

REGULATORS FOR HIGH-PERFORMANCE AUDIO

By Walt Jung



Power-supply regulation is an important issue when highest audio system performance is your goal. While this may seem obvious, power-supply limitations can be quite pervasive. Power supplies can, to some degree, affect virtually all audio stage performance, since supply rails are a hidden source of crosstalk and noise coupling.

For example, at very low frequencies (<100Hz), op amps have very high power-supply rejection. However, this degrades in the audio range and may also be different for the plus/minus supplies. In another case, wideband IC video amplifiers and some discrete circuits generally have supply rejections which are flat to much higher frequencies, but are also lower—as much as 60–70dB—at the start. Given that they will inevitably have finite power-supply rejection, all amplifying stages can thus benefit from better power supplies.

This article focuses on relatively low-level power supplies, those suitable for analog preamp and line-level stages, digital logic systems, and other +5 to ±20V and less applications with current drains of 300mA or less. It emphasizes extracting the highest performance from both the power-supply regulation stage and its application within a system. The article's scope includes detailed design, testing, and performance information on plus/minus output regulators, from simple fixed and adjustable three-terminal types up through more sophisticated regulators, both discrete and IC-based.

I discuss comparative test perfor-

mance data for *line rejection* or *LR*, *noise*, and *output impedance* or Z_O for a wide variety of regulators, but do not include more basic design information on the raw DC supplies to feed these regulators. The article provides an overview perspective of power regulation for audio uses.

Background

This magazine and others have already focused serious attention on power-supply regulation.^{1–5} One of the more highly developed regulator models in use since the '60s features a buffered op amp with a self-regulating reference diode in a DC control loop⁶ (see references therein, plus those of Chapter 4 of reference 2). However, for audio-oriented use, a more notable variation on this theme is the original Sulzer regulator,³ and its subsequent relatives.^{4,5} These regulator topologies are superb performers, but at the expense of greater complexity as compared with the simpler three-terminal types. It's still unclear, however, how distinct regulator types are differentiated in terms of various performance aspects.

Output impedance tests have covered

a wide range of regulators, and generally yield useful comparisons.⁷ However, while undoubtedly important, Z_O testing alone simply does not reveal the entire story of regulator performance. With the advent of digital technology and increased awareness of RFI, power regulator LR versus frequency becomes increasingly important and is one additional performance parameter worthy of more complete assessment. Similarly, regulator wideband noise is another useful performance-quality indicator.

With a good working knowledge of these parameters, you can choose a regulator type most appropriate to your desired quality level. This article addresses how to measure these performance factors in general, using sensitive tests with high-performance lab equipment. The tests are useful for both evaluating standard circuits and optimizing newer designs.

While the Sulzer regulator topology has become a standard for high-performance use, newer op amp devices introduced since 1980 offer potential for even further improvements in certain areas. In addition, very careful selection of the pass transistor allows currents well

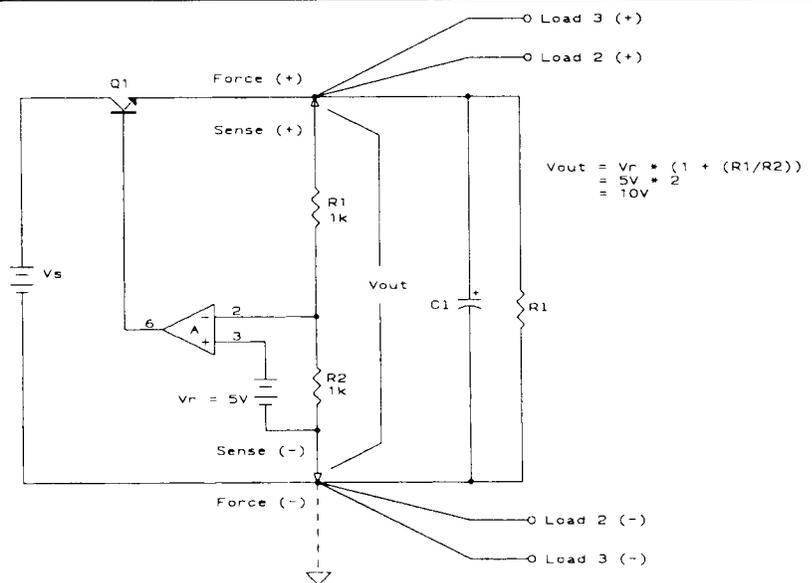


FIGURE 1: Series voltage regulator.

ABOUT THE AUTHOR

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above the $\approx 100\text{mA}$ of the original design.^{5,8} And, lower-voltage headroom regulator designs allow you to employ power-efficient low-voltage regulators within logic systems, where they have a positive impact on jitter and phase noise performance. Finally, in conjunction with cleaner and more noise-free regulation, quieter raw DC supplies also help improve overall system performance by lessening the burden on the regulator for noise rejection.^{8,9}

Regulation Basics

A brief review of regulation fundamentals as applicable to audio power supplies is helpful before discussing circuits and their testing. *Figure 1* shows a very general schematic of a *series-type* positive output voltage regulator, so-called because the NPN control transistor Q1 is in series with the load. To obtain a negative voltage, simply reverse V_S and V_r and use a PNP device for Q1.

This circuit produces a stable regulated output voltage V_{OUT} , which is programmed by resistors R1 and R2, given a stable reference voltage V_r . *Figure 1* assumes a V_r of 5V, so $1\text{k}\Omega$ R1-R2 values result in a 10V output. The high-gain amplifier A (either an op amp or a discrete circuit) compares the fixed reference V_r against a sample of the output, as selected by the divider resistors. With sufficiently high gain in A, the control loop adjusts the conduction of Q1 so the output remains stable, relatively independent of both load current and variations in V_S .

The key to high performance is the closed feedback loop around Q1, which automatically drives the base to a level that maintains the lowest possible DC and AC errors at the output. This is in distinct contrast to the simpler "emitter-follower"-type power supply (which is technically not a true regulator, since there is no overall feedback and closed loop control). Such circuits simply drive a pass device such as Q1 from a stabilized DC source such as a zener, and the load-dependent V_{BE} variations of Q1 appear at the output.

As you might expect, various *Fig. 1* circuit subtleties impact audio performance. First and foremost, you should note that this regulator only maintains the output voltage constant between the two points sensed by the divider. In this case, the applicable nodes are labeled "Sense," further denoted by their arrow-head connection to the positive and negative rails (amplified by the label " V_{OUT} "). Note that connections of loads to any other point than these will result in

some reduction of performance. Thus the "star" power connections are preferable for additional loads 2 and 3 (or more).

Regardless of the relative regulation quality, the best performance will always be obtained with the power distribution feeds taken from the sense points. By the same token, the most accurate performance measurement can only be made at these same sense points. At other points along the connecting wires, load-current-proportional voltage errors will occur. The driving connections to the sense nodes, labeled "Force (+)" and "Force (-)," connect to the control transistor Q1 and power supply return, respectively.

In terms of regulator performance, the major specifications mentioned above—LR, noise, and Z_O —are further qualified by how they vary with frequency. In addition, it makes sense to optimize the circuit for a minimum of operating headroom, so you can maintain a useful output for values of the unregulated input V_S just a few volts greater (or less) than V_{OUT} . The specifications for Q1 determine the maximum output current, maximum input voltage, and, to some degree, the operating bandwidth.

Devices most useful here are common-collector connected bipolar power types, which have the lowest output impedance before feedback and a reasonably low-voltage headroom (<1V). While MOSFETs might seem attractive on the surface, their very high voltage thresholds severely limit attempts for low dropout designs, and specified low ON impedances are available only with

ampere level conduction, not at the 100–200mA level of these audio regulators. By contrast, an emitter follower's (open loop) output impedance is roughly 1Ω at a current level of only 25mA.

Assessing Performance

Most other regulation performance attributes are determined by the design details of amplifier A. This circuit can be either discrete transistor or op-amp-based, and I've included developed examples of both. Or, the entire regulator function can also be completely integrated, such as in the popular three-terminal IC regulators.

Obviously, a complete regulator in a three-pin package is both space efficient and economical, making such designs attractive where simplicity is paramount. However, like most other things in life, with voltage regulators you get what you pay for (in complexity terms). We'll discover that the more complex regulator circuits definitely offer the highest possible performance on an absolute basis.

To assess regulator performance as applicable to audio use, three test setups are required to exercise a regulator in terms of LR, noise, and Z_O characteristics. These tests are shown in block diagram form in *Figs. 2a–2c*, and are described briefly below. All three tests are derived from my earlier test series developed for reference ICs,⁶ which, in turn, is partially based on the impedance measurement procedures of Brimacombe.¹⁰ The common theme of these tests is the use of a

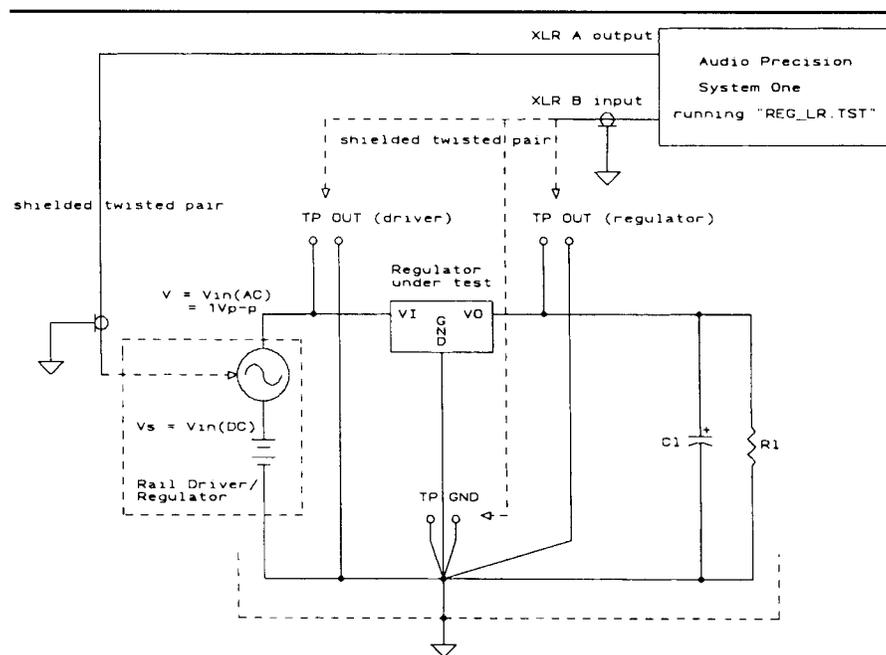


FIGURE 2a: Line rejection test.

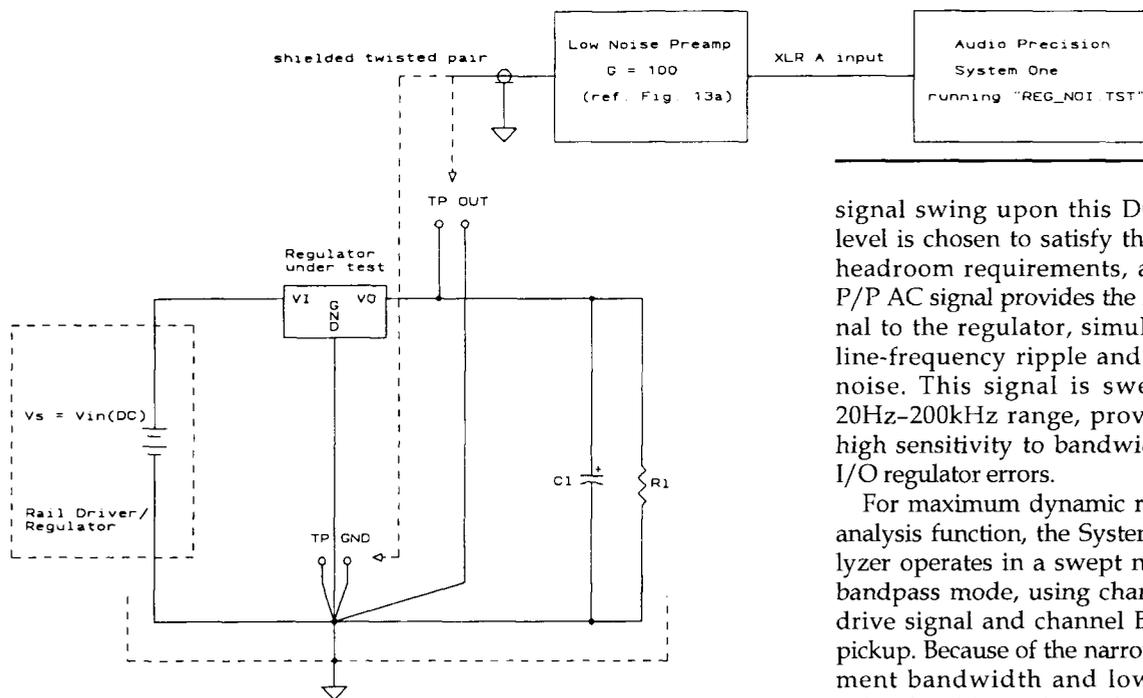


FIGURE 2b: Noise test.

signal swing upon this DC. The DC level is chosen to satisfy the regulator headroom requirements, and the 1V P/P AC signal provides the AC test signal to the regulator, simulating both line-frequency ripple and wideband noise. This signal is swept over a 20Hz–200kHz range, providing very high sensitivity to bandwidth-related I/O regulator errors.

For maximum dynamic range in the analysis function, the System One analyzer operates in a swept narrowband bandpass mode, using channel A as a drive signal and channel B for signal pickup. Because of the narrow measurement bandwidth and low analyzer noise, the ultimate dynamic range of this test approaches 140dB. Consequently, very careful screening and guarding of the test setup is necessary to minimize contamination of the output signal and to take full advantage of the test system's dynamic range.

If you eschew such precautions, then the very best regulator in LR terms may be indistinguishable from those more pedestrian. More importantly, you will be unable to fully optimize a high-per-

sensitive high-resolution test instrument, the Audio Precision System One (PO Box 2209, Beaverton, OR 97075-3070, 503-627-0832).

Line Rejection Tests

Figure 2a shows the setup for exercising a regulator for line rejection versus fre-

quency. The DC input to the regulator, V_S , is taken from a positive or negative rail driver/regulator stage. This stage functions as a low-impedance source for both AC and DC and produces a nominal regulated DC voltage of 18V, with polarity suitable to the regulator under test.

You can superimpose a 1V P/P AC

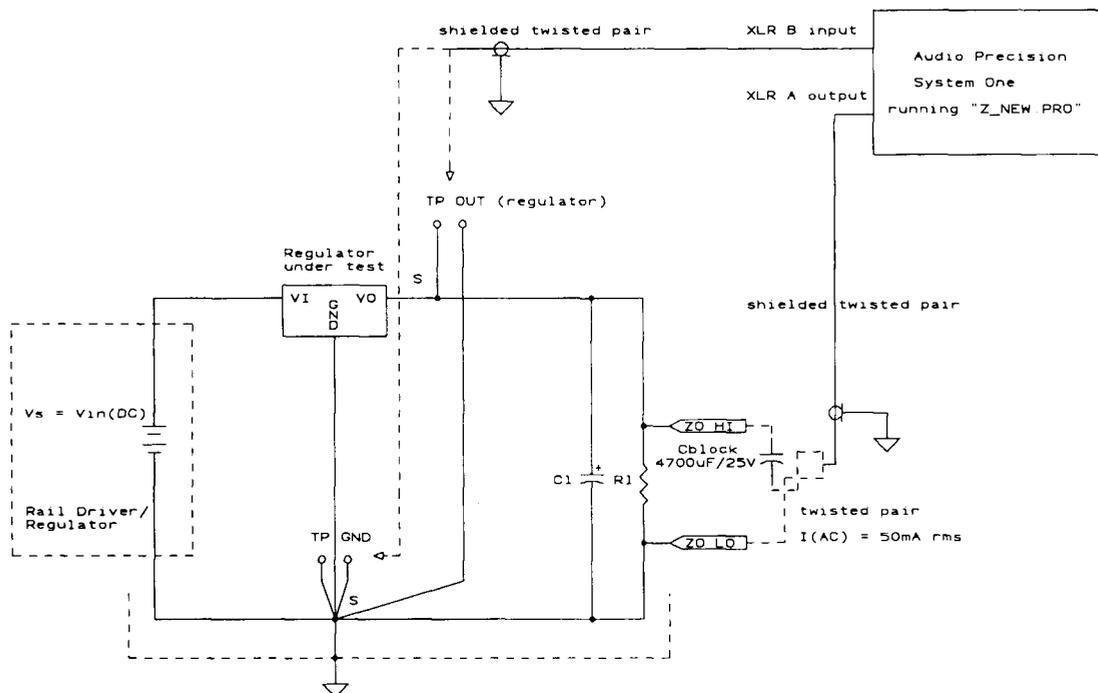


FIGURE 2c: Output impedance test.

formance design, unless the test setup is sufficiently sensitive.

In these tests, a grounded guard trace was used on three sides around all regulator circuits, which were built over a heavy ground plane. I also used shielded twisted pair construction on the analyzer I/O cabling, with plug-in tips for quick access to various sensitive circuit nodes. The TP OUT driver output two-terminal test jack provides a 0dB, 1V P/P input reference level, which calibrates the analyzer for full scale. All measured regulator output signals are referred to this 0dB level as it drives the input of the regulator under test.

The AC level measured at the TP OUT regulator jack represents the degree of isolation provided by the regulator, and is easily scaled and displayed in decibel versus frequency by the test analyzer. The TP GND jack provides a grounded-input, minimum signal reference for the analyzer.

To allow relatively easy comparison among various regulator types, all regulators under test used setups similar to this, regardless of their circuit topology. Thus with similar loading and input conditions, direct comparisons of measured performance between different circuits is possible. This test and the others operate with a common loading for all regulators of $C_1 = 100\mu\text{F}$ and $R_1 = 100\Omega$, except as otherwise noted.

With both positive and negative regulator circuits available, both positive and negative rail drivers are required to perform the LR tests quickly and accurately. I describe these in more detail later.

Noise Tests

Figure 2b shows the setup for testing regulator output noise. No AC input signal is provided, and the appropriate DC voltage V_S is supplied by the rail driver/regulator. For most of the circuits tested, this is also 18V, with polarity as appropriate. The only output signal is the AC noise level, as measured at the TP OUT test point of the regulator under test.

Because many regulators have very low noise levels, a preamplifier circuit is required to raise the AC output signal to a level where it can be readily measured by the analyzer. For this a balanced input, gain of 100 circuit was used, coupled to the regulator under test by shielded twisted pair cabling. This preamp's output is coupled into the analyzer, which operates in a swept, narrow-band pass mode.

A given noise test provides a 100x scaled display of regulator output voltage noise as a function of frequency. A

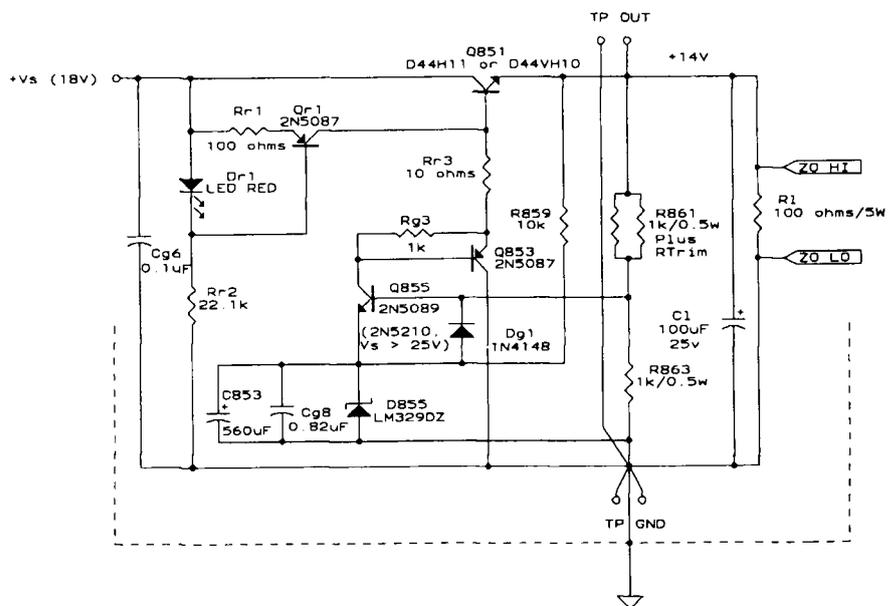


FIGURE 3: POOGE 5.51 positive regulator.

fundamental limitation of this setup is that the measurement preamp noise cannot be distinguished from the regulator noise, when they are of the same order. The preamp circuit's noise is about $2.6\text{nV}/\sqrt{\text{Hz}}$, so this only becomes an issue for regulators with noise levels of about $7\text{nV}/\sqrt{\text{Hz}}$ or less. I describe the low-noise preamp circuitry in greater detail later.

Output Impedance Tests

Figure 2c shows the setup for testing regulator output impedance (Z_O). As with the noise test, an appropriate rail driver/regulator supplies an appropriate DC voltage V_S . To measure output impedance as a function of frequency, the analyzer is programmed to produce a constant 2.5V RMS behind a 50Ω resistance. This results in an AC current flow or $I(\text{AC})$ of 50mA RMS for load impedances low with respect to 50Ω .

An appropriately polarized $4,700\mu\text{F}$ DC blocking capacitor couples the AC test current directly across the load resistance of the regulator under test, through twisted pair wiring. This completely balanced signal transmission method was found necessary for the very highest-resolution measurements, where the equivalent amplifier input voltages to the analyzer are around the microvolt level in the highest-performance circuits.

In this test, the regulator is called upon to absorb the test signal AC current to maintain the output voltage at the DC design level. Since an AC signal is bipolar in nature, the regulator can only totally absorb this signal if it is pre-biased to a DC load current higher than

that of the highest AC signal peak (about 70mA). For these tests, all regulators were operated with DC loads of 100mA or more.

Of the three tests, this one is the most difficult in terms of wide dynamic range implementation. The location of the TP OUT test points must be accurately fixed at the true physical/electrical sensing points of the circuit (Fig. 1). No load currents must be allowed to flow in the wires to the test points; otherwise, the advantages of this four-wire sensing will be lost. This point is amplified by the "S" notations on the Fig. 2c diagram.

Overall sensitivity of this test setup is such that equivalent impedances of less than $10\mu\Omega$ can be resolved at low frequencies, and $1\text{m}\Omega$ or less at 100kHz. The respective figures list the test software, which is available by simply sending me a formatted 3.5" MS-DOS disk, with a mailer including return postage.

POOGE 5.51 Regulators

The discrete regulator of Fig. 3 is an enhanced version of the POOGE 5 regulator described in Part 1 of Gary Galo's article.¹¹ For this article, it provides an example of a medium-to-high-performance discrete circuit regulator, and aside from the present comparative discussions, is practical and useful as shown. Those using this regulator must add some protection against overcurrent (this also applies to all others, with the exception of the internally protected IC types). Since there is no internal current limiting, a simple series fuse on the unregulated input side is sufficient protection.

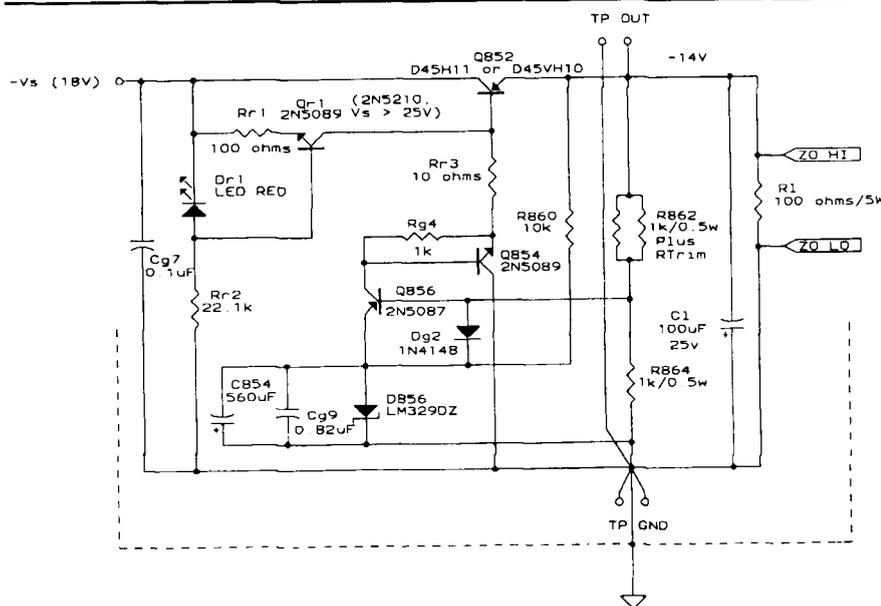


FIGURE 4: POOGE 5.51 negative regulator.

Close comparison of this schematic with the original version shows two main differences. One is Q851, either a D44H11 or D44VH10, both improved pass transistors as described in POOGE 5.5.⁸ The other is a refined current source drive for Q851, Qr1, and the associated parts (such as Rr1).

The new current source functionally replaces the selected 2N5458 JFET in the original version, and allows improved performance with lower I/O voltages, i.e., lower dropout. While the simpler POOGE-5-style JFET current source works fine with medium-to-high I/O voltages, it requires 4-5V of bias to achieve highest LR. Since the combination of these two changes enhances the performance, I designated these new circuit versions as POOGE 5.51.

The LED-biased bipolar transistor source works well down to 1.5V of dropout voltage. This current source's output is set by Rr1 at approximately 10mA, which allows regulator output currents of up to 500mA, with a Q851 β of 50. Resistor Rr3 provides additional stability for Q851 in the presence of capacitive loads. When connected as shown, Rr3 has no negative effect on overall dropout voltage.

The negative version of the new regulator (Fig. 4) works identically in concept to Fig. 3, with, of course, the obvious polarity reversals and transistor complements. In both forms of the circuit, use the 2N5210 in place of the 2N5089 when input voltages are 25V or greater. For these tests, I set up this regulator (and most of the others, except as noted) with an output of 14V (trimmed just as

described in Gary's POOGE 5.5 article) and a 140mA load, R_i.

Circuit Layout

As noted above, I built this circuit (and the others) in a small "cell" area surrounded on three sides by a grounded guard trace (#16 gauge, dotted lines in the schematic). In addition, a double-sided circuit board with a ground plane was used. (Breadboards for these tests are "IVANBOARD," an 8.5" x 11" RF design breadboard using a 0.1" grid surface mount pattern over a 2 oz copper ground plane.)

The standard dual test points are pro-

vided for ease-of-measurement via plug-in twisted pair cable connectors. One is at the TP GND reference point, provided at the circuit's common point, the common physical/electrical junction of reference diode D855 and divider resistor R863. The other is the TP OUT sense point, electrically connected between the above described TP GND point and the output node connection of divider sense resistor R861.

In the test strategy, I included a given test cell's TP OUT connection for all three tests, and used TP GND as a dynamic range and S/N reference check. For the Z_O tests, ZO HI and ZO LO provide access for the 50mA AC current test signal connections directly to R_i. I used similar test points and connections in all regulator test circuits.

Since the three-terminal regulator types tested are much simpler in their application, they are not shown in schematic detail. All types tested were by the original manufacturers, using the TO-220 package and carrying either a 1.5 or 3A rating. Note that many different versions of these regulators are available, some with much lower maximum current ratings. I did not test these types, but anticipate that those with lower current ratings (and associated higher output impedance) will not likely exceed the performance of the 1.5/3A versions.

The fixed 15V types (LM7815 and LM7915) are connected in their standard mode, with output loading of C₁ = 100 μ F and R₁ = 100 Ω . The adjustable three-terminal regulators (types LM317, LT1085,

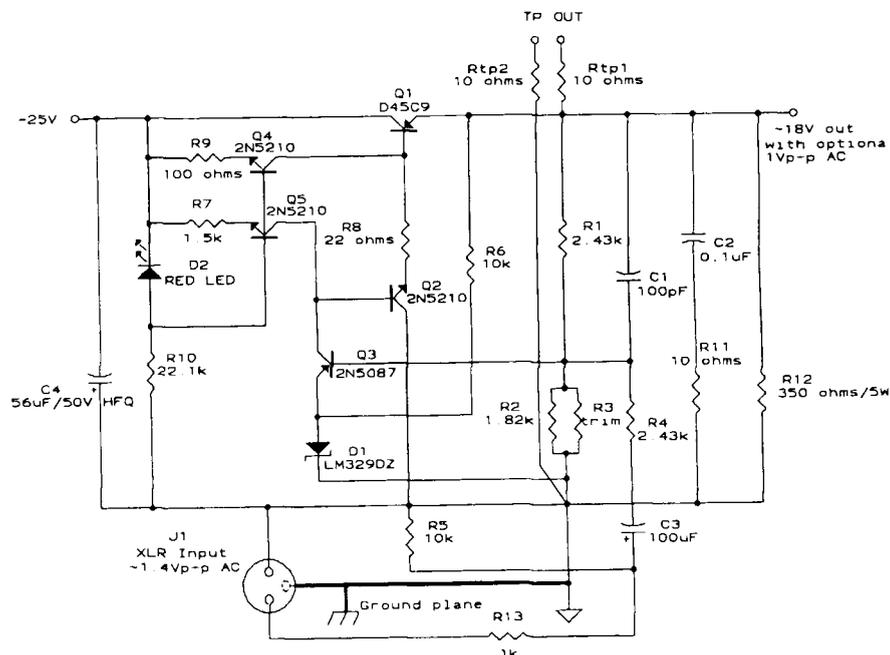


FIGURE 5: Negative rail driver/regulator.

LM337, and LT1033) are connected with an OUT-ADJUST pin resistance of $1k\Omega$ and an ADJUST-GND pin resistance of $10k\Omega$, which programs them to a nominal 14.2V. These also used a C_{ADJ} bypass capacitance of $100\mu F$, plus the loading of $C_1 = 100\mu F$ and $R_1 = 100\Omega$. It is worth noting that this relatively high divider impedance works to advantage for audio applications, since a given size C_{ADJ} capacitor is more effective across a $10k\Omega$ resistor than with a $1k\Omega$ value.¹²

Rail Driver/Regulators

For a controlled AC source test environment, the discrete regulators of Figs. 3 and 4 are adapted to operate as low-impedance rail drivers. From an unregulated $\pm 25V$ DC source, these drivers provide a regulator signal source environment which allows a fixed DC input level of $\pm 18V$, upon which you can optionally superimpose a 1V P/P AC test signal. In the line rejection tests, the $\pm 18V$ output rails carry this AC signal, which is swept from 20Hz–200kHz.

This requirement demands a small-scale power amplifier, due to the fact that the various test regulators in many cases require a minimum value $0.1\mu F$ input bypass capacitor for stability.

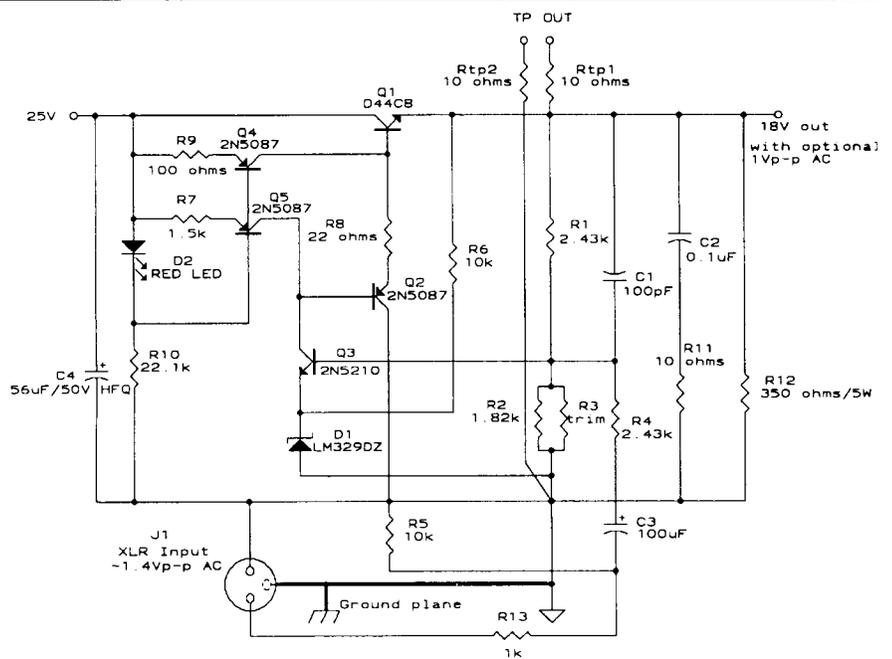


FIGURE 6: Positive rail driver/regulator.

Driver circuits suitable for negative and positive 18V plus AC outputs are shown in Figs. 5 and 6, respectively.

The voltage slewing to maintain a flat-frequency response into the $0.1\mu F$

load capacitance of a test regulator requires a substantial standing current in Q1, part of which is provided by the brute force load R12. As with the POOGE 5.51 plus/minus regulators, the

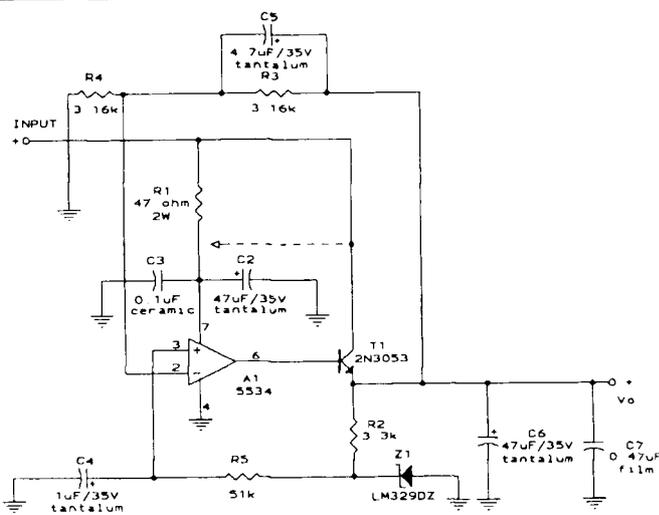


FIGURE 7a: Positive output Sulzer regulator.

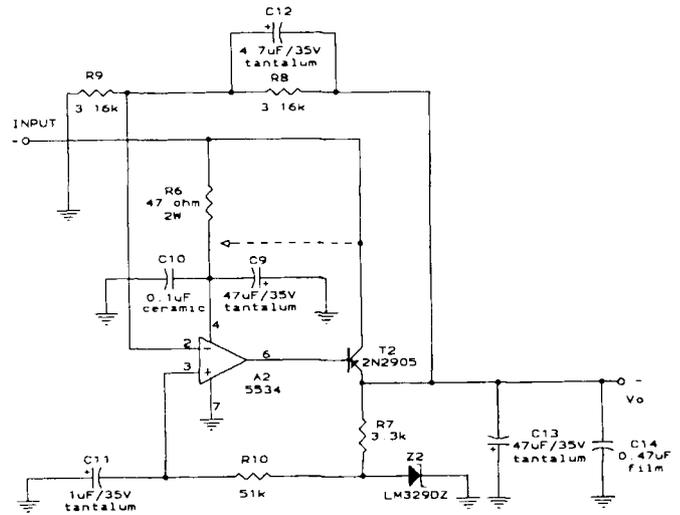


FIGURE 7b: Negative output Sulzer regulator.

output divider ratio and a reference voltage of $\approx 7.5V$ ($6.9V$ plus $1V_{be}$) set output voltage. In this case, the bottom resistance $R2$ is trimmed by shunt $R3$ to eliminate interaction with the AC gain. $R3$ is trimmed for an output of $18 \pm 0.1V$ with the driver/regulator loaded. Loads of up to $500mA$ are possible. AC test signals at input $J1$ are passed to the output bus with less than unity scaling, since $R1 < (R4 + R13)$.

In these drivers, the TP OUT test plug is used to verify the $0dB$, $1V$ P/P

$20Hz-200kHz$ AC swept reference signal as it is applied to the specific regulator under test for LR. The Audio Precision System One's function key F4 provides calibration to a specific measured output level for the $0dB$ amplitude reference for these test conditions. This calibration feature allows a measurement's $0dB$ reference to vary somewhat in absolute terms about the same nominal level ($1V$ P/P or other), but still references all subsequent readings to this level, which is an extremely useful trick.

Another difference of this circuit in relation to the PEOGE 5.51 regulators is the LED/bipolar transistor current source load $Q5$, which allows higher amplifier gain. This provides the driver with an output impedance measured at TP OUT of less than $5m\Omega$ below $100kHz$.

Some initial positive rail regulator testing was accomplished using a 317-

type regulator as an $18V$ regulator/driver, with the AC test signal coupled into the normally grounded C_{ADJ} capacitor. While much simpler than the discrete circuit driver of Fig. 6, this setup was not completely satisfactory, since spurious resonances occurred at certain frequencies.

Sulzer Regulators

The original Sulzer regulators³ for positive/negative supplies are shown in Figs. 7a and 7b, respectively. These are reproduced almost identically to the original versions, with a couple of small but important exceptions. One change is the connection of the pass transistor's collector, which is taken directly back to the input, as opposed to passing the output current through $R1$ (or $R6$). This step allows more effective decoupling of the op amp rail, and will increase available

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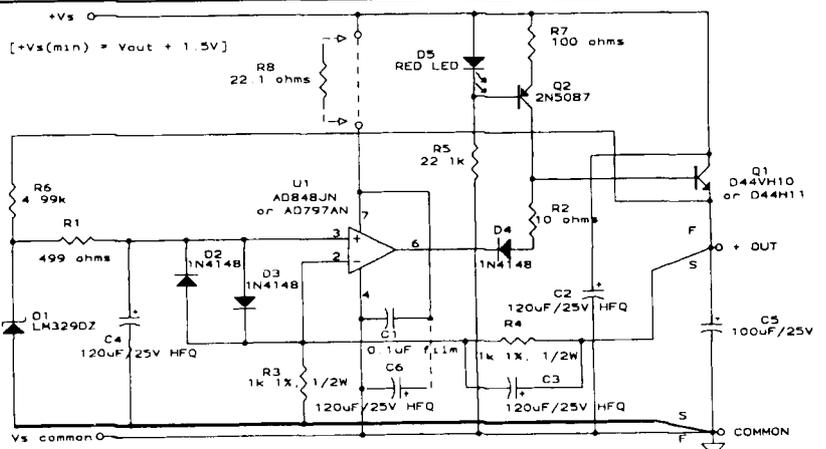


FIGURE 8a: Positive output, low-noise, low-dropout regulator. For this figure and Figs. 8b and 9, unless otherwise specified, all resistors are $\frac{1}{4}W$, 1% metal film. A heatsink is required on $Q1$ for $P_d > 0.5W$. In this figure and Fig. 8b only, minimize lead length from unregulated input and return. "S" indicates Sense lead; connect at point-of-load for best regulation.

headroom. It was also advocated by Sulzer in the "revisit."⁴

That article also suggested the use of "high quality zener, composed of an integrated circuit," which was attributed to Joe Curcio. Presumably, this was the lower noise LM329 IC zener as shown here and used in these tests (the LM329 was used also by Breakall, et al⁷). The only other variations are minor ones in resistance values, based on available values (R5/R10 and the output divider). With equal divider resistors, the circuits produce about $\pm 14V$.

Sulzer rated the original circuit at 100mA, so in this case I set load resistor R_L at 150 Ω (not shown). I used no additional C_f , beyond the values for C_6 and C_{13} , and built up the test circuit in the manner described above, being careful to locate the TP OUT test points appropriately at the sense points, to connect ZO HI and ZO LO to R_L and control (well) the high-current paths and grounding.

Low-Noise, Low-Dropout Regulators

Over the last two years, I've been working on a new family of high-performance, op-amp-based regulators. This work started shortly after the publication of the POOGE 5 regulator,¹¹ and

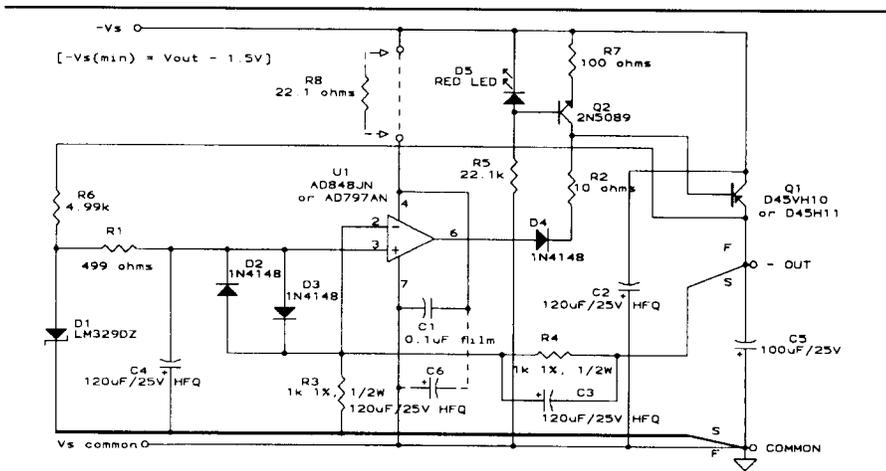


FIGURE 8b: Negative output, low-noise, low-dropout regulator.

sought to examine pass devices, amplifiers, and overall topologies to improve their performance. My goals were to extend a design allowing use at low output voltages such as 5V and to enhance dropout performance so DC regulation could be maintained down to $V_{OUT} + 1.5V$ (1.5V dropout). In addition to achieving Z_O performance similar to the already excellent Sulzer regulator, I wished to push LR and noise performance to levels as high as possible.

In general all of these goals were met, but the route to the final result has been quite an adventure. The testing has been among the more fascinating parts of the development, and, as I'm sure most will agree, it is full of surprising results. This will not be at all obvious just by examining the circuits, but it may become clearer as I explain the various test results.

Some audio designers simply prefer discrete circuits for regulation. Even given this preference, however, premi-

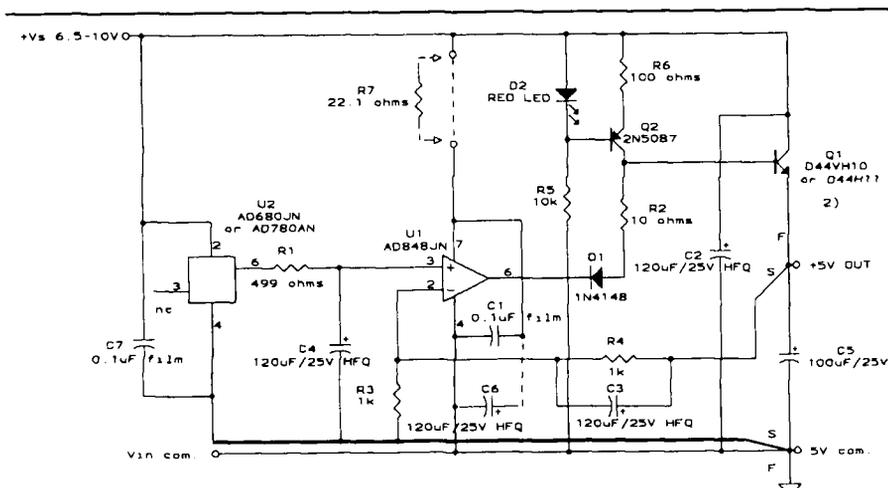


FIGURE 9: 5V, low-noise, low-dropout regulator. Minimize lead length from +Vs and return.

um-level results for Z_O , LR, and noise takes both a skilled designer, plus lots of parts. For example, the POOGE 5.51 circuits illustrate this problem. The performance is excellent for their relative simplicity, but if you wish to lower output noise, for example, you will not accomplish this simply.

You'll need additional parts to implement zener noise filtering and buffering, which may have a negative effect on Z_O

performance. It also becomes extremely difficult to get a comparable level of all-around performance working at a 5V output level, since the reference voltage needs to be $<5V$, a level which typically is more noisy because of the physical limitations of available bandgap-based voltage references.⁶

This leaves the topology of choice a low-noise, wideband differential input amplifier which operates down to 8-9V (or less), can be configured for low dropout, and has high inherent LR properties. This is a tall order for a simple discrete amplifier, and most would agree that there might be quite an increase in parts count over Fig. 3 or 4, just to implement such an amplifier. At this point, a very carefully selected op amp sounds much more efficient. Unfortunately, the 5534 of the Sulzer design does not operate well at low voltages, so this leaves newer devices as potential candidates.

The circuits of Figs. 8a and 8b represent the new positive/negative design solutions, the result of more than a few iterations with amplifiers and related components. Superficially, these designs look much like the Sulzer circuit, but with both major and minor differences. The circuit discussion that follows is in terms of the positive regulator of Fig. 8a, but the negative form works in a similar fashion, given polarity normalization.

The Circuit

A major departure from a straightforward U1/Q1 drive topology is the use of a current source drive for Q1's base, composed of Q2 and the associated parts. As with the POOGE 5.51 circuits, the LED-biased current source allows Q1 to operate down to 1.5V or less of differential, lending the circuit low dropout features.

The potential for a limited swing of the op amp to affect dropout is lessened by operating it in a current sinking mode, which is enabled via D4.

Typically, this circuit achieves dropouts of 1.2V with several hundred milliamp outputs, making it suitable even for logic supplies. Note that high regulator dropout is a serious issue for a logic regulator, where a 3V dropout can increase the power dissipated in Q1 to an intolerable level.

A second important change in the new regulator is the addition of amplifier input clamp diodes, D2-D3. These normally zero-biased diodes protect the op amp input stage, in the presence of ON or OFF transient voltage differentials greater than 5V. Such a large voltage can harm an unprotected input stage by breaking down either transistor's E-B junction.¹³

With a 7V reference voltage, the possibility that U1 can be damaged (or subtly degraded for noise) exists, if the input stage is allowed to break down differentially. The clamp diodes prevent this from happening, and should be used in this circuit for cases where the op amp does *not* have such diodes internally. The AD848 doesn't, so use D2-D3 as an ounce of prevention.

With lower-level reference voltages (such as 2.5V), you can eliminate the clamping diodes in many instances. As a general rule for most unprotected op amps, the worst-case differential transient error should be maintained $<5V$ for safety.

While the presentation of the reference voltage to the op amp is similar to the Sulzer configuration, as is the feedback network, the general impedances are lowered and made symmetrical for both AC and DC. The matched 500Ω DC source resistances enhance overall DC stability at little or no cost, and the 100% AC feedback around R4 lowers both output impedance as well as noise.

This latter technique, one hallmark of the Sulzer configuration, is a significant key to achieving the highest possible performance with a given op amp. It allows the net regulator output noise to approach that of the op amp itself, plus the filtered noise level of the reference input at Pin 3. With an ultra-low-noise op amp such as the AD797, 1kHz output noise levels approaching $1nV/\sqrt{Hz}$ are possible.¹⁴ To realize the highest possible attenuation in the single-section reference noise filter, a low-ESR capacitor is used for C4, a 120μF/25V-type HFQ. A relatively high voltage rating also helps lower leakage, as well as ESR.

Network Advantages

With wide-bandwidth op amps for U1, supply bypassing is critical for stability. The small RF-quality film bypass C1 is located close to the device pins, and is mandatory. The minimal operating hookup consists of just C1 at U1, along with C2 close to the collector contact of Q1. Optionally, you can use extra noise filtering via R8 and C6 to increase the high-frequency supply rejection of U1.

The net advantage of using this network depends upon several factors. One is the specific part used for U1; another is whether a positive or negative output is being implemented (since the plus/minus supply rejection of many op amps differs). As shown, the corner frequency is about 60Hz, and while not absolutely necessary, a low-ESR HFQ type for C6 allows greater HF noise rejection working against the relatively low value of R8. Finally, this network increases the DC/LF supply impedance seen by the op amp, and you should apply it very carefully to op amps with less than 100dB of supply rejection (such as the AD848). Needless to say, substitutions of op amps in these circuits are strongly discouraged.

To set up this regulator for voltages

other than the nominal $2 \times V_r$ or $\cong 14V$, change the R3-R4 resistors as shown generally in Fig. 1, keeping in mind the 6.9V reference voltage used. You can expect some trim when the loose tolerance "DZ" version of the industry standard 329 diode is used. However, the exact DC output voltage is not likely to be critical, except as it may affect dropout with a marginally low raw-DC supply. For test purposes, I loaded this circuit with the standard loading of $C_1 = 100\mu F$ and $R_1 = 100\Omega$ (not shown in these figures) and was careful, as with the Sulzer circuits, in the physical wiring/layout.

Closely related to the Fig. 8a circuit is the 5V regulator shown in Fig. 9, which evolved from reference 15. It operates with a lower voltage three-terminal 2.5V bandgap reference at U2, an AD680, or an AD780, but is otherwise similar to the Fig. 8a positive regulator. It is tested at a 300mA current level with $V_{IN} = 8V$, as suitable to logic systems.

In Part 2 we will more closely examine the three test setups used, in conjunction with the Audio Precision System One, to determine regulator performance. The differences between regulators easily stands out, making an optimum performance choice easy. \square