

High Power Density in a Small Form Factor

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Background

Sophisticated high power density digital integrated circuits (ICs), such as graphics processor units (GPUs) and field programmable gate arrays (FPGAs), can be found in a broad range of feature-rich electronic environments, including:

- ▶ Automotive
- ▶ Medical
- ▶ Telecom
- ▶ Datacom
- ▶ Industrial
- ▶ Communications
- ▶ Gaming
- ▶ Consumer audio/video

With this level of market penetration, it is no surprise that the global demand for high current, low voltage digital ICs is exploding. The current global market is assessed at more than US \$1.8B, and this is expected to rise annually by 10.87% to reach US \$3.7B over the 2018 to 2025 period. As one of the biggest slices of this market, FPGAs account for a projected US \$1.53B by the end of 2025. The rest of the digital IC market is represented by GPUs, microcontrollers and microprocessors, programmable logic devices (PLDs), digital signal processors (DSPs), and application-specific integrated circuits (ASICs).

High power density digital ICs have penetrated virtually every embedded system. FPGAs enable cutting-edge applications in the market segments listed above. For example, in automotive applications, advanced driver assistance systems (ADASs) and collision avoidance systems prevent catastrophe due to human error. Likewise, government-mandated safety features such as antilock brake systems, stability control, and electronically controlled independent suspension systems require FPGAs to function.

In consumer electronics, the demand for Internet of Things (IoT) functionality, sophisticated graphic engine functionality, and machine-to-machine (M2M) functionality call for advanced digital ICs. Massive data storage and cloud computing centers and expansive networks of optical networking modules drive the need for FPGAs and digital ICs.

These digital ICs are powerful, yet temperamental, especially regarding power requirements. Traditionally, efficient switching regulator controllers that drive high power MOSFETs have been used to power FPGAs and ASICs, but these controller-based power schemes have potential noise interference issues, relatively slow transient response, and layout limitations. In recent years, small and quiet low dropout (LDO) regulators that minimize heat have been used as an alternative, but not without their own set of limitations. Recent power conversion innovations have introduced high power monolithic switching regulators that are able to efficiently power digital ICs with low noise and high efficiency while minimizing space requirements.

Switching Regulators vs. Charge Pumps vs. LDO Regulators

Low voltage, high current step-down conversion and regulation can be achieved via a variety of methods, each with its own performance and design trade-offs. Switching regulator controllers feature high efficiency at high load currents over a wide range of voltages, but they require several external components such as inductors, capacitors, and FETs to operate; and they can be a source of high and low frequency noise. Inductorless charge pumps (or switched capacitor voltage converters) can also be used to produce low voltages, but are limited in output current capability, suffer from poor transient performance, and require several external components. For these reasons, charge pumps are not commonly found in digital IC power applications. Linear regulators—especially LDO regulators—are simple in that they only require two external capacitors to operate. However, they may be power limited depending on the size of the input-to-output voltage differential across the IC and how much current is demanded by the load, plus the thermal resistance characteristics of the package. This certainly limits their ability to power digital ICs.

Monolithic Buck Converter Design Challenges

Moore's Law has proven to be visionary and valid since its debut in 1965. Wafer fabrication technology line widths are continually being reduced, pushing digital IC voltages lower. Smaller geometry processes allow higher integration of more power-hungry features in the end product. For example, modern computer servers and optical communication routing systems demand higher bandwidth to process more computing data and internet traffic; these systems also generate a lot of heat, and therefore highly efficient

ICs are required. Cars have more on-board electronics for entertainment, navigation, self-driving features, and even engine control. As a result, there is an increase in both the system's current consumption and the associated total power required. Therefore, state-of-the-art packaging and innovative, internal power-stage design are required to drive the heat out of the power IC while delivering unprecedented power.

High power supply rejection ratio (PSRR) and low output voltage noise, or ripple, are important considerations. A device with high supply rejection can filter and reject noise at the input, resulting in a clean and stable output. Furthermore, power solutions with low output voltage noise across a wide bandwidth or low output ripple are desirable—modern digital systems have several rails where noise sensitivity is a major design consideration. As speed requirements for high end FPGAs increase, supply noise tolerance decreases in order to minimize bit errors. Noise-induced digital faults drastically reduce the effective data throughput speeds for these high speed PLDs. Input supply noise at high current is one of the more demanding specifications placed on power supplies.

Higher transceiver speeds—in FPGAs, for example—dictate high current levels due to high power consumption from fine geometry circuit switching. These ICs are fast. They may cycle load current from near-zero to several amps within tens to hundreds of nanoseconds, requiring a regulator with ultrafast transient response.

With board area reserved for the power regulators ever-decreasing, many system designers turn to monolithic switching regulators operating at fast switching frequencies to reduce the size of external components and total solution size—accepting the trade-off of some efficiency loss due to switching losses at higher frequencies. This trade-off is eliminated by a new generation of monolithic switching regulators. These new regulators feature synchronous operation with integrated high-side and low-side switches, allowing for tight control of switch gate voltages, greatly reducing dead time, and resulting in higher efficiencies even at high frequencies.

One of the biggest challenges with high current monolithic switchers is their ability to dissipate heat that results from power loss in the IC. This challenge can be met by using multiple power and ground pins, plus thermally enhanced laminate-based packages with copper (Cu) pillars where the heat can be easily transferred from the IC into the board. The large copper planes on the board connected to these power pins allow for the heat to spread more evenly.

New Family of Silent Switcher Buck Converters

It's clear that buck converter solutions for high performance digital ICs must have the following attributes:

- ▶ Fast switching frequency to minimize the size of external components
- ▶ Zero dead-time design to maximize efficiency at high frequency
- ▶ Monolithic chip on-board power device for smaller solution size

- ▶ Multiphase operation enables parallel operation for high output currents and reduced ripple
- ▶ Low EMI to meet low system noise requirements
- ▶ Synchronous operation for high efficiency and minimal power loss
- ▶ Easy design simplifies design cycle, qualification, and testing
- ▶ Very low output ripple
- ▶ Fast transient response time
- ▶ Operation over a wide input/output voltage range
- ▶ High output current capability
- ▶ Excellent thermal performance
- ▶ Compact footprint

These features can be found in Analog Devices' Power by Linear™ LTC33xx family of monolithic high, medium, and low current buck regulators. The highest current member is the **LTC3310S**, a 5 V, 10 A, high power density, low EMI, Silent Switcher® 2, monolithic, synchronous buck converter in a 9 mm² package (power density = 1.11 A/mm²). The device's fixed frequency peak current-mode architecture is ideal for applications that demand fast transient response. The LTC3310S uses the Silent Switcher 2 architecture with integrated hot loop bypass capacitors to deliver a highly efficient, small footprint solution at frequencies up to 5 MHz with excellent EMI performance. Multiphase operation enables direct paralleling of up to four devices for higher current up to 40 A.

The LTC3310S' 2.25 V to 5.5 V input range supports a wide variety of applications, including most intermediate bus voltages. Integrated low on-resistance MOSFETs deliver continuous load currents as high as 10 A with minimal thermal derating. Output voltages ranging from 0.5 V to V_{IN} are ideal for point-of-load applications such as high current, low voltage DSP/FPGA/GPU/ASIC designs. Other key applications include optical networking, telecom/datacom, automotive systems, distributed power architectures, or any medium-to-high power density systems. Figure 1 shows the simplicity of a typical design, while Figure 2 shows how easy it is to produce a 4-phase, 40 A configuration.

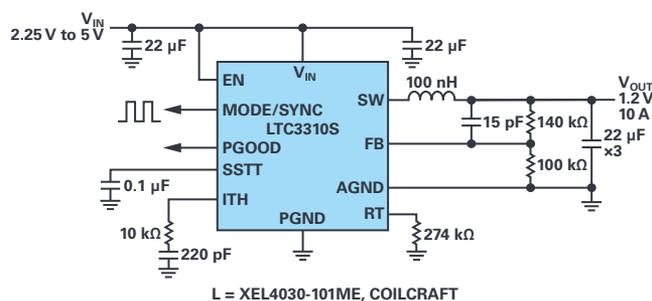
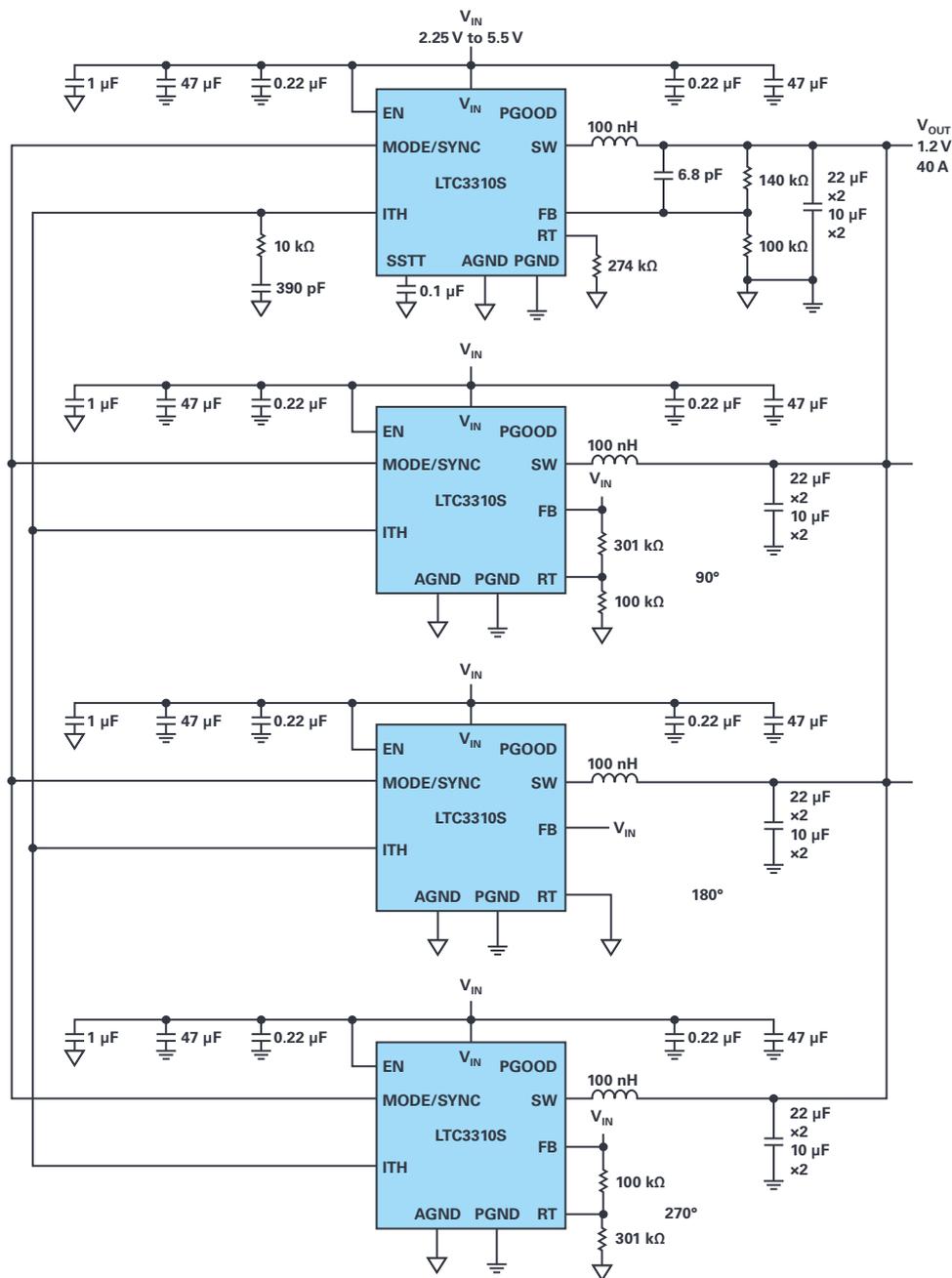


Figure 1. LTC3310S typical application.



L = COILCRAFT, XEL4030-101ME

Figure 2. Four LTC3310S monolithic regulators in parallel, forming a 4-phase, 40 A step-down regulator.

The LTC3310S' low 35 ns minimum on-time enables a large step-down ratio at high frequency, and 100% duty-cycle operation delivers low dropout performance when the input and output voltages are close in value. The operating frequency can be synchronized to an external clock. The LTC3310S total reference voltage accuracy is better than $\pm 1\%$ over the -40°C to $+125^{\circ}\text{C}$ operating junction temperature range. Additional features include a power good signal when the output is in regulation, precision enable threshold, output overvoltage protection, thermal shutdown, die temperature monitor, programmable soft start, tracking, clock synchronization, mode selection, and output short-circuit protection.

The LTC3310S is available in a thermally enhanced 18-lead, $3\text{ mm} \times 3\text{ mm} \times 0.94\text{ mm}$ LQFN package. The E- and I-grades are specified from the -40°C to $+125^{\circ}\text{C}$ operating junction temperature range, while the J- and H-grades are specified from the -40°C to $+150^{\circ}\text{C}$ operating junction temperature range.

High Efficiency, Low EMI, and Fast Transient Response

Silent Switcher buck regulator designs offer high efficiency at high switching frequencies ($>2\text{ MHz}$) with ultralow electromagnetic interference (EMI) emissions, offering very compact and quiet step-down solutions. The Silent Switcher family uses special design and packaging techniques to enable $>92\%$ efficiency at 2 MHz while easily passing the CISPR 25 Class 5 peak EMI limits. The next-generation Silent Switcher 2 technology internal construction uses copper pillars in lieu of bond wires, adds internal bypass capacitors, and an integrated substrate ground plane to further improve EMI, which is not sensitive to PCB layout, simplifying designs and reducing performance risks.

The “S” in the LTC3310S part number indicates its second-generation Silent Switcher technology. The IC has integrated V_{IN} ceramic capacitors to keep all fast ac current loops small, improving the EMI performance. This technology allows fast switching edges for high efficiency at high switching frequencies, while simultaneously achieving good EMI performance (see Figure 3, Figure 4, and Figure 5). Furthermore, it allows for faster, cleaner, low overshoot switching edges, greatly improving efficiency at high switching frequencies. The graph in Figure 6 shows the LTC3310S’s high efficiency performance.

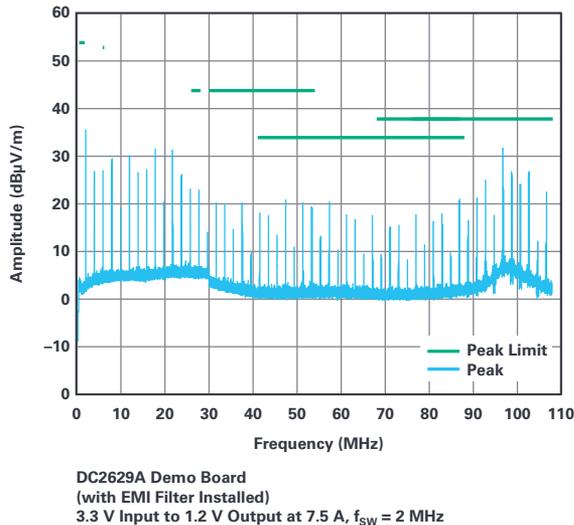


Figure 3. CISPR 25 conducted EMI emissions with Class 5 peak limits (voltage method).

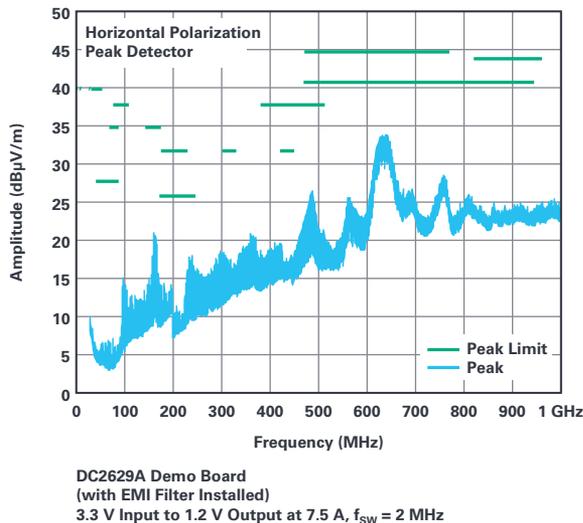


Figure 4. Radiated emissions for horizontal polarization.

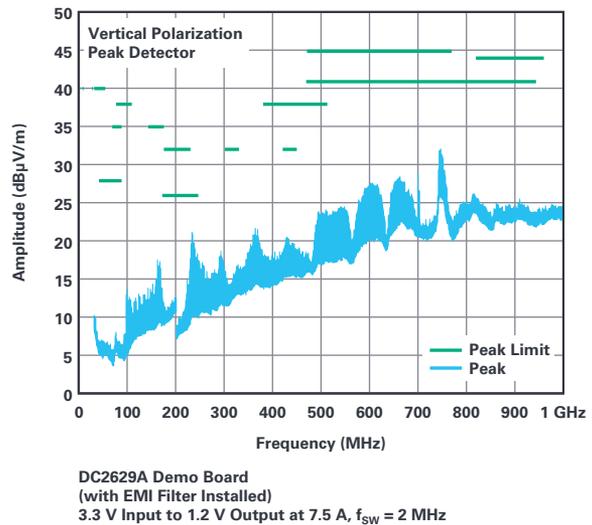


Figure 5. Radiated emissions for vertical polarization.

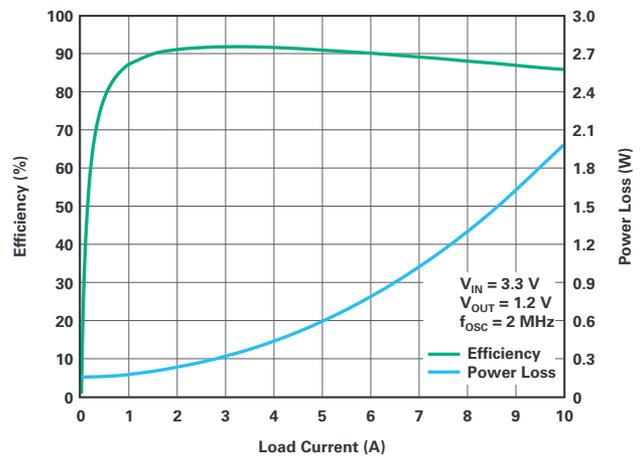


Figure 6. LTC3310S efficiency performance.

The LTC3310S’s fixed frequency peak-current mode architecture eases compensation and allows the IC to rapidly respond to transient steps. External compensation components allow the control loop to be optimized for the highest bandwidth and fastest transient response.

6 A, 4 A, and 3 A Silent Switcher Bucks in a 2 mm × 2 mm Package

For increased power density, first-generation Silent Switcher architecture is a good solution. Silent Switcher topology is like Silent Switcher 2 topology except the V_{IN} bypass capacitors are external instead of within the plastic encapsulation flip-chip laminate style package. For full Silent Switcher, low EMI performance, external V_{IN} bypass capacitors are placed symmetrically, external to the package. This split cap, symmetrical arrangement minimizes the effective hot loop area, thereby reducing EMI and allowing for a smaller package footprint size.

LTC3309A, LTC3308A, and LTC3307A are 5 V input regulators that can support 6 A, 4 A, and 3 A (respectively), for high power density, low EMI monolithic synchronous buck conversion. They all operate at up to 3 MHz in a 4 mm² footprint package (LTC3309A power density = 1.5 A/mm²).

Figure 7 shows a typical LTC3309A application. The fixed frequency peak current-mode architecture is ideal for fast transient response, including fast transient response during Burst Mode® operation (see Figure 8). The LTC3309A features Silent Switcher architecture, utilizing external hot loop bypass capacitors. This design enables highly efficient, small footprint solutions at high operating frequencies with excellent EMI performance.

The family's 2.25 V to 5.5 V input voltage range supports a wide variety of applications, including most intermediate bus voltages, and is compatible with lithium and nickel-based battery types. Integrated low on-resistance MOSFETs deliver continuous load currents as high as 6 A. Output voltages, ranging from 0.5 V to V_{IN} , are ideal for point-of-load applications such as high current/low voltage DSP/FPGA/GPU/ASIC reference designs. Other key applications include telecom/datacom and automotive systems, distributed power architectures, and general-purpose power systems.

The LTC3309A, LTC3308A, and LTC3307A operate in forced continuous or pulse skip modes for low noise, or low ripple, low I_0 Burst Mode operation for high efficiency at light loads, ideal for battery-powered systems. Low 22 ns minimum on-time enables high step-down ratios even as the power supply operates at high frequency, and 100% duty cycle operation delivers low dropout performance when input and output voltages are the same. The operating frequency can be synchronized to an external clock. The total reference voltage accuracy is better than $\pm 1\%$ over the -55°C to $+150^\circ\text{C}$ operating junction temperature range. The device safely tolerates inductor saturation in overload. Additional features include a power good signal when the output is in regulation, internal soft start, precision enable threshold, output overvoltage and short-circuit protection, thermal shutdown, and clock synchronization.

The LTC3309A, LTC3308A, and LTC3307A are all pin-compatible devices available in a thermally enhanced, compact, and low profile 12-lead, $2\text{ mm} \times 2\text{ mm} \times 0.74\text{ mm}$ LQFN package. The E- and I-grades are specified from a -40°C to $+125^\circ\text{C}$ operating junction temperature range. The J- and H-grades are specified from a -40°C to $+150^\circ\text{C}$ operating junction temperature range, and the MP-grade is specified from a -55°C to $+150^\circ\text{C}$ operating junction temperature range.

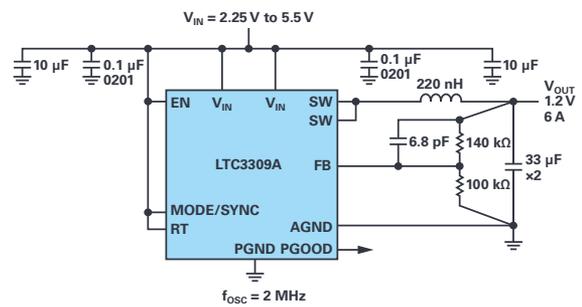
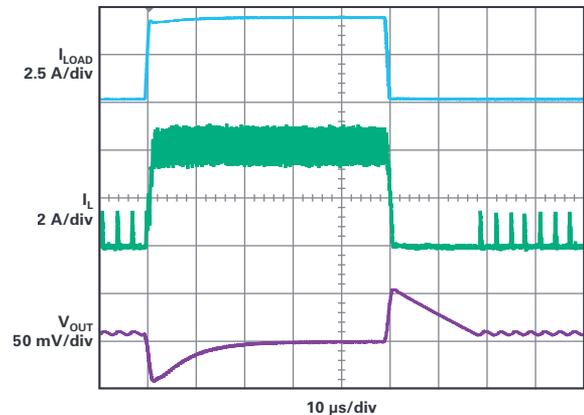


Figure 7. LTC3309A typical application circuit.



3.3 V_{IN} to 1.2 V_{OUT} , 2 MHz Typical Application
 $C_{OUT} = 66\ \mu\text{F}$, $L = 220\ \text{nH}$
 Load Step: 0.1 A to 4.5 A in 1 μs

Figure 8. LTC3309A transient response in Burst Mode operation.

Table 1 compares the features of the members of the LTC33xx Silent Switcher and Silent Switcher 2 family.

Table 1. Fault Mode and Supported Range

Vendor	ADI	ADI	ADI	ADI
Part #	LTC3307A	LTC3308A	LTC3309A	LTC3310S
Topology	Single synchronous monolithic, Silent Switcher	Single synchronous monolithic, Silent Switcher	Single synchronous monolithic, Silent Switcher	Single synchronous monolithic, Silent Switcher 2
V_{IN} Range	2.25 V to 5.5 V			
V_{OUT} Range	0.5 V to V_{IN}			
Output Current	3 A	4 A	6 A	10 A
Efficiency	92% (3.3 V_{IN} /1.2 V_{OUT} /2 A)	92% (3.3 V_{IN} /1.2 V_{OUT} /2 A)	92% (3.3 V_{IN} /1.2 V_{OUT} /2 A)	92% (3.3 V_{IN} /1.2 V_{OUT} /3 A)
Switching Frequency	1 MHz to 3 MHz	1 MHz to 3 MHz	1 MHz to 3 MHz	500 kHz to 5 MHz
Control Mode	Constant-frequency, peak current mode	Constant-frequency, peak current mode	Constant-frequency, peak current mode	Constant-frequency, peak current mode
V_{REF} Accuracy Room/Temp	$\pm 0.2\%/\pm 1\%$	$\pm 0.2\%/\pm 1\%$	$\pm 0.2\%/\pm 1\%$	$\pm 1\%$
Current Limit Accuracy	$\pm 15\%$	$\pm 15\%$	$\pm 15\%$	$\pm 9\%$
Minimum On-Time	22 ns	22 ns	22 ns	35 ns
Directly Parallelable x Phase?	No	No	No	Yes, 4 phase
I_0 Supply Burst Mode/Non-Burst	40 μA BM/1.3 mA	40 μA BM/1.3 mA	40 μA BM/1.3 mA	1.3 mA
Package Theta JA	51°C/W	51°C/W	51°C/W	40°C/W
Solution Size	$\sim 20\ \text{mm}^2$	$\sim 20\ \text{mm}^2$	$\sim 20\ \text{mm}^2$	47 mm^2
Package	2 mm \times 2 mm \times 0.74 mm, 12-lead LQFN	2 mm \times 2 mm \times 0.74 mm, 12-lead LQFN	2 mm \times 2 mm \times 0.74 mm, 12-lead LQFN	3 mm \times 3 mm \times 0.94 mm, 18-lead LQFN

Conclusion

The trend in high performance digital ICs—such as GPUs, FPGAs, and microprocessors—is rapidly raising current demands coupled with dropping operating voltages, a result of shrinking line width wafer fabrication technologies. Current and voltage demands are only part of the power supply picture. Digital IC advancements come with a host of other requirements, including fast transient response, low EMI, low noise/ripple, and efficient operation to minimize heat.

Traditionally, digital ICs has been powered by LDO regulators or inductor-based switching regulator controllers with off-board power devices. With increased power supply performance and space requirements, in many cases these traditional approaches are not up to the task. ADI's new generation of monolithic power supplies are up to the task, including the LTC3310S, LTC3309A, LTC3308A, and LTC3307A, which support 10 A, 6 A, 4 A, and 3 A, respectively. These high power density Silent Switcher and Silent Switcher 2 buck regulators are housed in thermally efficient, compact flip-chip laminate packages, and have a variety of feature sets to satisfy the requirements of a wide range of digital IC power problems.



About the Author

Steve Knoth is a senior product marketing manager in Analog Devices' Power Group. He is responsible for all power management integrated circuit (PMIC) products, low dropout (LDO) regulators, battery chargers, charge pumps, charge pump-based LED drivers, supercapacitor chargers, and low voltage monolithic switching regulators. Prior to rejoining Analog Devices in 2004, Steve held various marketing and product engineering positions since 1990 at Micro Power Systems, Analog Devices, and Micrel Semiconductor. He earned his bachelor's degree in electrical engineering in 1988 and a master's degree in physics in 1995, both from San Jose State University. Steve also received an M.B.A. in technology management from the University of Phoenix in 2000. In addition to enjoying time with his kids, Steve is an avid music lover and can be found tinkering with pinball and arcade games or muscle cars, and buying, selling, and collecting vintage toys, movie, sports, and automotive memorabilia. He can be reached at steve.knoth@analog.com.