Tube Amplification Guitar Pedal

Rishi Nandha V

With Guidance & Help from Mr. Peter Bossier and Mr. Bart Boydens

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1 Background

Before the age of semiconductors, for the purpose of signal amplification, Vacuum Tube Triodes were used. These got replaced by transistors eventually due to the uncertainity in behaviour of these tubes and the variation induced by the surroundings of the Tube. Nevertheless, a good amount transistor circuit design ideas originate from our experience with these Tubes that preceded them: Class-A and Class-AB amplifiers especially.

Although these Tubes are deprecated in most electronics applications, these are particularly sought after in the Music world. The iconic "distortion" sound that guitarists use til-date is but an artefact of amplification using such tubes. The classic amplifier heads used in the 80s and 90s were all using tubes and rectifiers to process the signal that comes out of a guitar, and are considered the peak of guitar signal processing even today.

Even though amplifier simulations model this distortion from the tubes well, there is still some scope to try out using actual tubes to do the same. Moreover, with the amount of transparency that has been achieved today with solid state or digital amplifiers and nearly-flat response speakers, the iconic "distortion" sound could potentially be captured in a guitar pedal that adds a pre-amplification audio effect instead of a full-size amplifier head. Hence we try to build a Guitar Pedal with a Tube Amplifier with knobs controlling key parameters that affect the response.

2 Schematic Design

We divide the schematic into 5 sections for convenience:

1. Input Stage
2. Tube Amplification Stages
3. Tone Control
4. Output Stage
5. Power Regulation

2.1 Input Stage

The Input Stage includes a fuse and a non-inverting Op-Amp amplifier. This stage is connected with a dual switch to bypass it when we choose to. This stage is to be used **1.** When we are still prototyping and testing the tube stage of the circuit just so that any human error won't affect the Guitar's electronics or **2.** When we need more control on the Input Volume that is being fed into the Tube Amplification Stage. In cases when this stage is not absolutely necessary, we bypass it so as to cut down on the noise introduced by this stage.

The fuse is essentially a measure to protect the guitar from any large surge of current in case the experimentation in the pedal main amplification stages causes one. This is followed by biasing the signal to a DC value of 6V so that we can use the Op-Amp with just our 12V and GND lines as the power lines. The non-inverting amplifier with a potentiometer in the feedback path lets us control the input volume that is being fed into the grid of the first tube amplification stage thus giving us more control on over-driving the tube or not. Moreover a non-inverting amplifier is chosen so that the amount of current drawn from the guitar pickup itself is minimized.
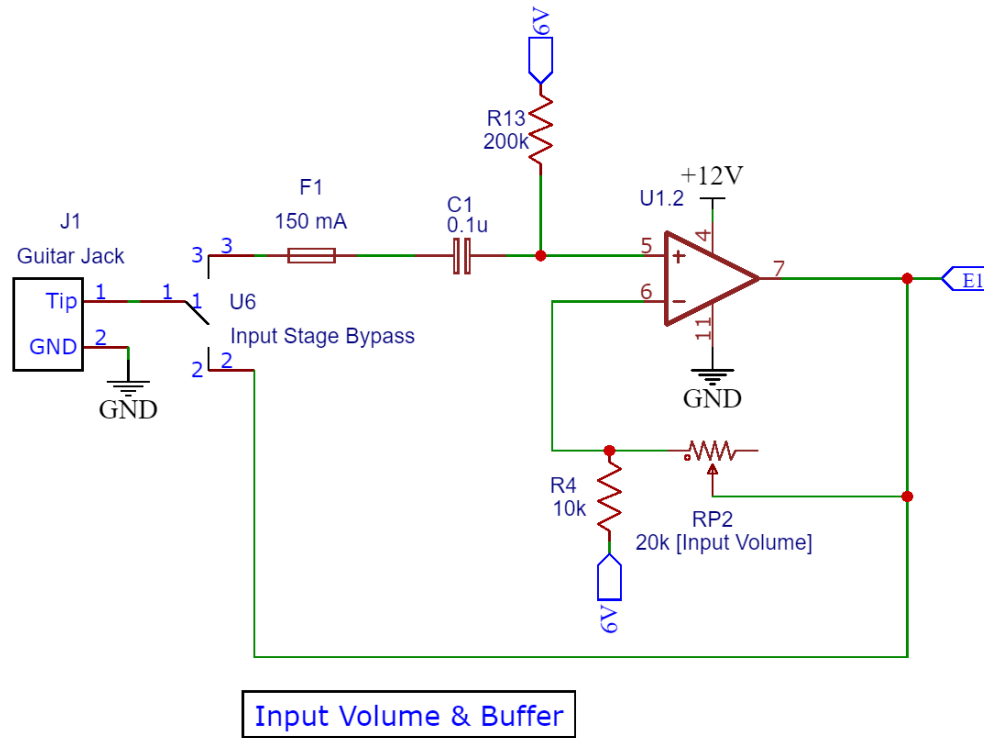

Figure 1: Schematic - Input Stage

As for the values of used, we estimate that 150mA is a safe amount of current to flow (even though not much should flow because we have connect it such that not much current will flow). The non-inverting amplifier's R1 and RP2 values are chosen to emulate the typical range of the output impedance of guitar pickups ($5k\Omega - 25k\Omega$). Moreover, R4 is chosen to allow an input volume control from $1\times$ to $3\times$. Note here that Guitar Signal can be anywhere from $100mV - 1V$.

2.2 Tube Amplification Stages

Let us motivate how a tube works a little before diving in. The tube's cathode is heated with the rated voltage to initiate electron generation. The relative voltage between the anode and cathode drives current flow. This is controlled using the potential at the grid that comes in between the cathode & anode, which resists the flow from cathode across itself before it reaches the anode.

The tube amp stage consists of two **Class-A Amplifiers** (See the figure below). The tube's three terminals are biased to a DC point of operation by setting the resistances and V_A. The point of operation is decided against the characteristic in the data-sheet based on the desired small signal behaviour.
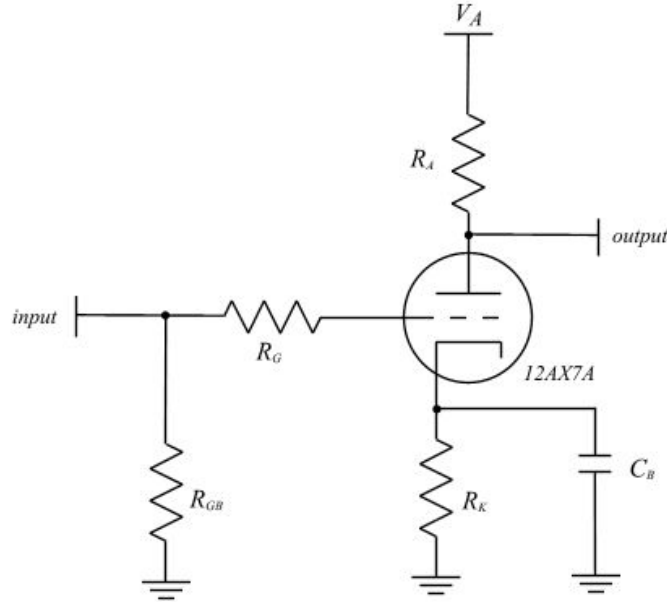

Figure 2: Class-A Tube Amplifier

Going in an orderly fashion from left to right: R_{GB} must be a high resistance that makes the input impedance large ("Hi-Z") and sets the grid's DC point at $0V$. R_G is used to damp oscillations higher than 20kHz. To explain this, we think about what happens once we amplify the AC small signal, the amplified output will cause miller effect making the parasitic capacitance C_{GA} between grid and anode in the tube a large capacitance with which R_G interacts to give a dominant pole in the system. R_K is used to bias the Cathode. R_A is used to bias the Anode and control the small signal gain . We'll discuss the exact calculation of these two resistances soon. C_B is essentially a decoupling capacitor (In-fact, we'll benefit from having several different valued capacitors in parallel combination in-place of C_B).

Let us calculate two different set of values for the resistances by setting the value of $V_a = 140V$ as our starting point: One for a fairly clean tone; One for a characteristic distorted tone. This choice of V_a allows for a maximum output voltage a $140V$ after the two amplification stages and anymore will clip. Then let us add potentiometers to switch between the two accordingly and resistance values that work for both of them accordingly. Note that the second stage is just the first stage without the input handling, hence we use the same values for both. Also we can set $R_{GB} = 1Meg$; $C_B = 33\mu$ for both cases. Before we dive into the calculations we also attach the important characteristics from the 12AX7 data-sheet that we will be constantly referring to for calculations purposes.
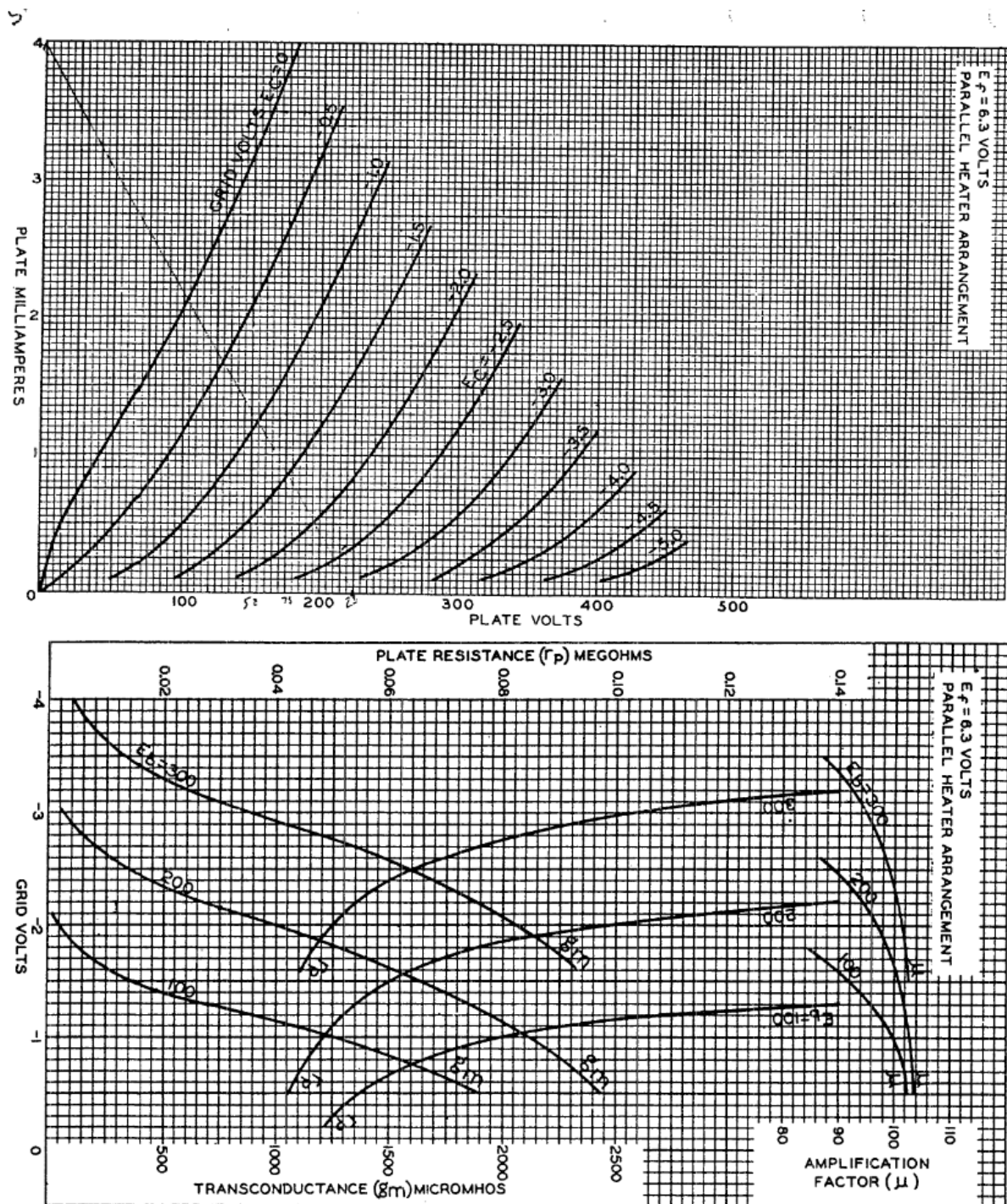
Figure 3: 12AX7 Characteristics

Note here that operating in the fairly linear part of each line given in the first graph gives us a fairly clean tone. And the distorted tone is achieved by operating at the bottom parts of the graph, which is essentially where the non-linear effects are happening and harmonics of the signal will be generated. This harmonics generation is the very reason why we are choosing to use Tubes to process our Guitar.

2.2.1 Clean Tone

Let us begin with setting Plate Voltage (Anode - Cathode) $= 100V$ because of having concrete data to work with. Similarly the grid bias could be chosen to be $-1V$. This sets us into a region on the first graph where the behaviour is fairly linear. We need to define small signal gain A_v. The small signal equation for the Tube Class-A Amplifier is:

$$i_p = \left(-\frac{v_{\text{out}}}{R_A}\right) = g_m v_{\text{in}} + \left(-\frac{v_{\text{out}}}{r_p}\right)$$

$$\implies A_v = g_m \left(R_A \parallel r_p\right)$$

According to the first graph, for $100V$ DC plate voltage and $-1V$ DC grid voltage, we will have a plate current of $0.5mA$. Which implies that:

$$R_A \left(\frac{0.5}{1000}\right) = 140 - 100$$

And also implies that

$$R_K \left(\frac{0.5}{1000}\right) = 1$$

Thus for $V_A = 140V, E_P = 100V, V_G = -1V$, we have:

$$\boxed{R_A = 80k\Omega \quad R_K = 2k\Omega}$$

According to the second graph, we have $g_m = 1250 \cdot 10^{-6} \ \Omega^{-1}$ and $r_p = 80k\Omega$.

$$A_v = 1.25 \cdot 40 = 50$$

Clipping occurs when $100 + 50V_i < 140V$ as long as the input is smaller than 0.8V, which it is. Further, for the choice of R_G we need to consider the parasitic capacitance between the Anode and Grid $C_A G$ (found in the data-sheet) which due to miller effect will have an apparent capacitance of $A_v C_{AG}$. Although the exact transfer function between the input and the output is complicated, we can simply mention here without proof that the dominant pole is associated with the interaction of R_G and $A_v C_{AG}$ hence we choose an R_G such that

$$\frac{1}{2\pi R_G(50)C_{AG}} > 20kHz \implies \boxed{R_G < 93k}$$

2.2.2 Distorted Tone

Like mentioned earlier we need to operate at the bottom non-linear region of the characteristics. Let us proceed by choosing the operating point of $I_P = 0.25mA$, with $V_G = -1V$ and $V_P = 75V$. This is a nice common point for us since it lies almost right in between our dynamic range.

$$R_A \left(\frac{0.25}{1000}\right) = 140 - 75$$

And also implies that

$$R_K \left(\frac{0.2}{1000}\right) = 1$$

Thus for $V_A = 140V, E_P = 75V, V_G = -1V$, we have:

$$\boxed{R_A = 260k\Omega \quad R_K = 5k\Omega}$$

Second graph doesn't have data for our chosen point of operation direction. But since visually the curves seem as if the E_P is just shifting the curves to the left, let us proceed with the same assumption. Thus we can estimate $g_m = 0.775 \cdot 10^{-6} S$ and $r_p = 120k\Omega$

$$A_v = 0.775 \cdot 82 = 63.55$$

So we need to have $75 + 63.55 \cdot V_i < 140$ which will hold good. And for R_G, we have:

$$\frac{1}{2\pi R_G(63.55)C_{AG}} > 20kHz \implies \boxed{R_G < 73k}$$
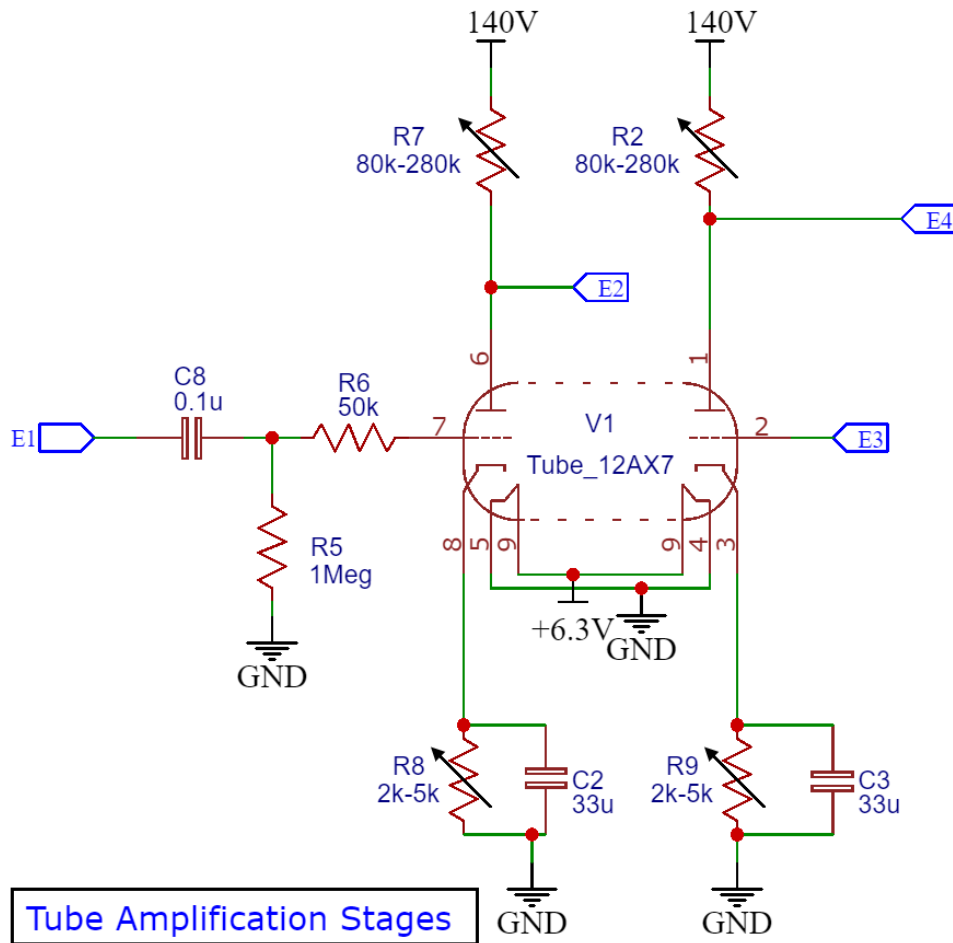
2.3 Combining Both

Figure 4: Schematic - Tube Amplification Stages

In the above schematic, R_G was chosen to be $50k$ just to be on the safer side with not scooping out audible frequencies. R_K has been made a combination of a $2k\Omega$ resistor and a $3k\Omega$ potentiometer. R_A has been made a combination of an $80k\Omega$ resistance and a $200k\Omega$ potentiometer. This allows us to transition to both the configurations with also an option to explore other possibilities like reducing the grid bias alone while keeping the R_A unchanged or changing R_A alone while keeping R_K unchanged.

2.4 Tone Control

For tone control we aim to have one knob that takes the response form a bass-heavy to a high-presence. To achieve this with only passive elements, a decent amount of hit-and-miss was used by simulating different ideas and values in LTSpice. This was achieved using LTSpice:
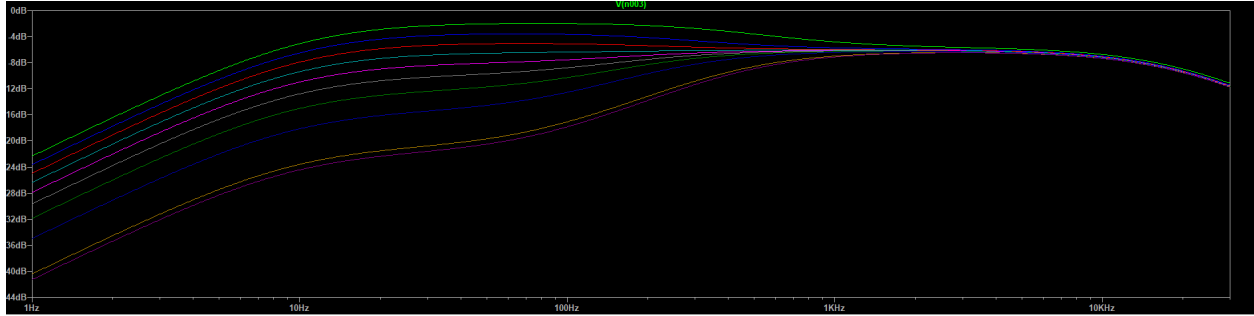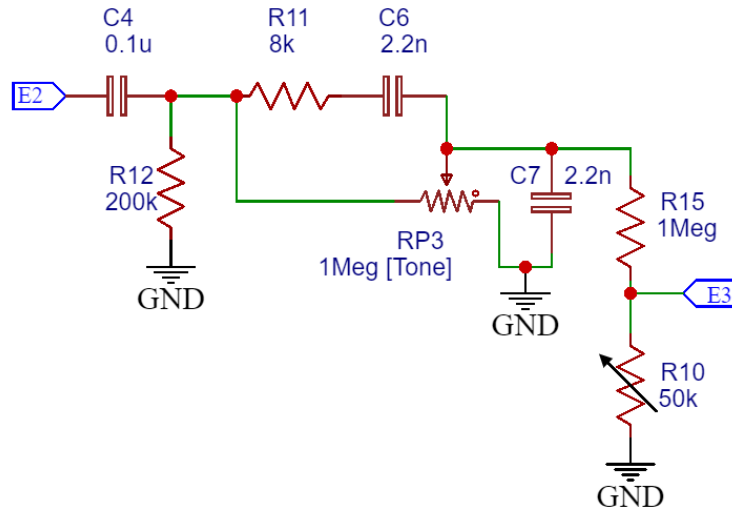

Figure 5: Tone Control Response

Figure 6: Schematic - Tone Control

Although this was achieved with hit-and-miss and LTSpice simulation, this isn't to say there is not motivation behind this. Note that we can't use a simple bandpass owing to the fact that the signal coming out of the amplifier's first stage has a passive highpass for AC coupling. But we can try to cascade this with two paths resembling a low pass and a high pass respectively but with a potentiometer to control the response and a resistance in series with C6 to avoid having a purely capacitive path (otherwise AC coupling won't happen). We include the transfer function below for completeness.

$$\text{Work} = \frac{\text{In}}{\text{Progress}}$$

Note here that the signal was amplified to almost 50 to 65 times in the first tube stage. Hence we need to attenuate it at the end. Thus there is a 1 Meg resistance in series with a $50k\Omega$ potentiometer to do the attenuation but also give some control on how much the second stage is driven.

2.5   Output Stage

By the time we reach here we have amplified our signal by another factor of 50 or so, which is possibly not what a digital practice amplifier or any home speaker is designed to take. This is the distinction between building a pre-amplifier for an upcoming power amplification stage and building a guitar pedal. The output stage includes a powered path and a passive path. We use the powered path **1.** When we are still prototyping and need to protect the amplifier with a fuse until the circuit is tried and tested or **2.** When our practice amplifier is not a "Hi-Z" amplifier in which case the current through the Amplifier will affect our 2nd Tube stage. When the powered path isn't necessary we switch to the passive path so as to cut down on the noise introduced by the powered amplification and fuse.
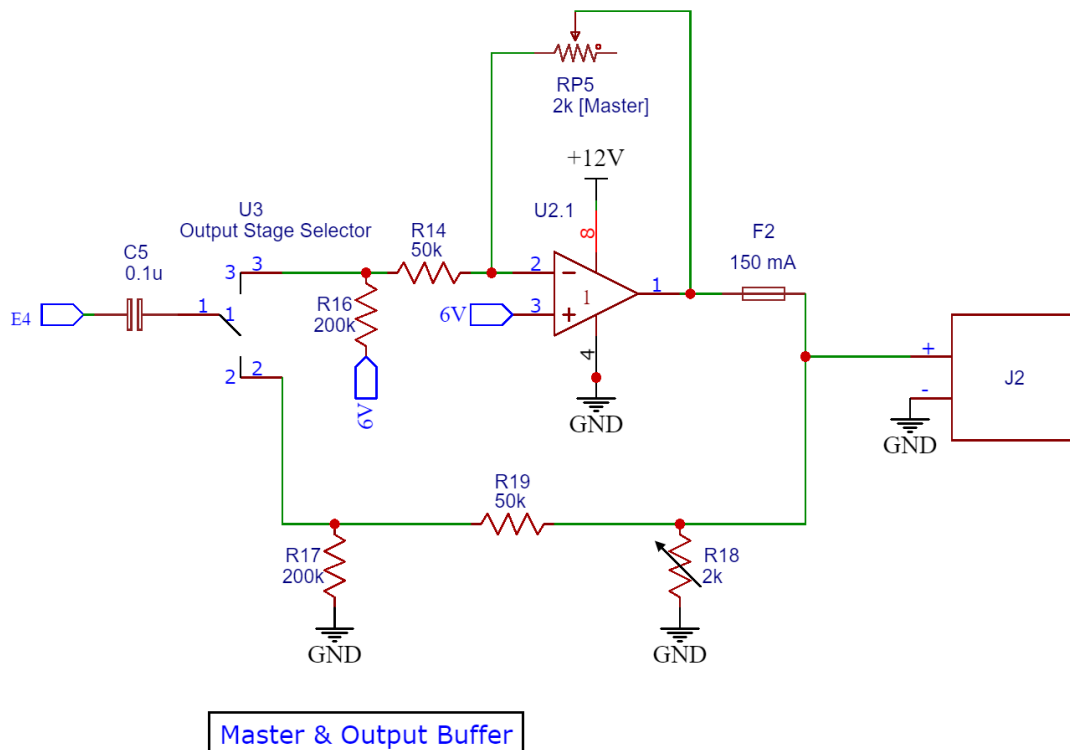

Figure 7: Schematic - Output Stage

The values of potentiometers and resistances were decided so as to give us a master volume factor between 0 to about 0.04.

2.6   Power Regulation

12V, 6V, 140V, 6.3V are all the four power lines required in the pedal. Since tubes consume a lot of energy, taking these off from 9V batteries is infeasible, hence we are left with options to either use transformers with AC or use DC adapters and then use DC-DC converter. Since the latter is a more handier option, we'll proceed with it. Below are the methods used to get these power lines.
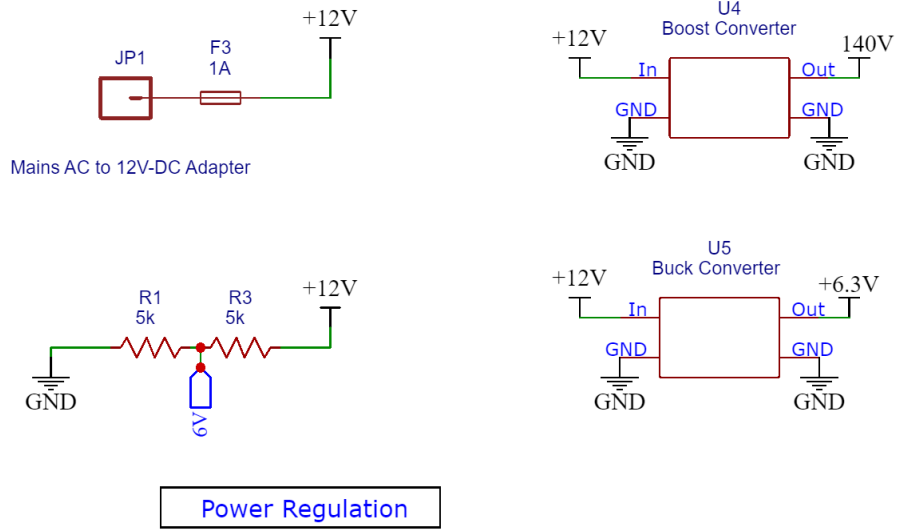
Figure 8: Schematic - Power Management

3 Methodology & Practical Implementation

4 Results