Comparison of different power supplies for portable DSP solutions working from a single-cell battery

By Juergen Neuhaeusler
Power Management Systems Engineer

Introduction

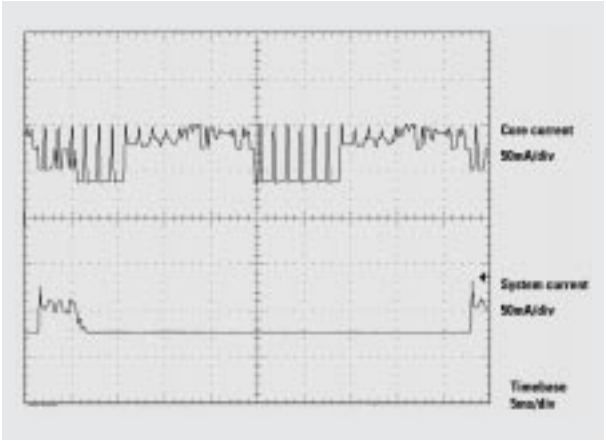
There are different ways to approach today´s requirements for power supplies in portable DSP solutions. Normally two system voltages are needed, one for the DSP core and the other for DSP I/O and the rest of the system. A major concern is that the power supply needs to be highly efficient to extend battery life. This article introduces different configurations of DC/DC converters that address these requirements. With an MP3 Internet audio player used as an example, the system designs are explained and analyzed for performance, total efficiency, and cost.

The problem

Because modern DSPs require dual supply voltages with restricted voltage tolerances, it is impossible to supply circuits directly from the batteries; so suitable DC/DC converter solutions have to be designed.

Another design challenge is the load behavior, as can be seen in the transients in the core and system supply current of an Internet audio evaluation module (EVM) shown in Figure 1. There are different tasks running in the software that are reflected as transients in core and system current, such as waking up the DSP to service DMA interrupt and performing decode and media access. Because both core and system have to be supplied by the same energy source, additional problems can occur through superimposition of these current pulses. Engineers are faced with a demand for designs that offer good performance at low cost—especially for battery-powered equipment, where good performance of the power supply circuit means the highest efficiency and long battery life.

Figure 1. DSP input currents (core and system) for an Internet audio EVM

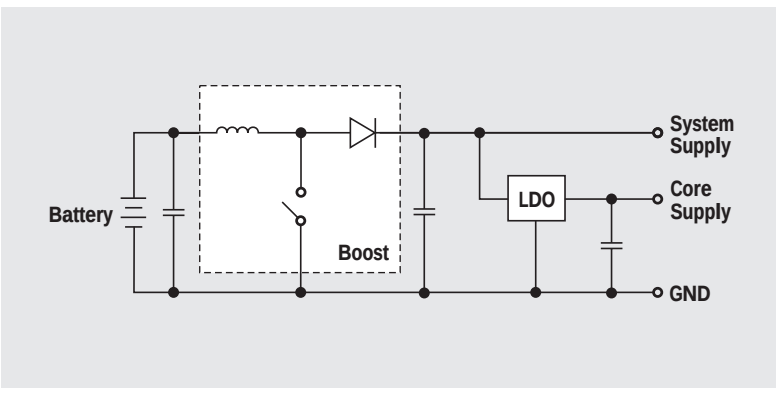


DC/DC converter solutions

In the following discussion, different designs of DC/DC converters are introduced that can be used to supply DSP core and system circuits with the typical two supply voltages. The designs are demonstrated on TI's Internet audio EVM, based on the TMS320VC5410 DSP, which requires 3.3 V for the system and 2.5 V for the core.

All of the DC/DC converters described are capable of operating from alkaline, NiCd, or NiMH batteries, so they must handle an input voltage range from 0.9 V up to 3.0 V. Because the system voltage is at 3.3 V and therefore higher than the maximum input voltage, a boost-based solution always must be used. Three different circuits are discussed. The first configuration is a boost converter with a cascaded LDO, the second is a dual-output flyback converter, and the third is a boost converter with a cascaded buck converter.

Figure 2. Boost converter with cascaded linear regulator



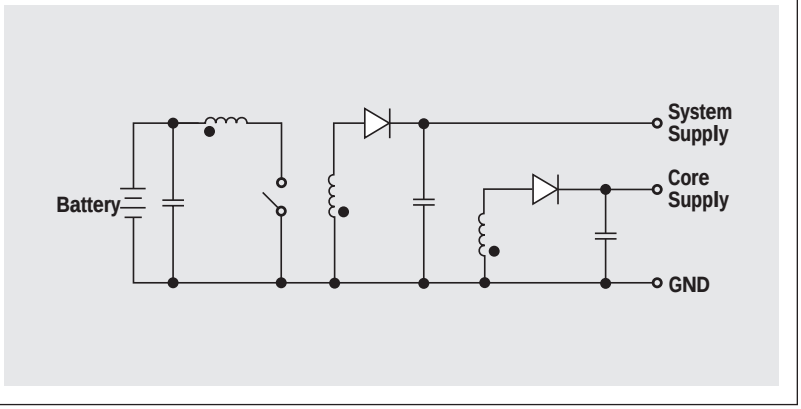
Boost converter with a cascaded linear regulator

The first and simplest solution is the boost converter with a cascaded linear regulator. As shown in Figure 2, the boost converter stage is connected directly to the battery with a blocking capacitor. At the output of the boost (which is also the system supply), the linear regulator is connected to generate the lower core voltage.

The standard boost converter shown in Figure 2 operates with one active switch, which is controlled by a pulse-width modulation (PWM) scheme. When the switch is closed, the inductor is charged by the battery. Opening the switch redirects the current through the rectifier to the output capacitor, which then is charged. The ratio between input and output voltages is determined by the duty cycle. Details about the design and operation of a boost converter can be found in References 1 and 2.

Due to the nature of boost converters, the input current is continuous and the output current is discontinuous. This is important to consider when choosing the capacitors around the converter and will be explained later in this article. To increase efficiency, use of a converter with synchronous rectification is highly recommended, because it uses a MOSFET switch instead of the diode to reduce the conduction losses. To generate the core voltage, a linear regulator is used. The nominal dropout in this design is 0.8 V (3.3 V to 2.5 V), so a linear regulator with low dropout (LDO) has to be chosen. For details of operation and design, refer to the appropriate LDO datasheets.

Figure 3. Dual-output flyback converter



Dual-output flyback converter

The second solution provided is a flyback converter with a dual output, shown in Figure 3. The input to the flyback stage is connected directly to the battery.

From a battery standpoint this input is similar to the boost input, except that the rectification is done differently. The inductor is divided into three windings. It is charged through the primary winding (similar to the boost) and discharged through the two secondary windings. Regulation is also achieved by a PWM scheme, but only one output can be regulated. The second output will follow this regulation indirectly through the winding ratio of the two secondary windings. The inductor discharge current will always flow into the output where the voltage is lowest. Under special operating conditions, the unregulated output can break down when it is under full load and the regulated output is under a light load or freewheeling. To avoid problems this must be taken into consideration when choosing the output that is regulated by the PWM controller that controls the flyback switch. When selecting the capacitors it is important to know that the input and output currents are discontinuous. Details about design and operation of flyback converters can be found in References 1 and 3.

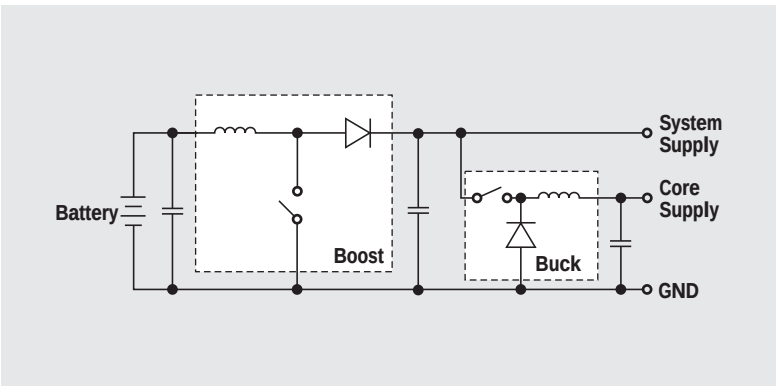
Because no converters for synchronous rectification of multiple-output flyback applications are available, it is not possible to design a small, highly efficient circuit. The voltages of the system and core supplies have a difference of only 0.8 V in our test circuits, so there is no gain in efficiency using the non-synchronous flyback solution compared to the synchronous boost + LDO solution. In addition, the design of the flyback solution is significantly more costly and requires more board space due to the customized inductor, which is larger and more expensive than a standard boost inductor. Therefore this solution is not considered in this article.

Boost converter with cascaded buck converter

The third solution, a boost converter with a cascaded buck converter, is the most costly but also the most efficient. It consists of the same boost converter as the solution with the LDO; but, instead of the LDO, a buck converter is added. The block diagram is shown in Figure 4. The standard buck converter also operates with one active PWM-controlled switch. When the switch is turned on, the inductor is charged. Turning off the switch leads to a freewheeling phase where the inductor current flows through the buck rectifier diode. The ratio between input and output voltage is also determined by the duty cycle. Details about the design and operation of buck converters can be found in References 1 and 4.

For defining the input and output capacitors, it is important to know that in a buck converter the input current is discontinuous and the output current is continuous. This also helps in design optimization. When the buck converter is controlled in a way that requires input current in the switching phase, where the boost converter delivers output current, the stress to the storage capacitors for the system voltage can be reduced by

Figure 4. Boost converter with cascaded buck converter



Continued on next page

Continued from previous page

trailing edge/leading edge synchronization. This means that the buck switch will be turned on after the boost switch is turned off. The efficiency of a buck converter also can be increased by using synchronous rectification with a MOSFET instead of using a diode.

The capacitors

The boost input capacitor serves to decouple the boost input from the battery and its connection (battery terminal, cables, and PCB traces). In general, it can be said that the more capacitance you add, the better it will be for the battery. But this will be effective only if the equivalent series resistance (ESR) of the capacitance is lower than the series resistance and impedance of the battery and its connection. Optimization can be done when these design parameters are known. Due to the continuous current at the boost converter input, the input capacitor is needed only for decoupling and lowering the current ripple of the input current. Therefore it will not affect power conversion efficiency to leave out this capacitor in very cost-sensitive designs. It is normal to use a 10-µF X7R or X5R ceramic capacitor, as in the designs described here.

The boost/flyback output capacitor is needed to supply the load during the charging phase of the inductor in normal operation. So its value and ESR are the main determining factors for the output ripple. Relevant parameters for the calculation of the minimum capacitance are the maximum output current and the desired voltage ripple on the output voltage, as well as the duty cycle and the operating frequency. The output capacitor also can be used to cover a current transient impulse with a corner frequency above the crossover frequency of the boost converter. Because of this, high-performance capacitors such as ceramic capacitors or low-ESR/ESL tantalum capacitors are a good choice.

The LDO output capacitor is used to stabilize the control loop of the LDO. Due to the high loop-gain bandwidth, the LDO normally requires no additional output capacitance to cover current transient impulses. Energy storage is better done at the input of the LDO. The buck input capacitor also has a storage function because of the discontinuous current of the buck converter input. It dampens the input current impulses and so reduces the stress on the supplying components. In this design the buck input is connected to the boost output, where the same considerations on the capacitors have to be made. Due to the synchronization with the boost converter and the output capacitors of the boost converter already on the board, no additional capacitors are necessary for the buck input.

The output current of the buck converter is continuous. Ideally, no capacitor is necessary, but stabilizing the control loop and covering fast-transient current pulses with a corner frequency above the crossover frequency of the buck converter requires capacitance. For this task, a high-performance capacitor is recommended. Storing energy to cover current pulses with a corner frequency below the crossover frequency is better done at the input of the buck converter. Due to the higher operating voltage at the input, more energy will be stored in the same capacitance and volume, assuming that the voltage ratings of the capacitors are the same.

Final designs and measurement results

Power supply needs

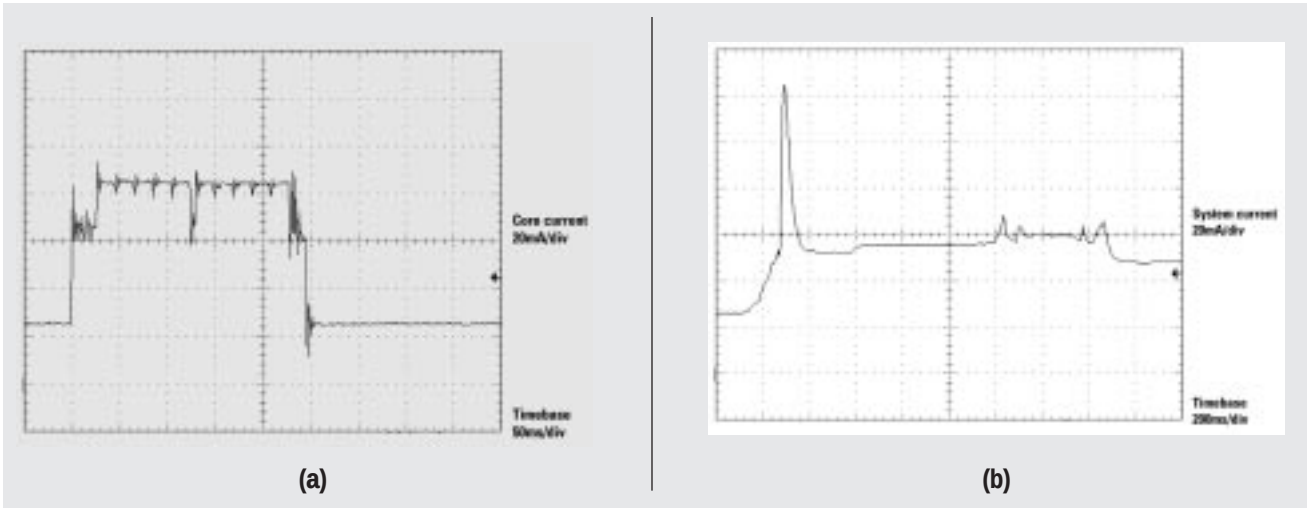
The Internet audio EVM used for this article requires 2.5-V core voltage with a maximum current of 120 mA. The average is in the range of 90 mA. The system supply is 3.3 V and requires a maximum current of 90 mA, with an average of 70 mA.

Identifying the corner frequencies of core and system current

The oscilloscope plots in Figure 5 show the rising edge of the fastest current pulses of core (a) and system (b) supply current.

With the rise time of the rising edges, the corner frequency can be calculated ($f_c = 0.35/t_r$). The result for core current is in the range of 230 kHz. Because DC/DC converters usually have crossover frequencies in the range

Figure 5. Fastest load transients of core and system supply



of 10 kHz, this corner frequency must be lowered by using additional storage/blocking capacitance. An additional 10-µF tantalum capacitor with an ESR lower than 3 ohms would reduce this corner frequency to the range of 1 kHz, well within the acceptable range. The same is done for the system supply. A corner frequency of 20 kHz is calculated with the data of the shown pulse. To ensure proper operation, this frequency should be lowered to a value of 1 kHz by using additional output capacitance in the range of 10 µF.

Identifying the maximum current pulses for system supply

The worst case of the total system current is shown in the oscilloscope plot in Figure 6. Because the peak of this current pulse lies above the maximum operating current, the pulse was covered by increasing the storage capacitance of the system supply (boost output). With the parameters from this pulse it is possible to calculate the required capacitance by allowing a maximum voltage decrease of 0.1 V caused by this current pulse. A minimum storage capacitance of 225 µF with a total ESR lower than 0.1 ohms can be calculated. To achieve this, two additional 120-µF tantalum capacitors with low ESR of 0.85 ohms were added in parallel to the output of the boost in both configurations previously discussed. Another way to cover this kind of pulse is to oversize the basic DC/DC converter, which usually is more costly and requires more board space.

Description of boost + LDO circuit

Figure 7 shows a test circuit that uses a boost converter with a cascaded LDO. For this design the TI TPS61016 boost converter is used. It is a synchronous boost converter with integrated switches and a fixed output voltage of 3.3 V. This device is capable of covering the whole input voltage range from 0.9 V up to 3.0 V. As shown in the figure, it requires a small number of external components to operate. Input and output capacitors (defined earlier) are added. The TPS76925 is used as the LDO. A small tantalum capacitor is added at the output for stable operation.

Table 1 shows the parts list for this circuit with the cost added for each component.

Continued on next page

Figure 6. Worst-case total system current

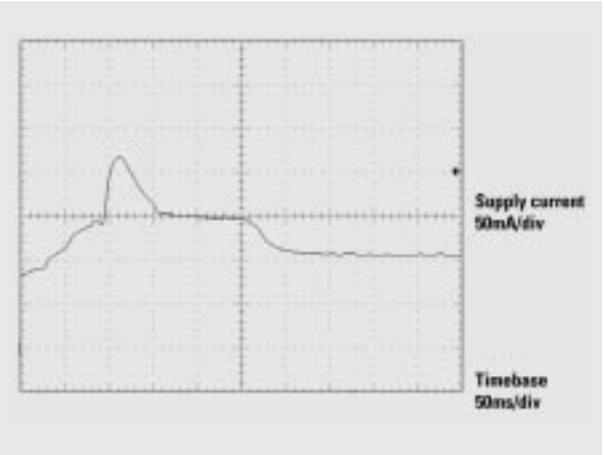
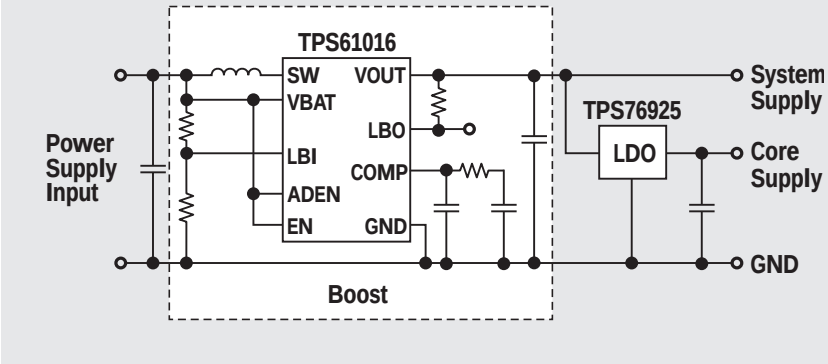


Table 1. Parts and cost of boost + LDO circuit

COMPONENT	DESCRIPTION	COST (%)
Input capacitor	10 µF X5R 6.3 V	10
Boost output capacitors	2 x 120 µF 594D 6.3 V	34
LDO input capacitor	1 µF X5R 6.3 V	1
LDO output capacitor	10 µF 293D 10 V	7
Boost inductor	CDR63	7
Boost converter	TPS61016DGS	30
LDO	TPS76925DBV	10
Various passive components		1
	TOTAL	100

Figure 7. Complete schematic of boost + LDO solution

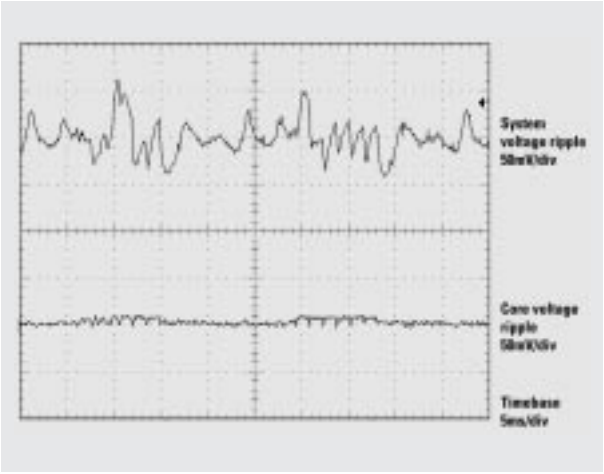


Continued from previous page

Figure 8 shows the ripple of core and system voltage during operation at an input voltage of 1.2 V (single battery NiXX).

It can be seen that the ripple is lower as designed. Figure 9 shows, in the upper trace (100-mV ripple), the power consumption of the Internet audio EVM under normal operation (playing music) versus the input voltage. The power losses in the boost input circuit increase due to the higher current at lower voltages.

Figure 8. Ripple of core and system voltage of a boost + LDO solution during operation



Description of a boost + buck circuit

Figure 10 shows a test circuit that uses a boost converter with a cascaded buck converter. The boost circuit is the same as in the boost + LDO solution, and the buck circuit is based on the TPS62006*, a synchronous buck converter IC with integrated switches. It offers a fixed output voltage of 2.5 V and is easiest to synchronize with the boost converter. There are only a few external components required for operation. Input and output capacitors also are added as suggested before.

Table 2 shows the cost calculation based on the parts list for the total circuit.

*Future product. Contact TI for availability.

Table 2. Parts and cost of boost + buck circuit

COMPONENT	DESCRIPTION	COST (%)
Input capacitor	10 µF X5R 6.3 V	10
Boost output capacitors	2 x 120 µF 594D 6.3 V	34
Buck input capacitor	1 µF X5R 6.3 V	1
Buck output capacitor	22 µF X5R 6.3 V	17
Boost inductor	CDR63	7
Buck inductor	LQH4C	3
Boost converter	TPS61016DGS	30
Buck converter	TPS62006DGS	30
Various passive components		1
	TOTAL	133

Figure 9. Power consumption of boost + LDO and boost + buck solutions

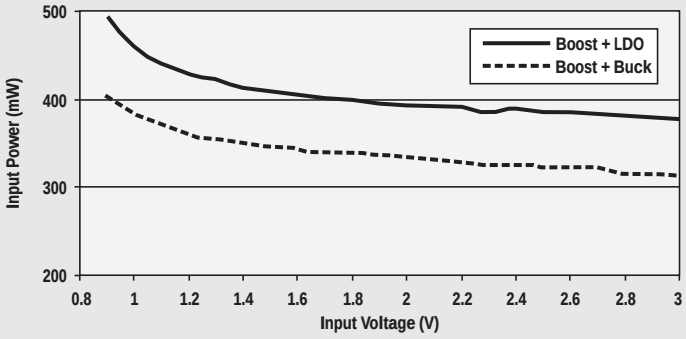
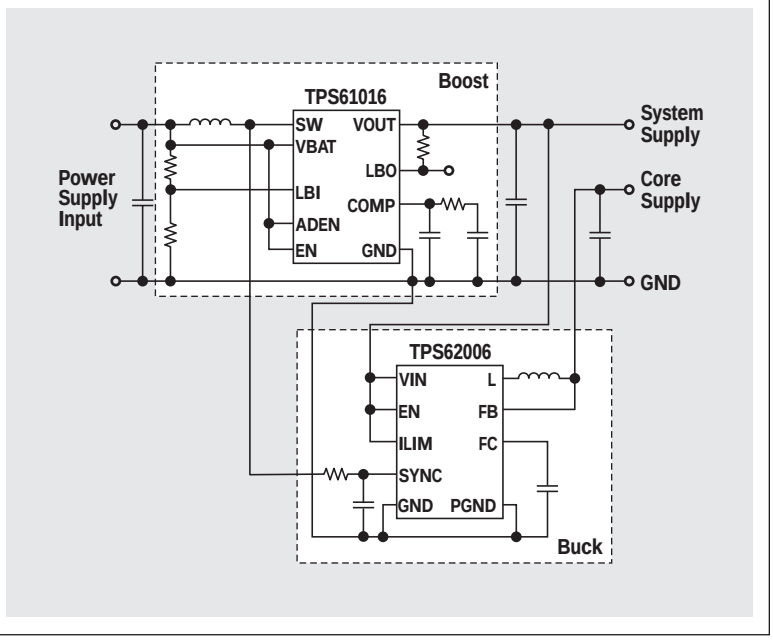


Figure 11 (voltage waveforms) and Figure 9 (power consumption, lower trace) show the results of the measurements.

Conclusion

From comparing the results of the power consumption measurements, it is clear that the boost + buck configuration is significantly more efficient. A single battery supply provides about 4.2 hours of operating time for the boost + LDO solution and 5 hours for the boost + buck solution, so the latter offers an improvement of about 20% in battery life. The trade-off is higher power supply system cost. The boost + buck solution is 33% more expensive and requires more board space. There is no doubt that the boost + LDO circuit is much easier to design. Fewer calculations have to be made to select the right components, and no synchronization has to be implemented. Regarding the future development of DSPs, the gap between core and I/O (system) voltage is increasing, leading to an increasing gap in power consumption between the two solutions. This could make the flyback solution more attractive. In the end, the designer has to decide whether he wants a simple and small solution or a more expensive, larger, but more efficient power supply.

Figure 10. Complete schematic of boost + buck solution

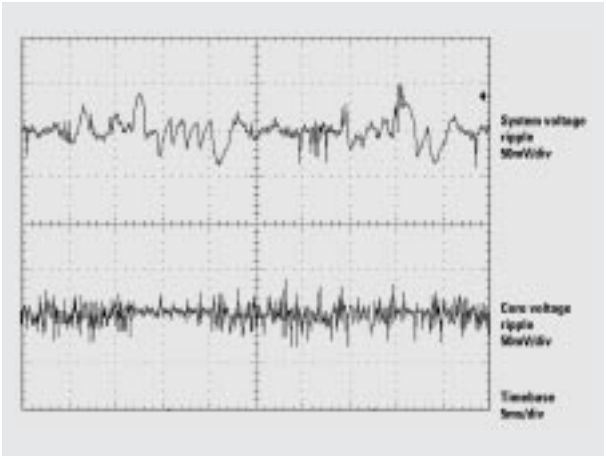


References

For more information related to this article, you can download an Acrobat Reader file at www-s.ti.com/sc/techlit/*litnumber* and replace "*litnumber*" with the **TI Lit. #** for the materials listed below.

Document Title	TI Lit. #
1. Robert W. Erickson, *Fundamentals of Power Electronics*, ISBN 0-412-08541-0.	—
2. "Understanding Boost Power Stages in Switchmode Power Supplies," Application Report	slva061
3. "Understanding Buck-Boost Power Stages in Switchmode Power Supplies," Application Report	slva059
4. "Understanding Buck Power Stages in Switchmode Power Supplies," Application Report	slva057

Figure 11. Ripple of system and core voltage of a boost + buck solution during operation



Related Web sites

http://power.ti.com
www.ti.com/sc/docs/products/analog/tps61006.html
www.ti.com/sc/docs/products/analog/tps76925.html
www.ti.com/sc/docs/products/dsp/tms320vc5410.html