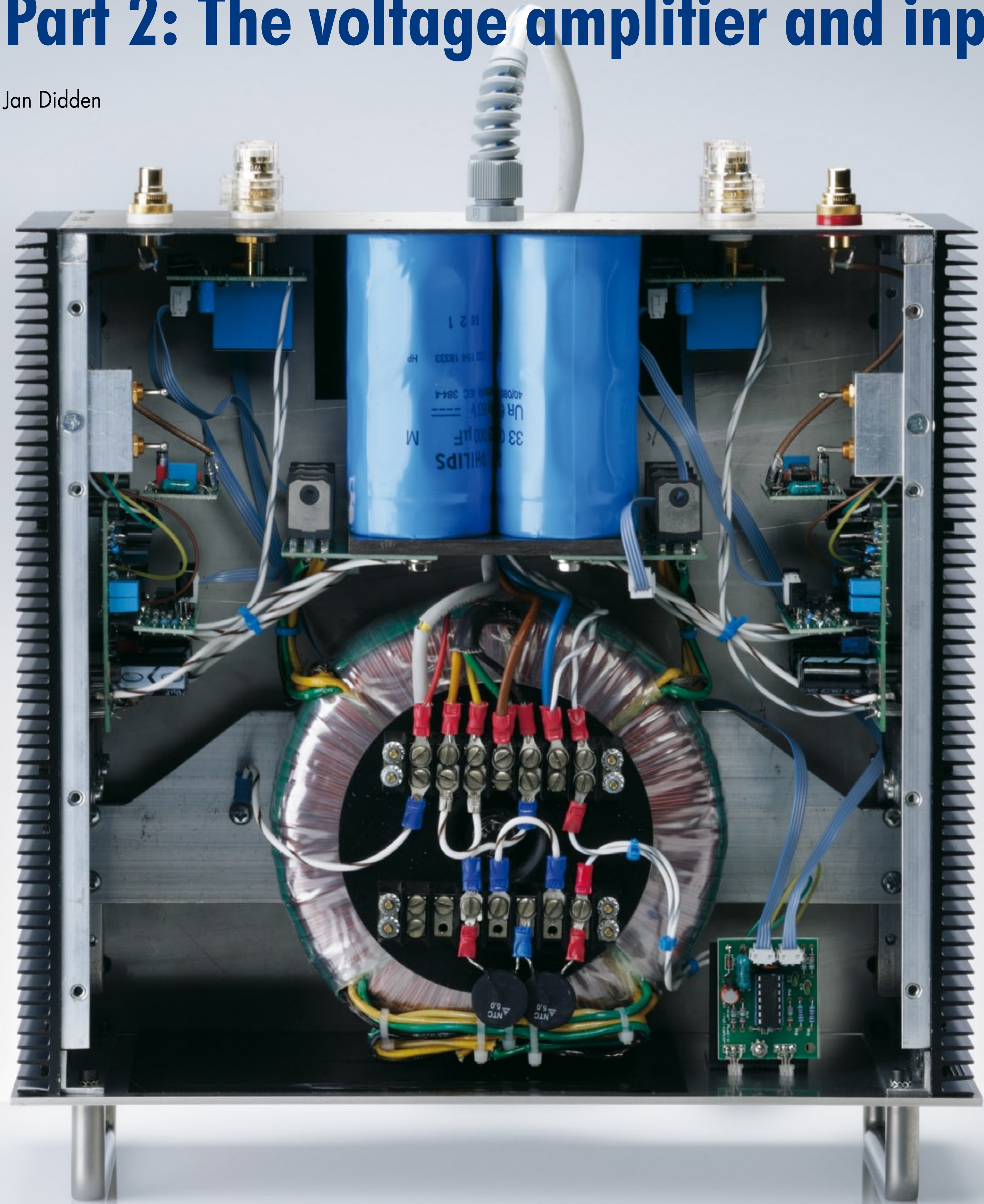
paX: a Power Amplifier w

Part 2: The voltage amplifier and input

Jan Didden



ith Error Correction

buffer stages

Last month we discussed the principle of error correction and developed an error-correction power output stage. In this instalment we will use H.ec in a voltage amplification stage and present the complete amplifier.

Let's revert to the conceptual circuit of error correction as defined by Malcolm Hawksford, shown in **Figure 1a**. We know that if summing circuits S1 and S2 are unity gain summers, we get $V_{out} = V_{in}$, an ideal gain-of-one amplifier stage. But for our voltage amplification stage (V_{as}) that drives the output stage, we need much more than unity gain. Common amplifier gains are around 26 to 30 dB, a gain of some 20 to 30 times. I like the lower value because it is better to have less gain in the power amp than to have a lot of unnecessary gain, only to turn down the volume control to get rid of it. It turns out we can use H.ec in voltage amplifiers quite easily if we insert an attenuator in the V_{out} sense leg, similar as we would do in a regular negative feedback circuit. We do that in **Figure 1b**. The sums are slightly different:

$V_c = (V_{out}/ß) - V_e$,
but still
$V_e = V_{in} - V_c$. .

Substitution and rearranging shows us that $V_{out}/V_{in} = 1/ß$. So, if we make ß, as is customary, from a simple resistive 1:20 voltage divider, we have now an amp with gain, linearised by error correction.

There is one other very important thing to note here. When we found that the open loop gain no longer is part of the amplifier transfer equation, we said that the gain of the amplifier block no longer has any bearing on the final result. That is true in theory, but not in practice. In the case of the power output stage, we said the gain is 'about 1'. A realistic value would be 0.98 at mid frequencies and light load, down to 0.95 at higher frequencies and higher loads. That means that the error correction circuit needs to add 0.02 to 0.05 times the signal level to the input to straighten out the amp. Intuitively we feel that it is advantageous to have only small signals in the error correction circuitry that helps it to work linear and with low distortion. But in the case of the V_{as}, if the forward gain block would have only a gain of 1, the error correction circuit would have to add 19 times the signal level, and it would be much more difficult to design simple circuits that could handle those levels with high linearity. So, what we would want is to make the open loop gain of the V_{as} amplifier block such that the signal levels in the error correction circuit are minimized. This will be the case when the open loop gain is as close as possible to the closed loop gain. Then, there will be quite small differences between the input of the actual amplifier and the scaled down output (by ß), and that small difference then is the error signal. This limits the signal levels in the error correction circuit, greatly relieving the burden on the H.ec loop. In other words, you set the V_{as} open loop gain as close as possible to the required amplifier closed loop gain. This of course is totally at odds with what you would do for a negative feedback amp. There, you would try to get the highest open loop gain you can get away with, stability wise, to have a lot of excess gain for the feedback loop to work with. Not so with H.ec, and a corollary to this is that your V_{as} can now be a very simple gain-of-20 amp.

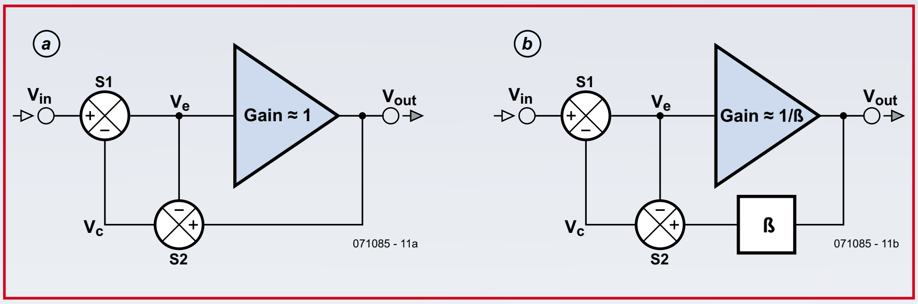


Figure 1. **Basic H.ec topology for gain-of-1 stage (a) and arbitrary gain stage (b).**

Voltage amplifier

The particular topology I chose is in **Figure 2**. It's very simple. U1 is a unity-gain buffer. V_{in} applied appears at the buffer output across R7. The output current through R7 comes from the supplies, of course, so we find a signal current V_{in}/R7 in the current mirrors formed by Q1 and Q3. The quiescent current for the buffer (I will tell you later which buffer type I used) happens to be about 7 mA. With an R7 value of 220 Ω, and a current of 14 mA peak-to-peak available, this buffer can handle a little over 3 V peak (about 2 V_{RMS}) before running out of class-A, which of course is good for linearity. With an amplifier gain of 20 that is enough to deliver 100 W in 8 Ω.

That same signal current in Q1 and Q3 is mirrored through Q2 and Q4, and flows through R16 to generate the output voltage. As a first approximation, because the same signal current flows through R7 and R16, and the signal across R7 is the same as V_{in}, the gain (open loop) of this circuit is simply R16/R7 which is then set to 20. So, this is our V_{as} stage. But in the discussion in Part 1 we said that the amplifier output stage needs to be driven by a low (and constant) source impedance (ideally zero) for the output stage H.ec to work; so we add a low output impedance emitter follower stage to the basic V_{as} stage (Q10, Q9). This emitter follower stage is also biased at about 7 mA. Because of D3, the voltage drop across R6 and R8 is about the same, so if we chose R6 = R8, the same current flowing through Q2 and Q4 will flow through Q10 and Q9. D3 and D4 also provide a measure of temperature stabilization to the emitter follower output stage bias current.

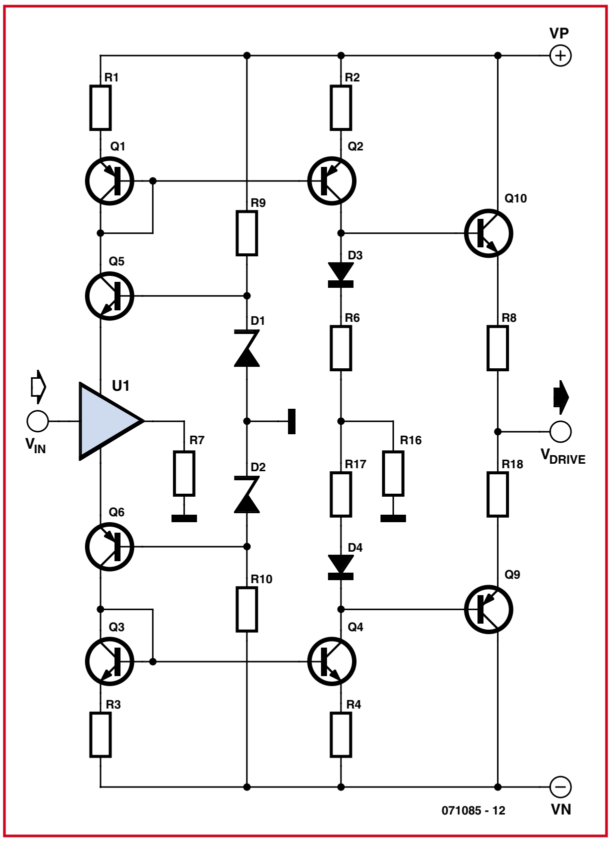


Figure 2. V_{as} basic circuit.

Now that we have the main gain block for the V_{as}, we enclose it in an error correction loop similarly as we did with the output stage: **Figure 3**. There are a few things to note here. Although both the ec sense and the ec generation resistors are given as '*R*', they are not equal. The sense resistance actually is the sum of resistor *R* plus the output resistance of the ß-network (R11//R12). It is the total resistance of R plus R11//R12 that determines the error current into the CCII. That same current generates the ec voltage when flowing through the left side *R*, and these voltages should be equal, so similarly, the left side *R* is actually the series resistance of the nominal *R* and the output resistance of whatever will drive the V_{as}. We'll revert to this issue later.

The second thing to note is that the gain of this amp is not strictly 1/ß. Terminal Y is a virtual earth point. To calculate the exact attenuation from V_{out} to the node R11, R12 and R, we need to account for the fact that for the attenuation, seen from the V_{as} output V_{drive}, *R* appears in parallel with R12. So, the attenuation, and thus the gain, is slightly higher than 1/ß. We need to consider both of these issues when we dimension the error correction sense and generation resistors. Just as with the output stage, we will use an AD844 for the ec circuit, while the buffer is used in the amplifier input stage to drive R7. The complete V_{as} circuit is shown in **Figure 4**.

What we haven't mentioned yet are the diodes D9, D12, D13 and D14. In Part 1 of this article we have discussed what would happen if we overdrive the amplifier. The positive feedback loop is regenerative and will continue to increase the input signal until stopped by some physical limit like the supply voltage or current or voltage limitations in the circuit. (We also saw in part 1 that, because of the lower open loop gain, overdrive can be expected to be less severe; but we still need to deal with it). In the V_{as} stage, this is taken care of by the four diodes across the error correction generation resistor R29 (Figure 4). When the amplifier is overdriven, the error correction current out of pin 5 of the AD844 CCII will increase considerably. This current will start to generate a large correction voltage across R29, to the point that the threshold voltage of the diodes is reached. At that point, the impedance of R29 collapses to just the dynamic diode impedance that is only a few tens of ohms. Further increases in the error correction current will not generate more error correction voltage and the positive feedback loop is broken. This makes the clipping clean, and recovery fast. But we run the risk that the diodes increase the distortion because they may already conduct a small current before the threshold, upsetting the error correction accuracy. It turns out that because of the very small error correction voltages across R29, this can be avoided. In **Figures 6 and 7** you see that if we would use a single pair of soft clipping diodes, the distortion starts to rise before maximum output. With the dual pairs, the difference is very small.

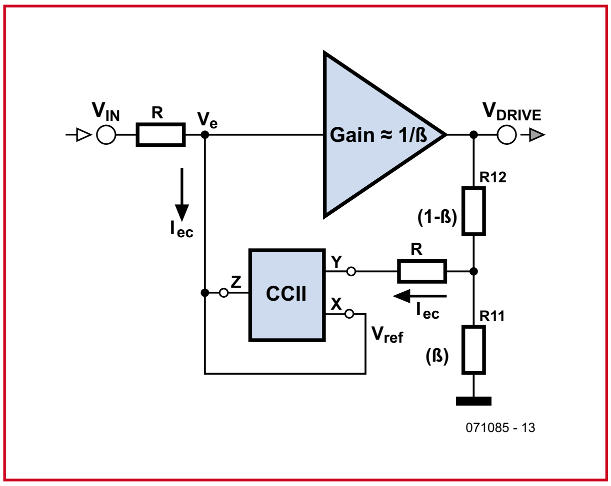


Figure 3. The CCII as the H.ec element for the V_{as} stage.

Figure 8 shows this effect from a different perspective. The soft clipping diodes for the negative signal part have been temporarily removed so only the positive signal is affected. You can see that without the diodes, clipping recovery is delayed (negative part), while with the diodes (positive part) there is only a hint of delay.

Buffer stage and DC offset

All that is needed now for a complete amplifier is the input buffer and the DC offset servo. This is shown in **Figure 5**. Just as with the output stage, we need to drive the V_{as} input resistor, which develops the ec voltage (R29), with a low impedance source. You guessed it: we will again call upon the open loop buffer in an AD844 to drive the V_{as} from V_{in}. The signal enters the buffer in U2 through R51 and R33 at pin 5 and exits at pin 6.

The enemy of your loudspeakers (and the amp as well) is DC offset at the output terminal. Most amplifiers have some sort of means to avoid that. In this amplifier, the output stage doesn't need any additional measures: the error correction ideally duplicates the driving voltage (from the V_{as})

to the output terminal, with zero offset, although there will still be some offset from the error-correcting AD844, which will generate a small DC offset of a few millivolts. The only requirement is that the V_{as} has negligible DC offset. The V_{as} however has higher gain and will amplify its own AD844 offset with that gain. I decided to implement a DC servo to keep the V_{as} offset under control. The servo uses a low offset opamp, a TL051CP. We will use the uncommitted current conveyor in that input AD844 (U2, Figure 5) to couple the servo signal to the amplifier.

The way this works is as follows. Remember that whatever current flows in or out of the low impedance input pin 2, also flows (in opposite direction) out of or into pin 5. We also know that the voltage at pins 2 and 3 will track accurately. When we couple the servo signal to the reference input pin 3, it will cause a current in R50 to keep pin 2 at the same level. That same current will flow through R33 in R49 (and R1 if the source is DC coupled), and in this way the offset correction will be added to V_{in}. R49 assures that this current, which essentially is DC, can flow even if the V_{in} comes from a coupling capacitor. Finally, this input buffer and servo amp have their own ±15 V supply from two zener diodes, D5 and D6. With this circuit, composite offset of the whole amp is just a few millivolts.

Protection circuitry

There is a separate protection system for this amplifier that protects the speakers against DC output as well as the output devices against overload. It also provides delayed switch-on and immediate switch-off. This is described in a separate article in this issue.

Power supply

The power supply for this amplifier should deliver about 2 × 44 V_{DC}. Although the output devices are rated for higher voltages, it is not advisable to increase the supply in trying to get more output power. The allowed dissipation at higher V_{ce} is much less than the rated DC dissipation due to secondary breakdown limitations of the SOA (Safe Operation Area). With loads that dip substantially below 4 Ω, even temporarily, the SOA may be exceeded and an output Darlington destroyed (or the protection activated). The supply

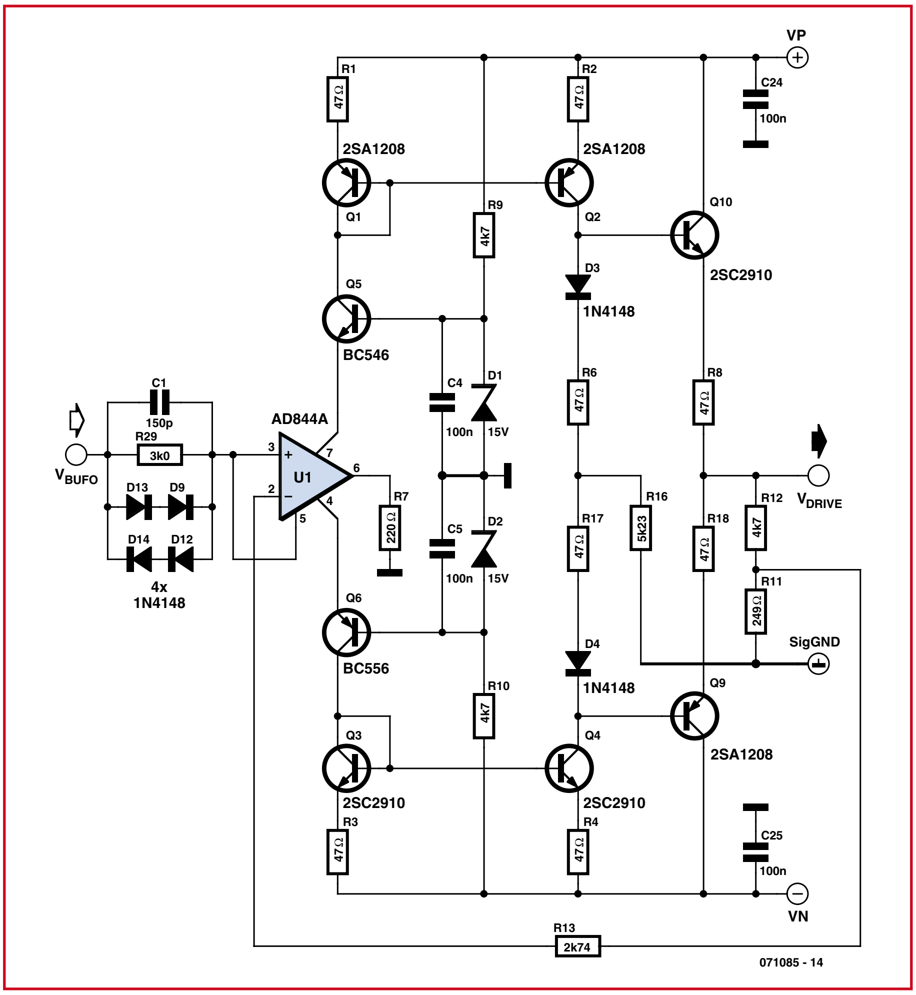


Figure 4. Full circuit of the H.ec V_{as} stage.

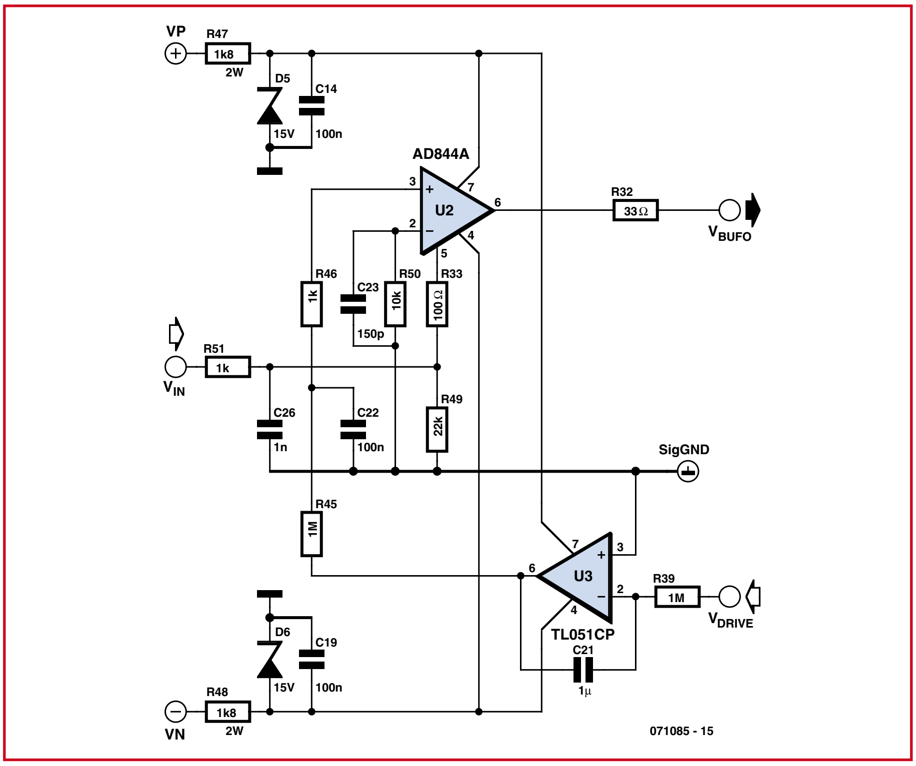


Figure 5. Input buffer and offset servo circuit to drive the V_{as} stage.

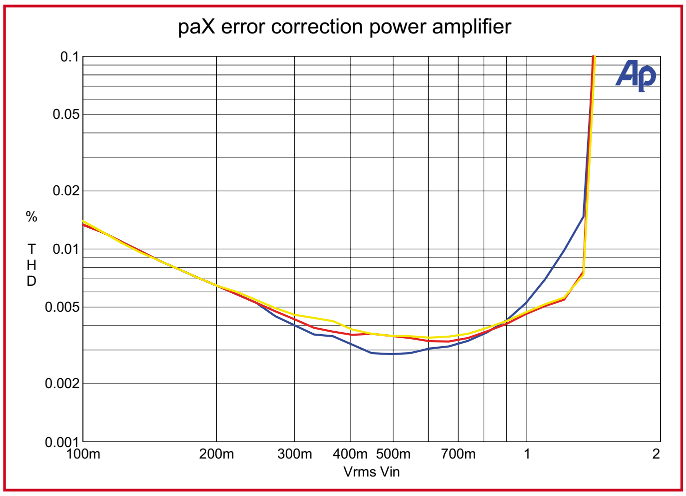


Figure 6. Amplifier distortion as a function of output level, with single diode (blue), dual diode (red) and without soft-clipper diodes (yellow).

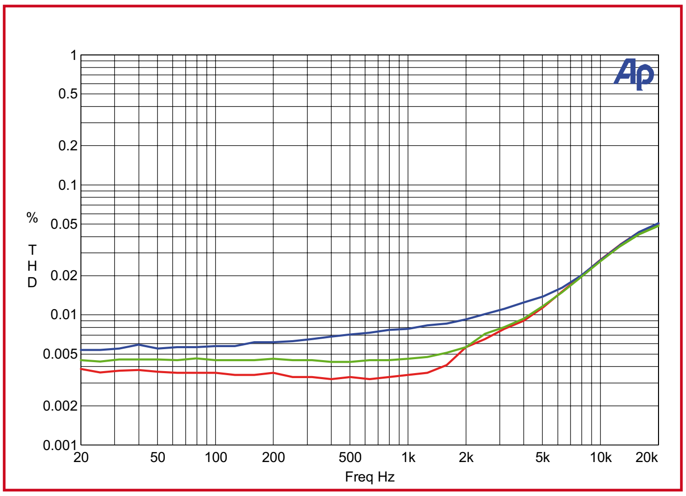


Figure 7. Amplifier distortion vs. frequency at 50 W in 8 Ω, with single diode soft clipper (blue), dual diode soft clipper (green), no soft clipper (red).

for the error correction circuit in the output stage is bootstrapped from the output; that part of the circuit can actually drive the output devices beyond the supply voltage. Consequently, it is the V_{as} that determines how close the output can get to the supply rails. Since the V_{as} will clip first, there is no clipping overdrive and overdrive delay in the output stage. The output can swing within a few volts of the supply, which is better than in most amplifiers (unless separate, higher voltage, V_{as} supplies are used).

The power supply for this amplifier is uncritical. The error correction not only corrects internal amplifier non-linearities, but also any power supply ripple or noise that makes it into the circuits. (The supplies for the error correction AD844's is stabilized separately with zener diodes). Therefore, a classic rectifier-and-reservoir capacitor supply delivering 2 × 44 V_{DC} under load is sufficient for about 100 W in 8 Ω, 200 W in 4 Ω. The power supply circuit details are given in **Figures 9 and 10**. For a stereo version, a 300 or 400 VA transformer should be sufficient; after all, you will not drive both channels at full power for a long period (except maybe on the test bench). You can use the common transformer with a centre-tapped secondary, but other configurations can also be used. One nice option for a stereo amp is to use two completely separated supplies, each with a 250 or 300 VA transformer. That would make it easier to maintain strict star point grounding.

It is important to get the grounding right. Ground currents back to the supply from the speaker, as well as from the reservoir electrolytics, can be quite large and have all kinds of ripple and noise. Such ground currents generate voltages across the ground return wiring. If the ground for the signal is connected to this ground wire at another point, you have effectively created a small ripple signal that appears in series with the input signal. This may seem far fetched, but with very low distortion and very clean amplifiers, even a few mV of these noise signals can be enough to ruin the linearity and distortion figures of an otherwise very good amplifier. Usually one tries to prevent this by using a star ground: All ground returns come together at a single point, and no signal return runs through the same ground wire with another return loop. If you look at the amplifier PCB layout you see that the power connections get to a central star point. On the PCB itself, care has been taken to do the same. There are two or three separate traces that bring the returns for the regulator zener diodes and the decoupling capacitors to the same point. The signal returns from the input network, the gain setting resistors R7, R16 and the error attenuation network R11, R12 are also brought to this point separately. All return wires from the supply, the transformer and the speaker are returned to the star ground. The signal grounds in the amplifier are then returned to this point via a low-value resistor R28, which is then by definition the 'clean' ground point (pad J1 on the PCB is the clean ground and should be used as 'ground' for measurements as well). Any error voltages generated by ripple and pulsating currents in the ground wires cannot end up in the signal, except through radiation. This in turn we can minimize by making all high-current wires short and as far away from sensitive signal areas as possible.

Finally, the rectifier diodes should be types that recover quickly from voltage reversal when switching off, and do so 'softly', that is, without very sharp current steps. Diodes that take a long time to reverse themselves and in the process generate sharp current steps may cause high-

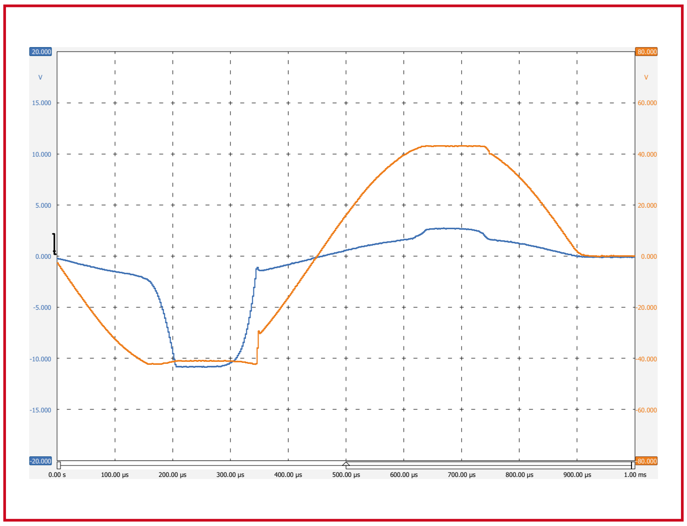


Figure 8. Error correction current (blue) and amplifier output clipping (amber) with soft clipper (positive signal) and without soft clipper (negative signal).

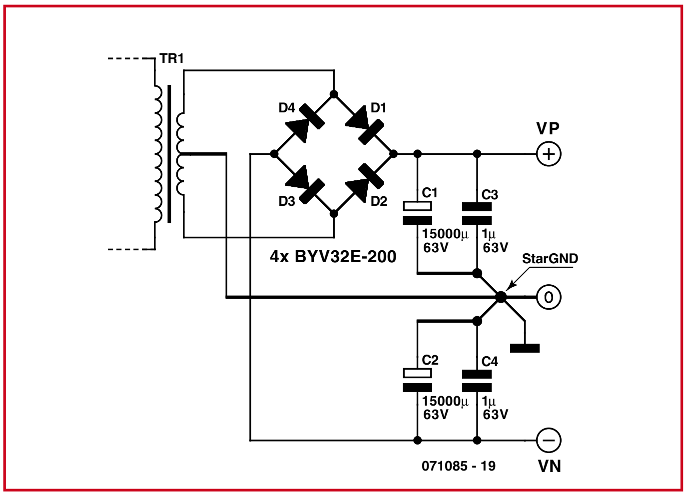


Figure 9. DC power supply. Diodes are paralleled, dual, fast, soft recovery 3-pin TO220 types.

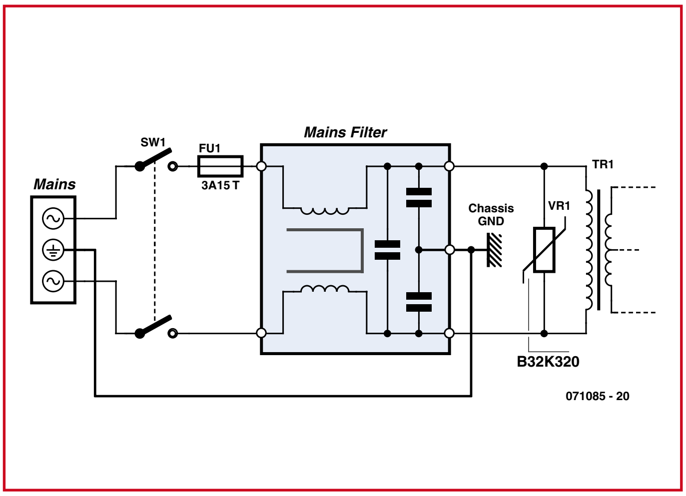


Figure 10. Mains wiring for the power supply, mains filter, overvoltage clamp and fuse.

frequency noise that is difficult to filter out. Fast, soft recovery types don't need capacitors or snubbers; indeed, such capacitors would only increase the transmission of mains-borne noise to the amplifier. My recommendation is to use Philips BYV32E-200 diodes. These are TO220 dual types with a common cathode; the two diodes should be paralleled. They have a relatively low threshold voltage, and are quite inexpensive. They don't need to be heatsinked so they can be put on a PCB in free air. For the reservoir capacitors, a minimum of 15,000 µF should be used per supply polarity. 63 V rating is adequate.

A mains filter as shown in **Figure 10** should be used to keep out high frequency noise and switching pulses riding on the mains. Good mains filters are not cheap but worthwhile; use a type with at least 6 A rating. Ground the filter ground lug as well as the mains safety ground wire to the chassis only. Use a slow-blow fuse of 3.15 A for a stereo version, larger if you use larger reservoir capacitors. A 275 V_{AC} varistor clamps any high-level pulses that make it out of the filter.

Conclusion

So, there you have it, a complete, high quality yet simple error correction power amplifier. The parts list shows all components for one (mono) amplifier. Note that the values of C11, C12, C17 and C18 (output stage) were given as 330 µF in Part I but 470 µF fits on the PCB so these should be used. A separate *Construction Guide* is available as free download from the Elektor website as archive file # **071085-w.zip**.

Although harmonic distortion measurements do not always correlate with sound quality, they do give an indication of linearity and behaviour of an amplifier. Therefore, a few performance curves are given in Figures 6 and 7. If you work in a step-by-step fashion as described in the Construction Guide, checking your work after each major part, it will help to avoid errors and, if errors are made, to quickly isolate and fix them. Also check on my website for any last-minute information, additions or corrections.

This is not a very difficult project but it provides you with an excellent amplifier, which reproduces your source music faithfully, adding nothing, taking nothing away. This amplifier is stable and will happily drive a wide range of different speakers. In short, an amplifier that will let you enjoy your music for many years to come!

(071085-I)

Additional information

www.linearaudio.nl

Availability of construction kits:
www.pilghamaudio.com