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New 5-Lead SOT-23 Oscillator is Small, Very Stable and Easy to Use

by Andy Crofts

Introduction

Generating a periodic waveform of arbitrary frequency is not always a trivial task. Low cost RC oscillators can be built using discrete components such as comparators, resistors and capacitors, or by using simple integrated circuits such as the industry-standard 555 timer in conjunction with several discrete components. These solutions are bulky and inaccurate, especially at frequencies above a few hundred kilohertz.

Very accurate oscillators with a predetermined frequency may be realized using either crystals or ceramic resonators as stable frequency elements; crystal oscillators offer the highest performance, although they are costly. These circuits are also bulky, sensitive to acceleration forces and tend to be less robust than RC oscillators. Generating various frequencies from a single crystal or ceramic oscillator requires additional circuitry that will add to the component list and consume PC board space.

Enter the LTC1799

The LTC1799 offers an alternative that combines the frequency stability and accuracy of a ceramic resonator with the flexibility and ease of use of an RC oscillator, while requiring less space than either.

The LTC1799 is the only oscillator IC that can accurately generate a square wave signal at any frequency from 5kHz to 20MHz without the use of a crystal, ceramic element or existing clock reference. A complete oscillator circuit requires only an LTC1799, a frequency-setting resistor (R_{SET}) and a bypass capacitor, as illustrated in Figure 1. With a 0.1% resistor, the frequency accuracy is typically better than $\pm 0.6\%$. The LTC1799's internal master oscillator is a resistance to frequency converter with an output range of 500kHz to 20MHz. A programmable on-chip frequency divider divides the frequency by 1, 10 or 100, extending the frequency range to greater than three decades (5kHz to 20MHz).

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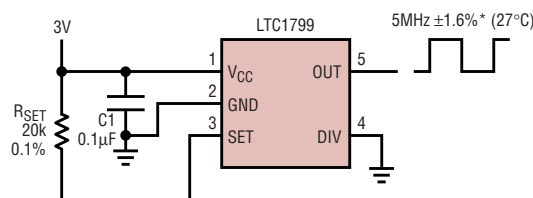


Figure 1. A complete oscillator solution

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Issue Highlights

Happy New Year and welcome to our first issue of 2001, beginning the eleventh year of *Linear Technology* magazine.

Our lead article in this issue introduces the LTC1799, a new oscillator IC in a SOT-23 package. The LTC1799 offers the frequency stability and accuracy of a ceramic resonator with the flexibility and ease of use of an RC oscillator, while requiring less space than either. It is the only oscillator IC that can accurately generate a square wave at any frequency from 5kHz to 20MHz without the use of a crystal, ceramic element or existing clock reference. A complete circuit requires only an LTC1799, a frequency-setting resistor and a bypass capacitor. With a 0.1% resistor, the frequency accuracy is typically better than $\pm 0.5\%$.

In the filter realm, we present the LTC1566-1, a new monolithic 7th order continuous time lowpass filter featuring differential input and output terminals. The LTC1566-1 operates from a single 5V supply and dual supplies of up to $\pm 5V$, comes in an SO-8 package and requires no external components other than power supply decoupling capacitors. The filter is designed to have a flat passband from DC to 2MHz and a steep transition band. The filter cut-off is set at 2.3MHz to accommodate differential filtering needs in wide-band CDMA base stations.

Also introduced in this issue is the new LT1711/12/13/14 family of UltraFast comparators, which has fully differential rail-to-rail inputs and outputs and operates on supplies as low as 2.4V, allowing unfettered application on low voltages. The LT1711 (single) and LT1712 (dual) are specified at 4.5ns of propagation delay and 100MHz toggle frequency. The low power LT1713 (single) and LT1714 (dual) are specified at 7ns of propagation delay and 65MHz toggle frequency.

As usual, this issue introduces a variety of new power products. The

newly released LT1618 DC/DC converter provides USB devices with accurate input current control. Several requirements must be met by a device powered from the USB connector: input capacitors smaller than 10 μ F are required to minimize inrush currents at plug-in; upon power-up, the device must draw less than 100mA of current from the USB bus and can increase its input current to 500mA only when given permission by the USB controller. These requirements can be easily met using the LT1618. The part combines a traditional voltage feedback loop with a unique current feedback loop to operate as a constant-current, constant-voltage source.

The LTC1734 is a precision, low cost, single-cell, linear Li-Ion battery charger with constant voltage and constant current control. The small quantity and low cost of external components results in a very low overall system cost and the part's 6-pin SOT-23 package allows for a compact design solution. Previous products usually required an external current sensing resistor and blocking diode whose functions are included in the LTC1734.

The LTC1773 is a synchronous DC/DC controller that packs high output current capability and low operating quiescent current in a small MSOP-10 package. Its input voltage range is from 2.65V to 8.5V, ideal for 1- or 2-cell Li-Ion batteries as well as 3- to 6-cell NiCd and NiMH battery packs. A precise internal undervoltage lockout circuit prevents deep discharge of the battery below 2.5V. The LTC1773's high operating frequency of 550kHz allows the use of small, surface mount components to provide a compact power supply solution.

The LTC1778 and the LTC3711 are buck regulators that deliver the low output voltages and high efficiencies required by today's portable supplies. The LTC1778 is a step-down controller that provides synchronous

LTC in the News...

On January 16, Linear Technology Corporation announced its financial results for the 2nd quarter of fiscal year 2001. Robert H. Swanson, Chairman & CEO, stated, "Once again we had a strong financial performance. We achieved record levels of sales and profits with sales increasing 11% and profits 12% sequentially from the September quarter. Our return on sales was a record 44.4%. As with other semiconductor companies, we have seen a slowdown in net bookings from the very robust levels experienced in previous quarters. Interestingly, gross bookings in this quarter still exceeded our net billings, however cancellations of some bookings from previous quarters caused our net bookings to be slightly less than our net billings. Nevertheless, our backlog continues to be strong and demand for product in the near term appears to be firm. Consequently, we currently estimate that we will grow sales and profits sequentially in the 8%-10% range for the March quarter."

The Company reported sales of \$258,450,000, and net income of \$114,758,000 for the 2nd quarter. Net sales were up 59% over the same quarter last year. Diluted earnings per share were \$0.34, an increase of 77% over the 2nd quarter last year. 

drive for two external N-channel MOSFET switches. Its true current mode architecture has an adjustable current limit, can be easily compensated, is stable with ceramic output capacitors and does not require a sense resistor. The LTC1778 operates on input voltages from 4V to 36V and output voltages from 0.8V up to 90% of V_{IN} . Switching frequencies up to nearly 2MHz can be chosen, allowing wide latitude in trading off efficiency for component size. The LTC3711 is essentially the same as the LTC1778 but includes a 5-bit VID interface.

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Table 1. Frequency range vs divider setting

Divider Setting	DIV (Pin 4) Connection	Frequency Range
-1	GND	> 500kHz*
-10	Floating	50kHz to 1MHz
-100	V+	≤ 100kHz

*At frequencies above 10MHz ($R_{SET} < 10k$), the LTC1799 may suffer reduced accuracy on supplies less than 4V.

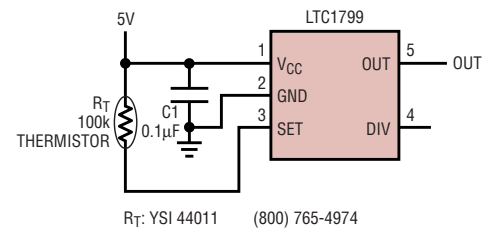


Figure 4. Temperature-to-frequency converter

LTC1799, continued from page 1

Selecting the proper resistor is straightforward because the LTC1799 follows a simple relationship between R_{SET} and frequency:

$$f_{OSC} = 10\text{MHz} \cdot 10k\Omega / (N \cdot R_{SET})$$

where N is the on-chip divider setting of 1, 10 or 100, depending on the state of the DIV pin. A proprietary feedback loop maintains this accurate relationship over all operating conditions, providing a temperature coefficient that is typically less than $\pm 0.004\%/^{\circ}\text{C}$. The LTC1799 operates over a 2.7V to 5.5V supply range, with a voltage coefficient of 0.05%/V. It

typically draws 1mA of supply current. Figure 1 shows a circuit that generates a precision 5MHz signal.

LTC1799: Advantages in Precision, Resolution and Size

With a frequency tolerance 0.5% typical and 1.5% worst-case, the performance of the LTC1799 is similar to that of ceramic resonators and vastly superior to oscillators that use discrete resistors and capacitors. Its stingy temperature and voltage coefficients (typically $\pm 0.004\%/^{\circ}\text{C}$ and 0.05%/V, respectively) maintain accuracy over all operating conditions.

Unlike oscillators using crystals, the LTC1799 has infinite frequency resolution; the output frequency can be set to any value in the 5kHz to 20MHz range. The programmed frequency is limited only by the choice of R_{SET} . This feature allows the clock frequency to be changed late in a design cycle by changing the value of a resistor instead of stocking crystals in many different frequencies.

The LTC1799's SOT-23 package and low component count (one resistor, one capacitor) result in an efficient use of PCB space, requiring less space than any crystal, ceramic resonator or discrete oscillator solution.

Frequency Set by Single Resistor and Ranged by an Internal Frequency Divider

The heart of the LTC1799 is a master oscillator that performs a precise resistance-to-frequency conversion. R_{SET} can be any value from 3.32k to 1M, generating master oscillator frequencies between 30MHz and 1kHz with guaranteed 1.5% accuracy for resistors between 5k and 200k. To extend its frequency range, the

LTC1799 includes a programmable frequency divider. The DIV input pin may be connected to GND to pass the master oscillator output directly to the OUT pin. When the DIV pin is left floating, the LTC1799 divides the master oscillator frequency by 10 before driving OUT. Connect DIV to V+ to divide the master oscillator by 100 to generate frequencies below 100kHz. Table 1 suggests the proper DIV pin setting for the desired frequency. The frequency ranges overlap near 100kHz and 1MHz, allowing a choice of settings. Since the supply current increases with smaller values of R_{SET} , the lower divider setting is usually preferred.

Once the divider setting has been selected, calculate the proper resistor value using this simple equation:

$$R_{SET} = 10k\Omega \cdot 10\text{MHz} / (N \cdot f_{OSC})$$

Since the oscillator frequency, f_{OSC} , is dependent on the resistor value, R_{SET} , any error in the resistor will create error in f_{OSC} .

Performance Rivals Ceramic Resonators

The LTC1799 obeys its frequency vs R_{SET} equation within 1.5% at room temperature with any R_{SET} from 10k

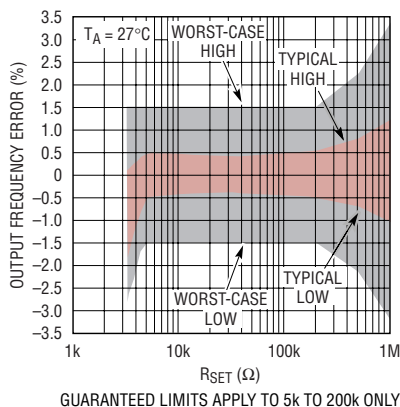


Figure 2. Accuracy of the output frequency equation

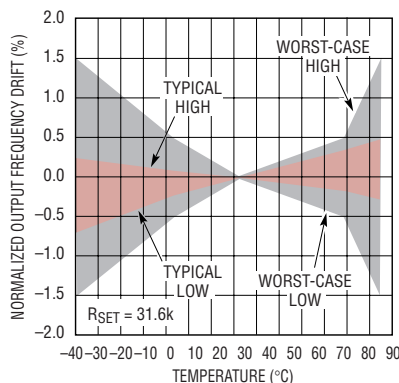


Figure 3. Output frequency temperature drift

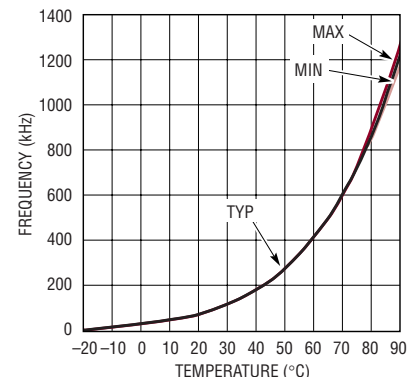


Figure 5. Output frequency vs temperature for Figure 4's circuit

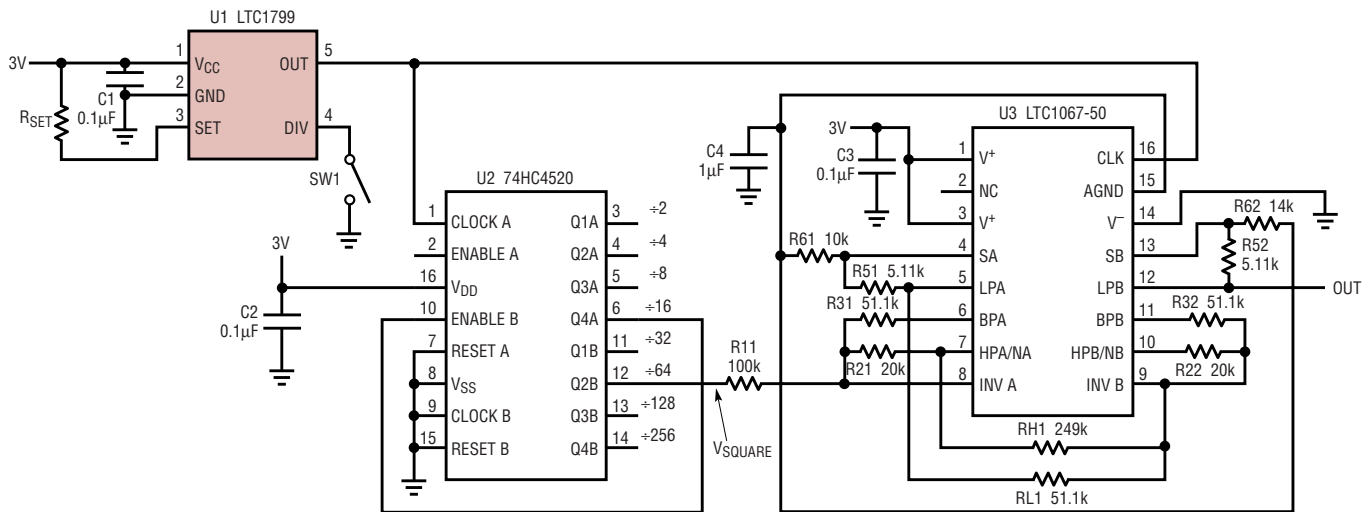


Figure 6. 80Hz to 8kHz sine wave generator

to 200k for a frequency range of 5kHz to 10MHz. With a 5V supply, this range is extended to resistors as low as 5k, for frequencies up to 20MHz. Figure 2 shows the frequency deviation from the equation over the range of possible values for R_{SET} . Figure 3 shows the output frequency variation over the industrial temperature range.

Applications

Temperature-to-Frequency Converter

In Figure 4, the frequency-setting resistor is replaced by a thermistor to create a temperature-to-frequency converter. The thermistor resistance is 100k at 25°C, 333k at 0°C and 16.3k at 70°C, a span that fits nicely in the LTC1799's permitted range for R_{SET} . With its low tempco and high linearity, the LTC1799 adds less than

±0.5°C of error to the output frequency. Figure 5 plots the typical and worst case output frequency vs temperature (error due to the thermistor is not shown).

80Hz to 8kHz Sine Wave Generator

Figure 6 shows the LTC1799 providing both the clock source and the input to a switched capacitor filter to generate a low distortion sine wave output. The 74HC4520 counter divides the frequency by 64 before driving the filter with a square wave. An ideal square wave will have only odd harmonics. The LTC1067-50 filter building block is configured as a lowpass filter with a stopband notch at the third harmonic of the desired sine-wave frequency. The fifth and higher-order harmonics are attenuated by 60dB or greater. The resulting

sine wave has less than 0.1% distortion. This design can generate any tone from 78Hz (the LTC1799 minimum output frequency of 5kHz/64) to 8kHz, limited by maximum clocking frequency of the LTC1067-50 at a 3V supply. Figure 7 shows a scope capture for a 1kHz tone ($R_{SET} = 158k\Omega$).

Digital Frequency Control

Figure 8 shows the details of an LTC1799 controlled by a 12-bit voltage output D/A converter. Since the LTC1799 is a resistance-to-frequency converter, the input voltage between V_{CC} and SET must be measured and used to create a current. Therefore, the DAC and op amps create a digitally controlled resistor between V_{CC} and SET. Figure 9 shows the measured output frequency vs input code. The linearity is excellent except at the endpoints; the low frequency accuracy

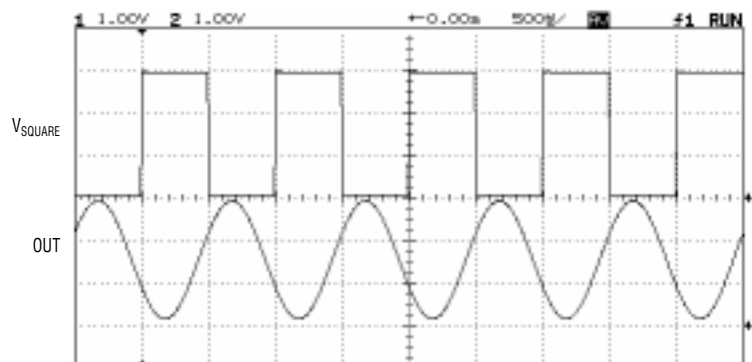


Figure 7. Scope capture for a 100kHz tone ($R_{SET} = 158k$)

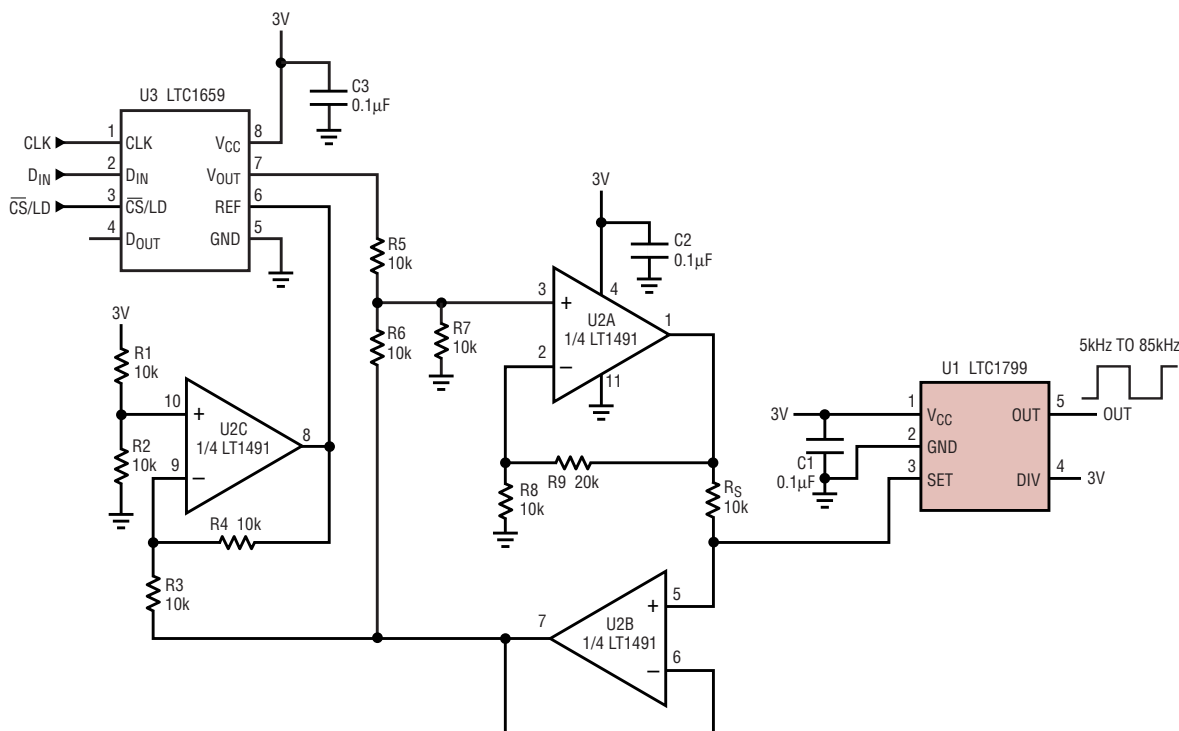


Figure 8. Digitally controlled oscillator with 5kHz to 85kHz range

is limited by op amp offset and gain errors, while the highest frequency is limited by the op amp's maximum output voltage.

Conclusion

The LTC1799 is a tiny, accurate, easy-to-use oscillator that is programmed by a single resistor. With a typical frequency accuracy of better than 0.5% and low temperature and supply dependence, the LTC1799 provides

performance that approaches that of crystal oscillators and ceramic resonators without sacrificing PCB space. Furthermore, the output frequency has unlimited resolution because it is resistor-programmable. With its resistance-to-frequency conversion architecture, the LTC1799 delivers an unprecedented combination of simplicity, stability, precision, frequency range and resolution in a tiny SOT-23 package. 

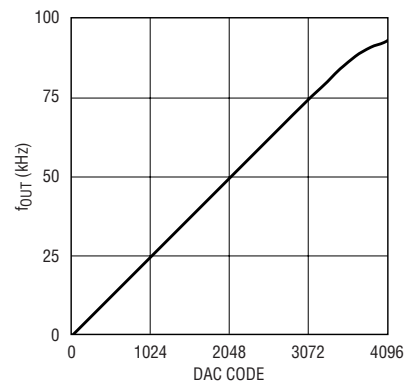


Figure 9. Input code vs output frequency for Figure 8's circuit

Issue Highlights, continued from page 2

The LTC1700 synchronous PWM controller boosts input voltages as low as 0.9V to 3.3V or 5V. It uses a constant frequency, current mode PWM architecture but does not require a current sense resistor; instead, it senses the V_{DS} across the external N-channel MOSFET. This reduces component count and improves high load current efficiency. The LTC1700 offers high efficiency over the entire load current range. During continuous mode operation, the LTC1700

consumes 540µA; it drops to 180µA in Sleep mode. In shutdown, the quiescent current is just 10µA.

Our Design Information section introduces the LTC1654, a 14-bit rail-to-rail voltage output dual DAC in the 16-pin SSOP package. This part offers a convenient solution for applications where density, resolution and power are critical. The LTC1654 is guaranteed to be 14-bit monotonic over temperature with a typical differential nonlinearity of only 0.3LSB.

Our Design Ideas section features a number of novel circuits, including a white LED driver, a 48V Hot Swap™ circuit with reverse-battery protection, a collection of circuits using a dual DAC to adjust gain and phase in RF applications, a high current, multioutput PolyPhase™ supply for computer and networking applications and an ultralow noise 48V to 5V step-down converter. The issue concludes with a trio of New Device Cameos. 

Current-Limited DC/DC Converter Simplifies USB Power Supplies

by Bryan Legates

Introduction

Many portable Universal Serial Bus (USB) devices power themselves from the USB host or hub power supply when plugged into the USB port. Several requirements must be met to ensure the integrity of the bus: the USB specification dictates that the input capacitance of a device must be less than 10 μ F to minimize inrush

currents when the device is plugged into the USB port; when first plugged in, the device must draw less than 100mA from the port and, for high power devices, the current drawn from the port can increase to 500mA only after it is given permission to do so by the USB controller. These requirements can be easily met using the

LT1618 DC/DC converter, which provides an accurate input current control ideal for USB applications. The LT1618 combines a traditional voltage feedback loop with a unique current feedback loop to operate as a constant-current, constant-voltage source.

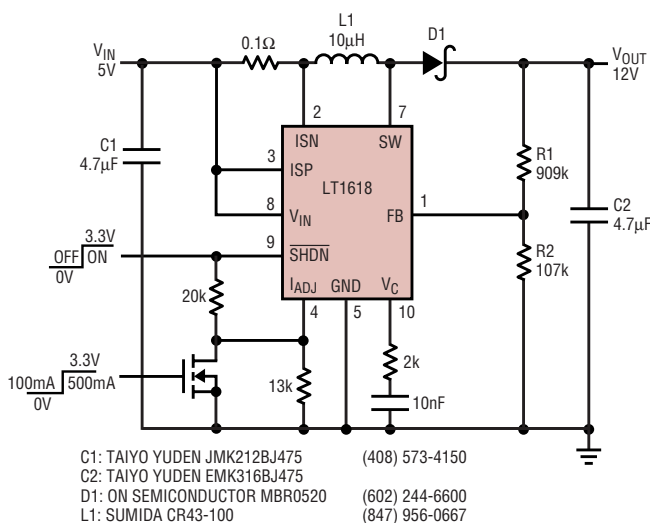


Figure 1. USB to 12V boost converter with selectable 100mA/500mA current limit

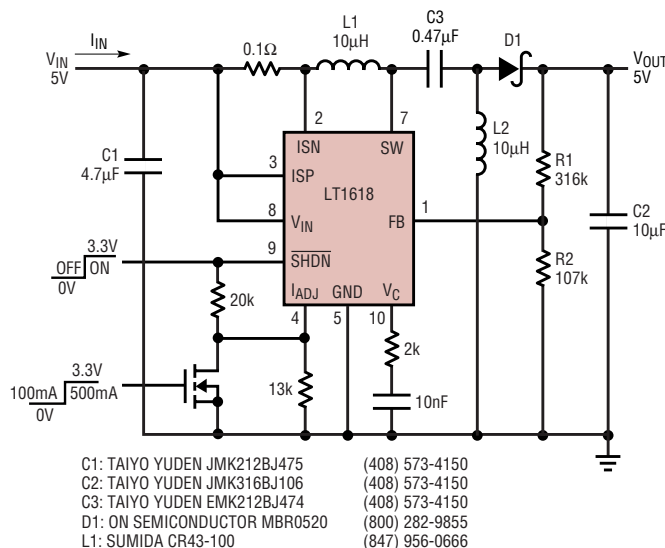


Figure 3. USB to 5V SEPIC converter

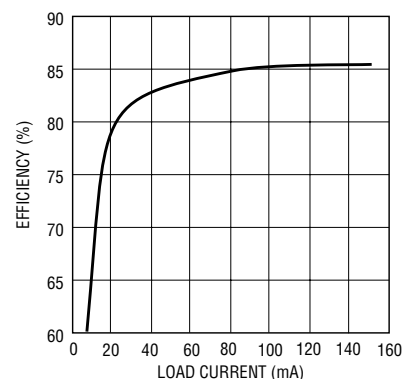


Figure 2. USB to 12V boost efficiency

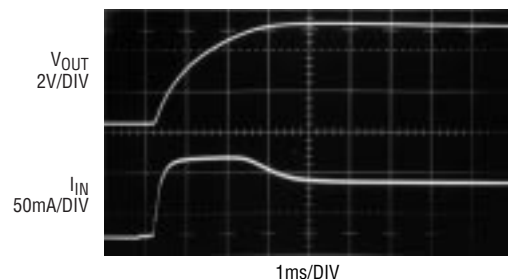


Figure 4. USB to 5V SEPIC during start-up

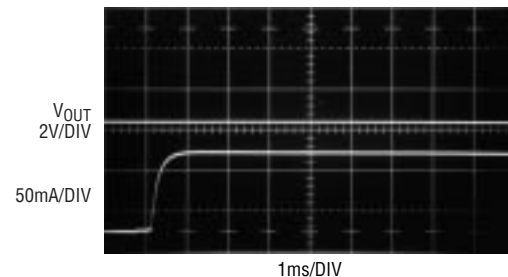


Figure 5. USB to 5V SEPIC start-up with shorted output

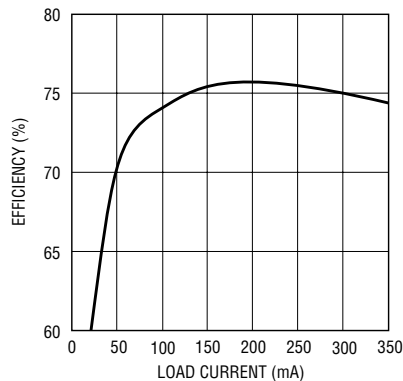


Figure 6. USB to 5V SEPIC efficiency

In addition to providing an accurate input current limit, the LT1618 can also be used to provide an accurately regulated output current for current-source applications. Driving white LEDs is one application for which the device is ideally suited. With an input voltage range of 1.6V to 18V, the LT1618 works from a variety of input sources. The 36V switching allows output voltages of up to 35V to be generated, easily driving up to eight white LEDs in series. The 1.4MHz switching frequency allows the use of low profile inductors and capacitors, which, along with the LT1618's MSOP-10 package, helps to minimize board area.

USB to 12V Boost Converter

Figure 1 shows a 5V to 12V boost converter ideal for USB applications. The converter has a selectable 100mA/500mA input current limit, allowing the device to be easily switched between the USB low and high power modes. Efficiency, shown

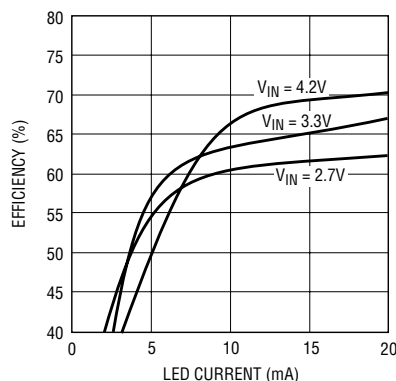


Figure 8. Li-Ion white LED driver efficiency

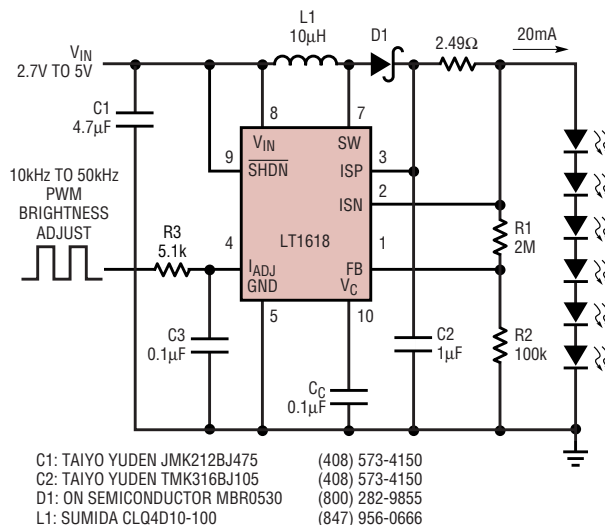


Figure 7. Li-Ion white LED driver

in Figure 2, exceeds 85%. If the load demands more current than the converter can provide with the input current limited to 100mA (or 500mA), the output voltage will simply decrease and the LT1618 will operate in constant-current mode. For example, with an input current limit of 100mA, about 35mA can be provided to the 12V output. If the load increases to 50mA, the output voltage will reduce to approximately 8V to maintain a constant 100mA input current.

USB to 5V SEPIC Converter with Short-Circuit Protection

Unlike boost converters, SEPICs (single-ended primary inductance converters) have an output that is DC-isolated from the input, so an input current limit not only helps soft start the output, but also provides excellent short-circuit protection. The 5V SEPIC converter shown in Figure 3 is ideal for applications that need the output voltage to go to zero during shutdown. The accurate input current limit ensures USB device compliance even under output fault conditions. Figure 4 shows the start-up characteristic of the SEPIC converter with a 50mA load. By limiting the input current to 100mA, the output is effectively soft started, smoothly increasing and not overshooting its final 5V value. Figure 5 shows that the input current does not exceed 100mA even with the out-

put shorted to ground (thus the flat output voltage waveform in the oscilloscope photo). Efficiency is shown in Figure 6. This converter also has a selectable input current limit of either 100mA or 500mA, making it ideal for high power USB applications.

Li-Ion White LED Driver

The circuit in Figure 7 is capable of driving six white LEDs from a single Li-Ion cell. LED brightness can be easily adjusted using a pulse width modulated (PWM) signal, as shown, or using a DC voltage to drive the I_{ADJ} pin directly, without the R3, C3 low-pass filter. If brightness control is not needed, simply connect the I_{ADJ} pin to ground. The typical output voltage is about 22V and the R1, R2 output divider sets the maximum output voltage to around 26V to protect the LT1618 if the LEDs are disconnected. The LT1618's constant current loop regulates 50mV across the 2.49Ω sense resistor, setting the LED current to 20mA. Efficiency for this circuit, shown in Figure 8, exceeds 70%, which is significantly higher than the 30% to 50% efficiencies obtained when using a charge pump for LED drive. No current flows in the LEDs when the LT1618 is turned off. Their high forward voltages prevent them from turning on, ensuring a true low current shutdown with no excess battery leakage or light output.

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2.3MHz Monolithic, Continuous Time, Differential Lowpass Filter Provides Solutions for Wide Band CDMA Applications

by Nello Sevastopoulos and Mike Kultgen

Introducing the LTC1566-1: 2.3MHz Lowpass in SO-8

The LTC1566-1 is a new monolithic 7th order continuous time lowpass filter featuring differential input and output terminals; it operates from a single 5V supply and dual supplies of up to $\pm 5V$ and it is packaged in an 8-pin surface mount SO-8 package. The LTC1566-1 requires no external components other than power supply decoupling capacitors. It replaces bulky discrete designs built from differential amplifiers, op amps, precision resistors and capacitors. The filter is designed to have a flat passband from DC to 2MHz and a steep transition band. The $-3dB$ cutoff frequency is 2.3MHz and the attenuation at 3.5MHz is in excess of 38dB. The filter gain gradually rolls off past 5MHz

and the 85dB attenuation floor extends beyond 100MHz. This gain performance cannot be obtained with discrete components without trimming passive components. The filter cutoff is set at 2.3MHz to accommodate differential filtering needs in wide band CDMA base stations. Figure 1 shows the measured amplitude response and group delay.

The LTC1566-1 is a fully integrated, continuous time, differential filter; its passband, its cutoff frequency and its transition band are fixed. Depending on demand, other filter cutoff frequencies as well as other lowpass filter responses up to 7th order can be provided. The passband gain is internally set to 4V/V (12dB); it can be lowered with three external resistors.

Setting the Input and Output Common Mode Levels

Figure 2 shows the block diagram of the LTC1566-1. The high input impedance of "floating amplifiers" A1 and A2 allows external resistors R1

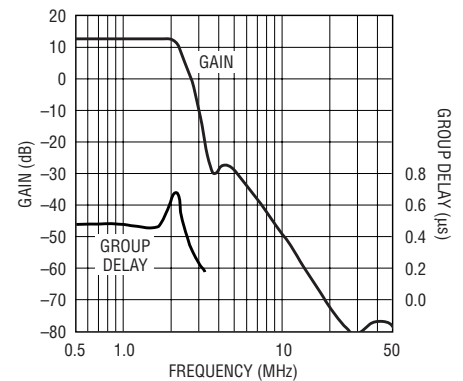
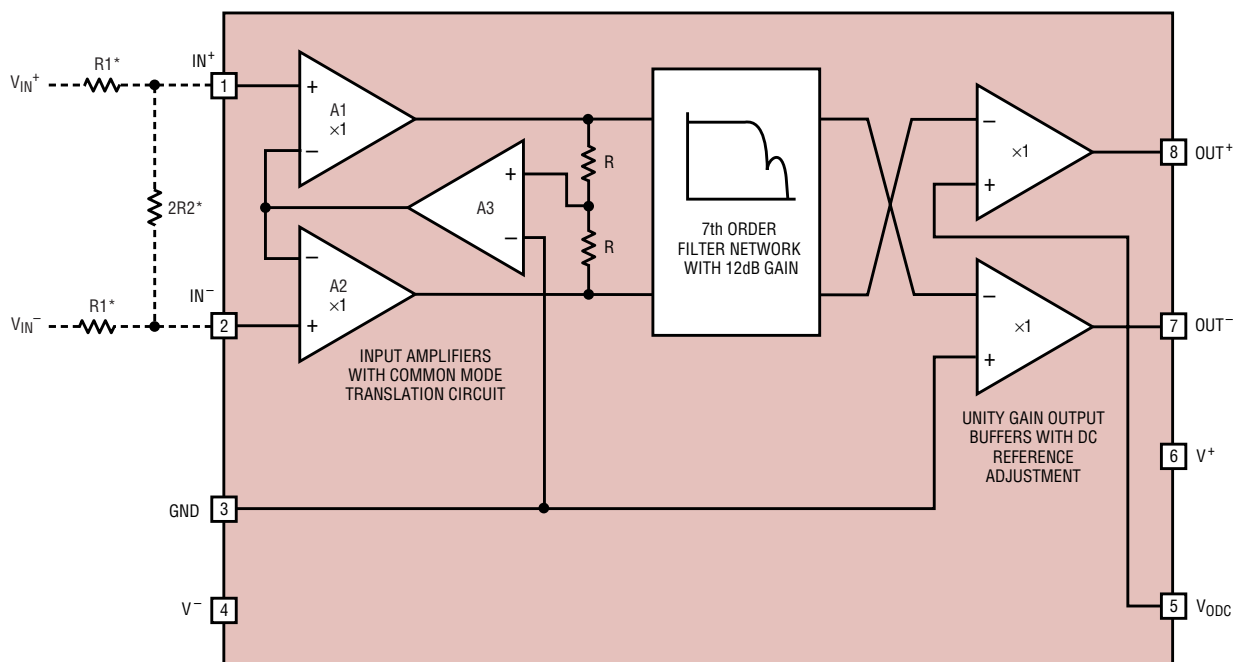


Figure 1. LTC1566-1 gain and group delay vs frequency



*NEEDED ONLY FOR PASSBAND GAIN < 12dB,

$$(IN^+ - IN^-) = (V_{IN}^+ - V_{IN}^-) \cdot \frac{R_2}{R_1 + R_2}$$

Figure 2. LTC1566-1 block diagram

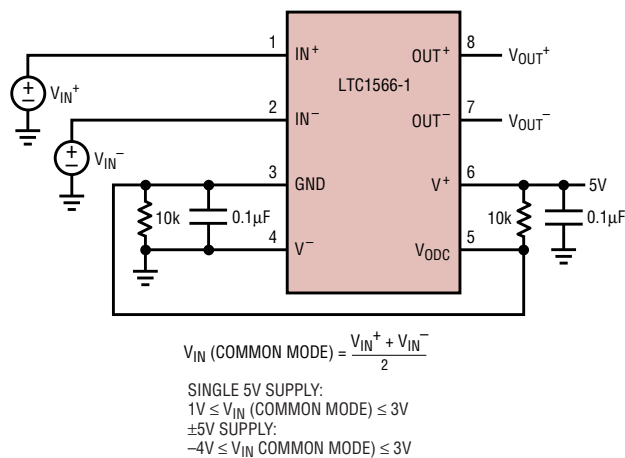


Figure 3. Single 5V supply operation, DC-coupled inputs

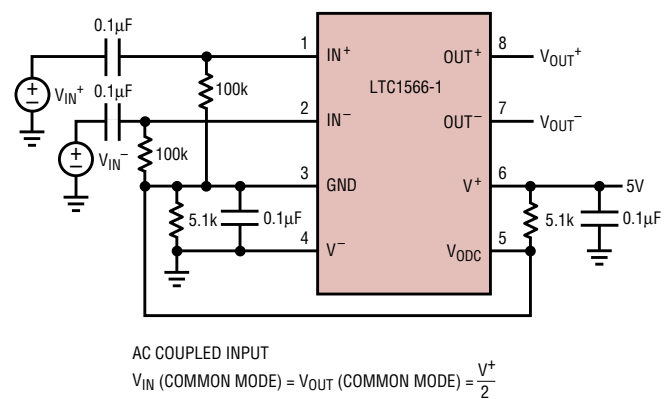


Figure 4. Single 5V supply operation, AC-coupled inputs

and 2R2 to be added to attenuate the differential input signal and to lower the effective passband gain of the circuit, if necessary. For example, if a gain of 2 (6dB) is desired, $R1 = R2$.

The LTC1566-1 is also capable of providing common mode voltage level shifting; that is, it can process differential input signals and provide filtered output differential signals with different common mode voltage levels. This is quite desirable, as components along a differential signal path may be optimized for a specific DC common mode level. For instance, the common mode output of a differential demodulator can be different than the required common mode input of a differential A/D converter.

The common mode translation is performed through unity-gain input buffers A1 and A2 and op amp A3 (Figure 2). Amplifier A3 forces the input amplifiers to operate with a common mode voltage dictated by the biasing of pin 3 (the ground pin) while

allowing floating amplifiers A1 and A2 to operate at an input common mode voltage dictated by the differential signal source driving the filter.

Another unique feature of the LTC1566-1 is the ability to introduce a differential offset voltage at the output of the filter. As seen in the block diagram, Figure 2, if a DC voltage is applied at pin 5 with respect to pin 3, it will be added to the differential voltage seen between pins 7 and 8. The DC output common mode voltage is therefore the arithmetic average of the DC voltages applied at pin 3 and pin 5. This output DC offset control can be used for sideband suppression of differential modulators, calibration of A/Ds or simple signal summation.

Figure 3 shows a typical connection for single-supply operation where the differential output is DC biased at one-half the power supply voltage. The input can be DC or AC coupled (Figure 3, Figure 4). AC coupling should be used if the common mode input voltage is outside the input range of the filter, as illustrated in Figure 4.

Dynamic Range

The total output in-band noise (DC to 2MHz) is typically $230\mu V_{RMS}$. Figure 5 shows the output signal-to-noise ratio vs differential output voltage. With a $1V_{RMS}$ output level ($2.8V_{P-P}$ differential) the filter features 73dB SINAD (S/N and THD). Note that the maximum dynamic range of the IC is independent of its power supply volt-

age. With dual 5V supplies, however, the filter can accept differential signals with wider common mode levels. The out-of-band noise is almost negligible due to the steep roll-off of the filter transition band. Input referred, the noise at each input terminal of the filter (pins 1 and 2) is $41\mu V_{RMS}$ or $-138dBm/Hz$.

Intermodulation

The coexistence of AMPS (American Mobile Phone System), CDMA (Code Division Multiple Access), and wide-band CDMA (WCDMA) cellular systems has increased the need for linearity in the transmitter and receiver circuits. In a CDMA or WCDMA transmitters, intermodulation of components in the spread-spectrum signal creates spectral regrowth and, consequently, adjacent channel interference. CDMA and WCDMA must operate in the presence of AMPS signals in the same channel (cochannel interference). Intermodulation between the AMPS signal and the CDMA/WCDMA signal desensitizes the receiver. Intermodulation is reduced by making the circuit as linear as possible. Both receiver and transmitter linearity can be characterized by measuring the intermodulation of two tones in the passband.

When two tones of equal amplitude are simultaneously applied to a weakly nonlinear circuit, the output spectrum above the two fundamentals will include the second and third harmonics of the input sources, the sum

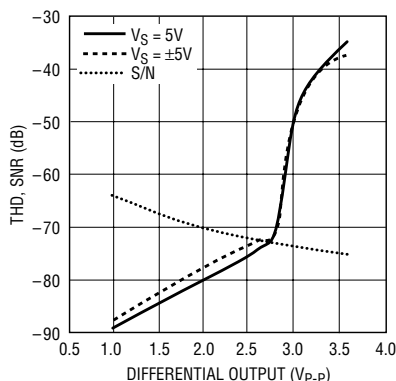


Figure 5. Total harmonic distortion and signal-to-noise ratio vs differential output voltage for single 5V and ±5V supplies

A Brief Overview of Filter Technologies.

Switched capacitor filter technology allows the filter cutoff frequency to be tuned with an external or internal clock, the value of the cutoff frequency being a multiple of the clock frequency. This highly convenient feature is always mitigated by the "sampled data" nature of the filter that always requires a clock, a "digital" element in the middle of a pure analog function. If a clock is not available, the clock must be designed as a separate circuit. If a clock is available, it often has to be conditioned to provide the appropriate multiple of the required cutoff frequency (for example, 100 times the filter cutoff). Typically, the clock will be routed from the digital part of the system into the analog board space, creating board layout issues.

Today, fully integrated switched capacitor lowpass filters are widely available. Most of them require an external clock because either the filter product by choice did not integrate the clock or the inaccuracy of the internal clock makes it useless. The cutoff frequency of most of these products is well below 100kHz.¹

RC active filter technology provides wide dynamic range and much higher cutoff frequencies than monolithic switched capacitor filters. RC active filters are mainly realized with discrete components (op amps, resistors and capacitors). With the availability of high speed op amps, cutoff frequencies of a few MHz or more can be obtained. The filter shape and cutoff frequency are determined by the appropriate choice of the discrete passive components required to build the filter.

LTC's newer RC active "monolithic" filters (the LTC1562, LTC1562-2 and LTC1563-X) integrate the op amps, the precision capacitors and some resistors to provide a compact filtering solution for cutoff frequencies up to 300kHz. The cutoff frequency, the filter type and the filter shape are programmed with external resistors. The internal capacitors are trimmed to better than 1% to provide more accurate filtering than their discrete counterparts. Furthermore, the newer FilterCAD 3.0 filter design software (see *Linear Technology X:3*, September 2000) allows the system designer to easily realize simple or complex filter functions using the above ICs.

Fully integrating a discrete RC active filter implies integrating both the active components and all passive components, thus losing the tunability of the filter. However, it is worth mentioning that *tunable* monolithic continuous time filters have been realized for specific high speed applications with reduced dynamic range. The tuning elements are either transconductors or MOSFETs, replacing the traditional resistor of an RC active filter.

For applications where the filter cutoff frequency is fixed, monolithic continuous time filters with preset cutoff frequencies can provide most of the advantages of the discrete RC active filters and eliminate the cumbersome, and sometimes hard to get, external passive components. Furthermore, if the signal path is differential, a discrete differential RC active design becomes complex and a fully integrated solution is desirable. 

¹ The new 10th order linear phase lowpass filter family, the LTC1569-X, is the only IC to solve the clock generation and clock routing problem by providing a precision internal clock that can be easily programmed via a single external resistor.

and the difference frequencies of the two input sources (IM2) and the sum and differences of twice one input source and the other (IM3).

Furthermore, if the same two tones are applied to an LTC1566-1 lowpass filter, the filter selectivity will attenuate the out-of-band spurs. The 2nd order intermodulation products (IM2) and some 3rd order intermodulation

products (IM3), however, may fall within the passband or in the vicinity of the band edge of the circuit and their presence can limit system performance. Figure 6 shows the actual test circuit with 455kHz and 2MHz tones simultaneously applied at the filter's differential inputs. Figure 7 shows the measured IM3 products ($2 \times 2\text{MHz} - 455\text{kHz} = 3.55\text{MHz}$, and 2

$\times 455\text{kHz} - 2\text{MHz} = 1.1\text{MHz}$). The IM2 products, $2\text{MHz} + 455\text{kHz}$ and $2\text{MHz} - 455\text{kHz}$, are also shown and are weaker than the IM3s, as expected. The suppression of the IM2 products is due to the fully differential nature of the LTC1566-1, which tends to cancel them. Furthermore it can be proven that the IM3 products increase by approximately 3dB for each dB of

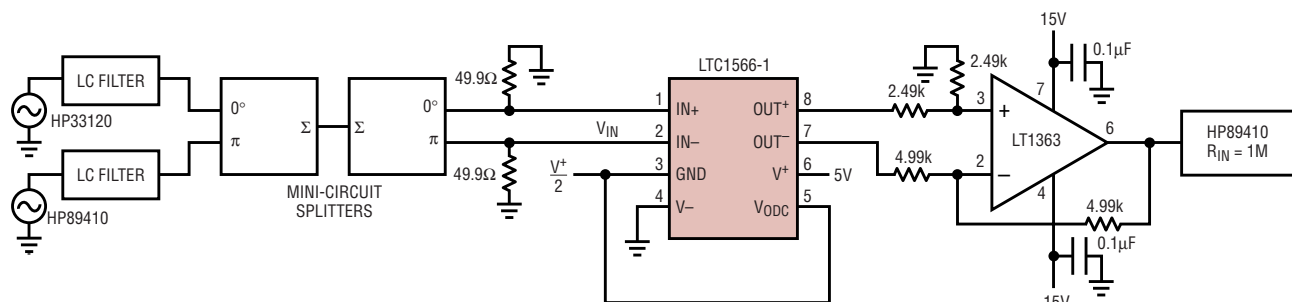


Figure 6. Test circuit for intermodulation distortion

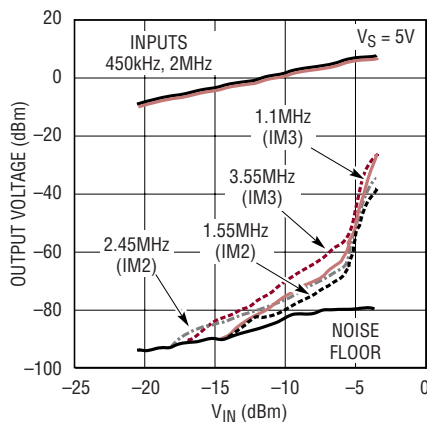


Figure 7. 450kHz/2MHz intermodulation, $V_S = 5V$

input signal increase, so their presence in the passband must be minimized or eliminated.

As shown in Figure 7, the excellent linearity of the LTC1566-1 provides an intermodulation ratio (IM) of better than 70dB for output levels of -3Bm or lower. The IM performance of the LTC1566-1 is better than some commercially available passive LC filter modules.

Out-of-Band Attenuation

The amplitude response of a filter is routinely tested with an input signal of varying frequency and constant amplitude; yet, a common requirement in communication systems is

the ability to process an in-band signal in the presence of large out-of-band interference. The active filter should be designed to meet these stringent requirements. Figure 8 shows a test circuit that simulates the case where the LTC1566-1 receives a constant-amplitude, in-band signal in the presence of strong out-of-band interference. Figure 9 shows the measured filter output. Three out-of-band tones (3MHz, 5MHz, 10MHz) are summed with a -2dBm (0.5V_{P-P}) 2MHz in-band signal. Figure 9 should be compared with the gain response of the filter shown in Figure 1. As can be seen in Figure 9, the LTC1566-1 can attenuate a 12dBm (2.52V_{P-P}) 10MHz out-of-band signal by 50dB, while amplifying an in-band 0.5V_{P-P} (-2dBm) 2MHz signal without gain error. The maximum allowable amplitude of the 10MHz out-of-band signal is 13dBm (2.82V_{P-P}); a larger signal will warp the passband gain. This excellent dynamic performance is attributable to the internal architecture of the LTC1566-1, which provides band-limiting at early stages.

Similar observations can be made for the 5MHz and 3MHz cases of Figure 9, although large 3MHz signals will warp the passband gain sooner; this is expected, because high ampli-

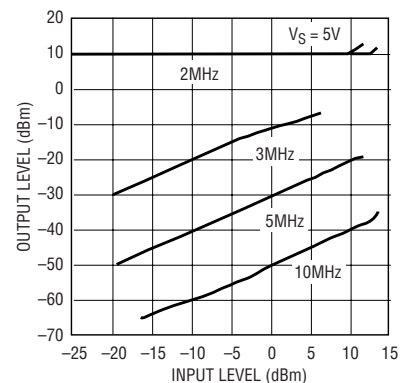


Figure 9. Out-of-band rejection, $V_S = 5V$

tude out-of-band 3MHz tones will also form in-band IM3 and IM2 products. To conclude, the LTC1566-1 attenuates out-of-band signals that are smaller than, equal to or larger than in-band signals.

Conclusion

The LTC1566-1 is a monolithic, self-contained, fully differential lowpass filter with outstanding linearity; it can process a wide spectrum of input signals and, in addition to filtering, it can provide common mode DC level shifting. 

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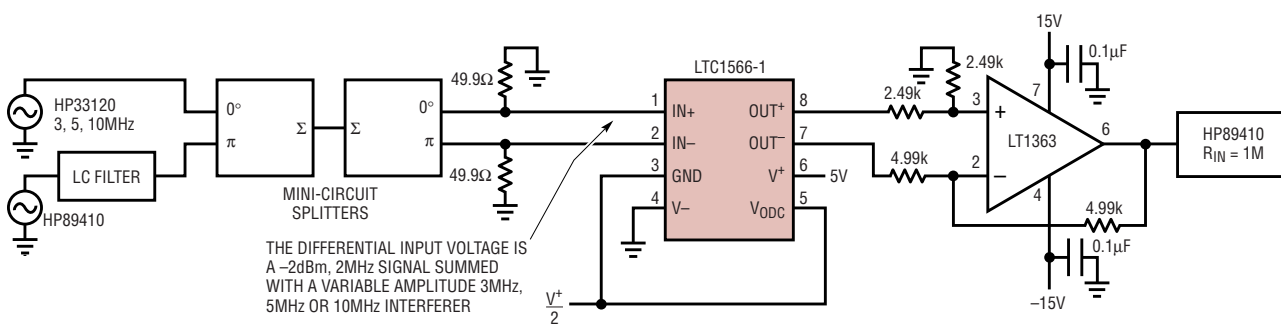


Figure 8. Test circuit for out-of-band rejection

Very Low Cost Li-Ion Battery Charger Requires Little Area and Few Components

by David Laude

Introduction

The LTC1734 is a precision, low cost, single-cell, linear Li-Ion battery charger with constant voltage and constant current control. The small quantity and low cost of external components results in a very low overall system cost and the part's 6-pin SOT-23 package allows for a compact design solution. Previous products usually required an external current sensing resistor and blocking diode whose functions are included in the LTC1734. Other features include:

- ❑ 1% accurate float voltage options of 4.1V or 4.2V
- ❑ Programmable constant current range of 200mA to 700mA
- ❑ Charging current monitor output and manual shutdown for use with a microcontroller
- ❑ Automated shutdown with no battery drain after supply removal
- ❑ Undervoltage lockout
- ❑ Self protection for overcurrent and overtemperature

Applications include such compact devices as cellular phones, digital cameras and handheld computers. The LTC1734 can also be used as a general purpose current source or for charging nickel-cadmium or nickel-metal-hydride batteries.

A Simple, Low Cost Li-Ion Charger

A battery charger programmed for 300mA in the constant current mode with a charge current monitoring function is shown in Figure 1. The PNP transistor is needed to source the charging current and resistor R1 is used to program the maximum charging current. Note that no external current sense resistor or diode to block current is required. When the supply is opened or shorted to ground, the charger shuts down and no quiescent current flows from the battery to the charger. This feature extends battery life. Capacitor C2 can consist of up to 100µF of bypass caps, which would normally be distributed along the battery line. The supply voltage can range from 4.75V to 8V, but power dissipation of the PNP may become excessive near the higher end.

The programming pin (PROG) accomplishes several functions. It is used to set the current in the constant current mode, monitor the charging current and manually shut down the charger. In the constant current mode, the LTC1734 maintains the PROG pin at 1.5V. The PROG pin voltage drops below 1.5V as the constant voltage mode is entered and charge current drops off. The charge

current is always one thousand times the current through R1 and is therefore proportional to the PROG pin voltage. At 1.5V the current is the full 300mA, whereas at 0.15V the current is 300mA/10 or 30mA. If the grounded side of R1 is pulled above 2.15V or is allowed to float, the charger enters the manual shutdown mode and charging ceases. These features enable smarter charging by allowing a microcontroller to monitor the charging current and shut down the charger at the appropriate time. The I_{SENSE} and BAT pins are used to monitor charge current and battery voltage, respectively; the DRIVE pin controls the PNP's base.

A Programmable Constant Current Source

An example of a programmable current source is shown in Figure 2. To ensure that only the constant current mode is activated, the BAT pin is tied to ground to prevent the constant voltage control loop from engaging. The control inputs either float or are connected to ground. This can be achieved by driving them from the drains of NMOS FETs or from the collectors of NPNs. When both inputs are floating, manual shutdown is

continued on page 15

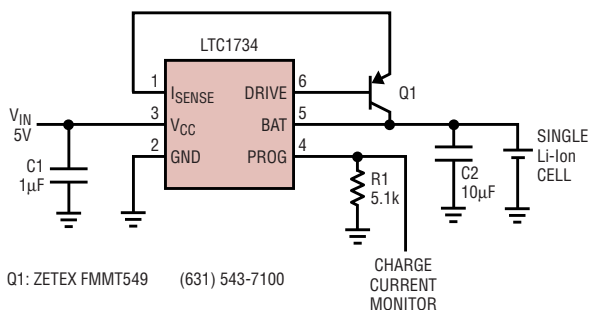


Figure 1. Simple, low cost charger programmed for 300mA output current

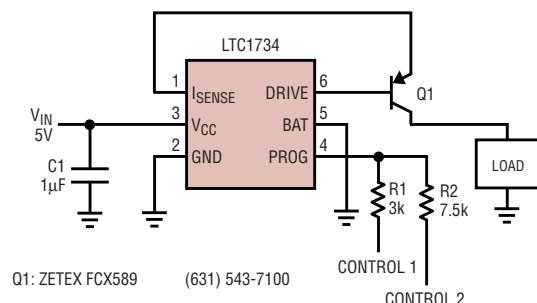


Figure 2. Programmable current source with output current of 0mA, 200mA, 500mA or 700mA

Synchronous Buck Controller Extends Battery Life and Fits in a Small Footprint

by Peter Guan

Introduction

Portable electronic devices continue to decrease in size and their supply voltages are also falling, but load current requirements are increasing as a result of higher processing speed and improved features. This trend places more constraints on today's portable power supplies, but Linear Technology has the solution. The LTC1773 is a synchronous DC/DC controller that packs high output current capability and low operating quiescent current in a small MSOP-10 package. Its input voltage range is from 2.65V to 8.5V; this is ideal for 1- or 2-cell Li-Ion batteries as well as 3- to 6-cell NiCd and NiMH battery packs because it allows the batteries to operate near end of charge. A precise internal undervoltage lockout circuit prevents deep discharge of the battery below 2.5V. Popular features such as OPTI-LOOP™ compensation, soft start and Burst Mode™ operation are also included. Combined with its small MSOP package, the LTC1773's high operating frequency of 550kHz allows the use of small, surface mount components to provide a compact power supply solution.

Operation

Figure 1 shows a typical application of the LTC1773 in a 5V to 2.5V/3A step-down converter. Figure 2 shows its efficiency vs load current. The LTC1773 uses a constant frequency, current mode architecture to drive an external pair of complementary power MOSFETs. An internal oscillator sets

Portable electronic devices continue to decrease in size and their supply voltages are also falling, but load current requirements are increasing as a result of higher processing speed and improved features. This trend places more constraints on today's portable power supplies, but Linear Technology has the solution.

the operating frequency of the device. The P-channel MOSFET turns on with every oscillator cycle and turns off when the internal current comparator trips, indicating that the inductor current has reached a level set by the I_{TH} pin. An internal error amplifier, in turn, drives the I_{TH} pin by monitoring

the output voltage through an external resistive divider connected to the V_{FB} pin. While the P-channel MOSFET is off, the synchronous N-channel MOSFET turns on until either the inductor current starts to reverse, as indicated by the SW pin going below ground, or until the beginning of the next cycle.

Synchronous, Burst Mode and Forced Continuous Operation

Three modes of operation can be selected through the SYNC/FCB pin. Tying it above 0.8V or leaving it floating will enable Burst Mode operation, which increases efficiency during light load conditions. During Burst Mode operation, the peak inductor current limit is clamped to about a third of the maximum value and the I_{TH} pin is monitored to determine whether the device will go into a power-saving Sleep mode. The I_{TH} level is inversely proportional to the output voltage error. When the inductor's average current is higher than the load requirement, the output voltage rises while the I_{TH} level drops. When I_{TH} dips below 0.22V, the device goes into Sleep mode, turning off the external

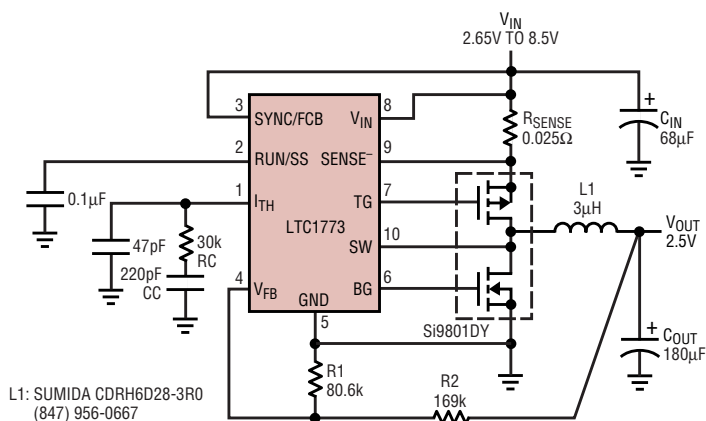


Figure 1. 5V to 2.5V/3A step-down converter

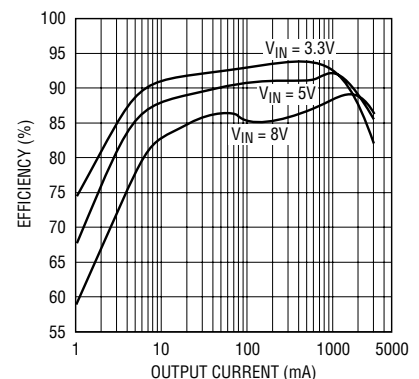


Figure 2. Efficiency of Figure 1's circuit with several input voltages

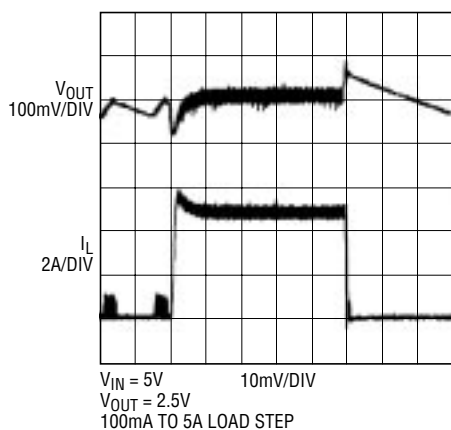


Figure 3a. Load-step response, Burst Mode operation

power MOSFETs and most of the internal circuitry; in this state, the LTC1773 consumes only 80 μ A of quiescent current. At this point, the load current is being supplied by the output capacitor. As the output droops, I_{TH} will be driven higher. When I_{TH} rises above 0.27V, the device resumes normal operation.

For frequency-sensitive applications, Burst Mode operation can be inhibited by tying the SYNC/FCB pin to below 0.8V to force continuous operation, which will continually drive the external power MOSFETs synchronously regardless of the output load. The inductor current is allowed to reverse in this case.

In addition to being a logic input threshold, the 0.8V threshold of the SYNC/FCB pin can also be used to regulate a secondary winding output by forcing continuous synchronous operation regardless of the primary output load. A logic-level clock signal connected to the SYNC/FCB pin synchronizes the operating frequency to an external source between 585kHz and 750kHz. Burst Mode operation is automatically disabled during synchronization to reduce noise. Instead, cycle skipping occurs under light load conditions because current reversal is not allowed. This boosts the low current efficiency while providing low output ripple.

Run/Soft Start

Upon power up, the RUN/SS pin is pulled high by an internal current source; an external capacitor can be

placed at the pin to program its rise time to ensure a soft start at the output by limiting the amount of charge current into the output capacitors. The RUN/SS pin also serves another function: if the pin is tied below 0.65V, the part goes into shutdown and consumes less than 10 μ A of input current.

Fault Protection

The LTC1773 incorporates protection features such as programmable current limit, input undervoltage lockout, output overvoltage protection and frequency foldback when the output falls out of regulation.

One of the advantages of a current mode switching regulator is that current is regulated during every clock cycle, thus providing current overload protection on a pulse-by-pulse basis. Current limit is programmed through an external high-side sense resistor. The maximum sense voltage across this resistor is 100mV. But taking into account current ripple, input noise and sense resistor tolerance, 70mV should be used in choosing the proper sense resistor ($R_{SENSE} = 70\text{mV}/I_{OUT}$).

To protect a battery power source from deep discharge near its end of charge, an internal undervoltage lockout circuit shuts down the device when V_{IN} drops below 2.5V. This reduces the current consumption to about 2 μ A. A built-in 150mV hysteresis ensures reliable operation with noisy supplies.

During transient overshoots and other more serious conditions that may cause the output to rise out of regulation (>7.5%), an internal overvoltage comparator will turn off the main MOSFET and turn on the synchronous MOSFET until the overvoltage condition is cleared. During this time, if the main MOSFET is defective or shorted to ground, current will flow directly from V_{IN} to ground, blowing the system fuse and saving the other board components.

In addition, if the output is shorted to ground, the frequency of the oscillator is reduced to about 55kHz, 1/10 of the nominal frequency. This fre-

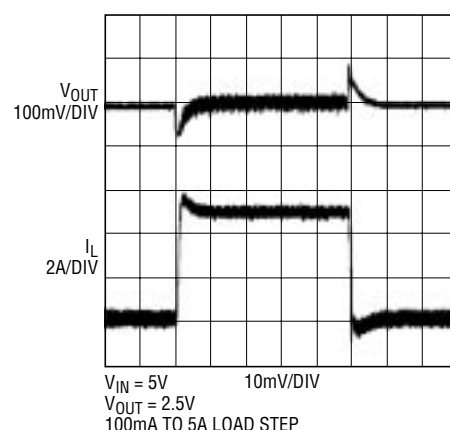


Figure 3b. Load-step response, continuous mode operation

quency foldback ensures that the inductor current has enough time to decay, thereby preventing runaway. The oscillator's frequency will gradually increase back to 550kHz when the V_{FB} pin rises above 0.4V.

Dropout Operation

During the discharging of a battery source, when the input supply voltage decreases toward the output voltage, the duty cycle increases toward the maximum on-time. The output voltage will then be determined by V_{IN} minus the $I \cdot R$ voltage drops across the external P-channel MOSFET, the sense resistor and the inductor.

OPTI-LOOP Compensation

To meet stringent transient response requirements, other switching regulators may need to use many large and expensive output capacitors to reduce the output voltage droop during a load step. The LTC1773, with OPTI-LOOP compensation, requires fewer output capacitors and also allows the use of inexpensive ceramic capacitors. The I_{TH} pin of the LTC1773 allows users to choose the proper component values to compensate the loop so that the transient response can be optimized with the minimum number of output capacitors.

Line and Load Regulation

The current mode architecture of the LTC1773 ensures excellent line and load regulation without cumbersome compensation and excessive output

capacitance. Figures 3a and 3b show the response of the LTC1773 to a 100mA to 5A load step during Burst Mode and continuous mode operations, respectively.

1.8V/7A Application

Figure 4 shows a step-down application from 3.3V to 1.8V at 7A. When operating below 5V, care should be taken to choose the proper sublogic-level MOSFETs that have relatively low gate charge. For high current (>3A) applications, single P-channel and N-channel MOSFETs should be used instead of complementary MOSFETs in one package. A good figure of merit for MOSFETs is the $R_{DS(ON)}$ gate-charge product. The lower this value is, the higher the application's efficiency will be.

In addition to normal step-down applications, the LTC1773 can also be used in a zeta converter configuration that will do both step-down and step-up conversions, as shown in Figure 5. This application is ideal for battery-powered operation, in which a regulated 3.3V output is maintained during the entire discharge cycle of a Li-Ion battery from 4.7V to 2.5V.

Conclusion

The LTC1773 offers flexibility, high efficiency and many other popular features in a small MSOP-10 package. For low voltage portable systems that require small footprint and high efficiency, the LTC1773 is the ideal solution. 

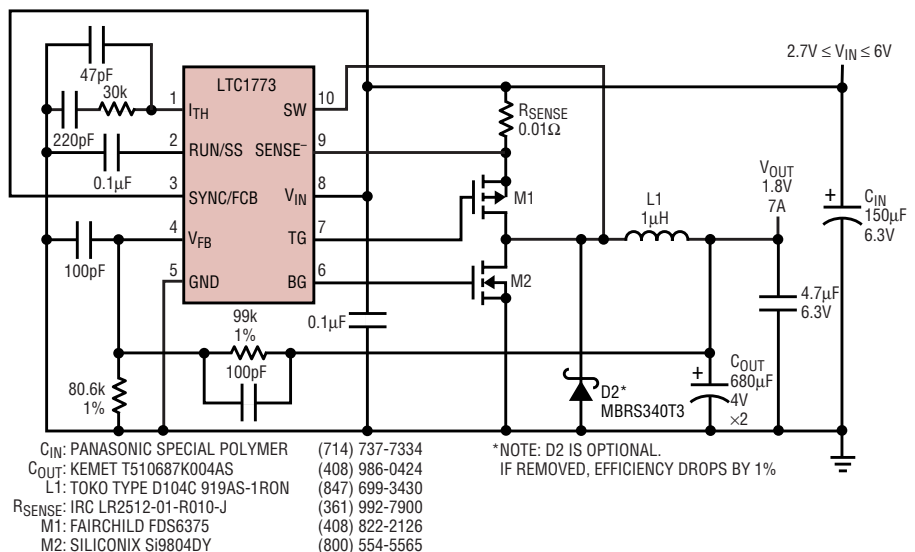


Figure 4. 3.3V to 1.8V/7A regulator

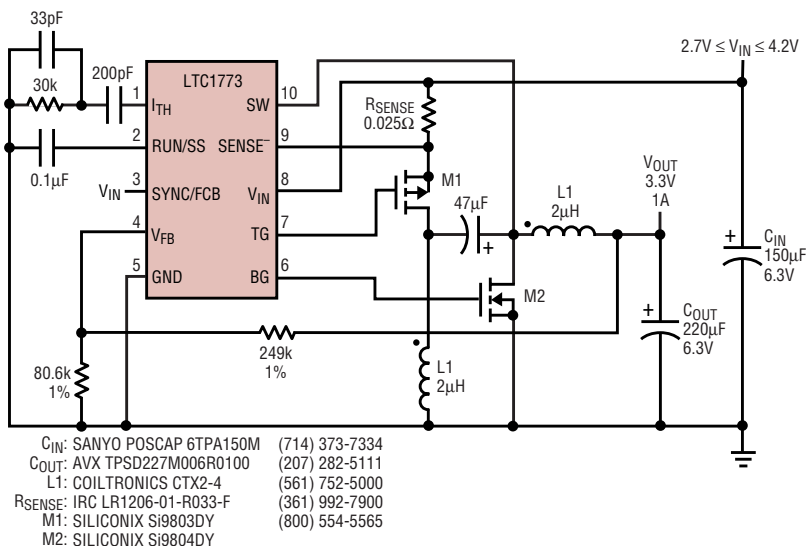


Figure 5. Single Li-Ion cell to 3.3V/1A synchronous zeta converter

LTC1734, continued from page 12

entered. Connecting Control 1 to ground causes 500mA of current to flow into the load, whereas Control 2 results in 200mA of current. When both control inputs are grounded the current is 700mA. A voltage DAC,

connected to the PROG pin through a resistor, could also be used to control the current. Applications include charging nickel-cadmium or nickel-metal-hydride batteries, driving LEDs or biasing bridge circuits.

Conclusion

Low cost, small footprint, reduced component count, precision and versatility make the LTC1734 an excellent solution for implementing compact and inexpensive battery chargers or constant current sources. 

New No R_{SENSE} Controllers Deliver Very Low Output Voltages

by Christopher B. Umminger

Introduction

Digital system voltages are dropping ever lower, yet battery voltages are not. This forces DC/DC step-down converters in portable products to operate at lower duty cycles. Unfortunately, low duty cycle operation decreases efficiency due to both increased switching losses and the increased importance of I^2R losses at low output voltages. Furthermore, conventional control architectures often have difficulty operating with very short switch on-times. The LTC1778 and LTC3711 with VID address these problems with a new architecture for buck regulators that delivers the low output voltages and high efficiencies that modern portable supplies require.

The LTC1778 is a step-down controller that provides synchronous drive for two external N-channel MOSFET switches. It comes with a variety of features to ease the design

of very high efficiency DC/DC step-down converters. The true current mode control architecture has an adjustable current limit, can be easily compensated, is stable with ceramic output capacitors and does not require a power-wasting sense resistor. An optional discontinuous mode of operation increases efficiency at light loads. The LTC1778 operates over a wide range of input voltages from 4V to 36V and output voltages from 0.8V up to 90% of V_{IN} . Switching frequencies up to nearly 2MHz can be chosen, allowing wide latitude in trading off efficiency for component size. Fault protection features include a power-good output, current limit fold-back, optional short-circuit shutdown timer and an overvoltage soft latch. The LTC3711 is essentially the same as the LTC1778 but includes a 5-bit VID interface.

Valley Current Control Enables $t_{ON(MIN)} < 100ns$

Power supplies for modern portable computers require that voltages as high as 24V from a battery pack or wall adapter be converted down to levels from 2.5V to as low as 0.8V. Such a large ratio of input to output voltage means that a buck regulator must operate with duty cycles down to 3%. At 300kHz operation, this implies a main switch on-time of only 110ns. Conventional current mode regulators have difficulty achieving on-times this short, forcing lower frequency operation and the use of larger components.

To overcome this limitation, the LTC1778 family uses a valley current control architecture that is illustrated in Figure 1. Current is sensed by the voltage drop between the SW (or SENSE⁺) and PGND (or SENSE⁻) pins while the bottom switch, M2, is turned on. During this time the negative

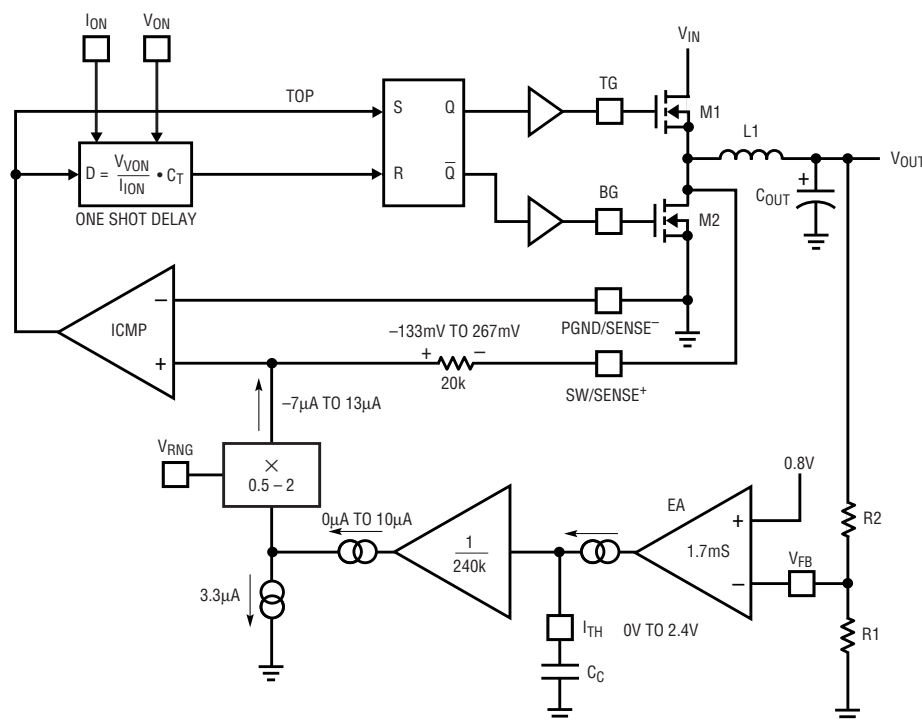


Figure 1. LTC1778 main control loop

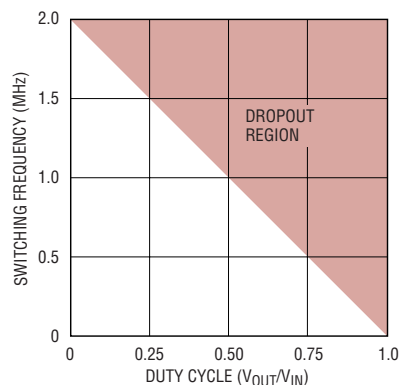


Figure 2. Maximum switching frequency vs duty cycle

voltage across inductor L1 causes the current flowing through it to decay. When it reaches the level set by the current-control threshold (I_{TH}) voltage, the current comparator (ICMP) trips. This sets the latch, turning off the bottom switch and turning on the top (or main) switch, M1. After a controlled delay determined by a one-shot timer, the top switch turns off again and the cycle repeats. The current-control threshold is set by an error amplifier (EA) that compares the divided output voltage with a 0.8V reference in order to keep the threshold at a level that matches the load current.

This control loop has several advantages compared to peak-cur-

rent controllers that use an internal oscillator. Because only a one-shot timer determines the top switch on-time, it can be made very short for low duty cycle applications. Another advantage is that slope compensation is not required. Furthermore, response to a load step increase can be very fast since the loop does not have to wait for an oscillator pulse before the top switch is turned on and current begins increasing.

Flexible One-Shot Timer Keeps Frequency Constant

Although the LTC1778 does not contain an internal oscillator, switching frequency is kept approximately constant through the use of a flexible one-shot timer that controls the top switch on-time. A current entering the I_{ON} pin (I_{ION}) charges an internal timing capacitor (C_T) to the voltage applied at the V_{ON} pin (V_{ON}) to determine the on-time: $t_{ON} = C_T \cdot V_{ON} / I_{ION}$. For a buck regulator running at a constant frequency, the on-time is proportional to V_{OUT} / V_{IN} . By connecting a resistor (R_{ON}) from V_{IN} to the I_{ON} pin and connecting V_{OUT} to the V_{ON} pin (if available), the one-shot duration can be made proportional to V_{OUT} and inversely proportional to V_{IN} . The converter will then operate at an ap-

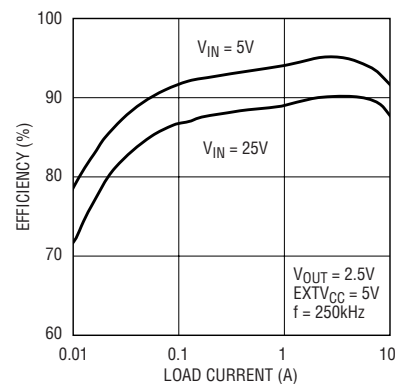


Figure 4. Efficiency vs load current for Figure 3's circuit

proximately constant frequency equal to $(R_{ON} \cdot C_T)^{-1}$. In most applications, the output voltage is not intended to change. Thus, some versions of the LTC1778 do not make the V_{ON} pin available and it defaults internally to 0.7V. By adjusting the value of R_{ON} , a wide range of operating frequencies can be selected. However, an important limit is set by the 500ns minimum off-time of the top switch. This is the minimum time required by the LTC1778 to turn on the bottom switch, sense the current and then shut it off. At a given switching frequency, it places a limit on the maximum duty cycle as illustrated in Figure 2. For example, at 200kHz operation, the LTC1778 can accommodate duty cycles up to 90%. Attempting to

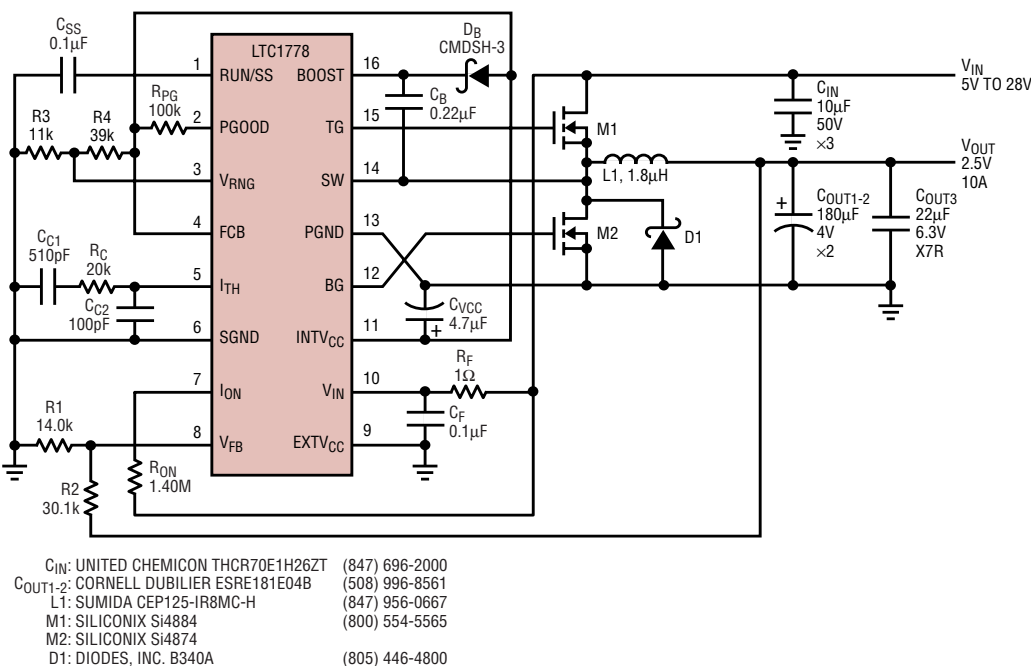


Figure 3. 2.5V/10A converter switches at 250kHz

operate at duty cycles above this limit will cause the output voltage to drop out of regulation, down to a value that satisfies the duty cycle limit. Thus, the LTC1778 can be used in exceptionally high frequency buck converters, provided that the duty cycle is low enough. For example, a 10V to 2.5V converter can be run at frequencies as high as 1.5MHz.

No R_{SENSE} Operation Raises Efficiency at Low V_{OUT}

The LTC1778 offers true current mode control without the need for a sense resistor, an expensive component that is sometimes difficult to procure. The current comparator monitors the voltage drop between the SW and PGND pins, determining inductor current using the on-resistance of the bottom MOSFET. In addition to eliminating the sense resistor, this technique also simplifies the board layout and improves efficiency. The efficiency gain is especially noticeable in low output voltage applications where the resistor sense voltage is a significant fraction of the output voltage. For example, a 50mV sense voltage reduces efficiency by 5% in a 1V output converter.

The LTC1778 allows the current sense range to be adjusted using the V_{RNG} pin to accommodate a variety of MOSFET on-resistances. The power supply designer can easily trade off efficiency and cost in the choice of

MOSFET on-resistance. The voltage presented at the V_{RNG} pin should be ten times the nominal sense voltage at maximum load current, for example, $V_{RNG} = 1V$ corresponds to a nominal sense voltage of 100mV. Connecting this pin to $INTV_{CC}$ or ground defaults the nominal sense voltage to 140mV or 70mV, respectively. Current is limited at 150% and -50% of the nominal level set by the V_{RNG} pin.

For those applications that require more accurate current measurement, the LTC3711 and some versions of the LTC1778 make available one or both of the current comparator inputs as separate $SENSE^+$ and $SENSE^-$ pins. Connecting the inputs to a precise sense resistor placed in series with the source of the bottom MOSFET switch determines current more accurately. This is especially beneficial for applications that need a more accurate current limit or seek to actively position the output voltage as the load current varies.

Output is Protected from a Variety of Faults

The LTC1778 comes with a number of fault protection features. The output voltage is continuously monitored for out-of-range conditions. If it deviates by more than $\pm 7.5\%$ from the regulation point, an open drain power-good output will pull low to indicate the out-of-regulation condition. In an overvoltage situation, the top switch

will be turned off and the bottom switch turned on until the output is pulled back below the power-good threshold. In an undervoltage condition, if the output falls by 25%, a short-circuit latch-off timer will be started. If the output has not recovered within this time, both switches will be shut off, stopping the converter. Undervoltage/short-circuit latch-off can be overridden. In this case, if the output voltage continues to fall below 50% of the regulation point, the current limit will be reduced, or folded back, to about one fourth of its maximum value.

Popular Features from Other Controllers Remain

Continuous synchronous operation at light loads reduces efficiency due to the large amount of current consumed by switching losses. Efficiency is improved by operating the converter in discontinuous mode. In this mode, the bottom switch is turned off at the instant that inductor current starts to reverse, even though the current control threshold (I_{TH}) is below that level. The top switch, however, is not turned on until the I_{TH} level rises back to the point corresponding to zero inductor current. During the time both switches are off, the output current is provided solely by the output capacitor and switching losses are avoided. The switching frequency becomes proportional to the load current in this mode of operation.

The LTC1778 contains its own internal low dropout regulator that provides the 5V gate drive required for logic-level MOSFETs. However, it is also able to accept an external 5V to 7V supply if one is available. Connecting such a supply to the $EXTV_{CC}$ pin disables the internal regulator; all controller and gate drive power is then drawn from the external supply. If the external drive comes from a high efficiency source, overall efficiency can be improved. Furthermore, connecting the V_{IN} and $EXTV_{CC}$ pins together to an external 5V supply allows the controller to convert low input voltages such as 3.3V and 2.5V.

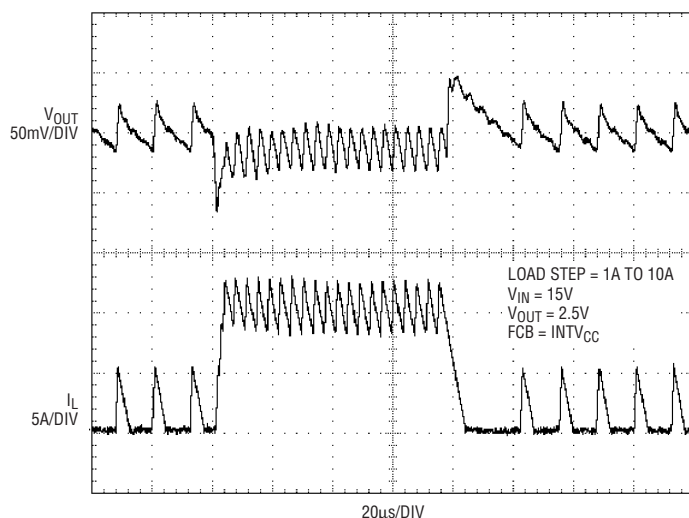


Figure 5. Transient response of Figure 3's circuit

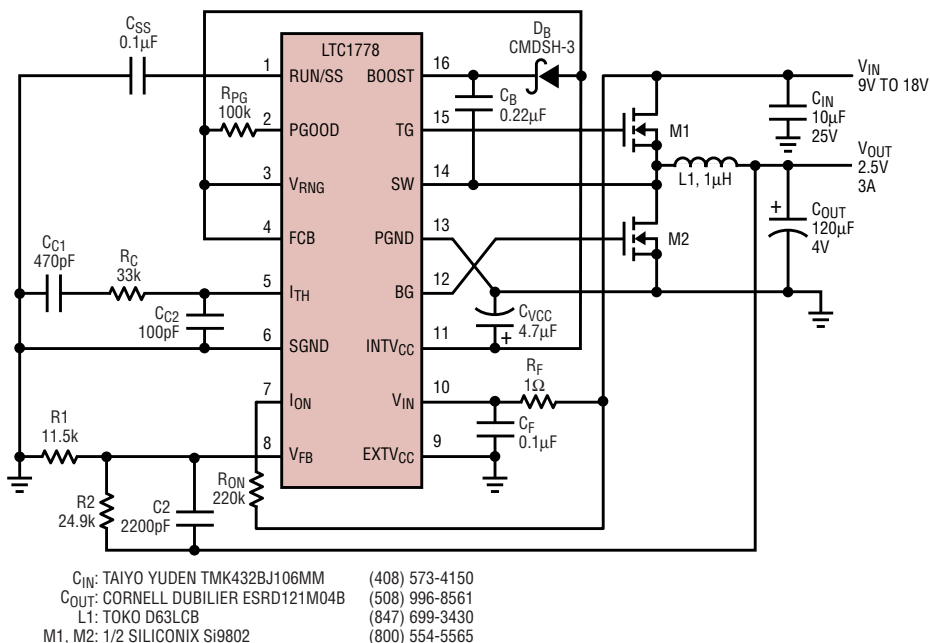


Figure 6. 2.5V/3A converter switches at 1.4MHz

Design Examples

Figure 3 shows a typical application circuit using the LTC1778EGN. This 16-pin SSOP version of the part does not make all of the pin functions available. The V_{ON} input is internally set to 0.7V and the SENSE⁺ and SENSE⁻ pins are cobonded with the SW and PGND pins, respectively. The circuit delivers a regulated 2.5V output at up to 10A from input voltages between 5V and 28V. The power MOSFETs from Siliconix are optimized for low duty cycle applications. The 1.4MΩ R_{ON} sets the 250kHz switching frequency. This switching frequency yields good efficiency with reasonable component sizes. Figure 4 shows that the efficiency of this circuit ranges from 90% to 95%, depending upon output current and input voltage. At light loads, below about 2A, the circuit enters discontinuous mode to keep the efficiency high. The response to a 1A to 10A load step is shown in Figure 5. Note the discontinuous mode operation with the 1A load and the rapid increase in inductor current after the load step.

Figure 6 shows a very high switching frequency buck regulator that allows the use of small power components. This circuit delivers a 2.5V output at up to 3A while switching at

1.4MHz. The minimum off-time constraint limits the duty cycle in this circuit to below 30%, as illustrated in Figure 2. Thus, the minimum permissible V_{IN} to avoid dropout is 9V. A pair of low-gate-charge MOSFETs in a single SO-8 package was chosen to minimize the significant switching losses at this high frequency. Efficiency runs about 80% to 85% with a 12V input.

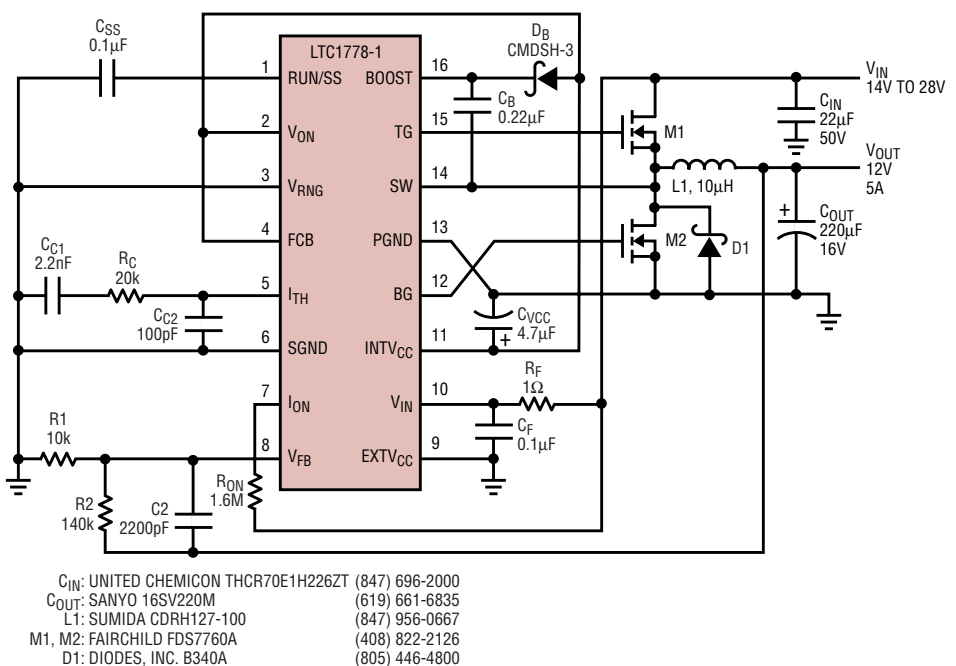


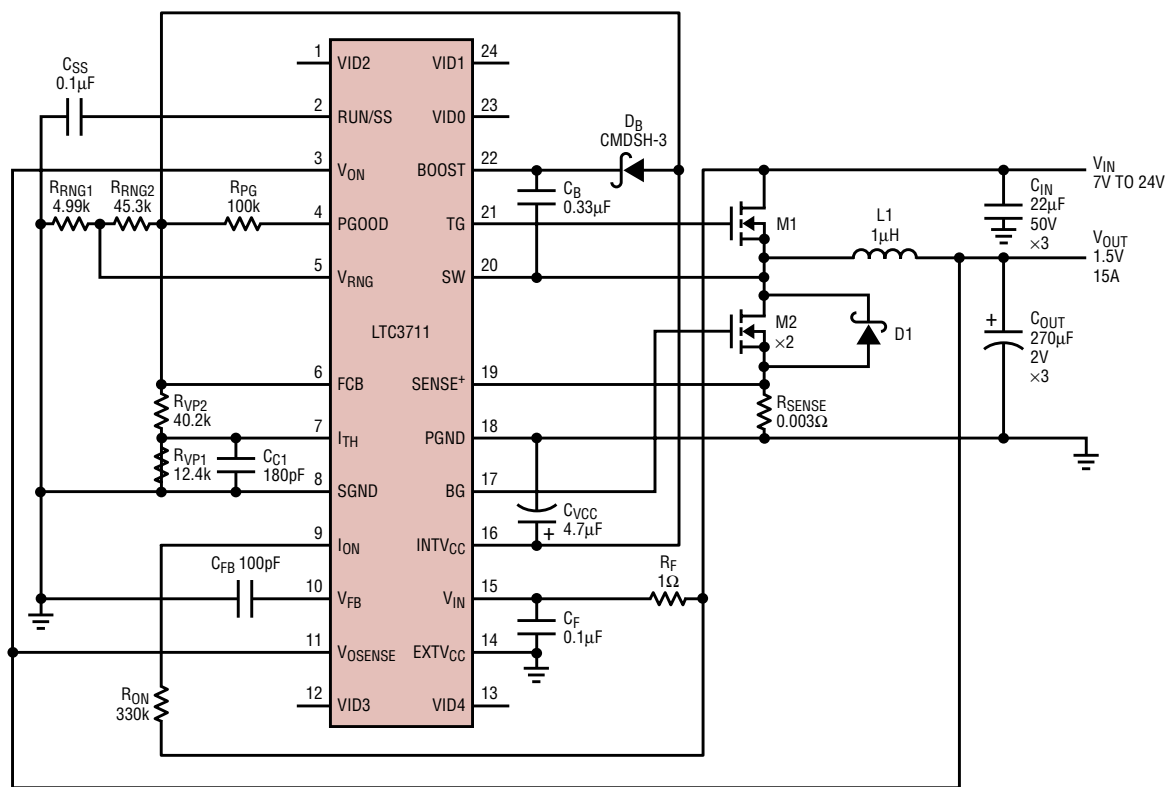
Figure 7. 12V/5A converter switches at 300kHz

Unlike many other current mode controllers, the LTC1778 can also be used in applications with a high output voltage, nearly up to the full input voltage. Figure 7 illustrates this with a 12V output circuit that can deliver up to 5A. This circuit uses the LTC1778EGN-1, which replaces the PGOOD pin with the V_{ON} pin. Tying this pin high sets the internal V_{ON} level to 2.4V, reducing the required value of the R_{ON} resistor for 300kHz operation. This circuit has excellent efficiency, reaching 97% at 5A with a 24V V_{IN} .

LTC3711 Adds VID Interface for 0.9V – 2.0V Microprocessor Core Supplies

Many low voltage microprocessors now require digital control of the output voltage and active voltage positioning to improve load transient response. The LTC3711 specifically addresses these needs. It uses the LTC1778 control architecture for handling the low duty cycles while adding a 5-bit VID interface. The VID code selects an output voltage in the range of 0.9V to 2.0V, compatible with Intel mobile Pentium[®] processors. The LTC1778 and LTC3711 both include a trimmed error amplifier

Pentium is a registered trademark of Intel Corp.



C_{IN}: UNITED CHEMICON THCR70E1H26ZT (847) 696-2000
 C_{OUT}: CORNELL DUBILIER ESRE271M02B (508) 996-8561
 L1: SUMIDA CEP125-IR0MC-H (847) 956-0667
 M1: INTERNATIONAL RECTIFIER IRF7811A (310) 332-3331
 D1: MICROSEMI UPS840 (617) 926-0404

Figure 8. 1.5V/15A CPU core voltage regulator with active voltage positioning

transconductance that is constant over temperature. This feature allows more aggressive compensation of the control loop for faster transient response as well as enabling accurate active voltage positioning. Active voltage positioning lowers the output voltage in a controlled manner as the load current increases. This is useful in microprocessor power supplies where large load current transients are the main cause of output voltage error.

An example of a VID controlled LTC3711 application with active voltage positioning is shown in Figure 8.

To facilitate the voltage positioning, the SENSE⁺ pin is used with a current sense resistor at the source of M2. The voltage positioning gain is accurately set using resistors R_{VP1} and R_{VP2} along with the trimmed transconductance of the error amplifier. This circuit positions the output voltage about 65mV above a 1.5V nominal output at no load, drooping to 65mV below the nominal output at full load. Voltage positioning allows the number of output capacitors to be reduced from five to three and still maintain a ±100mV specification on the output voltage.

Conclusion

The LTC1778/LTC3711 step-down DC/DC controllers are designed for power supplies operating over a wide input and output range. The valley current control architecture enables very low voltage outputs to be obtained from high input voltage sources such as battery packs and wall adapters. Eliminating the sense resistor improves efficiency and saves both board space and component cost. The LTC1778 and LTC3711 are excellent choices for delivering the low output voltages and high efficiencies required by modern portable power supplies. 



New UltraFast Comparators: Rail-to-Rail Inputs and 2.4V Operation Allow Use on Low Supplies

by Glen Brisebois

Introduction

The new LT1711 family of UltraFast comparators has fully differential rail-to-rail inputs and outputs and operates on supplies as low as 2.4V, allowing unfettered application on low voltages. The LT1711 (single) and LT1712 (dual) are specified at 4.5ns of propagation delay and 100MHz toggle frequency. The low power LT1713 (single) and LT1714 (dual) are specified at 7ns of propagation delay and 65MHz toggle frequency. All of these comparators are fully equipped to support multiple-supply applications, and have latch-enable pins and complementary outputs like the popular LT1016, LT1671 and LT1394. They are available in MSOP and SSOP packages, fully specified over commercial and industrial temperature ranges on 2.7V, 5V and $\pm 5V$ supplies.

Circuit Description

Figure 1 shows a simplified schematic of the LT1711 through LT1714. The front end consists of eight cur-

rent sources and sinks feeding the NPN and PNP differential pairs formed by Q3-Q4 (protected by fast diodes D11-D12) and Q1-Q2 (protected by D1-D2). This approach makes the inputs truly fully differential and noninteracting, unlike approaches that resort to resistors and diode clamps. Even with the inputs at opposite rails, the input bias currents are still a simple function of the input transistor base currents and remain in the μA region. Both input stages feed the level shifting transistors Q5-Q6, and the remainder of the differential voltage gain circuit flows with a delightful symmetry towards the output. Note that the channels are identical, with polarity yet unassigned, and are therefore interchangeable in layout. The symmetry, broken only by the latch-enable circuit, is enhanced by the fact that all of the transistors are well matched, complementary 6GHz f_T BJTs. Each output stage ends in two Baker-clamped common emitter transistors,

allowing full rail-to-rail output swing. All the comparators guarantee full 5V TTL output capability over temperature, even when supplied with only 3V. Output rise and fall times are fast, at 2ns for the LT1711 and LT1712 and 4ns for the LT1713 and LT1714. Jitter is among the lowest for any monolithic comparator, at 11ps_{RMS} for the LT1711 and LT1712 and 15ps_{RMS} for the LT1713 and LT1714.

Some Applications

Simultaneous Full-Duplex 75MBaud Interface with Only Two Wires

The circuit of Figure 2 shows a simple, fully bidirectional, differential 2-wire interface that gives good results to 75MBaud, using the low power LT1714. Eye diagrams under conditions of unidirectional and bidirectional communication are shown in Figures 3 and 4. Although not as pristine as the unidirectional

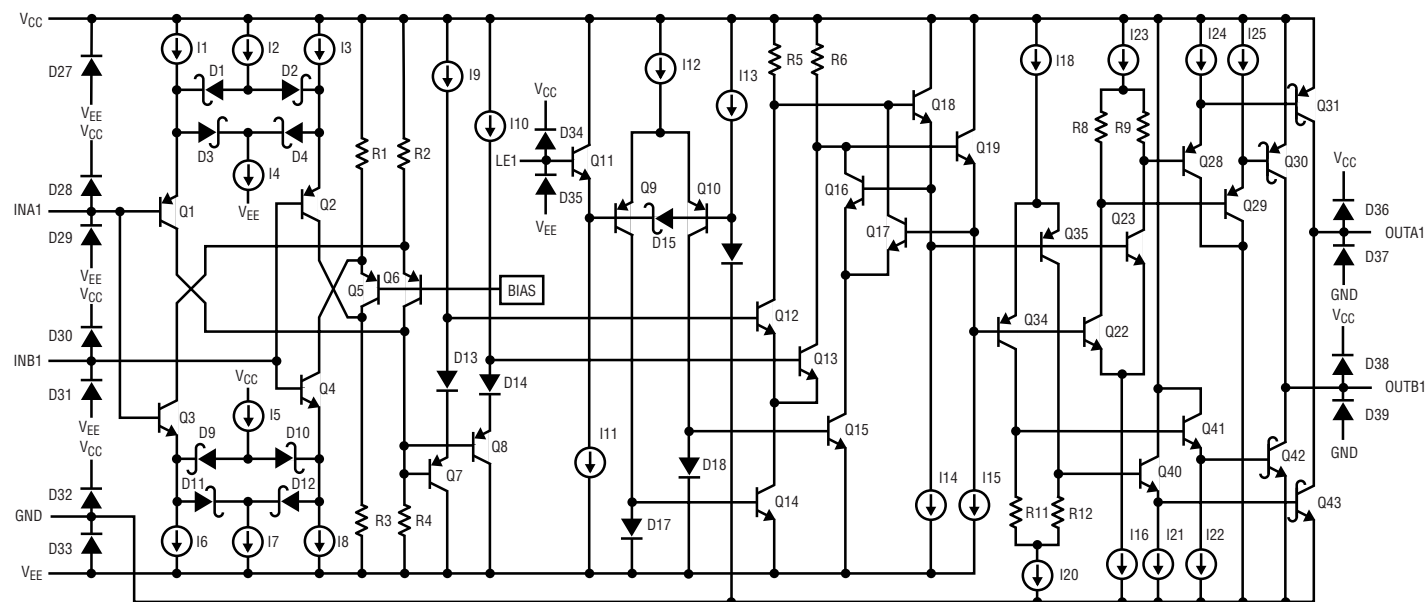


Figure 1. LT1711-LT1714 simplified schematic

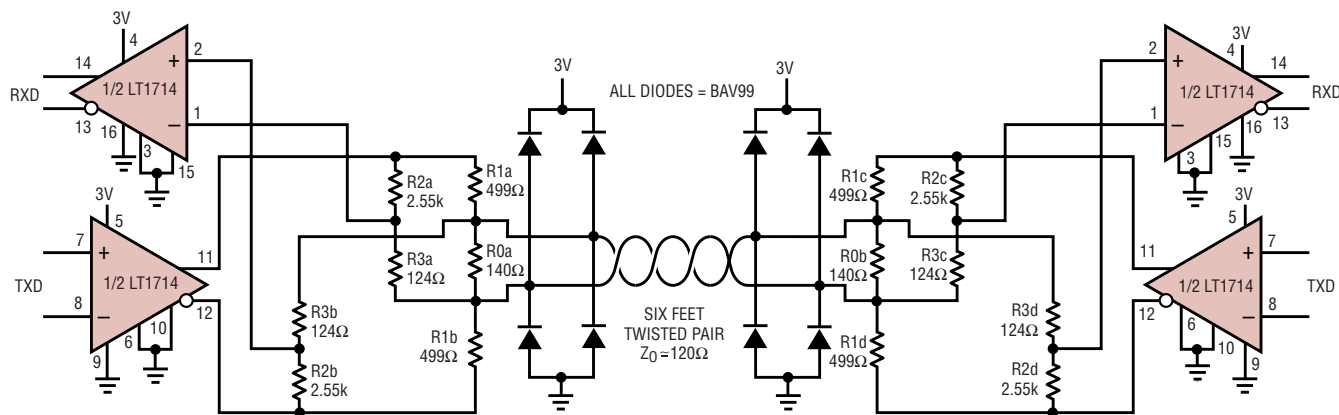


Figure 2. 75MBaud full-duplex interface on two wires

performance of Figure 3, the performance under simultaneous bidirectional operation is still excellent. Because the LT1714 input voltage range extends 100mV beyond both supply rails, the circuit works with a full $\pm 3V$ of ground potential difference.

The circuit works well with the resistor values shown, but other sets of values can be used. The starting point is the characteristic impedance, Z_0 , of the twisted-pair cable. The input impedance of the resistive network should match the characteristic impedance and is given by:

$$R_{IN} = \frac{2 \cdot R_0 \cdot (R_1 || (R_2 + R_3))}{(R_0 + 2 \cdot (R_1 || (R_2 + R_3)))}$$

This comes out to 120 Ω for the values shown. The Thevenin equivalent source voltage is given by:

$$V_{Th} = \frac{V_S \cdot (R_2 + R_3 - R_1)}{(R_2 + R_3 + R_1)} \cdot \frac{R_0}{(R_0 + 2 \cdot (R_1 || (R_2 + R_3)))}$$

This amounts to an attenuation factor of 0.0978 with the values shown. (The actual voltage on the lines will be cut in half again due to the 120 Ω Z_0 .) This attenuation factor is important because it is the key to deciding the ratio of the R2, R3 resistor divider in the receiver path. This divider allows the receiver to reject the large signal of the local transmitter and instead sense the attenuated signal of the remote transmitter. Note

that in the above equations, R2 and R3 are not yet fully determined because they only appear as a sum. This allows the designer to now place an additional constraint on their values. The R2, R3 divider ratio should be set to one-half of the attenuation factor mentioned above or $R_3/R_2 = 1/2 \cdot 0.0976$.¹

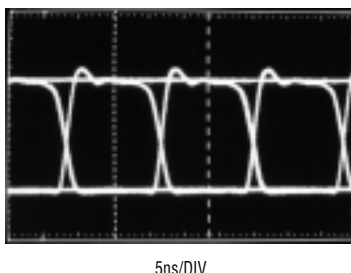


Figure 3. Performance of Figure 1's circuit operated unidirectionally; eye is wide open (cursors show bit interval of 13.3ns or 75MBaud).

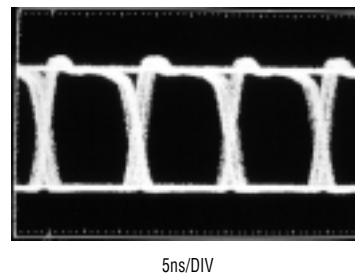


Figure 4. Performance of Figure 1's circuit operated simultaneous-bidirectionally; crosstalk appears as noise. Eye is slightly shut but performance is still excellent.

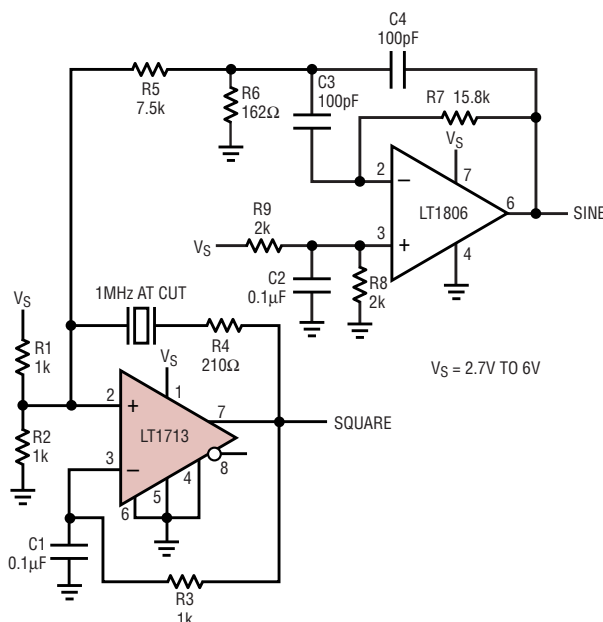


Figure 5. LT1713 comparator configured as a series-resonant crystal oscillator; the LT1806 op amp is configured as a bandpass filter with a Q of 5 and f_c of 1MHz.

1MHz Series-Resonant Crystal Oscillator with Square and Sinusoid Outputs

Figure 5 shows a classic 1MHz series-resonant crystal oscillator. At series resonance, the crystal is a low impedance and the positive feedback connection brings about oscillation at the series resonance frequency. The RC feedback to the $-$ input ensures that the circuit does not find a stable DC operating point and refuse to oscillate. The comparator output is a 1MHz square wave (top trace of Figure 6), with jitter measured at 28ps_{RMS} on a 5V supply and 40ps_{RMS} on a 3V supply. At pin 2 of the comparator, on the other side of the crystal, is a clean sine wave except for the presence of the small high frequency glitch (middle trace of Figure 6). This glitch is caused by the fast edge of the comparator output feeding back through crystal capacitance. Amplitude stability of the sine wave is maintained by the

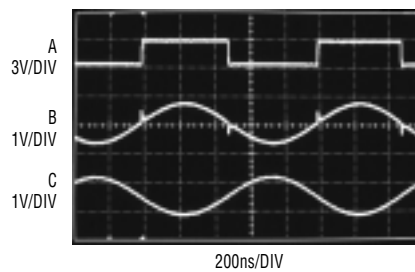


Figure 6. Oscillator waveforms with $V_S = 3\text{V}$:
Trace A = comparator output; Trace B = crystal feedback to pin 2 of the LT1713; Trace C = buffered, inverted and bandpass filtered output of LT1806

fact that the sine wave is basically a filtered version of the square wave. Hence, the usual amplitude-control loops associated with sinusoidal oscillators are not necessary.² The sine wave is filtered and buffered by the fast, low noise LT1806 op amp. To remove the glitch, the LT1806 is configured as a bandpass filter with a Q of 5 and unity gain center frequency of 1MHz. The final sinusoidal output

is the bottom trace of Figure 6. Distortion was measured at -70dBc and -55dBc on the second and third harmonics, respectively.

Conclusion

The fully differential rail-to-rail inputs of the new LT1711 family of fast comparators make them useful across a wide variety of applications. The high speed, low jitter performance of this family, coupled with their small package sizes and 2.4V operation, makes them attractive where PCB real estate is at a premium and bandwidth-to-power ratios must be optimized. 

¹ Using the design value of $R2 + R3 = 2.653\text{k}$ rather than the implementation value of $2.55\text{k} + 124\Omega = 2.674\text{k}$.

² Amplitude will be a linear function of comparator output swing, which is supply dependent and therefore adjustable. The important difference here is that any added amplitude stabilization or control loop will not be faced with the classical task of avoiding regions of nonoscillation vs clipping.

LT1618, continued from page 7

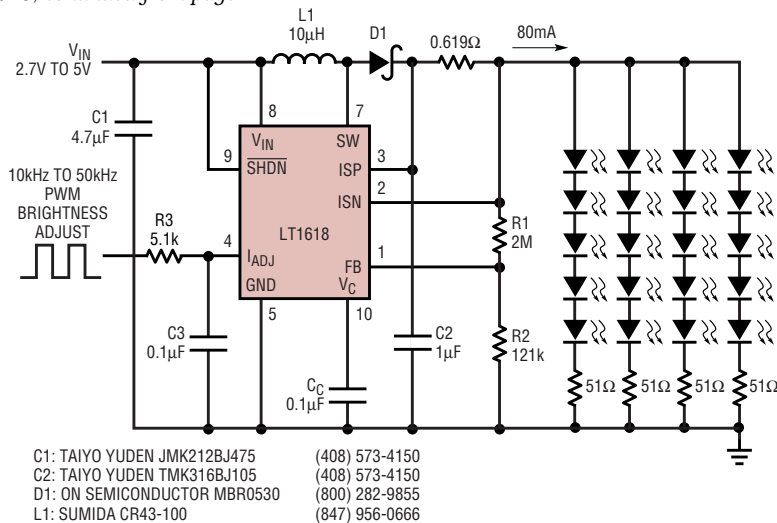


Figure 9. High power white LED driver

High Power White LED Driver

For larger LCD displays where a greater amount of light output is needed, multiple strings of LEDs can be driven in parallel. When driving parallel strings, ballast resistors should be added to compensate for LED forward voltage variations. The amount of ballasting needed depends on the LEDs used and how well they

are matched. The circuit in Figure 9 is ideal for larger displays, providing constant current drive for twenty white LEDs from a single Li-Ion cell. Efficiency reaches a respectable 82%, as seen in Figure 10.

Conclusion

The constant-current/constant-voltage operation of the LT1618 makes the device an ideal choice for a variety

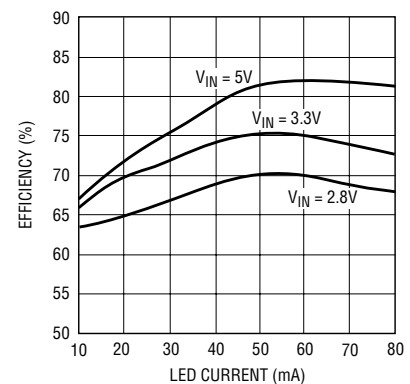


Figure 10. High power white LED driver efficiency

of constant-current designs. The device provides accurate output current regulation or input current limiting, along with excellent output voltage regulation. With a wide input voltage range and the ability to produce outputs up to 35V, the LT1618 works well in many different applications. 

References

1. Kim, Dave. "Tiny Regulators Drive White LED Backlights." Linear Technology Design Note 231 (May 2000).

High Efficiency Synchronous PWM Controller Boosts 1V to 3.3V or 5V

by San-Hwa Chee

Introduction

CPU power supplies continue to fall toward the 1V level, although other circuits still require the traditional 3.3V or 5V rails. Since the LTC1700 is capable of operating at an input voltage as low as 0.9V, it can boost the latest CPU power supply voltages to provide the missing 3.3V or 5V rail. The LTC1700 uses a constant frequency, current mode PWM architecture but does not require a current

sense resistor; instead, it senses the V_{DS} across the external N-channel MOSFET. This reduces component count and improves high load current efficiency. Efficiency is further increased at high load currents through the use of a synchronous P-channel MOSFET. With Burst Mode operation selected, efficiency at low load currents is enhanced, thereby providing high efficiency over the

entire load current range. The LTC1700 operates at 530kHz but can be externally synchronized to frequencies between 400kHz and 750kHz. During continuous mode operation, the LTC1700 consumes 540 μ A; it drops to 180 μ A in Sleep mode. In shutdown, the quiescent current is just 10 μ A. The LTC1700 is available in the 10-lead MSOP package.

3.3V to 4.2V Input, 5V/2A Output Regulator

Figure 1 shows a 10W output application circuit. Since the LTC1700 is operating at 530kHz, a small valued inductor is sufficient for this circuit. The input capacitors consist of a small 22 μ F ceramic capacitor in parallel with a B-case size tantalum capacitor. The ceramic capacitor provides a low overall ESR while the tantalum provides the bulk capacitance. In applications where the input is connected very close to a low impedance supply, the input tantalum capacitor may not be needed. A Sanyo POSCAP capacitor is used for the output capacitor because of its high ripple

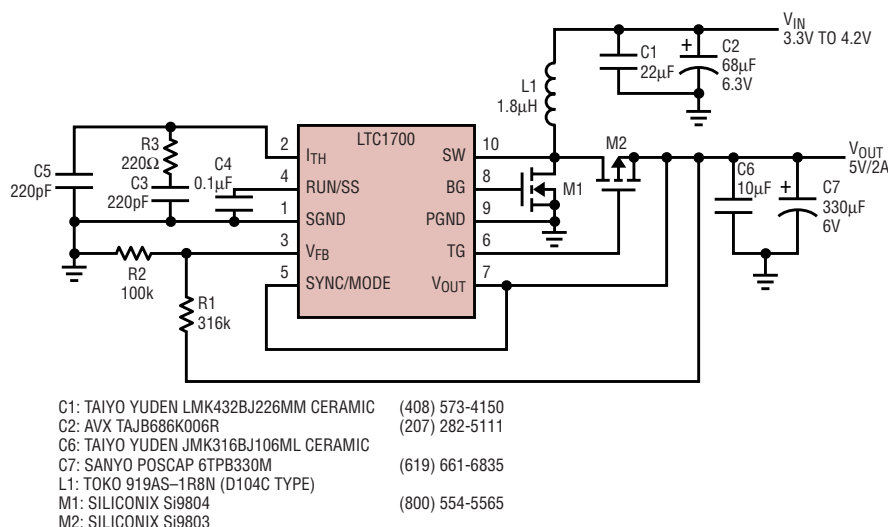


Figure 1. 3.3 to 4.2V input, 5V/2A output converter

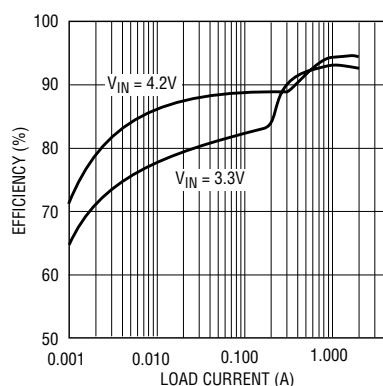


Figure 2. Efficiency of Figure 1's circuit

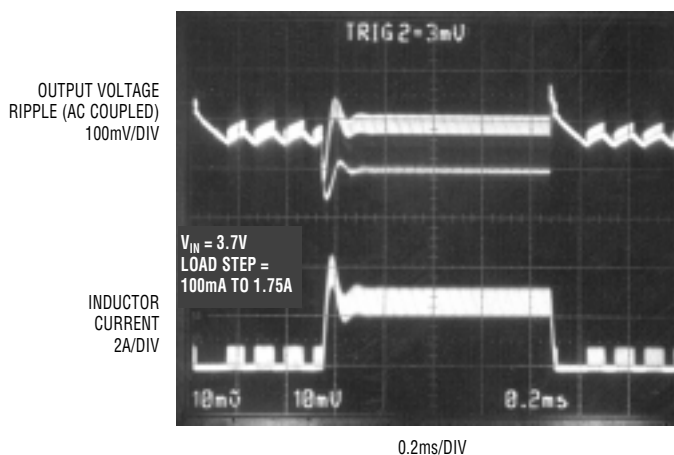


Figure 3. Load-step response of Figure 1's circuit

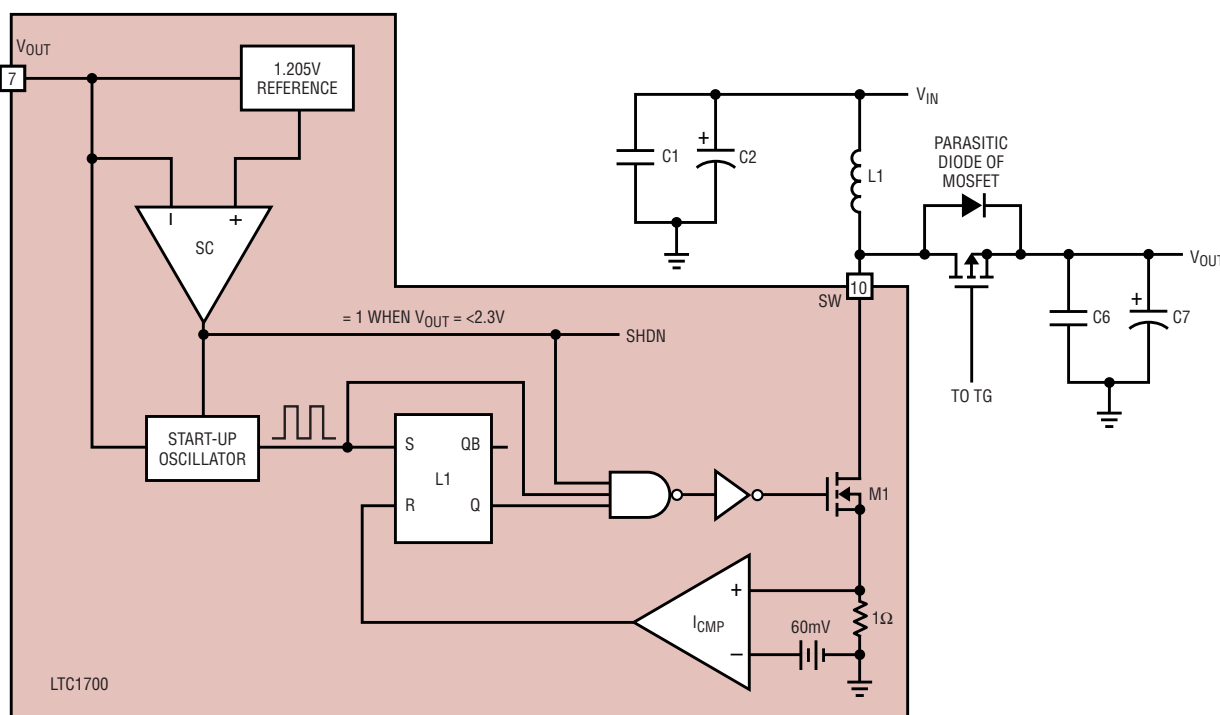


Figure 4. Start-up components of the LTC1700

Start-Up and MOSFET Selection

current rating. Once again, a ceramic capacitor is used in parallel with the POSCAP for reduced ESR and high frequency decoupling.

Figure 2 shows the efficiency curves for input voltages of 3.3V and 4.2V. Note that the maximum efficiency reaches 95% at a load current of 2A. A load step from 100mA to 1.75A was applied and its response is shown in Figure 3.

When the voltage at the V_{OUT} pin is below 2.3V, the LTC1700 operates in the start-up mode. In this mode, only the start-up circuitry in the LTC1700 is active and both of the external MOSFETs are turned off. Figure 4 shows the components that control start-up. In this mode, the current limit is set at 60mA and the internal MOSFET is used to bring the output voltage up. The start-up oscillator,

which is different from the main oscillator, runs at 210kHz at a duty cycle of 50%. Due to the low current limit, the output should not be heavily loaded during the start-up phase, as this will cause the output to "hang." Once the output rises above 2.3V, the rest of the internal circuitry of the LTC1700 comes alive and the external MOSFETs begin switching. The start-up circuitry will then be shut down.

In some applications, the input voltage is high enough that start-up mode is not needed, resulting in the

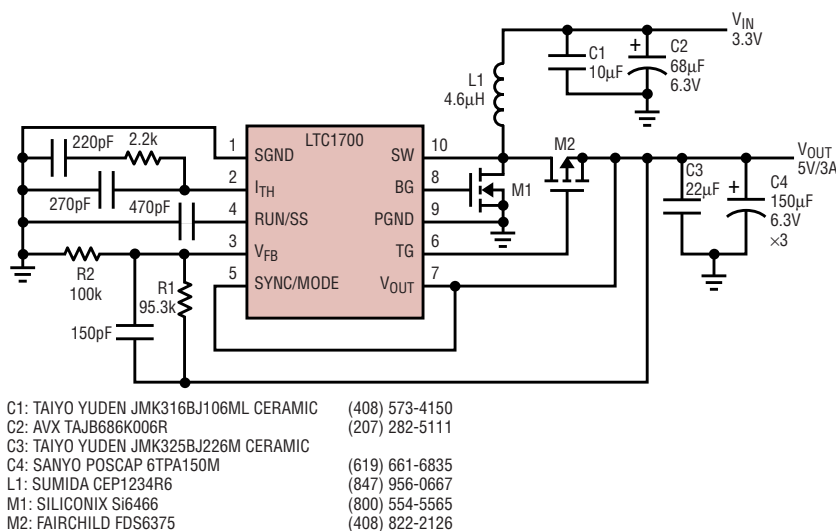


Figure 5. 3.3V input to 5V/3A output regulator

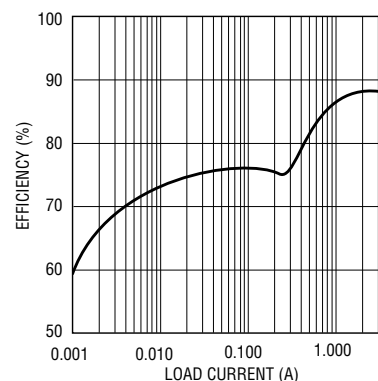


Figure 6. Efficiency of Figure 5's circuit

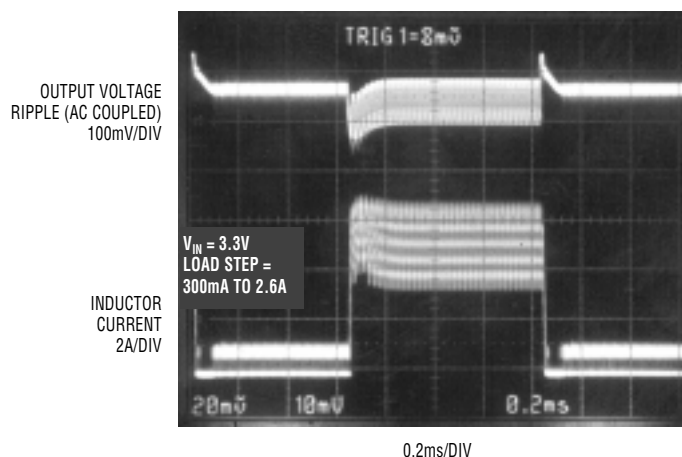


Figure 7. Load-step response of Figure 5's circuit

circuit being able to power up at full load current. Figure 1 shows an example of this. The required input voltage to power up with full load current is:

$$V_{IN} > 2.3 + V_F$$

where V_F is the forward voltage of the parasitic diode across the external P-channel MOSFET, which is dependent on the load current. For a load current less than 3A, a V_F of 0.75V can be used.

Since the switchover from the internal MOSFET to the external MOSFETs occurs at $V_{OUT} = 2.3V$, the MOSFETs selected should have a

threshold of 2.5V or lower. This will guarantee a smooth transition out of the start-up mode.

3.3V Input, 5V/3A Output Regulator

Figure 5 shows a 3.3V input to 5V output circuit that can provide a maximum of 3A output current. Like the circuit in Figure 1, this circuit will bypass the start-up mode and therefore is capable of starting up at full load. Figure 6 shows that its efficiency reaches 88% at load currents of 2A to 3A. Figure 7 shows the load step response.

3.3V Input, 5V/4A Output Regulator

The circuit shown in Figure 8 is capable of supplying 4A of load current. To obtain this output current capability, two IRF7811A N-channel MOSFETs are paralleled to obtain the required peak inductor current. Two Si9803DY are used for the synchronous P-channel MOSFET because of the amount of RMS current through these devices. The Si9803DYs are mounted on an area of copper adequate to effectively remove the maximum amount of heat. Due to the

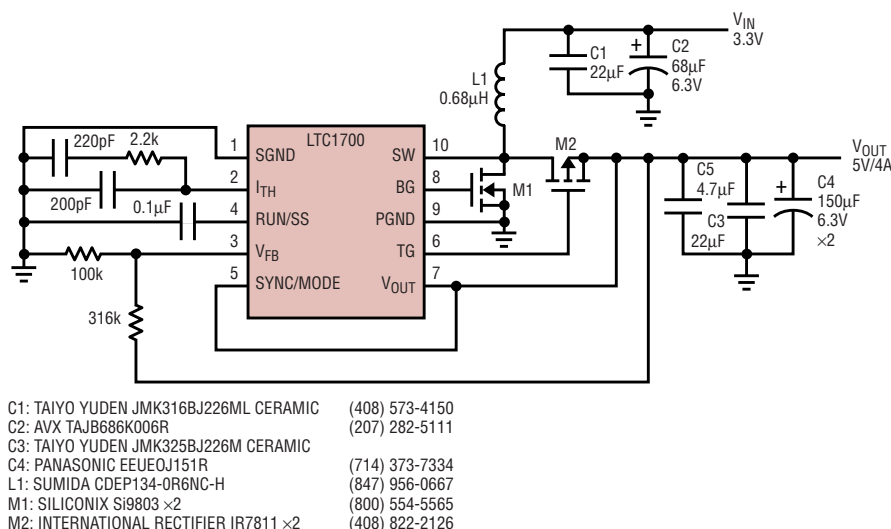
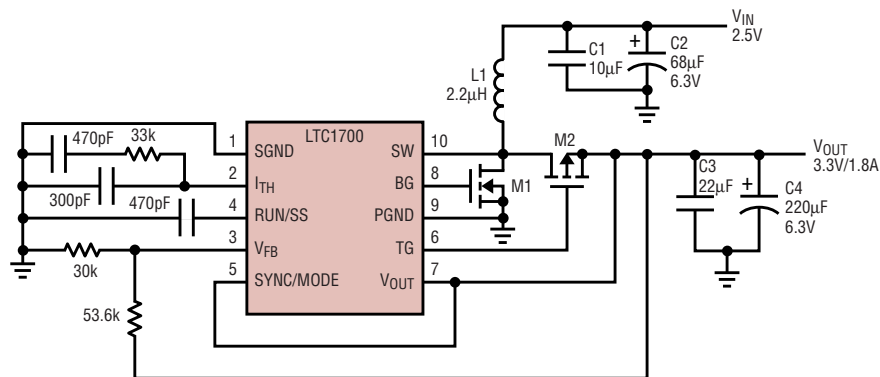


Figure 8. 3.3V input, 5V/4A output regulator



C1: TAIYO YUDEN JMK316BJ106ML CERAMIC (408) 573-4150
 C2: AVX TAJB686K006R (207) 282-5111
 C3: TAIYO YUDEN JMK325BJ226M CERAMIC
 C4: KEMET T520D227M00AS (408) 986-0424
 L1: MURATA LQN6C (814) 237-1431
 M1: SILICONIX Si9802 (800) 554-5565
 M2: SILICONIX Si9803

Figure 9. 2.5V input, 3.3V/1.8A output regulator

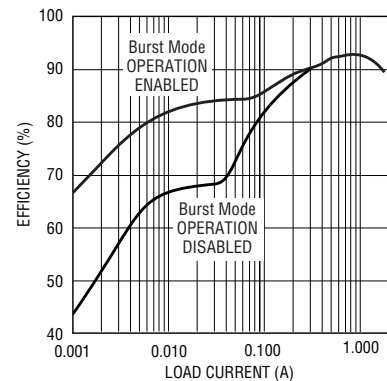


Figure 10. Efficiency of Figure 9's circuit

high RMS ripple current going into the output capacitors, two Panasonic SP capacitors are required. The maximum efficiency of 92% occurs at load currents between 2A to 3A. This circuit has no problem starting up into a load that exhibits a resistive characteristic.

2.5V Input, 3.3V/1.8A Output Regulator

Figure 9 shows a circuit that takes an input of 2.5V and steps it up to 3.3V. Both MOSFETs are selected with a guaranteed threshold voltage of 3V. Its efficiency and load step response are shown in Figures 10 and 11, respectively. Due to its low input voltage, this circuit cannot start up into a heavy load.

Conclusion

Through the use of V_{DS} sensing and a synchronous topology, the LTC1700 provides high efficiency at high load currents. Selectable Burst Mode operation allows high efficiency to be obtained at low load currents. With its low operating voltage, the LTC1700 can easily be used to step up low voltages to the traditional 3.3V or 5V supply rails. 

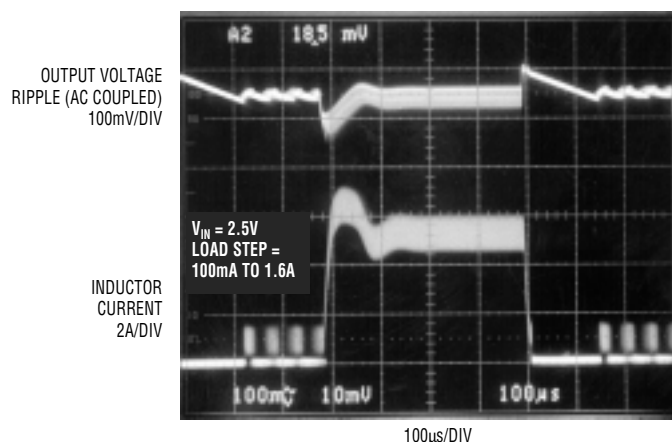


Figure 11. Load-step response of Figure 9's circuit

Rail-to-Rail 14-Bit Dual DAC in a Space Saving 16-Pin SSOP Package

by Hassan Malik

Linear Technology introduces the LTC1654, a 14-bit rail-to-rail voltage output dual DAC in a space saving 16-pin SSOP package. This part offers a convenient solution for applications where density, resolution and power are critical parameters. The LTC1654 is guaranteed to be 14-bit monotonic over temperature with a typical differential nonlinearity of only 0.3LSB. The supply voltage range is 2.7V to 5.5V.

The LTC1654 is software programmable for two different speed/power modes of operation: a FAST mode with 3.5 μ s settling time and 750 μ A supply current and a SLOW mode with 8 μ s settling time and 450 μ A supply current. Either of the two DACs can be independently set to the FAST or the SLOW mode of operation. The

output amplifiers swing to within 450mV of either supply rail when sourcing or sinking 5mA and are capable of driving over 300pF of load capacitance. The output noise voltage density at 1kHz is 540nV/ $\sqrt{\text{Hz}}$ in SLOW mode and 320nV/ $\sqrt{\text{Hz}}$ in FAST mode.

The LTC1654 has separate REFHI and REFLO pins for each DAC and two different gain modes. A gain of one is set by connecting the $X_1/X_{1/2}$ pin to REFLO and a gain of one-half is set by connecting this pin to V_{OUT} . The two different gain modes allow the user to set different output spans. The REFHI inputs have an operating range from ground to V_{CC} and the REFLO inputs have an operating range from ground to $V_{\text{CC}} - 1.5\text{V}$. A block diagram of the part is shown in Figure 1.

The LTC1654 allows each of the DACs to be individually shut down, in which state they consume less than 4 μ A/DAC. The REFHI input goes into a high impedance state when the DAC is in shutdown. The respective speed states are retained in shutdown as long as the supply voltage is maintained above the minimum value of 2.7V. When the supply voltage is first applied, both DACs are active and in SLOW mode, with all zeros loaded in the input shift register and DAC latches.

The LTC1654 has a double-buffered 3-wire serial interface consisting of clock, data and chip select pins. This interface is SPI/QSPI and

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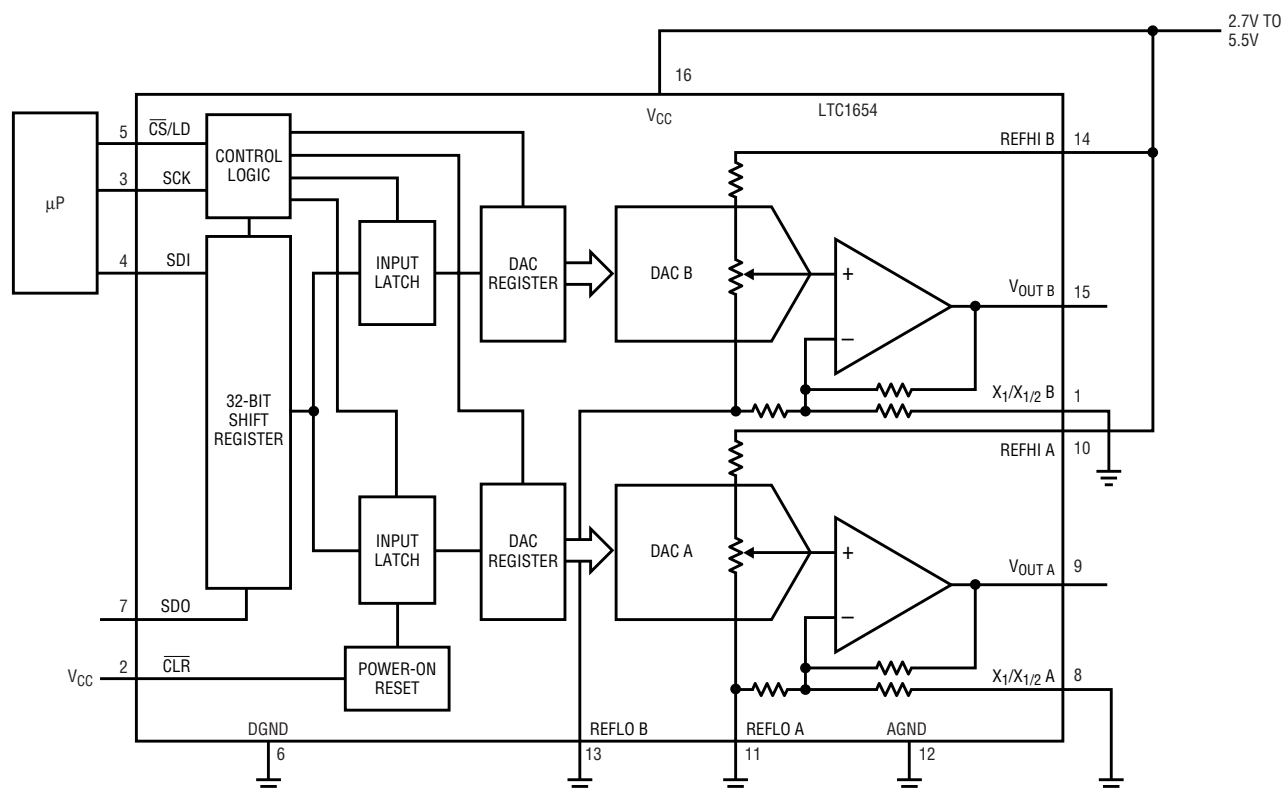


Figure 1. LTC1654 block diagram

Charge Pump Powers White LEDs

by Steven Martin

Introduction

Most of today's portable equipment uses a liquid crystal display to convey information to its user. Until recently, those displays have been monochrome and have used a low voltage light emitting diode (LED) such as red or green for backlighting. With the advent of color liquid crystal displays, a white backlight source is needed. Recently, a revolution in LED technology has lead to the long-coveted white LED. However, white LEDs, which are actually blue LEDs with a special phosphor in the lens, operate at a considerably higher voltage than red or green LEDs. White LEDs can require anywhere from 3.5V to 3.9V to operate at 15mA. In battery powered systems, it's impractical to drive the LEDs directly from the battery and still control the LED current. To properly control the LED current a somewhat larger voltage is needed, where the excess is used for control.



Figure 1. LTC3200 evaluation circuit

Figure 1 shows the LTC3200-5 constant frequency voltage doubler used to drive five white LEDs. Figure 2 is the schematic diagram of this circuit. The LTC3200-5 produces a regulated 5V output from an input as low as 3V. Switching at 2MHz, the constant frequency operation of the charge pump is ideal for low noise environments such as cellular telephones or internet communication devices.

Since it produces a regulated 5V output, the additional voltage dropped across the resistors controls the LED current. The resistors also provide ballasting to ensure that the LEDs

run at similar currents despite moderate differences in forward voltage.

Figure 3 shows how the adjustable LTC3200 can be used to control the LED current directly by controlling the voltage on the ballast resistors. The LTC3200 regulates the anodes of the LEDs until the FB pin comes to balance at 1.268V. The feedback LED's current is precisely controlled and the remaining LEDs are moderately well controlled by virtue of their similarity and the 1.268V ballast voltage. Since the current is more precisely controlled, up to six LEDs can be powered by the adjustable LTC3200.

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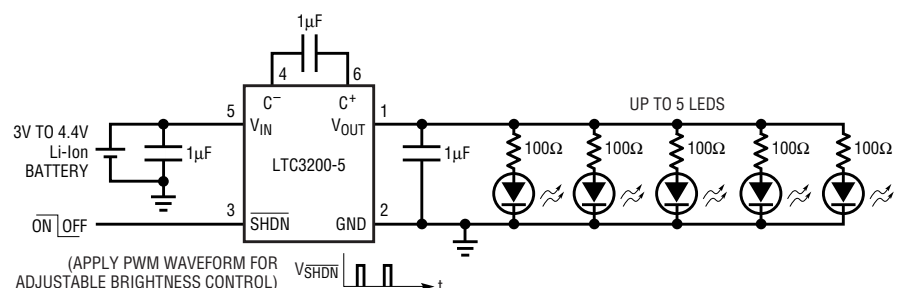


Figure 2. Li-Ion battery-powered 5V white or blue LED driver

48V Hot Swap Circuit Blocks Reverse Battery Voltage

by Mitchell Lee

Hot Swap controllers guard against inrush current and short circuits, but reverse battery installation is another matter. In central office applications, OR-ing diodes block reversed input voltages. In systems with a single power source OR-ing diodes become unnecessary; although a single diode could be retained for reverse conditions, its forward drop loss is a significant penalty.

The circuit shown in Figure 1 eliminates the loss associated with a blocking diode. The LT1641 and Q1 handle familiar hot swap chores of undervoltage lockout, inrush control, short circuit protection and system reset, while Q2 and Q3 handle reverse input situations.

Under positive input conditions, Q2's body diode is forward biased and power reaches the LT1641 and Q1, allowing them to function in the normal manner. When the LT1641 is

commanded to turn on, GATE (pin 6) and R7 slowly charge C1, thereby limiting the inrush current to C_{LOAD} . The LT1641 drives both Q1 and Q2 fully into enhancement mode, minimizing losses and eliminating the drop in Q2's body diode.

Q3 is included as part of the circuitry that blocks reverse inputs, yet it must "get out of the way" when positive inputs are present. With a positive input, Q3's emitter is pulled up, dragging along its base via D2. Since the base is slightly negative with respect to the emitter, Q3 is off. A small current flows through resistor R9 to ground, but this is of no consequence. If the LT1641 is in the off state, GATE pulls low. Current flows from the forward-biased collector-base junction of Q3 to the LT1641's GATE pin, but is limited by R7. When the LT1641 turns on, GATE pulls up above the input supply and

the collector-base junction of Q3 becomes reverse-biased. Q3 is off, so no collector current flows and the LT1641's GATE output is not loaded by Q3.

If a reverse input polarity is applied, Q3 goes to work and ensures that Q2 is held off. Negative inputs pull the emitter of Q3 below ground. Q3 turns on, biased by R9, and the collector effectively shorts Q2's gate and source. With Q2 in the off state, no current can flow into R_S , the LT1641 or Q1. The circuit can take up to -100V in this condition. Of course, some leakage current does flow in Q2; this is absorbed by D3.

This circuit can handle instantaneous steps from zero to $\pm 75V$. As shown, short circuit protection limits the output to 2.5A. Q1, Q2, and R_S can be scaled to handle loads in excess of 1kW. 

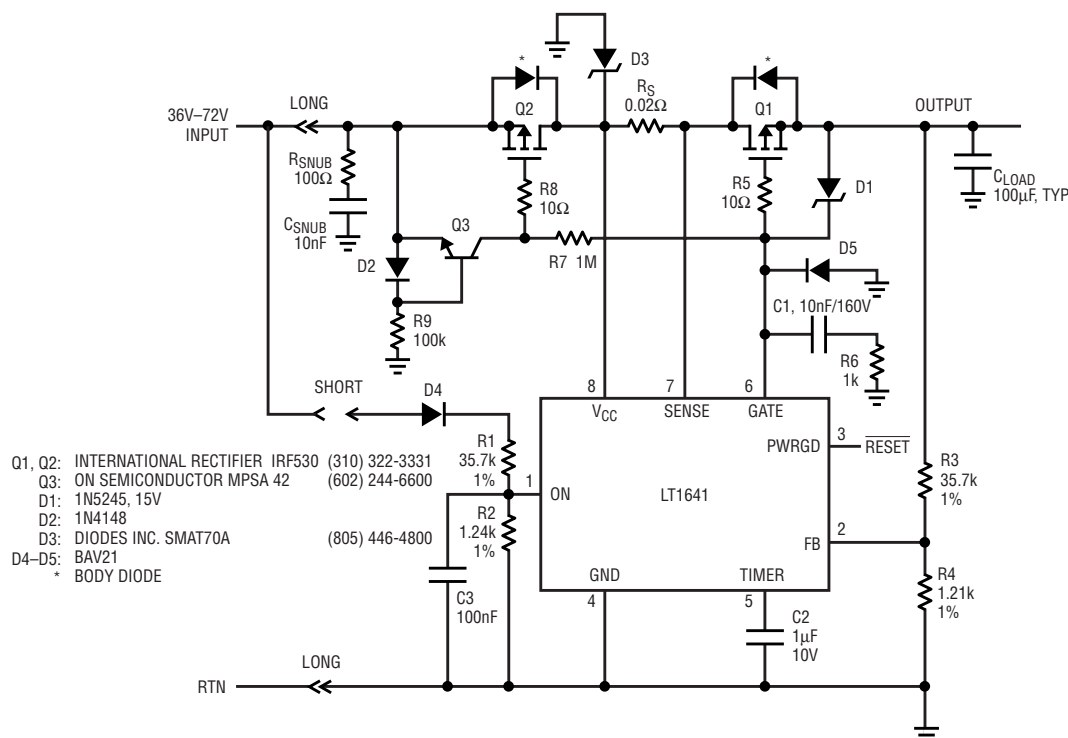


Figure 1. Reverse-battery protected LT1641 48V Hot Swap circuit

Using the LTC1662 3 μ A DAC to Cure RF Implementation Ills

by Derek Redmayne

Introduction

The small form factor and almost nonexistent power consumption of the LTC1662 dual 10-bit DAC make it attractive as a “tweak” to a design that has already gone through initial qualifications and requires some additional improvements. The small size may allow the system designer to add it to a design without altering those areas that have already passed UL or FCC certification. In other words, the part is so small that it can be added to a design without ripping up and rerouting the entire circuit.

The power consumption of the LTC1662 is so low that even very restricted power budgets in isolated or solar powered applications remain intact, or even unchanged. The examples shown demonstrate only a few of many possible uses.

Minimizing Carrier Feedthrough in IQ Modulation

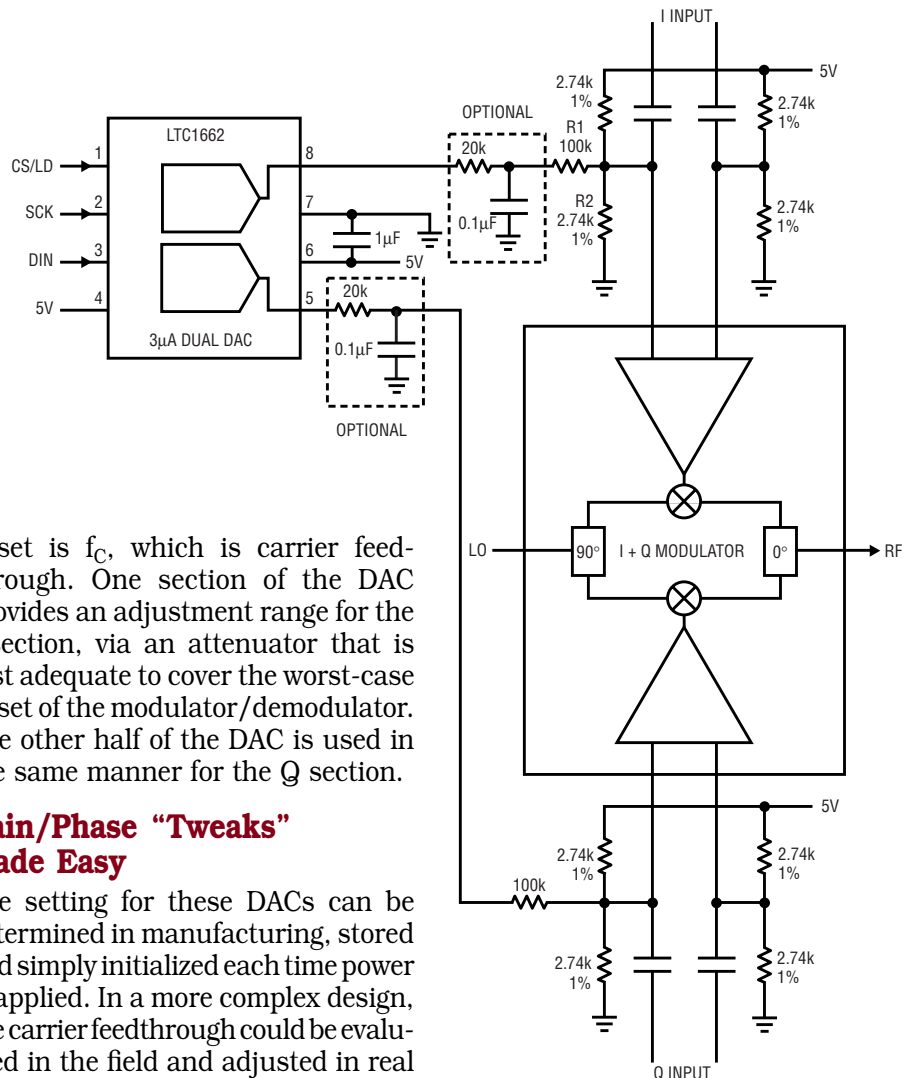
In Figure 1, the DAC adjusts bias voltage in an I and Q modulator to minimize carrier feedthrough. The output of the modulator is ideally one frequency only, the sum of the carrier and the modulation. This frequency is the upper sideband, where the carrier and lower sideband are suppressed. The two channels of the DAC allow I and Q to be adjusted independently. In addition to being suitable for sealed, encapsulated, immersed or otherwise physically inaccessible locations, the LTC1662 does not have the shock and vibration sensitivity of potentiometers and is less expensive than a good potentiometer.

If the I and Q components are added (the Q being a 90-degree-shifted version of both the carrier and the modulation), the lower sideband is suppressed and a single sideband (SSB) results. A single sideband is used in many RF applications, as it

allows all the transmitted energy to be contained within the one sideband. Without the carrier present, at low modulation depths, minimal energy is required. Single sideband also occupies less spectrum for a given bandwidth. This technique can also be used to synthesize frequencies.

The balanced modulator/demodulator will produce carrier feedthrough if a DC offset is present at the modulation terminal. The sum and difference of the carrier and the DC

In Figure 2a, the DAC adjusts gain and phase by use of a varactor diode. Because it is not a multiplying DAC, it is not readily adaptable for direct DC or low frequency gain control, at least not high precision gain control over wide dynamic ranges. It can, however, be used to subtly adjust gain in cases where an excitation current needs to be adjusted; in the case of high frequencies, it can be used in conjunction with varactor diodes, PIN diodes or modulator/



offset is f_c , which is carrier feedthrough. One section of the DAC provides an adjustment range for the I section, via an attenuator that is just adequate to cover the worst-case offset of the modulator/demodulator. The other half of the DAC is used in the same manner for the Q section.

Gain/Phase “Tweaks” Made Easy

The setting for these DACs can be determined in manufacturing, stored and simply initialized each time power is applied. In a more complex design, the carrier feedthrough could be evaluated in the field and adjusted in real time or as temperature changes.

Figure 1. Using the LTC1662 to trim for minimum carrier feedthrough

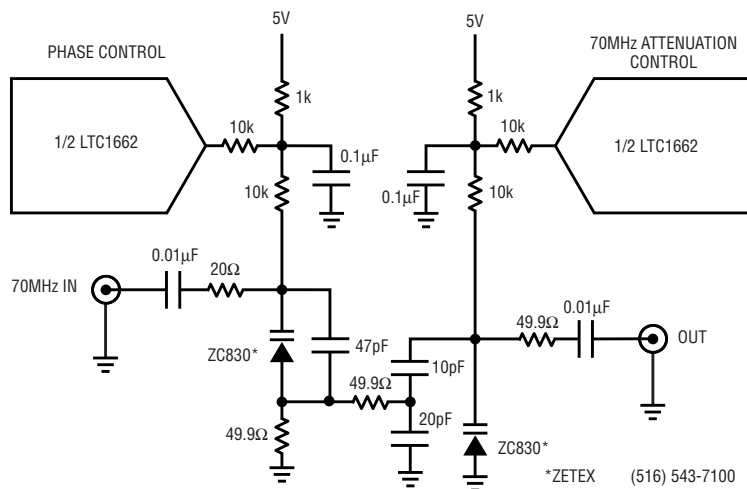


Figure 2a. 70MHz attenuation control

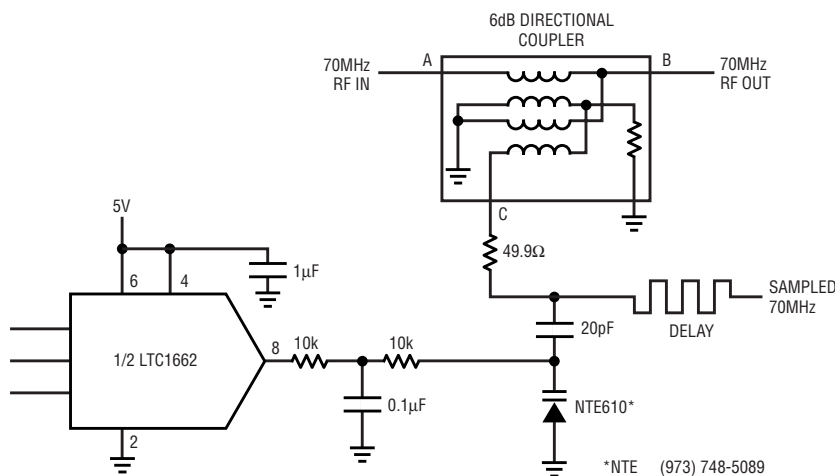


Figure 2b. Using a varactor to tweak delay through a directional coupler

physical implementation, this circuit produces nominally zero degrees of phase shift at 70MHz and nominal insertion loss of 12dB.

Figures 2b–2d show a few additional examples of how a micropower DAC can be used to produce subtle changes in gain or phase in RF circuitry. This type of tweak is often required in RF circuitry; if it is required at inaccessible points in a device or when installed in inaccessible locations, the ability to implement these tweaks remotely, with no space or power penalty, is valuable.

The circuit in Figure 2b shows how one may adjust the phase of a signal from the isolated port of a 6dB directional coupler over a range of approximately 2.5 degrees at 70MHz. This is of the order that may be required to compensate for phase variation in the coupler or delay variation in transmission lines. The photos taken from a network analyzer (Figures 3a and 3b) show the maximum phase adjustment range vs frequency, as well as the variation in the attenuation factor over the range of phase adjustment.

The examples shown in Figures 2c and 2d show examples of varactors used to reduce even-order harmonic distortion by using cancellation in two diodes. Figure 2d produces greater delay than Figure 2c and the circuit may be extended to produce yet more delay. In all of these circuits, the performance is very much dependent on physical implementation.

demodulators to adjust IF or RF gain. It can also be used to tweak VCOs, phase-locked loops, biasing schemes for power devices, avalanche photodiodes or optical tuning or modulating devices that rely on electrostatic fields.

The circuit in Figure 2a produces a range of phase adjustment of approximately 2 degrees and a range of amplitude adjustment of 3.5dB at 70MHz. The two adjustments are somewhat interactive. Depending on

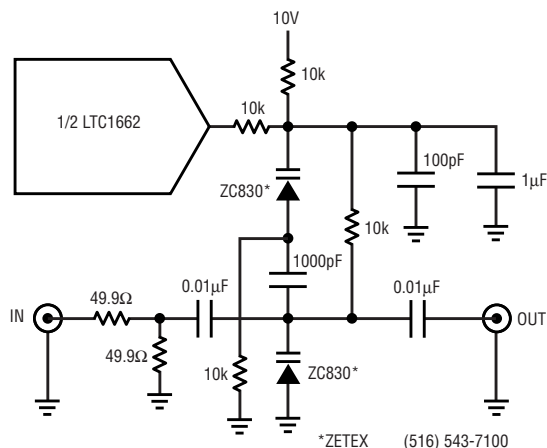


Figure 2c. Low distortion phase control

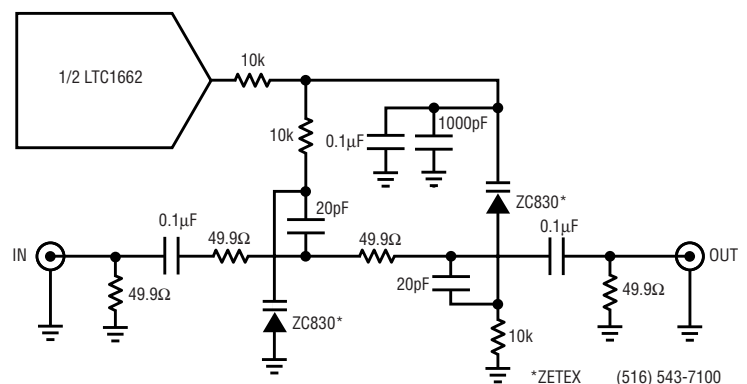


Figure 2d. Greater phase control

In all cases, the adjustment range of trimmer circuits should be minimized, either by adjustment of the DAC output signal or by padding the varactor with series and parallel capacitance.

This will reduce the phase noise contribution from the DAC and offset

variation effects, as well as to minimize the harmonic distortion introduced by the varactor. The wideband noise of the LTC1662, as with any micropower DAC, is a potential pitfall in these applications, as it may degrade phase noise performance; however, the

LTC1662 has the virtue of very low 1/f noise. Bandwidth limiting the output to less than 1Hz will produce the benefit of low noise. If your application is not sensitive to low frequency phase noise, the output filters may not be necessary. 

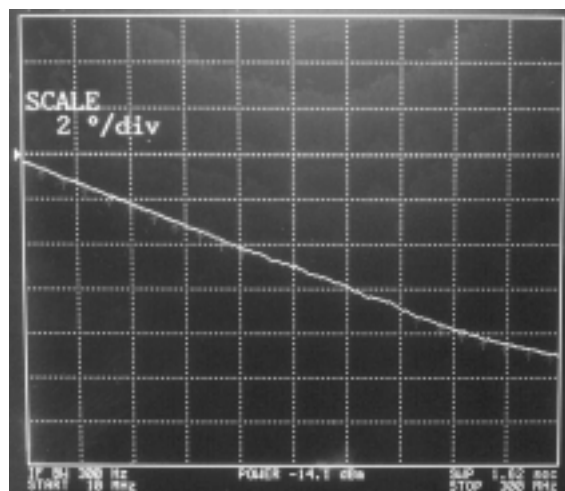


Figure 3a. Range of phase shift vs frequency for Figure 2b's circuit

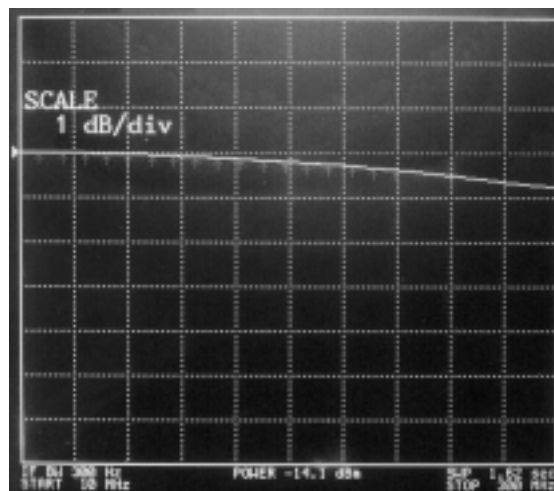


Figure 3b. Maximum gain variation vs frequency for Figure 2b's circuit

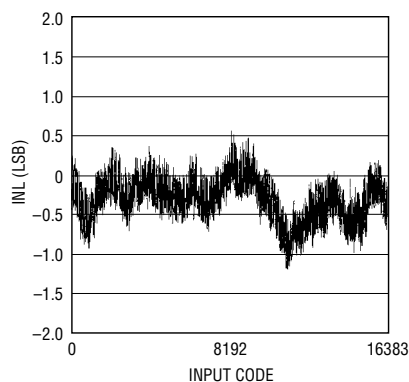


Figure 2. LTC1654 typical integral nonlinearity (INL)

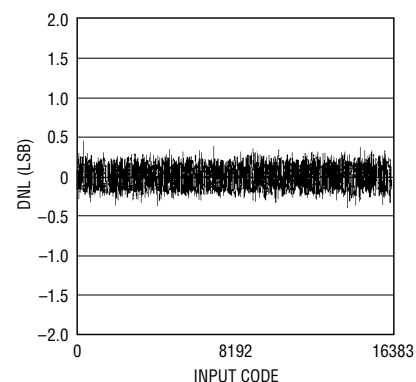


Figure 3. LTC1654 typical differential nonlinearity (DNL)

LTC1654, continued from page 28

MICROWIRE™ compatible. The maximum clock rate is 33MHz. Double buffering allows individual load and update capability for each DAC. There are three different methods for loading data into the serial interface: a 24-bit word without daisy chaining, a 32-bit word without daisy chaining and a 32-bit word with daisy chaining. The 24-bit word loading method requires eight bits for control and address followed by sixteen bits of data. The last two LSBs in the 16-bit

data segment are "don't cares." The 32-bit word loading method without daisy chaining requires eight "don't cares" followed by eight bits for control and address and sixteen bits of data. The 32-bit word loading method with daisy chaining is the same as above except that the D_{OUT} pin is used.

When the REFHI pins are connected to V_{CC} and the LTC1654 is configured for a gain of one, the voltage outputs swing from ground to V_{CC}. The typical differential and integral nonlinearities are shown in Figures 2 and 3, respectively. V_{OUT} is as follows for the two different gain configurations:

Gain of one (X₁ / X_{1/2} pin connected to REFLO):

$$V_{OUT} = (V_{REFHI} - V_{REFLO}) \cdot (SDI/16384) + V_{REFLO}$$

where SDI is the decimal representation of the digital data input.

Gain of one-half (X₁ / X_{1/2} pin connected to V_{OUT}):

$$V_{OUT} = (1/2)(V_{REFHI} - V_{REFLO}) \cdot (SDI/16384) + V_{REFLO}$$

In any rail-to-rail DAC, the output swing is limited to voltages within the supply range. If the DAC offset is negative, the output for the lowest codes limits at 0V. Similarly, limiting can occur near full-scale when the REFHI pin is tied to V_{CC}. This can be avoided by ensuring that V_{REFHI} is less than V_{CC} by at least 15mV or by using the gain of one-half configuration. 

LTC1628-SYNC Minimizes Input Capacitors in a Multioutput, High Current Power Supply

by Wei Chen

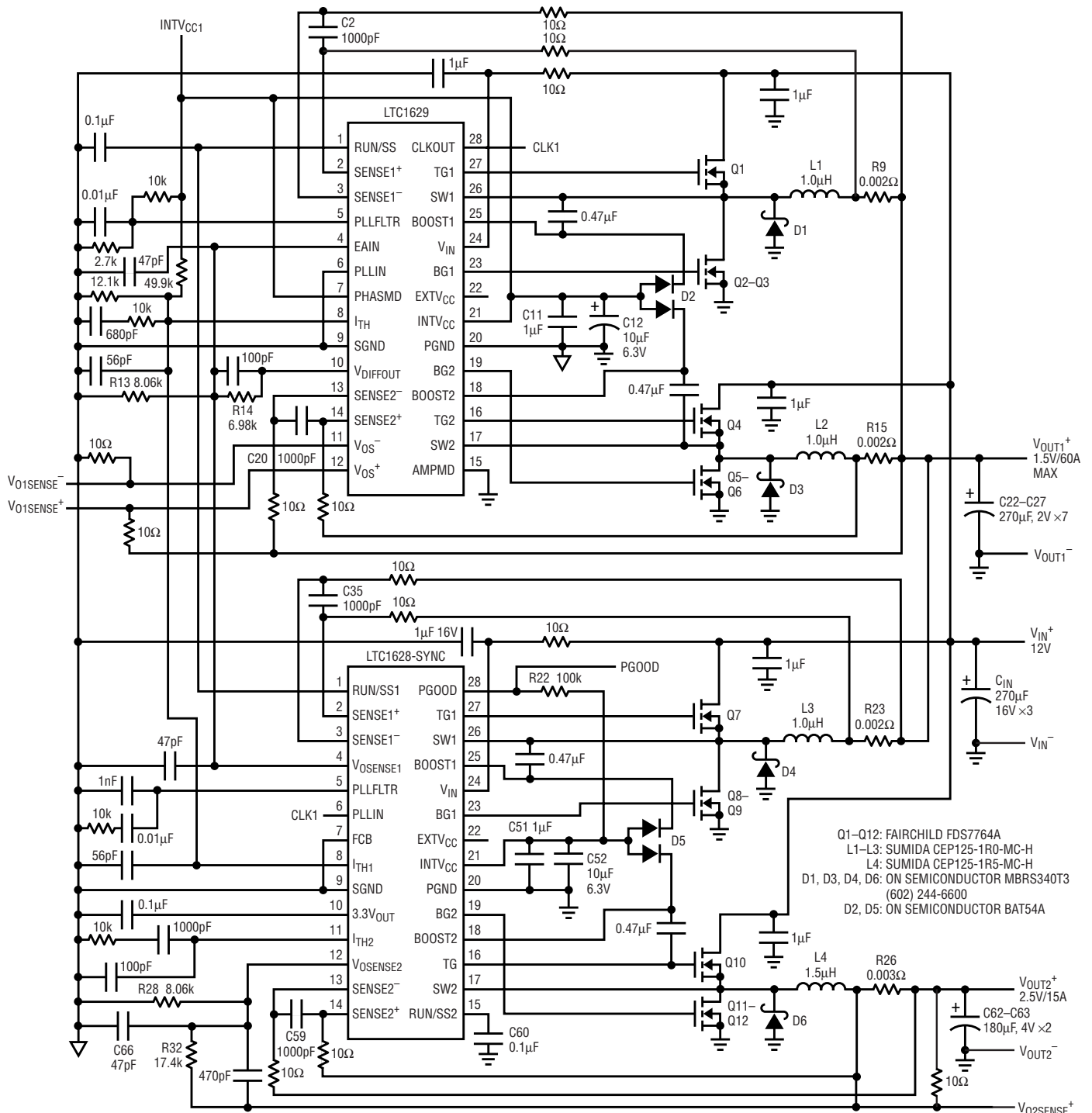


Figure 1. LTC1628-Sync/LTC1629 2-output PolyPhase supply

Table 1. Comparison of input ripple current and input capacitors for single-phase and PolyPhase configurations

Phases	Worst-Case Input Ripple Current (A_{RMS})	Number of Input Caps (OSCON 16SP270M) at 65° C)
Single-Phase	23.4	7
PolyPhase (LTC1629 + LTC1628-SYNC)	10.2	3

Introduction

In broadband networking and high speed computing applications, multiple output, high current, low voltage power supplies are needed to power FPGAs, flash memories, DSPs and microprocessors. One such example calls for a maximum current of 60A to power the CPU and up to 15A to power the memory. A custom DC/DC module is usually expensive and the external circuitry for synchronization further increases the cost of individual supplies.

This design idea presents a low cost, high efficiency, dual-output power supply design using LTC's latest PolyPhase products, the LTC1628-

SYNC and LTC1629. The input is 12V and the outputs are 1.5V at 60A max for the CPU and 2.5V at 15A max for the memory. The design uses the LTC1629 and one channel of the LTC1628-SYNC to configure the 3-phase supply for the CPU power and the remaining channel of LTC1628-SYNC for the memory supply. With only twelve SO-8 MOSFETs and two SSOP-28 controllers, the complete power supply occupies a footprint of only 3" x 3". Efficiencies of 85% and 89% are achieved for outputs of 1.6V/60A and 2.5V/15A, respectively.

Design Details

The newly released LTC1628-SYNC is a dual-output, PolyPhase, current mode controller. Unlike other versions of the LTC1628, it has a PLLIN pin that enables external synchronization. In conjunction with the LTC1629, it can be used to implement a true 3-phase circuit for CPU power while the second output of the LTC1628-SYNC is used to generate the memory power supply. Because the channel used for the memory power switches at 300 degrees with respect to the other three channels used for CPU power, the net ripple

current seen by the input bus is further reduced. In addition, the differential amp within the LTC1629 enables true remote sensing to ensure accurate voltage regulation at the CPU supply pins.

Table 1 compares the input ripple current requirements of the multiphase design and a conventional single-phase design. The multiphase technique reduces input capacitance by almost 60%.

The complete schematic diagram and efficiency measurements are shown in Figures 1 and 2, respectively. With a 12V input and 250kHz switching frequency, greater than 80% efficiency is maintained for both outputs over most of the load range.

Other Applications

For applications with more than two outputs, several LTC1628-SYNCS can be teamed with the LTC1629 for greater than 2-phase operation. Figure 3 shows an example using the LTC1629 and LTC1628-SYNC in a 3-output, 4-phase application. Because four synchronous buck circuits are interleaved 90 degree out of phase, the net input ripple current is greatly reduced.

Conclusion

The synchronization capability of the LTC1628-SYNC helps minimize input capacitance and avoid beat frequencies. Teamed with LTC1629, it can effectively provide a 3-phase solution for multiple output applications and minimize the size and cost of the complete power supply. 

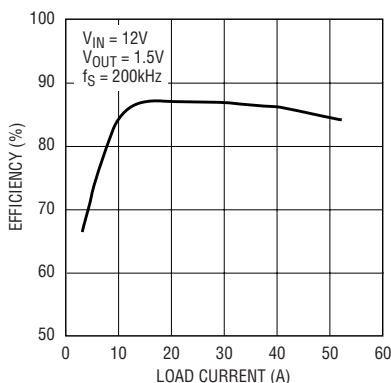


Figure 2. Efficiency vs load current for Figure 1's circuit

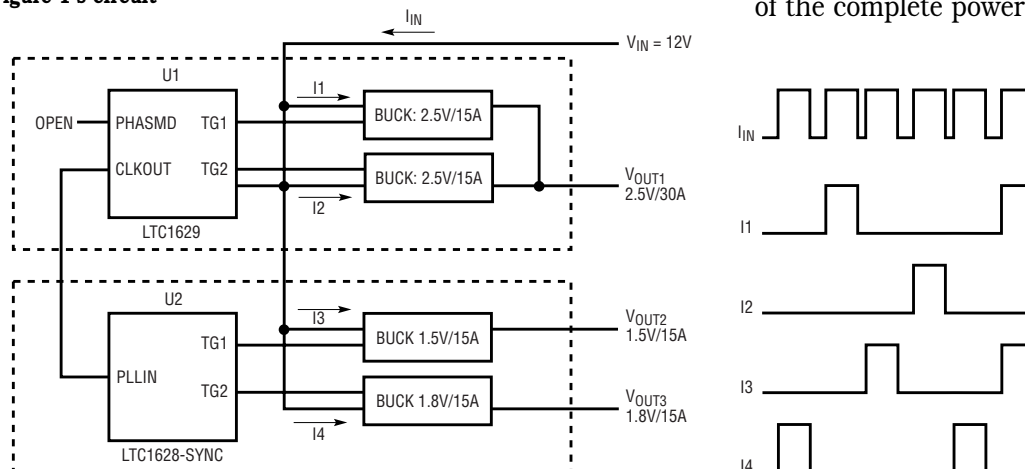


Figure 3. Block diagram of LTC1628-Sync/LTC1629 3-input, 4-phase application

Reduce EMI with Ultralow Noise 48V to 5V, 10W DC/DC Converter

by Rick Brewster

Introduction

Increasingly, designers are using ultralow noise controllers to avoid EMI problems. Lower operating voltages and more sensitive measurements have created the need for quieter supplies. Extra filtering components and shielding are usually required, as is a careful board layout. Ultralow noise switching regulator controllers such as the LT1683 reduce or eliminate the need for extra filtering. The LT1683 controller uses external MOSFETs to create ultralow noise DC/DC converters. Control of the switch voltage and switch current slew rates reduces switcher noise. The LT1683's use of external switches allows for greater flexibility in the selection of voltage and current ratings of the supply.

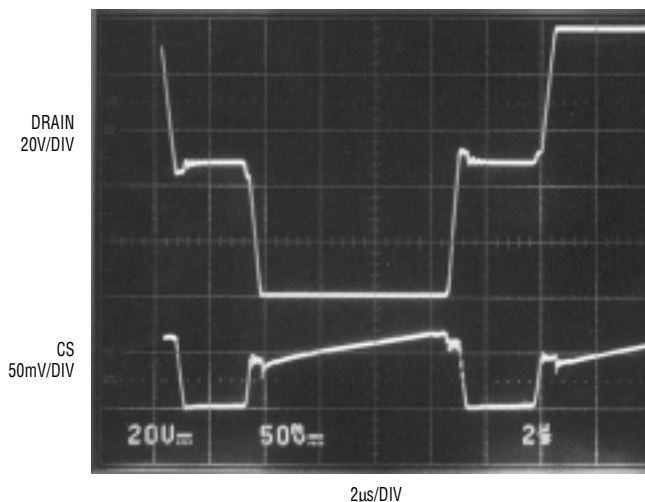


Figure 2. Voltage on one of the MOSFET drains and on the sense resistor

Circuit Details

Figure 1 shows the schematic of an ultralow noise 48V to 5V converter using a push-pull forward converter topology. The output broadband noise is a very low 200µV (bandwidth =

100MHz) at 2A output (10W). The LT1683 contains all the control circuitry for the converter: oscillator, error amp, gate drivers and protection circuitry. The low noise is achieved by controlling the voltage slew rate of the MOSFET drain and the current slew rate of the MOSFET current. The capacitor divider network from the drain to Cap A or Cap B yields an effective 0.33pF capacitor that provides the voltage slew rate feedback information. The current slew feedback occurs internal to the LT1683 by means of the 100mΩ sense resistor.

The resistors on the R_{VSL} and R_{CSL} pins allow the user to optimize the slew rates. The trade-off is between noise and converter efficiency. During design, monitor the output supply noise while slowing down the slew rates via the slew control resistors. Adjust the slew rate until the noise requirement is satisfied. In general, the efficiency loss is only a few percent.

Figure 2 shows the voltage on the drain of one of the MOSFETs and the voltage across the sense resistor.

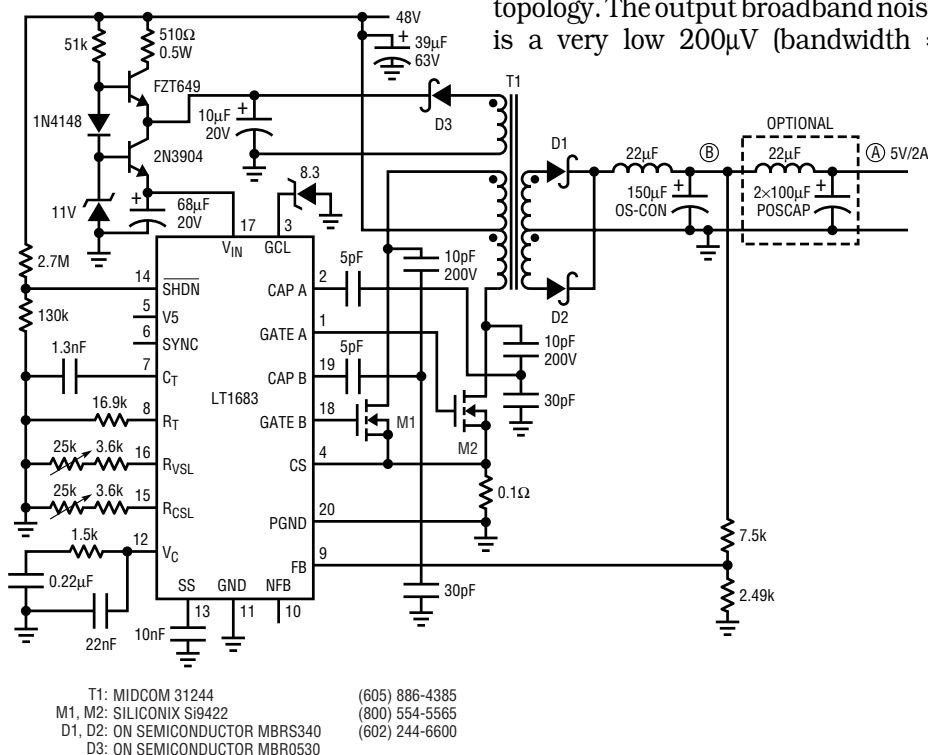


Figure 1. Ultralow noise 48V to 5V DC/DC converter

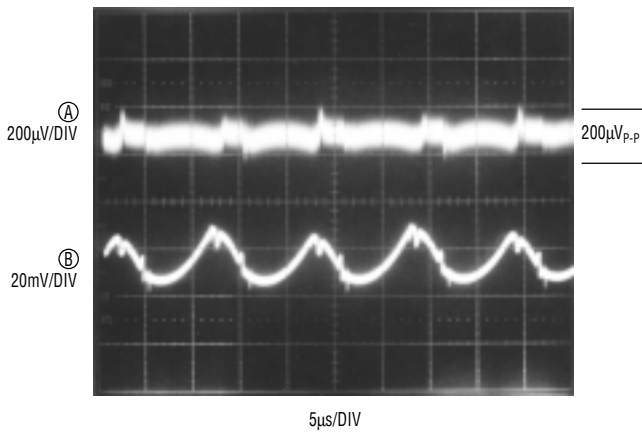


Figure 3. 5V output noise (bandwidth = 100MHz)

Because of the voltage slew control, clamps or snubbers on the MOSFET drains are not required and switch ringing is greatly reduced. Figure 3 shows the noise at the outputs. The output noise is a very low $200\mu\text{V}_{\text{P-P}}$.

The $\overline{\text{SHDN}}$ pin provides the supply

with undervoltage lockout, ensuring that the input is up and running before the converter is allowed to start. In addition, the GCL pin prevents excessive gate voltage on the MOSFET and protects against the MOSFETs turning on without sufficient gate

voltage. The CS pin provides the feedback for pulse-by-pulse current control and slew control. A large signal on CS, indicative of a fault, also shuts the MOSFETs off.

Converter efficiency is improved by use of a bootstrap winding that powers the part when the converter is up and running. Efficiency at the low noise setting is approximately 77%.

Conclusion

The LT1683 provides a unique way to produce an efficient, ultralow noise supply. Novel control circuitry quiets the switcher, allowing a new supply solution for sensitive electronic systems. The use of external MOSFET switches allows the voltage and current ratings of the supply to be tailored to the application. 

LTC3200, continued from page 29

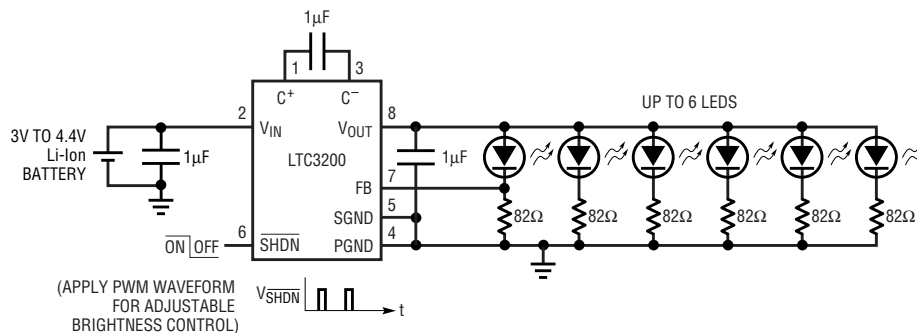


Figure 3. White or blue LED driver with LED current control

Conclusion

In either constant voltage or current controlled applications of the LTC3200, the LED brightness can be controlled by applying a PWM signal (approximately 100Hz) to the $\overline{\text{SHDN}}$ pin. Varying the pulse width from 4% to 100% gives the LEDs a linear appearance of brightness control from full-on to full-off.

In the tiny 6-pin SOT or 8-pin MSOP packages, the LTC3200 family of charge pumps provides a simple solution for powering white LEDs. Its small size, low external parts count and low noise, constant frequency operation is ideally suited for both communications and other portable products. 

the LINEAR zone

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Articles, Design Ideas, Tips from the Lab...

New Device Cameos

LTC1701B: Tiny Step-Down Regulator Switches at 1MHz

For low to medium power applications that must fit in small spaces, the LTC1701B provides a DC/DC converter that consumes less than 0.3in² of PC board space. The part's 1MHz switching frequency allows the use of tiny, low cost capacitors and inductors, which, along with the tiny SOT-23 package, results in a very compact solution. The LTC1701B operates continuously down to very low load currents to provide low output ripple at the expense of light load efficiency, while the LTC1701 incorporates automatic power saving Burst Mode operation to reduce gate charge losses, providing better efficiency at light loads.

The LTC1701/LTC1701B operate from an input supply from 2.5V to 5.5V; the output voltage is adjustable from 1.25V to 5V. A built-in 0.28 Ω P-channel MOSFET switch allows up to 500mA of output current at high efficiencies (up to 94%). In dropout, the internal switch can be turned on continuously, maximizing the usable battery life.

Its combination of a high switching frequency, low ripple and an onboard P-channel MOSFET in a tiny SOT-23 package makes the LTC1701B ideal for low noise, space-critical portable applications.

LTC Releases Popular High Speed Amplifiers and Comparators in the Space-Saving SOT-23 Package

Ideal for saving board space, the new SOT-23 versions of Linear Technology's high speed amplifiers and comparators feature the same performance as their SO counterparts but require much less board area.

The 400MHz LT1395S5/LT1395S6 current feedback amplifiers provide the bandwidth and output current required for cable driver and video applications. A gain flatness of 0.1dB to 100MHz ensures signal fidelity and

the 80mA output current is sufficient for cable drivers. The parts draw only 4.6mA and operate on all supplies from a single 4V to $\pm 6V$. A shutdown feature is included in the LT1395S6.

The 100MHz LT1812S5/LT1812S6 voltage feedback amplifiers have a maximum offset voltage of 1.5mV and a maximum input offset current of 400nA. Drawing only 3mA supply current, the devices have a slew rate of 750V/ μ s and can drive a 100 Ω load to $\pm 3.5V$ with $\pm 5V$ supplies. These easy-to-use devices are stable with load capacitances as high as 1000pF. The LT1812S6 includes a power-saving shutdown feature.

Operating from supplies as low as 2.5V, the 325MHz LT1806S6 and the 180MHz LT1809S6 amplifiers provide the distortion and noise performance required by low voltage signal conditioning systems. Rail-to-rail inputs and outputs allow the entire supply range to be used and the high output current capability, 60mA typical on a 3V supply, is ideal for cable driver applications. The LT1806S6 is optimized for noise and DC performance, featuring a low voltage noise of 3.5nV/ $\sqrt{Hz}$ and a maximum offset voltage of 700 μ V. The LT1809S6 is optimized for slew rate and distortion, featuring a slew rate of 350V/ μ s and low harmonic distortion of -90dBc at $f_c = 5MHz$ ($V_S = 5V$, $V_O = 2V_{P-P}$). Both parts are fully specified for 3V, 5V and $\pm 5V$ operation. A shutdown function is included.

The LT1719S6 4.5ns comparator makes fast comparisons painlessly on 3V and 5V supplies while consum-

ing only 4.2mA. Internal hysteresis ensures clean transitions even on slow-moving input signals. The input common mode range extends to 100mV below ground and the outputs are rail-to-rail. The propagation time is 4.5ns with 20mV overdrive and 7ns with 5mV overdrive. A shutdown pin reduces the supply current to 80 μ A max.

LT1494 and LT1672/LT1673/LT1674 Ultralow Power Rail-to-Rail Op Amps

The LT1494 and LT1672/73/74 are the newest members of the industry's lowest power, precision, rail-to-rail op amp family. All devices have excellent amplifier specifications: 375 μ V max input offset voltage, 100pA max input offset current and 0.4 μ V/ $^{\circ}C$ typical drift while operating from a maximum of only 1.5 μ A supply current for the LT1494 and 2 μ A/amplifier for the LT1672-74. A minimum open-loop gain (A_{VOL}) of 100V/mV ensures that gain errors are small. Both the supply rejection and the common mode rejection ratios are greater than 90dB. All devices exhibit little change in characteristics over the wide supply range of 2.2V to $\pm 15V$. They feature reverse battery protection ($-18V$ min) and Over-The-TopTM operation (the ability to operate with the inputs above the positive supply).

The LT1494 is a single rail-to-rail amplifier with a gain bandwidth product (GBW) of 3kHz and a slew rate (SR) of 0.4V/ms. The LT1672/73/74 are single, dual and quad decompensated versions of the LT1494. They are stable with a gain of five and are four times faster than the LT1494 (GBW = 12kHz, SR = 1.6V/ms), with an increase in supply current of only 500nA/amp.

The LT1494 and LT1672 single come in 8-lead MSOP, SO and PDIP packages. The LT1673 dual comes in 8-lead SO and PDIP packages and the LT1674 quad comes in 14-lead SO and PDIP packages. 

Information furnished by Linear Technology Corporation is believed to be accurate and reliable. However, no responsibility is assumed for its use. Linear Technology Corporation makes no representation that the interconnection of its circuits as described herein will not infringe on existing patent rights.

For further information on any of the devices mentioned in this issue of *Linear Technology*, use the reader service card or call the LTC literature service number:

1-800-4-LINEAR

Ask for the pertinent data sheets and Application Notes.

DESIGN TOOLS

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