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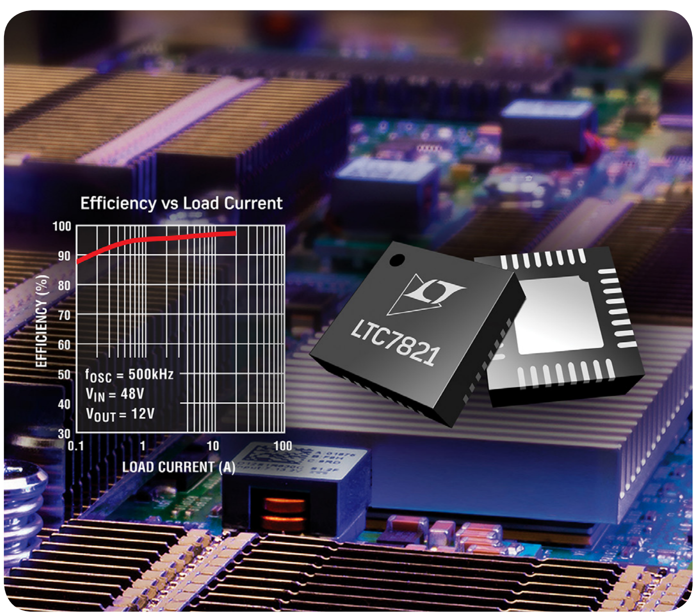
Hybrid Converter Simplifies 48V/54V Step-Down Conversion in Data Centers and Telecom Systems

Ya Liu, Jian Li, San-Hwa Chee and Marvin Macairan

There has been a shift in data center and telecom power system design. Key applications manufacturers are replacing complex, expensive isolated 48V/54V step-down converters with more efficient *nonisolated*, high density step-down regulators (Figure 1). Isolation is not necessary in the bus converter since the upstream 48V or 54V input is already isolated from hazardous AC mains.



High efficiency, compact footprint and easy scalability: the LTC7821 hybrid converter upgrades telecom and data center applications by replacing complex and expensive isolated bus converters.

For a high input/output voltage application (48V to 12V), a conventional buck converter is not an ideal solution because component size tends to be larger. That is, a buck converter must run at low switching frequency (e.g., 100kHz to 200kHz) to achieve high efficiency at high input/output voltage. The power density of a buck converter is limited by the size of passive components, especially the bulky inductor. The inductor size can be reduced by increasing the switching frequency, but this reduces converter efficiency because of switching-related losses and leads to unacceptable thermal stress.

Switched capacitor converters (charge pumps) significantly improve efficiency and reduce solution size over conventional inductor-based buck converters. In a charge pump, instead of an inductor, a flying capacitor is used to store and transfer the energy from input to output. The energy density of capacitors is much higher than inductors, improving power density by a factor of 10 over a buck regulator. However, charge pumps

(continued on page 4)

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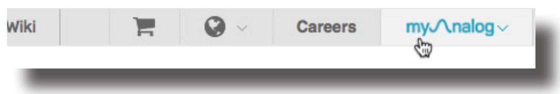

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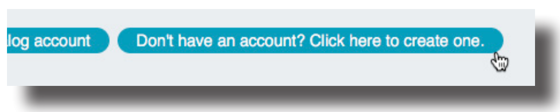

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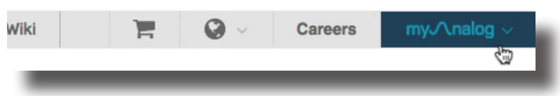

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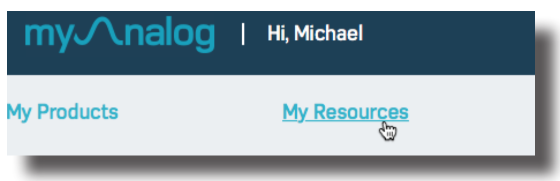

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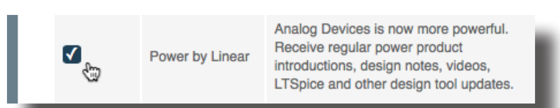

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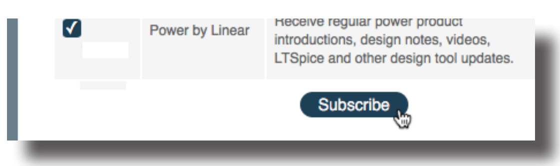


Open Circuit

A SINGLE CHIP AUTOMOTIVE INFOTAINMENT POWER SOLUTION

Ultralow quiescent current is a mission critical requirement of modern automotive power systems. The modern automobile may need to sit unused for a month or more as critical always-on electronic systems run without draining the battery. At the other end of the spectrum, an increasingly harsh automotive battery environment further necessitates electronics with high voltage input capability and the ability to regulate through wide input transients.

Start-stop technology magnifies the extreme conditions that electronics must face, specifically through repeated engine cranking. A start-stop enabled car restarts the engine repeatedly and critical systems must remain operational even as the battery supply goes through a cold crank.

Analog Devices Power by Linear LTC3372 all-in-one high voltage controller is capable of maintaining regulation through the extreme voltage changes in automotive battery environments. It combines four configurable monolithic regulators to provide up to five output channels for infotainment or other electronic systems.

The LTC3372 enables new always-on applications when its total bias I_Q for five channels is comparable to a single channel using older technology. By integrating a controller and monolithic regulators, LTC3372 can provide up to five separate rails from high input voltage in compact size at low cost.

Automotive Multichannel Power

The LTC3372 combines our proven high voltage automotive controller technology with four configurable monolithic bucks to create a cost-efficient automotive multichannel power solution. The high voltage buck controller input can operate through input surges up to 60V, such as those seen during a load dump. It can also regulate through input dips as low as 4.5V in a standard buck configuration and down to 3V in a SEPIC configuration. This allows continuous power without interruption.

The low voltage bucks offer four independent regulators and eight 1A power stages. The multichannel power solution can be configured into eight unique output channel configurations directly from an automotive battery source.

Ultralow Quiescent Current Preserves Battery Charge in Always-On Systems

A benefit of a combined multichannel power solution is the shared internal voltage references and bias supplies. This bias sharing permits lower per channel I_Q specifications for multichannel power than would be available with independent ICs. For a single channel always-on supply, the V_{IN} referenced bias I_Q is 23µA typical and 45µA maximum at 150°C. With all five channels regulating in Burst Mode operation, the typical bias current is only 60µA total or 12µA per channel. A total bias I_Q for five channels is comparable to that of a single channel using prior technologies. This efficiency improvement gives applications designers the freedom to add always-on applications, otherwise precluded due to battery energy constraints. ■

All switches in a hybrid converter see half of input voltage in steady state operation, enabling the use of low voltage rating MOSFETs to achieve good efficiency. The switching-related losses in a hybrid converter are lower than a conventional buck converter, ensuring high frequency switching.

(LTC7821, continued from page 1)

are fractional converters—they do not regulate output voltage—and are not scalable for high current applications.

A LTC7821-based hybrid converter has the benefits of both conventional buck converters and charge pumps: output voltage regulation, scalability, high efficiency and high density. A hybrid converter regulates its output voltage with closed-loop control just like a buck converter. With peak current mode control, it is easy to scale the hybrid converter up for higher current levels (e.g., a single-phase design for 48V to 12V/25A, a 4-phase design for 48V to 12V/100A).

All switches in a hybrid converter see half of the input voltage in steady state operation, enabling the use of low voltage rating MOSFETs to achieve good efficiency. The switching-related losses in a hybrid converter are lower than a conventional buck converter, enabling high frequency switching.

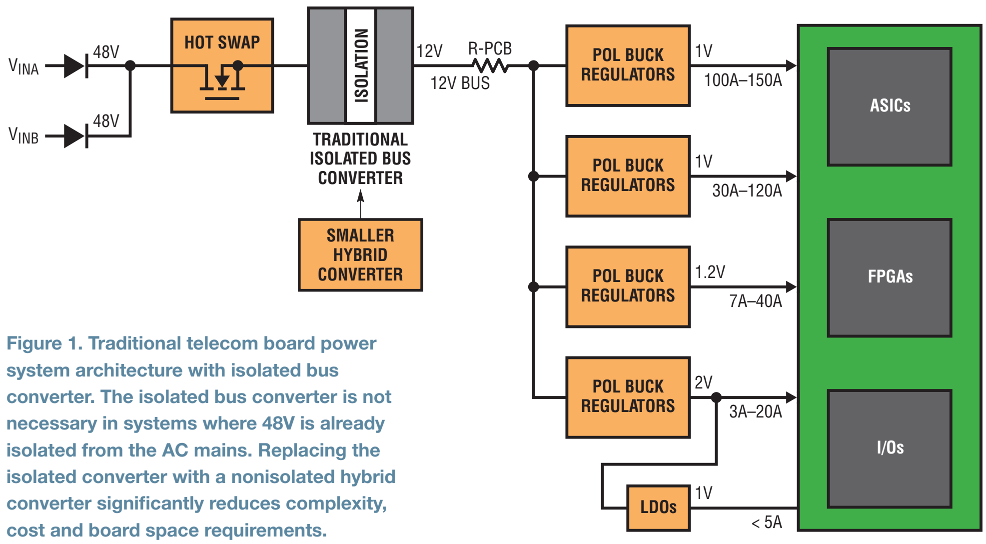


Figure 1. Traditional telecom board power system architecture with isolated bus converter. The isolated bus converter is not necessary in systems where 48V is already isolated from the AC mains. Replacing the isolated converter with a nonisolated hybrid converter significantly reduces complexity, cost and board space requirements.

In a typical 48V to 12V/25A application, efficiency above 97% at full load is attainable with the LTC7821 switching at 500kHz. To achieve similar efficiency using a traditional buck controller it would have to operate at a third the frequency, resulting in a much larger solution size. Higher switching frequencies allow the use of smaller inductances, which yield faster transient response and smaller solution size (Figure 2).

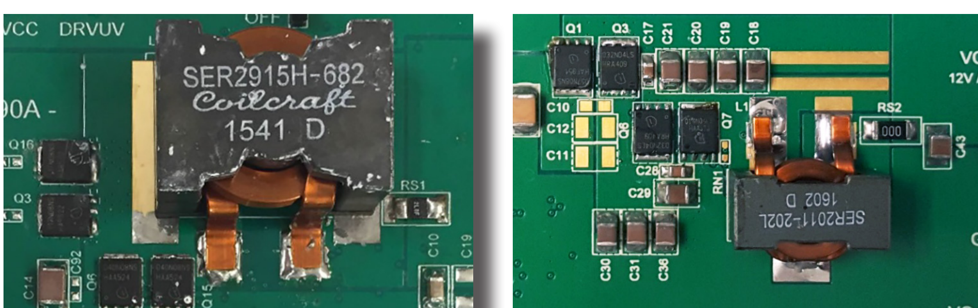
Figure 2. Size comparison of nonisolated buck converter and equivalent 48V to 12V/20A hybrid converter

BUCK CONVERTER

- 1.1in × 0.78in × ≥0.6in Inductor
- 0.514in^3 volume, body only
- 2× 80V top FETs
- 2× 80V bottom FETs
- f_{SW}: 125kHz~200kHz
- Same C_{IN} as hybrid converter

HYBRID CONVERTER (SMALLER, FASTER)

- 0.76in × 0.37in × 0.42in Inductor
- 0.118in^3 volume, body only (77% savings)
- 1× 80V FET (Q1)
- 3× 40V FETs (Q2, Q3, Q4)
- f_{SW}: 500kHz~1MHz
- Same C_{IN} as buck converter



The LTC7821 is a peak current mode hybrid converter controller with the features required for a complete solution of a nonisolated, high efficiency high density step-down converter for intermediate bus converter in data centers and telecom systems. The LTC7821's key features include:

- Wide V_{IN} range: 10V to 72V (80V abs max)
- Phase-lockable fixed frequency 200kHz to 1.5MHz
- Integrated quad ~5V N-channel MOSFET drivers
- R_{SENSE} or DCR current sensing
- Programmable CCM, DCM, or Burst Mode® operation

In a typical 48V to 12V/25A application, efficiency above 97% at full load is attainable with the LTC7821 even while switching at 500kHz. To achieve similar efficiency using a traditional buck controller it would need to operate at a third the frequency, resulting in a much larger solution size.

- CLKOUT pin for multiphase operation
- Short-circuit protection
- $EXTV_{CC}$ input for improved efficiency
- Monotonic output voltage start-up
- 32-pin (5mm × 5mm) QFN package

48V TO 12V/25A HYBRID CONVERTER FEATURING 640W/IN³ POWER DENSITY

Figure 3 shows a 300W hybrid converter using the LTC7821 switching at 400kHz. The input voltage range is 40V to 60V and the output is 12V at loads up to 25A. Twelve 10μF (1210 size) ceramic capacitors are used for each flying capacitor, C_{FLY} and C_{MID}. The relatively small size 2μH inductor (SER2011-202ML, 0.75 inch × 0.73 inch) can be used because of the high switching frequency and the fact that the inductor only sees half of V_{IN} at the switching node (small volt-second). The approximate solution size is 1.45 inch × 0.77 inch as shown in Figure 4, resulting in a power density of about 640W/in³.

As the bottom three switches always see half the input voltage, 40V rated FETs are used. An 80V rating FET is used for the very top switch because it sees input voltage at the beginning of the precharge of C_{FLY} and C_{MID} during start-up (no switching). During steady state operation, all four switches see half of the input voltage. Therefore, the switching losses in a hybrid converter are much smaller compared to a buck converter in which all switches see the full input voltage. Figure 5 shows the efficiency of the design. The peak efficiency is 97.6% and the full load efficiency is 97.2%. With high efficiency (low power loss), thermal performance is very good, as shown in the Figure 6 thermograph. The hot spot is 92°C at an ambient temperature of 23°C, no forced airflow.

The LTC7821 implements a unique C_{FLY} and C_{MID} prebalancing technique, which prevents input inrush current during start-up. During initial power-up, the voltage across the flying capacitor C_{FLY} and C_{MID} are measured. If either of these voltages are not at $V_{IN}/2$, the TIMER capacitor is allowed to charge up. When the TIMER capacitor voltage reaches 0.5V, internal

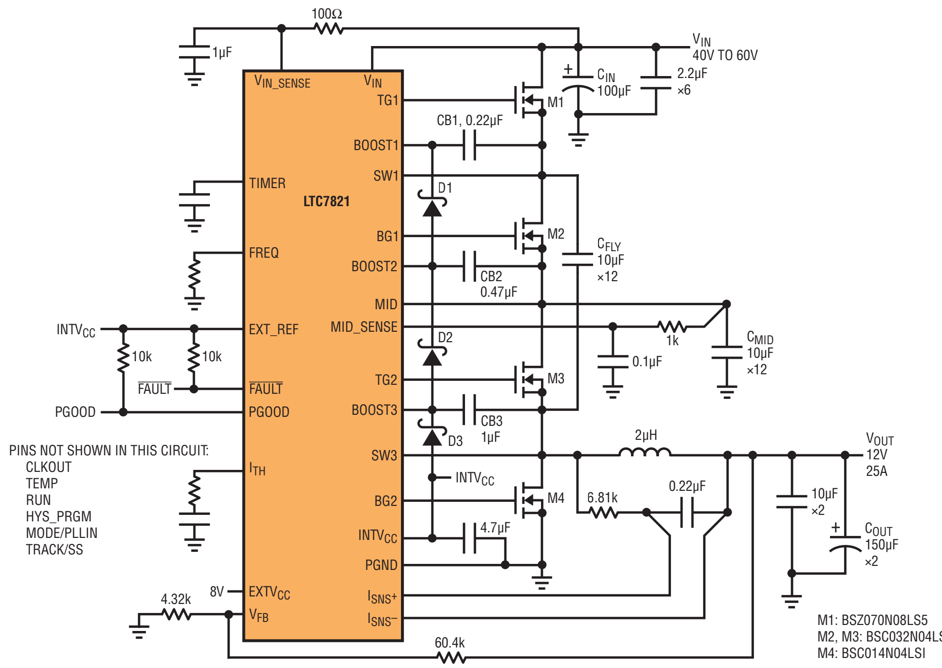
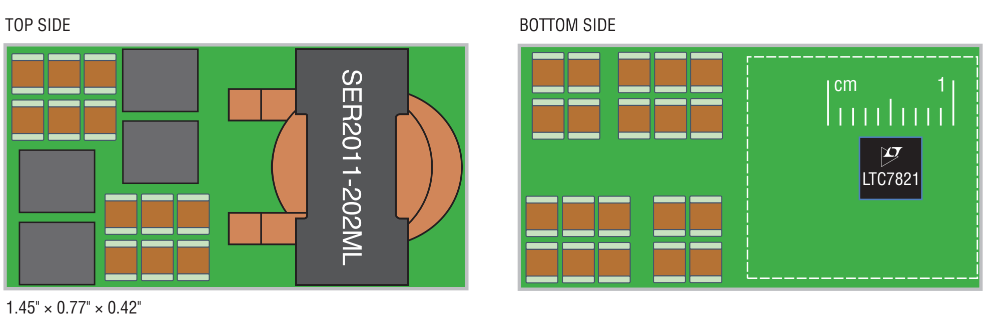


Figure 3. A 48V to 12V/25A hybrid converter using the LTC7821

Figure 4. Possible layout for a complete bus converter uses the top and bottom sides of the board, requiring only 2.7cm² of topside of the board



The easy scalability of the LTC7821 makes it a good fit for high current applications, such as those found in telecom and data centers. Paralleling devices for high current is easy: the PLLIN pin of one LTC7821 and CLKOUT pin of the other LTC7821 are tied together to synchronize the PWM signals. For a design with more than two phases, the PLLIN and CLKOUT pins are simply connected in a daisy chain.

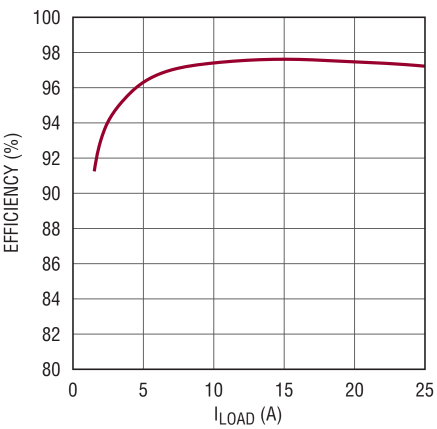


Figure 5. Efficiency at 48V input, 12V output and 400kHz f_{SW}

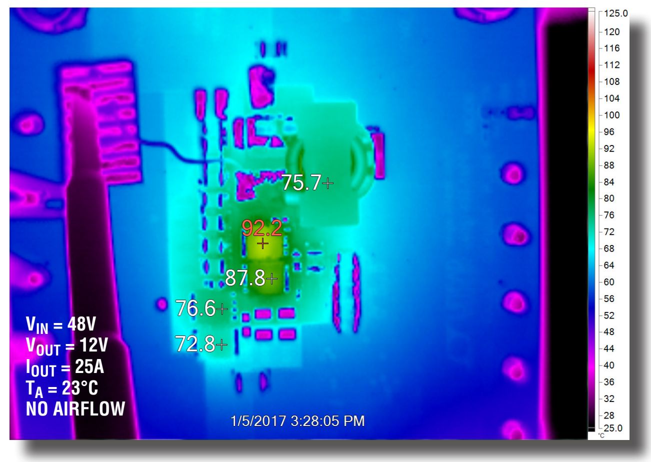


Figure 6. Thermograph of the hybrid converter solution in Figure 2

current sources are turned on to bring the C_{FLY} voltage to $V_{IN}/2$. After the C_{FLY} voltage has reached $V_{IN}/2$, C_{MID} is charged to $V_{IN}/2$. The TRACK/SS pin is pulled low during this duration and all external MOSFETs are shut off. If the voltages across C_{FLY} and C_{MID} reach $V_{IN}/2$ before the TIMER capacitor voltage reaches 1.2V, TRACK/SS is released, and a normal soft-start begins. Figure 7 shows this prebalancing period and Figure 8 shows the V_{OUT} soft-start at 48V input, 12V output at 25A.

1.2kW MULTIPHASE HYBRID CONVERTER

The easy scalability of the LTC7821 makes it a good fit for high current applications, such as those found in telecom and data centers. Figure 9 shows the key signal connections for a 2-phase hybrid converter using multiple LTC7821s. The PLLIN pin of one LTC7821 and the CLKOUT pin of the other LTC7821 are tied together to synchronize the PWM signals.

For a design with more than two phases, the PLLIN pin and CLKOUT pin are connected in a daisy chain. Since the clock output on the CLKOUT pin is 180° out of phase with respect to the main clock of LTC7821, even numbered phases are in phase with each other, while those with odd numbers are anti-phase to the evens.

A 4-phase 1.2kW hybrid converter is shown in Figure 10. The power stage of each phase is identical to the single-phase

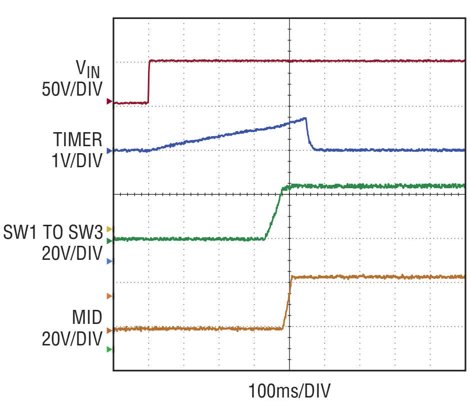


Figure 7. Prebalancing period in the LTC7821 start-up avoids high inrush currents

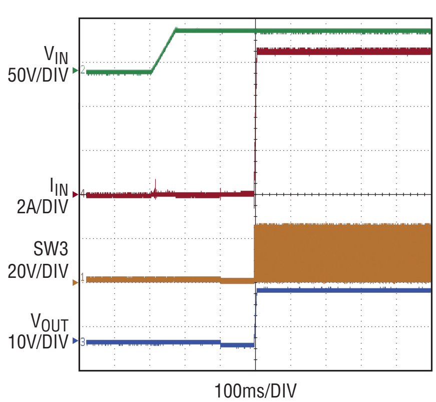


Figure 8. LTC7821 start-up at 48V input, 12V output at 25A (no high inrush current)

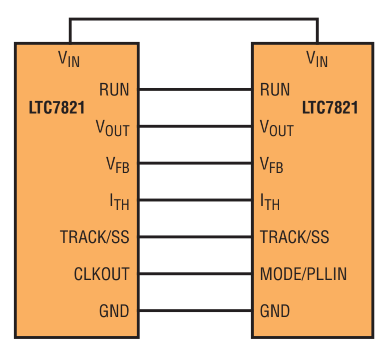
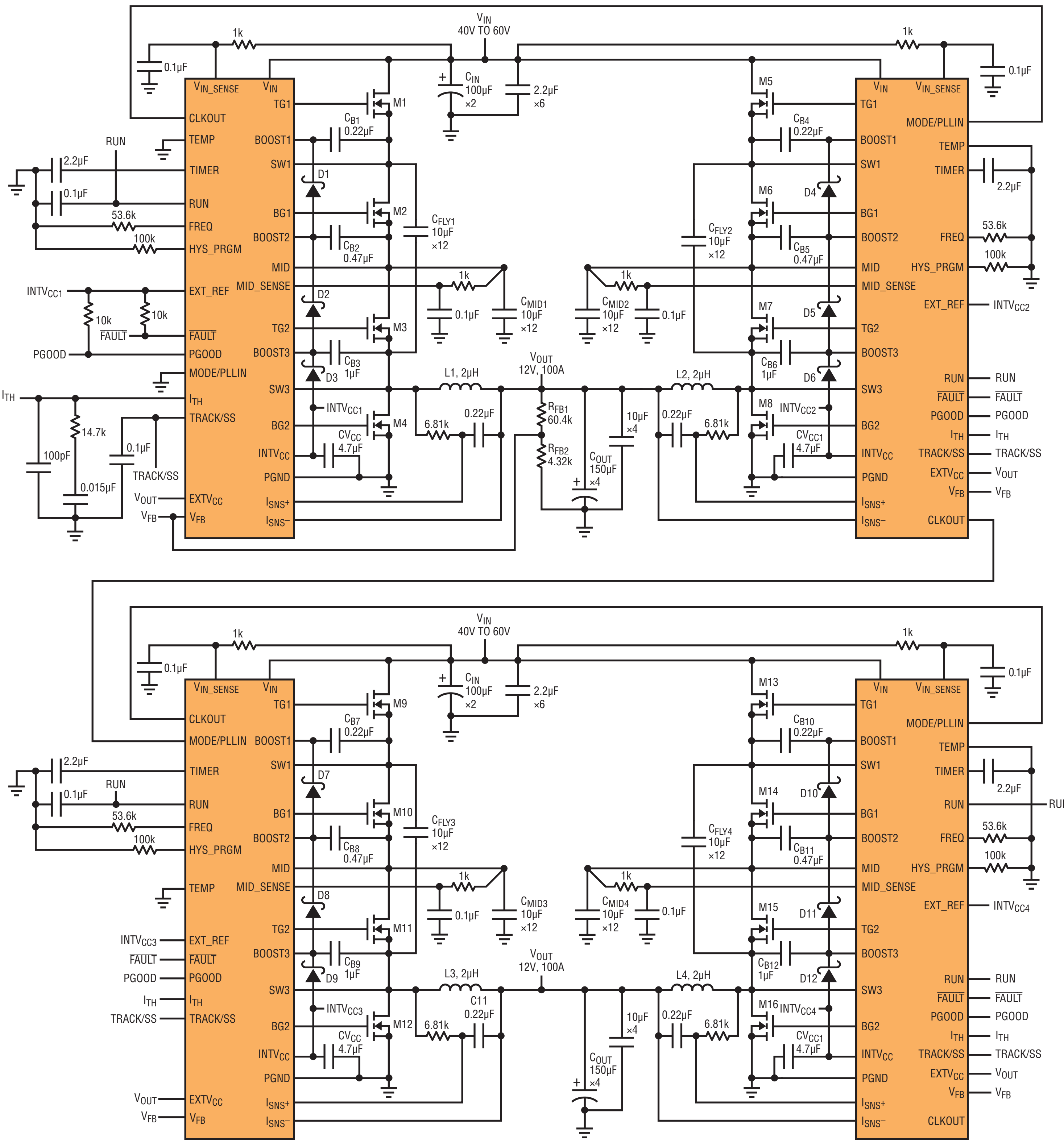


Figure 9. Connection of key signals of LTC7821 for a 2-phase design

Figure 10. A 4-phase 1.2kW hybrid converter using four LTC7821s



M1, M5, M9, M13: INFINEON BSZ070N08LS5
M2, M3, M6, M7, M10, M11, M14, M15: INFINEON BSC032N04LS
M4, M8, M12, M16, : INFINEON BSC014N04LSI
L1, L2, L3, L4 : COILCRAFT SER2011-202ML
D1–D12: CENTRAL SEMICONDUCTOR CMDSH-4
C_{FLY}, C_{MID}: MURATA GRM32ER71H106KA12

The LTC7821 is a peak current mode hybrid converter controller, which enables an innovative simplified approach to intermediate bus converter implementation in data centers and telecom systems.

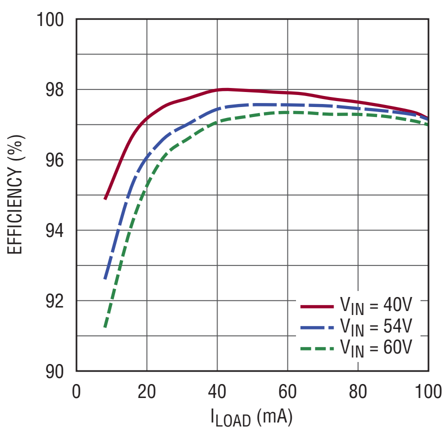


Figure 11. Efficiency for a 4-phase, 1.2kW design

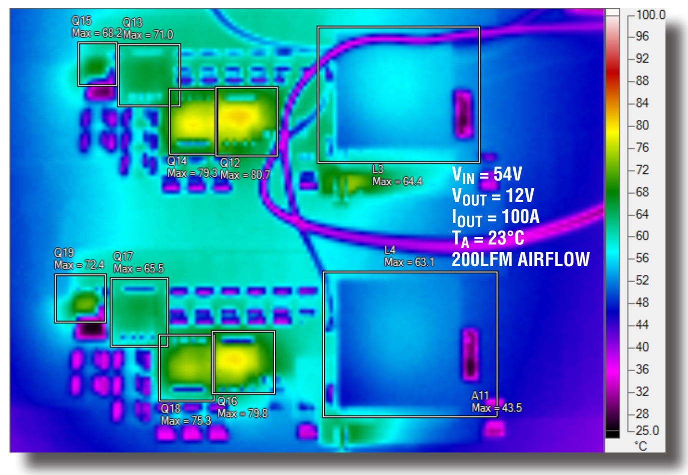


Figure 12. Thermograph of the multiphase converter shown in Figure 9

design in Figure 3. The input voltage range is 40V to 60V and the output is 12V at load up to 100A. The peak efficiency is 97.5% and the full load efficiency is 97.1% as shown in Figure 11. The thermal performance is shown in the Figure 12. The hot spot is 81°C at an ambient temperature of 23°C, with 200LFM forced airflow. Inductor DCR sensing is used in this design. As shown in Figure 13, current sharing is well balanced among the four phases.

CONCLUSION

The LTC7821 is a peak current mode hybrid converter controller, which enables an innovative simplified approach to intermediate bus converter implementation in data centers and telecom systems. All switches in a hybrid converter see half of the input voltage, significantly reducing the switching related losses in high input/output voltage applications. Because of this, a hybrid converter can run at 2× to 3× higher switching frequency than a buck converter without compromising efficiency.

A hybrid converter can be easily scaled for higher current applications. Lower overall cost and easy scalability differentiate hybrid converters from traditional isolated bus converters. ■

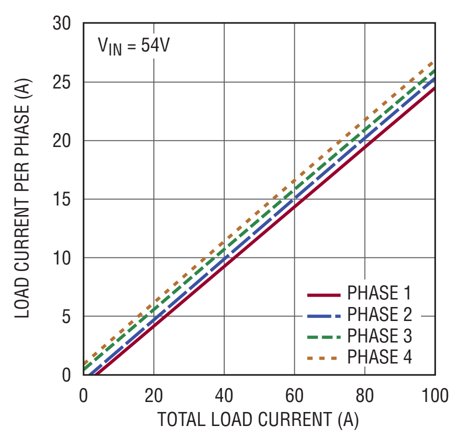


Figure 13. Current sharing for the multiphase converter shown in Figure 9

Comprehensive Power Supply System Designs for Harsh Automotive Environments Consume Minimal Space, Preserve Battery Charge, Feature Low EMI

Bin Wu and Zhongming Ye

Advances in automotive technology have significantly increased the electronic content of modern automobiles to enhance safety, improve the driving experience, enrich entertainment functions, and diversify the power and energy sources. We continue to commit engineering resources to improving power management solutions for the automotive market. Many of the technologies from that effort have resulted in significant advances in power supply efficiency, compactness, robustness and EMI performance.

Power supplies for automotive applications must perform without failure in the face of harsh conditions—the designer must consider all exigencies, including load dump and cold crank conditions, reverse battery, double battery jump, spikes, noise, mechanical vibration and extremely wide temperature ranges. This article focuses on the critical requirements in automotive power supply specifications and solutions to meeting automotive specifications, including:

- input voltage range
- output voltage/current
- low quiescent current (I_Q)
- electromagnetic interference (EMI)

Several example solutions are shown to illustrate how combinations of high performance devices can easily solve what would otherwise be difficult automotive power supply problems.

HARSH AUTOMOTIVE ENVIRONMENTS

Figure 1 illustrates a complete power solution that meets the demanding requirements of automotive applications. At the front-end, the LT8672 acts as an ideal diode, protecting the circuit from brutal under-the-hood conditions and destructive faults, such as reverse polarity. Following the ideal diode is a family of low quiescent current (I_Q) buck regulators that feature wide input ranges—working down to 3V and up to 42V—to deliver regulated voltages for the cores, I/O, DDR and other rails required by peripheral devices.

These regulators feature ultralow quiescent current, extending battery run time for always-on systems. Low noise power conversion technology minimizes the need for costly EMI mitigation as well as design and test cycles to meet stringent automotive EMI standards. For many critical functions that must ride through cold crank events, the LT8603 multichannel low I_Q buck regulators with built-in pre-regulation boost controller delivers a compact solution with at least three regulated voltage rails. The LT8602 can deliver four regulated voltage rails required for many Advanced Drive Assistance System (ADAS)

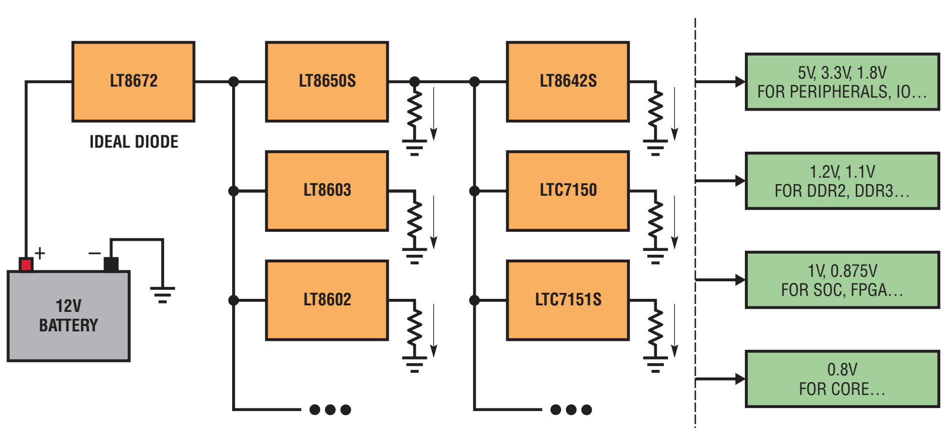


Figure 1. Overview of ADI Power by Linear solutions for automotive electronics that meet transient immunity requirements

Many Power by Linear high voltage step-down regulators, such as the Silent Switcher® and Silent Switcher 2 families, including the LT8650S, LT8640S (Table 1) operate up to 42V, exceeding the requirement to survive a doubled nominal battery voltage. In contrast, lower voltage rated options would require a clamp circuit, adding cost and lowering efficiency.

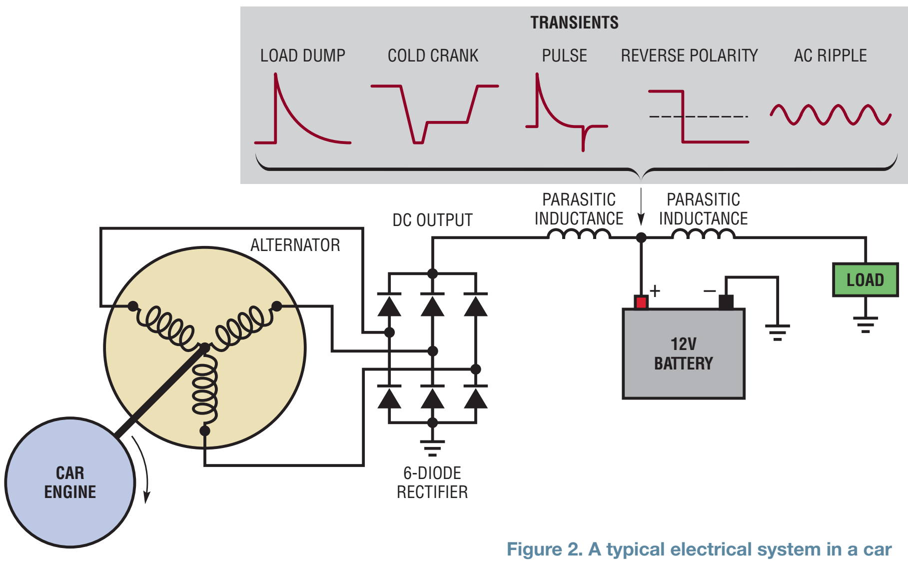


Figure 2. A typical electrical system in a car

applications, such as collision warning, mitigation, and blind spot monitoring.

Figure 2 shows a traditional automotive electrical system, where the engine drives an alternator. The alternator is essentially a 3-phase generator, with its AC output rectified by a full diode bridge. The output of this rectifier is used to recharge a lead-acid battery and power 12V circuits and devices. Typical loads include the ECU, fuel pump, brakes, fan, air conditioner, sound systems and lighting. Increasing numbers of ADAS are added to the 12V bus, including peripherals, I/Os, DDRs, processors and their power supplies.

Electric cars change the picture somewhat. The engine is replaced with an electric motor, where a DC/DC converter converts a 400V high voltage Li-ion battery stack to 12V, instead of an alternator. Nevertheless, traditional 12V alternator devices are here to stay, along with their transient pulses—including fast pulses.

An engine runs at its peak efficiency in a narrow range of RPMs, so the steady state output of the alternator and the battery voltage are relatively stable, say ~13.8V, under most conditions (more about that below). Every circuit powered directly from the car battery must run reliably over the range 9V to 16V, but robust automobile electronic designs must also operate during outlier conditions that will inevitably occur at the most inconvenient time.

Although output of the alternator is nominally stable, it is not stable enough to avoid the need for conditioning before it powers the vehicle's other systems. Unwanted voltage spikes or transients are harmful to downstream electronic systems, and if not properly addressed, can cause these systems to malfunction or cause permanent damage. In the past few decades, many automotive standards such as ISO 7637-2, ISO 16750-2, LV124, TL82066 have been produced to define the spikes and voltage transients that automotive power supplies will face, and set design expectations.

One of the most critical and challenging high voltage transients is load dump. A load dump happens when a large load, such as an air conditioner, is turned off concurrent with a battery disconnection. Even as the load is turned off, the excitation field of the alternator remains high given its large time constant—the alternator still outputs high power even without the load. A battery is a big capacitor, and will normally absorb the extra energy, but when it is disconnected due to a loose terminal or other issue, it can no longer provide this service. As a result, all the other electronics see the voltage jump and thus must be able survive load dump events. An unsuppressed load dump could generate voltages upwards of 100V. Thankfully, modern car alternators use avalanche-rated rectifier diodes, limiting the load dump voltage to 35V, still a significant diversion from the norm. A load dump event lasts about 300ms.

Another high voltage event is jump start. Some tow trucks use two batteries in series to assure effective jump starts, so an automobile's circuits must survive the doubled nominal battery voltage of 28V for a couple of minutes. Many Power by Linear high voltage step-down regulators, such as the Silent Switcher and Silent Switcher 2 families, including the LT8650S, LT8640S (Table 1) operate up to 42V, exceeding this

Some Power by Linear regulators, such as the LT8645S, LT8646S are rated for 65V to accommodate truck and airplane applications, where 24V system is the norm.

Table 1. Silent Switcher and Silent Switcher 2 monolithic buck regulators for automotive applications

DEVICE	# OF OUTPUTS	V_{IN} RANGE	OUTPUT CURRENT	PEAK EFFICIENCY f_{SW} = 2MHz V_{IN} = 12V V_{OUT} = 5V	I_Q AT 12V INPUT (TYP)	EMI FEATURE	PACKAGES
LT8650S	2	3V–42V	4A on both channels 6A on either channel	94.60%	6.2µA	Silent Switcher 2	6mm × 4mm × 0.94mm LQFN
LT8645S	1	3.4V–65V	8A	94%	2.5µA	Silent Switcher 2	6mm × 4mm × 0.94mm LQFN
LT8643S	1	3.4V–42V	6A continuous 7A peak	95%	2.5µA	Silent Switcher 2 external compensation	4mm × 4mm × 0.94mm LQFN
LT8640S	1	3.4V–42V	6A continuous, 7A peak	95%	2.5µA	Silent Switcher 2	4mm × 4mm × 0.94mm LQFN
LT8609S	1	3V–42V	2A continuous 3A peak	93%	2.5µA	Silent Switcher 2	3mm × 3mm × 0.94mm LQFN
LT8641	1	3V–65V	3.5A continuous 5A peak	94%	2.5µA	Silent Switcher	3mm × 4mm QFN–18
LT8640 LT8640–1	1	3.4V–42V	5A continuous 7A peak	95%	2.5µA	Silent Switcher LT8640: pulse skipping LT8640–1: forced continuous	3mm × 4mm QFN–18
LT8614	1	3.4V–42V	4A	94%	2.5µA	Silent Switcher low ripple Burst Mode operation	3mm × 4mm QFN–18
LT8642S	1	2.8V–18V	10A	95%	240µA	Silent Switcher 2	4mm × 4mm × 0.94mm LQFN
LT8646S	1	3.4V–65V	8A	94%	2.5µA	Silent Switcher 2	6mm × 4mm × 0.94mm LQFN

requirement. In contrast, lower voltage rated options would require a clamp circuit, adding cost and lowering efficiency. Some Power by Linear regulators, such as the LT8645S, LT8646S are rated for 65V to accommodate truck and airplane applications, where 24V system is the norm.

Another voltage transient occurs when a driver starts an automobile, and the starter draws hundreds of amperes of current from the battery. This pulls down the battery voltage for a short period of time. In a traditional automobile, this happens only occasionally, for instance when one starts a car to drive the supermarket and again to drive back home. In modern automobiles with start-stop features to save fuel, start-stop events can occur a number of times on that supermarket trip—at every stop sign and every red light. The additional start-stop events put significantly more strain on the battery and starter than in a traditional automobile.

Under normal conditions, the LT8672 controls an external N-channel MOSFET to form an ideal diode. The GATE amplifier senses across DRAIN and SOURCE and drives the gate of the MOSFET to regulate the forward voltage to 20mV. D1 protects SOURCE in the positive direction during load steps and overvoltage conditions.

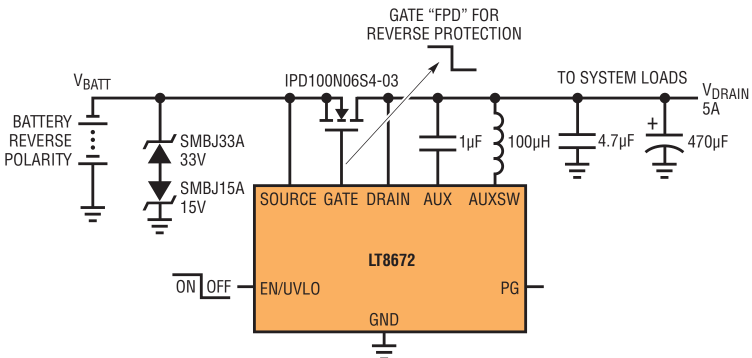


Figure 3. LT8672 response to battery reverse polarity

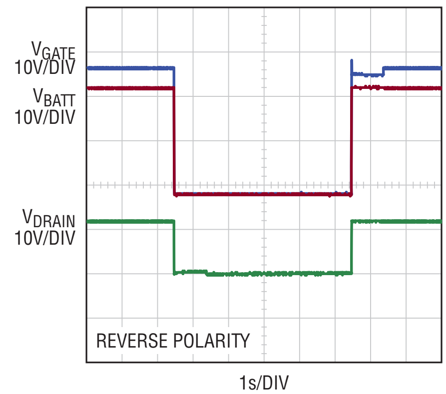


Figure 4. Waveform of LT8672 response to reverse polarity

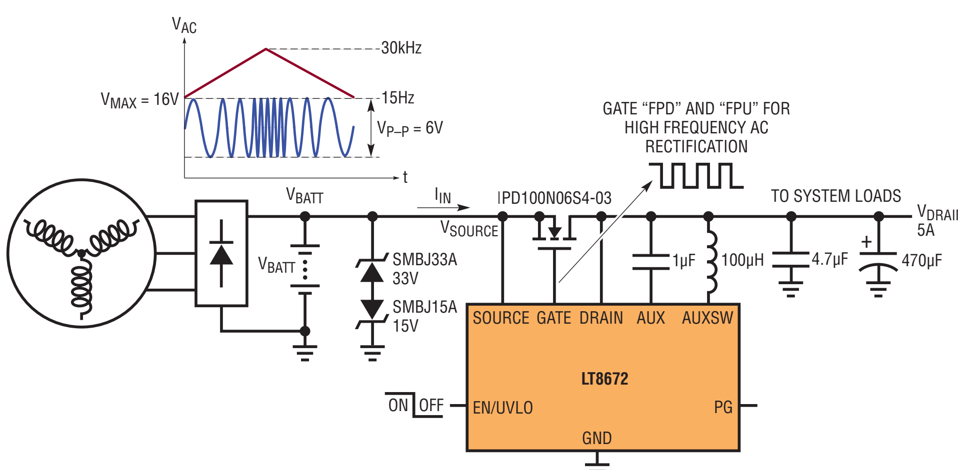
Furthermore, if a start event happens on a cold morning, the starter draws more current than at higher ambient temperatures, pulling the battery down to 4V or lower for 20ms—this is called cold crank. There are functions that must remain active even in cold crank conditions. The good thing is that, by design, such critical functions typically do not require significant power. Integrated solutions, such as the LT8603 multiple channel converter, can maintain regulation even if their inputs drop below 3V due to cold crank conditions.

ISO7637-2 and TL82066 define many other pulses. Some have higher positive or negative voltages but also higher source impedances. Those pulses have relatively low energy compared to the events described above, and can be filtered or clamped with proper designs.

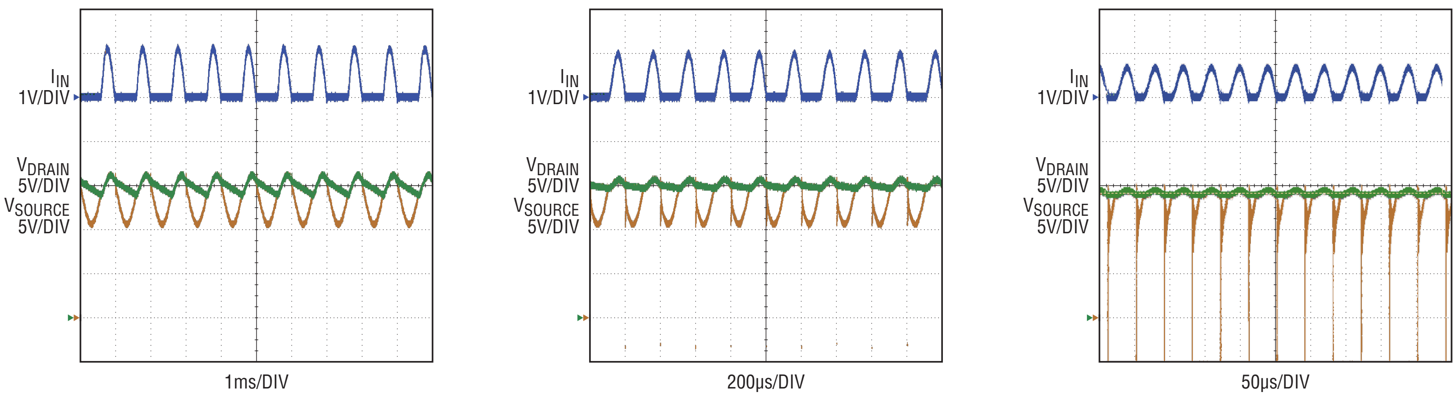
AN IDEAL DIODE SATISFIES AUTOMOTIVE IMMUNITY NORMS

The active rectifier controller LT8672, featuring high input voltage rating (+42V, –40V), low quiescent current, ultrafast transient response speed, and ultralow external FET voltage drop control, provides protection in 12V automotive systems with extremely low power dissipation.

Figure 5. LT8672 response to superimposed alternating voltage



When a negative voltage appears in the input side, GATE is pulled to SOURCE when SOURCE goes negative, turning off the MOSFET and isolating DRAIN from the negative input. With its fast pull-down (FPD) capability, LT8672 can quickly turn off the external MOSFET because of its large sinking current capability.



(a) 1kHz (a) 5kHz (a) 25kHz

Figure 6. Waveform of LT8672 response to superimposed alternating voltage

Battery Reverse Polarity

Whenever the battery terminals are disconnected there is a chance the car battery polarity is reversed by mistake, and the electronic systems can be damaged from the negative battery voltage. Blocking diodes are commonly placed in series with supply inputs to protect against supply reversal, but blocking diodes feature a voltage drop, resulting in an inefficient system, and reducing the input voltage, especially during a cold crank.

The LT8672 is an ideal diode replacement to the passive diode to protect the downstream systems from the negative voltages, as shown in Figure 3. Under normal conditions, the LT8672 controls an external N-channel MOSFET to form an ideal diode. The GATE amplifier senses across DRAIN and SOURCE and drives the gate of the MOSFET to regulate the forward voltage to 20mV. D1 protects SOURCE in the positive direction during load steps and overvoltage conditions. When a negative voltage appears in the input side, GATE is pulled to SOURCE when SOURCE goes negative, turning off the MOSFET and isolating DRAIN from the negative input. With its fast pull-down (FPD) capability, LT8672 can quickly turn off the external MOSFET because of its large sinking current capability.

Superimposed Alternating Voltage

A common disturbance on the battery rail is a superimposed alternating voltage (AC). This AC component can be an artifact of the rectified alternator output or a result of frequent switching of high current loads, such as motors, bulbs or PWM controlled loads. According to automotive specifications ISO16750 or LV124, an ECU may be subjected to an AC ripple superimposed on its supply, with frequencies up to 30kHz and amplitudes of up to $6V_{P-P}$. In Figure 5, a high frequency AC ripple is superimposed on the battery line voltage. Typical ideal diode controllers are too slow to react, but the LT8672 generates high frequency gate pulses up to 100kHz to control external FETs as needed to reject these AC signals.

The unique ability of the LT8672 to reject common AC components on a power rail are a function of its fast pull-up (FPU) and fast pull-down (FPD) control strategy and its strong gate driving capability, where the gate driver is powered by an integrated boost regulator. Compared with a charge pump gate power solution, this boost regulator enables the LT8672 to maintain a regulated 11V voltage to keep the external FET on, avoiding gate power refreshment resulting from constantly turning off the MOSFET. The LT8672 is able to control the external MOSFET rapidly enough even at these frequencies. Fast turn-on of the FET minimizes power dissipation, and fast turn-off minimizes the reverse current conduction. In addition, this significantly reduces the ripple current in the output capacitor. Typical rectification waveforms for a superimposed alternating voltage are shown in Figure 6.

The unique ability of the LT8672 to reject common AC components on a power rail are a function of its fast pull-up (FPU) and fast pull-down (FPD) control strategy and its strong gate driving capability, where the gate driver is powered by an integrated boost regulator.

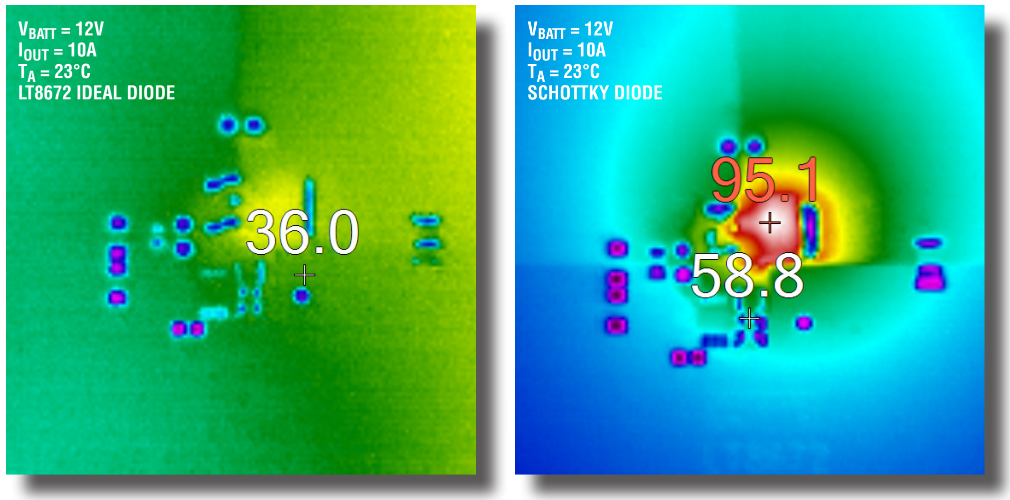
The LT8672 effectively suppresses ripple from the 12V bus and reduces the perturbation on the downstream system. As seen in the thermal images of Figure 7, the solution using the LT8672 is almost 60°C degree cooler than a traditional diode based solution. It not only improves the efficiency, but also eliminates the need for a bulky heat sink.

High peak, narrow pulses that appear on input of automotive electronic systems usually come from two sources:

- The disconnection of input power supply when there is inductive load in series or parallel.
- The switching processes of a load influencing the distributed capacitance and inductance of a wire harness.

Some of these pulses could have high voltage peaks. For example, pulse 3a defined in ISO7632-2 is a negative spike whose peak voltage exceeds –220V, while pulse 3b defines a pulse with maximum peak voltage of 150V, on top of the battery initial voltage. Although they feature a large internal impedance and very narrow duration time, downstream electronics could be easily damaged if they see these pulses.

Two properly sized TVSs are installed in the front-end to suppress such spikes. In fact, some of the low energy pulses could be absorbed directly by filter effect of input capacitor and parasitic wire inductance.



(a) LT8672 controlled system

(b) Schottky diode system

Figure 7. Thermal performance comparison

MULTIPLE RAIL REGULATOR RIDES THROUGH COLD CRANK EVENTS

The LT8602 provides compact solutions for up to four regulated rails with input voltage ranges from 5V to 42V, suitable for functions that do not necessarily need to be on during a cold crank. Otherwise, for those functions that must be functional even during cold crank—such as the spark plug controller or alarm—we offer an array of devices that work down to 3V, or lower, inputs.

LV124 has defined the worst case of cold crank, shown in Figure 8. It indicates that the lowest battery voltage can go down to 3.2V and last for 19ms at car start-up. This specification in reality challenges applications to keep running as low as 2.5V when faced with the extra diode voltage drop from battery reverse protection in a traditional (non-ideal diode) solution. In a passive diode protection scheme, buck-boost regulators may be required instead of less complex and more efficient buck regulators to provide a stable 3V supply often required by many microcontrollers.

The LT8672 controller features a minimum input operating voltage of 3V V_{BATT}, enabling the active rectifier to operate through the cold crank pulse with a minimum drop (20mV) between input and output. Downstream power supplies during a cold crank event see an input voltage no lower than 3V. This allows use of a buck regulator with a minimum operating voltage of 3V and low dropout characteristics, such as the LT8650S, to generate a 3V supply.

Like the LT8650S, many ADI Power by Linear automotive ICs feature minimum input voltage rating of 3V.

The LT8672 controller features a minimum input operating voltage of 3V V_{BATT}, enabling the active rectifier to operate through the cold crank pulse with a minimum drop (20mV) between input and output. Downstream power supplies during a cold crank event see an input voltage no lower than 3V.

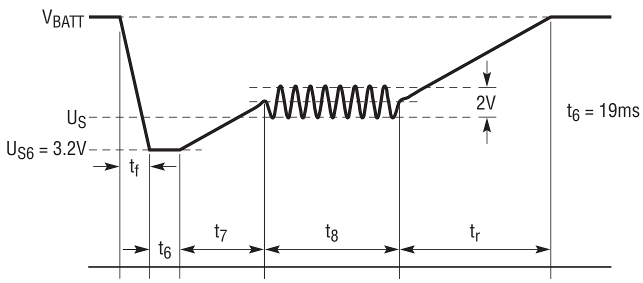


Figure 8. "Severe" cold crank for the 12V system defined in LV124.

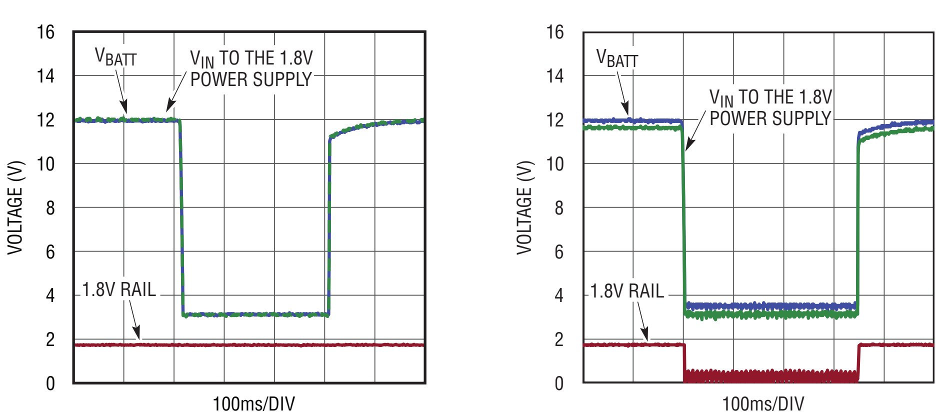
Figure 9 shows the comparison of 1.8V power supply with LT8672 and with traditional diode. The step-down regulator works down to 3V. As shown, with a traditional diode, V_{IN} to the buck regulator drops to near 2.7V when the battery voltage V_{BATT} drops to 3.2V, due to high voltage drop of the diode, triggering the UVLO shutdown of the downstream switching regulator, and its 1.8V output collapses. In contrast, voltage remains nearly constant at the LT8672 output during a cold crank event, and the downstream step-down regulator is able to maintain a 1.8V output. Note that active rectifier controllers with a charge pump gate power solution are unable to keep the system continuously operating during cold crank. This is because the charge pump requires constant power refreshment, requiring the body diode of the external FET to conduct periodically.

Numerous critical functions require regulated 5V and 3.3V rails plus sub-2V rails to power content, processor I/O and core in analog and digital ICs. If V_{BATT} drops below its outputs or $V_{IN(MIN)}$, a pure buck regulator would lose regulation if directly powered from V_{BATT}. However, such critical functions typically do not require much power, so a highly integrated compact solution can be used, such as the 6mm × 6mm LT8603 quad output, triple monolithic buck converter plus boost controller.

The LT8603's integrated boost controller works down to below 2V, making it an ideal pre-regulator to its three buck regulators. Figure 10 shows a Power by Linear state of art solution for these applications that can ride through a cold crank event. The two high voltage buck regulators are powered from the pre-boost converter. When V_{BATT} drops below 8.5V, the boost controller starts switching and the output (OUT4) is regulated to 8V. It can keep the output regulated with the input voltage down to 3V once it is started. Therefore, the two high voltage bucks can ride through the cold crank condition, while providing constant 5V and 3.3V outputs, as shown in Figure 11. Once V_{BATT} recovers to above 8.5V from cold crank, the boost controller simply works as a diode pass through. The high voltage bucks can handle V_{BATT} up to 42V. The low voltage buck is powered from OUT2, providing 1.2V through the cold crank event.

Figure 9. Cold crank event

(a) LT8672 solution **(b) Traditional diode solution**



For always-on systems connected to V_{BAT} for weeks or even months without a battery recharge, light load and no-load efficiency are, in some cases, more important than full load efficiency.

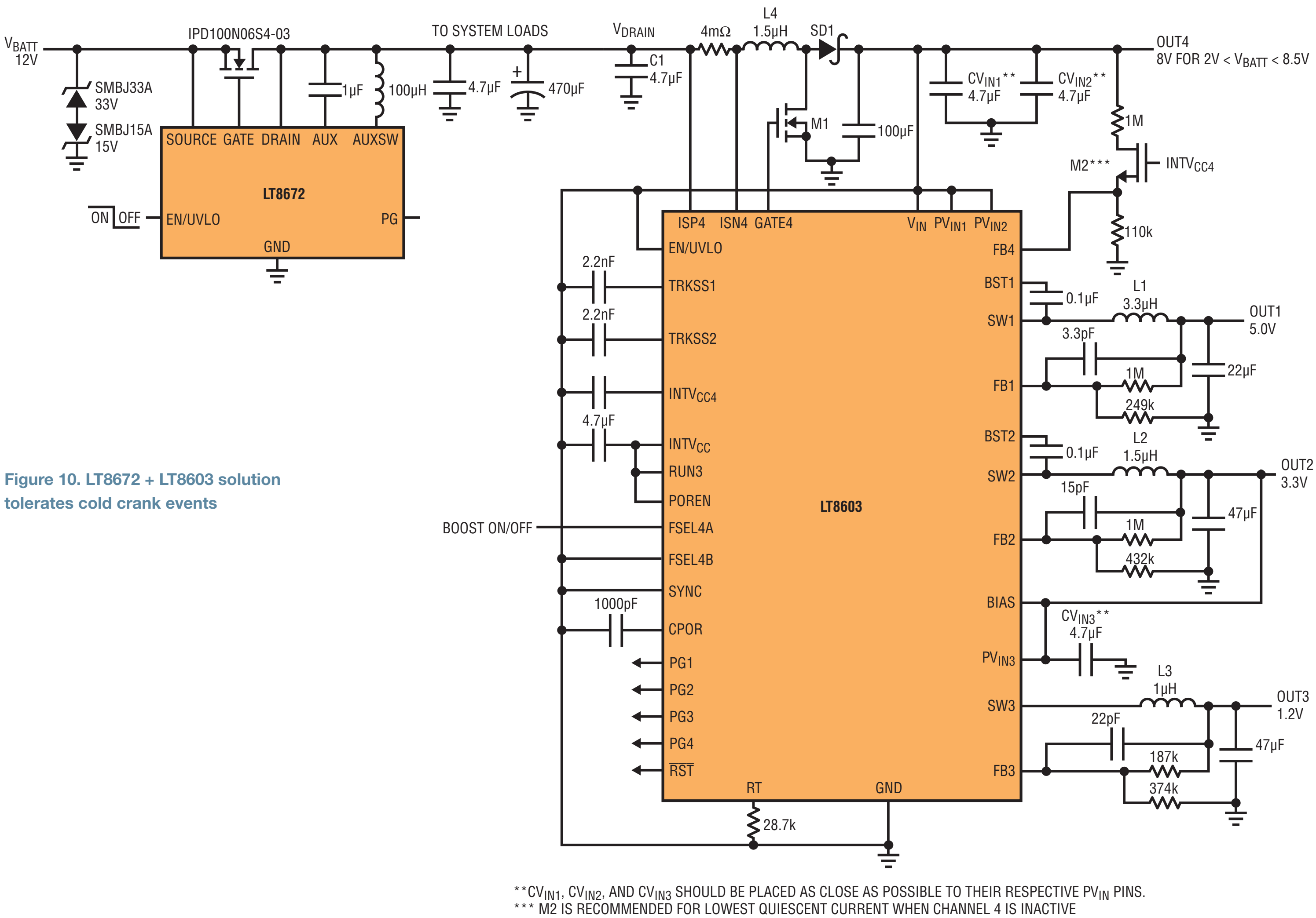


Figure 10. LT8672 + LT8603 solution tolerates cold crank events

ULTRALOW I_Q EXTENDS BATTERY RUN TIME FOR ALWAYS-ON SYSTEMS

For always-on systems connected to V_{BATT} for weeks or months without a battery recharge, light load and no-load efficiency are, in some cases, more important than full load efficiency. The Power by Linear family of ultralow quiescent current (I_Q) devices preserve battery charge while withstanding challenging transient conditions and wide input voltage ranges, from 3V to 42V, and wide temperature ranges. To optimize efficiency and maintain regulation at light loads and no load, the regulator features Burst Mode operation. Between bursts, all circuitry associated with controlling the output switch is shut down, reducing the input supply current to few microamps. In contrast, a typical buck regulator might draw hundreds of hundreds of microamps from V_{BATT} when regulating with no load, draining the battery orders of magnitude faster.

The Burst Mode efficiency at a given light load is mainly affected by the switching loss, which is a function of switching frequency and gate voltage. Because a fixed amount of energy is required to

The LT8650S ultralow I_Q synchronous buck regulator enables solutions that feature high efficiency over wide input voltage and load current ranges. With integrated MOSFETs, this device can deliver up to 8A total output current at fixed output voltages of 3.3V or 5V.

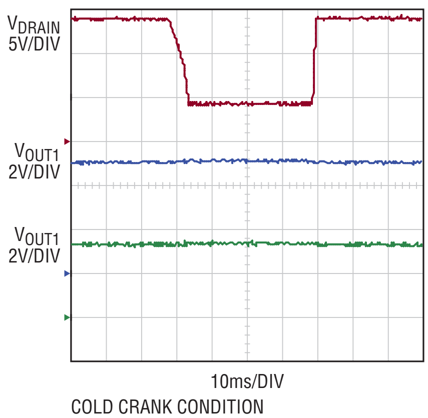


Figure 11. The LT8672 + LT8603 combination produces 5V and 3.3V outputs that ride though cold crank events

switch the MOSFET on and off, and keep the internal logic alive, a lower switching frequency reduces gate charge losses and increases efficiency. The switching frequency is primarily determined by the Burst Mode current limit, the inductor value and the output capacitor. For a given load current, increasing the burst current limit allows more energy to be delivered during each switching cycle, and the corresponding switching frequency is lower. For a given burst current limit, a larger value inductor stores more energy than a smaller one, and the switching frequency is lower as well. For the same reason, a bigger output capacitor stores more energy and takes longer to discharge.

Figure 12 shows the ultralow I_Q synchronous buck regulator LT8650S in a solution that features high efficiency over wide input voltage and load current ranges. With integrated MOSFETs, this device can deliver up to 8A total output current at fixed output voltages of 3.3V or 5V. Despite the simple overall design and layout, this converter includes options that can be used to optimize performance of specific applications in battery-powered systems.

Table 1 lists low I_Q monolithic regulators that are well suited to the automotive market, with inputs up to 42V or 65V. Typical quiescent current for these devices is only 2.5µA, thanks to the low I_Q technologies developed by Analog Devices. With minimum turn-on time of 35ns, these regulators deliver 3.3V output voltage from input 42V at switching frequency of 2MHz, which is common in automotive industry.

SILENT SWITCHER TAKES COMPLEXITY OUT OF EMI DESIGN

Automotive applications demand systems that do not produce electromagnetic noise that could interfere with the normal operations of other automotive systems. For instance, switching power supplies are efficient power converters, but by nature generate potentially unwelcome high frequency signals that could affect other systems. Switching regulator "noise" occurs at the switching frequency and its harmonics.

Ripple is a noise component that appears at the output and input capacitors. Ripple can be reduced with the low ESR and ESL capacitors, and low pass LC filters. A higher frequency noise component, which is much more difficult to tackle, results from the fast switching on and off of the power MOSFETs. With designs focused on compact solution size and high efficiency, operating switching

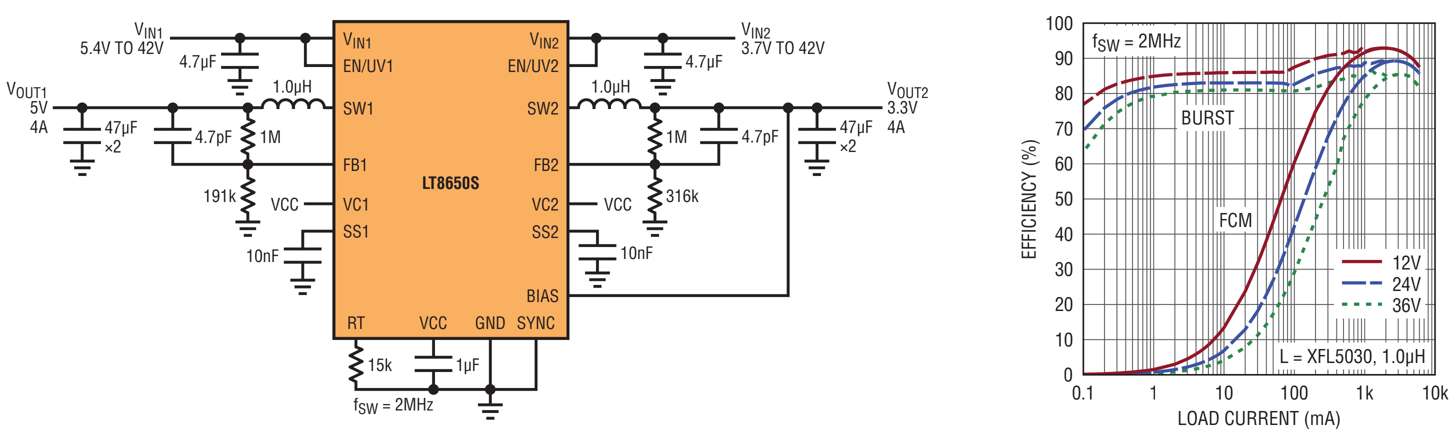


Figure 12. Low I_Q LT8650S maintains very high light load efficiency to support always-on applications without significantly draining the battery

In Silent Switcher 2 devices, the hot loop and warm loop capacitors are integrated into the packaging and laid out to minimize EMI. This reduces the effect of final board layout on the EMI equation, simplifying design and manufacturing.

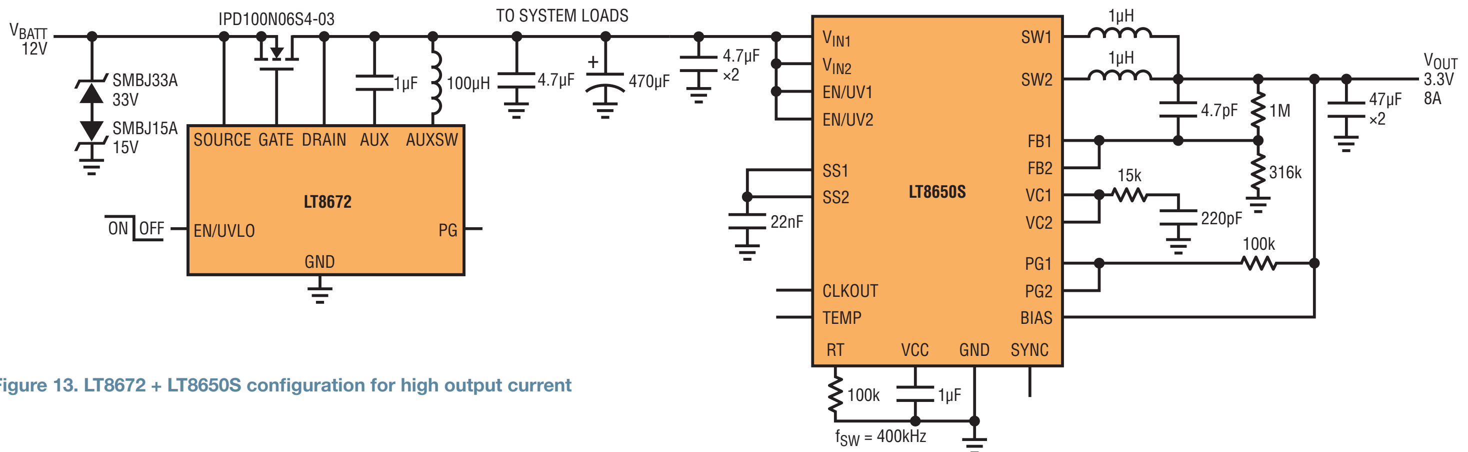


Figure 13. LT8672 + LT8650S configuration for high output current

frequencies are now pushed to 2MHz to reduce the passive component size, and also avoid the audible band. Furthermore, switching transition times have been reduced to the nanosecond realm to improve efficiency—by reducing switching losses and duty ratio losses.

Parasitic capacitance and inductance from both the package and PCB layout play important roles in distributing noise, so if the noise is present, it can be difficult to eliminate. EMI prevention is complicated by the fact that switching noise covers the domain from tens of MHz to beyond GHz. Sensors and other instruments subjected to such noise could malfunction, resulting in audible noise or serious system failure. Therefore, stringent standards have been set up to regulate EMI. The most commonly adopted one is the CISPR 25 Class 5, which details acceptable limits at frequencies from 150kHz to 1GHz.

Passing automotive EMI regulation at high current usually means a complicated design and test procedure, including numerous trade-offs in solution footprint, total efficiency, reliability and complexity. Traditional approaches to controlling EMI by slowing down switching edges or lowering switching frequency come with trade-offs such as reduced efficiency, increased minimum on- and off-times and larger solution size. Alternative mitigation, including a complicated bulky EMI filter, snubber or metal shielding, adds significant costs in board space, components and assembly, while complicating thermal management and testing.

Our Silent Switcher technology addresses the EMI issue in an innovative way, enabling impressive EMI performance in high frequency, high power supplies. Second generation, Silent Switcher 2, devices simplify board design and manufacture by incorporating the hot loop capacitors into the packaging. For a buck regulator such as the 42V/4A LT8650S, the hot loop consists of input capacitor, the top and bottom switches. Other noisy loops include the gate drive circuit, and boost capacitor charge circuit. In Silent Switcher 2 devices, the hot loop and warm loop capacitors are integrated into the packaging and laid out to minimize EMI. This reduces the effect of final board layout on the EMI equation, simplifying design and manufacturing. Further peak EMI reduction can be achieved by using the optional spread spectrum frequency modulation feature incorporated into these parts, making it even easier to pass stringent EMI standards.

Figure 13 exhibits a low I_Q, low noise solution for a high current application for automotive I/Os and peripherals. The LT8672 at the front-end protects the circuit from reverse battery faults and high frequency AC ripple with only tens of mV forward drop. The LT8650S switches at 400kHz with input ranging from 3V to 40V, and an output capability of 8A by operating two channels in parallel. Two decoupling capacitors are placed close to the input pins of the LT8650S. With Silent Switcher 2 technology, the high

These innovative solutions specifically address automotive requirements: ultralow quiescent current, ultralow noise, low EMI, high efficiency, wide operating ranges in compact dimensions and wide temperature range.

frequency EMI performance is excellent even without an EMI filter installed. The system passes the CISPR 25 Class 5 peak and average limit with significant margins. Figure 14 shows the radiated EMI average test results over the range of 30MHz to 1GHz, with vertical polarization. A complete solution features a simple schematic, minimal overall component count, compact footprint, and EMI performance that is immune to changes in board layout (Figure 15).

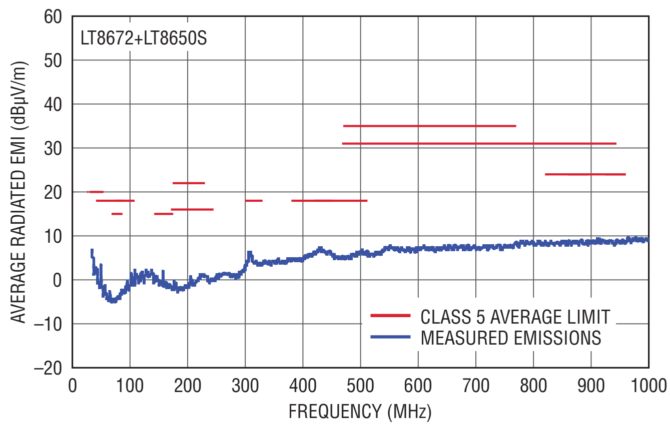
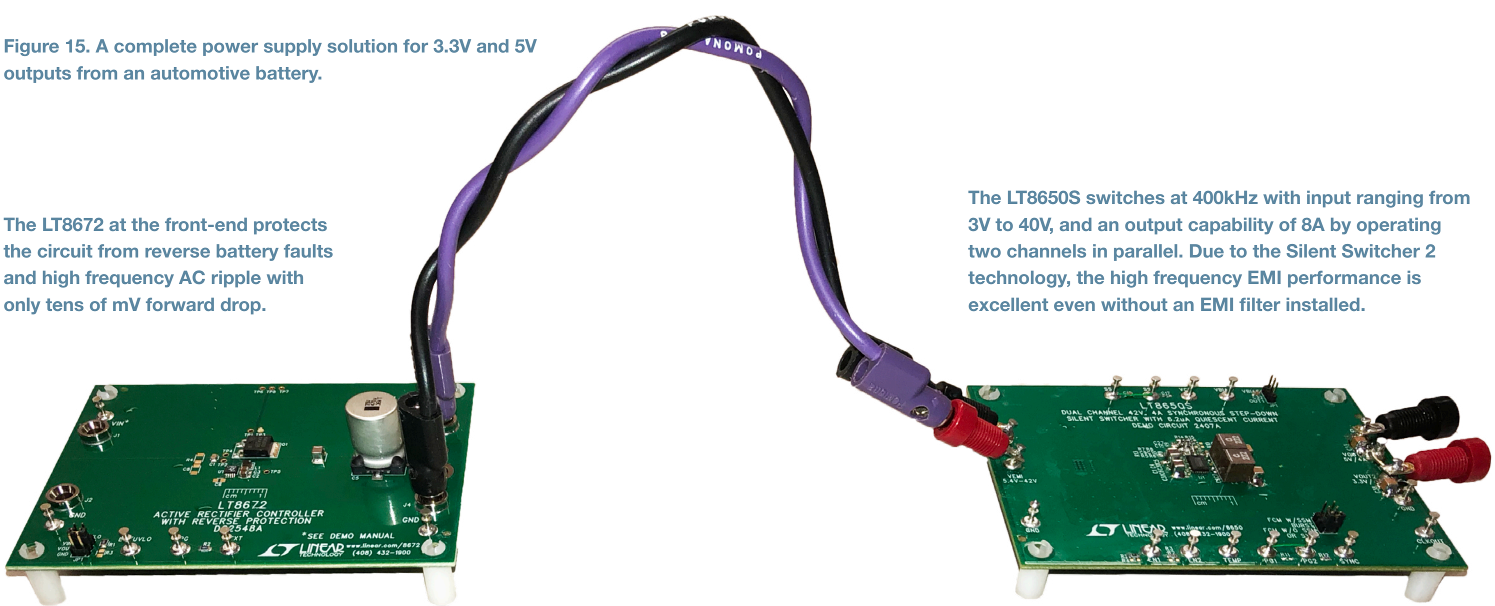


Figure 14. LT8672 + LT8650S EMI performance: 30MHz to 1GHz

CONCLUSION

Automotive applications call for low cost, high performance, reliable power solutions. The cruel under-the-hood environment challenges power supply designers to produce robust solutions, taking into account a wide variety of potentially destructive electrical and thermal events. Electronic boards connected to the 12V battery must be carefully designed for high reliability, compact solution size and high performance. The Power by Linear device catalog includes innovative solutions specifically addressing automotive requirements: ultralow quiescent current, ultralow noise, low EMI, high efficiency, wide operating ranges in compact dimensions and wide temperature range. By eliminating complexity while improving performance, Power by Linear solutions reduce power supply design time, lower solution costs and improve time to market. ■

Figure 15. A complete power supply solution for 3.3V and 5V outputs from an automotive battery.



The LT8672 at the front-end protects the circuit from reverse battery faults and high frequency AC ripple with only tens of mV forward drop.

The LT8650S switches at 400kHz with input ranging from 3V to 40V, and an output capability of 8A by operating two channels in parallel. Due to the Silent Switcher 2 technology, the high frequency EMI performance is excellent even without an EMI filter installed.

Synchronous Boost Converter Powers High Current LEDs Even at Low Input Voltages

Kyle Lawrence

High power LEDs continue to proliferate in modern lighting systems, spanning automotive headlights, industrial/commercial signage, architectural lighting, as well as a variety of consumer electronics applications. The industry's transition toward LED technology is driven by the distinct advantages that solid state lighting offers over conventional light sources: high efficiency conversion of electrical power to light output, as well as long operational life spans.

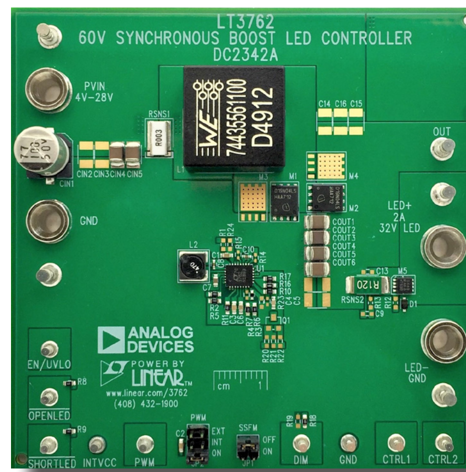


Figure 1. The LT3762 demonstration circuit (DC2342A) powers up to 32V of LEDs at 2A over a wide input voltage range. This demo circuit can easily be modified with additional MOSFETs and capacitors to increase the output power.

As LED lighting is incorporated into an expanding array of applications, the demand for higher LED currents for increased light output also grows. One of the biggest challenges for powering strings of high current LEDs is maintaining high efficiency in the power converter stage responsible for providing a well regulated LED current. Inefficiency in the power converter presents itself in the form of unwanted heat, which originates from the switching elements of the current regulator circuitry.

The LT3762 is a synchronous boost LED controller designed to curtail the sources of efficiency loss common in high power step-up LED driver systems. This device's synchronous operation minimizes

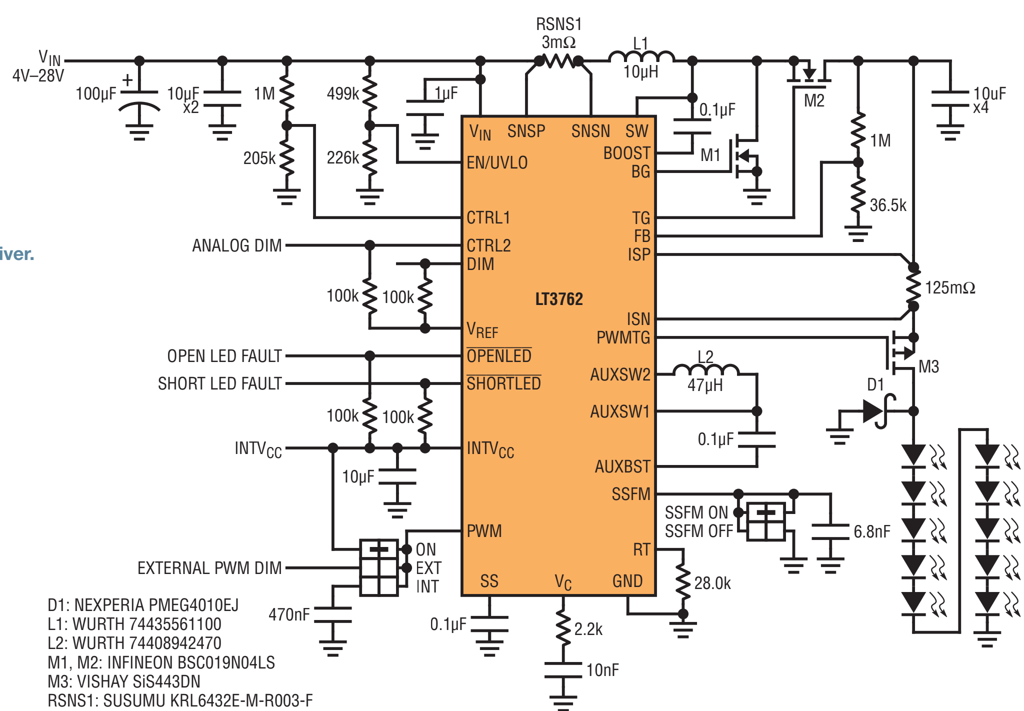


Figure 2. 32V, 2A LT3762 boost LED driver.

The LT3762 features an internal PWM generator, which uses a single capacitor and a DC voltage to set the frequency and pulse width for up to a 250:1 PWM dimming ratio, and can alternatively use an external PWM signal to achieve ratios as high as 3000:1.

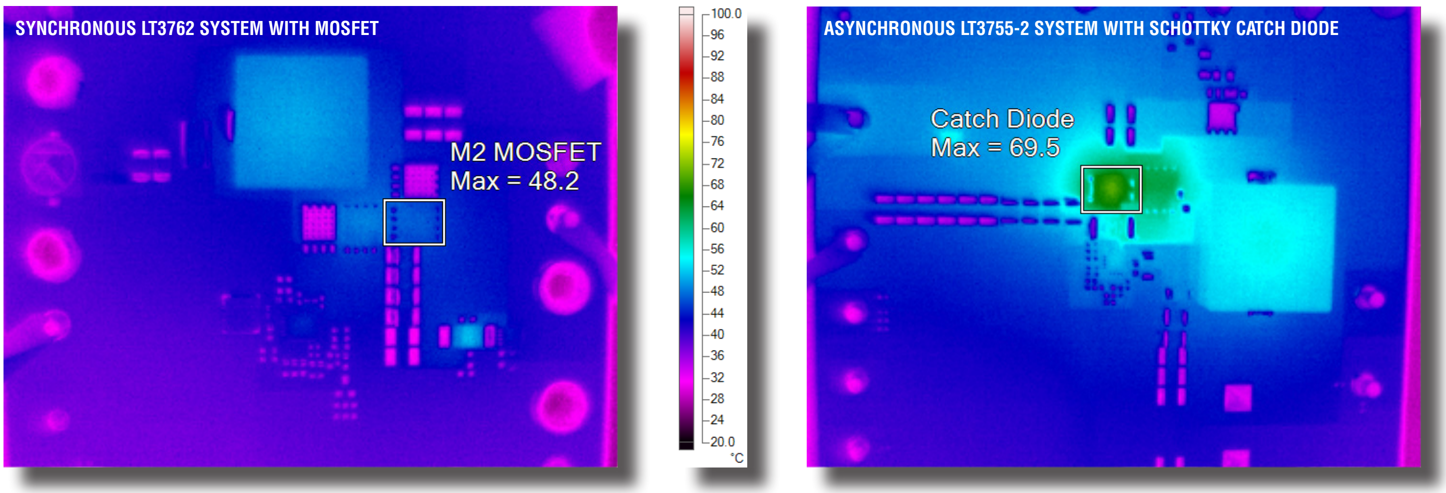


Figure 3. Under identical test conditions and using similar component selection, the synchronous LT3762 (left) powers a 32V string of LEDs at 2A with far less temperature rise than observed in an asynchronous LT3755-2 circuit (right). This increase in thermal performance is attributed to replacing the Schottky catch diode with a synchronous MOSFET, eliminating the loss caused by the forward voltage drop of the diode.

the losses normally incurred from the forward voltage drop of a catch diode in an asynchronous DC/DC converter. This increased efficiency allows the LT3762 to deliver much higher output current than similar asynchronous step-up LED drivers, especially at low input voltages. In order to improve low input voltage operation, an on-board DC/DC regulator provides 7.5V to the gate drive circuitry, even when the input drops below 7.5V. The result of having a strong gate drive voltage source at low input voltages is that the MOSFETs generate less heat as the input voltage decreases, which extends the low end of the operational input range to 3V.

This step-up LED controller can be configured to operate between 100kHz and 1MHz fixed switching frequency, with optional –30% • f_{SW} spread spectrum frequency modulation to reduce switching-related EMI energy peaks. The LT3762 can be run in a step-up, step-down, or step-up/step-down topology for powering LEDs. A high side PMOS disconnect switch facilitates PWM dimming, and protects the device from potential damage when the LEDs are placed in an open/short-circuit condition.

The LT3762 features an internal PWM generator, which uses a single capacitor and a DC voltage to set the frequency and pulse width for up to a 250:1 PWM dimming ratio, and can alternatively use an external PWM signal to achieve ratios as high as 3000:1. The schematic in Figure 2 shows the demonstration circuit application (DC2342A) using the LT3762, which is configured to power up to 32V of LEDs at 2A from an input voltage range of 4V to 28V. The LT3762 synchronous boost LED controller is offered in a 4mm × 5mm QFN package, as well as a 28-lead TSSOP package.

SYNCHRONOUS SWITCHING

In asynchronous DC/DC converter topologies, Schottky catch diodes are used as passive switches to simplify the control scheme of the converter to pulse-width modulating a single MOSFET. While this does simplify things from a control perspective, it limits the amount of current that can be delivered to the output. Schottky diodes, like PN junction devices, experience a forward voltage drop before any current can pass through the device. As the power dissipated in the Schottky is the product of its forward voltage drop and current, conduction-related power dissipation can result in several of watts of loss at excessive output current levels, resulting in the Schottky diode heating up, causing inefficiencies in the converter.

The LT3762 synchronous switching converter does not encounter the same

This buck-boost regulator only consumes three pins of the LT3762 IC, and requires only two additional components. Compared to internal LDO controller devices, which have minimum input voltages of 4.5V and 6V, the LT3762 is able to extend its input operating range down to 3V.

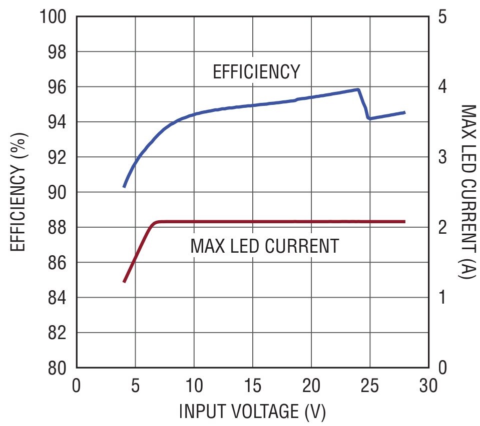


Figure 4. 32V, 2A LT3762 LED driver maintains high efficiency over a wide input range. Low V_{IN} foldback helps avoid excessive switch/inductor currents. Asynchronous switching starts at 24V input.

output current limitations that asynchronous converters do. This is because synchronous converters replace the Schottky diode with a second MOSFET. Unlike Schottky diodes, MOSFETs do not have a forward voltage drop. Instead, MOSFETs feature a small resistance that is formed from drain to source when the device is fully enhanced. The conduction losses incurred from a MOSFET are much lower than Schottky diodes at high current, as power lost is proportional to the product of the square of the drain-source resistance and the current through the device. Even at the lowest full power input voltage of 7V, the MOSFETs only experience a temperature rise of roughly 30°C, as shown in Figure 3.

LOW INPUT VOLTAGE OPERATION

Another challenging region for high power boost LED controllers occurs during low input voltage operation. The majority of boost DC/DC regulator ICs use an internal LDO voltage regulator powered from the input of the device to provide lower voltage power to the analog and digital control circuitry within the IC. Of the circuitry that draws power from the internal LDO, the gate driver consumes the most power, and its performance is affected by fluctuations in the output of the LDO. As the input voltage drops below the LDO output voltage, the LDO output begins to collapse, limiting the gate driver's ability to properly enhance the MOSFETs. When MOSFETs are not fully enhanced, they operate in a higher resistance state, causing them to dissipate power in the form of heat as current is passed through the device.

Low input voltage operation in step-up converter topologies results in higher input current, which, when having to pass through a more resistive MOSFET device, exacerbates conduction losses. Depending on the gate drive voltage of the regulator IC, this can severely limit the low input voltage range that the device can successfully achieve without overheating.

The LT3762 features an integrated buck-boost DC/DC regulator, instead of an LDO, which provides 7.5V to power the internal circuitry even when the input voltage is low. This buck-boost regulator only consumes three pins of the LT3762 IC, and requires only two additional components. Compared to internal LDO controller devices, which have minimum input voltages of 4.5V and 6V, the LT3762 is able to extend its input operating range down to 3V. The 7.5V output of the buck-boost converter supplies power to the gate driver, and allows for 6V/7V gate drive MOSFETs to be used. Higher gate drive voltage MOSFETs tend to have lower drain-source resistances, and (barring switching losses) operate more efficiently than their lower gate drive voltage counterparts.

FLEXIBLE TOPOLOGIES

Like most other boost LED drivers from ADI, the LT3762 can be reconfigured to power LEDs in a step-up configuration, and also as a step-down (buck mode), and step-up/step-down (buck-boost mode and boost-buck mode). Of these boost converter topology variants, the ADI-patented boost-buck mode configuration offers the ability to operate as step-up/step-down converter with the added benefit of low EMI operation. This topology utilizes two inductors, one input facing and the other output facing, to aid in filtering noise generated by switching. These inductors help suppress EMI from coupling to the input supply and the other devices that may be connected, as well as the LED load.

Additional circuitry can be added on to the boost-buck mode topology to offer short-circuit protection of the LED^- node

Like most other boost LED drivers from ADI, the LT3762 can be reconfigured to power LEDs in a step-up configuration, and also as a step-down (buck mode), and step-up/step-down (buck-boost mode and boost-buck mode). Of these boost converter topology variants, the ADI-patented boost-buck mode configuration offers the ability to operate as step-up/step-down converter with the added benefit of low EMI operation.

to GND. The schematic in Figure 5 shows the LT3762 in a boost-buck mode configuration with this protection circuitry added. In the event that LED⁻ is shorted to GND, M4 is forced to turn off, blocking the conduction path to the input through the inductors and preventing excessive current draw. While M4 is forced to turn off, D3 pulls the EN/UVLO pin low to stop the converter from switching until the short circuit has been removed. The addition of this protective circuitry used in conjunction with the LT3762's built-in open/short-circuit detection results in a robust solution capable of surviving a variety of fault conditions in harsh environments.

CONCLUSION

Asynchronous boost converters often struggle to provide high output current without experiencing substantial power losses and heating of the catch diode under normal operation. In addition to loss generated by the Schottky, such converters struggle to maintain maximum power output capabilities as the input voltage decreases, limiting the power delivery across the input range. Asynchronous DC/DC converters are simply not suited for higher power levels, and a synchronous switching scheme must be implemented to meet application specifications. The LT3762 boost LED controller addresses the issues of delivering high output current with its synchronous switching, is capable of operating at much lower input voltages thanks to its onboard DC/DC converter, and has the flexibility to be used in a variety of circuit topologies. ■

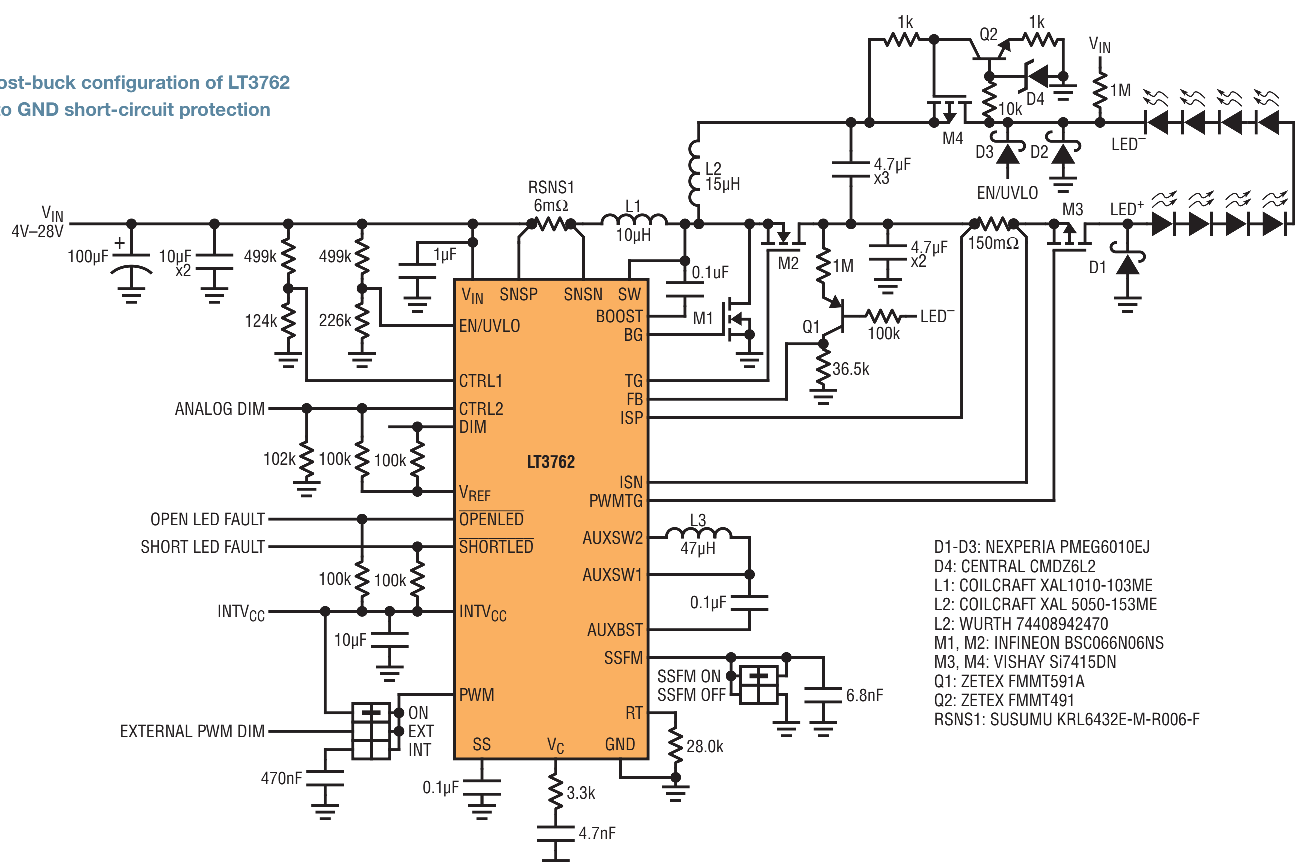


Figure 5. 25V, 1.5A boost-buck configuration of LT3762 with additional LED⁻ to GND short-circuit protection

Negative Linear Regulator Features 0.8µV_{RMS} Noise and 74dB Power Supply Rejection Ratio at 1MHz

Molly Zhu

Low dropout (LDO) linear regulators have been widely used in noise-sensitive applications for decades. Nevertheless, noise requirements have become tougher to meet as latest precision sensors, high speed and high resolution data converters (ADCs and DACs), and frequency synthesizers (PLLs/VCOs), challenge conventional LDOs to produce ultralow output noise and ultrahigh power supply ripple rejection (PSRR). For instance, when powering a sensor, the supply noise directly affects the measurement result accuracy. Switching regulators are often used in power distribution systems to achieve higher overall system efficiency. To build a quiet power supply, an LDO usually post-regulates the output of a relatively noisy switching converter without using bulky output filtering capacitors. The high frequency PSRR performance of the LDO becomes a predominant feature.

The LT3042, introduced in 2015, is the industrial's first linear regulator with only 0.8µV_{RMS} output noise and 79dB power supply rejection ratio (PSRR) at 1MHz. Two similar devices, the LT3045 and LT3045-1 increased the higher rating and added features. All of these devices are positive LDOs. When a system has bipolar instruments, such as op amps or ADCs, a negative LDO must be used in a polarity power supply design. LT3094 is the first negative LDO that has ultralow output noise and ultrahigh PSRR. Table 1 lists the main features of the LT3094 and related devices.

TYPICAL APPLICATION

The LT3094 features a precision current source reference followed by a high performance output buffer. The negative output voltage is set with a –100µA precision current source flowing through a single resistor. This current-reference based architecture offers wide output voltage range (0V to –19.5V) and provides virtually constant output noise, PSRR, and load regulation independent of the programmed output voltage. Figure 1 shows a typical application, and the demonstration board is shown in Figure 2. The overall solution size is only about 10mm × 10mm.

The LT3094 has ultralow output noise, 0.8µV_{RMS} from 10Hz to 100kHz, and ultrahigh PSRR, 74dB at 1MHz. Moreover, the LT3094 has programmable current limit, programmable power good threshold, fast start-up capability, and programmable input-to-output voltage control (VIOC). When the LT3094 post-regulates a switching

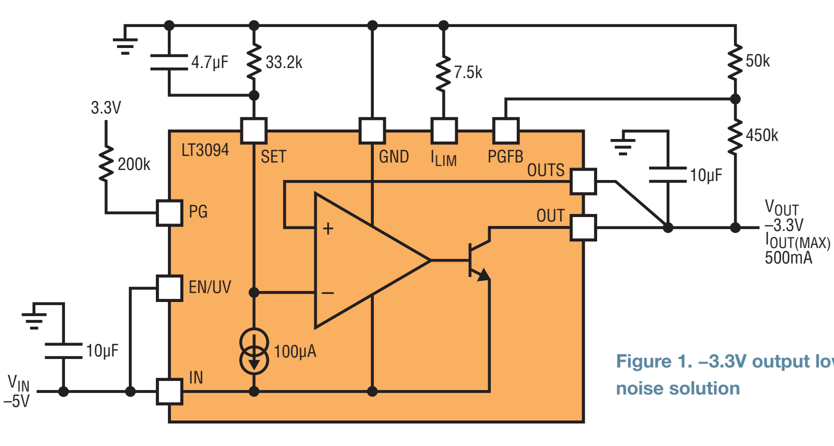


Figure 1. –3.3V output low noise solution

Figure 2. Demo circuit shows tiny –3.3V solution

The LT3094 has ultralow output noise, $0.8\mu V_{RMS}$ from 10Hz to 100kHz, and ultrahigh PSRR, 74dB at 1MHz. Moreover, the LT3094 has programmable current limit, programmable power good threshold, fast start-up capability, and programmable input-to-output voltage control (VIOC).

converter, the voltage across the LDO remains constant by the VIOC function if the LDO's output voltage is variable.

The LT3094 avoids damage through internal protection, including internal current limit with foldback, thermal limit, reverse current and reverse voltage.

DIRECT PARALLELING FOR HIGHER CURRENT

The LT3094 can be easily paralleled to increase output current. Figure 3 shows a solution using two LT3094s paralleled to achieve 1A output current. To parallel two devices, the SET pins are tied together, and one SET resistor, R_{SET}, is placed between SET pin and ground.

Table 1. Features of the LT3094 and low noise LDOs

	LT3015	LT3090	LT3042	LT3045-1	LT3094
Positive/Negative Output	Negative	Negative	Positive	Positive	Negative
Output Current (A)	1.5	0.6	0.2	0.5	0.5
Output Noise (10Hz to 100kHz) (µV)	60	18	0.8	0.8	0.8
Spot Noise at 10kHz (nV/√Hz)	240	57	2	2	2
PSRR at 1MHz (dB)	30	20	79	76	74
Programmable Current Limit		✓	✓	✓	✓
Programmable Power Good			✓	✓	✓
VIOC				✓	✓
Directly Parallelable		✓	✓	✓	✓
Fast Start-Up Capability			✓	✓	✓

Figure 3. Schematic of two paralleled LT3094s

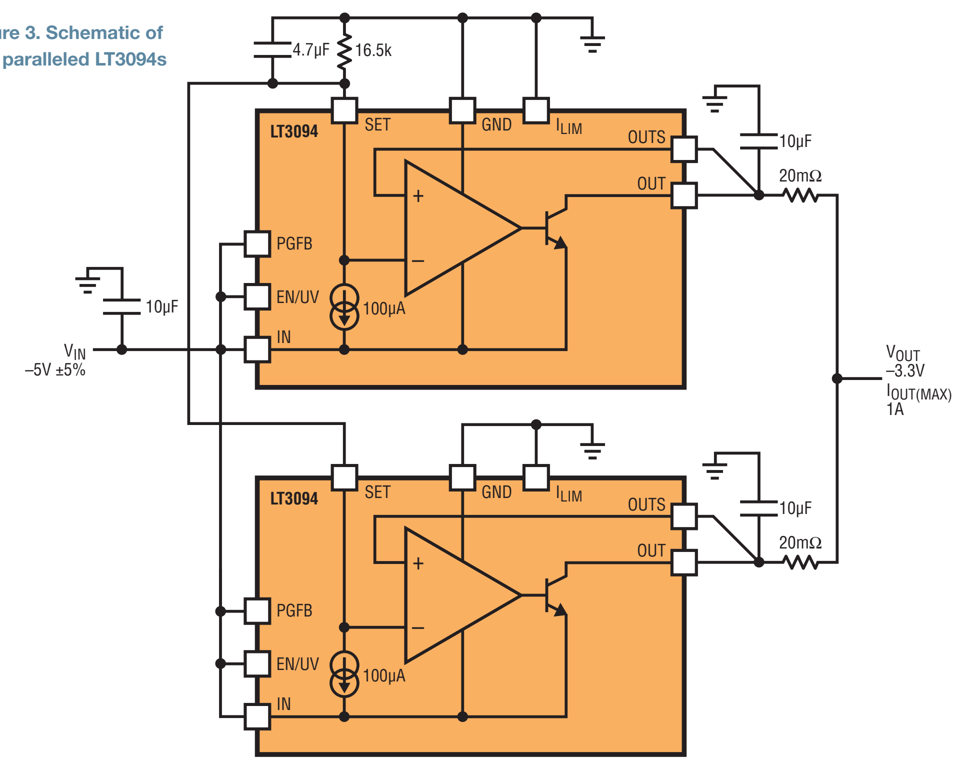
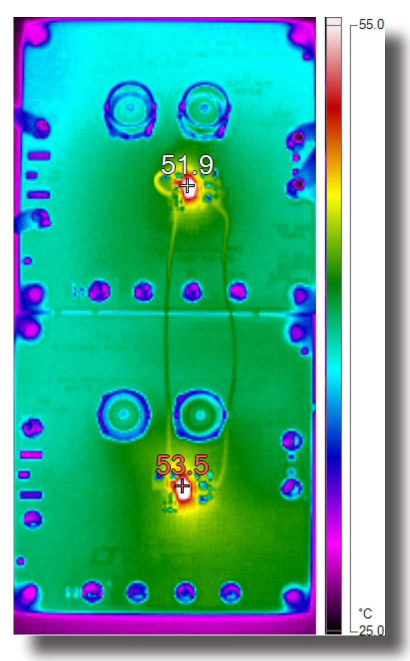


Figure 4. Thermal image of two paralleled LT3094s



The LT3094 is a negative LDO featuring ultralow noise and ultrahigh PSRR. It features a current-reference based architecture, keeping noise and PSRR performance independent of the output voltage, and enabling multiple LT3094s to be easily paralleled for increased load current and reduced output noise.

The current flowing though R_{SET} is 200µA, twice the amount of the SET current in one device. For good current sharing, a small 20mΩ ballast resistor is used at each output of the LT3094.

Figure 4 shows the thermal performance of the circuit in Figure 3 with –5V input voltage and –3.3V output voltage running at 1A load current. The temperature of each part rises to about 50°C, indicating the heat is distributed equally. There is no limit on the number of devices that can be paralleled for even high output current and low output noise.

DUAL POSITIVE AND NEGATIVE POWER SUPPLY WITH VARIABLE OUTPUT VOLTAGES

A power supply is generally built with a switching converter post-regulated by an LDO to achieve low output noise and high system efficiency. The optimized voltage difference between the LDO's input and output is about –1V in order to maintain a good trade-off between power dissipation and PSRR. Maintaining this voltage difference is complicated in a variable output voltage system, but the LT3094 includes a tracking feature, input-to-output voltage control (VIOC), which keeps the voltage across the LDO constant even as the output voltage must vary.

Figure 5 is the schematic of a dual power supply using LT8582, LT3045-1 and LT3094. The LT8582 is a dual channel PWM DC/DC converter with internal switches that can generate both positive and negative outputs from a single input. The first channel of LT8582 is configured as a SEPIC to generate a positive output, and the second channel is an inverting converter to generate the negative rail. In the negative rail, the voltage across the LT3094 is controlled by VIOC voltage as

$$V_{LDO(IN2)} - V_{LDO(OUT)} = VIOC$$
$$= V_{FBX2} - R2 \bullet I_{FBX}$$

where V_{FBX2} is 0mV and I_{FBX} is 83.3µA. Setting R2 to 14.7k sets the VIOC voltage at 1.23V over the variable output voltage.

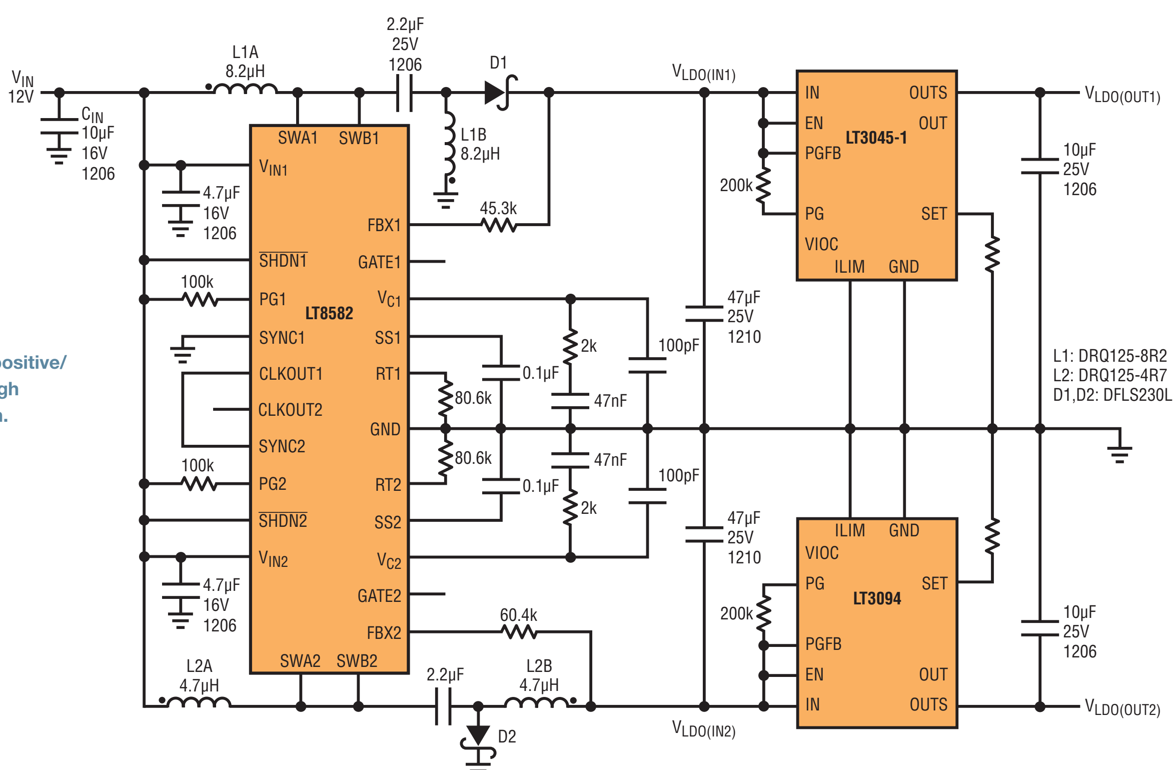
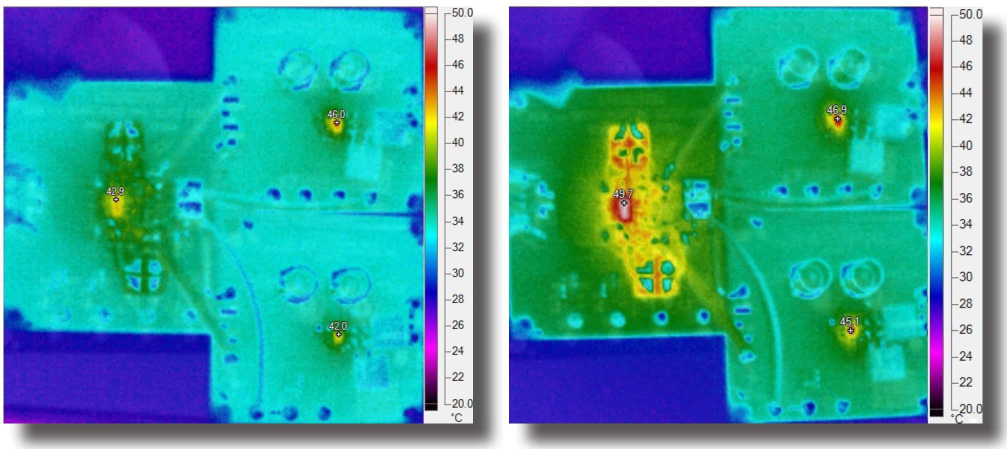


Figure 5. Adjustable dual output, positive/negative power supply features high ripple rejection and cool operation.

Table 2. Circuit performance of dual output positive/negative power supply at 12V input, ±500mA load

$V_{LDO(OUT)}$ (V)	$V_{LDO(IN)}$ (V)	V_{DROP} (V)	LT3094 TEMPERATURE RISE	I_{IN}(A)	SYSTEM EFFICIENCY
± 3.3	± 4.55	1.25	8°C	0.48	57%
± 5	± 6.25	1.25	8°C	0.65	65%
± 12	± 13.22	1.22	9°C	1.25	78%



(a) ±5V output, ±500mA load

(b) ±12V output, ±500mA load

Figure 6. Thermal Image of dual power supply at 12V input

The resistor R1, at 133kΩ, limits the input voltage of LT3094 to 16.5V, calculated by

$$V_{LDOIN(MAX)} = V_{FBX}(1 + R1/40k) - R1 \bullet I_{FBX}$$

The thermal images of the circuit running at 12V input are shown in Figure 6. When output voltage changes from ±3.3V to ±12V, the temperature rise of the LT3094 remains constant. Table 2 lists the voltage and current of all three devices. Figure 7 shows the transient response of the ±5V power supply running at 12V input.

In Figure 5, no additional capacitor other than the output capacitors at LT8582 is placed at the input of the LT3094. Generally, an input capacitor reduces the output ripple, but this is not the case for the LT3094. If the LT3094 has input capacitors, the switching currents from the switching converter will flow though the input capacitor, causing the electromagnetic coupling from the switching converter to the LT3094's output. The output noise will be increased, degrading the PSRR. Provided that the switching regulator is placed within two inches of the LT3094, we recommend not placing a capacitor at LT3094's input to achieve best PSRR performance.

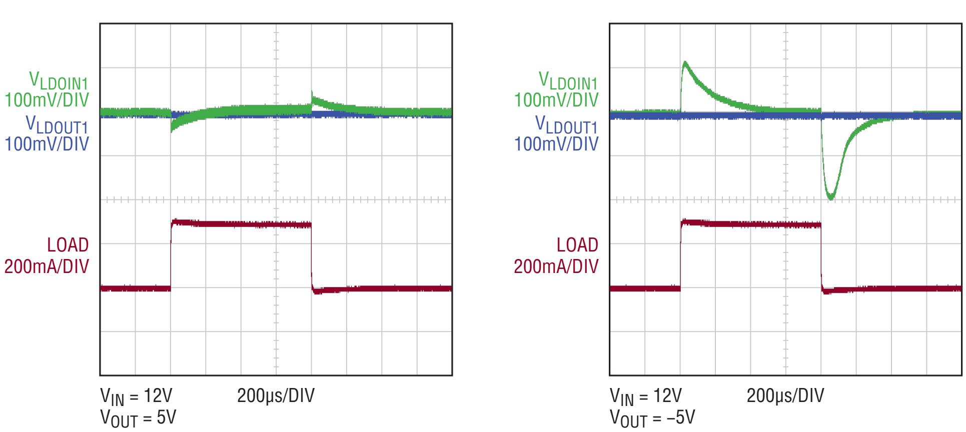
CONCLUSION

The LT3094 is a negative LDO featuring ultralow noise and ultrahigh PSRR. It features a current-reference based architecture, keeping noise and PSRR performance independent of the output voltage, and enabling multiple LT3094s to be easily paralleled for increased load current and reduced output noise. The VIOC function minimizes the power dissipation of the LDO when the LT3094 post-regulates a switching converter, making it ideal in variable output voltage applications. ■

Figure 7. Transient response of dual power supply at 12V input , ±5V output

(a) 5V output

(b) –5V output



High Efficiency, High Density PSM µModule Regulator with Programmable Compensation

Haihua Zhou and Jian Li

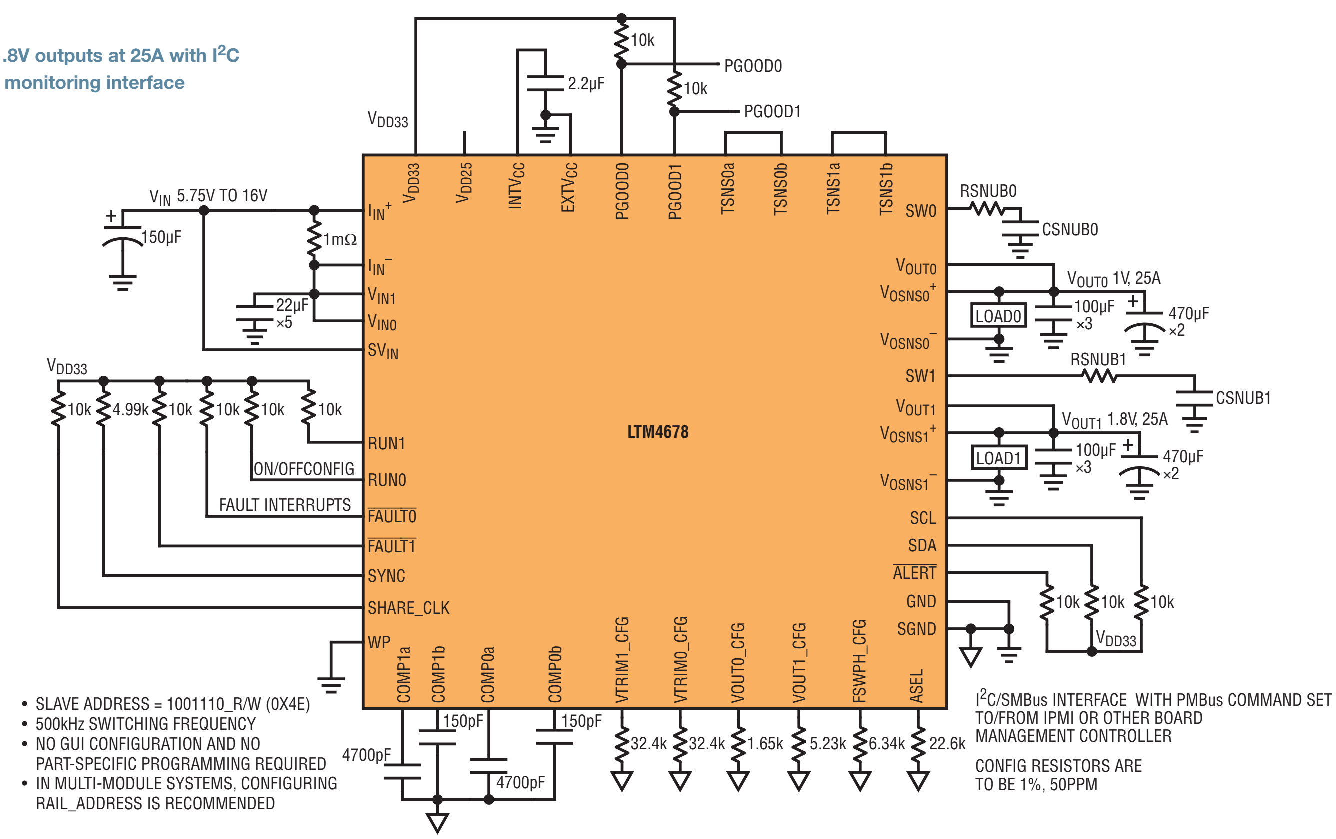
FPGA boards, prototype, testing and measurement applications demand versatile and high density power solutions. The LTM4678 is a dual 25A or single 50A µModule® regulator with digital power system management (PSM) in a small 16mm × 16mm footprint. It features:

- dual digitally adjustable analog loops with digital interface for control and monitoring
- wide input voltage range: 4.5V to 16V
- wide output voltage range: 0.5V to 3.3V
- ±0.5% maximum DC output error over temperature
- ±5% current readback accuracy
- sub-milliohm DCR current sensing
- integrated input current sense amplifier
- 400kHz PMBus-compliant I²C serial interface
- telemetry polling rates up to 125Hz
- an integrated 16-Bit ΔΣ ADC
- constant frequency current mode control
- parallel operation with balanced current sharing
- 16mm × 16mm × 5.86mm CoP-BGA

I²C BASED PMBus INTERFACE AND PROGRAMMABLE LOOP COMPENSATION

The LTM4678 is a member of ADI's power system management (PSM) µModule family, so it can be configured and monitored through a PMBus/SMBus/I²C digital interface. The PC-based LTpowerPlay® tool enables visual monitoring and control of power supply voltage, current, power use, sequencing, margining and fault log data. The LTM4678 is the first µModule regulator with programmable loop compensation: g_m and R_{TH}, which greatly reduces design time, since dynamic performance tuning is done without the hassle of iterative PCB board builds or modifications.

Figure 1. 1V and 1.8V outputs at 25A with I²C serial control and monitoring interface



The LTM4678 is a member of ADI's PSM µModule family, so it can be configured and monitored through a PMBus/SMBus/I²C digital interface. The PC-based LTpowerPlay enables visual monitoring and control of power supply voltage, current, power use, sequencing, margining and fault log data.

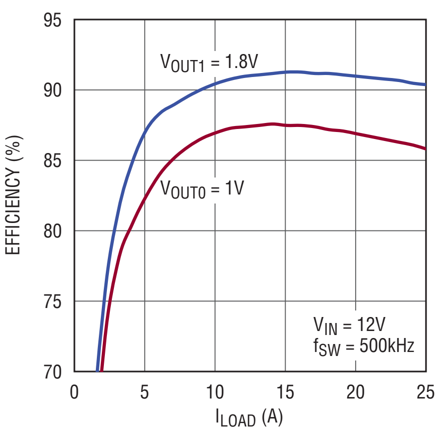


Figure 2. Efficiency of the two outputs

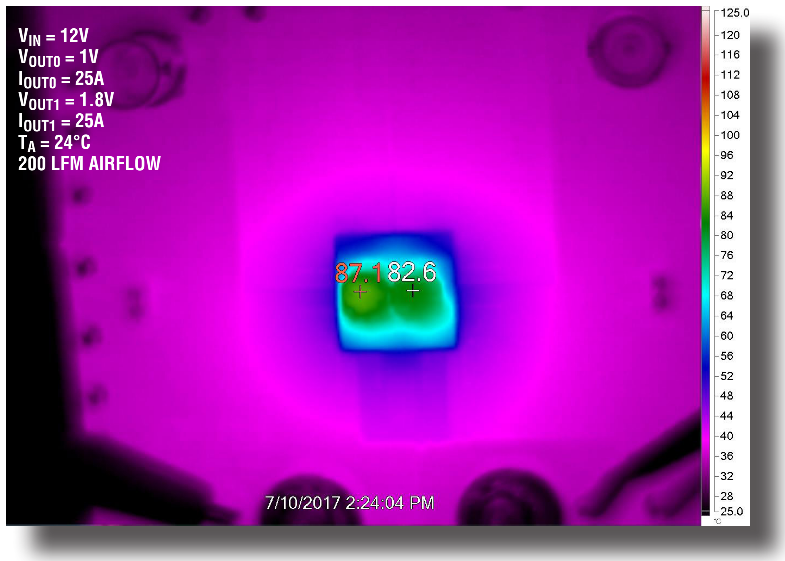


Figure 3. Thermal performance of the dual output converter

COP-BGA PACKAGE FOR ENHANCED THERMAL PERFORMANCE, SMALL SIZE AND HIGH POWER DENSITY

A thermally enhanced component on package (CoP) BGA package enables the high power LTM4678 to fit a small 16mm × 16mm PCB footprint. Inductors are stacked and used as a heat sink to enable efficient cooling.

EASILY SCALE TO HIGHER CURRENT WITH CURRENT MODE CONTROL

The LTM4678 uses peak current mode control. Current is monitored and controlled cycle by cycle. This enables equal current sharing among phases.

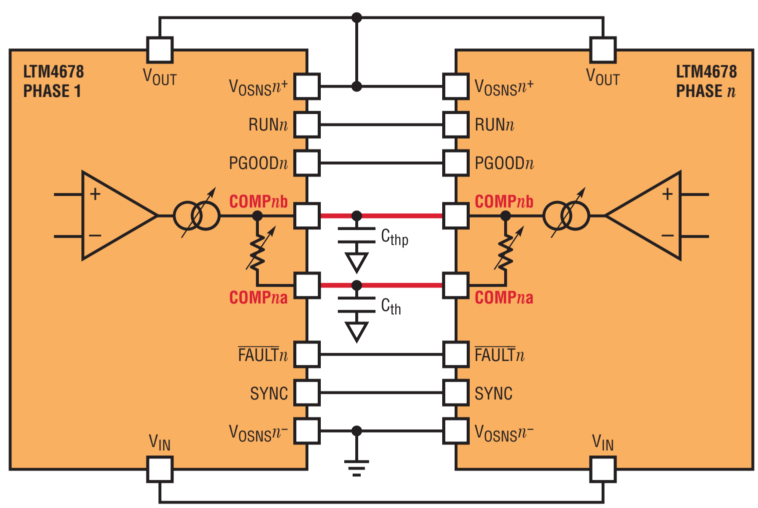
OTHER UNIQUE FEATURES

- Dual remote output sensing compensates for the voltage drop on traces in high current application
- ±0.5% maximum DC output error over temperature provides additional regulation margin
- Direct input current sense measures the precise input current and power
- Dedicated PGOOD pins provide signal for downstream system when output voltage is in regulation range
- $EXTV_{CC}$ pin maximizes efficiency at high V_{IN} conditions

DUAL-OUTPUT CONVERTER (1V AT 25A AND 1.8V AT 25A)

Figure 1 shows a typical 5.75V–16V input, dual-output solution. The LTM4678's two channels run with a 180° relative phase shift, reducing the input RMS current ripple and capacitor size.

Figure 4. Block diagram showing the simplicity of multiphase operation



The LTM4678 can be configured as a polyphase single-output converter for higher current solutions. To increase output current, just add additional LTM4678s and connect the respective V_{IN}, V_{OUT}, $V_{OSNS}+$, $V_{OSNS}-$, PGOODs, COMPa/b, SYNC, RUN, $\overline{FAULT}$ and GND pins together.

As shown in Figure 2, the total solution efficiency in forced continuous mode (CCM) is 85.8% at 1.0V/25A output, and 90.4% at 1.8V/25A.

Figure 3 shows the thermal performance of the LTM4678 running at V_{IN} = 12V, V_{OUT0} = 1.0V/25A and V_{OUT1} = 1.8V/25A with 200LFM. The hot spot (inductor on CH1) temperature rise is 63°C, where the ambient temperature is about 24°C.

POLYPHASE, SINGLE OUTPUT HIGH CURRENT (12V TO 1V AT 250A)

The LTM4678 can be configured as a polyphase single-output converter for higher current solutions. Figure 4 shows a block diagram for connecting multiple LTM4678s. To increase output current, just add additional LTM4678s and connect the respective V_{IN}, V_{OUT}, V_{OSNS}^+, V_{OSNS}^-, PGOODs, COMPa/b, RUN, $\overline{FAULT}$, SYNC and GND pins together.

Figure 5 shows the current from each phase when five LTM4678 (ten phases) are paralleled. The maximum current difference among ten phases is 0.75A (3% based on 25A), representing balanced current sharing.

Figure 6 shows the thermal image for the five parallel LTM4678s at 220A output with 450LFM air flow applied. Maximum thermal difference between the five µModule regulators is 10°C. Figure 7 shows the full schematic for an 8-phase solution.

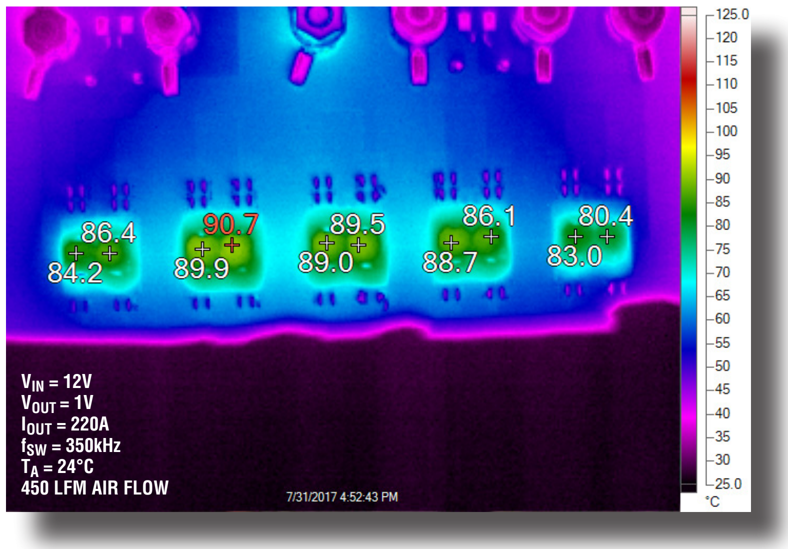


Figure 6. Thermal performance of multiphase converter

CONCLUSION

The LTM4678 µModule regulator is a versatile high performance power solution that delivers high efficiency and high power in a small 16mm × 16mm footprint. The small form factor and ease of use make the LTM4678 ideal for space-constrained designs, such as FPGA boards. Multiple LTM4678s can be operated in parallel polyphase operation for higher current applications, such as required in telecom and datacom systems, industrial and computer systems applications. ■

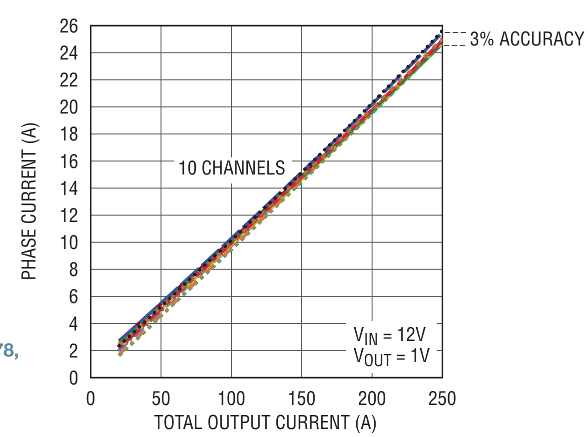


Figure 5. Current sharing among 5XLTM4678, ten phases in parallel

The LTM4678 µModule regulator is a versatile high performance power solution, delivering high efficiency and high power in a small 16mm × 16mm footprint. The small form factor and ease of use make the LTM4678 ideal for space-constrained applications.

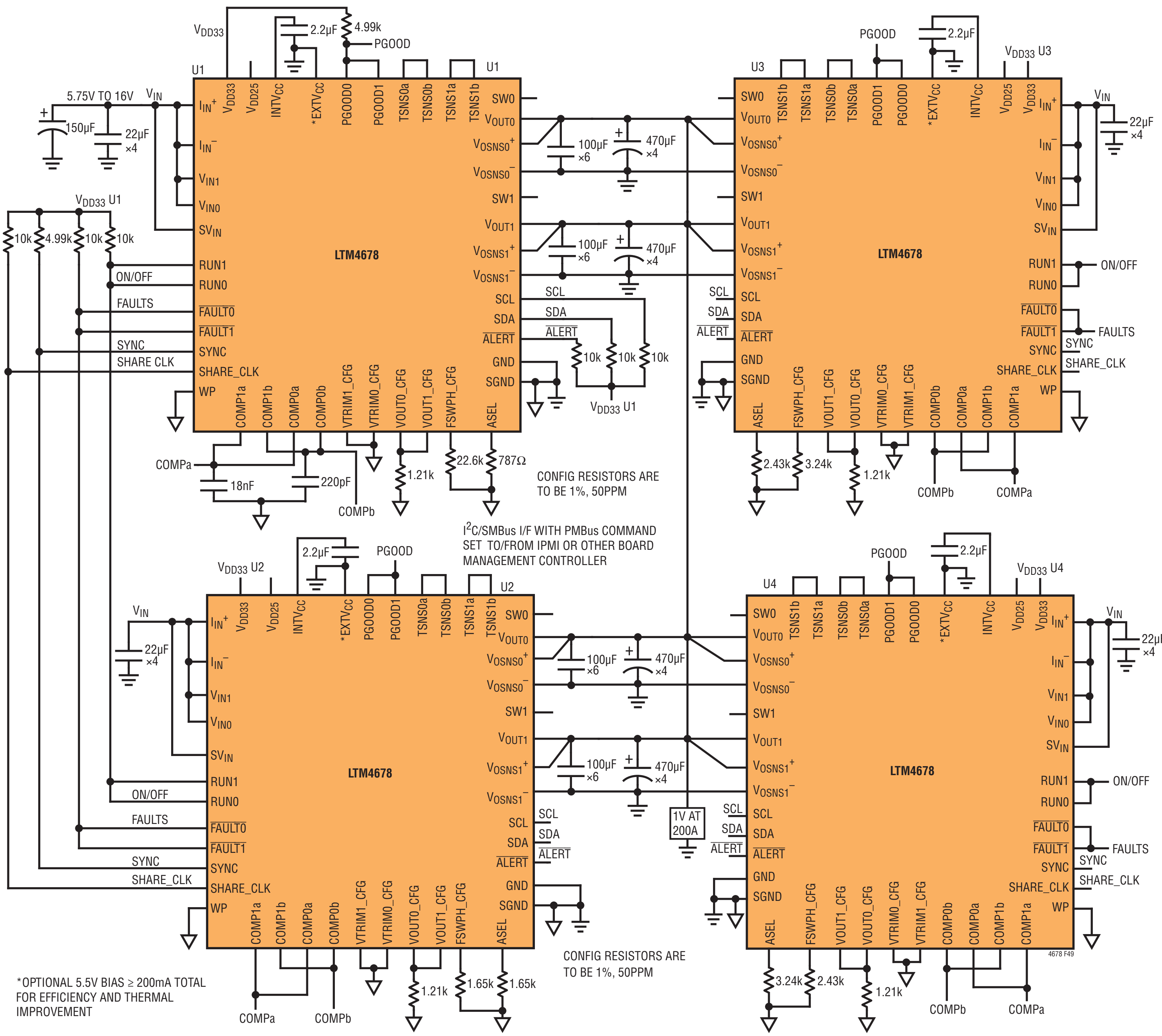
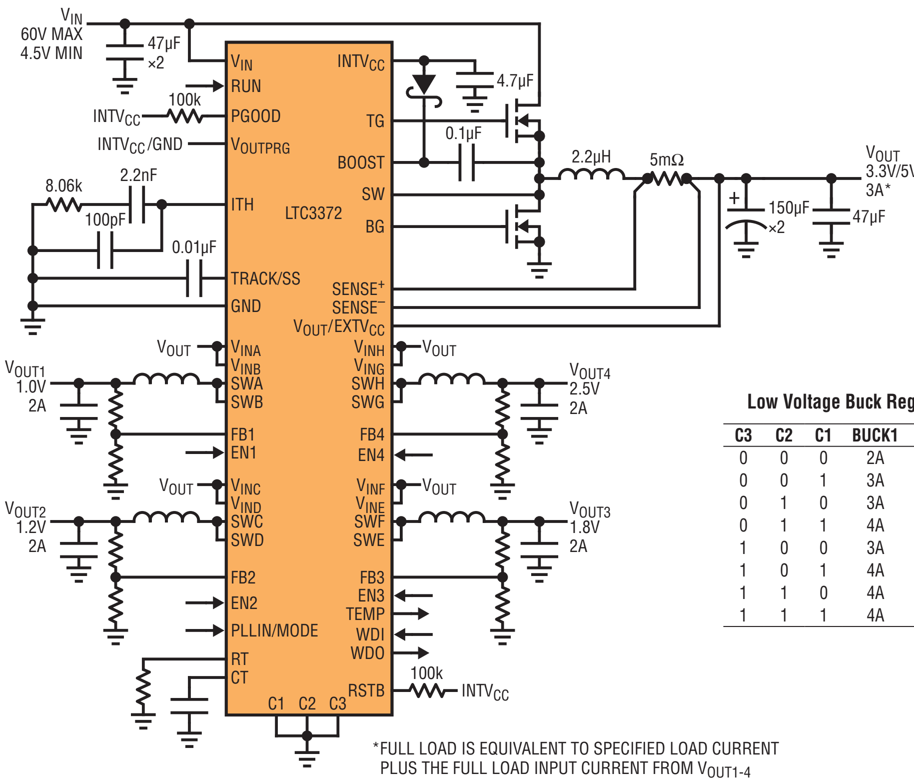


Figure 7. 8-phase operation with four LTM4678s producing 1V at 200A

MULTICHANNEL AUTOMOTIVE INFOTAINMENT POWER SOLUTION

LTC3372 is a front-end 60V high voltage (HV) buck controller plus four low voltage (LV) 5V monolithic buck regulators with low I_Q Burst Mode operation. By integrating a controller and monolithic regulators, LTC3372 can provide up to five separate rails from high input voltage in compact size at low cost. The output voltage of the HV controller can be selected between 3.3V and 5V depending on the level of $V_{OUTPROG}$ pin. The output voltages of the LV regulators can be individually programmed with external resistors through FB1–FB4 pins. While the HV controller is typically used for feeding the LV regulators, each regulator has its own enable and input pins to operate independently. For additional flexibility, the maximum output current of each of the four LV power stages can be digitally configured through the C bit (C1, C2, C3). In this way, the available 8A (1A times eight switches, see table) of total current supported by the IC can be distributed as needed to each rail, maximizing usage. The table lists all configurations of maximum current limit and regulator number corresponding to different C bit settings. The LV efficiency graph shows how efficiency varies with load when various numbers of switches are combined in parallel.

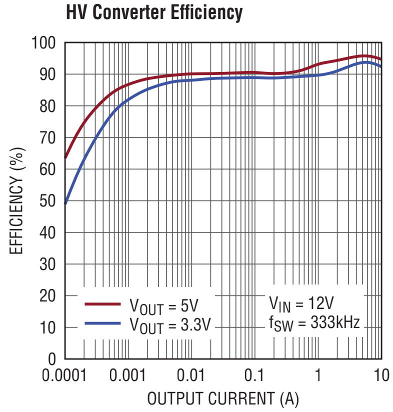


*FULL LOAD IS EQUIVALENT TO SPECIFIED LOAD CURRENT PLUS THE FULL LOAD INPUT CURRENT FROM V_{OUT1-4}

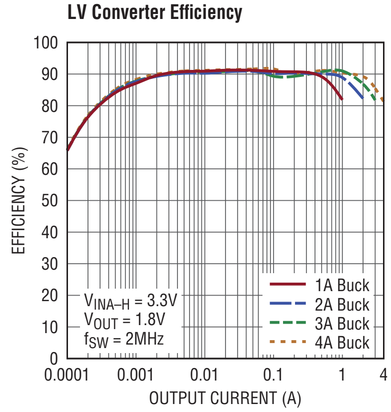
Low Voltage Buck Regulator Configurations

C3	C2	C1	BUCK1	BUCK2	BUCK3	BUCK4
0	0	0	2A	2A	2A	2A
0	0	1	3A	1A	2A	2A
0	1	0	3A	1A	1A	3A
0	1	1	4A	1A	1A	2A
1	0	0	3A	2A	–	3A
1	0	1	4A	–	2A	2A
1	1	0	4A	–	1A	3A
1	1	1	4A	–	–	4A

HV Converter Efficiency



LV Converter Efficiency



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