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Minimizing switching-regulator residue in linear-regulator outputs

BANISHING THOSE ACCURSED SPIKES TAKES ATTENTION TO DETAIL AND UNDERSTANDING THE SUBTLETIES.

Designers frequently use linear regulators to postregulate switching-regulator outputs. The benefits of this approach include improved stability, accuracy, and transient response, along with lower output impedance. Ideally, markedly reduced switching-regulator-generated ripple and spikes would accompany these performance gains. In practice, all linear regulators encounter some difficulty with ripple and spikes, particularly as frequency rises. The regulator's small input to output differential voltages magnify these effects; this situation is unfortunate, because such small differentials are desirable for maintaining efficiency.

Input-filter capacitors smooth the ripple and spikes before they reach the regulator (**Figure 1**). The output capacitor maintains low output impedance at higher frequencies, improves load transient response, and supplies frequency compensation for some regulators. Ancillary purposes include minimizing both noise and the appearance of residual-input-derived artifacts at the regulator's output. These artifacts are of concern because these high-frequency components, even though of small amplitude, can cause problems in noise-sensitive video, communication, and other types of circuitry. Designers expend large numbers of capacitors and aspirin in attempts to eliminate these undesired signals and their resultant effects. Although these signals are stubborn and sometimes seemingly immune to any treatment, understanding their origin and nature is the key to containing them.

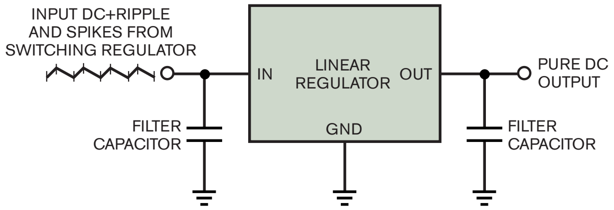

Figure 1 A conceptual linear regulator and its filter capacitors theoretically reject switching-regulator ripple and spikes.

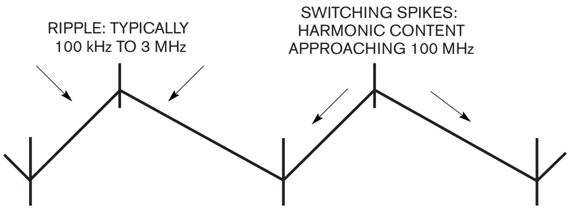

Figure 2 A switching-regulator output contains relatively low-frequency ripple and high-frequency "spikes," derived from regulators' pulsed-energy delivery and fast transition times.

SWITCHING-REGULATOR AC-OUTPUT CONTENT

Figure 2 details a switching regulator's dynamic ac-output content. It comprises relatively low-frequency ripple at the switching regulator's clock frequency—typically, 100 kHz to 3 MHz—and high-frequency content "spikes" associated with power-switch transition times. The switching regulator's pulsed

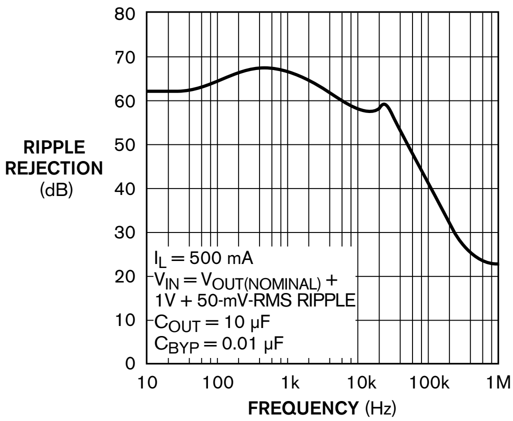

Figure 3 Ripple-rejection characteristics for an LT1763 low-dropout linear regulator show 40-dB attenuation at 100 kHz, rolling off toward 1 MHz. Switching-spike harmonic content approaches 100 MHz and passes directly from input to output.

energy delivery creates the ripple. Filter capacitors smooth—but do not eliminate—the ac content. The spikes, which often have harmonic content approaching 100 MHz, result from high-energy, rapidly switching power elements within the switching regulator. Slowing the regulator's repetition rate and transition times can greatly reduce ripple and spike amplitude, but the size of the magnetic elements increases, and their efficiency falls. Circuitry employing this approach has significantly reduced harmonic content but sacrificed the magnetics' size and efficiency (**Reference 1**). The same rapid clocking and switching that allows the use of small, highly efficient passives results in the presentation of high-frequency ripple and spikes to the linear regulator.

The regulator is better at rejecting the ripple than the wideband spikes. In a typical example, the rejection performance for an LT1763 low-dropout linear regulator, 40 dB of attenuation at 100 kHz rolls off to about 25 dB at 1 MHz (**Figure 3**). The more wideband spikes pass directly through the regulator. The output-filter capacitor, which absorbs the spikes, also has high-frequency performance limitations. The imperfect response of the regulator and filter capacitors, due to high-frequency parasitics, reveals **Figure 1** to be too simplistic. Including parasitic terms and some new components shows the regulation path with emphasis on high-frequency parasitic terms (**Figure 4**). It is important to identify these terms because they allow ripple and spikes to propagate into the nominally regulated output.

Additionally, understanding the parasitic elements permits a measurement strategy, facilitating reduction of high-frequency output content. The regulator includes high-frequency parasitic paths, primarily capacitive, across its pass transistor and into its

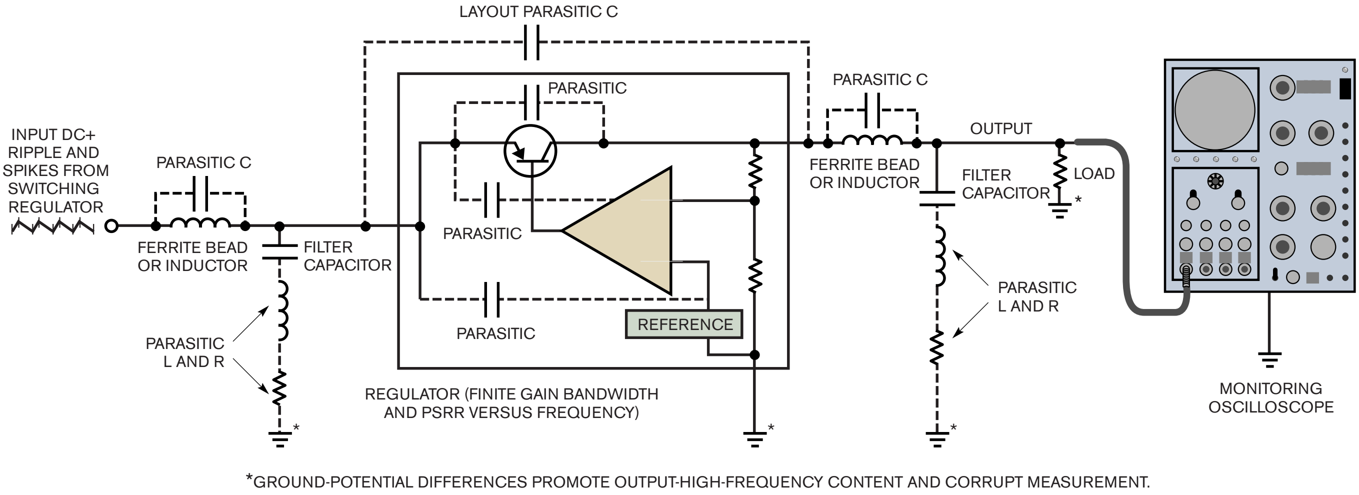

Figure 4 A conceptual linear regulator shows high-frequency-rejection parasitics. The finite-gain-bandwidth product and power-supply-rejection-ratio versus frequency limit the regulator's high-frequency rejection. Passive components attenuate ripple and spikes, but parasitics degrade effectiveness. The layout capacitance and ground-potential differences add errors and complicate measurement.

THE TRUTH ABOUT FERRITE BEADS

A ferrite bead enclosing a conductor provides the highly desirable property of increasing impedance as frequency rises. This effect suits high-frequency noise filtering of conductors carrying dc and low-frequency signals. The bead is essentially lossless within a linear regulator's passband. At higher frequencies, the bead's ferrite material interacts with the conductor's magnetic field, creating the loss characteristic. Various ferrite materials and geometries result in different loss factors versus frequency and power level (Figure A).

Impedance rises from 0.01Ω at dc to 50Ω at 100 MHz. As dc current and, hence, constant magnetic-field bias rise, the ferrite becomes less effective in offering loss. Note that you can stack beads in series along a conductor, proportionally increasing their loss contribution. A variety of bead materials and physical configurations are available to suit requirements in standard and custom products.

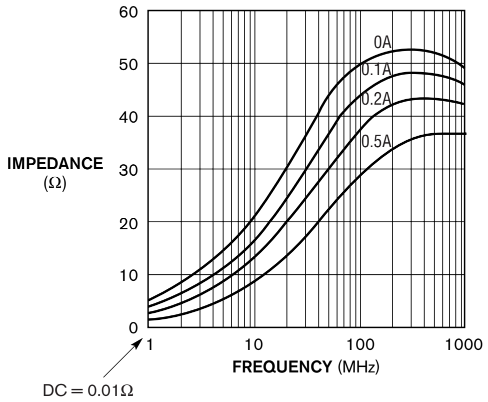

Figure A Impedance versus frequency at various dc-bias currents for a surface-mounted ferrite bead shows essentially zero impedance at dc and low frequency, rising above 50Ω depending on frequency and dc current (courtesy Fair-Rite).

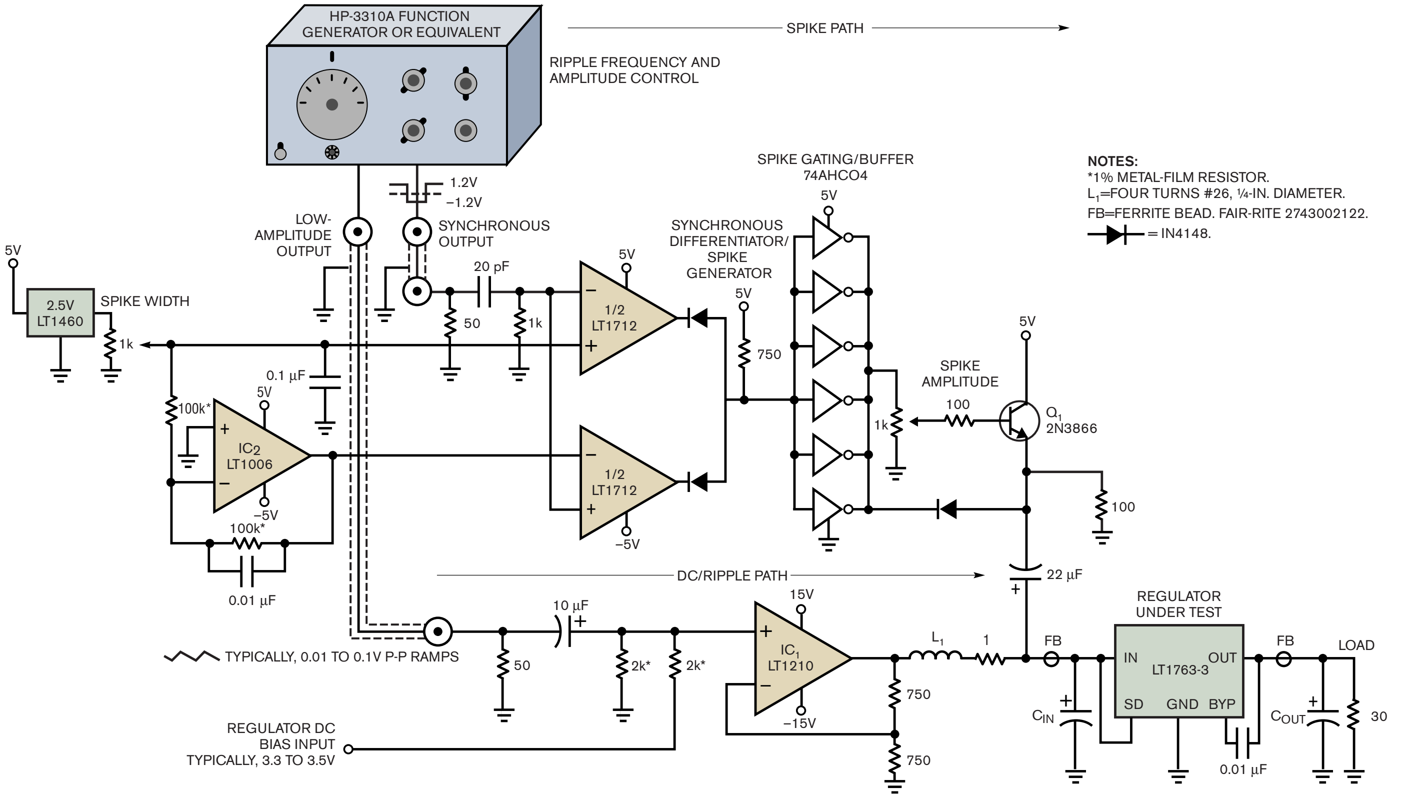

Figure 5 This circuit simulates switching-regulator output. You can independently set ripple amplitude, dc, frequency, and spike duration and height. A split-path scheme sums wideband spikes with dc and ripple, presenting the linear regulator with simulated switching-regulator output. A function generator sources waveforms to both paths.

USING INDUCTORS AS HIGH-FREQUENCY FILTERS

You can sometimes use inductors instead of beads for high-frequency filtering. Typically, values of 2 to 10 µH are appropriate. Advantages include wide availability and better effectiveness at frequencies of less than 100 kHz. Figure A shows that the disadvantages are increased dc resistance in the regulator path due to copper losses, addition of parasitic shunt capacitance, and potential susceptibility to stray switching-regulator radiation. The copper loss appears at dc, reducing efficiency, and parasitic shunt capacitance allows unwanted high-frequency feedthrough. The position and orientation of the inductors on the pc board may allow stray magnetic fields to impinge its winding, effectively turning the winding into a secondary transformer. The resulting observed spike- and ripple-related artifacts masquerade as conducted components, degrading performance.

Figure B shows a form of inductance-based filter constructed from a pc-board trace. Such extended-length traces, formed in spiral or serpentine patterns, look inductive at high frequencies. They can be surprisingly effective in some circumstances, although they introduce less loss per unit area than ferrite beads.

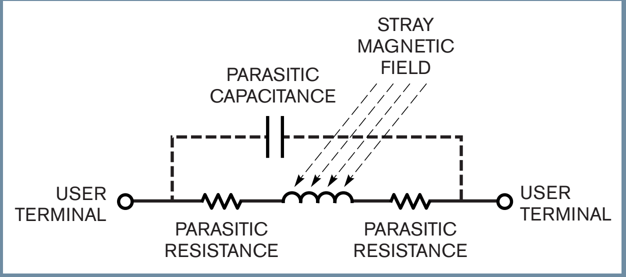

Figure A Some parasitic terms of an inductor show that parasitic resistance decreases voltage, degrading efficiency, and unwanted capacitance permits high-frequency feedthrough. The stray magnetic field induces erroneous inductor current.

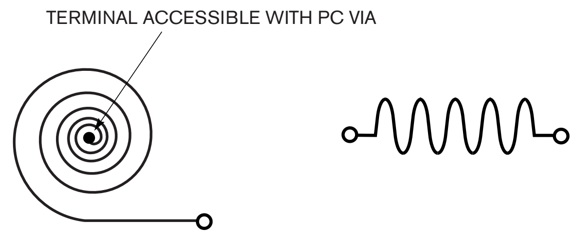

Figure B Spiral and serpentine pc-board patterns sometimes act as high-frequency filters, although they are less effective than ferrite beads.

reference and regulation amplifier. These terms combine with finite regulator gain bandwidth to limit high-frequency rejection. The input- and output-filter capacitors include parasitic inductance and resistance, degrading their effectiveness as frequency rises. Stray layout capacitance provides additional unwanted feedthrough paths. Ground-path resistance and inductance promote ground-potential differences, which add error and also complicate measurement.

Some new components, not normally associated with linear regulators, also appear. These additions include ferrite beads or inductors in the regulator input and output lines. These components have their own high-frequency parasitic paths but can considerably improve overall regulator high-frequency rejection (see **sidebar** "The truth about ferrite beads").

BUILD A RIPPLE/SPIKE SIMULATOR

Understanding the problem requires observing regulator response to ripple and spikes under a variety of conditions. You should independently vary ripple and spike parameters, including their frequency, harmonic content, amplitude, duration, and dc level. This capability is versatile, permitting real-time optimization and sensitivity analysis to various circuit variations.

PROBING TECHNIQUE FOR SUBMILLIVOLT-WIDEBAND-SIGNAL INTEGRITY

Obtaining reliable, wideband, submillivolt measurements requires attention to critical issues before measuring anything. It is essential that you design the pc-board layout for low noise. Consider current flow and interactions in power distribution, ground lines, and ground planes. Examine the effects of component choice and placement. Plan radiation management and disposition of load-return currents. The circuit must be sound, the board layout must be proper, and the circuit must use the appropriate components before you can begin meaningful measurements.

The most carefully prepared breadboard cannot fulfill its mission if signal connections introduce distortion. Connections to the circuit are crucial for accurately extracting information. Low-level, wideband measurements demand care in routing signals to test instrumentation. Issues to consider include ground loops between pieces of test equipment, including the power supply connected to the breadboard, and noise pickup due to excessive test-lead or trace length.

Minimize the number of connections to the pc board and keep leads short. Route wideband signals to or from the breadboard in a coaxial environment with attention to where the coaxial shields tie into the ground system. A strictly maintained coaxial environment is critical for reliable measurements.

Figure A shows a believable presentation of a typical switching-regulator spike measured within a continuous coaxial signal path. The spike's main body is reasonably well-defined, and disturbances after it are contained. Figure B depicts the same event with a 3-in. ground lead connecting the coaxial shield to the pc-board ground plane. Pronounced signal distortion and ringing occur. The photographs were taken at 0.01V/division sensitivity. More sensitive measurement requires proportionately more care.

Figure C details the use of a wideband, 40-dB gain preamplifier permitting a 200-μV/division measurement in Figure 12 of the main text (pg 90). Note the purely coaxial path, including the ac-coupling capacitor, from the regulator, through the preamplifier, and to the oscilloscope. The coaxial-coupling capacitor's shield directly connects to the regulator board's ground plane with the capacitor's center conductor going to the regulator output. There are no noncoaxial-measurement connections. Figure D, repeating Figure 12, shows a cleanly detailed rendition of the 900-mV output spikes. In Figure E, 2 in. of ground lead is present at the measurement site, violating the coaxial regime. The result is corruption of the waveform presentation. As a final test to verify measurement integrity, it is useful to repeat Figure D's measurement with the signal-

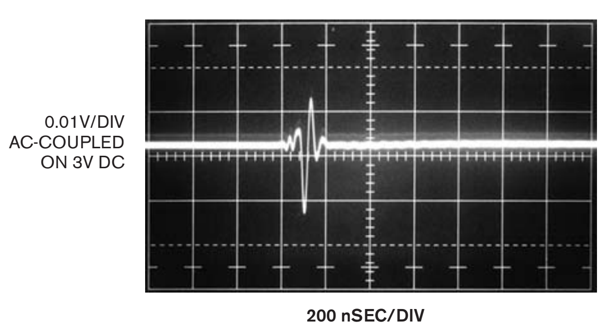

Figure A Spike measured within a continuous coaxial-signal path displays moderate disturbance and ringing after the main event.

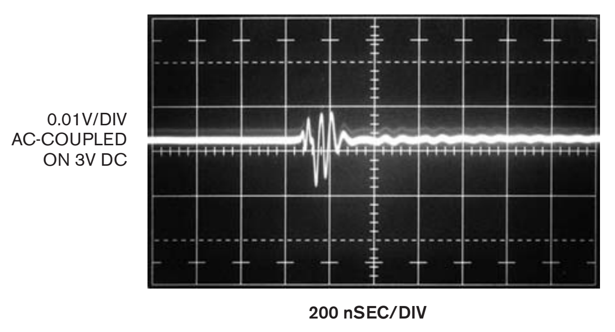

Figure B Introducing a 3-in., noncoaxial ground connection causes pronounced signal distortion and postevent ringing.

Although no substitute exists for observing linear-regulator performance under actual switching-regulator-driven conditions, a hardware simulator reduces the likelihood of surprises (**Figure 5**). It simulates a switching regulator's output with independently settable dc, ripple, and spike parameters.

The design combines a commercially available function generator with two parallel signal paths to form the circuit. It transmits dc and ripple on a relatively slow path and processes wideband spike information through a fast path. The two paths combine at the linear-regulator input. The function generator's settable ramp output (**Figure 6**, Trace A) feeds the dc/rip-

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path input—for example, the coaxial-coupling capacitor's center conductor—grounded near the measurement point, as in Figure 13 of the main text. Ideally, no signal should appear. Practically, some small residue, primarily due to common-mode effects, is permissible.

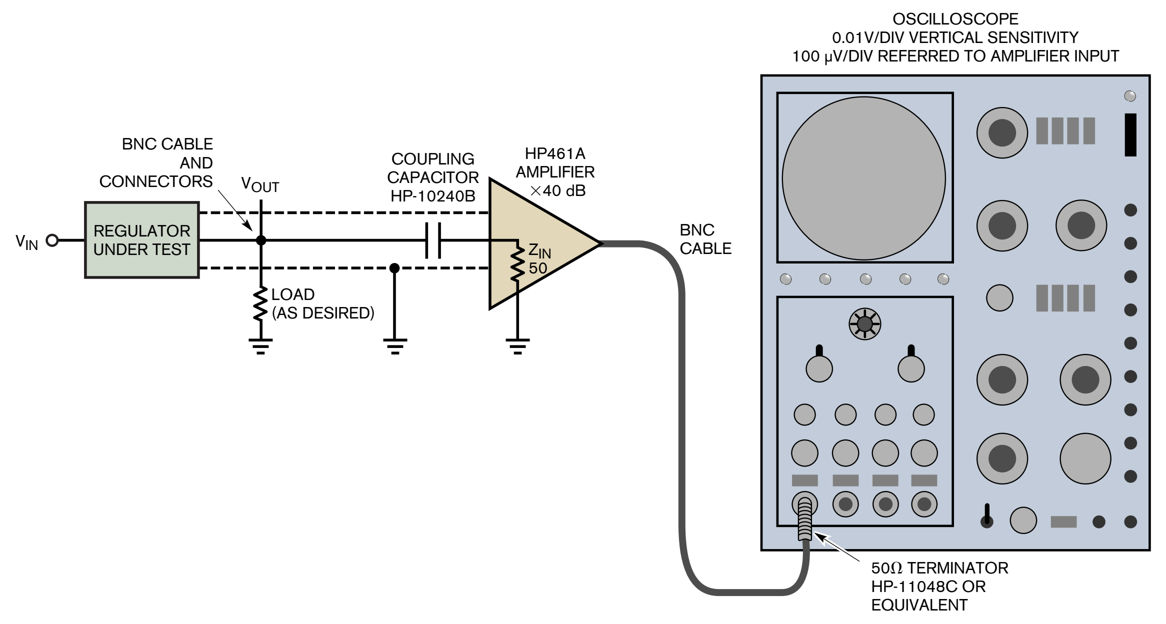


Figure C A wideband, low-noise preamplifier permits submillivolt-spike observation. The coaxial connections must remain to preserve measurement integrity.

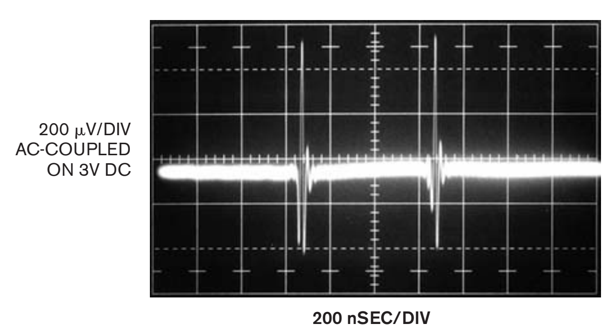


Figure D A low-noise preamplifier and strictly enforced coaxial signal path yield Figure 12's 900-mV p-p presentation. The trace's baseline thickening represents the preamplifier's noise floor.

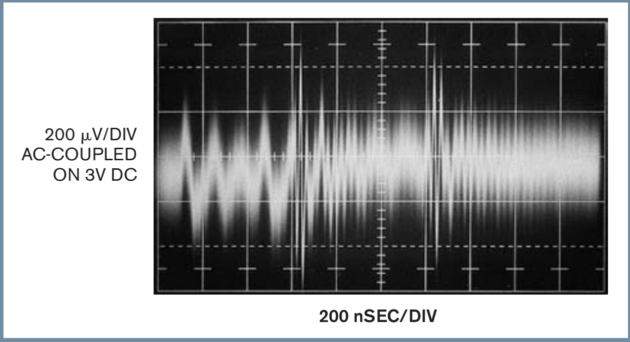
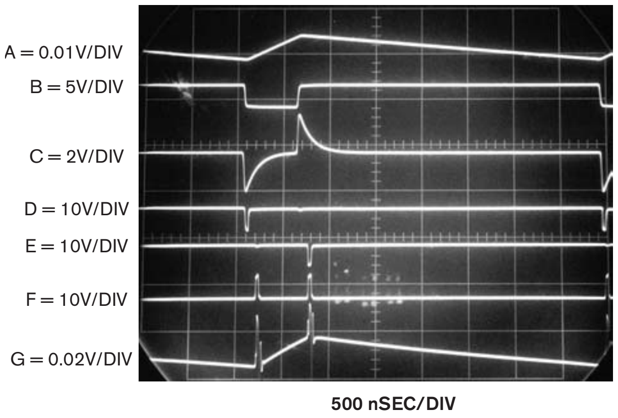


Figure E A 2-in. noncoaxial ground connection at the measurement site violates the coaxial regime, resulting in complete corruption of the waveform presentation.



NOTE: AC-COUPLED ON 3.3V DC.

Figure 6 A switching regulator outputs simulator waveforms, in which the function generator supplies ripple-path (Trace A) and spike-path (Trace B) information. C$_1$ and C$_2$ compare the differentiated spike information's bipolar excursion (Trace C), resulting in Traces D and E's synchronized spikes. Diode-gating inverters present Trace F to spike-amplitude control. G$_1$ sums spikes with dc-ripple path from power amplifier IC$_1$, forming linear-regulator input (Trace G). (Spike width is abnormally wide for photographic clarity.)

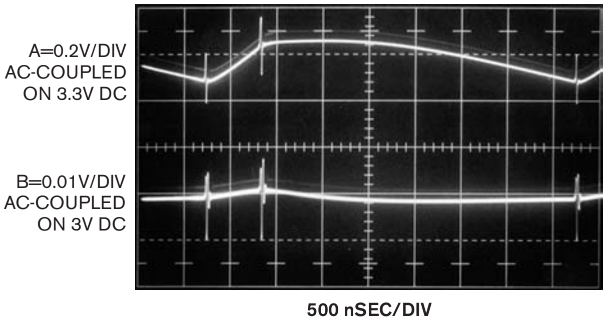


Figure 8 C$_{IN}$ of 1 µF and C$_{OUT}$ of 33 µF result in the same trace assignments as Figure 7. Output ripple decreases fivefold, but spikes remain. Spike rise time appears unchanged.

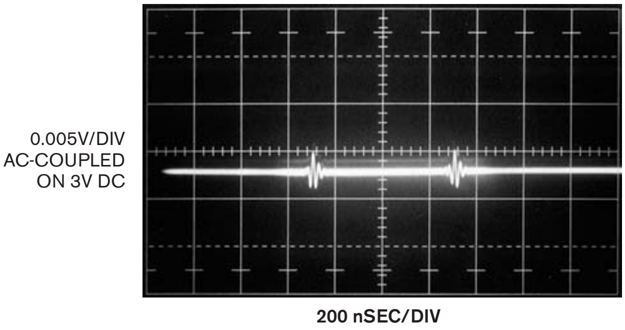


Figure 10 Adding a ferrite bead to the regulator input increases high-frequency losses, dramatically attenuating spikes. (The trace center-screen area is intensified for photographic clarity.)

ple path, which is made up of power amplifier IC$_1$ and associated components. IC$_1$ receives the ramp input and dc-bias information and drives the regulator under test. L$_1$ and the 1Ω resistor allow IC$_1$ to drive the regulator at ripple frequencies without instability.

The function generator's pulsed synchronous output (Trace B) sources the wideband spike. Amplifier IC$_2$ differentiates the output's edges (Trace C) and feeds bipolar comparator IC$_{3A}$ and

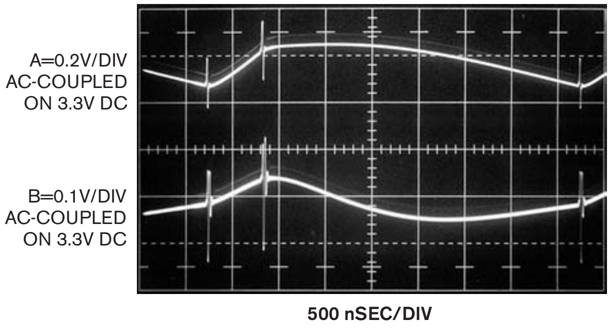


Figure 7 C$_{IN}$ of 1 µF and C$_{OUT}$ of 10 µF result in linear-regulator input (Trace A), output ripple (Trace B), and switching-spike content. Output spikes, driving 10 µF, have lower amplitude, but rise time remains fast.

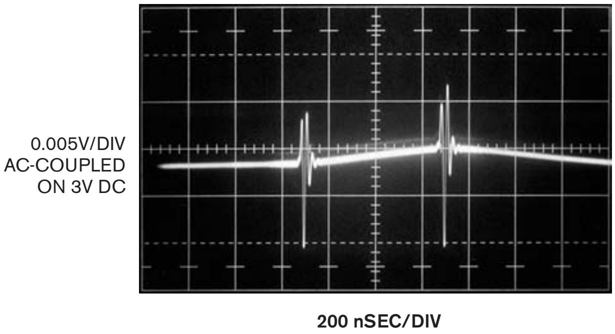


Figure 9 A time and amplitude expansion of Figure 8's output trace permits higher resolution study of spike characteristics. (The trace center-screen area is intensified for photographic clarity.)

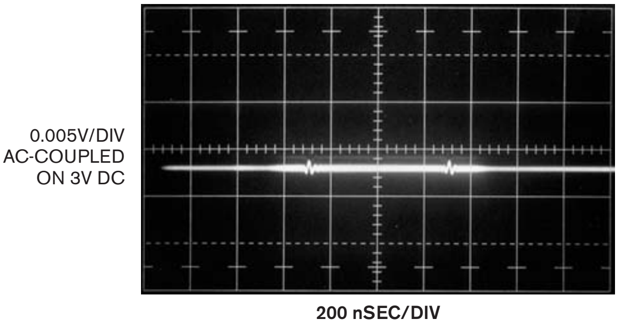


Figure 11 A ferrite bead in the regulator output further reduces spike amplitude. (The trace center-screen area is intensified for photographic clarity.)

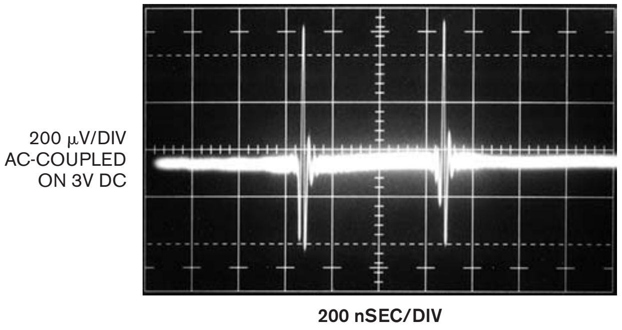


Figure 12 In this higher gain version of Figure 11, spike amplitude measures 900 µV—almost 20 times lower than without ferrite beads, whereas the instrumentation noise floor causes trace baseline thickening. (The trace center-screen area is intensified for photographic clarity.)

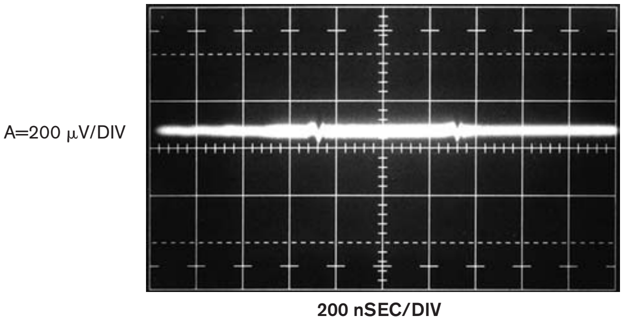


Figure 13 Grounding the oscilloscope input near the measurement point verifies that Figure 12's results are nearly free of common-mode corruption. (The trace center-screen area is intensified for photographic clarity.)

IC_{3B}. The comparator-output spikes (traces D and E) are synchronized to the ramp's inflection points. Complementary dc-threshold potentials applied to IC_{3A} and IC_{3B} with the 1-kΩ potentiometer and IC_2 control the spike width. Diode gating and the paralleled logic inverters present Trace F to the spike-amplitude control. Follower Q_1 sums the spikes with IC_1's dc/ripple path, forming the linear regulator's input (Trace G).

LINEAR-REGULATOR REJECTION EVALUATION

The circuit in **Figure 5** facilitates evaluation of linear-regulator high-frequency rejection. The waveform in **Figure 7** shows **Figure 5**'s LT1763 3V regulator response to a 3.3V-dc input with Trace A's ripple/spike contents, C_{IN}=1 µF, and C_{OUT}=10 µF. Regulator output (Trace B) shows ripple attenuated by a factor of approximately 20. Output spikes see somewhat less reduction, and their harmonic content remains high. The regulator offers no rejection at the spike's rise time. The capacitors must do the job. Unfortunately, inherent high-frequency loss terms prevent the capacitors from filtering the wideband spikes; Trace B's remaining spike shows no rise-time reduction. Increasing the capacitor value has no benefit at these rise times. **Figure 8**, with the same trace assignments as **Figure 7** but with a value of 33 µF for C_{OUT}, shows a fivefold ripple reduction but little spike-amplitude attenuation.

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Figure 9's time and amplitude expansion of **Figure 8**'s Trace B permits high-resolution study of spike characteristics, allowing the following evaluation and optimization. **Figure 10** shows dramatic results when a ferrite bead immediately precedes C_{IN}. Spike amplitude drops about fivefold. The bead presents loss at high frequency, severely limiting spike passage. The dc and low-frequency components pass unattenuated to the regulator. Placing a second ferrite bead at the regulator output before C_{OUT} produces **Figure 11**'s trace. The bead's high-frequency loss characteristic further reduces spike amplitude below 1 mV without introducing dc resistance into the regulator's output path. You can sometimes use inductors in place of beads, but make sure that you understand inductors' limitations (see **sidebar** "Using inductors as high-frequency filters").

Figure 12, which shows a higher gain version of **Figure 11**, measures 900-µV spike amplitude—almost 20 times lower than without the ferrite beads. Complete the measurement by verifying that common-mode components or ground loops do not corrupt the indicated results. You achieve this goal by grounding the oscilloscope input near the measurement point. Ideally, no signal should appear. **Figure 13** shows almost no signal, indicating that **Figure 12**'s display is realistic. Faithful wideband measurement at submillivolt levels requires special considerations (see **sidebar** "Probing technique for submillivolt-wideband-signal integrity"). The articles, application notes, and books in **references 2** through **9** are also helpful to serious designers.

AUTHOR'S BIOGRAPHY

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