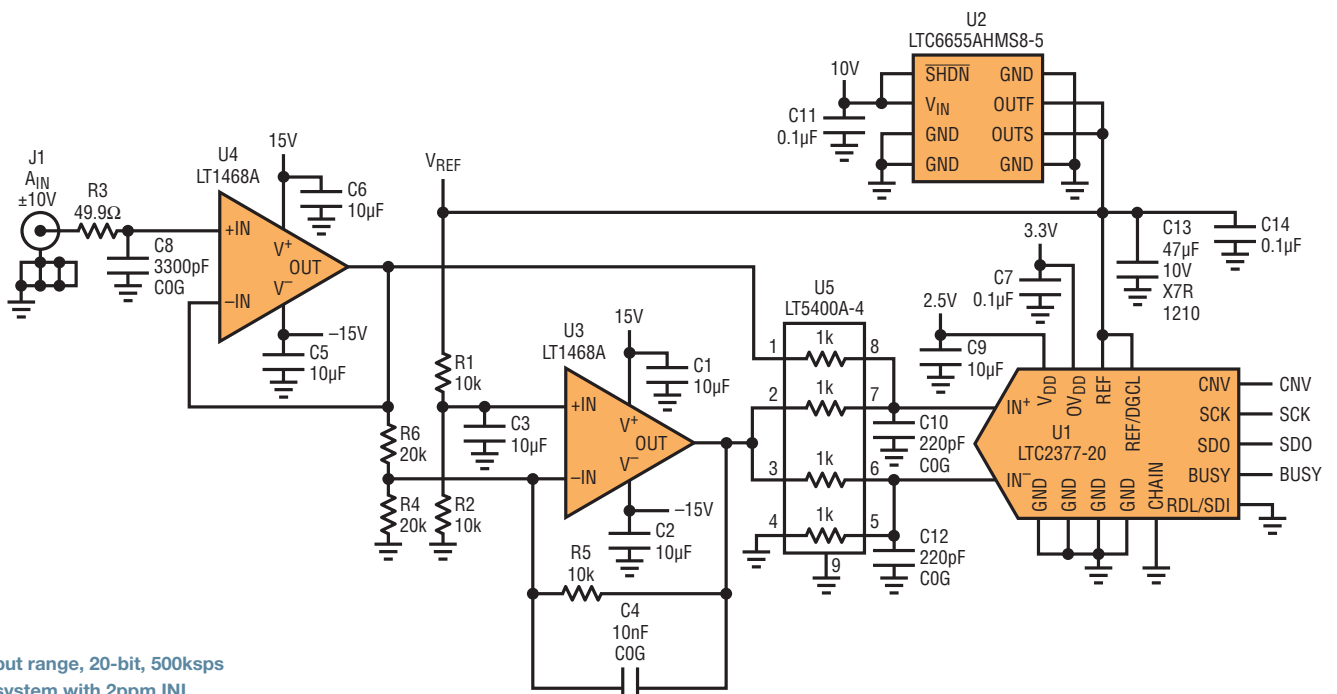


Figure 1. $\pm 10\text{V}$ input range, 20-bit, 500ksps data acquisition system with 2ppm INL

The ADC driver circuit shown here converts a single-ended $\pm 10\text{V}$ signal into a $\pm 5\text{V}$ fully differential signal for the LTC2377-20 500ksps SAR ADC. Combined circuit performance achieves $50\mu\text{V}$ offset, 2ppm INL, 102.7dBFS SNR and -123.5dB THD.

R_5 and R_6 set the gain of inverting amplifier U_3 at -0.5 . C_{10} and C_{12} , in combination with the resistors of U_5 , form 1.4MHz filters on the ADC inputs. Additionally, the resistor between pins 1 and 8 of U_5 helps to isolate the output of U_4 from the charge spike that occurs when the ADC goes from hold mode to sample mode. The LTC6655A-5 (U_2) is selected as the reference for this circuit due to its ability to settle quickly from the transients that occur on the REF pin during conversions and because of its low noise.

CIRCUIT PERFORMANCE

Typical AC performance for this circuit includes THD of -123.5dB and SNR of 102.7dBFS at a sample rate of 500ksps with a 100Hz input signal. This performance can be seen in the FFT of Figure 2. The THD and SNR performance are close to the typical numbers found in the LTC2377-20 data sheet, indicating minimal performance degradation when using this driver.

Typical linearity performance for the combined circuit over the entire $\pm 10\text{V}$ input signal range, as shown in Figure 3, is $+2\text{ppm}$, -1.3ppm at a sample rate of 500ksps. Linearity is limited by the INL of the ADC and the CMRR of op amp U_4 .

The combined offset at the ADC input, including the contributions of U_4 , U_5 and U_1 , is measured at $+50\mu\text{V}$. The offset of U_3 has no effect on the offset of this driver. A worst case analysis of offset at the ADC input is calculated by adding the maximum offsets of U_1 , U_4 and U_5 :

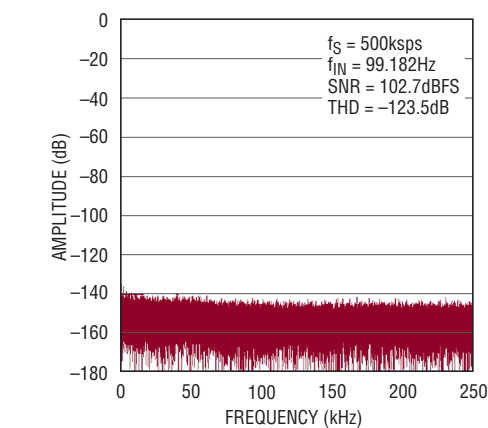


Figure 2. Combined circuit FFT

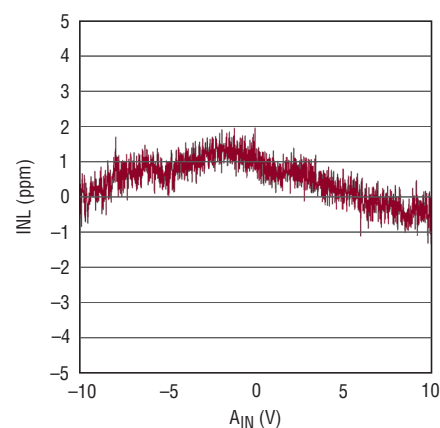


Figure 3. Linearity vs input voltage

$$V_{OS(\text{MAX})} = BZE(\text{MAX})U_1 + \frac{V_{OS(\text{MAX})}U_4}{2} + \left(\frac{V_{REF}}{2} - \frac{V_{REF}}{2 + \frac{\Delta R}{R(\text{MAX})}U_5} \right)$$

$$V_{OS(\text{MAX})} = 13\text{ppm} \cdot 10\mu\text{V/ppm} + 75\mu\text{V}/2 + (5/2 - 5/(2.0001)) \cdot 1\text{E}6\mu\text{V}$$

$$V_{OS(\text{MAX})} = 292\mu\text{V} = 29.2\text{ppm}$$

The LT1468A has a maximum input bias current of $\pm 40\text{nA}$. For applications that require higher input impedance, U_4 can be replaced with the LT1122A. The LT1122A is a fast settling, JFET input op amp with a maximum input bias current of 75pA . Using the LT1122A in this circuit, the INL is $+6\text{ppm}$, -1.1ppm , as shown in the op amp performance comparison in Table 1.

The LTC2377-20 ADC has a typical supply current of 4.2mA at its full sample rate of 500ksps. The LTC2377-20 automatically powers down after a conversion and does not power up until the next conversion is started. This auto power-down feature reduces the power dissipation of the ADC as the sample rate is reduced to as little as $1\mu\text{A}$ for very low sample rate applications.

For low sample rate applications where supply current is important, the 5.2mA maximum supply current of the LT1468A may be too high. The LT1012A picoamp input current, microvolt offset, low noise op amp with a maximum supply current of $500\mu\text{A}$ at

(continued on page 38)

Table 1. Op amp performance comparison

	MAX V_{OS} (μV)	MAX I_B (pA)	TYP I_{SY} (mA)	MAX f_S (ksps)	TYP INL (ppm)
LT1468A	75	40,000	5.2	500	+2, -1.3
LT1122A	600	75	10	500	+6, -1.1
LT1012A	90	150	0.6	125	+0.9, -0.5

Complete Single IC Power Management Battery Maintenance/Backup System for 48V Supplies

Jay Celani

A common trend for electronic devices is increased portability; it is no longer universally acceptable for a device to turn off simply because somebody “pulled the plug.” In order to implement portable functionality, devices must include advanced power management systems that can control the path of power from available sources to appropriate system outputs, keep a backup element charged and ready, and ensure that a system has adequate power at all times.

Elegant, single-IC power management solutions are readily available for many portable devices, such as smart phones or tablets, which operate at low voltages and low power levels. Power management solutions for high power and high voltage systems, such as those required for many industrial or medical devices, generally require cumbersome and complex specialized discrete component solutions. The LTC4020 simplifies power management in these environments by incorporating advanced power management functions into a high voltage and high power single-IC solution.

The LTC4020 features an advanced 4-switch buck/boost DC/DC power converter, support for optimized battery charging, and Linear Technology’s proprietary PowerPath™ system/battery power management functionality. The LTC4020 manages power distribution between the system input supply, the backup battery, and the converter output in response to load variations, battery charge requirements and input power limitations.

The single-inductor DC/DC buck/boost controller can accept input voltages up to 55V and produce voltages that are lower, higher, or the same as the input voltage. The onboard battery charger can be

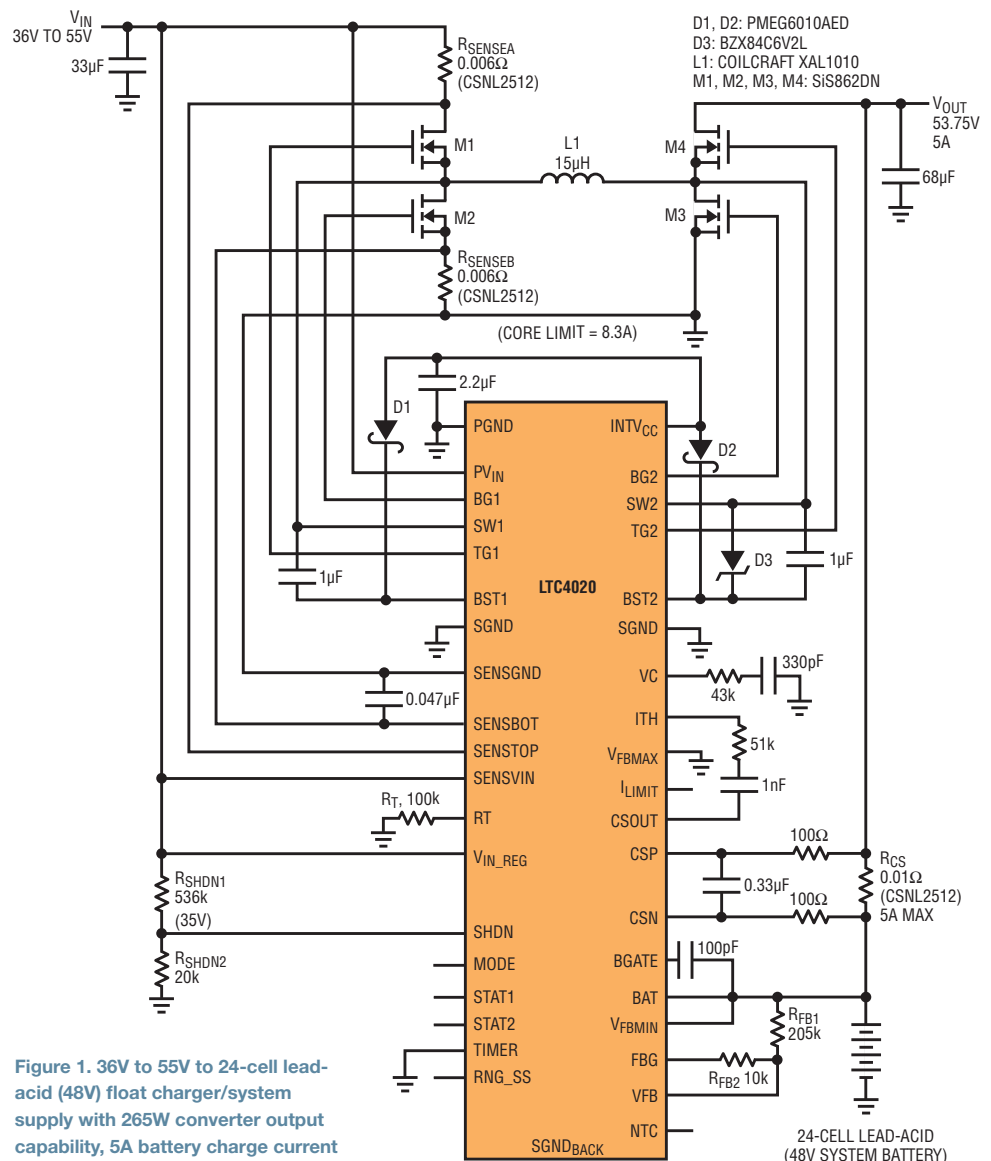


Figure 1. 36V to 55V to 24-cell lead-acid (48V) float charger/system supply with 265W converter output capability, 5A battery charge current and 53.75V system/float charge voltage output

The LTC4020 features an advanced 4-switch buck/boost DC/DC power converter, support for optimized battery charging, and Linear Technology's proprietary PowerPath system/battery power management functionality. The LTC4020 manages power distribution between the system input supply, the backup battery, and the converter output in response to load variations, battery charge requirements and input power limitations.

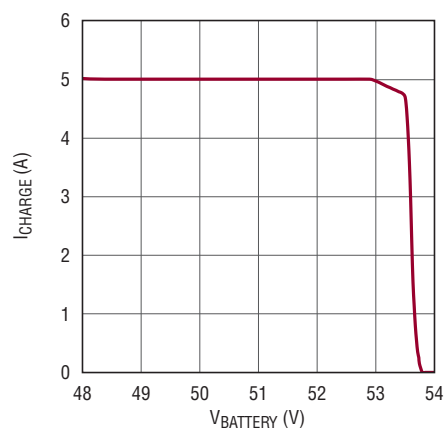


Figure 2. Maximum battery charge current for the circuit shown in Figure 1

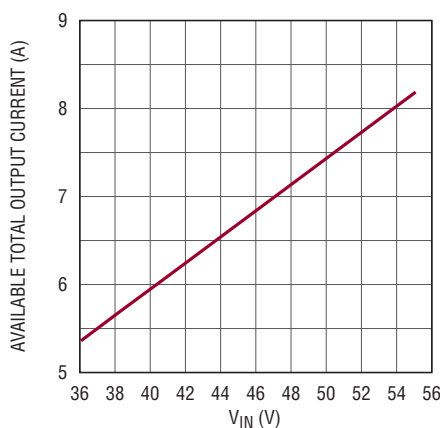


Figure 3. Available converter output current (system load current + battery charge current) vs input voltage

configured to provide a constant-current/constant-voltage (CC/CV) charge profile optimized for lithium-based batteries, a 3-stage lead-acid battery charge profile, or a modified timer-terminated constant-current algorithm (CC), which is similar to the lithium profile but does not incorporate low voltage precondition and charge cycle restart functions.

USING CC MODE CHARGING TO BEND THE RULES FOR A 48V LEAD-ACID CHARGER

When the LTC4020 is configured in the charge mode optimized for lead-acid batteries, the regulation voltage during absorption charging is 120% of the typical battery system voltage, or 14.4V for a “12V” lead-acid battery. Unfortunately, the built-in lead-acid charge algorithm cannot be used for a 48V system battery, since the absorption charge voltage would exceed the operating maximum voltage for the LTC4020. This can be easily addressed by implementing a

high current float charger using the constant-current (CC) charge algorithm.

The CC charge algorithm is enabled by leaving the LTC4020's MODE pin unconnected. A feedback resistor divider programs the desired battery float charge voltage, corresponding to $V_{FB} = 2.5V$. The CC charge algorithm enables the full programmed charge current until the float regulation voltage is achieved. While maintaining the float regulation voltage, a lead-acid float charger must be able to continuously source current into the battery, so the charge function cannot terminate. CC charge mode can accommodate this by setting $TIMER = 0V$, which disables the timer function and thus disables charge termination, so the charge cycle will continue indefinitely.

48V SYSTEM POWER SUPPLY WITH LEAD-ACID BATTERY BACKUP

Figure 1 shows an LTC4020 configured as a 48V system supply with an integrated backup battery float charger. The central component of this supply is an average current-mode buck/boost DC/DC controller, employing four external NFETs as switching elements, which provides 265W of available output system power.

The converter operates from a 36V–55V input supply, with the converter limited to 8.3A of average inductor current. The converter current limit is programmed by two 6mΩ sense resistors (R_{SENSE1} and R_{SENSE2}) placed in series with SiS862DN switching FETs M1 and M2. The DC/DC converter supports at least 5A at its output over the entire operating voltage range.

R_{SHDN1} and R_{SHDN2} form a divider at the SHDN pin, which sets the input shut-down voltage at $V_{IN} = 35V$, disabling

The LTC4020 preferentially provides power to the system load and battery charging functions—the system load is always prioritized over charging power—so battery charge current is reduced when necessary during periods of heavy loads. Should the system load exceed the capabilities of the LTC4020 DC/DC converter, battery current will change direction, and load current will be sourced from the battery to supplement the converter output.

the DC/DC converter and battery charger functions when the input is below 35V, so full load current is available whenever the supply is enabled. The SiS862DN switch FETs used here have a typical Q_G of about 10nC each, so with the operating frequency set to 250kHz by resistor R_T , the $Q_{G(TOTAL)} \cdot f_O$ at $V_{IN} = 55V$ falls within the LTC4020's specified $INTV_{CC}$ pass element SOA guidelines.

The IC charges and maintains a 24-cell (48V) lead-acid backup battery using a constant-current/constant-voltage charge profile as previously described. The maximum battery charge current is programmed by R_{CS} to 5A, which is available until the full-charge float voltage of 53.75V is achieved. The battery voltage is monitored by a resistor divider (R_{FB1} and R_{FB2}), which programs the full-charge float voltage of 53.75V (or 2.24V/cell). This divider is referenced through the FBG pin, which is shorted to ground when the LTC4020 is operating, but becomes high impedance when the IC is disabled, reducing the parasitic load on the battery.

The LTC4020 preferentially provides power to the system load and battery charging functions—the system load is always prioritized over charging power—so battery charge current is reduced when necessary during periods of heavy loads. Should the system load exceed the capabilities of the LTC4020 DC/DC converter, battery current will change direction, and load current will be sourced from the battery to supplement the converter output.

When the V_{IN} supply is disconnected, all LTC4020 functions cease and the battery supplies required power to the output. Reverse conduction from the battery through the converter is blocked by the switch FET M4, the battery voltage monitor resistor divider is disconnected via pin FBG, and total battery current into the IC is reduced to less than 10 μ A, maximizing battery life should a no-load storage condition be required.

CONCLUSION

The LTC4020 is a single-IC power management solution for any high power device that requires battery backup or battery-powered remote operation. The integrated buck/boost DC/DC controller can provide power to a voltage rail that is above, below or equivalent to the input voltage. The IC employs an intelligent PowerPath topology, merging the controller output to a full-featured multi-chemistry battery charger. The charger includes an internal onboard timer for charge cycle control and real-time charge cycle monitoring using binary-coded status pins. Three pin-selectable charging profiles provide versatility to accommodate most common battery types with optimized charging characteristics. ■

(LT1468A) continued from page 35)

$\pm 15V$ can replace the LT1468A for these applications. With sample rates up to 125ksps, the LT1012A achieved a linearity of +0.9ppm, -0.5ppm, as shown in the op amp performance comparison in Table 1. At sample rates above 125ksps, the INL performance begins to degrade, as the op amp cannot settle fast enough to accurately drive the ADC.

CONCLUSION

The ADC driver circuit shown here converts a single-ended $\pm 10V$ signal to a $\pm 5V$ fully differential signal for the LTC2377-20 500ksps SAR ADC. Combined circuit performance achieves 50 μ V offset, 2ppm INL, 102.7dBFS SNR and -123.5dB THD. The driver consists primarily of two LT1468A op amps and a LT5400A matched

resistor array. Alternative versions of this circuit use the LT1122A op amp to provide 75pA max input current or the LT1012A op amp at reduced sampling rates to reduce supply current. DC2135, a demo board version of this circuit, is available from Linear Technology. ■

New Product Briefs

SLAVE CURRENT-MODE STEP-DOWN PHASE EXTENDER FOR UP TO 300A WITH SUB-MILLIOHM DCR SENSING

The LTC3874 is a dual phase synchronous step-down slave controller that generates currents up to 300A when paired with a companion master controller by extending the phase count in multiphase applications. Compatible master controllers include the LTC3866, LTC3875 and LTC3774, which all have true current-mode control and enable the use of low (0.2mΩ) DC resistance (DCR) power inductors without any sense resistor to maximize converter efficiency and increase power density.

The LTC3874 complements Linear Technology's low DCR peak current mode controllers and provides all functions needed for multiphase slave designs, including accurate phase-to-phase current sharing even for dynamic loads. It operates over an input voltage range of 4.5V to 38V and produces a fixed output voltage up to 5.5V. Up to 12 phases can be paralleled and clocked out-of-phase to minimize filtering. Applications include power distribution, redundant (n+1) supplies, industrial systems, DSP and ASIC power.

The LTC3874 operates at a fixed operating frequency from 250kHz to 1MHz, or it can be synchronized to an external clock. The powerful 1.1Ω onboard gate drivers minimize MOSFET switching losses. Precise programmable current sense threshold limits from 16mV to 72mV minimize power loss and accurately set the overcurrent trip point.

17V, 2.25MHZ, SYNCHRONOUS STEP-DOWN REGULATOR DELIVERS 2A AND REQUIRES ONLY 3.5μA OF QUIESCENT CURRENT

The LTC3624 is a high efficiency, 17V input-capable synchronous buck regulator from Linear Technology that delivers up to 2A of continuous output current to outputs as low as 0.6V. Synchronous rectification delivers efficiencies as high as 95% while Burst Mode operation requires only 3.5μA of no load quiescent current. The LTC3624 switches at a fixed 1MHz frequency, whereas the LTC3624-2 switches at 2.25MHz.

Their constant frequency, current-mode architecture minimizes switching noise while offering very fast line and load transient response. The LTC3624/-2 operates from an input voltage range of 2.7V to 17V, making it ideal for single cell or multicell Li-ion stack inputs as well as 12V intermediate bus-powered systems. The combination of its 3mm × 3mm DFN package, high switching frequency and tiny, low cost capacitors and inductors ensures a highly compact solution footprint.

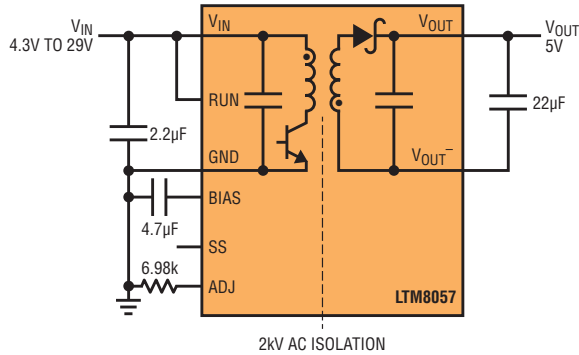
The LTC3624EDD and LTC3624EDD-2 are available in a 3mm × 3mm DFN-8 package. Industrial grade versions, the LTC3624IDD and the LTC3624IDD-2 are guaranteed to operate over the -40°C to 125°C operating junction temperature range.

DUAL MULTITOPOLGY DC/DC CONVERTERS WITH 50V, 2A INTERNAL SWITCHES

The LT8471 is a dual DC/DC converter that utilizes two internal 2A, 50V switches and an additional 500mA switch to facilitate step-down, step-up and inverting conversions. Each 2A channel can be independently configured as a buck, boost, SEPIC, flyback, ZETA or inverting DC/DC converter. This broad range of topologies and output configurations makes it ideal for a wide range of industrial and automotive applications. The LT8471 operates from an input voltage range of 2.6V to 50V, making it suitable for applications with input sources ranging from a single-cell Li-ion to automotive batteries.

The LT8471's 50V internal switches can accommodate applications with inputs and outputs as high as 45V. The device is capable of generating both positive and negative outputs from a single converter, making it ideal for a wide array of biasing applications. A small, integrated 500mA boost converter facilitates both buck and single inductor inverting applications at optimal efficiencies. The LT8471's switching frequency is programmable and synchronizable from 100kHz to 2MHz, which keeps externals very small. The combination of a TSSOP package and tiny externals ensures a very compact footprint while minimizing solution cost.

The LT8471's high efficiency 50V switches deliver overall efficiencies up to 85% for buck and inverting applications. From a 6V to 32V input, the LT8471 delivers up to 1.5A at 5V and 650mA at -5V. ■

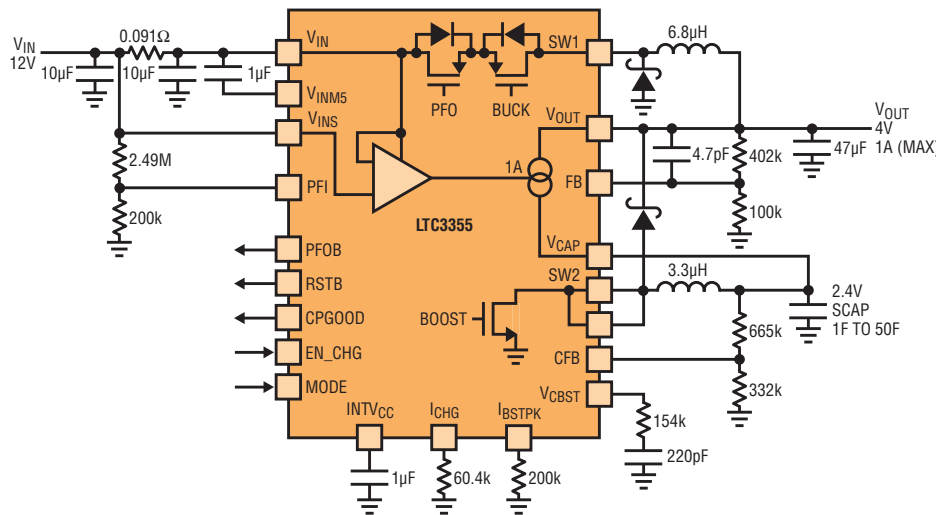
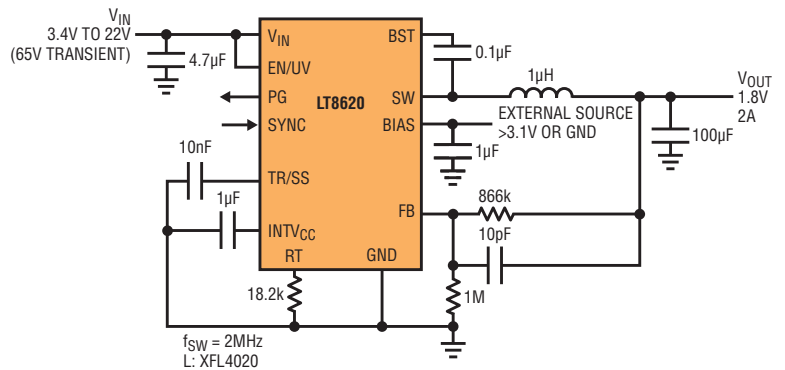


LTM8057 2KV AC ISOLATED 5V μModule REGULATOR

The LTM[®]8057 is a 2kV AC isolated flyback μModule[®] (micromodule) DC/DC converter. Included in the package are the switching controller, power switches, transformer and all support components. Operating over an input voltage range of 3.1V to 31V, the LTM8057 supports an output voltage range of 2.5V to 12V, set by a single resistor. Only input and output capacitors are needed to complete the design. Other components may be used to control the soft-start control and biasing. www.linear.com/solutions/5104

LT8620 1.8V 2MHz STEP-DOWN CONVERTER

The LT8620 is a compact, high efficiency, high speed synchronous monolithic step-down switching regulator that accepts a wide input voltage range up to 65V and consumes only 2.5μA of quiescent current. Top and bottom power switches are included with all necessary circuitry to minimize the need for external components. Low ripple Burst Mode operation enables high efficiency down to very low output currents while keeping the output ripple below 10mV_{p-p}. A SYNC pin allows synchronization to an external clock. Internal compensation with peak current mode topology allows the use of small inductors and results in fast transient response and good loop stability. The EN/UV pin has an accurate 1V threshold and can be used to program V_{IN} undervoltage lockout or to shut down the LT8620, reducing the input supply current to 1μA. A capacitor on the TR/SS pin programs the output voltage ramp rate during start-up. The PG flag signals when V_{OUT} is within ±9% of the programmed output voltage as well as fault conditions. The LT8620 is available in small 16-lead MSOP and 3mm × 5mm QFN packages with exposed pads for low thermal resistance. <http://www.linear.com/solutions/5108>



LTC3355 SUPERCAPACITOR CHARGER AND RIDE-THROUGH POWER SUPPLY

The LTC3355 is a complete input power interrupt ride-through DC/DC system. The part charges a supercapacitor while delivering load current to V_{OUT}, and uses energy from the supercapacitor to provide continuous V_{OUT} backup power when V_{IN} power is lost. The LTC3355 contains a nonsynchronous constant frequency current mode monolithic 1A buck switching regulator to provide a 2.7V to 5V regulated output voltage from an input supply of up to 20V. www.linear.com/solutions/5112

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