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

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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, cold crank, battery reverse polarity, double battery jump, spikes, and other transients defined in LV 124, ISO 7637-2, ISO 17650-2, and TL82066, as well as mechanical vibration, noise, extremely wide temperature ranges, etc. This article focuses on the critical requirements in automotive power supply specifications and solutions to meeting automotive specifications, including:

- Automotive input transients
- 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 conditions under the hood 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 3 V and up to 42 V—to deliver regulated voltages for the cores, I/O, DDR, and other rails required by peripheral devices.

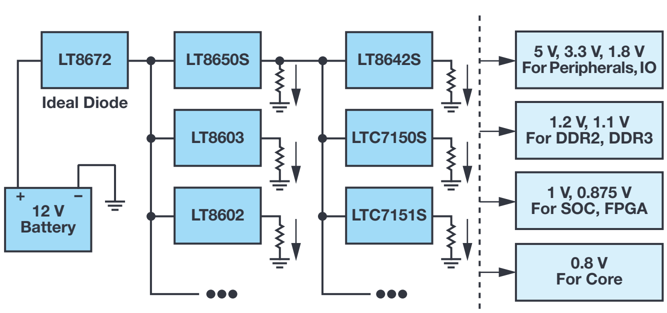

Figure 1. Overview of ADI's Power by Linear solutions for automotive electronics that meet transient immunity requirements.

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 a built-in preregulation 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) 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 12 V 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 12 V bus, including peripherals, I/Os, DDRs, processors, and their power supplies.

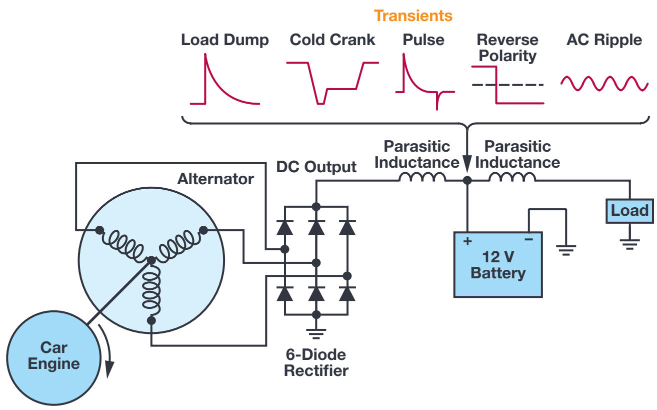

Figure 2. A typical electrical system in a car.

Electric cars change the picture somewhat. The engine is replaced with an electric motor, where a dc-to-dc converter converts a 400 V high voltage lithium-ion (Li-Ion) battery stack to 12 V, instead of an alternator. Nevertheless, traditional 12 V 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 ~13.8 V, under most conditions (more about that below). Every circuit powered directly from the car battery must run reliably over the range of 9 V to 16 V, 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, LV 124, 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. In automotive electronics, load dump refers to the disconnection of the vehicle battery from the alternator while the battery is being charged. During a load dump transient, 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 issues, it can no longer provide this service. As a result, all the other electronics see the voltage surge and must be able to survive load dump events. An unsuppressed load dump could generate voltages upward of 100 V. Thankfully, modern car alternators use avalanche-rated rectifier diodes, limiting the load dump voltage to 35 V—still a significant diversion from the norm. A load dump event can last up to 400 ms.

Another high voltage event is jump-start. Some tow trucks use two batteries in series to assure effective jump starts to revive a dead car battery, so an automobile's circuits must survive the doubled nominal battery voltage of 28 V 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 and LT8640S (Table 1) operate up to 42 V, exceeding this 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 and LT8646S, are rated for 65 V to accommodate truck and airplane applications, where a 24 V system is the norm.

Table 1. Silent Switcher and Silent Switcher 2 Monolithic Buck Regulators for Automotive Applications

Device	Number of Outputs	V_{IN} Range (V)	Output Current	Peak Efficiency f_{SW} = 2 MHz V_{IN} = 12 V V_{OUT} = 5 V	I_Q at 12 V Input (TYP) (µA)	EMI Feature	Packages
LT8650S	2	3 to 42	4 A on both channels 6 A on either channel	94.60%	6.2	Silent Switcher 2	6 mm × 4 mm × 0.94 mm LQFN
LT8645S	1	3.4 to 65	8 A	94%	2.5	Silent Switcher 2	6 mm × 4 mm × 0.94 mm LQFN
LT8643S	1	3.4 to 42	6 A continuous 7 A peak	95%	2.5	Silent Switcher 2 external compensation	4 mm × 4 mm × 0.94 mm LQFN
LT8640S	1	3.4 to 42	6 A continuous 7 A peak	95%	2.5	Silent Switcher 2	4 mm × 4 mm × 0.94 mm LQFN
LT8609S	1	3 to 42	2 A continuous, 3 A peak	93%	2.5	Silent Switcher 2	3 mm × 3 mm × 0.94 mm LQFN
LT8641	1	3 to 65	3.5 A continuous, 5 A peak	94%	2.5	Silent Switcher	3 mm × 4 mm 18-Lead QFN
LT8640 LT8640–1	1	3.4 to 42	5 A continuous 7 A peak	95%	2.5	Silent SwitcherLT8640: pulse skipping LT8640–1: forced continuous	3 mm × 4 mm 18-Lead QFN
LT8614	1	3.4 to 42	4 A	94%	2.5	Silent Switcher low ripple Burst Mode operation	3 mm × 4 mm 18-Lead QFN
LT8642S	1	2.8 to 18	10 A	95%	240	Silent Switcher 2	4 mm × 4 mm × 0.94 mm LQFN
LT8646S	1	3.4 to 65	8 A	94%	2.5	Silent Switcher 2	6 mm × 4 mm × 0.94 mm LQFN

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 when the car is started by the driver—for instance, when one starts a car to drive to the supermarket and starts it 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.

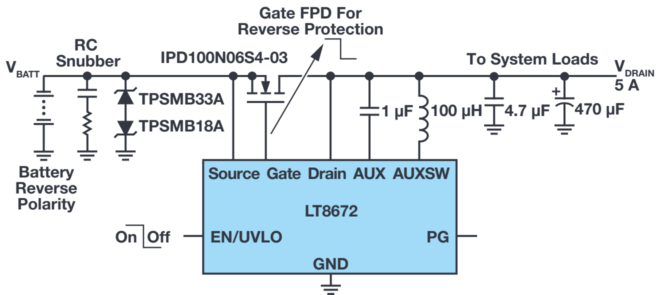

Figure 3. LT8672 response to battery reverse polarity.

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 3.2 V or lower for around 20 ms—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 3 V.

ISO 7637-2 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 selection of input TVS.

An Ideal Diode Satisfies Automotive Immunity Norms

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

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 20 mV. 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.

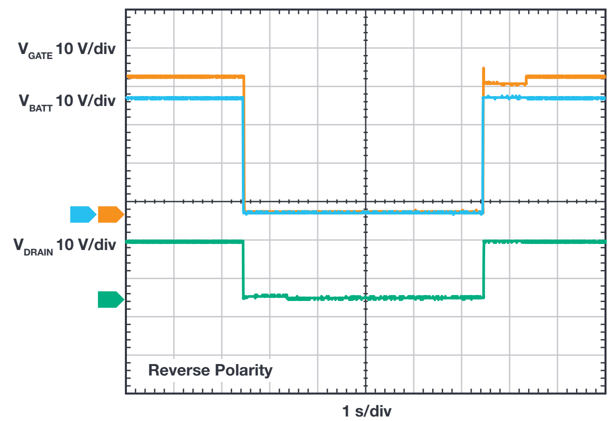

Figure 4. Waveform of LT8672 response to reverse polarity.

Superimposed Alternating Voltage

A common disturbance on the battery rail is a superimposed ac voltage. 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 ISO 16750 and LV 124, an ECU may be subjected to an ac ripple superimposed on its supply, with frequencies up to 30 kHz and amplitudes of up to 6 V 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 100 kHz to control external FETs as needed to reject these ac ripples.

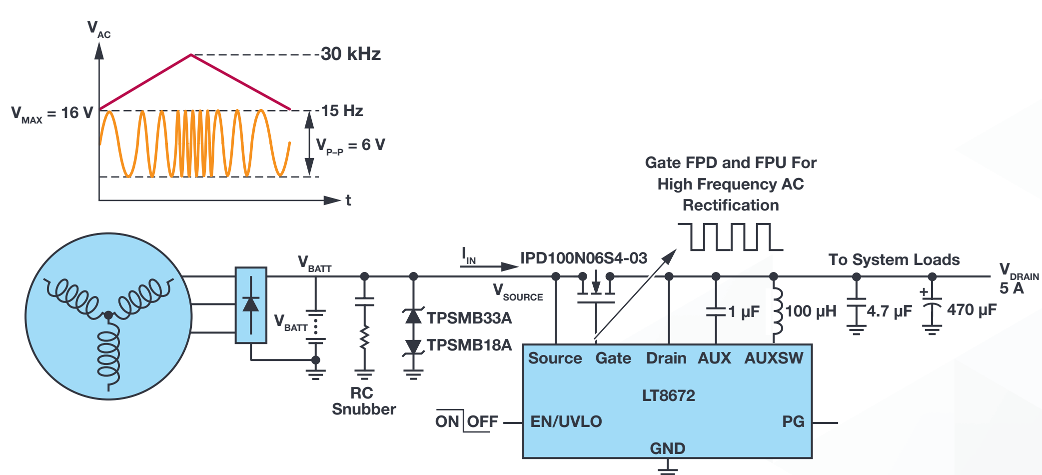

Figure 5. Waveform of LT8672 response to superimposed alternating voltage.

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 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 11 V voltage to keep the external FET on, while providing strong gate souring current to reduce switching loss for high frequency ac ripple rectification. Its 50 mA source current capability enables super-fast turn-on of the FET, minimizing power dissipation; its 300 mA sinking current capacity realizes fast turn-off, minimizing 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.

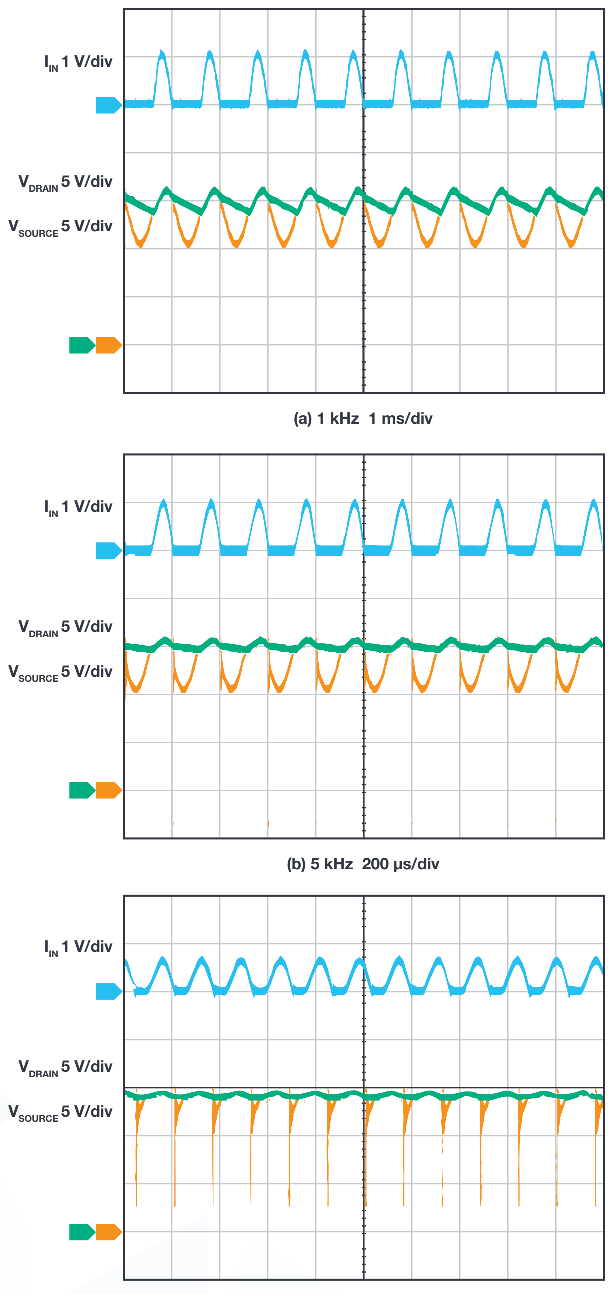

Figure 6. Waveform of LT8672 response to superimposed alternating voltage.

In addition, the LT8672 effectively reduces conduction losses when compared with a traditional Schottky diode solution under the same load conditions. As seen in the thermal images of Figure 7, the solution using the LT8672 is almost 60°C 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.

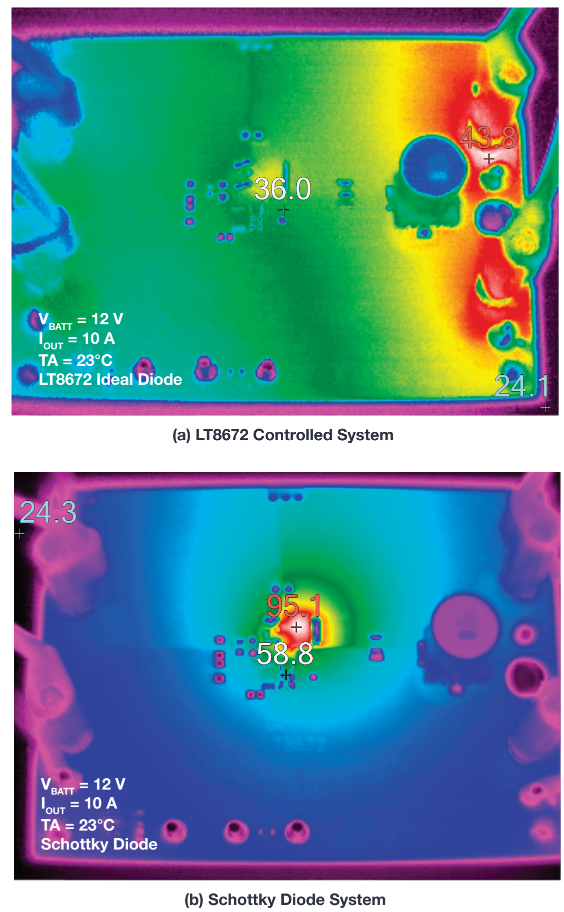

Figure 7. Thermal performance comparison.

Some of these pulses could have high voltage peaks. For example, pulse 3a defined in ISO 7632-2 is a negative spike whose peak voltage exceeds –220 V, while pulse 3b defines a pulse with maximum peak voltage of 150 V, on top of the battery's 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.

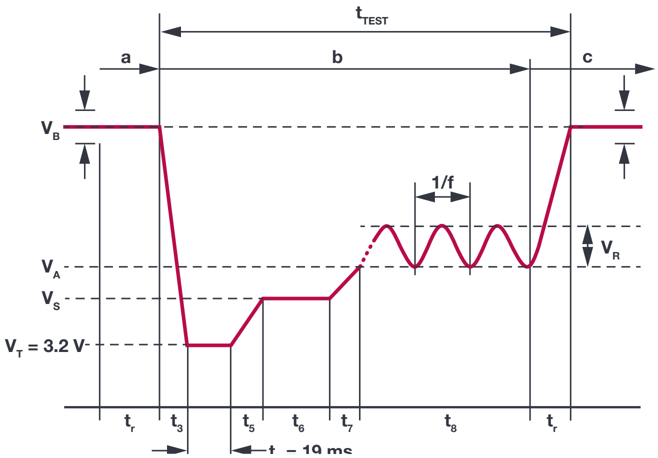

Figure 8. Severe cold crank for the 12 V system defined in LV 124.

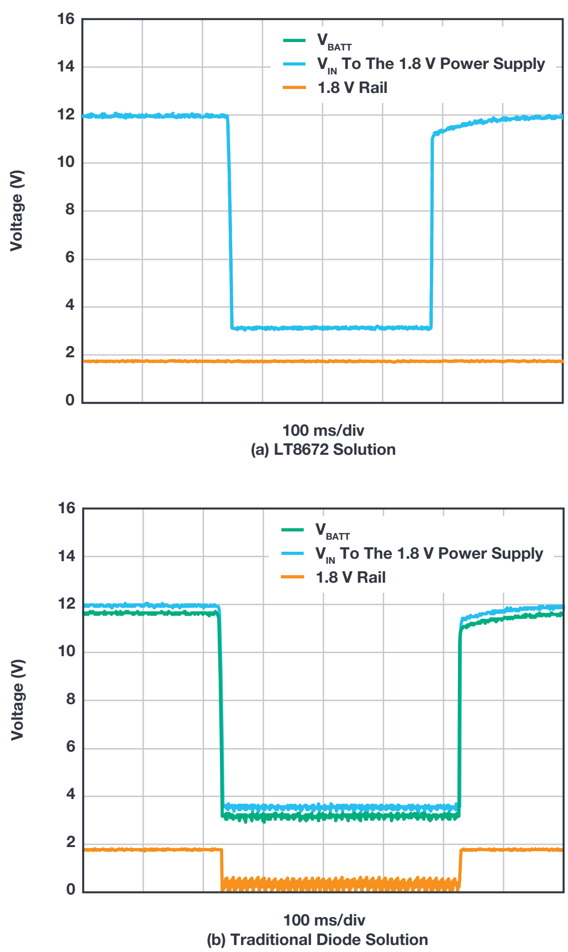

Figure 9. Cold crank event.

Multiple Rail Regulator Rides Through Cold Crank Events

The LT8602 provides compact solutions for up to four regulated rails (for example, 5 V, 3.3 V, 1.8 V, 1.2 V) with an input voltage range from 5 V to 42 V, suitable for functions that do not necessarily need to be on during a cold crank. Otherwise, for functions that must operate even during cold crank— such as the spark plug controller or alarm—solutions like the LT8603 work down to 3 V (or lower) inputs.

LV 124 has defined the worst case of cold crank, shown in Figure 8. It indicates that the lowest battery voltage can go down to 3.2 V and last for 19 ms at car start-up. This specification challenges applications to keep running as low as 2.5 V when faced with the extra diode voltage drop from battery reverse protection in a traditional (nonideal 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 3 V supply often required by many microcontrollers.

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

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

Figure 9 shows the comparison of 1.8 V power supply with the LT8672 and with a traditional diode. The step-down regulator works down to 3 V. As shown, with a traditional diode, V_{IN} to the buck regulator drops to near 2.7 V when the battery voltage V_{BATT} drops to 3.2 V, due to high voltage drop of the diode, triggering the UVLO shutdown of the downstream switching regulator, and its 1.8 V 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 1.8 V output.

Numerous critical functions require regulated 5 V and 3.3 V rails, plus sub-2 V 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 6 mm × 6 mm LT8603 quad output, triple monolithic buck converter plus boost controller.

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

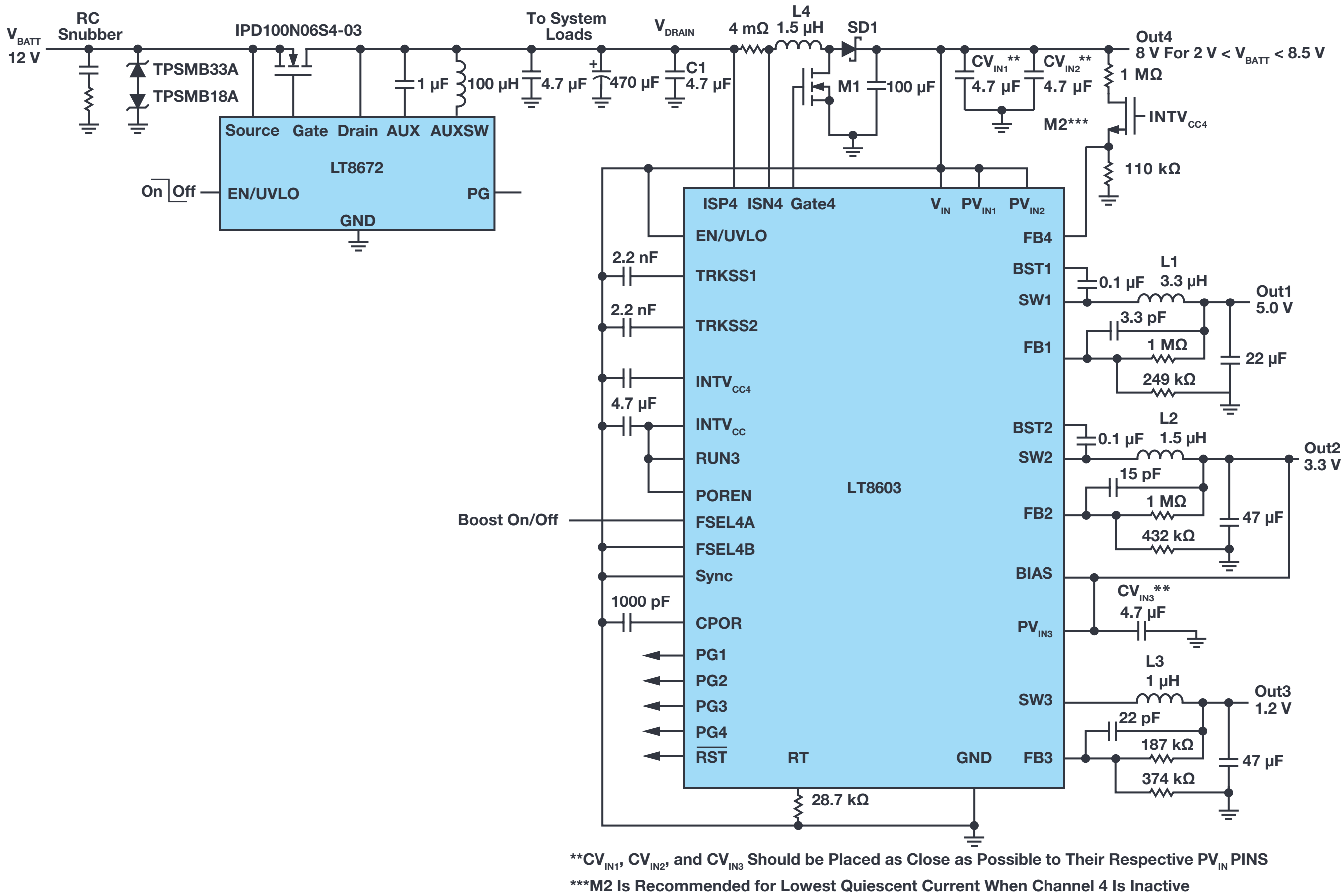

Figure 10. LT8672 and LT8603 solution tolerates cold crank events that ride though cold crank events.

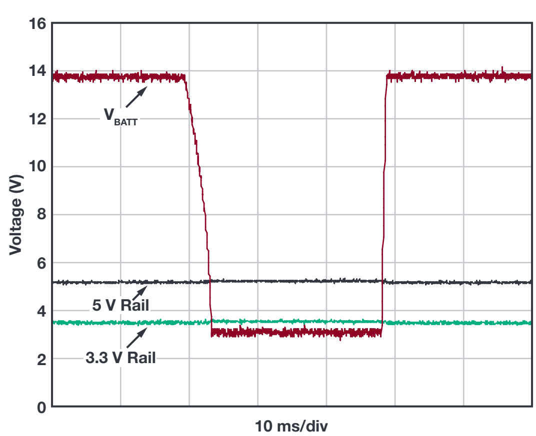

Figure 11. The LT8672 and LT8603 combination produces 5 V and 3.3 V outputs that ride though cold crank events.

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 3 V to 42 V, 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 a few microamps. In contrast, a typical buck regulator might draw hundreds of hundreds of micro-amps 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 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.

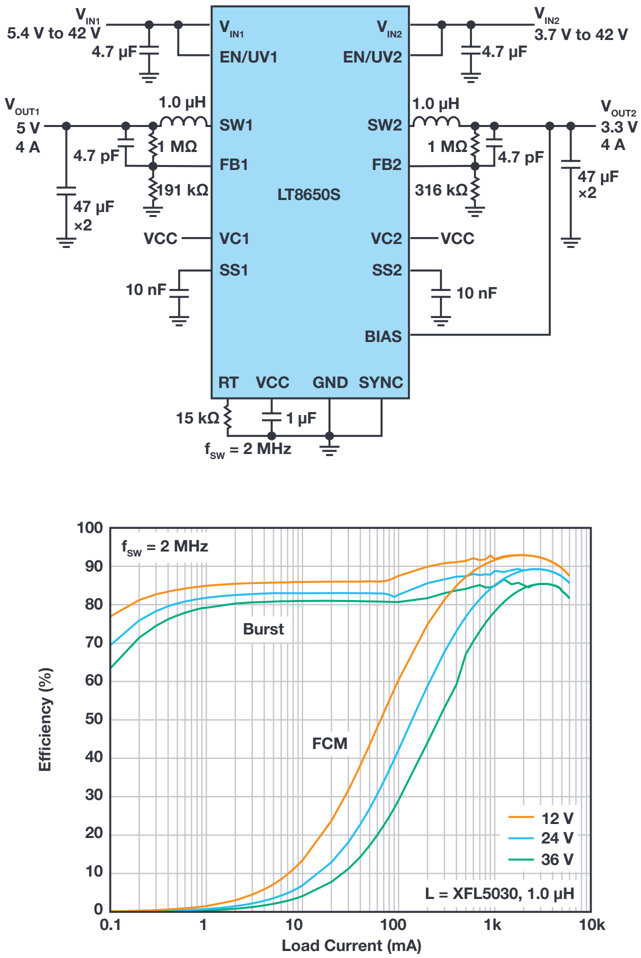

Figure 12. Low I_Q LT8650S maintains very high light load efficiency to support always-on applications without significantly draining the battery.

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 8 A total output current at fixed output voltages of 3.3 V or 5 V. Despite the simple overall design and layout, this converter includes options that can be used to optimize the 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 42 V or 65 V. Typical quiescent current for these devices is only 2.5 µA, thanks to the low I_Q technologies developed by Analog Devices. With minimum turn-on time of 35 ns, these regulators deliver 3.3 V output voltage from input 42 V at switching frequency of 2 MHz, which is common in the automotive industry.

Silent Switcher Portfolio 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 frequencies are now pushed to 2 MHz to reduce the passive component size and 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 150 kHz to 1 GHz.

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 42 V/4 A LT8650S, the hot loop consists of an input capacitor and 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.

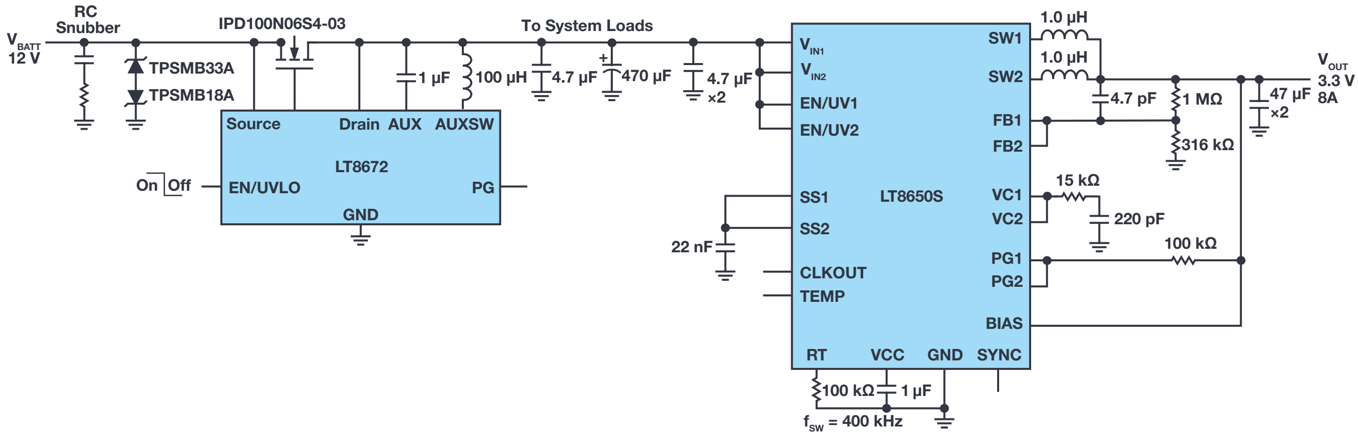

Figure 13. LT8672 and LT8650S configuration for high output current.

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 of forward voltage drop. The LT8650S switches at 400 kHz with input ranging from 3 V to 40 V, and an output capability of 8 A 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 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 30 MHz to 1 GHz, 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).

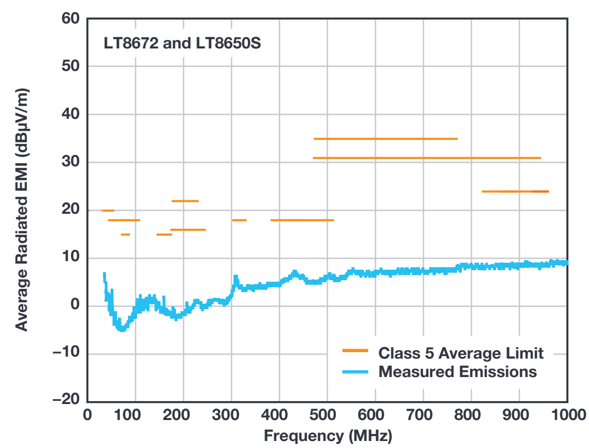

Figure 14. LT8672 and LT8650S EMI performance: 30 MHz to 1 GHz.

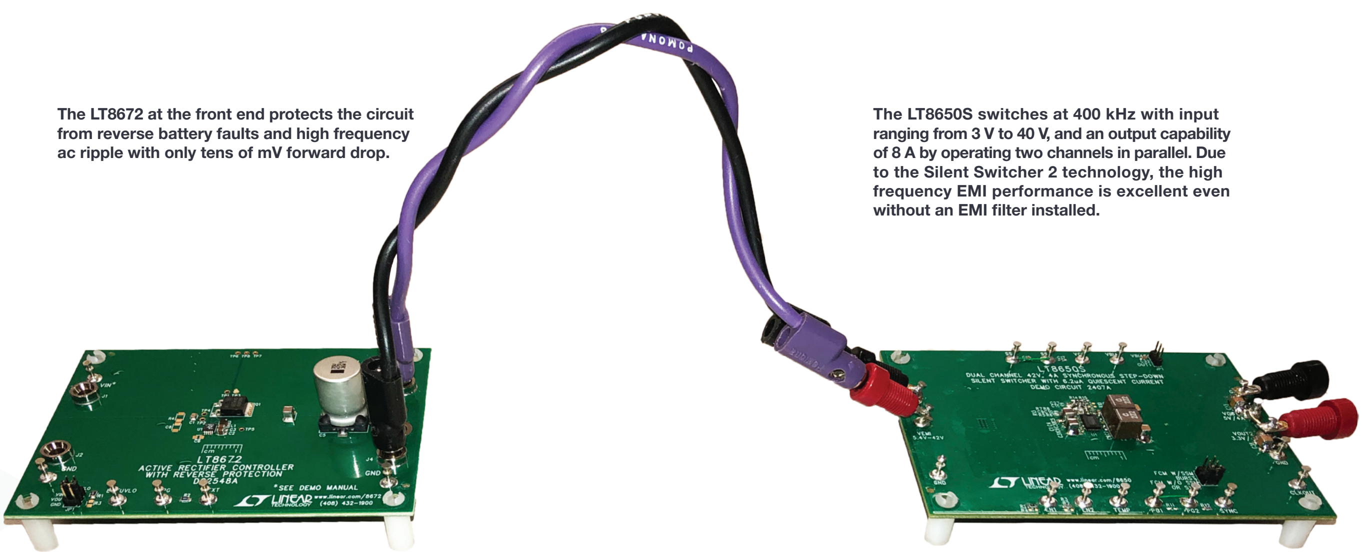

Figure 15. A complete power supply solution for 3.3 V and 5 V outputs from an automotive battery.

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 12 V 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.

About the Author

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