Triodes at Low Voltages

Linear amplifiers under starved conditions.

By Merlin Blencowe

Introduction:

Traditionally, the term 'starved amplifier' was once synonymous with a pentode operating with a very-low screen voltage, but still using a conventional high-voltage anode supply. It was found that under optimum conditions such circuits could provide extremely high gain –even more than at high voltages– and some engineers exploited this property for DC instrumentation amplifiers. With so much raw gain available, plenty of negative feedback could be used.[1]

However, I do not intend to discuss starved pentodes; plenty of information on this already exists.[2,3] Instead, I will examine the use of ordinary triodes operating under *really* starved conditions, that is, below 12V. I have chosen this figure as it is the highest voltage that most voltage-regulated wall warts / mains adapters will provide. It is also widely acknowledged that linear amplification is practically impossible under such conditions but, as I hope to demonstrate, this is not necessarily true.

Anode characteristics:

Data sheets do not provide any useful information for very low-voltage operation, and SPICE models are also useless. In fact, **fig. 1** should give an idea of just how far off the map we are venturing! Therefore, I decided to measure the anode characteristics of four popular valve types at anode voltages up to 10V (because my oscilloscope conveniently has ten horizontal divisions). I also measured the grid current, the significance of which will become clear in due course.

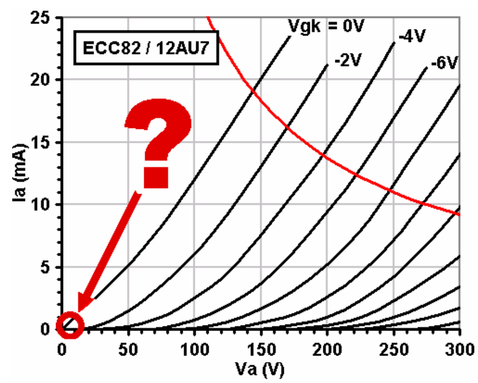

Fig. 1: Sub-12V operation is well off the beaten track!

I found that matching between triodes in the same bottle is generally fair; almost as good as you would expect for ordinary high-voltage operation, but variation between different samples of the same valve type is much wider, particularly with the ECC81 and ECC83 where anode resistance (r_a) can vary by as much as ±50% around the average value. However, this variation is not so wide that it cannot be accommodated with variable-bias circuits, as shown later.

Fig. 2 shows the anode characteristics I obtained. These were produced by measuring ten random samples of each valve type (of varying makers and provenance), and then averaged the results. Although the shape of the curves is very different from the ones we expect to see at high voltages, the basic 'flavour' of each valve type still remains. For example, the ECC88 shows the best linearity, highest g_m and lowest r_a. The ECC83 has high μ and the highest r_a, while the ECC81 also has high μ but lower r_a, similar to that of the ECC82.

At first we might expect the ECC88 to be the best choice for fooling around at low voltages, as it appears to offer the highest gain and best linearity. Indeed, it can work very well in a hybrid circuit. However, for reasons which will become obvious, the ECC82 is the valve of choice, so I used this for most of my test circuits.

Grid current:

Fig. 3 shows the average grid current for the same valves, and the results are not surprising. Grid current generally increases with g_m because it demands close grid-cathode spacing. The ECC82 is an exception as it has a coarsely wound grid (low μ), so does not attract many electrons despite its close grid-cathode spacing. The Achilles' heel of the otherwise impressive ECC88 is that it draws twice as much grid current as the ECC81, and about eight times more than the ECC82 or ECC83!

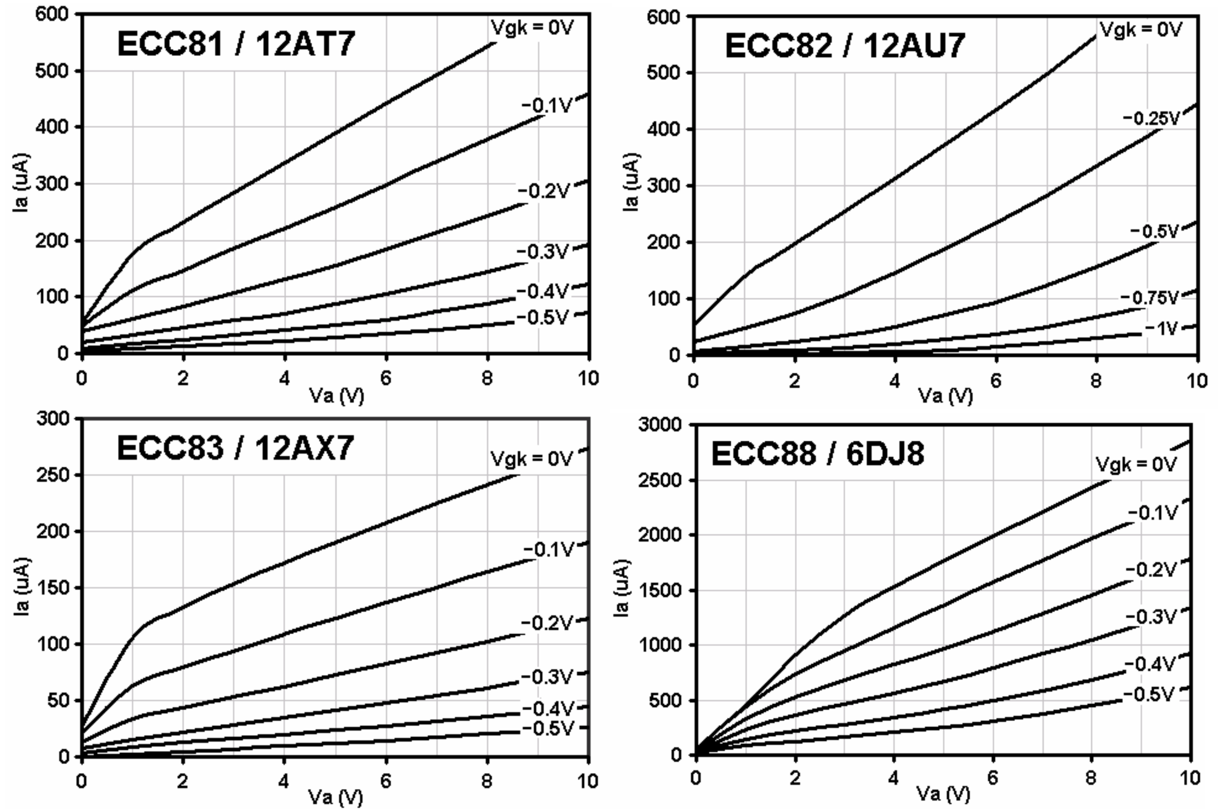

Fig. 2: Starved anode characteristics of some popular triodes.

Grid current is what really matters in starved amplifier design, because we have no option but to operate with very little grid bias in the region where grid current cannot be avoided.[4] When working at high voltages we don't normally worry about this, and the input resistance of the grid is assumed to be infinite, but this is emphatically not the case now we are stuck in the grid current region.

The inverse of the gradient of the grid-current curve is the input resistance of the grid, and at a bias voltage of about –0.25V it is ~20kΩ for an ECC82 or ECC83, while for the ECC81 it is ~7kΩ and for the ECC88 it is a mere 3.6kΩ! As the grid is driven more positive the input resistance drops even more. For this reason, starved circuits will nearly always need to be driven from low source impedances.

Strictly, these curves only apply to an anode voltage of 12V. At lower anode voltages the grid current will increase, since the anode becomes less effective at attracting electrons towards itself and away from the grid. Fortunately, however, the variation is negligible for anode voltages between about 3V and 15V, at least in this region of interest.

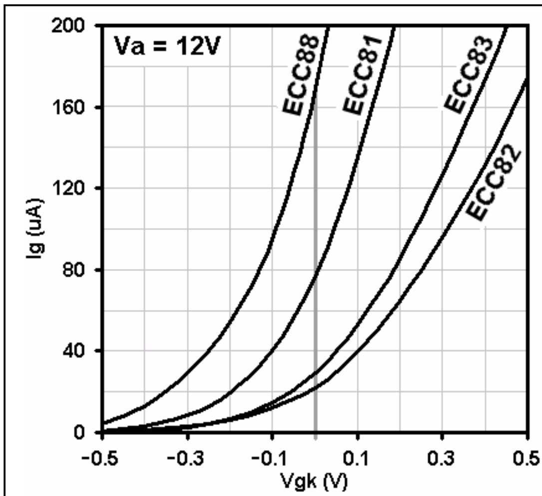

Fig. 3: Average grid-current characteristics for some popular triodes.

Out of the four valve types tested the ECC82 was the most favourable because it has the lowest grid current, good consistency between different samples, and it is also the cheapest of the bunch (at least where I live). Although it has the lowest μ of the lot, this makes it a lot less fiddly to bias than the others, and with so little voltage swing available we probably don't need oodles of gain anyway.

Because we now have to contend with grid current, we need to treat the valve more like a transistor and bias it by manipulating the grid voltage; ordinary cathode biasing is no longer a convenient option. Instead, the three most practical biasing methods are:

- Drive the grid directly from a low-impedance DC source (e.g., opamp).
- Traditional grid-leak biasing.
- Pull-up grid-leak biasing.

These methods are explored below.

Hybrid circuits:

Fig. 4 shows an example circuit that uses an opamp to drive the grid. Since the opamp cannot swing its output all the way to ground, a cathode resistor is added so that the working cathode voltage will be about 3V, and the grid voltage just under this.

By varying the trimpot the DC output of the opamp –and therefore the grid bias– can be altered to suit different valves, allowing the optimum working conditions to be found quite easily. The opamp could be configured for more than unity gain, of course.

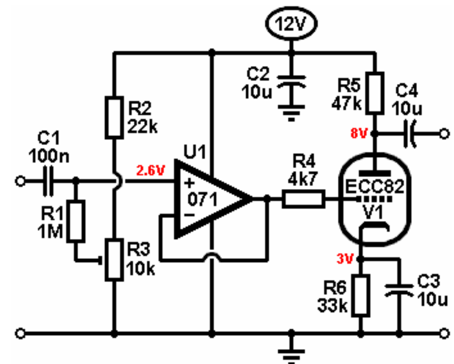

Fig. 4: An opamp used to buffer the low impedance grid.

The grid stopper R4 may need some explaining, as its job is very specific. Without this resistor the distortion of the circuit is what you would expect from a triode: mainly 2nd and 4th harmonic, with some 3rd and higher. However, by allowing the non-linear grid current to flow through a grid stopper, the signal voltage appearing on the grid will be pre-distorted or compressed on the positive side. The valve then amplifies this signal and distorts it yet again, but this time on the opposite side, so the final output signal ends up being *less* distorted than before the resistor was added! The price paid for this is a reduction in gain, since the grid stopper forms a potential divider with the input resistance of the grid.

The value of grid stopper that optimises this distortion cancellation must be found by experimentation. I found 4.7kΩ to be about right for the ECC82, and was still pretty close with the ECC81/3. Too high a value tends to pre-distort the signal too much and shifts the harmonic signature of the circuit from mainly even-order to mainly odd-order. (Music makers might want to exploit this fact!).

The voltage gain of this circuit was 7.5 with an ECC82, and the maximum output before visible distortion on a triangle wave was 1.5Vp-p. At 4Vp-p the THD exceeded 3%.

The output impedance of the previous circuit was high, around 20kΩ, but it could be buffered with another opamp. This opens up the possibility for bootstrapping the anode resistor, as shown in **fig. 5**. The anode load has been split into two parts and the output of the opamp is coupled to the junction via a capacitor. This magnifies the effective value of R6, making it look like several meg-ohms, and by doing this the current through the triode becomes constant (the load line becomes horizontal) and the gain of the stage becomes equal to the µ of the triode. What's more, since the anode current is now constant and µ doesn't vary much, distortion generated by the valve is reduced and we no longer need a grid stopper for distortion cancellation (unless we deliberately want to add distortion). A small value has been left in for good measure though, mainly to isolate the opamp from stray capacitance.

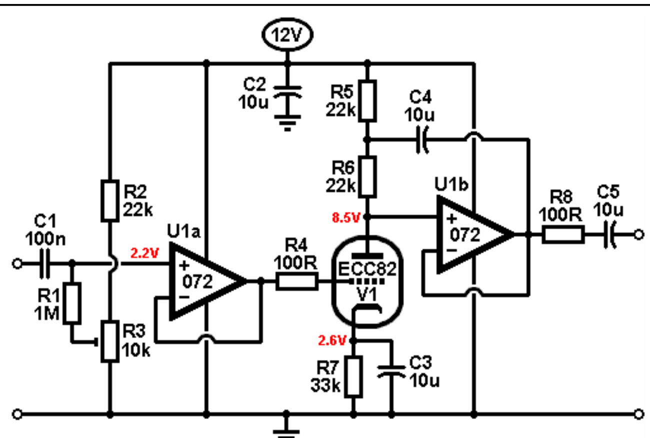

Fig. 5: A second opamp buffers the output and also bootstraps R6, for higher gain and better linearity.

Thanks to bootstrapping the gain of this circuit jumped to 15 with an ECC82, or 35 with an ECC81. The distortion at 4Vp-p output was too low for me to detect with the FFT function on my oscilloscope! Thanks to the low gain inherent with starved triode design, and the freedom to use large coupling capacitances, the -1dB bandwidth of all the circuits I tried was greater than 10Hz-100kHz.

However, some readers will be quick to point out that, as far as linear amplification goes, using opamps to support the valve makes little sense; after all, we could simply build an opamp circuit and not bother with the valve as it contributes nothing but distortion, noise and other limitations.
On the other hand, if we actually *want* the valve distortion for a musical effect, say, then this approach does make a lot of sense. Opamps can facilitate high input impedance, low output impedance, additional gain for overdriving the valve, clickless electronic switching and a host of other conveniences. The only thing they *don't* provide is graceful distortion, unlike the valve, so the marriage becomes a sensible one! This should be of particular interest to anyone who plays electric guitar...

Pure-tube circuits:

If we actually want to design a simple, *pure-tube* line stage for hifi (I use the term loosely) then we must turn to grid-leak biasing. Traditional grid-leak biasing simply connects a grid-leak resistor directly between grid and cathode, and the grid current which then flows around the loop causes a negative voltage to develop at the grid, as illustrated in **fig. 6** (if you're wondering what drives this current, it is the space charge itself).

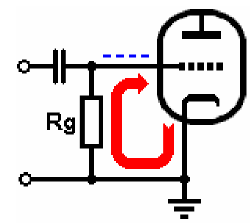

Fig. 6: Traditional grid-leak biasing is unsuitable for starved operation.

However, some people make the mistake of trying to use a familiar value for the grid-leak, like 1MΩ, but this value is *far* too large for starved operation; it will bias the triode practically to cut-off! Doing it properly, if we aimed for a bias of –0.2V with the ECC82, then from **fig. 3** the grid current is estimated to be about 9μA. Ohm's law gives us the necessary resistance: $Rg = 0.2 / 9\times10^{-6} = 22k\Omega$.

Even the correct grid-leak has a big shortcoming; the input resistance of the valve was rather low to begin with, but with another resistor in parallel it is made even lower still! Since there don't seem to be any advantages to this biasing method under starved conditions, it can be discarded.

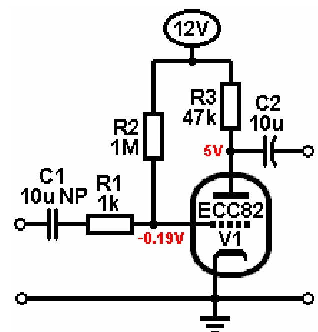

Fig. 7: Pull-up grid-leak biasing maximises input impedance and allows a greater range of grid bias than traditional grid-leak biasing.

A more useful approach is pull-up grid-leak biasing. This involves nothing more than connecting the grid-leak to the supply voltage rather than to the cathode. For example, if the supply voltage is 12V and we again want a grid voltage of –0.2V then the voltage dropped across the pull-up resistor must be 12.2V. The grid current was already shown to be 9μA, so the pull-up resistor must be: $Rg = 12.2 / 9\times10^{-6} = 1.4M\Omega$. This is large enough that is has almost no effect on the input impedance of the circuit.

This may sound a little strange –obtaining a negative grid voltage from a resistor connected to the positive supply– but that's just how things work in the world of starved circuits. What's more, this method even allows you to play with zero and positive grid bias (in such a low-voltage circuit no harm will come to the triode by doing this). Incidentally, this biasing method is mentioned in a patent for an electric guitar distortion pedal, although the designers apparently didn't know why it worked![5]

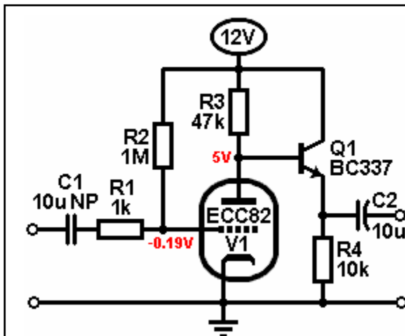

Fig. 8: Output buffered by a high-gain transistor.

Fig. 7 shows a first-principle circuit using pull-up biasing. The optimum bias for best performance was found by experimentation. The earlier distortion-cancelling technique can be used here, but gain will be sacrificed (with a hybrid circuit, lack of gain is not usually a problem since it can be made up with opamps). A compromise value of 1kΩ was used in my test circuit, giving a measured input impedance of around 11kΩ. C1 must be a non-polarized type (NP) since the grid voltage is usually negative, but will be positive before the cathode warms up.

The output impedance from the anode is rather high, of course, but it could be buffered with a high-gain transistor. **Fig. 8** shows a version that will drive a 10kΩ load without too much trouble.

However, we are now back to a hybrid circuit, so let's replace the transistor with a cathode follower and produce the circuit in **fig. 9**. This is the simplest pure-tube starved line stage that I can envisage, while still achieving tolerable performance. The pull-up resistor is replaced with a trimpot, which allows just about any ECC81/2/3 to be used. The pot should be adjusted until the anode voltage measures 5 to 6V, or you can use your ears to find the sweet spot. Using an ECC82 I measured the gain at 8.5, and the maximum output before visible distortion was 2Vp-p. At 4Vp-p the THD was still less than 2%, mainly second harmonic. This is actually better than the hybrid circuit in **fig. 4**, suggesting the cathode follower may be contributing some of its own distortion cancellation…

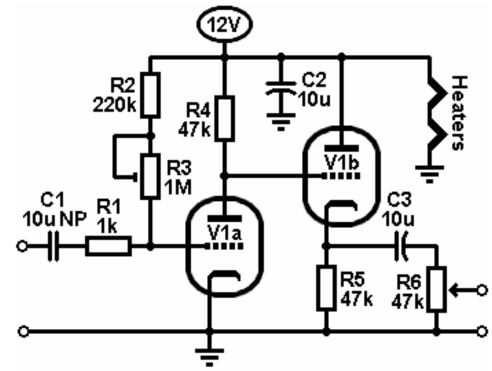

Fig. 9: Practical line stage that accepts ECC81 / 12AT7, ECC82 / 12AU7 or ECC83 / 12AX7.

The heaviest load this circuit can reasonably drive (after the volume pot) is about 100kΩ. Trying to get more drive by reducing R5 will result in more grid current in V2, which ruins the performance of V1. You might be tempted to move the volume control to the input, but distortion will suffer due to the low, non-linear input impedance; this circuit really needs to be driven from a low impedance source.

The power supply *must* be voltage regulated if low hum/noise is to be expected, so if you use an ordinary wall wart / mains adapter, make sure it is the kind that says 'regulated' on it! (But avoid the switch-mode variety as they can still be pretty noisy.) The anode current is less than 1mA but the heaters will need 150mA, or 300mA if you make a stereo version, of course. Fortunately, it is easy to buy 300mA or 500mA regulated wall warts.

Conclusions:
I hope this article has shed some light on the peculiarities of starved circuits. Is linear amplification possible at low voltages? The answer is certainly yes, and practical circuits *are* entirely feasible (and fun!), but we must be willing to accept the unavoidable shortcomings of low input impedance, limited gain and little headroom, or else we must look to hybrid circuits to fix these problems. The ideas presented in this article may serve as a reliable platform for further experimentation, and I hope you will devise some really imaginative starved circuits!

I am indebted to Stephen Keller for his help in sourcing reference material.

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[1] Volkers, W. K. (1951). Direct-Coupled Amplifier Starvation Circuits. *Electronics*. (March), pp126-9.
[2] Callahan, R. G. (1964). Simple High Gain DC Amplifier. *Review of Scientific Instruments*, **35** (6), pp759-60.
[3] Kaufer, G. E. (1955). How to Design Starved Amplifiers. *Tele-Tech and Electronic Industries*. (January), pp68-70 +104+106-11.
[4] Bisso, R. J. (1957). Tube Design Considerations for Low-Voltage Operation in Hybrid Circuitry. *The Sylvania Technologist*. **10** (2), (April), pp38-41.
[5] Butler, B. (1991). *Tube Overdrive Pedal Operable Using Low Voltage DC Battery Eliminator*. US Patent 5022305.