Since like charges repel, a sufficiently negative grid can stop electrons from traveling to the anode. As the grid is made less-negative, the flow of electrons to the anode steadily increases. In other words, a positive-going, albeit negative polarity, grid-voltage causes an increasing flow of electrons between the cathode and the anode. The reverse is also true: a negative-going grid-voltage causes a decreasing flow of electrons from the cathode to the anode. As long as the grid remains negative with respect to the cathode, the relationship between grid-to-cathode voltage and anode-current is fairly linear.

When an appropriate load resistor is connected between the anode and its positive voltage source, the changes in anode-current produced by changes in grid-voltage create a proportional, typically much larger, voltage change across the resistor. The ratio of changes in voltage across the load resistor to changes in grid-voltage is the voltage amplification factor. It is designated by the Greek letter Mu. Since Mu is higher at high anode-voltages than it is at low anode-voltages, average Mu is a more meaningful number than maximum Mu. Average Mu ratings vary from about 2 to 240. Mu is partly determined by the spacing between the grid wires and the distance between the grid and the cathode..

Classes of Operation

The duration of anode-current conduction per cycle determines the class of amplifier operation. A conduction angle of 360 degrees means that the anode is conducting current during 100% of the input sine wave cycle. A conduction angle of 90 degrees means that the anode is conducting current during 25% of the input sine wave cycle. Long conduction angles produce a more linear representation of the input sine wave. Short conduction angles produce more efficiency--and less linearity.

Class A is defined as a conduction angle of 360 degrees. Class B is defined as a conduction angle of 180 degrees. Class C is defined as a conduction angle of less than 180 degrees. The subscript 1 indicates that no grid-current flows. The subscript 2 indicates that grid-current flows--the result of driving the grid into the positive voltage region.

When the conduction angle is less than 360 degrees, the missing part of the sine wave must somehow be filled in. One way of filling in the missing part of the sine wave is by utilizing the flywheel effect of an output tank circuit. Another way to produce a smooth sine wave is to use a push-pull configuration. If each device in a push-pull circuit conducts for at least 180 degrees, a smooth sine wave can be produced.

Class A Operation

Class A is the most linear class of amplifier operation. Class A amplifiers produce only about 1/100,000 part, or minus 50dB, distortion. The theoretical efficiency of a Class A amplifier is 50%. The practical efficiency is slightly lower. Class A is used mainly in low level amplifiers--where efficiency is not much of an issue. Since Class A operates with continuous (360 degrees) conduction, no tank circuit is needed to complete the sine wave. Class A is ideal for wide band amplification.

The zero-signal anode-current [ZSAC] in Class A is set to roughly half of the electron tube's maximum anode-current rating. Although the meter-indicated anode-current remains constant from zero signal to maximum signal, the instantaneous anode-current typically varies from just above zero to many times the meter-indicated anode-current.

The maximum available power in Class A is roughly equal to the anode-dissipation rating of the electron tube.

The Class A amplifier can be compared with a gas turbine engine. Both have a smooth, continuous power stroke--and neither one is very efficient.

Class AB1 Operation

Class AB1 amplifiers are roughly 60% efficient. The trade-off for increased efficiency is slightly more distortion--roughly 1/10,000 part, or minus 40db. Since most transceivers produce more than minus 36db of IMD, such an amplifier would not add significant distortion.

The anode-current in Class AB1 varies in proportion to the grid-voltage for about 60% of the input sine wave cycle. Thus, the anode-current is off for about 40% of each input sine wave cycle. The missing 40% in the output sine wave is filled in by the flywheel effect of the output tank circuit.

In Class A or Class AB1 a somewhat unusual relationship exists between the work being performed by the tube and the grid voltage. The grid is operated in the zero to negative voltage region. Maximum instantaneous anode-current, maximum anode voltage swing and maximum peak power output coincide with an instantaneous grid-voltage of zero--i.e., maximum stoke equals zero grid volts.

The grid must not be allowed to become positive. If the grid became positive, electrons from the cathode would begin flowing into the grid. Whenever grid-current flows, the linear relationship between grid-voltage and anode-current deteriorates.

Since there is zero grid-current in Class A or Class AB1 operation--and any voltage multiplied by zero amperes is zero watts--the driving power is usually stated as zero on the tube manufacturer's technical information sheet. However, because charging and discharging a capacitor requires current flow, in the real world of conductor RF resistance, charging/discharging the grid capacitance at an RF rate consumes some power. In a typical HF amplifier, the drive power required for Class AB1 MF/HF operation is roughly 1% to 2% of the output power. Thus, the typical power gain is roughly 50 to 100. As frequency increases, conductor resistance increases due to skin-effect. More R causes more I^2 R loss. As frequency increases, the amount of current needed to charge and discharge the grid capacitance also increases--causing even more I^2 R loss. These losses can only be compensated for by adding more drive power.

Drivers (usually a transceiver) require a resistive load--which the capacitive grid does not provide--so a suitable resistance must be connected from the grid to RF-ground..

The zero-signal anode-current [ZSAC] in a Class AB1 amplifier is normally set to about 20% of the maximum-signal single-tone anode-current.

Tubes that are designed for Class A and Class AB1 service produce high peak anode-current when the instantaneous grid-voltage is zero. Typically, the peak anode-current is about three times the maximum rated (average) anode-current. Most of the tubes that are used in Class A and Class AB1 RF amplifier service are tetrodes and pentodes--devices that have the advantage of grid-to-screen amplification. Triodes are seldom used because the only grid designs that can produce high anode-current with zero grid volts are those that have a Mu of 2 to 5. Low Mu triodes require much more driving voltage than a comparable tube with a screen requires. Since imposing a high RF voltage across the capacitive grid is difficult, low Mu triode Class A and Class AB1 power amplifiers are only practical up to a few hundred kHz.

Class AB1 Cathode-Driven Operation

The most common configuration for Class AB1 operation is grid-driven. Since grid amplification as well as grid-to-screen amplification takes place, the resulting power gain is high. Class AB1 amplifiers can also be cathode-driven if the tube is a tetrode or pentode. The grid is tied to the cathode. Thus, the grid-voltage is always 0V--so no grid-current flows. The screen is grounded. The input signal is applied to the cathode/grid. Because input signal voltage is applied between the grid and the screen, grid-to-screen amplification takes place. However, since the grid is tied to the cathode, no grid amplification takes place. Although the power gain is relatively low, linearity is excellent. The Collins 30S-1 is an example of a cathode-driven Class AB1 amplifier.

The Class AB1 amplifier is like a 2-cycle, single-cylinder engine. The power stroke is roughly half of each crankshaft revolution--it has a flywheel (the tank circuit) that supplies power between power strokes--and it is more efficient than a gas turbine (Class A).

Class AB2 Operation

Class AB2 is similar to Class AB1 except that the grid is driven into the positive voltage region during a part of the anode conduction period. A Class AB2 amplifier can be grid-driven or cathode-driven.

Grid-Driven Class AB2 and Negative-feedback

When the grid is driven positive, it attracts and accelerates the cathode's electrons. Some of the electrons stick to the grid, resulting in grid-current. Electrons that miss the grid travel to the anode. The accelerated head start causes a sharp increase in instantaneous anode-current--and a sharp decrease in linearity. The distortion products from a single-ended, Class AB2 grid-driven amplifier are roughly 1/100 part [minus 20db]. In SSB service, this level of distortion is virtually certain to cause interference to other stations using adjacent frequencies. However, by limiting grid-current and by adding an unbypassed, low-L cathode feedback resistor (to develop an out-of-phase {negative} feedback voltage) it is possible to achieve acceptable linearity in grid-driven Class AB2 operation--but only if the grid current produced is small.

An unbypassed cathode resistor is also useful for improving linearity in Class AB1. For example, the 4CX250B has a somewhat objectionable distortion level in Class AB1, SSB service. Adding a 25 Ohm resistor between the unbypassed cathode and chassis ground improves linearity. The trade-off is that slightly more grid drive voltage is needed to achieve the same output level. Cathode negative-feedback is also useful with TV sweep tubes--devices that were originally designed for switching--the opposite of linear amplification. When an appropriate cathode resistor is used with a sweep tube, reasonable linearity can be achieved.

Class AB2 Grounded-Grid Operation

Even though Class AB2 cathode-driven/grounded-grid operation produces grid-current, it is never the less fairly linear due to the laundering effect of negative-feedback. This is the result of the input and output signals being in series with each other and out of phase. Due to the negative-feedback, the distortion level in Class AB2 grounded-grid service is low--typically about 40db below PEP.

High-Mu triodes work well in Class AB2 grounded-grid operation. Medium-Mu triodes can be used, but they have less power gain. Tetrodes and pentodes usually work well in grounded-grid operation. Since tetrodes and pentodes typically have a grid-to-screen amplification factor of about 5, its easy to assume that they offer an advantage over triodes in Class AB2 grounded-grid operation. However, RF-grounding the grid and the screen stops grid-to-screen amplification. Applying DC screen-voltage does NOT increase gain because grid-to-screen amplification can not take place unless input signal voltage is applied between the grid and the screen.

The maximum available power in Class AB2 is roughly double the anode-dissipation rating.

Class B Operation

Class B is defined as a conduction angle of 180 degrees. Class B RF amplifiers produce unacceptable distortion in SSB operation.

Class C Operation

Class C is defined as an anode conduction angle of less than 180 degrees. In Class C, the amplifying device is deliberately not operated linearly. Instead, it is operated as a switch in order to reduce resistance loss. The anode conduction angle in Class C operation is usually made as short as is possible. In effect, the tank circuit makes the RF output sine wave--like a bell that is struck at a constant rate by a hammer. This is similar to the principal behind the spark transmitter.

The efficiency of a typical Class C amplifier is high. When compared to a Class AB1 or Class AB2 amplifier operating at the same power input, a Class C amplifier will deliver a received signal increase of about 1db--in other words, 1/6 of 1 S-unit. However, significant trade-offs are required to achieve that 1/6 of 1 S-unit. As is the case with Class B operation, the distortion from Class C operation is so high that SSB operation is precluded. Only CW, FM or FSK operation is practical. The harmonic output level from a Class C amplifier is substantial. Extra filtering is usually needed to control harmonic radiation.

The maximum available power in Class C operation is roughly three to four times the anode-dissipation rating of the electron tube.

Class D Operation

Class D is used up to about 1.6MHz--mostly in AM broadcast service. In Class D operation, the amplifying device rapidly switches on and off at a fixed rate--like a switching power supply--except that the output voltage varies at an RF rate. The amplitude of the RF is controlled by varying the on period of the switch. Smoothing is accomplished by a complicated filter that converts some of the odd-harmonic energy from the rectangular waves back to fundamental frequency energy. Class D is highly efficient--but it is limited in frequency capability and frequency agility.

Amplifier Design Considerations

Arriving at an amplifier design that will give years of surprise-free service involves many considerations. Merely copying circuits from published amplifier designs or commercial amplifiers is not necessarily the best approach. Doing so may result in copying someone's mistakes. The best approach is to learn what you can about each section of an amplifier, discuss it with others--then reach your own conclusions.

Basic prerequisites for getting a handle on what's going on inside an amplifier are an understanding of Ohm's Law, inductive and capacitive reactance, impedance, resonance, how gridded electron tubes function, and some knowledge of L and pi networks.

A useful book on amplifier design is Eimac®'s ***Care and Feeding of Power Grid Tubes***. I will minimize the discussion of topics that are covered adequately in this book.

Tubes vs. FETs

When the first RF power FETs were introduced, it was commonly thought that FETs would eventually replace bipolar transistors and gridded electron tubes in HF power amplifiers. Since RF power FETs work better at 50V than they do at 12V, FETs have not replaced bipolar transistors in 12V mobile applications. Another difficulty with FETs is cost. A pair of FETs that can produce 1200W PEP at 29MHz cost about six times more than an electron tube, or tubes, that can do the same job. The FETs' input power requirements are 50V at 50A, i.e., 2500W--so there's considerable heat to dispose of. Meeting the cooling requirement is not nearly as easy as it is with tubes because tubes operate quite happily at surface temperatures that destroy silicon devices.

In low power applications at room-temperature, solid-state devices can last 100 years. However, at the junction temperatures encountered in high power applications, the P and N doped layers slowly diffuse into each other--thereby steadily eroding the device's amplifying ability. A relatively-large rigorous cooling system is needed to achieve a reasonable operating life from high power solid-state RF amplifying devices.

Another difficulty with solid-state high power RF amplifiers is their power supply requirements. Tubes are quite tolerant of moderate variations in their anode supply voltage. Transistors, however, are fatally sensitive to over-voltage. It is much easier to build a 3000V, 0.8A unregulated supply for a tube than to build a regulated 50V, 50A power supply with over-voltage, over-current and over-temperature protection circuitry for high-power solid-state devices.

The bottom-line is that 1500W, HF, gridded electron tube amplifiers are more efficient, more forgiving, easier to cool, more compact, weigh less, are more tolerant of high SWR and are less costly than 1500W HF semiconductor amplifiers. For instance, a pair of legal-limit FETs cost about $800 from Motorola®. The efficiency is about 10% less that what one can achieve with gridded electron tubes.

Grounded-Grid Versus Grid-Driven

For at least the last three decades, the vast majority of amateur radio amplifier designs have been Class AB2 cathode-driven--a.k.a. 'grounded-grid'. One reason for this is simplicity--or at least the appearance of simplicity. Ground the grid(s), drive the cathode. Only three supplies are needed--the T-R switching supply, the filament supply and the anode supply. Neutralization is theoretically not needed because the grounded grid(s) shield the output element, the anode, from the input element, the cathode. This theory works **almost** perfectly. Grounded-grid amplifiers are virtually always stable at the operating frequency because the reactance of the feedback C is too high at HF to allow regeneration. This is fortunate because there is no way of neutralizing a single ended grounded-grid amplifier. Another advantage is flexibility. Almost any tetrode, pentode, or high-Mu triode from the junk box will work. Linearity is usually good and the typical power gain--10db to 14db--is acceptable. So far, so good. Now for the trade-offs.

What goes on inside a grounded-grid amplifier is not as simple as it looks. The AC component of the anode-current and the grid-current, i.e., the RF cathode current, passes entirely through the cathode coupling capacitor and the tuned-input circuit--so the input circuit is in series with (and out of phase with) the output circuit. The components in the tuned circuit must be able to handle a substantial amount of RF current. Manufacturers of tubes that are designed for grounded-grid operation typically recommend using a tuned input pi-network with a Q of 2 to 5. To maintain an acceptable SWR and Q when the operating frequency changes appreciably, all three reactances in the tuned input must change proportionally. However, if Q is allowed to change, L can be left as is providing that C1 and C2 are retuned. [For more information on this problem, see the section titled "Tuned Input Circuits."]

Even though HF grounded-grid amplifiers are stable at their operating frequency, at VHF the grid looses its ability to shield the input from the output. HF grounded-grid amplifiers have a less-than-pristine reputation for VHF stability.

For wide frequency coverage, the Class AB1 grid-driven amplifier requires a much simpler tuned input than a grounded-grid amplifier requires. Typically, grid-driven amplifiers have more power gain than grounded-grid amplifiers. One Class AB1 grid-driven amplifier has about as much gain as two Class AB2 grounded-grid amplifiers in series. The trade-off is two additional DC supplies--a grid bias supply and a screen supply. Both of these supplies need to be adjustable. HV power FETs make this task easy.

Cathodes

There are two types of cathodes--directly-heated and indirectly-heated. In a directly-heated cathode, a ditungsten carbide layer on the hot (c.1800 degrees K) tungsten, alloyed with about 1.5% thorium--a.k.a. 'thoriated-tungsten', filament wire emits electrons. In an indirectly-heated cathode, the filament (a.k.a. heater) heats a metal cylinder that is coated with strontium oxide and barium oxide. This coating is relatively frangible--but highly emissive.

Ditungsten carbide is commonly formed by heating tungsten in an atmosphere of acetylene (C_2H_2) gas. Carbon atoms in the gas break their electron bonds with hydrogen atoms and bond with tungsten atoms to form ditungsten carbide on the surface of the filament wire. Since it is atomically linked to the underlying tungsten, the ditungsten carbide layer is very durable. During use, the process reverses. Ditungsten carbide gradually looses carbon and changes back to tungsten. Extra heat exponentially accelerates this process. A cathode is worn out when the carbon is mostly used up.

After their cathodes grow tired of emitting electrons, large external-anode amplifier tubes are commonly "recarburized" with acetylene, vacuum-pumped and resealed. This restores full emission. Although it is possible to recarburize a 3-500Z, doing so is not economically feasible. The smallest tube that is currently being recarburized is the 3CX1000A7.

Each type of cathode has advantages and disadvantages. Indirectly-heated cylinder [8877] and planar [3CX100A5] cathodes have much less inductance than a directly-heated cathode made from wires. Thus, indirectly-heated cathodes are more frequency-capable. Some indirectly-heated cathode tubes can perform satisfactorily at 2500MHz. The 3CX100A5 is an example.

Directly-heated/thoriated-tungsten cathodes are more resistant to damage from electrons that bounce off the anode. It's possible to use up to 22kV with the larger thoriated-tungsten cathode tubes. Electrons that have been accelerated by such voltages move at very high velocities. When they strike the anode, they produce X-rays.

A thoriated-tungsten cathode typically warms up in one second, while few indirectly-heated cathodes can warm up safely in one minute--and three to five minutes is not uncommon. For HF operation, indirectly-heated cathode tubes have a much higher cost to watt ratio than thoriated-tungsten cathode tubes. For VHF and especially for UHF operation, indirectly-heated cathode tubes are often the only choice. For super-power HF operation, thoriated-tungsten cathode tubes are the only choice.

Cathodes deserve respect. Filament-voltage and filament inrush current are the prime areas for concern.

Filament / Heater Considerations

For optimum life from a thoriated-tungsten cathode, the filament-voltage should be just above the voltage where PEP output begins to decrease. As a thoriated-tungsten cathode ages, filament-voltage needs to be increased incrementally to restore full PEP. By using this technique, commercial broadcasters typically achieve an operating life of more than 20,000 hours from thoriated-tungsten cathode tubes.

According to Eimac®'s *Care and Feeding of Power Grid Tubes*, "every 3% rise in thoriated-tungsten cathode filament-voltage results in a 50% decrease in life due to carbon loss." Each additional 3% rise in filament-voltage decreases the life by half. Thus, cathode life is proportional to [E1/E2]^23.4 where E1 is the lowest filament-voltage at which normal PEP output is realized--and E2 is the increased filament-voltage. However, for heater-type oxide cathodes, if the heater potential is allowed to fall below the specified level, the emissive material may flake off of the cathode, and cause a cathode-grid short. On the other hand, excessive heater potential causes barium migration to the grid - which results in primary grid emission.

Controlling Filament-Voltage

It's simple to make the filament voltage adjustable when the filament is powered by its own transformer. All that's needed is a small rheostat in series with the primary. For dual voltage, dual primary transformers, a dual ganged rheostat is required. However, when the filament is powered by a winding on the HV transformer, making the filament-voltage adjustable is more difficult since a dual ganged, very low resistance, high current rheostat must be connected to the low-voltage high-current secondary winding. The typical value needed for a pair of 3-500Zs would be (2) adjustable 0.01 Ohm @ 30A--most definitely not a common rheostat. A reasonable substitute can be made from a double pole, c.10 position, 30A rotary switch and short lengths of resistance wire or ribbon bridging the fixed contacts.

An indirectly-heated cathode can be ruined by operating it below the rated minimum filament-voltage. When operated above its maximum filament-voltage rating, an indirectly-heated cathode boils off emissive material (principally barium) onto the grid and other parts. This results in decreased cathode life and undesirable grid-emission when the grid warms up during transmit. This condition is indicated when the output power steadily drops off in AØ (max. signal, key-down, a.k.a. NØN) operation. The decrease in power normally begins within two seconds.

For maximum cathode life in HF communications service, an indirectly-heated cathode should be operated at the rated minimum filament-voltage. This can be accomplished best with a regulated DC supply.

Controlling Filament-Voltage During Receive

In a typical amateur radio amplifier, the filament-voltage rises about 5% during receive due to decreased load on the electric-mains. Not only is a 5% increase in filament-voltage during receive useless, it uses up thoriated-tungsten cathode emission life about three times as fast as during transmit. However, if an appropriate resistor is placed in series with the filament transformer primary, and shorted out by a relay during transmit, the filament-voltage will not change appreciably between transmit and receive. An appropriate type of relay for shorting the resistor on transmit is a 'power' reed-relay.

Filament Inrush Current

Thoriated-tungsten filaments commonly consist of two vertical intermeshing helices (coils) of tungsten wire that are suspended by their ends. (see Sept. 1990 QST, p.15) The conductance of tungsten at room temperature is about 8.33 times the conductance at the normal operating temperature. Thus, the start-up current for a 15-ampere filament can exceed 100 amperes. Needless to say, 100 amperes makes for a dandy electromagnet.

In a high amplification triode such as the 3-500Z, the filament helices clear the grid cage by a matter of thousandths of an inch. If the position of the filament changes, a grid-to-filament short may result. Therefore, it is prudent to limit filament inrush current in order to minimize thermal and magnetic stress.

Since the grid-to-cathode clearance in an indirectly-heated cathode is not affected by movement of the heater inside the rigid cathode cylinder, indirectly-heated cathodes are not affected by inrush current.

For many of its smaller thoriated-tungsten cathode amplifier tubes--such as the 3-400Z and 3-500Z--Eimac® recommends that filament inrush current be limited to no more than double the normal current. This rating is easily exceeded unless a special current-limiting filament transformer or a step-start circuit is used.

END PART 1

Grid Protection in G-G Service

Transmitting AØ for long periods on 10m with the load capacitor set for maximum C would result in very high grid-current and almost no RF output. Under such a condition it might be possible to overheat a grid. However, since most people tune an amplifier for maximum output--and maximum output virtually coincides with normal grid-current--very few people are likely to overheat a grid. Thus, complex electronic grid-protection circuits are seemingly unnecessary.

A disadvantage of electronic grid-protection circuits is that they are not effective against the most common source of grid damage--intermittent VHF parasitic oscillation.

Glitch Protection

During a major problem, the anode (plate) current meter and other amplifier components can be subjected to a large current surge as the HV filter capacitors discharge. The peak discharge current can exceed 1000a if a series resistor is not used to limit the short circuit current that can be delivered by the HV filter capacitors. The current limiting resistor is placed in series with the positive output lead from the filter capacitors. A wire wound resistor with a high length to diameter ratio works best. A 10 ohm, 10W wire wound resistor is adequate for up to about 3kV & 1A. For higher voltages, additional 10 ohm, 10W resistors can be added in series to share the voltage drop during a glitch. Wire wound resistors with a high length-to-diameter ratio are best for this type of service. Since about 1985, Eimac® has recommended the use of a glitch protection resistor in the anode supply circuit. Svetlana® typically recommends using a 10 to 25 ohm glitch resistor.

A HV current limiting/glitch resistor may disintegrate during a major glitch--so it should be given a wide berth with plenty of chassis clearance. If the chassis clearance is minimal, its a good idea to cover the chassis with electrical insulating tape. Glass-coated (a.k.a. vitreous) wire wound resistors are the most suitable type of resistor for this application. If a glass-coated resistor comes apart during a major glitch, it won't be throwing chunks of shrapnel around--like a less-expensive rectangular ceramic-cased resistor often does. Metal-case power resistors should not be used in this application. If a glass-coated glitch resistor is damaged during a glitch, it should be replaced with two such resistors in series to reduce the peak V-gradient per unit of length during a problem.

If the positive HV arcs to chassis ground--due to lint, a hapless insect, a VHF parasitic oscillation, or moisture--the negative HV circuit will try to spike to several kilovolts negative in the typical 1500W amplifier. In the real world, this type of glitch is not an uncommon occurrence. Anything that gets in the way of the negative spike may be damaged. Since the grid-current meter is normally connected between chassis ground and the negative HV circuit, the meter can be exposed to kilovolts at hundreds of amperes.

The easiest way to protect a current meter is to connect a silicon rectifier diode across it, or across its shunt resistor. Usually, only one diode {cathode band to meter negative} is needed in parallel with a DC meter. In some circuits, it is best to use two diodes in parallel [anode to cathode] with the meter movement to protect against positive and negative surges.

It may take more than one diode to protect a meter shunt resistor. A silicon diode begins to conduct at a forward voltage of about 0.5V. To avoid affecting meter accuracy, the operating voltage per glitch protection diode should not exceed 0.5V. For example, a 1 ohm shunt, at a reading of 1A full-scale, has 1V across it. Thus, two protection diodes in series would be needed to preserve meter accuracy. Similarly, if the shunt resistor for a 1A full-scale meter is 1.5 ohm, the maximum shunt voltage is 1.5V--so three diodes are needed.

Glitch protection diodes should not be petite. Big, ugly diodes with a peak current rating of 200a or more are best. Smaller diodes--and the meter they were supposed to be protecting--can be destroyed during a glitch. Suitable glitch protection diodes are 1N5400 (50PIV) to 1N5408 (1000PIV). In this application, PIV is not important. The 1N5400 family of diodes is rated at 200a for 8.3mS.

During an extremely high current surge, a glitch protection diode may short out--and by so doing protect the precious parts. Replacing a shorted protection diode instead of a kaput meter is almost fun.

To reduce the chance of the negative HV circuit spiking to several kilovolts, connect a string of glitch protection diodes from the negative terminal on the HV filter capacitor to chassis. At 200a, each diode will limit the surge voltage across it to about 1.5v. Typically, three diodes are needed--thusly limiting the negative spike to about 4.5 volts. Diode polarity is: cathode band toward the negative HV. With one simple wiring change, the same string of diodes can also protect the grid I meter and the anode I meter. This dual protection technique is incorporated into the Adjustable Electronic Cathode Bias Switch on Figure 7.

Design Considerations for Indirectly-Heated Cathode Tubes

A HV arc can destroy an indirectly-heated cathode tube. Here's how it happens: In some amplifiers, one side of the filament/heater is grounded. The cathode is connected to the negative HV circuit. If the negative HV spikes to several kilovolts, the cathode will often arc to the grounded heater. At a minimum, this breaks down the insulation between the heater and the cathode. Sometimes the heater wire burns out--and sometimes the cathode arcs to the grounded grid. Either way the tube is kaput.

Grounding one side of the heater is an invitation for cathode-to-filament breakdown. Instead, let both heater wires float. If the heater is fed through an c.40micro H bifilar RFC, one side of the heater can be wired to the cathode. Even though this arrangement can not protect against cathode-to-grid breakdown, it assures that the voltage between the filament and the cathode is unlikely to rise to dangerous levels.

Safety Devices

HV-Shorting

Manufactured amplifiers typically use a safety device to automatically short the +HV supply to chassis ground when the output section cover is removed. If the cover is removed before the HV filter capacitors have discharged, the resulting positive HV to ground short can damage the amplifier. In most g-g amplifiers, the only DC current path between the negative HV circuit and chassis ground is the grid-current meter and its shunt resistor. Even if the remaining charge in the HV filter capacitors is only 200V when the short from positive to ground occurs, without glitch protection diodes, the entire 200V appears across the grid-current meter shunt and the grid-current meter. Many potentially-fatal amperes can flow into the grid meter as the HV filter capacitors finish discharging. If the amplifier is accidentally switched on with the cover removed, rectifier diodes are a common casualty.

Automatic-shorting safety devices are not only dangerous to amplifier components, they can be dangerous to operators. It is dangerous to assume that an amplifier is safe to work on because it contains a safety device. Even though an amplifier's HV supply is shorted, if the amplifier is plugged in, its electric-mains circuitry is still alive and potentially fatal. Amplifiers are inherently dangerous. They should not be worked on casually--even if they have so-called safety devices.

The safest quick method of discharging HV filter capacitors is through a paralleled pair of wire wound resistors. The resistors limit the discharge current to a safe amount. In the unlikely event that one resistor opens, the remaining resistor will do the job. For the average 1500W amplifier, a paralleled pair of non-adjustable 1k ohm to 5k ohm, 50W resistors will do the job. **Its always a good idea to check the anode supply voltmeter before putting your hands inside an amplifier.**

Fuses

Fuses have current and voltage ratings. For a fuse, the real test is opening safely--not operating without opening during normal operation. A fuse's maximum voltage rating is important. In some amplifiers, ordinary 250V 3AG fuses are casually used in circuits where they may be required to interrupt several kilovolts. Examples are the anode or cathode circuit. All's well until a problem occurs. When a 250V fuse attempts to interrupt a potentially-damaging flow of current in such circuits, the frangible link inside the fuse parts as it should. However, due to the available voltage, when the link melts, a metal vapour arc forms in its place. Metal vapour arcs typically have a voltage drop of around 20V--so the unsafe current will continue to flow in the circuit. At some point, the fuse will eventually explode--usually after serious damage has been done to other components.

During a glitch, circuits which normally carry low voltages can spike to several kilovolts. For example, cathode circuits normally see a maximum voltage of 30V to 100V. Thus, it might seem appropriate to use a 250V fuse to protect the cathode from excessive current. However, when a glitch occurs, several kilovolts can appear across anything that attempts to interrupt the flow of cathode current. The safest place to use ordinary 250V fuses is in the primaries of transformers.

Power Supplies

Ripple Filters

There are basically two types of DC filters: inductor-input / capacitor-output, and capacitor. Each type of filter has advantages and trade-offs.

Capacitor filters have good transient response. Since no inductor and resonating capacitor are used, the capacitor filter is simple to build, compact, cost-effective, requires no tuning and it is lightweight. The main disadvantage of a capacitor filter is that the capacitor is charged only during a small fraction of the waveform supplied by the transformer. No charging current flows until the instantaneous output voltage from the rectifiers exceeds the instantaneous voltage on the filter capacitor. This means that the transformer is either not loaded or severely loaded at different times during each cycle.

For example, with a electric-mains frequency of 60Hz, the duration of a half cycle is 8.333mS. Under load, using a capacitor filter, the capacitor charging time per half-cycle is typically only about 1mS out of the 8.333mS. This means that the ratio between output current and peak charging current can be 8 to 1. To combat I^2 R loss in a capacitor filter power supply, the transformer, all circuitry in the primary (including the electric-mains) and the filter capacitor should have low resistance. Capacitor filters are not appropriate for use with older-design transformers that were intended for use with inductor filters. Typically, such transformers have high winding resistance.

Inductor-input / capacitor filters can be of the resonated type or the non-resonated type. A non-resonated inductor tries to maintain a constant DC-current despite changes in the load current. This is the nature of any inductor. It always tries to maintain constant current by temporarily increasing the output voltage when the load current decreases suddenly, or by decreasing the output voltage when the load current increases suddenly.

When a conventional voltmeter is used to monitor the output voltage from a non-resonated inductor / capacitor filter power supply, the transient unregulation characteristic will usually not be detected because of the damped response in the meter movement. If a DC oscilloscope is used to monitor the output voltage while a string of caround 5 WPM CW dashes are sent, the instantaneous output voltage swings can be easily observed. On make, the output voltage spikes downward. On break, the output voltage spikes upward. The amplitude and width of the spike depends on how much filter capacitance is used after the inductor and on the change in current. Upward and downward voltage spikes of more than ±50% are possible during a sudden load change on a non-resonated inductor / capacitor filter power supply.

- Transient unregulation is probably not an important consideration unless SSB operation is used. With SSB, the PEP output and the linearity of the amplifier would be adversely affected by a non-resonant inductor DC filter.

The resonant DC filter maintains a fairly constant output voltage during rapid or slow changes in current demand--provided that a minimum current passes through the inductor. This minimum current can be the zero-signal anode-current [a.k.a. 'idling current'] of the tube itself. The inductor is resonated with a parallel capacitor. In actual practice, the value of capacitance used--as well as the bleeder resistance--is that which produces satisfactory voltage regulation. The resulting resonant frequency is usually slightly higher than double the frequency of the electric-mains. Resonant L/C pairs are available from Peter W. Dahl, Inc.

DC filter inductors come in two types, fixed-inductance and swinging-inductance. A swinging-inductor changes its inductance according to the current that is passing through it. Obviously, a swinging inductor can not stay tuned correctly with changes in current. Therefore, resonated-inductor filters can **only** use a **fixed** inductor.

The disadvantages of a resonant inductor filter are:

- The resonating capacitor must have a DC-working voltage rating of about three times the DC output voltage of the supply Typical values are 0.1 to 0.15 micro F @7.5kV to 15kV.
- To maintain voltage regulation during standby, a minimum 'bleeder' current must flow in the inductor. Typically, the bleeder current is 10%. Considerable heat is dissipated by the bleeder resistor(s). However, if the filter capacitor can withstand the approximately. 50% increase in voltage during receive, the 10% standby bleeder current requirement can be reduced to 0.5%.
- The inductor is heavy and costly.
- A resonant inductor filter usually makes an audible noise--unless the inductor has been potted in plastic resin.

The advantages of a resonant-inductor DC filter are:

- Excellent voltage regulation.
- Greatly reduced peak current demand on the transformer and the electric-mains. Most importantly, this reduces transformer heating.
- Transformers have about double the output current capability when a resonant inductor filter is used instead of a capacitor filter. However, the output V from a capacitor filter is higher.

The resonant filter is used extensively by commercial and military amplifier manufacturers. Since a resonant filter demands much less peak power from the electric-mains than a capacitor filter demands, for 120V operation, where available power is typically much more limited than with 240V operation, a resonant filter is clearly the best choice. The resonant filter is also the best choice for high duty-cycle modes such as RTTY, FM or AM.

Rectifier Circuits

- Half wave. ----**Advantages**: may be used where one side of the AC input is grounded. **Disadvantages**: requires highest filter C; causes DC current to flow in the transformer; poor voltage regulation; transient-voltage protection is needed to protect the rectifier from reverse voltage spikes.
- **Fullwave-centertap----** The fullwave-centertap rectifier circuit was used in ancient times when

tube-type rectifiers were the only game in town. Only one rectifier filament-winding was needed to produce full wave rectification, so the center-tapped secondary winding was the norm in older transformers. If a more efficient fullwave-bridge rectifier circuit had been used, three rectifier filament windings would have been needed. **Advantage**: if needed, reduces output voltage to one-half or to approximately. one-fourth of the DC voltage that would be obtained with a full wave bridge or full wave voltage-doubler. **Disadvantage**: inefficiently utilizes only half of the secondary winding at any instant--resulting in less than optimum transformer efficiency.

- **Full wave bridge---- Advantages**: full utilization of the transformer's capability; may be used with a resonant filter. **Disadvantage**: requires twice as many transformer secondary turns as the full wave voltage-doubler requires. This means more layers of insulating paper--and that takes up winding space--so smaller wire must be used.
- **Full wave voltage doubler---- Advantages**: full utilization of the transformer's capability; to achieve a specific DC voltage, only half as many transformer secondary turns are needed compared to a fullwave-bridge circuit. This means that the power transformer secondary will have a higher ratio of copper to paper. If switched secondary taps are used to control the DC output-voltage, the voltage stress on the switch is only half of what it would be with full wave bridge rectification. Full wave doubler supplies typically have a remarkably low ripple content. This is because one half of the filter capacitance is being charged at the same time the other half is being discharged. Since the charging sawtooth waveform is similar and opposite to the discharging sawtooth waveform, the result is a fairly smooth DC output. **Disadvantages**: To achieve acceptable voltage regulation, the full wave doubler requires twice as much filter capacitance as a fullwave-bridge. This is the case because each of the two filter capacitor sections is charged once per cycle versus being charged twice per cycle with the fullwave-bridge circuit. Thus, in a full wave doubler, the filter-capacitors must be able to hold their charge twice as long--so twice as much filter capacitance is needed. The capacitance requirement is easily met with modern aluminum electrolytic capacitors. They provide a large amount of capacitance in a small space at a reasonable cost. Full wave voltage doublers are not practical for use with a resonant inductor filter

Transformers

Transformers are available in two basic types: E-I (conventional) core and toroidal core. The E-I core is made from a stack of thin E-shaped and I-shaped iron plates. When placed together they form a rectangle with two windows for the windings. A stack of E-I rectangles make the completed core. The toroidal core is made from a continuous tape of grain-oriented material that contains iron and silicon plus other elements that increase the permeability of the core and decrease loss. This core material is known as Hipersil. Westinghouse Corp. was the original patent and copyright holder. Their patent expired decades ago. There are different grades of Hipersil tape. Grade 5 has the highest performance. Grade 22 has the lowest performance.

Higher permeability means that fewer turns are needed to achieve the required inductance in each winding. This means that larger diameter wire can be used. The end result is a transformer with low resistance and high efficiency. The Hipersil core is so efficient that the principal loss factor is the resistive loss in the copper wire. Hipersil core transformers are capable of producing extremely high peak currents. Thus, the Hipersil core transformer is ideally suited for capacitor filter power supplies.

It is difficult and time-consuming to thread a continuous tape core through the completed transformer windings--so someone came up with a faster way of uniting the core with the windings. Here's how it's done: The tape is wound on a form of the appropriate dimensions. The tape is spot welded together, removed from the form, and annealed at about 700 degrees C to relieve internal stresses. After cooling, the core is varnished and dried. Then the core is cut in half with a machine that makes a precise square cut. The faces of the cut are then polished flat. Thus, the halves of the core can slip into the completed windings, contact each other closely--restoring nearly perfect magnetic coupling between the halves of the core. The matched halves of the core are marked so that they can not be inadvertently mixed up with other core halves. The reunited halves of the core are held together tightly by steel bands like those used for binding heavy cartons and crates. If future access to the primary and secondary windings is needed, a Hipersil transformer can be disassembled by cutting the steel bands and removing the core halves.

Hipersil is no longer the most efficient type of core material. The new amorphous core transformer is starting to come into use by electric utilities. An amorphous core transformer is so efficient that if the secondary is unloaded and the primary is disconnected from the electric-mains, the collapsing magnetic field generates a voltage spike that can destroy the transformer. To avoid this problem, one winding is paralleled with a suitable voltage surge absorber.

Transformer Power Ratings

Transformers are commonly rated in maximum "volt-amperes" [VA]. Maximum VA are roughly equal to maximum RMS watts when the rated RMS current is flowing in each transformer winding and the transformer is operated from the rated input voltage at the design frequency. If the electric-mains voltage is reduced, the VA capability of the transformer decreases.

For SSB and CW operation, a lighter transformer may do the job just as well as a much heavier and more costly transformer. Manufactured 1500W amplifiers typically use a HV transformer with a continuous capability of roughly 600W--or VA. Such transformers are completely satisfactory for normal SSB operation. Such transformers are also capable of handling brief FM and RTTY transmissions--provided that the lower voltage tap is used.

If a power supply's DC output voltage drops more than about 10% under modulation, it's a fairly safe assumption that a more capable transformer is needed. Of course, not using enough filter capacitance or excessive electric-mains resistance can also cause poor regulation.

Transformer Current Ratings

Increasing the current in any conductor causes a square-law increase in the amount of power dissipated in the conductor. Since P=I^2 x R, doubling the current causes a 4 times increase in dissipation. This is an especially important consideration with transformers because they have considerable difficulty dissipating the heat that is generated deep inside their windings. This problem is compounded because copper has a positive, resistance versus temperature, coefficient. Thus, as the copper heats up, its resistance increases--which increases the dissipation--which increases the resistance, et cetera. This can lead to thermal runaway and transformer failure.

If a transformer has a secondary rating of 1A RMS, it means 1A with a resistive load. If connected to a rectifier and DC filter, the 1A rating does not necessarily apply. For example, if a fullwave-bridge rectifier, resonant filter circuit is used, the RMS current rating can be multiplied by at least 1.2. The DC output voltage will be about 0.85 times the RMS voltage. If a fullwave-bridge rectifier, capacitor-filter circuit is used, the loaded DC output voltage will be about 1.3 times the RMS voltage. A 30% increase in voltage sounds good, but obviously you don't get something for nothing. The trade-off for the increase in voltage is a decrease in current capability. The high peak current demanded by the capacitor filter translates into a substantive current capability decrease. .

Any formula for converting a transformer's RMS current rating to a DC output current rating is bound to be problematic due to the large number of variables. Here's a rule-of-thumb that is fairly accurate. If, after about an hour of typical operation, the outside of the transformer is uncomfortably hot for one's thumb, the internal parts of the transformer are probably deteriorating. Reducing the average load current slightly will greatly reduce transformer heating because of the square-law relationship between current and power dissipation. For example, reducing the current by 30% will reduce winding dissipation by about 50%.

There is a simple, reasonably accurate, 2-step approximation for determining the safe SSB, maximum current rating for a specific transformer for use with a capacitor filter and a full wave bridge rectifier. A slightly different approximation is used for a full wave voltage-doubler. These approximations are based on the DC resistance and the AC-voltage of the transformer's secondary winding. These approximations are useful when shopping around surplus stores or swap meets. All that's needed is an ohm-meter and a clip-lead. The clip-lead is used to short the primary of the transformer. This dampens the inductive voltage spike that occurs when the ohm-meter is disconnected.

The fullwave-bridge, capacitor filter approximations are: Multiply the secondary winding resistance by 70 to find the minimum intermittent load resistance that can be placed on the power supply. To find the DC output voltage under load, multiply the secondary RMS-voltage by 1.3. To find the safe intermittent current rating for SSB service, use Ohm's law and divide the output voltage by the minimum load resistance. For a more accurate evaluation, use the appropriate graphs in this book.

For example, a 2000V RMS secondary winding has a DC-resistance of 60 ohms. A full wave bridge rectifier, capacitor filter, circuit will be used. The safe, minimum, intermittent load resistance is approximately 70 x 60 ohm = 4200 ohms. The approximate voltage delivered under load would be 1.3 x 2000V = 2600V DC. Thus, the maximum intermittent load current is 2600V ÷ 4200 ohms = 0.62a.

Another approximation can be used to find the amount of filter capacitance needed. The approximation is 50,000 divided by the minimum load resistance. In the above example this is 50,000 ÷ 4200 = 12micro F.

For a full wave voltage-doubler, capacitor filter, power supply, the SSB-service approximations are: Minimum intermittent DC-load resistance equals 300 times the winding resistance; DC-output voltage, under load, equals 2.5 times the secondary RMS voltage.

For example: A 1000VRMS transformer has a winding resistance of 10 ohms, the minimum load resistance for full wave doubler operation would be 300 x 10 ohms=3000 ohms and the output voltage would be 2.5 x 1000V=2500V. The maximum intermittent load current is 2500V ÷ 3000 ohms = 0.83A.

The amount of filter capacitance needed for each half of the full wave voltage-doubler circuit is approximately 200,000 divided by the minimum load resistance. In the above example each of the two capacitors should have a minimum of 200,000 ÷ 3000 = 67micro F.

There is more to transformer performance than secondary resistance. If a Hipersil® core is used, core loss is minimal and the maximum intermittent power capability increases. Primary resistance is another factor to consider since it is effectively in series with the electric-mains resistance. Electric-mains resistance can cause a voltage drop problem if the amplifier is a fair distance from the service entrance box and you are using a capacitor filter power supply. One solution is to use larger diameter wires than the electric code requires. Another solution is to install the power supply near the service box and bring the HV DC to the amplifier.

END OF PART 2

Changing Voltage

It's nice to have the ability to reduce the output power from an amplifier. One way to do this is to reduce the anode-voltage and anode-current simultaneously so that the output load-R of the amplifier tube or tubes does not change appreciably. This allows the tank circuit to function at its design Q for both high and low power.

Switching primary taps is not an efficient method of reducing output voltage because in order to do so extra turns must added to the primary. To make room for the extra turns, the primary's wire diameter must be decreased--and that increases R. An efficient method of reducing the DC output voltage in a HV power supply is by switching secondary taps on the transformer. If a fairly ordinary ceramic rotary switch is insulated from the chassis, it can easily perform this job. The taps should not be switched under load.

If no secondary tap is provided on a transformer, it is possible to lower the output voltage 50% by switching from fullwave doubler to fullwave bridge rectification. All that's needed is a suitable SPST vacuum relay, or well-insulated ceramic switch, two filter capacitors and four strings of rectifiers. For example, a power supply that produces 4000V for SSB could be operated at 2000V for RTTY, CW, or FM. The DC output current capability doubles when the output voltage is halved during fullwave bridge operation--just what's needed for FM's and RTTY's much higher duty-cycle. When switching the voltage output, it is best to temporarily switch the power supply off and then restart. The output voltage may be switched down without switching the supply off--provided that the amplifier is in standby.

Variable Electric-Mains Transformers

On paper, the variable auto-transformer, a.k.a. Variac® or Powerstat®, looks good. Variacs/Powerstats are intended to be used with resistive loads. When a Variac is set at or near 100% of the input voltage, it adds only a small amount of series R. However, when a Variac is set to produce a fraction of the input voltage it adds more series R. This is of little consequence with resistive loads. However, when the load is a capacitor filter DC supply, due the demand for high peak current, additional series R is most unwelcome. Although Variacs perform acceptably with resonant choke filter power supplies, using a Variac to control the output voltage from a capacitor filter supply is not good engineering practice.

A Variac can be used in place of a step-start relay. Provided that the operator always remembers to set the Variac to near-zero before switching the amplifier on, all will be well. A step-start relay offers some advantages: it is cheaper, mistake-proof, saves many kilograms, and it adds substantially less series R.

There is, however, an appropriate step-start application for a Variac. Eimac® recommends using a motor-driven Variac, feeding the filament transformer primary, to bring up and bring down the filament-voltage (over a period of two minutes each) on its tubes which incorporate water-cooled filament supports. An example is the 8973 tetrode--just what you need if you are building a 600kW linear amplifier.

Transformer Insulation

Most transformers use paper to separate and insulate each layer of windings. Paper is hygroscopic--i.e., it absorbs water vapour from the air. The presence of water reduces the insulating ability of the paper. In time, insulation breakdown is likely. The solution is to pot the windings. Plastic resins are best. Petroleum tar is next best. Since potting fills up the air spaces in the windings--and air is a poor heat conductor--potting also improves heat transfer--thereby reducing internal temperature and increasing MTBF. Potting adds very little to the initial cost of a transformer and subtracts substantially from the long-term cost. Some custom transformer manufacturers offer potting as an extra-cost option. Peter Dahl Co. has a potting option.

Transformer Potting

Commercial transformer potting is normally done in a vacuum chamber to facilitate the evacuation of air bubbles. However, with a little patience, it is possible to pot transformers satisfactorily without special equipment. Bake the transformer in an oven at a temperature of about 175 degrees F/80 degrees C. Bake for two to three hours per pound. Baking drives out internal moisture. After baking, place the transformer on a table covered with a thick layer of newspapers. Position the transformer so that the leads or lugs are down. Using masking tape, seal the end of the transformer windings opposite the leads/lugs so that liquid can not escape easily when the transformer is inverted.

Polyester fiberglass laminating resin is designed to flow into small spaces and expel air bubbles. It can be used for potting transformers.

In a clean tin-can, pour in a quantity of laminating resin that will fill up the air spaces in the bottom 5% of the transformer's windings. Using pliers, bend the rim to facilitate pouring the resin. Mix in about 5 drops of catalyst per ounce of resin. Depending on the ambient temperature and humidity, this amount of catalyst will result in a moderately fast gel time. Pour the resin slowly into the windings. Resin pouring should be done steadily and from only one area of the windings to avoid trapping air bubbles. Any leaks from the bottom can be patched by forcing raw silicone rubber into the area of the leak. When the resin gels, it forms a thin bottom plug. The bottom plug need not be more than about 5mm thick.

Pour an amount of resin into the can that will fill the remainder of the windings. For a several-kVA transformer, use about 1.5 drops of catalyst per ounce of resin. For smaller transformers, slightly more catalyst is needed. The resin must not gel before the air bubbles have had a chance to escape--so it is better to err on the light side for the amount of catalyst.

Heat increases the fluidity of the resin--hastening the exit of bubbles. However, heat tends to decrease gel-time. Internal transformer heating is accomplished by forcing current through the windings with a Variac. Connect the Variac to the highest voltage winding. Short the highest current winding with an AC ampmeter. Increase the voltage until the ampmeter indicates the rated winding current. At this level fairly normal internal heating results. As soon as the resin begins to gel, stop the current and direct a cooling fan at the transformer. Resin-gelling is an exothermic reaction.

Rectifiers

The most frequent failure mechanism for HV power supply rectifiers is too much reverse current. This problem can be virtually eliminated in 50Hz/60Hz, fullwave bridge and fullwave doubler, capacitor filter circuits if the total PIV in each string of diodes exceeds the no-load DC output voltage by at least 50%. For operation in high-temperature environments, a 100% factor may be needed.

Modern solid-state rectifiers are made differently than they were 30 years ago. In those ancient times, same-type rectifiers did not have uniform reverse characteristics. Rectifier failure was common. In an attempt to compensate for the inherent weaknesses in early solid-state devices, rectifier protection schemes were used. Resistors and capacitors were paralleled with series rectifiers--probably a take-off on the practice of using equalizer resistors on electrolytic filter capacitors. However, in any series circuit, the currents in all of the elements are exactly equal. Thus, when rectifiers are in series, the reverse current burden is exactly the same for each rectifier--provided that no parallel resistors are used. Manufacturers of series rectifier units long ago abandoned the practice of using parallel resistors and capacitors. The 1995/6/7 Radio Amateur's Handbook explains why rectifier 'equalization' is prone to cause premature rectifier failure.[page 11-9, middle column, top]

Series-connected rectifiers should be of the same type. Mixing rectifiers types in the same series string could cause a problem during the reverse half-cycle.

When a rectifier has been conducting, it takes a finite amount of recovery time for the rectifier to stop conducting after the source of forward current reaches zero. It is important that a rectifier not be conducting when the reverse voltage arrives. This can be a problem when rectifying high frequency AC or when rectifying square waves. Paralleling a capacitor with each rectifier may help the rectifiers to stop conducting sooner. If you need to rectify high frequency AC, one solution is to use fast-recovery epitaxial rectifiers. 1000PIV, 1A, 70 nanosecond recovery time units are currently priced at about 50¢ each in quantities of 100.

Packaged HV Rectifiers

Rectifiers that have a rating above 1kV PIV are typically made from a series of individual rectifiers that are entombed in an epoxy package. This arrangement makes for a neat-appearing installation--but there is a trade-off. Epoxy is a poor conductor of heat. Individual series-connected diodes mounted on perfboard and exposed to open air dispose of heat much more efficiently than do multi-diode packages.

Filter Capacitors

Filter capacitors usually have a ripple-current rating. The ripple-current rating should be at least equal to the maximum DC output current capability of the supply. Quality filter capacitors are designed to minimize equivalent series resistance [ESR]. Low ESR ohms translates into a high ripple-current rating.

Oil-filled capacitors are available in two types: filter service, for use in power supplies, and flash service for use in photography or pulsed laser applications. The flash capacitor is designed for maximum capacitance per unit volume. To reduce volume, very thin metal foil is used to make the plates of a flash capacitor. Thin plates have more ESR--so they dissipate more I-squared times R power when they are subjected to ripple-current.

For longest life in high duty-cycle applications, cool air should be allowed to circulate freely around filter capacitors.

According to some manufacturers, flash capacitors can be used in filter service if they are operated at 60% of their rated peak volts. In intermittent duty applications, it may be possible to use flash capacitors at more than 60% of their rated peak-voltage. To discover how a flash-capacitor is faring in ripple-current service, after about an hour of contesting, if the capacitor is warm to the touch, an internal heating problem is indicated. Internal heating causes expansion and stresses the capacitor's case--which may eventually come apart at the seams and begin to leak dielectric oil.

If not plainly stated on its label, there is a way of determining the intended type of service for an oil-filled capacitor. Flash-capacitors usually have a peak voltage [PV or VP] rating. Filter-service capacitors are usually rated in DC working volts [DCWV]. Capacitors can also be rated in AC working volts. To convert AC-working volts to DC-working volts, multiply the AC voltage by three.

There have been instances where surplus flash capacitors were offered for sale with altered or counterfeit markings. For example, a capacitor that was originally marked "3.5kVP" was changed to "5kV" by erasing characters. Thus, a capacitor that should have been de-rated to 0.6 x 3.5kV = 2100V for filter service would appear to be good for 5kV. A practical way of determining whether an oil-filled capacitor can withstand ripple-current is to connect it in series with an AC-ampere meter and an AC voltage source. The voltage is adjusted until the AC current is equal to the expected maximum output current of the power supply. If, after an hour, the capacitor shows little or no internal heating, you have a winner.

There is also a flash service type of aluminum electrolytic capacitor, that is not designed to handle ripple-current.

Electrolytic filter capacitors are intolerant of reverse current and heat. Electrolytic capacitor working voltage [WV] ratings should be treated with respect. The WV rating is virtually the maximum voltage rating. Despite their more delicate nature, electrolytic filter capacitors offer substantial advantages over oil-filled filter capacitors. The main advantages are more joules of energy storage per dollar, reduced weight and reduced volume.

When electrolytic capacitors are operated in series, they should share the voltage equally. In order to do this, a voltage equalizer resistor is connected across each capacitor. Equalizing resistors must have fairly equal resistance--and their resistance should not change appreciably during aging. If an equalizer resistor changes value appreciably, domino-effect destruction of an entire section of filter capacitors may result.

There is no formula for determining the optimum resistance for an equalizer resistor. Less resistance equals less bleed-down time. However, less resistance produces more heat. A compromise is in order.

Carbon-composition resistors change resistance with age. This characteristic is unacceptable for equalizer resistor service. High resistance, wire wound resistors are wound with extremely fine resistance wire. They are not remarkably reliable. Metal oxide film [MOF] resistors are more reliable. The initial resistance of a MOF resistor is typically much closer to the labeled value--and it will stay that way for many years. A Matsushita/Panasonic® 3W, 100k ohm MOF resistor makes a good equalizer resistor for 450V capacitors. It produces a reasonable bleed-down time and a reasonable amount of heat. These resistors are available from Digi-Key.

Electrolytic filter capacitors are ruined quickly by reverse current. Reverse current often occurs when a rectifier fails. To protect electrolytic capacitors from reverse current, connect a >600PIV diode across each capacitor. The cathode band of the diode connects to the capacitor's positive terminal.

Biasing

When a grounded-grid amplifier's operating bias is obtained from a single Zener diode, there is no way to compensate for tube variation. One solution is to obtain the operating bias from a series string of forward biased rectifier diodes. By switching the number of diodes in and out with a rotary switch, the bias can be changed in approximately 0.7V increments.

Traditionally, a mechanical relay has been used to switch amplifier bias between receive and transmit. An optoisolator coupled to a transistor switch, i.e., an electronic bias switch, can do this job faster, more reliably, sans-noise, and cheaper.

There are principally two means of actuating electronic bias switches--RF-actuation and coil-current actuation. Although it sounds hip, RF-actuation creates two problems. The amplifier rapidly switches between linear bias and non-linear bias during softly-spoken syllables of speech. This causes choppy-sounding audio and splatter. When the electronic bias switch is controlled by the current that passes through the RF relays' coils, it is not possible to intermittently switch the amplifier into non-linear bias during transmit. Coil current actuated bias switching can be accomplished with an optoisolator. The optoisolator's input LED is driven by the coil-current. The output of the optoisolator drives the bias switch transistor.

Class AB1 Grid Bias

Since the grid draws virtually zero current, it is easy to make the bias continuously adjustable in Class AB1 operation. Typically, the cutoff bias voltage during receive will be about 50% higher than the transmit bias voltage. An optoisolator driving a HV FET can be used to switch the bias between transmit and receive. A circuit is provided.

High Speed RF Switching

A conventional relay switches in roughly 25mS. Such relays have traditionally been used for RF and bias switching in RF amplifiers. This was acceptable when transceivers also used conventional relays. Currently manufactured transceivers are designed for AMTOR, QSK telegraphy, and unobtrusive SSB VOX operation. Modern transceivers T/R and R/T switch quietly, and do so in as little as 5mS. Such radios typically use a high-power SPDT reed relay to switch the antenna between transmit and receive. Similar relays can be used for amplifier input RF switching. Jennings and Kilovac manufacture high speed, SPDT vacuum-relays that have a continuous rating of 7A at 32MHz [2450W into 50 ohms]. The Jennings relay is the RJ-1A. Kilovac's relay is the HC-1. When used with a speedup-circuit, either relay can switch in under 2mS. Although both manufacturers make DPDT RF vacuum-relays, none are as speedy as their fastest single pole models. Thus, separate input and output relays are usually faster than a single DPDT relay.

PIN Diode Switching

Another device that can be used for high-speed RF switching is the PIN [P-Intrinsic-N] diode. PIN diodes are similar to 1000PIV rectifier diodes--i.e., they have a wide intrinsic region. PIN diodes are utilized extensively in radars as transmit-receive switches.

A PIN diode is switched off by applying DC reverse voltage to widen its intrinsic region. The PIN diode is switched on by passing DC current in the forward direction to fill its intrinsic region with current carriers. PIN diodes are extremely fast switches. Their lifetime is virtually unlimited as long as the allowable PIV is not exceeded.

The typical reverse breakdown voltage rating for a PIN diode is around 1000V. A legal-limit amateur radio amplifier produces an output voltage of about 800 volts peak-to-peak [p-p] into a 50 ohm load--so a 1000PIV PIN diode is more than adequate. When the load Z is higher, due to a somewhat less than wonderful SWR, the switching device may be exposed to more than 1000Vp-p. This poses no problem for a typical high-speed vacuum-relay. Even if a vacuum-relay's breakdown voltage is temporarily exceeded, there is little likelihood that permanent damage to the vacuum-relay's contacts will result. However, solid-state devices are not so forgiving. A single voltage-transient can destroy a PIN diode.

For 100 WPM computer-CW, the PIN diode is clearly the only choice. For 30 WPM CW, AMTOR and high-speed VOX, a vacuum-relay has advantages.

Solid-state Component Ratings

Different types of solid-state components are rated somewhat differently. Some ratings are realistic. Some ratings are not realistic. The maximum ratings of large transistors and large Zener diodes can not be realized unless drastic, extreme measures are used to keep the case temperature below the maximum allowable 25 degrees C at full ratings. In the real world, operation at 30% of a published dissipation or current rating is usually safe. Additionally, bipolar power transistors suffer from a generic weakness called secondary-breakdown phenomenon. For example, a "1500V, 8A, 150W" power transistor may only be able to safely dissipate 15W at moderate collector-to-emitter voltages. T-MOS power FETs are much more resistant to secondary-breakdown.

Wire-lead rectifier current ratings are fairly realistic when they are mounted on perfboard and cooling air is allowed to circulate freely around individual rectifiers.

Measuring PIV

There is some variation in the inverse breakdown voltage of solid-state rectifiers of the same type. Measuring the breakdown voltage of each rectifier diode is a good precaution. When a diode's reverse current reaches 1 to 2 uA, the voltage across the diode is the breakdown voltage. Exceeding this voltage is likely to be fatal. As operating temperature increases, breakdown voltage decreases.

Breakdown Voltage Testers

A breakdown voltage tester (a.k.a. high-pot) could be described as a variable HV Ohmmeter that does not read directly in ohms. It is a useful tool. Breakdown testers are essential for testing vacuum relays, vacuum capacitors, blocking capacitors, air-variable capacitors, rectifiers, and for finding problems with insulation. Building or troubleshooting a tube-type RF amplifier without a breakdown tester is like crossing an ocean without a navigation instrument. For most amateur radio applications, the highest voltage component rating commonly encountered [with vacuum-capacitors and vacuum-relays] is 15kVDC/9kV RF peak, so a 0 to 15kV breakdown tester should suffice.

Although commercial breakdown testers are available, they are not inexpensive. A suitable breakdown tester can easily be constructed from mostly-surplus parts. The main parts are a 50/60Hz low-current HV transformer, a >1A, 120V variable transformer, a 120V incandescent bulb, some diodes, resistors, a sensitive uA meter and two HV filter capacitors.

Commercial, low-current HV DC supplies may also be used provided that they are connected to a Variac in series with a 120V incandescent light bulb to limit current. The bulb limits the short-circuit current to a safe value--obviating the need for a fuse. The wattage of the bulb is roughly proportional to the wattage of the supply. The rated [I=P/E] bulb current should be similar to the appropriate fuse rating for the HV supply primary. A multi megohm resistor is used to limit the current flow into the device under test. The uA meter should be protected with back to back 1A diodes. A circuit is provided.

Step-Start

Most power supplies benefit from something to soften the shock of start-up. A 10A DPST-NO or 10A DPDT relay and two approx..25 ohm 10W resistors are just about all that's needed to add a step-start circuit to the average 1500W amplifier. The step-start circuit goes in series with the mains fuses or circuit breakers. With this arrangement the filaments, the HV supply and the LV supplies enjoy the benefit of a kinder and gentler start-up.

VHF Stability

Every HF amplifier has at least two resonant circuits in its output circuitry. The more obvious one is the HF-resonant tank circuit. A less obvious one is the VHF-resonant circuit that is principally formed by the anode capacitance and the inductance of the conductors between the tank circuit and the anode. In 1500W amplifiers, anode resonance typically occurs around 100MHz--well within manufacturers' ratings for "Amplifier and Oscillator Service" for the tubes that are commonly used in such amplifiers.

The equivalent resistance of a high Q parallel resonant circuit is virtually infinite. A low Q parallel resonant circuit has a relatively low equivalent resistance.

The voltage gain of an amplifier tube is roughly proportional to the load resistance. High load resistance produces more gain. Low load resistance produces less gain.

If the conductors in the anode resonant circuit have a high VHF Q, the equivalent load resistance presented to the anode will be high and the tube will exhibit increased voltage gain at the VHF resonance. If the conductors in the anode resonant circuit have a low VHF Q, the load resistance presented to the anode will be low and the voltage gain at the VHF anode resonant frequency will be reduced. Of course, if no VHF energy were present, it would make no difference how much VHF gain an HF amplifier had.

When a transient current passes through a resonant circuit, the resonant circuit rings like a bell--producing a damped sine wave signal. This is how ancient spark transmitters produce RF--and the larger ones produced many kilowatts of it.

Whenever the anode-current in an HF amplifier changes, a small VHF damped sine wave signal is produced in the anode's VHF resonant circuit. This signal can be observed with a VHF oscilloscope or a spectrum analyzer. The amplitude of the RF voltage produced is proportional to the Q of the anode resonant circuit. If none of this damped wave signal were fed back to the input, there would be no problem.

In a grounded-grid amplifier, the grid appears to shield the input from the output. In a grid-driven Class AB1 amplifier, The RF-grounded screen appears to shield the input from the output. However, no grid and no screen is perfect--so some of the damped wave VHF signal at the anode is capacitively fed back to the input--and amplified.

Although it's unlikely, if the phase and amplitude of the damped wave signal happens to be just right, oscillation at the anode's VHF resonance can occur. If the VHF energy that is produced could find its way to a load, no danger would be posed by a VHF oscillation. However, the HF tank circuit is a low pass filter that effectively blocks VHF energy. Thus, the oscillator is unloaded and the resulting grid-current is very high. The unloaded condition can cause VHF voltage transients in the anode circuit. These transients may cause tune-capacitor arcing and band switch arcing across open contacts. Since they are closest to the anode resonant circuit, open tune-capacitor padder contacts, as well as open 10m contacts are most vulnerable to parasitic-instigated arcing. Band switch contacts can be melted and/or vapourized by such occurrences.

Parasitic Suppression

On page 72, the 1926 Edition of ***The Radio Amateur's Handbook*** tells us how to build an improved VHF parasitic suppressor The logic was elementary. A suppressor is supposed to dampen the anode circuit. Since low Q is synonymous with high dampening, why not decrease Q by using resistance-wire? Quoting from page 72:........ *"The combination of both resistance and inductance is very effective in limiting parasitic oscillations to a negligible value of current."*

After 1929, someone forgot to include this information in the Handbook. In those days, the oversight probably didn't matter very much. Large amplifier tubes generally had low VHF amplification, so VHF instability was not a major issue. During the ensuing decades, people got into the habit of using parasitic suppressors made from copper or silver-plated copper. This was an easy habit to get into since copper and silver can be soldered more easily and cheaply than nickel/chromium [nichrome] resistance wire. Meanwhile, the performance of amplifier tubes kept improving. Because of these improvements, modern high-amplification tubes appear to benefit more from 1926-vintage low VHF-Q parasitic suppressors than 1926-vintage tubes. NOTE: In 1926, a 'high-mu' triode had a mu of around 40.

Anti-parasitic Techniques

Low VHF-Q conductor material can be used to increase VHF loading in the anode resonant circuit. Nickel-chromium-iron alloys are best, Nickel-chromium (nichrome) and some types of stainless-steel are almost as good. The use of copper, aluminum, and silver should be kept to a minimum. However, good conductors are desirable beyond the tune capacitor, which marks the end of the anode VHF resonant circuit and the beginning of the HF tank circuit.

Output Z: The output impedance of most tubes is a matter of kilo-ohms--not ohms. There is no scientific reason to use "heavy duty" conductors between the anode and the tune capacitor. If good VHF stability is a design goal, it's best to use conductors that are no larger than is necessary to carry the highest current present, i.e., the 10m RF circulating current between the anode (output) capacitance and the tune capacitor. Round conductors have a lower VHF Q than flat conductors. To increase current handling ability, or to reduce inductance, two paralleled round conductors, separated by a wide air-gap, are better than a flat conductor of the same overall width.

- When designing the layout for an HF amplifier, locate the tune capacitor fairly close to the anode. This reduces the inductance in the anode resonant circuit--increasing the VHF resonant frequency. If the distance from the anode to the tune capacitor is grossly excessive, the 3/4 wave anode resonance may cause instability problems--especially with tubes that are UHF-rated like the 8877, 8874, and 3CX800A7.
- In order to prevent a conductor from sharing the anode VHF-resonant circuit with the HF tank circuit, connect the tank inductor directly to the tune capacitor. It is best not to connect the tank inductor directly to the blocking capacitor.
- The output enclosure in an HF amplifier is a high Q VHF-resonant cavity. The output enclosure can become a player in parasitic oscillations. Cavity dampening may be needed. This is a