Low-Noise Power For Analog Circuits

This "Analog Special" ***Tools & Tips*** column focuses on methods of reducing power-bus-related noises in your analog system. While linear voltage regulators are hardly new, the continuing performance increases demanded of them can present challenges to the designer. This column will show examples of circuit techniques useful in combating different types of power-supply noise. These noise sources can either originate within the regulator, or come from the raw supply preceding it. In either case, knowledge of noise minimization procedures beforehand can be instrumental in designing a clean system.

Let's start with the basic concept of a linear voltage regulator, which by definition operates from some higher unregulated voltage (V_{in}), and produces a regulated noise-free output (V_{out}). Simple task, you say—just drop in a 7805 3-pin IC, and be done with it. Functionally, that could be all you'd need, provided you don't care much about power dissipated in the regulator. The 78xx genre of regulators use a design which operates with a minimum of 2-V input-output (dropout voltage), due largely to the use of a Darlington pass transistor. So, while this type of regulator is generally good for ripple rejection (75 dB at 1 kHz; 50 dB at 100 kHz) as well as noise (~120 $nV/\sqrt{Hz}$), there are situations where the net performance combination just isn't enough. Modern system designs quite often demand lower dropout and lower overall power loss.

In recent years, the appearance of a host of low-dropout (LDO) regulator types have appeared.[1,2] In an LDO regulator, the regulated output is maintained down to input-output differentials of 1 V, or in some cases, much less. In general, this newer generation of regulator has effectively addressed the problems of excessive power loss within the regulator. This is accomplished by using a variety of pass transistor types with a common theme that they all work down to low saturation voltages for bipolar types, or low $R_{ds(on)}$ for FET types. The modern LDO requires at best just a few hundred mV of input-output differential to sustain operations. With the emphasis on battery power, every mW of input power lost can be crucial to the designer, so the high power efficiency of an LDO is quite important.


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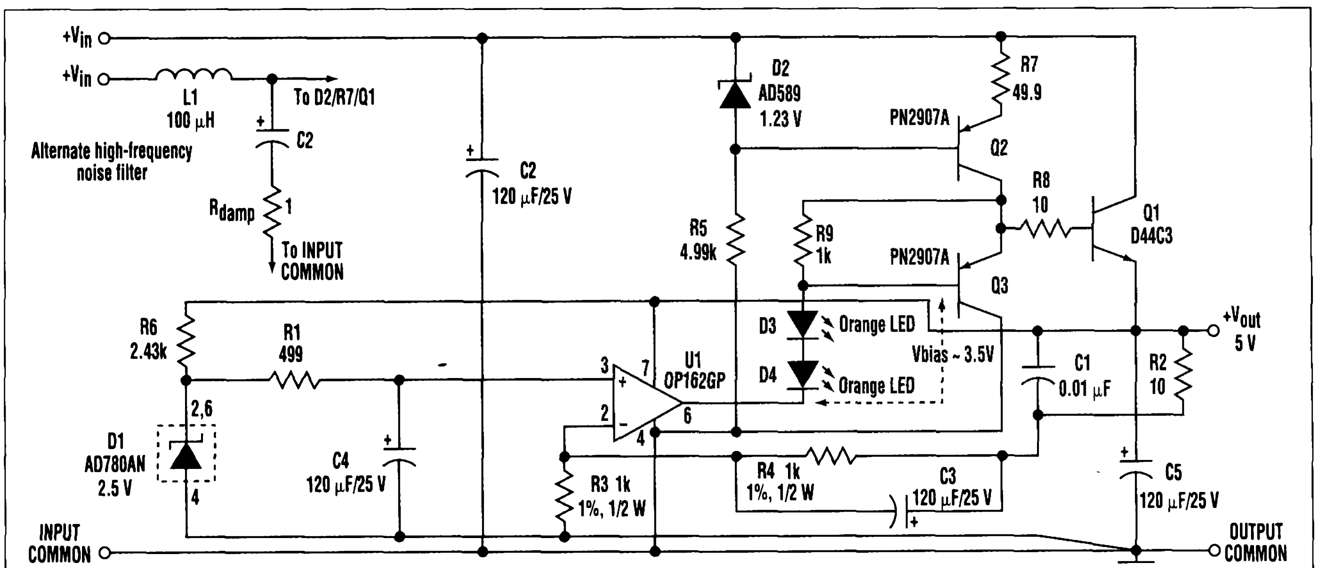
However, in going to today's LDO IC designs from an older NPN-based 7805 topology, there can actually be some performance areas where ground may be lost, depending upon circuit particulars. Speaking more specifically, such areas as ripple rejection and noise are very much device and exact LDO load condition-dependent. Exacerbating this situation is the fact that nowadays, many LDOs are called upon to operate from switching supply sources, pushing ripple frequencies upward and increasing noise susceptibility. Due to general industry driving factors of low standby power (and also the inevitable size and cost constraints), which shifts design emphasis to power as a priority, an LDO regulator probably won't excel in the above areas, vis-à-vis an older design such as the 7805. So, when supply noise performance is critical, a designer needs to be aware of these factors to make the best system choice. While a modern LDO is likely to be the best choice from a dc and power-loss standpoint, ripple rejection and noise performance isn't so clear-cut.

Using a system designer's building-block approach, one can improve the basic noise performance of a given LDO in some regards rather easily, and not so easily in others. For example, if high-frequency output noise is excessive due to low ripple rejection, then a relatively



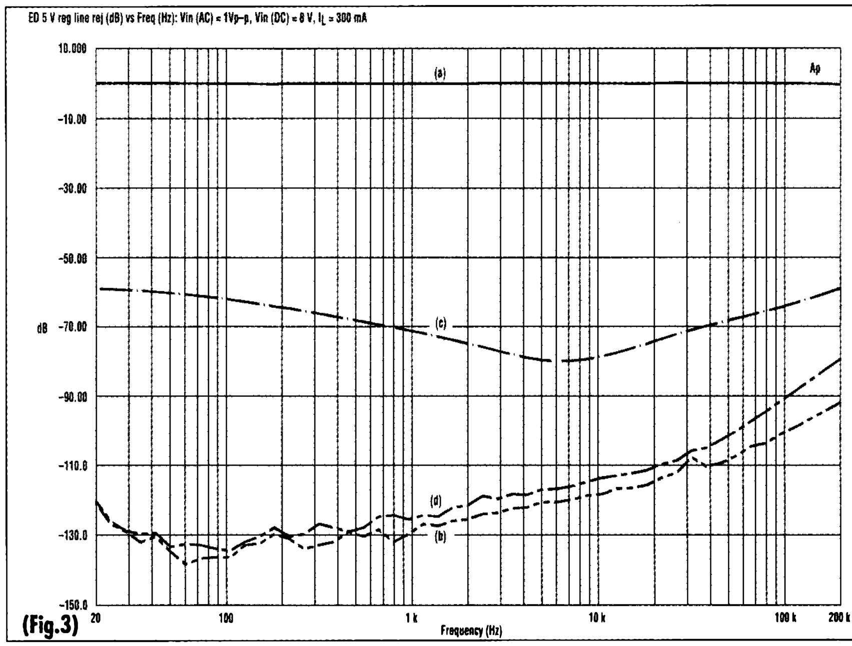
(Fig. 1)

simple LC low-pass input filter may be a cure. The self- generated noise of an IC LDO may also possibly be improved, dependent upon the specific design. Look here for accessible noise-reduction pins, where bypass caps can be optionally connected to effect lower output noise.

At the expense of greater circuit complexity, component count, and most likely power consumption, a designer also can build a regulator with discrete and IC parts to match specific requirements. This would likely be a secondary choice against an off-the-shelf IC approach, useful when nothing commercial matches the exact needs.

In the circuit shown in Figure 1, an example high-performance roll-your-own type of 5-V regulator, a number of design steps have been taken to lower noise. Droput voltage is about 1 V @ 300 mA, output noise density is 10 nv/√Hz, and line rejection is 90 dB or better below 100 kHz.

While the design is workable as shown, it is intended here to illustrate some general concepts of how the various power related noises can be reduced. While the design as shown won't win power-efficiency awards, it certainly is capable of low noise. In discussing it, we'll explore things from dual noise-reduction standpoints: Its own self-generated noise, and the relative immunity to noise components on an unregulated source (V_{in}).

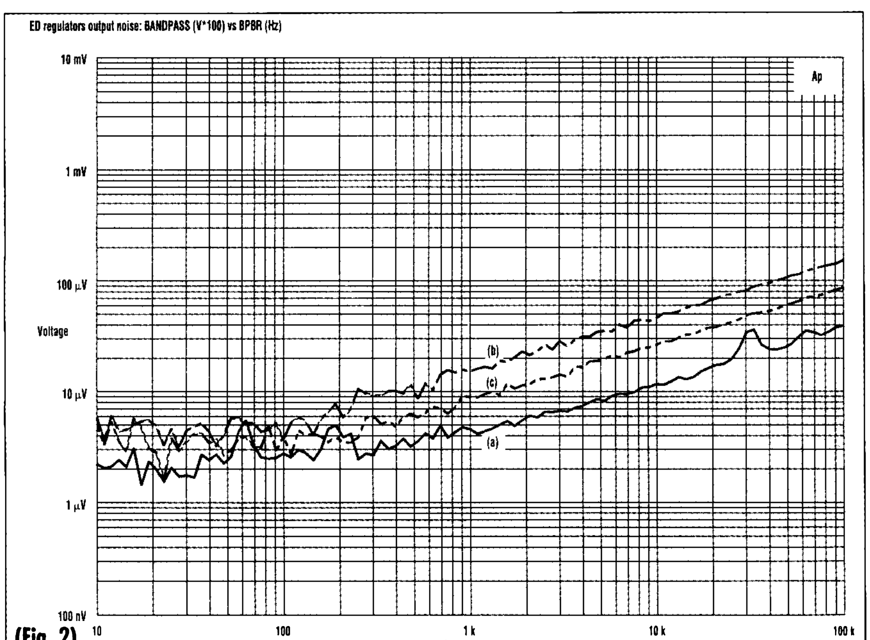


(Fig.3)

Quiet, please! Taking the regulator's internal noise first, this can be broken out into three basic components. These are:

1. The noise of the reference diode used for D1.
2. The noise of the reference and divider source resistance(s).
3. The noise of 1 and 2, as scaled up by the amplifier stage consisting of U1 and Q1. Note—the apparent overly-complex drive to Q1 doesn't enter into the self-generated noise, and is discussed further below.

Reference-diode noise is the noise that is associated with diode D1 at the bias current used. Since this is a low-voltage (5 V) design, the choice for D1 is strongly weighted toward lower-voltage bandgap-type references, and the use of a 2.5-V diode greatly simplifies a 5-V design. Using a shunt IC reference type for D1 (as opposed to series) greatly expands circuit flexibility, and allows for negative-output-voltage designs to be set up simply by "mirror imaging" everything of polarity, so as to produce –5V. Without using R2, equal-value scaling resistors R3-R4 can be a standard ratio-matched pair, if desired, for the highest dc accuracy and stability. R2 and C1 are an optional isolation network, and are used when point-of-load sensing is desirable.



(Fig. 2)

The D1 IC shown has a noise density of 100 nV/√Hz ; low for a 2.5-V reference. This is lowered further for frequencies above 2.7 Hz by noise filter R1-C4, before finally driving amplifier U1. The filter effectively makes the audio-frequency-range noise of the circuit more a function of the U1 noise characteristics than those of D1. The dc accuracy and stability will, of course, be highly dependent upon the specific device used for D1. While a premium version for D1 is shown here, standard 2.5-V two-terminal references also function well when tight output accuracy isn't required.

Source resistance noise is minimized in the circuit by ac-bypassing both R1 and R4, again essentially eliminating their noise contribution at audio frequencies. Further, with R4 so bypassed by C3, the high-frequency gain of U1 is unity.

With reference and scaling noise sources effectively minimized, the largest contribution to self-generated noise in this circuit is op amp U1. Basically, choice of this amplifier will essentially determine the bulk of the regulator's high- frequency output noise. While instrumentation op amps like the AD797 allow higher- output regulators to be built with noise levels approaching 1 $nV/\sqrt{Hz}$,[3] this cannot be extended to 5-V designs like the one here, because the op-amp rails are powered directly from V_{out}. For this reason (and others cited below), a 5-V compatible device is required for U1.

The U1 device shown has an input noise specification of 9.5 $nV/\sqrt{Hz}$, and is compatible with 2.7 to 12 V (or less) supplies. Noise performance of the regulator is shown by the plots of Figure 2. In these and the following plots, software/hardware techniques previously described[4] are used with a high-sensitivity analyzer.[5] For the noise-analysis plots, this analyzer is preceded by a low-noise gain-of-100 preamp, where the preamp noise is about 2.6 $nV/\sqrt{Hz}$. For noise measurements below about 10 $nV/\sqrt{Hz}$, this noise isn't entirely negligible, as will be noted.

The measured residual noise of this preamp as measured by the analyzer is shown by the lower trace (a) of Figure 2. In these tests, the analyzer's tracking, constant-Q-type bandpass filter sweeps over a 10-Hz to 100-kHz range of frequencies. Because of the constant-Q filter, as the center frequency increases, filter bandwidth increases. Thus, spectrally-flat noise measured through the filter rises as frequency ascends, with a 3 dB/octave slope. For example, a white noise source measuring 10 $nV/\sqrt{Hz}$ at 1 kHz would appear as 14 $nV/\sqrt{Hz}$ at 2 kHz.

For these data, equivalent preamp input-voltage noise density at a given frequency "F" can be found by dividing the measured voltage by a factor of approximately $48\sqrt{F}$. For example, at 1 kHz, the division factor is ≅1518; at 100 Hz, it is 480; at 10 kHz, it is 4800. For the gain-of-100 preamp residual, the input-referred noise at 1 kHz is measured at 4 $\mu V/1518 \cong 2.6\ nV/\sqrt{Hz}$.

The two upper curves of Figure 2 represents operation of the Figure 1 circuit with an OP162 (b) and OP113 (c) devices for U1, respectively. The apparent 1-kHz noise of trace (b) works out to be just about 10 $nV/\sqrt{Hz}$; while the trace (c) noise appears to be about 5.6 $nV/\sqrt{Hz}$. When corrected for the measuring-preamp noise, these figures are generally consistent with the respective device specifications of 9.5 and 4.7 $nV/\sqrt{Hz}$.

TIP: Using these noise-minimization steps, the self-generated noise of regulators like Figure 1 can be reduced to essentially that of the U1 op amp.

Of course, there are some optional intermediate steps, which can be used to lower noise more moderately. At the same time, this can save space and cost. For example, noise-filter caps C3-C4 can be reduced in size, along with a general scaling upward of R3-R4 and R1. This sacrifices some overall dc stability, but can be a worthwhile trade-off considering the bulk and cost of large electrolytic values.

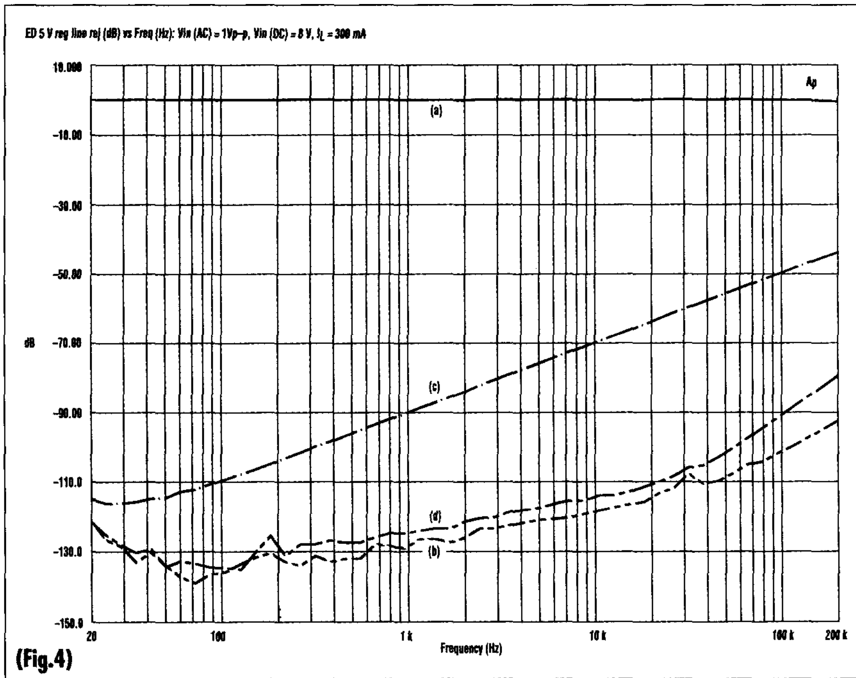
Finally, as noted above, some current low-dropout IC regulators also allow for a noise-reduction hookup, for the lowest output noise.

A hard barrier against input noise. As mentioned, the second major component of noise which a linear regulator can produce is ripple related to the V_{in} source. Nowadays, one cannot simply assume that this ripple frequency is 120 or 100 Hz, as many linear regulators must operate from switching supplies, where ripple can be as high 1 MHz. Unfortunately, study of low-dropout-regulator data sheets indicates that this is where they are often inferior to our friend, the 7805. Not only are 100-kHz line rejection (LR) figures sometimes on the order of 30 to 50 dB, the LR can go through varying levels as input frequency and output loading changes.

Clearly, this performance area is not a strength of some of today's low-dropout IC regulators, as high-frequency LR may have been traded off for lower quiescent current, etc., in design. But, there is some saving grace to this—100-kHz noise is a lot easier to filter than 120-Hz noise!

The circuit of Figure 1 illustrates two distinct design steps that enhance wideband LR of the regulator-circuit system. The first may be described as a form of pre-regulator, but without the dropout voltage problems pre-regulation typically entails. A brute force pre-regulator is just that; a cascade of regulator stages used for additional LR, with net LR typically the sum of the individual LR specs. Of course, the big drawback is the loss of headroom, which would typically be the dropout voltage of the pre-regulator higher than that of a single regulator.

A complementary Darlington connection is used for Q3-Q1, which avoids the 2 V_{be} buildup of the conventional hookup and loss of headroom. A relatively low threshold current



(Fig.4)

source made up of Q2, D2, and R7 drives the fast NPN (Q1). This provides the circuit with a dropout voltage of ~1V @ 300 mA of output, which is decent, but not spectacular.

But, one big payoff of this circuit comes from work of the mini-regulator, D3-D4 and Q3, which comprises a floating shunt regulator between the op amp and Q1's base. As seen from the standpoint of V_{in} noise components, the Q2 current source in series with this shunt-type mini-regulator has a high noise attenuation, due to their high/low relative impedances. As a result, the noise attenuation of this stage alone, *even without the op amp operating*, is about 70 dB up to 200 kHz.

This is shown by the composite LR plots of Figure 3, where V_{in} is the upper curve for full-scale reference (a), and the lowermost curve is a zero-scale reference trace (b), taken with the analyzer inputs shorted and grounded. With the op amp removed and D4's cathode grounded, the circuit will produce about 3.5 V from the mini-regulator. The LR of this hookup is shown by curve (c), and, as can be noted, is relatively frequency independent. With the OP162 operating normally, the mini-regulator of D3-D4 and Q3 operates effectively to increase LR just as a pre-regulator, but without a major hit in dropout voltage, curve (d).

The other key circuit ingredient that increases wideband LR is the use of a bootstrapped connection for the op-amp supply rail.[6] In a more conventional hookup for these regulators, the op-amp rail is powered from V_{in}. This mode of operation places great sensitivity to high-frequency LR on the CMRR and PSRR of the particular device chosen for this task. While it is certainly possible to achieve a LR of more than 100 dB at low frequencies, it is extremely difficult to do so at 100 kHz, particularly if limited to 5-V supply parts. The solution to this fundamental limit is to operate the op-amp rail *directly from the output* (as opposed to from V_{in}), or in a *bootstrapped* fashion.

The LR performance of the circuit with the op amp operating alternately from V_{in} and V_{out} is shown in Figure 4. These plots, similar to Figure 3, also show for reference the V_{in} (a) and ground reference curves (b). Curve (c) shows the LR of the circuit with U1's power pin connected to V_{in}, while LR of curve (d) results when U1 is connected to V_{out}, i.e., bootstrapped.

The relative improvement with the bootstrapping active is quite dramatic—more than 40 dB at some frequencies, with the LR-noise components approaching the noise floor at all frequencies roughly below 30 kHz.

TIP: This bootstrapping circuit step screens the V_{in} ac components away from the op amp's sensitive nodes, allowing the wideband LR of the circuit to approach the residual noise floor.

Of course, there are always cost versus complexity constraints that apply to any circuit, and whether or not both of these LR enhancement circuit options are applicable is an individual consideration. As noise frequencies go above 100 kHz, it becomes more difficult to make amplifiers achieve –100-dB-level LR performance, as the above illustrates.

To keep the LR matters in overall perspective, a relatively simple LCR input filter such as is shown in Figure 1's inset can be used ahead of *any* regulator, whether it is a discrete based design such, or an off-the-shelf IC LDO design. With a low-dcR, low-loss inductor for L1, this filter can greatly enhance high-frequency LR.

TIP: This simple low-pass circuit, with a corner of about 1 kHz, is capable of an additional 50 dB or more of noise attenuation at 1 MHz.[7]

Kick-start me, please! The bootstrap trick used in this circuit for increased LR is a good example of one of those "there's no free lunch" items. Please note that bootstrapping of the op-amp supply rails is not without due caveats! The op amp won't work without a supply, but the regulator can't produce a full output until the op amp is powered. So, this suggests that a positive kick-start mechanism is appropriate. In practice, it is absolutely necessary, as the circuit can potentially start with the op amp in a low state, and certain specific startup conditions are needed.

The circuit has these provisions built-in, but certain particulars must still be met. Part of the built-in mechanism is current source Q2, which always forces Q1 to conduct to some degree. To guarantee proper startup, select a V_{bias} voltage (the total forward drop of D3 and D4) so that this voltage is both greater than the reference voltage of D1, as well as sufficient to correctly operate the amplifier chosen for U1 for rail voltage and input common-mode range. Further, U1 should preferably be a rail-to-rail output swing type (or at least low-side compatible).

For the example shown, V_{bias} is ~3.5 V, which allows U1 to correctly sense a 2.5-V CM voltage and produces the proper output sign to get the circuit up and going. Once U1 sees some input voltage and the output responds, it will then be forced into the proper state (high), in this case about 1.5V, and full regulation is then maintained.

The example uses two high-brightness orange LEDs, which have a higher than typical V_f among LEDs. Other diode types also will work, as long as the net V_{bias} criteria for all operating conditions is met.

So, you now have a few circuit tips on keeping your voltage regulation systems as quiet as may be practical. These concepts can be applied as appropriate to a wide variety of systems, wherever low-noise operation may be required. Of course, comments on how they work out for you are welcome.

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