Tube Vs. Solid State Rectifiers for Tube Amplifier Power Supplies

Tube rectifiers are the simplest type of vacuum tube since they are two-element devices, or diodes. They provide no amplification or signal control. In comparison, triode tubes, pentodes, beam pentodes, and beam tetrodes are most commonly used in amplifying and output power stages.

As the name suggests, the tube rectifier acts as a diode to pass current in one direction. They are used to convert or rectify AC voltage to pseudo DC voltage. I say pseudo since the output of a rectifier varies with time. However, unlike AC from an outlet, the blockage of current in one direction ensures that the signal never goes negative relative to ground. Therefore, we can use capacitors to filter and hold the average voltage of this wave to create a DC power supply from an AC source, since the average voltage value is net positive.

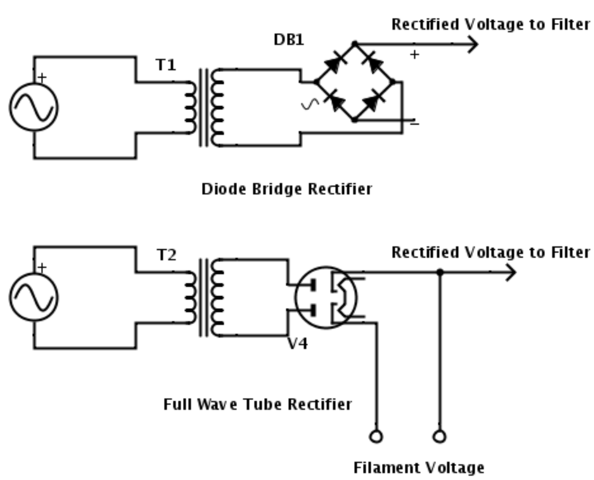

Figure 1: Diode Bridge and Full Wave Tube Rectifiers

Figure 1 shows a typical linear power supply arrangement where the AC wall voltage is stepped up through a transformer to the desired voltage. The desired voltage level is then rectified through a diode bridge top and a full wave rectifier bottom. The full wave type tube rectifier acts identically in function as the diode bridge. For this article, we will assume all power supplies in question are of the linear types above.

Today, there are little to no modern applications for tube rectifiers other than instrument and Hi-Fi tube amplifiers. Even then, only a selection of boutique amplifier manufacturers still design them into their equipment. Most commonly, a simple solid-state diode bridge configuration is used, costing less than a single dollar to implement!

So why use tube rectifiers at all?

1. Power Supply Noise Floor

A DC power supply is a voltage supply used to power the end equipment. Supply noise is characterized by small time-varying voltage fluctuations superimposed upon the DC voltage, called ripple. Any DC source will have small voltage fluctuations; however, the smaller they are the more ideal the power supply is. There is no such thing as a perfect noise-free DC source. In fact there is no such thing as noise-free anything. The spontaneity and randomness of nature makes this so. This is called 1/f or flicker noise. However, for this argument, power supply noise is caused by attempting to filter this pseudo DC into a pure DC wave. The more filtering we apply, the closer we can asymptotically approach ripple-free supply but never achieve zero ripple. See Figure 2.

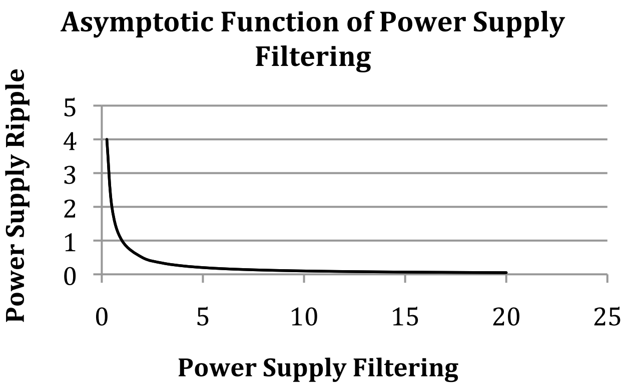

Figure 2: Power Supply Ripple

Vacuum tube rectifiers have inherently lower noise contributions to the DC voltage of a power supply than solid-state diodes. The physics that govern a semiconductor-based diode makes for significant switching noise every time the diode blocks the negative voltage swing and turns on and off. This can get coupled into the DC supply causing noise in sensitive equipment such as high gain amplifiers.

This is one reason why manufacturers claim to use tube rectifiers.

However, solid-state diodes can be implemented to achieve very low noise results with the addition of small capacitors across each of the diodes. These caps absorb any transient switching noise.

So, if a manufacturer states that they use a tube rectifier solely for lower noise, then they may as well use diodes.

2. Tone Shaping and Power Supply Sag

Tone shaping is particularly useful for instrument amplifiers. A tube rectifier can make a guitar amplifier sound very different at clipping than an amplifier that uses diodes. Therefore, a designer may choose to use them to achieve a particular feel and sound to an amplifier.

Tube rectifiers exhibit voltage loss or drop at high current demands. The larger the demand, the more loss the tube has. These drops can be anywhere from 10V for the larger 5AR4/GZ34 to 60 for a 5Y3GT! This means at high output levels, the rectifier will sag or droop its voltage delivery to the power supply of an amplifier.

This in turn will decrease the available energy the power supply can deliver to the amplifier. Eventually, the power consumed by the amplifier exceeds the available energy of the supply, at which point, distortion occurs. The peaks of the output will actually begin the squash and compress as the limitations of the power supply are reached. This type of distortion is known as sag since the supply voltage of the amplifier decreases or sags at high output. The stiffer or less sag a power supply has, the less it will become a limiting factor for the output power.

On the other hand, silicon diodes exhibit a very small voltage drop that only goes through minor voltage fluctuations under varying current demands. Diodes will provide a stiffer, more ideal supply with around 0.7V to 2V of voltage drop typically.

Figure 3 is taken from the original General Electric 5AR4 datasheet. This depicts the voltage drop versus the load. Figure 4 shows the voltage drop of a modern 1N4007 diode.

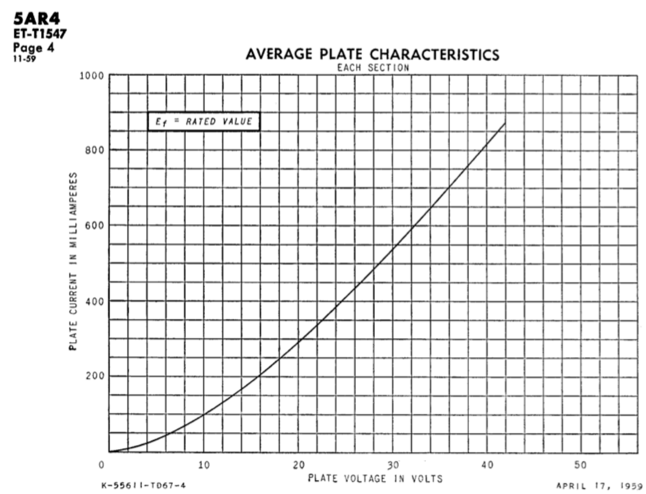

Figure 3: 5AR4 Voltage Drop Vs. Load Current

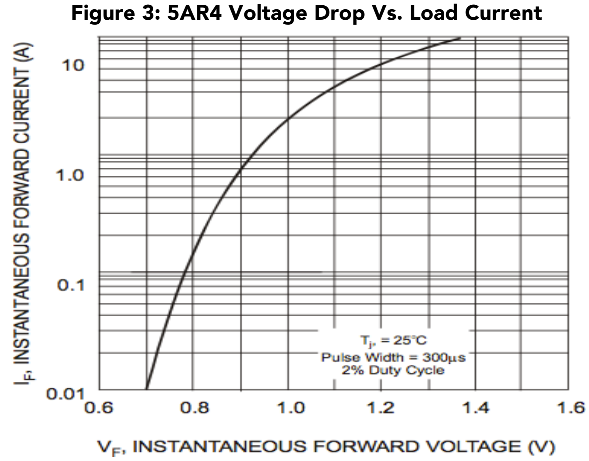

Figure 4: IN4007 Voltage Drop Vs. Load Current

In class AB and class B amplifier output stages, the load or current demand will increase with output power. The operating point of the rectifier will actually sweep along this curve in real time. The peak loss of a rectifier can be significantly more than twice the steady state or idle loss.

From Figure 1 we can see at 100mA of load current the 5AR4 exhibits a 10V drop. At 200mA, the rectifier exhibits 16V loss. If a ghost amp running a 5AR4 rectifier had a 100mA load at idle which changed to 200mA at full power, the rectifier would contribute a 6V change in loss to the power supply voltage.

Since most large tube power amplifiers have voltage supplies typically in the 300-600V range, 6 volts is a very minor loss. In fact for a 300V supply this would be a 0.02% loss. The 5AR4 is a very robust tube rectifier and the most commonly used for high power applications.

For the 1N4007 diode in figure 2, 1A of current draw exhibits less than 1V of drop!

Although desirable for guitar amplifiers, sag has no place in a Hi-Fi amp; so this will actually work against us. If we choose a rectifier carefully, the voltage drop can be designed out and have a negligible effect in the performance of an amplifier.

3. Soft Start Characteristics

Now we have come to the most important property of tube rectifiers and why they make sense in tube audio applications: the soft start and warm-up time characteristics.

A. Maximizing Filter Capacitor Lifespan

By their nature, vacuum tube amplifiers operate at very high voltages, requiring high voltage power supplies to run them. This raises the cost of a power supply design considerably. High voltage components, especially the large filter capacitors required to smooth the DC supply voltage after a rectifier, are specialized items. Due to their size and operating requirements, filter capacitors can cost well over $10 a piece. The large multi-section can style caps that have two or more capacitors in a cylindrical housing can cost upwards of $40!

The issue is that these large electrolytic construction capacitors have a limited life span. The electrolytic oils used inside the capacitors dissipate and leave the cap over time due to self-heating and general use during operation. This causes the capacitance to decrease over time and eventually the cap will fail from age and use. Visual indication of a failed electrolytic cap is marked by bulges in the casing or even bursts with signs of the electrolyte leaking out. Generally, the standard procedure is to replace filter capacitors at 15-year intervals for moderate reliability. In high reliability applications such as military or medical, the lifespan and recommended service intervals for equipment is well documented and strictly followed.

Due to the warm-up time required by the filament for full operating performance, tube rectifiers slowly rise in their voltage output from a cold start and in turn, trickle charge the reservoir filter caps in a power supply up to the full operating voltage. This soft start warm-up or turn-on time increases the lifespan of the capacitors dramatically. In fact there are some who "reform" vintage electrolytic caps by slowly bringing them up to operating voltage over many hours as some caps have the ability to heal leaks in the dielectric. Silicon diodes on the other hand require no warm up time and have next to zero turn-on time in comparison. This instantaneously jolts the power supply caps up to the full supply voltage, which for a tube amp is typically hundreds of volts! This is known as a dV/dT spike or a fast change in voltage with respect to time, a real killer of large electrolytic caps, especially those well over the 15-year mark. Every time the power supply is powered on and off, the capacitors' lifespan diminishes.

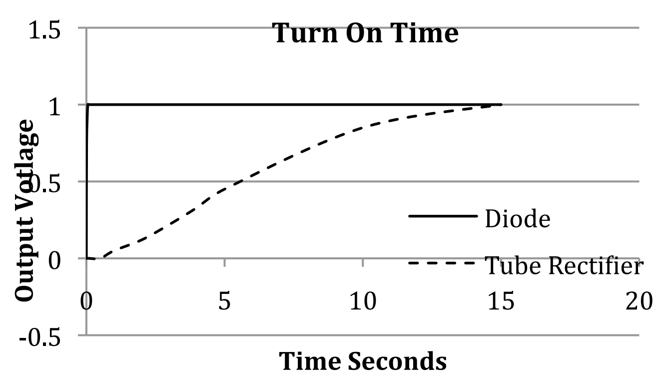

Figure 5: Diode Vs. Tube Rectifier Turn on Time

Figure 5 above illustrates the turn-on time for a solid-state diode versus a tube rectifier where a voltage of 1 indicates the steady state output voltage. The turn-on time for a tube rectifier is measured in seconds whereas diode is measured in milliseconds, orders of magnitude faster.

B. Over Voltage and Arc-Over Failures

There is a second benefit to tube rectifiers that also comes from their soft start characteristics, which is a reduction of arc-over failures that can occur in the preamp and power tubes.

Like tube rectifier warm-up time, preamp and power tubes in an amplifier have a warm-up time as well. Before which, the idle current is lower than normal. Once the amplifier has been powered on for a period of time, all of the amplifying and power stages have reached their operating temperature. The bias currents through each of those stages have also stabilized to the normal bias value. This change in current from cold turn-on to full operation has some interesting effects on the power supply, as I will soon discuss.

Although we may have minimized the sag from the tube rectifier there are other series elements in a power supply that add to the total losses in the power supply. This can include the resistance of the power transformer windings, inductor filter choke windings, and/or series resistors used to create RC filters. Although a poorly chosen tube rectifier (or one specifically chosen for tone shaping purposes) can dominate these losses, the other losses are non-negligible and usually need to be considered in the design. In the case of a Hi-Fi amplifier, these losses will almost always dominate over the loss of a tube rectifier since we can choose a tube with the lowest loss for a stiffer supply.

Because of these losses, a linear power supply will exhibit a change in voltage when it is unloaded versus loaded, i.e. no current demand versus normal current demand. When designing a linear power supply, these losses need to be calculated for so that the correct voltage is achieved under the desired loading conditions.

You can probably already see the parallel to powering on a tube amplifier. When the tubes are cold and no idle current is flowing, the power supply is essentially unloaded and the voltage will be at its highest potential. It may take as much as 30 seconds or more from turn on before all of the tubes are at their steady state operating points. Thus, once the warm-up time has passed, the power supply voltage will be loaded down to the desired operating voltage.

As already stated, a solid-state rectifier has essentially an instantaneous turn-on time so the power supply is up and running right away. However since the tubes are still cold, the current demand is low so the power supply voltage is higher than normal for tens of seconds until all the tubes are warmed up.

The higher than usual or over voltage can then cause damage in the power tubes if their maximum voltage rating is exceeded. This is quite common in amplifiers designed for maximum power with a given set of tubes since the operating voltages at steady state are already pushing the maximum tube specifications! Most commonly, excessive plate voltage on a tube will cause an arc inside the envelope of the tube from the plate to another electrode. This will usually permanently damage the tube. This is known as an arc-over failure.

With a tube rectifier, the slow warm-up time will generally be close to the warm-up time for all of the other tubes. This means that the power supply voltage will begin to rise as the preamp and power tubes begin to conduct and draw current from the supply. Thus, the potential for long periods of excessive power supply voltage on a cold tube is very minimal. The risk of arc-over failure on turn-on is significantly reduced!

Note: This needs to be accounted for when specifying the voltage rating of the filter caps as well. Make sure to have plenty of headroom in the caps' voltage rating.

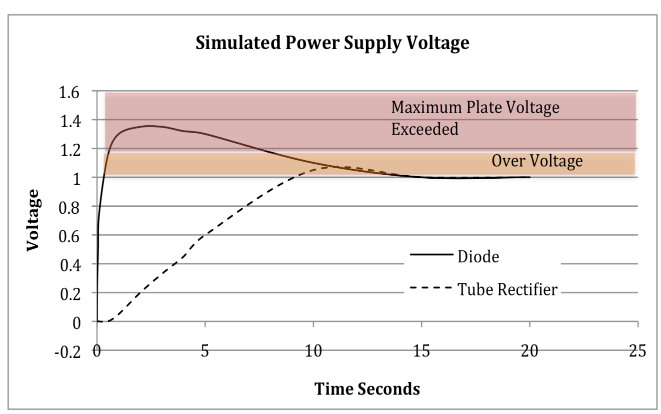

Figure 6: Simulated Power Supply Voltage

Figure 6 shows a simulated imaginary power supply implemented with both a diode bridge rectifier and tube rectifier. With a voltage level of 1 being the target idle supply voltage, the diode quickly goes into an over voltage condition above the desired operating voltage. Then, the voltage continues to rise, in this case, above the maximum plate voltage allowed by the tubes in the rest of the circuit. Eventually, the tubes begin to conduct and draw idle current, pulling the voltage back to the desired level. The tube rectifier undergoes a much shorter over voltage condition since its warm-up time gives the other tubes a chance to warm up and begin conduction before it is up to full operating temperature.

Although figure 6 is fictitious, it correctly illustrates the danger of running tubes close to their maximum voltage at steady state with a diode rectifier.

4. Standby Switches

The next logical step may be to add a standby switch in an attempt to let the power tubes reach operating temperatures before switching on the high voltage supply. This way, we can use either a diode rectifier or tube rectifier without arc failures in the tubes. It is also believed that the standby switch will increase tube life; however, this is not true. A standby switch does not add any real benefits from an amplifier perspective. It just adds user convenience for instrument amplifiers to keep them active but muted so there is no warm up time from mute to active.

A. Adding Other Problems

Although a standby switch will reduce the possibility of arc over failure in vacuum tubes during the startup sequence, they can have some other nasty effects, especially if improperly implemented.

The first issue with a standby switch is that they do not take care of the extremely fast voltage charging of the filter capacitors. In fact, when used with a tube rectifier, any filter caps down stream of the switch will no longer see the trickle charge benefit of the tube rectifier. With a solid-state rectifier, all capacitors upstream and downstream of the switch will be immediately charged with a large voltage spike; first on power on, and then the down stream caps after the standby switch is thrown. This often leads to a loud auditable pop through the speakers.

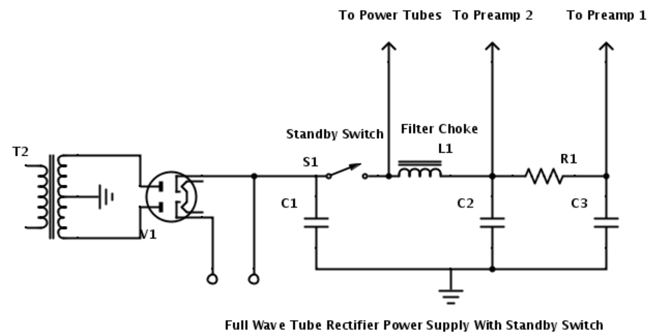

Figure 7: Tube Rectified Power Supply with Standby

Figure 7 depicts the basic topology commonly used for standby switches. C1 filter capacitor will be trickle charged by the tube rectifier on turn on. However C2, and to a slightly lesser extent C3, will be charged immediately once the standby switch is closed. This is assuming the rectifier is allowed to warm up completely first. C3 will be charged a little slower than C2 due to the addition of R1 which will create a charging time constant t = RC (where after 5t the capacitor is said to be fully charged). However, this will still be much faster than letting the rectifier naturally charge the caps directly from startup.

The second issue with the standby switch arrangement is that once the switch is closed, the rectifier will now have to supply tremendous amounts of current to charge the downstream caps C2 and C3 as well as supply the current draw for the attached tube stages. This commonly leads to an arc inside the tube rectifier, especially if filter capacitances are excessively large. This is the most common failure of a tube rectifier, excessive current on turn-on caused immediately after turning the amp off of standby. The standby switch saved the amplifying tubes, but sacrificed the rectifier tube and still charges the filter caps with a large voltage spike.

With a diode rectifier, the current spike is usually not an issue but now C1, C2, and C3 are all charged immediately. There is no trickle charge of C1.

The third issue occurs when a standby switch is used with a filter choke inductor supply L1 as above. Every time standby is turned on and off, extremely large voltage spikes occur across the inductor. This is known as flyback voltage. Over time, this can cause an arc between windings of the inductor, killing it. The amp will usually continue to work, but the filtering provided by the inductor will be severely diminished making the amp noisy when compared to new. This can be fixed with the addition of a diode across the inductor, which clamps the voltage across the inductor to the diode's threshold voltage. An easy fix to this issue, however it is rarely designed in*.

B. Tube Lifespan

Another common argument for adding a standby switch is to increase tube life. The common thought is that presenting the amplifying tubes with the supply plate voltage will cause cathode stripping if the tubes are not up to temperature.

Cathode stripping is a damaging effect where the high voltage pulls or strips electrons off the cathode before the cathode is up to temperature, thus damaging it and pulling the cathode coating off with the embedded electrons. This would be most prevalent with a non-standby amp with a diode rectifier since the plate voltage is available immediately after turn on. However, this effect is not even an issue for amplifying or receiving tube types. The voltages are too low for this effect*. This was more commonly an issue for Cathode Ray Tubes or CRTs.

Conclusion

The main benefit for the use of a tube rectifier is for its slow startup time. Not only can it help extend the life of the power supply components, it can also reduce over voltage turn on situations, reducing the risk of arcing from excessive plate voltages.

Although a tube rectifier introduces more series resistance and loss than solid state diodes, the correct choice of a rectifier with proper filtering can mitigate this effect and produce a very stable supply (unless you want an instrument amplifier with rectifier sag).

Lastly, we looked at how most commonly implemented standby switches remove the benefits of a tube rectifier and add additional problems. They can be designed correctly; however, most circuits copy the wrong way to do it over and over. Also, there is less benefit for Hi-Fi so this discussion has been shortened.

Bibliography and Extended Reading

*Blencowe, M. (2010). *Designing Power Supplies for Tube Amplififers*. Wem Publishing. Pg 94-95, 98