POWER BY LINEAR

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IN THIS ISSUE

High Power Monolithic Silent Switcher 2 Regulators Meet CISPR 25 Class 5 EMI, Fit Tight Spaces

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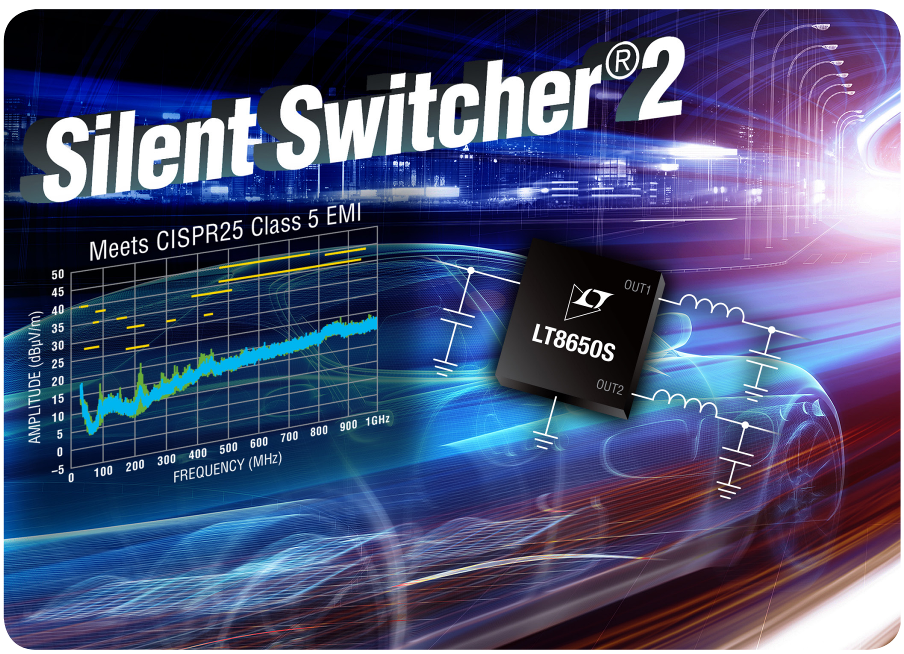
As the quantity of electronic systems in automobiles multiplies, so does the risk of intra-vehicle electromagnetic interference. For this reason, electronics in modern vehicles often must meet the CISPR 25 Class 5 test standard, which stringently limits conducted and radiated emissions. Switching power supplies, by their very nature, are rife with EMI, and proliferate throughout an automobile. Low EMI is now a key requirement for automobile power supplies, along with small solution size, high efficiency, thermal proficiency, robustness and ease-of-use. The Silent Switcher 2 regulator family meets the stringent EMI demands of automobile manufacturers while featuring compact size with integrated MOSFETs and high current capability.



Silent Switcher 2 regulators easily meet stringent EMI standards

The patented* Silent Switcher technology enables impressive EMI performance in high frequency, high power supplies. Silent Switcher 2, the next generation of this technology, simplifies board design and manufacture by incorporating the hot loop caps

(continued on page 4)

Open Circuit

In this issue...

Power by Linear, the world's premier source for power management products and expertise.

INTRODUCING Power by Linear™

Now that Linear Technology has merged with Analog Devices, the company's power products have a new name, Power by Linear. You can visit the Power by Linear page (www.linear.com/powerbylinear) for updates on the integration and learn more about this new brand. To research Power by Linear products, visit www.linear.com.

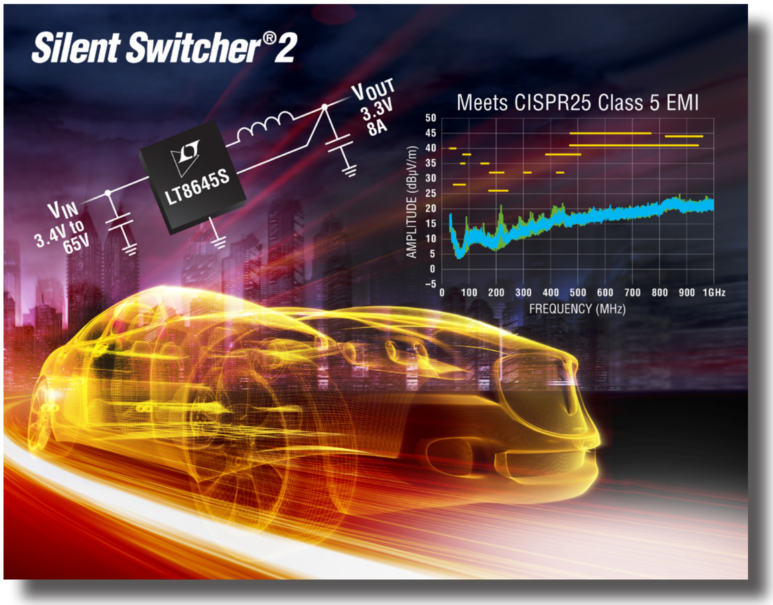
Power is Simple; Yet Complicated

Consider a DC/DC power supply: power in at one voltage; power out at another. Nothing could be simpler, but a design engineer tasked with adding power to a PCB faces a daunting array of choices. The market is flooded with power supply boxes, modules and ICs, widely varying form factors, features and solution cost. Those are just a few items from the long list of the metrics:

- V_{IN} and V_{OUT}
- Load capability
- Input current control
- Output current control
- Form factor
- Efficiency
- Thermal performance
- EMI performance
- Quiescent current
- Monitoring
- Sequencing
- Protection
- Ease-of-use
- Robustness
- Solution cost

Decisions are further complicated by the fact that choosing top-end performance in one parameter can mean settling for less than stellar performance in other important areas. A field of endless choices can be attractive, until the moment you must choose. To simplify the selection and design process, an applications engineer needs a power supply design guru in their back pocket. Power by Linear products offer that.

Now that Analog Devices has acquired Linear Technology, designers can count on continuation of deep engineering product support they've come to expect.



Power by Linear designers have the expertise to develop high efficiency, compact, low EMI power supplies for the next generation of automotive 48V systems.

Not Just Devices; Support

Power by Linear products build on the legacy of putting the best power supply and power management products and engineers at your fingertips. Power by Linear power supply designers and applications engineers are ready to assist. When you contact Analog Devices and ask to be connected to a Power by Linear engineer, you get an engineer.

Not Just Devices; Solutions

In many industries, a one-size-fits-all power supply solution won't cut it. For instance, power supplies found in automotive applications must meet increasingly stringent requirements. A modern combustion-engine powered, non-self-driving automobile is packed with electronics. If the car is electric and self-driving, the quantity of electronics multiplies. The space available to electronic systems is tight and getting tighter, and power supplies are not immune to the squeeze. As in any battery-powered system, supplies must be efficient in order to avoid running down the battery, especially when "off" actually means "always on." EMI is also a concern. This leads to three desirable features for any automotive electronics power supply:

- Small form factor
- High efficiency
- Low EMI

Until recently, these performance metrics were in opposition. In a traditional switching power supply, high efficiency came at the expense of form factor; low EMI at the expense of efficiency. No one had figured out how to produce a power supply that performs admirably in all three areas, until a few years ago when our designers made a breakthrough in the Silent Switcher technology (see cover article).

Silent Switcher supplies can be very small, and run efficiently enough to require minimal heat sinking (helping to reduce size). EMI standards can be met without compromise, with Silent Switcher and Silent Switcher 2 products emitting an order of magnitude less noise than competing products.

The Silent Switcher regulators and LED drivers presented in this journal show how Power by Linear designers are incorporating key requirements into industry leading solutions.

Not Just Devices; Solutions for Mission-Critical Applications

Mission-critical applications are becoming more complex and few suppliers have have the expertise and skill to deliver impactful innovation in the power realm. For example, if we look ahead to 2020 and beyond, two-battery systems will start to show up in automobiles: 12V and 48V.

The second 48V battery will power motors and pumps, and energy will need to be shuttled between this new battery and the legacy 12V battery. Bidirectional power conversion and even more output voltages at higher power levels will be required—all in a space that's shrinking every year. As electronics become more mission-critical, the quality and reputation of the power supplier become critical as well—Power by Linear products will continue to incorporate innovation and quality second to none.

Always Ahead

Power by Linear products have significant advantages, including a broad portfolio of high performance, highly innovative products, and a team of highly skilled power experts who live and breathe power, thrive in a culture of innovation, and have the tenacity to stay at the forefront of technology development.

No Obsolescence

If you are using a Power by Linear product, we will continue to support it. ■

Silent Switcher 2 provides an enhanced low EMI solution by easing board layout requirements. In a Silent Switcher 2 device, the hot loop and warm loop capacitors are integrated into the packaging and laid out for minimal EMI. The final PCB layout has little effect on EMI, simplifying design and manufacturing.

(Silent Switcher 2, continued from page 1)

into the packaging, so PCB layout has minimal effect on EMI (see sidebar).

SILENT SWITCHER 2 REGULATOR POWERS SOCs

The system-on-chip (SOC) devices found in today's (and future) vehicles bear little resemblance to those of previous generations. Exponential feature expansion of infotainment systems and vehicle safety systems call for SOCs to process data several orders of magnitude faster than before, including processing high resolution video data from multiple sources with minimum latency. For example, if a car's front camera "sees" a danger, the car must respond immediately,

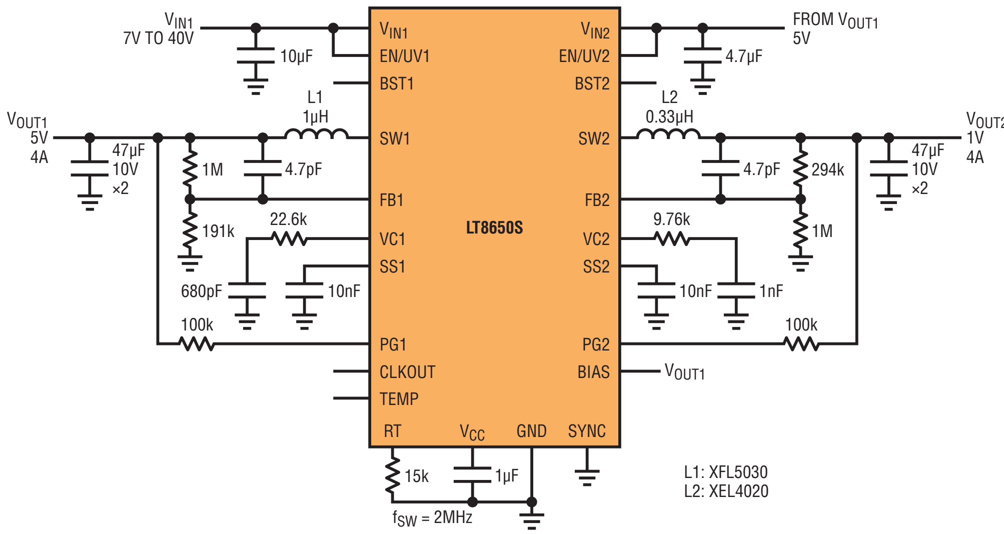
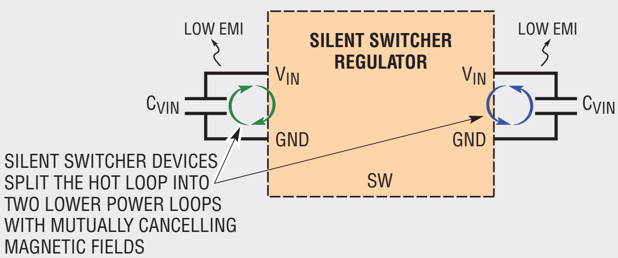


Figure 1. Dual output, 5V/4A and 1.0V/4A, using two channels of the LT8650S

Silent Switcher for Low EMI

SILENT SWITCHER

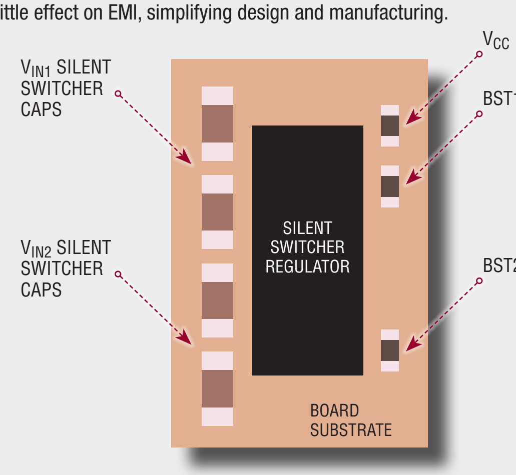
Silent Switcher power supplies improve EMI performance of switching mode power supplies by splitting the high frequency hot loop into two lower power loops. If properly laid out, this results in small loop area and mutually cancelling magnetic fields—the equivalent of putting the regulator in a shielded box. Note that Silent Switcher designs require careful layout to be effective.



Silent Switcher technology reduces EMI from the hot loop.

SILENT SWITCHER 2

Silent Switcher 2 provides an enhanced low EMI solution by easing board layout requirements. In a Silent Switcher 2 device, the hot loop and warm loop capacitors are integrated into the packaging and laid out for minimal EMI. The final PCB layout has little effect on EMI, simplifying design and manufacturing.



Silent Switcher 2 devices integrate the hot loop and warm loop caps into the package to simplify board layout.

The LT8650S, LT8609S, and LT8645S have much higher output current capabilities than typical monolithic regulators due to high efficiency and thermal management features.

either warning the driver or applying the brake. To satisfy modern computational demands, SOCs squeeze an increasing number of power hungry devices into their packages, but how will that power be delivered? In an automobile, power delivery must be efficient, compact and low EMI. The increased power demands of SOCs makes meeting them more difficult.

For example, an R-Car H3 SOC includes eight ARM cores, DSPs, video and graphic processors, plus ancillary support devices. Each of these components requires reliable power, including three rails (5V, 3.3V and 1.8V) for peripheral and auxiliary components, two (1.2 and 1.1V) for DDR3 and LPDDR4, and another 0.8V for cores.

To support the current levels demanded by SOCs, a switching power controller with external MOSFETs is the traditional choice over monolithic power devices. Monolithic devices are compelling because their internal MOSFETs minimize cost and solution size, but their traditionally limited current capability and thermal issues typically limit their use. The LT8650S and a new family of monolithic step-down Silent Switcher regulators have the current capability and thermal management features to support SOCs.

The Power by Linear™ LT®8650S, LT8609S, and LT8645S have much higher output current capabilities than typical monolithic regulators due to high efficiency and thermal management features. Input voltage ranges from 3V to 42V (65V for the LT8645S) cover the spectrum of automotive battery conditions. These monolithic ICs have integrated MOSFETs and can

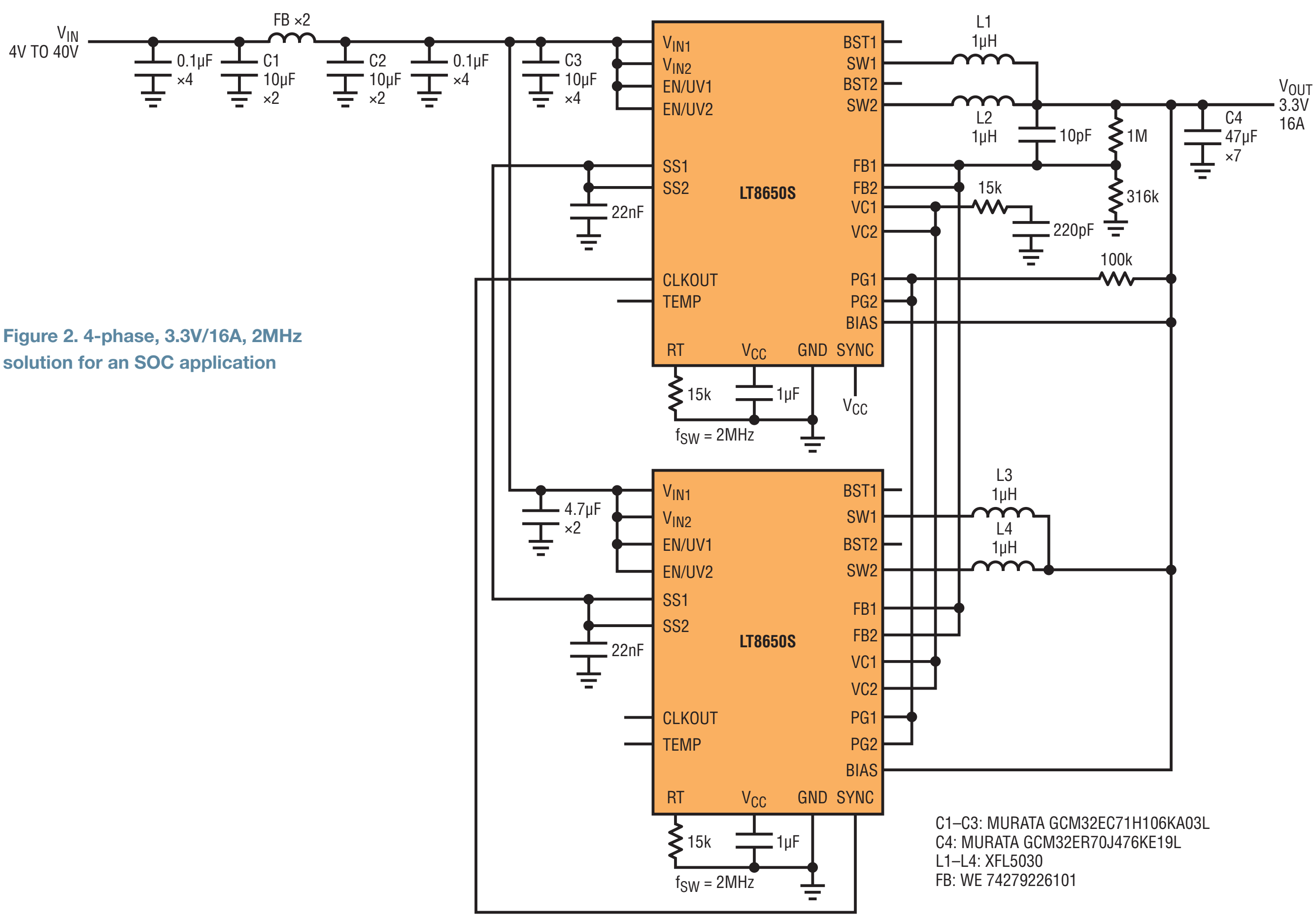


Figure 2. 4-phase, 3.3V/16A, 2MHz solution for an SOC application

These monolithic ICs have integrated MOSFETs and they can run at greater than 2MHz, resulting in reduced solution size and cost while avoiding the AM band.

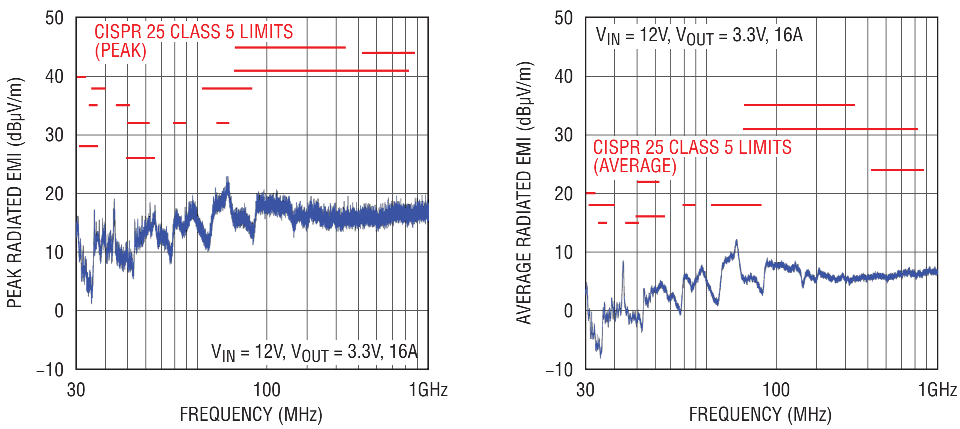


Figure 3. Radiated EMI test results of the solution in Figure 2

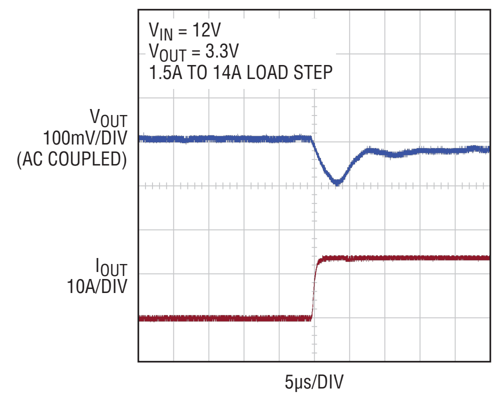


Figure 4. Load transient response of the Figure 2 solution

run at greater than 2MHz, resulting in reduced solution size and cost while avoiding the AM band. Silent Switcher regulators are designed to minimize EMI, making them a popular choice for SOCs.

DUAL OUTPUT: 5V/4A AND 1V/4A

Figure 1 shows a dual output, 2MHz 5V at 4A and 1V at 4A, solution using two channels of the LT8650S. This circuit can be easily modified to fit other output combinations, including, for example 3.3V & 1.8V or 3.3V & 1.1V, to take advantage of the wide input range of the LT8650S. The LT8650S can also be used as the first stage converter, followed by various lower power second-stage switching or LDO regulators for more outputs.

The LT8650S features the EMI cancelling Silent Switcher 2 design with integrated hot loop capacitors to minimize noisy antenna size. This, coupled with integrated MOSFETs, enables exceptional EMI performance.

16A SOLUTION FOR AN SOC

Figure 2 shows a 3.3V/16A, 4-phase solution for SOC power. Figure 3 shows the radiated EMI test results.

Automotive SOCs also place heavy demands on power supply load transient response. It is not uncommon to see a load current slew rate at 100A/μs for peripheral power supplies and higher for core supplies. Regardless of the changes in load, the power supply must minimize the output voltage transient. A fast switching frequency, such as the 2MHz capability of the LT8650S family helps speed transient recovery. Faster switching frequencies correspond to faster dynamic responses with proper loop compensation. Figure 2 shows the proper component values. It is also critical in board layout to minimize trace inductance from the output capacitors of the circuit to the load. Figure 4 shows the transient test results of the solution shown in Figure 2.

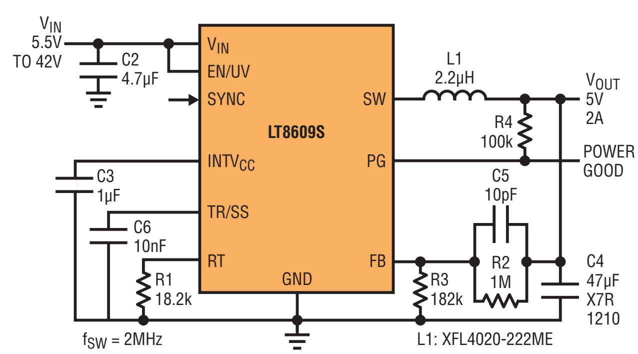


Figure 5. 2MHz 5V/2A application using the LT8609S.

In addition to the low voltage high current applications such as SOC and CPU, automobiles and other vehicles require power for numerous low current loads, such as dashboard instrument clusters, heads up displays, V2X, sensors, USB chargers, etc.

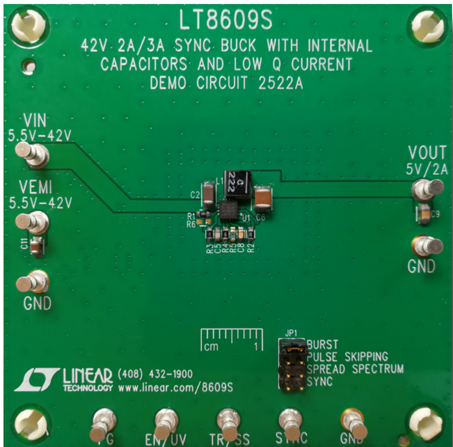
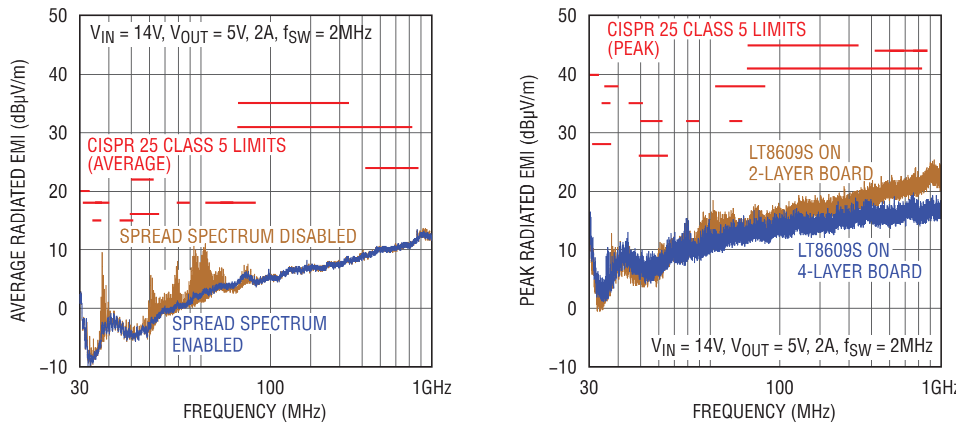


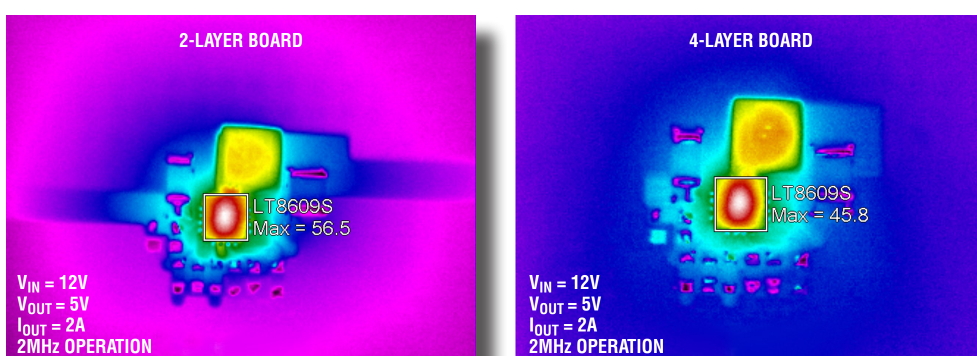
Figure 6. Small solution size of the LT8609S 2-layer board



(a) (b)

Figure 7. (a) Average radiated EMI test results of the LT8609S on a 2-layer board showing results with spread spectrum frequency modulation enabled for further EMI reduction. (b) Peak radiated EMI performance comparison between 2- and 4-layer boards with the LT8609S.

Figure 8. Thermal performance comparison between 2-layer and 4-layer boards with LT8609S.



HIGH EFFICIENCY, COMPACT SOLUTION FOR LOWER POWER APPLICATIONS

In addition to the low voltage high current applications such as SOC and CPU, automobiles and other vehicles require power for numerous low current loads, such as dashboard instrument clusters, heads up displays, V2X, sensors, USB chargers, etc.

Due to the limited space and limited battery power, high efficiency and small solution size are top requirements for power converters. Low noise is a given. LT8609S is a suitable solution for all these applications. It's designed with 3V to 42V input voltage range for automotive battery conditions. Integrated MOSFETs, built-in compensation circuit and 2MHz operation frequency minimize the LT8609S solution size. Silent Switcher 2 technology and integrated hot loop capacitors are used in the LT8609S to minimize noise levels and provide exceptional efficiency as well as excellent EMI performance. Figure 5 shows a 2MHz, 5V/2A application using LT8609S.

Figure 6 shows a complete LT8609S regulator on a 2-layer board. The integrated MOSFETs and built-in compensation circuit of the LT8609S reduce the component count to the device itself plus a few external components. Together with the high speed switching frequency, the total core solution size for this typical application is only 11.5mm × 12.3mm.

One way to reduce solution costs is to minimize the number of required PCB layers, but performance trade-offs are expected. For instance, a 2-layer board solution is not expected to produce equivalent EMI performance to a 4-layer solution. EMI results in Figure 7 show that

Thermal performance is another concern when fewer board layers are used, but is not a problem for the LT8609S. Silent Switcher 2 technology means lower noise level and greater efficiency, with less power loss generated from switching transitions.

the LT8609S on a 2-layer board satisfies CISPR 25 Class 5 EMI emissions. EMI performance is compared between equivalent solutions on 2- and 4-layer boards.

In general, Silent Switcher 2 technology yields excellent EMI performance with 2-layer boards and even single layer boards, which can greatly reduce manufacturing costs.

Thermal performance is usually a concern when fewer board layers are used, but not with the LT8609S. The Silent Switcher 2 technology's low noise level and high efficiency have the benefit of low power loss from switching transitions. This, combined with an enhanced thermal dissipation package, enables the LT8609S to demonstrate impressive thermal performance. Figure 8 shows the thermal performance comparison between 2- and 4-layer boards. For 12V battery inputs, the LT8609S operates with less than 11°C temperature rise differential at full load.

SILENT SWITCHER 2 SOLUTION FOR 48V AUTOMOTIVE SYSTEMS

Conventional vehicles use 12V batteries to supply the power for ignition, lighting, audio and infotainment electronic devices, safety features, among other systems. Unfortunately, the power capability of 12V automotive system is limited to 3kW, a line that is increasingly challenged by the prolific number of automotive electronics.

This, along with the advent of electric vehicles and self-driving systems, challenges the norms of power delivery, with the automotive industry turning to 48V battery power as a solution. Compared to a 12V electrical system, a 48V electrical system reduces distribution losses when power demands are high, improving overall efficiency.

The challenge posed to DC/DC converters in 48V systems is to maintain conversion efficiency, size and low EMI similar to a 12V system, when high step-down ratios make it more difficult to meet these specifications. The gains made by using 48V should not be lost in the DC/DC conversion process. Monolithic switching regulators that can run at 2MHz to avoid interference with the AM band are ideal for 48V automotive electrical systems so long as they can do so efficiently.

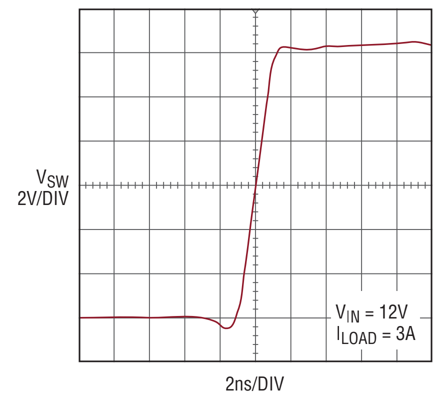


Figure 9. Monlothic Silent Switcher devices feature a MOSFET driver design that produces fast, clean switching edges. This results in high efficiency, even at high frequency operation. Innovative drivers also minimize overshoot, dampening ringing that would otherwise be a source of EMI.

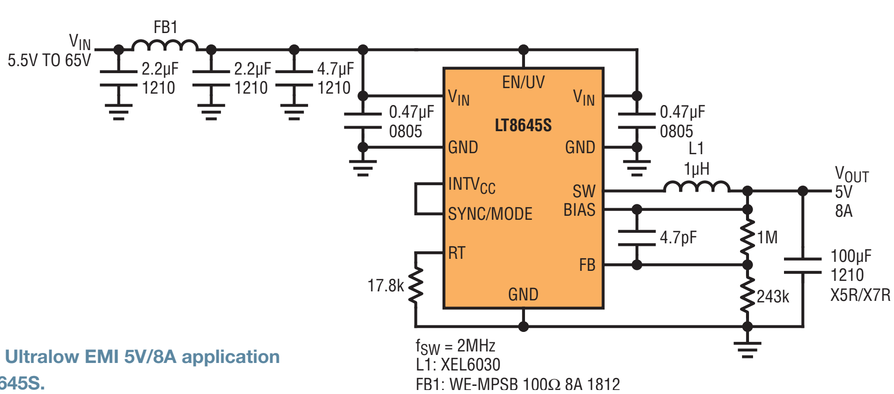


Figure 10. Ultralow EMI 5V/8A application using LT8645S.

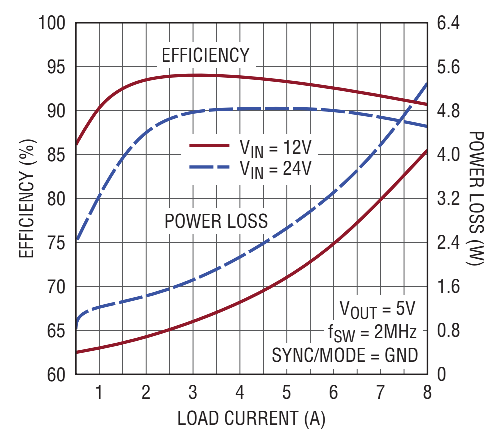


Figure 11. LT8645S efficiency for the ultralow EMI solution

The LT8645S high voltage, high current monolithic buck regulator easily satisfies the requirements of 48V bus applications. The LT8645A can handle 65V input voltages, with a maximum output capability of 8A.

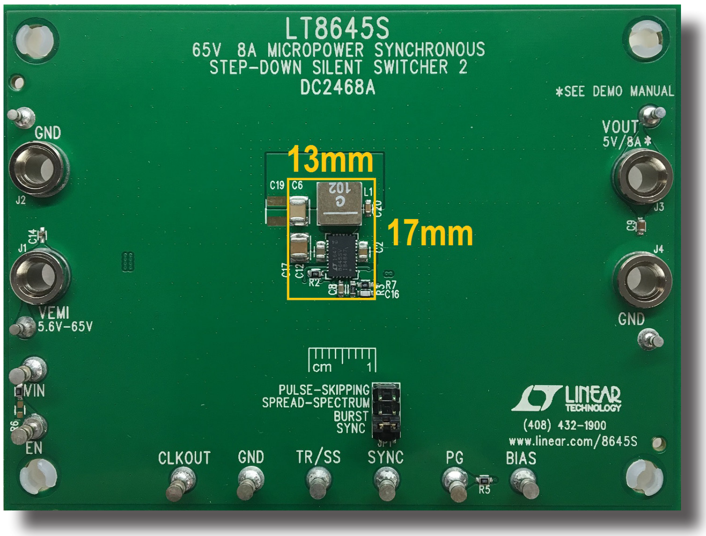


Figure 12. Small solution size of LT8645S deomonstration circuit

There are a limited number of monolithic buck regulators that can take 48V nominal inputs, most supporting less than 5A. The LT8645S monolithic buck regulator supports 8A loads, from input voltages up to 65V. Its 40ns minimum T_{ON} with fast clean switching edges (Figure 9) enable high switching frequencies and high efficiency, up to 94% at 2MHz.

Integrated compensation and bypass capacitors minimize the total solution size and simplify the low EMI layout. With a simple ferrite bead filter, the LT8645S can pass CISPR 25 Class 5 specs with margins.

Figure 10 shows an ultralow EMI 2MHz 5V/8A application using LT8645S. Figure 11 shows LT8645S efficiency and Figure 12 shows the LT8645S solution size.

The LT8645S has the unusual ability to support high step-down ratios even when operating at high switching frequencies, due to its 40ns minimum on-time. For example, the LT8645S can generate 1.8V from up to a 30V input at a 1MHz switching frequency. The input can go up to the absolute maximum rating of 65V if skipping switch cycles is acceptable.

When the output is lower than 3.1V, the BIAS pin of LT8645S should be connected to an external source that is higher than 3.1V, to improve efficiency. If such source is not available, tie the BIAS pin to GND. Figure 13 shows a 1MHz 1.8V/8A solution, that operates in the face of 65V input transients.

In addition to low EMI, high efficiency at high frequency, and a wide input voltage range, LT8645S features ultralow quiescent current and low dropout. The ultralow quiescent current can extend the battery run time in idle. The low dropout feature is critical to continuous operation in cold crank conditions.

Figure 13. 1MHz 1.8V/8A application with up to 65V input transient using the LT8645S

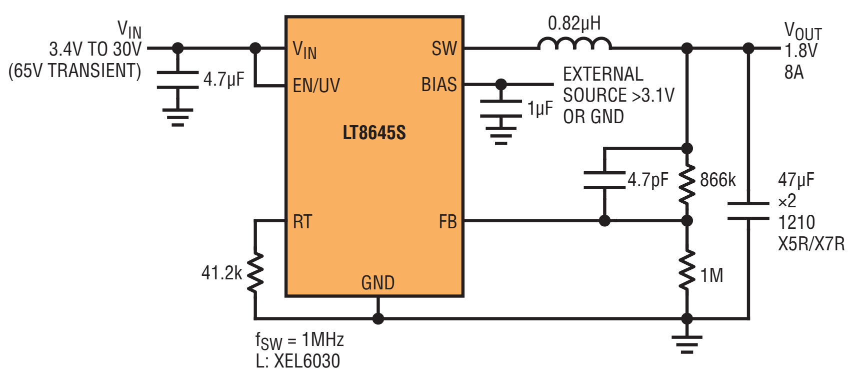


Table 1. Low EMI Silent Switcher and Silent Switcher 2 ("S") synchronous step-down regulators. Devices described in this article are highlighted.

DEVICE	# OF OUTPUTS	V_{IN} RANGE	OUTPUT CURRENT	PEAK EFFICIENCY AT 2MHz, 12V TO 5V	I_Q	FEATURES	PACKAGES
LT8650S	2	3V–42V	4A + 4A on both channels or 6A on either channel	94.60%	6.2µA	Silent Switcher 2	6mm × 4mm × 0.94mm LQFN
LT8645S	1	3.4V–65V	8A	94%	2.5µA	Silent Switcher 2	6mm × 4mm × 0.94mm LQFN
LT8643S	1	3.4V–42V	6A continuous 7A peak	95%	120µA	Silent Switcher 2, external compensation	4mm × 4mm × 0.94mm LQFN
LT8640S	1	3.4V–42V	6A continuous 7A peak	95%	2.5µA	Silent Switcher 2	4mm × 4mm × 0.94mm LQFN
LT8609S	1	3V–42V	2A continuous 3A peak	93%	2.5µA	Silent Switcher 2	3mm × 3mm × 0.94mm LQFN
LT8641	1	3V–65V	3.5A continuous 5A peak	94%	2.5µA	Silent Switcher	3mm × 4mm QFN-18
LT8640, LT8640-1	1	3.4V–42V	5A continuous 7A peak	95%	2.5µA	Silent Switcher, LT8640 pulse skipping, LT8640-1 forced continuous	3mm × 4mm QFN-18
LT8614	1	3.4V–42V	4A	94%	2.5µA	Silent Switcher Low ripple Burst Mode operation	3mm × 4mm QFN-18

CONCLUSION

Silent Switcher and Silent Switcher 2 regulators meet the demanding EMI emissions requirements of automotive environments. See Table 1 for a list of Silent Switcher devices, including those presented here.

Of the parts highlighted here, the LT8650S dual-channel synchronous monolithic Silent Switcher 2 regulator offers SOC applications a wide input voltage range, exceptional EMI performance, and small solution size, while providing multiple high current outputs and fast transient response. The LT8609S synchronous monolithic Silent Switcher 2 regulator offers a wide input voltage range, low quiescent current, excellent EMI performance, small solution size and high efficiency—it easily fills the ubiquitous power systems found in today's automobiles. The LT8645S (inputs to 65V) enables compact low EMI solutions for 48V automotive systems. ■

Notes

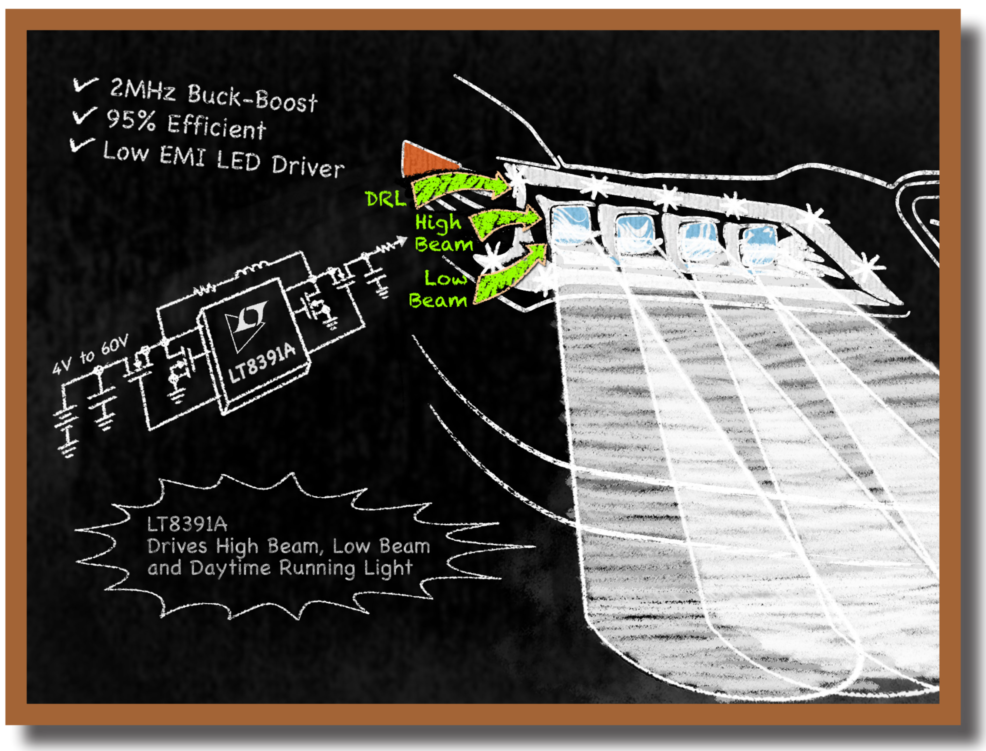
* Silent Switcher is patented technology, patent number 8823345.

Single 2MHz Buck-Boost Controller Drives Entire LED Headlight Cluster, Meets CISPR 25 Class 5 EMI

Keith Szolusha

Automobile LED headlight clusters combine high and low beams, daytime running lights, and sometimes signal and clearance lights into a single headlight cluster. The components of the cluster can have vastly different driver requirements, including voltage and current requirements, topologies, power levels or unique dimming functions. Meeting the range of requirements usually means employing separate driver solutions. Using multiple drivers not only complicates BOMs and production; it can make it difficult to meet EMI standards. Each additional driver adds its high frequency signals to the EMI mix, complicating EMI qualification, troubleshooting and mitigation.

Although the headlight cluster for each automobile make and model may be outfitted with a creative variety of LED currents and voltages, they commonly top out at 30W total. With that in mind, there *should* be a number of drivers that satisfy the power and feature requirements of every string in the cluster. There are not. Such a driver needs to take the relatively wide battery voltage range, and using a buck-boost topology, convert to the wide variety of string voltages. It needs to be small and versatile, to fit easily into the space constraints of the cluster, and produce little EMI, to minimize R&D efforts and eliminate the need for costly metal-shielded EMI cases. It should also be efficient. The Power by Linear LT8391A 2MHz buck-boost controller is unique in satisfying all of these requirements, making it possible to drive the entire headlight cluster, and more, with a single controller.



LT8391A 2MHz SYNCHRONOUS CONTROLLER WITH LOW EMI

The LT8391A is the first-of-its-kind 2MHz buck-boost controller for LED current regulation. The very high 2MHz switching speed enables the use of a single, small inductor and small overall solution size for high power LED applications. Unlike monolithic converters, whose power switches are contained within the IC package, controllers such as the LT8391A can drive external power switches with much higher peak currents, such as 10A. Such peak currents would burn up the small IC packages of typical integrated converters. In contrast, a controller with external 3mm × 3mm synchronous MOSFETs can deliver much higher power. These MOSFETs can be arranged in tight quarters with hot-loop capacitors for very low EMI. The unique peak switch current sense amplifier architecture places the sense resistor next to the power inductor, which is outside

The 2MHz LT8391A 16V, 1.5A (24W) buck-boost LED driver boasts as high as 93% efficiency with EMI filters and gate resistors. Efficiency is 1%–2% higher with the optional EMI components removed. With small 3mm × 3mm MOSFETs and a single high power inductor, the temperature rise for this converter is low, even at 24W.

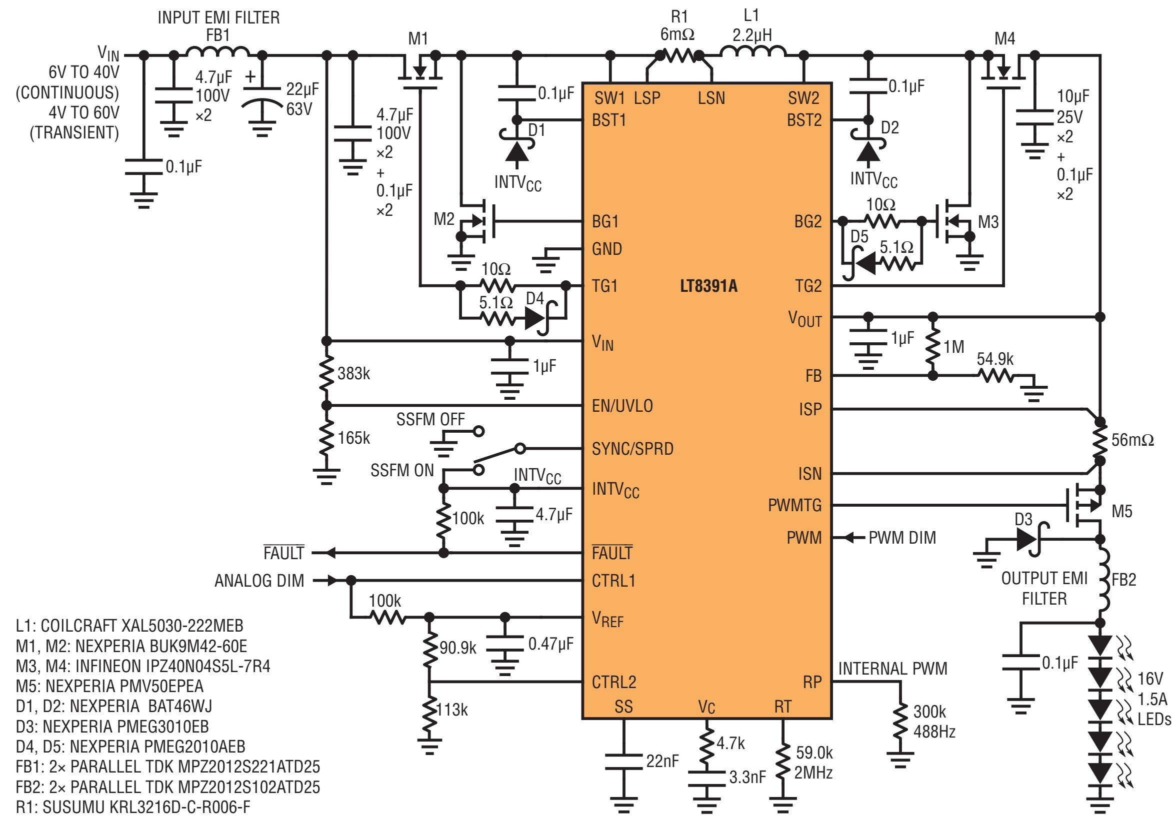


Figure 1. LT8391A 2MHz 16V, 1.5A automotive buck-boost LED driver passes CISPR 25 Class 5 EMI

of the critical input and output hot loops—reducing EMI. Optional spread spectrum frequency modulation (SSFM) further reduces the controller's EMI.

The 2MHz LT8391A 16V, 1.5A (24W) buck-boost LED driver in Figure 1 boasts as high as 93% efficiency with EMI filters and gate resistors as shown in Figure 2. Efficiency is 1%–2% higher with the optional EMI components removed. With small 3mm × 3mm MOSFETs and a single high power inductor, the temperature rise for this converter is low, even at 24W. At 12V input, no component rises more than 25°C above room temperature. At 6V input, the hottest component rises

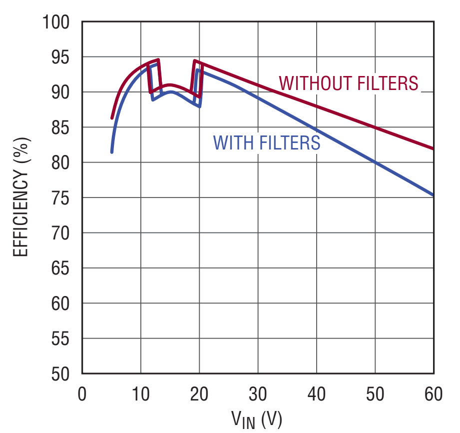


Figure 2. Efficiency of LED driver solution in Figure 1. Measurements made using 16V, 1.5A, demonstration circuit DC2575A LED driver with and without optional EMI components

less than 50°C with a standard 4-layer PCB and no heat sink or airflow. It continues to run at full 24W load in the face of input transients down to 4.3V; or reduced load current via analog or PWM dimming when the input drops for long periods. The 8A–10A sense resistor makes this high power at low V_{IN} possible.

The LT8391A includes the latest PWM dimming features and open LED fault protection. This synchronous buck-boost regulates current through a string of LEDs with a voltage that may or may not lie within the input voltage range, such as the 9V–16V car battery or a truck battery (18V–32V). It can run down to

Automotive EMI requirements are not easily met by high power converters. High power switches and inductors, placed on large PCBs next to large capacitors can create undesirable hot loops, especially when a large sense resistor is included. The unique LT8391A buck-boost architecture removes the sense resistor from both the buck and boost switch-pair hot loops. This enables the LT8391A to keep EMI low.

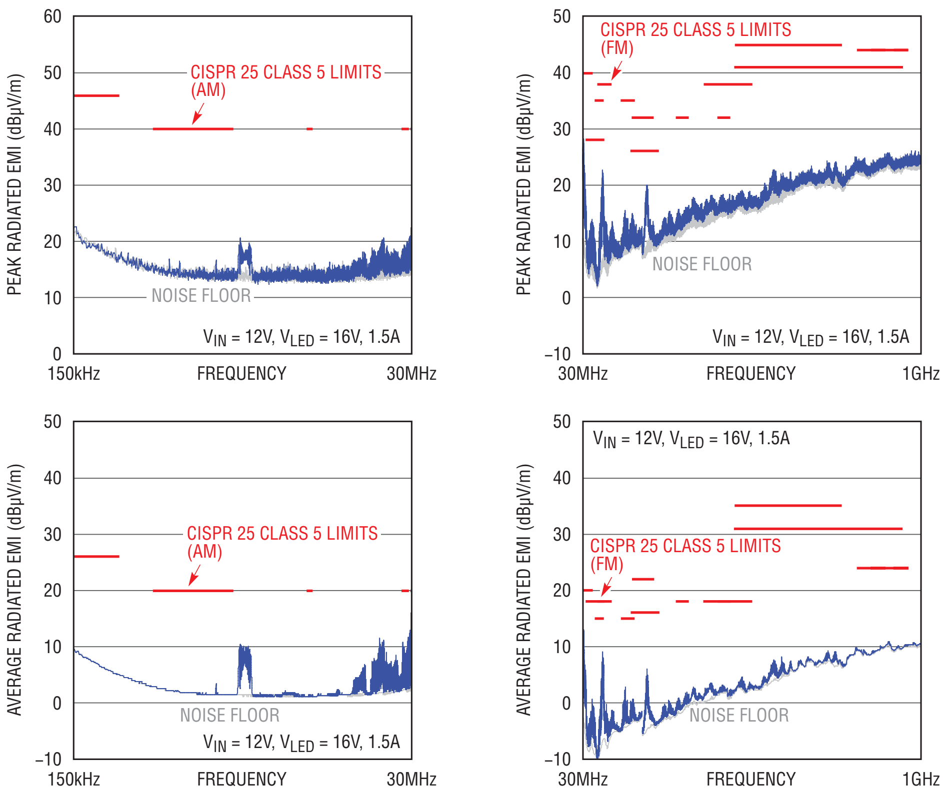


Figure 3. LT8391A demonstration circuit DC2575A passes CISPR 25 Class 5 automotive radiated EMI

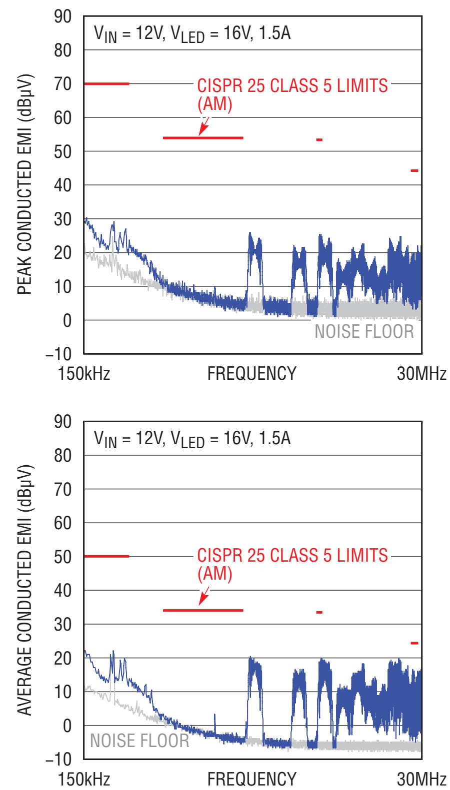


Figure 4. LT8391A demonstration circuit DC2575A passes CISPR 25 Class 5 automotive conducted EMI

4.0V cold crank input and can withstand up to 60V input transients. The LT8391A provides up to 2000:1 PWM dimming ratio at 120Hz and can use its internal PWM dimming generator for up to 128:1 accurate dimming ratio without the need for an externally supplied PWM clock.

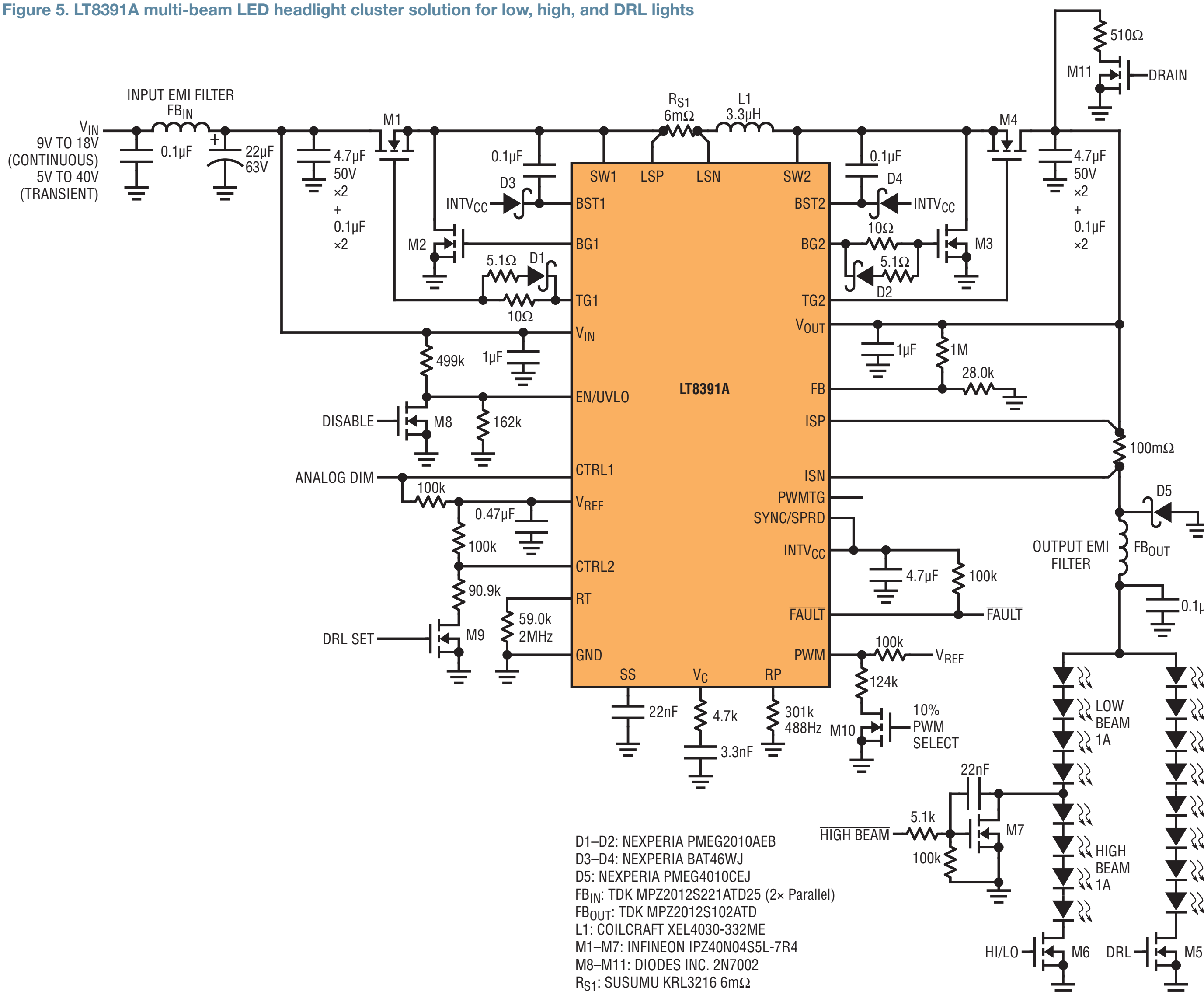
CISPR 25 EMI FOR AUTOMOTIVE APPLICATIONS

The 2MHz LT8391A LED driver in Figure 1 is designed for automotive headlights. It uses AEC-Q100 components and meets CISPR 25 Class 5 radiated EMI standards. Spread spectrum frequency modulation (SSFM) reduces EMI, and also runs flicker-free simultaneously with PWM dimming as shown in Figure 7. Its small size is highlighted by its small inductor and especially small input and output EMI filters. Large LC filters are not needed for 2MHz converters and only small ferrite beads are used for high frequency EMI reduction.

Automotive EMI requirements are not easily met by high power converters. High power switches and inductors, placed on large PCBs next to large capacitors can create undesirable hot loops, especially when a large sense resistor is included. The unique LT8391A buck-boost architecture removes the sense resistor from both the buck and boost switch-pair hot loops, enabling low EMI.

Figures 3 and 4 show measured EMI of the 24W LED driver of Figure 1. Despite this controller's 2MHz operating frequency and 24W of power, this buck-boost passes CISPR 25 Class 5 radiated and conducted EMI. Class 5 is the most stringent requirement and the goal of most automotive EMI testing. Converters that cannot pass Class 5 EMI either get designed out of automotive circuits or must be encased

Figure 5. LT8391A multi-beam LED headlight cluster solution for low, high, and DRL lights



in large metallic EMI shields. Even if the bulkiness of the shield does not create assembly issues, adding them is costly.

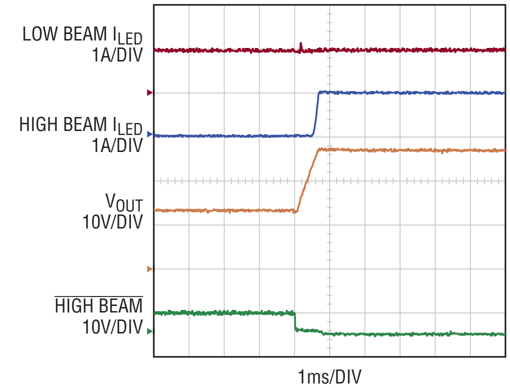
BUCK-BOOST FOR MULTI-BEAM APPLICATIONS

LED headlight clusters can be both innovative and artistically creative. High beams and low beams can be wrapped up with nifty and distinctive daytime running lights (DRL). Because the daytime running lights are only needed when high and low beams are off, a single LED driver can be used to power either the high and low beam LEDs or the daytime running lights. This only works if the LED driver has a flexible input-to-output ratio and can both step-up and step-down the input-to-output voltage. A buck-boost design satisfies this requirement.

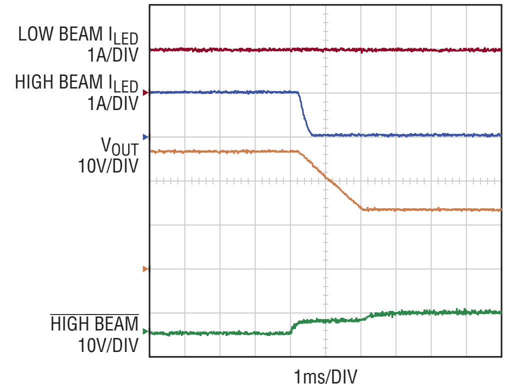
The multi-beam LT8391A buck-boost LED driver in Figure 5 can drive LED string voltages ranging from 3V to 34V. This enables it to drive both a low beam string and create a high beam by adding LEDs to the low beam string. The same driver switches over and drives a higher voltage, yet lower current, DRL. Switching from low-beam-only LEDs to a low/high beam combo string generates no spike on the output voltage or LED current as shown in Figure 6a. The LT8391A can transition between boost, 4-switch buck-boost, and buck regions of operation smoothly. Changing from a small number of LEDs to a high number of LEDs without an LED spike can be challenging for a converter, but this multi-beam circuit does this with ease. Switching back from high and low beams to just low beams is also very clean, without any harmful LED spikes, as shown in Figure 6b.

The same is true when switching to and from the DRL string. Figure 6c demonstrates how the low beam is turned off and the DRL is smoothly connected to the output capacitor. Even the LED current is changed from 1A (high and low beams) to 700mA (8 LEDs DRL) without any

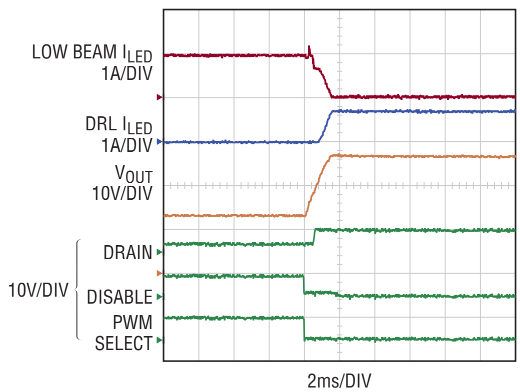
Figure 6. Waveforms show smooth switchover between high + low, low and DRL LED strings for the LT8391A multi-beam application in Figure 5



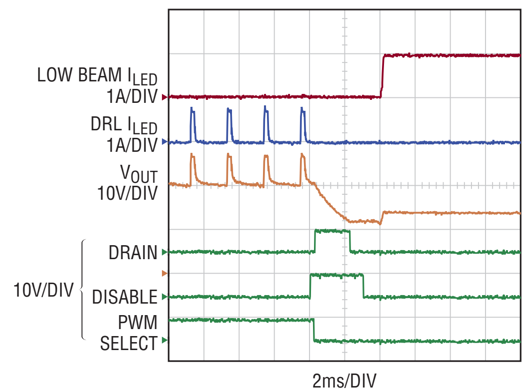
a. low beam to high + low beam



b. high + low beam to low beam



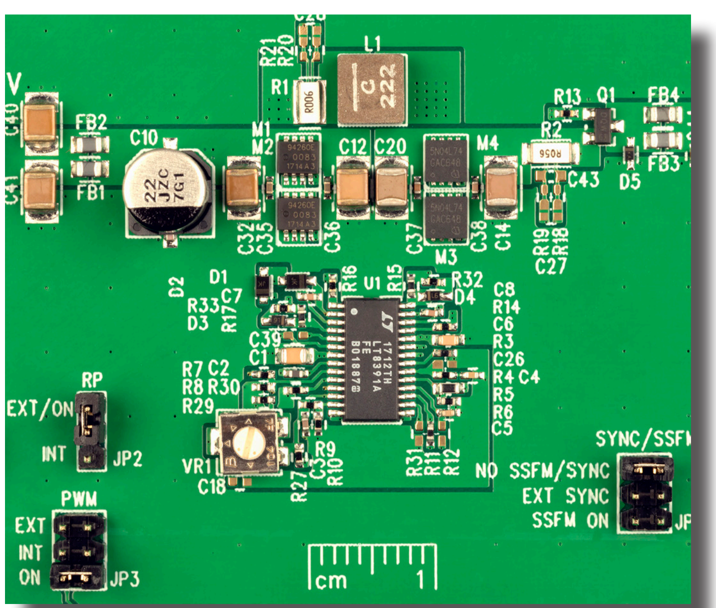
c. low beam to DRL



d. DRL 10% PWM to low beam

issues. Other trim or signal LEDs can be added in as well, and the DRL can be blinked as a signal light. Figure 6d shows how the DRL can be PWM dimmed with the internally set PWM generator and then switched over smoothly to low beams when darkness falls.

Figure 7. Compact solution: 2MHz demonstration circuit DC2575A, featuring LT8391A, drives 16V LEDs at 1.5A



Automotive environments require robust solutions in the face of short-circuits and open LEDs. Short- and open-circuit conditions are safely handled by the multi-beam solution shown in Figure 6, and reported via the converter's fault flag.

FE AND QFN PACKAGES FIT TIGHT SPOTS

The LT8391A is available in a 4mm × 5mm 28-lead QFN for small size and a 28-lead TSSOP FE package for automotive designs. Both packages have thermally enhanced GND pads for power dissipation of the internal $INTV_{CC}$ LDO from higher voltages.

The internal LDO $INTV_{CC}$ regulator of these converters can handle driving four synchronous MOSFETs at 2MHz with about 15nC gate charge. The small size of the LT8391A FE 2MHz 16V, 1.5A demonstration circuit (DC2575A, based on the design of Figure 1) is shown in Figure 7. Only a single 5mm × 5mm inductor is necessary for this high power, versatile application.

The LT8391A LED driver controller is unique in its ability to produce this level of power while operating at 2MHz. The high switching frequency is above the AM band, minimizing the need for EMI filtering.

CONCLUSION

The LT8391A 2MHz, 60V buck-boost LED driver controller powers LED strings in automotive headlights. Its features include its low EMI 4-switch architecture and spread spectrum frequency modulation for meeting CISPR 25 Class 5 EMI requirements. The unique, high switching frequency allows it to operate above the AM band, requiring very little EMI filtering. Its small size and versatility enable use in headlight cluster LED strings of a variety of voltages and currents. ■

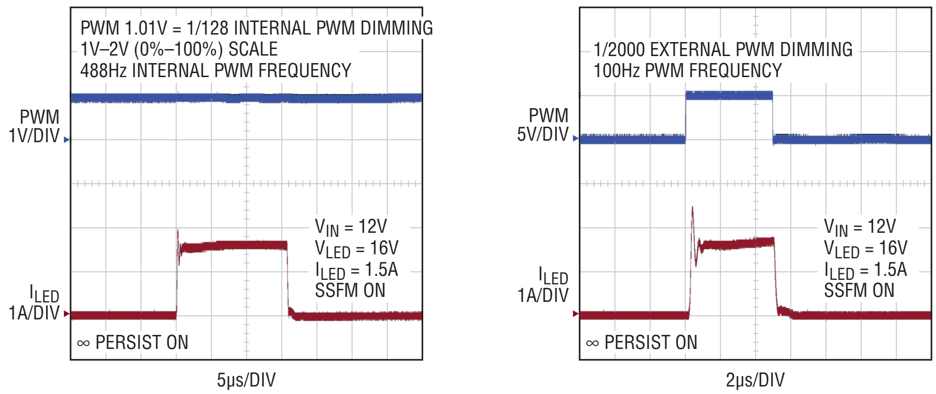


Figure 8. PWM dimming using internal and external PWM options; 1% and 0.05%, respectively

Table 1. High power, high efficiency synchronous buck-boost controllers for automotive power solutions

	LT8390	LT8390A	LT8391	LT8391A
Voltage regulator	✓	✓		
LED driver			✓	✓
Automotive input/output ranges to 60V	✓	✓	✓	✓
Switching frequency	150kHz-650kHz	600kHz- 2MHz	150kHz-650kHz	600kHz- 2MHz
Optimized hot loop layout for low EMI	✓	✓	✓	✓
Spread spectrum frequency modulation for low EMI	✓	✓	✓	✓
Output power	450W+	50W+	450W+	50W+
Package	4mm × 5mm 28-lead QFN, 28-lead TSSOP FE	4mm × 5mm 28-lead QFN, 28-lead TSSOP FE	4mm × 5mm 28-lead QFN, 28-lead TSSOP FE	4mm × 5mm 28-lead QFN, 28-lead TSSOP FE

The Refulator: Precision Voltage Reference is an Accurate Low Noise Regulator for 200mA Loads

Michael B. Anderson

Precision analog designers often lean on the quietly humble voltage reference to power their DAC and ADC converters. This job lies outside the fundamental purview of a reference—ostensibly designed to provide a clean, precise stable voltage to an actual power source, namely a power converter's reference input. With some caveats, references are usually up to the task, emboldening designers to ask references to power increasingly higher current applications. After all, if the reference can power the converter, why not the analog signal chain, or another converter, and on down the list?

The choice between precision and power comes up often in any design process. The brute force approach to making this decision suggests using a reference when precision is demanded, and an LDO when milliwatts of power are required. Besides the additional board space and cost, separate signals must be routed, even if their nominal voltages are the same. And, if a high precision voltage source is required to provide milliwatts of power, the designer is forced to buffer a reference. The LT6658 solves this dilemma by providing two low noise precision outputs with a combined 200mA output current and world-class reference specifications.

Figure 1. Typical application

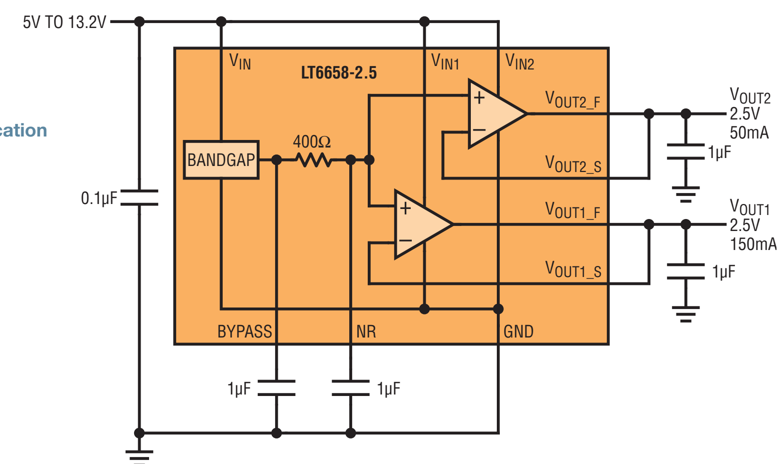
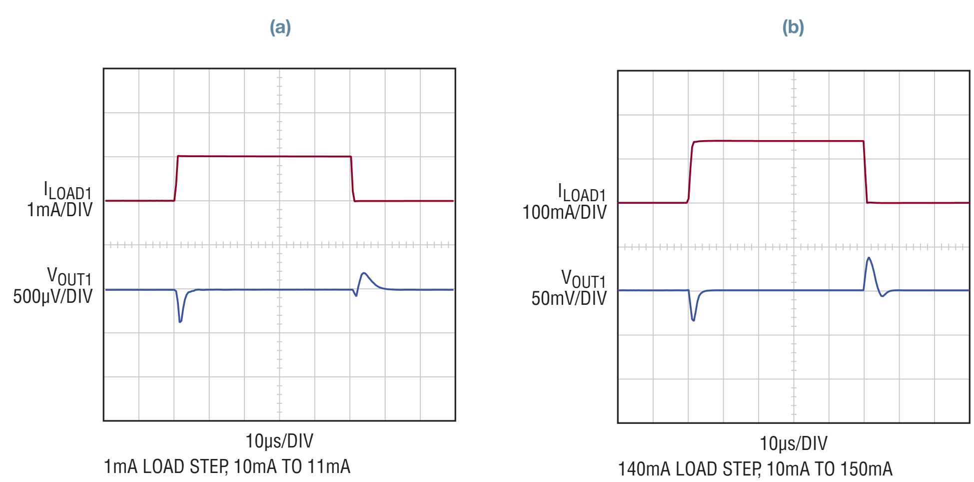


Figure 2. Load step response. (a) 1mA load step (b) 140mA load step



ABOUT THE LT6658 REFERENCE QUALITY LOW DRIFT REGULATOR

The LT6658 is a precision low noise, low drift regulator featuring the accuracy specifications of a dedicated reference and the power capability of a linear regulator. The LT6658 boasts 10ppm/°C drift and 0.05% initial accuracy, with two outputs that can support 150mA and 50mA, respectively, each with 20mA active sinking capability. To maintain accuracy, load regulation is 0.1ppm/mA. Line regulation is typically 1.4ppm/V when the input voltage supply pins are tied together and

The LT6658 is a precision low noise, low drift regulator featuring the accuracy specifications of a dedicated reference and the power capability of a linear regulator. The LT6658 boasts 10ppm/°C drift and 0.05% initial accuracy, with two outputs that can support 150mA and 50mA, respectively, each with 20mA active sinking capability.

less than 0.1ppm/V when the input pins are provided with independent supplies.

To better grasp the LT6658's features and how it achieves its level of performance, a typical application is shown in Figure 1. The LT6658 consists of a bandgap stage, a noise reduction stage and two output buffers. The bandgap and two output buffers are powered separately to provide exceptional isolation. Each output buffer has a Kelvin sense feedback pin for optimum load regulation.

The noise reduction stage consists of a 400Ω resistor with a pin provided for an external capacitor. The RC network acts as a low pass filter, bandlimiting the noise from the bandgap stage. The external capacitor can be arbitrarily large, reducing the noise bandwidth to a very low frequency.

FAST AND QUIET RESPONSE TO LOAD STEPS

As a regulator, the LT6658 supplies 150mA from the V_{OUT1_F} pin with excellent transient response. Figure 2a shows the response to a 1mA load step transient from 10mA to 11mA; Figure 2b shows the response to a 140mA load step from 10mA to 150mA. The source and sink capability of the output buffer enables fast settling of the output. The transient response is short, while excellent load regulation is maintained. Load regulation is typically only 0.1ppm/mA. The second output, V_{OUT2_F}, has a similar response with a 50mA maximum load.

STEP SUPPLY	V_{IN2} (5V-36V)	V_{IN1} (5V-36V)	V_{IN} (5V-36V)	$V_{IN}=V_{IN1}=V_{IN2}$ (5V-36V)	UNITS
BYPASS	0.01	0.02	1.36	1.36	ppm/V
V_{OUT1}	0.07	0.01	1.34	1.43	ppm/V
V_{OUT2}	0.03	0.06	1.39	1.37	ppm/V

Table 1. DC power supply rejection

OUTPUT TRACKING

For applications with multiple converters using different voltage references, the LT6658 outputs track, even if the outputs are set to different voltages, ensuring consistent conversion results. This is possible, because the two outputs of the LT6658 are driven from a common voltage source. The output buffers are trimmed, resulting in excellent tracking and low drift. As the load on V_{OUT1_F} increases from 0mA to 150mA, the V_{OUT2} output changes less than 12ppm as shown in Figure 3. That is, the relationship between the outputs is well maintained even over varying load and operating conditions.

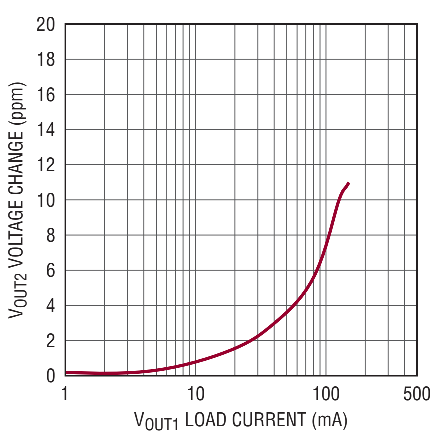


Figure 3. Channel-to-channel load regulation (effect of heating removed)

POWER SUPPLY REJECTION AND ISOLATION

To facilitate exceptional power supply rejection and output isolation, the LT6658 provides three power supply pins. The V_{IN} pin supplies power to the bandgap circuit while V_{IN1} and V_{IN2} supply power to V_{OUT1} and V_{OUT2}, respectively. The simplest approach is to connect all three supply pins together, delivering a typical DC power supply rejection of 1.4ppm/V. When the power supply pins are connected separately and the V_{IN1} supply is toggled, the DC line regulation for V_{OUT2} is 0.06ppm/V.

Table 1 summarizes power supply rejection as each of the power supply pins are changed from 5V to 36V. The V_{IN} supply has the most sensitivity, causing a typical 1.4ppm/V change on the outputs. Supply pins V_{IN1} and V_{IN2} have almost no effect. The measurements in the V_{IN1} and V_{IN2} columns are at the level of the output noise.

Two examples of AC PSRR are shown in Figure 4. The first example has a 1µF capacitor on the NR pin while the second example includes a 10µF capacitor on the NR pin. The larger 10µF capacitor extends the 107dB rejection to 2kHz.

The three supply pins help manage the amount of power dissipated in the package. When supplying a large current, lower the supply voltage to minimize the power dissipation in the LT6658. Less voltage will appear across the output device, resulting in less power consumption and higher efficiency.

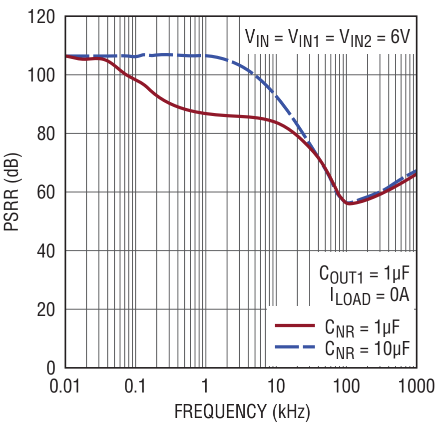


Figure 4. Power supply ripple rejection

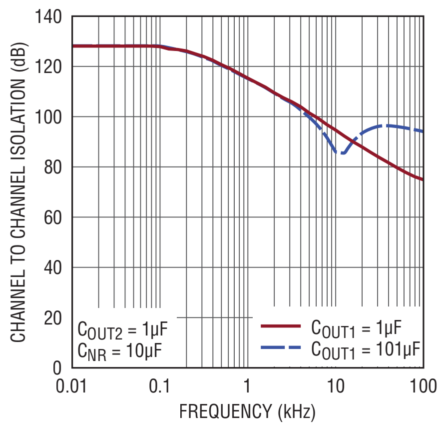


Figure 5. Channel-to-channel V_{OUT1} to V_{OUT2} isolation

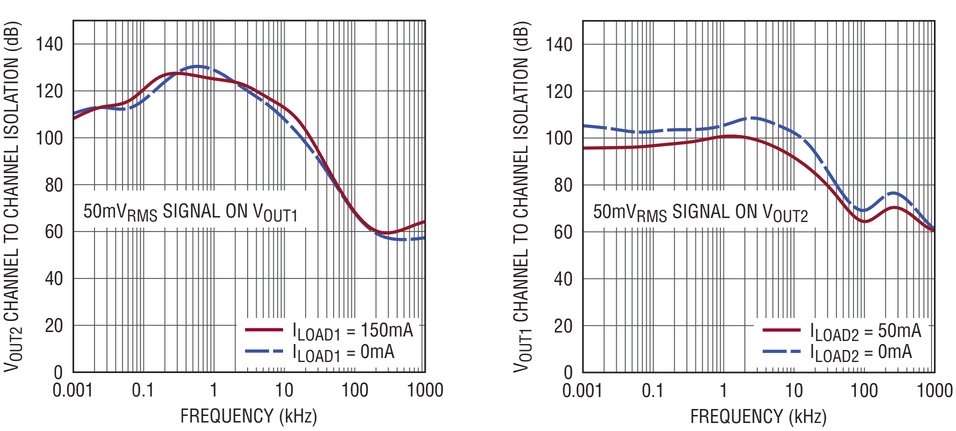
The AC channel-to-channel power supply isolation from V_{IN1} to V_{OUT2} is shown in Figure 5. Here the channel-to-channel power supply isolation is greater than 70dB beyond 100kHz when C_{NR} = 10µF.

Load transients have a minimal effect on the adjacent output. Figures 6a and 6b illustrate channel-to-channel output isolation. One output is wiggled at $50mV_{RMS}$, and the change in in the other is plotted.

Extraordinary AC PSRR can be achieved using the circuit shown in Figure 7. The V_{OUT1} output bootstraps the supplies V_{IN} and V_{IN2}, resulting in a recursive reference.

Figure 6. (a) Channel-to-channel V_{OUT1} to V_{OUT2} load isolation. (b) Channel-to-channel V_{OUT2} to V_{OUT1} load isolation.

(a) (b)



POWER MANAGEMENT AND PROTECTION

The three supply pins help manage the amount of power dissipated in the package. When supplying a large current, lower the supply voltage to minimize the power dissipation in the LT6658. Less voltage will appear across the output device, resulting in less power consumption and higher efficiency.

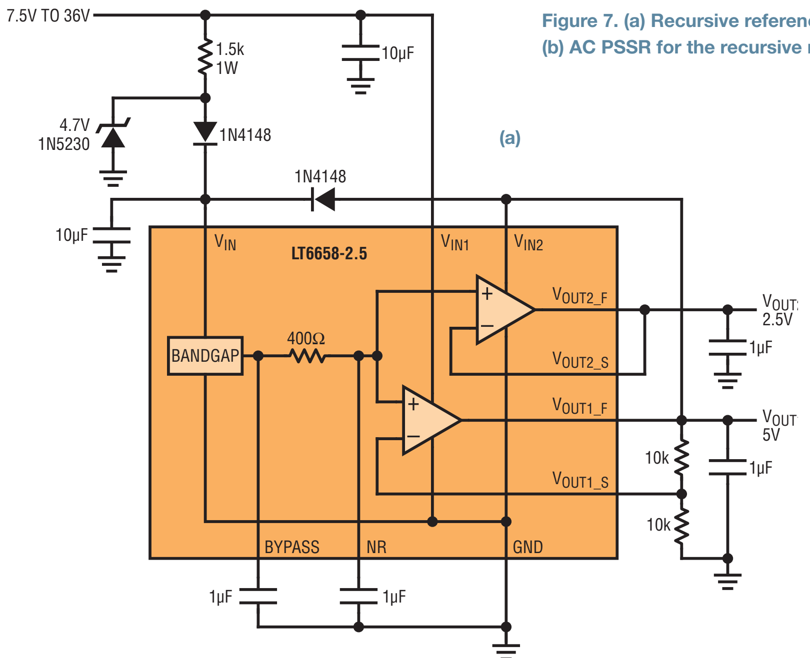
An output disable pin, OD, turns off the output buffers and places the V_{OUT_F} pins in a high impedance state. This is useful in the event of a fault condition. For example, a load may become damaged and shorted. This event can be sensed by external circuitry and both outputs can be disabled. This feature can be ignored and a weak pull-up current will enable the output buffers when the OD pin floats or is tied high.

The LT6658 comes in a MSE-16 exposed pad package with a θ_{JA} as low as 35°C/W. When the supply voltage is high, power efficiency is low, resulting in excessive heat in the package. For example, a 32.5V supply voltage at full load produces 30V • 0.2A of excess power across the output devices. Six watts of excess power would raise the internal die temperature to a dangerous 210°C above ambient. To protect the part, a thermal shutdown circuit disables the output buffers when the die temperature exceeds 165°C.

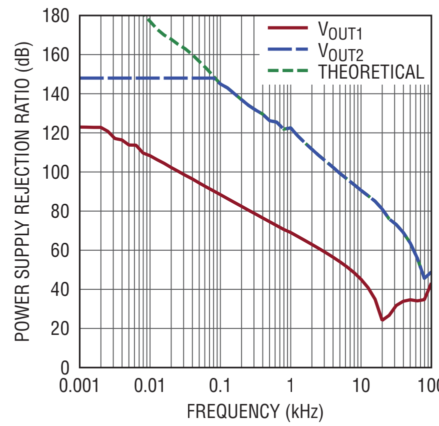
For data converter and other precision applications, noise is an important consideration. The low noise LT6658 can be made even lower with the addition of a capacitor on the NR (noise reduction) pin.

Figure 7. (a) Recursive reference solution (V_{OUT1} supplies power to V_{IN} and V_{IN2})
(b) AC PSSR for the recursive reference circuit

(a)



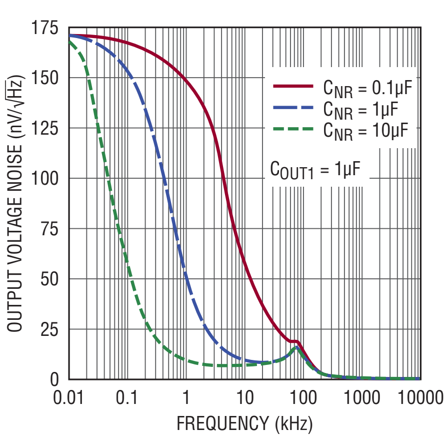
(b)



NOISE

For data converter and other precision applications, noise is an important consideration. The low noise LT6658 can be made even lower with the addition of a capacitor on the NR (noise reduction) pin. A capacitor on the NR pin forms a low pass filter with an on-chip 400Ω resistor. A large capacitor lowers the filter frequency and subsequently, the total integrated noise. Figure 8 shows the effect of increasing the values of the capacitor on the NR pin. With a 10µF capacitor the noise rolls off to about 7nV/√Hz.

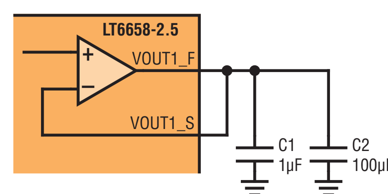
Figure 8. Noise reduction by increasing CNR



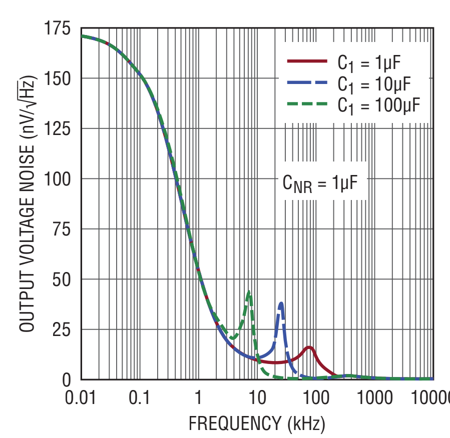
By increasing the output capacitor, the noise can be further reduced. When both the NR and output capacitors are increased, the output noise can be reduced down to a few microvolts. The LT6658 is stable with output capacitance, between 1µF and 50µF. The output is also stable with large capacitance if a 1µF ceramic capacitor is placed in parallel. For example, Figure 9a shows a circuit with 1µF ceramic capacitor in parallel with a 100uF poly-aluminum capacitor.

Figure 9. Noise reduction by increasing C1.

(a)



(b)



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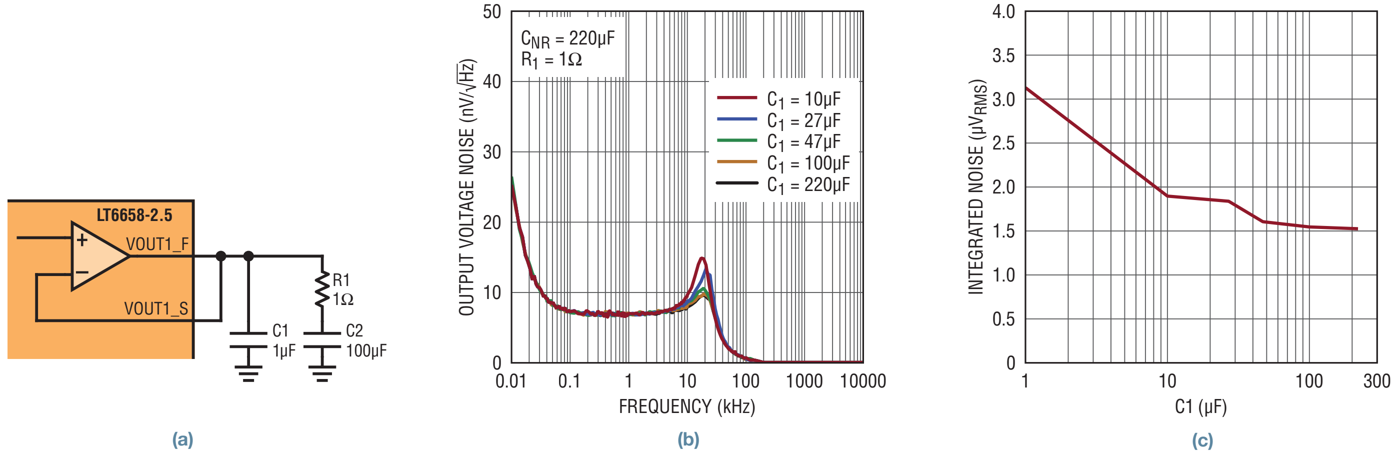


Figure 10. Reduce noise peaking by adding a 1Ω resistor in series with C2.

This configuration remains stable while lowering the noise bandwidth. Figure 9b illustrates the noise response for different values of output capacitance. In all three cases, there is a small 1µF ceramic capacitor in parallel with the larger capacitor.

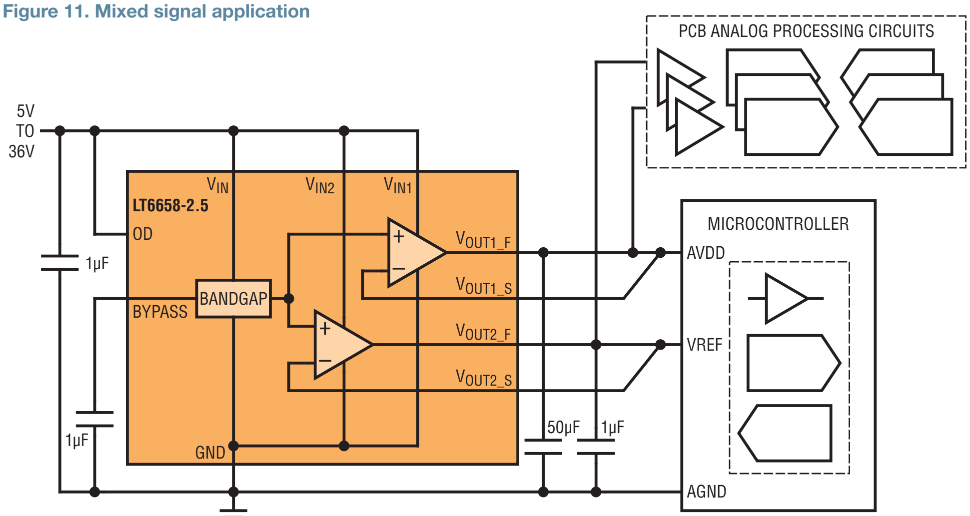
One drawback of this scheme is the noise peaking, which can add to the total integrated noise. To reduce the noise peaking, a 1Ω resistor can be inserted in series with the large output capacitor as shown in Figure 10a. The output voltage noise and total integrated noise are shown in Figures 10b and 10c, respectively.

APPLICATIONS

The LT6658 provides quiet, precise power for a number of demanding applications. In the mixed signal world, data converters are often controlled by microcontrollers or FPGAs. Figure 11 illustrates the general concept. Sensors provide signals to analog processing circuits and converters, all of which need clean power supplies. The microcontroller may have several supply inputs including analog power.

As a general rule, noisy digital supply voltages for the microcontroller should be isolated from the clean precise analog supply and reference. The two outputs of the LT6658 provide excellent channel-to-channel isolation, power supply rejection and supply current capability, ensuring clean power to multiple sensitive analog circuits.

Figure 11. Mixed signal application



The LT6658 is well suited to industrial environments since it can operate with noisy supply rails and where load glitches due to conversions on one output have little influence on the adjacent output. Moreover, when a load demands current on one output, the adjacent output continues to track.

Figure 12. Data acquisition solution

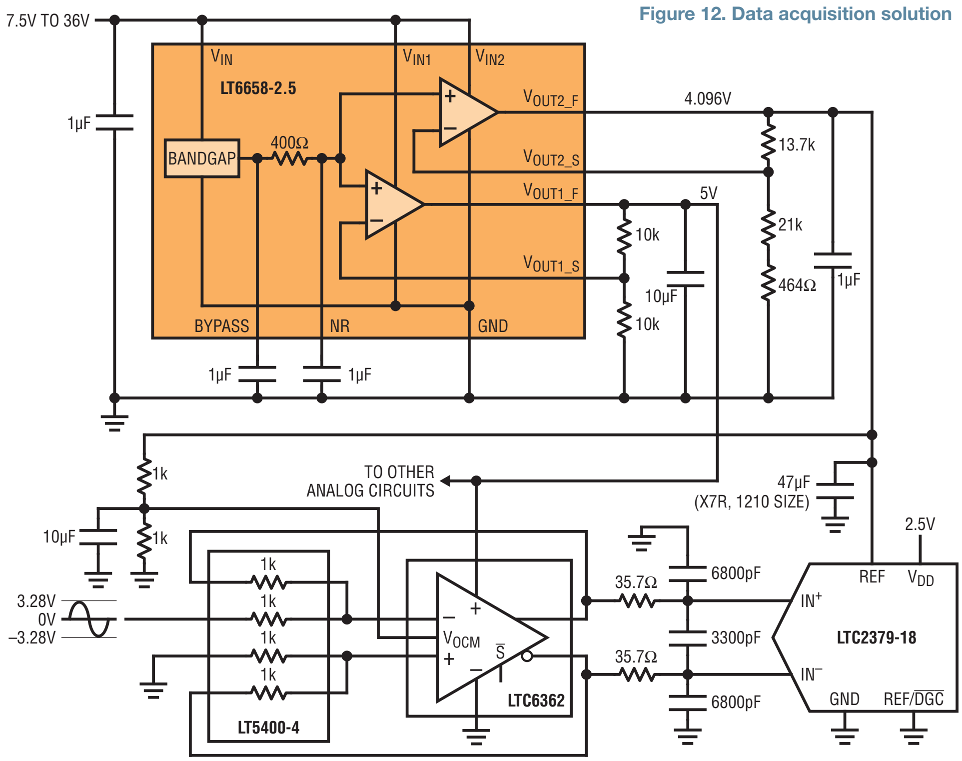


Table 2. Data acquisition circuit example from Figure 12.

PARAMETER	16-BIT SAR	18-BIT SAR
SNR	92.7dB	97.5dB
SINAD	92.1dB	95.9dB
THD	–101.2dB	–101.1dB
SFDR	101.6dB	103.2dB
ENOB	15.01 bits	15.64 bits

The LT6658 is also well suited to industrial environments since it can operate with noisy supply rails and where load glitches due to conversions on one output have little influence on the adjacent output. Moreover, when a load demands current on one output, the adjacent output continues to track.

A real-world example is shown in Figure 12, where the LTC2379-18 high speed ADC circuit is operated with an LT6658. The Kelvin sense input on V_{OUT2} is configured to gain up the 2.5V output to a 4.096V reference voltage and to provide a common mode voltage to the input amplifier, LTC6362. V_{OUT1} is gained up to 5V, providing power to the LTC6362 and other analog circuits that require a 5V rail. Both LT6658 outputs have the maximum load at 150mA and 50mA on V_{OUT1} and V_{OUT2}, respectively.

The SNR, ENOB and THD of this circuit verify the superior performance of the LT6658 as shown in Table 2.

The circuit in Figure 13 illustrates how the LT6658 can power noisy digital circuits while maintaining a quiet, precise reference voltage for a precision ADC. In this application, the LT6658 or a separate LDO supplies a 3.3V rail to a noisy FPGA supply (VCCIO) and some miscellaneous logic on one channel, and 5V to the reference input of the 20-bit ADC on the other channel.

By switching the digital supply between the LT6658 and the LDO, we can assess how well the LT6658 isolates digital noise on one channel from the channel driving the quiet reference input of the 20-bit ADC. Using a clean DC source on the input of the ADC, the noise can be inferred as shown in Figure 14. The histogram shows no appreciable difference in results between the LT6658 or the LDO supplying power to the VCCIO pins of the FPGA, demonstrating the LT6658's robust regulation and isolation.

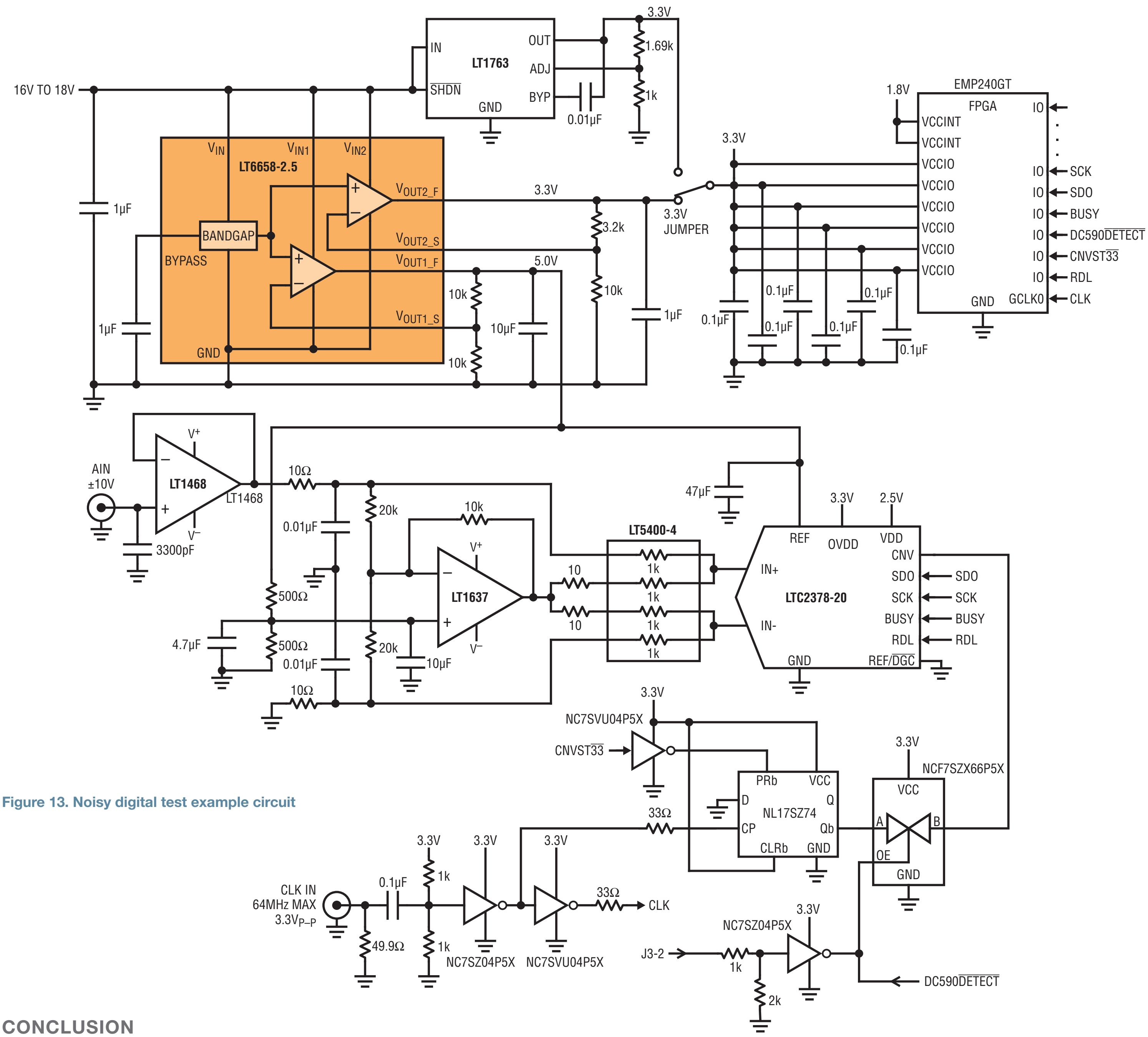


Figure 13. Noisy digital test example circuit

CONCLUSION

The LT6658 is the next step in the evolution of references and regulators. The precision performance and ability to provide a combined 200mA of current from a single package is a paradigm shift for precision analog power. Noise rejection, channel-to-channel isolation, tracking, and load regulation make this product ideal for precision analog reference and power solutions. With this new approach, applications do not need to compromise precision or power. ■

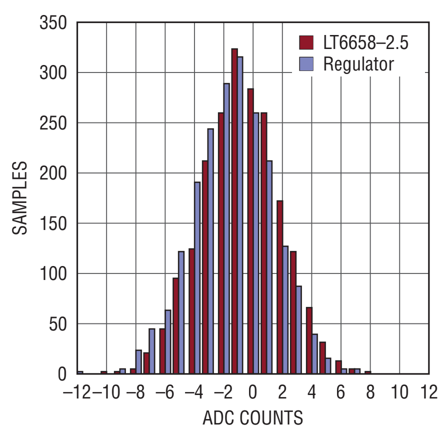


Figure 14. Histogram test results of the circuit in Figure 13

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WORST-CASE CIRCUIT ANALYSIS WITH MINIMAL SIMULATIONS RUNS

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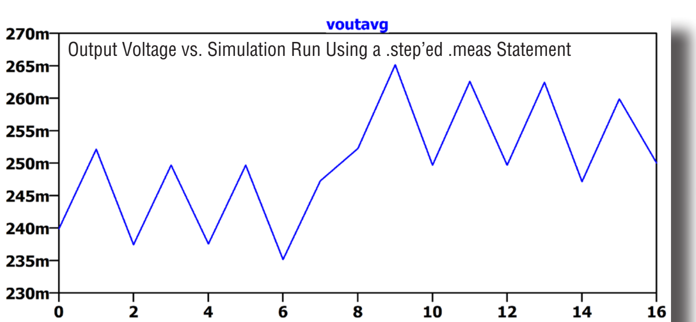
When designing in LTspice®, you may want to assess the impact of component tolerances. For example: what is the gain error introduced by non-ideal resistors in an op amp circuit? LTSpice offers several tools to vary parameters and examine circuit performance over parameter ranges, including use of the functions: .step param, gauss(x), flat(x), and mc(x,y). These functions are powerful, for instance, revealing design performance in terms of component value distributions. Nevertheless, they may not be the quickest way to zero in on worst-case performance.

Using gauss(x), flat(x) and mc(x,y), for example, to produce worst-case results requires a simulation to run a statistically significant number of times. From there, a distribution can be looked at and worst-case values calculated in terms of standard deviations. As the number of parameters multiplies, this can be a data heavy project. In many designs, the worst-case scenarios are often found by focusing on components' maximum deviations from nominal. This article shows how to quickly zero in on circuit performance by exploring circuit performance at the nominal component values and their tolerance limits.



Use LTspice to zero in on worst-case performance by exploring the tolerance limits of components. Here, 16 possible parameter combinations of four resistor values—at their tolerance limits—are simulated and graphed. The effects of tolerance are clearly shown.

SELECTED DEMO CIRCUITS

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

Buck Regulators

- **LT8607:** 2MHz low EMI high voltage synchronous buck regulator (5.5V–42V to 5V at 750mA) www.linear.com/solutions/7864
- **LT8609S:** 2MHz low EMI high voltage synchronous buck regulator (5.5V–42V to 5V at 2A) www.linear.com/solutions/7876
- **LTC3810-5:** High efficiency high voltage buck converter (12V–60V to 5V at 6A) www.linear.com/solutions/4900
- **LTM®4631:** High efficiency, high density, dual 10A buck regulator (4.5V–15V to 1V & 1.2V 10A) www.linear.com/solutions/7377

Operational Amplifiers

- **LT1997-3:** Conversion of single ended pulse to differential output www.linear.com/solutions/7898
- **LT5400/LTC2063:** RTD sensor circuit with ±1°C precision www.linear.com/solutions/7945
- **LT6200/LTC2050:** Low noise, low power photodiode transimpedance amplifier with DC precision www.linear.com/solutions/1205
- **LTC®6258/LTC6992:** Low power sine wave generator www.linear.com/solutions/7971

SELECT 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

- **ADP2443:** 3A, 36V synchronous step-down DC-to-DC regulator www.analog.com/adp2443
- **LT8606:** 42V, 350mA synchronous step-down regulator with 2.5µA quiescent current www.linear.com/LT8606
- **LT8645S:** 65V, 8A synchronous step-down Silent Switcher 2 with 2.5µA quiescent current www.linear.com/LT8645S
- **LTC3886:** 60V dual output step-down controller with digital power system management www.linear.com/LTC3886
- **LTM4650A:** Dual 25A or single 50A DC/DC µModule® buck regulator with 1% DC accuracy www.linear.com/LTM4650A

Multi-Topology Regulators

- **LTC3589:** 8-output regulator with sequencing and I²C www.linear.com/LTC3589

Buck-Boost, Boost, SEPIC & Inverting Regulators

- **LT8362:** Low I_Q boost/SEPIC/inverting converter with 2A, 60V switch www.linear.com/LT8362
- **LT8390A:** 60V synchronous 4-switch buck-boost controller with spread spectrum www.linear.com/LT8390A
- **LTC3106:** 300mA low voltage buck-boost converter with PowerPath™ and 1.6µA quiescent current www.linear.com/LTC3106

MOSFET Drivers

- **LTC7000:** Fast 150V protected high side NMOS static switch driver www.linear.com/LTC7000
- **LTC7003:** Fast 60V protected high side NMOS static switch driver www.linear.com/LTC7003

Operational Amplifiers

- **LTC2063:** 2µA supply current, low I_B, zero-drift operational amplifier www.linear.com/LTC2063
- **LTC6259:** Dual 1.3MHz, 20µA power efficient rail-to-rail I/O op amps www.linear.com/LTC6259

Voltage Monitors

LTC2965: 100V micropower single voltage monitor www.linear.com/LTC2965 ■

Power User Tip

ARBITRARY STATE MACHINE

LTspice now includes an arbitrary state machine, which operates on data structures with rules and functions. State machine models are arbitrary in their levels of abstraction, so they can provide encapsulation of any design with states, from hardware to software. Let's explore the classic "divide-by-two counter" with a reset as an example of a state machine in LTspice.

The state machine is encapsulated by its .machine and .endmachine statements in the schematic as a SPICE directive.

Each state of the state machine is defined using a .state command. The first state listed is the initial state, otherwise the order of the states makes no difference. The name of the state can be anything and the output of the state is defined by a value.

```
.state <name> <value>
```

The .rule command defines the transition between the old state to the new state using a condition statement.

In our case it is a set of expressions that evaluates if V(IN) is greater than or less than 0.5V.

There is no limit to the number of rules, but they are checked in order, with only one rule executing per time step.

```
.rule <old state> <new state> <condition>
```

The last command in the set of .rule expressions is the reset condition that uses a wildcard character '*' to match any of the old states. Using the wildcard character implies that this rule will be checked first and if true, trumps the next rule in the sequence.

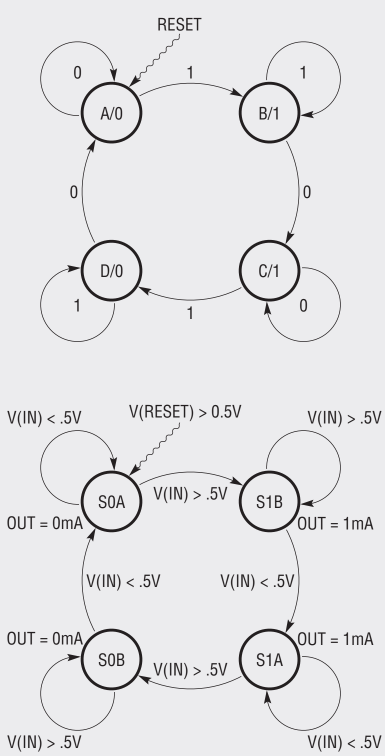
```
.rule * <new state> <condition>
```

The .output statement is implemented as a current source and requires an external device, such as a resistor, to read out the current. As shown in the example, a 1k ground-referenced resistor is used; and if needed to slow transitions, add some parallel capacitance. The expression can be a combination of logic or state. Even though the .output statement is implemented as a current source, it is not designed to directly connect to a device pin as in a current monitoring application.

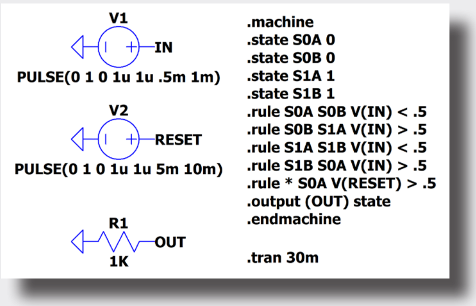
```
.output (node) <expression>
```

Happy simulations!

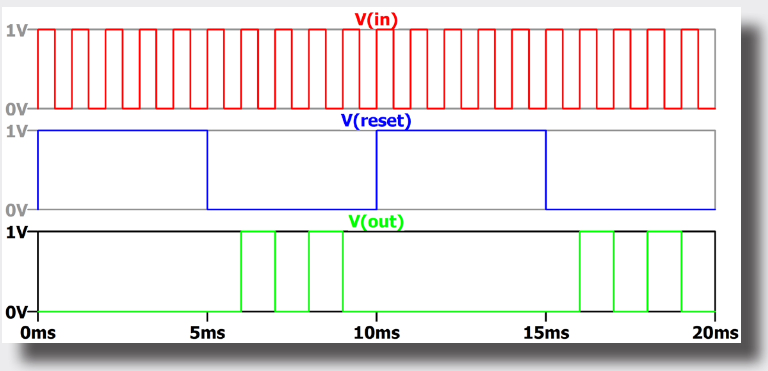
Simplified state diagram of divide-by-two counter; and state diagram showing the values in LTspice



LTspice schematic of state machine: divide-by-two counter with reset



LTspice waveform shows results of divide-by-two counter with reset



Pocket-Size White Noise Generator for Quickly Testing Circuit Signal Response

Aaron Schultz and Peter Haak

Noise in electrical circuits is typically the enemy. Any self-respecting circuit should output as little noise as possible. Nevertheless, there are cases where a well-characterized source of noise with no other signal is entirely the desired output.

Circuit characterization is such a case. The outputs of many circuits can be characterized by sweeping the input signal across a range of frequencies and observing the response of the design. Input sweeps can be composed of discrete input frequencies or a "swept sine." Extremely low frequency sine waves (below 10Hz) are difficult to produce cleanly. A processor, DAC, and some complex, precise filtering can produce relatively clean sine waves; but, for each frequency step, the system must settle, making slow work of sequential full sweeps featuring many frequencies. Testing fewer discrete frequencies can be faster, but increases the risk of skipping over critical frequencies where high Q phenomena reside.

A white noise generator is simpler and faster than a swept sine wave because it effectively produces all frequencies at the same time with the same amplitude. Imposing white noise at the input of a device under test (DUT) can quickly produce an overview of the frequency response over an entire frequency range. In this case, there is no need for expensive or complex swept sine wave generators. Rather, simply connect the DUT output to a spectrum analyzer and watch. Using more averaging and longer acquisition times produces a more accurate output response across the frequency range of interest.

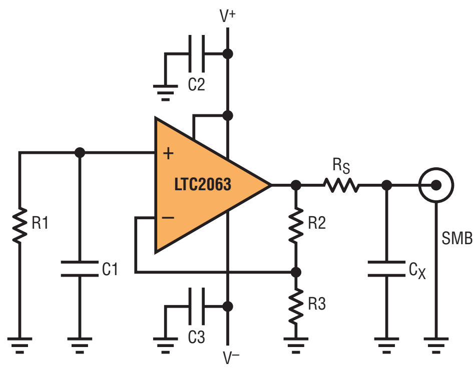


Figure 1. Full schematic of white noise generator. Low drift micropower LTC2063 amplifies the Johnson noise of R1.

The expected response of the DUT to white noise is frequency-shaped noise. Using white noise in this fashion can quickly expose unexpected behavior such as weird frequency spurs, strange harmonics and undesirable frequency response artifacts.

Table 1. Noise voltage density of various resistors

RESISTOR	NOISE VOLTAGE DENSITY
10Ω	0.402nV/√Hz
100Ω	1.27nV/√Hz
1k	4.02nV/√Hz
10k	12.7nV/√Hz
100k	40.2nV/√Hz
1M	127nV/√Hz
10M	402nV/√Hz

Furthermore, a white noise generator allows a careful engineer to test a tester. Lab equipment that measures frequency response should produce a flat noise profile when measuring a known flat white noise generator.

On the practical side, a white noise generator is easy to use, small enough for compact lab setups, portable for field measurements, and inexpensive. Quality signal generators with myriad settings are attractively versatile; however, versatility can hamper quick frequency response measurements. A well-designed white noise generator requires no controls, yet produces a fully predictable output.

NOISY DISCUSSION

Resistor thermal noise, sometimes called Johnson noise or Nyquist noise, arises from thermal agitation of charge carriers inside a resistor. This noise is approximately white, with nearly Gaussian distribution. In electrical terms, the noise voltage density is given by

$$V_{NOISE} = \sqrt{(4k_BTR)}$$

where k_B is the Boltzmann's constant, T the temperature in degrees Kelvin, and R the resistance. Noise voltage arises from the random movement of charges flowing through the basic resistance, a sort of $R \bullet I_{NOISE}$. Table 1 shows examples at 20°C.

A white noise generator is simpler and faster than a swept sine wave because it effectively produces all frequencies at the same time with the same amplitude. Imposing white noise at the input of a device under test (DUT) can quickly produce an overview of the frequency response over an entire frequency range.

A 10M resistor, then, represents a $402nV/\sqrt{Hz}$ wideband voltage noise source in series with the nominal resistance. A gained up resistor-derived noise source is fairly stable as a lab test noise source, as R and T variations affect noise only by square root. For instance, a change of 6°C from 20°C is a change of 293K to 299K. Because noise density goes as the square root of temperature, a change of 6°C temperature leads to a relatively small 1% noise density change. Similarly with resistance: a 2% resistance change leads to a 1% noise density change.

Consider Figure 1. A 10M resistor R1 generates white, Gaussian noise at the positive terminal of an op amp. Resistors R2 and R3 gain the noise voltage to the output. Capacitor C1 filters out chopper amplifier charge glitches. Output is a $10\mu V/\sqrt{Hz}$ white noise signal.

- Gain (1 + R2/R3) is high, 21V/V in this example.
- Even if R2 is high (1M), the noise from R2 compared to the gained up R1 noise is inconsequential.
- An amplifier for the circuit must have sufficiently low input-referred voltage noise so as to let R1 dominate as the noise source. The reason: the resistor noise should dominate the overall accuracy of the circuit, not the amplifier.
- An amplifier for the circuit must have sufficiently low input-referred current noise to avoid (I_N • R2) to approach (R1 noise • Gain) for the same reason.

HOW MUCH AMPLIFIER VOLTAGE NOISE IS ACCEPTABLE IN THE WHITE NOISE GENERATOR?

Table 2 shows the increase in noise from adding independent sources. A change from $402nV/\sqrt{Hz}$ to $502nV/\sqrt{Hz}$ is only 1.9dB in log volts, or 0.96 power dB. With op amp noise ~50% of the resistor noise, a 5% uncertainty in op amp V_{NOISE} changes the output noise density by only 1%.

A white noise generator could employ only an op amp, without a noise-generating resistor. Such an op amp must exhibit a flat noise profile at its input. However, often the noise voltage is not accurately defined, and has a large spread over production, voltage and temperature.

Other white noise circuits may operate based on a Zener diode with far less predictable characteristics. Finding an optimal Zener diode for stable noise with µA of current can be difficult however, particularly at low voltage (< 5V).

Some high end white noise generators are based on a long pseudorandom binary sequence (PRBS) and special filters. Using a small controller + DAC may be adequate; however, making sure that the DAC does not produce settling glitches, harmonics or intermodulation products is something for experienced engineers. Additionally, choosing the most appropriate PRBS sequence adds complexity and uncertainty.

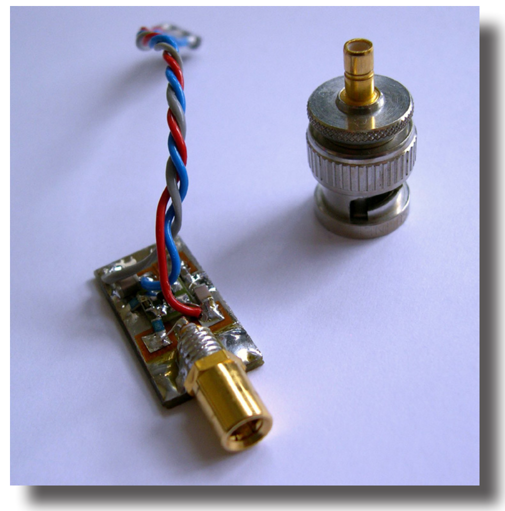


Figure 2. Prototype pocket-size white noise generator

Table 2. Contribution of op amp noise

$R_{NOISE}(nV/\sqrt{Hz})$	AMP e_n	TOTAL INPUT REFERRED
$402nV/\sqrt{Hz}$	300	$501.6nV/\sqrt{Hz}$
$402nV/\sqrt{Hz}$	250	$473.4nV/\sqrt{Hz}$
$402nV/\sqrt{Hz}$	200	$449.0nV/\sqrt{Hz}$
$402nV/\sqrt{Hz}$	150	$429.1nV/\sqrt{Hz}$
$402nV/\sqrt{Hz}$	100	$414.3nV/\sqrt{Hz}$

With approximately 300Hz–400Hz of flat bandwidth, the LTC2063 resistor-noise-based circuit could be useful to test some instruments for 50Hz/60Hz mains frequency, perhaps geophone applications. The range is suitable for testing various "VLF" applications (e.g., sensor systems), as the frequency range extends down to << 0.1Hz.

LOW POWER ZERO-DRIFT SOLUTION

Two project design goals dominate this project:

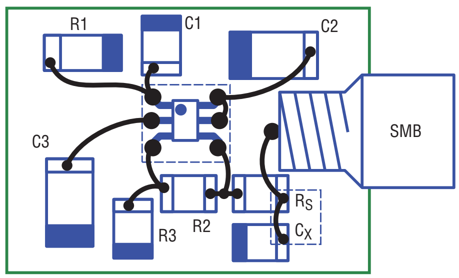
- An easy-to-use white noise generator must be portable, i.e., battery powered, which means micropower electronics.
- The generator must provide uniform noise output even at low frequencies, below 0.1Hz and beyond.

Considering the preceding noise discussion and these critical constraints, the LTC2063 low power zero drift op amp fits the bill.

The noise voltage of a 10M resistor is 402nV/√Hz; LTC2063's is roughly half. The noise current of a 10M resistor is 40fA/√Hz; the LTC2063's is less than half. The LTC2063 fits neatly into a battery application inasmuch as its supply current 1.4µA typical, and total supply can go down to 1.7V (rated at 1.8V). Since low frequency measurements by definition require long settling times, this generator must remain powered by a battery for extended periods of time.

Noise density of the LTC2063 input is roughly 200nV/√Hz, and noise is predictable and flat over the frequency range (within ±0.5dB). Assuming that the LTC2063's noise is 50% of thermal noise and op amp voltage noise changes 5%, output noise density changes only 1%.

Zero-drift op amps do not have zero 1/f noise by design. Some are better than others, and, especially for current noise, it is more common that the wideband spec is wrong or that 1/f noise is much higher than suggested in the data sheet. For some zero-drift op amps, the data sheet noise plot does not go down to the mHz frequency region, possibly masking 1/f noise.



NOTE: BLUE FILL SMD TERMINALS ARE GROUNDED
R1 = 10MΩ MMA0204 (MINIMELF)
VISHAY/BEYSCHLAG 1% TC50 (= THIN FILM)
R2 = 1M, R3 = 49k9; R_S = 10k; all 1% TC100 THICK FILM
C1 = 22pF COG 5%; C2/C3 = 0.1µF COG
C_X = 47nF COG 5% (SEE TEXT: "OPTIONAL TUNING")

Figure 3. Gizmo layout

A chopper stabilized op amp could be a solution to keep the noise "flat" at very low frequency. That said, the high frequency noise bump and switching noise must not spoil the performance. The data shown here supports the use of LTC2063 in the face of these challenges.

CIRCUIT DESCRIPTION

The thin film R1 (Vishay/Beyschlag MMA0204 10MΩ) generates most of the noise. The MMA0204 is one of few 10M options to combine high quality with low cost. In principle, R1 could be any 10M, as signal current is very small, so 1/f noise can be neglected. It is best to avoid low cost thick film chips of questionable accuracy or stability for the primary element of this generator.

For best accuracy and long term stability, R2, R3, R_S could be 0.1% thin film, e.g., TE CPF0603. C2/C3 could be one of most dielectrics; CoG can be used to guarantee low leakage current.

IMPLEMENTATION DETAILS

Loop area R1/C1/R3 should be minimized for best EMI rejection. Additionally, R1/C1 should be very well shielded from electrical fields; see "EMI Considerations" below. Although not critical, as noted above, R1 should be shielded from large temperature changes. With good EMI shielding, thermal shielding is often adequate.

The LTC2063 rail-to-rail input voltage transition region of the V_{CM} range should be avoided, as crossover may result in higher, less stable noise. For best results, use at least 1.1V for V^+ with the input at 0 common mode.

Note that R_S of 10k may seem high, but the micropower LTC2063 presents a high output impedance; even 10k does not fully decouple the LTC2063 from load capacitance at its output. For this white noise generator circuit, some output capacitance that leads to peaking can be a design feature rather than a hazard.

The output sees 10k R_S and a 50nF C_X to ground. This capacitor C_X will interact with the LTC2063 circuit, resulting in some peaking in the frequency response. This peaking can be used to extend the flat bandwidth of the generator, in much the same way that port holes in loudspeakers attempt to expand the low end. A high-Z load is assumed (> 100k), as a lower-Z load would significantly reduce output level and may also affect peaking.

Zero-drift op amps do not have zero 1/f noise by design. Some are better than others, and, especially for current noise, it is more common that the wideband spec is wrong or that 1/f noise is much higher than suggested in the data sheet. For some zero-drift op amps, the data sheet noise plot does not go down to the mHz frequency region, possibly masking 1/f noise.

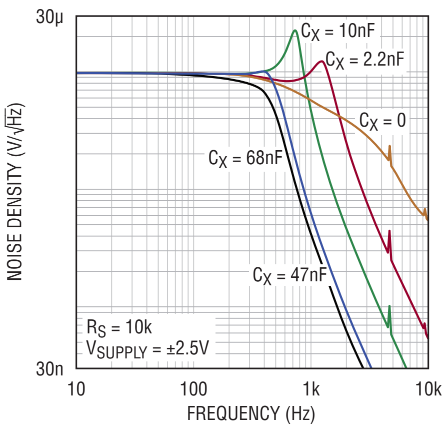


Figure 4. Output noise density of design in Figure 1

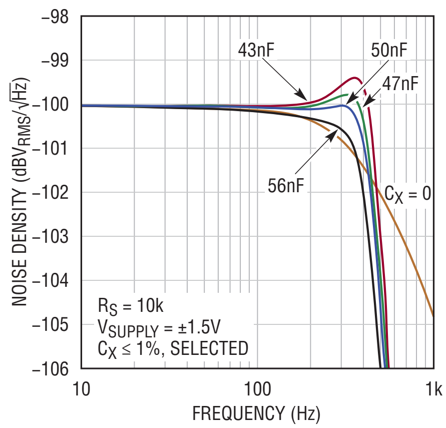


Figure 5. Zoomed in view of output noise density of design in Figure 1

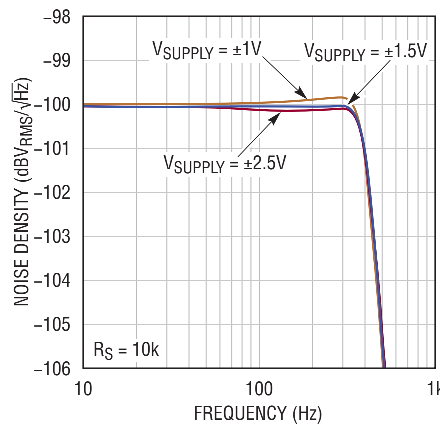


Figure 6. Output noise density for various supply voltages

OPTIONAL TUNING

Several IC parameters (e.g., R_{OUT}, GBW) affect flatness at the high frequency limit. Without access to a signal analyzer, the recommended value for C_X is 47nF, which typically yields 200Hz–300Hz (–1dB) bandwidth.

Nevertheless, C_X can be optimized for either flatness or bandwidth, with C_X = 30nF–50nF typical. For wider bandwidth and more peaking, use a smaller C_X. For a more damped response, use a larger C_X.

Critical IC parameters are related to op amp supply current: parts with low supply current may require a somewhat larger C_X, while parts with high supply current most likely require less than 30nF while achieving wider flat bandwidth.

Plots shown here highlight how C_X values affect closed loop frequency response.

MEASUREMENTS

Output noise density vs C_X (at R_S = 10k, ±2.5V supply) is reported in Figure 4. The output RC filter is effective in eliminating clock noise. The plot shows output vs frequency for C_X = 0 and C_X = 2.2nF/10nF/47nF/68nF.

C_X = 2.2nF exhibits mild peaking, while peaking is strongest for C_X = 10nF, gradually decreasing for larger C_X. The trace for C_X = 68nF shows no peaking, but has visibly lower flat bandwidth. A best result is for C_X ~ 47nF; clock noise is three orders of magnitude below signal level. Due to limited vertical resolution, however, it is impossible to judge with fine precision the flatness of output amplitude vs frequency. This plot was produced using ±2.5V battery supply, though the design allows use of two coin cells (about ±1.5V).

Figure 5 shows flatness "magnified" on the Y-axis. For many applications, flatness within 1dB is enough to be useful, and < 0.5dB is exemplary. Here, C_X = 50nF is best (R_S = 10k, V_{SUPPLY} ±1.5V); C_X = 45nF … 55nF is acceptable.

High resolution flatness measurements take time: for this plot (10Hz–1kHz, 1000 averages) about 20 minutes per trace. The standard solution uses C_X = 50nF. The traces shown for 43nF, 47nF and 56nF, all Cs < 0.1% tolerance, show a small but visible deviation from best flatness. The orange trace for C_X = 0 was added to show that peaking increases flat bandwidth (for Δ = 0.5dB, from 230Hz to 380Hz).

2× 0.1µF C0G in series is probably the simplest solution for an accurate 50nF. 0.1µF C0G 5% 1206 is easy to procure from Murata, TDK, Kemet. Another option is a 47nF C0G (1206 or 0805); this part is smaller, but may not be as commonly available. As stated above, optimum C_X varies with actual IC parameters.

Flatness was also checked vs supply voltage; see Figure 6. The standard circuit

The white noise generator shown here is a small but essential tool. With long measurement times the norm for LF applications, a simple, reliable, pocketable device that can produce near instantaneous circuit characterization is a welcome addition to the engineer's toolbox. Unlike complex instruments with numerous settings, this generator requires no user manual.

is ±1.5V. Changing supply voltage to ±1.0V or ±2.5V shows a small change in peaking as well as a small change in the "flat" level (due to V_N changing vs supply, with thermal noise dominant). Both peaking and "flat" level change ~0.2dB over the full range of supply voltage. The plot suggests good amplitude stability and flatness when the circuit is powered from two small batteries.

For this prototype at ±1.5V supply, flatness was within 0.5dB up to approximately 380Hz. At ±1.0V supply, flat level and peaking slightly increase. For ±1.5V to ±2.5V supply voltage, output level does not visibly change. Total V_{P-P} (or V_{RMS}) output level depends on the "fixed" $10\mu V/\sqrt{Hz}$ density, as well as on bandwidth. For this prototype, output signal is ~$1.5mV_{P-P}$. At some very low frequency (mHz range), noise density may increase beyond the specified $10\mu V/\sqrt{Hz}$. For this prototype it was verified that at 0.1Hz, noise density is still "flat" at $10\mu V/\sqrt{Hz}$.

Stability vs temperature: thermal noise dominates, so for T = 22(±6)°C, amplitude change is ±1%, a change that would barely be visible on a plot.

EMI CONSIDERATIONS

The prototype uses a small copper foil with Kapton insulation as a shield. This foil, or "flap," is wrapped around the input components (10M + 22pF), and soldered to ground on the PCB backside. Changing the position of the flap has significant effect on sensitivity to EMI and risk of low frequency (LF) spurs. Experimentation suggests that LF spurs that occasionally show are due to EMI, and that spurs can be prevented with very good shielding. With the flap, the prototype gives a clean response in the lab, without any additional mu-metal shielding. No mains noise or other spurs appear on a spectrum analyzer. If excess noise is visible on the signal, additional EM-shielding might be needed.

When an external power supply is used instead of batteries, common mode current can easily add to the signal. It is recommended to connect the instrument grounds with a solid wire and use a CM-choke in the supply wires to the generator.

LIMITATIONS

There are always applications that require more bandwidth, like full audio range or ultrasound range. More bandwidth is not realistic on a few µA of supply current. With approximately 300Hz–400Hz of flat bandwidth, the LTC2063 resistor-noise-based circuit could be useful to test some instruments for 50Hz/60Hz mains frequency, perhaps geophone applications. The range is suitable for testing various "VLF" applications (e.g., sensor systems), as the frequency range extends down to << 0.1Hz.

The output signal level is low (< $2mV_{P-P}$). A follow-on LTC2063 configured as a non-inverting amp with a gain of five and further RC output filter can provide a similarly well controlled flat wideband noise output to 300Hz, with larger amplitude.

In the case that does not maximize the closed loop frequency range, a capacitor across the feedback resistor can lower the overall bandwidth. In this case the effects of R_S and C_X will have less, or even negligible effect at the edge of the closed loop response.

CONCLUSION

The white noise generator described here is a small but essential tool. With long measurement times the norm for LF applications, a simple, reliable, pocketable device that can produce near instantaneous circuit characterization is a welcome addition to the engineer's toolbox. Unlike complex instruments with numerous settings, this generator requires no user manual. This particular design features low supply current, essential for battery-powered operation in long duration VLF application measurements. When supply current is very low, there is no need for on/off switches. A generator that works on batteries also prevents common mode currents.

The LTC2063 low power zero-drift op amp used in this design is the key to meeting the constraints of the project. Its features enable use of a noise generating resistor gained up by a simple noninverting op amp circuit. ■

Power Shorts

150V FAST HIGH SIDE PROTECTED N-CHANNEL MOSFET DRIVER: 100% DUTY CYCLE CAPABILITY

The Power by Linear LTC7000/-1 is a high speed, high side N-channel MOSFET driver that operates up to a 150V supply voltage. Its internal charge pump fully enhances an external N-channel MOSFET switch, allowing it to remain on indefinitely. The LTC7000/-1's powerful 1Ω gate driver can drive large gate capacitance MOSFETs with very short transition times, ideal for both high frequency switching and static switch applications.

The LTC7000/-1 operates over a 3.5V to 135V, 150V (max) input supply range with a 3.5V to 15V bias voltage range. It detects an overcurrent condition by monitoring the voltage across an external sense resistor placed in series with the drain of the external MOSFET. When the LTC7000/-1 senses that the switch current has exceeded a preset level, a fault flag is asserted and the switch is turned off for a period of time set by an external timing capacitor. After a predetermined time period, the LTC7000/-1 automatically retries.

The LTC7000/-1 is designed to receive a ground referenced, low voltage digital input signal and quickly drive a high side N-channel power MOSFET whose drain can be as high as 150V above ground. The fast 13ns rise and fall times, when driving a 1,000pF load, minimize switching losses. The LTC7000 is the full featured device and has additional features over the LTC7000-1, including enable, overvoltage lockout, adjustable current limit and current monitoring.

The LTC7000 is available in an MSOP-16 package; the LTC7000-1 in an MSOP-16 (12) with high voltage spacing.

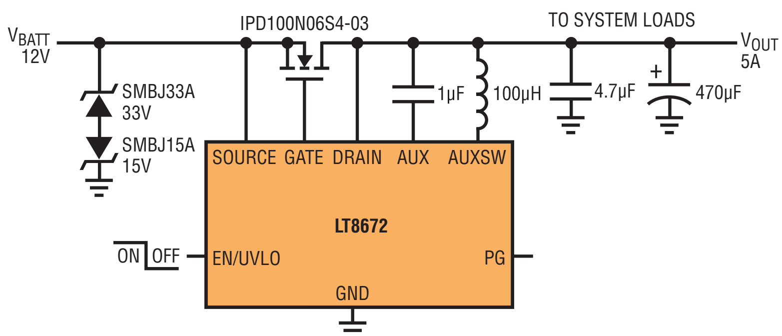
105V, 2.3A SYNCHRONOUS STEP-DOWN REGULATOR: 96% EFFICIENCY, ULTRALOW EMI/EMC

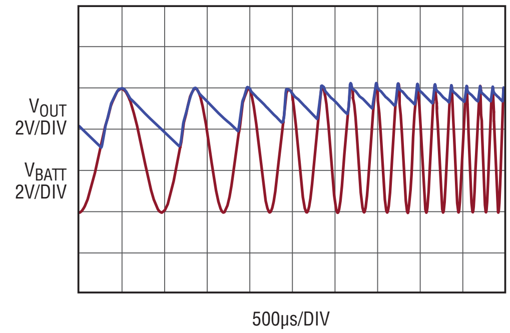
The Power by Linear LTC7103 is a 2.3A, 105V input capable synchronous step-down switching regulator. Its wide 4.4V to 105V input voltage range is designed for operation from a continuously high voltage input source or from an input that has high voltage surges, eliminating the need for external surge suppression devices. This makes the LTC7103 ideal for a variety of transportation, industrial and communications applications such as 48V automotive, 36V to 72V telecom, avionics and dual battery vehicle systems.

The LTC7103's high efficiency internal power switches can deliver up to 2.3A of continuous output current. The LTC7103 incorporates proprietary technology that reduces EMI/EMC emissions to an ultralow level, easily passing automotive CISPR 25, Class 5 limits without sacrificing efficiency. The LTC7103 delivers efficiencies over 96% while regulating a 12V output and over 90% while regulating a 3.3V output. To avoid noise-sensitive frequency bands, the switching frequency can be set between 200kHz and 2MHz, or synchronized anywhere in this range using the LTC7103's internal phase-locked loop.

The LTC7103 uses a unique constant frequency average current mode control architecture. This enables a fast transient response with excellent loop stability as well as fast and accurate output current programming and monitoring with no external sense resistor. This adjustable, brick-wall style current limit feature makes the LTC7103 well suited for current source applications such as battery or capacitor charging and LED lighting.

The LTC7103 draws only 2μA of input quiescent current while regulating the output voltage at no load, extending battery life in always-on applications. Low ripple Burst Mode® operation maintains high efficiency at light load currents while keeping output ripple small. To further minimize ripple, a pulse-skipping mode can also be selected. The LTC7103 features a low minimum on-time of 40ns and a maximum duty cycle of 100%, enabling the output voltage to be set anywhere from 1V up to the input voltage. The LTC7103 features eight pin-selectable fixed output voltage set points that include commonly used rails from 1.2V to 15V. Preprogrammed output voltages save board space and reduce the no-load quiescent current by eliminating the need for an external resistor divider. Internal voltage loop compensation automatically adjusts based on the switching frequency to ensure both speed and stability. Alternatively, the voltage loop can be optimized externally using OPTI-LOOP® compensation. The LTC7103 is packaged in a thermally enhanced 5mm × 6mm QFN-36(26) package with high voltage pin spacing. ■





LT8672 12V, 5A AUTOMOTIVE REVERSE BATTERY PROTECTION

The Power by Linear LT®8672 is an active rectifier controller for reverse input protection. It drives an external N-channel MOSFET to replace a power Schottky diode. Its very low quiescent current and fast transient response meet the tough requirements in automotive applications where AC input signals of up to 100kHz are present. These signals are rectified with minimum power dissipation on the external FET, simplifying thermal management on the PCB.

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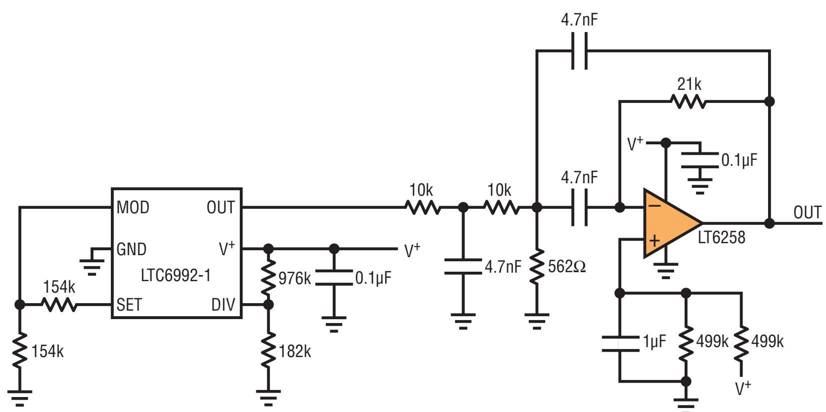

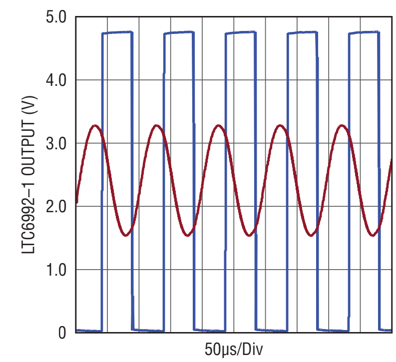

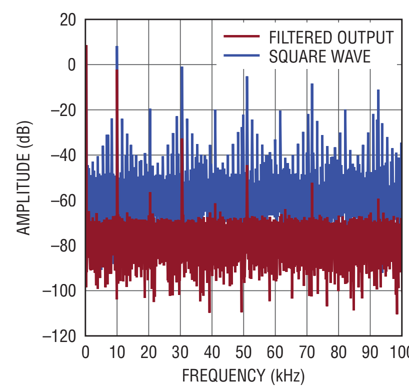

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LTC6258 LOW POWER SQUARE WAVE/SINE WAVE OSCILLATOR

A low power sine wave generator can be derived by driving a square wave into the bandpass filter. The LTC6992-1 easily configures as a 50% duty cycle 10kHz square wave, and can drive the relatively benign loading seen in the bandpass filter. The LTC6992-1 output and bandpass filter output show THD of the sine wave is –30.5dBc. Note, even harmonics that appear in the distortion products of the filtered output already appear in the source square wave.

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