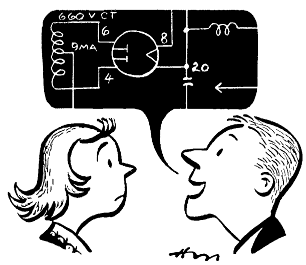
Audio Classroom

Practical Audio Design Part 1: Power Transformers and Rectifiers

This article (reprinted from Audiocraft, *January 1956) on designing power supplies kicks off our new* GA *series entitled Audio Classroom. We'll be publishing a collection of reprints—mostly from the 1950s—focusing on the basics to help you better understand tube design.*

BY JOSEPH MARSHALL



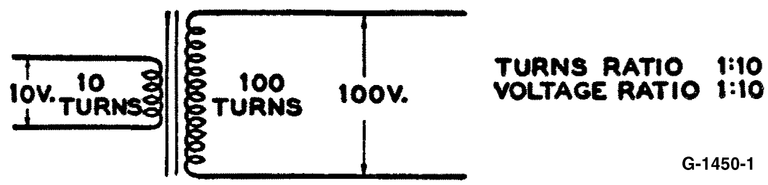


FIGURE 1: Voltage ratio equals turns ratio.

One of the most frequent of problems faced by the amateur constructor—and one of the simplest to solve—is that of modifying a power supply design to suit some specific need (or to build a power supply using components on hand rather than those specified). These components account for an appreciable part of the cost of audio equipment; one of the easiest ways to reduce the cost is to make use of salvaged or bargain components rather than the ones called for in the circuit diagram.

POWER-SUPPLY FUNCTIONS

The power supply performs two functions. It must convert the normal house-current line voltage to the higher and lower voltages required by the tubes, and it must convert high-voltage alternating current (AC) to single-direction (DC) current. Vacuum tubes used in audio equipment need a source of filament voltage ranging from 5–12V AC or DC. They also require a source of high-voltage DC ranging from 100–400V or more. But the power line voltage is, in most parts of this country, an arbitrary 115–125V AC.

Voltage conversion is easily achieved with a transformer, which consists of two or more coils of wire in close proximity; when AC is passed through one coil it induces voltages in the other coils. In power transformers the coils are wound on a common metal core, which increases the efficiency of coupling between them. If we have a transformer with two windings, and feed AC of a given voltage into one winding, the other winding will deliver a voltage proportional to the turns ratio of the two windings. Assume a transformer with one winding of 100 turns and the other of ten turns: if we feed 100V AC into the 100-turn winding we will get 10V out of the ten-turn winding or, conversely, if we feed the 100V into the ten-turn winding, the 100-turn winding will deliver 1,000V (*Fig. 1*).

We can use several windings with different turns ratios to obtain a variety of voltages. For example, we can have one winding of 115 turns, one of five turns, one of six turns, and one of 400 turns. If we feed 115V to the 115-turn winding, which we can call the primary, we will get 5V from the five-turn winding, 6V from the six-turn winding, and 400V from the 400-turn winding; this would give us the proper voltages for the rectifier tube filament, the filaments of the other tubes, and for the plate supplies of the amplifying stages.

There are various considerations such as efficiency, power factor, and regulation which determine the physical size of the coils, core material, diameter of wire, and so on. These are things nobody but engineers working for transformer companies need worry about. As a user you need only know what transformer to use for a given application or how to make a given transformer serve in a particular application.

CHOOSING A TRANSFORMER

Most commercial transformers suitable for audio use have a single primary and three secondaries—one supplying 5V for a rectifier, another supplying 6.3V for the other tubes, and a high-voltage secondary which can supply voltages between 100–500 or more. The only worry about the filament secondaries is whether they can supply enough current to meet the needs of all the tubes used. A tube data book (such as the *RCA Receiving Tube Manual*[1]) will help answer this question. Each table of characteristics begins with the filament voltage and current. Large power tubes of the 6L6-KT66 class draw between 1–1.25A each at 6.3V.

The typical voltage amplifier tubes used in audio circuits each requires from 0.15–0.6A. It is only necessary to add the currents drawn by the tubes of the projected circuit and compare this with the specifications of the transformer. Catalog listings of transformers always show the maximum current that may be taken from each winding. A typical transformer for an audio amplifier may have a 6.3V winding capable of supplying either 3.5 or 4.5A, and a rectifier filament winding capable of supplying either 2 or 3A.

Some small transformers suitable for control units, preamplifiers, and other small units have a single 6.3V filament winding and no separate rectifier filament winding. In such cases a rectifier must be used which has a 6.3V filament and a separate cathode (like the 6AX5, 6X5, or 6W4). The filament of the rectifier is connected in parallel with the other tube filaments, and the power supply filter is connected to the cathode.

Determining the suitability of a high-voltage winding is more complicated because both the voltage and current delivered depend to a considerable degree on the rectifier employed and the type of filter used. The purpose of the rectifier is to convert AC voltage into DC, and the purpose of the filter is to smooth the DC and reduce the residual AC ripple which would produce hum. Conversion to DC can be accomplished by connecting a diode rectifier in series with the load and the AC source (*Fig. 2*). A diode conducts only when its plate is positive with respect to the cathode, and this condition occurs during every other half-cycle of an alternating current.

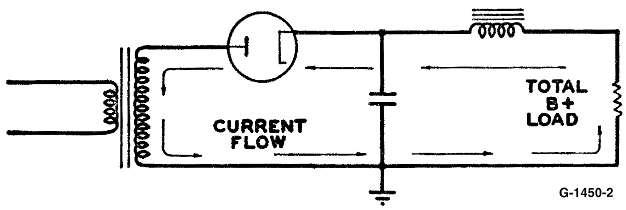


FIGURE 2: A diode permits one-way current.

The diode passes this half-cycle and, in effect, clips off the negative half-cycle (*Fig. 3*). A is the waveform of a normal AC current and B is the waveform after it has been rectified by a diode. This is not yet a suitable DC voltage. It can be turned into a pretty good facsimile of a direct current by passing it through a filter network consisting of a choke (or resistance) and a capacitor. Empty spaces between the peaks are filled in because the capacitor charges during the peaks and discharges during the nulls. The result is C, a current which is almost, but not quite, constant in amplitude.

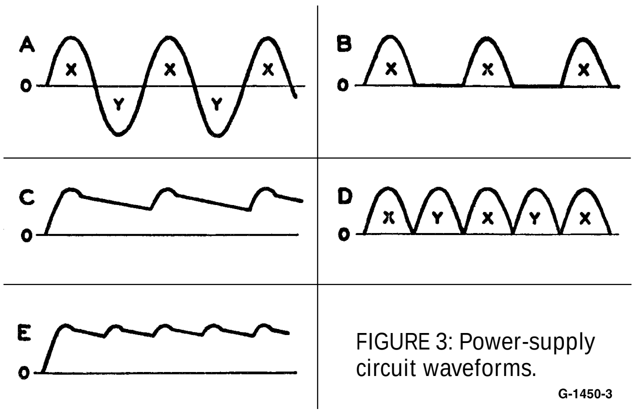


FIGURE 3: Power-supply circuit waveforms.

A smoother job can be done by full-wave rectification, achieved by connecting two diodes to a center-tapped transformer secondary winding (*Fig. 4*). The outputs of the two diodes will intermesh as indicated in D (*Fig. 3*). This produces a much smoother approximation of a direct current, and makes the filter's job easier. *Figure 3E* shows the output of a simple filter following a full-wave rectifier.

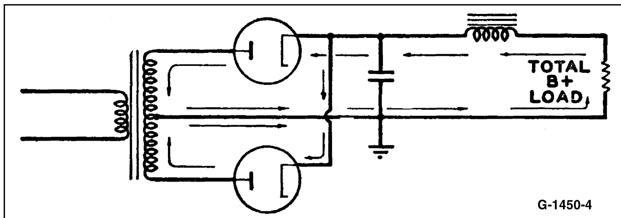


FIGURE 4: A full-wave rectifier circuit.

With few exceptions, most power transformers suitable for audio use have center-tapped high-voltage windings designed for full-wave rectification. Catalog information on such transformers gives the AC voltage available across the *entire* winding. When two rectifiers (or two halves of a dual rectifier) are used in full-wave rectification, the DC voltage output of the supply will be a little higher or lower than one half of this—a little more or a little less than 350V in the case of a 700V CT (volts, center-tapped) winding, depending on the type of power-supply filter used.

FILTER TYPES

There are two basic types of power-supply filters. In a choke-input filter (*Fig. 5A*), a choke coil is the first filter element after the rectifiers; in a capacitor-input filter (*Fig. 5B*), the first filter element is a capacitor. In general, with a choke-input filter the DC voltage will be *lower* than the AC voltage applied to the plates of the rectifier. With a capacitor-input filter it can be considerably higher.

A rectifier working into a series inductance produces a DC voltage which is slightly less than the RMS (root-mean-square, or effective) value of the AC voltage; but a rectifier working into a capacitor input produces a DC voltage somewhat less than the *peak* value of the AC voltage, which is about 1.4 times higher than the RMS value. Unless specified otherwise, sine-wave AC voltages are understood to be RMS values. On each side of the center tap of a 700V CT transformer winding, the unrectified voltage would be 350V RMS, and 495V peak.

There is a further complication. Rectifier tubes have internal resistance; therefore, the internal voltage drop is higher with high currents than with low currents. Accordingly the DC voltage available from a rectifier connected to a given transformer is determined not only by the transformer specifications, but also by the type of filter used and the current drawn. Fortunately the tube manuals provide charts, curves, and tables which reduce these apparently complicated interrelating factors to simple form. You can find what DC voltage can be expected for various AC voltage inputs, given load currents, and either choke- or capacitor-input filters.

Figure 6 is a curve from the *RCA Re-*

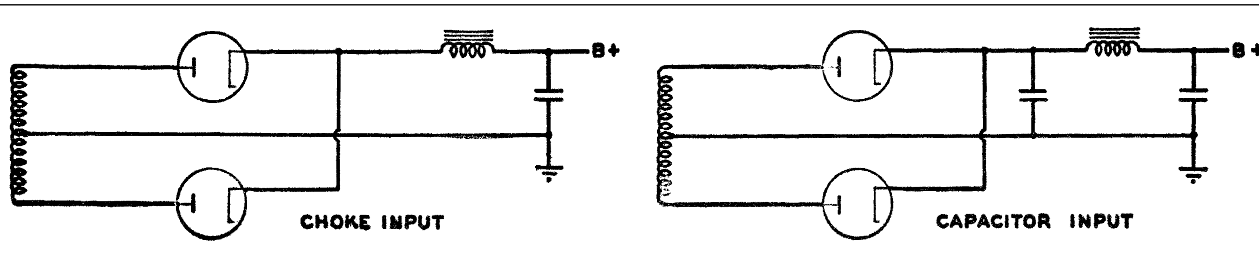


FIGURE 5A and 5B: Rectifier filters with choke and capacitor inputs.

ceiving Tube Manual for the 5V4. The curve shows, for example, that with 300V AC per plate, the 5V4 will deliver a little over 250V DC at 50mA and a little under 250V at 150mA, with a choke-input filter; but it will deliver about 375V at 50mA and about 325V at 150mA with a capacitor-input filter. It will be noted that while the capacitor-input filter produces a higher output voltage, the choke-input filter provides better regulation—that is, the difference in voltage between low and high current loads is much smaller.

Capacitor input, obviously, is preferable when a high voltage under a relatively constant load is required: choke input is preferable when the load varies widely but the voltage must be kept reasonably stable. High fidelity amplifiers using triode output tubes, or pentodes in an ultra-linear tapped-screen circuit present a fairly constant current load. For such amplifiers a capacitor-input filter is preferred because it permits the use of a less expensive power transformer for the same output voltage. On the other hand, amplifiers using pentodes in Class AB (for example) may have a current swing of 50% or more: it is then preferable to employ a choke-input filter so that the voltage may be kept fairly constant. If the voltage drops as the current rises, the maximum power output cannot be obtained and the advantages of using AB-type operation would be nullified to some extent.

MAKING THE RIGHT CHOICE

With this in mind, let us go through the steps of choosing a power transformer for a given job. Again a tube manual is an essential tool. First, we must establish the DC voltage and current needed. The *RCA Manual* rather falls down here, for it does not show operating conditions for the most frequently used hi-fi output tubes.

However, tubes of the 6L6, 807, 1614, KT66, and 5881 family require between 400–450V on the plate for triode or ultra-linear operation, and, with normal bias, pass about 100mA steady, possibly 125mA at full output peaks. Voltage amplifying stages, inverters, and drivers need 300V or less. An acceptable rule of thumb for estimating their current requirements is to allow 10mA for each low-gain triode (or half-section of a twin triode) and 2mA for each high-gain triode (or half-section of a twin triode). This leaves a large safety factor. The current requirements of the filament strings are easily totaled from the tube manuals.

Let us take an example. Assume that we are designing an amplifier using KT66s in an ultra-linear output circuit. We shall need 400V or a little more for the output stage, which will draw 100mA at normal levels and possibly 125mA on peaks. We will use two twin triodes (12AU7s, 12AX7s, or 6SN7s). By our rule of thumb, they will draw 40mA. Between 140–165mA DC at 400V will be adequate. The KT66s will need 2.5A at 6.3V AC for the filaments. The filaments of 6SN7s draw 0.6A apiece, while filaments of 6SL7s, 12AU7s, or 12AX7s draw 0.3A apiece. So we will need somewhere between 3.1–3.7A at 6.3V for the tube filaments.

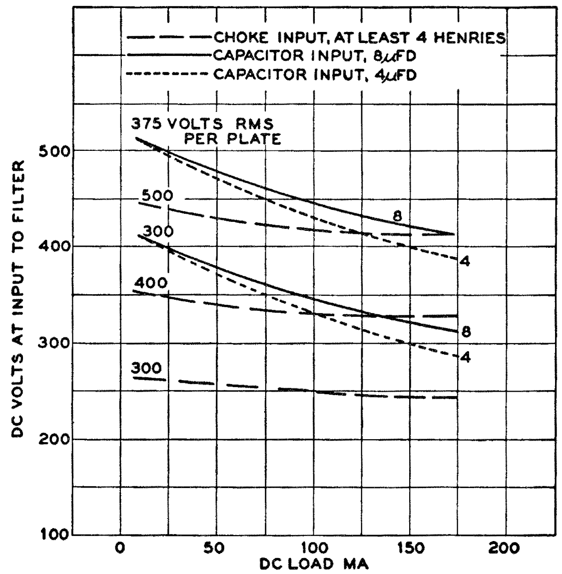


FIGURE 6: Tube manual rectifier data chart. G-1450-6

We will use a capacitor-input filter. A check of the rectifier tubes indicates that a 5Y3 will be rather hard pressed to deliver more than 125mA and, at 125mA, it would need at least 400V AC per plate to deliver 400V DC. On the other hand, a 5V4 is not only capable of delivering more than 150mA, but it can deliver 400V at 125mA with only 375V AC per plate, and needs no more filament current (2.0A at 5V) than the 5Y3. The 5U4 can supply about the same voltage and even more current, but needs 3A filament current.

In any case, we can set our minimum and maximum specs for the transformer. Minimum: 375V AC per plate (or 750V CT) and 150mA; 6.3V AC at 3.0 or 3.5A; and 5V at 2A. Maximum: 400V AC per plate (800V CT) at 150–200mA; 5V at 2 or 3A; 6.3V at 3.5A.

If we now consult the catalogs we find, for example, that the Stancor 8411 and Thordarson 22R33 each meets the minimum standard. The Stancor 8412 and Triad R-21A meet the maximum specs, while the Chicago PCC-200 (770V CT at 200mA), UTC S-39 (800V CT at 175mA), and Thordarson 22R34 (770V CT at 225mA) fit in between minimum and maximum. The minimum transformers are a little smaller and lighter, require less space, and will probably heat up more: the maximum and intermediate units provide a higher safety factor, will probably run cooler, but take more space and cost more.

However, any of them can do the job. The specific choice can be made on the basis of secondary requirements. For intermittent home use where the amplifier operates at low levels, the minimal transformer and even the minimal rectifier can be used. On the other hand, when the amplifier is used at high levels and/or for long continuous periods, it would be wiser to employ a maximal transformer.

MAKING AN OLD UNIT DO

A saving can often be made by using a transformer salvaged from an old amplifier or radio. Several problems may arise. The first problem may be that of determining the specifications of the transformer. This is easily solved with the help of any meter capable of reading AC volts in the range between 2.5–1,000V. But before measurement is possible it may be necessary to identify the windings. If the transformer has colored-wire leads, the windings may be identifiable by the color code:

Primary (115V AC)	Black

(If the primary is tapped, the black lead is the bottom of the winding, the black and yellow is the tap, and the black and red is the top.)

High-voltage winding	Red
Center tap	Yellow and Red
Rectifier filament winding	Yellow
Center tap	Blue and Yellow
Filament winding No. 1	Green
Center tap	Yellow and Green
Filament winding No. 2	Brown
Center tap	Yellow and Brown
Filament winding No. 3	Slate
Center tap	Yellow and Slate

But suppose the transformer has an unmarked terminal strip? An ohmmeter will help arrive at the truth here. First, by continuity tests identify the terminals for each winding. Now measure the DC resistance for each winding. The high-voltage winding invariably has an appreciable resistance—50Ω or more. The next highest resistance is that of the primary. The filament windings have very low resistances—1–5Ω or so.

Now get an AC cord with a regular plug at one end and stripped wire at the other end. Connect the stripped wire to the terminals you have decided represent the primary. Cautiously insert the plug into the power line receptacle, being ready to pull it out at the first sign of smoking or overheating. (Exercise caution to avoid any personal contact with the terminals.) If all looks well, measure the AC voltages across the other windings with an AC voltmeter. You can get a quick check of whether or not you really have the primary by noting the reading on the filament windings.

If it is correct, the voltage will be quite close to one or more of the following: 1.25, 3.1 (½ of a 6.3V winding), 5, 2.5, 6.3, 7.5, 10, or 12V—possibly also 24V. If the AC isn't connected to the primary, you will get various odd values. Assuming you are correct, measure the voltage across the high-voltage winding or each half of the high-voltage winding. Tabulate the voltages and there you are. If you have reason to suspect you have the incorrect winding for the primary, try shifting the AC to the next most likely winding and try again.

There is no simple way to determine exactly the current ratings of the various windings. If the transformer came from an old piece of equipment a pretty good idea of its capacity can be derived from a study of the equipment. The type of output stage will give a clue to the capacity of the high-voltage winding; the type and number of other tubes should give some idea of the capacity of the filament windings. If no such information is available, the size and weight of the transformer may be helpful. A large, heavy transformer can be expected to yield at least 150mA of high-voltage DC from 3–5A of filament current without overload.

There is one thing to watch out for. Some transformers used in Army-Navy equipment, especially aircraft, are designed for 400- or 800-cps rather than 60-cps AC; they will *not* operate on 60-cps house current. These are relatively easy to spot. They may be large, but they are light for their size because they have small cores (the main reason for using 400-cps power sources).

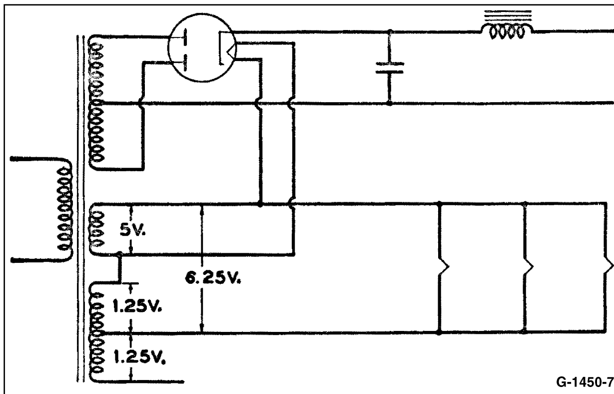


FIGURE 7: Old transformer filament wiring.

MODIFYING TRANSFORMERS

Unless you live on a desert island and components are just about impossible to obtain, there is no sense whatever in trying to rewind a transformer to produce desired voltages. It is simply too difficult a job. Sometimes, however, you can adapt a transformer to do a job which at first glance it might seem unable to do.

For example, many old radios have husky power transformers capable of delivering 250 or 300V at 125 or 150mA, but they often have 2.5V filament windings. It is quite possible to make shift with one of these for modern 6.3V tubes if the 2.5V winding is center tapped. This can be done by wiring the transformer as shown in *Fig. 7*. Half of a 2.5V winding is wired in series with the 5V rectifier winding to produce 6.25V. If the first connection doesn't give the 6.25V, reverse the leads from one of the windings: if the phase is incorrect, the voltages subtract instead of adding.

There are two disadvantages in this procedure which must be taken into account. First, the current drawn through the two windings in series should not exceed (at least not by much) that permissible for the winding with the lower capacity. Usually, the rectifier filament winding has the lower current capacity—2 or 3A.

There are several ways of holding down the total current drain. For one thing, you can use a rectifier with a lower filament current drain. The 6AX5 will draw only 1.2A compared to the 2A of the 5Y3, but will deliver 125mA of high-voltage DC. Its use would permit the employment of three 12AX7s or 12AU7s or some combination with a total drain of 2.1A, well within the capacity of a 2A winding.

In fact, four of these tubes and a total drain of 2.5A would not be a serious overload. If the high-voltage current doesn't exceed 50 or 60mA, you can provide for an even greater number of tubes by using the 6X4 rectifier whose filament draws only 0.6A. This would be all right for a control unit in which even five or six twin triodes would not require over 50mA plate supply current.

The other consideration is this: because the rectifier will operate from the same source of filament voltage as the other tubes, *it must have an independent cathode*. The 5V4, for example, cannot be used. With a filament-type rectifier the filaments of all the tubes would be at a DC potential above ground equal to the high voltage. Accidentally grounding one side or the other of the filament loop would burn all out immediately. In any case, the tubes could not tolerate the high filament-cathode bias very long.

By these expedients one of the old 2.5V transformers can be made to serve the needs of a control unit, tape recorder amplifier, or something similar. Tubes in a power amplifier, however, would draw too much current for this makeshift. For such heavier jobs you might use an old transformer's high-voltage windings and buy a separate filament transformer: that would probably save some money.

There is one other filament situation that may be troublesome. For lowest hum it is often advisable to apply DC to the filaments of phono preamplifiers. This requires the use of selenium rectifiers because the current is too high to be handled by normal tube rectifiers. To hold down the size of the selenium rectifiers and to allow for various circuit losses, it is preferable to have a voltage higher than 6V available. The various miniature tubes suitable for preamplifiers (12AU7, 12AX7, 12AT7) can be operated at 12V as well as at 6V, and they draw only half the current at 12V. There are also several small, inexpensive, bridge-type rectifiers which can deliver 12V DC at from 150–600mA. [Editor's note: Fortunately for us today, silicon rectifiers have solved these problems and transformers for low voltages are readily available.]

Strangely enough, however, transformers with 12V windings are almost unobtainable as stock items, and when obtainable are high in price. The ordinary small transformer with 5 and 6.3V filament windings is easily adaptable to the need and will still permit the use of the filament windings for normal AC filaments. How this can be done is shown in *Fig. 8*: the 5 and 6.3V windings are connected in series (if the first connection doesn't yield about 11V, reverse the leads from one of the windings). With a capacitor-input filter the output voltage will exceed 12V easily and can be set to the right value by adjustment of the series resistor. If a tube rectifier is used for the high-voltage DC, it must be a cathode-type tube, as indicated.

ADJUSTING HIGH VOLTAGE

If a power supply delivers a higher voltage than is required, it can be reduced easily. It can be dropped 25% or so by using choke input rather than capacitor input. Using a 6X4 rectifier in a small supply for a control unit, a 750V CT transformer winding would yield over 400V DC at 50 or 60mA. We should ordinarily need less than 300V. Removing the input capacitor and connecting it beyond the choke will drop the voltage to about 300V.

It may be preferable, however, to obtain the voltage drop in the hum and decoupling filters. The more excess voltage there is at the output of a rectifier, the better the filtering and decoupling possible with a given set of capacitors. An excess may permit dispensing with a choke in favor of a more compact and cheaper resistor.

It is more difficult to obtain an increase of voltage. To be sure, if the power supply now uses a choke-input filter, a considerable increase may be obtained by changing to capacitor input. Some improvement can be achieved by a careful choice of rectifier tubes. The bigger, huskier rectifiers, capable of handling higher currents, have lower internal resistance and will deliver a higher voltage at low current loads.

For example, if a 6X4 with 300V AC per plate delivers about 300V at 50mA, a 5Y3 would produce 340V at 50mA, and a 5U4 over 350. These differences in voltages would not be significant unless a power output stage were involved: even then a change of 10 or 15% in voltage would probably produce little more than 1dB difference in output power. But it is something to keep in mind, and occasionally it is useful.

TRANSFORMER RATINGS

Power ratings of commercial transformers are usually conservative. They can be exceeded by as much as 50%, at the price of severe overheating. A transformer rated at 150mA can deliver 200mA on peaks: a filament winding rated at 2A will not usually burn out with 3A. When operation is intermittent and the equipment is operated at low levels, the overload may not be serious at all. In fact, in the compulsion to produce more compact equipment, some commercial high fidelity manufacturers operate transformers far beyond their normal ratings, despite the fact that the compact and totally enclosed pancake designs lead to even more severe overheating than the transformer designer ever considered.

Personally, I prefer to stay within the conservative ratings and I recommend this strongly to others. An overloaded power transformer is not likely to burn out, but its overheating is likely to produce early failures in other components by operating them in an environment of excessive heat. Still, if it is a matter of tolerating an overload or doing without a gadget at all, it may be comforting to know that transformers not only can be overloaded, but that they often are.

THE AC LOAD

It is desirable to know how much current a power supply will draw from the 115V power line in order to determine the size of fuse needed to protect it. This is quite simple to calculate. The total power drawn at the primary will be equal to the total power delivered by the secondaries plus the losses within the transformer. Consider the hypothetical amplifier mentioned earlier: the high voltage power will be 400V at 150mA, 400 × 0.15, or 60W. The rectifier filament takes 5V at 3A, or 15W; and the other filaments 6.3V at 3.5A, or about 22W. The total is just under 100W.

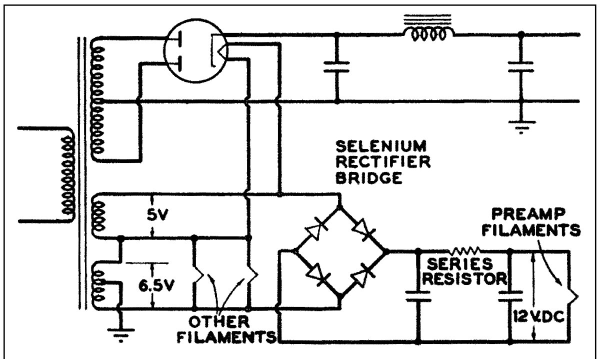


FIGURE 8: Filament windings in series for the DC preamplifier filament supply.

The power transformer can be considered to be 85–90% efficient, so we add 10 or 15% for the transformer losses. That gives us a total of 115W taken from the power line. The current drawn from the line is equal to watts divided by volts, since the load is essentially non-reactive. In this case, 115W divided by 115V gives us 1A. To minimize fuse blowing on momentary small overloads we can specify a 2A fuse. ❖

REFERENCE

1. The *RCA Receiving Tube Manual* is available from Old Colony Sound Lab (PO Box 876, Peterborough, NH 03458, 603-924-9464, FAX 603-924-6467, E-mail custserv@audioXpress.com).