T-reg revised – MOSFET-based high-voltage regulators for tube amps.

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In 2009 I designed a high-voltage regulator for tube equipment [1, 2]. Originally based on a series tube, I also gave circuit details for use with an enhancement mode MOSFET. However, the readily available enhancement mode MOSFETs like the DN2540 have limited short term current capacity; they do not have a short-term current capability larger than their continuous rating. Therefore, although sufficient for normal use they sometimes shorted out when a live regulator was connected to a (capacitive) load. Also, readers requested a simpler, stand-alone regulator not based on the motherboard approach and without the original switch-on delay circuit.
I redesigned the circuit for use with a more common depletion mode MOSFET. The circuit has slightly more parts but has a performance that is similar to the original design. The output voltage can still be set by a single resistor value.
For those of you who need a negative high-voltage regulator for biasing applications: the same circuit can also be used for a negative voltage version with pretty much the same performance.

The original design

The original design is simplicity itself (**fig 1**) [1,2]. This is possible because the control part of the circuit uses an auxiliary power supply that 'floats' on top of the high voltage output. Since the unit was originally based on a series tube, the tube heater winding could conveniently be used as the floating supply. The circuit is very simple: you generate a reference voltage with current source Q1 into R3. Then you build a difference amplifier with Q3 and Q2. One side (B-Q3) gets the reference voltage, and the other side (B-Q2) gets the actual output voltage. If the difference between ref and Vout is more or less than the Vbe of Q2 + Q3, Vgrid will be driven up or down in the right direction to restore the correct Vout and thus high voltage regulation is obtained.

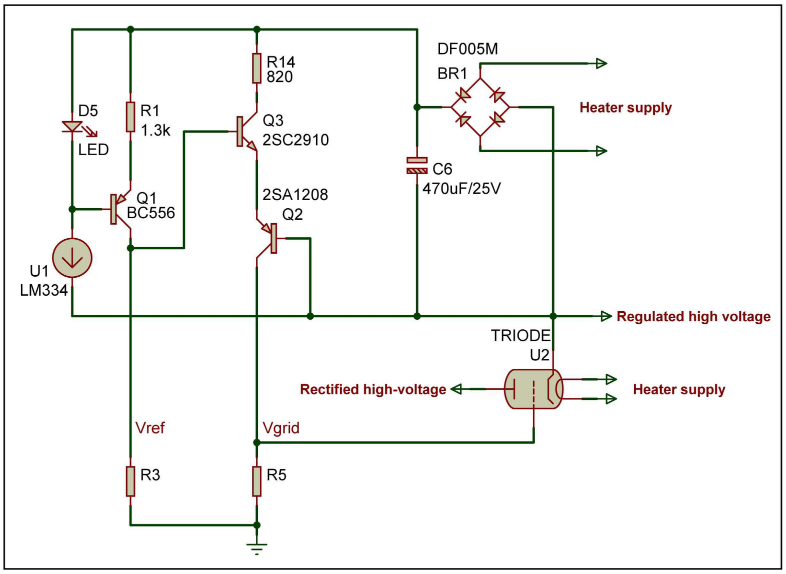

Fig 1 – original tube-based regulator design

For a more compact and less dissipative version you can replace the tube with a bipolar transistor or a MOSFET. One variant I build was based on an enhancement mode DN2540 or equivalent, because it reacts to its gate voltage just as a tube to its grid voltage: for the DN2540, the gate must be somewhat negative with respect to the source to obtain conduction. That worked very well, but there was a downside to the DN2540. Most MOSFETs have a pulse current capability many times their continuous current capability. The DN2540 has a 500mA continuous rating but also a 500mA pulse rating! So if, for instance, you connected a live regulator with a DN2540 to a load with an additional power supply capacitor, the near-short of an uncharged capacitor immediately destroys the DN2540. At the time, I could not find a similar but more robust high-voltage enhancement-mode MOSFET.
But if I could use a more rugged depletion device like the IRF 740 (400V, 10A continuously and 40A surge) this problem would vanish. However, such a device requires a gate voltage *above* the source voltage. In figure 1, that would translate to the collector voltage of Q2 having to rise above the regulated output voltage which obviously won't work.

Another issue I wanted to improve was the accuracy of setting the output voltage. As you can see in figure 1, this accuracy depends on the LED threshold voltage as well as the Vbe of Q1; the design values were for a reference current of nominally 1mA. In practice, that accuracy was not very good and it was almost always necessary to adjust either R1 or R3 to get the required Vout.

Lastly, I wanted to improve the supply for the control circuit. In figure 1 it's just a rectifier off the heater voltage, and it's very hard to avoid mains breakthrough in the output voltage. I had to revise this anyway because with the depletion IRF740-type pass device the control circuit needs more head room.

The improved design

This article describes the new circuit that allows the use of devices like the IRF740, making it virtually indestructible, as well as the other enhancements.

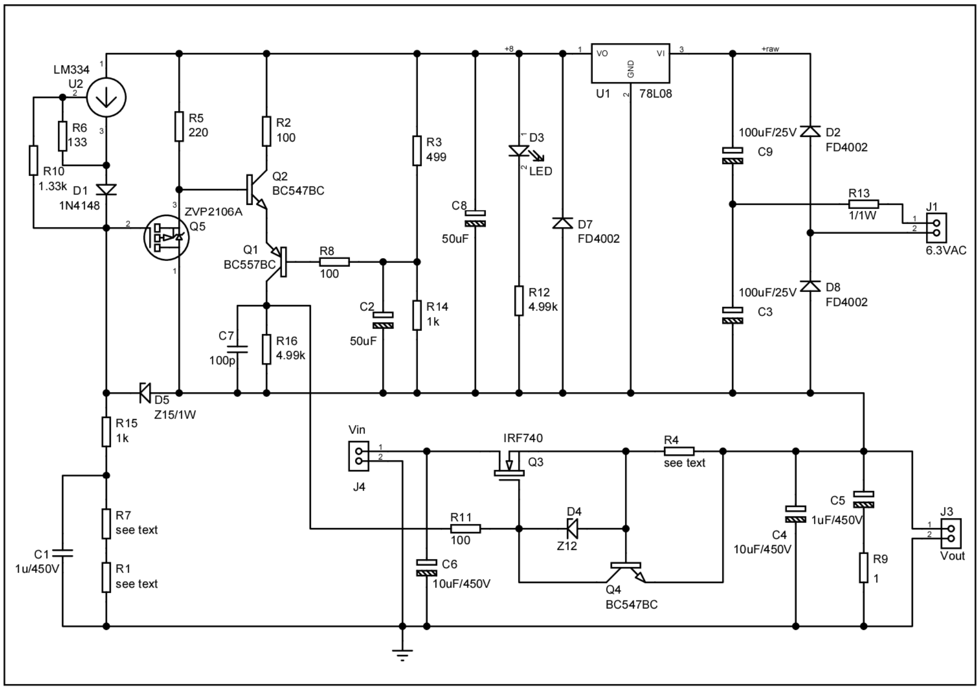

Fig 2: the new voltage regulator circuit

The new circuit is shown in **fig. 2**. You surely recognize the basic circuit of fig 1, with the MOSFET replacing the tube. A major change is that the output voltage is not connected to the base of the error amplifier Q2 but has added to it a voltage set by the divider R3/R14, which is 5.4V nominal. So the collector of Q2 which drives the gate of pass device Q4 can now rise almost 5V above Vout (which is also Vsource), which allows the use of a depletion mode MOSFET. Also, this allows loading Q2's collector - which drives the pass device - to Vout instead of to ground with R16, which deletes one high-voltage resistor (R5 in fig 1) from the BoM. C2 rolls off the loop gain at high frequencies for stability. The inaccurate and temperature dependent transistor/LED current source has been replaced by an LM334 programmable current source, with some additional parts around it. These compensate for the temperature coefficient of the LM334 stabilizing the reference voltage against temperature changes. Furthermore, the reference voltage is buffered with a P-channel JFET Q1. The differential pair Q2-Q3 has limited gain, and in the original version, the increase in base current for Q3 with increased load caused the output voltage to slightly drop which, of course, looks like an output resistance. With the buffer JFET the reference current cannot be syphoned off by Q3's base anymore.

There is also a simple but effective current limit option with Q5 – not that the pass device really needs it, but you may want to use it for protection of the amplifier connected to this supply. The current limit, of course, starts to come into effect with about 0.6V across R4; with a 3.9 Ω nominal resistor this happens at about 150mA load current. In fact, the whole supply is pretty much short-circuit proof (yes I tried it) due to the inclusion of D1. In normal use, D1 doesn't conduct. When current limiting starts, the output is drawn down and then D1 starts to conduct and draws down the reference also, insuring that voltage levels in the control section remain safe within limits. R15 is necessary to avoid blowing up D5 when it tries to empty C1 into a short. Of course, prolonged overload may damage the pass device – 150mA short-circuit current with a 400V DC input puts 60W into Q4 which will probably overheat eventually, so a fuse for long-term protection is prudent.

Finally, I split the reference resistors in two equal, half-value units (R1, R7), because as was pointed out to me, a single resistor might not be happy with 400+ volts between its terminals even if the dissipation is within specs. High-voltage resistors do exist but are not common and thus more expensive.

Control circuit supply
In the tube pass device version it was convenient to use the heater supply for the tube pass device for the control circuit (figure 1 again). We now no longer need to feed a heater, but we still need to feed the control circuit. In fact, because the collector (and thus the other terminals) of Q2 must be some 3-4V above Vout to be able to adequately drive the gate of Q4, the control circuit supply must be higher, especially since I decided to regulate it with a small TO92 8V regulator which needs a couple of volts dropout headroom too (U1). To make sure it still runs off a spare 6.3V heater winding, D5, D7, C2 and C3 implement a standard voltage doubler. The control circuit supply floats on top of the high voltage output so the transformer supplying it must be able to withstand Vout between the primary and secondary. Many tube power transformers have an additional winding for this purpose. Otherwise, use a small and cheap separate heater transformer – a standard 6.3VAC should do at any current capacity, as the control supply needs less than 10mA.

Performance.
Figures 3 and 4 show the supply noise and output impedance over the audio band. Figure 3 shows that the broadband noise is down to about 1 uV, with up to 50uV mains related harmonics. I split the Zout graph in two parts; the lower frequency part from 20Hz to 1kHz shows that the 'real' output impedance at lower frequencies is 'hidden' because the mains harmonics interfere with the measurements. Only at the extreme of the audio band does the output show the familiar rise but it is still very low. The overall performance is quite respectable for a high-voltage 'tube' supply.

The specs can be expected to vary somewhat with the pass device used. The IRF740 has a rather high Gm of almost 6 Siemens. When selecting a pass device, you'd first select for the voltage required (plus a safety margin) then for smallest input capacitance for highest response speed, and highest Gm. Selecting a device with lowest current capability compatible with the application also improves most performance figures compared to one with much higher current capability; the IRF740 I used because I had it is probably not optimal.

The line ripple rejection is better than 90dB. That means if you have say 10V ripple on the input voltage, the output ripple will be reduced to less than 300uV, which I think is respectable enough.

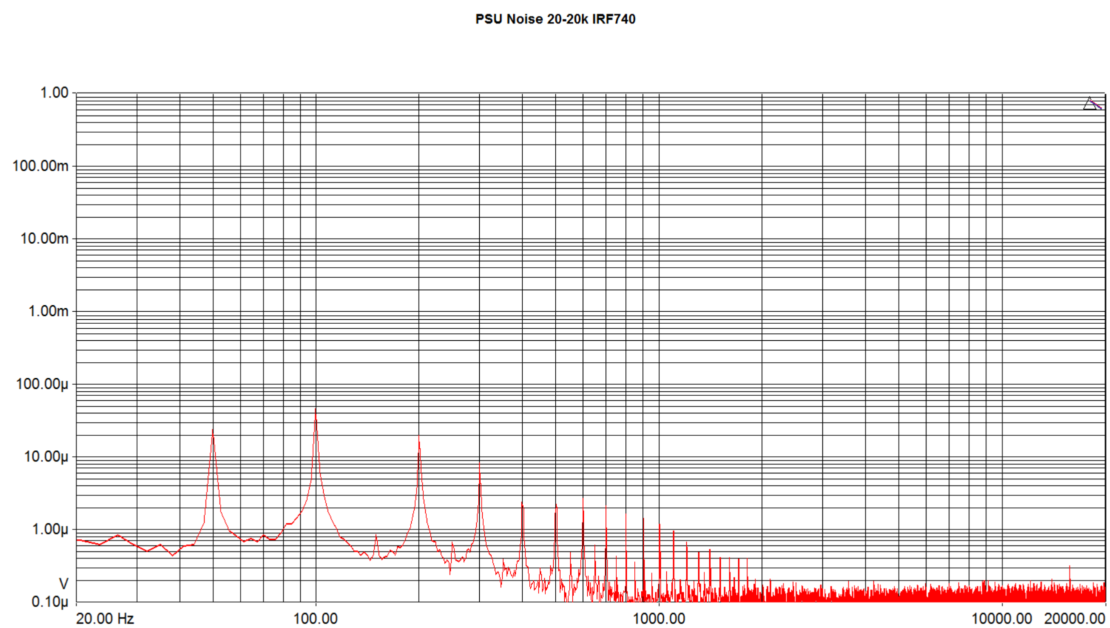

Fig 3 – Output noise over frequency is dominated by minuscule mains harmonics below 1kHz.

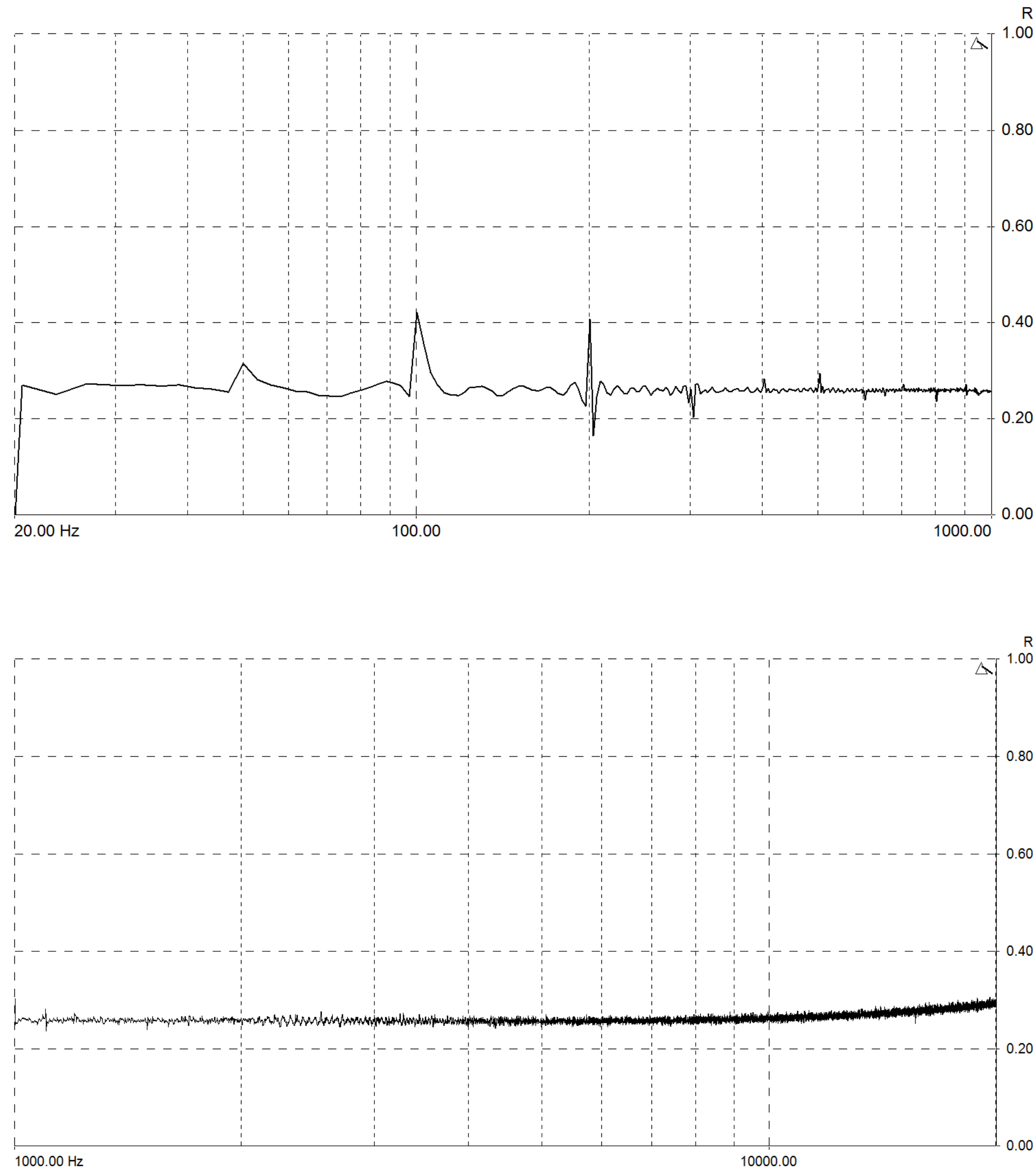

Fig 4 – Output impedance versus frequency; 20 Hz to 1 kHz (top); 1 kHz to 20kHz (bottom).

Customization.

Customization is *the* word here. The input and output voltage are limited by the pass device and capacitors used – there is no inherent circuit limit to it. The IRF740 can handle at most 400V, but higher voltage high speed devices up to 1000V or more are readily available. These generally have higher input capacitances so high frequency performance may be slightly lower and/or the compensation capacitor C7 may need adjustment. You should check the output for oscillations with a 'scope, and if resent you can increase C7. I tested with up to 1000pF with the only effect being that the rise in output impedance at higher frequencies becomes a bit more pronounced. The other limiting factors are the voltage rating of the high-voltage capacitors C1, C4, C5 and C6. These (and the MOSFET) should be rated to at least the maximum raw input high voltage under no-load conditions.

The output voltage is set by the values of R1+R7, at nominally 1V per kΩ. This is reasonable accurate with the new circuit to within a few percent.

There is another interesting option related to the use of these regulators in a system. Since the control section, with its own supply voltage, is floating on top of the regulated output and is not referenced to ground, you can ground either output terminal. For example, if you ground the 'Vout' terminal of the regulator, you can take off a regulated *negative* (bias) voltage from the 'Gnd' node on J3.

A note of warning: Of course this only works when the transformer secondary supplying the regulator is also fully floating and not connected to ground anywhere. If you mix positive regulators and these 'flipped' negative regulators in your system, be sure that each one has a dedicated secondary winding and rectifiers from the power transformer to avoid short-circuited rectifiers.
You can't supply two regulators from a center tapped secondary with the 'flipped' configuration because of the common center tap.

If you do use the 'flipped' configuration, the control supply is now grounded on one side, and you can, if available, take it from a suitable ground-referenced DC voltage of minimum 12VDC, with the obvious changes to the voltage doubler. See **fig 5** for this setup.

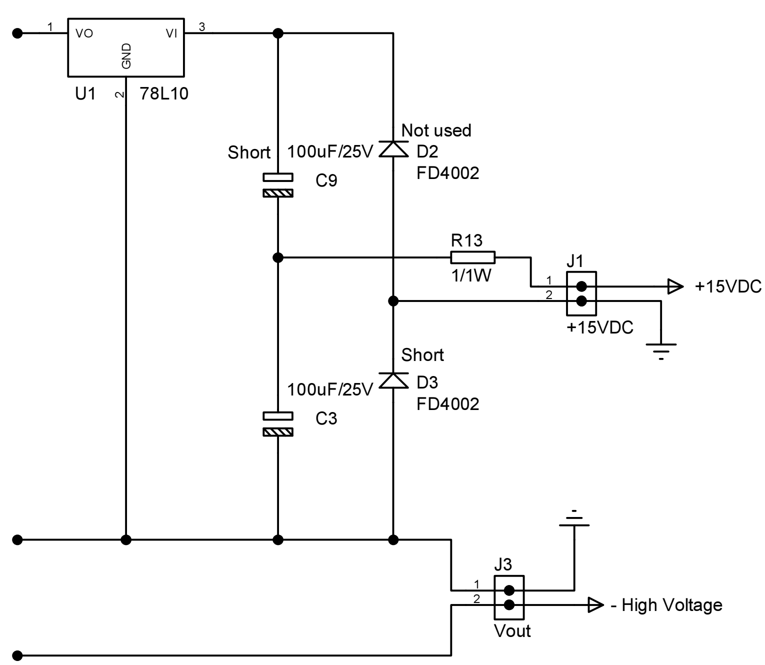

Fig 5 – use of regulator for negative output voltage and ground-referenced control power supply

Construction. Before starting construction, a word of caution is in order. This supply contains points with lethal voltages, possibly including the heat sink for the pass device. *You* are responsible for your own safety, not me, not the publisher. If you are not comfortable with high voltage stuff, get help from someone who is. Double check that the high-voltage input is disconnected or turned off before doing any work on the board. Discharge the high-voltage capacitors with a 1k resistor before working on the board. If you really must work on a live board, make it a practice to keep one hand in your pocket (and take off your watch!) when touching live boards with a meter probe or anything at all to avoid accidental body currents. Even when switched off, the high-voltage capacitors may still have a dangerous charge. Discharge them; even if it doesn't kill you, many an arm has been broken by an involuntary violent jerk smashing it into an unmoving object.

Construction is straight-forward when using the PCB I designed. **Fig 6** shows the component stuffing guide for the regulator. It is best to start with the small parts on the board like resistors, diodes, transistors and screw-headers, leaving the larger caps and the heat sink for last. Note that diodes D2, D3 and D7 are SMD parts, located on the solder side of the PCB. The MOSFET is positioned at the board edge so if you want you can leave off the heat sink and mount the MOSFET to the chassis of your amp. The specified heat sink comes with pins that can be soldered to the bottom of the board. Unless you use insulating mounting gear like an insulating shoulder washer and a thermal sheet or mica part with grease to insulate the MOSFET, the heat sink will carry the live output high voltage! In case you mount the MOSFET directly on the chassis or separate heatsink, such insulating gear is mandatory, of course; doubly double check that the device is properly insulated before powering up!

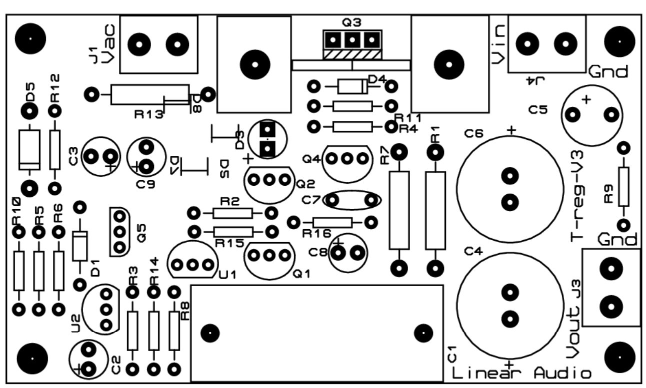

Fig 6 – Regulator component stuffing guide

Category	Quantity	References	Value
Capacitors	1	C1	1uF/450V film
	2	C2,C8	50uF
	2	C3,C9	100uF/25V
	2	C4,C6	10uF/450V
	1	C5	1uF/450V
	1	C7	100p
Resistors	1	R1	see text
	3	R2,R8,R11	100
	1	R3	499
	2	R4,R7	see text
	1	R5	220
	1	R6	133
	1	R9	1
	1	R10	1.33k
	1	R12	4.99k
	1	R13	1/1W
	1	R14	1k
	1	R15	1k
	1	R16	4.99k
ICs	1	U1	78L08 TO-92
	1	U2	LM334 TO-92
Transistors	1	Q1	BC557BC or eq.
	2	Q2,Q4	BC547BC or eq.
	1	Q3	IRF740
	1	Q5	ZVP2106A or eq.
Diodes	1	D1	1N4148
	2	D2,D8	FM4002
	1	D3	LED 0.1"pitch
	1	D4	Z12/0.5W
	1	D5	Z15/1W
	1	D7	FD4002
Miscellaneous	1	J1	6.3VAC connector
	1	J3	Vout connector
	1	J4	Vin connector

Table 1 – Bill of materials

References:

1 – *A high-voltage regulator for valve amps, Elektor issue 387, March 2009*

2 – *T-reg: A high-voltage regulator for tube amps, AudioXpress issue 4/2009*