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Breakthrough Buck-Boost Controller Provides up to 10A from a Wide 4V–36V Input Range

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Introduction

Many DC/DC converter applications require an output voltage somewhere within a wide range of input voltages. An everyday example would be a well-regulated 12V output from an automotive battery input, which has a full charge voltage around 14V and a fluctuating cold crank voltage under 9V.

There are a number of traditional solutions to this problem, but all have drawbacks, including low efficiency, limited input voltage range or the use bulky coupled inductors. Some even produce output voltages of polarity opposite to that of the input voltage. A system designer must often decide between an inefficient topology or a scheme that uses both a boost regulator and a buck regulator, which adds complexity with extra filter components and multiple control loops.

The LTC3780 offers a simpler solution with an approach that requires neither cumbersome magnetics nor additional control loops (see Figure 1). This 4-switch controller takes the form of a true synchronous buck or boost, depending on the input voltage. Transitions between modes depend on duty cycle (Figure 2) and are quick and automatic. The controller is versatile, providing three modes of operation, switching frequencies from 200kHz to 400kHz, and output currents from milliamps to tens of amps. The three operating modes permit the designer to choose between efficiency and low

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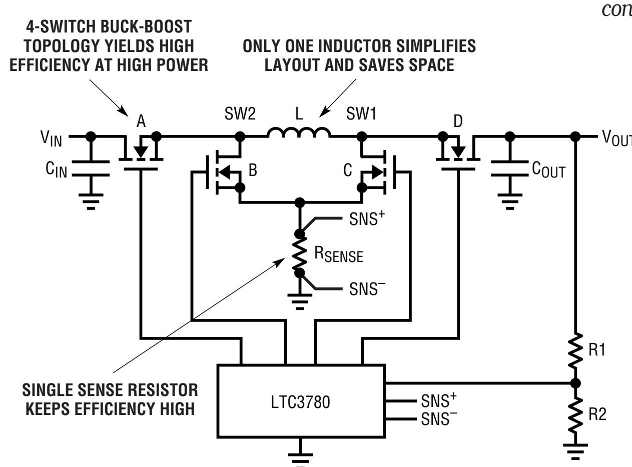

Figure 1. Simplified diagram of the LTC3780 topology, showing how the four power switches are connected to the inductor, V_{IN}, V_{OUT} and GND.

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ripple at light loads. The frequency can be selected by applying the proper voltage to the PLLFLTR pin, or the controller can be synchronized to an external clock via an internal phase-lock loop. The current sensing resistor programs the current limit, freeing the designer to choose among a broad array of power MOSFETs. Efficiency in a typical application reaches 97%, and exceeds 90% over more than a decade of load current (Figure 3). The output remains stable despite transients in load current (Figure 4) and line voltage (Figure 5).

A 12V, 5A Converter Operating from Wide Input Voltage Range

Figure 6 shows a versatile LTC3780-based converter providing 12V at up to 5A with inputs from 5V to 32V; the core circuit fits in a cubic inch with a footprint of only 2.5in^2 as shown in Figure 7. This converter can operate with any of three light-load operating modes, set at the three-state FCB pin: continuous current mode, discontinuous current mode and Burst Mode® operation (which becomes skip cycle mode at higher input voltages). These modes allow a designer to optimize efficiency and noise suppression. Continuous operation provides very low output voltage ripple, since at least one of the switch nodes is always cycling at a constant, programmed frequency. With at least one switch always on, the lowest possible noise is achieved since the output L-C filter is not permitted to ring.

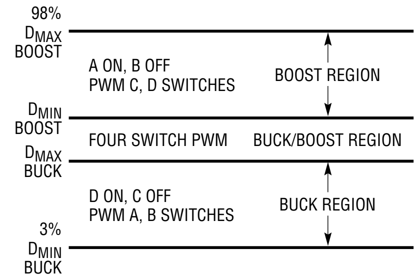


Figure 2. The duty cycle determines the operating mode, whether in continuous mode (pictured) or in any of the power saving modes. The power switches are properly controlled so the transfer between modes is continuous. When V_{IN} approaches V_{OUT}, the buck-boost region is reached; the mode-transition time is typically 300ns.

In continuous operation, the power switches' operating sequence depends on whether the input voltage is greater than, nearly the same as, or less than the desired output voltage. When the input is well above the output (buck mode), Switch D remains on and switch C shuts off. When each cycle begins, synchronous switch B turns on first and the inductor current is determined by comparing the voltage across R_{SENSE} to an internal reference. When the sense voltage drops below the reference, synchronous switch B turns off and switch A is turns on for the remainder of the cycle. Switches A and B turn on and off alternately, behaving like a typical synchronous buck regulator. The duty cycle of switch A increases until the maximum duty cycle of the converter in buck mode reaches 94%–96%.

Figure 8a shows conceptual waveforms in this buck region. When the input voltage comes close to the output voltage, maximum duty cycle is reached and the LTC3780 shifts to buck-boost mode. Figures 8b and 8c show the symmetrical, input voltage-

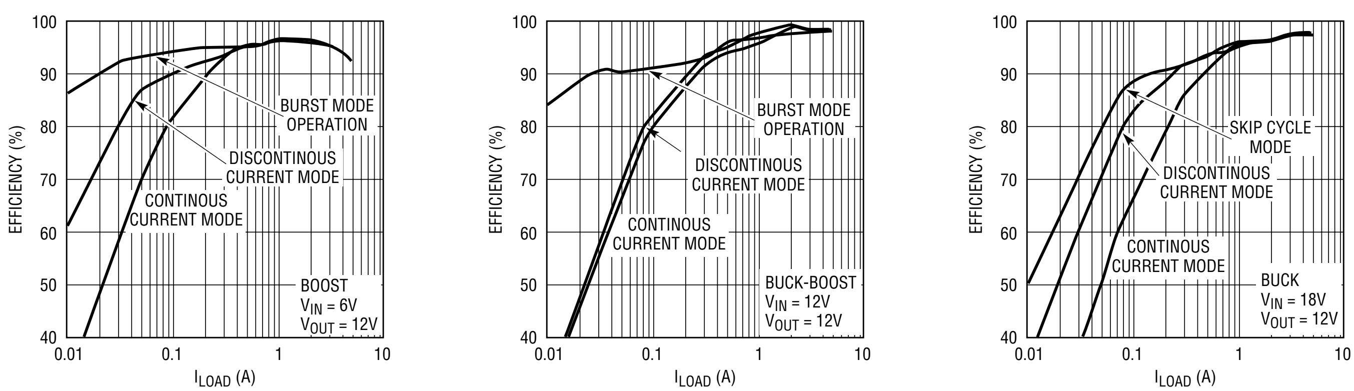


Figure 3. Efficiency is high throughout the range of load currents and operating modes.

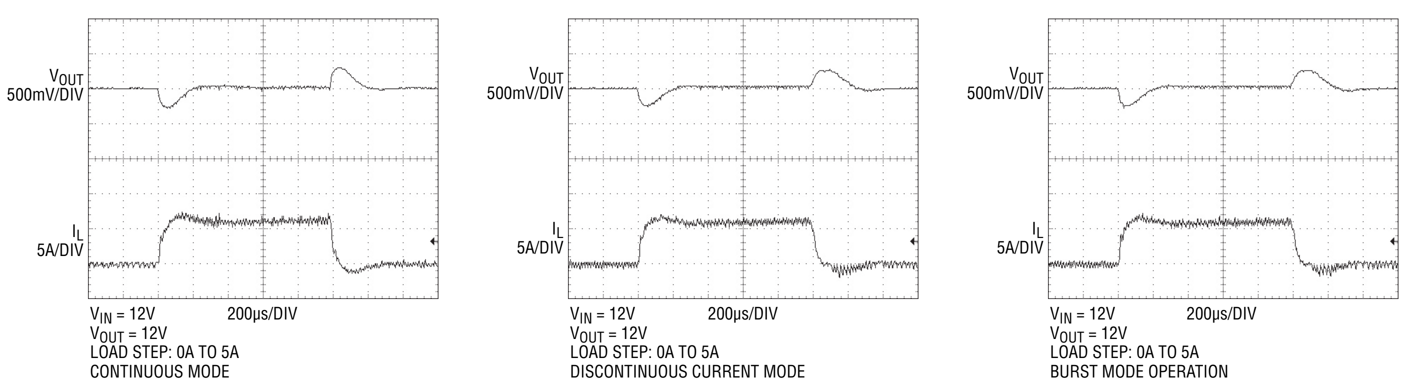


Figure 4. The LTC3780 provides excellent load transient response in any of its operating modes.

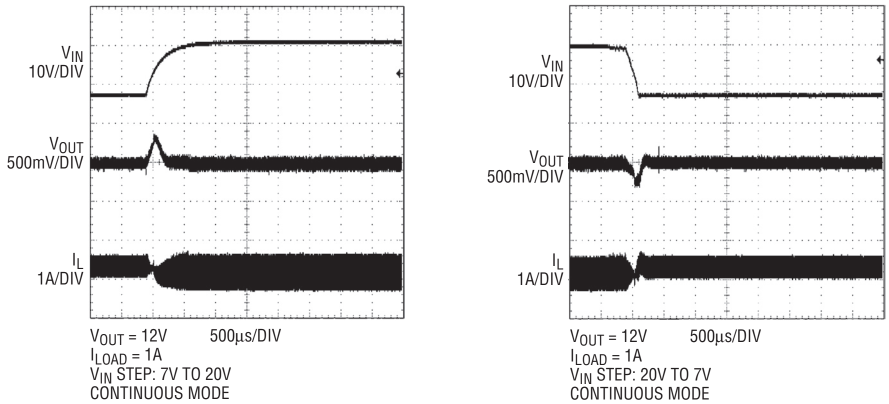


Figure 5. The LTC3780 responds quickly to changing input voltages.

dependent behavior of the switches in this region. If the cycle starts with switches B and D turned on, switches A and C turn on. Then, switch C turns off, switch A remains on, and switch D turns on for the remainder of the cycle; but if the controller starts with switches A and C turned on, switches B and D turn on. Then, switch B turns off, switch D remains on, and switch A turns on for the remainder of the cycle.

Figure 8d shows typical behavior when the input is well below the output (boost mode). Here, switch A is always on and synchronous switch B is always off. When each cycle begins, switch C turns on first and the inductor current is monitored via R_{SENSE}. When the voltage across R_{SENSE} rises above the reference voltage, switch C turns off and synchronous switch D turns on for the remainder of the cycle. Switches C and D turn on and off alternately, behaving like a typical synchronous boost regulator.

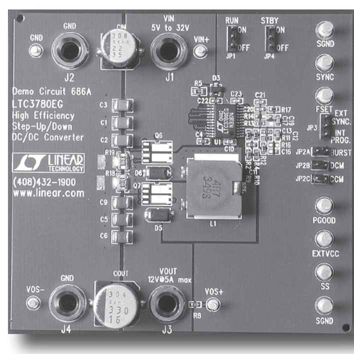


Figure 7. Typical LTC3780 layout. The four MOSFETs are on the reverse side, with space available on top for two dual MOSFETs.

The duty cycle of switch C decreases until the minimum duty cycle of the converter in boost mode reaches 4%–6%.

When this minimum duty cycle is reached, the LTC3780 shifts into buck-boost mode.

Like continuous current mode, discontinuous current mode features constant frequency and extremely low ripple, and improves efficiency at light loads by turning off the relevant synchronous switch (B or D). In boost mode, switch D remains off if the load is light enough. In buck mode, switch B turns on every cycle, just long enough to produce a small negative inductor current; this sequence maintains constant frequency operation even at no load (Figure 9).

Burst Mode (in boost operation, Figure 10) and Skip Cycle mode (in buck operation, Figure 11) provide the highest possible light load efficiency. In Burst Mode operation, switches C and D operate in brief pulse trains

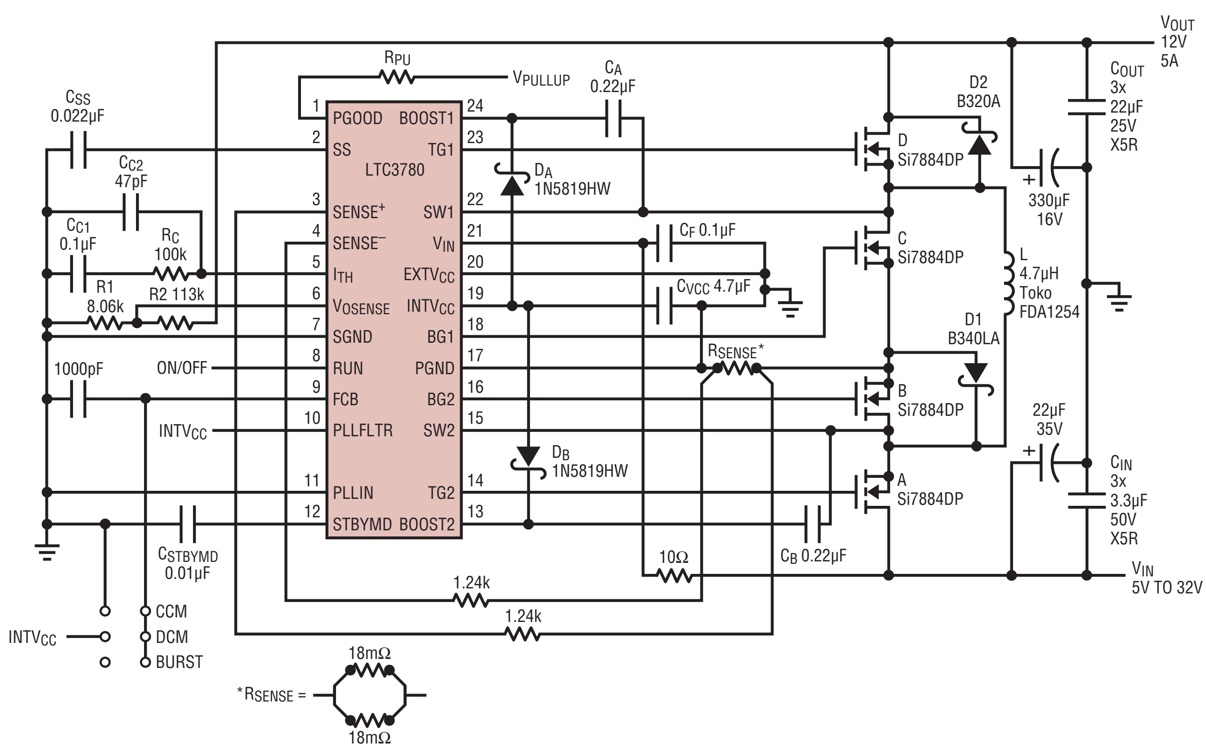
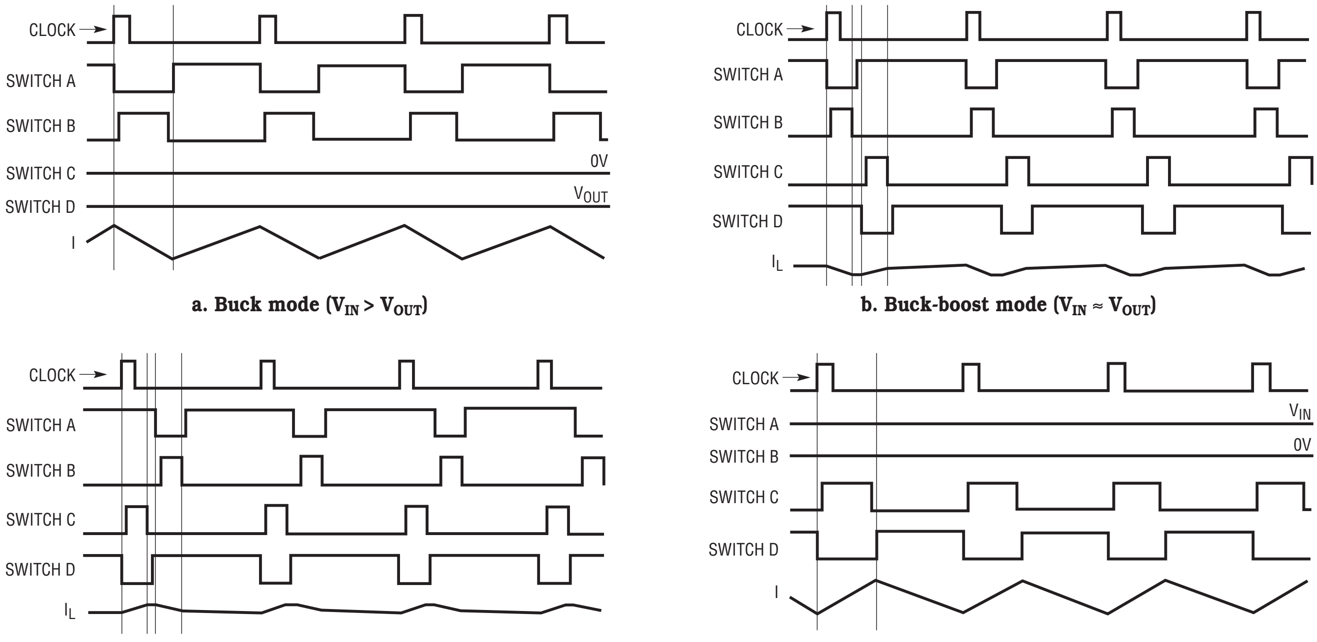


Figure 6. An LTC3780-based DC/DC converter delivering 12V/5A from a 5V–32V input.



a. Buck mode ($V_{IN} > V_{OUT}$)

b. Buck-boost mode ($V_{IN} \approx V_{OUT}$)

c. Buck-boost mode ($V_{IN} \approx V_{OUT}$)

d. Boost mode ($V_{IN} < V_{OUT}$)

Figure 8. Power switch gate drive control in continuous conduction mode, in various regions of operation.

while holding switch A on. Skip Cycle mode only turns on the synchronous buck switch B when the inductor current reaches a minimum positive level, which does not happen every cycle at very light loads. Since energy devoted to switching dominates the power loss picture at very light loads, both of these switching arrangements raise efficiency.

A single sense resistor placed between ground and the source terminals of both synchronous MOSFETs determines the current limit. It reliably governs the valley of the inductor current in buck mode and the maximum inductor peak current in boost mode. The LTC3780 monitors the current via an internal comparator. This single sense resistor structure dissipates little power (compared with multiple resistor sensing schemes) and provides consistent current information for short circuit and over current protection.

Flexible Power

Although the LTC3780 is ideal for applications where the range of possible input voltages straddles the output voltage in everyday operation, it is also useful as a dedicated synchronous buck or boost controller. Applications requiring a fixed output from a variety of input rails can benefit from the simplicity of a single drop-in design. At a minimum, the same layout can be repeated, with power switches and passive components scaled to the particular input voltage and output load requirements.

The LTC3780 is by itself an outstanding synchronous boost controller. Dedicated boost controllers typically have narrower input or output voltage ranges than the LTC3780, and nonsynchronous versions (the most common type) suffer from signifi-

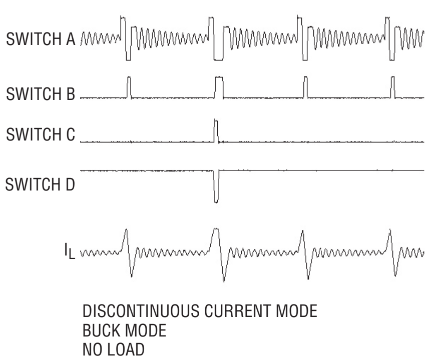


Figure 9. Switch operation in discontinuous current mode, buck mode, no load. Switch B turns on every cycle, until the inductor current goes slightly negative. The inductor current then free-wheels through the body diode of switch B (or a Schottky diode in parallel with it). Switches C and D occasionally trigger to refresh switch D's bootstrap capacitor.

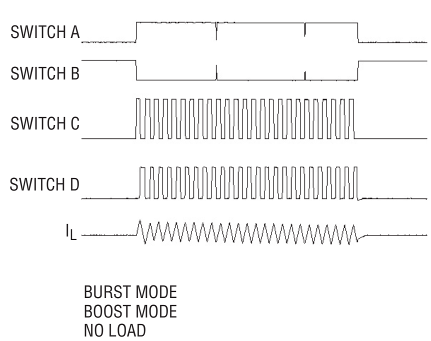


Figure 10. Switch operation in Burst Mode operation, boost mode, no load. Switches A and B are toggled to connect the true boost converter directly to the input rail, with occasional refresh pulses for switch A's bootstrap capacitor. During the sleep period between bursts, switches A, C, and D remain off.

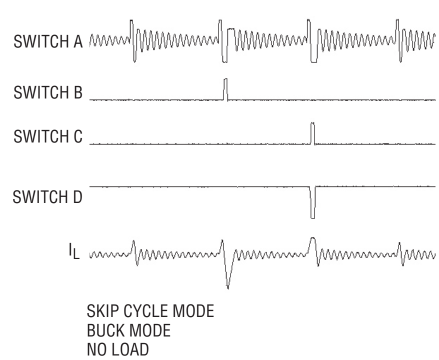


Figure 11. Switch operation in skip cycle mode, buck mode, no load. Note the similarity to discontinuous current mode, except switch B is not turned on every cycle. In this way, energy is saved by allowing the inductor to discharge through the body diode of switch B (or the Schottky diode across it, if there is one).

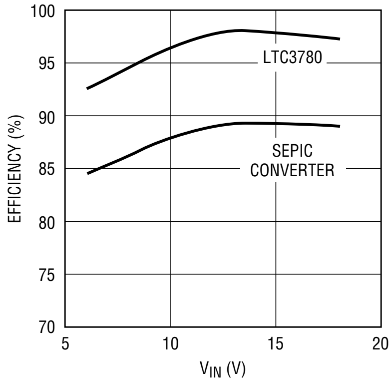


Figure 12. The LTC3780 12V/5A converter beats a SEPIC in efficiency across the board.

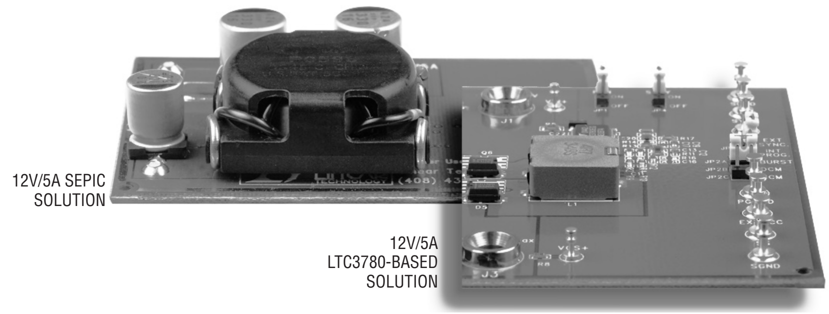


Figure 13. They may be similar in functionality, but not even close in size. The hulking inductor in the SEPIC on the left casts a big shadow on its counterpart in the LTC3780-based 12V/5A application on the right.

cant power loss in the free-wheeling Schottky diode. Compared to a typical non-synchronous boost converter, the circuit of Figure 6 can yield an increase of over 5% in efficiency at moderate loads.

Surpassing the SEPIC

Whatever the operating mode, the single inductor buck-boost structure has high power density and high efficiency. Compared with a coupled inductor SEPIC converter, its efficiency can be 8% higher. Figure 12 shows the efficiency comparison between a typical LTC3780 12V/5A application and a SEPIC converter, which is not only less efficient but quite a bit larger. A SEPIC transformer would occupy twice the footprint of the inductor in our buck-boost example, and would stand twice as high (Figure 13).

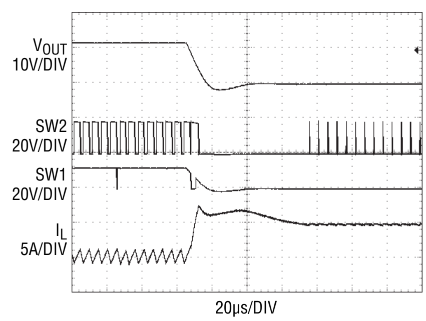


Figure 14. Current foldback handles short circuits without dragging down the input rail. V_{IN}, represented here by the peaks of SW2, remains solid.

Even the large off-the-shelf coupled inductor of Figure 13 would be insufficient for the current levels seen when boosting 5V to 12V at 5A—a safe minimum input voltage would be around 6V. To convert 32V to 12V, a SEPIC would require a power switch rated at 60V (the lowest prevailing drain-to-source voltage > V_{IN} + V_{OUT}), yet the output current would demand a low $R_{DS(ON)}$, requiring multiple SO-8 MOSFETs or a much larger TO-220. The coupling element would consist of large, expensive, high voltage ceramic capacitors, in addition to

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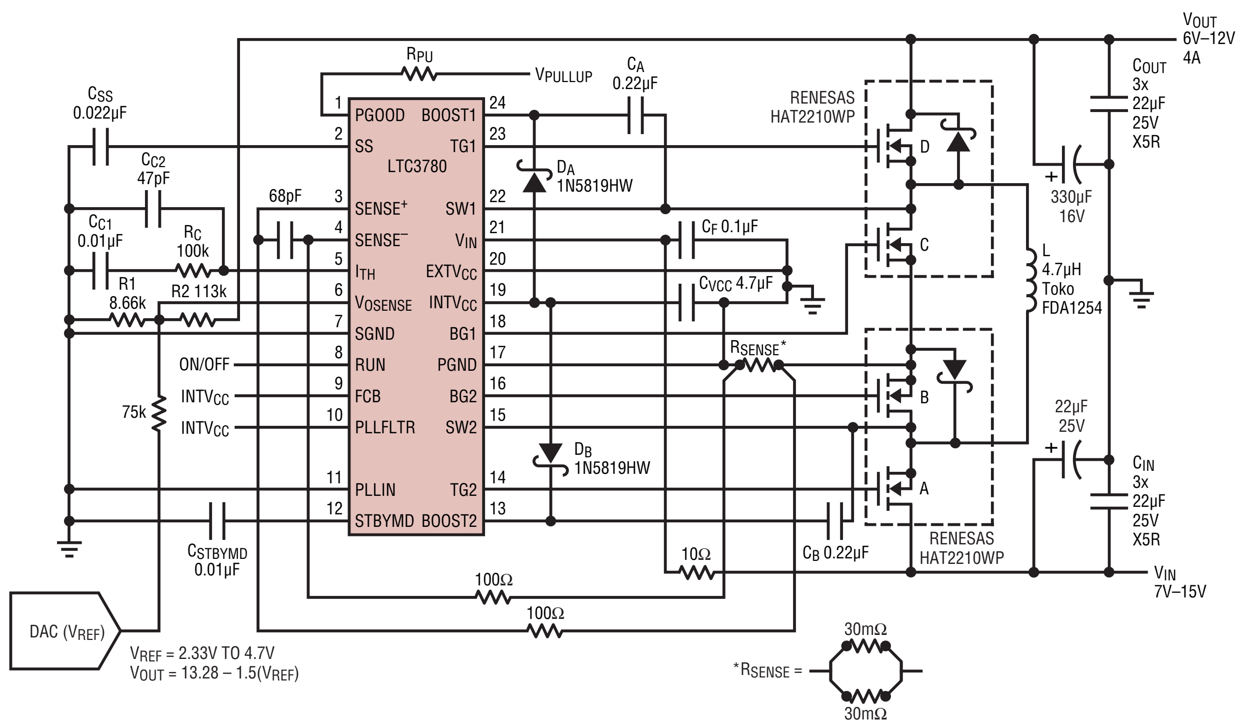

Figure 15. A compact, adjustable output supply

its nearest 14-bit competitor, the LTC2255 consumes 49% less power at just 395mW, significantly lowering the power budget and thermal considerations required for multiple channel devices. This provides a significant advantage in applications where efficiency and cooling is critical, such as satellite receivers, wireless base stations and portable electronics. As part of an extensive pin-compatible family, the LTC2255 comes in a conveniently small 5mm × 5mm QFN package with integrated bypass capacitors, requiring only a small number of tiny external components. The LTC2255 eliminates the need for large and costly decoupling capacitors, affording the smallest solution size available, which eases PCB space constraints and allows for more compact, cost effective designs. With its small dimensions, low power and reduced external component requirement, designers can easily fit four LTC2255 ADCs where just one competing solution would fit.

The LTC2255 is well placed to meet the needs of 3G and emerging 4G technologies, WiMAX and other wideband wireless applications where high performance ADCs play a key role in handling the demands of increasing network traffic. For wireless base station system designers, reduced power consumption is an important design consideration in helping to lower overall system operation costs. In addition, the combination of high sampling rate, low current and 14-bit resolution make it ideally suited to battery powered, high performance test and instrumentation equipment.

The LTC2255 offers exceptional low-level input signal performance due to its high linearity, and it is designed with good margin relative to the sample rate for reliable performance over a wide temperature range. At 125Msps sampling rate, it achieves excellent AC performance with 72.1dB SNR and 85dB SFDR at 70MHz.

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those required for input and output decoupling. The LTC3780 allows the designer to avoid these expensive, space-wasting complexities while increasing efficiency.

Short Circuit Protection

The basic boost regulator topology provides no short circuit protection. When the output is pulled low, a large current can flow from the input to the output. Nevertheless, if an overload causes an LTC3780 circuit to reach current limit, current foldback prevents the overload from carrying over to the input without shutting down the whole circuit. Figure 14 shows the result: the converter is forced into buck mode, and the duty cycle of SW2 is reduced such that the voltage at SW2 continues to swing between V_{IN} and ground. V_{IN} remains solid since current foldback limits the inductor current, so the supply only draws 100mA more than it would without any load. A power good output open-drain logic output signals whether the output voltage is in or out of regulation. When the overload disappears, the output voltage returns to its normal value—there is no need to shut down and restart the LTC3780.

Keep Alive

LTC3780 applications often work alongside related subsystems requiring very little current. The LTC3780's STDBYMD pin allows the internal low dropout regulator to remain functional even when the RUN pin disables all other functions of the controller. The LDO then provides 6V at up to 40mA at the INTVCC pin for neighboring "wake-up" circuitry.

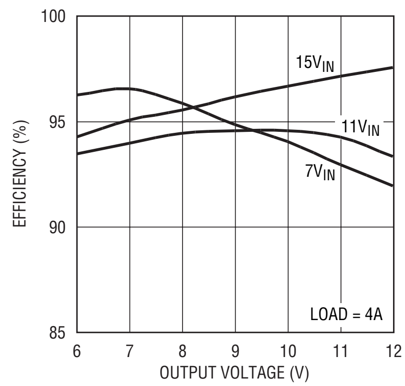

Figure 16. Efficiency for the adjustable output supply is consistently in the mid-90s.

Compact, Efficient Regulator with Programmable V_{OUT}

With an external voltage applied to its V_{OSENSE} pin through a resistor, the LTC3780 can control a supply capable of providing a 4A, 6V–12V output from a 7V–15V input (Figure 15). Efficiency is in the mid-90 percent range throughout a wide range of inputs and load currents, as Figure 16 illustrates. Dual MOSFETs with integrated Schottky diodes keep the footprint to a minimum. With the application of 0.85V to 4.9V to the feedback node through a 75kΩ resistor, the output varies from 12V down to 6V. The proper external voltage can be approximated from the equation $V_{OUT} = 13.28V – 1.5(V_{REF})$. Naturally, this implementation of the LTC3780 could be applied to many other ranges of input/output voltages and currents.

Conclusion

It is not a trivial task to deliver high current with tight regulation when the input voltage can be more than, less than, or equal to the output voltage. The LTC3780's proprietary architecture shoulders the complexity and simplifies the power supply designer's job. It is the first buck-boost controller to provide extremely high efficiency, seamless transitions between operating modes, and wide input voltage range, all without resorting to cumbersome magnetics or multiple control loops.

A converter designed around the LTC3780 naturally has a wide input voltage range, which gives it unparalleled versatility. A single converter design can be powered by any of a number of rails with the high efficiency of a true synchronous buck or boost converter. Its unique advantages over common designs make the LTC3780 ideal for automotive, telecom, industrial, and battery-powered applications.