ANALOG edge℠

Silently Powering Low-Noise Applications

Application Note AN-1950

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Highly-sensitive signal path applications such as those in the communications infrastructure need to be powered like any other electrical circuit. What makes this task especially difficult is that the power must be provided without generating unwanted noise and without passing it along into the sensitive signal path circuitry. The power supplies must be as efficient as possible to save energy and to reduce unwanted heat generation. Mostly switch-mode power supply circuits are implemented in such systems to fulfill the energy-efficiency requirement. Unfortunately, these circuits are inherently noisy.

This article will explain how to implement a low-noise switch-mode power supply solution. It will introduce the sources of noise and explain how to minimize them. A significant factor in noise generation and propagation is the printed circuit board layout. Important basics will be discussed. Circuit measurement techniques are also explained to guide a design engineer toward a low-noise, but efficient solution.

Powering Noise-Sensitive Circuitry

An example of noise-sensitive loads is an application used in wireless infrastructure systems; namely, a low-IF receiver reference design using National Semiconductor's ADC16V130 analog-to-digital converter as well as National's LMK04031B clock conditioner which provides digitization and clocking. This reference design, RD-170, can be downloaded from National's website: http://www.national.com/rd/RDhtml/RD-170.html. For noise purposes, linear regulators are often used as power supplies directly powering the load. Since linear regulators become very inefficient when the input-to-output voltage ratio becomes large, the combination of a switch-mode power supply with a linear regulator becomes necessary. In such systems, very special care must be taken to limit the influence of a noisy switch-mode power supply onto the signal path of the application.

There are three power management concepts often encountered to power very noise-sensitive signal path circuitry. *Figure 1* shows three typical concepts. In addition to the three concepts shown, there are many more related topologies. In this article we will focus mostly on the bottom concept in *Figure 1*. The reference design RD-170 includes linear regulators as local low-noise power supplies which provide a good solution for a switch-mode power supply powering the board RD-170 or other noise-sensitive circuitry as discussed in this article.

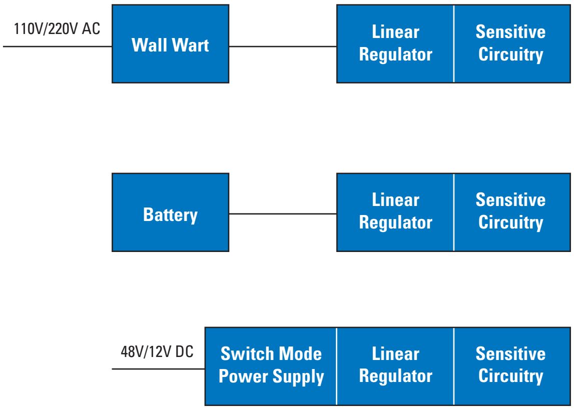

Figure 1. Typical Concepts of How to Power Noise-Sensitive Circuitry

Various Point-of-Load Topologies and Typical Noise

There are various switch-mode point-of-load power management topologies. *Figure 2* shows the most common basic topologies. Each topology uses an inductor and a power switch consisting of either two transistors or one transistor and a diode. When looking at the inputs and outputs of the different topologies, one can see that some are relatively silent and some are relatively noisy.

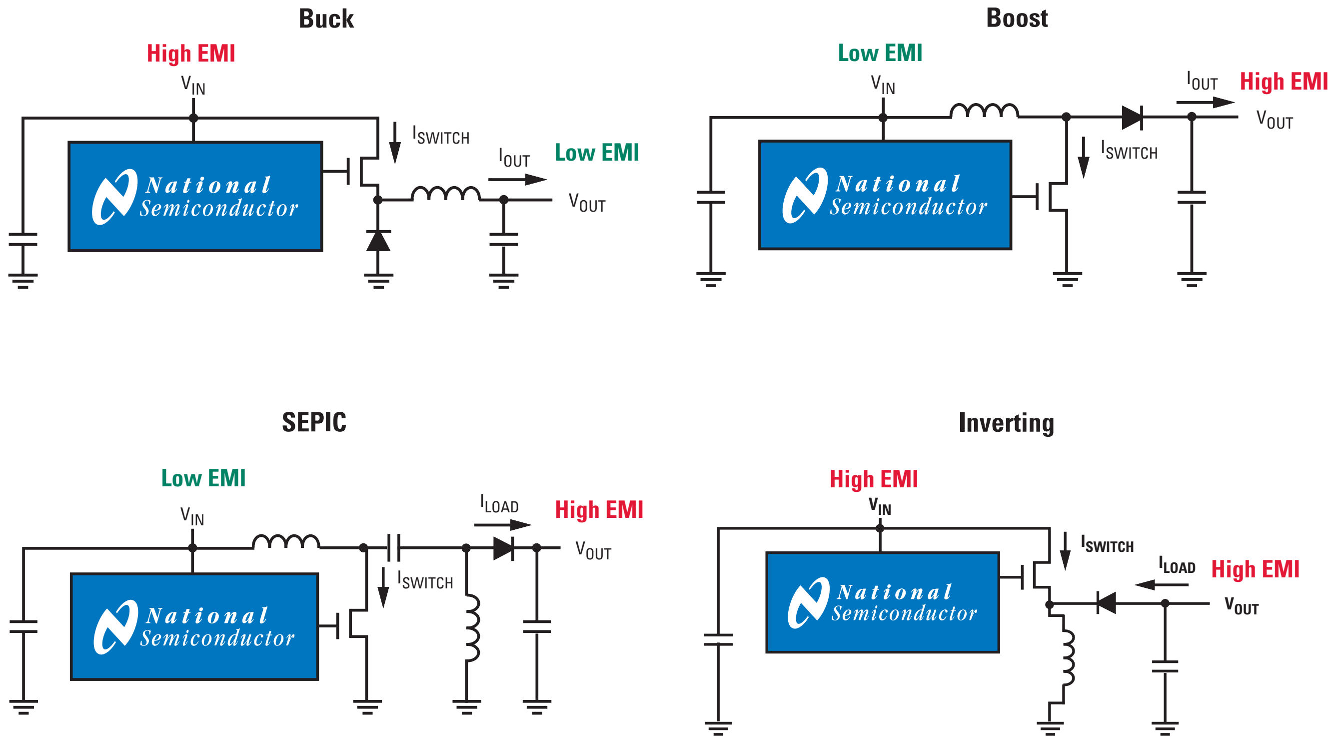

Figure 2. Low-EMI and High-EMI Terminals on Common DC-DC Topologies

The high noise (high EMI) is caused when there is no inductor close to the connection. In such cases, the connection sees large currents which are turning on and off in short amounts of time. In typical switch-mode power supplies, the transition from no current to full current at the switch node is 15 ns or less. This large di/dt causes high power-voltage noise in the system.

Besides different possible topologies, each one can be realized with different control modes. *Figure 3* shows a table of advantages and disadvantages of the most common control modes. Hysteretic mode control has only a hysteretic comparator regulating the output voltage. It is a very fast control method but does not have a fixed switching frequency. This makes it less suitable for low-noise applications because additional filtering can not be optimized easily and it is difficult to predict the frequency of generated noise. Another control mode is voltage mode control which regulates the output only by looking at the output voltage. It has unique stability behavior and usually has a little bit slower transient response compared to a current mode control system. In current mode control, besides the output voltage sensing, the switch current is also sensed. This makes the loop compensation a bit simpler and also may speed up transient responses.

	Voltage Mode Control	Current Mode Control	Emulated Current Mode Control	Hysteretic Mode Control	Hysteretic with Ripple Injection
Loop speed	+	0	0	++	++
Ease of compensation	-	+	+	No compensation	No compensation
Fixed switching frequency	+	+	+	-	-
Low dropout voltage at high switching frequency	+	+	-	+	+
Large V_{IN} to V_{OUT} difference at high switching frequencies	+	-	+	+	+
Low output voltage ripple possible	+	+	+	-	+

Figure 3. Advantages and Disadvantages of Various Control Modes

Designing a Switch-Mode Power Supply for Low Noise

One of the first tasks after having chosen the power conversion topology is the selection of external components, while keeping in mind the low-noise requirement. For the following considerations, the discrete components of a buck (step-down) topology are considered.

Input capacitors in buck regulators are especially critical. Input filtering is very important due to the fact that the input connection of a buck sees significant AC currents. Possibly even an additional LC filter on the input may be needed to reduce system noise. Low-ESR bypass capacitors are needed on the input to handle the fast di/dt currents. Often, higher-ESR input capacitors for input damping are required in addition to low-ESR input capacitors.

Regarding the power switch, options include MOSFETs as well as bipolar transistors. Bipolar transistors are usually lower noise due to longer transition times and rounder switching edges. MOSFETs, however, are usually preferred due to their higher efficiency.

In non-synchronous buck regulators, the low-side switch is a free-wheeling diode. A Schottky diode is a must due to its very small reverse-recovery effect. Other diode types are not recommended since Schottkys are much faster than other types such as 'ultra fast' diodes.

Shielded inductors are usually better than unshielded ones for low-noise applications. In general, the larger the inductance, the lower the inductor current ripple and the lower the output voltage ripple with a given output capacitor. However, if load transients are severe, a large inductance will show a larger load transient response.

The ESR and size of the output capacitors directly define the output ripple voltage with a given inductor size. Large low-ESR output capacitors are beneficial for low noise.

Layout is the Most Significant Factor for Low Noise

Printed circuit board (PCB) traces have inductance. Thicker traces, effectively larger wire diameter, will reduce the inductance, but only slightly. The area enclosed by the current loop - and there is always a loop - has the greatest effect on stray inductance. Current paths should be kept directly adjacent to their return paths, parallel on the same layer or directly above or below on an adjacent layer. A typical inch of PCB trace has about 20 nH of inductance. Assuming a transition time of 15 ns from 0A of current to 3A of current will yield a 4V potential offset across that inch-long trace. This illustrates how important a tight layout is to switch-mode power supplies, especially regarding noise.

Signals in a system are not voltages traveling from one pin to the next over wires. Signals are currents that must move from a source of energy and they must return to that same source of energy. Currents always take the path of least impedance and not the path of least resistance. For DC current, the path of least impedance is the same as the path of least resistance. For AC currents like those in switch-mode power supplies, the path of least impedance is often different than the path of least resistance.

Locating the AC Current Paths

In switch-mode power supplies, the most important board layout rule is to keep AC current traces with as low an inductance as possible. This means these traces should be kept as short as possible and also on one layer, with thick traces and preferably no vias. Any inductance in the AC current traces will cause large voltage off-sets which will produce excessive noise.

Current flow diagrams illustrate very quickly where these AC traces are located. They also show that ground traces are just as much AC traces as other traces. National's application note AN-1229 explains more details about this.

Figure 4 shows the current flow on the top circuit as a dotted line in a buck converter in the transistor on-state. The middle circuit shows the current flow as a dotted line during the transistor off-state. The bottom circuit shows all the critical AC traces where current flow is changing from on-state to off-state. ***Figure 5*** shows a layout implementation that keeps these critical AC-current traces as short as possible to avoid unnecessary trace inductance and to keep noise as low as possible.

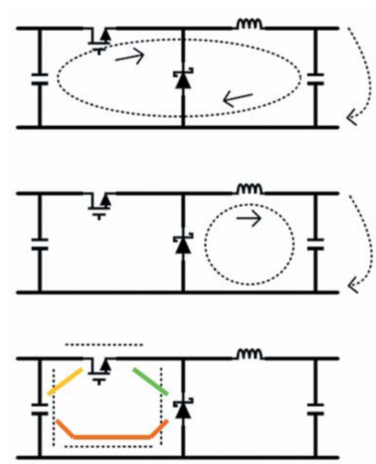

Figure 4. Current Flow in a Buck Converter

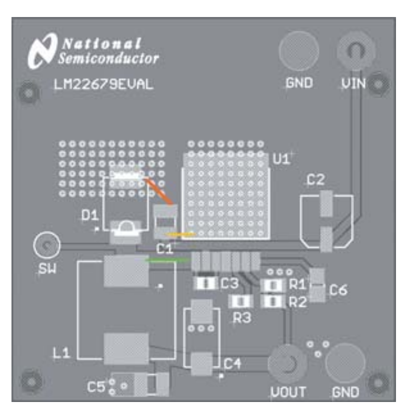

Figure 5. Layout Example with Short AC Traces from Figure 4 Indicated in Color

Keeping Things Stable

If a power supply should be low noise, a very important step is to stabilize the power supply. Since any regulated power supply has a control loop, it may be unstable. If the power supply is not stable, some over-voltage protection will usually limit the voltage on the output causing higher output voltage ripple as well as unpredictable switching frequencies which are difficult to filter. Instability can be observed by looking at the switch-node voltage and observing if the falling edge of the signal is randomly jumping back and forth or if it is calm. Some movement of the falling edge is quite common, but it should not move more than about five percent of one switching period. National's application note AN-1889 is a step-by-step guide to taking a Bode plot measurement with only a signal generator and a standard oscilloscope. No network analyzer is required to do a thorough control-loop measurement of a power supply.

The Beat Frequency Phenomenon

If more than one switch-mode power supply is present in a system, the beat frequencies must be considered. The power supply rejection ratio (PSRR) is usually very poor at high frequencies. The issue is that the switching noise from one switch-mode power supply will pass to the output of a second, parallel switch-mode power supply. One solution in such situations is to use additional LC filtering on the input of the supplies or to synchronize the point-of-load regulators to share one switching frequency.

Other Helpful Considerations

A snubber can silence the switch node. Typically the switch-node ringing is not a great concern regarding noise since it is a very low energy ringing. However in some applications, it is required to snub the high-frequency ringing away. The ringing can be dissipated with an RC circuit (snubber) from the switch node to ground.

Additional LC filtering on the output for a 'high-EMI' output topology such as a SEPIC topology (***Figure 2***) can reduce the output ripple voltage as well as noise dramatically.

In some systems, linear regulators are used in a cascaded fashion with a switch-mode power supply to filter noise. Such a linear regulator post filtering is only useful if there is a longer trace (distance) and decoupled grounds between the switch-mode power supply and the linear regulator. If they both are on the same board, a LC filter might be the less expensive and better alternative. A good application for using a low dropout (LDO) regulator is if the switch-mode power supply is on a different PCB than the linear regulator. Linear regulators also have the advantage of providing very good DC regulation compared to a LC-filter approach.

Ripple Voltage and How It is Measured

Common language is misleading when it comes to describing noise in power supplies. What is regarded as switching noise is actually not noise in the common sense of random occurrences in frequency. The noise is deterministic at the switching frequency, transition-period frequency, and multiples thereof. ***Figure 6*** shows a typical output voltage measurement of a step-down switch-mode power supply. There is some output ripple voltage which is about 5 mV. In addition to the ripple voltage, there is also some high-frequency transition amplitude right at the switch transitions of the switch node. This noise shows about 70 mV of spikes and it may be line bound or electro-magnetically coupled. The measurement was obtained by using an oscilloscope probe tip with a very short ground connection to the board under test. ***Figure 7*** shows a picture of a good measurement connection.

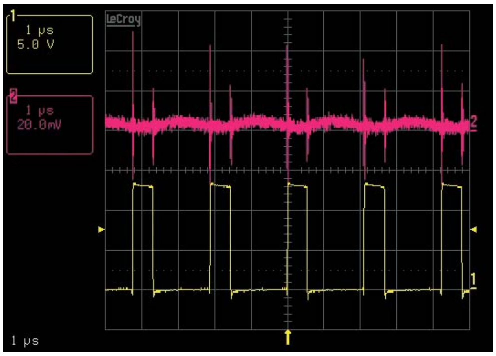

Figure 6. Typical Output Voltage and Switch-Node Waveform

Figure 7. Good Measurement Technique to Measure Output Ripple Voltage

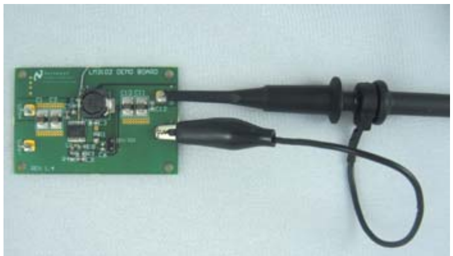

Figure 8. Poor Measurement Technique

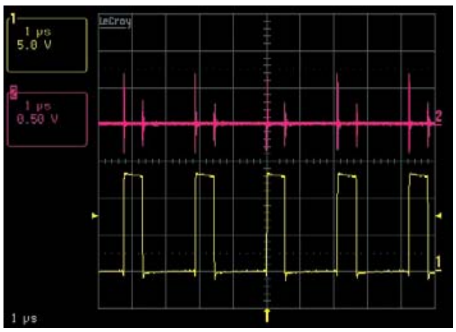

Figure 9. Measurement Results with a Poor Measurement Technique

Figure 8 shows a poor measurement technique with a long ground-trace connection. This ground cable is a high-impedance node and picks up switching noise like an antenna which is not real in that amplitude. *Figure 9* shows the measurement result with the same board and operating conditions as used for *Figure 6*, but with a careless measurement technique as shown in *Figure 8*. The measurement shows spikes up to 1V peak to peak, and they are only caused by poor measurement.

Silence is Golden

For low-noise signal path applications, power supply noise is a critical consideration. As described in this text, many factors are important to consider when designing a power supply to power applications such as wireless infrastructure systems. With a good understanding of the issues involved, the right topology, control mode, and layout can be selected and implemented. Also noise-measurement techniques are very important to consider when optimizing for low noise. ■

For further information on low-noise signal path design, please visit www.national.com/comms

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