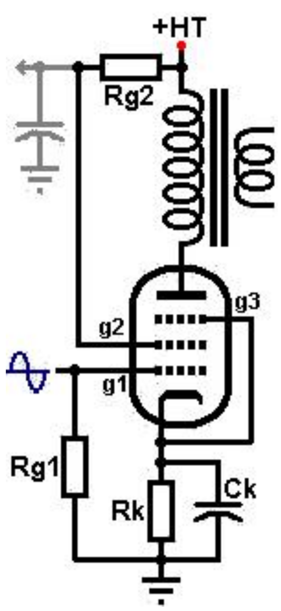
The Valve Wizard

The Single Ended Output Stage



Single-ended (SE) power output stages are probably the simplest form of power amplifier. They are usually used for relatively small amplifiers, e.g., less than 15W, and are invariably cathode-biased. Higher powers are obtainable with either very large power valves, or by using multiple valves in parallel, but beyond about 15W it is usual to use the more efficient push-pull system.
The sound produced by a single-ended amp is rather unique. SE can only operate *cleanly* in Class A, and whereas a push-pull output stage tends to cancel out even harmonic distortion, a single ended one won't. Since for power amplification it is usual to use pentodes or beam-tetrodes, which produce predominantly odd harmonics, we can expect all possible harmonics and a particularly rich sound from a SE amp.

Initial Criteria: The principle of operation for the cathode-biased single-ended output stage is somewhat simpler to understand than that of the push-pull amplifier, as a SE stage is similar to a typical pentode stage used in preamplifiers. Its only real difference is in using a transformer for an anode load, rather than the resistor that you'd see in a preamplifier stage.

The first two things to consider when beginning to design are: What sound are you looking to get from the power amp, and how much output power do you want?
These are important questions because they will dictate the choice of output valve - which itself will dictate the design of the rest of the output stage and power supply. If you already have an idea of the HT voltage and current available then this will also influence your choice. For illustration purposes we will say we've decided we need about 10W (which is enough for gigging at moderate to high distortion levels!).
The output power from a SE pentode stage will be roughly half the anode dissipation of the valve, so we'll need a valve capable of 20W or more. There is actually a wide range of valves that fit the bill, but the most common for guitar use are the EL34 (25W), 6L6GC (30W), or a pair of parallel EL84s (24W). We can disregard 'big bottle' valves such as the 6550, KT66, KT88 and KT90, as they will easily deliver more power than we want (or rather, *consume* more power than we might have available!) and are therefore 'wasted' in this application, unless they are otherwise desirable for their tone (there is of course, no reason why we *couldn't* use a powerful valve and run it well below maximum, though it would seem a waste). Your choice may also depend on the availability of valve types where you live. In Britain the power pentodes are generally cheaper and more widely available than the beam-tetrodes, which are more common in the US.

If we decide that we would like the stage to contribute an aggressive character to the sound of the amplifier as a whole then the EL34 is a good choice, and should deliver around 8W to 11W at a reasonably low HT of 250V and somewhat more at higher voltages.

Transformer Impedance: When selecting a transformer it is necessary to know what HT voltage is going to be used (at least roughly). Referring to the data sheet, we can see that an EL34 can be operated from a very wide range of HT potentials. Other single ended EL34 designs commonly use between 250V and 400V. The lower end of the range will suit lower transformer impedances, and vice versa. In the following example we'll use 300V.
Incidentally, although the El34 data sheet claims the maximum quiescent anode voltage is 800V, this applied to current production in the 1960's. Modern EL34's have questionable reliability at such high voltages, so it would be wise to restrict ourselves to an HT of less than 500V.

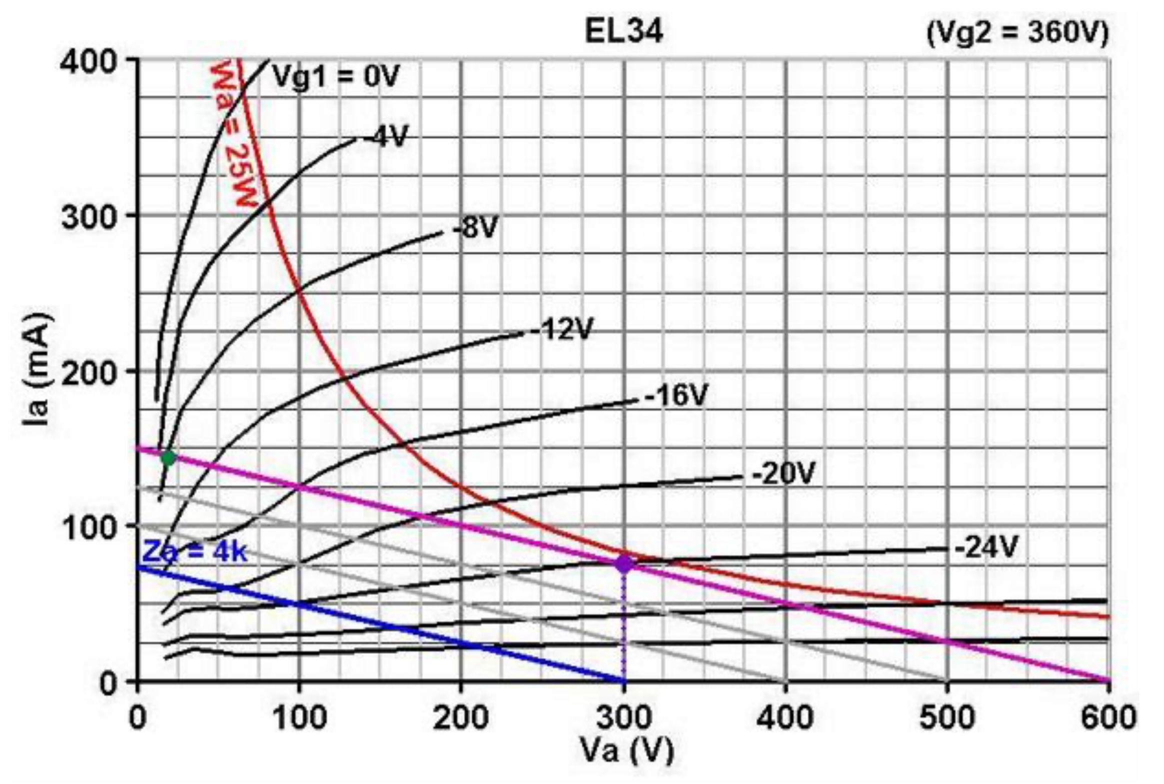
Transformer manufacturers generally state that an output transformer will show 'x' primary impedance with 'y' secondary load. For example: 5k primary impedance with an 8 ohms secondary (speaker). This is derived from the voltage and current ratio of the transformer, which are inversely proportional to each other. That is to say; if the voltage is stepped down, the current must step up:
The *turns ratio* can be given by:
Vin / Vout = Iout / Iin
Since each is the inverse function of the other, squaring the result will give us the *impedance ratio*:
Z = (Vin / Vout) squared.

It's easy to see that a transformer that exhibits a voltage and current ratio of 20 will have an impedance ratio of 400. This means that connecting a speaker of 8 ohms to the secondary will reflect an impedance of 3.2k to the primary. Doubling the speaker impedance to 16 ohms would also double the primary to 6.4k. (This is a useful trick that may allow you to obtain your ideal primary impedance by connecting the transformer to a speaker impedance other than the rated value.)

Because the grid curves of a pentode allow the signal voltage to swing almost to 0V on the anode, and because we would like to run the stage approximately centre biased, there is a rule of thumb we can use to find a suitable transformer impedance:
Z = Va^2 / Pa
Where:
Va = Anode voltage.
Pa = Maximum anode dissipation.

With our HT of 300V, and taking the data sheet value for maximum anode dissipation as 25W;
Zout = 300^2 / 25
= 3600 ohms
This gives the value of impedance that will yield perfect "centre biased" Class A operation when biased to the maximum anode dissipation. We might want to bias the valve slightly below maximum to ensure safe running and long life, in which case a slightly higher load impedance might be useful. A higher impedance or lower supply voltage would allow us to bias deeper into class A (i.e., hotter), for more second harmonic distortion. Using a slightly lower impedance would force us to bias colder, which tends towards a more 'raw' overdriven tone.

It is usually the case that there will be no 'off the shelf' output transformer that suits our ideal impedance exactly, so we would draw some load lines to find a transformer that is suitable. Plotting several load lines will show you how much you can afford to 'fudge' the impedance value to suit your power supply, or what transformers are available. For this example we will assume that the nearest transformer available with a *higher* impedance than we calculated is rated at 4k, 10W. Draw load line:



As you can see from the blue line, the load line is first drawn in the normal way, but this will not be the load line that the valve ends up operating on, it simply shows us the *gradient* of the load.

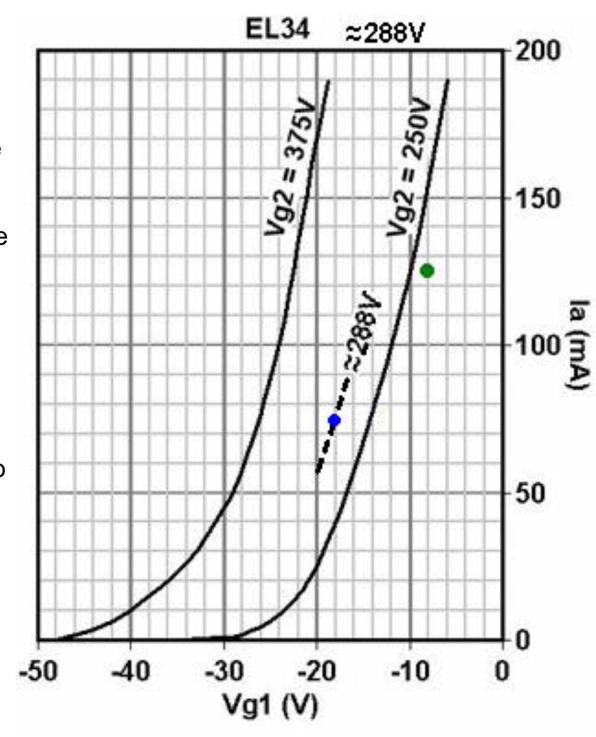
Choosing a bias point: Because we are using a *reactive load* rather than a resistive one (i.e., a transformer and not an anode resistor), the bias is not chosen in the same way as for a preamp stage.
The transformer primary has very low DC resistance so only a few volts will be dropped across it, which we usually ignore. **Therefore, the quiescent anode voltage will be the SAME as the HT, no matter how much quiescent anode current we choose.** We could draw a vertical line at the HT voltage and know that the bias point must be somewhere on it. You can now see that with the load line in its current position, the valve would be biased at cut-off and could only operate in class B!
So, instead of selecting a bias point somewhere on the load line, we slide the load line up the graph, whilst maintaining its gradient. The grey lines show this process. The load line must not go beyond the maximum dissipation curve, and it would be wise to choose a position slightly below the curve for safe running. Load lines for other impedances are drawn in the same way.
We decide that the quiescent anode current we want in this case is 75mA (purple dot), just below max dissipation, and you can see the valve is now operating close to centre-biased Class A (i.e., the bias point is roughly in the centre of the load line)

If you are wondering why it appears that the signal voltage can now swing higher than the HT voltage, it is because this is exactly what happens! Inductances abhor changes in current. When current through the transformer increases it stores energy, which is released when the current falls again, allowing up to twice the HT voltage to be developed. Because of this, the HT in a Class A amp must never be more than half the maximum *peak* anode voltage rating of the valve, given on the data sheet. For the EL34 this is 2000V so we are well within safe limits!
Now we have the load line we need to set the screen voltage before we can continue.

Screen Voltage: The screen voltage is usually set by a dropping resistor in the HT supply (Rg2) (see the section on smoothing and filtering), or a choke, plus a small screen-grid stopper. This will place the screen voltage at roughly the same voltage as the anode, or a little lower. Guitar amps usually sound best when the quiescent load line passes slightly below the knee of the curves. It is this interplay of load, anode and screen voltage that is the essence of pentode design.
The dropper (or choke) provides both filtering and a permenant voltage drop. The stopper provides current limiting and compression. To choose values for these resistors we need to know the screen current, plus any extra current that may be being delivered to the preamp through the dropper (Rg2). The current to the preamp can be estimated, and the screen current can be found either from a graph given in the data sheet, or by knowing that screen current is roughly a fixed ratio of anode current. The data sheet gives one example of anode current of 70mA, screen current 10mA, a ratio of 70/10 = 7:1.

We already know the quiescent anode current will be 75mA, so we can expect 75/7 = 10.7mA of quiescent screen current. We will assume the preamp in this amplifier draws an additional 5mA. The total current through the screen-grid dropper (Rg2) is therefore 15.7mA. The value of this resistor is usually in the region of 470 ohms to 1k simply because these are common values that provide a decent level of filtering in conjunction with the smoothing capacitor shown in grey. If we use 470R, the voltage dropped across this resistor will be:
470 * 0.0157 = 7.4V
and the power dissipated will be: 470 * (0.0157 * 0.0157) = 116mW

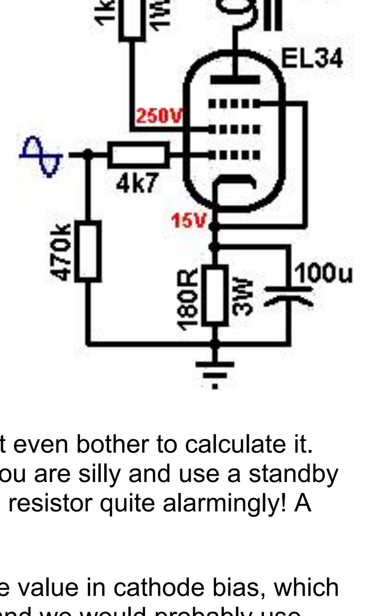
As mentioned, the *quiescent* load line will usually pass slightly below the knee, which is find for clean amplification. However, when it comes to overdrive it is a BAD IDEA, because once the operating point swings up to the 0V grid curve, the screen current rapidly increases. If the operating point hangs around this point for too long (as it does during clipping) it can easily cause the screen to overdissipate and be destroyed. To avoid this, a screen-grid stopper is added, which forces the screen voltage to drop as the screen current rises, limiting the dissipation. As the screen voltage drops, all the grid curves get squashed down, and as a rule of thumb we would like the knee to meet or pass below the load line under these dynamic conditions. This is known as 'sliding-screen' operation, and requires a certain amount of estimation and educated-guessing as we shall see.



Firstly we must know what voltage we need the screen to sag down to, and to do this we use the mutual characteristics graph. Unfortunately the mutual characteristic graph provided in the data sheet does not show screen voltage extending as far as zero grid volts. However, we can guess that if we want the zero volts curve to squash down to where the -8V line is initially, then the -8V grid line will move down to roughly where the -16V grid line is currently.
The -16V grid curve currently crosses the load line at Ia = 125mA. We look at the mutual characteristics graph and see what screen voltage corresponds to a grid voltage of *-8V* at 125mA anode current (green dot):
The screen voltage required is slightly below 250V, but we will round it off at 250V.
Therefore we need to drop roughly 300 - 250 = 50V across the screen stopper under *peak conditions*.

Now well introduce a big fudge factor and say that when the anode swings close to zero, *all* the current is stolen the by the screen (OK that isn't strictly true, but it'll do for now). From the load line, the peak anode current is about 150mA. Use Ohm's law to find the minimum value of screen-grid stopper:
50 / 0.150 = 333 ohms.
Since in reality the screen current will not quite attain this value we should use the next highest standard resistor, which is 470 ohms for a wire-wound, although 1k is more common and will cause the characteristics to compress more. The power dissipated in this resistor will be minimal, since the screen current will never reach 150mA in reality. A 2W should be plenty.

This resistor will also drop the *quiescent* screen voltage by 470 * 0.0107 = 5V, which is negligeable.



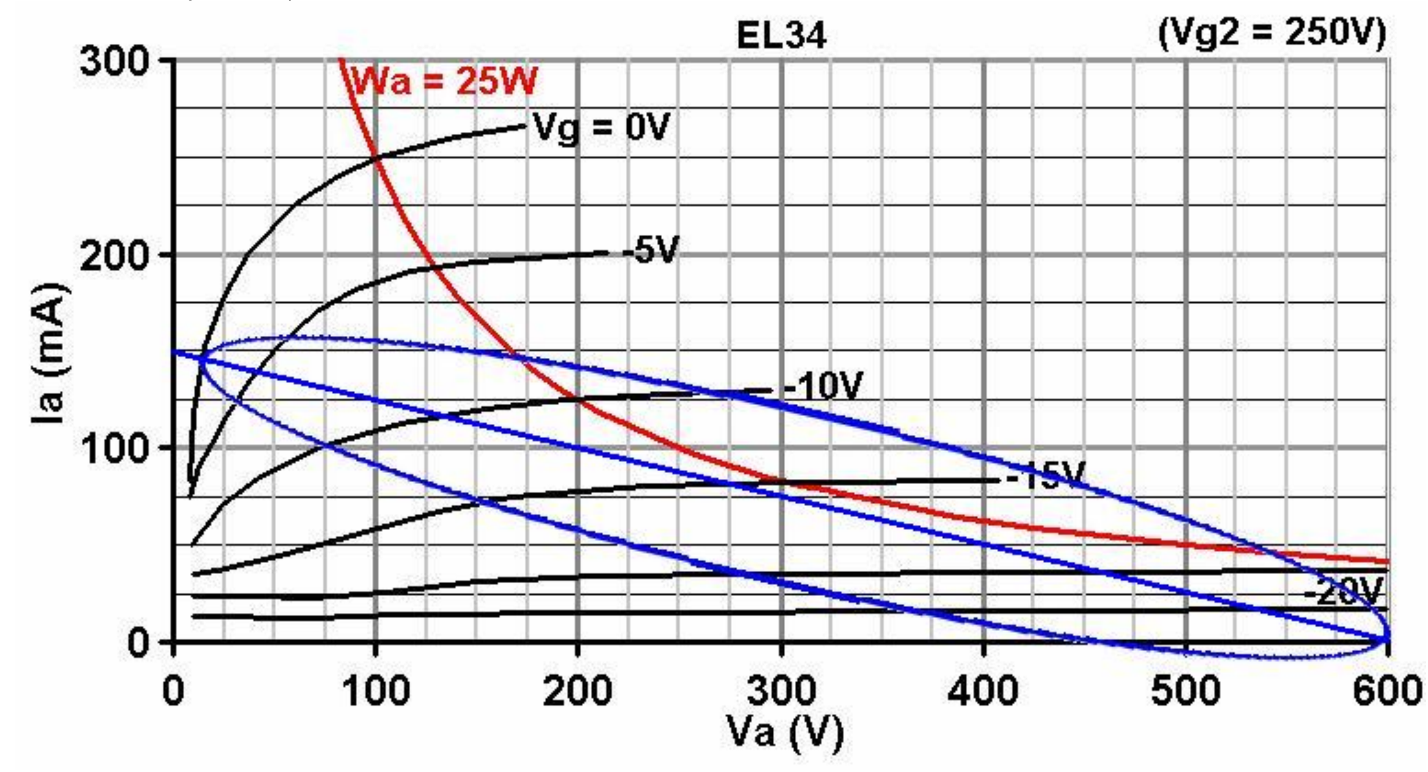
Biasing: Now we know the screen voltage will be 300 - 7.4 - 5 = 288V we could re-draw the new anode characteristics to find the bias voltage. However, a quicker way is simply to use the mutual characteristics graph again: We know our quiescent anode current will be 75mA, and our screen voltage is 300 - 7.4 - 5 = 288V, and this indicates a grid-to-cathode voltage of about -17V (blue dot), which is our required bias voltage. The total cathode current will be equal to the quiescent anode current plus the screen current, making 86mA in total. Use Ohm's law to calculate the value of cathode resistor (Rk):
17 / 0.086 = 198 ohms
The two closest standard values are 200R and 220R and either would probably work in this instance, since we are not operating right on maximum dissipation. However, some Class A circuits may be operated very close to that limit, and valve characteristics can vary wildly so it's usually better to go with the lerger option. We would use a 220R which will slightly raise the bias voltage, but not significantly, and would dissipate slightly less than:
(0.086 * 0.086) * 220 = 1.6W
So we would use a 3W resistor or better.

Cathode bypass capacitor: As with most single ended stages, fully decoupling the cathode will maximise gain by preventing internal feedback and so maximise output power and input sensitivity too (making the valve easier to overdrive).
For a low roll off of approximately 10Hz:
Ck = 1 / (2 * pi * f * Rk)
Ck = 1 / (2 * pi * 10 * 220)
= 72uF
So we would use 100uF. This is a pretty generic value for single ended amps and in many cases we wouldn't even bother to calculate it. Its voltage rating must be at least three times the expected cathode voltage. This is especially necessary if you are silly and use a standby switch, as there will be a brief surge of grid current at start up which will raise the voltage across the cathode resistor quite alarmingly! A 63V rated capacitor should be fine in this case.

The grid-reference resistor (Rg1) can be found by consulting the data sheet for the maximum allowable value in cathode bias, which will usually be less for a power valve than a preamp valve. For the EL34 the maximum value given is 700k, and we would probably use 470k.
A grid stopper MUST added to power valves to prevent HF oscillation, and the data sheet may or may not give some example values; 1k to 10k is common.
Another method of biasing is to ground the cathode and use a separate negative voltage supply to give the grid a negative voltage level. This is referred to as fixed bias, though it is usually adjustable, and is more usually used for fairly high power push-pull output stages.

Reactive Load: It is worth noting that an output transformer is reactive and so has a rising impedance with frequency, and is also coupled to a loudspeaker. A loudspeaker, particularly one designed for guitar amp use, does not exhibit a constant impedance across its frequency range. Because of the combination of capacitance, inductance and resistance that makes up a loudspeaker's impedance and the fact that it is deliberately tuned to produce a frequency response that will sound good with electric guitar, the impedance will vary quite considerably from the average quoted value. This has the effect of turning our straight load line into an ellipse, which will vary with frequency and go beyond the maximum anode dissipation curve. This is not a problem though, because on average the valve will still operate on the straight load line we drew.
The type of speaker used has an enormous impact on the ultimate sound of the amp, and contributes to the dynamic response and compression for which valve guitar amplifiers are admired. It is also remarkable how much a highly sensitive speaker can increase the relative volume of a given amp when compared with an insensitive speaker.

The graph below shows a load line with a screen voltage of 250V, and how it will in fact be an ellipse. We can see that the input sensitivity is just over 20V p-p. At full output before clipping, the maximum anode current is about 140mA peak (50mArms) and the maximum anode voltage is about 540V peak (191Vrms). This gives an average power output to the load of 0.05 * 191 = 9.5W (and an anode efficiency of 42%).



You should now be able to see that using a transformer with a lower primary impedance would permit a higher screen-voltage (and therefore more headroom) because the load line would be steeper, but would force us into cold Class A operation unless we lowered the anode voltage. Conversely, a higher load impedance would require a lower screen-voltage (less headroom), but would allow a higher anode voltage while still operating in centre-biased Class A. It is through drawing load lines in this way that a good-sounding and safe combination of all three can be found.

Remember though, the load line drawn is only correct provided the right impedance speaker is plugged in. Connecting a higher impedance speaker will cause the load line to rotate anti-clockwise around the bias point, possibly causing screen-grid failure due to passing below the knee of the grid curves (although if you're lucky, the screen resistor will fail open first). It can also cause arcing in the transformer due to much higher anode voltages being developed when the valve is overdriven. Connecting a lower impedance speaker will have the opposite effect; the load line will become more steep, pushing the valve into cold Class A operation which may or may not cause over dissipation of the anode (thankfully it usually doesn't). It is therefore always safer to plug in a lower impedance speaker than a higher one, if you have to.

Many thanks to Zoe and Iain Hartney for their contribution to this tutorial.