ANALOG
DEVICES
AHEAD OF WHAT'S POSSIBLE™

AnalogDialogue

DC-to-DC Conversion Directly from Automotive Battery Input: 5 A, 3.3 V, and 5 V Supplies Meet Stringent EMI Emission Standards

Zhongming Ye, System Applications Manager

Introduction

Noise-sensitive applications in harsh automotive and industrial environments require low noise, high efficiency buck regulators that can fit into tight spaces. Monolithic buck regulators, which include the MOSFET power switches in the package, are often chosen because of their small overall solution size relative to a traditional controller IC and external MOSFETs. Monolithic regulators that can operate at high frequency—in the 2 MHz territory well above the AM band—also help to reduce the size of external components. Furthermore, if a regulator offers a low minimum on time (T_{ON}), the regulator can directly operate from higher voltage rails without intermediate regulation, saving space and complexity. Low minimum on times require fast switching edges and minimum deadtime control to effectively reduce the switching loss and allow high switching frequency operation.

Another way to save space is to reduce the number of components required to meet electromagnetic interference (EMI) standards and thermal requirements. Unfortunately, in many cases, simply shrinking the converter makes meeting these requirements more difficult. This article presents state-of-the-art solutions that save space while also achieving low EMI and excellent thermal performance.

Switch-mode power converters are chosen for their efficiency, especially at high step-down ratios, but one trade-off is the switching-action induced EMI. In a buck converter, EMI arises from the fast current changes (high di/dt) in the switches and from switch ringing due to the parasitic inductance in the hot loop.

EMI is just one of the parameters that system design engineers must struggle with when trying to design a compact, high performance power supply. A number of critical design constraints are often at odds, requiring critical compromises within the design limits and time to market.

Improving EMI Performance

To reduce EMI in a buck converter, one must reduce the radiating effect of the hot loop as much as possible and minimize signals from the source. There are a number of ways to reduce radiated EMI, but many also reduce the performance of the regulator.

For instance, in a typical discrete FET buck regulator, the switching edge is slowed down, with an external gate resistor, BOOST resistor, or snubber, as a last rescue method to meet the stringent radiated emissions standards in the automotive industry. Such a quick fix for the EMI comes at the price of performance; namely lower efficiency, higher component count, and larger solution size. Slow switching edges increase switching losses, as well as duty ratio loss. The converter must operate at a lower frequency—for instance, 400 kHz—to achieve satisfactory efficiency and pass mandatory radiated EMI emission tests. Figure 1 shows typical switching node voltage waveforms with a fast switching edge and a slow switching edge, respectively. As shown, the switching edge is significantly slower, resulting in increased switching losses, and a significant increase in the minimum duty cycle, or step-down ratio, not to mention other negative effects on performance.

Slowing the switching frequency also increases the physical size of the converter inductor, output cap, and input cap. Meanwhile, a bulky π filter is necessary to pass the conducted emissions tests. The inductance, L, and capacitance, C, in the filter get bigger as the switching frequency goes down. The inductor current rating should be larger than the maximum input current at low line full load. Therefore, a bulky inductor and multiple capacitors are required on the front end to help pass the stringent EMI standards.

For example, at a 400 kHz switching frequency (as opposed to 2 MHz), in addition to increasing the size of the inductor and capacitor, the inductors and capacitors in the EMI filter must also be relatively large to pass the conducted EMI standard required in automotive applications. One reason is that they must not only attenuate the switching fundamental frequency at 400 kHz, but all of its harmonics up to 1.8 MHz. A regulator operating at 2 MHz does not have this problem. Figure 2 shows the size of a 2 MHz solution against a 400 kHz solution.

Shielding might be a last ditch remedy to reduce radiated emissions, but shielding takes space that might not be available in the application and would require additional mechanical design and test iterations.

To avoid the AM frequency bandwidth and maintain a small solution size, a 2 MHz or higher switching frequency is preferred in automotive applications. With the AM band avoided, it is just a matter of ensuring that higher frequency noise—also known as harmonics—and switch ringing are also minimized. Unfortunately, high frequency switching usually results in increased radiated emissions from 30 MHz to 1 GHz.

There are switching regulators that feature fast and clean switching edges, which reduce EMI, such as the Silent Switcher® devices in ADI's Power by Linear™ line. First, though, let's look at some other features that can help.
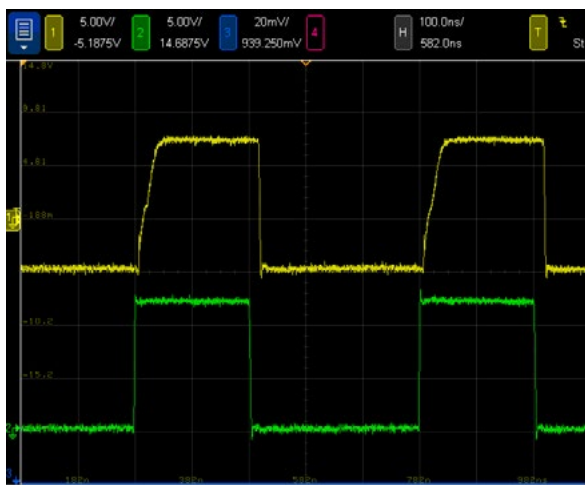

Figure 1. A slow switching edge means significant switching loss in addition to duty ratio loss.
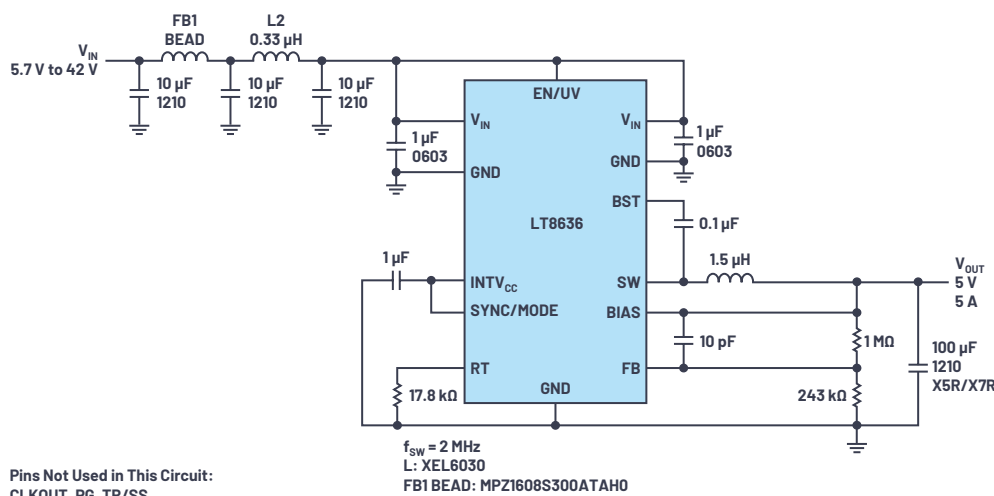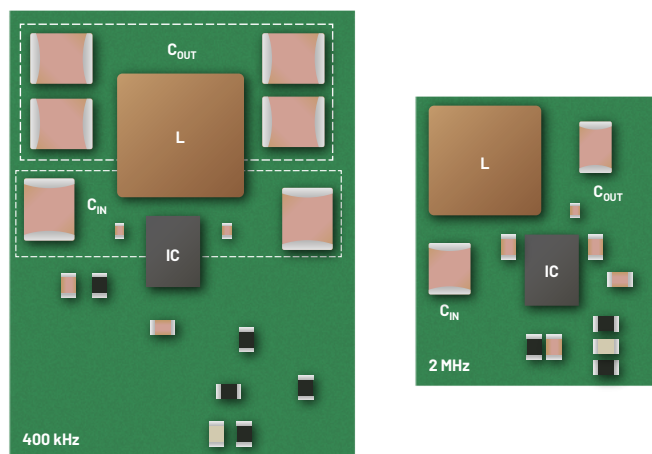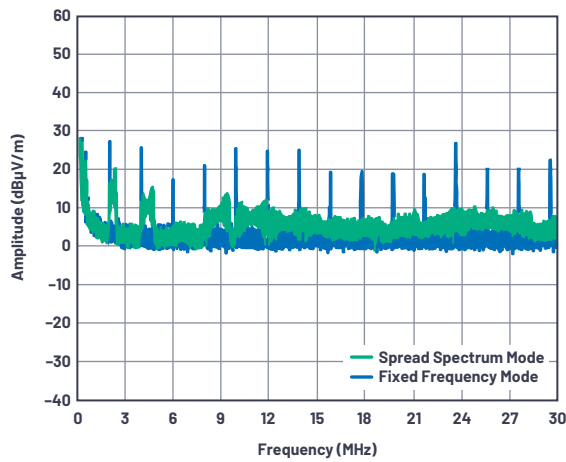

Figure 2. The size of a 2 MHz solution compared to that of a 400 kHz solution.

Spread spectrum frequency modulation (SSFM) is a technique that dithers the system clock within a known range, thus distributing the EMI energy over the frequency domain. Although the switching frequency is often chosen to be outside the AM band (530 kHz to 1.8 MHz), unmitigated switching harmonics can still violate stringent automotive EMI requirements within the AM band. Adding SSFM significantly reduces EMI within the AM band and other regions.

Figure 3 shows an ultralow EMI and high efficiency 12 V to 5 V/5 A converter that operates at a switching frequency at 2 MHz using the LT8636 Silent Switcher monolithic buck regulator. Figure 4 shows conducted and radiated EMI performance for a tested demonstration circuit at a 14 V input and an output of 5 A at 5 V. At the front end, a small inductor and ceramic cap helps to filter out the conducted noise, while the ferrite bead and the ceramic capacitor help to reduce the radiated noise. Two small ceramic caps are placed to the input and ground pins to minimize the area of the hot loop, while also splitting the hot loop, which helps to cancel out high frequency noise.

To improve the EMI performance, the circuit is set to operate in spread spectrum mode: SYNC/MODE = $INTV_{CC}$. A triangular frequency modulation is used to vary the switching frequency between the value programmed by R_T to approximately 20% higher than that value—that is, when the LT8636 is programmed to 2 MHz, the frequency will vary from 2 MHz to 2.4 MHz at a 3 kHz rate.

Figure 3. Ultralow EMI LT8636 5 V/5 A step-down converter in spread spectrum mode with 7 A peak works over 5.7 V to 42 V.

DC2918A Demo Board (With EMI Filter Installed)
14 V Input to 5 V Output at 5 A, f_{SW} = 2 MHz

Figure 4. CISPR 25 radiated EMI emission with and without spread spectrum mode.

From the conducted EMI spectrum, it is obvious the peak harmonic energy is spread out, reducing the peak magnitude at any particular frequency—noise is reduced due to the spread spectrum function by at least 20 dBμV/m. From the radiated EMI spectrum, it is also obvious that spread spectrum mode reduces the radiated EMI as well. This particular circuit meets the stringent automotive CISPR 25 class 5 radiated EMI specification with a simple EMI filter at the input side.

High Efficiency Over the Entire Load Range

The number of electronics devices in the automotive applications is only increasing, with most devices demanding more supply current with each design iteration. With active load currents so high, heavy load efficiency and proper thermal management are top priorities—robust operation depends on thermal management, with unmitigated heat production possibly resulting in costly design problems.

System designers are also concerned with light load efficiency, which is arguably just as important as heavy load efficiency, since battery life is mostly determined by the quiescent current at light load or no load. Trades-off in the silicon, as well as system level design, have to be made among full load efficiency, no load quiescent current, and light load efficiency.

It might seem straightforward that in order to achieve high efficiency at full load, the $R_{DS(ON)}$ of the FET, especially the bottom FET, should be minimized. However, a transistor with low $R_{DS(ON)}$ usually has a relatively high capacitance, with an associated increase in switching and gate drive losses, plus a larger die size and cost. In contrast, the LT8636 monolithic regulator has very low MOSFET conduction resistances, enabling exceptional efficiency in full load conditions. The maximum output current for the LT8636 is 5 A continuous and 7 A peak in still air without any additional heat sink, simplifying robust design.

To enhance light load efficiency, regulators that operate in low ripple Burst Mode® keep the output capacitor charged to the desired output voltage while minimizing the input quiescent current while minimizing output voltage ripple. In Burst Mode operation, current is delivered in short pulses to the output capacitor, followed by relatively long sleep periods, where most of the control (logic) circuits are shutdown.
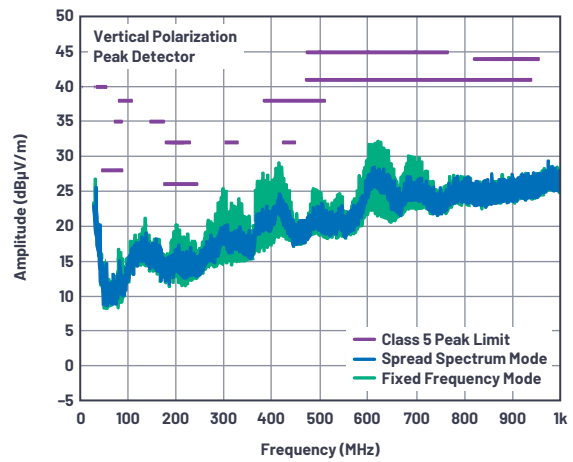
In order to achieve higher light load efficiency, a larger value inductor is preferred since more energy can be delivered to the output during the short pulses and the buck regulator can remain longer in sleep mode between each pulse. By maximizing the time between pulses, and minimizing the switching loss of each short pulse, monolithic buck converter quiescent current can approach 2.5 μA in a monolithic regulator, such as the LT8636. This number is compared with tens of μA or hundreds of μA of the typical parts on the market.

Figure 5 shows a high efficiency solution for 3.8 V/5 A output from 12 V input for automotive applications using the LT8636. The circuit runs at 400 kHz for very high efficiency, and an XAL7050-103 10 μH inductor is used. It maintains efficiency above 90% with loads as light as 4 mA and as high as 5 A. The peak efficiency is 96% at 1 A.
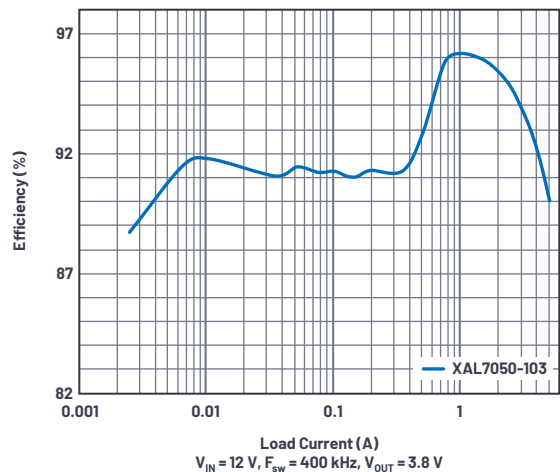

Figure 5. The efficiency of a 12 V to 3.8 V/5 A solution with an XAL7050-103 inductor (f_{SW} = 400 kHz).

Figure 6 shows the efficiency from µA to 5 A for this solution. The internal regulator is supplied from the 5 V output through the BIAS pin to minimize power dissipation. Peak efficiency reaches 95%; full load efficiency is 92% for a 5 V output from 13.5 V input. Light load efficiency remains at or above 89% for loads down to 30 mA for the 5 V application. The converter runs at 2 MHz and the inductor used for the test is an XEL6060-222 to optimize the efficiency in both heavy and light loads, in a relatively compact solution. Light load efficiency can be further improved—to above 90%—by using a larger inductor. The current in the feedback resistor divider is minimized as it appears to the output as load current.
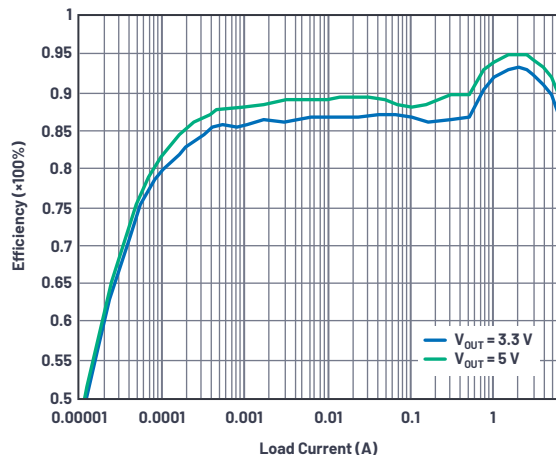

Figure 6. Efficiency of the LT8636 in a solution for 13.5 V to 5 V and 3.3 V using an XEL6060-222 inductor (f_{SW} = 2 MHz).

Figure 7 shows thermal performance for this solution under a 4 A constant load plus a 4 A pulsed load (8 A total at pulse) with a duty cycle of 10% (of 2.5 ms)—from a 13.5 V input and still air at ambient room temperature. Even at a 40 W pulsed power and 2 MHz switching frequency, the LT8636 case temperature remains below 40°C, enabling the circuit to run safely up to 8 A in short periods with no fans or heat sinks. This is possible with a 3 mm × 4 mm LQFN package because of enhanced thermal packaging technology and the LT8636's high efficiency at high frequency.

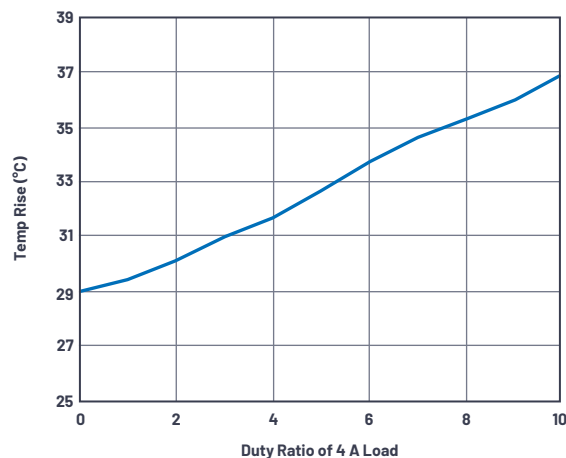*Figure 7. The 3 mm × 4 mm LT8636 in a 13.5 V to 5 V/4 A constant load plus a 4 A pulsed load (10% duty cycle) thermal picture showing temperature rise.*

Shrink Solution Size with High Frequency Operation

Space is an increasing premium in automotive applications, necessitating that power supplies shrink to fit costly board footprints. Increasing a power supply's switching frequency enables the use of smaller external components such as capacitors and inductors. Plus, as previously mentioned, in automotive applications, switching frequencies above 2 MHz (or below 400 kHz) keep the fundamental out of the AM radio band. Let's compare a commonly used 400 kHz design to a 2 MHz design. In this case, quintupling the switching frequency to 2 MHz reduces the required inductance and output capacitance to one-fifth of the 400 kHz design. Seems easy. Nevertheless, even ICs that are high frequency capable may not be usable in many applications because of some of the trade-offs inherent in using a high frequency solution.

For instance, high frequency operation in high step-down ratio applications requires a low minimum on time. According to the equation $V_{OUT} = T_{ON} \times f_{SW} \times V_{IN}$, at a 2 MHz operating frequency, an on time for the top switch (T_{ON}) of about 50 ns is required to produce 3.3 V from 24 V input. If the power IC cannot achieve this low on time, pulses must be skipped to maintain the low regulated output—essentially defeating the purpose of the high switching frequency. That is, the equivalent switching frequency (due to pulse skipping) is likely in the AM band. With minimum top switch on time of 30 ns, the LT8636 allows direct high V_{IN} to low V_{OUT} conversion at 2 MHz. In contrast, many devices are limited to a >75 ns minimum, requiring they be operated at low frequency, 400 kHz, for higher step-down ratios to avoid skipping pulses.

Another common issue with high switching frequency is that switching losses tend to increase. The switching related losses include the switch turn on loss, turn off loss, and gate drive loss—all roughly linearly dependent on the switching frequency. Nevertheless, these losses can be improved with faster switch turn-on and turn-off times. The LT8636 switching turn-on and turn-off times are very short, less than 5 V/ns, resulting in minimum deadtime and minimum diode time, reducing the switching losses at high frequency.

The LT8636 used in the solutions here is assembled in a 3 mm × 4 mm LQFN, using a monolithic construction with integrated power switches and inclusion of all necessary circuitry yields a solution with a minimal PCB footprint. The large area exposed ground pad under the IC guides heat to the PCB through a very low thermal resistance (26°C/W) path, reducing the need for additional thermal management. The package is designed for FMEA compatibility. Silent Switcher technology reduces the PCB area of the hot loop, so radiated EMI with such high switching frequency can be easily addressed with simple filters, as shown in Figure 3.

Conclusion

With careful IC selection, it is possible to produce compact high performance power supplies for automotive applications without the usual trade-offs. That is, high efficiency, high switching frequency, and low EMI can all be achieved. To exemplify the types of compact designs that can be achieved, the solutions shown in this article use the LT8636, a 42 V, 5 A continuous/7 A peak monolithic step-down Silent Switcher regulator in a 3 mm × 4 mm LQFN package. In this IC, the V_{IN} pins are split and placed symmetrically on the IC, splitting the high frequency hot loop, mutually cancelling the magnetic fields to suppress the EMI radiated emission. Also, a synchronous design and fast switching edges improve efficiency at heavy load, while the light load efficiency benefits from the low ripple Burst Mode operation.

The LT8636 also fits automotive applications with a 3.4 V to 42 V input range and low dropout, enabling it to operate in automotive crank or load dump scenarios. In automotive applications, system designers are accustomed to facing a number of trade-offs when trying to shrink power supply solution size, but with the designs shown here, designers can achieve all their performance goals without trade-offs.

About the Author

Zhongming Ye is an applications engineering manager for power products at Analog Devices in Santa Clara, California. He has been working at Linear Technology (now part of Analog Devices) since 2009, providing application support for various products including buck, boost, flyback, and forward converters. His interests in power management include high performance power converters and regulators of high efficiency, high power density, and low EMI for automotive, medical, and industrial applications. Prior to joining Linear Technology, he worked at Intersil for three years on PWM controllers for isolated power products. He obtained a Ph.D. degree in electrical engineering from Queen's University, Kingston, Canada. Zhongming was a senior member of the IEEE Power Electronics Society. He can be reached at zhongming.ye@analog.com.