How the Smart Hardware Engineer Can Easily Design Power Supplies: Mini Tutorial

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Abstract

This mini tutorial gives an overview of the possibilities for power supply design. It will address the basic and commonly used isolated and nonisolated power supply topologies along with their advantages and disadvantages. We will also cover electromagnetic interference (EMI) and filtering considerations. This mini tutorial aims to provide a simplified understanding and renewed appreciation for the art of power supply design.

Introduction

Most electronic systems require some sort of voltage conversion between the voltage of the energy supply and the voltage of the circuitry that needs to be powered. As batteries lose charge, the voltage will drop. Some DC-to-DC conversion can ensure that much more of the stored energy in the battery is used to power the circuitry. Also, for example, with a 110 V AC line, we cannot power a semiconductor such as a microcontroller directly. Since voltage converters, also named power supplies, are used in almost every electronic system, they have been optimized for different purposes over the years. Certainly, some of the usual targets for optimization are solution size, conversion efficiency, EMI, and cost.

The Simplest Power Supply: The LDO

One of the simplest forms of a power supply is the low dropout (LDO) regulator. LDOs are linear regulators as opposed to switching regulators. Linear regulators put a tunable resistor between the input voltage and the output voltage, which means the output voltage is fixed independent of how the input voltage changes and which load current is running through the device. Figure 1 shows the basic principle of this simple voltage converter.

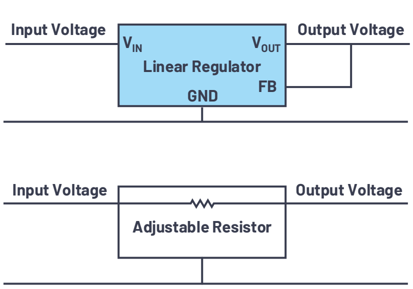

Figure 1. A linear regulator converts one voltage into another.

For many years, a typical power converter consisted of a 50 Hz or 60 Hz transformer, connected to the power grid, with a certain windings ratio to generate a nonregulated output voltage, a few volts higher than the needed supply voltage in a system. Then, a linear regulator was used to convert this voltage to a well-regulated one as needed by the electronics. Figure 2 shows the block diagram of this concept.

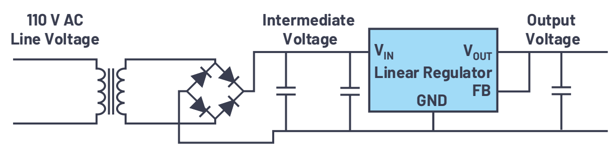

Figure 2. A line transformer followed by a linear regulator.

The problem with the basic setup in Figure 2 is that the 50 Hz/60 Hz transformer is relatively bulky and expensive. Also, the linear regulator dissipates quite a lot of heat, so the total system efficiency is low and getting rid of the generated heat is difficult with high system power.

Switch-Mode Power Supplies to the Rescue

To avoid the disadvantages of a power supply as shown in Figure 2, switch-mode power supplies were invented. They do not rely on 50 Hz or 60 Hz AC voltage. They take a DC voltage, sometimes rectified AC voltage, and generate a much higher frequency AC voltage to use a much smaller transformer or, in nonisolated systems, to rectify the voltage with an LC filter to generate a DC output voltage. The advantages are small solution size and relatively low cost. The AC voltage being generated does not need to be a sine voltage waveform. A simple PWM signal shape will work just fine and is easy to generate with a PWM generator and a switch.

Up until the year 2000, bipolar transistors were the most commonly used switches. They would work well but had relatively slow switching transition speed. They were not very power efficient, limiting the switching frequency to 50 kHz or maybe 100 kHz. Today we use switching MOSFETs instead of bipolar transistors, allowing for much faster switching transitions. This in turn gives us lower switching losses, allowing for switching frequencies of up to 5 MHz. Such high switching frequencies enable the use of very small inductors and capacitors in the power stage.

Switching regulators bring a lot of benefits. They generally offer a power efficient voltage conversion, allow voltage step-up and step-down, and offer relatively compact and low cost designs. The disadvantages are that they are not so simple to design and optimize, and they generate EMI from the switching transitions and the switching frequency. The availability of switch-mode power supply regulators, along with power supply design tools such as LTpowerCAD® and LTspice® have greatly simplified this difficult design process. With such tools, the circuit design process of a switch-mode power supply can be semi-automated.

Isolation in Power Supplies

When designing a power supply, the first question to answer is whether or not galvanic isolation is required. Galvanic isolation is used for multiple reasons. It can make circuits safer, it allows for floating system operation, and it prevents noisy ground currents from spreading through different electronic devices in one circuitry. The two most common isolated topologies are the flyback and forward converters. However, for higher power, other isolated topologies such as push-pull, half-bridge, and full-bridge are used.

If galvanic isolation is not required, in most cases a nonisolated topology is used. Isolated topologies always require a transformer and such a device tends to be expensive, bulky, and often difficult to get off-the-shelf with the exact requirements that a custom power supply requires.

Most Common Topologies When Isolation Is Not Required

The most common nonisolated switch-mode power supply topology is the buck converter. It is also known as the step-down converter. It accepts a positive input voltage and generates an output voltage lower than the input voltage. It is one of the three most basic switch-mode power supply topologies that only require two switches, an inductor, and two capacitors. Figure 3 shows the basic principle of this topology. The high-side switch pulses a current from the input and generates a switch node voltage alternating between the input voltage and ground voltage. The LC filter takes that pulsed voltage on the switch node and generates a DC output voltage. Depending on the duty cycle of the PWM signal controlling the high-side switch, a different level of DC output voltage is generated. This DC-to-DC buck converter is very power efficient, relatively easy to build, and requires few components.

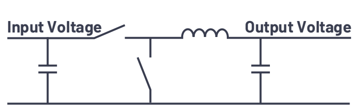

Figure 3. Concept of a simple buck step-down converter.

The buck converter pulses current on the input side, while the output side has continuous current coming from the inductor. This is the reason why a buck regulator is very noisy on the input side and not so noisy on the output side. Understanding this is important when low noise systems need to be designed.

Besides the buck topology, the second basic topology is the boost, or step-up, topology. It uses the same five basic power components as the buck converter, but rearranged, so that the inductor is placed on the input side and the high-side switch is placed on the output side. The boost topology is used to step up a certain input voltage to an output voltage that is higher than the input voltage.

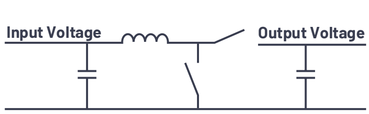

Figure 4. Concept of a simple boost step-up converter.

When selecting a boost converter, it is important to note that boost converters always specify the maximum rated switch current and not the maximum output current in their data sheets. In a buck converter, the maximum switch current is directly related to the maximum achievable output current, independent of voltage ratio between the input voltage and the output voltage. In a boost regulator, the voltage ratio directly affects the possible maximum output current based on a fixed maximum switch current. When selecting a suitable boost regulator IC, you need to not only know the desired output current, but also the input and output voltage of the design in development.

A boost converter is very low noise on the input side, since the inductor in line with the input connection prevents rapid changes in current flow. However, on the output side this topology is quite noisy. We only see pulsed current flow through the outside switch, and thus output ripple is more of a concern compared to the buck topology.

The third basic topology, only consisting of the five basic components, is the inverting buck-boost converter. The name is derived from the fact that this converter takes a positive input voltage and converts it into a negative output voltage. Besides this, the input voltage may be higher or lower than the absolute of the inverted output voltage. For example, –12 V output voltage may be generated out of 5 V or 24 V on the input. This is possible without making any special circuit modifications. Figure 5 shows the circuit concept of the inverting buck-boost converter.

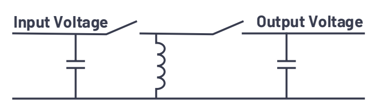

Figure 5. Concept of a simple inverting buck-boost converter.

In the inverting buck-boost topology, the inductor is connected from the switch node to ground. Both the input side as well as the output side of the converter see pulsed current flow, making this topology relatively noisy on both the input side as well as the output side. In low noise applications, this nature is compensated by adding additional input and output filtering.

One quite positive aspect of the inverting buck-boost topology is the fact that any buck switching regulator IC may be used for such a converter. It is as simple as attaching the output voltage of the buck circuit to system ground. The buck IC circuit ground will become the adjusted negative voltage. This trait yields a very large selection in switching regulator ICs on the market.

Specialized Topologies

Besides the three basic nonisolated switch-mode power supply topologies previously discussed, there are many more topologies available. However, they all require additional power components. This typically makes them higher cost with lower power conversion efficiency. While there are certain exceptions, generally, adding additional components in the power path will add losses. Some of the most popular topologies are SEPIC, Zeta, Ćuk, and the 4-switch buck-boost. They each offer features that the three basic topologies do not offer. The following is a list of the most important features of each topology:

- SEPIC
  The SEPIC can generate a positive output voltage out of a positive input voltage that may be higher or lower than the output voltage. Boost regulator ICs may be used to design a SEPIC power supply. The drawback of this topology is the need for a second inductor or one coupled inductor and also a SEPIC capacitor.
- Zeta
  The Zeta converter is similar to the SEPIC, but it is capable of generating a positive or negative output voltage. Also, it does not have a right-half-plane

zero (RHPZ), thereby simplifying the regulation loop. A buck converter IC can be used for such a topology.

- Ćuk
  The Ćuk converter offers an inversion of a positive input voltage into a negative output voltage. It uses two inductors, one on the input side and one on the output side, making it quite low noise on the input and output sides. The drawback is that there are not very many switch-mode power conversion ICs supporting this topology, since a negative voltage feedback pin is required for the regulation loop.
- 4-Switch Buck-Boost
  This converter type became quite popular in recent years. It offers a positive output voltage from a positive input voltage. The input voltage may be higher or lower than the adjusted output voltage. This converter replaces a lot of SEPIC designs, as it offers higher power conversion efficiency and only requires one inductor.

Most Common Isolated Topologies

Besides nonisolated topologies, some applications require galvanically isolated power converters. The reasons may be safety concerns, the need to have floating grounds in larger systems where different circuits are interconnected, or the prevention of ground current loops in noise sensitive applications. The most common isolated converter topologies are the flyback and forward converters.

The flyback converter is typically used for power levels up to 60 W. The circuit operates in a way that during the on-time, energy is stored in a transformer. During the off-time, this energy is released to the secondary side of the converter, powering the output. This converter is simple to build, but it requires relatively large transformers to store all the energy necessary for proper operation. This aspect limits the topology to lower power levels. Figure 6 shows a flyback converter on the top and a forward converter on the bottom.

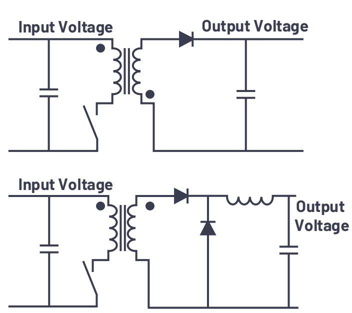

Figure 6. A flyback converter (top) and a forward converter (bottom).

Besides the flyback converter, the forward converter is also very popular. It uses a transformer in a different way than the flyback. During the on-time, while there is current flow through the primary side winding, there is also current flow through the secondary winding. Energy should not be stored in the core of the transformer. After each switching cycle, we have to make sure that all the magnetization of the core is released to zero, so that the transformer will not saturate after a number of switching cycles. This energy release out of the core can be achieved with a few different technologies. One popular way is to use an active clamp with a small additional switch and capacitor.

Figure 7 shows the LTspice simulation environment schematic of a forward active clamp design using the ADP1074. In the forward converter, there is an additional inductor in the output path compared to the flyback, as shown in Figure 6. While this is one additional component with associated space and cost implications, it helps to generate a lower noise output voltage compared to a flyback converter. Also, the transformer size needed for a forward converter at the same power level as a flyback may be much smaller.

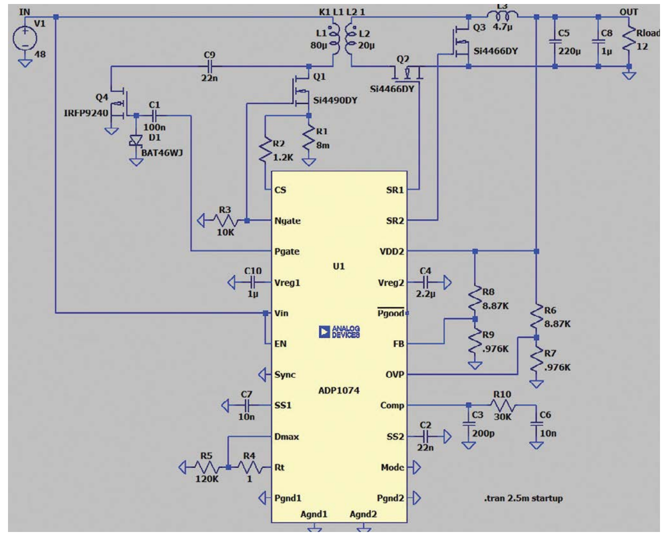

Figure 7. A forward active clamp circuit using the ADP1074 for generating an isolated output voltage, as simulated in LTspice.

Advanced Isolated Topologies

Besides the flyback and the forward topologies, there are very many different transformer-based galvanically isolated converter concepts. The following list gives some very basic explanations about the most common converters:

- Push-Pull
  The push-pull topology is similar to that of the forward converter. However, instead of one low-side switch, this topology requires two active low-side switches. Also, it requires a primary transformer winding with a center tap. The advantage of the push-pull is an operation with generally lower noise compared to a forward converter, and also a smaller transformer is needed. The hysteresis of the BH curve of a transformer is utilized in two quadrants rather than just one.
- Half-Bridge/Full-Bridge
  These two topologies are typically used for higher power designs starting at a few hundred watts all the way to a few kilowatts. They require high-side switches besides low-side switches but enable very high power transfer with relatively small transformers.
- ZVS
  This term comes up often when discussing high power isolated converters. It stands for zero voltage switching. Another term for such converters is LLC (inductor-inductor-capacitor) converters. These architectures aim for very high efficiency conversion. They generate a resonance circuit and switch the power switches while the voltage or current across the switches is close to zero. Thus, the switching losses are minimized. However, such designs may be difficult to design and the switching frequency is not fixed, sometimes yielding EMI problems.

Switched Capacitor Converters

Besides linear regulators and switch-mode power supplies, there is also a third group of power converters: the switched capacitor converters. They are also referred to as charge pumps. They use switches and capacitors to multiply or invert voltages. They offer the big advantage of not needing any inductor. Typically, such converters are used for low power levels of below 5 W. However, recently major advancements have been made to allow for much higher power switched capacitor converters. Figure 8 shows the LTC7820 in a 120 W design at 98.5% efficiency, converting 48 V to 24 V.

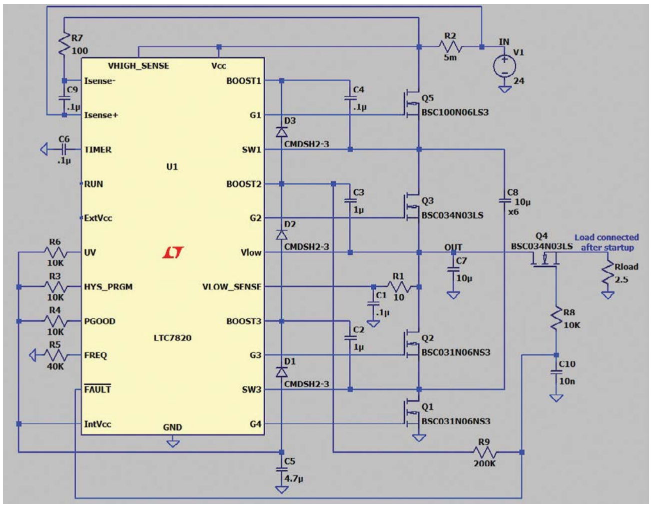

Figure 8. An LTC7820 fixed ratio high power charge pump DC-to-DC controller.

Digital Power Supplies

All the power supplies discussed in this article can be implemented as analog or digital power supplies. What are digital power supplies, really? Power must always run through an analog power stage with switches, inductors, transformers, and capacitors. The digital aspect is introduced by two digital building blocks. The first one is digital interfacing, which allows an electronic system to "talk" and "listen" to a power supply. Different parameters may be set on-the-fly to optimize the power supply for different operating conditions. Also, the power supply can communicate with a main processor and raise warning or fault flags. For example, load current, crossing a preset threshold, or excessive temperature of a power supply may easily be monitored by a system.

The second digital building block replaces an analog regulation loop with a digital loop. This can work successfully, but for most applications, the optimum is a standard analog feedback loop with some digital influence on some parameters, such as adjusting the gain of the error amplifier on-the-fly or dynamically setting the loop compensation parameters to enable a stable but fast feedback loop. An example of a device with a purely digital control loop is the ADP1046A from Analog Devices. One example of a digitally interfaced buck regulator with an analog control loop, optimized by digital influences, is the LTC3883.

EMI Considerations

Electromagnetic interference (EMI) is always a topic to pay attention to when designing switch-mode power supplies. The reason is that switch-mode power supplies switch high current flow on and off within very short periods of time. The faster the switching, the better for total system efficiency. Faster switching transitions reduce the time during which the switch is partially turned on. During this partial turn-on time, most switching losses are generated. Figure 9 shows the waveform of the switch node of a switch-mode power supply. Let's imagine a buck regulator. High voltage is defined by current flow through the high-side switch, and low voltage is defined by lack of current flow through the high-side switch.

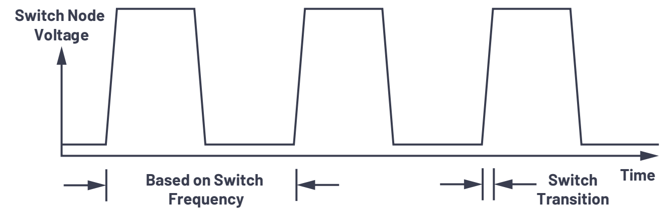

Figure 9. Switching transition speed as well as switching frequency of a switch-mode power supply.

In Figure 9 we can see that a switch-mode power supply does not only generate noise coming from the adjusted switching frequency, but also from the switching transition speed, which is much higher in frequency. While the switching frequency usually runs between 500 kHz and 3 MHz, the switching transition time may be a few nanoseconds long. At 1 ns switching transition time, we will see 1 GHz corresponding frequency in the spectrum. At least both of those frequencies will be seen as radiated and conducted emissions. Other frequencies may also show up coming from oscillations of the regulation loop or interactions between the power supply and filters.

There are two reasons why EMI should be reduced. The first reason is to protect the functionality of the electronic system that a specific power supply is powering. For example, a 16-bit ADC that is used in the signal path of the system should not pick up switching noise coming from the power supply. The second reason is to fulfill certain EMI regulations that are put in place by governments all over the world to protect reliable functionality of different electronic systems simultaneously.

EMI comes in two forms, radiated EMI and conducted EMI. The most effective ways of reducing radiated EMI is to optimize the PCB layout and to use technologies such as the Silent Switcher® technology from Analog Devices. Certainly, it is also effective to put the circuit into a shielded metal box. However, this may not be practical and in most cases is very costly.

Conducted EMI is typically attenuated by additional filtering. The next section will discuss additional filtering to reduce conducted emissions.

Filtering

RC filters are basic low-pass filters. However, in power supply design, every filter is nothing but an LC filter. Often, just adding some inductance in series is enough, since it will form an LC or CLC filter together with the input or output capacitors of a switch-mode power supply. Sometimes only capacitors are used as filters, but, considering the parasitic inductance on power cables or traces, together with a capacitor we form an LC filter as well. The inductor L may be an inductor with a core, or it may be a ferrite bead. The purpose of the LC filter really is a low-pass effect, so that DC power can run through and higher frequency disturbances are attenuated to a large degree. An LC filter has a double pole, so we get a high frequency attenuation of 40 dB per decade. This filter has a relatively sharp drop-off. Designing a filter is not rocket science; however, since parasitic components of the circuit, such as trace inductance, have an effect, modeling a filter also requires modeling the major parasitic effects. This can make simulating a filter quite time consuming. Many designers with filter design experience know which filters have worked before, and they may iteratively optimize a certain filter for a new design.

In all filter design, one needs to not only consider the small signal behavior, such as a transfer function of a filter in a Bode plot, but one also needs to be aware of the large signal effect. In any LC filter, power runs through the inductor. If that power

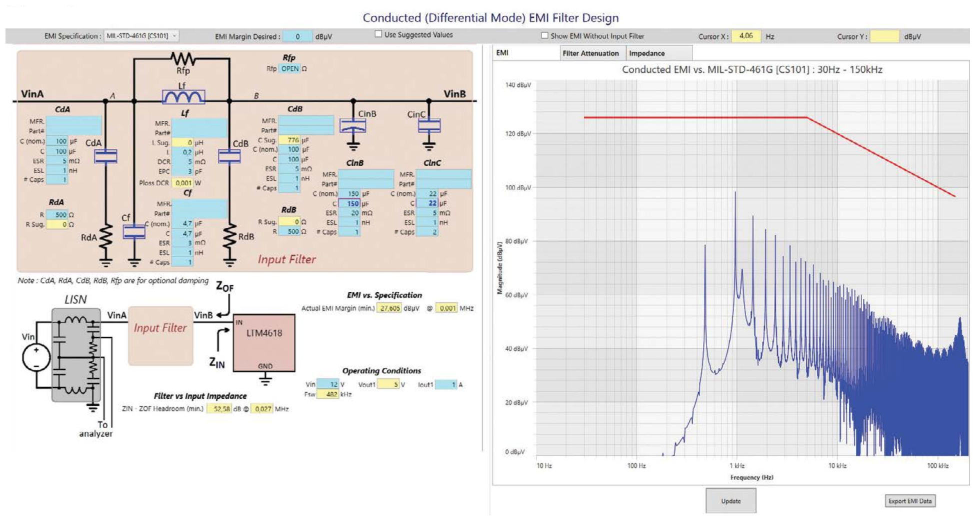

Figure 10. Designing an input filter for a buck regulator with LTpowerCAD.

is not needed at the output anymore, due to a sudden load transient, the energy stored in the inductor needs to go somewhere. It charges up the capacitance of the filter. If the filter is not designed for such worst-case conditions, that stored power may cause voltage overshoots that can possibly harm circuitry.

Finally, filters have a certain impedance. That impedance interacts with the impedances of the power converters that are attached to the filter. This interaction may lead to instabilities and oscillations. Simulation tools such as LTspice and LTpowerCAD from Analog Devices can be a big help in answering all these questions and designing a perfect filter. Figure 10 shows the graphical user interface of the filter designer within the LTpowerCAD design environment. With this tool, filter design is very simple.

Silent Switchers

Radiated emissions are difficult to block. A special shielding with some metal material is needed. This can be very costly. For a long time, engineers were looking for ways to reduce the radiated emissions that switch-mode power supplies generated. A few years ago, a great breakthrough was made with Silent Switcher technology. By reducing the parasitic inductances in the hot loops of a switch-mode power supply, and by splitting the hot loops into two and setting them up in a very symmetrical way, radiated emissions mostly cancel each other out. Today, many Silent Switcher devices are available offering much lower radiated emissions than heritage products. Reducing the radiated emissions allows for switching transition speeds to increase without a serious EMI penalty. Making the switching transitions faster reduces switching losses and thus allows for much higher switching frequencies. One example of this innovation is the LTC3310S, which can operate at 5 MHz switching frequency, enabling extremely compact designs with very low cost external components.

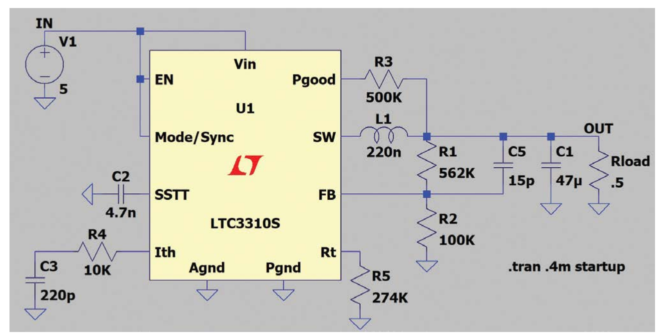

Figure 11. LTC3310S Silent Switcher design for the lowest radiated emissions.

Power Management Is a Necessity but Can Be Enjoyable Too

In this tutorial we looked at many aspects of power supply design, including the different power supply topologies and their advantages and disadvantages. For power supply engineers, this information can be very basic, but for experts and non-experts alike, it is helpful to have software tools such as LTpowerCAD and LTspice to aid in the design process. With these tools, power converters can be designed and optimized in very little time. Hopefully this tutorial inspired you to look forward to your next power supply design challenge.

About the Author

Frederik Dostal studied microelectronics at the University of Erlangen in Germany. Starting work in the power management business in 2001, he has been active in various applications positions including four years in Phoenix, Arizona, where he worked on switch-mode power supplies. He joined Analog Devices in 2009 and works as a field applications engineer for power management at Analog Devices in München. He can be reached at frederik.dostal@analog.com.

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