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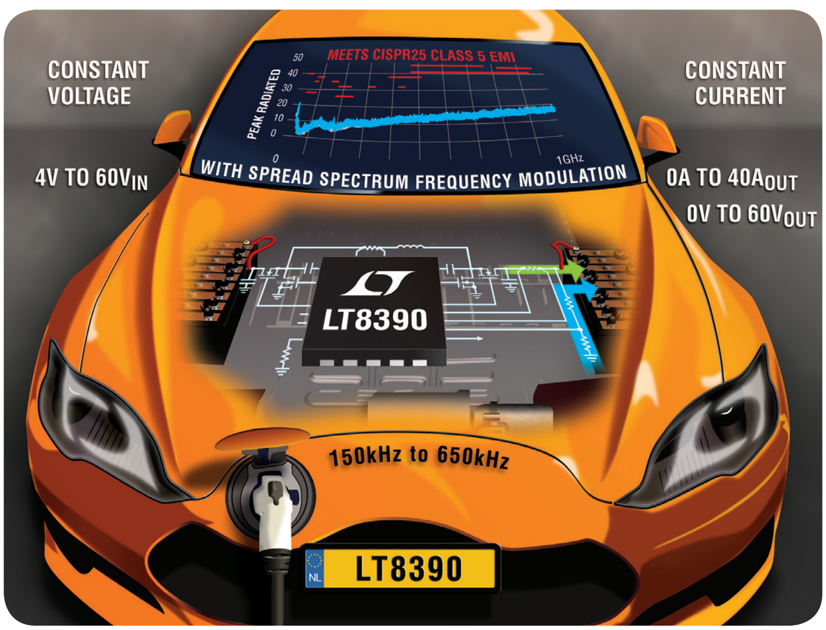
IN THIS ISSUE

60V Synchronous, Low EMI Buck-Boost for High Power and High Efficiency

Dawson Huang, Kyle Lawrence and Keith Szolusha

Electric vehicle, solar power and industrial power applications place significant power and efficiency demands on DC/DC converters. In these environments, complex electronic controls and displays, battery chargers, and high power electric motors operate from wide-ranging battery voltages, various battery chemistries and solar panels. DC/DC regulators must be able to both step-up, and step-down their input voltages. Likewise, loosely regulated high voltage industrial power systems require well regulated high voltage and high current buck-boost bus power. The single-inductor 4-switch buck-boost DC/DC converter excels in these areas, with its easy to use, efficient and rugged structure.



The LT8390 is a synchronous 4-switch buck-boost DC/DC controller that solves many of the issues found in automotive, solar and industrial solutions.

The LT®8390 is a synchronous 4-switch buck-boost DC/DC controller that solves many of the issues found in automotive, solar and industrial solutions. Its wide 4V-to-60V operating range can handle high voltage and low voltage automotive transients or the wide-ranging outputs of solar panels. It is ideal for high power 12V and 24V systems, but can regulate an output anywhere between 0V and 60V.

Proprietary peak current mode architecture produces smooth transitions between buck and boost operation,

(continued on page 4)

In this issue...

Linear in the News

WIRELESS BMS CONCEPT CAR

At the Electronica Show in Munich and at the CES Show in Las Vegas, Linear demonstrated the industry's first wireless battery management system (BMS) concept car, built in collaboration with LION Smart. This wireless BMS concept car combines Linear's highly accurate battery stack monitors with its SmartMesh® wireless mesh networking products in a BMW i3, replacing the traditional wired connections between the battery packs and the battery management system. This demonstration of a fully wireless BMS car represents a significant breakthrough that offers the potential for improved reliability, lower cost and weight, and reduced wiring complexity for large multicell battery stacks for electric and hybrid/electric vehicles.

Automakers are challenged to ensure the driving public that electric and hybrid/electric vehicles are both safe and reliable. Linear's road-proven high voltage battery stack monitors deliver industry leading accuracy and reliability, enabling battery management systems that maximize battery pack performance and longevity. The LTC®6811 is a complete battery measuring device for hybrid/electric vehicles that can measure up to 12 series-connected battery cell voltages with better than 0.04% accuracy. Combining the LTC6811 with Linear's SmartMesh wireless mesh networking system addresses the persistent reliability issues associated with automotive wiring harnesses and connectors.

Field-proven in industrial Internet of Things applications, SmartMesh embedded wireless networks deliver >99.999% reliable connectivity in harsh environments by employing path and frequency diversity. In addition to improving reliability by creating multiple points of redundant connectivity, the wireless mesh network enables additional BMS capability. Wireless connectivity enables more flexible placement of battery modules, and makes possible the installation of sensors in locations previously unsuitable for a wiring harness. Wireless sensors integrated into the SmartMesh network, such as current and temperature monitors, offer the potential for synchronizing these measurements with cell voltages.

Erik Soule, Vice President, Signal Conditioning Products for Linear Technology, stated, "Linear's innovations in two critical industry leading technologies enables wireless battery management at automotive reliability levels. New designs of electric and hybrid/electric vehicles are increasing rapidly and all of the major automotive manufacturers are searching for ways to improve the performance and reliability of their battery management systems as they move into higher volume production. The wireless BMS concept car, realized through the expertise of LION Smart's BMS design, showcases our product vision."

At Electronica, Munich, Linear demonstrated the industry's first wireless battery management system (BMS) concept car, built in collaboration with LION Smart. The wireless BMS concept car combines Linear's highly accurate battery stack monitors with its SmartMesh wireless mesh networking products in a BMW i3, replacing the traditional wired connections between the battery packs and the battery management system.

CUSTOMER DEMOS

At Electronica, Linear demonstrated solutions for a broad range of markets:

- Smart Industry—Focus on the Industrial Internet of Things, demonstrating applications in Smart Factories, Smart Hospitals, Smart Traffic Control and Smart Homes.
- Smart Energy—Showcasing benefits in battery monitoring systems, battery backup systems, grid energy storage, and high power portable equipment.
- Smart Measurement—Focusing on a range of embedded applications, including testing and powering FPGA-based systems.
- Smart Mobility—Showcasing a range of automotive and transportation applications. These include battery monitoring systems for hybrid and electric vehicles, LED driver systems, and Silent Switcher® technology for automotive power.

Specific customer demos included:

- Automotive 48V/12V dual battery system
- Matrix LED dimmer
- Battery management system for powerful and reliable automotive control
- Wireless sensor networks for industrial applications
- High performance SAR ADCs for precision data acquisition and control
- Linear inside: automatic weather station
- Digital power system management

CONFERENCES & EVENTS

9th International Automotive Electronics Technology Expo, Tokyo Big Sight, Tokyo, Japan, January 18–20—Presenting Linear's products and solutions for car electronics. More info at www.car-ele.jp/en/Home/

Electronica China, Shanghai New International Expo Centre, March 14–16, Hall E-4, Booth 4401—Presenting Linear's products and solutions, including the wireless BMS car. More info at www.electronica-china.com ■

Table 1. Feature comparison of the LT8390 and buck-boost converter ICs

	LT8390	LT3790	LTC3789	LT8705
Control scheme	Peak-Buck Peak-Boost	Valley-Buck Peak-Boost	Valley-Buck Peak-Boost	Valley-Buck Peak-Boost
SSFM	✓			
Integrated bootstrap diode	✓			
f_S range	150kHz–650kHz	200kHz–700kHz	200kHz–600kHz	100kHz–400kHz
V_{IN} range	4V–60V	4.7V–60V	4V–38V	2.8V–80V
DCM	✓	✓		✓

(LT8390, continued from page 1)

provides reverse current protection, and smoothly transitions to DCM operation at light load. The LT8390's unique architecture, matched with spread spectrum frequency modulation (SSFM) enables low EMI solutions, not typically common in buck-boost converters.

For space-constrained designs, the integrated bootstrap diodes and the tiny 4mm × 5mm QFN package minimize required PCB space. For very high power applications, the LT8390 can be paralleled and can be switched as low as 150kHz.

COMPACT, LOW EMI, 12V, 4A BUCK-BOOST

Low EMI is a requirement in most automobile electronics. Switching regulator EMI is commonly mitigated with EMI filters and electronic shielding, which add to the cost and size of the regulator. The supply designer can also carefully select the switching frequency to avoid some EMI constraint bands, but this severely limits the power supply designer's options with respect to efficiency and solution size.

To reduce design time and cost, the LT8390 includes a number of built-in low EMI features, such as SSFM. For instance, with minimal filtering, the powerful 48W converter in Figure 1 passes CISPR 25 Class 5 radiated and conducted EMI (Figure 3). The IC is designed to reduce the complexity of meeting stringent EMI requirements, unique among 4-switch buck-boost controllers.

The obvious benefit of SSFM is that it reduces the required size of the input EMI filter in this 400kHz converter. One can see that both the peak and average conducted EMI in the AM band is below the requirement, with only a 1.5µH inductor and a

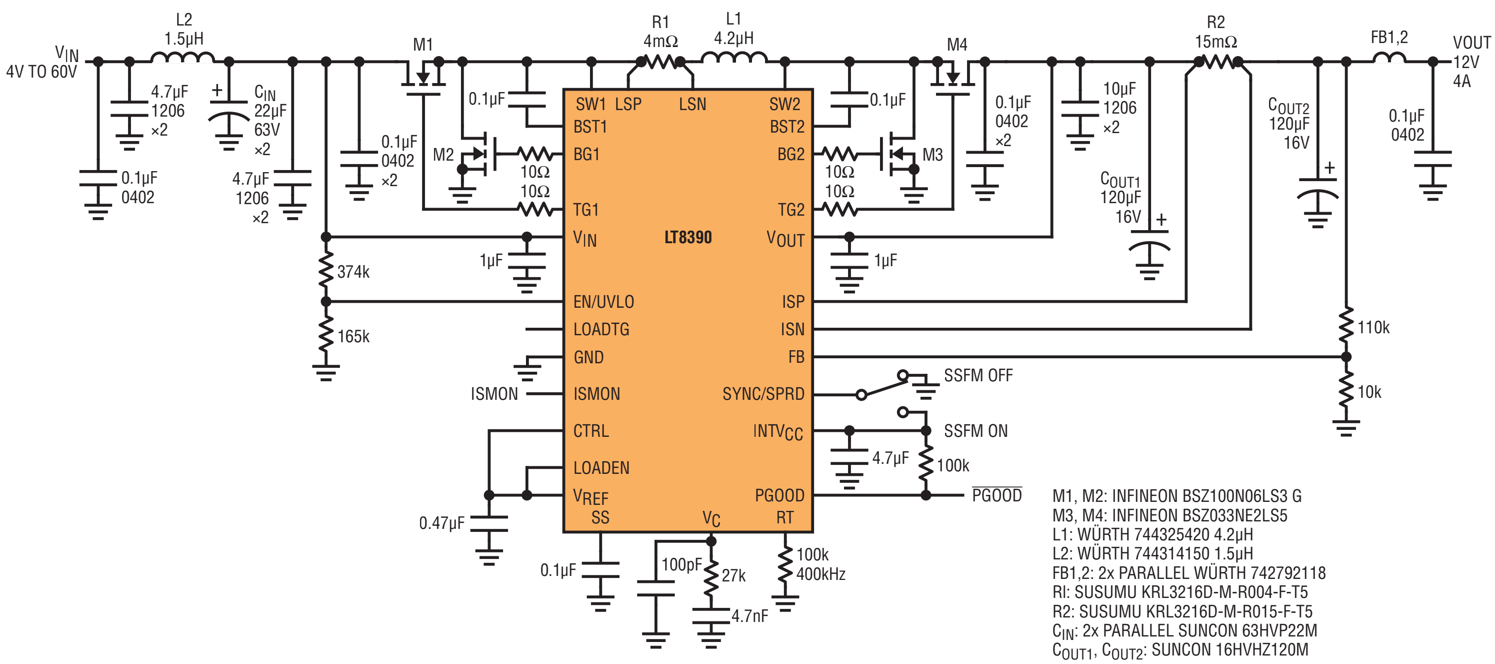


Figure 1. Compact 48W buck-boost converter meets automotive EMI requirements.

To reduce design time and cost, the LT8390 includes a number of built-in low EMI features, such as SSFM. For instance, with minimal filtering, the powerful 48W converter passes CISPR 25 Class 5 radiated and conducted EMI. The IC is designed to reduce the complexity of meeting stringent EMI requirements—unique among 4-switch buck-boost controllers.

few small ceramic capacitors as the input filter. Compact layout and the use of small 3mm × 3mm MOSFETs minimizes hot-loop size and high frequency radiated EMI (Figure 3). The LT8390 gate drivers are designed for high power, but also low EMI when it is needed. This low EMI 12V regulator is available for testing as a standard demonstration circuit, DC2457A.

The efficiency of the low EMI converter remains high, as shown in Figure 4. It can handle transients up to 60V and down to 4V while maintaining regulation of the 12V output. The 4V operation meets new, low voltage requirements for electric vehicles with energy-saving start-stop requirements and very low voltage transients.

Figure 3. Demonstration circuit DC2457A: 48W, 12V at 4A, buck-boost converter QFN layout is small and compact with four 3mm × 3mm power MOSFETs and a single power inductor.

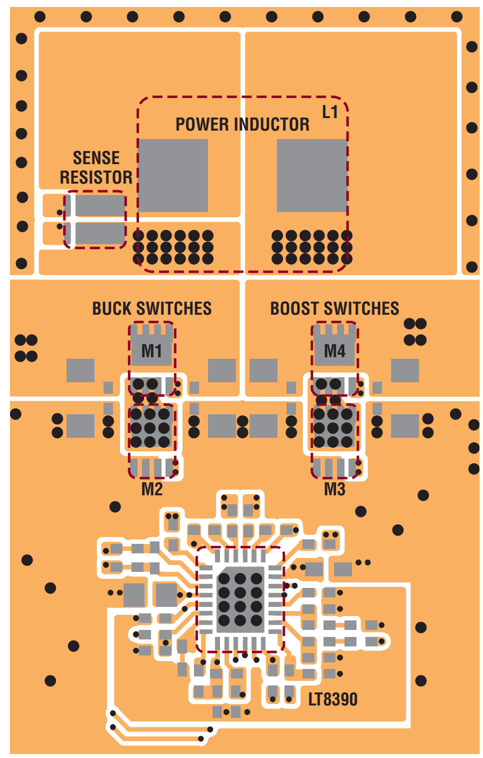


Figure 2. The LT8390 12V, 4A converter shown in Figure 1 passes CISPR 25 Class 5 peak and average conducted and radiated EMI.

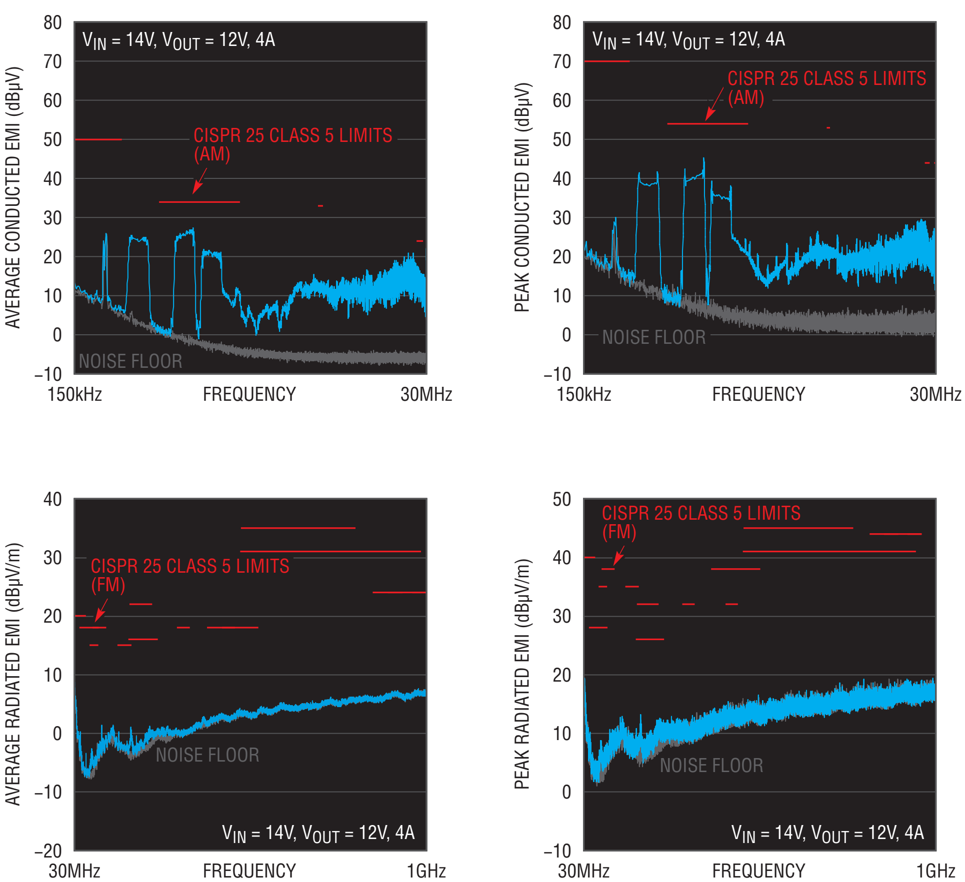
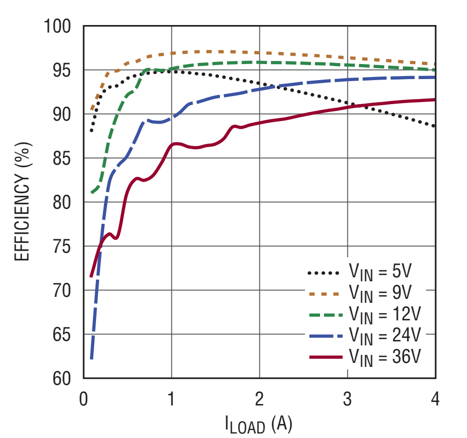


Figure 4. Efficiency of the converter in Figure 1



The LT8390 is capable of high power operation. In high power designs, synchronous switching and 150kHz operation limit switching losses and thermal dissipation. This enables design of very high power and high current converters.

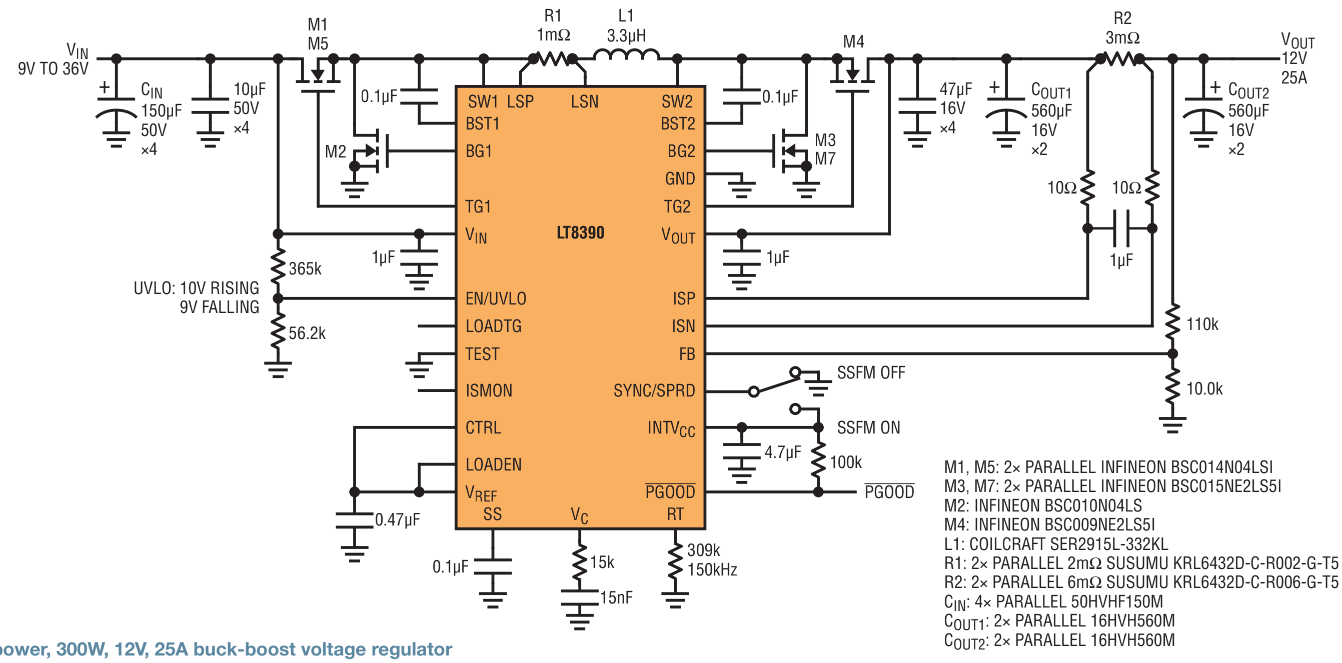


Figure 5. High power, 300W, 12V, 25A buck-boost voltage regulator

HIGH POWER BUCK-BOOST SINGLE STAGE

The LT8390 is capable of producing very high power operation. In high power designs, synchronous switching and 150kHz operation limit switching losses and thermal dissipation. This enables design of very high power and high current converters.

The buck-boost converter shown in Figure 5 is a typical example, supporting V_{IN} = 9V–36V, V_{OUT} = 12V and I_{OUT} = 25A, capability for a 300W power output. At full load, efficiency remains high (Figure 6) in all modes—boost, buck and buck-boost. This enables the LT8390 to regulate under all input conditions without overheating, doing so

Figure 6. Efficiency vs V_{IN} at full load

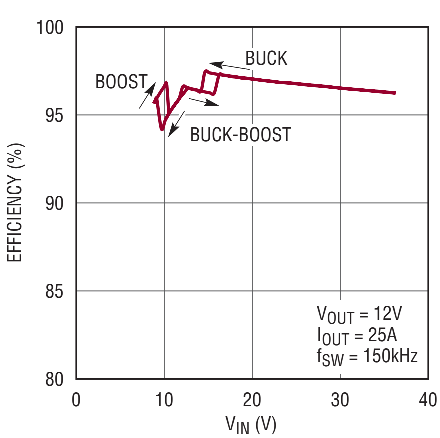
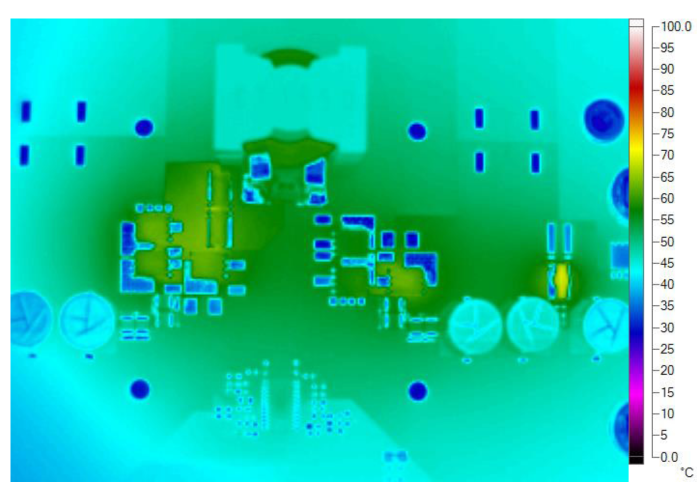


Figure 7. At 12V input and 300W output, the converter in Figure 5 remains cool, under 66°C. At 9.5V input, its worst-case thermal condition, the hottest components remain below 100°C.



For high efficiency at light load, the LT8390's proprietary peak current mode buck-boost architecture ensures it runs either in discontinuous conduction mode (DCM) or pulse-skipping mode (PSM) without reversed inductor current.

without the expense of a heat sink or fan. Nevertheless, cooling components can be added to increase power capability.

The gate drivers support high power parallel MOSFETs, such as the M1/M5 and M3/M7 pairs designated in Figure 5.

The 300W converter in Figure 5 has excellent thermal performance without the use of a fan or heat sink. With only a standard 4-layer PCB, the 300W converter reaches a worst-case high temperature of 66°C at 12V input as shown in Figure 7. The power MOSFETs remain relatively cool even with the 4-switch operation and high current. Its worst-case thermal condition is at 9.5V

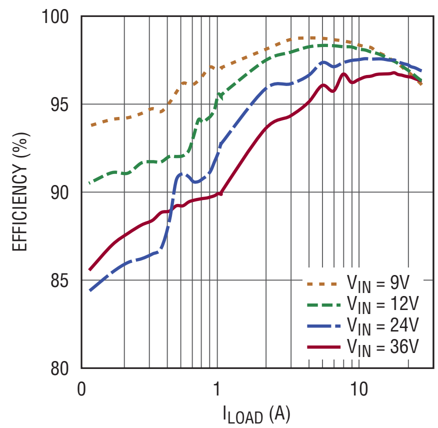


Figure 8. Efficiency vs load at various V_{IN} for high power converter shown in Figure 5

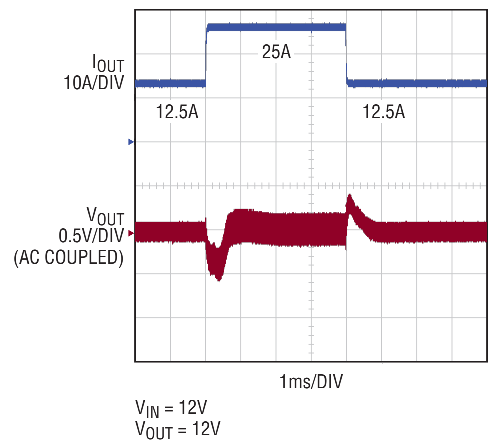


Figure 9. Load transient for high power converter shown in Figure 5

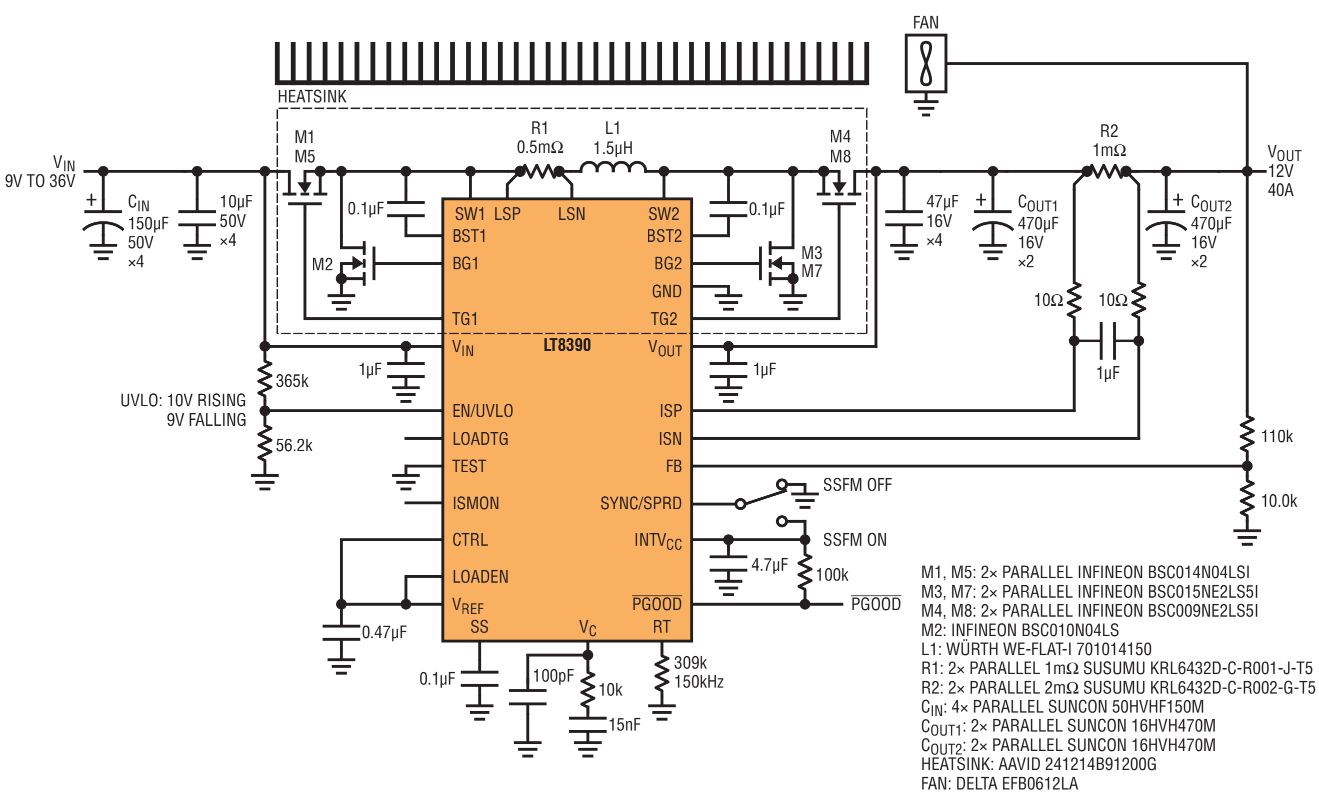


Figure 10. 12V, 40A (480W) single buck-boost with heat sink and fan

At full load, efficiency of the 300W converter remains high in all modes—boost, buck and buck-boost. This enables the LT8390 to regulate under all input conditions without overheating, doing so without the additional expense of a heat sink or fan. Nevertheless, cooling components can be added to increase power capability.

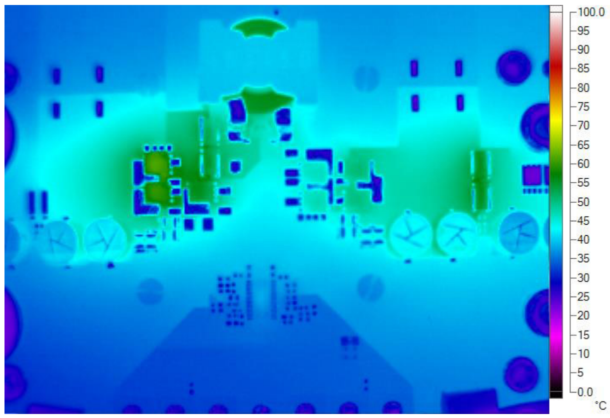


Figure 11. 12V, 40A (480W) converter in Figure 10 thermal scan at 12V input

input. This is the highest input current and lowest input voltage of the 4-switch buck-boost operation region. At 9.5V input, the hottest component is the power inductor, which remains below 100°C.

For high efficiency at light load, the LT8390's proprietary peak current mode buck-boost architecture ensures it runs either in discontinuous conduction mode (DCM) or pulse-skipping mode (PSM) without reversed inductor current. Efficiency over the load range is shown in Figure 8. It can achieve more than 90% efficiency at 0.1% load when V_{IN} = 12V. Figure 9 shows the load transient response at 12V input, 12V output between half load and full load.

Add a heat sink and a fan to push the output power of LT8390 buck-boost to 12V at 40A, 480W, as shown in Figure 10. The heat sink and fan are attached to the back side of PCB board that features an isolated thermal pad. The fan can be powered by the 12V output. Figure 11 shows the thermal at 12V input, 12V output at 40A. The hottest part is the top MOSFET at 62°C.

PARALLEL HIGH POWER CONVERTER

When thermal performance becomes the limiting factor in creating a high power voltage regulator system, the LT8390 is capable of parallel operation to increase total output power capability while maintaining an acceptable operating temperature over the input voltage range. Even at much higher output power, parallel LT8390 systems exhibit thermal performance similar to a single-phase LT8390 system, since output power and thermal dissipation are split between two converters. Along with improved thermal performance, parallel LT8390 systems are driven out of phase, effectively reducing the output ripple of the system.

The LT8390 has a number of features that enable it to be easily paralleled, including the its ability to operate as both a constant voltage and constant current regulator. This enables a single LT8390 to monitor and regulate the output voltage, while additional LT8390s operate as constant current regulators.

In this master-slave parallel system, the voltage regulator (master) senses the total output current of the system, and scales that current information to that of a single phase to be sent to the current regulators (slaves). Output current information provided at the ISMON pin of the voltage regulator is scaled and buffered inside LT8390 to match the CTRL pin operating voltage range. This allows the current regulator boards to be driven directly by the voltage regulator, ensuring balanced current sharing between phases. LT8390's ability to share current equally using the ISMON and CTRL pins of the part enables independent optimization of the voltage and current regulators before being combined into a single system.

In the example circuit shown in Figure 12, two 300W LT8390 demo circuits are optimized independently: one circuit is set up for constant voltage operation, and the other for constant current at the same output power. The two optimized converters are connected in parallel with the voltage regulator sending its ISMON signal to the current regulator's CTRL pin. Load sharing is maintained even during transients, as shown in Figure 13.

A complementary clock source, such as LTC6908-1, is the only external circuitry needed to complete the parallel system. A final optimization of the combined system's loop response resulted in a stable parallel system capable of delivering 600W of output power at the same operating temperature as a single 300W LT8390 voltage regulator.

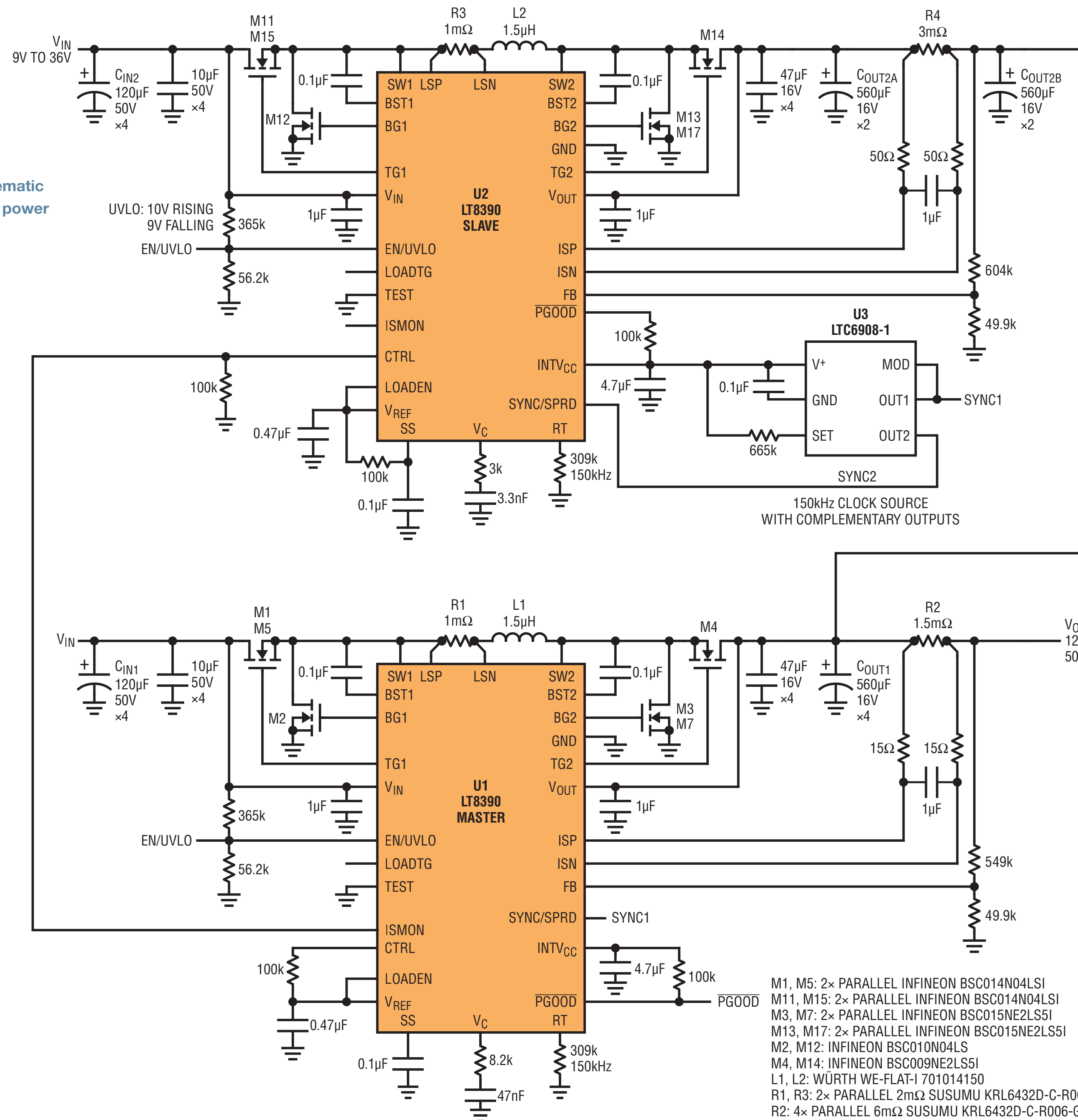
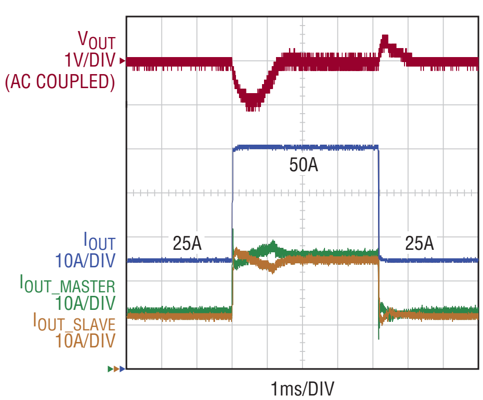


Figure 12. Schematic of parallel high power converter

M1, M5: 2× PARALLEL INFINEON BSC014N04LSI
M11, M15: 2× PARALLEL INFINEON BSC014N04LSI
M3, M7: 2× PARALLEL INFINEON BSC015NE2LS5I
M13, M17: 2× PARALLEL INFINEON BSC015NE2LS5I
M2, M12: INFINEON BSC010N04LS
M4, M14: INFINEON BSC009NE2LS5I
L1, L2: WÜRTH WE-FLAT-I 701014150
R1, R3: 2× PARALLEL 2mΩ SUSUMU KRL6432D-C-R002-G-T5
R2: 4× PARALLEL 6mΩ SUSUMU KRL6432D-C-R006-G-T5
R4: 2× PARALLEL 6mΩ SUSUMU KRL6432D-C-R006-G-T5
C_{IN1}: 4× PARALLEL SUNCON 50HVPF120MT
C_{IN2}: 4× PARALLEL SUNCON 50HVPF120MT
C_{OUT1}: 4× PARALLEL SUNCON 16HVH560M
C_{OUT2A}: 2× PARALLEL SUNCON 16HVH560M
C_{OUT2B}: 2× PARALLEL SUNCON 16HVH560M



V_{IN} = 12V
V_{OUT} = 12V

Figure 13. Load sharing during a load transient for the high power parallel converter

With flexible location current sensing, LT8390 can regulate input or output current by CTRL voltage. For instance, for a solar powered battery charger, the input current of the converter, the photovoltaics (PV) current, is sensed and sent to maximum power point tracking (MPPT) controller. With PV voltage and current, the MPPT controller calculates the maximum power point and sends the current command to CTRL for regulation.

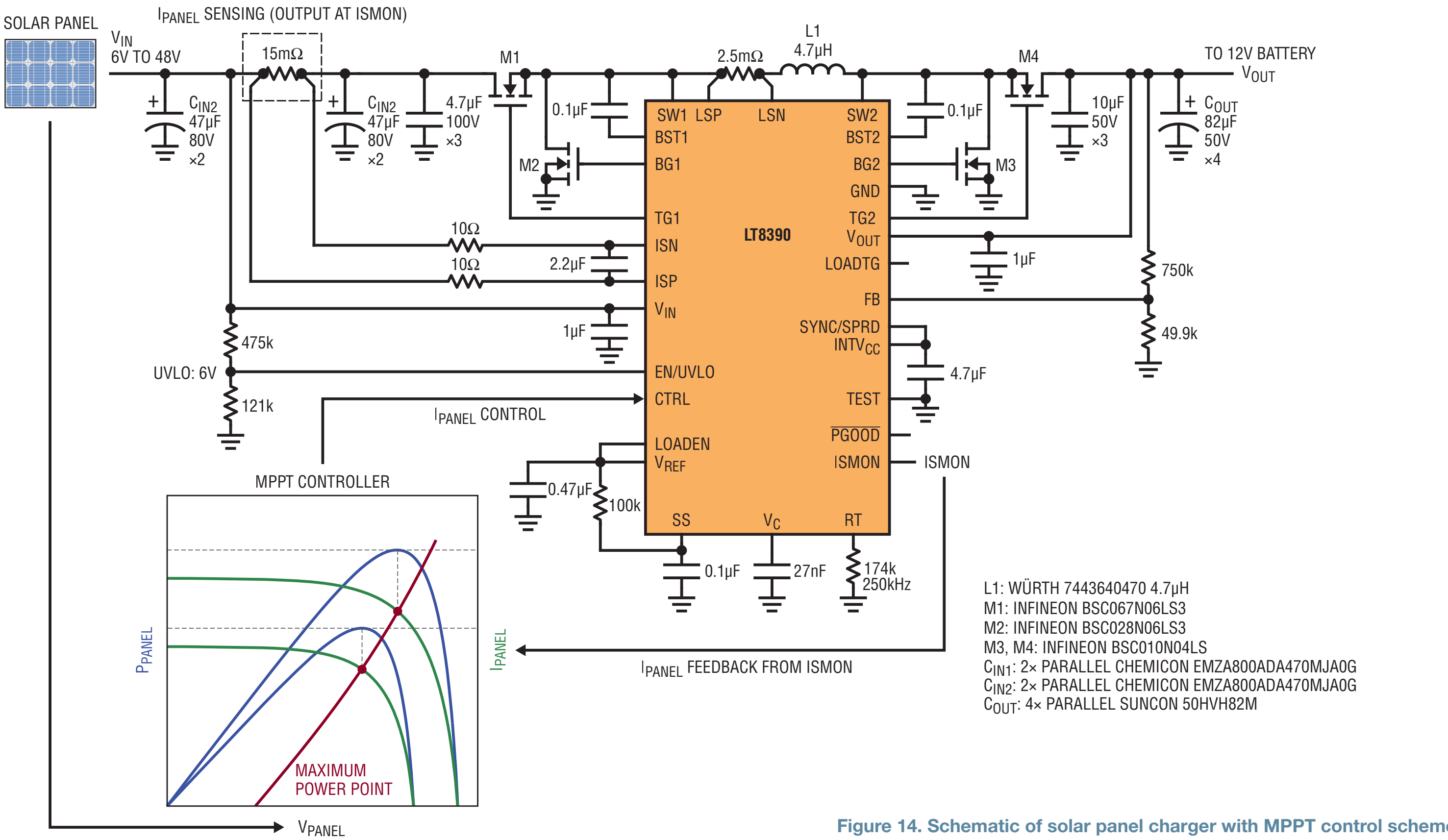


Figure 14. Schematic of solar panel charger with MPPT control scheme

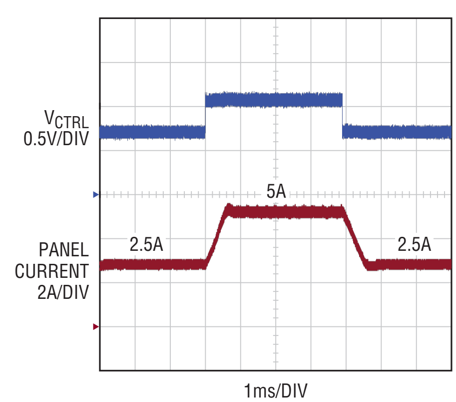
SOLAR PANEL CHARGER

With flexible location current sensing, the LT8390 can regulate input or output current by CTRL voltage. Figure 14 shows a solar panel charger with input current regulation. The input current of the converter, I_{PANEL}, is sensed and sent to the maximum power point tracking (MPPT) controller. With panel voltage and current, the MPPT controller calculates the maximum power point and sends the current command to CTRL for regulation. Figure 15 shows the transient waveform when panel current follows V_{CTRL} command.

CONCLUSION

The LT8390 4-switch buck-boost controller simplifies the design of demanding industrial and automotive power supply designs. Its application is hardly limited to these areas, as its myriad features—including high efficiency over a wide output load range, low EMI, compact solution size and very high output power capability—are ideal for emerging renewable energy and energy harvesting systems. ■

Figure 15. Panel current controlled by V_{CTRL}



Low I_Q Ideal Diode Controller with Reverse Input Protection for Automotive and Telecom Power Solutions

Meilissa Lum

Blocking diodes are widely used in power supplies to solve a variety of problems. In automotive systems, a series blocking diode protects against accidental reverse battery connections when the battery is replaced or the car is jump started. High availability systems and telecom power distributions employ blocking diodes to achieve redundancy by paralleling power supplies. Diodes are also used to prevent discharge of reservoir capacitors in situations where some temporary holdup of output voltage is necessary to ride through input dropouts or noise spikes, or to allow the load to gracefully power down when the input supply abruptly fails.

While blocking diodes are easy to understand and apply, their forward drop results in significant power dissipation, making them unsuitable in both low voltage and high current applications. In low voltage applications, the forward voltage drop becomes a limiting factor for a circuit's operating range, even when using a Schottky barrier diode. At least 500mV of supply headroom is lost across a series diode—a substantial degradation in 12V automotive systems where the supply can drop to as low as 4V during cold crank.

Since diodes operate at a fixed voltage drop of 400mV to 700mV minimum, regardless of current rating, power dissipation becomes an issue in the 1A–2A range, for surface mount applications. In applications greater than 5A, power dissipation becomes a major issue, requiring elaborate thermal layouts or costly heat sinks to keep the diode cool. Circuit designers need a better solution.

One solution is to replace diodes with MOSFET switches. The MOSFET is connected so that its body diode points in the same direction as the diode it replaces, but during forward conduction the MOSFET is turned on, shorting the body diode with a low loss path through the MOSFET channel. When the current reverses, the MOSFET is turned off, and the body diode blocks the flow of current, thus maintaining the diode behavior. The forward drop and power dissipation are reduced by as much as a factor of 10. This forms the basis of an "ideal" diode, when compared to conventional p-n or Schottky barrier diodes.

The LTC4357 and LTC4359 are ideal diode controllers, designed to drive N-channel MOSFETs in a wide variety of power supply reverse blocking, ORing and holdup applications. MOSFETs with $R_{DS(ON)}$ specifications as low as 1mΩ are readily available, so ideal diodes can be built to handle currents in excess of 50A using a single pass device while maintaining voltage and power loss levels 10 times better than any diode solution.

The LTC4357 and LTC4359 both replace a diode, but the latter has a wider operating range down to 4V and its quiescent current is a quarter of the former. The LTC4359's $\overline{\text{SHDN}}$ pin reduces the quiescent current and turns the LTC4359 solution into a load switch, a feature the LTC4357 and diode solutions do not have. Table 1 highlights the features of the LTC4357 and LTC4359.

The LTC4359 is a low quiescent current controller with a wide operating range of 4V–80V. The 4V end of the operating range is particularly important in low

Table 1. Ideal diode controllers

PART NUMBER	OPERATING VOLTAGE	SUPPLY CURRENT AT 12V	$I_{GATE(UP)}$	FEATURES
LTC4357	9V–80V	650µA	20µA	0.5µs turn-off time with 2A gate pull-down
LTC4359	4V–80V	155µA	10µA	Low I_Q shutdown mode, reverse input protection to −40V, controls single or back-to-back MOSFETs

The LTC4359 is a low quiescent current controller with a wide operating range of 4V–80V. The 4V end of the operating range is particularly important in low voltage applications, where the diode drop is not tolerable, while the 80V rating allows it to operate and survive transients in 48V telecom systems and automotive environments.

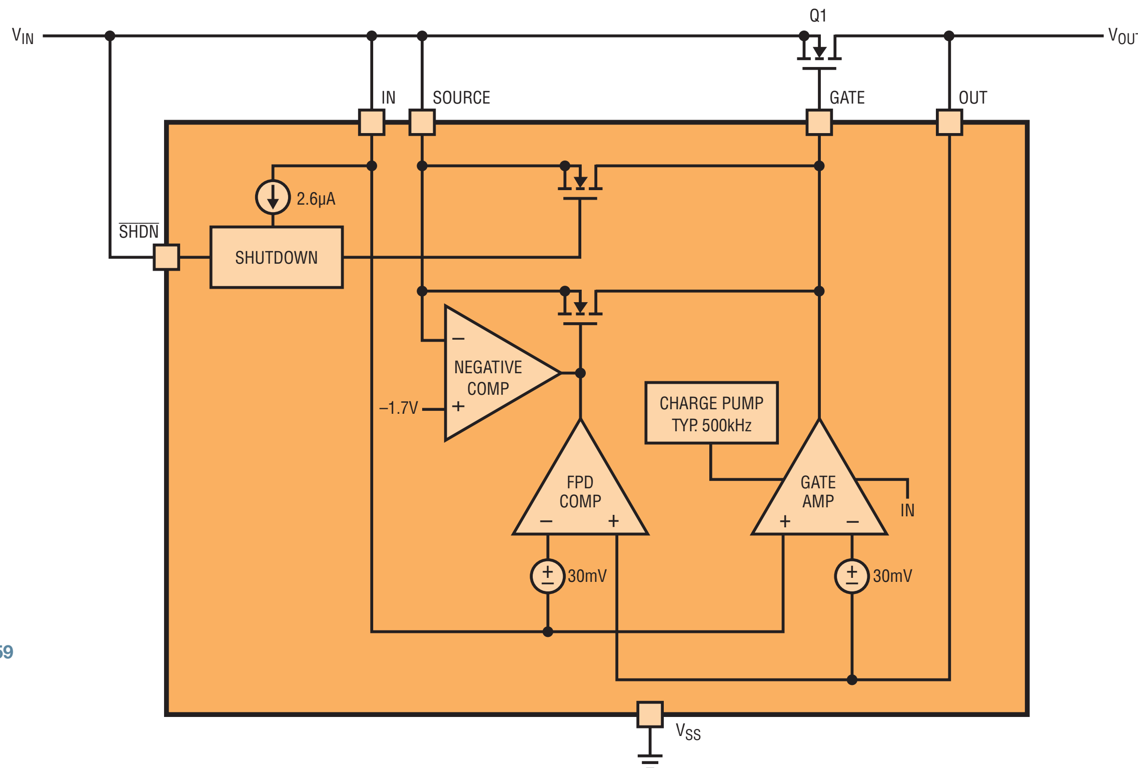


Figure 1. Block diagram of the LTC4359

voltage applications, where the diode drop is not tolerable, while the 80V rating allows it to operate and survive transients in 48V telecom systems and automotive environments. The LTC4359 protects downstream circuitry from reverse inputs down to –40V, seen when battery terminals are misconnected.

When operating from a battery, minimizing discharge current is important in normal operation, and becomes crucial when the load is off. The LTC4359 features a low quiescent current of 155µA typical, which can be further reduced to 14µA when placed in shutdown. Although the MOSFET is turned off in shutdown, its body diode can still conduct forward current. Some applications require the ability to turn on/off a load or to control the delivery of power independent of supply voltage. The LTC4359 accomplishes this by driving two N-channel MOSFETs as a load switch to block forward and reverse current.

HOW IT WORKS

The LTC4359 controls an N-channel MOSFET, shown as Q1 in the block diagram of Figure 1. The MOSFET source is connected to the input supply and acts like the anode of the diode, while the drain is the cathode. When power is first applied, the load current initially flows through the body diode of the MOSFET. The LTC4359 senses the voltage drop from IN-OUT and drives the MOSFET on. The internal amplifier (GATE AMP) and charge pump try to maintain 30mV drop across the MOSFET. If the load current causes more than 30mV of voltage drop, the MOSFET is driven fully on, and the forward drop increases according to $R_{DS(ON)} \bullet I_{LOAD}$.

If the load current is reduced, the GATE AMP drives the MOSFET gate lower to maintain a 30mV drop. If the forward current is reduced to a point where 30mV cannot be supported, the GATE AMP drives the MOSFET off. This prevents DC reverse current and allows smooth

A MOSFET based diode solution reduces the power dissipation and forward voltage drop over a Schottky diode, and is more versatile, with a vast selection of MOSFETs available for virtually any voltage and current combination.

switchover without oscillation in redundant power supply applications.

In the event of an input short, the current quickly reverses and is supplied by output capacitance or another supply. The fast pull-down comparator (FPD COMP) senses reverse current by measuring the drop across the MOSFET between IN and OUT. When there is more than –30mV across the MOSFET, the FPD COMP comparator responds by pulling the MOSFET gate low in less than 500ns.

The $\overline{\text{SHDN}}$ pin controls the IC and the external MOSFETs. Pulling $\overline{\text{SHDN}}$ pin low turns off the IC and external MOSFETs, while reducing the current to a mere 14μA. To turn the IC on, the $\overline{\text{SHDN}}$ pin can either be left floating or driven high. If left floating, an internal 2.6μA current source pulls up $\overline{\text{SHDN}}$.

BETTER THAN A SCHOTTKY DIODE

A MOSFET based diode solution reduces the power dissipation and forward voltage drop over a Schottky diode, and is more versatile, with a vast selection of MOSFETs available for virtually any voltage and current combination.

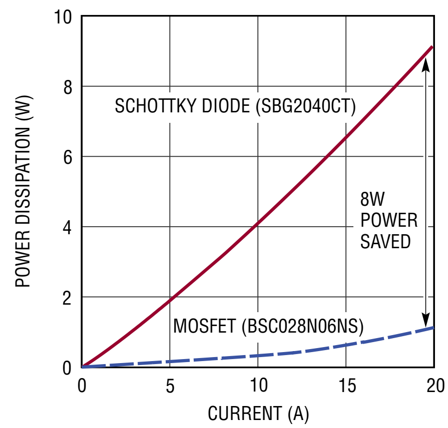


Figure 2. Power dissipation vs load current

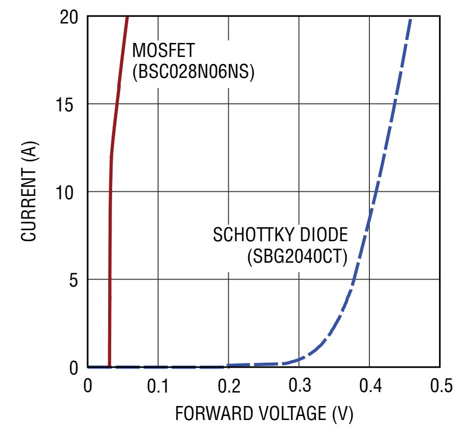


Figure 3. Load current vs forward voltage drop

Figures 2 and 3 compare the power dissipation and forward voltage drop of an SBG2040CT Schottky diode to a BSC028N06NS MOSFET. At 20A, the BSC028N06NS 2.8mΩ MOSFET dissipates only 1W, saving 8W of power dissipation over the SBG2040CT Schottky diode. The MOSFET's greatly reduced forward voltage drop of $R_{DS(ON)} \bullet I_{LOAD}$ = 56mV, compared to 450mV with the Schottky diode, enables circuits to operate at a lower voltage.

12V/20A AUTOMOTIVE DIODE WITH REVERSE INPUT PROTECTION

Figure 4 shows a typical 12V, 20A application that can handle reverse inputs to –40V. The forward drop is a mere 56mV at full load current, due to the MOSFET's low on-resistance of 2.8mΩ.

During input shorts, potentially destructive transients can appear at the IN, SOURCE and OUT pins. D1 and D2 protect IN and SOURCE by clamping the voltage transients to less than –40V. Q1, a 60V BVDSS MOSFET with avalanche rating of 50A, absorbs the inductive energy and prevents IN, SOURCE and OUT from exceeding their absolute maximum ratings.

Downstream circuitry, such as DC/DC converters and linear regulators require protection against voltages seen by reverse inputs and misconnected battery terminals. The LTC4359's input pins are rated to –40V. To keep the MOSFET off, an internal NEGATIVE COMP comparator senses when the SOURCE pin is negative with respect to

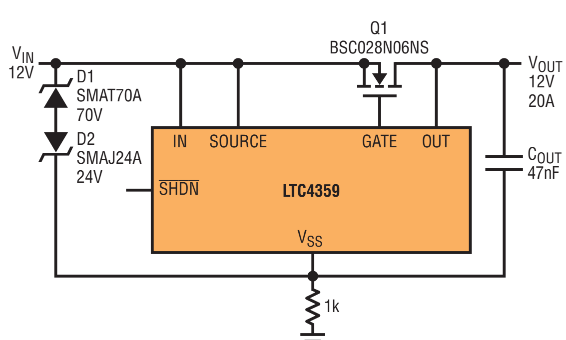


Figure 4. 12V/20A ideal diode with reverse input protection

Multiple LTC4359s can be used to combine the outputs of two or more supplies for redundancy or for droop sharing. For redundant supplies, the supply with the highest output voltage sources most or all of the load current.

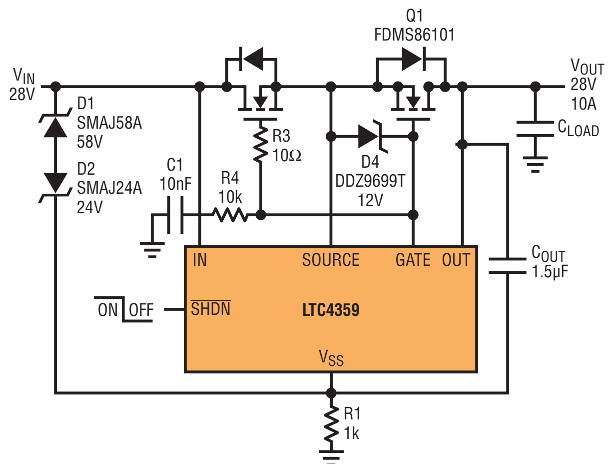


Figure 5. 28V load switch and ideal diode with reverse input protection

V_{SS} by at least 1.7V, and pulls down on the GATE pin. With the MOSFET off, the negative voltage is prevented from reaching the load. Reverse input protection is limited to about –40V by the dissipation in R1.

DIODE AS A LOAD SWITCH

The LTC4359 can be used as a switch to control delivery of power to the load. A diode, whether it's a Schottky diode or the circuit of Figure 4, always conducts forward current. In shutdown, the LTC4359 turns off the MOSFET, but its body diode still conducts forward current.

To block forward current, an additional MOSFET, Q2, is added as shown in Figure 5. The $\overline{\text{SHDN}}$ pin serves as the control signal to turn on/off the load switch. Pulling $\overline{\text{SHDN}}$ low turns off both MOSFETs: Q2 blocks forward current, while Q1 prevents reverse current. The MOSFET body diodes point in opposite directions, which blocks forward and reverse current flow. Floating or driving $\overline{\text{SHDN}}$ high turns on the IC and enables diode behavior in the MOSFETs. During turn-on, inrush current can be limited by controlling the slew rate at the GATE pin with the gate capacitor, C1, and the LTC4359's controlled gate current.

For multiple power supplies, duplicating Figure 5 enables active power source selection regardless of relative source voltage. This is in contrast to a passive selection scheme where strict diode behavior simply selects the input source with the highest voltage supply.

PARALLELING SUPPLIES

Multiple LTC4359s can be used to combine the outputs of two or more supplies for redundancy or for droop sharing, as shown in Figure 6. For redundant supplies, the supply with the highest output voltage sources most or all of the load current. If the supply's output is shorted to ground while delivering load current, the current temporarily reverses, flowing backward through the MOSFET. The LTC4359 senses this reverse current and activates the fast pull-down comparator (FPD COMP) and turns off the MOSFET in 500ns.

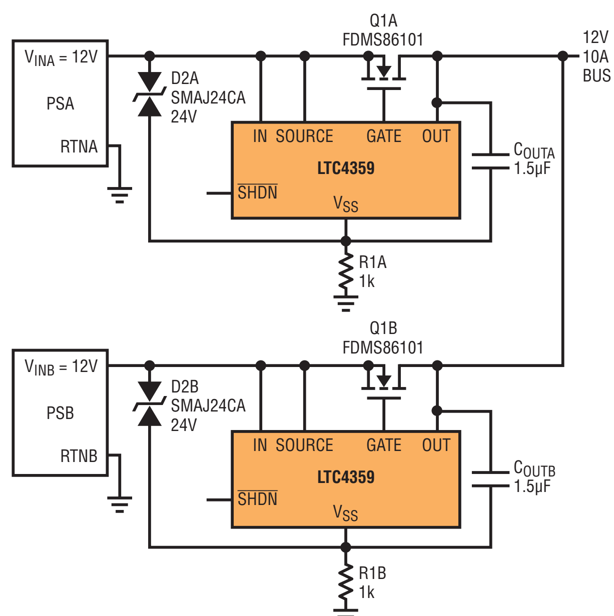


Figure 6. Redundant power supplies

The LTC4359 ideal diode controller replaces Schottky diodes, and also can drive a load switch. At currents of 1A–2A or more, the LTC4359 is superior to Schottky diode solutions. With its wide 4V–80V operating range and reverse input capability, the LTC4359 maintains low forward drop in low voltage applications through automotive cold crank, and protects the load from reverse battery connections.

If the other, initially lower, supply is not delivering any load current at the time of the fault, the output falls until the body diode of its OR-ing MOSFET conducts. Meanwhile, the LTC4359 charges the MOSFET gate with 10µA until the forward drop reduces to 30mV. If this supply is sharing load current at the time of the fault, its associated OR-ing MOSFET simply drives the MOSFET gate harder in an effort to maintain a drop of 30mV.

Droop sharing can be accomplished if both power supply output voltages and output impedances are nearly equal. The 30mV regulation technique ensures smooth load sharing between outputs without oscillation. The degree of sharing is a function of MOSFET $R_{DS(ON)}$, the output impedance of the supplies and their initial output voltages, as prescribed by Ohm's law.

EXTENDING REVERSE INPUT PROTECTION RANGE

Figure 7 shows the LTC4359 configured as a 48V ideal diode protected against reverse input voltage. R2 is added to extend the V_{IN}–V_{OUT} range to –100VDC with the effect of reducing the forward regulation by 10mV. In applications where the output is held up at +48V by a second supply or by charged capacitors, Q1 will block a reversed 48V input supply. In non-redundant applications where the output can be expected to fall to zero when the input supply is removed or accidently reversed, inputs of up to –100VDC are successfully blocked from reaching the output.

R2 is a pulse-rated component so that V_{IN}–V_{OUT} transients in excess of –100V are easily tolerated. Q1 was selected for its combination of 250V BV_{DSS} and exceptionally low $R_{DS(ON)}$ of 20mΩ, but its avalanche rating is a modest 320mJ with 47A maximum avalanche current. In the event the reverse current exceeds the MOSFET avalanche current rating, D6 can be added to protect Q1 by absorbing any avalanche energy, and this limits the peak V_{IN}–V_{OUT} voltage to –150V. Beyond this point D6 breaks down and passes transient current pulses through to the output.

CONCLUSION

The LTC4359 ideal diode controller replaces Schottky diodes, and also can drive a load switch. At currents of 1A–2A or more, the LTC4359 is superior to Schottky diode solutions. With its wide 4V–80V operating range and reverse input capability, the LTC4359 maintains low forward drop in low voltage applications through automotive cold crank, and protects the load from reverse battery connections. Shutdown mode further reduces the already low quiescent current of 155µA down to 14µA and can be used as an on/off control signal for a load switch. The LTC4359 is an excellent fit for automotive as well as telecom and redundant power supply applications. ■

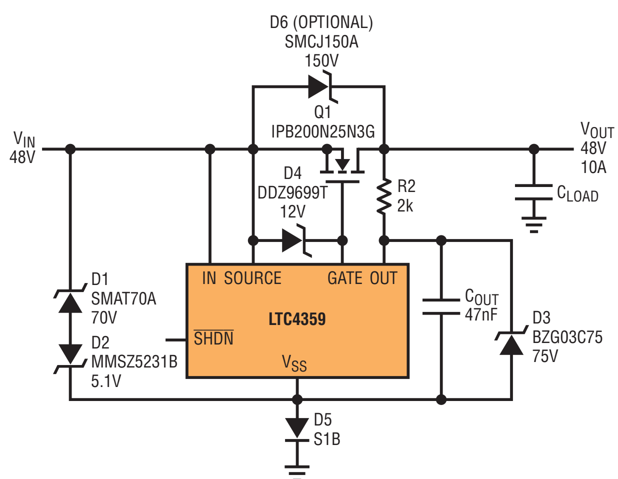


Figure 7. 48V ideal diode with reverse input protection

Low Quiescent Current Surge Stopper: Robust Automotive Supply Protection for ISO 7637-2 and ISO 16750-2 Compliance

Dan Eddleman

Automotive power supplies produce formidable transients that can readily destroy exposed onboard electronics. Over time, as electronics have proliferated in vehicles, automotive manufacturers have duly noted failures, compiling a rogues' gallery of the responsible power supply transients. Manufacturers have independently created standards and test procedures in an effort to prevent sensitive electronics from falling prey to these events. Recently, though, automotive manufacturers have combined efforts with the International Organization for Standardization (ISO) to develop the ISO 7637-2 and ISO 16750-2 standards, which describe the possible transients and specify test methods to simulate them.

ISO 7637-2 AND ISO 16750-2 STANDARDS

ISO 7637 is entitled "Road vehicles—Electrical disturbances from conduction and coupling" and is an electromagnetic compatibility (EMC) specification. This article addresses the second of the three parts of this document, ISO 7637-2 "Part 2: Electrical transient conduction along supply lines only."

Although ISO 7637 is primarily an EMC specification, prior to 2011 it also included transients related to power supply quality. In 2011, those portions related to power supply quality and not EMC were moved to ISO 16750, "Road vehicles — Environmental conditions and testing for electrical and electronic equipment" in the second of five parts, "Part 2: Electrical Loads."

Independent Test Report

The LTC4380 has been tested for ISO 7637-2 and ISO 16750-2 compliance by an independent test facility. The full test report is available at www.linear.com/docs/56650.

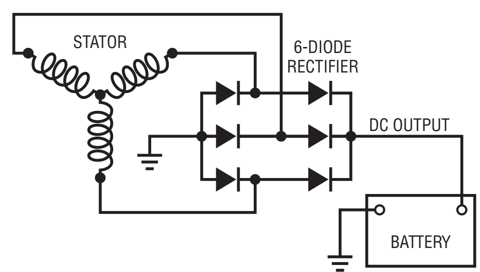


Figure 1. A standard alternator's 3-phase stator windings and 6-diode rectifier produce a DC output voltage.

While most manufacturers still maintain their own specifications and requirements rather than adopt ISO 7637-2 and ISO 16750-2 verbatim, there is a trend toward more closely conforming to the ISO standards, with manufacturer specifications following the international standards with minor variations.

ISO 7637-2 and ISO 16750-2 provide specifications for both 12V and 24V systems. For simplicity, this article only describes 12V specifications and presents a circuit for protecting electronics connected to an automotive 12V power supply.

LOAD DUMP

Load dump is the most challenging of the power supply transients because of the substantial energy in the event. It occurs when the alternator is charging a battery, and the battery connection is lost.

Alternators without Internal Voltage Clamps

Originally, alternators in cars were unclamped and could produce extraordinarily large voltages during load dump, about 100V for 12V systems. Newer alternators are clamped internally to limit the maximum voltage to a lower value during load dump. Because older alternators, and some modern alternators, do not include internal clamps, the load dump specification in ISO 16750-2 is split into "Test A—without centralized load dump suppression" and "Test B—with centralized load dump suppression."

Figure 1 shows a schematic of an alternator's 3-phase stator windings and the 6-diode rectifier that converts the stator's AC output to the DC that charges the battery. When the battery connection is lost, the resulting current flow is as shown in Figure 2. Without the battery to absorb

The LTC4380 surge stopper solution presented here provides uninterrupted operation when faced with load dump pulses from a modern, clamped alternator. When faced with more extreme unclamped load dump pulses, it shuts off to protect the downstream electronics. The result is a robust solution for ISO 16750-2 and ISO 7637-2 compliance for electronics that draw up to 4A of supply current.

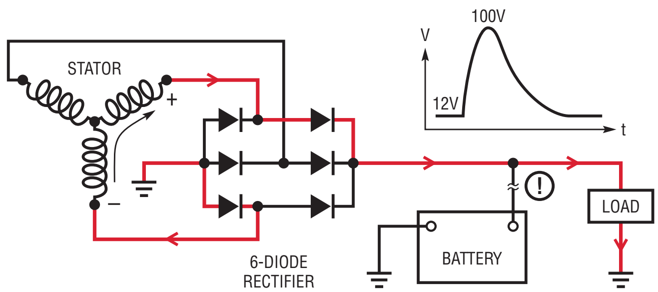


Figure 2. Unclamped load dump: If the battery connection is lost during charging, the alternator's output voltage can surge to 100V.

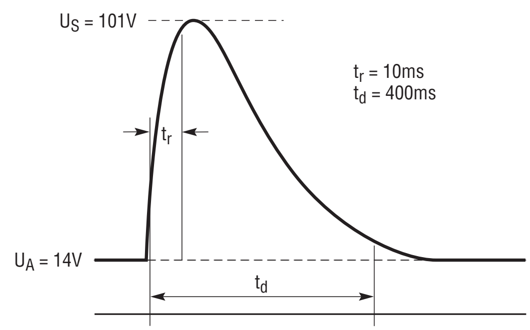


Figure 3. Unclamped load dump pulse shape as described in ISO 16750-2 specification ("Test A…")

the stator's current, the output voltage surges to the very high voltages seen during unclamped load dump, as shown in Figure 3 from the ISO 16750-2 specification. This corresponds to the unclamped alternator scenario in "Test A—without centralized load dump suppression."

Alternators with Internal Voltage Clamps

Newer alternators use avalanche diodes that have well specified reverse breakdown voltages which limit the maximum voltage during load dump. Figure 4 shows current flow during a load dump fault in a clamped alternator that uses avalanche rated diodes in the six diode rectifier. When a clamped alternator is mandated by the automotive manufacturer, "Test B—with centralized load dump suppression" applies. Figure 5 shows the clamped waveform from Test B in ISO 16750-2. Although ISO 16750-2 specifies a 35V maximum voltage for this clamped scenario, be aware that many manufacturers deviate from ISO 16750-2 by providing their own maximum voltage specification.

Also, be aware that when load dump was part of ISO 7637-2, only one pulse was specified, but when the load dump specification moved to ISO 16750-2 in 2011, the minimum test requirements increased to include multiple pulses with a one minute interval between pulses.

TVS Protection Problems

The internal resistance, R_i, of the alternator in both Test A and Test B is specified to be between 0.5Ω and 4Ω in ISO 16750-2. This limits the maximum energy that is delivered to protection circuits.

Nevertheless, one fact is frequently overlooked by those implementing protection from the ISO 16750-2 load dump transient: the internal resistance, R_i, does not appear in series with the 35V clamped voltage. R_i actually appears before the avalanche diode, as shown in Figure 6.

Figure 4. Clamped load dump: An internally clamped alternator has diodes with well specified reverse breakdown voltages that limit the output voltage to 35V during load dump.

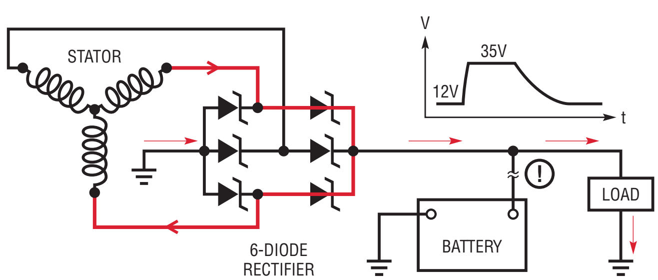
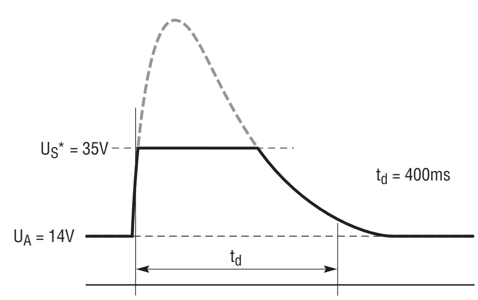


Figure 5. Clamped alternator load dump pulse shape



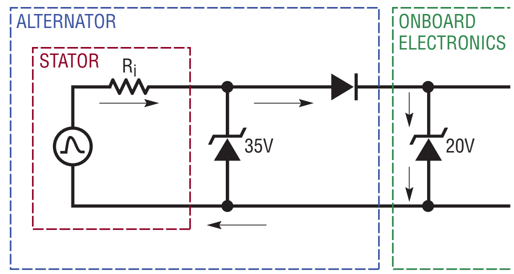


Figure 6. If the onboard electronics are protected by TVS diodes that break down at a lower voltage than the alternator's clamped voltage, the TVS diodes will be forced to absorb all of the alternator's energy.

If the onboard electronics are locally protected by a shunt device such as a TVS (transient voltage suppressor) diode with a breakdown voltage less than 35V, the TVS may be forced to absorb the alternator's energy. In this scenario, the internal clamps in the alternator are of little benefit. The entire load dump energy is delivered to the TVS in the onboard electronics.

Sometimes a series resistor is placed in front of the electronics and the TVS diode, but unfortunately this introduces a voltage drop and extra power dissipation in the resistor even during normal operation.

ISO 16750-2 Requirements

While load dump is typically the most demanding condition described in ISO 16750-2, there are many additional requirements.

REVERSE BATTERY

Section 4.7 of ISO 16750-2 describes "Reversed Voltage" or what most automotive engineers simply refer to as "Reverse Battery." As you would expect, this specification covers the human error scenario where someone connects a battery with the polarity reversed. Obviously, this can result in destruction unless adequate protection is provided.

ISO 16750-2 requires that a 14V reverse test voltage be applied at all inputs for 60 seconds to ensure that the system survives without any damage. An alternative test condition of 4V reverse voltage is also allowed by ISO 16750-2 if no fuse is present in series with the alternator and the alternator's rectifier diodes limit the voltage by conducting the substantial current delivered by the reverse connected battery.

MINIMUM AND MAXIMUM SUPPLY VOLTAGES

The minimum and maximum supply voltages are specified in section 4.2 "Direct current supply voltage." The maximum supply voltage for 12V systems is 16V, and the minimum is as low as 6V. For hardware that is not capable of operating as low as 6V, other "codes" are assigned in ISO 16750-2 to classify the minimum operating voltage of the device. For this requirement, the equipment is expected to operate continuously.

OVERVOLTAGE

Section 4.3 of ISO 16750-2 describes "Overvoltage" requirements. The first requirement simulates the condition where the voltage regulator has failed. In this test, 18V is applied for 60 minutes. Depending on the application, it might not be necessary for the equipment to operate normally while the test is performed, but it must return to normal operation after the test condition is removed.

The second test condition simulates a jump-start with 24V applied for 60 seconds. Once again, it may not be necessary for the equipment to operate normally during the test.

SUPERIMPOSED ALTERNATING VOLTAGE

Section 4.4.2 provides test conditions to "simulate a residual alternating current on the direct current supply." A peak to peak AC voltage of 1V, 2V, or 4V (specified as a "severity level") is swept from 50Hz to 25kHz multiple times. The upper peaks of the voltage are at 16V and the series impedance is between 50mΩ and 100mΩ.

SUPPLY DIPS

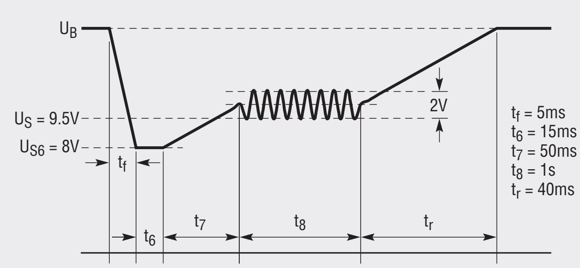
Sections 4.5 and 4.6 of ISO 16750-2 address conditions where the input supply dips, either due to the battery discharging, another device in the automobile failing and blowing a fuse, or when the starter causes the supply voltage to dip.

Section 4.5 "Slow decrease and increase of supply voltage" simulates a battery being slowly discharged and then recharged. The supply voltage is discharged to 0V over a matter of minutes, and is then slowly brought back up. Obviously, it is not necessary to operate continuously, but this test verifies that the hardware does not fail in a destructive manner, and that it operates normally when power is restored.

In contrast, Section 4.6 "Discontinuities in supply voltage" is a much faster condition that attempts to simulate a failure in another circuit that causes the supply to dip until the other circuit's fuse blows open. In this scenario, the supply dips to 4.5V for 100ms and then recovers with a rise time and fall time faster than 10ms.

The next part of Section 4.6 specifies a series of 5-second supply dips, with each pulse at a lower voltage than the previous one. The purpose is to verify that the device resets properly following a supply dip.

The third and last part of Section 4.6 specifies a waveform representative of a vehicle's starting profile. It is applied to the device being tested 10 times. The exact voltages and durations required depend on the desired Level I, II, III or IV, which is determined by the application. The limits of Level I are shown in the figure below.



OPEN CIRCUIT AND SHORT-CIRCUIT PROTECTION

Section 4.9 covers "line interruption" tests and describes procedures to ensure that a device resumes normal operation after connection is removed and then restored. Section 4.10 describes "short-circuit protection" tests and requires connecting each input and output to the maximum supply voltage and ground for 60 seconds.

A better solution is to use a series active protection device, such as the LTC4380 low quiescent current surge stopper. By its very nature, a surge stopper protects the downstream electronics from load dump as well as the other conditions in ISO 16750-2 and ISO 7637-2 without relying on the internal resistance of the alternator.

ADVANTAGES OF ACTIVE PROTECTION WITH A SURGE STOPPER

A better solution is to use a series active protection device, such as the LTC4380 low quiescent current surge stopper. The LTC4380 block diagram is shown in Figure 7. A complete automotive protection solution is shown in Figure 8.

By its very nature, a surge stopper protects the downstream electronics from load dump as well as the other conditions in ISO 16750-2 and ISO 7637-2 without relying on the internal resistance of the alternator. The surge stopper solution shown in Figure 8 provides uninterrupted power while operating from a clamped alternator. Furthermore, if it is subjected to load dump from an unclamped alternator, it will not be damaged. In the unclamped scenario, it may shut off to protect itself and then automatically reapply power to the load after a cool-down period. It is important to note that power is only shut off in the presence of multiple simultaneous faults: an improper unclamped alternator is installed and the battery connection is lost during charging.

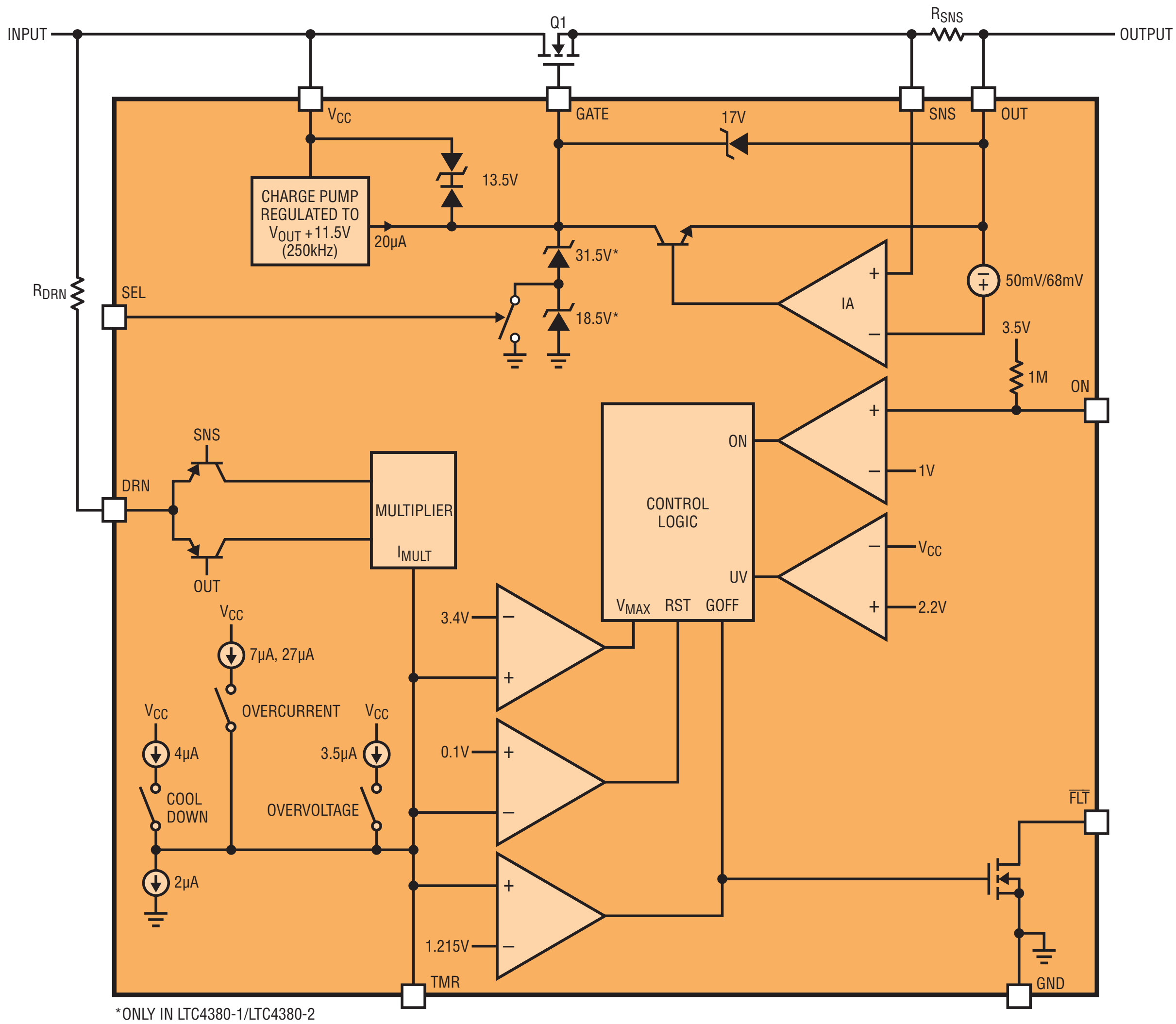


Figure 7. Block diagram of the LTC4380 surge stopper

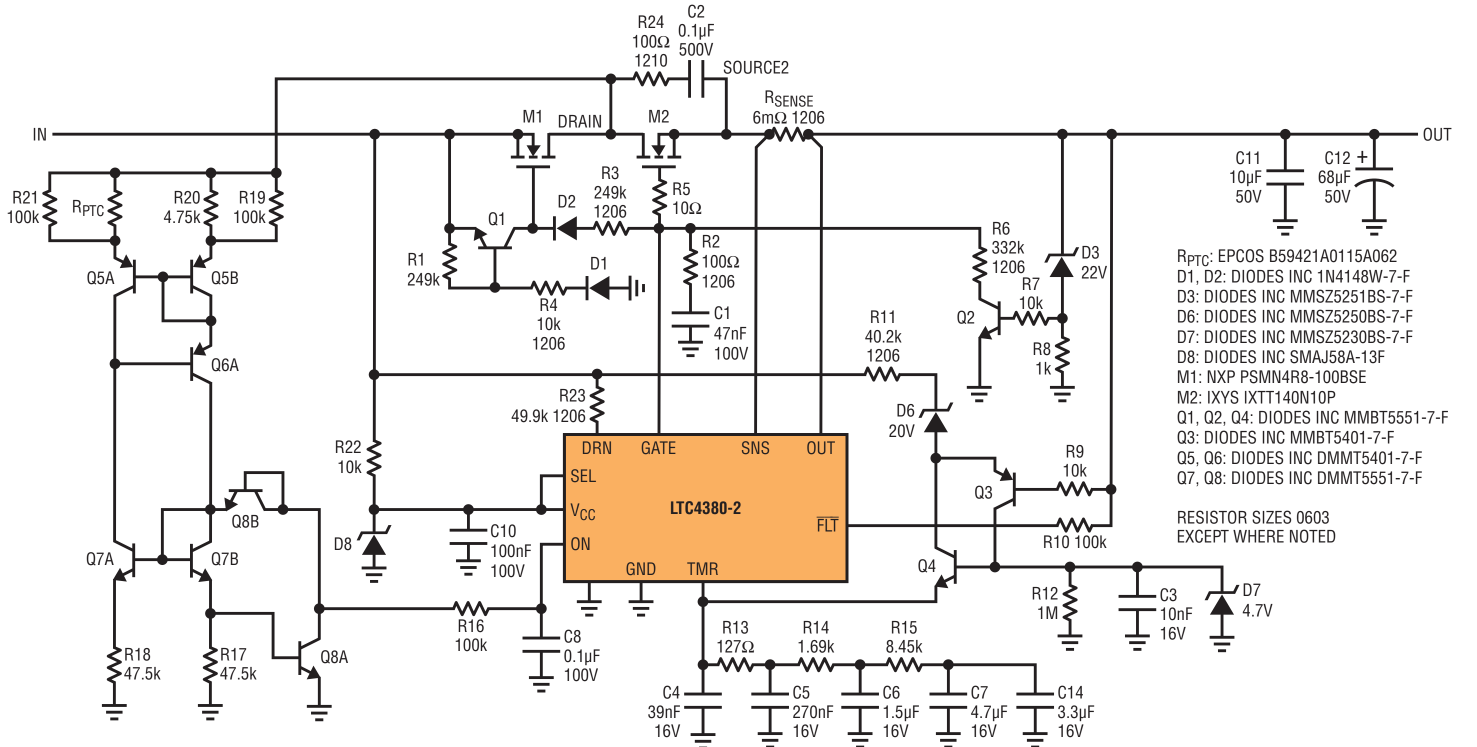


Figure 8. An LTC4380-based circuit protects downstream electronics from ISO 16750-2 and ISO 7637-2 transients while providing up to 4A of output current.

OPERATION OF THE SURGE STOPPER PROTECTION SOLUTION

The design in Figure 8 protects downstream electronics from ISO 16750-2 and ISO 7637-2 transients while providing up to 4A of output current. At the same time, it protects the upstream system from overcurrent events caused by conditions such as short-circuit faults in the downstream electronics. As it does this, it consumes a miserly 35µA of quiescent current, an important consideration in modern automobiles featuring countless battery-draining loads while the vehicle is not running.

This protection solution is based on the LTC4380 low supply current surge stopper, limiting the output voltage to 22.7V from input voltages as high as 100V at the input—sufficient protection against an ISO-16750-2 load dump as well as ISO 7637-2 pulses 1, 2a, 2b, 3a, and 3b. It also prevents current flow during reverse battery conditions, and provides continuous power during the ISO 16750-2 superimposed alternating voltage test at severity level 1 where the peak-to-peak AC voltage is 1V. (It may temporarily shut off power in the presence of larger AC voltages.) Continuous power is provided to the load when the input voltage drops as low as 4V to satisfy the minimum supply voltage requirements of ISO 16750-2.

The MOSFETs in this circuit are protected by limiting the time spent in high power dissipation conditions, such as when the input voltage surges high during load dump or when the output is shorted to ground. If a fault exceeds the conditions specified in ISO 16750-2 and ISO 7637-2, MOSFET M2 shuts off to protect the circuit, reapplying power after an appropriate delay.

For example, a sustained 100V input voltage, or a downstream short-circuit fault causes the surge stopper to self-protect by limiting the current in M2 and then completely shutting off if the fault persists. This method has a distinct advantage over shunt-type protection, which must dissipate continuous power—blowing fuses in the best case; lighting fires in the worst.

Load Dump and Overvoltage Protection

To understand the operation of the circuit in Figure 8, consider a simplified description of the LTC4380. During normal operation, the LTC4380's internal charge pump drives the GATE pin to enhance M2. The voltage at GATE is clamped to a maximum of 35V above ground (when the SEL = 0V), thereby limiting the output voltage at M2's source to less than 35V.

The circuit in Figure 8 further improves on that voltage limit by adding a 22V avalanche diode D3, in combination with R6, R7, R8, and Q2 to regulate the output voltage to a maximum of the avalanche diode voltage, 22V, plus the base-emitter voltage of Q2, roughly 0.7V. When the output voltage exceeds 22V + 0.7V = 22.7V, Q2 weakly pulls down on M2's GATE to regulate M2's source and the output voltage at 22.7V.

Reverse Protection

MOSFET M1, in conjunction with D1, D2, R1, R3, R4, and Q1, protects the circuit from reverse voltage conditions. When the input falls below ground, Q1 pulls M1's gate down to the negative input voltage, keeping the MOSFET off. This prevents reverse current flow when the battery is connected backward and protects the output from the negative input voltages.

D2 and R3 allow the LTC4380's internal charge pump to enhance M1 during normal operation when the input is positive so that M1 is effectively a simple pass-through device, dissipating less than $I^2R = (4A)^2 \bullet 4.1m\Omega = 66mW$ of power in the NXP PSMN4R8-100BSE.

SOA Limit

When the input voltage is high, the output voltage of this circuit is limited to a safe level by controlling MOSFET M2. This results in significant power dissipation as voltage is dropped across M2 while current is delivered to the load at the output.

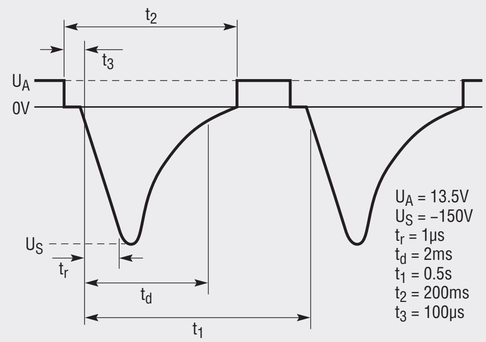
If the input is subjected to a sustained overvoltage condition, or an overcurrent fault condition occurs in the onboard electronics at the circuit's output, M2 is protected by shutting off after a duration configured by the timer network made up of R13, R14, R15, C4, C5, C6, and C14. The output current at the LTC4380's TMR pin is proportional to the voltage across MOSFET M2 while M2 is in current limit.

ISO 7637-2 Requirements

While the power quality portions of ISO 7637-2 moved to ISO 16750-2 in 2011, pulses 1, 2a, 2b, 3a, and 3b are still contained in ISO 7637-2.

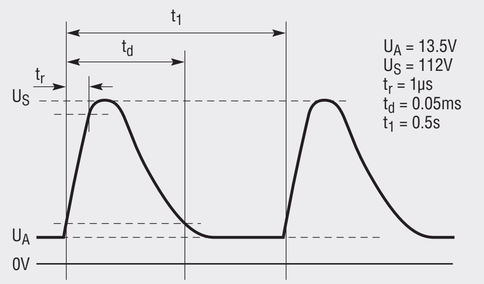
PULSE 1

Pulse 1 describes the negative transient observed by electronics connected in parallel with an inductive load when the connection to the power supply is interrupted. Pulse 1 begins with the supply voltage collapsing to 0V as the supply voltage is removed. Soon thereafter, a −150V pulse is applied with a 2ms decay time. The energy of the negative pulse is limited by the 10Ω series resistance.



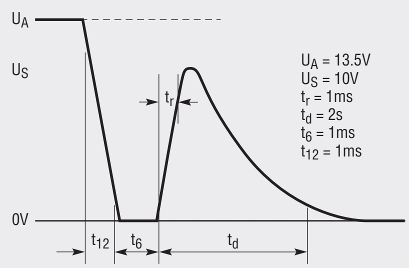
PULSE 2A

Pulse 2a describes the positive voltage spike that may occur when current is interrupted to a circuit in parallel with the electronics being tested. If current is built up in the wiring harness, when a device suddenly stops sinking current, the energy stored in the wiring harness inductance may cause a voltage spike. The energy of this positive spike is limited by a 2Ω series resistance.



PULSE 2B

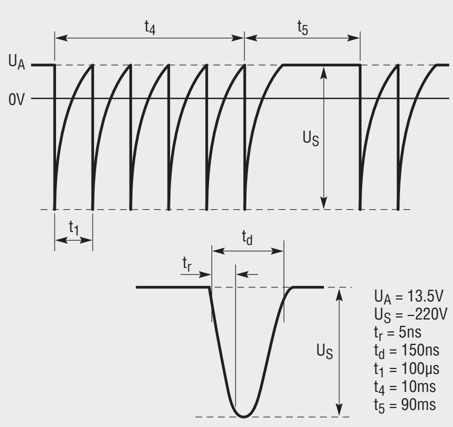
Pulse 2b defines a situation that occurs when the ignition is switched off and DC motors act as generators. For example, if the heater is running when the driver turns off the car, for a short time the blower motor can supply DC power to the system while it spins down.



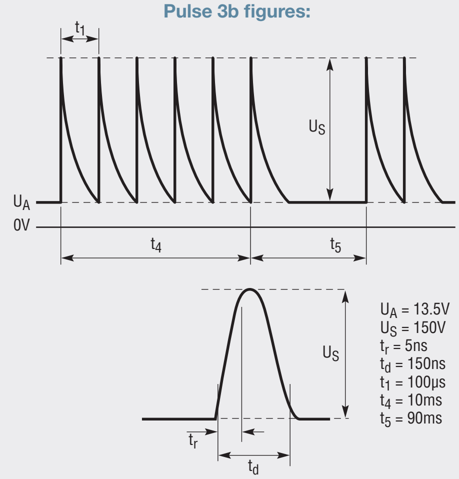
PULSES 3A AND 3B

Pulses 3a and 3b are the negative and positive spikes that may occur as a result of switching processes including arcing across switches and relays. For this specification, the energy is limited by a 50Ω series resistance.

Pulse 3a figures:



Pulse 3b figures:



In addition to protecting downstream electronics from ISO 16750-2 and ISO 7637-2 transients while providing up to 4A of output current, the surge stopper solution protects the upstream system from overcurrent events caused by conditions such as short-circuit faults in the downstream electronics. As it does this, it consumes a miserly 35µA of quiescent current, an important consideration in modern automobiles featuring countless battery-draining loads while the vehicle is not running.

Effectively, the TMR current is proportional to the power dissipated in MOSFET M2. The resistor/capacitor network at the TMR pin is similar to an electrical model of the MOSFET's transient thermal impedance. This serves to limit the maximum temperature rise of the MOSFET to keep it within its rated safe operating area.

Because allowable MOSFET SOA current falls off at high drain-to-source voltages, the 20V avalanche diode D6, in conjunction with R9, R11, and Q3 provides extra current into the timer network when the IN-to-OUT voltage exceeds 20V plus Q3's base-emitter voltage. The 4.7V avalanche diode D7 works with Q4, R12, and C3 to prevent this extra current from pulling the TMR pin above its maximum rated voltage of 5V.

This SOA tracking circuit allows the output to remain safely powered when the input rises to a high voltage. But, if a sustained high power fault condition lasts too long, the circuit self-protects by shutting off M2.

Thermal Protection

The resistor/capacitor network on the LTC4380's TMR pin protects against events that are faster than about one second. For slower events, the case temperature of M2 is limited by the circuit connected to the LTC4380's ON pin.

The thermistor, R_{PTC}, is a small surface mount 0402-size component with a resistance of 4.7k at 115°C. Above 115°C, its resistance rises exponentially with temperature. To prevent the timer network from falsely integrating offsets in the power multiplier, the LTC4380 does not generate timer current at the TMR pin until M2's drain-to-source voltage reaches 0.7V. With 4A and 0.7V, the MOSFET could dissipate 0.7V • 4A = 2.8W continuously without the TMR network detecting the MOSFET's temperature rise. The PTC resistor, R_{PTC}, in conjunction with resistors R17–R21 and transistors Q5A, Q5B, Q6A, Q7A, and Q7B shuts down the circuit if MOSFET M2's case temperature exceeds 115°C.

Do not be dismayed by the number of components in the thermal protection circuit. The overall solution is relatively easy to implement and consists of small components that consume little board area. It is a self-biased circuit that is balanced when R_{PTC} equals R20's 4.75kΩ value. When the temperature of R_{PTC}, which is placed in close proximity to M2, exceeds 115°C, its resistance grows and causes more current to flow through Q5B than Q5A. Because that results in more current through R17 than R18, Q8A's base voltage rises and Q8A's collector pulls the ON pin of the LTC4380 low, turning off M2. At lower temperatures, Q5A's current is greater than Q5B's, and Q8A remains off, allowing the ON pin's internal pull-up to keep the ON pin high. Note that the ON pin current is used as the start-up current of this self-biased circuit through the diode-connected device Q8B.

CONCLUSION

The ISO 16750-2 and ISO 7637-2 specifications describe the challenging electrical transients that can occur in automotive systems. The LTC4380 low quiescent current surge stopper can be used to protect the onboard electronics from these transients, including both the clamped and unclamped load dump pulses. The circuit presented in this article provides uninterrupted operation when faced with load dump pulses from a modern, clamped alternator. When faced with more extreme unclamped load dump pulses, it shuts off to protect the downstream electronics. The result is a robust solution for ISO 16750-2 and ISO 7637-2 compliance for electronics that draw up to 4 amps of supply current. ■

Dual Input, 42V, 2.5A Synchronous Buck Converter Features Seamless, Automatic Transition Between Two Input Power Sources and Meets Stringent CISPR 25 Class 5 EMI Limits

John Canfield

Many electronic devices must seamlessly transition between a wide variety of input power sources—such as batteries, automotive rails, wall adapters and USB ports. Traditionally, power supply designers rely on Schottky diodes or a prioritized PowerPath (IC controlled MOSFET switches) to combine input sources. Since both methods require additional components in front of the switching power supply, solution size and design complexity increase while overall supply efficiency is reduced. With its ability to operate directly from two different input power sources, the LTC3126 eliminates these disadvantages and enables smaller and higher efficiency multisource power supplies.

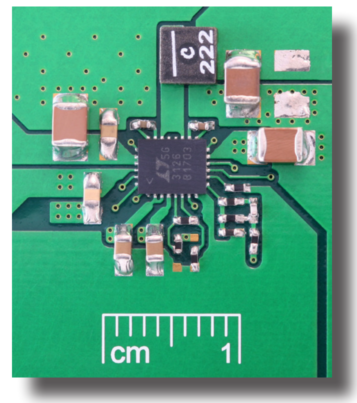


Figure 1. The LTC3126 provides a complete dual input power supply solution in 3.4cm².

The LTC3126 operates directly from two independent power sources, drastically simplifying the design of such systems by minimizing component count and solution size, as shown in Figure 1, while maintaining high overall system efficiency. Ease of use is enhanced by its expansive input voltage range, low total power supply quiescent current of just 2µA, and radiated emissions below the stringent CISPR 25 Class 5 automotive limits, as shown in Figure 2.

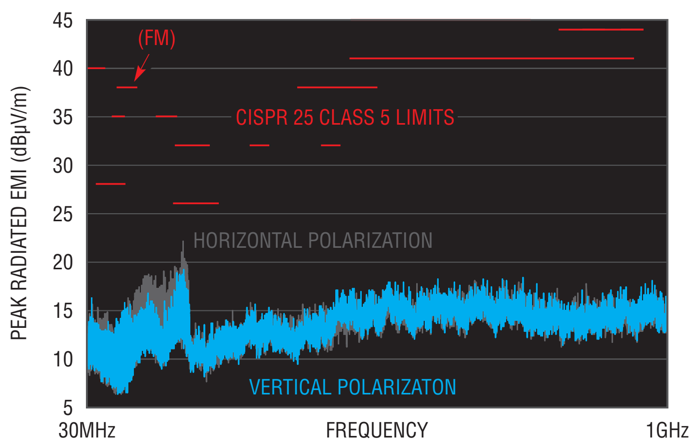


Figure 2. Operating on the standard demo PCB, the LTC3126 passes the CISPR 25 Class 5 radiated emission limits shown in red.

IDEAL DIODE-OR MODE

The LTC3126 supports two pin selectable PowerPath™ control modes: ideal diode-OR mode (described here) and priority channel mode (described below). In ideal diode-OR mode, as shown in Figure 3, the LTC3126 emulates an ideal diode-OR circuit, where the buck converter automatically operates from the higher voltage of two input power sources. This mode of operation is useful in applications where the two power sources have non-overlapping voltage ranges, for example, a rechargeable lithium battery with a voltage range of 3V to 4.2V and a wall adapter with a nominal 12V output.

The LTC3126 contains two internal low resistance, high side switches arranged in the topology shown in Figure 4, allowing the buck converter to operate directly from either input power source with no additional power path components. This has several advantages over the traditional Schottky-diode approach, where discrete devices are used to accomplish this task:

- A typical 40V, 2A Schottky diode has a forward voltage drop of at least 500mV at full current. This voltage drop increases the required operating headroom, making it impossible to run from input voltage sources that are close to the voltage of the regulated rail, thereby reducing the usable portion of the battery discharge curve. For a 3.3V

The LTC3126's two internal low resistance, high side switches allow it to operate directly from two independent power sources, simplifying the design of such systems by minimizing component count and solution size while maintaining high overall system efficiency. Ease of use is further enhanced by its expansive input voltage range and low total power supply quiescent current of just 2µA.

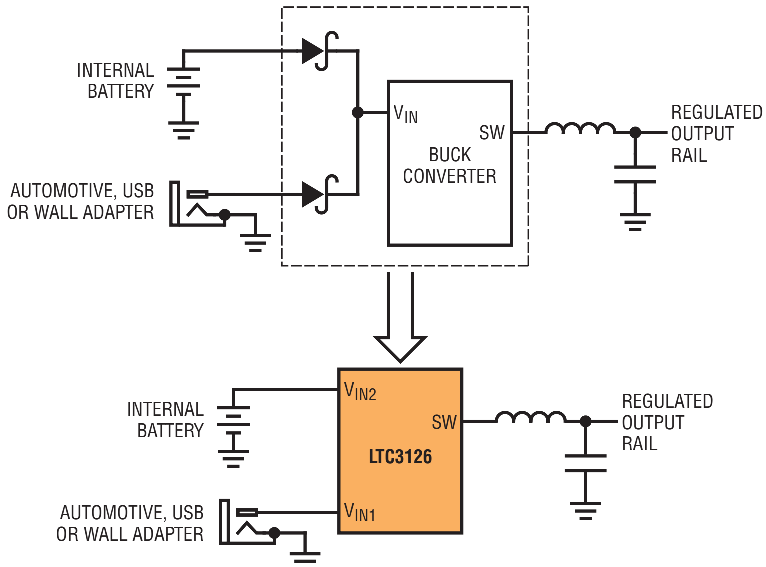


Figure 3. In ideal diode mode, the LTC3126 emulates a discrete diode-OR circuit while eliminating the Schottky's power loss, voltage drop and reverse leakage current.

output, Figure 5 shows the typical extra headroom voltage eliminated by using the LTC3126 rather than a Schottky-OR followed by a buck converter.

- The Schottky forward voltage drop also results in significant efficiency loss. At full load this can account for 1 watt of additional power loss, representing a 4% to 5% reduction in overall power conversion efficiency, as shown in Figure 6. The LTC3126 eliminates this power loss.
- The discrete Schottky approach suffers from high leakage current into the unused input. A typical 40V, 2.5A Schottky may have 500µA of leakage current at 25°C, increasing to tens of milliamps at 100°C—significant current into the unused input—which is virtually eliminated by using the LTC3126.

PRIORITY CHANNEL MODE

In many dual power source applications, the two inputs may overlap in functional voltage ranges, with one input required to be preferentially utilized whenever possible, making a diode-OR solution (higher voltage wins) undesirable. For example, a device that operates from both a 12V sealed lead-acid battery and an automotive power rail is usually designed to operate from the automotive input whenever it is present in order to preserve battery life.

This requires a more involved power path solution than can be provided via Schottky diodes, requiring the use of a dedicated PowerPath controller IC and MOSFET switches. Figure 7 shows

Figure 4. The power switch topology of the LTC3126 provides optimal efficiency and minimum solution size, given the buck converter's ability to operate directly from either input, V_{IN1} or V_{IN2}, with no additional power path components.

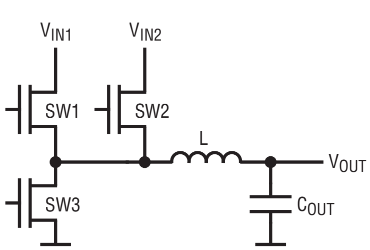


Figure 5. The lossless PowerPath design of the LTC3126 allows operation to lower input voltages while maintaining regulation of a 3.3V output.

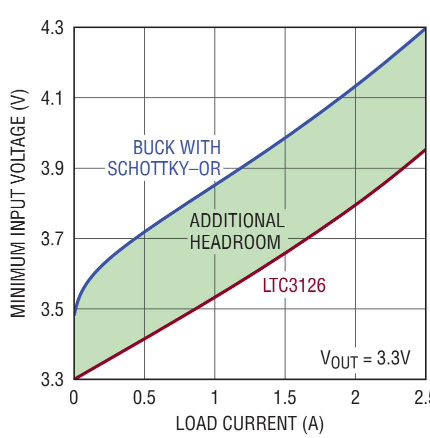
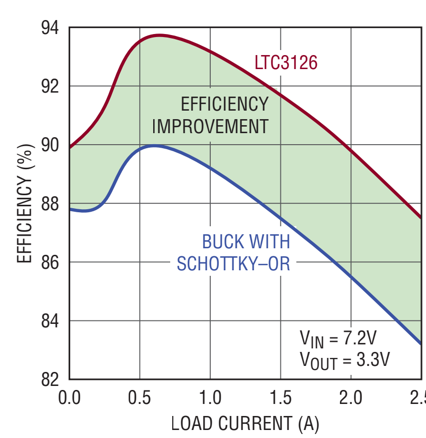


Figure 6. The LTC3126's lossless PowerPath design generates a significant improvement in efficiency.



In priority channel mode, each input to the LTC3126 features a user-configurable minimum voltage threshold, above which the channel is considered valid. The internal buck converter operates directly from the priority channel, V_{IN1}, whenever it is valid, regardless of the voltage present at the secondary input. The buck converter only reverts to operation from the secondary channel, V_{IN2}, when the priority channel is invalid.

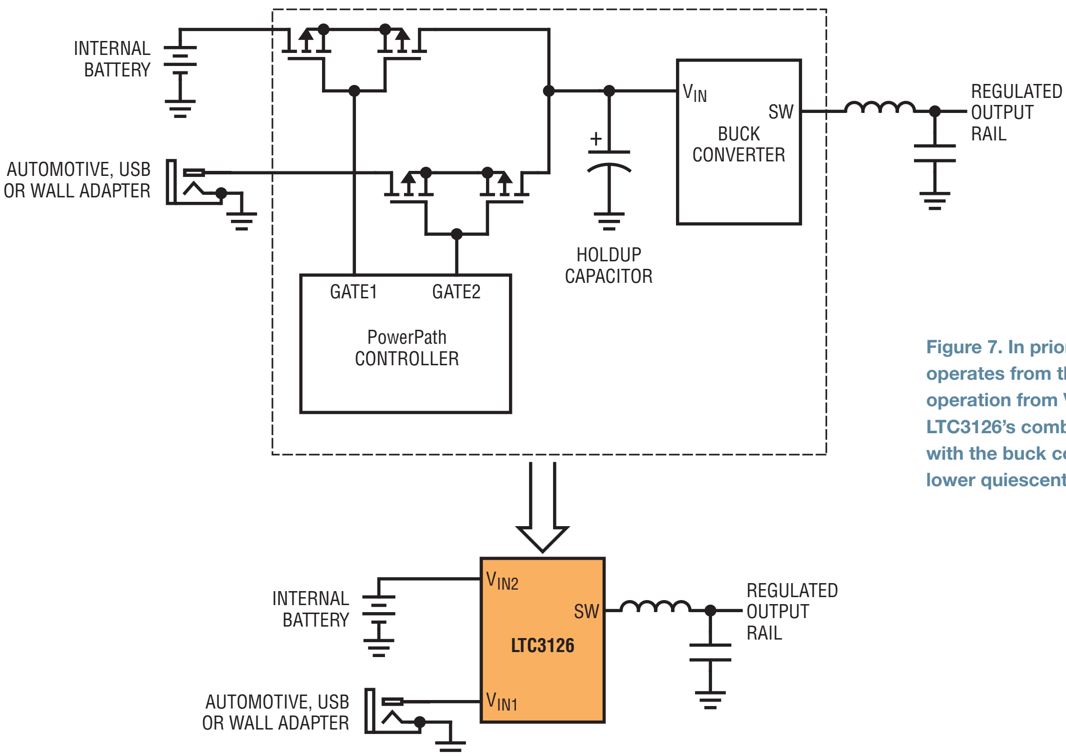


Figure 7. In priority channel mode, the LTC3126 preferentially operates from the V_{IN1} input whenever it is valid and reverts to operation from V_{IN2} only if the voltage on V_{IN1} is invalid. The LTC3126's combination of the PowerPath selection circuitry with the buck converter IC results in higher efficiency and lower quiescent current, as well as a smaller, simpler design.

that the LTC3126 and its pin-selectable priority channel mode integrate this capability with the switching converter, eliminating the need for series MOSFET switches (and a controller) in the power path. This innovation simplifies design, reduces board area requirements, improves efficiency and minimizes the total quiescent current of the power stage.

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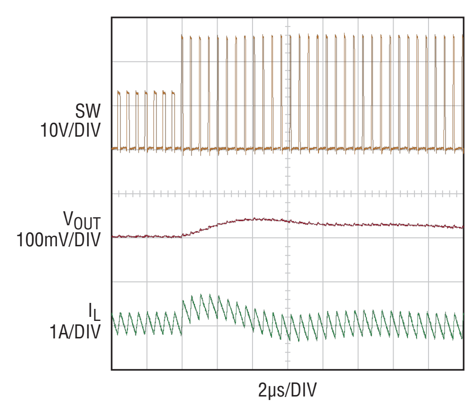
SINGLE SWITCHING CYCLE TRANSITION BETWEEN INPUTS

PowerPath controllers that use external MOSFETs typically require substantial time to switch between channels to avoid transients caused by fast switching events. When a channel is switched off, the controller must do so slowly enough to avoid rapidly interrupting the input current flow. Likewise, when a channel is activated, the PowerPath controller must soft-start the external MOSFETs for that channel.

Figure 8. The LTC3126's single cycle transition between input channels reduces holdup capacitance requirements and minimizes output voltage perturbations.



PowerPath controllers that use external MOSFETs typically require substantial time to switch between channels to avoid transients caused by fast switching events. In contrast, the proprietary configuration of switches in the LTC3126 allows it to transition from one input to another in a single switching cycle. This nearly instantaneous switchover minimizes the amount of holdup capacitance required on the channel that is being unplugged and reduces any disturbance in the output voltage.

Figure 9. The LTC3126 utilizes a novel approach for establishing the UVLO thresholds, which minimizes quiescent current by eliminating the need for resistor dividers connected to the input voltage sources.

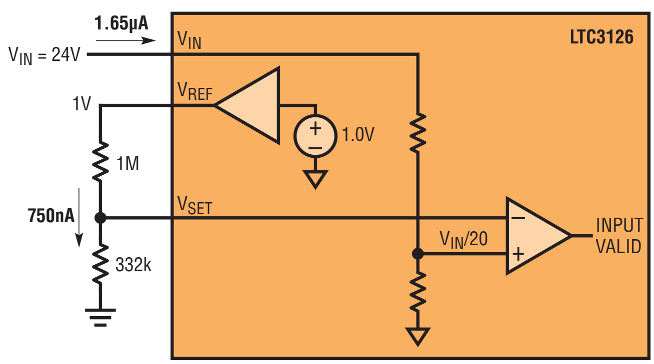
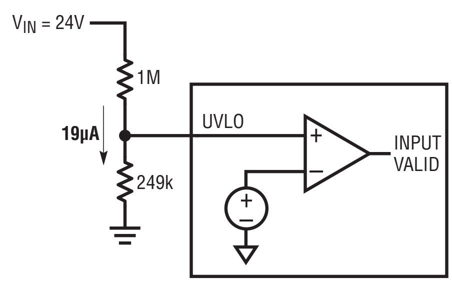


Figure 10. The traditional method used to define UVLO thresholds for a PowerPath device utilizes a significant amount of quiescent current in the V_{IN}-connected resistor dividers.



To avoid power interruption to the load when an input is unplugged, a large holdup or reservoir capacitor must be present to provide enough charge to support the load until the power path has fully transitioned to the alternate input. The large value capacitor required and the fact that it must be rated at the maximum voltage of either input often results in it being the largest component in the system.

In contrast, the proprietary configuration of switches in the LTC3126 allows it to transition from one input to another in a single switching cycle. Figure 8 shows the switch pin, output voltage and inductor current waveforms during the single cycle switchover produced by the LTC3126 when transitioning from a 13.8V input on V_{IN1} to a 24V input on V_{IN2}. This nearly instantaneous switchover minimizes the amount of holdup capacitance required on the channel that is being unplugged and reduces any disturbance in the output voltage. In this case, the output voltage perturbation during the channel transition is under 40mV, approximately 1% of the 3.3V output.

2µA TOTAL QUIESCENT CURRENT

Programmable PowerPath controllers use resistor dividers to set the valid threshold voltages for each input channel, as illustrated in Figure 10. The divider outputs are compared to an internal reference voltage via comparators.

Due to concerns of PCB leakage, the highest usable resistor value in most applications is approximately 1M, resulting in an appreciable current draw from the input rail through the resistor divider, even when the part is in shutdown. For a 24V input, the current could easily be 19µA per input channel.

Furthermore, in many high reliability applications, such as automotive environments, the maximum allowable resistor value is limited to 100k. This can result in over 100µA consumed per input channel by the resistor dividers alone.

To minimize input current losses in threshold-setting resistor dividers, the LTC3126 uses the novel architecture shown in Figure 9 to establish the minimum input voltage threshold for each channel. The V_{REF} output is internally regulated to a precise, temperature stable 1.00V and is used as a reference for the external resistor dividers used to set the undervoltage lockout threshold for each input channel.

Each UVLO threshold is equal to 20 times the voltage at the respective V_{SET} pin. For example, programming the V_{SET1} pin to 0.5V results in a UVLO threshold of 10V for the V_{IN1} channel. Because the voltage across each divider is only 1V, rather than the full input voltages, quiescent current is reduced by more than an order of magnitude. This feature, in conjunction with low quiescent current Burst Mode® operation, reduces the LTC3126's total quiescent current to ~2µA when operating from a 24V input, while maintaining regulation on the output rail. Even when using sub-100k resistor values, the typical quiescent current remains under 10µA.

To minimize input current losses in threshold-setting resistor dividers, the LTC3126 uses a novel architecture to establish the minimum input voltage threshold for each channel. The V_{REF} output is internally regulated to a precise, temperature stable 1.00V, and is used as a reference for the external resistor dividers, which establish the undervoltage lockout threshold for each input channel.

The V_{REF} output can also be used as a temperature stable reference for other comparators or data converters in the system, further reducing IC requirements.

RADIATED EMISSIONS BELOW CISPR 25 CLASS 5 LIMITS

CISPR 25 provides a standardized means of testing electronic devices intended for automotive use to ensure that electrical subsystems don't interfere with common RF receivers including satellite navigation, Bluetooth, cellular telephone and broadcast receivers. Interference in vehicles due to unintentional emissions is an increasing concern for the manufacturers of such systems, given the expanding number of electrical subsystems in vehicles in conjunction with the rising quantity of RF receivers.

Switching power converters can be a particular concern for radiated emissions, given their high power, fast switching edges and the presence of numerous components carrying switched large amplitude currents, which can all become sources of troublesome emissions. The LTC3126 uses proprietary techniques to minimize radiated emissions without degrading efficiency or reducing operating frequency.

With its low noise fixed frequency operation, the LTC3126's radiated emissions fall well below the CISPR 25 Class 5 limits as shown in Figure 2. The CISPR 25 Class 5 compliance testing shown here was performed at a nationally recognized independent EMI testing laboratory where measurements were taken using the standard LTC3126 demo printed circuit board operating at both 0.5A and 1A loads from a 12V input. The two radiated emission curves shown in Figure 2 are for horizontal and vertical polarization of the receiver antenna as required by the CISPR 25 specification. Although the CISPR 25 specification governs radiated emissions over the frequency range of 150kHz to 1Ghz, the data in Figure 2 is plotted on a linear axis over the range of 30MHz to 1GHz. This is generally the range of most interest, given that the lower frequency emissions below 30MHz lie over 30dBμV/m below the CISPR limits for that band.

"LAST-GASP" BACKUP POWER SUPPLY

A "last-gasp" backup power capability is becoming a requirement in many systems where functionality must be maintained for a brief duration after power loss in order to perform a controlled shutdown, store vital information to nonvolatile memory or alert other systems of an imminent shutdown. The solid state disk drive, perhaps the highest profile example of this, utilizes a backup power

Table 1. Feature summary of multi-input monolithic converters

	LTC3126	LTC3118
Mode	Buck	Buck-boost
Programmable input UVLO thresholds		
Ideal diode or priority V_{IN} select modes		
Input range	2.4V to 42V	2.2V to 18V
Output range	0.818V to V_{IN}	2V to 18V
Output current capability	2.5A	5V at 2A for V_{IN} > 6V
Operating frequency	200kHz to 2.2MHz	1.2MHz
Quiescent current	2μA in Burst Mode operation, 1μA in shutdown	50μA in Burst Mode operation, 2μA in shutdown
Packages	28-lead 4mm × 5mm QFN and 28-lead TSSOP	4mm × 5mm 24-lead QFN or 28-lead TSSOP

With its low noise fixed frequency operation, the LTC3126's radiated emissions fall well below the CISPR 25 Class 5 limits. The CISPR 25 Class 5 compliance testing shown here was performed at a nationally recognized independent EMI testing laboratory where measurements were taken using the standard LTC3126 demo printed circuit board operating at both 0.5A and 1A loads from a 12V input.

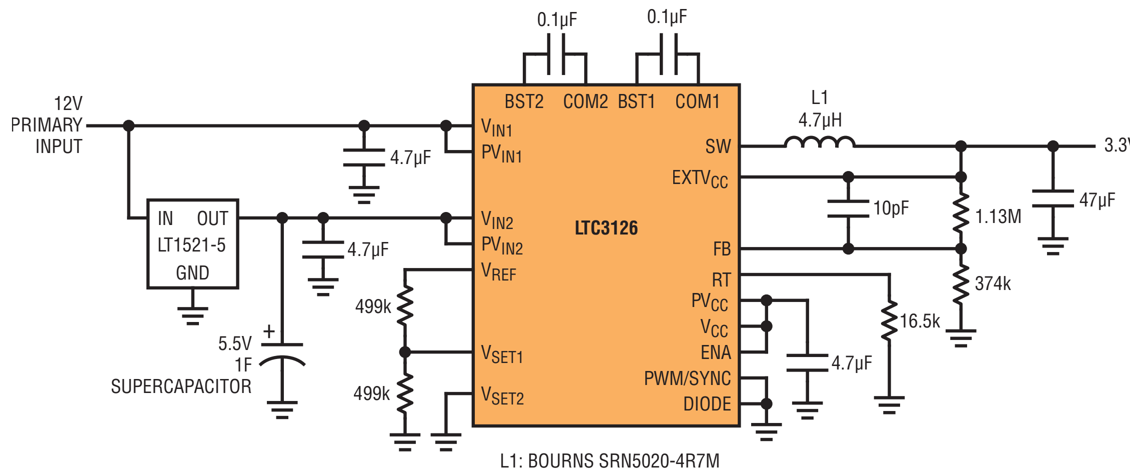


Figure 11. The LTC3126 is used in conjunction with a reverse blocking LDO to provide a complete last-gasp supercapacitor backup supply.

supply to store cached data in SDRAM into nonvolatile flash memory on power failure to prevent data loss. However, this last-gasp capability is now being extended to a wide variety of systems, from industrial controllers to medical devices.

An increasing number of these last-gasp power supplies rely on supercapacitors as the backup power source, given their virtually unlimited cycle life and maintenance-free operation. Figure 11 shows a last-gasp power supply circuit using the LTC3126 to transition glitch-free to backup power when the primary power source is removed. A PNP-based LDO is used to charge the supercapacitor to 5V and provides reverse blocking to ensure there is no discharge path from the supercapacitor when the primary power source collapses. In this example, the LTC3126 is configured to utilize the primary 12V input down to a UVLO threshold of 10V, at which point the part automatically transitions to the supercapacitor source on the secondary input.

The holdup time of the output rail depends on the charging voltage of the supercapacitor, V_{CAP}, the voltage of the output rail, V_{OUT}, the load current, I_{LOAD}, the size of the supercapacitor, C, and the average efficiency of the converter, η. The variable V_{MIN} is the minimum input voltage required to maintain the required output rail voltage. If the output must remain in regulation, then V_{MIN} is equal to the output rail voltage plus the dropout voltage of the buck converter at the required load current.

$$T_{HOLDUP} = \frac{\eta\left(V_{CAP}^2 - V_{MIN}^2\right)C}{2V_{OUT} \bullet I_{LOAD}}$$

For a 1A output load on the 3.3V rail, the dropout voltage is approximately 300mV. Therefore, a minimum input voltage of 3.6V is required to maintain regulation of the output rail. Assuming an average efficiency of 90%, the estimated holdup time is 1.6s, which is in close agreement with the measured holdup time of 1.5s shown in Figure 12.

$$T_{HOLDUP} = \frac{0.9\left((5V)^2 - (3.6V)^2\right)1F}{2(3.3V)(1A)} = 1.6s$$

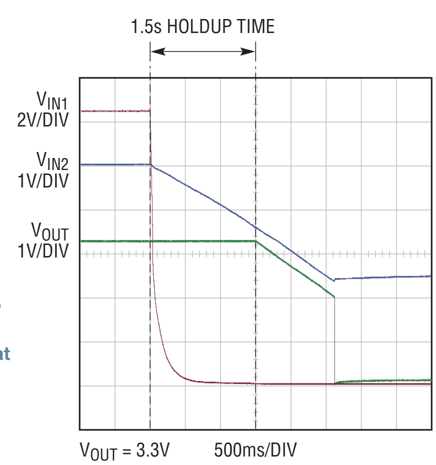


Figure 12. In conjunction with a 1F, 5.5V supercapacitor, the LTC3126 can provide 1.5 seconds of holdup time on power failure for a 3.3V output rail with a 1A load. At that point, the output degrades gracefully as the part enters dropout operation.

Its low 1µA current in shutdown and 2µA current in Burst Mode operation make the LTC3126 ideal for battery powered applications where low current consumption allow it to remain enabled continuously, avoiding the overhead of a supervisory circuit to power up/down the supply.

HIGH EFFICIENCY SYNCHRONOUS OPERATION

The LTC3126 incorporates an internal synchronous rectifier, which reduces power dissipation, improves efficiency and minimizes solution size. Synchronous rectification is particularly beneficial when operating at lower output voltages, where the voltage drop of an external Schottky diode represents a large relative portion of the output voltage. Pin-selectable Burst Mode operation optimizes efficiency at light loads, as shown in Figure 13. The converter maintains over 87% efficiency across the entire range of load currents from 1mA to 2.5A.

High efficiency simplifies thermal management, minimizing component count and easing design concerns. Figure 14 shows that even at a relatively high step-down ratio at full load, the LTC3126 die temperature rises only 36°C.

The switching frequency can be programmed as high as 2.2MHz to eliminate interference within the AM band for noise-sensitive automotive applications, and switching can be synchronized to an externally supplied clock for further noise reduction. As the input voltage decreases to the programmed output voltage, the LTC3126 maintains regulation by keeping the high side switch on for multiple cycles. This produces an effective high side switch duty cycle of over 99%, minimizing dropout voltage to 280mV for a 1A load, thus extending the usable input voltage range to maximize utilization of the battery discharge range.

SUMMARY

The LTC3126 is a dual input, single-IC solution for high efficiency, compact power supplies. Because the lossless PowerPath functionality is integrated into the buck converter, the LTC3126 achieves unrivaled efficiency, application size and low quiescent current. Its wide 2.4V to 42V input voltage range supports a wide variety of power sources, including automotive, most battery chemistries, multicell battery stacks, USB and poorly regulated wall adapters.

Its low 1µA current in shutdown and 2µA current in Burst Mode operation make the LTC3126 ideal for battery powered applications where low current consumption allow it to remain enabled continuously, avoiding the overhead of a supervisory circuit to power up/down the supply. The LTC3126 is the perfect match for high performance mobile devices, uninterruptible supplies and industrial test equipment powered from dual input power sources. ■

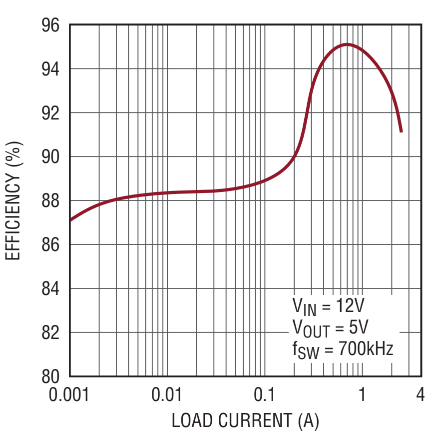


Figure 13. In Burst Mode operation the efficiency exceeds 87% over a wide range of load currents from 1mA to 2.5A.

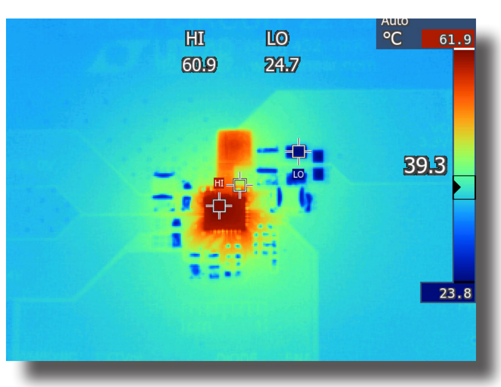


Figure 14. Operating with V_{IN} = 12V, V_{OUT} = 3.3V at a switching frequency of 2MHz, the die temperature rise is only 36°C above ambient at the full rated load current of 2.5A.

What's New with LTspice?

Gabino Alonso

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SOATHERM SUPPORT FOR PCB AND HEAT SINK THERMAL MODELS by Dan Eddleman

Typically, a circuit designer uses the LTspice® SOAtherm-NMOS symbol standalone to verify that a particular MOSFET's SOA (Safe Operating Area) is suitable for a given application; no additional heat sink or PCB thermal model is necessary. However, in some particularly demanding applications, especially those where high power transients last longer than 10 milliseconds, it may be desirable to take advantage of the extra thermal capacity and dissipation provided by a heat sink or the PCB. Previously, this was implemented by connecting a resistor-capacitor network to the SOAtherm-NMOS model's Tc pin. Now, with the SOAtherm-PCB and SOA-HeatSink symbols, it is possible to model heat sink and PCB thermal behavior by specifying a few physical parameters rather than calculating an array of component values from formulas. www.linear.com/solutions/7415

SELECTED DEMO CIRCUITS

For a complete list of examples, please visit www.linear.com/democircuits.

Linear Regulators

- **LT3066:** 3.3V supply with 497mA precision current limit (3.6V–45V to 3.3V at 450mA) www.linear.com/solutions/7178
- **LT3091:** Negative LDO with 1.6A current limit (−1.5V to −36V input, −2.5V output at 1.5A) www.linear.com/solutions/5977

Buck Regulators

- **LT8601:** Triple automotive buck regulator (5.5V–42V to 5V at 1.0A, 3.3V at 2.0A, 1.8V at 1A) www.linear.com/solutions/7157
- **LT8641:** 2MHz µPower ultralow EMI buck converter (5.5V–65V to 5V at 3.5A) www.linear.com/solutions/7183
- **LTC3649:** Holdup circuit using a buck regulator with input boost capabilities (5.5V–60V to 5V at 4A, 8V holdup) www.linear.com/solutions/7412
- **LTM®8003:** Low EMI buck µModule® regulator (6V–40V to 5V at 3.5A) www.linear.com/solutions/7352

Boost Converter

- **LT8335:** 12V boost converter (3V–10V to 12V at 275mA) www.linear.com/solutions/7426

Inverting Regulators

- **LTC3630:** Positive to negative converter with variable output www.linear.com/solutions/5936
- **LTC7149:** Inverting buck regulator with output voltage control (3.4V–50V input, 2.5 to −10V output at 2A) www.linear.com/solutions/7229

Isolated Converter

- **LTM8068:** 2kVAC isolated low noise µModule regulator with post LDO regulator (4.5V–40V to 5.6V at 460mA, 5V at 300mA) www.linear.com/solutions/7169

LED Driver

- **LT3909:** 2-string, 2MHz LED driver for 10-white-LED strings (7V–36V to 35V LED & 40mA) www.linear.com/solutions/5978

Op Amps

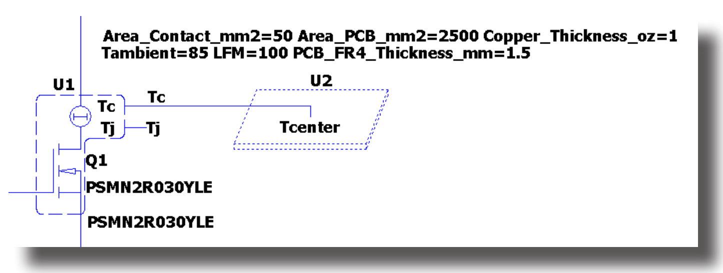
- **LT6201:** Single-ended to differential amplifier SAR ADC www.linear.com/solutions/7600
- **LTC6244:** 60kHz, positive and negative peak detector www.linear.com/solutions/7161
- **LTC6362:** Low power I/Q modulator driver www.linear.com/solutions/7116

Filter

- **LTC1068:** 8th order linear phase bandpass filter www.linear.com/solutions/7217

Reference

- **LT6703-2:** AC line overcurrent indicator www.linear.com/solutions/7181



The SOAtherm-PCB and SOA-HeatSink symbols make it possible to model heat sink and PCB thermal behavior by specifying a few physical parameters rather than calculating an array of component values from formulas.

SELECTED MODELS

To search the LTspice library for a particular device model, press F2. To update to the current version, choose Sync Release from the Tools menu.

Buck Regulators

- **LT3668:** 40V 400mA step-down switching regulator with dual fault protected tracking LDOs www.linear.com/LT3668
- **LT8608:** 42V, 1.5A synchronous step-down regulator with 2.5µA quiescent current www.linear.com/product/LT8608
- **LTM4642:** 20V input, dual 4A or single 8A DC/DC µModule step-down regulator www.linear.com/LTM4642
- **LTM8053:** 40V input, 3.5A/6A step-down µModule regulator www.linear.com/LTM8053
- **LTM8064:** 58V input, 6A CVCC step-down µModule regulator www.linear.com/LTM8064

Buck or Boost Controller

- **LTC3871:** Bidirectional PolyPhase® synchronous buck or boost controller www.linear.com/LTC3871

Isolated Flyback Converter

- **LT8304:** 100V input µPower no-opto isolated flyback converter with 150V/2A switch www.linear.com/LT8304

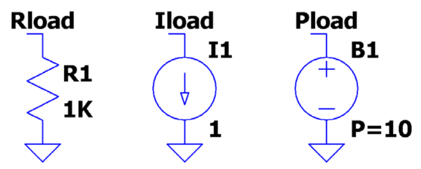
Hot Swap, Surge Stopper & Protection Controllers

- **LTC4236:** Dual ideal diode-OR and single hot swap controller with current monitor www.linear.com/LTC4236
- **LTC4367:** 100V overvoltage, undervoltage and reverse supply protection controller www.linear.com/LTC4367
- **LTC4380:** Low quiescent current surge stopper www.linear.com/LTC4380 ■

Power User Tip

MODELING CONSTANT POWER LOADS IN LTSPICE

There are several types of constant loads used in simulating a power supply system: constant resistance, constant current and constant power loads. For instance, a constant current load dynamically adjusts its resistance as the load voltage varies, such that the load current remains constant, I = V/R. Constant resistance and constant current loads are available as dedicated symbols in LTspice, while a constant power load is available via the arbitrary behavioral source.

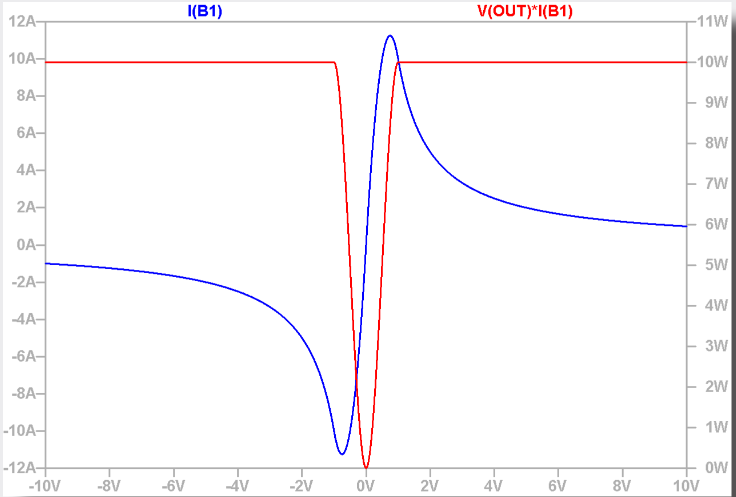


Constant resistance, constant current and constant power loads

A constant power load is designed to dynamically adjust the load current inversely with the load voltage so that the load power is constant, P = VI. It is this inverse property of a constant power load that is often useful in stability analysis of simulations like those of a switching mode power supply.

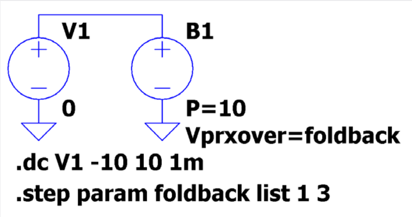
Normally, arbitrary behavioral voltage and current sources are defined by the syntax of V=<expression> or I=<expression>. However, you can modify either of these behavioral source symbol attributes to define a constant power load, P=<expression>. It does not matter which arbitrary (current or voltage) sources symbol you use for the expression, since the *syntax* (V, I or P) describes the behavior, not the symbol.

In the schematic shown, a DC source sweep analysis is performed to plot the characteristic curves. Shown here are the current and instantaneous power in the constant power load, B1, vs voltage. (To plot instantaneous power, Alt-Left Click a symbol.)



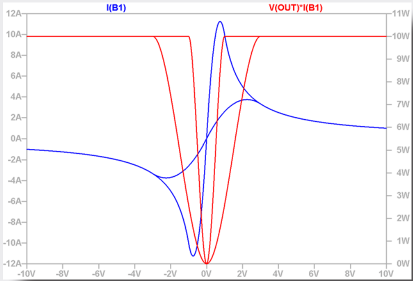
DC source sweep analysis of a constant power load, B1. Output current (blue trace) and instantaneous output power (red trace) vs output voltage. Note that the smooth transition at zero volts avoids infinite current draw.

Notice that the waveform shows the constant power load smoothly transitioning from a constant power load to zero watts at zero volts. This prevents the constant power load from drawing infinite load current as it nears zero output voltage. This foldback point is by default set to 1V, but can be modified by using the vprxover parameter.



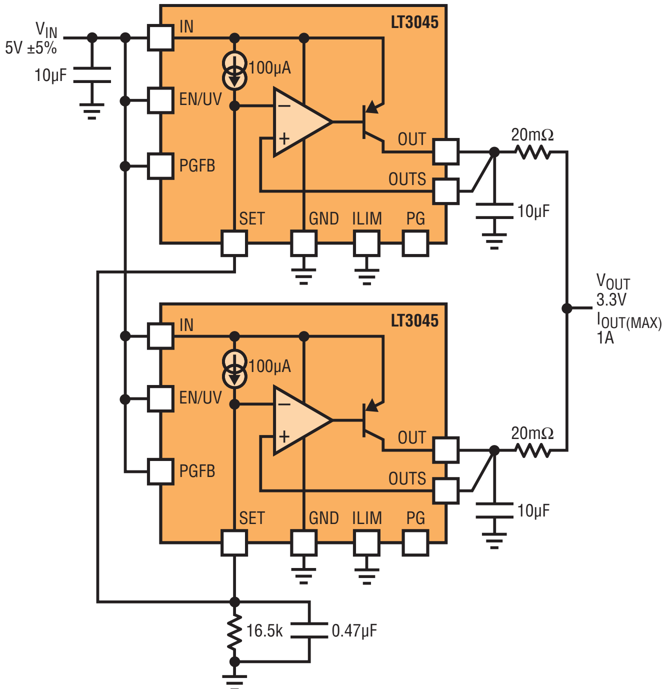
Schematic of a constant power load using a DC source sweep analysis and a .step command of the vprxover parameter of 1V and 3V

The schematic above uses the .step command to perform repeat simulations of the vprxover parameter with waveform results shown here for comparison.



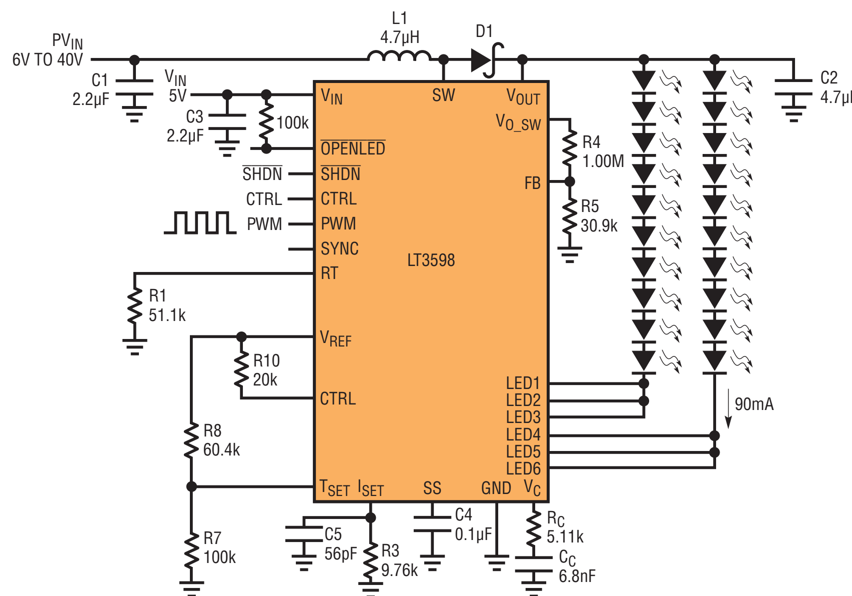
Waveform of constant power load with vpxover parameter of 1V and 3V

Happy simulations!



LT3045 PARALLEL DEVICES FOR 5V INPUT TO 3.3V OUTPUT AT 1A WITH ULTRALOW NOISE

The LT3045 is a high performance low dropout linear regulator featuring Linear's ultralow noise and ultrahigh PSRR architecture for powering noise sensitive applications. Designed as a precision current reference followed by a high performance voltage buffer, the LT3045 can be easily paralleled to further reduce noise, increase output current and spread heat on the PCB.
http://www.linear.com/solutions/7596



C1: NIPPON CHEMI-CON KTS500B225M32NOTOO
C2: MURATA GRM32ER71H475KA88L
C3: TAIYO YUDEN LMK212BJ225MG
D1: VISHAY SS3H9
L1: WÜRTH ELEKTRONIK 7447785004

LT3598 LED DRIVER FOR 30 WHITE LEDS WITH 60mA EACH STRING

The LT3598 is a fixed frequency step-up DC/DC converter designed to drive up to six strings of LEDs at an output voltage up to 44V. LED dimming can be achieved with analog dimming on the CTRL pin, and with pulse width modulation dimming on the PWM pin. The LT3598 accurately regulates LED current even when the input voltage is higher than the LED output voltage. The switching frequency is programmable from 200kHz to 2.5MHz through an external resistor.
http://www.linear.com/solutions/7632

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