Part 3

REGULATORS FOR HIGH-PERFORMANCE AUDIO

By Jan Didden

Walt Jung's articles on high-performance regulators for audio (*TAA* 1/95, p. 8, 2/95, p. 20) clearly show that the state of the art in this field is very high-performance indeed. His new regulators approach the ideal—a DC voltage source with zero impedance for AC signals, which is beneficial for the total audio system. After all, these systems are normally designed assuming that the power supply acts as such an ideal voltage source.

But in practice, power supplies deliver a DC voltage contaminated with noise, mains ripple, and signal-voltage residues, which are caused by the frequency- and level-dependent currents produced by the supply. The varying currents are delivered through the supply's output impedance Z_O, and current times Z equals volts.

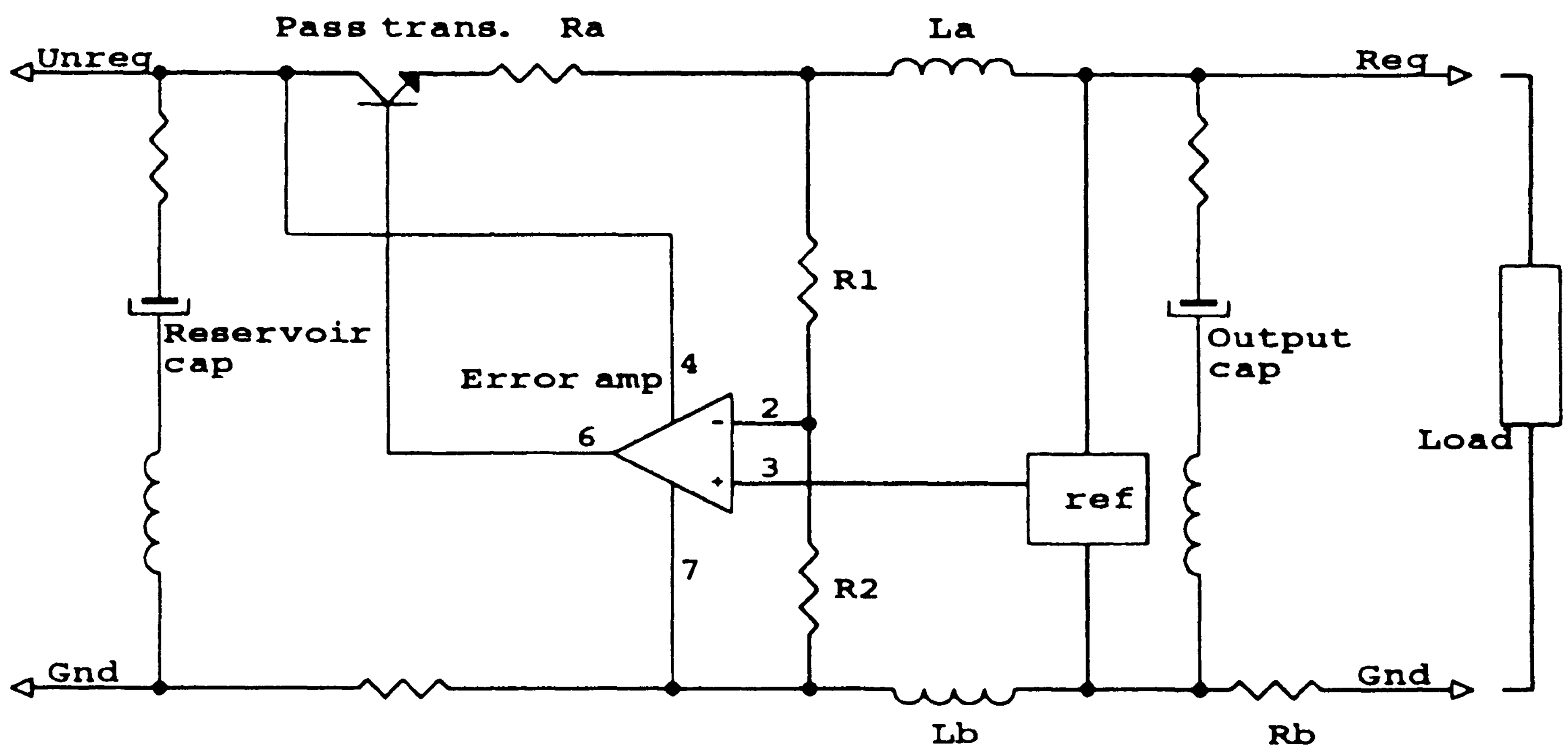

FIGURE 1: Real-world circuit, with parasitic components.

Of course, various smart-circuit topologies can make the amplifier stages relatively insensitive to supply variations, but there will inevitably be some effect. Nonideal supply rails not only are detrimental to a stage's performance, but also are responsible for mutual interference between stages in a channel, or between channels in a system. This occurs because the contaminations caused by one stage or channel are coupled to another part of the circuit through the supply lines (unless each stage has a completely separate supply, which I haven't seen yet).

Again, you can take steps to limit this, but it is always better to avoid it in the first place. This article attempts to preserve as much of the excellent performance as possible in a real-world application, and is based on the high-performance regulators in Figs. 8a and 8b of the referenced articles.

The Map Is Not the World

The key to successfully building the regulators is, surprisingly, a bit philosophical. We are so accustomed to viewing schematics as accurate depictions of the circuits that we rarely realize there are many components not shown in the diagram. But they are there, and the more you tune the cir-

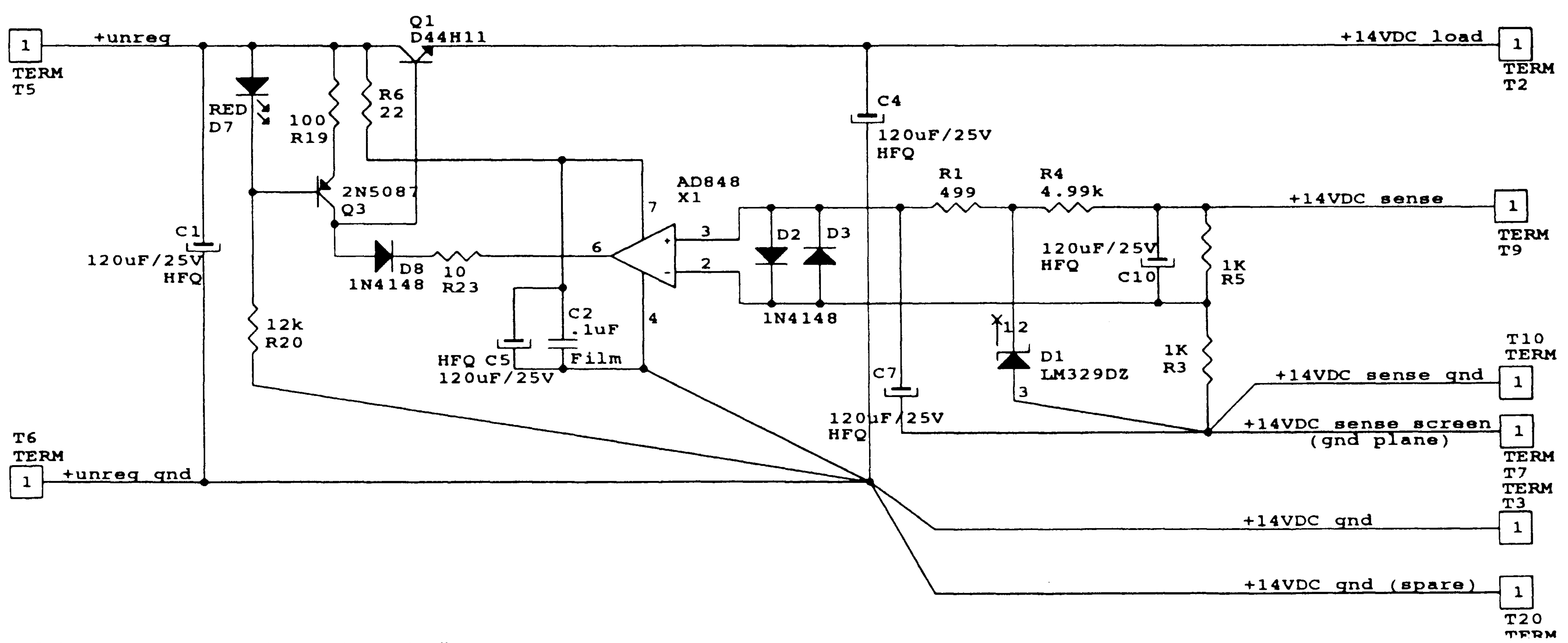

FIGURE 2: Positive regulator schematic diagram.

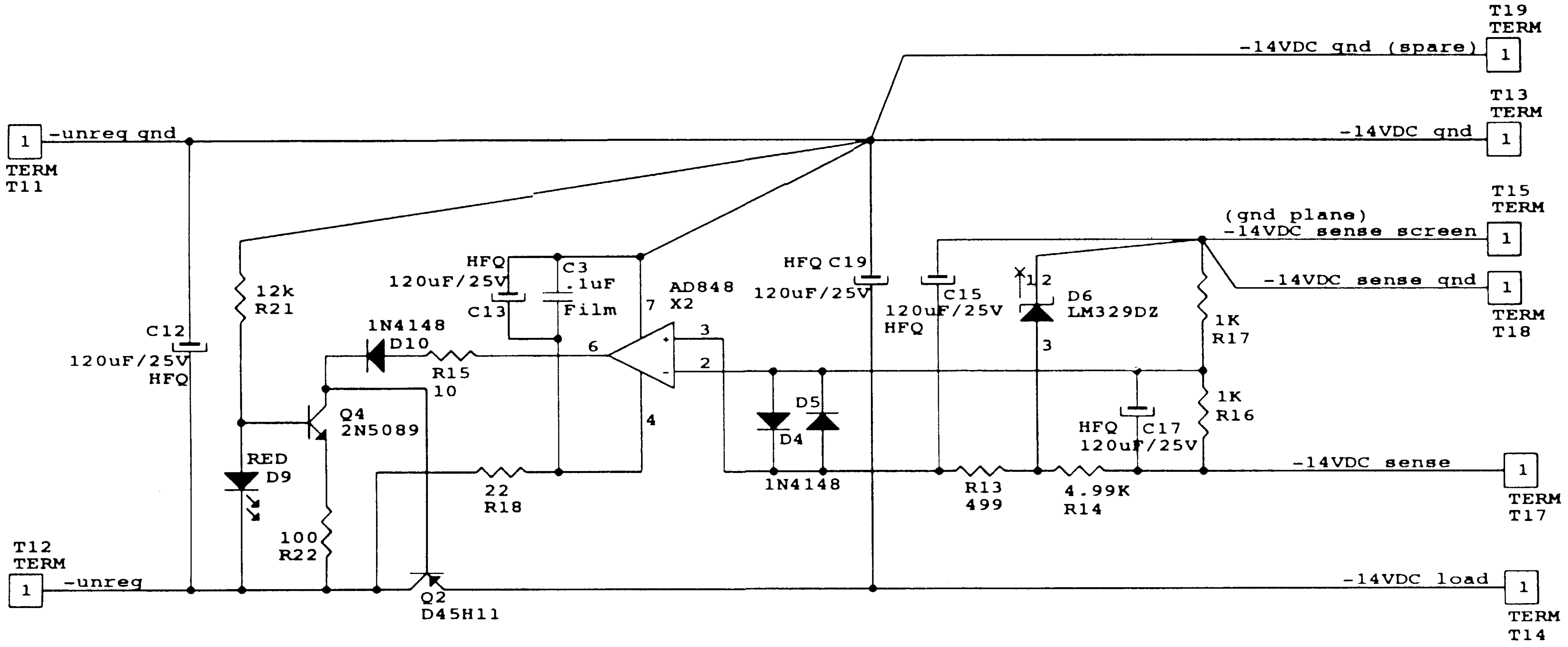

FIGURE 3: Negative regulator schematic diagram.

cuit, the more they become limiting factors.

Consider, for example, the rudimentary circuit of *Fig. 1*. Without going into details, let's just look at the input signals to the op amp. Here, you're looking for the reference at the noninverting input, and a sample of the output voltage at the inverting input. As you know, the op amp drives the series transistor to make the two inputs equal. You need the output voltage *at the load* to be clean and stable.

The load current runs through La, Lb, Ra, and Rb, which you won't find in the schematics, because they are the resistance and inductance of wiring and PC board tracks. The voltage at the inverting input depends on load-current amplitude and frequency. The reference voltage, which should really be developed relative to the common ground point, also depends on load current and frequency because of Lb and Rb.

So now you have a circuit in which the op amp works hard to accurately reproduce load- and frequency-dependent AC components at the supply output. Static DC errors normally are not problematic in audio; a nominal 15V DC supply works perfectly at 14.5V or 15.5V. The AC components cause the detrimental effects of supply ripple, which is really a manifestation of supply voltage varying with frequency and load current.

Unless you take adequate measures in the physical design, you cannot realize the superior regulator performance *at the load*, that is, at the circuit to be powered. If you need convincing, reread the sections on the measurement setups in the referenced articles.

The Way Ahead

So, what can you do? First, of course, use the best components you can afford. A capacitor should be a capacitor, not a series circuit that resonates at some inconvenient frequency. For this supply, Panasonic HFQs are the best available, and are prescribed for all electrolytics.

Second, avoid stray capacitances within the regulator circuit by using a sensible layout and screening where possible. Third, use short, thick, twisted wires for all external power connections to the raw supply and the load. This minimizes AC frequency- and load-dependent errors, as well as DC errors, caused by parasitic impedances.

All this can be quite effective, but the third measure is the most difficult. Remember that these regulators can provide output impedances lower than a standard "0Ω" jumper, coming very close to an AC short circuit. So, if you must use a few inches of wire to connect the regulator to, say, a preamp, you inevitably increase the output impedance Z_O at the load, which is where it matters. There's no use having zero ripple at the regulator board; you need it at the load.

Fortunately, you can take care of that, too, with a technique called Remote Sensing (RS). To clarify this and to focus on the physical layout of the boards, look at the familiar circuit diagrams. *Figure 2* shows the positive voltage regulator, and *Fig. 3* shows the negative voltage regulator. The specific RS provisions in *Fig. 2* are immediately apparent.

The circuit has four outputs: the

ABOUT THE AUTHOR

Johannes (Jan) Didden made his career in the Royal Netherlands Air Force, working in areas such as Air Defense, Software Development, Quality Assurance, and Communications. Several NATO assignments brought him to remote places such as Nashua, NH, and Torrance, CA. He has been building audio systems as long as he can remember, and has had several projects published in *TAA*. His other hobby is driving his Land Rover with his wife through famous tourist attractions such as the Libyan Desert and the interior of Iceland. He welcomes reactions to this article by FAX (+31 1680 23895) or by E-mail (didden@shape.nato.int).

TABLE 1

COMBINED POSITIVE/NEGATIVE REGULATOR BOARD PARTS LIST

REFERENCE	PART
C1, 4, 5, 7, 10, 12, 13, 15, 17, 19	120μF/25V Panasonic HFQ (Digi-Key P5698-ND)
C2, 3	0.1μF/50V film
D1, 6	LM329DZ National Semiconductor
D2–5, 8, 10	1N4148
D7, 9	Red LED
Q1	D44H11 Harris or Motorola
Q2	D45H11 Harris or Motorola
Q3	2N5087 (or equivalent)
Q4	2N5089 (or equivalent)
R1, 13	499 0.25W film
R3, 5, 16, 17	1k 0.5W film
R4, 14	4.99k 0.25W film
R6, 18	22 0.25W film
R23, 15	10 0.25W film
R19, 22	100 0.25W film
R20, 21	12k 0.25W film
X1, 2	AD848JN or AD797JN, ADI

MISCELLANEOUS

Heatsink (Digi-Key HS112-ND or equivalent), circuit board(s), mounting hardware, transformer(s), rectifiers (see text).

load connections indicated by "+14V DC load" and "+14V DC gnd" and a pair of separate connections for the sense points, called "+14V DC sense" and "+14V DC sense gnd." The aim is to take the sense connections "as close as possible to the load," which may require some pondering, and I'll examine this later.

So, now we feed the regulator feedback circuitry (R5, R3 in *Fig. 2*) with the actual output voltage at the load. Furthermore, the reference voltage is developed from the same points as well. The currents through the sense wires are very small and constant, and thus do not affect the performance. You have now all but eliminated the influence of the connecting wiring on both the feedback and the reference.

The supply current for the op amp and the current source around Q3, however, vary with frequency and load current. After all, these currents vary with the pass transistor's base current demand, and are thus clearly load- and frequency-dependent. Therefore, these circuit points are not returned to the clean sense points, but to a star ground as a "next best" alternative. Parts 1 and 2 already addressed the rest of the circuitry, so I won't go into further details. The negative version (*Fig. 3*) is, of course, just the twin of *Fig. 2*.

Getting Physical

Figure 4 shows the actual solder-side board layout. One board holds one positive and one negative regulator. The circuits are completely separate, so you can, if you wish, cut the two halves apart for your specific mounting/space requirements.

When the load exceeds 50mA or so, you should mount the pass transistor on a heatsink. As you can see, the board layout has provisions for that. The outline on the stuffing guide (*Fig. 5*) is a heatsink from Fischer in Switzerland; I couldn't find an exact US replacement type. However, you can use the one in the parts list (*Table 1*), available from Digi-Key. Again, you have the flexibility to cut off those areas of the boards. You can then mount the pass transistor on the enclosure wall or other heatsink, positioned perpendicular to the board. I tried to keep this layout as flexible as possible, as many readers might wish to use the new supplies in existing equipment.

The board also has a screened area on the component side, which extends underneath the sensitive control circuitry (*Fig. 5*). It purposely does not cover the higher-current areas to avoid possible capacitive coupling of ripple currents into the control section. In addition, you'll get best results if you mount the board closely over a metal sheet or enclosure wall to provide further screening. Such practice results in measurably lower noise and lower Z_O.

Use 18 AWG or heavier wiring for the raw supply input and load connections. Twist the hot wiring with the corresponding ground return line and route them away from the board and active circuitry as much as possible. Use a balanced screened cable for the sense connections, and connect the screen to the provided pad only at the board. The sense lines carry very little

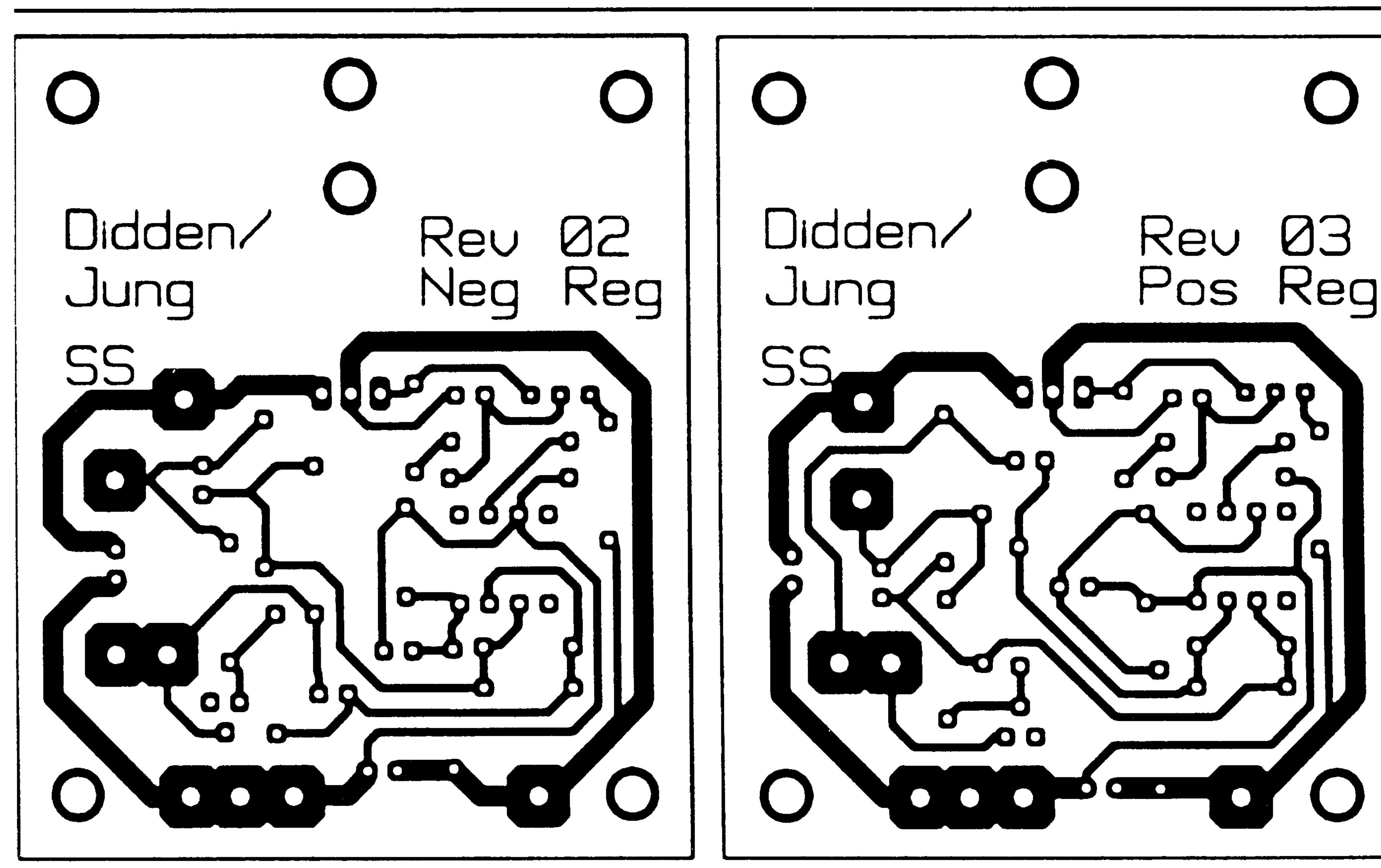

FIGURE 4: The board layout holds one positive and one negative regulator.

current (roughly 8.5mA), so a good-quality stereo lead should be adequate.

The two "sense gnd" and "sense screen" pads on the proposed boards (T7 and T10) are plated through, which will automatically connect the screened board area to this point as well. Of course, you should make every effort to keep the wiring as short as possible. These requirements are conflicting, so spend some time figuring out the best layout.

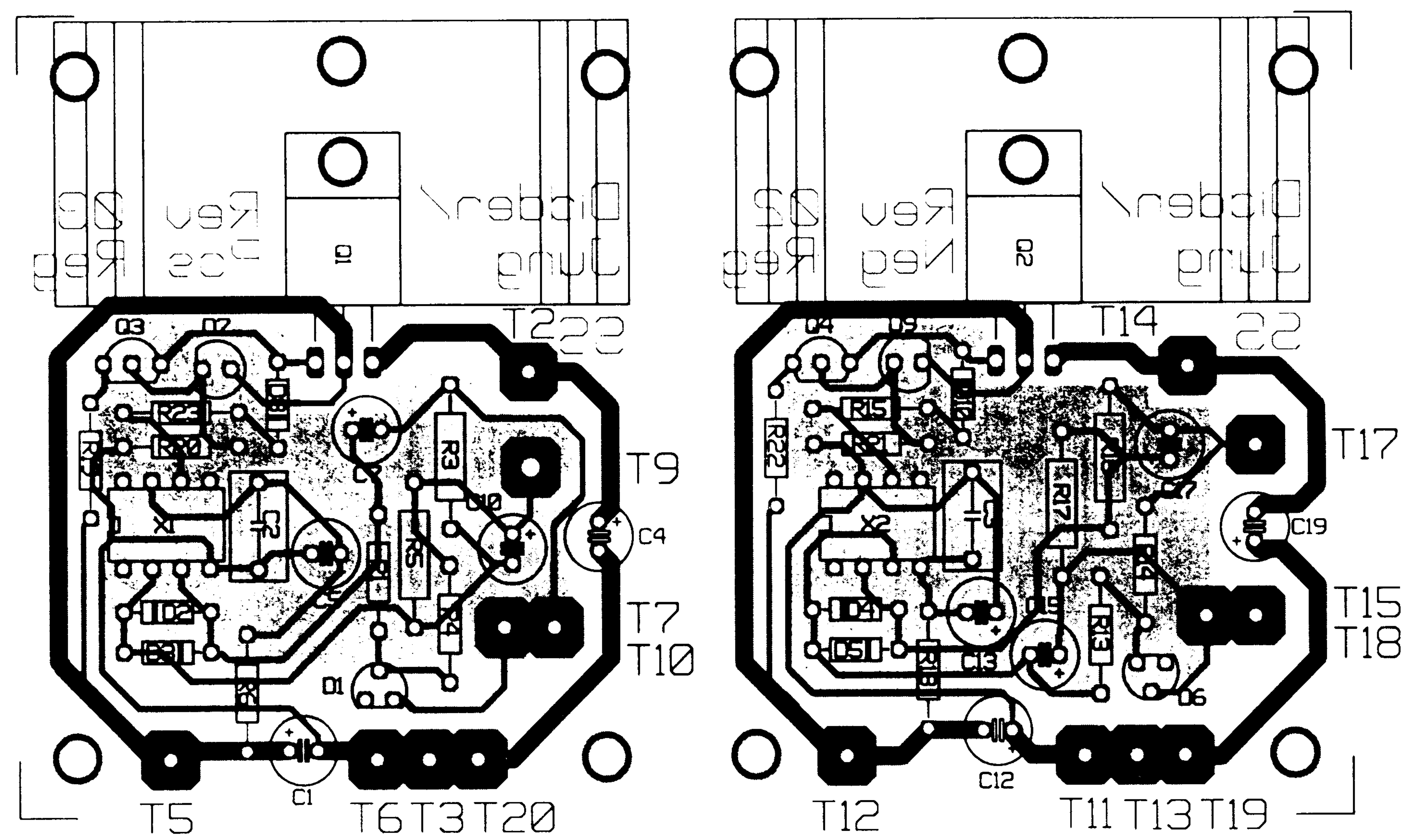

FIGURE 5: Stuffing guide for the combined positive/negative regulator board.

Stuffing Techniques

Stuffing the boards should not pose any problems. They are quite compact, but careful soldering will ensure that they will work straightaway. The easiest way is to start with the low-profile components (resistors and diodes), then the film caps, transistors, LED, and finally the electrolytics.

Figure 5 shows the stuffing guide and *Table 1* the parts list. Select the parts with care, because they and the layout determine the ultimate performance. I've already mentioned using HFQs for all electrolytics. The specified op amp and the reference diode are crucial to the wide bandwidth and the low noise. You could use an AD797 instead of an AD848, but limit yourself to these two types.

The best way to mount the op amps is to solder them directly to the board. This gives you the fewest problems with stray capacitances and intermittent contacts. Many readers might prefer to use sockets for easy swapping in case of problems, but the op amps are virtually indestructible in this application, and if the boards don't work, it is probably due to a wrong component value or polarity. I strongly recommend direct soldering.

The other parts should be as good as those in a high-quality preamp. Use good film caps and low-noise metal film resistors throughout. The board will hold 0.5W resistors for the feedback dividers R3, R5 (positive regulator) and R16, R17 (negative regulator). Their dissipation is much lower, but the physically larger resistors ensure very low temperature drift and high reliability. All other resistors can be 0.25W types that offer adequate overcapacity.

The output voltage is set by the ratio of the two feedback resistors. You can adapt it for other voltages, as explained in the referenced articles. These voltages are normally not critical for powering nominally 15V DC circuits. You should, of course, stay below the maximum ratings. Most op amps used in audio have maximum

Supply Decoupling: A "Yes, But" Story

The proposed regulators use an extra RC decoupling for the op amp supply. (In the positive regulator, *Fig. 2*, these are R6 and C5, C2.) Such a network, often seen in low-level circuitry, has been the source of some controversy. I have done some research into the effects and offer my findings here, for whatever it's worth.

The network has two effects, working against each other. Whether the result is positive or negative therefore depends on the relative magnitude of the effects.

Let's first look at the raw supply. As discussed in the article, the raw supply line has AC components from the mains, and from the frequency- and level-dependent load current. (Because the raw supply has an internal impedance, the varying load current results in a varying ripple component.) We need to keep these unwanted artifacts out of the op amp supply. We can attenuate them greatly with the RC network mentioned before, which looks quite attractive.

Now consider the op amp. Generally, the current that the op amp draws from its supply varies with the frequency and level of the output voltage and current that the op amp must deliver. Part of these current variations are short-circuited by the RC network's capacitor, but some current variations will result through the resistor and thus cause a ripple voltage across this resistor. The ripple voltage that finally appears on the op amp's supply pin is the sum of this ripple, plus the one on the raw supply line.

Many factors determine the net result. The two ripple voltages could be equal in magnitude but opposite in phase and cancel each other, which makes the RC network extremely useful. On the other hand, they could reinforce each other, in which case you would be better off without it.

In considering the positive regulator (the following holds equally well for the negative supply), the base current for the pass transistor is furnished by the current source. This current is way too high, and the op amp must siphon off the excess. By taking away just enough to maintain the output voltage at the set value, regulation is obtained. The op amp output current flows from the current source *into* the output pin to ground; no current is drawn from the op-amp positive supply point. (The only current the op amp takes from its supply is for internal biasing, which basically is for constant-current sources.)

So, with the above in mind, I conclude that there is no frequency- or load-dependent op-amp supply current and no ripple component developed across the resistor of the RC network. My measurements confirm that, with the network, the supply-output ripple is slightly lower. Which is why I recommend its use here.—**JD**

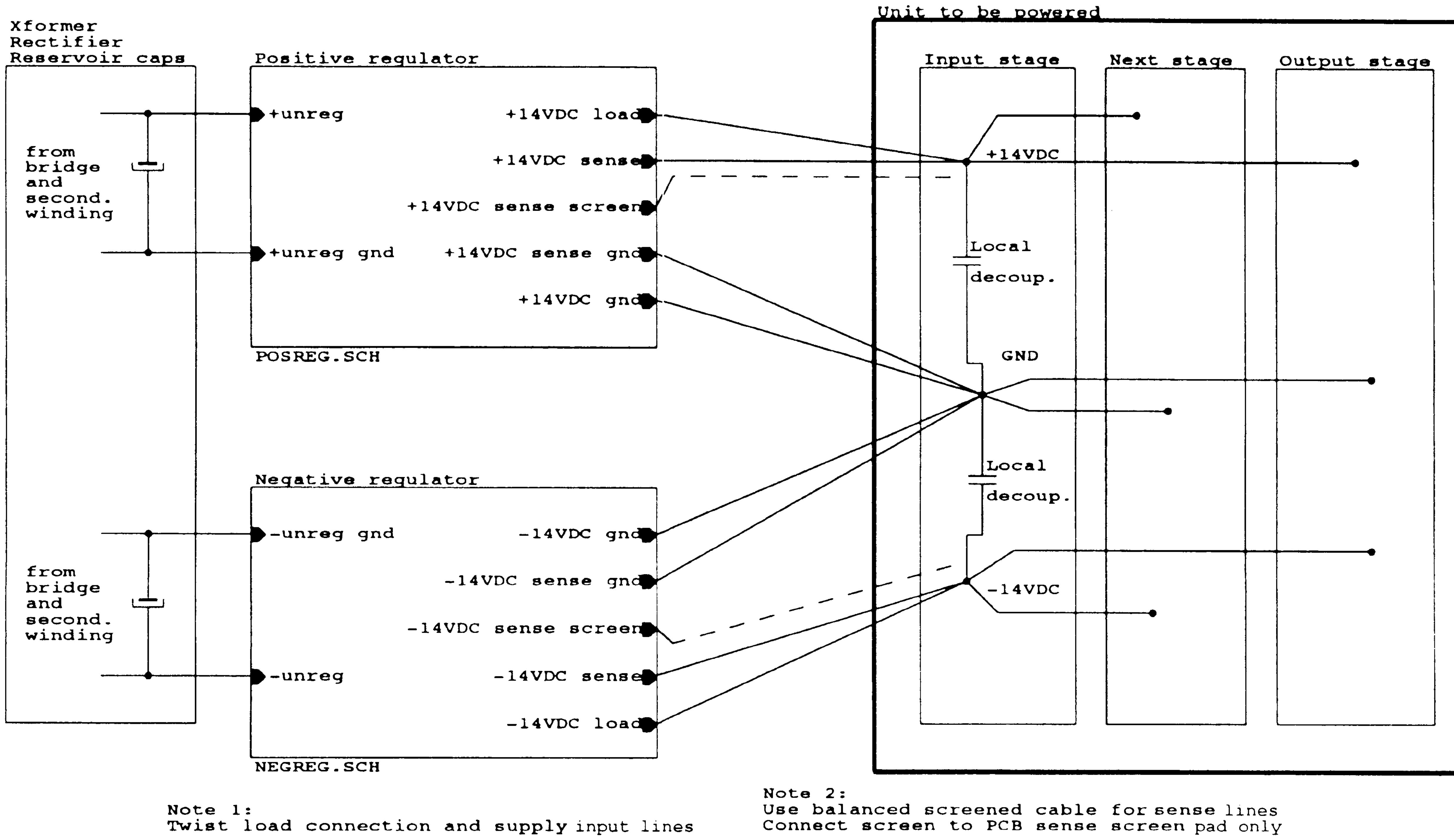

FIGURE 6: Generic connection diagram for one channel.

ratings of ±18V, and operation within a volt of the recommended ±15V DC is OK. A higher voltage causes higher dissipation, but not higher fidelity.

Make sure that the input supplies deliver at least 2V above the set output level under all load conditions. Higher input voltages don't improve the performance, but they do increase dissipation, which is undesirable. Discrete circuits have more variation in operating voltage. These boards can supply up to about 26V DC, with a raw input of 30V DC, limited by the AD848 operating maximum. The board implements the extra filter for the op-amp supply, and I recommend its use. The extra cost is small, and it provides additional attenuation of any "dirt" on the raw supply (see "Supply Decoupling" sidebar).

Getting Connected

Now I'll return to the issue of connecting the load. Your circuit may consist of several stages, and there is probably only a single connection for the supply. This may not be optimal for your purpose. However, if you take the time to examine the layout, you can locate the most sensitive stage, which normally is the input stage. This is where the supply voltage should be sensed. Toward the circuit's output stage(s), load current generally increases, and with it the ripple voltages.

Connecting the supply directly to the input stage has two important advantages. First, it ensures that the most sensitive stage gets the cleanest power available. Second, because of the extremely low supply-internal impedance (Z_O), any ripple voltages generated elsewhere are effectively short-circuited at the input stage. You should not underestimate this last effect. It prevents ripple voltage and signal residue from one channel's supply lines from entering the other channel.

The flip side of this is that you need to use a separate pair of supply boards for the left and right channels in the system. Only this will give you the cleanest supply at each channel and minimum interchannel crosstalk. You can realize the highest performance only at a single point: where the sense lines are connected.

Normally, a decoupling capacitor will be very close to the input stage, which is a good point to connect the sense and power lines. Connect the other stages of the particular circuitry you need to power to these points as well. *Figure 6* shows a generic example for one channel.

A few words on the raw supply are also in order. Ideally, you should use one transformer per channel, each transformer having two separate secondary windings (2 × 15V AC for a standard 15V DC supply). You could also use a transformer with four secondaries. Each secondary then would feed a diode bridge and a reservoir cap (*Fig. 6*). Combining regulator boards or transformer secondaries, or using center-tapped windings will be less effective, generally leading to ground loops.

What's in It for Me?

How does this compare to the best theoretical performance? Parts 1 and 2 addressed three significant performance indicators. The input-line rejection is not really influenced by the output/sense configuration you choose, but it depends mostly on the circuit topology itself. Therefore, my application duplicates the performance for this area.

A similar argument can be made for the output noise level. The circuit topology, specifically the selection of op amp and reference, and the reference filter, determines the noise performance. Again, this implementation essentially is equivalent to the "laboratory" results.

Large differences can occur in the output impedance Z_O. This is clearly illustrated by the plots I made with my Audio Precision system (*Figs. 7* and *8*). I used the same measurement technique (with the same software) that Walt Jung used for his plots.

In each plot, the graphs represent the Z_O as measured at the load. For the top graphs, the sense lines are connected at the board to the terminals of the R3, R5/R16, R17 feedback divider. This is the way you would normally connect a supply. In this case, the at-the-

ACKNOWLEDGMENTS

I am grateful to Walt Jung for involving me in this project. Most people do not realize how much time and effort are absorbed by such undertakings, and this was no exception. But working with like-minded people on projects of interest is quite enjoyable, and you always learn from it. Also, I am indebted to Gary Galo for his review of my manuscript and for testing my prototype boards. Finally, I recommend reviewing the references, which I won't repeat here, at the ends of Parts 1 and 2. They apply to Part 3 as well.

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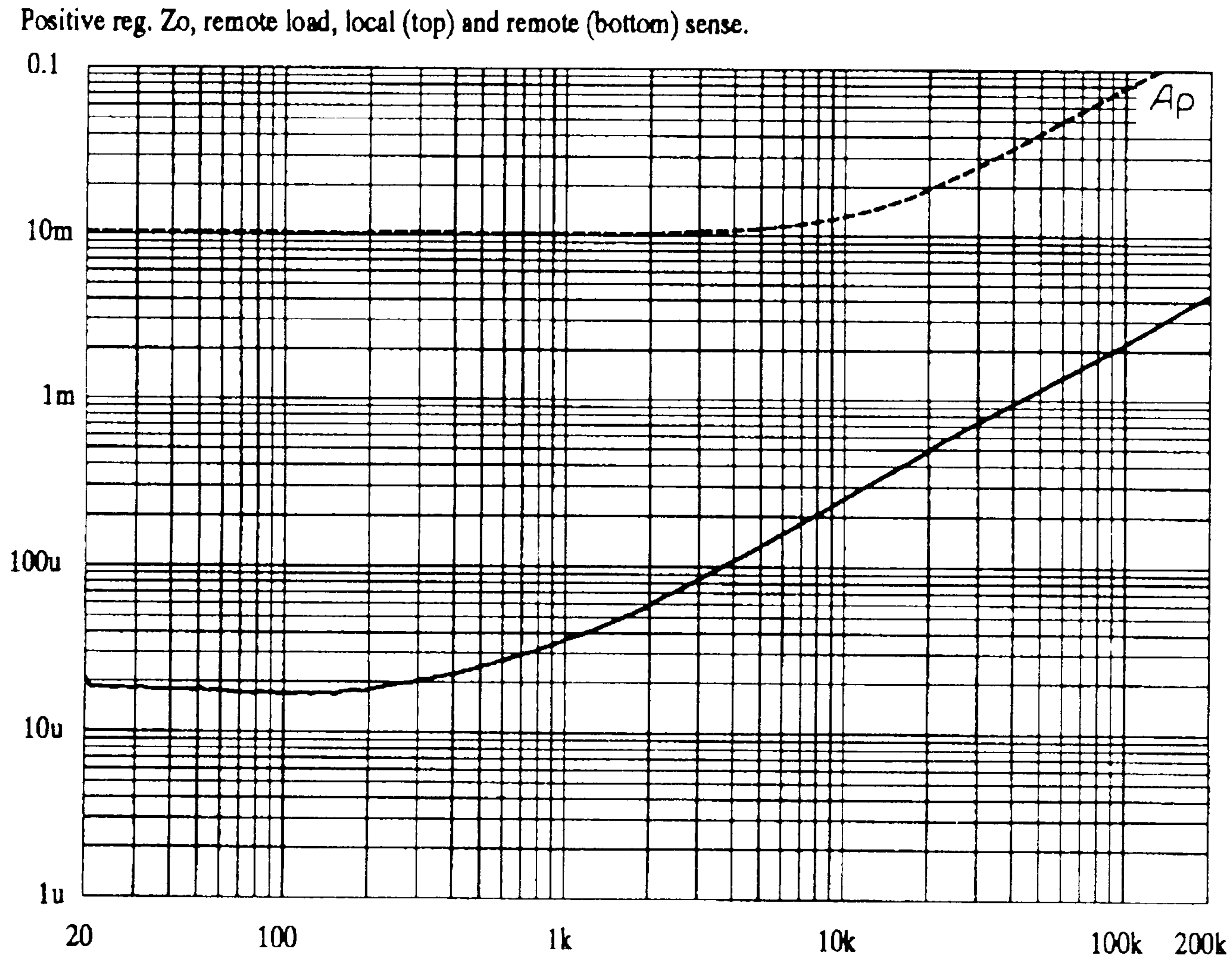

FIGURE 7: Positive regulator output impedance (Z_O) plots.

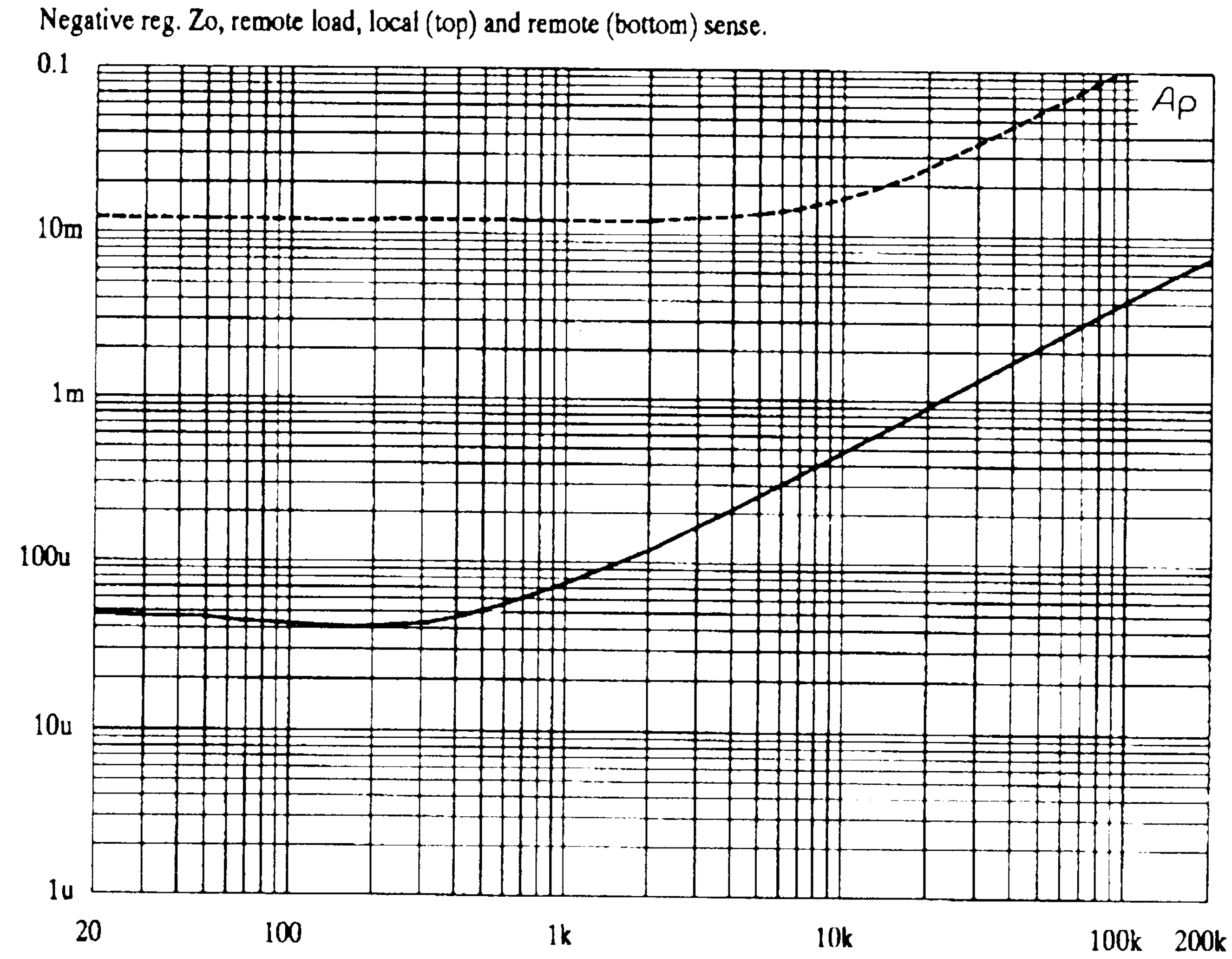

FIGURE 8: Negative regulator output impedance (Z_O) plots.

load Z_O is several orders of magnitude worse (higher) than the lab results.

However, when you connect the sense lines directly to the load point, you notice a vast improvement (the lower graph). It is not exactly equal to the lab curves, but it comes quite close. For both regulators, Z_O is now below 1MΩ up to 20kHz, where moving the actual sense points fractions of an inch on the load connections produces a readily measurable difference. These measurements are made with AD484 op amps in the prototypes. Using AD797 types gave similar or slightly better results.

But the measurements are only part of the story. At the end, we need an improvement in the sound of our systems. (See Gary Galo's article in the next issue on listening tests with the supplies.)

These regulators are as good as present state-of-the-art components permit. The limiting factor is the environment in which they are used, the connections to the load, and the lead lengths. With the remote-sensing setup, it is unlikely that significant improvements

to page 30

from page 27
are possible in this "POOGE" manner.

The only improvement I can think of at this time is to design your circuits from the ground up with integral supply regulators for each stage and each polarity. Human nature being what it is, someone will probably eventually try that. Powering your circuits with these new regulators gives you an immediately clear improvement that will be very hard to surpass in the years to come. This is another step toward that elusive ideal, and it puts the bar another notch higher. □