

IN THIS ISSUE...

COVER ARTICLE

Video Instrumentation Amplifier Easily Extracts Clean Video Signals from Noisy Environments..... 1
Raj Ramchandani and Jon Munson

Issue Highlights 2

LTC in the News..... 2

DESIGN FEATURES

1.1A Boost Provides Soft-Start Capability in Tiny ThinSOT™ Package 5
Brian Adolf

Versatile 80V Hot Swap Controllers Drive Large MOSFETs; Improve Accuracy and Foldback Current Limiting..... 7
Mark Belch

Triple-Output Regulator Reduces EMI; Provides Two Step-Down and One Step-Up or Inverting Output ... 9
John Tilly

Synchronous Switching Regulator Controller Allows Inputs up to 100V..... 13
Greg Dittmer

2-Phase Dual Synchronous DC/DC Controller with Tracking Provides High Efficiency in a Compact Footprint..... 17
Jason Leonard

PWM Controller Offers High Performance, Low Cost, Single Transistor Forward Converter Solutions..... 20
Mark Marosek and Goran Perica

Replace -48V ORing Diodes with FETs to Reduce Heat and Save Space 26
James Herr

DESIGN INFORMATION

Accurate and Simple AC Measurement to 500kHz 28
David Hutchinson

DESIGN IDEAS

..... 30-36
(complete list on page 30)

New Device Cameos..... 37

Design Tools 39

Sales Offices..... 40



Video Instrumentation Amplifier Easily Extracts Clean Video Signals from Noisy Environments

by Raj Ramchandani and Jon Munson

Introduction

The LT6552 is a single-IC solution for converting high frequency difference video signals into a single-ended output, while rejecting common mode (ground) noise—with an exceptional 60dB rejection at 10MHz.

A complete video amplifier circuit requires only the LT6552 and a few external components (Figure 1a). There is no need for matching gain setting resistors since the gain is set without loading the input signal. Unlike conventional op amps, LT6552 features an additional pair of uncommitted high input impedance (+) and (-) inputs. The other set of inputs provide feedback and DC control to the differential amplifier.

Dual Input Pair Zaps Common-Mode Noise Pickup

The simple circuit in Figure 1a is especially effective in removing common mode noise from video signals in vehicular and industrial applications, offering better performance and fewer required components than other op amp based topologies.

The oscilloscope photo in Figure 1b shows the output response to a differential video test signal with 0.5V_{RMS} additive common mode white noise.

Only two resistors are required to set the difference gain (Gain = 2 in this example), no additional components are required for unity gain. The 8pF feedback capacitor is used to reduce peaking in the frequency response and eliminates time domain overshoot.

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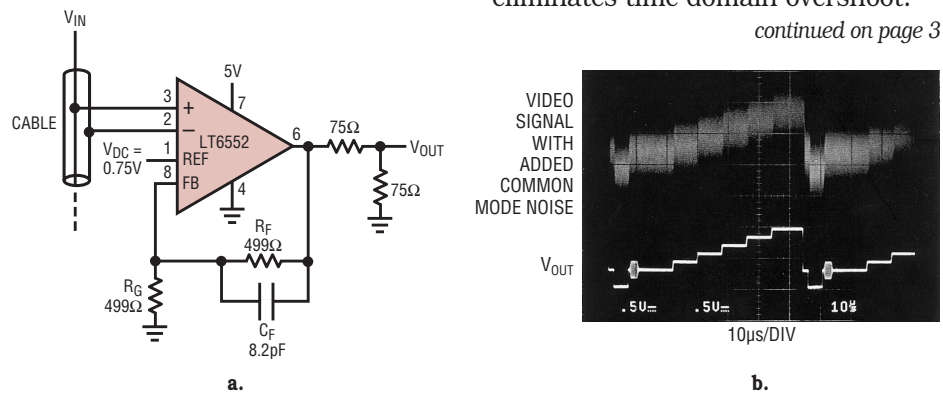


Figure 1. Differential cable sense amplifier (a) and its ability to recover a differential video signal from common mode noise (b). The input in (a) is not loaded by gain setting resistors.

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Issue Highlights

High fidelity video is making its way into automobiles and other environments where signal noise can be a significant problem. It is nearly impossible to shield the system from all noise, so a video display system must be able to extract a clean signal from a noisy one.

The LT6552 answers the call, and it works from just a 3V supply. It converts high frequency differential signals into a single-ended output, while rejecting common mode noise, but is versatile enough for application in a wide range of consumer and industrial devices.

Featured Devices

Below is a summary of the other devices featured in this issue.

High Voltage Hot Swap Controller

The LT4256 Hot Swap™ Controller is designed to turn on a board's supply voltage in a controlled manner, allowing the board to be safely **inserted or removed from a live backplane having a supply voltage from 10.8V to 80V**. (Page 7)

DC/DC Converters

The LT3467 **step-up DC/DC converter provides 1.1A switch current limit in a SOT-23**—ample current in a small package. It also features a soft-start feature to limit the inrush current drawn from the supply during startup. The LT3467 is up to 90% efficient for a single Li-Ion cell to 5V boost converter. (Page 5)

The LT1941 is a current mode **DC/DC converter with three internal power switches**. Two of the regulators are step-down converters with 3A and 2A switch current limits. The third regulator can be configured as a step-up, inverter, SEPIC or flyback converter and has a switch current limit of 1.5A. The two step-down converters run with opposite phases, reducing input ripple current and associated EMI. (Page 9)

The LTC®3736 is a **feature-rich 2-phase dual synchronous step-down**

DC/DC controller that requires few external components. Its No R_{SENSE}™, constant frequency, current mode architecture eliminates the need for current sense resistors and improves efficiency, without requiring a Schottky diode. The two controllers are operated 180 degrees out of phase, reducing the required input capacitance and power loss and noise due to its ESR. A tracking input allows the second output to track the first output (or another supply) during startup. (Page 17)

High Voltage Converters

The LTC3703 is a **100V synchronous switching regulator controller** that can directly step-down high input voltages using a single inductor, thus providing a compact high performance power supply for harsh environments. (Page 13)

Replace power modules in telecom and industrial applications **at less than half the cost**; without the headaches that designing a traditional forward converter would cause. A LT1952-based forward converter is ideal for 25W to 500W systems that require high performance, reliability, design simplicity, low cost and minimal space usage. (Page 20)

PowerPath™ Control


The LTC4354 is a **negative voltage diode-OR controller** that replaces ORing diodes by driving two external N-channel MOSFETs as pass transistors. The device maintains a small 30mV voltage drop across the MOSFET at light load, while at heavy load, the low R_{DS(ON)} of the external MOSFET reduces the power dissipation. (Page 26)

RMS-to-DC Conversion

The LTC1967 and LTC1968 provide the easiest way to **accurately measure the RMS value of any AC waveform with input signal frequencies as high as 500kHz**. They have 1% gain accuracy and noise out to 100kHz and 500kHz, respectively. Their phenom-


LTC in the News...

On July 20, 2004, Linear Technology Corporation announced its financial results for its fiscal year 2004, ending June 27, 2004. According to Robert H. Swanson, Chairman of the Board and CEO, "Fiscal 2004 was a very strong year for Linear with momentum building steadily as each of the quarters had accelerated year over year growth in sales and profits. Accordingly, we closed the year with our strongest quarter growing sales 14% and profits 16% sequentially over the March quarter. Typically the summer quarter, which we are entering, is the quarter with the lowest sequential growth, generally low single digits. However, this year, given the broad based strength we are experiencing in our marketplace, should these current trends continue, we expect to have a seasonally strong start to our new fiscal year with sales growing roughly 5% to 7% sequentially from the quarter just completed."

The Company reported net sales for Fiscal 2004 of \$807,281,000 and net income of \$328,171,000. Diluted earnings were \$1.02 per share for the year. A cash dividend of \$.08 per share, will be paid on August 18, 2004 to stockholders of record on July 30, 2004. 

enal linearity of 0.02% allows easy RMS-to-DC conversion without the need for the calibration. (Page 28)

Design Ideas and Cameos

Starting on page 30 are four new Design Ideas including a design for a four-quadrant (\pm voltage, \pm current) bench power supply, and one for Power over Ethernet port current detection. At the back are eight New Device Cameos. Visit www.linear.com for complete device specifications and applications information. 

LT6552, continued from page 1

Amplifier Features

As supply voltages decrease, increasing demands are placed on analog signal handling characteristics. For example, a 3.3V video amplifier not only requires high slew rates and fast settling times, but must also have wide input and output voltage swing ranges to avoid clipping any portion of the video waveform. Current feedback amplifiers are a poor choice as they lack sufficient signal swing at low supplies and they require input signals that operate above ground.

The LT6552 utilizes a voltage feedback topology and features a 70MHz (–3dB) closed loop gain of 2 bandwidth, 450V/μs slew rate and a fast 20ns settling time, making it ideal for low voltage video signal processing. The LT6552 also includes a shutdown feature to allow power management

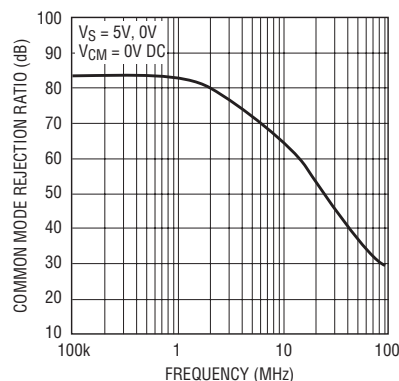


Figure 2. Input referred CMRR vs frequency

in supply-current sensitive applications.

The LT6552 operates from 3V to 12.6V and is fully specified on single 3.3V and 5V supplies as well as ±5V supplies. The device is available in an 8-pin SO package as well as a tiny, dual fine pitch leadless package (DFN). Performance is guaranteed over the industrial temperature range.

Amplifier Characteristics

The LT6552 features exceptional high-frequency common-mode rejection, over 60dB at 10MHz. Figure 2 shows the input referred CMRR vs frequency. Other features include a rail-to-rail output and an input common mode range that includes ground. On a single 3.3V supply, the input voltage range extends from ground to 1.55V. The output swings to within 400mV of the supply voltage while driving a 150Ω load which ensures a full video waveform including the sync pulse. Table 1 summarizes the major performance specifications.

Figure 3 shows a simplified schematic of the LT6552. There are two input stages: the first consists of transistors Q1 to Q8 for the (+) and (–) inputs while the second consists of transistors Q9 to Q16 for the reference and feedback inputs. This topology allows for high slew rates at low supply voltages.

Transistors Q3 to Q6 are biased class AB, as are transistors Q11 to Q14. The input stage transconductance is derived from $1/g_m$ of these transistors and resistors R1 or R2. The inputs are taken from the base of the PNP transistors allowing the common mode range to include ground. The input common mode range extends from ground to typically 1.75V from V_{CC} , and is limited by two base emitter drops plus a saturation voltage of current sources I1–I4.

Each input stage drives the folded cascode degeneration resistors of PNP and NPN current mirrors, Q17 to Q20 that convert the differential signals into a single ended output. The complementary drive generator supplies current to the output transistors, which swing from rail-to-rail. The LT6552 can be shutdown by bringing the SHDN pin within 0.5V of V^- . In normal operation the SHDN pin can be tied to V^+ or left floating—an internal pull up will keep the device fully operational.

Perform Video Rate Analog Arithmetic

Because of its dual differencing input structure, the LT6552 is able to readily process both additive (non-inverting) and subtractive (inverting) variables without complicated resistor networks. This unique property provides a useful means of differential to single

Table 1. LT6552 performance specifications

Parameter	Conditions	Typical Values at 3.3V, 0V	Typical Values at 5V, 0V
–3dB Bandwidth	$A_V = 2$, $R_L = 150\Omega$	65MHz	70MHz
Output Voltage Swing High	$R_L = 150\Omega$	2.5V Min	3.6V Min
Output Voltage Swing Low	$I_{SINK} = 10mA$	200mV Max	200mV Max
CMRR	$V_{CM} = 0$ to $V_S - 2V$	83dB	83dB
Slew Rate	$A_V = 2$, $R_L = 150\Omega$	350V/μs	450V/μs
Settling Time to 3%	$V_{OUT} = 2V$ step, $R_L = 150\Omega$	20ns	20ns
Differential Gain	$A_V = 2$, $R_L = 150\Omega$	0.4%	0.25%
Differential Phase	$A_V = 2$, $R_L = 150\Omega$	0.15°	0.04°
Supply Current		12.5mA	13.5mA
Supply Current in Shutdown	$V_{SHDN} = 0.5V$	300μA	400μA

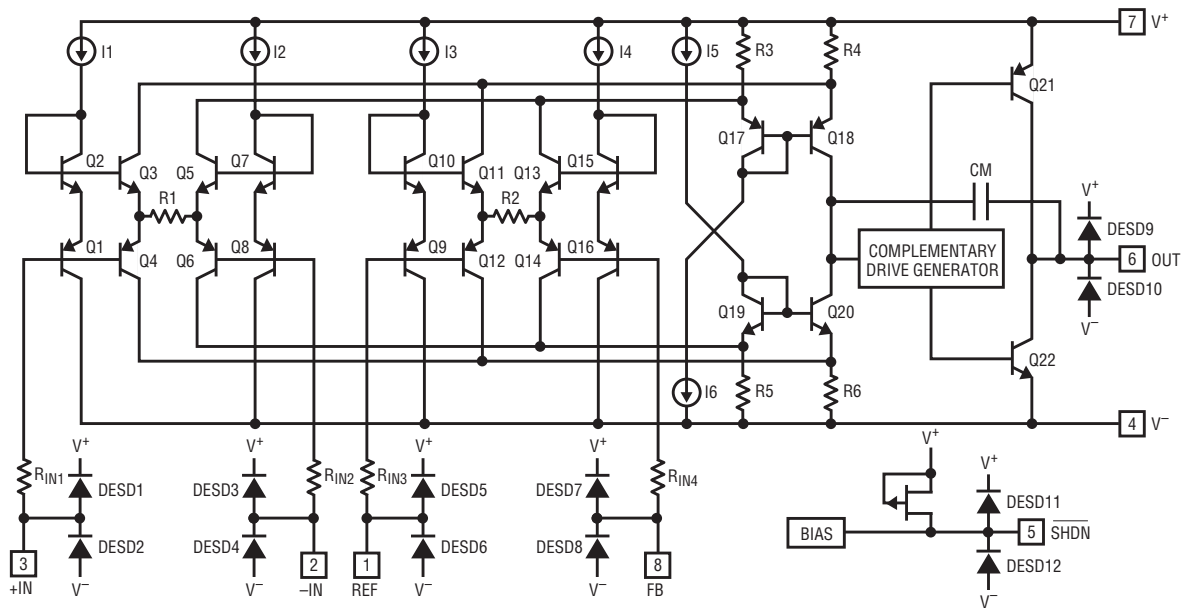


Figure 3. Simplified schematic of the LT6552

ended conversion with offset control, or performing multi-variable functions.

Figure 4 shows the LT6552 dealing with multiple variables in a $Y P_B P_R$ -to- RGB component video converter. The $Y P_B P_R$ format has a luminance signal and two color weighted difference signals. The circuit in Figure 4 uses the least number of possible amplification stages to accomplish the needed matrix functions while operating on low supply voltages ($\pm 3V$). The circuit maps sync-on-Y to sync on all RGB channels and for best results should have input black-levels at 0V nominal to prevent clipping.

Conclusion

The LT6552 video difference amplifier is well suited for use in a variety of video applications. By virtue of its dual-differencing input structure and ability to operate from low supply voltages, the LT6552 provides a versatile and high performing gain block. Its high slew rate, fast settling time, and wide input and output ranges make it an excellent choice for 3.3V applications. Of particular value is the device's ability to recover difference signals in the presence of common mode interference.

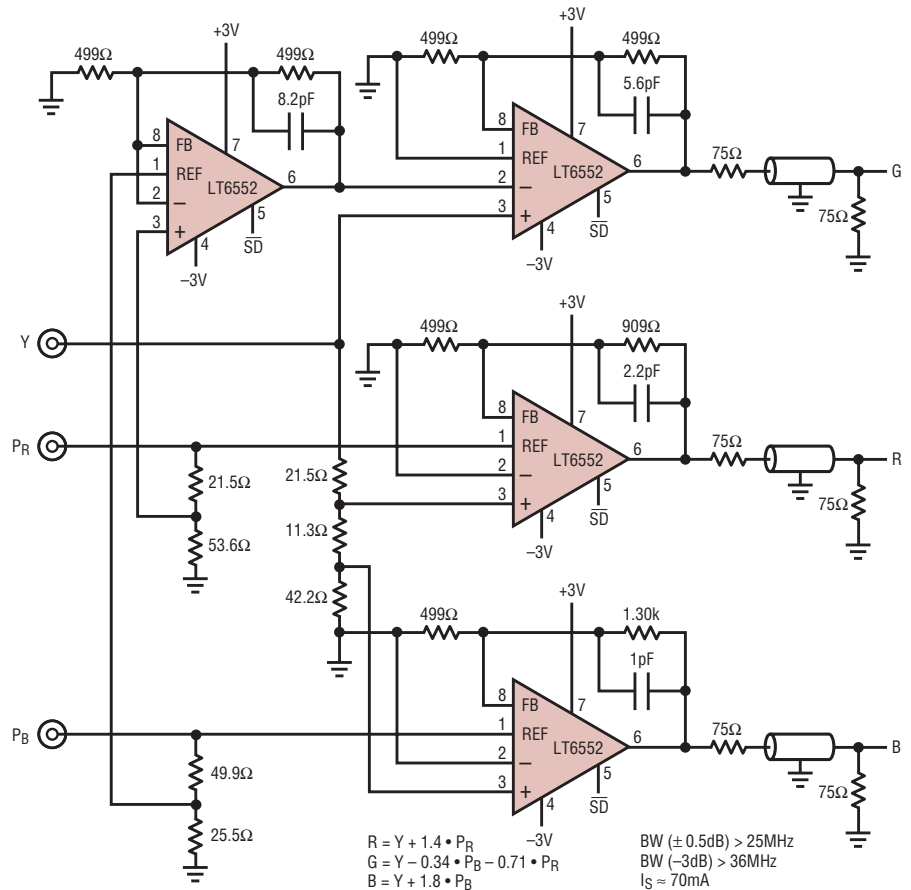


Figure 4. $Y P_B P_R$ to RGB component-video converter

$$\begin{aligned}
 R &= Y + 1.4 \cdot P_R \\
 G &= Y - 0.34 \cdot P_B - 0.71 \cdot P_R \\
 B &= Y + 1.8 \cdot P_B
 \end{aligned}$$

$BW (\pm 0.5dB) > 25MHz$
 $BW (-3dB) > 36MHz$
 $I_S \approx 70mA$

For more information on parts featured in this issue, see <http://www.linear.com/go/ltmag>

1.1A Boost Provides Soft-Start Capability in Tiny ThinSOT Package

by Brian Adolf

Introduction

Linear Technology's new LT3467 step-up DC/DC converter provides 1.1A switch current limit in a SOT-23—ample current in a small package. It also features a soft-start feature to limit the inrush current drawn from the supply during startup. Figure 1 shows that the LT3467 can deliver up to 540mA at 5V from an input of 3.3V with 84% efficiency. The LT3467 is up to 90% efficient for a single Li-Ion cell to 5V boost converter.

The high switching frequency of 1.3 MHz means low cost and low height inductors and capacitors can be used. Moreover, the fixed frequency current mode PWM architecture yields low noise that is predictable and easy to filter.

Application of the LT3467 is not limited to boost configurations, but can be used in a variety of other topologies such as SEPIC and flyback converters. The LT3467 has an internal 1.1A switch, and is capable of delivering up to 40V output. It has a dedicated soft-start pin: simply place an appropriately valued external capacitor on that pin to limit the inrush current by ramping up the voltage slowly (typical startup times are a few milliseconds).

The LT3467 is a pin-for-pin replacement of the LT1930 and LT1613, so applications using these parts can be easily updated to take advantage of the soft-start feature, higher efficiency and increased current capability.

Soft-Start

Normally, when a step-up DC/DC converter is first turned on, the output is low. This results in large current spikes as the output is quickly brought into regulation. Many applications with DC/DC converters use a battery for V_{IN} , or possibly another voltage supply that can only provide a limited amount of current, so these large current spikes can collapse the supply voltage.

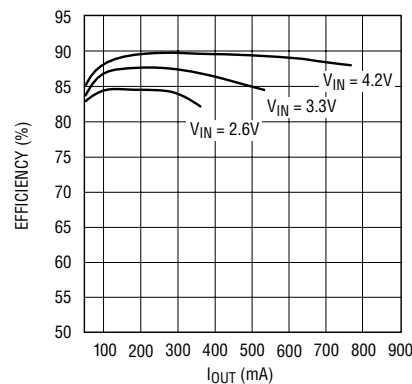
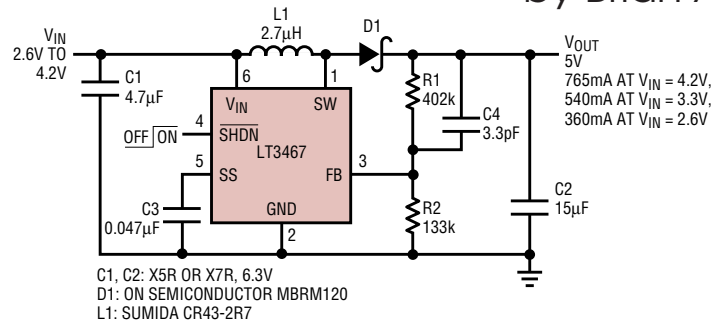


Figure 1. Single Li-Ion cell to 5V boost converter and its efficiency

If, during startup, a step-up DC/DC converter's switch is forced to turn on for a shorter duration than normal, the current in the inductor (and thus from the supply) grows moderately. During this time, the output voltage is brought up to its final regulated value much more slowly. Figures 2 and 3 show an example. Once the target output voltage is reached, the switch is no longer forced to short on-times, and is allowed to act on its own so the converter can regulate the output volt-

age under varying load conditions. This function is known as soft-start.

To implement the soft-start feature of the LT3467, simply place an external capacitor on pin 5. Upon startup, this capacitor is pulled high by an internal 250k Ω resistor. While the capacitor is being pulled high, the duration the switch is allowed to turn on is proportional to the voltage on the soft-start capacitor. Thus the output voltage and the supply current follow a segment of the familiar RC exponential, before

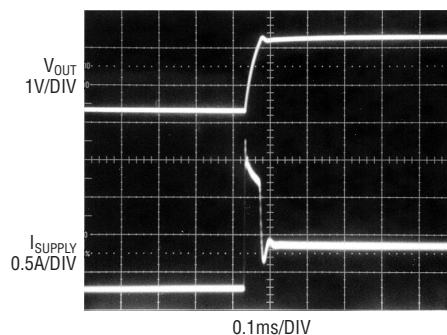


Figure 2. Supply current of Figure 1 during startup without soft-start capacitor

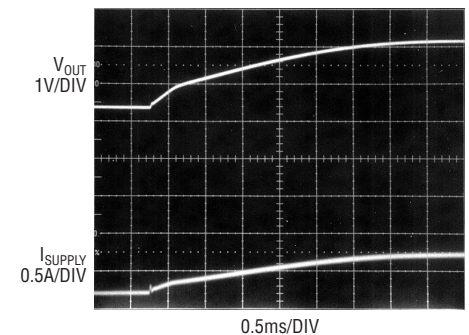


Figure 3. Supply current of Figure 1 during startup with 47nF soft-start capacitor

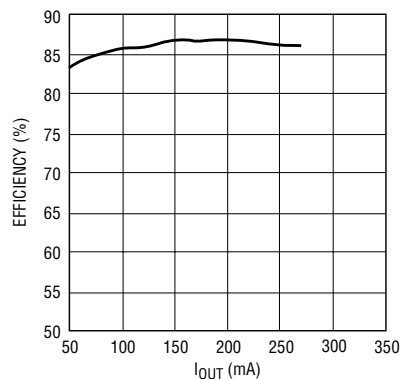
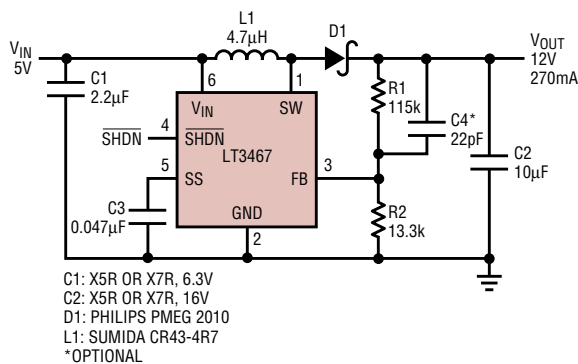


Figure 4. 5V to 12V, 270mA step-up converter and its efficiency

the capacitor charges high enough that the soft-start action goes away. Refer to the data sheet for a more detailed description of soft-start and a block diagram explaining the operation of the LT3467.

Applications and Features

The LT3467 can be used in many different applications where voltage conversion is necessary. For example, in a boost topology, any voltage up to 40V can be produced from a lower voltage assuming the duty cycle of the application is within the ability of the part (see the data sheet for more information). Figure 4 shows a 5V to 12V application capable of up to 270mA. The efficiency peaks at 87%.

Figure 5 shows an application powering a Lumiled from a Li-Ion supply. In this application, the output is the current through the LED, which can vary from 20mA for a “flashlight mode” when the Flash signal is low, up to 280mA when the Flash signal is high (at 2.5V). This is useful, for example, when a small amount of light is normally required, but where a brief burst

of bright light is occasionally useful, such as in a camera flash for a cell phone. An extra supply, $V_{CC} = 2.0V \pm 2\%$ is required to reduce the power dissipated in the sense resistor string. Instead of placing the sense resistor directly on the feedback pin, which will servo to 1.255V and dissipate $1.255V \cdot I_{OUT(MAX)}$, we use an extra 100µA to level shift the sense resistor voltage. By selecting $R1 = 8.5k\Omega$, we reduce the voltage by 0.85V, thus reducing the power wasted in the sense resistor chain to $0.405V \cdot I_{OUT(MAX)}$, less than a third of the original power dissipated in this resistor.

The current through the LED varies according to:

$$I_{OUT} = \frac{1.255 - V_{CC} \cdot \frac{R1}{R2} + 1.255 \cdot \frac{R1}{R2}}{R_S}$$

where R_S is the equivalent resistance of R_{S1} , R_{S2} and M1.

By varying R_S from 20Ω to 1.44Ω, the current through the LED varies from 20mA to 280mA. When switching to this heavier load, the part reaches

current limit unless soft-start is used. One solution is to briefly ground the soft-start pin—which discharges the soft-start cap—each time the Flash signal goes high (shown in Figure 5).

Another interesting feature of the LT3467 concerns its current limit. At lower duty cycles, the switch is on for less time and consumes less power as a result. This fact can be taken advantage of in a very useful way: by making the current limit higher at lower duty cycles, the part can deliver more power than if it were simply fixed at 1.1A. For example, at the lowest duty cycle, around 10%, the minimum current limit is guaranteed to be 1.4A (typically it is around 1.8A.) In fact, the current limit is guaranteed at all operable duty cycles.

In addition to the features mentioned above, the LT3467 also comes in a higher frequency version: the LT3467A. This can be useful when a switching frequency above 1.6MHz is required, or when even smaller components must be used. The LT3467A switches at 2.1MHz, and has a slightly lower maximum duty cycle, but is otherwise identical to the LT3467. See the data sheet for more details.

Conclusion

The LT3467 is an efficient boost converter, both electrically, and in its space requirements. Its operation at a high fixed frequency allows external components to be quite small, and with the added soft-start feature, input supplies won't be brought down when the part is turned on. The LT3467 is ideal in applications where high currents are required in small spaces.

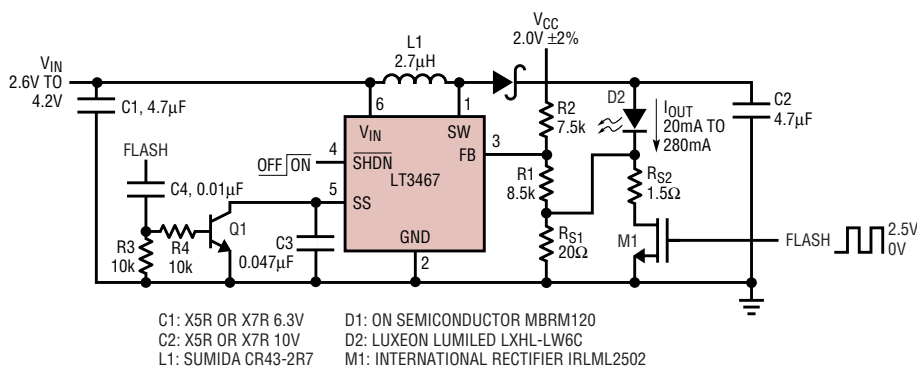


Figure 5. Li-Ion powered LED flash driver

Versatile 80V Hot Swap Controllers Drive Large MOSFETs; Improve Accuracy and Foldback Current Limiting

by Mark Belch

Introduction

Routine maintenance and upgrades to high reliability computing, networking and telecommunications systems require that new or replacement circuit boards be inserted into a powered 48V(typical) bus. When a circuit board is inserted into a live backplane, the input capacitors on the board can draw high inrush currents from the backplane power bus as they charge. The inrush current can permanently damage the connector pins and board components as well as glitch the system supply, causing other boards in the system to reset. The new LT4256 family (LT4256-1 and LT4256-2) provides a compact and robust solution to eliminate these hot plugging issues.

The LT4256 is designed to turn on a board's supply voltage in a controlled manner, allowing the board to be safely inserted or removed from a live backplane having a supply voltage from 10.8V to 80V. The device features programmable inrush current control, current foldback, programmable undervoltage threshold with a

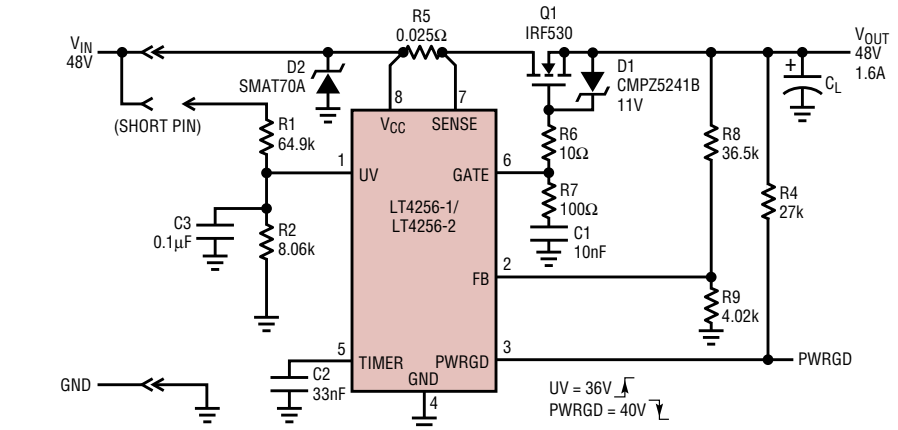


Figure 1. Typical application

1% tolerance, overcurrent protection, and a power good output signal that indicates when the output supply voltage is ready.

The LT4256-1 and LT4256-2 are offered in an 8-pin SO package and are pin compatible with the LT1641-1 and LT1641-2. The LT4256 family upgrades the LT1641 and offers several superior electrical specifications (see Table 1), requiring only a few minor component modifications.

Power-Up Sequence

Figure 1 shows a typical LT4256 application. An external N-channel MOSFET pass transistor (Q1) is placed in the power path to control the turn-on and turn-off characteristics of the supply voltage. Capacitor C1 controls the GATE slew rate, R7 provides compensation for the current control loop and R6 prevents high frequency oscillations in Q1. When the power pins first make contact, transistor Q1 is

Table 1. Differences between LT1641 and LT4256

SPECIFICATION	LT1641	LT4256	COMMENTS
UV Threshold	1.233V	4V	Higher 1% Reference for Better Noise Immunity and System Accuracy
FB Threshold	1.233V	3.99V	Higher 1% Reference for Better Noise Immunity and System Accuracy
TIMER Current	±70%	±26%	More Accurate TIMEOUT
TIMER Shutdown V	1.233V	4.65V	Higher Trip Voltage for Better Noise Immunity
GATE I _{PULLUP}	10μA	30μA	Higher Current to Accommodate Higher Leakage MOSFETs or Parallel Devices
GATE Resistor	1kΩ	100Ω	Different Compensation for Current Limit Loop
Foldback I _{LIM}	12mV	14mV	Slightly Different Current Limit Trip Point
I _{LIM} Threshold	47mV	55mV	Slightly Different Current Limit Trip Point

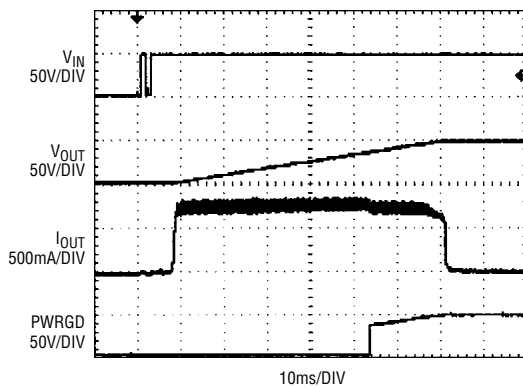


Figure 2. Startup waveforms

held off. The V_{CC} and GND connector pins should be longer than the pin that goes to R1 so they connect first and keep the LT4256 off until the board is completely seated in its connector. When the voltage on the V_{CC} pin is above the externally programmed undervoltage threshold, transistor Q1 is turned on (Figure 2). The voltage at the GATE pin rises with a slope equal to $30\mu\text{A}/C1$ and the supply inrush current is:

$$I_{\text{INRUSH}} = C_L \cdot \frac{30\mu\text{A}}{C1}$$

where C_L is the total load capacitance. If the voltage across the sense resistor reaches 55mV (typical), the inrush current is limited by the internal current limit circuitry. When the FB pin voltage goes above 4.45V, the PWRGD pin goes high.

Short-Circuit Protection

The LT4256 features a programmable foldback current limit with an electronic circuit breaker that protects against short circuits or excessive load currents. The current limit is set by placing a sense resistor (R5) between V_{CC} and SENSE. To limit excessive power dissipation in the pass transistor and to reduce voltage spikes on the input supply during short-circuit conditions at the output, the current folds back as a function of the output voltage, which is sensed internally on the FB pin. When the voltage at the FB pin is 0V, if the part goes into current limit, the current limit circuitry drives the GATE pin to force a constant 14mV drop across the sense resistor.

Under high current (but not short-circuit) conditions, as the FB voltage increases linearly from 0V to 2V, the controlled voltage across the sense resistor increases linearly from 14mV to 55mV (see Figure 3). With FB above 2V, a constant 55mV is maintained across the sense resistor.

During startup, a large output capacitance can cause the LT4256 to go into current limit. The current limit level when V_{OUT} is low is only one quarter of the current limit level under normal operation, and it is time limited, so careful attention is needed to insure proper start up. The maximum time the LT4256 is allowed to stay in current limit is defined by the TIMER pin capacitor.

The current limit threshold (during normal operation) is:

$$I_{\text{LIMIT}} = \frac{55\text{mV}}{R5}$$

where R5 is the sense resistor. For a 0.02Ω sense resistor, the current limit is set at 2.75A and folds back to 700mA if the output is shorted to ground.

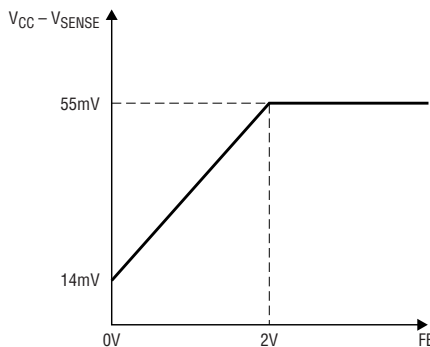


Figure 3. Current limit sense voltage vs FB pin voltage

For a 48V application, MOSFET peak power dissipation under short circuit conditions is reduced from 132W to 33.6W.

The LT4256 also features a variable overcurrent response time. The time required for the part to regulate the GATE pin voltage is proportional to the voltage across the sense resistor, R5. This helps to eliminate sensitivity to current spikes and transients that might otherwise unnecessarily trigger a current limit response and increase MOSFET dissipation.

Current Limit TIMER

The TIMER pin provides a method for programming the maximum time the part is allowed to operate in current limit. When the current limit circuitry is not active, the TIMER pin is pulled to GND by a $3\mu\text{A}$ current source. When the current limit circuitry becomes active, a $118\mu\text{A}$ pull-up current source is connected to the TIMER pin and the voltage rises with a slope equal to $115\mu\text{A}/C2$. Once the desired maximum current limit time is chosen, the capacitor value is:

$$C(\text{nF}) = 25 \cdot t(\text{ms})$$

If the TIMER pin reaches 4.65V (typ), the internal fault latch is set causing the GATE to be pulled low and the TIMER pin to be discharged to GND by the $3\mu\text{A}$ current source. The LT4256-1 latches off after a current limit fault. The LT4256-2 does not turn on again until the voltage at the TIMER pin falls below 0.65V (typ).

Undervoltage Detection

The LT4256 uses the UV (undervoltage) pin to monitor V_{IN} and allow the user the greatest flexibility for setting the operational threshold. Figure 1 also shows the UV level programming via a resistor divider (R1 and R2). If the UV pin goes below 3.6V, the GATE pin is immediately pulled low until the UV pin voltage goes above 4V. The UV pin is also used to reset the current limit fault latch after the LT4256-1 has latched off. This is accomplished by grounding the UV pin for a minimum of 5 μs .

continued on page 29

Triple-Output Regulator Reduces EMI; Provides Two Step-Down and One Step-Up or Inverting Output

by John Tilly

Introduction

Today's electronics systems continually increase the number of required power supply voltages as they squeeze more features into smaller spaces.

Linear regulators often are too big, or dissipate too much heat. Switching controllers are more efficient, but as they multiply on the board, space disappears and EMI (Electro-Magnetic Interference) between controllers becomes a problem. The LT1941

eliminates these problems by providing two step-down regulators and a third step-up or inverting regulator in a compact 28-pin TSSOP package.

The LT1941 is a current mode DC/DC converter with three internal power switches. Two of the regulators are step-down converters with 3A and 2A switch current limits. The third regulator can be configured as a step-up, inverter, SEPIC or flyback converter and has a switch current

limit of 1.5A. All are synchronized to a 1.1MHz oscillator. The two step-down converters run with opposite phases, reducing input ripple current and associated EMI.

The output voltages are set with external resistor dividers, and each regulator has independent shutdown and soft-start circuits. Each regulator generates a power good signal when its output is in regulation, enabling power

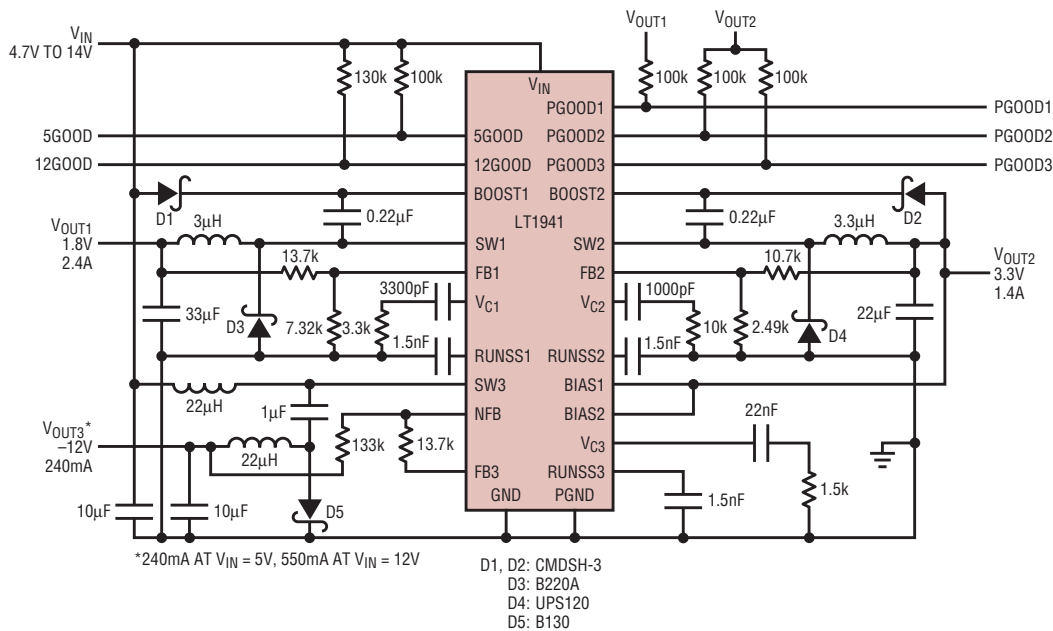


Figure 1. The typical application, a triple output power supply, generates 3.3V, 1.8V and -12V.

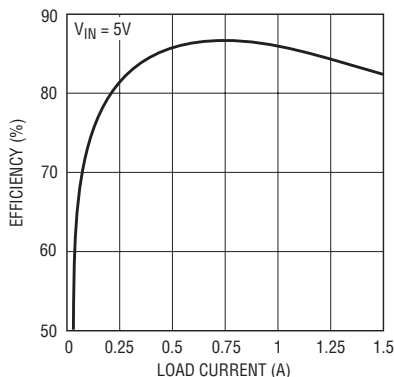


Figure 2. Efficiency for the 3.3V output of the circuit in Figure 1

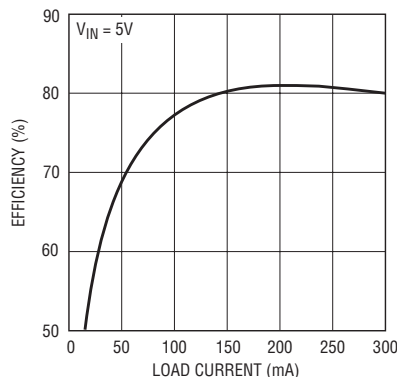


Figure 3. Efficiency for the -12V output of the circuit in Figure 1

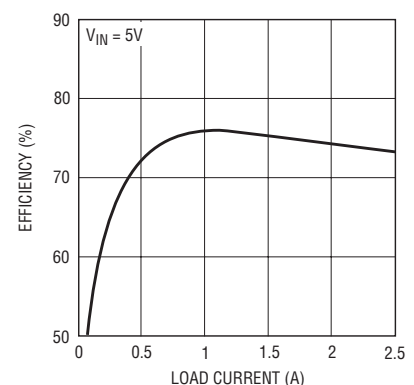


Figure 4. Efficiency for the 1.8V output of the circuit in Figure 1

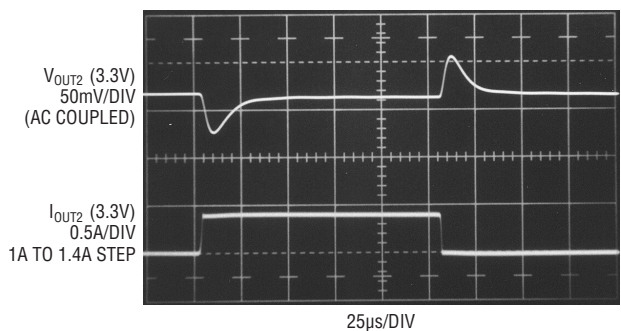


Figure 5. Load current step (1A to 1.4A) for 3.3V output of Figure 1's circuit

supply sequencing and interfacing with microcontrollers and DSPs.

The high switching frequency offers several advantages by permitting the use of small inductors and ceramic capacitors. Small inductors and capacitors combined with the LT1941's TSSOP-28 surface mount package help to minimize space requirements and cost. The constant switching frequency combined with low-impedance ceramic capacitors results in low, predictable output ripple.

A typical application, shown in Figure 2, generates 2.4A at 1.8V, 1.4A at 3.3V, and 240mA at -12V. For a 5V input and at maximum load the efficiency of the 3.3V output is 83%, the efficiency of the -12V output is 80% and the efficiency of the 1.8V output is 74% (Figures 2-4). Figure 5 shows the clean transient response of the 3.3V output to a 1A to 1.4A load step.

About the LT1941

The LT1941 is a constant frequency triple output regulator with a wide

input range of 3.5V to 25V. The three regulators share common circuitry including a voltage reference and oscillator, but are otherwise independent. Operation can be best understood by referring to the block diagram (Figure 8).

If all the RUN/SS pins are tied to ground, the LT1941 is shut down and draws 50µA from the input source tied to V_{IN}. Internal 2µA current sources charge external soft-start capacitors, generating voltage ramps at these pins. If any of the RUN/SS pins exceed 0.6V, the internal bias circuits turn on, including the internal regulator, reference and 1.1MHz master oscillator.

The master oscillator generates three clock signals, with the two signals for the step-down regulators out of phase by 180°. Each switcher contains an extra, independent oscillator to perform frequency foldback during overload conditions. This slave oscillator is normally synchronized to the master oscillator. A comparator senses when V_{FB} is less than 50% of

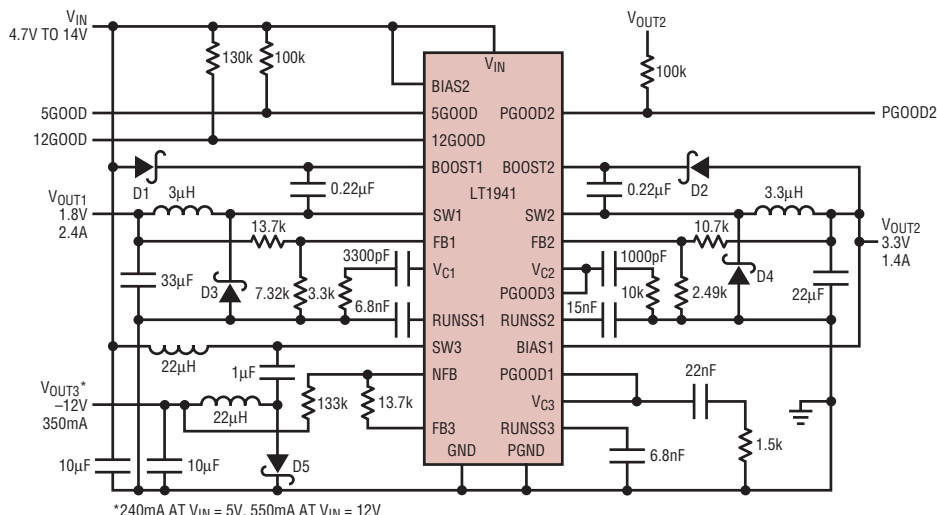


Figure 6. This 3.3V/1.8V/-12V circuit uses the power good pins to sequence the three outputs.

its regulated value and switches the regulator from the master oscillator to a slightly slower slave oscillator. The slave oscillator gradually reduces in frequency the further V_{FB} falls below 50% of its regulated value. The V_{FB} pin is less than 50% of its regulated value during startup, short circuit and overload conditions. Frequency foldback helps limit switch current under these conditions.

The BIAS1 and BIAS2 pins allow the internal circuitry to draw current from a lower voltage supply than the input, reducing power dissipation and increasing efficiency. A power good comparator trips when each FB pin is at 90% of its regulated value. The PGOOD output is an open collector transistor that is off when the output is in regulation, allowing an external resistor to pull the PGOOD pin high.

Power good comparators also monitor the input supply. The 5GOOD and 12GOOD pins are open-collector outputs of internal comparators. The 5GOOD pin remains low until the input is greater than 90% of 5V. The 12GOOD pin remains low until the input is greater than 90% of 12V. The open collector outputs of the power good indicators can be tied to the input or a positive output supply.

2-Phase Switching Eases EMI Concerns

A step-down regulator draws pulses of current from its input supply, resulting in large AC currents that can cause EMI problems. The LT1941's two step-down regulators are synchronized to a single oscillator, and switch out of phase by 180°. This substantially reduces the input ripple current, thereby lowering EMI. Synchronization also

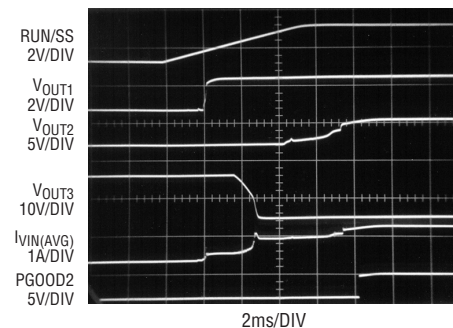


Figure 7. Start-up waveforms with sequencing

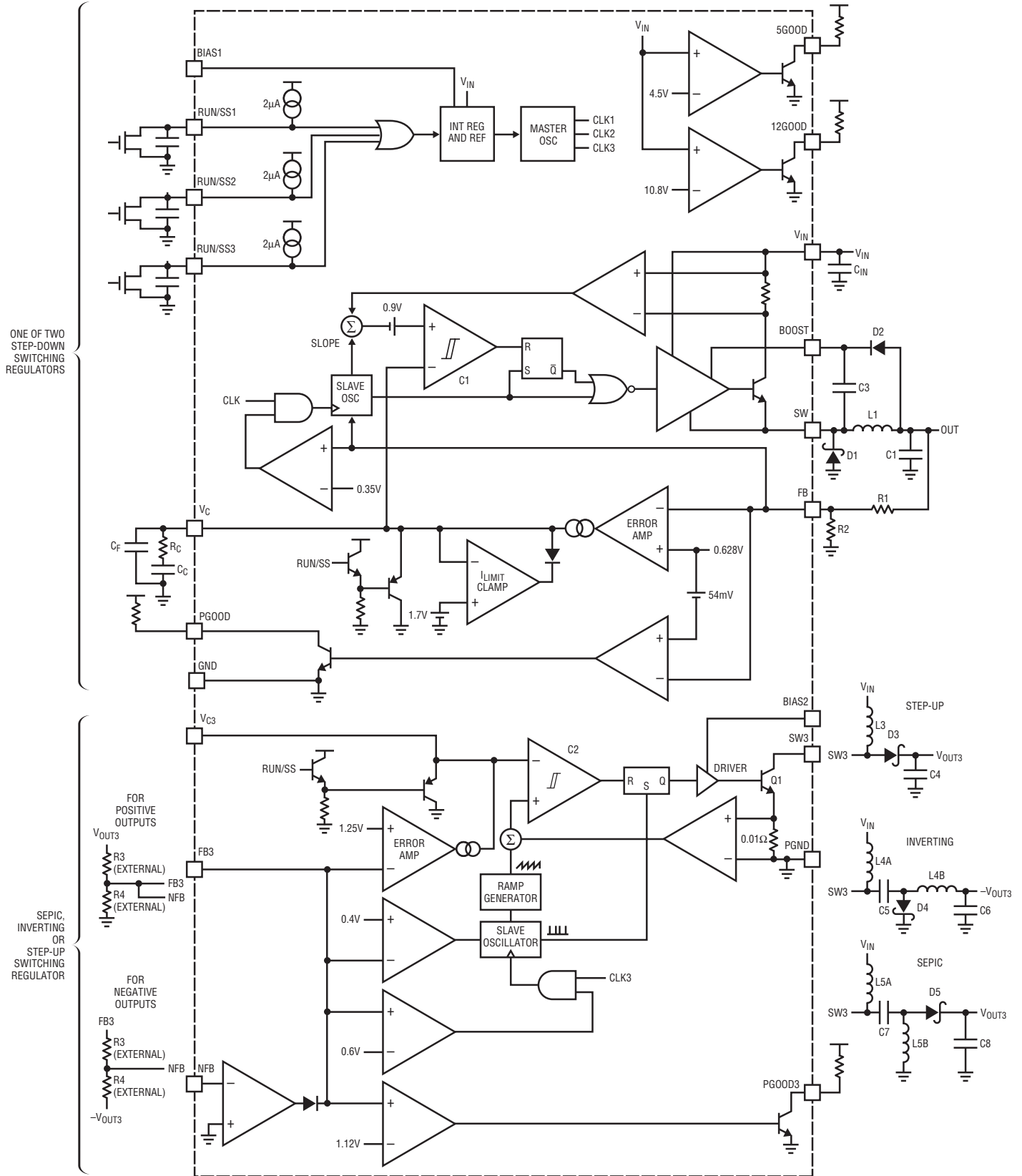


Figure 8. LT1941 block diagram shows two of its three built-in switching regulators (one of the two step-down switching regulators and the inverting/step-up switching regulator)

eliminates the audible noise (beat frequency) that can occur when two switchers run at slightly different frequencies.

Amplifier Allows Direct Regulation of Negative Voltages

The LT1941 can generate negative output voltages with greatly improved performance over unregulated charge pump and auxiliary transformer winding solutions.

An internal op amp allows the part to regulate negative voltages using only two external resistors. The LT1941 contains an op amp with its non-inverting terminal tied to ground and its output connected to the FB3 pin. Use this op amp to generate a voltage at FB3 that is proportional to V_{OUT} . Choose

the resistors according to (reference designers refer to Figure 8):

$$R4 = \frac{R3|V_{OUT}|}{1.24V}$$

Soft-Start and Power Good Pins Simplify Supply Sequencing

Multi-supply systems often require output sequencing. For example, a microprocessor's core supply should be in regulation before power is applied to the I/O circuits. Figure 6 shows a simple way to sequence the three outputs of the LT1941. Channel 1 produces the 1.8V core supply. Its power good pin pulls V_{C3} low, disabling channel 3 until the 1.8V output is in regulation. Channel 3 produces the -12V output. Its power good pulls V_{C2} low, disabling channel 2, a 3.3V

output, until the -12V output is in regulation.

The soft-start function helps limit input current during startup. If a capacitor is tied from the RUN/SS pin to ground, then the internal pull-up current generates a voltage ramp on this pin. This voltage clamps the V_C pin, limiting the peak switch current and therefore input current during start up.

A good value for the soft-start capacitor is $C_{OUT}/10,000$, where C_{OUT} is the value of the output capacitor. A single capacitor can be used to program soft-start by tying the three soft-start pins together, or each channel can be individually programmed. Figure 7 shows the output voltages with sequencing, as well as the input current slowly ramping up to its nominal level without overshooting. This is

continued on page 16

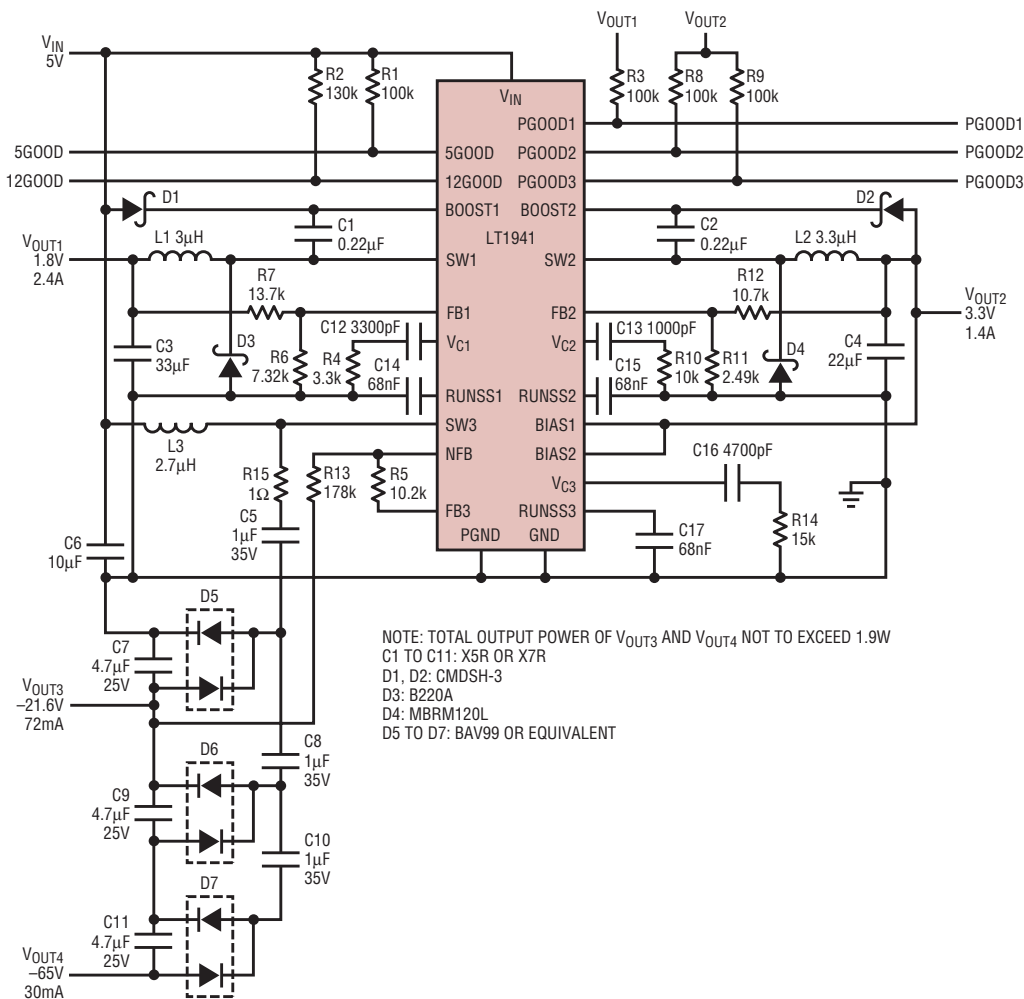


Figure 9. SLIC power supply generates -21.6V, -65V, 3.3V and 1.8V with soft-start.

Synchronous Switching Regulator Controller Allows Inputs up to 100V

by Greg Dittmer

Introduction

Industrial, automotive, and telecom systems create harsh, unforgiving environments that demand robust electronic systems. In telecom systems the input rails can vary from 36V to 72V, with transients as high as 100V. In automotive systems the DC battery voltage may be 12V, 24V, or 42V with load dump conditions causing transients up to 60V.

Until now, no synchronous buck (or boost) control IC has been capable of operating at 100V, so solutions have been limited to low-side drive topologies that utilize expensive and bulky transformers. The LTC3703 is a 100V synchronous switching regulator controller that can directly step-down high input voltages using a single inductor, thus providing a compact high performance power supply for harsh environments.

Key Features for High Voltage Applications

The LTC3703 drives external N-channel MOSFETs using a constant frequency, voltage mode architecture. A high bandwidth error amplifier and

patented line feed forward compensation provide very fast line and load transient response. Strong 1Ω gate drivers allow the LTC3703 to drive multiple MOSFETs for higher current applications. A precise internal 0.8V reference provides 1% DC accuracy. The operating frequency is user programmable from 100kHz to 600kHz and can also be synchronized to an external clock for noise-sensitive applications. Selectable Pulse Skip Mode operation improves light load efficiency. Current limit is user programmable and utilizes the voltage drop across the synchronous MOSFET to eliminate the need for a current sense resistor. A low minimum on-time allows high input-to-output step-down ratios such as 72V-to-3.3V at 200kHz. Shutdown mode reduces supply current to 50 μ A. An internal UVLO circuit guarantees that the driver supply voltage is high enough to sufficiently enhance the MOSFETs before enabling the controller ($UV^+ = 8.7V$, $UV^- = 6.2V$). The LTC3703 is available in a 16-pin narrow SSOP package or, if high voltage

pin spacing is required, in a 28-pin SSOP package.

Strong Gate Drivers and Synchronous Drive for High Efficiency

Because switching losses are proportional to the square of input voltage, these losses can dominate in high voltage applications with inadequate gate drive. The LTC3703 has strong 1Ω gate drivers that minimize transition times and thus minimize switching losses, even when multiple MOSFETs are used for high current applications. Dual N-channel synchronous drives combined with the strong drivers results in power conversion efficiencies as high as 96%.

The LTC3703 provides a separate return pin for the bottom MOSFET driver (see Figure 1), allowing the use of a negative gate drive voltage in the off state. In high voltage switching converters, the switch node dv/dt can be many volts/ns, which pulls up on the gate of the bottom MOSFET through its Miller capacitance, especially in applications with multiple MOSFETs. If this Miller current, times the combined internal gate resistance of the MOSFET plus the driver resistance, exceeds the threshold of the MOSFET, shoot-through will occur, degrading efficiency. By using a negative supply on this pin, the gate can be pulled below ground when turning the bottom MOSFET off. This provides a few extra volts of margin before the gate reaches the turn-on threshold of the MOSFET.

Fast Load Transient Response

The LTC3703 uses a fast 25MHz op amp as an error amplifier. This allows the compensation network to be optimized for better load transient response. The high bandwidth of the amplifier, along with high switching frequencies and low value inductors,

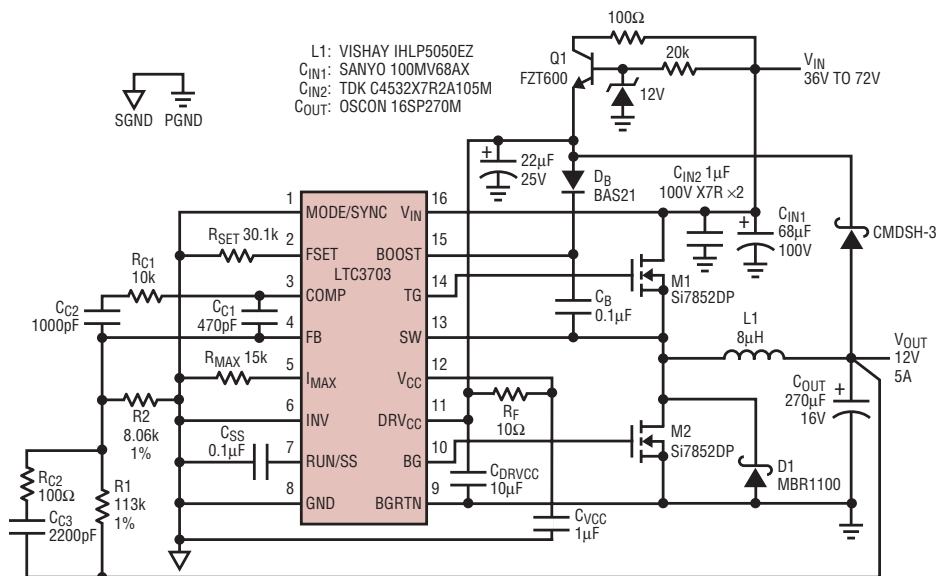


Figure 1. 36V-72V to 12V/5A synchronous step-down converter

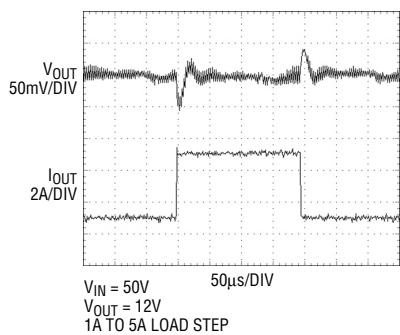


Figure 2. Load transient performance

allow very high loop crossover frequencies. Figure 2 illustrates the transient response of a 50V input, 12V output power supply (1A to 5A load step).

Outstanding Line Transient Rejection

The LTC3703 achieves outstanding line transient response using a patented feedforward correction scheme. With this circuit the duty cycle is adjusted instantaneously to changes in input voltage without having to slew the COMP pin, thereby avoiding unacceptable overshoot or undershoot. It has the added advantage of making the DC loop gain independent of input voltage. Figure 3 shows how large transient steps at the input have little effect on the output voltage.

Overcurrent Protection

Current limiting is very important in a high voltage supply. Because of the high voltage across the inductor when the output is shorted, the inductor can saturate quickly causing excessive currents to flow. The LTC3703 has current limit protection that uses V_{DS} -sensing of the bottom-side MOSFET to eliminate the need for a current sense resistor. The current limit is user programmable with an external resistor on the I_{MAX} pin to set the maximum V_{DS} at which the current limit kicks in.

Current limit works by discharging the RUN/SS capacitor when the V_{DS} exceeds the programmed maximum. The voltage on RUN/SS controls the LTC3703's maximum duty cycle, so discharging this capacitor reduces the duty ratio until the output current

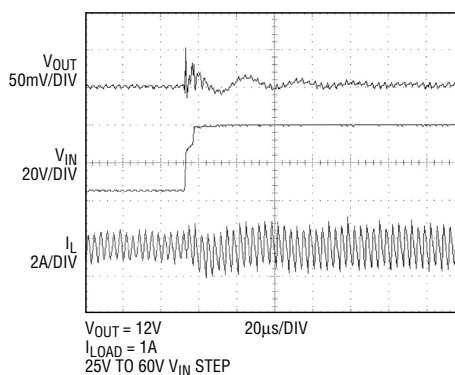


Figure 3. Line transient performance

equals the current limit. During the transient period while the capacitor is being discharged to the proper duty ratio, a cycle-by-cycle comparator guarantees that the peak inductor current remains in control by keeping the top MOSFET off when the V_{DS} of the bottom MOSFET exceeds the programmed limit by more than 50mV. The top MOSFET stays off until the inductor current decays below the limit ($V_{DS} < V_{IMAX}$). Figure 4 shows the inductor current waveforms during a short-circuit condition.

Application Examples

36V-72V to 12V/5A Synchronous Step-Down Regulator

The circuit shown in Figure 1 provides direct step-down conversion of a typical 36V-to-72V telecom input rail to 12V at 5A. With the 100V maximum rating of the LTC3703 and the MOSFETs, the circuit can handle input transients of up to 100V without requiring protection devices. The frequency is set to 250kHz to optimize efficiency and output ripple.

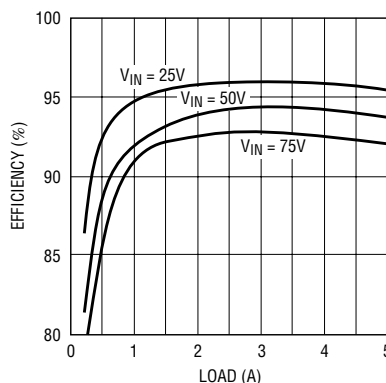


Figure 5. Efficiency of the circuit in Figure 1

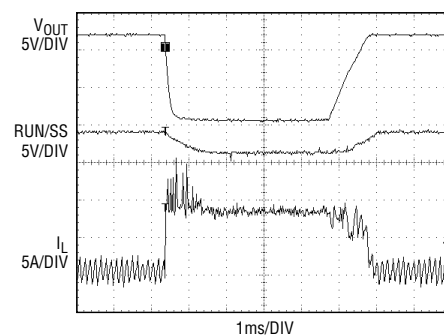


Figure 4. Short circuit performance

Figure 5 shows a peak efficiency of almost 95% at 50V input and 93% at 75V input. The loop is compensated for a 50kHz crossover frequency which provides $\sim 10\mu s$ response time to load transients. The IC and driver bias supply is derived from the 12V output when the output is in regulation, improving the efficiency. During startup or in a short circuit condition when the 12V output is not available, Q1 provides this IC bias voltage from the input supply.

For input voltages $>30V$, the practical choices for input capacitors are limited to ceramics and aluminum electrolytics. Ceramics have very low ESR but bulk capacitance is limited, while aluminum electrolytics have higher bulk capacitance but with much higher ESR. To meet RMS ripple and bulk capacitance requirements, using a combination of the two types is usually the best approach and also prevents excessive LC ringing at the input (by lowering the high Q of the ceramics) when the supply is connected.

Another consideration in high voltage converters such as this one is the boost diode. Low leakage and fast reverse recovery is essential. In order to limit power dissipation when this diode is reverse biased at high voltage, ultra-fast reverse recovery silicon diodes such as the BAS21 are recommended.

48V-to-12V 360W Isolated Power Supply

The circuit shown in Figure 6 can be used to generate a loosely regulated 12V, 30A isolated power supply for a

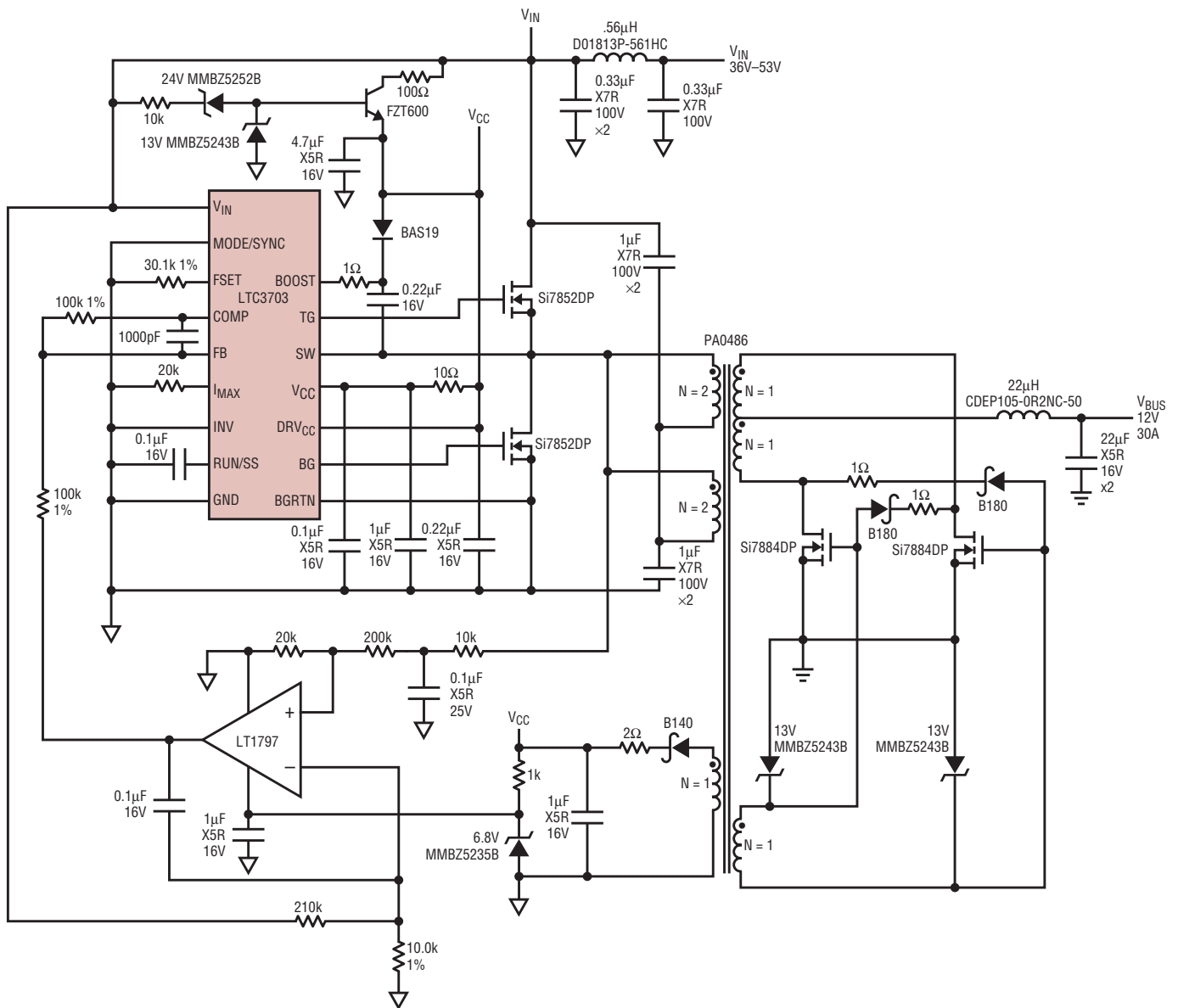


Figure 6. 48-to-12V 360W isolated power supply

360W intermediate bus that can then be stepped down with additional buck regulators to generate multiple low voltage high current outputs. Using this LTC3703-based DC/DC push-pull converter allows one to replace a conventional power module at a lower cost, smaller size and with superior efficiency. The push-pull topology has the advantage over forward/flyback topology of less voltage stress on the MOSFETs, allowing the use of a lower voltage, lower $R_{DS(ON)}$ device to improve efficiency.

The LTC3703 runs open loop using the LT1797 amplifier to force 50% duty cycle by driving the FB input of the LTC3703. The 2-to-1 transformer

step-down ratio thus generates an output voltage equal to $0.25 \cdot V_{IN}$. Running open loop in this fashion eliminates the need for complex feedback circuitry

over the isolation barrier. The second stage step-down regulators can then convert this intermediate bus voltage to more tightly regulated outputs. Figure 7 shows that an efficiency of almost 94% can be achieved at 30A.

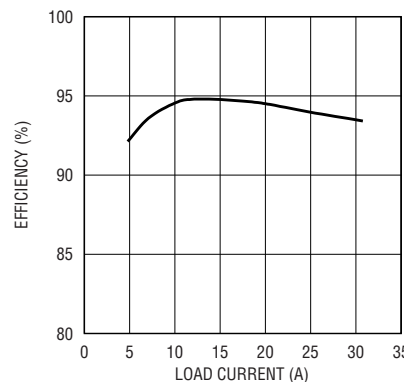


Figure 7. Efficiency of Figure 6

High Efficiency 12V-to-24V 5A Synchronous Step-Up Regulator

Synchronous boost converters have a significant advantage over non-synchronous boost converters in higher current applications due to the low power dissipation of the synchronous MOSFET compared to that of the diode in a non-synchronous converter. The high power dissipation in the diode requires a much larger package,

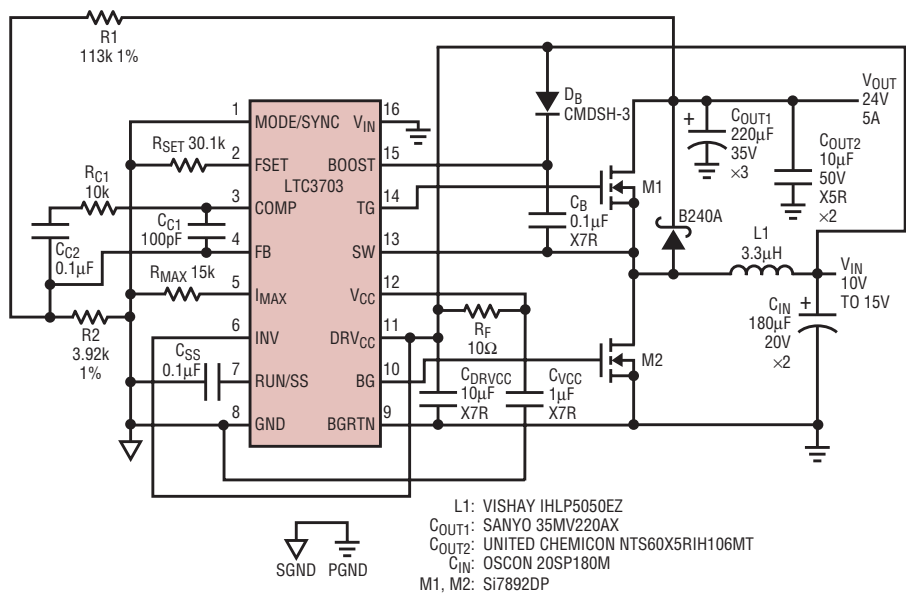


Figure 8. 12-to-24V, 5A synchronous boost converter

e.g. D²PAK, than the small SO8-size package required for the synchronous MOSFET to carry the same current.

Figure 8 shows the LTC3703 implemented as a synchronous 12V-to-24V/5A step-up converter that achieves a peak efficiency over 96%. The LTC3703 is set to operate as a synchronous boost converter by simply connecting the INV pin to greater than 2V. In boost mode, the BG pin becomes the main switch and TG, the synchronous switch; and aside from

this phase inversion, its operation is similar to the buck mode operation. In boost mode, the LTC3703 can produce output voltages as high as 80V.

Conclusion

The LTC3703 provides a set of features that make it an ideal foundation for a high input voltage, high performance, high efficiency power supplies. Those features include: 100V capability, synchronous N-channel drive, strong gate drivers, outstanding line and load

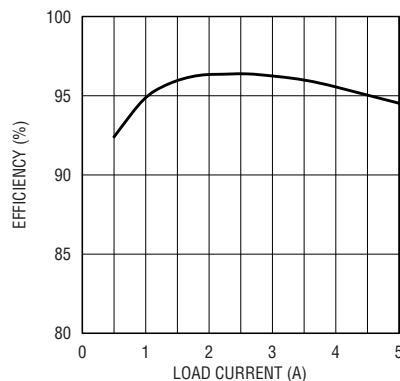


Figure 9. Efficiency of Figure 8's circuit

regulation, overcurrent protection, and 50µA shutdown current. It is particularly well suited to the harsh environments presented by automotive, telecom, avionics and industrial applications.

Its ability to directly step-down input voltages from up to 100V without requiring bulky transformers, or external protection, makes for low cost and compact solutions.

The LTC3703 is also versatile—easily applied to a wide variety of output voltages and power levels—mainly due its low minimum on-time (which allows low duty ratios), programmable frequency, programmable current limit, step-up or step-down capability, and package options.

LT1941, continued from page 12 useful because a switching regulator without soft-start can trip a current limited input supply during startup.

SLIC Power Supply with Soft-Start

SLICs (Subscriber Line Interface Circuits) require many voltages to

operate. The LT1941 can supply all of them. Figure 9 shows a typical SLIC. The two step-down switching regulators provide the 3.3V and 1.8V logic supplies. The inverting switching regulator generates both the -21.6V and -65V outputs using a charge pump configuration. The PGOOD3 pin indicates if the -21.6V output is

in regulation. Figure 10 shows the output voltages and input current during startup. Soft-start helps limit the peak input current.

Conclusion

The LT1941 is a monolithic triple output switching regulator that has the features and size to fit in a wide variety of applications. The high switching frequency allows the use of small external components, minimizing the total solution size. An internal op amp allows the part to directly regulate negative voltages. The wide input range of 3.5V to 25V and soft-start feature allow the LT1941 to regulate a broad array of power sources. Power good indicators and 2-phase switching help the LT1941 to work with almost any system.

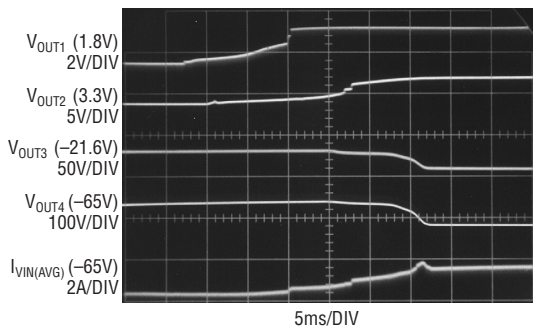


Figure 10. SLIC start-up waveforms with soft-start

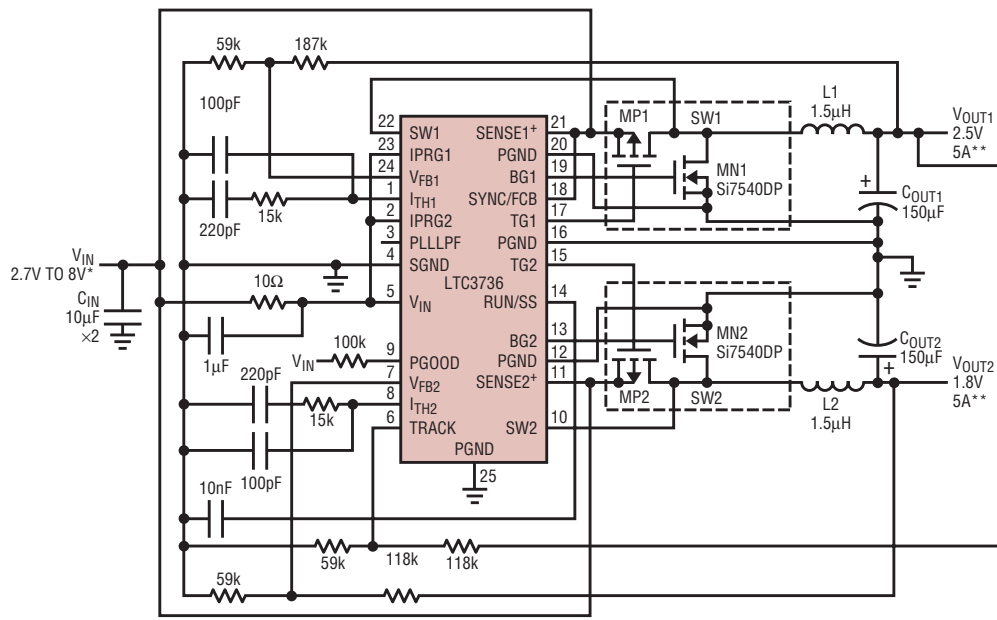
2-Phase Dual Synchronous DC/DC Controller with Tracking Provides High Efficiency in a Compact Footprint

Introduction

The LTC3736 is a 2-phase dual synchronous step-down DC/DC controller that requires few external components. Its No R_{SENSE} , constant frequency, current mode architecture eliminates the need for current sense resistors and improves efficiency, with-

out requiring a Schottky diode. The two controllers are operated 180 degrees out of phase, reducing the required input capacitance and power loss and noise due to its ESR. A tracking input allows the second output to track the first output (or another supply) dur-

ing startup, allowing the LTC3736 to satisfy the power-up requirements of many microprocessors, FPGAs, DSPs and other digital logic circuits. The LTC3736 is available in a tiny 4mm x 4mm leadless QFN package and 24-lead narrow SSOP package.



L1, L2: IHLP-2525CZ-01-1.5
 MP1/MN1, MP2/MN2: Si7540P COMPLEMENTARY P/N
 COUT1, COUT2: SANYO 4TPB150MC
 * THE LTC3736 IS ABLE TO OPERATE WITH INPUT VOLTAGES UP TO 9.8V.
 IN THIS CIRCUIT, V_{IN} IS LIMITED TO 8V BY THE MAXIMUM V_{GS} RATING OF THE POWER MOSFETS.
 ** MAXIMUM LOAD CURRENT IS DEPENDENT UPON INPUT VOLTAGE.
 THIS CIRCUIT CAN PROVIDE 5A WITH A 5V INPUT, 4A WITH A 3.3V INPUT.

Figure 1. 5V input, 2.5V and 1.8V dual output step-down converter

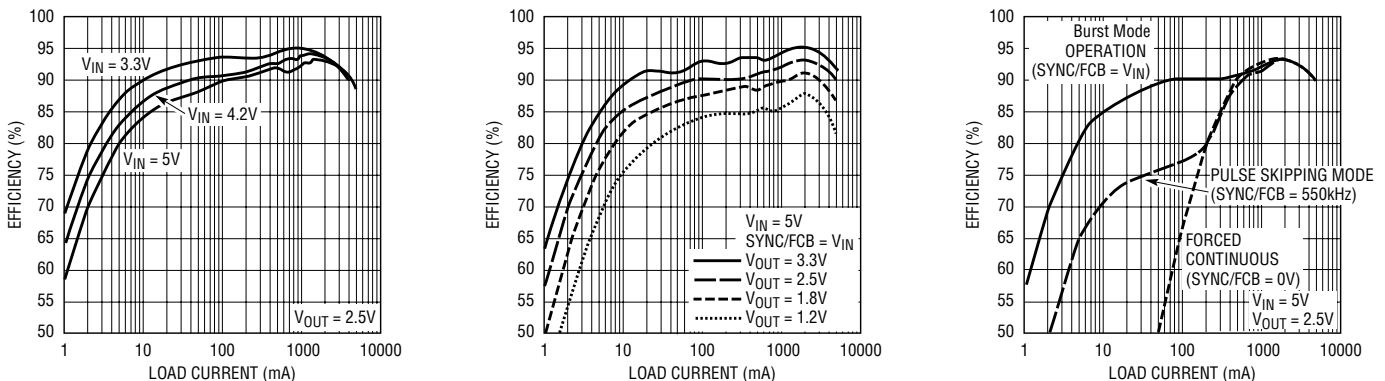


Figure 2. Measured efficiencies for Figure 1's circuit for various input voltages, output voltages, and modes of operation

LTC3736 Features

- ❑ 2-Phase, dual output synchronous controller
- ❑ No R_{SENSE} current mode architecture
- ❑ No Schottky diodes required
- ❑ Internal/external soft-start or tracking input ramps V_{OUT}
- ❑ Wide V_{IN} range: 2.75V to 9.8V
- ❑ $0.6V \pm 1.5\%$ over temperature reference
- ❑ Selectable frequency, current limit, and light load operation
- ❑ Power Good (PGOOD) indicator
- ❑ Available in 4mm × 4mm leadless QFN package or 24-lead narrow SSOP package

providing small output ripple at the expense of light load efficiency. In pulse skipping mode, inductor current is not allowed to reverse and cycles are skipped only as needed to maintain regulation, providing smaller output ripple but lower efficiency than Burst Mode operation. The inductor current waveforms for these three modes are shown in Figure 3.

Switching frequency may be selected from 300kHz, 550kHz, or 750kHz using the PLLPF pin, or the LTC3736 can be synchronized to an external clock signal between 250kHz and 850kHz using the LTC3736's phase-locked loop (PLL). High frequency operation permits the use of smaller inductors and capacitors, further

Circuit Description

Figure 1 shows a typical application for the LTC3736. This circuit provides two regulated outputs of 2.5V and 1.8V from a typical input voltage of 5V, but it can also be powered from any input voltage between 2.75V and 9.8V (depending on the voltage rating of the power MOSFETs). This wide input range makes the LTC3736 suitable for a variety of input supplies, including 1- and 2-cell Li-Ion and 9V batteries, as well as 3.3V and 5V supply rails.

The LTC3736 uses the drain to source voltage (V_{DS}) of the power P-channel MOSFET to sense the inductor current. The maximum load current that the converter can provide is determined by the $R_{DS(ON)}$ of the PFET, which is a function of the input supply voltage (which provides the gate drive). The maximum load current can also be changed independently for each channel using the three-state current limit programming pins IPRG1 and IPRG2. In this circuit, each output can provide up to 5A from a 5V input supply. Efficiency for this circuit is as high as 95%, as shown in Figure 2. In drop-out, the LTC3736 can operate at 100% duty cycle, providing maximum operating life in battery powered systems.

At light loads, the LTC3736 offers several modes depending on the needs of the application: Burst Mode® operation, forced continuous operation, or pulse skipping mode (when synchronized to an external clock). The mode is selected at the SYNC/FCB pin as seen in Figure 2c. Burst Mode operation provides the highest efficiency, but at the expense of increased

output voltage ripple at light loads. In forced continuous operation, the power MOSFETs continue to switch every cycle (constant frequency) and inductor current is allowed to reverse,

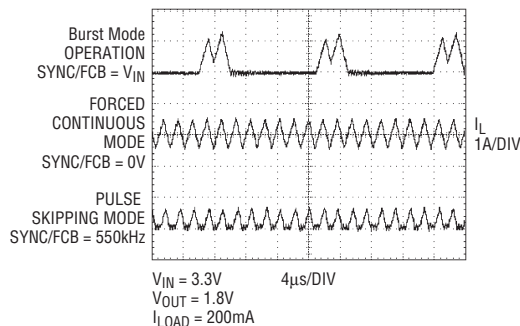


Figure 3. Inductor current at light load

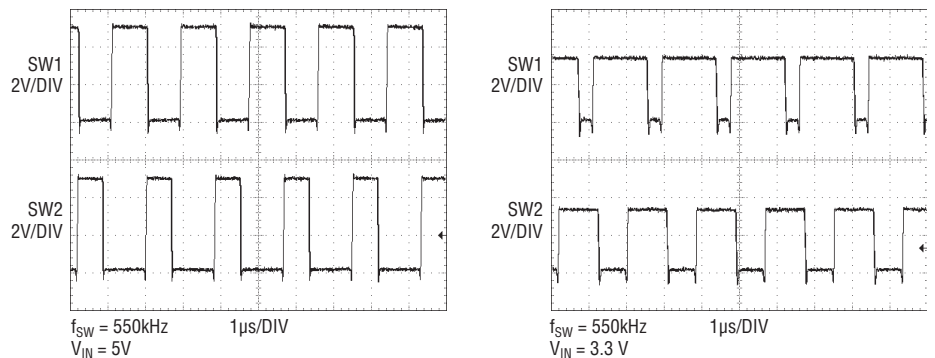


Figure 4. SW node waveforms depicting out-of-phase (2-phase) operation

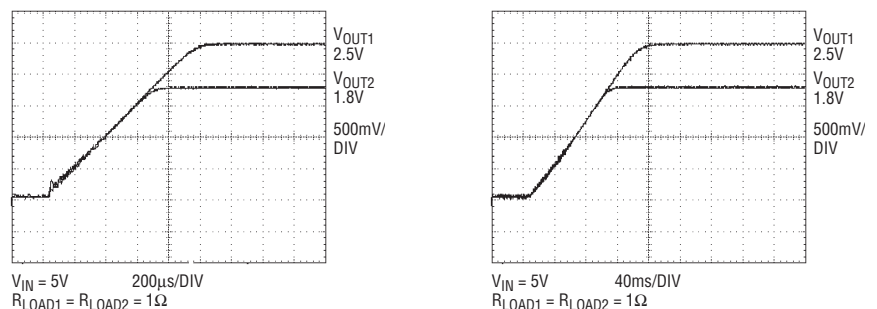


Figure 5. Startup waveforms showing soft-start and tracking (internal 1ms soft-start on the left and external 150ms soft-start on the right)

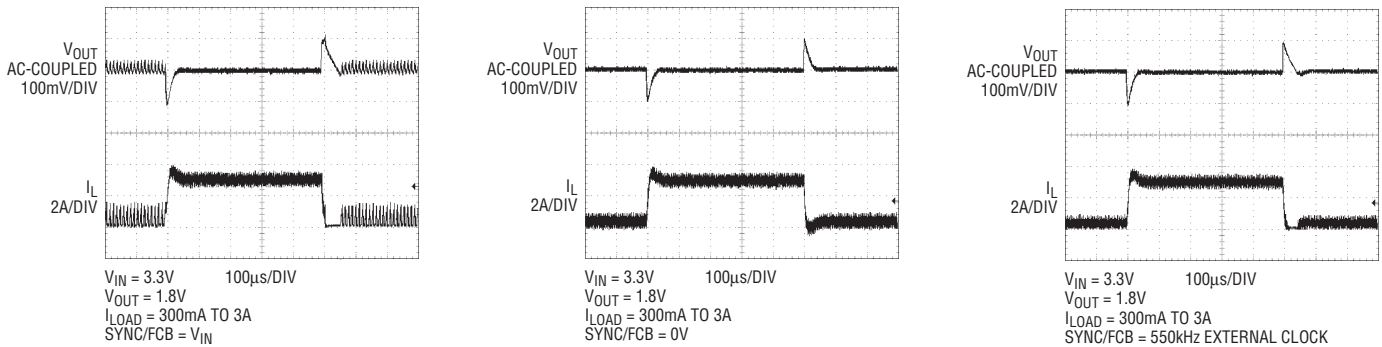


Figure 6. Transient response to a 300mA to 3A load step (left to right, Burst Mode operation, forced continuous, and pulse skipping mode)

reducing the total solution size. The 2-phase switching behavior of the LTC3736 is depicted by the SW node waveforms in Figure 4.

Tracking

The LTC3736 features an internal soft-start that ramps V_{OUT1} smoothly from 0V to its final value in 1ms. This soft-start time can be increased externally by connecting a capacitor on the RUN/SS pin to ground. The startup of V_{OUT2} can be programmed externally (with two resistors) to track V_{OUT1} (or

any other supply or reference) using the LTC3736's TRACK pin input. Use of the TRACK pin permits ratiometric or tracking startup of V_{OUT2} . The open-drain PGOOD output indicates when both outputs are within $\pm 10\%$ of their regulated values. Figure 5 shows the startup waveforms for the outputs of the Figure 1 circuit using the internal soft-start and an optional external soft-start capacitor, with V_{OUT2} programmed to track V_{OUT1} in a 1:1 ratio.


Stable with All Types of Output Capacitors

The compensation components on the I_{TH} pins can be easily adjusted to make LTC3736-based power supplies stable for a wide variety of output capacitors, including tantalum, aluminum electrolytic, and ceramic capacitors. Figure 6 shows the transient response to a load step for the circuit in Figure 1.

3.3V to 2.5V at 8A 2-Phase, Single Output Regulator

Figure 7 shows the LTC3736 configured in a 2-phase, single output converter. This regulator can provide 8A of load current to a 2.5V output from a 3.3V input supply. The two output stages of the LTC3736 continue to operate out of phase, but supply power to a single output. This 2-phase, single output operation reduces not only the required input capacitance by up to 50%, but also the required output capacitance.

Conclusion

LTC3736-based power supplies can deliver high efficiency for input voltages up to 9.8V and output load currents as high as 5A. The tracking input allows the two outputs to smoothly track during startup. Its 2-phase, high frequency, No R_{SENSE} , synchronous current mode architecture results in a small solution size with no Schottky diodes and no current sense resistors. 

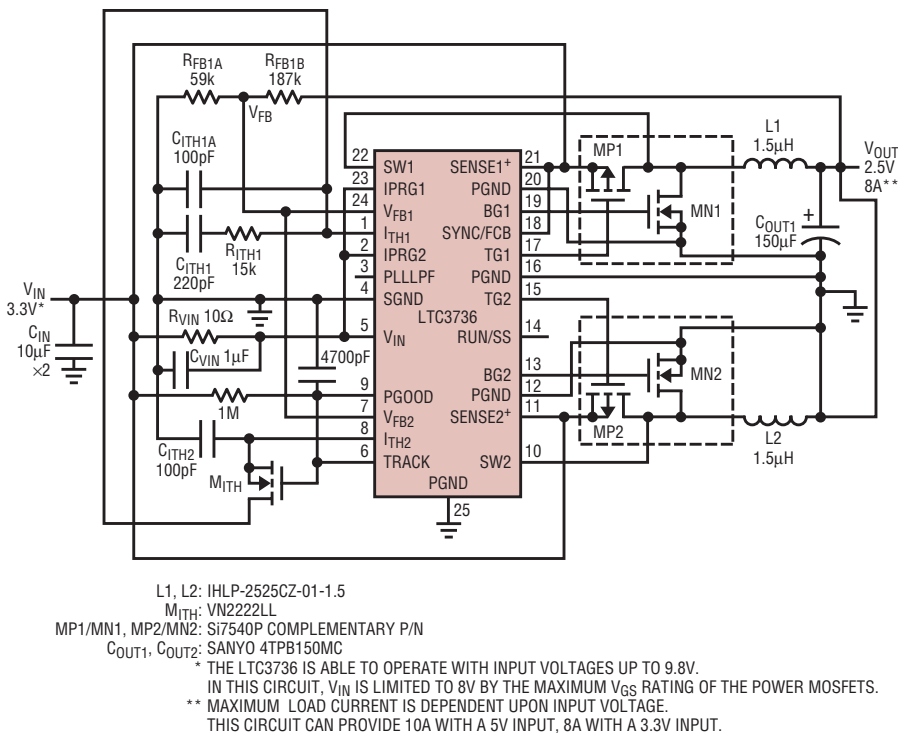


Figure 7. 3.3V to 1.8V at 8A 2-phase step-down converter

For more information on parts featured in this issue, see <http://www.linear.com/go/ltmag>

PWM Controller Offers High Performance, Low Cost, Single Transistor Forward Converter Solutions

by Mark Marosek and Goran Perica

Introduction

An LT1952-based forward converter can be used to replace power modules in telecom and industrial applications at less than half the cost; without the headaches that designing a traditional forward converter would cause. The LT1952-based forward converter is ideal for 25W to 500W systems that require high performance and reliability combined with design simplicity, low cost and minimal space usage.

The LT1952 is a single switch, current mode PWM controller with integrated synchronous control output, wide range programmable volt-second clamp and precision over-current limit threshold—all features which make it simple to create high performance forward converters.

The LT1952 includes key features such as a synchronous control output with programmable delay for achieving the highest efficiencies. A new wide range programmable volt-second clamp allows a designer to minimize transformer and MOSFET

size, increase reliability and improve power-per-component utilization. The volt-second clamp accuracy also allows semi-regulated bus converter applications without the need for an optocoupler, optocoupler driver, reference or feedback network.

The LT1952 uses a new architecture for current overload detection to improve accuracy, allowing a significant reduction in power component sizing. The LT1952 has integrated soft start for controlled exit from shutdown or undervoltage lockout. Soft start logic provides low stress output short circuit protection by implementing a repeated soft start re-try hiccup mode. The LT1952 allows for programming of undervoltage lockout (UVLO) with hysteresis, switching frequency from 100kHz to 500kHz, linear slope compensation and blind-blanking to remove the need for external RC filtering at the current sensing inputs.

Programming these features is remarkably simple and allows the

converter solution to be optimized for smallest component size, lowest cost and highest performance. The LT1952 low startup current feature also improves efficiency and reduces external component count by allowing bootstrap startup from high input voltages. It is available in a small 16-pin SSOP package and supports both isolated and non-isolated outputs.

Features

The LT1952 is a fixed frequency, current mode, synchronous PWM controller designed to improve performance and reduce solution size for boost, flyback and forward converters. It is specifically optimized for control of a single switch synchronous forward converter topology. The block diagram in Figure 4 shows all of the key functions.

The LT1952 operates with input voltages between 8.75V and 25V. In normal operation the SD_VSEC (shutdown/volt-second) pin must

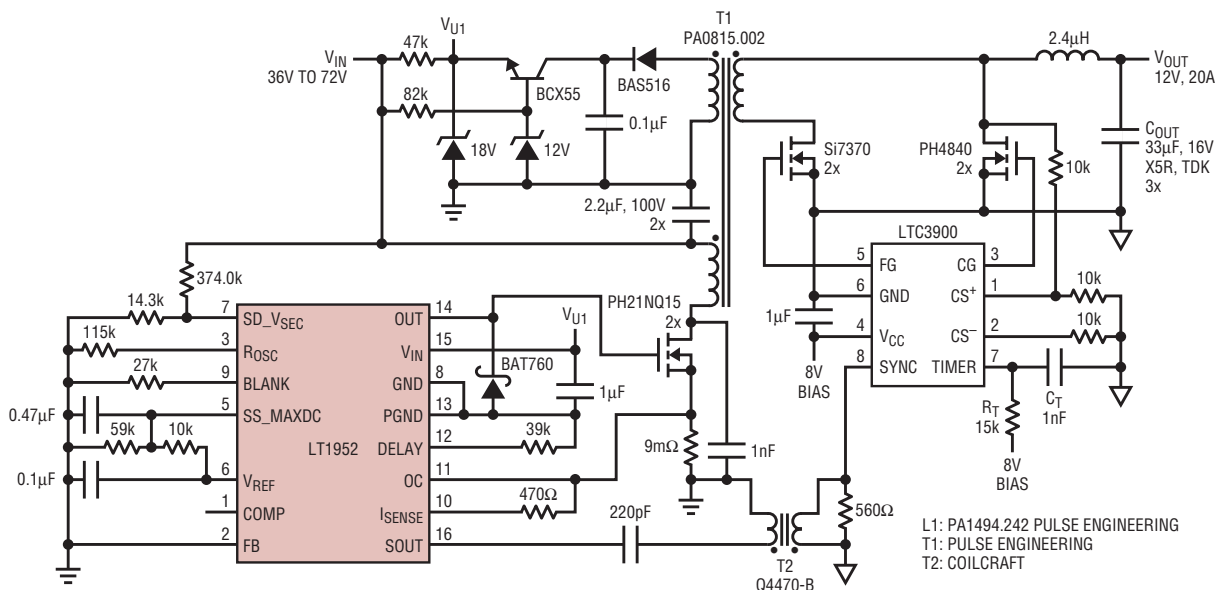


Figure 1. 36V to 72V input, 12V at 20A, no optocoupler synchronous bus converter

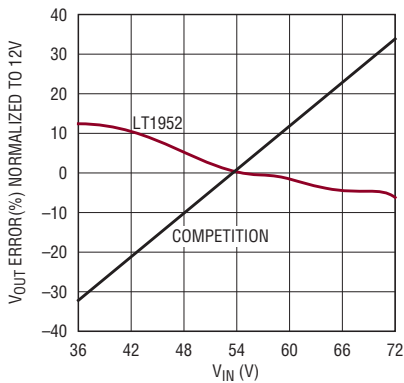


Figure 2. V_{OUT} error (normalized to 12V) vs V_{IN} for the bus converter in Figure 1

exceed 1.32V and the V_{IN} pin must exceed 14.25V to allow the part to turn on. This combination of pin voltages allows the 2.5V V_{REF} pin to become active, supplying the LT1952 control circuitry and providing up to 2.5mA external drive. SD_VSEC threshold

can be used for externally programming an undervoltage lockout (UVLO) threshold on the system input voltage. Hysteresis on the UVLO threshold can also be programmed since the SD_VSEC pin draws 11 μ A just before part turn on and 0 μ A after part turn on. The LT1952 460 μ A start-up current allows low power startup with a single high value resistor that charges a small input capacitor, which in turn provides sufficient power during converter startup.

An internal bandgap voltage reference provides an accurate 1.23V to the positive input of the LT1952 error amplifier. This allows precision programming of output voltages referenced to the error amplifier FB pin in non-isolated applications. The error amplifier is a true op amp allowing a wide range of compensation networks

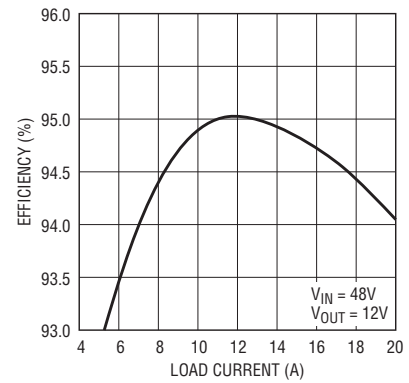


Figure 3. Efficiency vs load current for bus converter in Figure 1

and can also be used to provide a bias to the optocoupler in isolated applications. The error amplifier COMP output can be disabled for apps that require direct control over switch current by connecting the FB pin to the 2.5V V_{REF} pin.

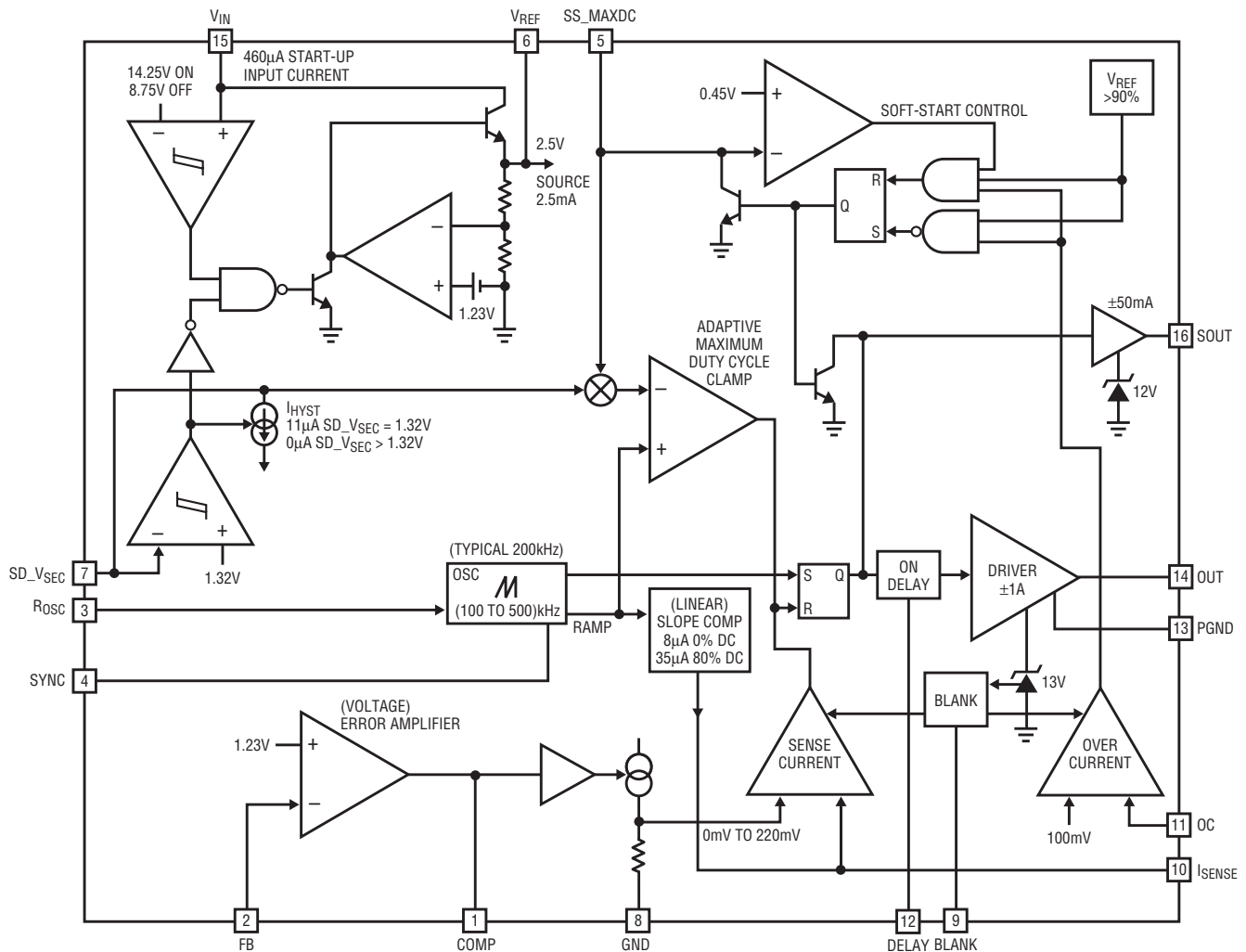


Figure 4. LT1952 block diagram

Precision Overcurrent Detection Reduces Size and Cost

The current mode architecture of the LT1952 uses the COMP pin voltage to define a cycle-by-cycle current limit threshold between 0mV and 220mV at the I_{SENSE} pin (Figures 4 and 5). Slope compensation required for current mode control is programmed by inserting a resistor in series with the I_{SENSE} pin to optimize loop bandwidth for various inductors.

The LT1952 also includes a unique architecture for accurate overcurrent detection. A precision 100mV threshold at the OC pin—separate from the conventional cycle-by-cycle current sensing input at the I_{SENSE} pin—is used to detect current overload. This separate OC pin threshold provides a precision brick wall overcurrent limit— independent of duty cycle, regardless of the amount of slope compensation programmed externally. This allows a significant reduction in power component size and cost. Exceeding the OC pin threshold triggers immediate turn off of the LT1952 output drivers and initiates a soft start hiccup mode.

Synchronous Control Output Provides High Efficiency

The LT1952 has two PWM outputs, OUT and SOUT. The OUT pin provides a ±1A peak gate drive clamped to 13V for driving the main power MOSFET. The SOUT pin has a ±50mA peak drive clamped to 12V. The synchronous control signal provided by SOUT is a key feature of the LT1952. It allows a secondary side controller (LTC1698 or LTC3900) to drive synchronous rectifier MOSFETs with extremely high efficiency.

A programmable delay between SOUT and OUT allows for cancellation of system delays through the secondary side controller to achieve

high efficiency (Figure 6). An increase of resistor value in the DELAY pin increases the programmed delay. The fixed switching frequency at SOUT and OUT is programmable using a resistor from the R_{OSC} pin to ground for a switching frequency range from 100kHz to 500kHz. The LT1952 also allows synchronization to an external clock at the SYNC pin at up to 1.5 times the natural programmed frequency.

Blind Blanking Ignores All Leading Edge Spikes Without RC Filtering

With extremely low current sensing thresholds to minimize power dissipation, the LT1952 uses a new blind blanking approach to avoid the need for RC filtering of its current sensing inputs.

Leading edge voltage spikes generated during MOSFET turn on can cause false trip of current sensing comparators. The solution to this problem is to blank the current comparator latch during MOSFET turn on (Figure 4). Conventional current mode controllers only blank their current limit threshold partially; any leading edge spikes 2–3 times above the nominal current limit threshold can still cause erroneous termination of the PWM output. To solve this problem, conventional controllers require external RC filtering which can distort the current sensing waveform causing large errors in the converter’s overload current level.

The LT1952 blind blanking strategy allows optimal performance by ignoring all leading edge spikes during the blanking period without distortion of the current sense signal. Even the low 100mV overload threshold of the LT1952 requires no RC filtering. Since the LT1952 has built in soft start, any output overload condition detected outside of the blanking period immediately

turns off the power MOSFET and triggers a soft start sequence before current can increase in the output inductor. The blanking period is programmed with a resistor from the Blank pin to ground. Increased resistance extends the blanking period.

Volt-Second Clamp: Avoiding Transformer Saturation without Increasing Transformer and MOSFET Size

A key feature of the LT1952 is a wide range programmable volt-second clamp. It adjusts maximum switch duty cycle inversely proportional to system input voltage, independent of the main control loop of the converter (Figure 7). In a single switch forward converter this provides a safeguard against transformer saturation (and catastrophic damage to power components) during load and line transients—when the main control loop tries to push the duty cycle towards 100%.

A programmable and accurate volt-second clamp allows the smallest sizing for the transformer and power components. The conventional alternative is to have a fixed maximum switch duty cycle—as high as 80%—in order to achieve output regulation at minimum input voltage. If a load step occurs at the high input line, however, where the natural duty cycle of the converter is <40%, the loop tries to force the highest duty cycle possible (80%) set for the part. The result is a volt-second product in the transformer that is twice the typical value during normal operation, thus dictating a much larger transformer than is needed for normal operation.

A big transformer is not the only problem. For the transformer to properly reset and avoid saturation, the transformer reset voltage is twice the worst-case expected during normal operation, so higher-voltage-rated power MOSFETs are also required.

The LT1952 volt-second clamp programmed for the same application, automatically adjusts maximum possible duty cycle close to 40% at high input voltage. The result is an LT1952 volt-second product that is half of that

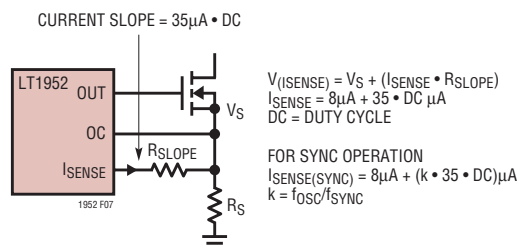


Figure 5. Current sensing, slope compensation and overcurrent limit

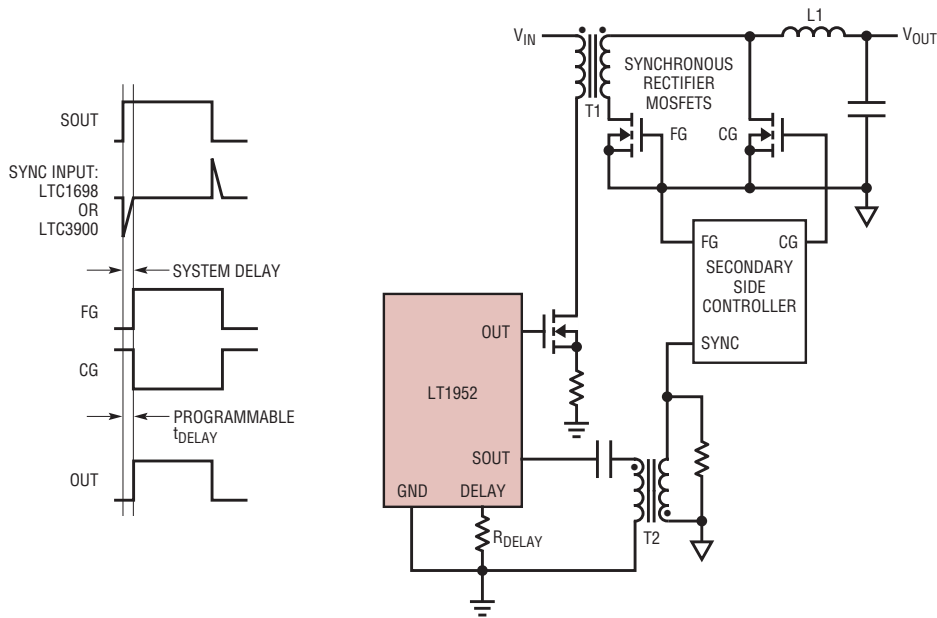


Figure 6. Synchronous control output (SOUT) and programmable delay

allowed by a conventional controller during load transients, allowing for a smaller transformer and power components. Conventional controllers attempt to solve the problem by limiting the maximum duty cycle of the switch to less than 50% (reducing power-per-component utilization) or by using more robust power components leading to a larger, more costly and less reliable solution.

Since the SD_VSEC pin is externally divided down from system input voltage to set the undervoltage lockout threshold for the converter (see Figure 7), the SD_VSEC pin already provides transformer input voltage information to the LT1952 volt-second clamp. An increase in transformer input voltage by a factor X causes SD_VSEC voltage to increase by the same factor and the

maximum on time of the OUT pin to change by 1/X. The result is a maximum switch duty cycle that adapts to keep the volt-second product (input voltage times maximum switch on time) constant.

The minimum voltage on the SD_VSEC pin, which defines the point where maximum switch duty cycle is at its greatest, is set by the fixed turn-on threshold of the LT1952. A separate pin with a wide programmable range, SS_MAXDC (soft start, max duty cycle adjust), allows this maximum switch duty cycle to be adjusted in order to program the volt-second product for the transformer. SS_MAXDC is easily programmed with a resistor divider from the VREF pin. An increase of SS_MAXDC voltage increases maximum switch duty cycle.

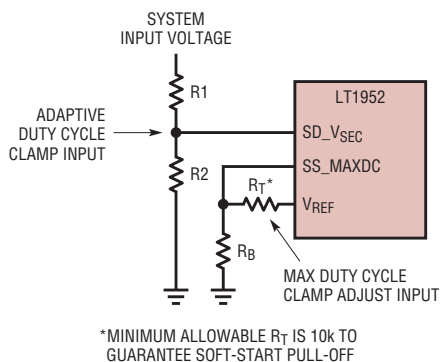
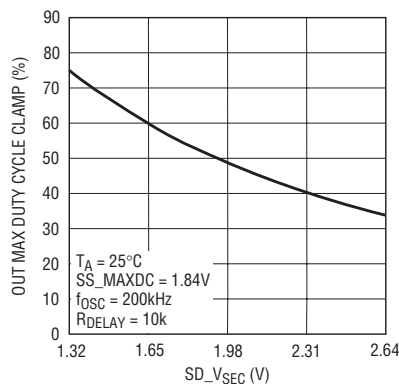


Figure 7. LT1952 volt-second clamp



Soft Start

The SS_MAXDC pin is also used as a soft start pin. The external resistor divider used to set the SS_MAXDC pin voltage provides the soft start charging supply for the SS_MAXDC pin. Simply adding a capacitor from the SS_MAXDC pin to ground completes the soft-start function (Figure 8).

Whenever the LT1952 shuts down, a system undervoltage lockout or current overload fault occurs, the SS_MAXDC pin is discharged with 800µA to ground and the LT1952 output drivers are immediately turned off. The SS_MAXDC pin is only released for charging when it has been discharged below its reset threshold of 0.45V and all faults have been removed.

The LT1952 integrated soft start logic controls exit from shutdown and undervoltage lockout and provides a low stress soft start re-try (hiccup mode) during a converter output short circuit. As the SS_MAXDC pin charges up in a soft-start sequence, the maximum possible duty cycle at the OUT pin increases. The result is a converter output that rises with the smooth RC charging characteristic of the SS_MAXDC pin voltage.

Applications

36V to 72V Input to Isolated 12V at 20A (No Optocoupler) Bus Converter

The wide programmable range and accuracy of the LT1952 volt-second clamp makes the LT1952 an ideal choice for bus converter applications where the volt-second clamp provides line regulation for the converter output. The 12V at 20A bus converter application in Figure 1 provides a semi-regulated isolated output without the need for an optocoupler, optocoupler driver, reference or feedback network.

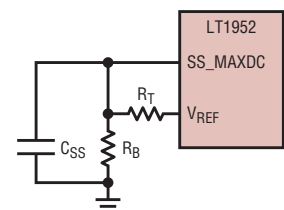


Figure 8. Soft start programming

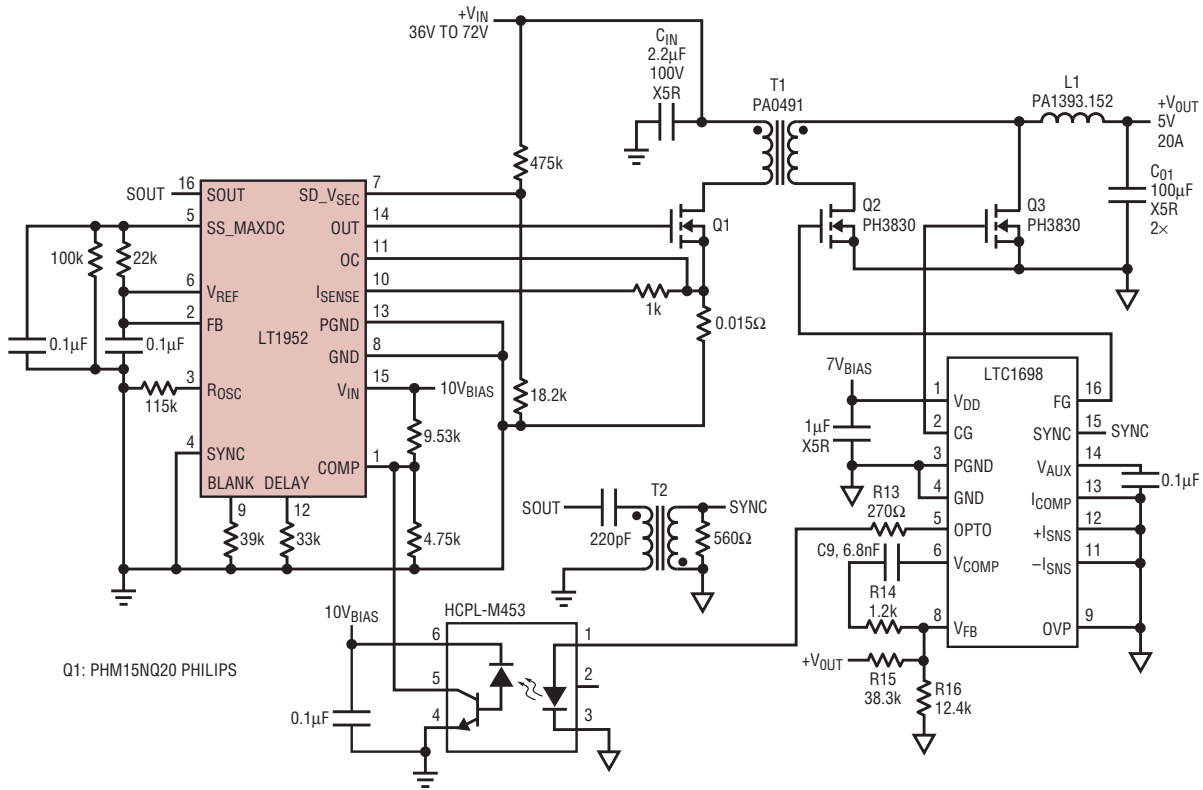


Figure 9. 36V to 72V input, 5V at 20A 1/8th brick synchronous forward converter

In the application shown in Figure 1 the volt-second clamp keeps the 12V output within $\pm 10\%$, even with a wide 36V to 72V input range (see Figure 2).

Most bus converter solutions can only run with a narrow 44V to 52V input range. Some solutions accept input ranges of 36V to 72V, but they typically use a fixed duty cycle architecture, which allows the output voltage to vary by $\pm 33\%$. The LT1952-based bus converter provides a tighter supply for point-of-load converters. This enables optimized sweet spot

efficiency and expands the range of usable downstream converters to those that would typically not run from the poorly controlled outputs of a fixed duty cycle bus converter.

Efficiency for the LT1952-based bus converter in Figure 1 peaks at 95% and achieves 94% at 20A (Figure 3). The solution is only slightly larger than 1/4 brick size and utilizes all-ceramic capacitors for high reliability. The transformer and inductor are standard components. The DC/DC converter delivers over 240W, is only 0.4" high and measures a mere 2.25" by 1.5".

The converter can be used as a front end (isolating) converter in telecom systems with multiple outputs. Once the isolation boundary is established, buck converters such as LTC1778, LTC3728/29, LTC1735 and LTC3731 can be used to generate low voltage (1.5V, 1.8V, 2.5V and 3.3V), high current core voltages.

Simple 5V at 20A 1/8 Brick Converter

An LT1952-based synchronous forward converter provides a highly efficient 36V to 72V input, 5V at 20A 1/8 brick converter (Figure 9). The single switch topology keeps the solution simple. The LT1952 volt-second clamp allows the power components in this solution to be operated at up to 75% duty cycle, achieving 100W of output power using only a single primary MOSFET. The LT1952 synchronous control output with programmable delay allows optimum timing for the LTC1698 to drive synchronous rectifier MOSFETs.

The advantage of system board thermal conduction, precision over-current control and 95% peak

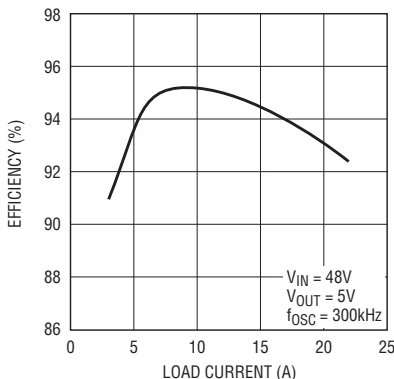


Figure 10. Efficiency vs load current for 5V at 20A 1/8th brick in Figure 9

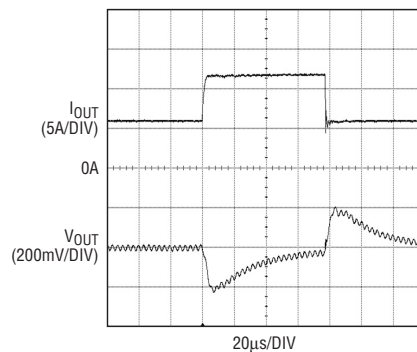


Figure 11. Output transient response for circuit in Figure 9 (load step 6A to 12A)

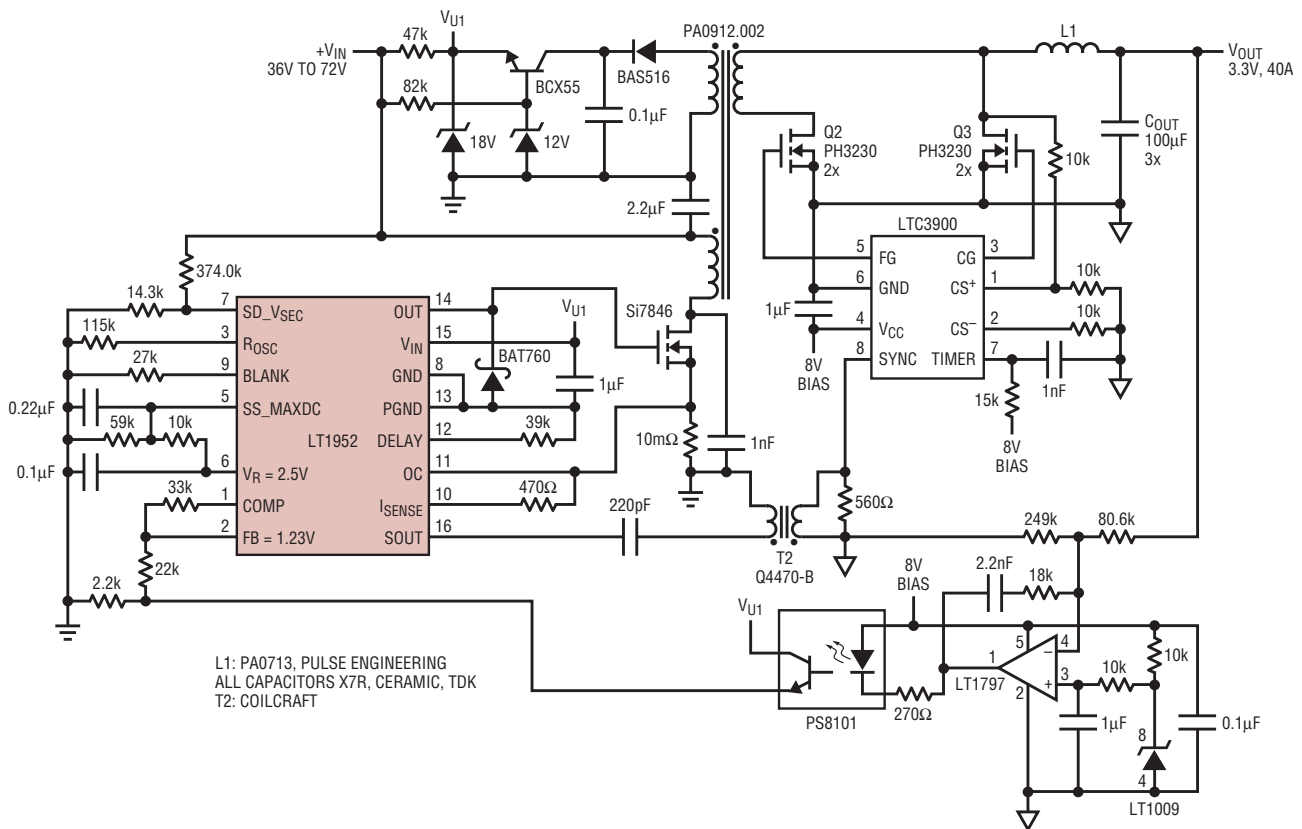


Figure 12. 36V to 72V input, 3.3V at 40A output synchronous forward converter

efficiencies from synchronous rectification (Figure 10) reduces component temperature rise and eliminates the need for bulky heat sinks.

The LT1952-based forward converter has an ultrafast transient response that is superior to power module solutions (Figure 11) and uses only ceramic capacitors for improved reliability, small size and low output ripple voltage. The 7mm height allows dense packaging and higher currents are achievable by simple scaling of the power components.

36V to 72V input, 3.3V 40A Converter

An LT1952-based synchronous forward converter provides the ideal solution for power supplies requiring high efficiency at low output voltages with high load currents. The 3.3V 40A solution in Figure 12 achieves peak efficiencies of 92.5% (Figure 13) by minimizing power loss due to rectification at the output.

It is well known that replacing Schottky rectifier diodes with synchronous rectifier MOSFETs significantly

increases efficiency. Further efficiency gains are achieved by driving the MOSFETs with the optimum control timing (to avoid primary and rectifier MOSFET cross conduction or MOSFET body diode conduction). The LT1952 synchronous rectifier control output SOUT, with programmable delay, optimizes timing control for a secondary side synchronous MOSFET controller (LTC3900), which results in high efficiency synchronous rectification.

At high output currents, such as the 40A delivered in Figure 12,

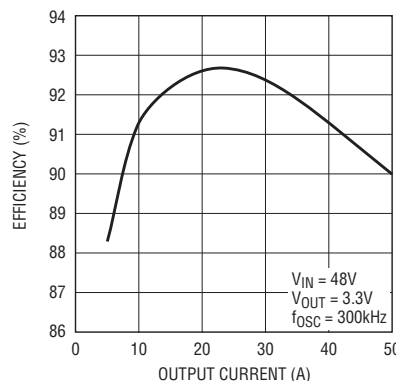



Figure 13. Efficiency vs load current for 3.3V at 40A converter in Figure 12

typical overcurrent detection inaccuracies and poorly thought out timing control schemes can require power components rated at over 100A. The LT1952 provides a precision current limit detection scheme combined with soft start control logic to limit maximum peak currents to less than 10% above the rated 40A. This allows a significant reduction in power component sizing.

An output short circuit results in immediate turn off of the LT1952 output drivers and initiation of a soft start hiccup mode—resulting in a low stress protection mode running at as low as 15% of maximum rated power.

Conclusion

An LT1952-based single switch forward converter is ideal for 25W to 500W power systems where high performance, high efficiency and high reliability are required in a small space with low complexity and low cost. A simple LT1952-based forward converter offers superior performance over power module solutions and is far less expensive. 

Replace -48V ORing Diodes with FETs to Reduce Heat and Save Space

by James Herr

Introduction

Critical high availability telecom systems often employ parallel-connected power supplies or battery feeds to achieve redundancy and enhance system reliability. Power supply selection is usually left to ORing diodes, but there is significant forward voltage drop in diodes, which reduces efficiency. The voltage drop also reduces the available supply voltage and dissipates significant power. A better solution would retain the diode behavior without the undesirable voltage drop and the resulting power dissipation.

The LTC4354 is a negative voltage diode-OR controller that replaces ORing diodes by driving two external N-channel MOSFETs as pass transistors. The device maintains a small 30mV voltage drop across the MOSFET at light load, while at heavy load, the low $R_{DS(ON)}$ of the external MOSFET reduces the power dissipation. Lower power dissipation saves the space and cost of extra heat sinks.

For example, in a 10A, -48V application, the voltage drop across a 100V Schottky diode (MBR10100) is around 620mV. Extra PCB space or additional heat sinking is required to handle the 6.2W of power dissipation. A LTC4354 with a 100V N-channel MOSFET (IRFS4710) as the pass transistor dissipates only 1.4W of power—due to the low 14mΩ(max) $R_{DS(ON)}$ of the MOSFET—that can be easily dissipated across the existing PCB. Figure 1 compares the power dissipation of the Schottky diode and the MOSFET.

Regulated MOSFET Drop Ensures Smooth Switchover

The LTC4354 controls two external N-channel MOSFETs with the source pins connected together. This common source node is then connected to the V_{SS} pin, which is the negative supply of the device. The positive supply for the device is derived from -48V_RTN

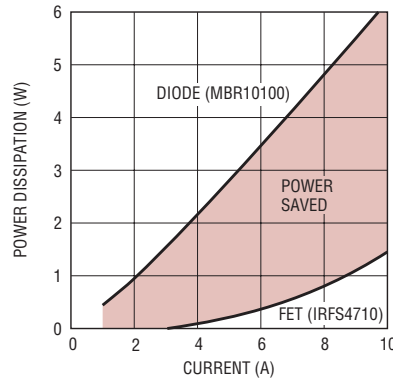


Figure 1. FET-based diode circuit saves power

through an external current limiting resistor (R_{IN}). An internal shunt regulator clamps the voltage at the V_{CC} pin to 11V above V_{SS} . At power-up, the initial load current flows through

the body diode of the MOSFET and returns to the supply with the lower terminal voltage. The associated gate pin immediately starts ramping up and turns on the MOSFET. The amplifier regulates the voltage drop between the source and drain connections to 30mV. If the load current causes more than 30mV of drop, the gate rises to further enhance the MOSFET. Eventually the MOSFET is driven fully on and the voltage drop is equal to $R_{DS(ON)} \cdot I_{LOAD}$ (see Figure 2).

When the power supply voltages are nearly equal, this regulation technique ensures that the load current is smoothly shared between them without oscillation. The current level flowing through each pass transistor

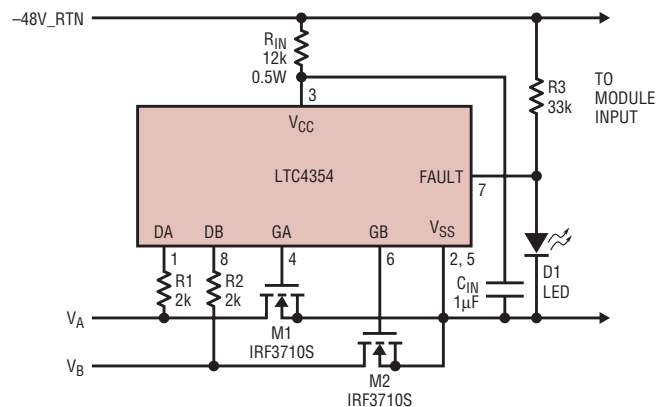


Figure 2. -36V to -72V at 5A typical design example

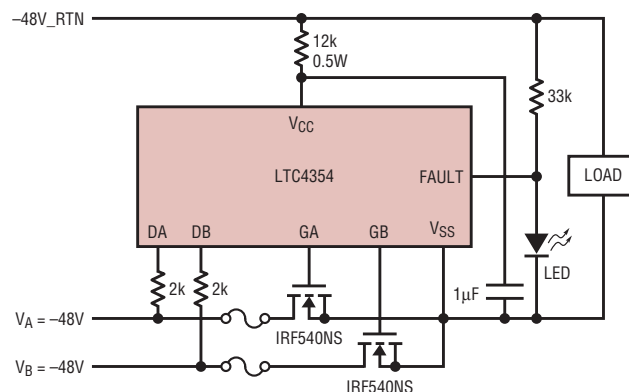


Figure 3. -48V diode-OR controller monitors and reports open fuses

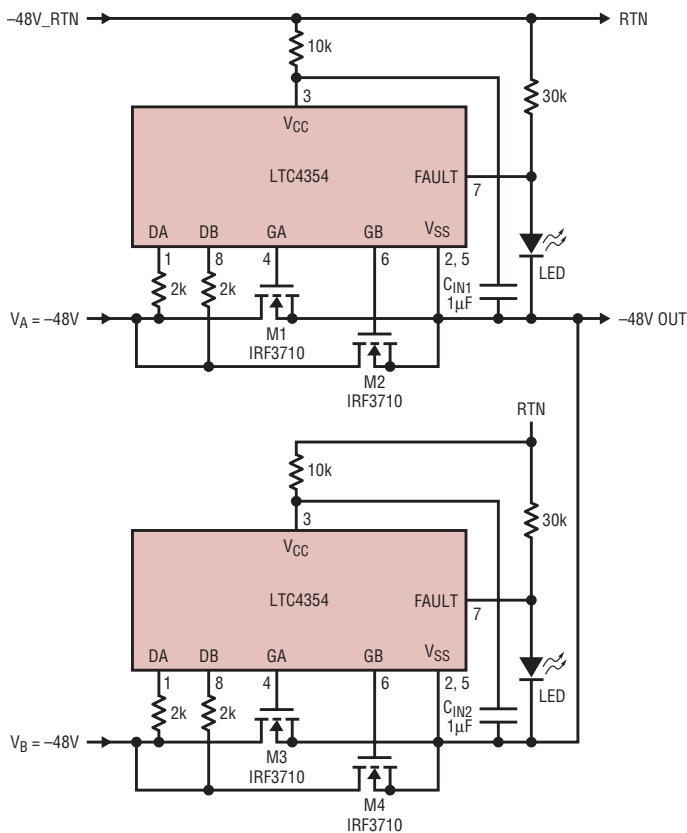


Figure 4. Parallel MOSFETs for high current (up to 20A) application

remaining MOSFET. This raises the potential at the V_{SS} pin and causes a large voltage drop across the failed MOSFET. This can also indicate a blown fuse in series with the MOSFET (see Figure 3).

MOSFET short: The MOSFET that is conducting most or all of the current has failed short. In normal operation this does not trigger the fault flag. But should the power supply with the lower terminal voltage rise up, due to excessive load current or it is replaced by another supply with higher terminal voltage, a large cross conduction current will flow between the supplies. In this case, the voltage drop across the MOSFET that is not damaged can easily surpass the fault threshold.

Handle Large Currents with Multiple LTC4354s

Multiple LTC4354s can be connected in parallel to accommodate large supply currents (see Figure 4). Multiple MOSFETs can also be connected in parallel to a single gate drive pin but at the cost of a longer turn-off time when the current reverses.

Low Voltage Operation

Multiple low voltage supplies can also be diode-ORed together using LTC4354 to increase reliability. Figure 5 shows the LTC4354 controlling two logic level N-channel MOSFETs providing the diode-OR function for two $-5.2V$ power supplies. The current limiting resistor at the V_{CC} pin is not needed since the LTC4354 can

continued on page 36

depends on the $R_{DS(ON)}$ of the MOSFET and the output impedance of the supplies.

In the case of supply failure, such as an input supply short to $-48V_{RTN}$, a large reverse current flows from the $-48V_{RTN}$ terminal through the MOSFET that is on. This charges up the load capacitance, and eventually flows through the body diode of the other MOSFET to the second supply. The LTC4354 detects this failure condition as soon as it appears and turns off the MOSFET in less than $1\mu s$. This fast turn-off prevents the reverse current from ramping up to a damaging level.

Fault Output Detects Damaged MOSFETs and Fuses

The LTC4354 monitors each FET and reports any excessive forward voltage that indicates a fault. When the pass transistor is fully on but the voltage drop across it exceeds the 250mV fault threshold, the FAULT pin goes high impedance. This allows an LED or optocoupler to turn on indicating

that one or more of the following conditions exist.

Current overload: The load condition is too high for the $R_{DS(ON)}$ of the MOSFET. Extra heat is being generated due to the large voltage drop across the pass transistor. A larger MOSFET with lower $R_{DS(ON)}$ should be used in the application.

MOSFET open: The MOSFET that was conducting most or all of the current has failed open. The load current is being diverted to the other supply with the higher potential through the

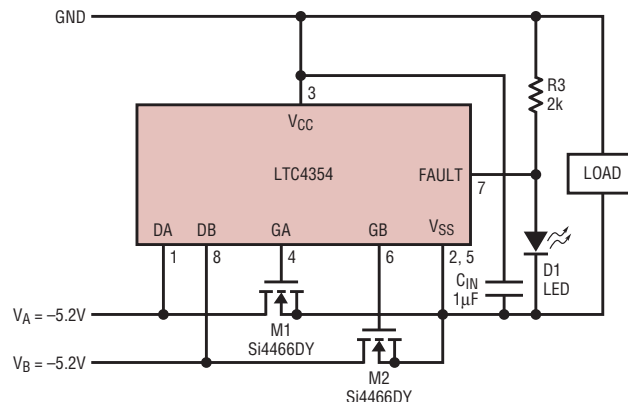


Figure 5. Low voltage diode-OR saves power and improves reliability

Accurate and Simple AC Measurement to 500kHz

by David Hutchinson

Introduction

The LTC1967 and LTC1968 provide the easiest way to accurately measure the RMS value of any AC waveform with input signal frequencies as high as 500kHz. They have 1% gain accuracy and noise out to 100kHz and 500kHz, respectively. Their phenomenal linearity of 0.02%, derived from the use of a Delta Sigma architecture, allows easy RMS-to-DC conversion without the need for the calibration that is expected in log-antilog implementations. They also provide much more stable performance over temperature.

Figure 1 shows how easy it is to use the LTC1967 or LTC1968. Each requires only one averaging capacitor and one supply bypass capacitor. The input can be driven differentially or single ended, AC or DC coupled, with a common mode range anywhere between GND and V⁺. The output has a return pin that provides easy level shifting anywhere between GND and V⁺.

A designer needs only to select an averaging capacitor big enough to provide the required low and high frequency accuracy, and small enough to meet settling time requirements. That is the only design decision.

Table 1 summarizes the features of the LTC1967 and LTC1968.

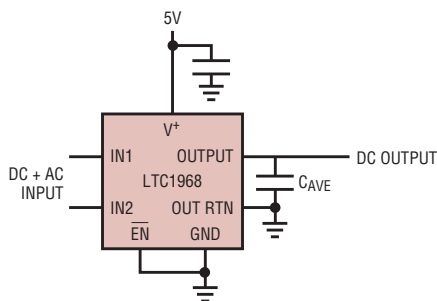


Figure 1. The LTC1967, LTC1968 are easy to hook-up. The only external components are an averaging capacitor and a bypass capacitor.

Advantages of the $\Delta\Sigma$ Topology

The $\Delta\Sigma$ topology used in the LTC1967 and LTC1968 has several advantages. First, the linearity of the RMS-to-DC conversion is unsurpassed. Figure 2 shows the output error versus input. Linearity is typically better than 0.02%. This linearity comes from the fact that the multiplication and division performed using the modulator operates at only two gains: -1 and 1.

A second advantage from this architecture is that not much changes over temperature. For example, the gain drifts less than 10ppm/°C. This is an order of magnitude better than converters made using older log-antilog implementations.

The bandwidth and response time of the LTC1967 and LTC1968 is inde-

pendent of the input amplitude being converted. This again is in contrast to older implementations which have their bias linked to the input amplitude, and therefore slow down with smaller inputs.

Finally, the switched capacitor architecture makes it easy to get rail-to-rail operation at the input and the output. Level shifting the output is as easy as tying the OUT RTN pin to the desired output level.

Selecting the Averaging Capacitor

The only external component that requires careful selection is the averaging capacitor. There are three considerations when selecting the averaging capacitor:

- ❑ The accuracy of the conversion at low input frequencies,
- ❑ The noise at high input frequencies, and
- ❑ The settling time required.

There are two errors at low frequency to consider. One is the DC error in the output and the second is the AC ripple in the output. In the data sheet are curves that show these two errors versus frequency for different values of the averaging capacitor. The larger the averaging capacitor, the smaller both of these errors become.

At higher input frequencies, the

Table 1. Feature summary

Feature	LTC1967	LTC1968
Typical Linearity	±0.02%	±0.02%
Maximum Gain Error	±0.3%	±0.3%
Bandwidth to 0.1% Additional Error	40kHz	150kHz
Bandwidth to 1% Additional Error	100kHz	500kHz
Input/Output Common Mode Range	Rail-to-Rail	Rail-to-Rail
Supply Voltage	5V ±0.5V	5V ±0.5V
Supply Current	330µA	2.3mA
Package	8-lead MSOP	8-lead MSOP

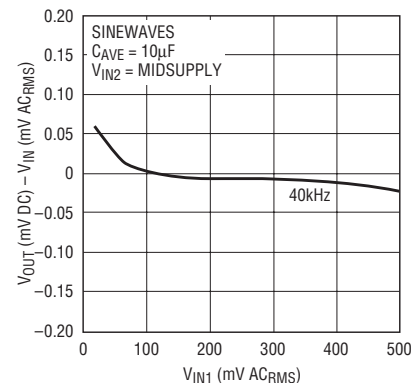


Figure 2. Linearity is typically better than 0.02%.

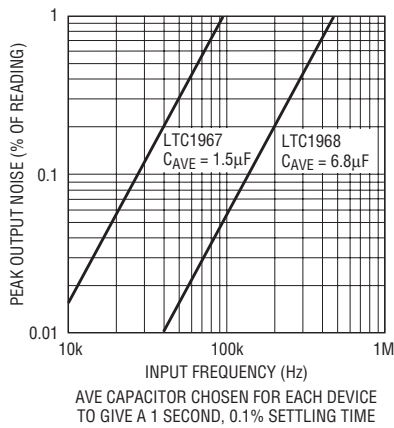



Figure 3. Output noise vs input frequency

noise in the DC output increases because the noise increases with frequency in the $\Delta\Sigma$ modulator. This noise aliases to low frequencies in the DC output. The increased averaging from a larger averaging capacitor lowers this noise. Figure 3 shows the output noise versus input frequency for the LTC1967 and LTC1968. The LTC1968 has lower noise than the LTC1967 at higher frequencies.

Finally, one must consider the settling time of the device. With larger averaging capacitors, the settling time increases. Since accuracy at low and high frequencies both increase with a

larger averaging capacitor, one should use the largest averaging capacitor possible while still meeting settling time requirements. The data sheet has a graph of the settling time versus averaging capacitor.

Conclusion

The LTC1967 and LTC1968 simplify AC measurement by providing calibration-free accuracy, flexible input/output connections, and temperature stability. They maintain their accuracy over a large input frequency range. Both are available in a tiny 8-pin MSOP package. 

LT4256-1/-2, continued from page 8

Automatic Restart and Latch Off Operation

Following a current fault, the LT4256-2 provides automatic restart by allowing Q1 to turn on when voltage on the TIMER pin has ramped down to 650mV. If the overcurrent condition at the output persists, the cycle repeats itself until the overcurrent condition is relieved. The duty cycle under short-circuit conditions is 3%, which prevents Q1 from overheating (see Figure 4).

The LT4256-1 latches off after a current fault (see Figure 5). After the LT4256-1 latches off, it can be commanded to restart by cycling UV to ground and then above 4V. This command can only be accepted after the TIMER pin discharges below the 0.65V (typ) threshold (to prevent overheating transistor Q1).

Power Good Detection


The LT4256 includes a comparator for monitoring the output voltage. The output voltage is sensed through the FB pin via an external resistor string. If the FB pin goes above 4.45V, the comparator's output releases the PWRGD pin so it can be externally pulled up. The comparator's output (PWRGD pin) is an open collector capable of operating from a pull-up voltage as high as 80V, independent of V_{CC} .

GATE Pin

The GATE pin is clamped to a maximum of 12.8V above the V_{CC} voltage. This clamp is designed to sink the internal charge pump current. An external Zener diode must be used from V_{OUT} to GATE. When the input supply voltage is between 12V and

15V, the minimum gate drive voltage is 4.5V, and a logic level MOSFET must be used. When the input supply voltage is higher than 20V, the gate drive voltage is at least 10V, and a MOSFET with a standard threshold voltage can be used.

Conclusion

The LT4256's comprehensive set of advanced protection and monitoring features make it applicable in a wide variety of Hot Swap™ solutions. It can be programmed to control the output voltage slew rate and inrush current. It has a programmable undervoltage threshold, and monitors the output voltage via the PWRGD pin. The LT4256 provides a simple and flexible Hot Swap solution with the addition of only a few external components. 

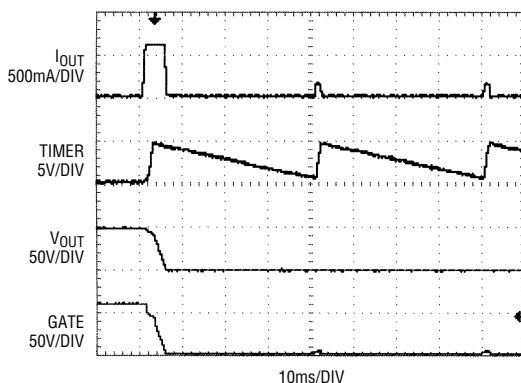


Figure 4. LT4256-2 current limit waveforms

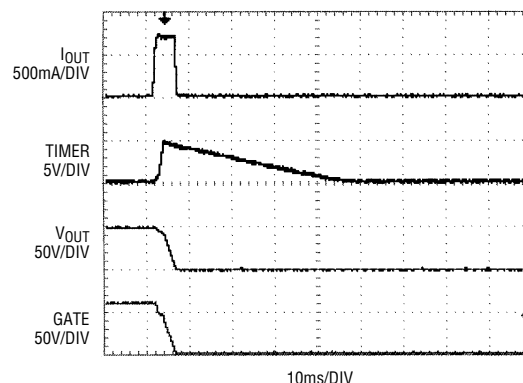


Figure 5. LT4256-1 current limit waveforms

Constant Current, Constant Voltage Converter Drives White LEDs

by Keith Szolusha

Introduction

LEDs are usually driven with a constant DC current source in order to maintain constant luminescence. Most DC/DC converters, however, are designed to deliver a constant voltage by comparing a feedback voltage to an internal reference via an internal error amplifier. The easiest way to turn a simple DC/DC converter into a constant current source is to use a sense resistor to turn the output current to a voltage, and use that as the feedback. The problem is that 500mA of output current over a 1.2V drop (typical reference voltage) in the sense resistor incurs relatively high power losses, and thus a drop in efficiency. One solution is to use an external op amp to amplify the voltage drop across a low value resistor to the given reference voltage. This saves converter efficiency, but significantly increases the cost and complexity of a simple converter with additional components and board space.

A better solution is to use the LT1618 constant current, constant voltage converter, which combines a traditional voltage feedback loop and a unique current feedback loop to operate as a constant voltage, constant current DC/DC converter. Figure 1 shows the LT1618 driving a

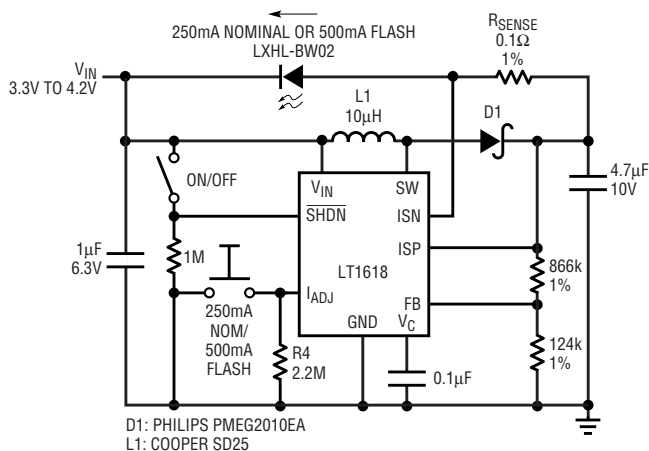



Figure 1. The LT1618 white LED driver drives a Lumileds LXHL-BW02 at 250mA constant current or a 500mA flash from a lithium-ion battery and consumes low quiescent current when off.

Lumileds 1W LXHL-BW02 white LED. No external op amps are required for this extremely compact solution. The LXHL-BW02 white LED has a forward voltage range of 3.1V to 3.5V with 250mA of current. Although the maximum DC rating of the LED is 350mA, it can be pulsed up to 500mA for use as camera flash. R4 is set for a 250mA torch or dimming operation. The I_{ADJ} (current adjustment) pin provides the ability to dim the LED during normal operation by varying the resistor setting or injecting a PWM signal.

Access to both the positive and negative inputs of the special internal constant current amplifier allows the sense resistor to be placed anywhere in the converter's output or input path and provide constant output or input current. Without access to both inputs, a ground referenced sense resistor would be required, or some additional level-shifting transistors or op amp. In this case, the floating sense resistor is only 100mΩ—at 500mA, it consumes an average of 50mW power—and it is tied directly to the positive and negative input pins of the LT1618.

Although the LT1618 is conventionally used as a high frequency boost converter with the load being driven between V_{OUT} and ground, the unique

method shown here of tying the load from V_{OUT} back to V_{IN} allows it to be used to drive the LXHL-BW02 from a Lithium Ion battery input. Tying the load back to V_{IN} allows the forward voltage of the LED (the load voltage) to be either above or below the input voltage as the battery voltage changes. This topology avoids the need for an additional inductor. The single inductor used here is extremely small and low cost, matching the all-ceramic capacitors and low-profile IC. Tying the load back to V_{IN} increases the inductor current by summing both the input and output currents. The internal switch losses are doubled and the overall efficiency of the solution is approximately 70% over the input voltage range. Even at this efficiency, it is difficult to match the compactness and low cost of this solution. 

DESIGN IDEAS

Constant Current, Constant Voltage Converter Drives White LEDs 30
Keith Szolusha

Continuously Adjustable Bench Power Supply Provides Any-Polarity Voltage and Current 31
Jon Munson

Accurate Current Monitoring for Power over Ethernet (PoE) Ports ... 33
Mark Thoren

Quarter Brick Distributed Supply Produces a Regulated 12V at 240W from a 42V-56V Input..... 34
Kurk Mathews



Continuously Adjustable Bench Power Supply Provides Any-Polarity Voltage and Current

by Jon Munson

Introduction

Continuously adjustable power supplies are indispensable tools in any electronics lab for driving or loading circuits under test. Some tests require a power supply that can change polarity and/or change current direction, traditionally implemented with made-to-suit equipment such as active load units or DC offset generators. The power supply described here provides this same capability in a simple power supply design that takes advantage of the versatile LT1970 power op amp, which includes built-in adjustable closed-loop current-limiting functions.

The polarity of power supply output voltages and currents can be summed up in a 4-quadrant diagram, as shown

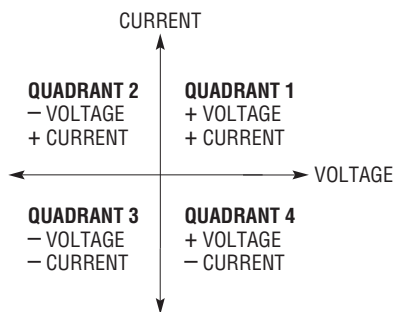


Figure 1. Quadrants of supply operation

Figure 1. A conventional power supply is limited to operation in either Quadrant 1 or 3—it operates with positive voltage output and current sourced to a load (Quadrant 1) or with a deliberate miswire of the output, statically as a minus supply (Quadrant 3). A

conventional supply cannot operate in Quadrant 2 (for example, as an adjustable load for a minus-supply), nor can it operate the Quadrant 4 (for example, discharge testing a battery with a specific constant current), nor can it transition seamlessly between the quadrants as a function of load condition or control input.

Full 4-quadrant capability is possible with an output topology similar to that of an ordinary audio power amplifier, having a complementary pass-transistor configuration. The complementary section can be a basic op amp output in lower-current designs, or external power devices (e.g. MOSFETs) in higher power designs, such as the example below. The

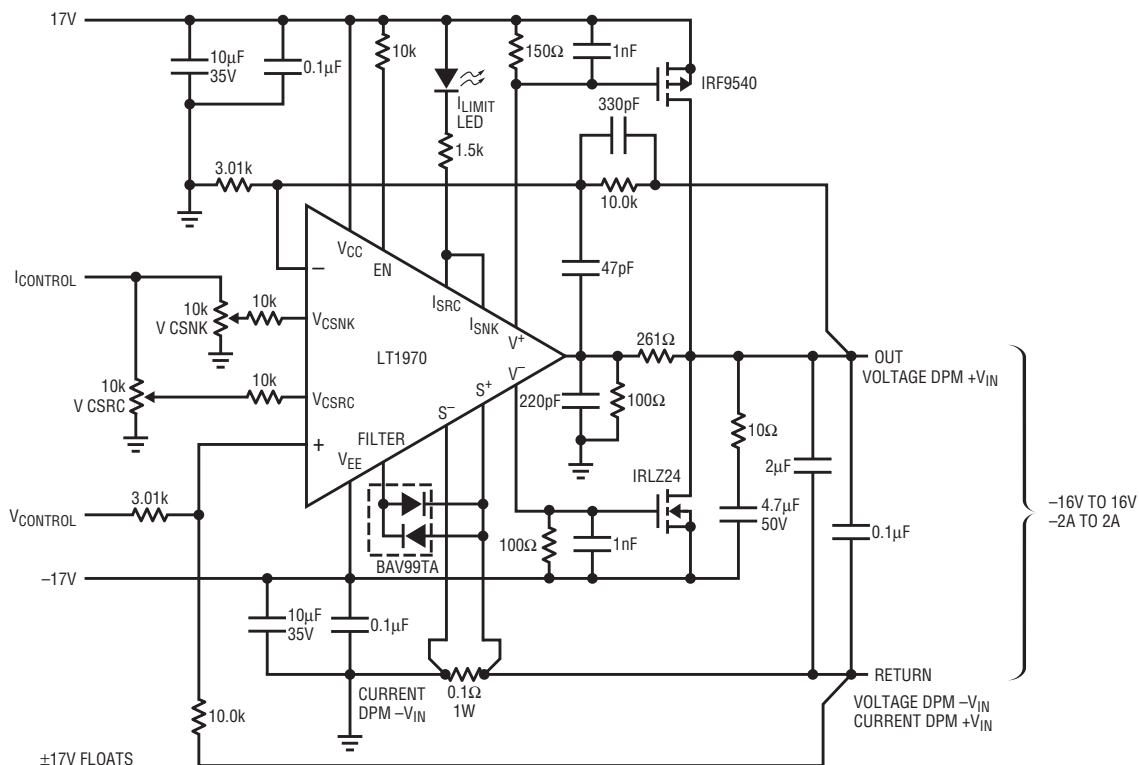


Figure 2. 4-Quadrant supply output section

LT1970 power op amp simplifies the control of the output in the various modes, thanks to its built-in closed-loop current-limiting features.

Design Details

Figures 2 and 3 show a 4-quadrant supply designed to provide at least $\pm 16V$ adjustability with up to $\pm 2A$ output capability. Figure 2 shows the basic LT1970-based regulator section. Figure 3 shows the user control analog section, utilizing an LT1790-5 reference and an LT1882 quad precision op amp. The entire circuitry operates from a pre-regulated $\pm 17V$ bulk power source (not shown).

The user control potentiometers, V Set and I Limit (in Figure 3), are configured to provide buffered command signals $V_{CONTROL}$ and $I_{CONTROL}$, respectively. $V_{CONTROL}$ is adjustable from $-5V$ to $+5V$ and is amplified by the LT1970 regulator circuit to form the nominal $\pm 16.5V$ output range. $I_{CONTROL}$ is adjustable from $0V$ to $+5V$, with $+5V$ representing the maximum user current limit command. The $I_{CONTROL}$ signal is attenuated by trimmers VCSNK and VCSRC to set the precise full-scale currents for sink and source modes, respectively.

The output current is sensed using a 0.1Ω resistor in the load return and provides the LT1970 with feedback during current limiting operation. With this sense resistance, setting the current-limit trimmers to 100% would allow the LT1970 to limit at about $\pm 5A$, but since a $2A$ maximum current is desired in this application, the trimmers are set to about 40% rotation when calibrated.

To prevent internal control contention at low output current, the LT1970 sets a minimum current-limit threshold that corresponds to about $40mA$ for the sense resistance used here. Another feature of the LT1970 is the availability of status flags, which in this case, provide a simple means of

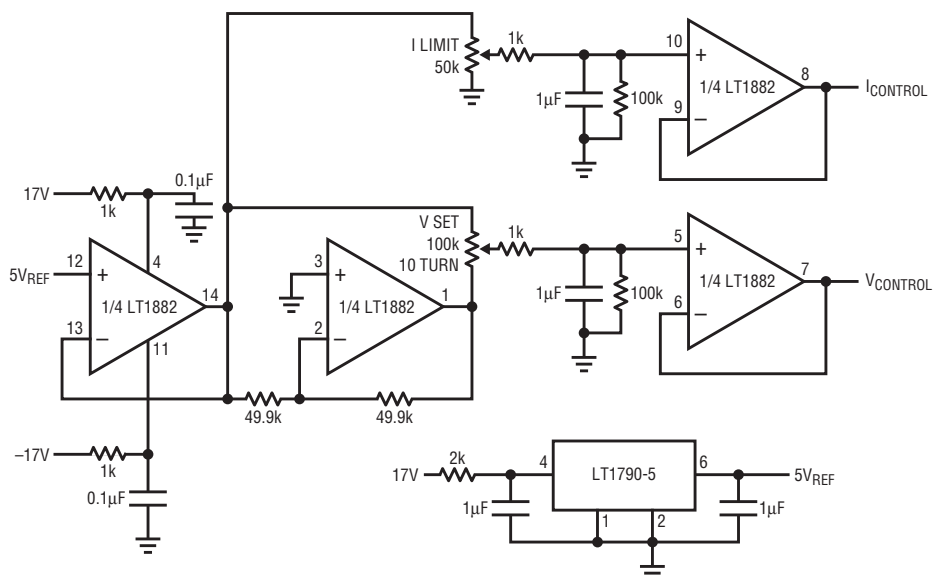


Figure 3. 4-Quadrant supply user controls section

driving a front panel LED to indicate when current limiting is active.

The LT1970 features split power connections that allow for the amplifier output section to be powered independently from the analog control portion. The flexibility of this configuration allows direct sensing of the op amp output current via resistance in the V^+ (pin 19) and V^- (pin 2) connections. This forms a convenient means of establishing class-B operation of the MOSFET output devices using a current-feedback method, where the op amp output current is converted to a gate-drive potential, thereby having the MOSFETs turn on only to the extent needed to help the op amp provide the output demand.

Since power supplies must inherently drive heavy C-loads (i.e. circuits with high-value bypass capacitors), and any over-voltage would present a damage potential (no pun intended!), careful attention was given to compensating the op amp for minimal overshoot under all loading conditions. As with most op amps, C-load tolerance is accomplished with the LT1970 by inner- and outer-loop feedback, where the op amp itself is resistively

decoupled from the load. DC-feedback for the LT1970 uses differential voltage sensing to eliminate the regulation error that would otherwise occur with the current-sense and lead resistances in series with the load.

A pair of inexpensive digital panel meters (DPM) may be connected to the output as indicated in Figure 2 to monitor the output conditions in real time (the two DPM common connections are not shared, which may complicate the circuitry used to power some DPM types). Notice the selection of current-sense resistance was made to optimize a DPM display with the usual $\pm 200mV$ full-scale sensitivity (to present up to $\pm 1.999A$, for example).

One word of caution: when using this supply to power sensitive electronics (in place of a conventional single-quadrant supply), it's good practice to connect a reverse-biased Schottky diode to the output binding-posts (e.g. 1N5821, cathode to more positive connection) or use a disconnect relay and power sequencer in the design so to protect the load from any energetic reverse transients during turn-on and turn-off of the main bulk supply.

For more information on parts featured in this issue, see <http://www.linear.com/go/ltmag>

Accurate Current Monitoring for Power over Ethernet (PoE) Ports

by Mark Thoren

The IEEE 802[®].3af specification for powered Ethernet recommends allocating power based on each port's powered device (PD) power class rather than actual measured load current. This ensures that a device with low idle current has enough power available when it must draw its full class current. Nevertheless, many legacy PDs (Powered Devices) do not provide classification and have non-compliant input circuits. For these devices to interoperate with the PoE environment, it is important to know if these devices are drawing current and how much. Accurate per-port current measure-

ment is important, especially at very low levels, in systems where legacy devices might be found.

Even in legacy-free systems, per port current measurement is useful. For instance, in a system with redundant power supplies, where one supply cannot handle the entire load, knowing the individual current demands along with port prioritization can provide a graceful means to shed excess load should one of the supplies fail.

The LTC2439-1 16-bit delta sigma analog to digital converter has many features that make it ideal for measuring powered Ethernet port current.

Using an LT1790 1.25V reference and a 0.5Ω sense resistor results in a resolution of 38μA, which is more than adequate considering the 270mA maximum load current of a single PD. The 2.5μV typical offset error allows open fuse detection by adding a 33k pull-up resistor from the negative side of the fuse to V_{CC}. Any ports that are turned off will read -100μA if the fuse is not blown. Sixteen ports can be monitored with an update rate of 6.8 ports per second when using the LTC2439-1's the internal conversion clock.

Another feature of the LTC2439-1 is its ability to measure voltages up to

continued on page 36

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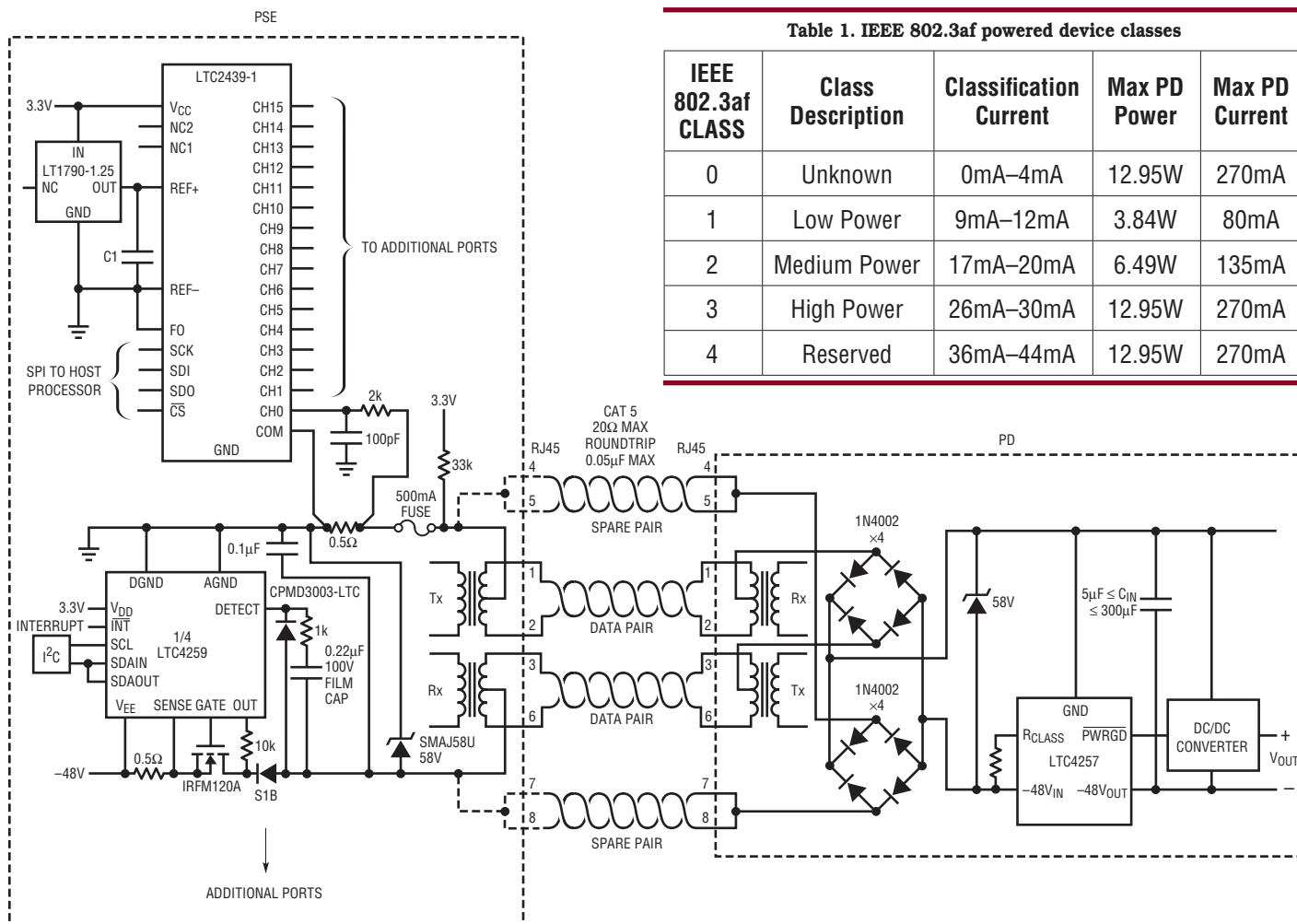


Figure 1. Power over Ethernet port current monitor. Although the PoE standard specifies power classes, some legacy devices may not provide classification, so it's important to know how much current these devices are drawing.

Quarter Brick Distributed Supply Produces a Regulated 12V at 240W from a 42V–56V Input

by Kurk Mathews

Introduction

When telecom power requirements include multiple and/or high power isolated outputs, a distributed bus approach offers many advantages. For example, three isolated output voltages (such as 2.5V, 3.3V and 12V) can be generated by providing individually isolated power supplies (e.g. 48V to 2.5V, 48V to 3.3V, 48V to 12V), or by distributing the bus via a single isolated supply (e.g. 48V to 12V) with individual buck regulators at the load points (See Figure 1).

Advantages of the distributed bus approach include the simplicity of requiring only a single isolated converter combined with low cost, un-isolated point-of-load converters, instead a number of costly isolated modules. The disadvantage can be lower overall efficiency—two stages of conversion can quickly reduce the overall system efficiency considerably (e.g. $92\% \times 92\% = 85\%$).

The choice of intermediate bus voltages is complicated by competing parameters—higher voltages tend to increase the efficiency of the bus converter but can lower the efficiency of low voltage downstream converters. A 7V to 14V intermediate bus provides a reasonable compromise. The LTC3723 controller, combined with a Linear Technology FET driver (i.e. LTC3900, LTC3901, and LTC4440), offers a high efficiency, low cost, compact solution for a distributed bus converter.

Figures 2 and 3 show the LTC3723-1 current-mode controller in a 42V–56V input to isolated 12V at 20A full-bridge converter with synchronous rectification. The quarter brick design measures 2.3" x 1.45" and uses standard surface mount components (0.34" top, 0.1" bottom side maximum component height). 48V input peak efficiency is over 95% (see Figure 4). The circuit is designed to supply

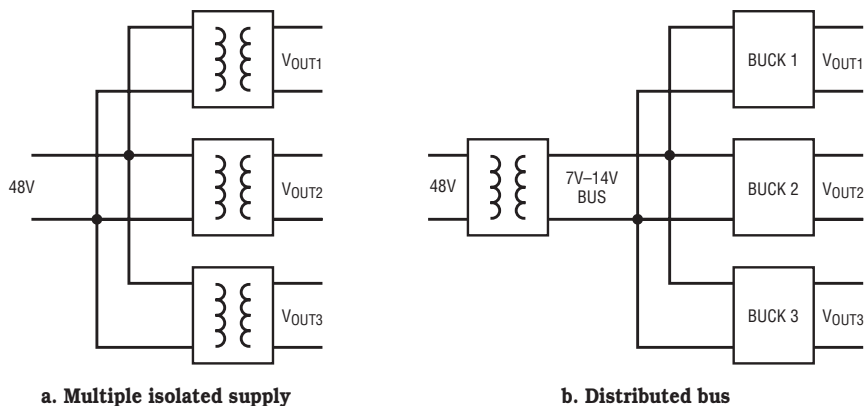


Figure 1. Multiple isolated supply approach (a) vs distributed bus approach (b). Advantages of the distributed bus approach (b) include the simplicity of requiring only a single isolated converter combined with low cost, un-isolated point-of-load converters. The disadvantage can be lower overall efficiency—two stages of conversion can quickly reduce the overall system efficiency considerably (e.g. $92\% \times 92\% = 85\%$).

240W at 50°C with 200 linear feet per minute of airflow without the use of a heat sink.

The primary challenge in designing high efficiency isolated bus supplies is optimizing size and efficiency. Although often reserved for higher power levels, the full-bridge converter was primarily chosen for its superior transformer utilization. This allowed the use of a reasonably sized (0.92" x

0.79") transformer, leaving room for the rest of the power components on the top of the board.

The other major decision involves the input and output voltages. Limiting the input range to 42V–56V (versus 36V–72V) and/or allowing the output voltage to vary with the input (semi-regulated or unregulated output) results in significant efficiency gains. This is primarily the result of

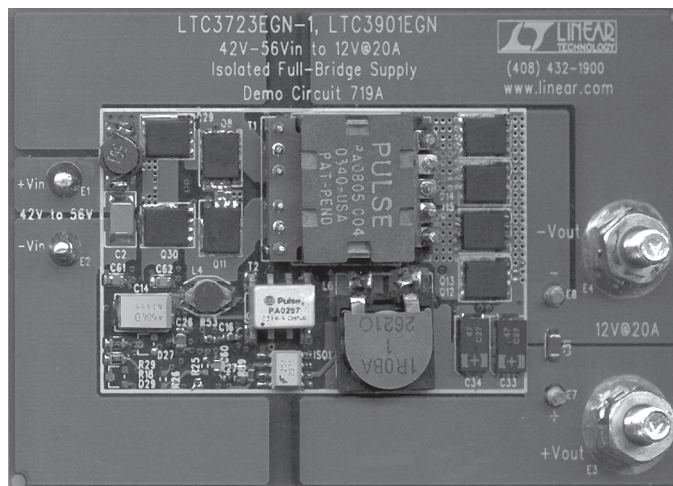


Figure 2. LTC3723 240W quarter brick

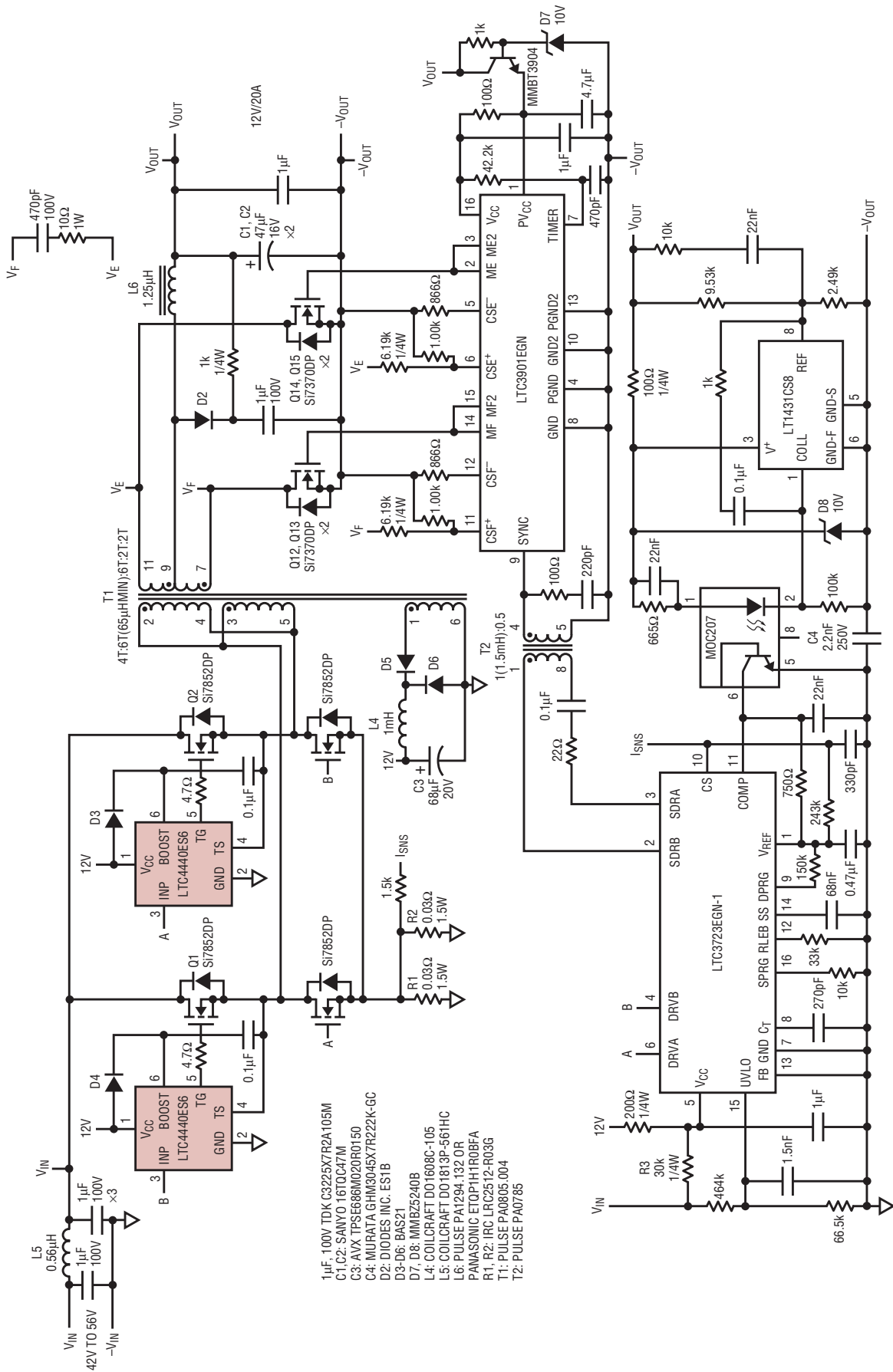


Figure 3. LTC3723 42V-56V input to 12V at 20A isolated synchronous full bridge converter

increased primary to secondary turns ratio which reduces primary current and allows the use of lower voltage, lower loss primary and secondary MOSFETs.

Operation

The LTC3723 controller's basic features, its flexibility and support for secondary synchronous rectifiers (with adjustable timing) make it an excellent choice for virtually all isolated, synchronous topologies. In this full-bridge application, the SOT23, LTC4440, 100V, 2.4A high side driver is used to translate the gate drive signal to the upper MOSFETs, Q1 and Q2. The LTC3723 integrated driver switches the lower MOSFETs directly. The LTC3723 initial bias voltage is derived via trickle-start resistor R3. Once switching begins, the IC is powered from transformer T1.

Output MOSFETs Q12-Q15 are controlled by the LTC3901 secondary side synchronous MOSFET driver,

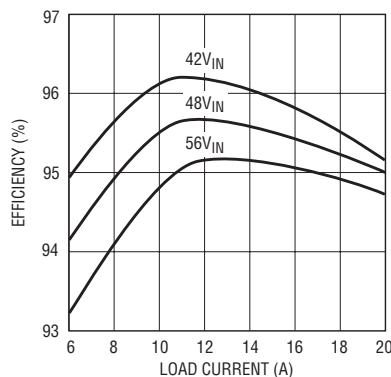


Figure 4. Efficiency of the circuit in Figure 3

which includes a number of unique features to ensure safe operation of the synchronous MOSFETs under all conditions. The LTC3901 receives a sequence of alternating input positive and negative input pulses from the LTC3723 through T2. Zero voltage on the SYNC input (indicating the freewheeling period) turns both synchronous MOSFETs on after an initial negative pulse. Subsequent positive and negative pulses determine

which synchronous MOSFET should be off. Incorrect sequences of pulses cause both synchronous MOSFETs to turn off. Missing pulses initiate a user programmable time-out. This avoids potentially harmful negative output inductor currents result from the synchronous MOSFETs being left on too long (during power down, for example). Finally, the LTC3901 V_{DS} comparators monitor the voltage drop across the synchronous MOSFETs, offering a second level of protection against excessive negative inductor currents.

Conclusion

The LTC3723-1 controller teams up with the LTC4440 and LTC3901 to squeeze 240W into 3.3 square inches of board space. The 12V application circuit shown takes advantage of the full bridge transformer utilization and reduced input range to increase efficiency beyond 95%. **LT**

PoE Port Current, continued from page 33

0.3V outside the supply rails. Thus, the maximum current is 600mA when using a 0.5Ω sense resistor. This is sufficient to handle an overcurrent condition before the recommended 500mA fuse blows. The 2kΩ series resistors limit current in the event of a fault. The LTC2439-1 is trimmed to provide greater than 87dB rejection of both 50Hz and 60Hz, and wideband

noise rejection is better than 140dB. 100pF capacitors provide RFI suppression.

Figure 1 shows a typical powered Ethernet application that supports both 802.3af-compliant devices and legacy devices. The LTC4259 controls the actual switching of power to the individual ports. The LTC4257 in the powered device provides classification

information to the LTC4259, which is then made available to the host processor via the I²C bus for power allocation purposes. Up to 16 LTC4259s can be connected to the I²C bus, and additional LTC2439-1s may be added to the SPI bus by providing each with a separate CS line. **LT**

LTC4354, continued from page 27

be powered directly from a supply as low as 4.5V.

Conclusion

The trend in today's telecom infrastructure is toward higher current and

smaller module space. The traditional Schottky diode ORing circuit is increasingly cumbersome. The LTC4354 provides an improved ORing solution by controlling low R_{DS(ON)} N-channel MOSFETs. The reduced power dis-

sipation saves board space and cost associated with extra heat sinks. Furthermore, the LTC4354 monitors and reports fault conditions, information not provided by a traditional diode-OR circuit. **LT**

For more information on parts featured in this issue, see <http://www.linear.com/go/ltmag>

New Device Cameos

Dual Channel Low Voltage Hot Swap Controller Features Multiple Levels of Overcurrent Control

The LTC4221 positive Hot Swap controller provides control over two channels: one channel for input voltages ranging from 2.7V to 13.5V, and the other channel for inputs from 1V to 13.5V.

The Hot Swap controller features start up inrush current control via a current foldback technique without the need for an external gate compensation capacitor. The controller also allows the two channels to be configured to simultaneously ramp up and down, or for independent operation.

The LTC4221 provides a dual level and dual speed overcurrent circuit breaker protection for each channel. A slight overcurrent trips the circuit breaker only if it persists beyond a user-programmed time period. Catastrophic overcurrent conditions from short-circuits cause the fast comparator to trip immediately, protecting the load and the MOSFET. The device also provides monitoring of each channel output voltage and overvoltage protection. Each channel's power good status and a common fault signal are available to a microprocessor or a load supply module.

The LTC4221 is offered in a narrow 16-pin SSOP package and is screened to commercial and industrial temperature ranges.

16-Bit DAC Has Tiny 3mm × 3mm Footprint

The LTC2601 integrates a high-performance, voltage output 16-Bit DAC in a tiny 3mm × 3mm 10-pin DFN package. No other available product matches its performance and functionality in such a small footprint. At this size, the LTC2601 fits into space-constrained applications and it can be placed at an optimal board location.

Multiple DACs can be controlled over 3 wires using a daisy-chainable SPI serial interface. The LTC2601's guaranteed monotonic performance is

ideal for digital calibration, trim/adjust, and level setting applications.

Its output buffer provides excellent drive capability over its entire 2.5V to 5.5V supply voltage range. The output can directly drive capacitive loads up to 1000pF or current loads up to 15mA and maintains good linearity to within millivolts of both supply rails. The low output offset (9mV max) provides a zero-scale voltage closer to 0V than competitive devices.

The LTC2601's low noise reduces the need for output filtering, and its 0.1Hz to 10Hz noise (15 μ V_{P-P}) is much lower than competitive devices. The LTC2601's low 300 μ A supply current and 1 μ A maximum shutdown current are ideal for battery-powered applications.

The LTC2601's asynchronous update pin allows the DAC update to be synchronized to a hardware signal and allows simultaneous updates of multiple DACs in a system. A power-on reset clears the LTC2601 to zero-scale on power up. The LTC2601 provides an asynchronous clear pin, which is required in many servo and control applications.

The LTC2601 is only one of many devices in a family of compact DACs. The LTC2611 and LTC2621 are pin-compatible 14-bit and 12-bit DACs, thus allowing a single design to have multiple price and performance options. The family also includes octal, quad and dual DACs that feature superior performance in the smallest available footprints.

Li-Ion Battery Charger with Programmable Current Termination

The LTC4068 is a complete single-cell linear Li-Ion battery charger that adds a new feature: programmable current termination to increase design flexibility. Like the other members of the Linear Technology monolithic Li-Ion battery charger family the LTC4068 is a constant-current/constant-voltage linear charger. No external sense resistor or external blocking diode is

required due to the internal MOSFET architecture. Its 3mm × 3mm DFN package and low external component count make the LTC4068 ideally suited for portable applications. The LTC4068 is also designed to work within USB power specifications.

The LTC4068 is the first of the family to provide programmable current termination. In the same manner that charge current can be programmed using a single external resistor, the output current at which the LTC4068 terminates a charge cycle can also be programmed using another external resistor. This design flexibility allows the user to take into account typical load currents that may always be present in parallel with the battery. For example, if an application always has a 75mA load in parallel with the battery and the typical charge current is 700mA, then a C/10 termination current might never be reached. However, using an LTC4068, the termination current can be adjusted to C/5 (140mA) to maintain a reasonable charge time.

The user can also make trade-offs between the charge time and the battery charge capacity at which the LTC4068 terminates. For example, given an 800mAh battery the termination current can be set to 40mA for a very complete charge. Although the time required for this charge cycle is relatively long, the battery is at full capacity when the charge cycle ends. On the other hand, the termination current can be set for 160mA. In this case, the charge cycle is much shorter, but the battery is close to full capacity. Without programmable current termination, this trade-off cannot be made.

The LTC4068 is a full-featured charger including the patented Linear Technology thermal feedback system which regulates the charge current to limit the die temperature during high power operation or high ambient temperature conditions. The final float voltage is preset to 4.2V with 1% accuracy. The PROG pin voltage provides

continuous information on the magnitude of the charge current and the $\overline{\text{CHRG}}$ open-drain output indicates the status of the charge cycle. Automatic recharge ensures that the battery is maintained at, or near, a fully charged condition and eliminates the need for periodic charge cycling. The $\overline{\text{ACPR}}$ open-drain output indicates whether or not enough voltage is present at the input to allow battery charging.

Push-Pull Controller Enables Compact and Highly Efficient Isolated Power Converters

The LTC3721-1 push-pull PWM controller provides all of the control and protection functions necessary for compact and highly efficient, isolated power converters. High integration minimizes external component count, while preserving design flexibility.

The robust push-pull output stages switch at half the oscillator frequency. Dead-time is independently programmed with an external resistor. A UVLO program input provides precise system turn-on and turn off voltages. The LTC3721-1 features peak current mode control with programmable slope compensation and leading edge blanking.

The LTC3721-1 features extremely low operating and start-up currents and reliable short-circuit and overtemperature protection. The LTC3721-1 is available in 16-pin SSOP and (4mm x 4mm) QFN packages.

600mA, 500kHz Step-Down Switching Regulator in SOT-23

The LT1933 is a current mode PWM step-down DC/DC converter with an internal 0.75A power switch, packaged in a tiny 6-lead SOT-23. The wide input range of 3.6V to 36V makes the LT1933 suitable for regulating power from a wide variety of sources, including unregulated wall transformers, 24V industrial supplies and automotive batteries. Its high operating frequency allows the use of tiny, low cost inductors and ceramic capacitors, resulting in low, predictable output ripple.

Cycle-by-cycle current limit provides protection against shorted

outputs, and soft-start eliminates input current surge during start up. The low current (<2 μ A) shutdown provides output disconnect, enabling easy power management in battery-powered systems.

$\pm 250\text{V}$ Input Range $G = 1, 10$, Micropower, Difference Amplifier

The LT1990 is a micropower precision difference amplifier with a very high common mode input voltage range. It has pin selectable gains of 1 or 10. The LT1990 operates over a $\pm 250\text{V}$ common mode voltage range on a $\pm 15\text{V}$ supply. The inputs are fault protected from common mode voltage transients up to $\pm 350\text{V}$ and differential voltages up to $\pm 500\text{V}$. The LT1990 is ideally suited for both high side and low side current or voltage monitoring.

On a single 5V supply, the LT1990 has an adjustable 85V input range, 70dB min CMRR and draws less than 120 μ A supply current. The rail-to-rail output maximizes the dynamic range, especially important for single supplies as low as 2.7V.

The LT1990 is specified for single 3V, 5V and $\pm 15\text{V}$ supplies over both commercial and industrial temperature ranges. The LT1990 is available in an 8-pin SO package.

12-Bit, 105Msps/80Msps ADCs

The LTC2222 and LTC2223 are 105Msps/80Msps, sampling 12-bit A/D converters designed for digitizing high frequency, wide dynamic range signals. The LTC2222/LTC2223 are perfect for demanding communications applications with AC performance that includes 68dB SNR and 80dB spurious free dynamic range

for signals up to 170MHz. Ultralow jitter of 0.15ps_{RMS} allows undersampling of IF frequencies with excellent low noise performance.

DC specs include $\pm 0.3\text{LSB INL}$ (typ), $\pm 0.2\text{LSB DNL}$ (typ) and no missing codes over temperature. The transition noise is a low 0.5LSB_{RMS}.


A separate output power supply allows the outputs to drive 0.5V to 3.3V logic.

The ENC⁺ and ENC⁻ inputs may be driven differentially or single ended with a sine wave, PECL, LVDS, TTL, or CMOS inputs. An optional clock duty cycle stabilizer allows high performance at full speed for a wide range of clock duty cycles.

300mA Micropower VLDO Linear Regulator

The LTC3025 is a micropower, VLDO™ (very low dropout) linear regulator which operates from input voltages as low as 0.9V. The device is capable of supplying 300mA of output current with a typical dropout voltage of only 45mV. A BIAS supply is required to run the internal reference and LDO circuitry while output current comes directly from the IN supply for high efficiency regulation. The low 0.4V internal reference voltage allows the LTC3025 output to be programmed to much lower voltages than available in common LDOs (range of 0.4V to 3.6V). The output voltage is programmed via two ultras small SMD resistors.

The LTC3025's low quiescent current makes it an ideal choice for use in battery-powered systems. For 3-cell NiMH and single cell Li-Ion applications, the BIAS voltage can be supplied directly from the battery while the input can come from a high efficiency buck regulator, providing a high efficiency, low noise output.

Other features include high output voltage accuracy, excellent transient response, stability with ultralow ESR ceramic capacitors as small as 1 μ F, short-circuit and thermal overload protection and output current limiting. The LTC3025 is available in a tiny, low profile (0.75mm) 6-lead DFN (2mm x 2mm) package. 

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

Databooks

Linear Technology currently has a set of seven databooks organized by product family. This set supersedes all previous Linear databooks. Each databook contains all related product data sheets, selection guides, QML/space information, package information, appendices, and a complete reference to all of the other family databooks.

For more information, or to obtain any of the databooks, contact your local sales office (see the back of this magazine), or visit www.linear.com.

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Applications Handbooks

Linear Applications Handbook, Volume I—Almost a thousand pages of application ideas covered in depth by 40 Application Notes and 33 Design Notes. This catalog covers a broad range of real world linear circuitry. In addition to detailed, systems-oriented circuits, this handbook contains broad tutorial content together with liberal use of schematics and scope photography. A special feature in this edition includes a 22-page section on SPICE macromodels.

Linear Applications Handbook, Volume II—Continues the stream of real world linear circuitry initiated by Volume I. Similar in scope to Volume I, this book covers Application Notes 40 through 54 and Design Notes 33 through 69. References and articles from non-LTC publications that we have found useful are also included.

Linear Applications Handbook, Volume III—This 976-page handbook includes Application Notes 55 through 69 and Design Notes 70 through 144. Subjects include switching regulators, measurement and control circuits, filters, video designs, interface, data converters, power products, battery chargers and CCFL inverters. An extensive subject index references circuits in Linear data sheets, design notes, application notes and *Linear Technology* magazines.

Brochures

Power Management & Wireless Solutions for Handheld Products—The solutions in this product selection guide solve real-life problems for cell phones, digital cameras, PDAs and other portable devices. Circuits are shown for Li-Ion battery chargers, battery managers, USB support, system power regulation, display drivers, white LED drivers, photoflash chargers, DC/DC converters, SIM and smart card interfaces, photoflash chargers, and RF PA power supply and control. All solutions are designed to maximize battery run time, save space and reduce EMI where necessary—important considerations when designing circuits for handheld devices.

Automotive Electronic Solutions—This selection guide features recommended Linear Technology solutions for a wide range of functions commonly used in today's automobiles, including telematics and infotainment systems, body electronics and engine management, safety systems and GPS/navigation systems.

Linear Technology's high-performance analog ICs provide efficient, compact and dependable solutions to solve many automotive application requirements.

Software

SwitcherCAD™ III/LTC SPICE—LTC SwitcherCAD III is a fully functional SPICE simulator with enhancements and models to ease the simulation of switching regulators. This SPICE is a high performance circuit simulator and integrated waveform viewer, and also includes schematic capture. Our enhancements to SPICE result in much faster simulation of switching regulators than is possible with normal SPICE simulators. SwitcherCAD III includes SPICE macromodels for 80% of LTC's switching regulators and over 200 op amp models. It also includes models of resistors, transistors and MOSFETs. With this SPICE simulator, most switching regulator waveforms can be viewed in a few minutes on a high performance PC. Circuits using op amps and transistors can also be easily simulated. Download at www.linear.com

FilterCAD™ 3.0—FilterCAD 3.0 is a computer aided design program for creating filters with Linear Technology's filter ICs. FilterCAD is designed to help users without special expertise in filter design to design good filters with a minimum of effort. It can also help experienced filter designers achieve better results by playing "what if" with the configuration and values of various components and observing the results. With FCAD, you can design lowpass, highpass, bandpass or notch filters with a variety of responses, including Butterworth, Bessel, Chebychev, elliptic and minimum Q elliptic, plus custom responses. Download at www.linear.com

SPICE Macromodel Library—This library includes LTC op amp SPICE macromodels. The models can be used with any version of SPICE for analog circuit simulations. These models run on SwitcherCAD III/LTC SPICE.

Noise Program—This PC program allows the user to calculate circuit noise using LTC op amps, determine the best LTC op amp for a low noise application, display the noise data for LTC op amps, calculate resistor noise and calculate noise using specs for any op amp.

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