HOW2POWER TODAY
Your Power Design Newsletter

Exclusive Technology Feature

ISSUE: January 2017

Automotive Front-End Buck-Boost Regulator Actively Filters Voltage Disturbances

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The proliferation of electronic subsystems in automobiles has created tremendous traction for small, inexpensive and highly reliable power converters that can operate under the challenging conditions presented by the automotive environment.[1,2,3] An automotive 12-V battery's steady-state voltage ranges from 9 V to 16 V, depending on its state of charge, ambient temperature and alternator operating condition.

But it is also subject to a wide range of dynamic disturbances, including start-stop, cold-crank and load-dump transient profiles. Each automotive manufacturer has a unique and extensive conducted immunity test suite in addition to the standardized pulse waveforms given by industry standards such as ISO 7637 and ISO 16750.[4,5] Table 1 identifies several undervoltage (UV) and overvoltage (OV) automotive battery transients.

Table 1. Automotive 12-V and 24-V battery line continuous and transient conducted disturbances and related test levels.

Transient	Cause	Amplitude & duration	Relevant standard
Load dump	Disconnection of discharged battery from alternator at high output current	Clamped to U_S* = 35 V, subject to alternator's centralized clamp and voltage regulator's response time	ISO 16750-2:2012, section 4.6.4, test B
Cold crank	Battery voltage reduction and subsequent recovery upon energizing the starter motor	Initial low-voltage plateau (U_{56}) as low as 2.8 V for 15 ms during a cold-crank period	ISO 16750-2:2012, section 4.6.3 (OEM variants of this also)
Double-battery jump start	Jump-start from commercial vehicle with a dual-battery electrical system	24 V for 2 minutes	ISO 16750-2:2012, section 4.3.1
Alternator regulator failure	Alternator's voltage regulator malfunction, causing full application of charging current to the battery	18 V for 1 hour	OEM specific
Reversed voltage	Negative voltage applied by misconnection at the battery terminals	−14 V for 1 minute	ISO 16750-2:2012, section 4.7
Inductive loads	Switching or disconnection of high-current inductive loads (fans, window motors, HVAC, ABS, etc.)	−150 V for 2 ms (pulse 1) +150 V for 50 μs (pulse 2a)	ISO 7637-2:2011, pulses 1, 2a, 2b, 3a, 3b
Superimposed alternating voltage	AC voltage riding on dc battery voltage due to alternator's 3-phase bridge-rectified output voltage	1 V to 4 V amplitude at 50 Hz to 25 kHz sweep over 2 minutes duration	ISO 16750-2:2012, section 4.4

More broadly, the LV124 template,[6] compiled by representatives from automobile OEMs such as BMW, Daimler, Volkswagen and others, describes various electrical transient tests (numbered from E-01 to E-22) and their requirements.

Alternator sinusoidal-profiled noise superimposed on the dc line poses a deleterious effect, particularly on the vehicle's infotainment and lighting systems.[1] In most vehicles, a centralized passive circuit protection network consisting of a low-pass LC filter and transient voltage suppressor (TVS) diode is used as a first line of defense for transient disturbance rejection. Automotive electronics located downstream from the protection network are then rated to survive up to a 40-V transient without damage. However, the required cutoff frequency of the LC filter to attenuate disturbances at low frequencies makes the required footprint and profile of the filter inductor and electrolytic capacitor undesirable.

This article details an active filter implementation using a four-switch synchronous buck-boost dc-dc regulator with high power supply rejection ratio (PSRR) that offers a high-density and cost-effective solution (Fig. 1.) The circuit implementation is based on Texas Instruments' LM5175-Q1 controller, which is an automotive qualified device. This approach eliminates the need for bulky passive filter components while simultaneously providing both battery voltage regulation and rejection of voltage transients.

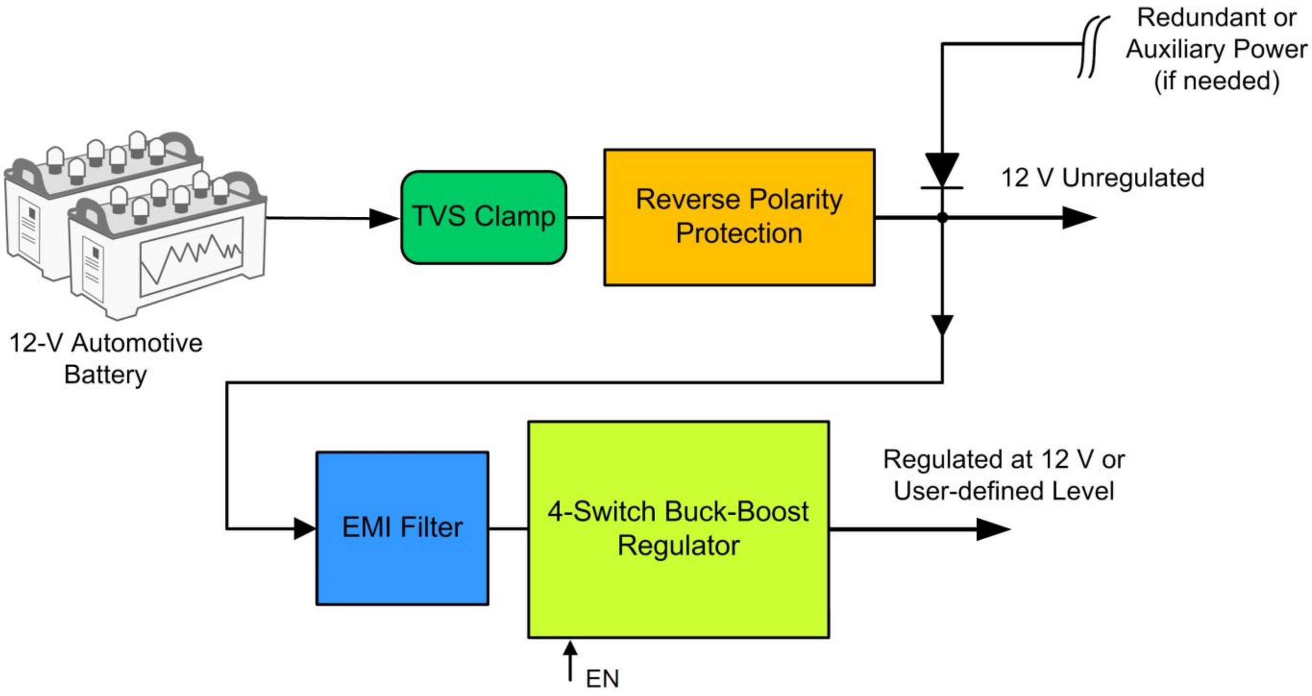


Fig. 1. Block diagram of an automotive system front-end with a four-switch buck-boost dc-dc regulator.

Four-Switch Synchronous Buck-Boost Regulator

The task of regulating and conditioning the automotive battery source using a dc-dc converter becomes more challenging when the converter's non-regulated input voltage is expected to vary continuously above, equal to, and below the regulated output voltage setpoint, calling for buck-boost conversion. A traditional buck or boost converter is deemed inadequate here because only a stepdown or stepup conversion is possible, respectively.

Illustrated in Fig. 2 is a complete schematic diagram of a four-switch synchronous buck-boost regulator designed to output a tightly-regulated 12-V rail. This solution is ideal for engine management units (EMU) and other critical automotive functions including drive train, fuel system, body and safety subsystems where loads must remain powered without glitch during even the most severe battery voltage transients.

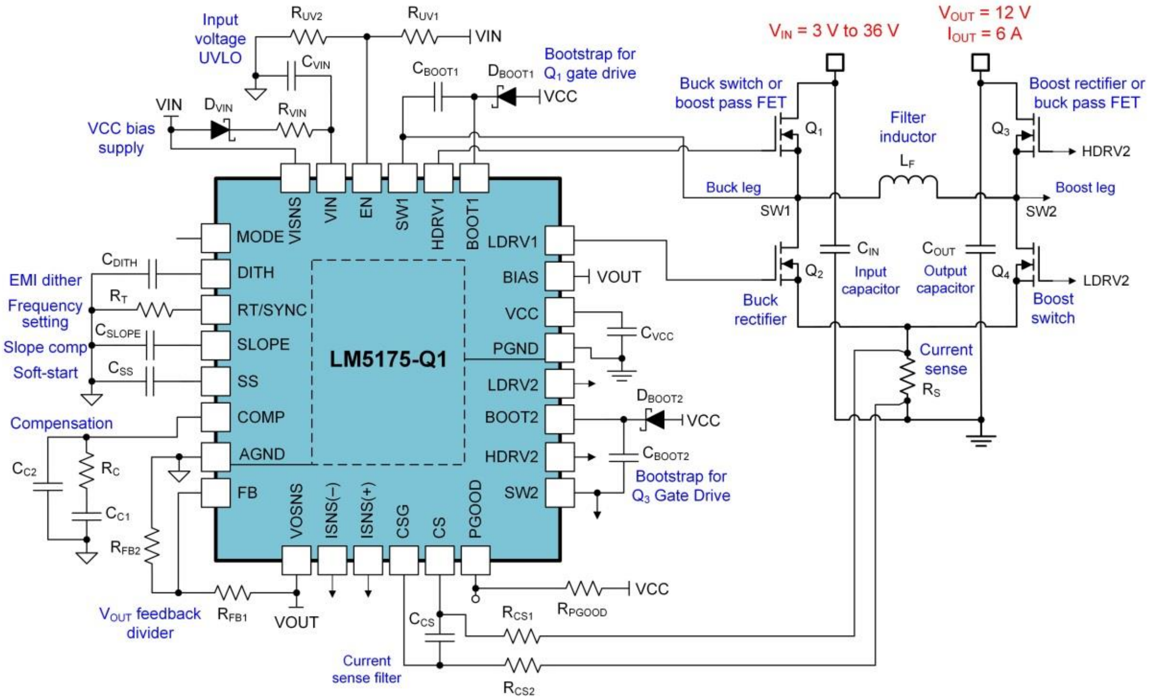


Fig. 2. Circuit schematic of a four-switch synchronous buck-boost regulator with wide V_{IN} range.

The main attraction of this "contemporary" buck-boost power stage is that simple buck or boost operating modes are used to achieve very high conversion efficiency. It produces a positive output voltage—in contrast to the "classic" single-switch (inverting) buck-boost. And, by virtue of its simple magnetic component, it offers lower power loss and higher power density relative to SEPIC, flyback, Zeta, and cascaded boost-buck topologies.[7]

Also in its favor, the four-switch buck-boost converter has an intuitive topology approach, compact solution size, controlled startup and short-circuit protection in boost mode, output disconnect in shutdown, simple control and compensation, and a constant switching frequency. As such, it becomes an ideal fit for automotive battery voltage regulation.

The schematic of Fig. 2 specifies components for the power stage and controller, including integrated gate drivers, bias supply, current sensing, output voltage feedback, loop compensation, programmable undervoltage lockout (UVLO), and dither option for lower noise signature. A switching frequency of 400 kHz minimizes the solution footprint and reduces interference within the AM broadcast band.

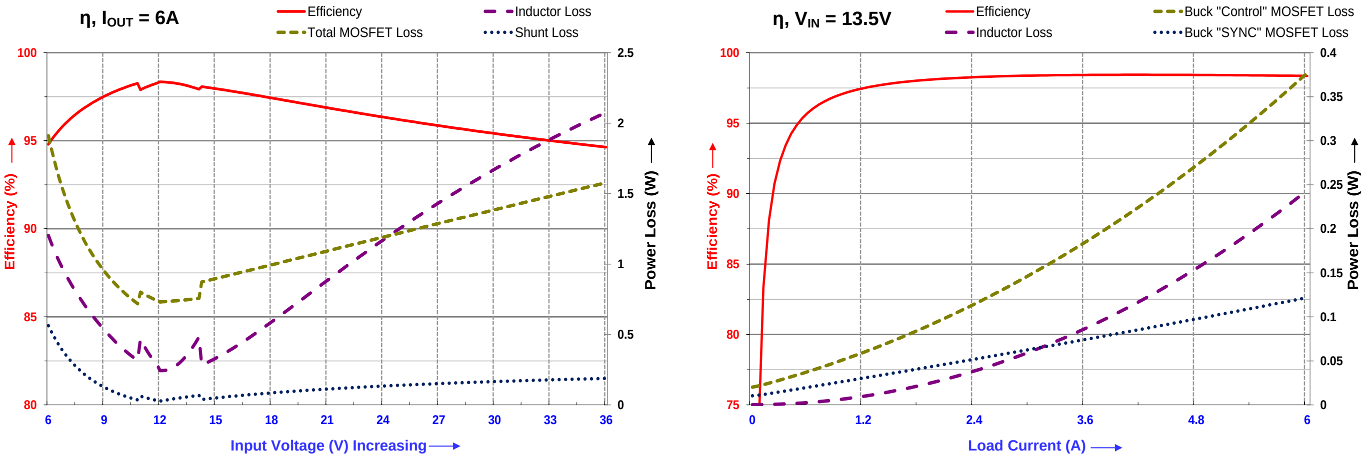
Four power MOSFETs are arranged as buck and boost legs in an H-bridge configuration, with switch nodes SW1 and SW2 connected by an inductor designated L_F. Conventional synchronous buck or boost operation occurs when the input voltage lies suitably above or below the output voltage, respectively, and the high-side MOSFET of the opposite, non-switching leg conducts as a pass device.

However, the most compelling feature of this particular buck-boost implementation is that a unique scheme is employed in the buck-boost (B-B) transition region when the input is close to the output voltage setpoint. Then, both buck and boost legs each switch at half of the switching frequency in a phase-shifted, interleaved manner that is particularly advantageous for efficiency.[7, 8] A control architecture that combines peak current-mode control in boost and valley current-mode control in buck enables seamless mode transitions, requiring just one low-side configured shunt resistor for current sensing.

Fig. 3 provides plots of efficiency and component power dissipations versus line and load. The regulator design from which the efficiency results are recorded is based on the schematic of Fig. 2. The essential circuit components are specified in Table 2. Considering losses in totality, a converter with 12-V regulated output quite readily provides efficiencies in excess of 95% across wide ranges of output current and input voltage.

Table 2. Synchronous buck-boost converter components.

Component	Part number	Footprint and profile (mm)
Wide V_{IN} buck-boost controller	Texas Instruments LM5175-Q1	9.7 × 6.4 × 1.2 (HTSSOP-28)
Inductor, 3.3 μH, 6 mΩ, 26 A	Panasonic ETQP6M3R3YLC	10.7 × 10.0 × 6.0
Input capacitors, 10 μF, 50 V, X7S	Murata GCM32EC71H106KA03 (4 per)	3.2 × 2.5 × 2.5 (EIA 1210)
Output capacitors, 22 μF, 25 V, X7S	Murata GCM32EC71E226KE36 (6 per)	3.2 × 2.5 × 2.5 (EIA 1210)
Buck leg MOSFETs, 60 V, 6 mΩ	Texas Instruments CSD18563Q5A	4.9 × 6.0 × 1.0
Boost leg MOSFETs, 25 V, 4 mΩ	Texas Instruments CSD16340Q3	3.3 × 3.3 × 1.0



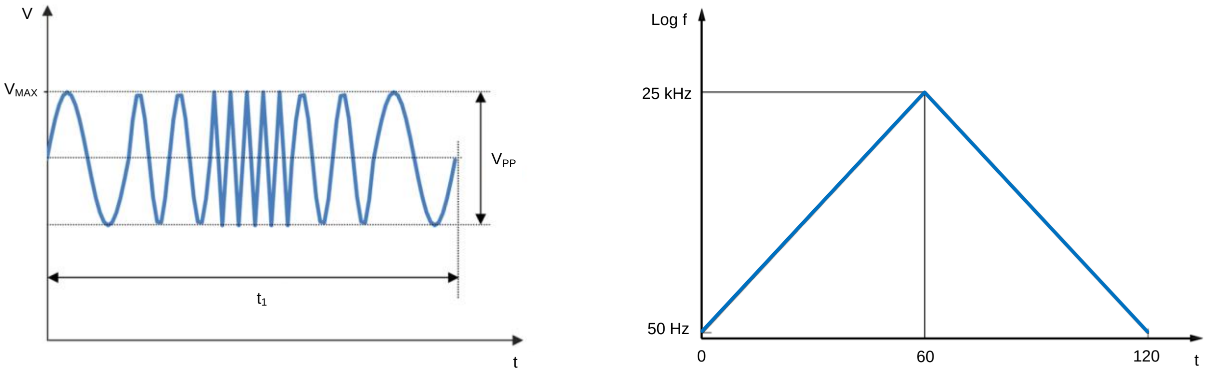
(a) (b)

Fig. 3. Buck-boost regulator efficiency and component power losses versus input voltage (a), and load current (b).

Alternator-Induced Sinusoidal Ripple Voltage

Conducted transient immunity within the audio frequency range is an important requirement. One culprit is the automotive alternator causing a residual alternating current on its output, leading to alternator "whine" and supply modulation issues. The alternator's stator winding is basically a three-phase sinusoidal current source with high impedance output feeding into a diode full-wave rectifier. The rectification creates overlapping current pulses and the ripple is determined from the three phases.

As referenced in Table 1, ISO 16750-2 section 4.4 describes a ripple voltage on the alternator's output in the frequency range of 50 Hz to 25 kHz with a peak-to-peak amplitude V_{PP} of 1 V, 2 V and 4 V, depending on the test pulse severity level (Fig. 4.) Test number E-06 in the LV124 standard describes a similar ripple voltage waveform.



(a) (b)

Fig. 4. ISO 16750-2 superimposed alternating voltage test (a) and log frequency sweep profile from 50 Hz to 25 kHz over a two-minute sweep duration (b).

Maximizing PSRR

The PSRR of a dc-dc converter is related to and affected by its control loop bandwidth, typically limited to 20% of the switching frequency or lower depending on the frequency of the right-half-plane zero (RHPZ) when operating deep in boost mode. In a controller such as TI's LM5175-Q1, PSRR performance is largely independent on V_{IN} and load changes, thanks to a current-mode control scheme with adaptive slope compensation based on the difference of V_{IN} and V_{OUT} that is designed to maximize PSRR and reject line transients.[7]

The slope compensation amplitude, established by the capacitor designated C_{SLOPE} in Fig. 2**,** is chosen for an idealized deadbeat response by setting the slope compensation ramp at the classic one times the inductor upslope (downslope) in valley (peak) current-mode buck (boost) mode of operation. While a setting of half the applicable inductor slope theoretically provides optimal line rejection, this represents the minimum slope compensation for loop stability. The plot in Fig. 5 illustrates via simulation the converter's open-loop gain and phase plots at input voltages of 9 V and 16 V. Fig. 6 shows the corresponding PSRR performance.

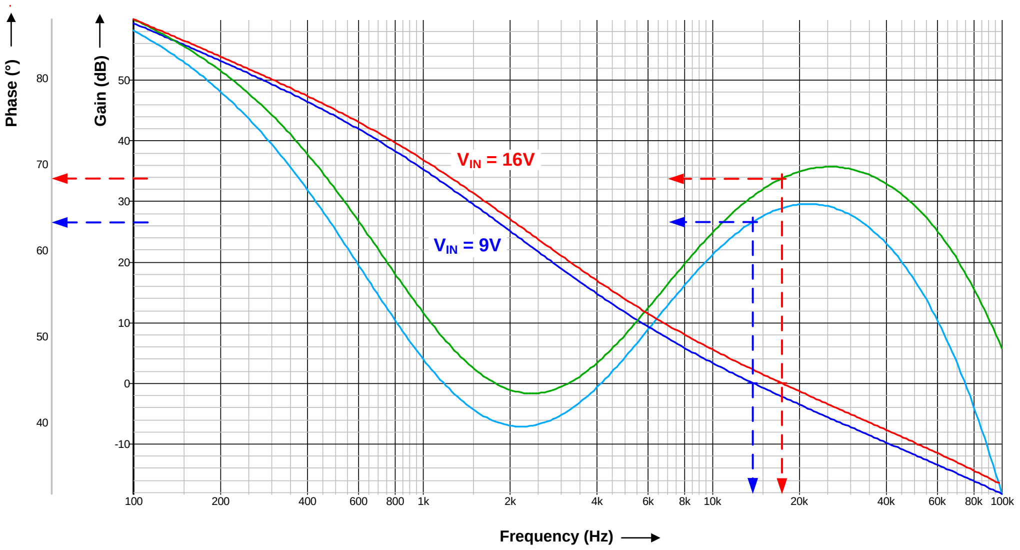


Fig. 5. Simulated bode plots at 9-V and 16-V input with loop crossover frequencies of 14 kHz and 17 kHz, respectively.

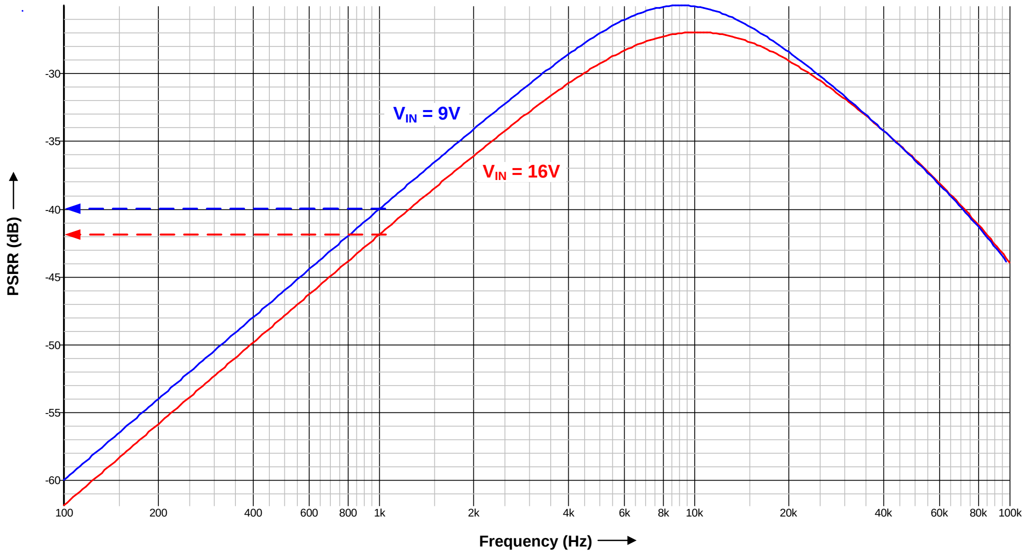
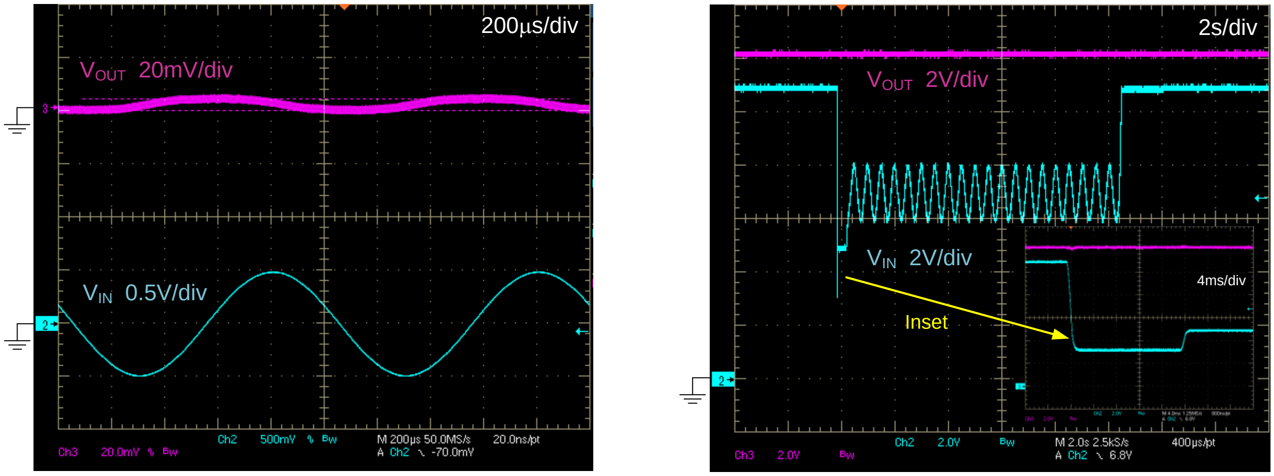


Fig. 6. Simulated PSRR plot showing attenuation at 1 kHz of 40 dB and 42 dB at 9-V and 16-V input, respectively.

Bench Measurements

Fig. 7a shows the synchronous buck-boost regulator's output voltage waveform when a 9-V dc input has a superimposed 1-kHz sinusoidal ripple of 1-V peak-to-peak amplitude. All voltages are measured with an ac-coupled probe with the switching frequency noise removed. The input voltage modulation is achieved using a series n-channel MOSFET connected as a source follower. The input ripple is attenuated by approximately 40 dB as predicted by simulation.

Fig. 7b shows the output voltage during a cold-crank transient down to 3 V for 20 ms using an automotive cold-crank simulator. The four-switch buck-boost converter regulates seamlessly through the cold-crank profile. Also noteworthy, the power MOSFETs have adequate gate-drive amplitude at low input voltage as the regulated V_{OUT} rail powers the controller's BIAS pin input.



(a) (b)

Fig. 7. Measured four-switch buck-boost converter ripple rejection at 9-V dc input (a), and cold-crank performance (b).

The regulator can be designed to meet the CISPR 25 automotive EMI standard using an appropriate EMI filter[8] together with recommended printed circuit board (PCB) layout[9] and component selection guidelines.[10]

Summary

Testament to its high PSRR and transient immunity, high efficiency, and low overall bill-of-materials cost, the four-switch synchronous buck-boost regulator offers a compact and cost-effective solution for tight voltage regulation and transient disturbance rejection in automotive applications. The LM5175-Q1 buck-boost controller featured in this article is automotive qualified to AEC-Q100 grade 1 to facilitate its integration into vehicular 12-V single-battery and 24-V dual-battery systems.

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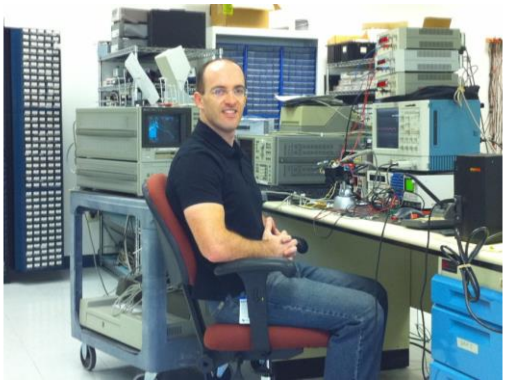
About The Author



Timothy Hegarty is a systems and applications engineer for Power Products Solutions at Texas Instruments. With 20 years of power management engineering experience, he has written numerous conference papers, articles, seminars, white papers, application notes and blogs.

His current area of interest is focused on enabling technologies for high-frequency, low-EMI, isolated and nonisolated regulators with wide input voltage range, targeting industrial, communications and automotive applications in particular. Timothy is a member of the IEEE Power Electronics Society and the IEEE EMC Society.

For further reading on buck-boost voltage regulator design, see the How2Power Design Guide, locate the "Topology" category and select "Buck-boost."