THE AX84 AMP (REV 10)- THEORY OF OPERATION

Let's take a walk through the inner workings of this amp. Along the way, I will be including some math and electronic theory. To fully understand how a guitar amp works, even a simple one like the AX84, you must know how to read schematic diagrams, and know what things like resistors and capacitors are. You also need some knowledge of electronic theory, but not much. If you don't know what resistors and capacitors are, or don't know what Ohm's law is, I suggest a quick trip to your favorite search engine or library and find out.

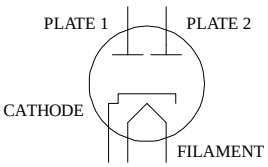
HOW THE HECK DO TUBES WORK ANYWAY?

So you run to the bookstore and buy a book on basic electronics. Hmmm, no tube chapter. Even some 'good' tube amp books don't do a good job of explaining how these work. There are many different tube types out there, but guitar amps use three types of tubes: triodes, pentodes, and rectifiers.

RECTIFIER TUBES

Let's start with the rectifier, because it is the simplest type of tube. Inside the glass bottle, there are a few metal parts: filament, cathode, and plate. The filament is sometimes called the heater, because that is exactly what it does - it heats the cathode. Like the filament in a light bulb, the tube filament is a thin length of wire that gets quite hot when electricity flows through it.

When the filament heats the cathode, electrons 'boil' off the cathode and flow toward the plate. Electrons flow from negative to positive, so the cathode is negatively charged and the plate has a positive charge. This flow is a sort of one way valve. Remember that electron flow is the opposite of 'conventional' current.



DUAL RECTIFIER

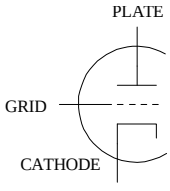
(The ancients did not know which way the electrons really flowed. They knew that there were invisible bits of charge that flowed through wire in a circuit, but had no way of determining the direction the bits traveled. They took their best guess. Bzzzzt! Wrong! By the time the not-so-ancients realized the mistake, it was too late. To this day, when we talk of electric current, we really mean 'the negative flow of electron current'.)

So, current flows from the positive charged plate to the negative charged cathode, just like current flows through a solid-state diode, from its anode to cathode. But the rectifier tube used in the AX84 has two plates. Just think of it as two diodes with the cathodes connected. In our circuit, it is used as a full-wave rectifier.

TRIODE TUBES

The grid in a triode is a mesh of thin wire or wires positioned between the plate and cathode - very close to the cathode. If you were to connect the grid to the cathode, the tube would behave somewhat like a rectifier. Most of the electrons flow right past the grid on their way to the plate. Please do not try this. Most triodes are not designed to be operated this way.

When charge on the grid is made negative with respect to the cathode, the electron flow starts to get 'pinched off'. The electrons are repelled by the negative charge on the grid. Now, make the grid voltage negative enough, and the electron flow will stop.



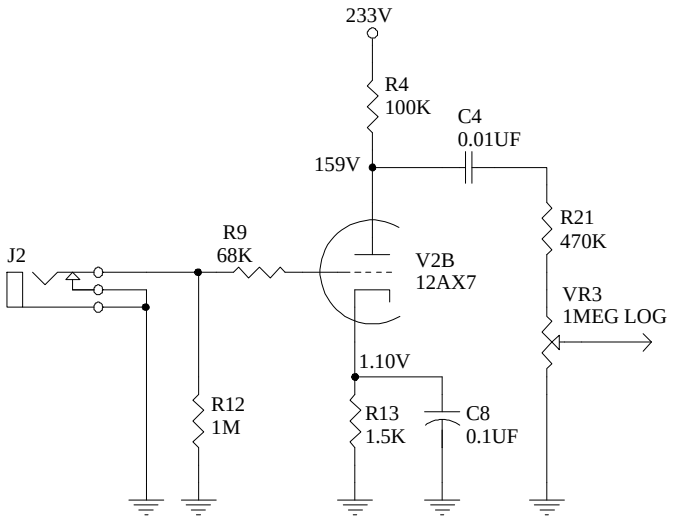
TRIODE

This DC voltage applied to the grid is called bias. The voltage that cuts plate current to zero is called cut-off bias. Increase the bias voltage and more plate current flows, up to a limit. The point where plate current no longer increases, regardless of increases in bias voltage, is called the saturation point. Between cut-off and saturation, a triode behaves as a linear device.

How do we make sure the tube operates in this linear range? By setting the grid bias about halfway between cut-off and saturation.

BIASING V2B

Take a look at Preamp Stage 1 in the AX84 schematic. When no signal is present at the input, the grid of V2B is connected to ground through resistors R9 and R12. So the DC voltage at V2B's grid is 0V. The data sheet of a 12AX7 has a graph showing plate current as a function of grid voltage for different plate voltages. Looking at the schematic, we see the plate voltage on V2B is 159V. Back to the 12AX7 data sheet - at a plate voltage of 150V, plate current is 0mA when grid voltage is about -2.2V. Saturation occurs when the grid voltage is 0V. So we want a bias point halfway between these two points: -1.1V.



Uh oh! Didn't we just determine the grid voltage at V2B is 0V? How do we make the grid voltage negative? Don't have to! We raise V2B's cathode voltage to 1.1V. Look at Preamp Stage 1 in the AX84 schematic. The voltage across R4 is:

$$(\text{voltage across R4}) = (233\text{V} - 159\text{V}) = 74\text{V}$$

Using Ohms law, the current through R4 is:

$$(\text{current through R4}) = \frac{74\text{V}}{100\text{K OHMS}} = 0.74\text{mA}$$

So, 0.74mA flows into the plate of V2B. This current has to go somewhere. It just does not disappear inside the tube. A tiny fraction of the plate current exits through the grid, but it is such a miniscule amount that we can disregard it. For practical purposes, all of the plate current flows out through the cathode. We use this to our advantage to set the bias on V2B. V2B's cathode current flows through R13. Now, using Ohms law again, we can determine V2B's cathode voltage:

$$(\text{voltage at cathode of V2B}) = (0.74\text{mA}) * (1.5\text{K OHMS}) \cong 1.10\text{V}$$

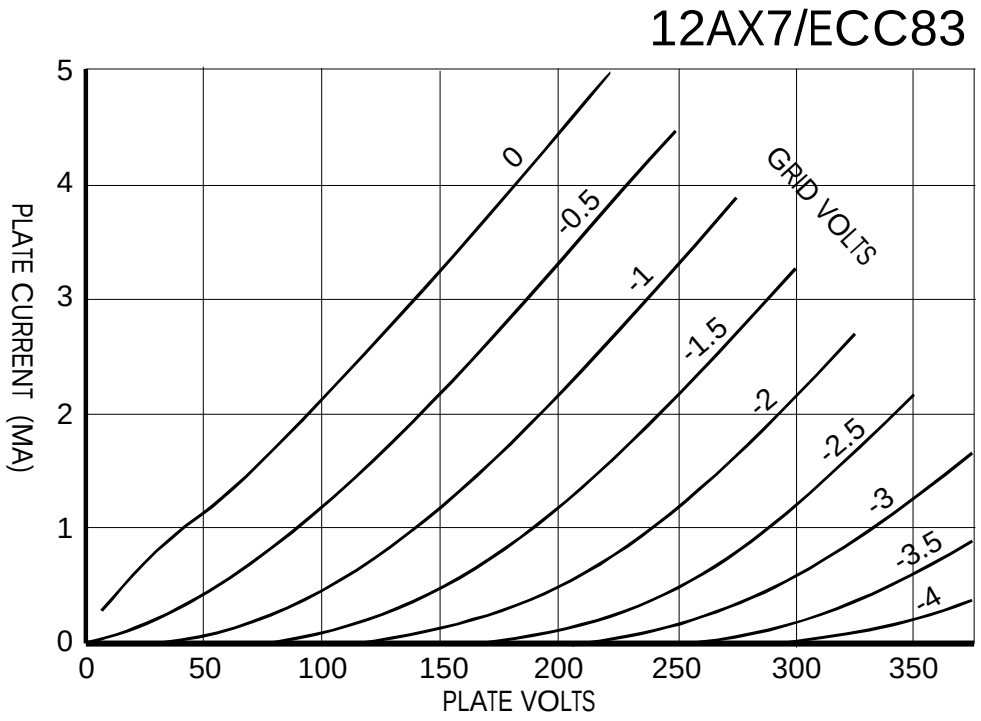
Remember that the bias is the grid voltage, referenced to the cathode voltage. Now, we can easily calculate the bias of V2B:

$$(\text{V2B grid bias voltage}) = (\text{grid voltage}) - (\text{cathode voltage}) = -1.10\text{V}$$

Good. That is the bias voltage we wanted. So you see that having a resistor between the cathode and ground is used to set bias - the technique is called self-bias or cathode-bias.

Wasn't it convenient that we knew what the plate voltage was! If you were designing your own preamp stage from scratch, you would have to calculate the plate voltage. There are a few ways to do this. Perhaps the easiest way would be to model the circuit using PSPICE (models for popular tubes are available on Duncan Munro's website).

How about doing it the old way, which would mean looking at the tube data books. An example of an Ep-Ip chart for the 12AX7 is shown here.



Once built, it is very easy to measure actual voltages and current, then fine tune a design.

AMPLIFYING THE INPUT SIGNAL

We carefully calculated the bias point to keep the tube operating in the linear part of the curve. In plain English, this means the tube circuit is designed so the input signal is amplified with no distortion. Now, a tube is not a perfect linear device, so there is a slight amount of distortion. We won't worry about this here, it would be too complicated to add this non-linearity into the calculations below.

The three tube stages in the AX84 amplify the input signal. V2B amplifies the input, V2A amplifies this some more, and V1 boosts this even more - enough to drive the output transformer/speaker load. The gain of each stage can be determined mathematically. To do this, we need to understand tube parameters.

In the linear region, the ratio of change in plate current to the change in grid voltage remains constant. Well, not perfectly, but close enough for rock-and-roll. This ratio is called the transconductance (or mutual conductance) of the tube, and is usually specified in a tube data sheet. The formula for transconductance is:

Transconductance (Gm) = (change in plate current)/(change in grid voltage)

Transconductance is measure in units called MHO. It is the opposite of resistance, thus the name (OHM spelled backwards). A tube datasheet usually specifies the transconductance at a couple different plate voltages. For instance, a 12AX7 data sheet I have indicates:

Plate Voltage	100	250	VOLTS
Transconductance (Gm)	1250	1600	uMHOS

We have to estimate what the transconductance will be. V2B has a plate voltage of about 150V, so Gm should be about 1400 uMHOS.

Another important parameter found in a tube datasheet is plate resistance. Think of a tube as a variable resistor. When the grid voltage is made more positive, more current flows through the tube. This means the effective resistance between the plate and cathode decreases. Make the grid voltage more negative, and this resistance increases. The formula for plate resistance is:

$$(\text{plate resistance}) = \frac{(\text{change in grid voltage})}{(\text{change in plate current})}$$

Like any other resistance, plate resistance is measured in ohms. My 12AX7 data sheet specifies plate resistance at two different plate voltages:

Plate Voltage	100	250	VOLTS
Plate Resistance	80K	62.5K	OHMS

We have to estimate the plate resistance since there is no spec for a plate voltage of 150V. I figure it would be about 75K OHMS. With these two parameters, we can calculate the voltage gain of Preamp Stage 1. Although there are many ways to calculate this gain, perhaps the easiest way is to use this formula:

$$\text{Gain} = \frac{(\text{plate resistance}) \,||\, (\text{plate load resistance}) \,||\, (\text{following grid resistance})}{(1/\text{ transconductance}) + (\text{cathode resistance})}$$

The symbol '||' is shorthand to indicate resistances in parallel. Transconductance and plate resistance is described above. The plate load resistance is simply the value of the plate resistor (R4 in our example). The following grid resistance is the total resistance of the circuit connected to the plate of the tube, not including the plate load resistor. The cathode resistance is the unbypassed part of the cathode circuit.

Since we are talking about AC signals, let's just imagine that C4 has no resistance at all to the AC output signal (in real life, its resistance varies with frequency). The only reason C4 is in the circuit is to block the 150V of DC voltage at the plate of V2B, and pass only the AC signal. That said, the following grid resistance seen by V2B is equal to 1.47M OHM (R21 + VR3).

C8 is used to allow a path for AC signals to bypass R13 - it functions as a cathode bypass capacitor. Consider what would happen if C8 was not installed. When an AC voltage is applied to the grid, it causes the current flow through the tube to change. The varying current through the tube would cause the cathode voltage to vary. That would mess with the bias voltage and reduce the gain of the stage. Since C8 is installed, Preamp Stage 1 has an effective cathode resistance of 0 OHMS to AC voltages.

Now, plugging these values into the formula we get:

$$\text{Gain} = \frac{(75\text{K OHMS}) \,||\, (100\text{K OHMS}) \,||\, (1.47\text{M OHMS})}{(1/1400\text{ uMHOS} + 0\text{ OHMS})} = 58.3$$

So, a 100mVAC signal at the input to V2B will result in a 5.83VAC signal present at the plate.

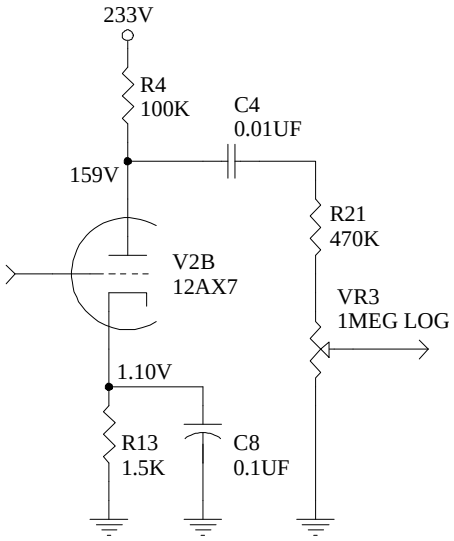
COUPLING CAPACITORS

In the last section, we made an assumption about C4. We made the assumption that it presents an infinite resistance to DC, and zero resistance to AC. High DC resistance is very important when a cap is used to couple amp stages.

Consider what happens if some of the DC voltage makes its way through C4. When we calculated the bias point for Preamp Stage 1, we knew that the grid is at a zero volt potential when no input signal is applied. If we applied a positive DC bias voltage to the grid, we would have to adjust the cathode resistor to maintain the desired bias voltage. Remember that bias is the difference between grid and cathode DC voltage.

So, if some of the DC voltage present at the plate of V2B were to get past C4, it would complicate the design of Preamp Stage 2. In fact, it would be almost impossible to get the next stage to work properly.

Thus, C4 needs to block DC voltages, but let the audio signal through. Used in this way, a capacitor is sometimes called a 'DC blocking cap'. It is more commonly called a coupling capacitor. The cap couples the output from one amp stage to the input of the next stage.



The combination of C4, R21, and VR3 create a high-pass filter. Lower frequency signals encounter more resistance than higher frequencies. In the AX84, C4 is selected such that the cutoff frequency of this high-pass filter is below the frequency range of a guitar. If you substitute a lower value capacitor for C4, you will decrease the bass response of the amp. Increasing the value of C4 will give more bass response.

VOLUME CONTROL

R21 and VR3 create a variable voltage divider. At the lowest setting of VR3, the grid of V2A is connected directly to ground. At the highest setting, the AC voltage applied to the grid of V2A is about two-thirds the AC voltage present at V2B's plate.

NEW IN REV 10:

R21 was added to attenuate the output of Preamp Stage 1. This was necessary to minimize blocking distortion.

The value of C8 was reduced to 0.1UF, and C4 was changed to 0.01UF to cut down the bass response of the first stage. This tweak also helped reduce blocking distortion.

C5 was removed. With the other Rev10 changes, there was just too much treble for low VR3 settings with the 'Bright' cap installed.

PREAMP STAGE 2

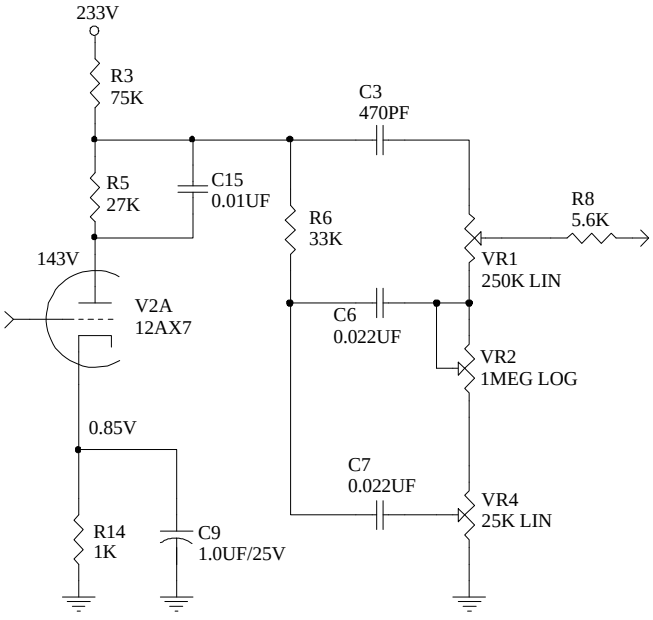
Using the same techniques as described much earlier, we can easily determine the bias current and voltage for V2A. Since the schematic shows the voltages, I will not bother with the math. Feel free to try your hand at the calculations and see if you come up with the same voltages as shown in the schematic.

Calculating the gain of this stage is much more cumbersome than the previous stage. First, we look up the transconductance and plate resistance from the data sheet:

Plate Voltage	100	250	VOLTS
Transconductance (Gm)	1250	1600	uMHOS
Plate Resistance	80K	62.5K	OHMS

The plate voltage of V2A is between 100V and 250V, so we must estimate again. Lets say Transconductance is 1400 uMHOS, and plate resistance is 75K.

The plate resistor is split into two separate resistors. This is done to attenuate (reduce) the effective gain of this stage, which we will talk about soon enough. The grid circuit of the next stage taps off the junction of these resistors (R3 and R5). This arrangement is called split load resistor.



Hanging off this point in the circuit, is a collection of capacitors, resistors, and potentiometers, which make up the 'tone stack'. Seems like it would be real difficult to determine the effective resistance of this circuit. Well, it is. Especially if we wanted to consider how the stage gain changed at different frequencies. Actually, we can simply pretend that this conglomeration of components does not exist, at least when we do the gain calculations for Stage 2. The reason will become clear very soon.

Remember the formula for gain:

$$\text{Gain} = \frac{(\text{plate resistance}) \,||\, [\,(\text{plate load resistance}) \,||\, (\text{following grid resistance})\,]}{(1/\,\text{transconductance}) + (\text{cathode resistance})}$$

Hey! There are a couple of parentheses there that weren't there before. I did that on purpose, because we are going to pull that term out and calculate separately. Here's the term all by itself:

$$(\text{plate load resistance}) \,||\, (\text{following grid resistance})$$

This term represents the effective resistance of the circuit attached to the plate of V2B. Figure this out and we can simply plug it into the formula above. Here's how:

$$(\text{effective resistanceon plate}) = \text{R5} + (\,\text{R3} \,||\, (\,\text{following grid resistance})\,)$$

Plug in the values for R5 and R3:

$$(\text{effective resistance on plate}\,) = 27\text{K} + (\,75\text{K} \,||\, (\,\text{following grid resistance}\,)$$

Now take a leap of faith. We are going to ignore the grid resistance of the following stage, which means we will be pretending that the tone stack does not exist. Then, the equation above reduces to:

$$(\text{effective resistance on plate}\,) = 102\text{K}$$

Plug the numbers into the formula for gain:

$$\text{Gain} = \frac{75\text{K} \,||\, 102\text{K}}{(\,1/1400\ \text{uMHOS}\,) + (\text{cathode resistance})}$$

Now, the 1K cathode resistor is bypassed by C9 and drops out of the equation. So we get a gain of:

$$\text{Gain} = \frac{43.2\text{K OHMS}}{(\,1/1400\ \text{uMHOS}\,) + (0\ \text{OHMS})} = 60.5$$

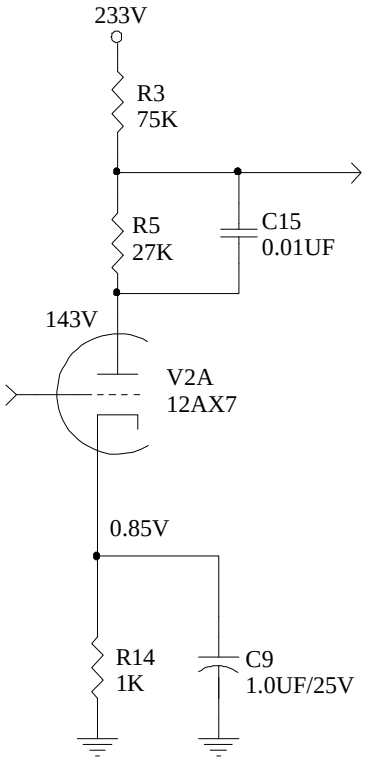
Gain is the ratio of AC voltage at the plate to the AC voltage at the grid. But the tone stack circuit does not connect to the plate. It connects to the junction of R3 and R5 - the split load resistor. It is a simple voltage divider. It may help to look at it upside down, really.

The top leg of R3 connects to the power supply, and there is a hefty 50uF filter capacitor right there. Although there is lots of DC voltage at this point, this node has (or at least it should have) no AC voltage present. To an AC signal, this looks like ground potential. With this knowledge, we can do the math:

$$(\,\text{AC voltage at junction of R3 and R5}\,) = (\text{V2A AC plate voltage}) \times \frac{\text{R3}}{(\text{R3+R5})}$$

Plug in the values for R3 and R5:

$$(\,\text{AC voltage at junction of R3 and R5}\,) = (\text{V2A AC plate voltage}) \times 0.74$$



NEW IN REV 10:

The values of R3 and R5 were changed to drive the EL84 a little hotter than the Rev9 circuit. This was necessary to compensate for the reduced gain of stage 1.

A new capacitor was added to the circuit: C15. This capacitor lets high frequencies bypass R5. The result is Preamp Stage 2 has more gain for high frequencies than for low frequencies. It was found that too much low frequency amplification in the preamp stages caused blocking distortion in the EL84.

The value of R14 was changed to bias V2A a little hotter. The original value caused just a bit too much asymmetrical clipping when driving this stage into clipping.

The Boost switch (S3) was removed. The prototype builders found that the tone was just not there when C9 was switched out of the circuit, so this feature was eliminated.

We call the ratio of R3 to the sum of R3 and R5 the divider ratio. It cancels out some of the gain if this stage. But isn't gain good? Up to a certain point it is, but too much can cause the next amp stage to distort in a very non-musical way. Some amp gurus use a very technical term for this. They call it 'farting out'. I'll leave it to you to guess what this sounds like.

The final step in calculating the gain of Preamp Stage 2 is to scale the tube gain by the divider ratio:

$$\text{Stage 2 Gain} = 60.5 \times 0.74 = 44.8$$

SKIP THIS SECTION UNLESS YOU REALLY LIKE MATH

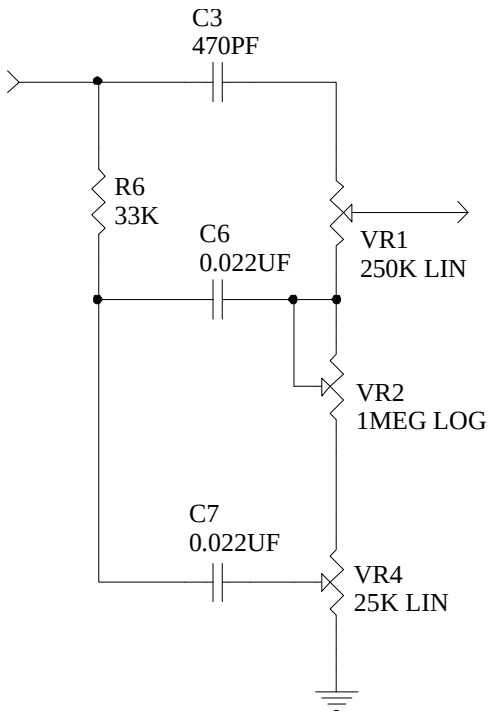
What would have happened if we did not ignore the tone stack circuit?

Imagine C3, C4, and C7 behave as a short circuit to AC voltages. In real life they don't, but just imagine they do here. Suppose also that the tone controls are set at the midpoint. The bass control (VR2) is shorted out when C6 and C7 become short circuits. The total AC resistance can be calculated now.

$$(\text{effective resistance of tone stack}) = (R6 \,||\, VR1) + (\text{resistance between VR4 wiper and ground})$$

Now, plug in the values:

$$(\text{effective resistance of tone stack}) = (33K \,||\, 250K) + 12.5K = 41.6K$$



The effective resistance on the plate turns out to be:

$$(\text{effective resistance on plate}) = 27K + (75K \,||\, 41.6K) = 53.7K$$

Plug the numbers in the formula for gain:

$$\text{Gain} = \frac{75K \,||\, 53.7K}{(1/1400\ \text{uMHOS}) + (\text{cathode resistance})}$$

$$\text{Gain} = \frac{31.3K\ \text{OHMS}}{(1/1400\ \text{uMHOS}) + (0\ \text{OHMS})} = 43.8$$

Now scale these figures by the voltage divider ratio:

$$\text{Stage 2 Gain} = 43.8 \times 0.74 = 32.4$$

Not much of a difference, huh? And we made some big assumptions about how the capacitors in the tone stack behave. In real life, these caps do not act as a short circuit to AC voltages, so the stage gain difference would be even less. And remember that volume control pot connected to the grid of V2A? A little twist of the knob can compensate for any mathematical sloppiness in gain calculations.

In fact, it is common practice to ignore the effective resistance of the following grid circuit when determining gain. Usually, this resistance is so high that it does not significantly affect gain calculations.

TONE STACK (THE LONG COMPLICATED EXPLANATION)

If you have looked at many schematics of tube guitar amps, the tone control circuitry should look familiar. Most amp companies have used this arrangement of components for their tone controls. The tube amp gurus call this circuit a FMV tone stack, which stands for Fender/Marshall/Vox.

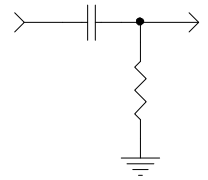
Technically speaking, the tone stack is a set of passive filters, each with its own -3db point. Another way to think of the tone stack is to call it a passive network with frequency dependent insertion loss. When a signal is inserted into this circuit, some frequencies are attenuated more than others.

It is probably easier to begin by describing the tone stack as three separate filters (bass, mid, and treble), then describe some of the interaction between the filters. As you will see, the three filters share some of the same components, so it is important to describe this interaction.

Let's first discuss two types of passive RC filters - high pass and low pass.

First the high pass filter: Imagine you have an input connection and an output connection. The signals share the same ground. Wire a capacitor between the input and output connection, and put a resistor between the output connection and ground. This creates an RC high pass filter that has a -3db cutoff frequency of:

HIGH PASS FILTER

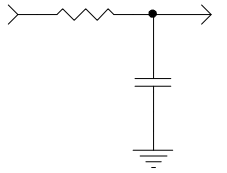


$$(\text{cutoff frequency}) = \frac{1}{2 \times Pi \times R \times C}$$

The -3db point refers to the frequency at which the output signal is 3db lower than the input frequency. In a high pass filter, lower frequencies are attenuated more.

A low pass filter is simply the opposite of a high pass. Again imagine you have an input connection and an output connection. The signals share the same ground. Wire a resistor between the input and output connection, and put a capacitor between the output connection and ground. This creates an RC low pass filter that has a -3db cutoff frequency of:

LOW PASS FILTER



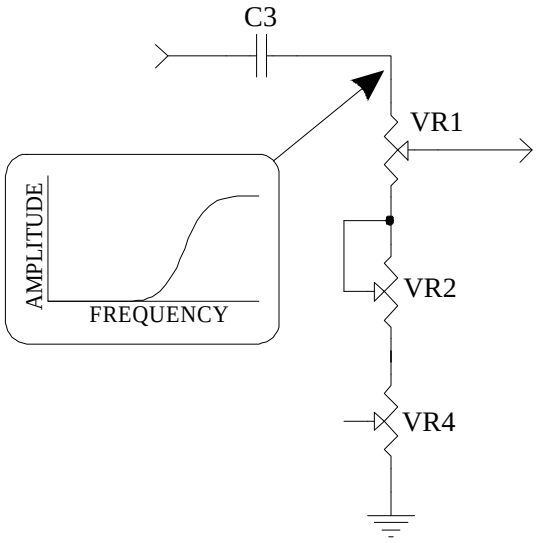
$$(\text{cutoff frequency}) = \frac{1}{2 \times Pi \times R \times C}$$

Yes, this is exactly the same formula as above. Convenient, huh?

If you feed the output of a high pass filter into the input of a low pass filter, you get a band pass filter.

Lets now dissect the AX84's tone stack starting with the treble control.

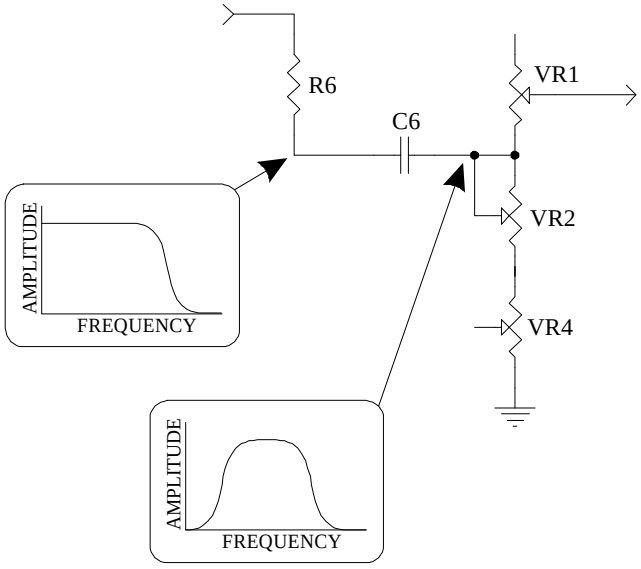
Imagine that R6, C6, and C7 are removed from the circuit. You are left with one capacitor between the input and output (C3), and a set of potentiometers across the output and ground (VR1, VR2, and VR4). The resistances of the potentiometers add up and can be thought of as a single resistor. So we are left with a simple high pass RC filter.

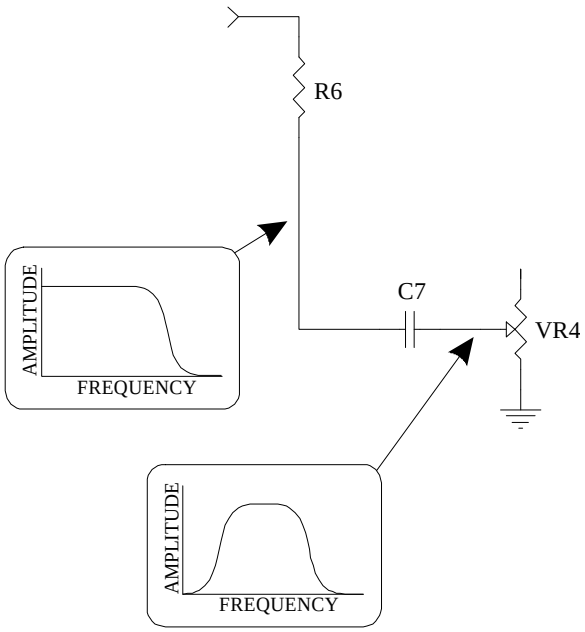


Now consider what is going on at VR1. Signals with a frequency greater than the cutoff frequency pass right through the capacitor to the top terminal of VR1. Frequencies lower than the cutoff are attenuated. Remember how the volume control works? It is a resistive voltage divider. Same thing happens with VR1 - the treble control. When the wiper is closer to the top of VR1, the signal that has just made its way through the high pass filter is attenuated less. Moving the wiper toward the bottom leg of VR1 causes more attenuation of the high pass filter output.

Take a close look at VR2. As the wiper moves toward the bottom leg of the potentiometer, the resistance of VR2 is reduced. This causes the cutoff frequency to increase as VR2 is rotated counterclockwise (moving wiper closer to the bottom leg).

Lets look at the bass control. Imagine that C3, C7, and VR1 are removed from the tone stack circuit. What remains is actually two filters in series. R6 and C6 form a low pass filter, and C6 and the combination of VR2 and VR4 form a high pass filter. Here again, The cutoff frequency of the high pass filter is dependent on the setting of VR2. At the highest bass control settings, the cutoff frequency (of the high pass created by C6, VR2, and VR4 is well above the frequency of the low E string. Lower settings of the bass control raise the cutoff frequency, attenuating the bass.





Moving on to the mid control (VR4), we have a circuit almost identical to the bass control. Imagine that C3, C6, VR1, and VR2 are removed from the circuit. R6 and C7 form a low pass filter, just like the bass control circuit. C7 and VR4 create a high pass filter, but with a much higher cutoff frequency than the high pass element in the bass control circuitry. The difference here is what happens to the output of this combination of filters. Think of it this way: the output of the filters that make up the mid control is present at the wiper of VR4. Move the wiper of VR4 towards the top leg (mid control up), and less of this output is shunted to ground through VR4. Turning down the mid control shunts more filtered signal to ground, attenuating the mid frequencies.

Not only does the mid control attenuate mid frequencies, it also attenuates the overall level of the output signal. Consider what happens when VR4 is turned all the way down, essentially shorting one side of C7 to ground. In this setting, C7 effectively shunts most of the signal present at the lower leg of R6 to ground. And for practical purposes, the lower leg of VR1 is also shunted to ground through the combination of C6 and C7, at least for AC signals. Thus, the mid control affects the overall output of the tone stack.

We took a huge assumption here when we 'took out' some of the tone stack components to analyze the high, mid, and bass control circuits separately. Doing this sure made it easy to see how each section worked, but we ignored the fact that the filters interact with each other. It would be way too complicated to try to explain this here. And it really does not matter. The FMV tone stack has been duplicated in hundreds of guitar amps in the last half century.

TONE STACK (THE SHORT SUMMARY)

TREBLE CONTROL - VR1
This potentiometer acts as a balance control between the output of a high pass filter formed by C3 and the three potentiometers, and the output of the complex filter created by R6, C6, C7, VR2, and VR4.

BASS CONTROL - VR3
This potentiometer sets the lower cutoff frequency of a band pass filter formed by R6, C6, VR2, and VR4. It also affects the cutoff frequency of treble control circuit.

MID CONTROL - VR4
This potentiometer controls the attenuation of the band pass filter formed by R6, C7, and VR4. It also acts as a variable attenuator for the tone stack output.

PENTODE TUBES

A thorough discussion about pentode tubes has to start with an examination of the limitations of triode tubes.

In the talk about triodes, we learned that that inside a triode is a few metal pieces, separated by a vacuum. Now, consider what a capacitor is - two conductive surfaces separated by an insulating dialectric. A vacuum is a sort of dialectric. So inside the triode, there are a couple of 'virtual' capacitors, one between the plate and grid, and one between the grid and cathode. In tube tech talk, these internal capacitances are called interelectrode capacitances.

Looking at the 12AX7 datasheet, we can find the interelectrode capacitance specifications:

	Triode Unit 1	Triode Unit 2	
Grid to Plate	1.7	1.7	pf
Grid to Cathode	1.6	1.6	pf
Plate to Cathode	0.46	0.34	pf

At very high frequencies, especially radio frequencies, the grid to plate capacitance can give rise to an oscillation problem. The varying plate voltage is coupled back to the grid and re-amplified. It is kind of an internal feedback loop inside the tube. Luckily, we do not have to worry much about this, since a guitar amplifier is not designed to amplify radio frequencies.

In fact, the AX84 is designed to filter out frequencies above the audio range. Take a look again at Preamp Stage 1. We never did talk about the real purpose of R9. This 68K ohm resistor (called the grid stopper) forms a low pass filter when combined with the capacitance between V2B's grid and cathode. This low pass filter has a cutoff frequency well above the audio range, so it should not interfere with guitar frequencies.

The grid stopper resistor has a second purpose, which is to limit the grid current when the grid voltage is more positive than the cathode voltage. The explanation is a bit technical, but it is well worth learning.

Suppose that you are driving the amp with a hot signal, such as a high-output humbucker. As you turn up the volume control on the amp, the AC voltage applied to the EL84's grid increases. At some point, the positive peaks of this AC voltage will exceed the cathode voltage. As I mentioned earlier, normally there is very little current that flows out of the grid in a tube. This is only true when the grid voltage is less than or equal to the cathode voltage. Once the grid voltage exceeds cathode voltage, current starts to flow INTO the grid. In essence, the grid and cathode behave as a diode. Almost instantly, the tube stops amplifying the signal. This is called blocking distortion. Now this condition does correct itself rather quickly if the grid stopper resistor is large enough. The grid stopper limits current flow into the grid when blocking distortion occurs, which reduces the time it takes the tube to recover from this condition.

Another limitation of triodes is that plate current depends not only on grid voltage, but also on plate voltage. For example, suppose you lower the grid voltage in a triode circuit. As we learned above, lowering the grid voltage results in an increase in plate current. And Ohm's law dictates that the voltage across the load resistor must increase as current through it increases. Now, the supply voltage is a constant, so the plate voltage must decrease as the voltage across the load resistor increases (the two voltages must add up to the supply voltage). Lowering the plate voltage results in reduced plate current. So, gain is kept down in a triode because of this. In a preamp stage, reduced gain presents no problem because we have to 'throw away' some of the gain between stages to prevent blocking distortion. However, in an output stage, interaction between plate voltage and plate current is not good - it only reduces the maximum output power of the amp.

OK, so triodes have two limitations that cause problems: interelectrode capacitance and the degenerative feedback thing. To eliminate these problems, early tube designers developed the tetrode. A tetrode is like a triode, with an extra element between the grid and plate. This fourth element is called the screen grid.

The tetrode's screen grid solves both problems with the triode. Adding an element between the grid and plate serves to act as a shield between the grid and plate, lowering the grid-plate capacitance. And the screen grid makes plate current independent of plate voltage (well, almost completely, but close enough for this discussion).

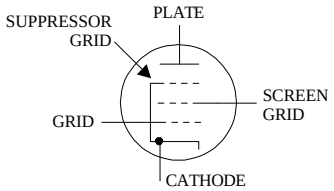
How does it do this? Remember our discussion of rectifier and triodes. The electrons streaming off the cathode are attracted to the plate, because the plate has a positive voltage potential compared to the cathode. You could say that the plate exerts a pulling force on the electrons. In a tetrode, the screen grid is operated at a voltage that is slightly less than the plate voltage. Now, because the screen grid is physically closer to the cathode than the plate, the screen grid exerts more pull on the electrons than the plate. Some of the electrons actually hit the screen grid, but most pass right through on the way to the plate. Thus, plate voltage has very little effect on electron flow in a tetrode. The steady voltage of the screen grid provides a nearly constant pulling force on the electrons. As a result, the grid has almost complete control over plate current, regardless of changes in plate voltage.

While we are talking about electrons whizzing around inside a tube, now is a perfect time to discuss the main limitation of a tetrode. Imagine what happens to an electron inside a tetrode tube. It gets knocked out of the cathode because of the heating effect of the filament. Then, the pull of the screen grid makes it speed away from the cathode. It accelerates past the grid and the screen grid. The short trip is over when it smashes into the plate. This impact actually causes some electrons to be knocked out of the atomic structure of the plate. For every electron that smashes into the plate, two or three electrons are knocked out of the plate.

We're talking about particle physics here! Impress your friends: tell them that small particle accelerators power your amp.

This phenomenon is called 'Secondary Emission'. Now, in a triode, the liberated plate electrons quickly make their way back to the positively charged plate. However, secondary emission can cause gain reduction and distortion in a tetrode. Suppose that a large signal is applied to the grid in a tetrode. Such a large signal could cause the plate voltage to fall below the screen grid voltage temporarily. At that instant, the secondary emission electrons would be attracted to the screen grid, and not make their way back to the plate. This would reduce the plate current and increase screen grid current, clipping the peak of the amplified signal.

To solve this problem, the pentode was developed. In a pentode, a third grid is inserted between the screen grid and the plate. This new element is called the 'Suppressor Grid'. It is usually connected to the cathode, sometimes internally. This connection means that the suppressor grid is at a voltage potential much lower than the plate. It does not interfere with the flow of electrons from the cathode, because these electrons are traveling at such a high velocity that they pass right through. However, secondary emission electrons travel at a much slower velocity and are pushed back to the plate rather easily.

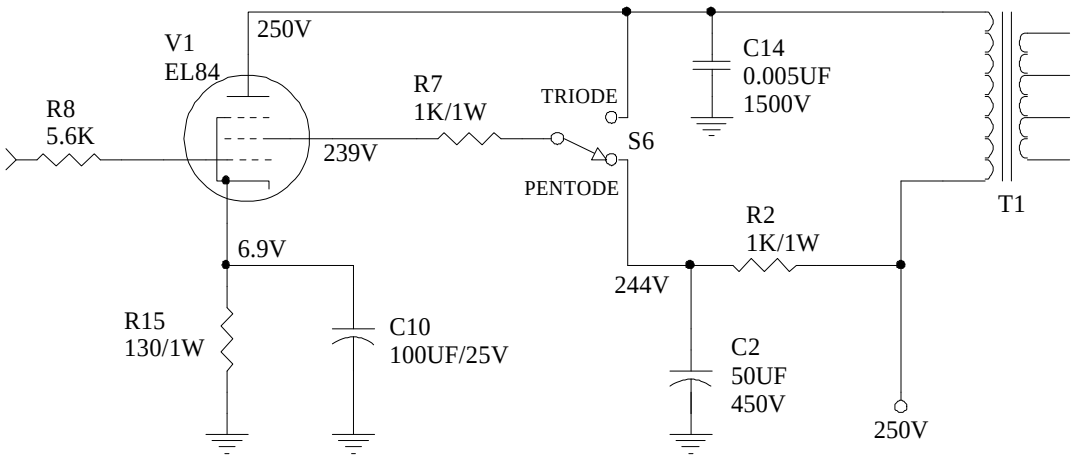


PENTODE

Thus ends our discussion about pentodes. Now, we can take an informed look at the output section of the AX84.

OUTPUT STAGE

Let's look at the output stage of the AX84. V1 is an EL84 wired as a cathode biased, class A, single ended output stage. Any good electronics book will have a detailed explanation of the different classes of amplifiers, so we won't be discussing that here. We have already discussed cathode biasing. Single ended describes an output configuration where one or more tube is connected to the one terminal of the load - in this case the output transformer. The other terminal of the load in a single ended amp is connected to the power supply.



R8 is the grid stopper resistor that is necessary to reduce blocking distortion when overdriving the EL84 grid.

Attached to the cathode of V1 is a circuit almost identical to the cathode circuit of the preamp stages. R15 is the cathode resistor, chosen to set the proper bias current. C10 is the cathode bypass cap.

Calculating the gain of the Output Stage is not really necessary. The design goal is not to provide a certain amount of gain, but to provide the maximum amount of amplification without burning up the tube. This is accomplished by setting bias correctly. Since the AX84 is a single ended class A amp, the output tube must be biased approximately half way between cutoff and saturation. Remember that cutoff is achieved by making the grid voltage sufficiently negative with respect to the cathode such that current does not flow through the tube. Saturation in a tube occurs when the grid voltage is equal to the cathode voltage.

NEW IN REV 10:

A new capacitor was added to the circuit: C14. This capacitor filters out some of the high frequencies. Some of the other tweaks mentioned earlier reduced bass response of the previous stages, so this addition helps balance the tone. Having a capacitor on the power tube plate is an ideal place to filter out excess highs.

The Gain switch (S2) was removed. The prototype builders did not like the tone when C10 was switched out of the circuit, so this feature was eliminated.

R7 was increased to 1K, slightly reducing screen grid voltage and current. This was done to simplify the mods required to use a Svetlana SV83 tube.

Now, to use an SV83 in place of the EL84, simply change R2 to 10K/1W. This will lower the screen grid voltage to within the SV83's safe operating limits. (SV83 max. screen grid voltage = 200V)

Keeping the tube from burning out is the most important issue to address when designing an output stage. Set the bias too far positive, and the tube will fail as it attempts to dissipate all that power. Remember from your basic electronic theory: P = I * E (power equals current times voltage). It is very simple to determine the power dissipated in a cathode biased tube stage such as the AX84 output stage. Since all the current in the tube must flow through the cathode resistor, divide the cathode voltage by the cathode resistor value to determine cathode current. Cathode current in tube V1 equals plate current plus screen grid current. According to the EL84 datasheet, screen grid current is typically 5mA when plate and screen grid voltage are both 250V. The actual screen grid voltage is less here, but it is close enough for our calculation.

Let's look at some more math:

$$\text{Plate Current} = \text{Cathode Current - Screen Grid Current}$$

The cathode current is easy to determine using a voltmeter:

$$\text{Cathode Current} = \frac{\text{Cathode voltage}}{\text{Cathode Resistor Value}}$$

And if we assume there is about 5mA going into the screen grid, plate current is easy to derive just from the voltage measured across the cathode resistor:

$$\text{Plate Current} = \frac{\text{Cathode Voltage}}{\text{Cathode Resistor Vaulue}} - 5\text{mA}$$

Plate dissipation can then be determined if you know the plate to cathode voltage:

$$\text{Plate Dissipation in Watts} = (\text{Plate Voltage - Cathode Voltage}) \times (\text{Plate Current})$$

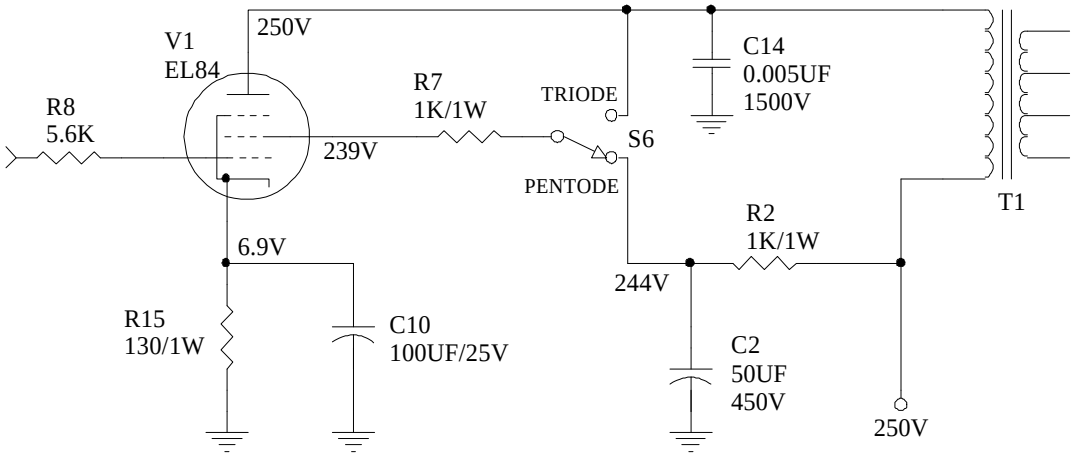
The datasheet indicates maximum plate dissipation for an EL84 is 12W. If we assume the voltages on the schematic will be the voltages measured in the actual circuit, the plate dissipation will be about 11.7W. Do not assume that your amp will behave exactly like this. It is very important that you measure the actual voltages and do the math. An EL84 with slighly higher gain will result in more plate current for a given grid voltage, and could be damaged if plate dissipation exceeds 12 watts. Increasing the value of the cathode resistor will decrease plate current. It is not a problem to run the tube slightly cold, in fact you may want to do this if you are using an expensive NOS EL84.

Again, I cannot stress this enough - check the bias current and adjust R15 as necessary. If you don't, you may burn up your EL84. When you switch tubes, do the measurements and the math. 'Nuff said.

Let's look at the PENTODE/TRIODE switch and R7. In PENTODE mode, the right side of R7 is connected to the 244VDC supply. The hefty filter capacitor (C2) keeps this voltage very steady. The left side of R7 connects to the screen grid of V1. Although R7 does drop the screen grid voltage slightly in PENTODE mode, R7's main purpose in this mode is to limit screen grid current. The screen grid in pentode mode behaves as described above - it provides a steady 'pull' on the electrons flowing thought the tube, making the plate current almost independent of plate voltage.

Now, in TRIODE mode, the right side of R7 is connected directly to the top of the output transformer. R7 limits the screen grid current and insures the screen grid voltage is slightly below plate voltage. In this mode, the screen grid acts like a second plate.

There is noticeable difference between the sound of triode and pentode modes in the AX84. The trode mode will give less volume and a different distortion sound than the pentode mode.



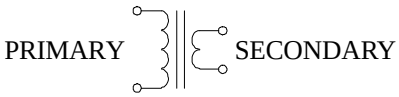
OUTPUT TRANSFORMER

The output transformer is one of the least understood components used in a tube amp. The construction is fairly simple: two coils of wire wound around a magnetic core. The coil on the input side is called the primary. The coil on the output side is called the secondary.

The name transformer is descriptive of its function - it performs a transformation of the voltage and current from the input to the output. For instance, in the AX84, the output transformer converts the high-voltage low-current output from the output tube to a low-voltage high-current signal suitable to drive a loudspeaker. Here are some basic transormer formulas:

$$\frac{\text{Primary AC Voltage}}{\text{Secondary AC Voltage}} = \frac{\text{Primary Turns}}{\text{Secondary Turns}}$$

$$\frac{\text{Secondary AC Current}}{\text{Primary AC Current}} = \frac{\text{Primary Turns}}{\text{Secondary Turns}}$$



TRANSFORMER

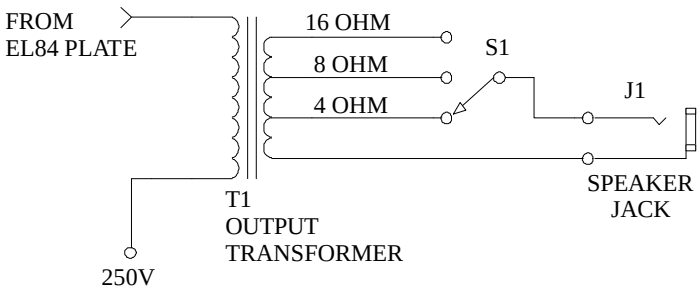
The formulas above assume an ideal transformer with no losses, but are close enough for our purposes here.

In a tube amp, the most important job of the output transformer is to reflect the low speaker impedance into a high impedance load needed by the output tube. A transformer alone has no primary or secondary impedance, it has a impedance ratio. Look in a tube amp parts catalog and you will see the primary and secondary impedances specified. Here is the formula:

$$\frac{\text{Primary Impedance}}{\text{Secondary Impedance}} = \left(\frac{\text{Primary Turns}}{\text{Secondary Turns}}\right)^2$$

Suppose you buy a transformer with the following specifications: 4K Ohm primary, 8 Ohm secondary. The turns ratio is:

$$\frac{\text{Primary Turns}}{\text{Secondary Turns}} = \sqrt{\frac{4000\ \text{Ohms}}{8\ \text{Ohms}}} = \sqrt{500} = 22.36$$



If you were to use a 4 ohm speaker with this same transformer, the impedance reflected on the primary would be 2K Ohms.

$$\frac{\text{Primary Turns}}{\text{Secondary Turns}} = \sqrt{\frac{2000\ \text{Ohms}}{4\ \text{Ohms}}} = \sqrt{500} = 22.36$$

The output transformer shown in the AX84 schematic has a 16 ohm secondary with taps at 8 and 4 ohms. Assuming you connect your speaker to the appropriate tap, the primary impedance will be 4000 Ohms. The primary impedance was not chosen by accident, the value is taken from design examples in the EL84 datasheet that are similar to the AX84 output stage (250V plate current, 48mA plate current, etc.). The general rule of thumb for a one-tube single ended output stage is to use a transformer with a primary impedance approximately 1/10th of the specified plate resistance.

An output transformer in a tube output circuit forms a band pass filter. For those interested, here are the formulas for calculating the corner frequencies:

$$\text{Lower - 3db Point} = \frac{Ra}{2 \times Pi \times L}$$

$$\text{Upper - 3db Point} = \frac{Rb}{2 \times Pi \times Ls}$$

Where:

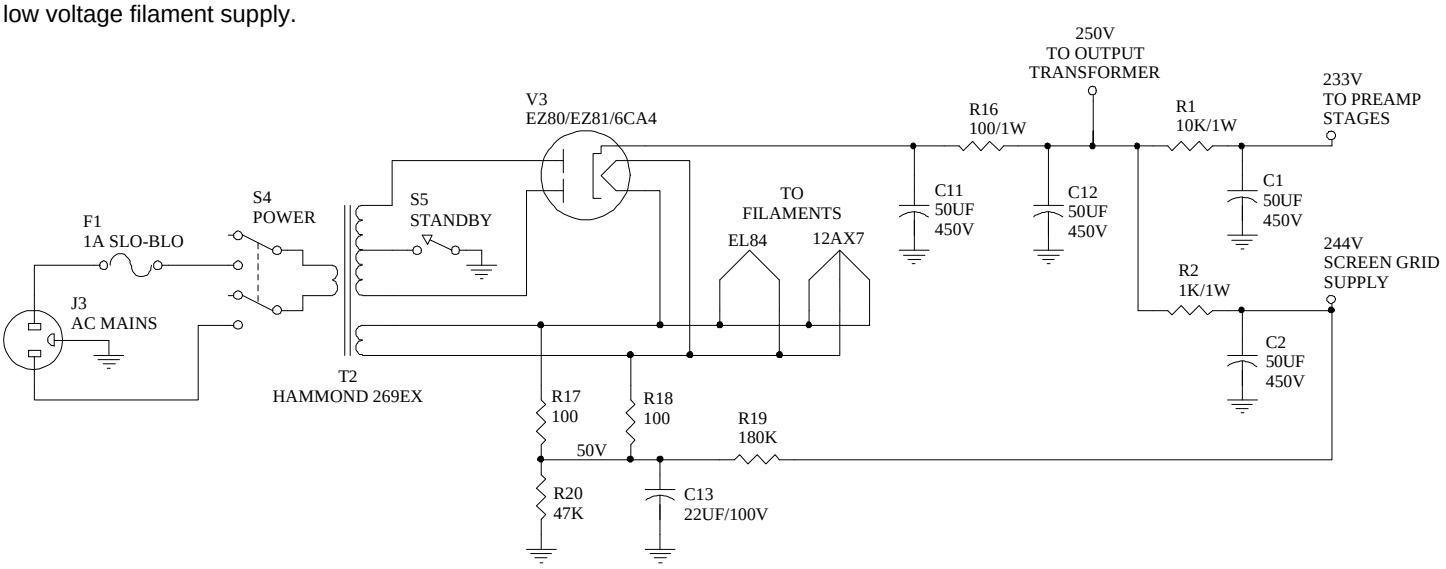
$$Ra = \frac{(rp + Rw) \times Rl}{rp + Rw + Rl}$$

$$Rb = rp + Rw + Rl$$

rp = plate resistance
Rw = primary DC winding resistance
Rl = reflected load resistance
L = primary inductance
Ls = total transformer leakage inductance referred to primary side

POWER SUPPLY

The power supply in the AX84 is a great example of a simple full-wave tube rectifier. The power transformer has two secondary windings, one is center tapped high voltage that provides the B+ power to the preamp and output stage, and the other secondary is a low voltage filament supply.



First, let's look at the B+ supply. The center tap of the power transformer high-voltage secondary winding is connected to ground through a switch. Opening the switch breaks the ground connection to the center tap - effectively turning off the supply voltage except for the tube filaments. This is the Standby switch, and is extremely important to prevent damage to the amp, especially if you use silicon rectifiers in the supply.

Consider what happens when a tube amp is turned on with the standby switch closed. The filaments inside the preamp and power tubes are cold, so no current flows from the plate to cathode. With silicon diodes as the rectifier, the B+ voltage jumps to full value almost instantly when power is applied. Remember when we determined the voltages present on the plates of the preamp tubes by multiplying current by the value of the plate load resistor. Well, when no current is flowing through the tube, there is no voltage drop across the plate load resistor. So, a fraction of a second after the power switch is thrown, the voltage at the plates rise to full power supply value. Ouch! A couple bad things happen. The coupling capacitors are subjected to the full B+ value, which is why all coupling caps in a tube amp should be able to withstand the full B+ voltage. More importantly, the bias voltage will be zero! No current through the tubes means no current through the cathode resistor. Once the cathode heats up enough, current will begin to flow through the tube. At that instant, there is full B+ on the plate, and zero bias voltage. Ouch again! (Go back a few pages and look at the12AX7's Ep-Ip chart – try to find the Ip at Ep=250v and zero grid voltage – it is off the scale!)

NEW IN REV 10:

A new capacitor was added to the circuit: C13. This capacitor eliminated the power supply hum present at the junction of R19 and R20. Without C13, there was just too much hum getting into the preamp stages.

In the previous schematic, R1 was placed in series with R2. This was not actually a problem when using an EL84, but when R2 was changed to a 10K resistor necessary to use the SV83, there was a 50V drop in plate voltage at the preamp stages. Moving R1 to be in parallel with R2 guarantees that changes in R2 will not affect the voltages of the preamp stages.

Again, to use an SV83 in place of the EL84, change R2 to 10K/1W. This change will lower the screen grid voltage to within the SV83's safe operating limits.

Using a tube rectifier helps minimize this potential problem (pun intended). Just like the preamp and power tubes, a tube rectifier has to heat up before current flows through it. Thus, tube rectifiers have an inherent soft-start behavior. Nevertheless, make sure you build your amp with the standby switch, and use it.

Each side of the high voltage secondary connect to a plate on the rectifier tube. The 6CA4/EZ81 tube is a dual rectifier. In the AX84 circuit, it functions as a full wave rectifier. The rectifier tube was discussed much earlier in this document, where it was described as a one-way valve. Current flows from the plates to the cathode in a rectifier tube.

Now, the output voltage at the cathode has a tremendous amount of power supply hum. This hum must be filtered out. C11 provides the first bit of filtering. In short, it smoothes out the ripples present on the rectifier tube cathode. A capacitor used for filtering is appropriately called a filter cap. In many situations, a small capacitance value filter cap can be safely replaced with a filter cap with more capacitance. However, it is very important not to use too large of a cap immediately after a tube rectifier. This first filter cap puts stress on the rectifier tube. Too large a cap here will destroy the rectifier. (This is not a concern with silicon diodes).

After the first filter cap, there is an RC lowpass filter built from R16 and C12. These two components smooth the B+ voltage even more, and drop the voltage slightly. C12 can be increased safely without stressing the rectifier tube. The output of this filter supplies the main B+ to the output stage.

Downstream from this first low pass filter is another RC filter built from R2 and C2. R2 lowers the voltage a tad, and C2 smoothes the voltage. The output of his filter supplies power to the screen grid when the amp is operating in Pentode mode.

Finally, a RC filter is built from R1 and C1. The output of this filter must be hum free because it supplies power to the preamp section. Any noise or hum on the power supply here will be greatly amplified.

FILAMENT SUPPLY

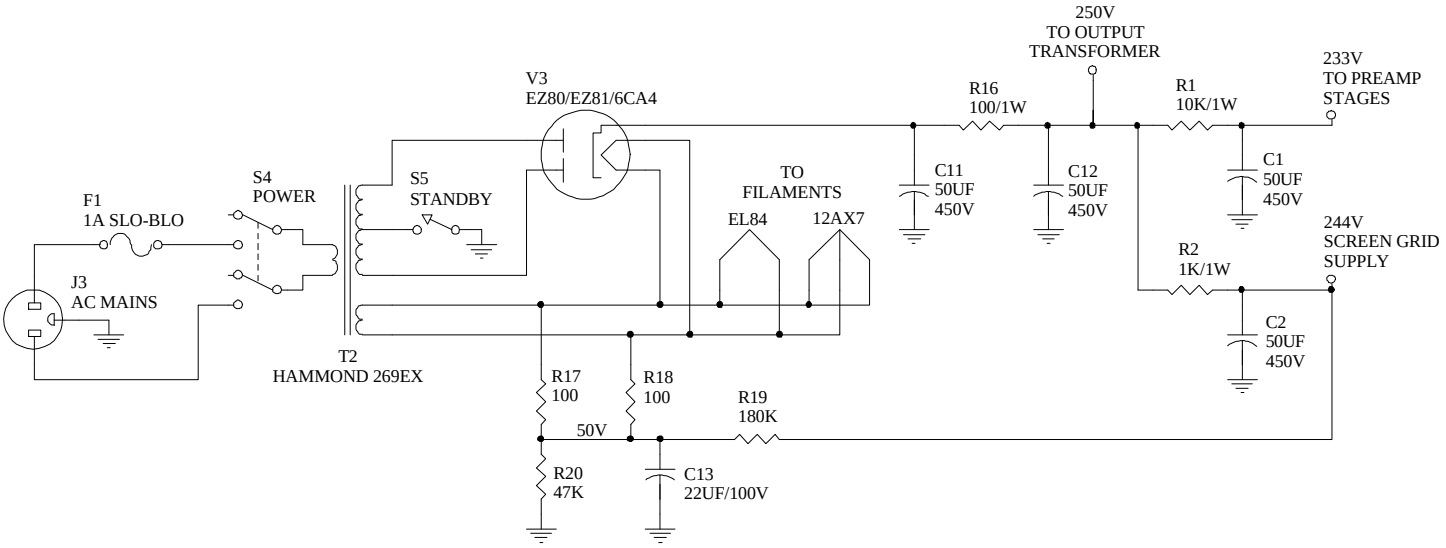
The other secondary of the power transformer supplies 6.3VAC to the tube filaments. When designing an amp, it is important to select a power transformer that can provide the current required by all the filaments. The Hammond 269EX can supply more than enough current for this little amp.

If you have looked at schematics of other guitar amps, you probably have seen 100 ohm resistors connected between each side of the filament supply and ground. These resistors would provide a ground reference for the filament voltage. It is important to provide a reference point for the filament supply, but there is a problem when this reference is the same as the amps ground reference.

To understand this, we have to go back to our tube theory. Remember that a heated cathode emits electrons. In fact, the cathode has a coating of material that is very good at spewing off electrons when heated. Even though the filament does not have this same coating, it does emit a field of electrons during normal operation. This is called an e-field. Since the filament is connected to unrectified 6.3VAC, this e-field will have a 60Hz 'signature'. For at least part of each 60Hz cycle, this e-field will have a potential that is less than the voltage present on the cathode and grid in our 12AX7 stages. During this time, a some electrons in the e-field will be attracted to the cathode and grid. The end result is power supply hum being introduced into the preamp stages.

The AX84 design uses a clever technique to avoid this problem. Instead of having the filament supply referenced to ground, it is referenced to a positive voltage. This is accomplished by using a voltage divider. Look at the schematic below. R19 and R20 form a voltage divider, dividing the 244V screen grid supply voltage down to about 50V. C13 is a filter cap which makes certain this 50V reference contains no power supply (or other) noise.

Each side of the filament supply is connected through 100 ohm resistors to this 50 volt reference. With this 50V reference, the e-field emitted by the filament stays where it should stay – close to the filament.



CREDITS

This document contains material from the following sources:

Ameco Ameteur Radio Theory Course
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Simple Tube Gain Calculations
(Online document)
By Steve Bench

Various posts from rec.audio.tubes and alt.guitar.amps by the following authors:
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