Subject: Long article on power supply design.

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I have been asked to provide some information on power supply design for tube gear, particularly the tradeoffs involved in solid-state versus vacuum rectification, choke-input versus capacitor-input filters, and various types of capacitors. The following is a lengthy and somewhat pedantic dump on the subject. Warning: It's rather self-indulgent in size. Accept my apologies in advance for errors, omissions, and sheer boredom. Maybe someone will find this useful. I'm too proud to edit it down to size.

Introduction.

In general, a power supply consists of a transformer that produces AC at some voltage, a rectifier that converts the AC into pulsating DC, and a filter that removes the pulsating components leaving only pure direct current. The following specifications are of particular concern to powersupply designers:

1) DC output voltage.

2) Maximum average load current.

3) Regulation.

4) Hum and noise.

5) AC impedance.

DC output voltage is self-explanatory, but note that in unregulated supplies the output voltage varies, and so must be specified at a given load current. Maximum average load current is the maximum DC current that may be drawn continuously without damaging the supply. Regulation, expressed in percent, refers to the change in output voltage as the current varies over some range, often from zero to the rated maximum average. Hum and noise refer to the voltage of AC components that appear at the supply output. AC impedance, given in Ohms, indicates the ability of the supply to maintain a constant voltage when the load current varies rapidly.

Transformers.

Power transformers are rated for secondary voltage, secondary current, primary Volt-Ampere capacity and temperature rise. It is meaningless to rate a transformer in Watts because the power delivered by the transformer and its efficiency depends on the load. For instance, a purely capacitive load can draw a high current from a transformer, resulting in excessive heating, yet consumes no power. The Volt-Ampere rating is determined by the maximum allowable internal temperature rise which is typically on the order of 50 degrees Centigrade. Heating is caused by power loss due to winding resistance and magnetic effects in the core. To some extent, a transformer with multiple secondaries can support a higher-than-rated current in one secondary if another is unloaded to compensate. In a properly designed transformer, most efficient operation is obtained when the secondary loads are balanced according to the manufacturer's ratings.

The specified secondary voltages are at the rated load current. When lightly loaded, the secondary voltage will rise. Typical regulation is on the order of 10%, but it can be as high as 30% for small, low-current transformers, and as low as 3% for a conservatively designed unit. The secondary current rating is often ambiguous. Some manufacturers rate their transformers for RMS current, while others specify DC current in capacitor-input and/or choke-input filter applications. The best bet is to look at the Volt-Ampere rating and work backwards to a secondary current spec. A rule of thumb for capacitor-input filters is to rate the power transformer Volt-Amperes at twice the DC power drawn by the load. For choke-input filters, perhaps 30% more power is available for a given temperature rise. It can be difficult to predict ahead of time the exact DC voltage a given transformer/rectifier/filter combination will provide, making the business of choosing power transformers somewhat of a black art.

Toroidal transformers are claimed to offer smaller size, lower weight, cooler operation and less electromagnetic interference to sensitive circuitry. Toroids seem to work well, but selection of toroids suitable for tube gear is limited compared to conventional E-I types. Some of the advantages may be hyped, although the low stray field argument is valid. Nevertheless, a quality conventional transformer runs quiet and cool and looks right on top of a tube amp chassis.

Rectifiers.

Most tube gear employs full-wave rectification with center-tapped transformer secondaries. The four-diode vacuum bridge configuration isn’t common because it imposes a double diode drop and doesn't seem to offer any significant advantages. The silicon diode full-wave bridge works just fine, but B+ transformers with secondary voltages suitable for bridge rectifiers aren't common (of course, this is not the case for low-voltage transformers used in solid-state equipment). When figuring secondary VA ratings, remember the duty cycle of current flow in a center-tapped secondary is 50% when two diodes are used, compared to 100% with the full-wave bridge.

The rectified output voltage is a pulsating waveform with a peak amplitude equal to the 1.414 times the secondary RMS voltage, minus the diode drop. A transformer rated X Volts center-tapped (VCT) has a secondary RMS voltage of X / 2. The pulsating DC has an average value about 0.9 times the peak voltage and a strong AC component at twice the power line frequency, with higher-order harmonics also present.

Rectifier diodes are rated for forward voltage drop, peak inverse voltage (PIV), and maximum average and peak average current. The forward voltage drop of a solid-state diode is less than a volt or two, depending on the type, and can be ignored in B+ applications. Vacuum diodes have forward drops from 20-50V in typical circuits. Current ratings for popular silicon diodes range from one to several Amps, with peaks ratings in the tens of Amps. Vacuum diodes provide typical average currents in the range of 100-300mA and peak currents of a few amps at the most. The impedance of a vacuum diode varies with current but is usually on the order of 50-100 Ohms. The impedance of a silicon rectifier is so low that it is inconsequential in B+ supplies.

Vacuum rectifiers require a filament supply, as do all vacuum tubes. Filaments are usually rated at 5VAC at an Amp or two. Vacuum diodes comes in directly- and indirectly-heated varieties. The latter give warm-up times in the range of 10-20 seconds whereas the former come up to temperature and begin conducting almost instantaneously. The delay time is a desirable feature in a rectifier, allowing signal tubes to warm up and stabilize before B+ is applied. Some audiophiles claim that directly-heated rectifiers offer better sonic performance than indirectly-heated types. In both types of rectifiers the heater terminals are electrically connected to the cathode. This means that heater supplies cannot be shared among rectifiers feeding separate circuits or providing different potentials.

Silicon diodes can withstand extremely high pulse currents of short duration whereas the peak current capacity of a vacuum diode is strictly limited. This is a major concern in the design of a power supply using vacuum rectifiers. The peak current that flows in a vacuum rectifier depends in part on the internal resistance of the rectifier. Vacuum rectifiers can be categorized into low and high internal resistance types, the latter having higher forward voltage drops (making them more suitable for low-current circuits) but greater immunity to excessive cathode current resulting from improper filter design.

Capacitor-input filters.

Capacitor-input filters place a capacitor from the rectifier output to ground. AC components in the rectifier output are short-circuited and largely eliminated by the input capacitor. A short-circuit implies high current flow, and for this reason, a capacitor-input filter leads to high peak rectifier and transformer secondary currents. This is a concern both from the point of view of component ratings and noise induction, particularly in ground circuits. Increasing the value of the capacitor decreases its AC impedance and increases the magnitude of the ripple current. When the capacitor becomes so large that it appears as a virtual dead short to harmonics of the power line frequency, further increases in capacitance do not significantly reduce the ripple voltage or increase the ripple current. This is because the ripple current is limited by the series resistance of the rectifier and transformer secondary circuit.

Most power supplies using solid-stage rectifiers operate with "large" input capacitors and will not be harmed in principle by the addition of more filter capacitance. This is not the case with vacuum rectifiers, and for this reason it is important to limit the value of the input capacitor if the rectifier is not to be damaged. The high ripple current flow has nothing to do with the initial inrush when the power supply is turned on, but is a continuous phenomenon with current pulses happening every 120th second. In supplies with very large filter capacitors, separate measures must be taken to limit the power- on surge in order to avoid damaging the rectifiers and power switch. This takes the form of some kind of "slow turn-on" circuit, possibly a thermistor in the primary wiring or a series resistor and time-delay relay to short it out.

A large filter capacity is beneficial in that it provides a reserve of energy for sustained high-current peaks such as are required by a bass drum roll. When vacuum rectifiers are used, a filter choke separating the small input capacitor from a larger downstream capacitor effectively contains the ripple current in the first capacitor, thereby protecting the rectifier. The high surge rating of both vacuum and silicon rectifiers usually allows them to supply large currents without damage while powering up the filter network. The choke serves the equally important function of attenuating hum in the supply output.

With a capacitor-input filter, rectifier current flows only when the transformer secondary voltage is greater than the DC voltage on the input capacitor. This happens at peaks of the secondary AC waveform. Consequently, the charging current waveform is a series of short pulses. The pulses tend to decrease in duration and increase in magnitude as the value of the filter capacitor increases. This is because the drop in voltage in the time interval between charging pulses is smaller for a large capacitor. The percentage of time during which the secondary voltage exceeds the filter voltage is therefore smaller. The load resistance in series with the secondary circuit resistance forms a voltage divider that determines the maximum DC output voltage for a given load current. As the load resistance drops relative to that of the secondary circuit, the DC filter voltage drops as well.

The DC voltage on the filter capacitor is determined by an equilibrium between current flow into the capacitor from the transformer and current flow out into the load. The resistance of the transformer secondary and rectifiers combined with the filter capacitance forms a low-pass filter having a well-defined time constant. For large RC products, the charging rate of the input capacitor will be fairly slow and the rising segment of the ripple waveform will lag behind the unloaded sinusoidal waveform. This increases the duty cycle of rectifier conduction and reduces the fraction of time during which the input capacitor delivers current on its own to the load. A new equilibrium is established at a lower output voltage. This is a rather more sophisticated way of thinking about capacitor-input filters than is taught in undergraduate circuits classes.

The DC output voltage, the ripple voltage, and the magnitude and duration of the charging pulses are complicated functions of the load impedance, the transformer secondary impedance and the rectifier dynamic characteristics. There is no simple equation for determining these values. Tube textbooks contain graphs and procedures that allow estimates of power supply performance given transformer, filter, and rectifier specifications.

Conservation of charge tells us that the total charge per unit time flowing into the filter must equal the charge per unit time flowing out. Therefore, the average DC input and output currents must be equal. However, heating in the transformer secondary and rectifiers is proportional to RMS value of current, which increases with the square of the peak current value. In cases where the charging pulses are of short duration, transformer heating is an issue. As mentioned in the section on transformers, a rule of thumb is that a power transformer used with a large capacitor-input filter should have a Volt-Ampere rating equal to twice the DC power consumed by the load. Alternatively, for the usual full-wave rectifier and center-tapped secondary, the maximum continuous DC current from the supply is about 3/4 the secondary current rating. The actual conversion factor depends on the exact component and load current values. Some transformers are already rated for DC current capacity given capacitor- or choke- input filters, which makes determining supply performance tricky. When in doubt, choose transformers conservatively, but remember a lightly-loaded transformer will produce more than its rated secondary voltage. This can be a problem when filter capacitors are used near their maximum voltages.

Choke-input filters.

The choke-input filter consists of a series inductor at the input followed by a capacitor to ground on the downstream side. Choke-input filters are the butt of derision by modern engineers who have little experience with them and do not understand their many advantages. Compared to capacitor-input filters, choke-input filters offer superior regulation and lower peak ripple currents, allowing higher DC currents to be drawn from the power transformer and rectifier. This is because the input choke presents a high impedance to ripple currents, rather than shorting them to ground. The disadvantage of the choke-input supply is that the output voltage under load is approximately 0.9 times the RMS secondary voltage, compared to 1.414 times VRMS for a lightly-loaded capacitor-input filter. The output voltage of the choke-input filter tends to rise sharply (to the secondary peak voltage, 1.414 times VRMS) when the load current falls below a critical value. This value, in milliamps, is approximately equal to the full-load supply output voltage divided by the input choke inductance in Henrys. For example, a 400V supply with a 10H input choke has a critical current of 40mA.

To avoid overvoltage conditions during warmup or in the event of a signal circuit failure, bleeder resistors are usually specified to insure the critical current is drawn at all times. For safety, the bleeder resistors should be rated conservatively for power dissipation to insure long-term reliability. In addition, it is wise to rate the filter capacitors for the full 1.414 times secondary VRMS in the event of a bleeder failure, since capacitors can fail spectacularly. The bleeder resistors consume significant power and tend to cancel out the higher transformer current capacity afforded by the choke-input filter. Since filter inductors generally have higher than rated inductance at low currents, the critical current may be lower than computed, allowing larger bleeder resistors to be selected experimentally, and lowering wasted current. Special chokes that are designed to "swing" from high inductance at low currents to low inductance at high currents are available for choke-input filter applications. Swinging chokes save space compared to conventional units that maintain their rated inductance over a wide current range.

As long as the load current exceeds the critical value, the input choke draws current continuously from the rectifier, in contrast to the capacitor-input fiter which is charged in short pulses. The output voltage is close to the average secondary voltage and does not vary substantially with the load current. The choke-input filter is preferred, therefore, for Class AB amplifiers, which draw widely-varying current and which require a stiffly regulated power supply. This is not so much a consideration nowadays given the very high volumetric capacity of modern electrolytic capacitors and the scarcity and cost of large inductors. For supplies using bulky oil or plastic film filter capacitors, or for designers who prefer to avoid the brute-force approach, the choke-input filter is an elegant solution.

Note that any choke-capacitor filter will resonate at the usual one-over-two-pi-root-L-C frequency. At this frequency, the filter impedance will rise. The impedance and Q at resonance depend on the filter topology and in particular on the value of the series resistance in the supply circuit. If the series resistance is low, the resonant Q will be high and the possibility of "filter bounce" (oscillations on the supply rail) arises. The resonant frequency must be lower than the fundamental ripple frequency, of course, but in a Class AB amplifier, the AC load current may contain envelope frequencies well below the cutoff frequency of the amplifier. This bears consideration in the design of a supply filter using chokes either as the input or secondary filter element.

Vacuum rectifiers vs. solid-state.

Solid-state diodes are simple, small, and rugged. They have very low voltage drop and are extremely efficient. They allow the use of large capacitor-input filters, eliminating the need for bulky and expensive series chokes and multi-section filters. A solid-state rectified power supply can have a very low output impedance and yet be low cost. The main disadvantage is the lack of turn-on delay and the possibility of tube damage due to cathode stripping. Slow turn-on circuits solve this problem but can be a nuisance to build. Some audiophiles feel that the switching behavior of solid-state rectifiers causes audible broadband noise to be introduced into signal circuits. Fast- and soft- recovery diodes designed for switching power supplies are available that address this problem.

Indirectly-heated vacuum rectifiers solve the soft-start problem simply and elegantly. Perhaps they are superior sonically. They have much higher internal impedance than solid-state diodes and require heater supplies. Small input capacitors and multi-section filters with chokes are required in most applications. The higher internal impedance may have a hidden benefit in that it will damp filter bounce in LC filters. I wonder if the reported sonic benefit of vacuum rectifiers is due to the smoothing effect of the high impedance looking into the filter network.

My preference is to use a vacuum rectifier. It's classic, it's funky, it may make less noise, it solves the slow-start problem, and it feels right. Solid-state fans, take heart; the legendary Marantz 8B uses solid-state rectifiers.

Henry A. Pasternack